15th International Conference on X-Ray Lasers 2016

Conference Program and Book of Abstracts

May 22nd - 27th, 2016

Nara Kasugano International Forum, Iraka

15th International Conference on X-Ray Lasers 2016

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Sergei Bulanov (National Institute for Quantum and Radiological Science and Technology)
Hiroyuki Daido (Japan Atomic Energy Agency)
Yoshiaki Kato (The Graduate School for the Creation of New Photonics Industries)

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Supporting Institutions

Kansai Photon Science Institute (KPSI), National Institutes for
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Japan Atomic Energy Agency (JAEA)
The Graduate School for the Creation of New Photonics Industries (GPI)
The Laser Society of Japan (LSJ)
The Japan Society of Plasma Science and Nuclear Fusion Research (JSPF)
The Physical Society of Japan (JPS)
The Ministry of Education, Culture Sports, Science and Technology Japan (MEXT)

General Information

Conference Place

The conference is held at the Nara Kasugano International Forum, in Nara park. It is approximately 2 km east from JR Nara station. To come to the conference place from the hotels, which are located in the central area of Nara city, take a bus, route no.2 ”Nara city loop, clockwise” from the bus stop no.2 at the east exit of JR Nara station, or from the bus stop no. 1 at Kintetsu Nara stations, and get off at ”Todaiji daibutsuden Kasuga taisha-mae”. The conference place is 3 minutes walk east toward hills in the lawn from the bus stop. You can also take another less frequent bus route no.7 ”Kasugataisha-honden” from the same bus stop at the JR and Kintetsu Nara station, and get off at ”Nara Kasugano International Forum Iraka mae”. It is approximately 30 minutes walk from the the JR Nara station along Omiya-dori street (see map).

Scientific Sessions

Oral sessions will be held in the Noh Theater. A poster session will be held in the room 3 at the 2nd floor. The poster room will be open from Tuesday afternoon through Thursday morning. The poster board is 120 cm wide and 180 cm tall.

Exhibition

The industry exhibition from sponsor companies is held at the lobby from Monday to Friday, outside the Noh theater and close to the drink corner.

Lunch

A box lunch will be provided in the room 1, Monday, Tuesday and Thursday. If you have special preferences on the meal, please check a mark at the registration web site, that is also for the conference dinner.

Welcome reception and conference dinner

We will have the welcome reception at the garden of the Nara Kasugano International Forum, Sunday evening from 6 PM. We will have the conference dinner Thursday evening from 7 PM at ”Half Time”, the restaurant of the Nara National Museum, which is 5 minutes walk toward the Nara stations from the conference place.

Excursion

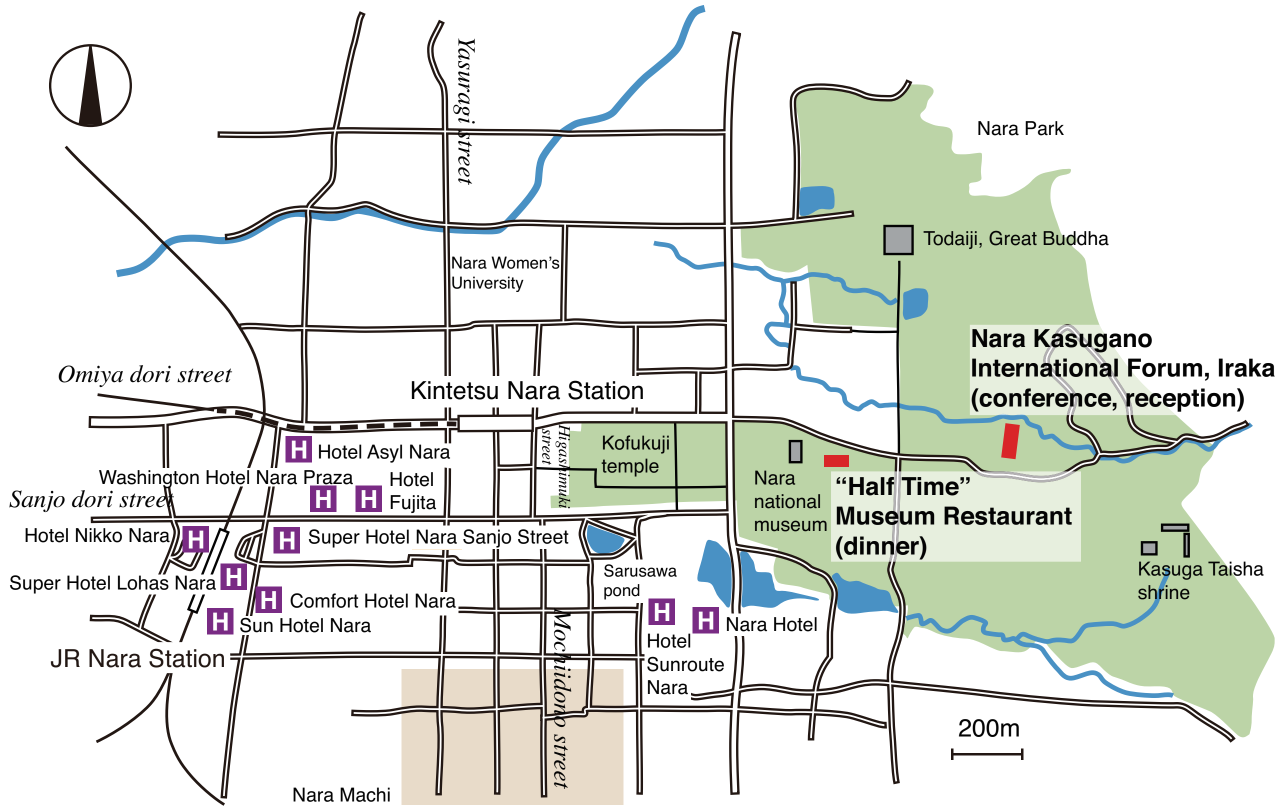
On Wednesday afternoon, we will have an excursion. We will take a bus from the conference place to get to Hozugawa, west of the Kyoto city, where we will have two hours long river boat ride. We will land at Arashiyama and after another hour for visiting nearby sightseeing spots and shops, we will return to the conference hotels. A box lunch will be provided on the bus. The fee for the excursion is included in the registration. As we need to decide number of boats, each of which has a limited capacity, participants who wish to join the excursion please check a mark at the registration web site.

Laboratory tour

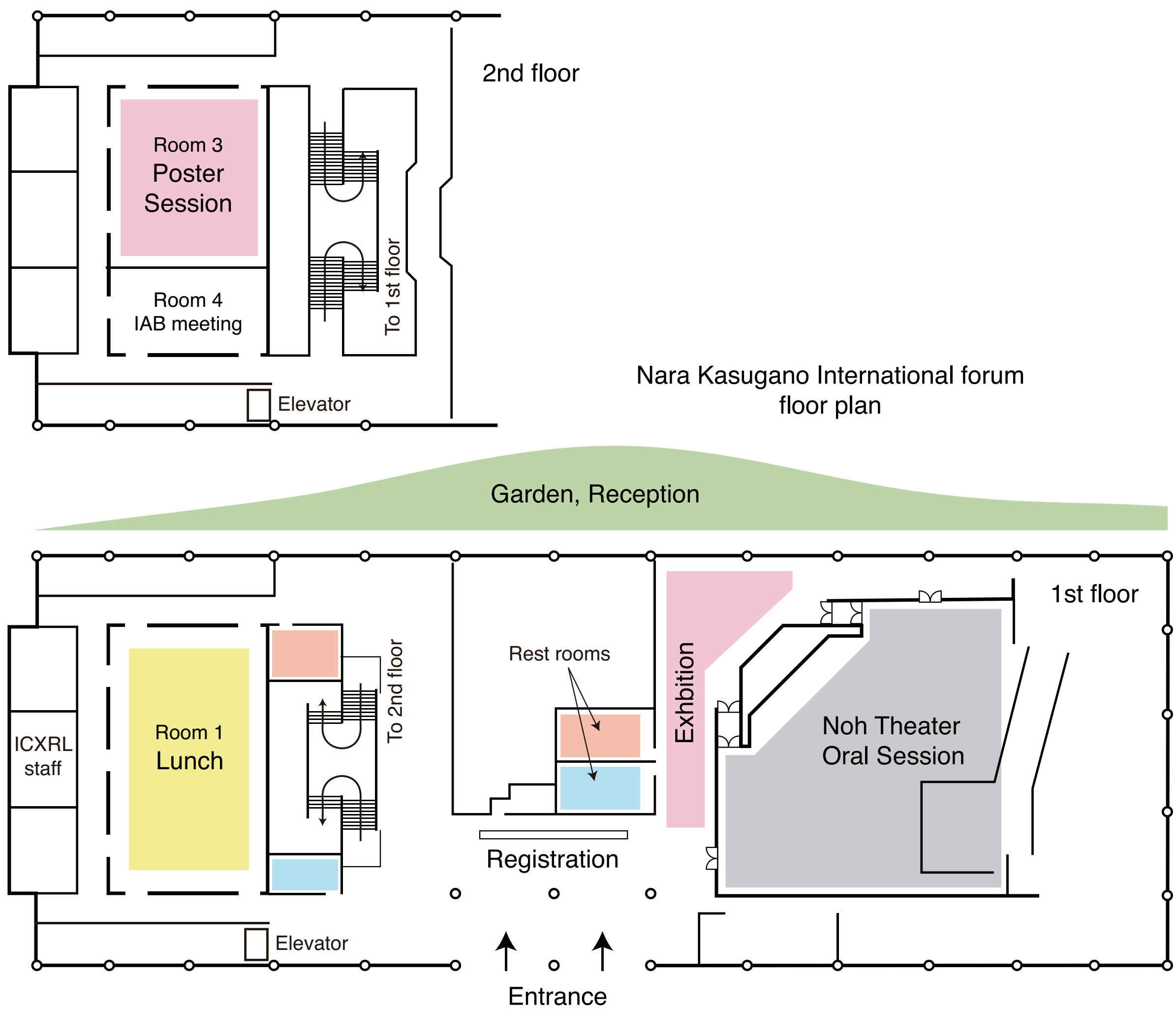
On Friday afternoon, we are planning to have a laboratory tour to the laser facility of Kansai Photon Science Institute (KPSI), National Institutes for Quantum and Radiological Science and Technology (QST). Transportation and lunch at the laboratory cafeteria will be provided. To join the tour, please sign up at the registration desk by Thursday morning.

Proceedings

We are planning to publish the conference proceedings from Springer. Length of the manuscript will be 7 pages for invited contributors and 4 pages for other contributors. Manuscripts should be prepared according to the format provided by Springer, and should be sent to the conference organizer by e-mail. The form for copyright transfer should be sent with the manuscript. The papers from author(s) of the oral and poster presentation, who attended and presented their paper, will be accepted. The manuscripts will be peer-reviewed by the local organizing committee (LOC), and the author(s) may be requested to make revisions before publication. The deadline of submission will be 2 months after the conference, end of Jul. 2016.



Yasuragi street
Nara Park
Todaiji, Great Buddha
Nara Women's University
Nara Kasugano International Forum, Iraka (conference, reception)
Omiya dori street
Kintetsu Nara Station
Hotel Asyl Nara
Higashimuki street
Kofukuji temple
Washington Hotel Nara Praza
Hotel Fujita
Sanjo dori street
Nara national museum
"Half Time" Museum Restaurant (dinner)
Hotel Nikko Nara
Super Hotel Nara Sanjo Street
Sarusawa pond
Kasuga Taisha shrine
Super Hotel Lohas Nara
Comfort Hotel Nara
Sun Hotel Nara
Nara Hotel
Hotel Sunroute Nara
Mochiidono street
JR Nara Station
200m
Nara Machi



2nd floor
Room 3
Poster Session
Room 4
IAB meeting
To 1st floor
Elevator
Nara Kasugano International forum floor plan
Garden, Reception
1st floor
Rest rooms
Exhbition
ICXRL staff
Room 1
Lunch
To 2nd floor
Noh Theater
Oral Session
Registration
Elevator
Entrance

CONFERENCE PROGRAM

Sunday, May 22nd

18:00-20:00	Registration, Reception at the garden of Nara Kasugano International Forum, Iraka

Monday, May 23rd

08:30-09:25	Registration

Opening Session, Chair: T. Kawachi

09:25-09:45	Opening addresses: Y. Tajima (QST, Japan), W. Utsumi (QST, Japan), Y. Kato (GPI, Japan)

Session 1: Prospect of coherent x-ray source-1, Session Chair: S. Bulanov

09:45-10:10	I-1	Fs-Laser driven secondary sources of x-rays and particles within ELI Beamlines G. Korn (ELI-BL, Czech Republic)
10:10-10:35	I-2	SACLA: Present and Future T. Ishikawa (RIKEN, Japan)
10:35-11:00	I-3	Towards laser plasma accelerators for future light sources and colliders W. Leemans (LBNL, USA)
11:00-11:15		Coffee break

Session 2: Prospect of coherent x-ray source-2, Session Chair: K. Kondo

11:15-11:40	I-4	Recent progress on attosecond science at RIKEN K. Midorikawa (RIKEN, Japan)
11:40-12:05	I-5	High average power table-top soft x-ray lasers using diode-pumped laseer drivers J. Rocca (CSU, USA)
12:05-12:30	I-6	Manipulating Electrons with Intense Laser Pulses V. Malka (LOA, France)
12:30-13:50		Lunch break

Session 3: Laser-driven X-ray Laser-1, Session Chair: J. Rocca

13:50-14:15	I-7	Investigation of ultrashort, partially coherent XUV lasers operated in the ASE mode A. Klisnick (U. Paris-Sud, France)
14:15-14:40	I-8	Progress on optical-field soft x-ray lasers at LOA S. Sebban (LOA, France)
14:40-15:05	I-9	Overview of laser-driven short-wavelength sources at PALS and ELI Beamlines J. Nejdl (ELI-BL, Czech Republic)
15:05-15:30	I-10	Implementing plasma XUV-lasing for table-top nano-science D. Bleiner (EMPA, Swiss)
15:30-15:55		Coffee break and Conference photograph

Session 4: X-ray imaging-1, Session Chair: A. Vinogradov

15:55-16:20	I-11	Soft X-ray Ablation Mass Spectrometry for Chemical Composition Imaging in Three Dimensions at the Nanoscale C. Menoni (CSU, USA)
16:20-16:45	I-12	X-ray phase imaging based on grating interferometry A. Momose (Tohoku-U. Japan)
16:45-17:10	I-13	Coherent Diffraction Imaging with Table-top XUV Sources M. Zuerch (U. of Berkley, USA)
17:10-17:35	I-14	High-resolution coherent X-ray diffraction imaging at SPring-8 and SACLA Y. Takahashi (Osaka-U. Japan)
17:35-18:00	I-15	X-ray reflection imaging of inclined and obliquely illuminated objects N. Popov (Lebedev Inst., Russia)
18:00-18:20	O-1	Femtosecond laser ablation: simulations and X-ray imaging N. Inogamov (Landau Inst., Russia)

Tuesday, May 24th

Session 5: Laser plasma physics and intense x-ray, Session Chair: G. Tallent

09:00-09:25	I-16	Quantitative X-ray Spectroscopy for Energy Trnasport Study in Fast Ignition Plasma Generated with LFEX PW Laser H. Nishimura (ILE Osaka-U. Japan)
09:25-09:50	I-17	Dynamic X-ray Thomson scattering from high-energy-density plasmas using an ultra-bright X-ray laser L. Fletcher (SLAC, USA)

09:50-10:15	I-18	Ultraintense X-ray radiation generated by Relativistic Laser Plasma in the Radiation-Dominated Kinetic Regime and its using for exotic dense matter states pumping A. Faenov (Osaka U. Japan)
10:15-10:35	O-2	Observation and Investigation of Intensive Directional Quasi-coherent X-Ray Radiation Generated at Interaction of Cavitating Liquid Jet with a Target V. Vysotskii (KNSU, Ukraine)
10:35-10:50		Coffee break

Session 6: Ultrafast coherent x-ray source and application, Session Chair: A. Klisnick

10:50-11:15	I-19	Probing ultrafast demagnetization with soft X-ray B. Vodungbo (LCPMR, France)
11:15-11:40	I-20	For Generation of Tera-watt Attosecond X-ray Laser Pulses D.-E. Kim (POSTECH/CASTECH, Korea)
11:40-12:00	O-3	Plasma Mirror Frequency-Resolved Optical Gating in Vacuum Ultraviolet Wavelength Region R. Itakura (QST, Japan)
12:00-12:20	O-4	Laser Compton Scattering Gamma-Ray Beam Source for Nuclear Physics and Material Research S. Miyamoto (Hyogo U. Japan)
12:20-13:45		Lunch break (International advisory board meeting)

Session 7: High order harmonic generation, Session Chair: S. Sebban

13:45-14:10	I-21	Investigations on Ultrafast Atomic and Molecular Dynamics with Harmonic Sources. C.-H. Nam (GIST/IBS, Korea)
14:10-14:35	I-22	High-order Harmonic Generation by Relativistic Plasma Singularities A. Pirozhkov (QST, Japan)
14:35-15:00	I-23	Characterization of Partially Coherent Ultrafast XUV Pulses C. Bourassin-Bouchet (U. Paris-Sud, France)
15:00-15:25	I-24	Inner Shell Excitation During High Harmonic Generation: The Giant Resonance in Xenon D. Villeneuve (NRC, Canada)
15:25-15:50	O-5	Wave-Mixing and Amplification in Extreme Ultraviolet Region L. Dao (Swinburne Uni., Australia)
15:50-16:05		Coffee break

Session 8: X-FEL and synchrotron radiation, Session Chair: T. Ishikawa

16:05-16:30	I-25	Using the X-FEL to drive gain in K-shell and L-shell systems using photo-ionization and photo-excitation of inner-shell transitions J. Nilsen (LLNL, USA)
16:30-16:55	I-26	Hard x-ray laser photonics H. Yoneda (ILS, Japan)
16:55-17:20	I-27	Amplification of X-ray Free Electron Laser using Core-hole Atoms Generated with Intense Optical Laser Pulse Y. Inubushi (JASRI, Japan)
17:20-17:40	O-6	Multiple-wavelength superfluorescence/superradiance in helium following free-electron-laser excitation J. Harries (QST, Japan)
17:40-18:00	O-7	A design of non-harmonic soft x-ray beam line at BSRF L. Wei (CAEP, China)

Poster Session (with light meal and refreshments), Session Chair: M. Nishkino (18:00-20:00)

Wednesday, May 25th

Session 9: Novel x-ray source and the applications, Session Chair: J. Nilsen

09:00-09:25	I-28	Single Cycle and Exawatt X-ray Pulse G. Mourou (Ecole Polytechnique, France)
09:25-09:50	I-29	Next Generation Laser-Compton Sources for Nuclear Photonics and Medicine C. Barty (LLNL, USA)
09:50-10:15	I-30	Research on Laser Acceleration and Coherent X-ray Generation using J-KAREN-P laser M. Kando (QST, Japan)
10:15-10:30		Coffee break

Session 10: Novel x-ray source and applications using LWFA electron beams-1, Session Chair: W, Leemans

10:30-10:55	I-31	Resonantly Excited Betatron X-rays/gamma-rays in a Laser Plasma Accelerator L. Chen (IOP, China)

10:55-11:15	O-8	Relativistic electron dynamics in high intensity optical lattice. Towards a table-top Raman XFEL M. Hadj-Bachir (CELIA, France)
11:15-11:35	O-9	Enhanced coherent Thomson scattering in the few-cycle regime K. Hu (IFTS, China)
11:35-11:55	O-10	Multilayer Mirror Objective for Focusing Isolated Attosecond Pulse in 40 nm Wavelength Region M. Toyoda (Tohoku-U. Japan)
12:20-19:20		Excursion, Kyoto, Hozugawa river boat ride

Thursday, May 26th

Session 11: Laser-driven x-ray lasers-2, Session Chair: C.-H. Nam

09:00-09:25	I-32	The creation of radiation dominated plasmas using laboratory x-ray lasers G. Tallents (York U. UK)
09:25-09:50	I-33	Laser driven plasma based incoherent X-ray sources at PALS M. Kozlova (ELI-BL, Czech Republic)
09:50-10:10	O-11	Progress and Prospects of X-ray Laser Research in QST M. Nishikino (QST, Japan)
10:10-10:30	O-12	Hydrodynamic and Maxwell-Bloch modelling of plasma-based soft X-ray amplifiers E. Oliva (Universidad Politecnica de Madrid, Spain)
10:30-10:45		Coffee break

Session 12: EUV light source and EUV lithography, Session Chair: A. Sasaki

10:45-11:10	I-34	Performance of over 100W HVM LPP-EUV light source S. Okazaki (Gigaphoton Inc., Japan)
11:10-11:35	I-35	EUV free-electron laser requirements for semiconductor manufacturing E. Hosler (GLOBALFOUNDRIES, USA)
11:35-12:00	I-36	Coherent Lithography with Table Top Soft X-ray Lasers: Latest Achievements and Prospects M. Marconi (CSU, USA)
12:00-13:20		Lunch break

Session 13: Capillary discharge plasma x-ray lasers, Session Chair: H.-T. Kim

13:20-13:45	I-37	Plasma Dynamics in Capillary Discharges P. Sasorov (Keldysh Inst., Russia)
13:45-14:10	I-38	Capillary Discharge - a Way for Recombination XUV Laser? A. Jancarek (TU, Czech Republic)
14:10-14:30	O-13	Interaction of capillary discharged soft-x-ray laser at 46.9nm with BaF_2 H. Cui (Harbin Inst. Tech.)
14:30-14:50	O-14	Towards generation of sub-fs pulses using lasing to ground states of H-like LiIII at 13.5nm and He-like CV at 4nm V. Antonov (A&M Uni, USA)
14:50-15:05		Coffee break

Session 14a: X-ray imaging-2, Session Chair: M. Kozlova

15:05-15:30	I-39	Nanoscale Imaging using a Compact Laser Plasma Source of Soft X-rays and Extreme Ultraviolet (EUV) H. Fiedorowicz (WAT, Poland)
15:30-15:50	O-15	X-ray characterization of a high performance hydrogen storage alloy with laser surface modification H. Daido (JAEA, Japan)
15:50-16:15	I-40	Spectrally resolved lensless imaging with ultra-broadband high-harmonic sources S. Witte (ARCNL, Netherlands)

Session 14b: X-ray imaging-3, Session Chair: A. Momose

16:15-16:40	I-41	Prospects of tomographic nanoscale imaging using high repetition rate laboratory based soft X-ray sources H. Stiel (MBI, Germany)
16:40-17:00	O-16	Broadband high-resolution imaging spectrometers for the soft X-ray range E. Ragozin (Lebedev Inst., Russia)
17:00-17:20	O-17	In situ characterization of XFEL beam intensity distribution and focusability by high resolution LiF crystal X-ray detector T. Pikuz (Osaka-U. Japan)
17:20-17:40	O-18	ERL-based Laser-Compton Scattering X-ray source for X-ray Imaging A. Kosuge (KEK, Japan)
19:00		Conference Dinner at Half Time, Meseum Restaurant

Friday, May 27th

Session 15: Novel x-ray source and applications using LWFA electron beams-2, Session Chair: L. Chen

09:00-09:25	I-42	Narrow bandwidth Thomson photon source using laser-plasma accelerators E. Esarey (LBNL, USA)
09:25-09:50	I-43	Short-pulse x-ray beams driven by intense laser pulses and their applications H.-T. Kim (GIST/IBS, Korea)
09:50-10:15	I-44	Ultrahigh Brilliance X-and Gamma-rays Generation Based on Laser Wakefield Accelerators at SIOM J. Liu (SIOM, China)
10:15-10:30		Coffee break

Session 16: Novel x-ray source and applications using LWFA electron beams-3, Session Chair: H. Daido

10:30-10:50	O-19	Laser-plasma accelerator driven soft-x-ray free-electron laser using beam phase-space manipulation C. Schroeder (LBNL, USA)
10:50-11:10	O-20	Tunable polarization plasma channel undulator for narrow-bandwidth photon emission S. Rykovanov (Helmholtz U., Jena, Germany)
11:10-11:30	O-21	Achieving Laser Wakefield Accelerated Electron Beams of Low Enough Energy Spread for an X-FEL J. Koga (QST, Japan)

Closing ICXRL-2016 S. Bulanov and T. Kawachi (QST, Japan) (11:30-12:00)

12:00-15:30	Laboratory Tour to KPSI, QST laser facility (Kizugawa-city, Kyoto)

Monday, May 23rd

Institute of Physics ASCR, v. v. i.
Na Slovance 2
182 21 Prague 8
info@eli-beams.eu
www.eli-beams.eu

Fs-Laser driven secondary sources of x-rays and particles within ELI-Beamlines

Author: Georg Korn

ELI-beamlines, Prague, Institute of Physics, Academy of Sciences Czech Republic, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic

We will be giving an overview on the development of the "ELI-beamline facility" built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.
The ELI project is constructing specialized branches (pillars) in several countries. ELI-Beamlines in the Czech Republic, which is a subject of this project, along with ELI-ALPS, the Attoseccond Laboratory (Szeged, Hungary) and ELI-NP, the Photonuclear Laboratory (Magurele, Romania). The Ultra High Field Science Laboratory as the fourth pillar (host country not yet determined) will be built later on. Individual pillars will be constructed and operated independently. After launching the individual pillars, it is proposed that the multi-sited infrastructure ELI will be managed and operated within central governance framework according to the model of ERIC (European Research Infrastructure Consortium). It is expected that the ELI-ERIC Consortium shall be established in 2018.

ELI-Beamlines will be the high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international facility for both academic and applied research, slated to provide first user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser system will be delivering pulses with length ranging between 15 and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining 1024 Wcm-2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser.
In this talk we will concentrate on the development of short wavelength (20 eV-100 keV) short pulse high intensity laser driven sources and their practical implementation in the ELI-beamline user facility. The sources are either based on direct interaction of

Fyzikální ústav
Akademie věd ČR, v. v. i.
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the laser beam with a gaseous or solid target (High order harmonics and x-ray lasers) or will first accelerate electrons which then will interact with laser produced wigglers (Betatron radiation) or directly injected into undulators (laser driven LUX or later X-FEL). The direct interaction (collision) of laser accelerated electrons with the laser again will lead to short pulse high energy radiation via Compton or Thomson scattering. The main planned short pulse laser driven x-ray sources and their parameters will be presented, together with the date of commissioning.
We will also touch the development and implementation of high energy laser driven electron (>1GeV) and proton (> 100 MeV) sources which are built as user beamlines for different applications like for instance in medical diagnostics or therapy.

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I-2

SACLA: Present and Future

Tetsuya Ishikawa

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Abstracts: *Present status of SACLA is introduced, with some retrospect and some foresight. SPring-8 site is heading to the future pulsed XFEL source as well as the future CW XFEL source.*

SACLA is the world's first compact X-ray free-electron laser using in-vacuum undulators and high-gradient C-band linac [1]. At the moment, SACLA is one of the only two operating hard X-ray free-electron lasers in the world next to the LCLS at SLAC in the US which is not compact. The R&D program toward a compact hard XFEL started in 2001 at the RIKEN Harima Institute, completed construction of prototype machine in 2005. Successful proof-of-principle operation of the SPring-8 Compact SASE Source concept leads to the launch of larger scale XFEL construction project, now known as SACLA, in 2006. The hardware construction was completed in 2011, and the first lasing at 10 keV was observed after three month commissioning. After a few months, the highest lasing energy reached 20 keV.

SACLA is designed to eventually have five FEL beamlines, as well as an electron beam transport to SPring-8 for the full-energy injection. User operation started in 2012 with two photon beamlines, one of which is an XFEL beamline and the other a lower-energy, short-pulse spontaneous beamline. SACLA's XFEL beam meets with SPring-8 SR beam in a newly constructed building where we can simultaneously irradiate a sample with both SACLA XFEL and SPring-8 SR. In collaboration with Osaka University, a suite of high-power lasers have been introduced in this building in order to expand the high-energy-density sciences.

The XFEL beamline was at first equipped with total 18 undulator units, each 5-m ling. One unit near the center was moved to the most downstream to make room for the self-seeding optics with a small electron-beam chicane. The test operation for self-seeding is continuing but not yet released for the user operation. The small chicane has been applied to make two-color, two-pulse operation with variable pulse separation time [2]. This two-color operation was used to demonstrate K-shell atomic laser with Cu [3] by tuning the first pulse just above the Cu K absorption edge and the second pulse to Cu Kα radiation.

In 2014 was completed the second XFEL beamline which enables us to make simultaneous operation of two XFEL lines even with different electron beam energies. The old prototype machine was relocated to the SACLA undulator hall and revitalized as a soft XFEL. A new initiative of smaller XFEL with laser plasma acceleration started. Another initiative is seeking the way to convert a 1 GeV storage ring to a CW EUV-FEL generating 13.5 nm. This would lead to the further step of converting SPring-8 to a CW XFEL machine.

[1] T. Ishikawa et al., Nature Photon. **6**, 540-544 (2012).

[2] T. Hara et al., Phys. Rev. ST-AB 16, 080701-1-5 (2013).

[3] H. Yoneda et al., Nature 524, 446-449 (2015).

Towards laser plasma accelerators for future light sources and colliders

Wim Leemans for the BELLA Center Team
BELLA Center, Accelerator Technology and Applied Physics Division

Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, USA
and University of California Berkeley, Berkeley, CA 94720, USA

Electron acceleration of electrons using intense laser pulses that excite tens of gigavolt per meter fields in plasmas will be discussed and the path forward to practical machines. The potential impact of compact laser plasma accelerators (LPA) ranges from providing the capability of producing high energy, ultra-short electron bunches and associated radiation pulses for forefront science in a small laboratory setting, to medical and security applications, to the development of high energy particle colliders for fundamental science into the origin of matter and energy.

Progress on addressing key challenges for the development of high energy electron accelerators with beam quality sufficiently good to drive free electron lasers and gamma ray sources, or serve as building blocks for a future laser plasma accelerator based colliders will be presented. This includes experiments that uses the high repetition rate (1Hz) Petawatt BELLA laser aimed at reaching 10 GeV in less than a meter long accelerator, staging two laser plasma accelerator modules and progress towards an extreme ultra-violet FEL and a gamma ray source.

I-4

Recent progress on attosecond science at RIKEN

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Abstracts: *We have been developing two types of intense attosecond beam lines for investigating attosecond wavepackt dynamics in atoms and molecules. One produces an attosecond pulse train for attosecond Fourier transform spectroscopy by attosecond-pump/ attosecond-probe scheme, while the other produces an intense isolated attosecond pulse for attosecond nonlinear optics.*

Firstly, a high-power attosecond pulse train (ATP) beamline has been upgraded by introducing 100 Hz 12 fs 50 mJ Ti:sapphire laser as a pump source and a velocity map imaging spectrometer. Using this beamline, we have implemented attosecond Fourier transform spectroscopy with attosecond pulse trains for observing ultrafast quantum wavepacket dynamics in diatomic molecules [1, 2]. We use attosecond-pump/ attosecond-probe scheme to measure the electronic and vibrational response of diatomic molecules in the intrinsic timescale of electrons. Our attosecond light source, a-few-pulse attosecond pulse train with a moderate spectral bandwidth, is a unique device for measuring ultrafast quantum dynamics in a molecule because it allows us to achieve sufficiently high intensity for performing attosecond-pump/ attosecond-probe measurements with moderate statistics and a sufficiently high spectral resolution for identifying the relevant states.

Secondly, an intense isolated attosecond beam line [3] has also been improved. The main pump source of the beam line is a CEP-stabilized high energy Ti:sapphire laser [4] operating at 10 Hz, with multi-TW peak power and 25-fs duration. Our two-color waveform synthesizer for generating an isolated attosecond pulse consists of a Ti:sapphire laser pulse (44 mJ, 28 fs, 0.8 μm) and an infrared OPA pulse (6 mJ, 33fs, 1.35 μm), which is pumped with a part of the Ti:sapphire pump pulse. The relative delay jitter of both constituent pulses is precisely suppressed to 360 as rms by an active feedback, and directly monitored with out-of-loop by a balanced optical cross-correlator. The two-color pulse energy reaches 50 mJ, which is sufficient for generating an isolated attosecond pulse with micro-joule class energy.

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I-5

High Average Power Table-Top Soft X-Ray Lasers Using Diode-Pumped Laser Drivers

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Abstract: *We discuss advances in the development of high repetition rate, high average power, table-top soft x-ray lasers operating at sub-20 nm wavelengths. We report the first operation of a table-top soft x-ray lasers at repetition rates up to 400 Hz*

Soft x-ray lasers (SXRLs) produce the highest energy pulses of coherent ultrashort wavelength radiation. Their large number of photons per pulse allows us to perform single shot imaging of nano-scale objects, to develop material composition sensitive nanoprobes, and to conduct interferometric diagnostics of bright dense plasmas. However, until recently, with the exception of capillary discharge lasers at 46.9 nm, their average power was been limited by the low repetition rate of the high energy optical pump lasers required to drive them and by the relatively low pumping efficiency. We have developed a diode-pumped, picosecond Yb:YAG CPA laser driver that allowed us to demonstrate the first table-top SXRL capable of 100 Hz repetition rate gain saturate operation. These new pump lasers combined with efficient plasma heating techniques enable the operation of SXRLs at four orders of magnitude higher repetition rate than the first plasma-based collisional SXRLs (Fig. 1). Laser operation at 100 Hz repetition rate generated an average power 0.2 mW at 18.9 nm (Ni-like Mo) , and an average power of 0.1 mW at $\lambda = 13.9$ nm (Ni-like Ag) [1]. We will discuss results of an initial demonstration of a compact table-top soft x-ray laser at a repetition rates up to 400 Hz.

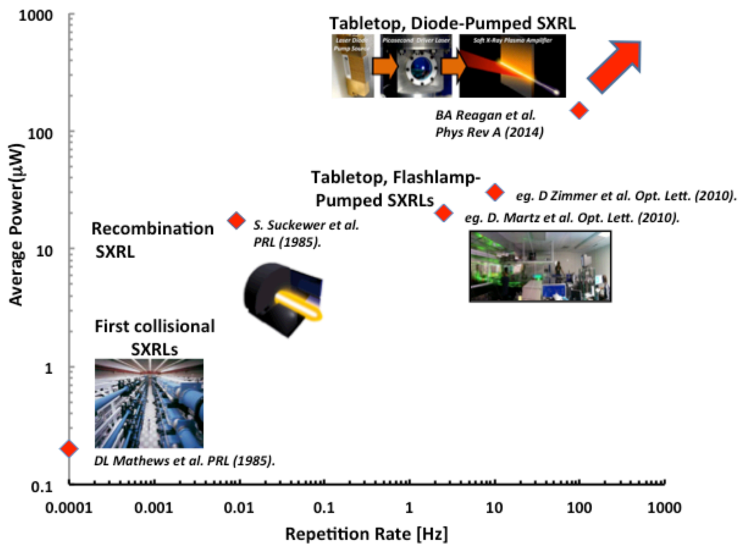

Fig. 1. Progress in the development of high repetition rate plasma-based soft x-ray lasers. plasma-based soft x-ray lasers have increased in average power and repetition rate by more than four orders of magnitude. Diode-pumped optical laser drivers now allow compact soft x-ray lasers to operate up to 400 Hz repetition rate (not shown in the plot]

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I-6

Manipulating Electrons with Intense Laser Pulses

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Laser Plasma Accelerators (LPA) rely on the control of the electronic motion with intense laser pulses [1]. The manipulation of electrons with intense laser pulses allows a fine mapping of the longitudinal and radial components of giant electric fields that can be therefore optimized for accelerating charged particle or for producing X rays.
To illustrate the beauty of laser plasma accelerators I will show different experimental results that we recently performed that allow to improve the quality of the electron beam, its stability [2] and its energy gain in longitudinal field [3], or the reduction of its divergence using radial field [4].
I'll then show how by controlling the quiver motion of relativistic electrons intense and bright X-rays beam are produced in a compact and elegant way [5,6]. Finally I'll show some examples of applications [7].

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I-7

Investigation of ultrashort, partially coherent XUV lasers operated in the ASE mode.

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XUV lasers pumped by collisional excitation of Ni-like and Ne-like ions can be generated in several types of hot and dense plasmas, produced by different pulse pumping techniques. These techniques involve either a high-power laser with short (0,5 ns to few ps) to ultrashort (~30 fs) duration, or a fast (few ns) electrical discharge. The duration of the pump pulse largely controls the timescale of the resulting population inversion, which in turns controls the duration of the output XUV laser pulse generated from amplification of spontaneous emission (ASE). As a result the duration of currently available ASE collisional XUV lasers typically range between 2 ps to 1 ns. On the other hand the coherence time of these pulses is related to the spectral width of the XUV laser line, which was shown to vary over a much smaller range from one system to the other (typically $\Delta\nu \sim 10^{11}$-10^{12} Hz [1]). This means that the different types of ASE XUV lasers with different pulse durations also have significantly different temporal coherence properties, with a number of longitudinal modes ranging from ~2 to more than 500.

Using numerical simulations based either on a partial coherence model [2], or on the Maxwell-Bloch code COLAX [3] we have recently investigated how the number of longitudinal modes can influence the behaviour of the field autocorrelation, when measured by scanning the pulse delay in an interferometer. The results of this study will be discussed and compared with measurements available from the literature. The short pulse case, with few longitudinal modes, is shown to exhibit specific features, which are also encountered in free-electron lasers operated in the self-amplified spontaneous emission (SASE) mode.

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I-8

Progress on Optical-Field Ionisation soft x-ray lasers at LOA

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We report here recent work on an optical-field ionized (OFI), high-order harmonic-seeded EUV laser. The amplifying medium is a plasma of nickel-like krypton [1] obtained by optical field ionization focusing a 1 J, 30 fs, circularly- polarized, infrared pulse into a krypton-filled gas cell or krypton gas jet. The lasing transition is the $3d^94p$ (J=0) −→ $3d^94p$ (J=1) transition of Ni-like krypton ions at 32.8 nm and is pumped by collisions with hot electrons.

The polarization of the HH-seeded EUV laser beam was studied using an analyzer composed of three grazing incidence EUV multilayer mirrors able to spin under vacuum [2]. For linear polarization, the Malus law has been recovered while in the case of a circularly-polarized seed, the EUV signal is insensitive to the rotation of the analyzer, bearing testimony to circularly polarized.

The gain dynamics was probed by seeding the amplifier with a high-order harmonic pulse at different delays [3]. The gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs FWHM as the amplification peak rose from 150 to 1,200 with an increase of the plasma density from 3×10^{18} cm^{-3} up to 1.2×10^{20} cm^{-3}. The integrated energy of the EUV laser pulse was also measured, and found to be around 2 μJ. It is to be noted that in the ASE mode, longer amplifiers were achieved (up to 3 cm), yielding EUV outputs up to 14 μJ.

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I-9

Overview of Laser-driven Short-wavelength Sources at PALS and ELI Beamlines

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Abstract: *We present recent activities at PALS research centre dedicated to development of short-wavelength radiation sources through various processes using 20 TW Ti:sapphire laser chain as well as kJ sub-ns iodine laser system and plans for the implementation of a high-order harmonic beamline employing 1 kHz 100 mJ 20 fs laser system at upcoming ELI Beamlines facility.*

There are two types of coherent XUV sources being developed at PALS research centre: high-order harmonic generation from various gaseous targets and collisionally pumped soft X-ray lasers. The study of conditions for improving conversion efficiency of high-order harmonic generation, such as Phase-Matching and Quasi-Phase-Matching in loose focusing geometry, will be presented. Overview of the local research dedicated to plasma-based soft X-ray lasers from solid targets driven either in a quasi-steady state regime using sub-nanosecond kJ laser system or transient regime with grazing incidence pumping driven by Ti:sapphire laser chain with pulse energy of 1 J and repetition rate of 10 Hz will be given.

Employing more powerful lasers, which should be soon available at ELI Beamlines facility near Prague, we suppose to scale-up the brightness of secondary sources of short-wavelength radiation by few orders of magnitude. Plans for the implementation of a high-order harmonic beamline driven by 1 kHz 100 mJ 20 fs laser system will be shown.

I-10

Implementing Plasma XUV-lasing for table-top nano-analytics

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Abstracts: *A comprehensive computational study of the main parameters involved in the generation of lasing across a plasma medium is presented. The latter served to optimize the design of a compact experimental demonstrator (Beagle^{Plus}), which is the platform for enabling proof-of-principle research on advanced analytical technologies for materials science and nano-technology.*

Laser action in the extreme ultraviolet and soft X-ray has been demonstrated using laser-produced and discharge-produced hot/dense plasmas as single-pass high-gain media. In the time of large *accelerator-based* X-ray lasers, fundamental and applied research on compact *plasma-driven* X-ray laser carries the promise of bridging the gap between the user and the tools. This demands contributions in (i) better quantitative understanding of the parameter effect on plasma-lasing, and generalization of the empirical models, (ii) assembling compact "table-top" demonstrators with the required robustness to address research and industry challenges, (iii) performing proof-of-principle experiments on “real world” advanced materials.

A comprehensive computational study was performed to understand the effect of pump pulse structure and characteristics on the plasma-lasing process. Laser-produced plasma optimum characteristics could be predicted by self-developed scaling laws, which help the design of an experimental setup of advanced capabilities.

Experiments were run using the newly installed *Beagle*$^{\text{Plus}}$ system at the Empa Laboratories. A 0.2ps Nd:glass oscillator feeds a chirped-pulse amplification stage to deliver Terawatt pulses on a target for TGRIP X-ray plasma lasing. The “*back-end system*”, i.e. compact and close to the application needs, uses also a self-developed pseudospark XUV source for imaging or spectroscopy. A parametric study is also presented.

Nano-analytics were indeed performed on certified reference materials as well as catalysts. Imaging was performed using a self-developed Schwarzschild microscope, with a back-end resolution well-below the resolution of commodity confocal microscopes and without the sample prep for super-resolution techniques. Proof-of-principle spectroscopy experiments using a home-built FT-Time-of-Flight Spectrometer as well as X-ray absorption and fluorescence measurements in the so-called HEROS (High-Energy Resolution Off-resonance Spectroscopy) configuration are discussed. The latter tests were validated at the Elettra beamline in Trieste, to be replicated on the *Beagle*$^{\text{Plus}}$.

I-11

Soft X-ray Ablation Mass Spectrometry for Chemical Composition Imaging in Three Dimensions at the Nanoscale

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Abstracts: *We demonstrate three dimensional (3-D) molecular composition imaging of inorganic and organic samples by soft x-ray laser ablation mass spectrometry. The method has a lateral resolution of 75 nm and a depth resolution of 20 nm. Results of imaging of a single micro-organism will be presented. This novel nanoscale resolution analytical chemical imaging method has potential applications in materials research, biology and medicine.*

Analytical probes capable of mapping molecular composition in 3-D at the nanoscale will transform materials research, biology and medicine. Mass-spectral imaging (MSI) is one of the most powerful methods to visualize the spatial organization of multiple molecular components on solid samples. However, it is challenging for MSI to map molecular composition in 3-D with submicron resolution. We have recently demonstrated a new MSI method that combines soft x-ray laser ablation with mass spectrometry to obtain 3-D composition images with nanoscale resolution.[1] In soft x-ray laser ablation MSI, bright laser pulses from a compact 46.9-nm-wavelength laser[2] are focused into nanometer size spots to ablate craters a few nanometers deep on selected regions of the sample. Elemental and molecular ions in the laser-created plasma are extracted and identified by their mass-to-charge ratio (m/z) using a time-of-flight mass spectrometer. Analysis of the spatially resolved mass spectra obtained as the sample is displaced with respect to the focused laser beam enables one to construct 3-D composition images with nanoscale resolution. In this talk I will describe recent advances of soft x-ray MSI that show the unique capabilities of the method to identify low concentration actinides in glass matrices, efficient ionization in dielectrics and that is capable to map molecular composition of single micro-organisms in 3-D at the nanoscale. These first results open up attractive opportunities to visualize composition in biological systems with unparalleled spatial resolution.

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I-12

X-ray Phase Imaging Based on Grating Interferometry

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Abstracts: *While X-ray phase imaging was studied at synchrotron radiation facilities since 1990s, X-ray grating interferometry has been attracting attention since early 2000s because X-ray phase imaging can be implemented with not only synchrotron radiation but also compact X-ray sources. Therefore, variety of configurations of grating interferometry are studied with the participation of industry for practical applications to medicine and non-destructive testing. Cutting-edge synchrotron-based X-ray phase imaging is also explored thanks to grating interferometry. In this presentation, our recent activities in this field are presented with the principle of grating-based X-ray phase imaging.*

Since the discovery of X-rays, X-ray transmission imaging relying on absorption contrast is widely utilized for various purposes. However, X-ray absorption contrast is not strong for the objects consisting of low-Z elements, X-ray transmission imaging is not effective for biological soft tissues and polymers. To overcome this problem, since 1990s X-ray phase imaging has been studied extensively. Various phase-contrast techniques were developed at synchrotron radiation facilities and excellent image quality beyond the common sense in conventional X-ray radiography was demonstrated. This is based on the fact that the interaction cross section of X-ray phase shift is about a thousand times larger than that of absorption for light elements. X-ray phase imaging has been one of key applications at synchrotron radiation facilities, and a spin-off movement is also expected strongly for its practical applications to medicine and industry. X-ray grating interferometry emerged in 2000s meets this demand.

X-ray grating interferometry, which consists of transmission gratings, is used to detect slight X-ray refraction caused by a sample. Unlike the phase-contrast methods based on the Bragg diffraction by single crystals, polychromatic plane-wave X-rays are available. This property allows us to establish various unexplored X-ray phase imaging setups. One is the combination with an X-ray imaging microscope equipped with a Fresnel zone plate for realizing X-ray phase imaging with a mesoscopic spatial resolution. Other is the operation of grating interferometry under white synchrotron radiation for realizing dynamic X-ray phase imaging and furthermore four-dimensional phase tomography. Outside the synchrotron radiation facilities, apparatuses for diagnosing joints by depicting cartilage and for mammography are under development in collaboration with Konica Minolta. The former is especially successful and prototypes have been installed in hospitals and used for the study of early diagnosis of rheumatoid arthritis. Statistical examination is in progress by the help of healthy volunteers and patients with informed consent. The developments for non-destructive testing was also launched successively in collaboration with Rigaku, and a scanner type X-ray phase imaging apparatus has been developed.

These activities both with synchrotron radiation and laboratory sources are presented with fundamental description of X-ray phase imaging principle.

I-13

Coherent Diffraction Imaging with Table-top XUV Sources

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Abstracts: *Coherent diffraction imaging at wavelengths in the extreme ultraviolet range has become an important tool for nanoscale investigations. Employing laser driven high harmonic sources allows for lab scale applications such as cancer cell classification and phase-resolved surface studies in reflection geometry. The excellent beam properties allowed for spatial resolutions below the wavelength close to the Abbe limit, while in general the photon flux of HHG sources limits the applicability. In comparison, table-top soft X-ray laser driven by moderate pump energies were recently employed for CDI featuring excellent temporal coherence and extraordinary high flux allowing for single-shot imaging.*

The short wavelength radiation in the extreme ultraviolet (XUV) and soft x-ray range together with a high photon flux are the key elements for imaging nanoscopic structures. Coherent diffraction imaging (CDI) suits the needs for imaging in the XUV by omitting optical elements that would typically introduce high losses and limit the numerical aperture and thus the achievable resolution. For broader application of this technique laboratory light sources of various kinds have been applied.

In this report, we will focus first on recent progress achieved with high harmonic generation sources. These sources, driven by an amplified ultrafast laser system, feature high spatial coherence with sufficient narrow-band emission lines such that temporal coherence allows imaging down to the wavelength levels as has been recently demonstrated [1]. The spectral range covered with high photon flux by these sources is typically several 10eV up to 100eV. Due to the low penetration depth at these photon energies, recent applications targeted the reflection geometry [2] where CDI becomes a powerful technique yielding three-dimensional information of the surface. The surface sensitivity becomes advantageous, when nano- and microscale objects of a certain morphology are to be compared or classified. As an example, recently it was demonstrated that reflection geometry CDI at 35eV photon energy can be used to classify different breast cancer cell expression profiles solely by investigation their diffraction pattern [3]. However, a major bottleneck of HHG powered CDI experiments is the limited photon flux and the resulting long integration times. Another promising source is a laser plasma based table-top soft X-ray laser (SXRL) [4]. In a recent experiment the coherence properties of a SXRL operated in the gracing incidence pumping geometry (GRIP) and emitting 300 nJ pulses at 18.9 nm were studied [5]. The extraordinary high photon flux and the narrow line width make this source interesting for CDI, which was studied with an apparatus and samples that were tested before at a HHG beamline allowing for a direct comparison and benchmarking between these two table-top sources.

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I-14

High-resolution Coherent X-ray Diffraction Imaging at SPring-8 and SACLA

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Abstracts: *Coherent X-ray diffraction imaging allows us to two-dimensionally or three-dimensionally visualize the electron density distribution of thick samples. We developed a method of high-resolution coherent diffraction imaging using a high-intensity X-ray beam focused by Kirkpatrick-Baez mirrors at SPring-8 and SACLA. We applied it to observe shape-controlled Au/Ag nanoparticles. The three-dimensional electron density distribution and Au-rich regions of individual particles were visualized at SPring-8. The relationship between the size distribution of particles and their internal structures were evaluated at SACLA.*

Coherent diffraction imaging with hard-X-ray beams allows us to two-dimensionally or three-dimensionally observe thick objects, and also provides us with structural information, such as the electron density distribution, that cannot be obtained by probe microscopy or electron microscopy. We have a method of developed high-resolution coherent diffraction imaging using a high-intensity X-ray beam focused by Kirkpatrick-Baez mirrors[1,2] at SPring-8 which is a third-generation synchrotron radiation facility in Japan. For example, we visualized the three-dimensional electron density distribution of a shape-controlled Au/Ag nanoparticle[3] and the Au-rich regions of ~450 individual Au/Ag nanoparticles[4] at sub-10-nm resolution.

Recently, X-ray free electron lasers (XFELs) have become available at the SPring-8 Angstrom Compact Free Electron Laser (SACLA) in Japan. XFELs provide almost completely transverse coherent X-rays with an extremely large number of photons in a single pulse and a duration of less than 100 fs. We first performed the coherent diffraction imaging analysis of nanoparticles using focused hard-X-ray free-electron laser pulses, allowing us to analyze the size distribution of particles as well as the electron density projection of individual particles[5]. We measured 1000 single-shot coherent X-ray diffraction patterns of shape-controlled Ag nanocubes and Au/Ag nanoboxes and estimated the edge length from the speckle size of the coherent diffraction patterns. We then reconstructed the two-dimensional electron density projection with sub-10-nm resolution from selected coherent diffraction patterns. This method enables the simultaneous analysis of the size distribution of synthesized nanoparticles and the structures of particles at nanoscale resolution to address the correlations between the structures of individual components and the statistical properties in heterogeneous systems such as nanoparticles and cells.

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I-15

X-ray reflection imaging of inclined and obliquely illuminated objects

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It is well known that contrast high resolution images are usually produced with normal incidence optics and samples observed normally to their surface. However a number of recent X-ray experiments from 0.1 to 10 kev demonstrate a quest for imaging of slanted objects and the objects illuminated at grazing angles. A survey of previous studies, theoretical consideration, simulation and application prospects of this new imaging technology is presented.

O-1

Femtosecond laser ablation: simulations and X-ray imaging

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Abstracts: *The report presents results of a set of simulations done to understand recent ultrafast pump-probe observations with optical pump and soft X-ray probe. The main feature of thermomechanical ablation is the kick-off of a spallation shell as a result of condensed matter – vapor phase transformation in a stretched warm dense matter with nucleation of voids and formation of a cavity between the spallation shell and the remnant of a target. We employ a combination of physical models and simulation approaches to describe the early stages of an ablation process and to compare with experimental data.*

Picosecond soft (photon energy 90 eV) X-ray laser made in KPSI is a peculiar tool for ultrafast diagnostics of ablation processes. It is employed in a pump-probe scheme of measurements with a femtosecond Ti:sapp optical laser as a pump. The pump sends ultrashort moderate fluence pulse on to a gold target. Soft X-ray laser with pulse duration 7 ps and wavelength 13.9 nm synchronized with the pump is used as a stroboscopic probe. A sequence of the probe flashes follows real time evolution of an irradiated spot on surface of a target.

Femtosecond optical pump excites an electron subsystem in a skin layer. During excitation the matter does not have time to expand according to temperature achieved because rate of heating is higher than sound speed. Warm dense matter expands later. Thanks to finite expansion velocities and inertia the substance expands over an equilibrium volume corresponding to temperature achieved. Thus stretching and tensile stress appear. Above a certain limit the stress causes nucleation of voids and spallation of a layer inside the irradiated spot. Thus formation of a cavity under spallation layer begins. The cavity locates between the spallation layer and the remnant of a target. Wavelength 13.9 nm of the X-ray probe is much shorter than the optical wavelengths previously used for probing of such spatial structures. Smallness of the soft X-ray wavelength allows us to follow the early stage of evolution of the shell because the short wavelength begins to resonate inside the cavity when the cavity is thin (geometrically cavity has a form of a thin undersurface disk).

Models and simulation approaches are developed in our work. The goal is to extract valuable data from experimental measurements. A scheme to calculate a two-dimensional X-ray snapshot image of an ablation area is created. Results of simulations are compared with the experimental images. A hydrodynamic code including full two-temperature physics is written. The two-temperature effects are especially important at the early stages. Molecular dynamics code is used to estimate electron pressure and to simulate nucleation in stretched matter.

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Tuesday, May 24th

I-16

Quantitative x-ray spectroscopy for energy transport study in fast ignition plasma generated with LFEX PW laser

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Abstracts: *Quantitative x-ray spectroscopy was made for the study of energy transfer in a PW-laser driven fast ignition plasma. A set of new type hard x-ray spectrometers have been developed and absolute sensitivity of them were calibrated with radio isotopes and radiation sources driven with an electron accelerator. Energy conversion from laser to hot electrons was derived in various types of targets mimicking the fast ignition plasma.*

Hard x-ray emission, caused by hot electrons propagation in a hot dense matter, can provide abundant information about laser plasma interactions. Quantitative x-ray spectroscopy is a potential method to derive energy transfer efficiency from laser to hot electrons. A Laue spectrometer, composed of a cylindrically curved crystal and a detector, has been developed and calibrated absolutely for high energy x-rays ranging from 17 to 77 keV. Either a visible CCD detector coupled to a CsI phosphor screen or a sheet of imaging plate can be chosen as detector. The absolute sensitivity of the spectrometer system was calibrated using pre-characterized laser-produced x-ray sources [1, 2] and radioisotopes, for the detectors and crystal respectively. The integrated reflectivity for the crystal is in good agreement with predictions by an open code for x-ray diffraction. In addition to the Laue spectrometer, new type of spectrometers have been developed to observe very hard x-ray emissions ranging from 0.1 to several 10 MeV by utilizing Compton scattering and photo-nuclear reactions [3, 4]

The energy transfer efficiency from incident laser beams to hot electrons, as the energy transfer agency is derived as a consequence of this work. The absolute yield of Au and Ta Kα lines were measured in the fast ignition experimental campaign performed at ILE Osaka U.. By applying the electron energy distribution from ESM data and scaling laws, energy transfer efficiency of incident LFEX, a kJ-class PW laser, to hot electrons was derived for various types of targets designed for fast ignition research.

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I-17

Dynamic X-ray Thomson scattering from high-energy-density plasmas using an ultra-bright X-ray laser

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Abstracts: *Recent x-ray scattering experiments performed at the MEC end-station of the LCLS, have demonstrated novel plasma measurements of the electron temperature, pressure, and density by simultaneous high-resolution angularly and spectrally resolved x-ray scattering from shock-compressed materials in the warm dense regime. Such measurements provide the structural properties relating the microscopic quantities in terms of thermodynamic properties using first-principles calculations.*

Our new high-energy-density science program at SLAC is aimed to take advantage of x-ray pulses with the highest peak brightness available today. This capability allows us to measure plasmons and to visualize the density and pressure evolution across melt lines by resolving correlations at distances comparable to atomic scales. We will show how LCLS data test our theoretical models of compressed matter at pressures exceeding 5 Mbar and will discuss future plans for the study of warm dense matter. These studies have led us on a path where we create conditions with increasing temperatures and pressures to explore the high-energy density phase space. Specifically, we have begun experiments on hot and dense hydrogen plasmas producing energetic proton beams that find applications in fusion research and astrophysical phenomena. For our experiments with the 25 TW short pulse laser we apply repetition rates and pulse widths with a good match to the LCLS x-ray beam capabilities allowing pump-probe experiments with ultrahigh temporal resolution with very high data throughput with shot rates of up to 5 Hz. In this talk we will discuss our recent measurements that have resolved the ultrafast structural response of hydrogen to intense heating and the comparison with density functional theory modeling.

* This work was performed at the Matter at Extreme Conditions (MEC) instrument of LCLS, supported by the DOE Office of Science, Fusion Energy Science under contract No. SF00515 and supported under FWP 100182 and DOE Office of Basic Energy Sciences, Materials Sciences and Engineering Division, contract DE-AC02-76SF00515.

I-18

Ultraintense X-Ray Radiation Generated by Relativistic Laser Plasma in the Radiation-Dominated Kinetic Regime and its using for Exotic Dense –matter States Pumping

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Abstracts: *The study of high energy-density matter motivates the development of powerful X-ray sources that can produce and probe exotic matter states with high densities and multiple inner-shell electronic excitations. Here, we present overview of our recent results, which via high-resolution X-ray spectroscopic measurements and kinetic simulations demonstrate that the energy of femtosecond laser pulses with relativistic intensity approaching to ~ 10^{21} W/cm^2 is efficiently converted to X-ray radiation emitted by "hot" electron component in collision-less processes and produced exotic states in solid density plasma periphery. Our results promote ultra - relativistic laser-produced plasma as unique ultra-bright X-ray sources that can reach already today intensities above 10^{17} W/cm^2 for studies of matter in extreme conditions as well as for radiography of biological systems and for material science studies.*

The radiation properties of high energy density plasma are under increasing scrutiny in recent years due to their importance to our understanding of stellar interiors, the cores of giant planets, and the properties of hot plasma in inertial confinement fusion devices. Recently, it was demonstrated[1-5] that conventional optical lasers with pulse duration of 40 – 1000 fs and laser intensity (0.3-1.0)x10^{21} W/cm^2 irradiating Al foils could generate very bright X-ray radiation with intensities exceeded 10^{17} W/cm^2 and efficiently produce exotic states of matter (so called Hollow ions), which are very far from equilibrium. Here we give overview of obtained results and present new set of measurements of high spectrally resolved K-shell emission of Si foils irradiated by sub picosecond laser pulses of Vulcan laser facility. Our investigations asserts that exotic Hollow ions states can be accessed and probed not only by X-ray radiation of XFEL lasers, but also upon using optical laser technology. In the latter case the generated X-ray radiation is polychromatic with its energy and intensity comparable or even exceeding that of current XFELs and complements the recent observations of such exotic states using XFELs. The results reported here suggest that radiation dominated atomic physics processes could be efficiently studied at high optical laser intensities.

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O-2

Observation and Investigation of Intensive Directional Quasi-coherent X-Ray Radiation Generated at Interaction of Cavitating Liquid Jet with a Target

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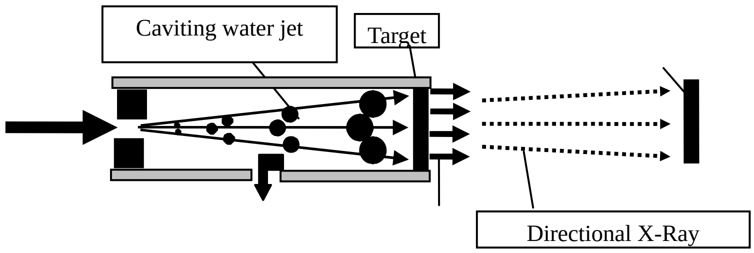
Abstracts: *In the report the results of investigation of intensive directed controlled quasi-coherent controlled X-Ray radiation connected with bubble cavitation phenomena in fast oil jet and supersonic water jet are presented and discussed. be less than 100 word.*

In the report the results of investigation of intensive directed controlled quasi-coherent X-Ray radiation connected with bubble cavitation phenomena and generated at interaction of both fast oil jet and supersonic water jet with different targets [1] are presented and discussed in details. The typical setup for generation of directional X-Ray is shown in Figure. The total activity of X-Ray generation was about Q≥0.1 Ci.



The mechanism of X-Ray generation is connected with the sequential tandem of cavitation and shock-wave processes inside liquid jet, in the volume of output channel and in the volume of target. We have investigated bubble cavitation and X-Ray generation phenomena at high pressures of machine oil (at P=30-90 atm) and at super-high pressures of water (P=200-2000 atm). The soft part of X-Ray radiation with energy E_x=0.8-1.1 keV was generated by the surface of supersonic free water jet in the area of cavitation at any pressure. The energy of radiation from the surface of oil or water output channel (made of plexiglas or stainless steel) was E_x=1.5-2.0 keV. In the case of additional heavy metal cover on outer surface of a target the energy of X-radiation increase up to E_x= 4.5 keV. This radiation has an essential transverse coherence and associated with a mutually phased excitation of surface atoms during action of shock acoustic waves on the outer side of the target [1,2]

It was shown also that the formation of shock waves and X-rays is accompanied by generation of undamped high frequency thermal waves [2].

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I-19

A soft X-ray view on ultrafast magnetization dynamics

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Abstracts: *Soft X-rays femtosecond sources are a powerful tool enabling the application of spectroscopy techniques to the study of ultrafast phenomena. Here, I will show how these sources can be applied to the study of ultrafast demagnetization to provide valuable new insights on the microscopic mechanisms governing this phenomenon.*

Since its discovery by Beaurepaire and coworkers in 1996, the phenomenon of laser induced ultrafast demagnetization has attracted world-wide attention and created an entirely new research field in magnetism. Despite nearly 20 years of ongoing experimental and theoretical research activities, the underlying mechanism of the rapid decrease of the magnetization of a ferromagnetic film on the femtosecond time scale after a femtosecond optical excitation remains debated intensively. The heart of this research is to explain this magnetization dynamics with its associated energy and angular momentum transfer between the electron/spin system and the crystalline lattice occurring on a sub-picosecond time scale. Further interest derives from the fact that this phenomenon paves the way to applications of magnetization control on the femtosecond time scale as shown by the demonstration of the all-optical magnetization reversal. This discovery could enable the realization of ultrafast magneto-electronic devices.

Typically, experiments exploring ultrafast magnetization dynamics are performed as a stroboscopic pump-probe measurement, in which the system is pushed out of equilibrium using a pulsed excitation (pump) and the subsequent relaxation dynamics is followed by applying a second pulse to determine the status of a particular property of the sample after a given delay (probe). Pump and probe are typically realized by near infrared (IR) laser pulses. However, with the advent of suitable femtosecond pulsed X-ray sources (X-ray free electrons lasers (XFELs), high order harmonic generation (HHG) or femto-slicing sources at synchrotron radiation storage rings), the application of X-ray pulses have attracted increasing attention as a probe. X-rays offer a rich variety of resonantly enhanced magnetic contrast mechanisms and thus provide an element-specific probe with remarkably higher sensitivity when compared to visible light or near IR radiation. X-rays furthermore enable experiments with sub-100 nm spatial resolution due to their short wavelength.

I will present an overview of the results we obtained on ultrafast magnetization dynamics with those sources in the past few years.

I-20

For Generation of Tera-watt attosecond X-ray laser pulse

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X-ray free-electron lasers (XFELs) are excellent tools for the study of ultrafast phenomena in atoms and molecules in the fields of biology, material science, chemistry and physics. XFEL facilities can currently supply femtosecond XFEL pulses with a few tens of gigawatt power, generated in the self-amplified spontaneous emission process. However, these pulses are not sufficiently fast to follow the dynamics of electrons in atoms, molecules and nanoscopic systems in their real time. To follow the electronic motions, an intense attosecond X-ray pulse is demanded. Such pulses would allow the investigation of phenomena that have not been previously explored in ultrafast science and X-ray nonlinear science. One of the immediate applications of such a pulse is the observation of real-time changes in the probability distribution of the electron's position. This apparent holy grail of diffraction experiments, paves the way to 4D imaging with picometer spatial and attosecond temporal resolutions.

Here, we discuss a new scheme for a terawatt attosecond x-ray pulse in X-ray free-electron laser controlled by a few cycle IR pulse, where one dominant current spike in an electron bunch is used repeatedly to amplify seeded radiation to a terawatt level. The generated attosecond x-ray pulse is synchronized to the driving few cycle pulse, well suited to the pump-probe experiments in the study of ultrafast dynamics. The viability of this scheme is demonstrated in simulations using Pohang accelerator laboratory (PAL)-XFEL beam parameters.

Also in this talk, the recent activities at CASTECH under Max Planck Center for Attosecond Science are also reviewed.

O-3

Plasma Mirror Frequency-Resolved Optical Gating in Vacuum Ultraviolet Wavelength Region

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Abstracts: *We demonstrate that the methodology of frequency-resolved optical gating (FROG) is applicable to time-resolved reflection spectroscopy of a plasma mirror in the vacuum-ultraviolet (VUV) region. A VUV waveform and a time-dependent reflectivity in the VUV region are simultaneously retrieved from a VUV reflection spectrogram of a plasma mirror formed on a fused silica surface by an intense femtosecond laser pulse. The present method enables us to fully characterize a significantly chirped VUV pulse whose duration is as long as 1 ps.*

Ultrashort light sources in the short wavelength region from vacuum ultraviolet (VUV) to hard X-ray have been rapidly developed based on free-electron laser and high-order harmonic generation (HHG). The characterization of VUV pulses is still difficult owing to the lack of efficient nonlinear optical material. In this study, we utilize a plasma mirror as an ultrafast optical switch in the VUV region ($\lambda \sim$ 160 nm). The plasma mirror is formed on a fused silica surface by an intense fs laser pulse (795 nm, 60 fs, ~ 3.3 J cm^{-2}) and time-resolved VUV reflection spectra of the plasma has been measured [1].

Figure 1(a) shows the time-resolved reflection spectra, which are regarded as a FROG trace. We call the present method plasma-mirror FROG (PM-FROG). Using the least-square generalized projections algorithm [2], the PM-FROG trace can be retrieved as shown in Fig. 1(b). The temporal VUV waveform is obtained as shown in Fig. 1(c). The VUV pulse is found to be significantly chirped, reflecting the group delay dispersion caused by the transmission of a lithium fluoride (LiF) lens. It should be noted that the time-dependent reflectivity caused by the plasma formation can be retrieved simultaneously without any model function.

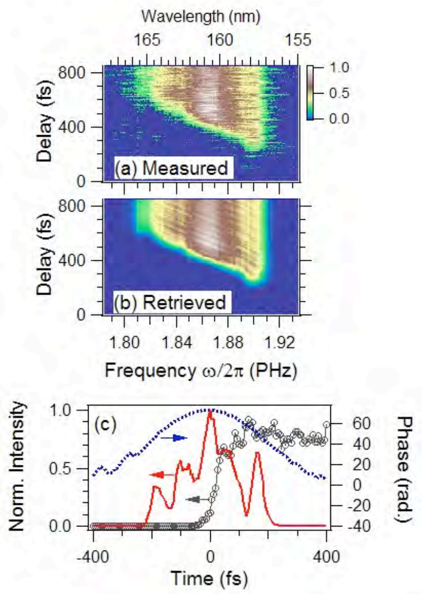

Fig. 1 (a) Measured PM-FROG trace. (b) Retrieved PM-FROG trace. (c) Retrieved temporal intensity (solid) and phase (dotted) of the VUV pulse, and time-dependent reflectivity of the plasma mirror (circle).

PM-FROG has advantages that (i) the applicable wavelength is extended to the shorter wavelength region where there are no transmission material, (ii) neither carrier envelope phase stabilization of laser pulses nor sufficient intensity of VUV pulses for a nonlinear process is required, and (iii) the VUV optical measurement is used in place of the photoelectron measurement, which is usually used in other methods.

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Laser Compton Scattering Gamma-Ray Beam Source for Nuclear Physics and Material Research

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Abstracts: *Laser Compton scattering gamma-ray beam source has been developed at the NewSUBARU synchrotron light facility. The available maximum Gamma-ray photon energy is 76 MeV. The flux of quasi-monochromatic gamma-ray photons (for example: 16.7 MeV, ΔE/E~5%) is more than 10^6 photons/sec using a 30 W Nd:YVO_4 laser combined with the 1 GeV storage electron beam with an intensity of 300 mA. Gamma-ray beams were used for application experiments, a nuclear physics research, a nondestructive inspection of thick material, a generation of positron by pair creation, a magnetic Compton scattering measurements, and a nuclear transmutation.*

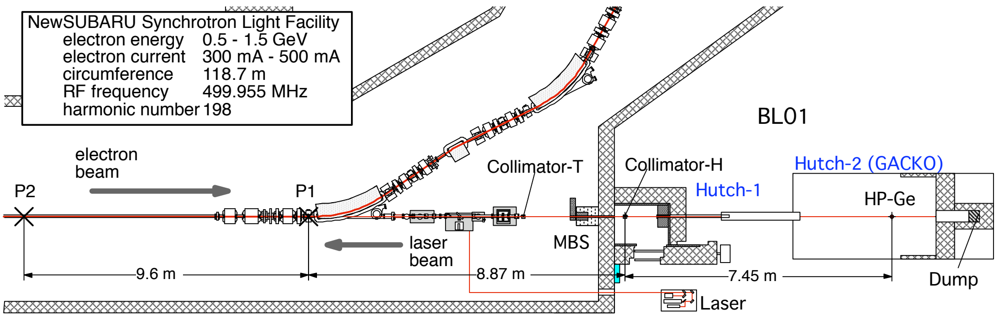
The laser Compton scattering (LCS) γ-rays have advantages that an energy tunable quasi-monochromatic and an almost 100% linearly (circularly) polarized γ-ray beam. The polarized γ-ray beams are powerful tools to study the material science and the nuclear physics such as a magnetic Compton scattering, polarized electron and positron generation, and measurement of transition strengths with parity assignments. The (γ, n) reactions with linearly polarized beam have not been studied well, since the 100% linear polarized photon beam has not been practically used before the developments of the LCS γ-ray facilities.

The synchrotron light facility NewSUBARU [1] is operated by the LASTI, University of Hyogo, Japan. The LCS gamma-ray beam-line BL01 [2] was started to operate from 2005 using the 0.5–1.5 GeV electron beams in the NewSUBARU storage ring. Lasers with different wavelengths are used to produce the LCS photon beam in the energy range from 0.5 MeV to 76 MeV. A experimental hutch, GACKO [3] (Gamma Collaboration Hutch of Konan University), was added to use at the BL01. Figure 1 shows a schematic layout of LCS gamma-ray beam-line.

Recently, we have measured the photo neutron distribution emitted from the interaction between linearly polarized gamma-rays and nuclei [4]. This was the first demonstration of a theory of photo-neutron emission which depend on the polarization.

This work was done by collaboration with Konan University, Osaka University, Osaka Prefecture University, Kyoto University, Ecole Polytechnique, JAEA, AIST, JASRI, RIKEN, KEK and SPring-8 team.

Fig.1



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I-21

Investigations on Ultrafast Atomic and Molecular Dynamics with Harmonic Sources

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Abstracts: *High harmonics have been applied for probing ultrafast atomic processes of He and also for revealing multi-orbital structure of CO_2 molecules.*

High harmonic light sources with attosecond duration in the EUV and soft x-ray spectral range can be applied to probe ultrafast dynamics of atoms and molecules. By tuning harmonic wavelength a specific state of an atom or molecule can be excited, which can be further excited or ionized by applying a time-delayed femtosecond laser pulse. This process of combining harmonic pulses and time-delayed femtosecond laser pulses was applied to investigate the dynamics of photoexcitation and photoionization processes of He. In addition high-harmonic radiation generated from molecules contains the information on the structure of molecules. When multiple molecular orbitals are exposed to a strong laser field, the highest-occupied molecular orbital (HOMO) is mostly ionized and thus emits strong high-harmonic radiation containing the characteristics of HOMO. In order to resolve multiple orbitals of CO_2 molecules we employed two-dimensional high-harmonic spectroscopy (HHS) by applying an orthogonally polarized two-color laser field consisting of the fundamental frequency and its second harmonic. In this case odd and even harmonics carried the characteristics of the HOMO and HOMO-1, respectively. The multi-orbital characteristics were thus revealed in the two-dimensional spectroscopy employing the two-color laser field.

I-22

High-order harmonic generation by relativistic plasma singularities

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Abstract: We discuss the new regime of high-order harmonic generation by relativistic-irradiance multi-terawatt femtosecond lasers focused onto gas jet targets [*PRL* **108**, 135004 (2012); *NJP* **16**, 093003 (2014)]. The laser induces multi-stream relativistic plasma flow resulting in the formation of density singularities: structurally stable, oscillating electron spikes coherently emitting high-frequency radiation. In this presentation we analyze the dependence of the harmonic yield on the laser power and focal spot quality, and derive the required laser parameters for efficient harmonics generation. We show the status of the J-KAREN-P laser and report on the progress towards satisfying these requirements.

In the new regime of high-order harmonic generation, intense (>10^{18} W/cm^2) high-power (multi-TW) femtosecond (30-50 fs) laser pulses focused onto gas targets induce multi-stream relativistic flows in underdense plasma ($n_e \sim 10^{19}$ cm^{-3}). This results in the formation of density singularities, which are structurally stable, oscillating electron spikes coherently emitting high-frequency radiation with spectra comprising high-order harmonics [1, 2]. The experiments with the J-KAREN laser [3] demonstrated strong dependence of the harmonics yield on the laser pulse energy and focal spot quality.

In this presentation we analyze the obtained dependences and derive laser parameters required for efficient harmonics generation. Apart from higher power, it turns out that the focal spot quality should approach the diffraction limit, i.e. the Strehl ratio should exceed 0.5. The focal spots of high-power lasers typically suffer from wavefront distortions and angular dispersion. For noise-like wavefront distortions, the above stated requirement corresponds to an rms wavefront error <100 nm. The angular dispersion should be kept smaller than a fraction of the diffraction divergence, i.e. μrad level for 100 to 300 mm beam diameters. The corresponding angular chirp should be <10^{-2} μrad/nm for 50 nm bandwidth. We show the status of the J-KAREN-P laser and report on the progress towards satisfying these requirements.

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Characterization of partially coherent ultrashort XUV pulses

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Modern ultrafast metrology relies on the postulate that the pulse to be measured is fully coherent, i.e. that it can be completely described by its spectrum and spectral phase. However, partial coherence can arise if the pulse varies in degrees of freedom that are averaged out during the measurement process (eg. shot-to-shot pulse fluctuations, the pulse space-time structure, or details of the pulse finer than the detector resolution). Therefore, fully coherent pulses are not always available in practice, especially in the domain of emerging ultrashort XUV sources where temporal metrology is strongly needed.

To sort out this issue, we have adapted Frequency-Resolved Optical Gating (FROG), the first and one of the most widespread techniques for pulse characterization, to enable the measurement of partially coherent XUV pulses even down to the attosecond timescale [1]. The technique has been successfully implemented on a high-harmonic beamline in CEA Saclay, which allowed the characterization of the complete state of coherence of an attosecond pulse train. Experimental results will be presented along with a theoretical study to explain the potential origins of the observed loss of coherence.

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I-24

Inner Shell Excitation During High Harmonic Generation: The Giant Resonance in Xenon

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Abstracts: *Recolliding electrons with energy greater than 100 eV are shown to cause inner shell excitation in xenon atoms. This leads to high harmonic emission associated with the 4d shell even though a 5p electron was initially ionized.*

Long-wavelength few-cycle laser sources can extend the photon energy of high harmonic sources into the water window and beyond. We report a high harmonic study of xenon atoms using a 1.8 µm, 2 cycle CEP-stable laser source [1]. These spectra contain features due to collective multi-electron effects involving inner shell electrons, in particular the giant resonance at 100 eV.

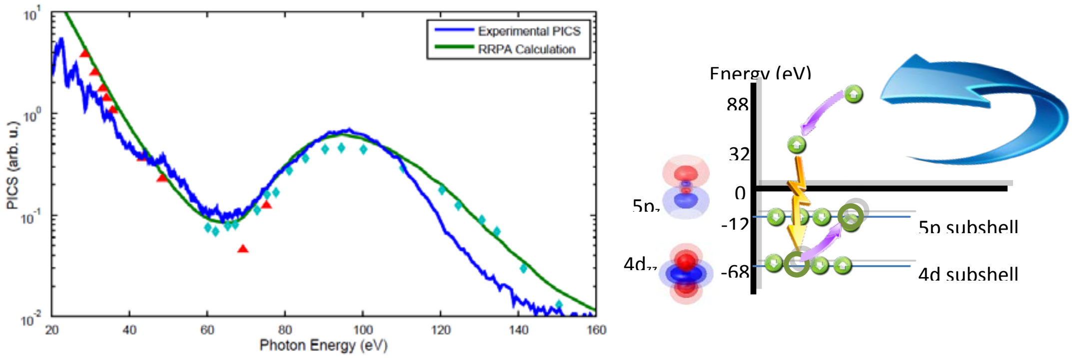

Fig. 1: (Left) The HHG spectrum from xenon. The blue curve is from the HHG experiment. The green curve is a multi-electron calculation of the photoionization cross section. The symbols are synchrotron measurements of the cross section. (Right) Effect of inelastic scattering on HHG. The returning electron can promote a lower lying electron into the valence band and then re-combine to the vacancy in the lower lying state. A 100 eV photon is emitted by recombination to the 4d vacancy.

The large enhancement seen at 100 eV is recognized from photoionization studies as the xenon giant resonance. The peak results from the influence of inner shell 4d electrons (binding energy 70 eV) which have a large photoionization cross section in this region. The recolliding electron has sufficient energy to cause an e-e Coulomb interaction with the 4d electron, which is promoted to fill the 5p hole. The 4d hole is later filled by the continuum electron, leading to the emission of an xuv photon. Remarkably, the process results in phase matched emission. This represents the first time that e-e correlations and excitation of the ion have been observed in gas phase HHG [2]. We show that high harmonic spectroscopy gives access to multi-electron dynamics through their spectral signature, much as in photoionization studies, but with the added potential of attosecond temporal resolution.

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O-5

Wave-Mixing and Amplification in Extreme Ultraviolet Region

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Abstracts: *We report the investigation of the wave-mixing and optical parametrical amplification process in extreme ultraviolet region. Using a non-collinear scheme for the two beams, which helps to spatially separate the extreme ultraviolet field according to the mixing condition, we study the properties of the high-order frequency mixing field. When very high intensity is used as pump pulse of parametrical amplification we are able to enhance the flux of the coherent extreme ultraviolet radiation in the photon energy range around 80 eV by more than an order of magnitude compared to the generation with a single-wavelength pulse.*

When atoms or molecules interact with an intense laser field, high-order harmonics (HHG) of the incident radiation may be generated. This process provides methods to produce short pulses of coherent radiation in the extreme ultraviolet (XUV) and soft x-ray region. From the point of view of fundamental research, high-order harmonic generation is an example of nonlinear physics, where simple pictures can be used to describe strongly non-perturbative processes with the time-dependent Schrödinger equation. On the other hand, the observation of nonlinear optical wave-mixing [1] and parametrical amplification [2] in XUV region suggest the possibility to treat the physics in the XUV range with a perturbative nonlinear optics theory although perturbative and non-perturbative nonlinear optics seem conceptually very different.

In our experiment an 800 nm, 9 mJ, 30 fs, 1 kHz repetition rate laser beam is split into two beams, with pulse energies of 4.5 mJ. One of 4.5 mJ beams is used to pump a three-stage optical parametric amplifier system to generate an infrared (IR) driving pulse at 1400 nm with energy of ~ 2 mJ and duration 40 fs. In the wave-mixing experiment the 1 mJ 800 nm beam is used to mix with the 1400 nm field. The 1400 nm IR pulse is used for phase-matched generation of XUV pulses and the 800 nm pulse, which is used to control the HHG output, is aligned at a very small angle (< 10 degree) to the direction of the 1400 nm beam by a dichroic mirror. For parametrical amplification high intensity 800 nm beam, which propagates in same direction of 1400 nm pulse, is used for pumping. When the 1400 nm and 800 nm pulses are overlapped, i.e., for zero time delay the intensity of the XUV radiation is much higher (by more than an order of magnitude) because of the presence of parametrical amplification. We confirm that a perturbative formalism can be developed around the amplification process, up to ultra-high orders of nonlinearity, even though the HHG is a highly non-perturbative process. This result is important for the application of IR and near-IR driving pulses for the generation of high order harmonic radiation and in strong field physics. When an IR driving pulse is used for generating high order harmonics, the parametric amplification can be used to enhance the efficiency.

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Abstract submitted to the 15th International Conference on X-ray Lasers
Nara, Japan, May 22-27, 2016

Using the X-FEL to drive gain in K-shell and L-shell systems using photo-ionization and photo-excitation of inner-shell transitions

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Many photo-pumped X-ray laser schemes have been proposed over the last four decades. Demonstrating these schemes has proven to be elusive because of the difficulty of finding a strong resonant pump line or X-ray source. The X-ray free electron laser (X-FEL) now provides a tunable X-ray laser source that can be used to replace the pump line or X-ray source in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. Many of these photo-pumped schemes are driven by photo-excitation from a resonant line source but others are driven by photo-ionization from a strong non-resonant X-ray source.

Four years ago an inner-shell X-ray laser was demonstrated at 849 eV (1.46 nm) in singly ionized neon gas using the X-FEL at 960 eV to photo-ionize the 1s electron in neutral neon followed by lasing on the 2p – 1s transition in singly-ionized neon. This work was done at the SLAC Linac Coherent Light Source (LCLS) by a multi-laboratory team led by Nina Rohringer and published in the January 26, 2012 issue of Nature. It took decades to demonstrate this scheme because it required a very strong X-ray source that could photo-ionize the 1s (K shell) electrons in neon on a time scale comparable to the intrinsic auger lifetime in the neon, which is typically 2 fsec.

In this work we model the neon inner shell X-ray laser under similar conditions to those used in the XFEL experiments at LCLS and show how we can improve the efficiency of the neon laser and reduce the drive requirements by tuning the XFEL to the 1s-3p transition in neutral neon in order to create gain on the 2p-1s line in neutral neon. We also show how the XFEL could be used photo-ionize L-shell electrons to drive gain on n=3-2 transitions in singly-ionized Ar and Cu plasmas. These bright, coherent, and monochromatic X-ray lasers may prove very useful for doing high-resolution spectroscopy and for studying non-linear process in the X-ray regime.

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I-26

Hard X-ray Laser Photonics

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Abstracts: *Recent x-ray free electron lasers open new chance to create x-ray active control science. Up to now, we already demonstrate saturable absorber, optical guiding, gain, and spectral control in hard x-ray region. By using these new phenomena, we are now creating x-ray coherent photonics with hard x-ray lasers.*

Recently, several nonlinear optical phenomena have been successfully observed in hard and soft x-ray wavelength lasers. Those include lasing[1,2], two-photon absorption[3], second harmonic generation[4], saturable absorption[5], control of the branching ratio in an atomic system[2] and self-guiding lasers[5]. These phenomena are actually key component for photonics. By combining them, we can make lasers with well-controlled waveform, spectrally controlled lasers, ultra-short pulse lasers in the x-ray range. Specially, to consider difficulties of preparation of wave-front-control or wave separation & combining optics in hard x-ray, it is suitable to develop functional medium, which generate controlled spectral and waveform x-ray laser pulses required from applications. .

To realize this goal, we demonstrated several x-ray lasers pumped by intense x-ray free electron lasers. Those include double-pulse generation, spectral shifted laser by materials, and spectral broadening by MOPA (master oscillator and amplifier) method. For example, in order to produce a double pulse in a single medium, we use gain dynamics after pump by the XFEL and using a nano-surface geometrical structure, we successfully achieved temporally coherent double pulse x-ray laser pulse. The separation of the pulses is several fs and each pulse has sub-fs pulse duration. With a crystal spectrometer, we observe high visibility interferometric fringes of frequency domain in hard x-ray. We are now trying to use such a pair of pulses for ultra-fast pump-probe experiments.

In this talk, the details of development of these functional devices will be reported together with their implications for future x-ray coherent photonics.

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I-27

Amplification of x-ray free electron laser using core-hole atoms generated with intense optical laser pulse

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Abstracts: *We demonstrated a new scheme for amplifying a power of X-ray Free Electron Laser (XFEL) pulse. Irradiation of an intense femtosecond optical laser to a copper target generated fast electrons, which created core-hole atoms in the target. By utilizing them as a gain medium, we achieved amplification of pulse energies of XFEL light at a photon energy of a copper Kα line (8.05 keV). The highest gain at a spectral peak reached close to a factor of ten.*

Recent advent of X-ray Free Electron Lasers (XFELs) [1,2] has opened the frontiers of various fields of science. However, a current output power of XFELs, which are limited by the FEL parameter, is still insufficient for conducting challenging applications, such as exploring photon-and-vacuum interactions [3], XFEL-pumped x-ray laser [4], and creating extremely high energy density states. On the other hand, state-of–the-art, high power optical lasers are now close to generating extreme outputs above a 10 PW level. Such a drastic enhancement of laser intensities has been realized through the development of an optical amplifier with an external pumping system. If the external amplifier scheme utilized for optical lasers were applicable in the X-ray range, one could directly enhance the power of XFEL pulses.

In this presentation, we will show an amplification of x-ray free electron laser using core-hole atoms generated with intense optical laser pulse. The experiment was performed at BL3 of SACLA [2]. A 20-μm-thick Cu foil was used as a gain medium. Intense Ti:Sapphire laser pulses synchronized with XFEL pulses were used to generate fast electrons. Here the fast electron energy was estimated to be 70 keV, which is high enough to create the core-hole atoms of Cu with an ionization energy of 8.98 keV for the K-shell electrons. A photon energy of XFEL pulses was tuned to be 8.05 keV, corresponding to the Cu-Kα1 line. The XFEL light was focused down to 10 μm irradiated to the Cu foil. To observe the amplification, we measured single-shot spectra of XFEL pulses [5] through the Cu foil. Intense peak at 8.05 keV was observed, and we confirmed that the divergence of the intense signal is same as that of XFEL pulses. From these results, we conclude achievement of x-ray amplification. The highest obtained gain at spectral peak was as high as ten. A scaling law indicates that an extreme output of monochromatic hard X-ray laser is achievable simply by increasing the power of the optical lasers.

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O-6

Multiple-wavelength superfluorescence/superradiance in helium following free-electron-laser excitation

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Abstract: *We describe experiments and simulations performed to study the production of superfluorescence pulses at visible wavelengths following the excitation of helium atoms using 30 fs, 5 muJ pulses from the SCSS extreme-ultra-violet free-electron laser.*

Superradiance is a fundamental effect which can occur when ultrafast, intense radiation is used to excite dense atomic samples. Its development is sensitive to the spectral and coherence properties of the incident radiation, and as such is an excellent test of our understanding of these properties – a characteristic particularly relevant when the excitation source is a SASE free-electron laser.

Following the observation of superfluorescence pusles at 502 nm (1s3p-1s2s) following excitation of helium at 53.7 nm [1], in further experiments using excitation at 53.7 nm and 52.2 nm [2,3] we also observed superfluorescence at 668 nm and 728 nm (1s3d-1s2p and 1s3s-1s2p). Detailed simulations have been performed to understand these results [4,5].

Prospects for experiments at SPring-8's new SACLA BL1 (wavelengths of 30 nm to 50 nm) will also be presented.

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O-7

A design of non-harmonic soft x-ray beam line at BSRF

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Abstracts: *High-order harmonic contaminates, originated in higher-orders diffraction of gratings, are inescapable in synchrotron radiation grating monochromators. A novel single-order grating for x-ray, proposed by Cao, can give only ±1st orders diffraction, and restrain high-orders effectually. It may blaze a new path in the purer monochromatic beam. In this report, it will be introduced that a laboratory prototype of the non-harmonic monochromator with single-order grating and its test results first, and then a new design of a non-harmonic beam line with single-order gratings at BSRF.*

The diffraction grating is a kind of ancient optical elements and has been thought as the most contributed single tool to the progress of modern physics and the single device giving most important information to every field of science. Synchrotron radiation as the most ideal vacuum ultraviolet (VUV) and soft x-ray light source so far has become an indispensable research tool in many frontier research fields, and also produced a spate of exciting and innovative research results. It is "processed" to some monochromatic light beams with strict requirements for the photon flux, spectral resolution, spectral purity, and spot sizes to meet different needs of kinds of experimental stations. In VUV and soft x-ray bands, the process is realized by the grating monochromator composed of reflection gratings, an imaging system and necessary slits for wavelength selection. Harmonics existed in the output monochromatic light come from the high-order diffraction of gratings, which are diffracted in the same direction as the fundamental and depress the spectrum purity terribly.

To solve the problem radically, a new single-order grating in x-ray region has been developed by Cao, which can suppress higher-order diffraction components effectively by quasi-randomly distributing a large number of nanometer scale pinholes on an aurum substrate.

In this report, based on single-order gratings, a laboratory prototype of the non-harmonic monochromator was built. To calibrate its energy resolution, the spectrum of the laser plasma of the argon was measured: the monochromator formed a sharp spectrum with $E/\Delta E>1000$. A transmission spectrometer was installed after the exit slit of the monochromator to test the spectral purity of the output beam when the monochromator equipped a single-order grating and a conventional grating. The comparison of spectrograms measured by the spectrometer illustrated that the harmonic elements were restrained effectively when equipped a single-order grating. In the end, a new design of a non-harmonic beam line working at 10~100 eV of the BSRF was introduced.

Wednesday, May 25th

I-28

Single-cycle and Exawatt X-ray Pulse

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Efficient multistage compression toward the single-cycle regime of petawatt laser pulses, such as those becoming available at laser facilities around the world, holds the promise to open up an entirely new realm of fundamental and applied physics both directly and by driving exawatt, X-ray pulses. A shorter route to the generation of Schwinger intensities with current day technology is now envisioned with the capability of producing high energy radiation and particle beams of extremely short, sub-attosecond timescales. The energies and timescales involved are far from traditional laser regimes and offer a new intersection of laser technology with the study of the structure of vacuum and numerous applications to subatomic physics. With this vision in mind, a plan for petawatt pulse compression shall be presented and the potential applications for such pulses discussed.

I-29

Next Generation Laser-Compton Sources for Nuclear Photonics and Medicine

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Abstract

Tunable, polarized, mono-energetic, laser-like beams of x-rays and gamma-rays may be created via the optimized Compton scattering of pulsed lasers off of ultra-bright, relativistic electron beams. At x-ray energies, these extremely compact sources rival the output of the world's largest synchrotrons, exceed the flux of the highest performance medical sources and are enabling to new techniques that may significantly reduce dose to the patient during imaging procedures and/or increase the efficacy of radiation treatments of cancer. Above 2 MeV, the peak brilliance of compact laser-Compton sources can exceed that of world's largest synchrotrons by more than 15 orders of magnitude.

These sources enable for the first time the efficient pursuit of nuclear science and applications with photon beams, i.e. Nuclear Photonics. Potential applications are numerous and include isotope-specific nuclear materials management, element-specific medical radiography and radiology, non-destructive, isotope-specific, material assay and imaging, precision spectroscopy of nuclear resonances and photon-induced fission. This presentation will review activities at the Lawrence Livermore National Laboratory related to the design and optimization of laser-Compton systems and to the development of the unique science and applications enabled by them.

I-30

Research on Laser Acceleration and Coherent X-ray Generation using J-KAREN-P laser

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Abstract: We present the progress on the upgrade status of the J-KAREN-P, which is a Ti:sapphire laser aiming a focused intensity of 10^{22} W/cm^2 at the repetition rate of 0.1 Hz. The upgrade includes two pilot experiments in order to show the availability of the laser performance on target. The first experiment is to generate high-energy ions from thin-foil target. The second experiment is the high order harmonic at a relativistic intensity. Currently, laser acceleration of protons is being tested and we have obtained 32 MeV protons from a 5-µm stainless steel target irradiated by a 14-J, 30-fs laser pulse.

In order to explore high-field science including laser particle acceleration [1,2] and photon beam generation [3] the upgrade of the J-KAREN laser [4] is in progress at Kansai Photon Research Institute, National Institutes for Quantum and Radiological Science and Technology (QST). The J-KAREN-P laser is Ti:sapphire, with double chirped pulse amplification (CPA) system enabling high-contrast ratio of 10^{-10} at -500 ps. The laser system successfully produces the pulse energy of 55 J after the final amplifier. The compressed pulse duration is ~30 fs at full width at half maximum (FWHM). Two target chambers allow us to perform short-focal-length (f/1.4) and long-focal-length (f/5-f/20) experiments.

Currently we increase the laser energy on target gradually in order to check the total system. In the March 2016 run the maximum proton energy of 32 MeV was achieved both with a stack of radio chromic films and a time-of-flight detector when a 14-J, 30-fs laser pulse irradiated a 5-µm stainless steel foil. A typical electron temperature was ~10 MeV.

In the presentation, detail of the ion acceleration experiment and planned HHG X-ray generation [3] and electron acceleration experiments will be reported.

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I-31

Resonantly excited betatron X-rays in a laser plasma accelerator

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Hard x-ray emission from fs laser produced plasmas have a number of interesting applications in the dynamic probing of matter and in medical/biological imaging. Betatron radiation is a highly collimated laser-driven hard x-ray source with fs duration which generated by electron transversely oscillation during acceleration in underdense plasmas. However, characters of this source are always limited by controdictory between parameters during electron acceleration. We will present our recent progress in enhancing acceleration to optimize the x-ray photon yield/energy.

1) A new method is demonstrated for generating intense betatron x-rays using a clustering gas target irradiated with an ultra-high contrast laser of 3 TW only [1]. The yield of the Ar x-ray betatron emission has been measured to be 2×10^8 photons/pulse. Simulations point to the existence of clustering as a contributor to the DLA mechanism, leading to higher accelerated electron charge (x40) and much larger electron wiggling (~8 μm) amplitudes in the plasma channel, thereby finally enhancing the betatron x-ray photons.

2) Another concept of generation of bright betatron radiation during electron acceleration was newly invented [2]. Two electron bunches with different qualities were injected sequentially into the wakefield driven by a super-intense laser pulse. The first one is a mono-energetic electron bunch with peak energy of GeV level, and the second one is injected continuously with large charge and performs resonantly transverse oscillation with large amplitude during the subsequent acceleration, which results in the enhancement of betatron x-ray emission. After optimize interaction conditions, γ-rays with yield reaches to 10^{11} can be obtained by using 200TW laser [3].

3) In order to control the stability of betatron x-ray generation as well as enhance its yield and energy, ionization injection with N_2 gas is studied. In experiment, we obtained stably accelerated monoenergetic electron beams with energy spread 5% only for the first time [4]. 10^9 photons in hard x-rays and 10^8 photons in γ-rays are stimulated, results in a peak brightness 10^{23} phs/s/mm^2/mrad^2/(0.1%BW). Quick injection, acceleration and oscillation in the wake of the ionization injected electron leads to the effective resonant betatron oscillation, which result in γ-ray photon energy and peak brilliance beyond that of 3rd generation synchrotron facilities [5].

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O-8

Relativistic electron dynamics in high intensity optical lattice. Towards a table-top Raman XFEL

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Abstracts: *A new scheme for an X-ray free electron laser is proposed, based on a Raman process occurring during the interaction between a relativistic bunch of free electrons issued from laser-plasma accelerated electrons, or from traditional Radio-Frequency LINACs, and twin intense short pulse lasers. I show the relativistic electron dynamics and the first experiment results in the high intensity regime of the Kapitza-Dirac effect.*

The quest for a compact X-rays laser has long been a major objective of laser science. Several schemes using optical ondulators are currently considered, in order to trigger the amplification of backscattered radiation, either in a Thomson or Compton regime. However, the practical conditions on the electron bunch parameters, in terms of mono-energeticity, emittance, divergence, and on those of the laser beams intensity constancy, are so stringent that no practical realization has yet been attempted. To overcome these limitations we have proposed a new concept of compact XFEL based on a combination between the physics of free electron lasers, of laser-plasma interactions, and of nonlinear optics [1]. This new scheme, the so called "Raman XFEL" is based on a Raman process occurring during the interaction between a moderately relativistic bunch of free electrons, and twin intense short pulse lasers interfering to form a transverse standing wave along the electron trajectories. The ponderomotive force can trap a relativistic electron bunch in the wells and results in transverse oscillations. This triggers a parametric process resulting in the emission of coherent radiation in the range of EUV or X-rays and the amplification of the Stokes component of the Raman-scattered radiation [1,2]. Analytical and numerical studies have demonstrated that very high gain values, with gain lengths in the sub-mm range, and high photon numbers can be expected [3]. In this talk we present a numerical study of the injection and trapping process of a bunch of relativistic free electrons into a transverse high intensity optical lattice, as required to achieve an all-optical Raman Free Electron Laser [3]. We unravel different injection regimes depending on the characteristic scale length of the onset of the optical lattice. We show some first experiment results obtained with the "Salle Jaune" laser at LOA, near Paris, of the interaction of a relativistic electron bunch issued from LWFA and an optical lattice. We will focus on the modification of the distribution function structures induced by the optical lattice and show some numerical modeling of LANEX diagnostics [3].

References:

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O-9

Enhanced coherent Thomson scattering in the few-cycle regime

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Abstracts: *We study nonlinear coherent Thomson scattering of few-cycle laser pulses by relativistic electron sheets. For an electron sheet of finite thickness, the scattering efficiency is found to increase more than one order of magnitude when laser pulses approach to the single-cycle regime. This enhancement is caused by the reduction of destructive interference in the scattering process, and occurs for the sheet thicker than the wavelength of produced x-rays. The scattering amplitude in this nonadiabatic regime is calculated and agrees well with particle-in-cell simulation. These results are important for developing more intense, shorter attosecond x-ray sources.*

The advent of coherent x-ray sources, such as free electron laser, high harmonics from gas and relativistic laser-plasma processes are opening new area of nonlinear x-ray optics and attosecond science. Among these schemes, coherent Thomson scattering (CTS) from relativistic electron sheets potentially produces isolated x-ray pulses of >10GW and <10as. The electron sheet takes a relativistic velocity β_0 along the direction of the sheet plane. When a counter-propagating laser pulse is reflected by this sheet, its frequency ω_0 is upshifted by relativistic Doppler effect. The Doppler shift factor $D_{nl} \propto (1+\beta_0)/(1-\beta_0)$, so x-rays can be generated at tens of MeV. An analytic theory has been established for flat-top or long incident laser pulses.

Here, we discuss nonadiabatic effects of nonlinear CTS in the few-cycle regime, and find that the efficiency increases more than one order of magnitude within a region of laser intensities (Fig. 1a). The dramatic scattering enhancement is due to two facts. First, peak scattering amplitude rises due to the weakening of destructive interference (Fig. 1b). Second, as the pulse duration T shrinks, the lower-frequency components are reflected more efficiently, which causes the scattering pulse has a central frequency lower than $\omega_0 D_{nl}$ (Fig. 1c), and a duration larger than T/D_{nl}. Both scattering amplitude and frequency are predicted by a revised analytic model, and agree well with particle-in-cell simulation by the code JPIC. Moreover, the enhancement condition is also obtained: the electron sheet should be thicker than the wavelength of produced x-rays.

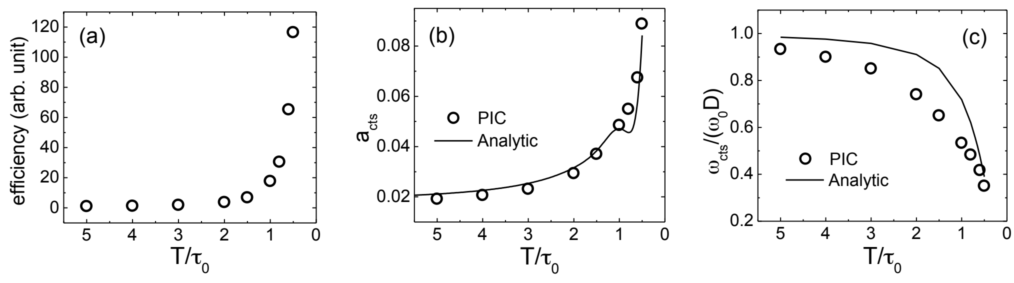

Fig. 1. Normalized efficiency (a), peak scattering amplitude (b) and central scattering frequency (c) as a function of pulse duration T/τ_0, where τ_0 is the light cycle.

O-10

Multilayer Mirror Objective for Focusing Isolated Attosecond Pulse in 40 nm Wavelength Region

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Abstracts: *Recently, isolated attosecond pulse (IAP) generation with pulse energy of a few μJ has been reported in a 40 nm wavelength region. For diffraction-limited focusing of the IAP, we are developing the Schwarzschild objective made of two-curved multilayer mirrors. To generate intense light fields with the maximum intensity of over 10^{16} W/cm^2 on focus of the objective, in this paper, we describe design, fabrication, and test of multilayer mirrors with three different material pairs, i.e., SiC/Mg, Cr/Mg, and Sc/Si, for practical high reflectivity in the 40 nm wavelength region.*

Recently, isolated attosecond pulse (IAP) generation in a 40 nm wavelength region has been reported, where an isolated intense pulse with pulse energy of a few μJ was demonstrated by applying the novel two-color gating method.[1)] When such the attosecond high-power extreme ultraviolet (EUV) pulse is focused with diffraction limited objective to produce a small focal spot with size of a few handled nanometers, we can generate extremely intense fields with the maximum intensity of over 10^{16} W/cm^2, which enables us to access the new frontier of nonlinear optics in EUV region. For the diffraction-limited focusing of the IAP, we are developing the Schwarzschild objective made of two-curved multilayer mirrors.[2)] The objective has two practical advantages, i.e., high spatial resolution resulting from large-numerical aperture optical design, and spectral selectivity based on the Bragg reflection on multilayer mirrors. To realize the objective, firstly, we need multilayer mirrors with practical high reflectivity. In this paper, we describe design, fabrication, and test of multilayer mirrors that is suitable for the focusing application in the 40 nm wavelength region.

After applying the selection rule for high reflectivity, which has been given by Yamamoto,[3)] three material pairs, i.e., SiC/Mg, Cr/Mg, and Sc/Si, were chosen. The period and thickness ratio of the mirror were numerically optimized to give the maximum reflectivity at a wavelength of 40 nm. The three multilayer coatings were deposited by using the magnetron sputtering apparatus (SPL-500, Canon Anelva Corp.). At-wavelength reflectivity was examined with the EUV reflectometer equipped on beamline BL5B of UVSOR. We observed relativity high reflectivity of over 30% on the Mg-based multilayer mirrors. Especially in SiC/Mg multilayer mirror, practical high reflectivity of 40% and wide band width were confirmed simultaneously, where we can expect the maximum intensity of over 10^{16} W/cm^2 with pulse duration below 800 attosecond on the focus of the two-mirror objective. In the presentation, we also report experimentally measured phase change on reflection, which corresponds to group delay dispersion modulating pulse duration on ultra fast optics.

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[2] M. Toyoda *et al.*, Appl. Phys. Exp. **5**, 112501 (2012).
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Thursday, May 26th

I-32

The Creation of Radiation Dominated Plasmas using Laboratory X-ray Lasers

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Abstracts: When short wavelength extreme ultra-violet (EUV) and x-ray laser radiation is focused onto solid targets, narrow deep features are ablated and a dense, low temperature plasma is formed. We examine the radiation dominated plasma formed by 46.9 nm laser radiation focused onto solids and show that ionization is significantly modified by electron degeneracy effects. A capillary discharge laser operating at wavelength 46.9 nm is to be installed at the University of York. Some experimental and theoretical considerations for investigating the laser interaction with solid targets will be presented.

Extreme ultra-violet (EUV) and x-ray lasers can be used to generate strongly coupled plasmas and 'warm dense' matter. Targets irradiated by EUV and x-ray lasers are heated predominantly by direct photoionization. With photo-ionization as a dominant heating mechanism, lower temperature and higher particle density plasmas are produced. With all laser-produced plasmas, an expanding plume of plasma allows only absorption where the electron density drops below a critical value ($\simeq 10^{21}/\lambda^2$ μm cm^{-3}, where λ is the laser wavelength in units of microns). By reducing the wavelength into the EUV to x-ray region, the critical electron density is greater than solid and the laser photon energy E_p becomes sufficient to directly photoionize elemental components (ionization energy E_i), transferring energy ($E_p - E_i$) to the ejected electron. As the critical electron density is higher than solid, the laser is able to penetrate any expanding plasma plume and heat solid material directly throughout the duration of a laser pulse.

We explore in this talk the potential for creating narrow and deep features by EUV laser ablation of solids, and also for using the plasma created by EUV lasers as sources for warm dense matter. Our calculations show that the ionization of plasma can be affected by free electron degeneracy effects with overlap to the plasma conditions found in inertial fusion, where degenerate plasma is created during x-ray driven compression of material. The use of a capillary laser operating at 46.9 nm in producing high density degenerate plasma will be explored.

I-33

Laser driven plasma based incoherent X-ray sources at PALS and ELI Beamlines

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Abstracts: *In this paper we report on development of incoherent secondary sources at the PALS Research Center and discuss the plan for the ELI Beamlines project. One of the approaches, how to generate ultrashort pulses of incoherent X-ray radiation, is based on interaction of femtosecond laser pulses with underdense plasma. This method, known as laser wakefield electron acceleration (LWFA), can produce up to GeV electron beams emitting radiation in collimated beam with a femtosecnond pulse duration. This approach was theoretically and experimentally examined at the PALS Center. The parameters of the PALS Ti:S laser interaction were studied by extensive particle-in-cell simulations with radiation post-processors in order to evaluate the capabilities of our system in this field. The compressed air, and mixture of helium and argon were used as accelerating medium. The accelerator was operated in the bubble regime with forced self-injection and resulted in the generation of stable relativistic electron beams with the energy between 10 and 80 MeV, hence the betatron X-ray radiation with critical energy in the keV range was generated. The extensions of this method to the ELI Beamlines facility will enable to generate much higher X-ray energies from 10 keV up to 1 MeV with 10 Hz repetition rate. Such source is suitable for various applications like phase contrast imaging or X-ray absorption experiments in single shot.*

O-11

Progress and Prospects of X-ray Laser Research in QST

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Abstracts: *Recent progress in X-ray laser and application research in National Institutes for Quantum and Radiological Science and Technology (QST) is reviewed. Recently, the soft x-ray laser is mainly used for the observation of nano-scale surface ablation dynamics. In the source development, the x-ray laser using the GRIP scheme is developed in parallel with the application research.*

Short pulse x-ray sources become indispensable diagnostic tools in modern science and technology and are widely used in probing substances for new material development, protein crystallography in innovative drug development, and non-destructive x-ray imaging etc. The improvement of the sources is also important subject, and in particular coherent x-rays in both the laser-based and accelerator-based are intensively studied, which enable us to achieve quite high spatial-resolution as the probe and quite intense x-ray as the pump. Besides the laser-driven sources have potentials to downsizing and table-top systems, therefore we carry out the development of fully spatially coherent soft x-ray laser (SXRL) at the wavelength of 13.9 nm and its applications. As an application using the SXRL, we have observed the spallative ablation process by the interaction with SXRL or femto-second (fs) laser. The dynamical processes of the SXRL and/or the fs laser- induced surface modifications come to attract much attention for the micro processing. In the case with SXRL irradiation (13.9 nm, 7ps, ~50 mJ/cm^2), we have observed the damage structures and the optical emission from the ablated materials. When focused SXRL pulses were have been irradiated onto the metal surface, we have confirmed damage structures.[1] In the case with fs laser irradiation (795 nm, 80fs, ~1.5 J/cm^2), we have observed the surface morphology of fs laser ablation by the SXRL interferometer and SXRL reflectometer. The time resolved image of nano-scaled ablation dynamics of metal surface was observed.[2] In the presentation, we will show the recent progress of application research and x-ray laser development.

[1] M. Ishino *et al*., in this conference.
[2] N. Hasegawa *et al*., in this conference.

O-12

Hydrodynamic and Maxwell-Bloch modelling of plasma-based soft X-ray amplifiers.

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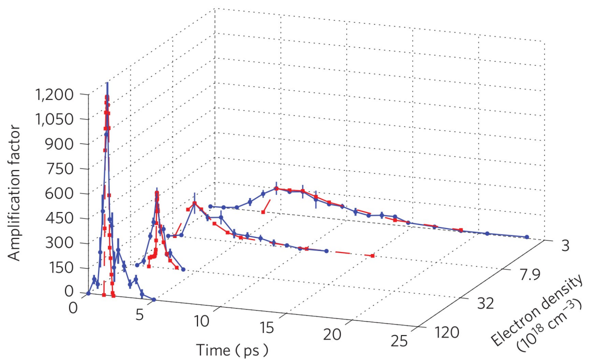
Recently, sub-picosecond pulses of High Order Harmonics (HOH) amplified in a dense plasma have been demonstrated [1]. In order to pump the amplifier, it is necessary to propagate an intense infrared (IR) laser through several milimetres of dense plasma. Deleterious effects, as overionization induced refraction, may appear hindering the propagation of the IR beam. A preformed plasma channel helps overcoming these effects [2]. However, critical parameters like the maximum propagation length of the IR beam, the maximum electron density at the centre of the channel and the degree of ionization vary in a fast timescale. In order to optimize the amplification scheme (i.e. Optimum pump time, optimum seeding time, etc ...) we have modelled the creation of the plasma channel with the 2D hydrodynamic code ARWEN [3]. The evolution of the plasma channel as given by the code can be compared with experimental results.

In addition to this, we have performed Maxwell-Bloch simulations of the amplification of seeded HOH in the previous amplifiers [1] and atmospheric nitrogen amplifiers [4]. The amplification curves as given by our code present an excellent match with experimental results (figure 1.) allowing us to diagnose plasma parameters as the collision frequency.



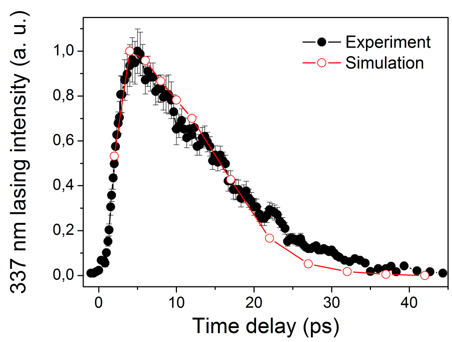


Figure 1: Experimental and modeled amplification curves of a Ni-like Kr plasma amplifier (left, from [1]) and an atmospheric nitrogen amplifier (right).

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I-34

Performance of over 100W HVM LPP-EUV light source.

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Abstracts: *We have been developing CO_2-Sn-LPP(Laser Produced Plasma) light source for HVM. By the use of Gigaphoton's original and unique Sn droplet shooting procedure, we have demonstrated 3 hours operation of 133W at intermediate focus(IF) position and 24 hours operation of 108W at IF position. We also attained conversion efficiency(CE) of 5.5% by the use of experimental set up. Based on these results, We are developing the first practical light source for HVM named "GL 200E". The system will use more than 20kW CO2 pulsed laser in corporation with Mitasubishi Electric Coraporation.*

EUV Lithography is the most promising technology for the fabrication of ULSIs at the 10 nm and further Nodes. The most critical issue for the practical use of EUV lithography is the availability of high power output and high reliability. According to this situation, we have been developing CO_2-Sn-Laser Produced Plasma (LPP) EUV light source for HVM use. Unique and original technologies such as ; the combination of pulsed CO_2 laser irradiation on Sn targets, dual wavelength laser pulses shooting and Sn mitigation with magnetic field, have been developed in Gigaphoton Inc.. The theoretical results and experimental data clearly showed the advantages of the proposed strategy. So far we have been reporting the highest output power of 133W average clean power at 100kHz with 3 hours operation and 108W average power at 80kHz with 24 hours operation. Based on these data, we are developing the first practical source for HVM named "GL200E". The source will use 20kW level CO_2 pulsed laser corporate with Mitsubishi Electric Corporation to obtain over 250W. We also obtained the highest conversion efficiency (CE) of 5.5 % in the experimental set up.

Further improvements are underway. We will report the newest experimental results at the conference.

EUV free-electron laser requirements for semiconductor manufacturing

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Abstract:

Laser-produced plasma extreme-ultraviolet (EUV) sources currently power EUV lithography tools, supporting advanced semiconductor manufacturing research and development. However, a source with sufficient power to support high-volume manufacturing has yet to be realized, but the sheer number of installed tools indicates the transition to EUV lithography is no longer a question of 'if' but 'when'. After the initial insertion of EUV lithography into manufacturing, the prerequisite dose scaling with technology node will be steep and therefore drive the EUV cost-per layer. Free-electron lasers (FEL) may offer a low-cost, high-power alternative and facilitate further expansion of lithographic capabilities, including the development of high-NA and high-throughput NA 0.33 scanners. Adaptation and development of existing scientific light source knowledge, components and infrastructure for the implementation of a viable industrial light source requires collaboration between academic and manufacturing communities. Considerations for an integrated FEL lithography light source are discussed, focusing on the specific needs of the semiconductor industry. Emitted power, reliability and stability requirements are outlined with the intent of supporting a manufacturing fab's entire EUV lithography module. Potential high-NA EUV cluster requirements and the further lithography wavelength reduction to 6.x nm are also explored as potentially benefiting from FEL source development.

I-36

Coherent Lithography with Table Top Soft X-ray Lasers: Latest Achievements and Prospects

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Abstract: *We will present the latest results in the development of a Talbot lithography technique utilizing table-top SXR lasers. The main characteristics of the method will be reviewed and a hybrid scheme that combines interferometric lithography with Talbot lithography will be presented. This approach that we named Talbot Interference Lithography allows to overcome resolution limitations typical of the classical Talbot imaging.*

We will describe lithography approaches utilizing a soft X-ray (SXR) tabletop laser emitting at 46.9nm. In particular the talk will focus on a lithographic method based on Talbot imaging. The characteristic of this approach is that it enables the fabrication of periodic nanostructures with arbitrarily complex design. Furthermore, a main advantage is that the lithographic step is by nature "defect free", allowing for defect free prints from defective lithography masks. Examples of structures fabricated with this method with feature sizes down to 40nm will be presented.

In addition we will describe a hybrid technique combining Talbot lithography and interference lithography that is capable to generate periodic nanostructures with an arbitrary lattice.[1] At a common Talbot plane, two Talbot images generated by coherent SXR laser illumination are superimposed. In this way, an interference pattern with high resolution is modified by a defined Talbot image. One of the advantages of this method is that it enables the printing of arbitrary shaped cells with high resolution drastically relaxing the fabrication constrains of the mask. The hybrid method that combines Talbot lithography and interferometric lithography was named Talbot Interference Lithography (TIL). It can claim the advantages of both lithography methods, allowing the printing of patterns that neither of them can accomplish separately.

In the talk we will present a description of the system, and a detailed modeling of the method. The capability and advantages will be also discussed. Finally experimental results using the tabletop SXR laser will be examined.

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I-37

Plasma Dynamics in Capillary Discharges

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Abstracts: *Capillary discharge plasma is used frequently as a source of UV radiation, as an active media for EUV and soft X-ray lasers, for formation of plasma wave-guides to transport high power laser beams, and as plasma lens to focus beams of accelerated charged particles. A review of physical processes responsible for dynamics of plasma in capillary discharges is presented. The review is based on results of a number of MHD simulations as well as on their comparisons with various experiments.*

A through duct in a dielectric filled initially with a gas may conduct electric current leading to plasma formation. Such the form of gas discharges is usually called the capillary discharge. Capillary discharge plasma has various applications: a) as a source of UV radiation; b) as an active media for EUV and soft X-ray lasers; c) as a plasma wave-guide for high power laser beam transportation over substantially long distances; d) as a plasma lens to focus beams of accelerated charged particles; etc.. The talk presents a review of physical processes governing main properties of the capillary discharge plasma. The review is based on an analysis of a number of MHD computer simulations and on their comparison with experimental data.

Electric current flowing through the capillary discharge acts on the capillary plasma mainly in two quite different ways. Firstly, the electric current $\boldsymbol{j}$ excites azimuthal magnetic field $\boldsymbol{B}$. Thus, Amper's force proportional to $\boldsymbol{j}\times\boldsymbol{B}$ pinches the plasma towards the capillary axis. Secondly, the electric current causes the Joule heating of the plasma. The heating rate is proportional to $\boldsymbol{j}^2/\sigma$, where σ is the electric conductivity of the plasma. Magnetic field may also lead to minor consequences like modifications of thermal conductivity, etc..

In the limit of high electric current values, hot plasma and large capillary diameters the first effect prevails leading to the strong plasma compression towards the capillary axis. Plasma dynamics in this case is similar to its dynamics in classic Z-pinches. Parameters of the prefilled gas, the electric current amplitude and the capillary diameter determine maximum temperature of the plasma at stagnation, its density and the stagnation time. These relationships are discussed in the talk.

For weaker electric currents, relatively cold plasmas and smaller capillary diameters, the relatively strong Joule heating leads to the regimes, when Ampere's force effects become negligible in comparison with the plasma pressure effects. As a result, a quite simple mechanical and thermal equilibrium of the capillary plasma may be established. A simple model describing such the equilibrium in the case of hydrogen filled capillary is developed. The model gives the distribution of the electron temperature and density across the discharge.

The capillary discharges are often accompanied by the capillary wall evaporation caused by the high enough thermal flux to the walls. Physical processes determining of the capillary wall temperature as well as the methods allowing to take into account the evaporation are also considered.

I-38

Capillary Discharge - a Way for Recombination XUV Laser?

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Abstracts *The study of capillary discharge taking into account the effect of wall ablation is reported. Results of electrical diagnostics and gated spectra measurements are compared with the results of computer simulations. We have approved that the ablation of capillary wall at high currents strongly influences the pinch dynamics. The most critical parameters for lasing are the peak value of electron temperature at the time of pinch contraction on the axis and the rate of temperature decrease during pinch decay. The possibility to achieve the necessary for lasing parameters in the experiment is discussed.*

Capillary pinch discharge has been demonstrated as a very successful way of pumping of compact and efficient extreme ultraviolet EUV lasers. Namely, pinching plasma column inside an argon-filled capillary has been shown to be very efficient way to achieve lasing at 46.9 nm. In this case, the active medium was formed by collisionaly excited neon-like argon ions Ar^{8+} created during the pinch compression stage [1, 2].

There is a significant interest in extending capillary discharge pumped lasers to shorter wavelengths. A recombination-pumping scheme leading to a population inversion of the Balmer alpha transitions of low *Z*-elements is, in principle, an alternative. In this scheme, the primary pumping process is three-body collision recombination, which takes place in the nonstationary undercooled plasma, created during the pinch expansion stage.

We have developed a computer model of active medium creation. The capillary discharge dynamics was modelled by means of hydrodynamic NPINCH code. The radiative properties of Z-pinch plasma were described using the kinetic code FLYCHK as a postprocessor [3]. Efficient amplification of spontaneous emission of Balmer alpha was predicted in nonablating capillary. But in the experiments [4-7] lasing was not observed. Wall ablation may be a serious obstacle to the way to capillary recombination pumping.

Here we report the study of capillary discharge taking into account the effect of wall ablation.

We have approved that the ablation of capillary wall at high currents strongly influences the pinch dynamics. The ablated material has a serious cooling effect; the electron temperature on the axis becomes lower than in the case without wall ablation. At the same time, the ablated material obstructs the rate of plasma cooling. Results of electrical diagnostics and gated spectra measurements are compared with the results of modified computer model.

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Interaction of capillary discharged soft-x-ray laser at 46.9nm with BaF_2

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Abstracts: *BaF_2 targets were ablated by a capillary-discharged 46.9nm laser beam focused by a toroidal mirror at grazing incidence. The peak power densities of the focal spot were about $2\times10^7 W/cm^2$ and $1.2\times10^8 W/cm^2$. Clear ablation patterns on the surfaces of BaF_2 were observed. In the damage area, the nanostructures induced by the soft-x-ray laser with different power densities were observed to show different features.*

Interaction of soft-x-ray laser with matters plays an important role in material nano-patterning, biologic detection, and surface modification. And capillary discharged soft-x-ray laser is a efficient radiation source to be utilized in these interaction experiments, because of its less expense, easy operation and long service life. Since J. J. Rocca's group reported the ablation of Cu by the laser at 46.9nm in 1999, a bunch of solid targets have been irradiated by x-ray laser in the experiments. Among these materials, dielectrics with a large bandgap (E_g) is supposed to be important research objects, since they can be efficient ablated by x-ray laser while be usually transparent to the sources from optical radiation radiation to the vacuum ultraviolet radiation.

The focusing of x-ray laser is a key point in the experiments. Spherical mirrors with a Sc/Si multilayer coating or an Ir coating are always used to focus a 46.9nm laser at normal incidence in the interaction experiments. These mirrors serve to reduce optical aberration and increase the power density of the focused beam. However, their reflectivity for 46.9nm laser is only 15%-40% and they are easily damaged by the laser and the ejection of the capillary discharge plasma. In this report, we describe the interaction of soft-x-ray laser with BaF_2 (E_g=9.1eV). The laser was focused by a toroidal mirror at glazing incidence with a reflectivity of 90%. And thanks to the aberration induced by the glazing incidence, patterns caused by the lasers of different power densities can be obtained in the same ablation area, which is helpful to study the damage mechanism.

The experiments were operated by capillary discharged 46.9nm x-ray laser generated by 35cm and 45cm-long Ar^{8+} plasma columns with the focused beam spots of a power density of 2×10^7W/cm^2 and 1.2×10^8W/cm^2. And the ablation patterns were detected by atomic force microscope (AFM). The ripple-like nanostrucures and fragmentation-like nanostrucures were found in the ablation area. In the presentation, we will show the details of the nanostructures comparison with different radiation shots and different laser power density. Also the beam path simulation by software ZEMAX will be mentioned.

O-14

Towards generation of sub-fs pulses using lasing to ground states of H-like LiIII at 13.5nm and He-like CV at 4nm

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Abstracts: *The method to generate sub-fs pulses in the process of x-ray plasma lasing from the first excited to the ground state is suggested. The method is based on adiabatic modulation of an upper lasing state under the action of an external IR field of a moderately strong intensity. The possibility to produce sub-fs pulses in H-like LiIII at 13.5nm and He-like CV at 4nm is theoretically shown.*

Sub-femtosecond XUV pulses provide a unique combination of high spatial and time resolution. Modern table-top plasma lasers are able to generate quite high energy (in the μJ up to several mJ range) soft X-ray pulses, but with relatively long duration in the range of few picoseconds. Thus, a highly efficient method of transformation of an output pulse of X-ray laser into the sub-fs pulses would be desirable. The water window wavelength range 2.3-4.4nm is of particular interest for applications.

Recently the technique for an efficient conversion of the quasi-monochromatic XUV field into the train of ultrashort pulses in the resonant absorbing medium of the H-like ions was suggested [1,2]. It is based on space-time modulation of the atomic levels of the first excited atomic state via the adiabatic (quasi-static) linear Stark effect caused by application of an external IR field. In this report we show that using of an IR field with the wavelength 2000nm and intensity $3.6\text{x}10^{14}\text{W/cm}^2$ under the experimental conditions described in [3], where lasing in H-like LiIII at 13.5nm was demonstrated, may result in formation of a train of 0.9 fs pulses. We show also that the technique of an excited state modulation by an IR field can be generalized to the case of He-like ions, providing the possibility for formation of the sub-fs pulses in the process of lasing in He-like CV at 4nm.

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I-39

Nanoscale Imaging using a Compact Laser Plasma Source of Soft X-rays and Extreme Ultraviolet (EUV)

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Abstracts: *Application of a compact laser plasma source of soft X-rays and extreme ultraviolet (EUV) in imaging with nanometer resolution is demonstrated. The source is based on a gas puff target irradiated with nanosecond laser pulses from a small commercial Nd:YAG laser. Soft X-ray radiation in the 'water window' range and EUV near 10nm is generated efficiently without production of target debris. Nanoscale imaging of biological samples as well as micro- and nanostructures using transmission soft X-ray and EUV microscopy based on Fresnel optics and soft X-ray contact microscopy is demonstrated.*

Soft X-ray and EUV microscopy provides information complementary to that obtained from optical, electron and atomic force microscopy techniques. Imaging of cellular structure and extended tissue in biological samples requires nanometer resolution and good sample penetration. It can be provided by current soft X-ray microscopic techniques operating in the 'water window' spectral range (wavelength: 2.3–4.4 nm; photon energy: 280–560 eV). The various techniques include transmission and scanning soft X-ray microscopy, 3D tomography, and soft X-ray contact microscopy. In this work a transmission soft X-ray microscope with a Fresnel zone plate and a contact soft X-ray microscope are presented. The microscopes are based on a compact laser plasma source with a double-stream gas puff target irradiated with a nanosecond laser pulses from a small Nd:YAG laser (4 ns/0.8J/10 Hz). The microscopes have been used for imaging of hydrated and dry biological samples with resolution less than 100 nm and relatively short exposition time.

Interest to nanoscale imaging in EUV spectral range is mainly connected with development of tools for inspection of masks for EUV lithography, however, it can be also useful for investigations of micro- and nanostructures, including nanowires and magnetic nanostructures. In this study a newly developed stand-alone desk-top EUV microscope is presented. The microscope is also based on a compact laser plasma EUV source and Fresnel optics. The experiments on imaging of different objects were performed and the spatial resolution below 50 nm was demonstrated. It was shown that the EUV microscopy can provide structural information that is not achievable by conventional optical or scanning electron microscopy techniques.

O-15

X-ray characterization of a high performance hydrogen storage alloy with laser surface modification

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Abstracts: *A femoto-second laser as well as a nano-second laser repetitively illuminates the whole surface sequentially on a hydrogen absorption alloy resulting in significant improvement of the hydrogen absorption rate. In order to characterize the surface layer, we perform x-ray diffraction experiment using SPring-8 BL-22XU synchrotron radiation facility*

For continuous human activities, electric storage techniques become important in the fields of electric power supply. For contributing such issue, we have been studying hydrogen absorption alloys with surface modification by short pulse lasers. The initial rates of hydrogen absorption and desorption of a hydrogen storage alloy are one of the important performances to be improved. On the basis of the previous experimental study using accelerators [1], charged particles cause surface modifications on the alloys resulting in improvement of the hydrogen absorption rate while these machines also cause radioactivity. The vacancies introduced into a hydrogen absorption alloy are found to be positive effect on the improvement of the initial hydrogen absorption rate. We also have tried to make an improvement of the absorption rate with an ultra-high intensity laser driven proton beam [2]. Based on these result we convince that direct laser illumination makes us good performance of the alloy. A femoto-second laser as well as a nano-second laser repetitively illuminates the whole surface on a tip of a few cm diameter $LaNi_{4.6}Al_{0.4}$ alloy resulting in significant improvement of the hydrogen absorption rate given by the electric-chemical experiments. In order to characterize the surface layer, we perform x-ray diffraction experiment using SPring-8 BL-22XU synchrotron radiation facility resulting in finding a suitable condition for enhancing absorption rates of the hydrogen storage alloys. From the result, the short laser hits the surface and it causes the pressure which is applied to the interior of the alloy. It makes suitable defects in the surface layer of the alloy. Based on the present experimental results, we discuss on the mechanisms of laser driven surface modification.

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I-40

Spectrally resolved lensless imaging with ultra-broadband high-harmonic sources

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Abstract: *We present a novel method for high-resolution coherent diffractive imaging using ultra-broadband sources. By generating coherent pulse pairs with a tunable time delay, Fourier-transform spectroscopy techniques can be combined with coherent imaging. In this way, all spectral bandwidth limitations in diffractive imaging can be removed, and spectrally resolved lensless imaging becomes possible with sources that extend into the soft-X-ray spectral range.*

Microscopy with extreme-ultraviolet (EUV) and soft-X-ray radiation has the potential to provide a unique window into the nanoworld. While the short wavelength radiation enables a resolution on the nanometer scale, inner-shell absorption edges of various elements provide intrinsic contrast and the ability to perform element-selective imaging. As the fabrication of efficient and aberration-free optical components becomes increasingly challenging for such short wavelengths, lensless imaging methods are a powerful alternative for the development of practical high-resolution EUV microscopes.

In lensless imaging a coherent diffraction of an object is recorded directly, and an image of the object is then reconstructed by numerical algorithms rather than physical optical components. The main challenge is to retrieve the phase associated with the diffraction pattern, as a camera only records intensity. One major requirement that has remained in diffraction-based imaging methods is the need for a well characterized spectrally narrowband source. To overcome this limitation and enable efficient imaging with table-top high-harmonic generation (HHG) sources, which are intrinsically ultra-broadband, we have developed a new imaging method based on the diffraction of coherent pulse pairs. By recording a series of diffraction patterns as a function of the time delay between two coherent pulses, a Fourier-transform spectrum can be recorded at each pixel in the diffraction pattern. From this dataset, quasi-monochromatic diffraction patterns can be reconstructed throughout the full source spectrum, and the full source flux is used to continuously illuminate the object. Combining this two-pulse approach with phase retrieval techniques enables spectrally resolved EUV imaging, or robust image reconstruction through the use of multiple Fresnel diffraction patterns in a multi-wavelength phase retrieval scheme.

To enable accurate time-delay scanning, we have developed an ultra-stable interferometer based on birefringent wedge pairs, which allows the generation of tunable and intense HHG pulse pairs with 2.7 attosecond timing stability (0.8 nm path length). HHG is produced by pairs of 1.5 mJ, 20 fs pulses at 300 Hz repetition rate, produced by an optical parametric chirped pulse amplification system. With this setup, Fourier transform scans have been produced with harmonics up to the Al absorption edge at 73 eV (17 nm wavelength). In this presentation, I will present the principles and capabilities of our approach, and show recent results on EUV imaging and spectroscopy.

I-41

Prospects of tomographic nanoscale imaging using high repetition rate laboratory based soft X-ray sources

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Abstracts: *We report about tomographic nanoscale imaging using a laboratory transmission x-ray microscope in the water window. In the second part of the talk we will present recent results on holography and coherent diffraction imaging using our high repetition rate XRL and discuss its potential for nanoscale imaging*.

Laboratory based laser driven short pulse x-ray sources like laser produced plasmas (LPP), high harmonic generation (HHG) and plasma x-ray lasers (XRL) exhibit a great potential for imaging and spectroscopy in the soft x-ray range. These sources are complementary to large scale facilities like synchrotrons or free electron lasers. LPP as well as XRL sources have been already successfully applied in nanoscale imaging in both life and material sciences. However, only few examples of high resolution three dimensional nanoscale images recorded with these sources exist. This is due to limited (in comparison with synchrotron sources) average photon flux and the lack of efficient x-ray optics. The first limitation can be overcome using high repetition rate (1 kHz and higher) pump lasers. The tremendous progress in development of multilayer x-ray optics for the extreme ultraviolet (EUV) range has also led to the availability of multilayer coatings for wavelengths outside the EUV region allowing e.g. efficiencies for a water window condenser optics of 2% or higher. For coherent lab based x-ray sources (e.g. HHG or XRL) new imaging schemes such like coherent diffraction imaging or Fourier transform holography paved the way to nearly wavelength limited resolution in 2D imaging.

In this talk, we report about tomographic nanoscale imaging using a LPP based laboratory transmission x-ray microscope (LTXM) in the water window. The soft X-ray radiation of the LTXM is provided by a laser-produced (1.3 kHz repetition rate, 0.5 ns pulse duration, 140 W average power) nitrogen plasma source, a multilayer condenser mirror, an objective zone plate (25/40 nm outermost zone width) and a back-illuminated CCD camera as detector. The sample stage of the LTXM allows a sample rotation in both directions, resulting in a total rotation angle of 120°. We will discuss the interplay between optimum average power of the driving laser, the efficiency of the condenser optics, the properties of the zone plate objective and the number of projections necessary to obtain a high resolution tomogram taking into account the depth of focus problem.

In the second part of the talk we will present recent results on holography and coherent diffraction imaging using our high repetition rate XRL. We will discuss advantages of these methods and its potential for nanoscale imaging.

O-16

Broadband high-resolution imaging spectrometers for the soft X-ray range

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Abstract: *We develop high-resolution (imaging) spectrometers with the use of VLS gratings and focusing multilayer mirrors, including broadband (aperiodic) multilayers.*

We develop an approach to high-resolution spectral imaging in the XUV (2 – 40 nm) [1]. A broadband stigmatic spectrometer makes combined use of a normal-incidence multilayer mirror (MM) (in particular, a broadband aperiodic MM) and a grazing-incidence varied line-space (VLS) reflection grating. The concave MM produces a slightly astigmatic image of the radiation source (for instance, the entrance slit), and the VLS grating produces a set of its dispersed stigmatic spectral images. The spectral width of the operating range is defined by the multilayer structure of the MM and may range up to more than an octave in wavelength (e.g. 12.5–30 nm for an aperiodic Mo/Si MM [2]). The stigmatism condition for the rays lying in the horizontal (dispersion) plane may be satisfied simultaneously for two wavelengths, e.g.14 and 27 nm. This is achieved at the expense of reducing by one the number of degrees of freedom of the optical configuration. In this case, the condition of non-rigorous stigmatism is fulfilled for the whole wavelength range selected. The residual astigmatism signifies that the spectrograph forms two-dimensional spectral images of an object with a good spatial resolution along and across the dispersion direction throughout the operating range. Numerical ray tracing for a 1-m long spectrometer shows that the spectral images of a point source are all confined in a detector cell size (13 mcm). Similarly, a stigmatic scanning spectrometer/monochromator with a constant deviation angle was designed. To this end, plane VLS-gratings with a central line density of 600 mm^{-1} were made by e-beam lithography (MIPT, Dolgoprudnyi) and interference (State Institute of Applied Optics, Kazan) lithography. Work is underway to make plane VLS-gratings by mechanical ruling on a programmable ruling engine.

This approach may be extended down to 6.9 nm using La/B_4C MMs with barrier layers [3].

Another practical way to obtain ~10-μm spatial resolution in combination with high spectral resolution throughout a broad operating spectral range involves the use of a spherical VLS-grating jointly with a crossed grazing-incidence concave mirror. Use should be made of a VLS-grating with a stronger line density variation across the aperture than for a Harada-type spectrograph. In this case, the grating–detector distance can be made constant – to within a fraction of a millimeter – which favors attainment of high spatial resolution [4].

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O-17

In Situ Characterization of XFEL Beam Intensity Distribution and Focusability by High Resolution LiF Crystal X-Ray Detector

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Abstracts: *We present here a new X-rays diagnostic based on using LiF X-ray crystal detectors that is able to perform in situ measurements the intensity distribution of X-rays beams with diameters ranging from some microns up to some centimeters with high spatial resolution (~ 1µm.) We demonstrated also, that by means of the LiF crystal submicron spatial resolution X-ray detector, in situ 3D visualization of SACLA XFEL focused beam profile along propagation, including propagation inside photoluminescence solid materials*

At coherent X-ray radiation facilities there is an urgent need for simple and efficient methods for *in situ* beamline metrology. Additionally, measurements of energy distribution of XFEL beams in the caustic of focusing system are very important both for correct evaluation of X-ray fluence in the different cross-sections of such beams and for future improving different focusing systems, which are now typically applied for such purposes. We present here a new X-rays diagnostic based on using LiF X-ray crystal detectors that is able to perform *in situ* measurements the intensity distribution of X-rays beams with diameters ranging from some microns up to some centimeters with high spatial resolution (~ 1µm). This diagnostic have an extremely limited cost and is relatively easy to set up. A first observation using this diagnostic at EH5 in SACLA shows that the presence of a slit in the XFEL beam highly structured it by generating diffraction patterns (Fig.1). An optimization of the distance between the slit and the sample position is presented to minimize the effect of the diffraction pattern induced by the slit. We demonstrated also, that by means of the LiF crystal submicron spatial resolution X-ray detector, *in situ* 3D visualization of SACLA XFEL focused beam profile along propagation, including propagation inside photoluminescence solid materials (See Fig.2), is possible [1].

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O-18

ERL-based Laser-Compton Scattering X-ray source for X-ray Imaging

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Abstracts: *Nowadays, the generation of high brightness X-rays via laser-Compton scattering (LCS) of laser photons stored in an optical cavity by a relativistic electron beam is expected for many scientific and industrial applications such as X-ray imaging. For the demonstration of the LCS X-ray generation, it is necessary to develop a high average power laser system. The construction of compact Energy Recovery Linac (cERL) is also now in progress at KEK to generate low-emittance and high-current electron beams. In this presentation, we will show the results of the LCS X-ray generation and the X-ray imaging.*

There has been a growing interest in the laser-Compton scattering (LCS) light sources because they are capable of producing quasi-monochromatic, bright and tunable X-rays with small source size. By combining a high average power laser and an enhancement cavity with a linac, high brightness LCS X-rays can be generated. In this presentation, we will show the results of the LCS X-ray generation and the LCS X-ray imaging.

For the LCS X-ray imaging experiment, we employ a commercial passively mode-locked diode pumped solid state laser system with maximum average power of 45 W, wavelength of 1064 nm, repetition rate of 162.5 MHz, and pulse duration of 10 ps. The ejected laser beam is passed through a mode matching telescope and injected to a four-mirror enhancement cavity with two concave mirrors to produce a small spot laser beam inside a cavity. The circling intracavity power is determined by measuring the power leaking from a cavity mirror. From this measurement, when the injection power was 24 W, a circulating power of 10.4 kW was obtained.

The cERL is a superconducting test accelerator to demonstrate both low-emittance and high average current operation in an energy recovery linac. The electron beam with bunch charge of 0.36 pC and bunch length of 3 ps was accelerated to 20 MeV and was transported to the collision point. The laser pulses and electron beam must be synchronized to achieve collision. This synchronization is realized with a Hänsch-Couillaud method and a phase locked loop method.

In the LCS X-ray generation experiment, around 7 keV X-ray was generated by collision of 1064 nm laser photons and 20 MeV electrons at an angle of 18 deg. A silicon drift detector (SDD) used for the LCS X-ray observation was placed 16.6 m from collision point. The central energy of 6.91 keV, the FWHM spectrum width of 0.173 keV and detector count rate of 1200 cps was obtained within a detector area, ϕ4.66 mm. From this measurement, the LCS photon flux at the collision point is estimated to be 4.3 x 10^7 photons/sec. We also performed the high contrast X-ray imaging of a hornet by using a 2D photo counting X-ray detector. From the obtained imaging, we confirmed that LCS X-rays from a small source size are useful for phase-contrast X-ray imaging.

Friday, May 27th

I-42

Narrow bandwidth Thomson photon source using laser-plasma accelerators

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Abstract: *Compact, high-quality photon sources at MeV energies are being developed based on Laser-Plasma Accelerators (LPAs). Simulations are presented on production of controllable, narrow bandwidth sources using LPAs. Appropriate pulse shaping and laser guiding of an independent scattering laser are required to realize high photon yield. Plasma optics are considered to tailor the beam divergence in cm-scale distances, reducing photon source bandwidth. Plasma-based methods to decelerate the electron beam after photon production are considered to reduce shielding requirements. Design of experiments combining these elements towards a compact photon source system will be presented.*

Near-monoenergetic photon sources at 1–10 MeV energies offer improved sensitivity at greatly reduced dose for detection and characterization of nuclear materials, contraband, and for other applications including industrial and medical radiography. Many of the issues with current broad-bandwidth photon sources, including unnecessary dose and restricted operations, can be resolved using near-monoenrgetic sources with the ability to select photon energy, energy spread, flux, and pulse structure. Many applications of near-monoenergetic photon sources have been limited by the size of the required electron accelerator, scattering laser, and electron beam dump.

To enable new applications outside of fixed facilities, compact tunable near-monoenergetic photon sources are desired with narrow divergence to allow high spatial resolution and dose control, and to reduce need for collimation. Thomson scattering of a laser from an electron beam is a well-established, tunable, and narrow divergence source (also referred to as Compton Scattering or Inverse Compton Scattering) whose application is currently limited by the need for high-energy electron linacs, which are large fixed facilities using conventional technology. More compact accelerators producing electron beams with hundreds of MeV energies, suitable for application needs of 1–10 MeV photons, are now possible using cm-scale laser-plasma accelerators (LPAs).

Heavy shielding is conventionally required due to the high electron beam energy in Thomson sources. The low photon production cross section of Thomson scattering has also required either high electron current (and thus heavier shielding) or large scattering lasers. Therefore it is critical to also develop techniques to reduce shielding needs and scattering laser size, which can dominate overall system size and weight, as the electron accelerator is made more compact.

In this talk, we show how a compact high-flux Thomson scattering source can be achieved by integrating a high-quality LPA with techniques for efficient scattering. In addition, it is shown how plasma-based techniques can be employed to decelerate the electron beam to low energy after photon production, greatly reducing shielding requirements.

Short-pulse x-ray beams driven by intense laser pulses and their applications

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Abstracts: *Ultrashort x-ray/gamma-rays from laser-plasma interaction are important radiation sources for applications to ultrafast spectroscopy, time-resolved nanoscopy and photonuclear excitations. Here, we present the developments of x-ray/gamma-ray sources from x-ray lasers, betatron radiation and Compton backscattering. In addition, we report the enhancement of the resolution of x-ray coherent diffraction imaging realized by introducing sharp phase gradient in samples illuminated with an x-ray laser at 13 nm.*

Short-pulse x-ray sources have become indispensable diagnostic tools for new material development, condensed matter physics and bio technology. During the past decade extensive progresses have been accomplished in the field of radiation sources based on laser-plasma interactions - x-ray lasers, betatron x-ray radiation and all-optical Compton gamma-rays. Rapid advancement of high intensity laser technology has prompted the investigation of relativistic laser-plasma interactions. At CoReLS two PW Ti:Sapphire laser beamlines with peak powers of 1.0 PW and 1.5 PW were developed and successfully applied to generate stable multi-GeV electron beams. Recently we observed MeV betatron gamma-ray beams in the laser wakefield electron acceleration with the PW laser. We plan to carry out the Compton backscattering to generate MeV gamma-rays from the interaction of a GeV electron beam and another PW laser beam. Here, we present the recent progress in the development of radiation sources based on laser particle acceleration and the plan for developing Compton gamma-ray sources driven by the PW lasers.

The plasma-based soft x-ray laser is one of useful x-ray sources having a large number of coherent soft x-ray photons sufficient for a single shot probe to observe non-repetitive and irreversible phenomena. We developed a Ni-like Ag x-ray laser pumped by a single-profiled pumping pulse in the GRIP scheme and successfully applied it to coherent x-ray diffraction imaging. We developed a method to enhance the spatial resolution of the coherent diffraction imaging by introducing steep phase variation in a sample. From the diffraction signal of the sample with steep phase variation, the sample image was successfully reconstructed with a resolution of 22 nm, close to the diffraction limited resolution. In this presentation, we also report the progress of coherent x-ray imaging obtained with soft x-ray lasers.

I-44

Ultrahigh brilliance X- and γ-rays generation based on laser wakefield accelerators at SIOM

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Abstracts: *We presented the latest experimental results of X- and γ-rays generation via three different schemes such as betatron radiation, synchrotron radiation with an undulator, and inverse Compton scattering based on a high-quality laser wakefield accelerator which was powered by a 1-Hz 200-TW femtosecond laser facility at SIOM.*

In a laser wakefield accelerator (LWFA), a relativistic femtosecond laser pulse can excite a plasma-density wake with ultra-high accelerating fields reaching 100 GV/m, in which trapped electrons can be accelerated to GeV-class over a distance of centimeter-scale. Remarkable progress has been made over the past decade in generating quasi-monoenergetic e-beams with energies extending up to multi-GeV, making the LWFA promising as a compact accelerator, which will have potential applications, such as x-ray free electron lasers, γ-ray radiation sources and particle colliders.

In this report, we presented the latest experimental results of X- and γ-rays generation via three different schemes such as betatron radiation, synchrotron radiation with an undulator, and inverse Compton scattering based on a high-quality cascaded LWFA which was powered by a 1-Hz 200-TW femtosecond laser facility at SIOM. The cascaded LWFA developed at SIOM has the ability to generate tunable high-quality e-beams (<1% rms energy spread, ~ 50 pC at the peak energy tunable from 200 to 500 MeV, < 0.4 mrad rms divergence), which were used to generate compact femtosecond X-ray sources. By employing a self-synchronized all-optical Compton scattering scheme, in which the electron beam collided with the intense driving laser pulse via the reflection of a plasma mirror, we produced tunable quasi-monochromatic MeV γ-rays (33% full-width at half-maximum) with a peak brilliance of ~3.1×10^{22} photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% BW at 1 MeV, which is one order of magnitude higher than ever reported value in MeV regime to the best of our knowledge. By manipulating the plasma density distribution, we obtained betatron radiation at several-tens keV controllable in yield and peak energy. Besides, an experimental setup for developing intense coherent x-ray radiation sources using the high-quality LWFA electron-beams, a linear transport system consisting of seven quadrupoles to focus the electron beam and one dipole for generating the dispersion, and a 6-meter-long undulator with a period of 2 cm has been recently assembled. The synchrotron radiation at ~30 nm based on the LWFA electron-beams has been detected in the first-phase experiments.

O-19

Laser-plasma accelerator driven soft-x-ray free-electron laser using beam phase-space manipulation

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Abstract: *Laser-plasma accelerators (LPAs) are a compact source of fs electron beams with kA peak currents and low (sub-micron, normalized) transverse emittance. Presently, the LPA beam energy spread (percent-level) hinders application to a free-electron laser (FEL). We discuss methods of beam phase-space manipulation after the LPA to achieve FEL lasing for experimentally demonstrated LPA electron beam parameters. We describe the application of a plasma-based lens for beam capture after the LPA and emittance preservation during transport to the FEL. Design of a demonstration LPA-driven FEL experiment will be presented. Methods of optical injection to improve the LPA beam brightness will also be discussed.*

Laser-plasma accelerators (LPAs) have the ability to generate ultra-high accelerating gradients (>10 GV/m), several orders of magnitude larger than conventional accelerators, and are actively being developed as compact sources of energetic electron beams. Electron beams with energies up to several GeV have been experimentally demonstrated using high-intensity lasers interacting in centimeter-scale plasmas. The electron bunches emerging from a laser-plasma accelerator are naturally short (of the order of a few fs, determined by the plasma wavelength), and intrinsically synchronized to the laser driver, making such a source ideal for ultra-fast science applications.

LPAs deliver high peak current beams (> kA) with low (sub-micron, normalized) transverse emittance, and, hence, it is natural to consider LPA beams as drivers for free-electron lasers (FELs). Although the 6-dimensional beam brightness of the LPA electron beam can be comparable to, or better than, state-of-the-art photo-cathode sources, the FEL application of LPA beams is presently hindered by the beam energy spread (few percent). Application of LPAs to FELs may be accomplished, using experimentally demonstrated LPA beam parameters, by beam phase-space manipulation and redistribution following the LPA. Longitudinal beam decompression, thereby reducing the beam slice energy spread, provides a path to FEL lasing. Transverse dispersion of the beam, coupled to a transverse gradient undulator may also be considered to mitigate the effects of the LPA beam energy spread.

Given the electron beam phase space characteristics exiting the LPA (large divergence and energy spread), beam transport presents a technical challenge, particularly in terms of beam quality preservation. Application of a plasma-based lens (capable of producing focusing field strengths >3000 T/m) for rapid beam capture and transport following the LPA greatly improves beam emittance preservation from the LPA to the FEL. A soft-x-ray FEL can be realized using experimentally demonstrated LPA beam parameters by employing plasma-based lenses for capture and a chicane for beam decompression. Shorter wavelength LPA-driven FELs may be realized using optical injection to improve the LPA beam brightness.

O-20

Tunable polarization plasma channel undulator for narrow-bandwidth photon emission

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Abstracts: *An undulator based on control of the focusing forces inside a laser-plasma accelerator is proposed. Controlling the focusing force is achieved by inducing laser pulse centroid oscillations in a plasma channel. The period of such a plasma undulator is proportional to the Rayleigh length of the laser pulse and can be sub-millimeter. The electron trajectories inside the plasma undulator are examined, expressions for the undulator strength are presented, and the spontaneous radiation is calculated. Multimode and multicolor laser pulses are considered for greater tunability. Effortless polarization control of the emitted light is demonstrated.*

Synchrotron radiation produced by the electrons travelling in bending magnets or insertion devices is essential for our understanding of the microcosm. X-ray pulses produced by the synchrotron facilities are widely used in, for example, chemistry, biology and material science. The brightest X-ray pulses are generated using the free- electron lasers (FELs) - a combination of a high-quality linear accelerator (LINAC) and magnetic undulators. Presently, the lower limit to the undulator period λ_u for magnetic undulators is on the order of 1 cm. Reducing λ_u is highly beneficial as it will decrease the required electron energy for the same specified radiation wavelength and, hence, decrease the size of the light source. Undulators with periods on the order of a millimeter, often referred to as micro-undulators, are, therefore, of great interest.

In this report, we propose a novel type of the undulator for the narrowband photon emission based on the laser pulse centroid oscillations inside a plasma channel. It has been theoretically shown [1] that the electrons injected into the wakefield created by the laser pulse undergoing centroid oscillations inside a parabolic plasma channel, wiggle with the characteristic wavelength of $\lambda_u=2\pi Z_R$, where Z_R is the Rayleigh length of the laser pulse. It is theoretically possible to achieve high undulator strength $a_u\sim 1$ for undulator periods of 1mm or less. This makes such a plasma undulator or plasma wiggler (PIGGLER) a promising way towards a "table-top" bright incoherent soft X-ray source, and, theoretically a "table-top" FEL with tunable polarization.

Using linear plasma theory and numerical simulations, the field structure of the plasma undulator is examined, electron trajectories and emitted radiation are calculated. Polarization control, achieved by the laser pulse injection into the parabolic channel off-axis and under some angle, is demonstrated. Additional control using higher-order Hermit-Gaussian laser modes is proposed. Analytical calculations are supported by the Particle-in-Cell (PIC) simulations. Beam loading and dephasing effects are discussed.

O-21

Achieving Laser Wakefield Accelerated Electron Beams of Low Enough Energy Spread for an X-FEL

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Abstracts: *We describe a method to obtain sufficiently low energy spread laser-wakefield accelerated electron beams for injection into a conventional undulator to obtain free electron lasing. This is done by the combination of two laser pulses and a tailored gas density profile. A moderate power laser is used to inject electrons into the wakefield which are then accelerated to sufficient energies for injection and further acceleration in a wakefield generated by a second more powerful laser pulse. If the electron bunch is accelerated to 1 GeV, an energy spread of ~0.1% is possible. The realization of such a bunch would make possible the construction of a compact x-ray free electron laser.*

Since the proposal for the laser wakefield acceleration of electrons [1], great progress has been made towards achieving such compact accelerators (see [2] and references cited therein). However, such beams do not yet have small enough energy spread and transverse emittance for efficient lasing in an x-ray free electron laser (X-FEL). In this paper we will address the issue of achieving such a sufficiently small energy spread. The concept involves the use of staging. In the first stage electrons are injected into the wakefield behind a moderate power laser pulse with a steep density gradient [3-5]. The density gradient allows us to control into which bucket the electrons are injected. After the injection the electrons are accelerated in a lower density plasma. The possibility to obtain high quality beams using such a combination has been shown previously [4]. By controlling the length of the acceleration we can obtain a minimal energy spread. We show this using 2D particle-in-cell simulations (PIC) [6]. After achieving electron bunches with energies of 26 MeV and energy spreads of ~5%, we propose further accelerating the bunches in a lower density plasma with a second more powerful laser. The key to achieving GeV level energy bunches with small energy spreads near 0.1% is the proper phase matching of the electron bunch into the wakefield. We show this using 1D theory [7]. Such beams would be a step closer towards achieving the goal of a compact X-FEL.

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Poster Session

18:00-20:00 Tuesday, May 24th

P-1

Betatron x-rays from laser-wakefield accelerators: a novel probe for time-resolved HED science experiments.

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Abstract: We present recent experiments on the development and use of betatron x-ray radiation for high energy density science experiments. This source, driven by laser-wakefield accelerated electrons, is broadband (1-100 keV), collimated (mrad), and ultrafast (sub-picosecond). The experiments were performed at the Linac Coherent Light Source (LCLS) and the Jupiter Laser Facility (JLF).

High Energy Density science laser and free electron laser facilities such as LCLS, SACLA, LFEX, OMEGA, or the National Ignition Facility are now uniquely able to recreate in the laboratory conditions of temperature and pressure that were thought to be only attainable in the interiors of stars and planets. To diagnose such transient and extreme states of matter, the development of efficient, versatile and fast (sub-picosecond scale) x-ray probes with energies larger than 50 kilo-electronvolts has become essential for HED science experiments. Betatron x-ray radiation, a source driven by laser-wakefield accelerated electrons, holds great promise in this field of research. We present recent experiments performed at the LCLS at SLAC and JLF at LLNL. At JLF, we used the Titan laser (150 J, 1 ps), showing evidence of betatron x-ray production in the self-modulated regime of laser wakefield acceleration (SMLWFA). Although Betatron radiation has been observed with picosecond-scale lasers in the direct laser acceleration regime, for normalized vector potentials a_0 greater than 10, this experiment constitutes the observation of Betatron radiation in the SMLWFA regime, for $a_0 \sim 1$-3. This was made possible by the addition of a long focal length optics (F/10), favorable for guiding laser pulses in gas targets. We will show a detailed Betatron x-ray source characterization, as well as electron spectra above 200 MeV and forward laser spectra indicating a strongly self-modulated laser wakefield acceleration regime. At LCLS, we have recently commissioned the betatron x-ray source driven by the MEC short pulse laser (1 J, 40 fs). The source is used as a probe by investigating the X-ray absorption near edge structure (XANES) spectrum at the K- or L-edge of several materials (iron, aluminum, silicon oxide) driven to a warm dense matter state (temperature of a few eV, solid densities). The driver is either LCLS itself or optical lasers. With these experiments we are able to study, with subpicosecond resolution, the electron-ion equilibration mechanisms in warm dense matter.

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P-2

Polarization measurements of odd and even low order harmonics for magnetism studies and FEL seeding

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Abstract: *Elliptically polarized light has a promising position in applications based on dichroism effects. Here we present a detailed study of the polarization properties of low order harmonics using a cross-polarized two-color laser field. The results show a high degree of polarization and, particularly, a significant degree of ellipticity. These, in addition, are fundamental investigations for another high potential application: the seeding of free-electron laser using harmonics.*

Recently, elliptical polarization through efficient high-order harmonic generation (HHG) in gas was observed. In this technique, highly coherent odd and even order harmonics, up to 70 eV, were generated using a cross-polarized two-color (ω + 2ω) laser field [1]. This result sets up a great outlook for various applications based on dichroism effects. Here, we present extended results to low order harmonics, which show, in addition, that a high degree of polarization is obtained.

HHG has also a high potential as a method of seeding free-electron laser (FEL) since the harmonics transfer its coherence properties to the FEL pulse. In our two-color configuration, the harmonic content is doubled and a higher number of photons is produced, which makes it an ideal source for seeding. In this regard, low-order harmonics, for which the corresponded FEL gain is considerably higher than for high order harmonics, were previously studied [2]. However, in this study, no analysis of the harmonics' polarization was performed.

The experiment was conducted at *Laboratoire d'Optique Appliquée (LOA)* using a 1 KHz laser system with a duration of 40 fs and a wavelength of 800 nm. More specifically, we investigated the degree and type of polarization of completely isolated low order harmonics, in particular the 3ω and the 4ω. Indeed, these harmonics can be spectrally isolated easily, using interferential filters, and then, their signals can be directly measured on a photodiode (without any gratings, focusing mirrors and CCD camera). To characterize experimentally the polarization properties, the Stokes' parameters [3] (S_0 to S_3) are evaluated through an entirely optical technique, for which a half waveplate, a fixed polarizing mirror and an analyzer are employed. For different rotation angle positions of the half waveplate, the analyzer rotates around the harmonic beam propagation axis, acquiring the harmonic signal on the photodiode. S_1 and S_2 give information on the linear polarization and S_3 on the degree of elliptical polarization. The analysis of the harmonics' polarization showed that the harmonics are fully polarized with a significant degree of ellipticity and that the helicity of consecutive harmonics can be different.

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P-3

A 10-Hz short pulse CO_2 laser system for extreme ultraviolet source

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Abstracts: *We produced 3−15 ns pulses at 10.6-μm wavelength required to driver an efficient short wavelength in extreme ultraviolet (EUV) and soft x-ray emission. A master oscillator power amplifier (MOPA) laser operated at a repetition rate of 10 Hz was built on transversely excited atmospheric pressure (TEA) CO_2 mediums with a Q-switched oscillator and a multi-pass amplifier. An optical semiconductor switch was employed to slice the pulse from the oscillator, in order to produce short pulses less than 15 ns. The output energies of the MOPA were 150 and 50 mJ per pulse at the pulse durations of 15 and 3 ns, respectively.*

The great interest of laser-produced high-*Z* plasmas is that the overlap in adjacent ion stages could yield intense unresolved transition arrays (UTA) lying within reflectance bandwidth of a multilayer mirror. This scheme can realize a powerful micro light source with a short wavelength. The ion stage distribution and density play a crucial role in the transport of radiation through the plasma due to opacity effects. The production of low-density plasma by use of CO_2 (carbon dioxide) laser-produced plasmas (LPPs) has been proposed. However, behavior of CO_2 LPP sources has been investigated with a long pulse duration longer than 15 ns. In this study, we generate 3−15 ns pulses CO_2 laser at 10.6-μm wavelength in order to investigate LPP sources for high resolution lithography and lab-scale soft x-ray imaging systems.

We show the production of short pulse CO_2 laser based on TEA gain mediums. The laser system consists of a *Q*-switched master oscillator and 14-pass amplifier, and operates at a repetition of 10 Hz. These laser units were modified by replacing internal cavity mirrors with ZnSe windows. The oscillator is an electro-optic (EO) *Q*-switched ring cavity with a TEM_{00} beam as the seeder for the multi-pass amplifier. In order to produce the short pulse less than 15 ns, the pulse slicing technique was used by the optical switching in the Ge substrate, which is coupled the short pulse solid-state laser at a wavelength of 1 μm for carrier production on the surface of Ge substrate. Two Nd:YAG lasers have been operated at 1064 nm produced maximum pulse energies of 5 mJ for a pulse duration of 150 ps (FWHM) and 40 mJ at a pulse duration of 10 ns (FWHM), respectively, with the pulse separation time of 40−100 ns between each peaks, keeping the plasma shutter lifetime. It is noted that the typical recombination time is the order of 50 ns. To overcome the short plasma mirror lifetime, two lasers should be irradiated to the Ge substrate. The output energies of the amplifier were 150 and 50 mJ per pulse at the pulse durations of 15 and 3 ns (FWHM), respectively, keeping a high quality beam of the MOPA system. This laser output provides the power density of the order of 10^{12} W/cm^2 and was sufficient to produce the EUV emissions at 13.5 nm and 6.*x* nm.

P-4

Laser Plasma X-ray Source Based on Cryogenic Targets

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Abstracts: *A laser plasma source based on cryogenic targets generating continuously repetitive X-ray pulses has been developed. It has a translating substrate system with a closed He gas cryostat that can continuously supply solid Ar, Kr and Xe targets for 1~ 10 Hz laser pulse, and stable output powers from the plasma emissions were achieved continuously. The average X-ray powers obtained were 19 mW at 3.2 nm, 33 mW at 10.0 nm and 66 mW at 10.8 nm, with 10% bandwidths, from the Ar, Kr and Xe solid targets, respectively, with a laser power of 1 W.*

Laser plasma radiation from high density, high temperature plasma which is achieved by illuminating a target with high-peak-power laser irradiation, constitutes an attractive, high brightness point source for producing X-ray radiation. There have been many studies on application of laser plasma X-ray sources such as X-ray microscopes, EUV lithography, micro processing, etc. To apply these studies in industry, plasma sources, which can generate high average X-ray power with continuous repetitive pulses, not a single shot, is required. Therefore, we have been studying such a continuously emitting plasma source based on a cryogenic target of solid rare gas. The rare gas is considered to be an ideal deposition-free target because of an inert gas, and its chemically inactive debris will vaporize instantly, rather than be deposited on mirrors near the plasma. This is an advantage in a continuous operation. We had also decided to use a cryogenic solid target to provide higher conversion efficiency and higher brightness because of its higher solid density. Additionally, a smaller gas load for evacuation by the exhaust pump system was also expected in the solid state when compared with gas and liquid jets.

To continuously supply cryogenic targets, we originally developed a target supplying system. The one-dimensionally translating substrate system with a closed He gas cryostat that can continuously supply various cryogenic targets for 1 ~ 10 Hz laser pulses has been developed. The system was successfully operated at a lowest temperature of 15 K and at a maximum up-down speed of 12 mm/sec. To supply a fresh target surface for every laser shot and generate stable repetitive X-ray pulses continuously, we studied optimum parameters of a translation speed and a gas flow rate for a laser frequency. Under the optimum conditions, we succeeded in supplying Ar, Kr and Xe solid targets continuously and demonstrated continuous generation of laser plasma emission up to a repetition rate of 10Hz, produced by a commercial Nd:YAG Q-switched rod laser.

The observed spectral peaks for the Ar, Kr and Xe targets are at 3.2, 10.0 and 10.8 nm. When the targets were irradiated with 1 J energy pulses at 1 Hz, the spatially integrated average powers with the 10% bandwidth were roughly estimated to be 19 mW at 3.2 nm, 33 mW at 10.0 nm and 66 mW at 10.8 nm, for the Ar, Kr and Xe solid targets, respectively. The solid Ar target emits strongly the soft X-ray in “water window” between 2.3 nm and 4.4 nm used for microscopy applications, and its power was estimated to be more than 100 mW. In this paper, we will show the details of characteristics of our developed X-ray source.

P-5

Characteristics of water window soft x-ray emission from dual laser-produced Bi plasmas

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Abstracts: *We characterized the water window soft x-ray emission from highly charged Bi ion plasmas produced by dual laser pulse irradiation for laboratory-scale single-shot x-ray microscope. The flux in water-window soft x-ray spectral region was increased at the pulse separation time of 8–10 ns and decreased at the pulse separation time around 100 ns, which was attributed to long scale length electron density gradient with the opacity effect, supporting by the hydrodynamic numerical simulation. The source size, which was measured by an x-ray pinhole camera, was almost same as the single pulse irradiation at the optimum separation time of 8 ns.*

Development of shorter wavelength sources in the extreme ultraviolet (EUV) and soft x-ray spectral regions has been motivated by their application in a number of high profile areas of science and technology. One such topic is the challenge of three-dimensional imaging and single-shot flash photography of microscopic biological structures, such as cells and macromolecules, *in vivo*. For x-ray microscopy, the x-ray source should emit a sufficient photon flux to expose the image of the biological sample on the detector. However, the total collected energy is low, when one combines the narrow line emission with the low reflectivity of the collector mirror. As a result, long exposures are needed to record an image and there is not yet published evidence of single-shot exposures using a laboratory-scale source. To overcome the low flux sources, we propose using high power water-window soft x-ray emission from laser-produced high-*Z* plasmas [1], analogous to the scheme used for efficient, high-volume manufacturing EUV sources. In addition, the dual laser pulse irradiation scheme would allow the effective utilization of the main laser pulse energy to heat a preplasma, which would otherwise be wasted to ionize the target material [2].

In this report, we characterize the water window soft x-ray emission from highly charged Bi ion plasmas produced by dual laser pulse irradiation. The spectral structure and spectral intensity in 1.5–2.5 and 3.5–4.5 nm were changed at various pulse separation times. The flux in water-window soft x-ray spectral region was increased at the pulse separation time of 8–10 ns and decreased at the pulse separation time around 100 ns, which was attributed to long scale length electron density gradient with the opacity effect, supporting by the hydrodynamic numerical simulation. The source size, which was measured by an x-ray pinhole camera, was almost same as the single pulse irradiation at the optimum separation time of 8 ns, resulting in 1.2 times as large as that produced by a single pulse. In the water-window soft x-ray microscope, the enhancement of the image intensity was reproduced by dual laser pulse irradiation at the pulse separation time of 8–10 ns.

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P-6

Photon flux Monte-Carlo estimations for linac-based laser-electron X-ray generators.

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The idea that laser beam Thomson scattering by relativistic electrons can be a route to X-ray generator to be used in medicine, science and industry appeared in nineties [1]. To increase X-ray yield laser beams can be stored in a cavity and reused. The electrons can be delivered by a linac or a cyclic accelerator. Early experimental study and applications of Thomson X-ray sources utilizing specially constructed linacs have been done by several groups [2-4]. Since then this research field considerably expanded. The efforts to build Thomson X-ray sources more efficient and appropriate for various applications are summarized in [5]. Such X-ray sources are expected to fill in the gap existing between conventional Roentgen tubes and large accelerator based facilities in respect of X-beam intensity, tunability, size, power supply, cost etc [6]. In this paper we present an approach to evaluation, design and conceptual choice of main components of linac-based laser-electron X-ray generators including lasers and photon storage device. The goal can be a multi-purpose facility as well as the one dedicated to definite application. In the latter case the X-ray photon flux in certain spectral and angular widths at a given sample area must be provided.

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P-7

MHD Simulation of Various Cross-Section Capillary Discharges

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Abstract: *The capillary discharges are widely used in experiments on the x-ray lasers and laser wakefield acceleration because of the emerging inside the capillary specific plasma density profile needed for these studies. The utilized capillaries typically have circular cross-section. Such configuration was thoroughly studied theoretically and using MHD computer simulations. Another possible capillary cross-section is a square one, which attracted less attention, but is more convenient for plasma diagnostics. Here we present the results of the MHD simulations of the square and circular capillary discharges and compare the established plasma density profiles.*

Many experiments on the laser based electron acceleration and on x-ray laser generation use capillary discharges as a simple and robust way to create plasma with required parameters. A majority of the experiments implement the capillaries with circular cross-section. Such capillary cross-section significantly simplifies the theoretical and computer simulations studies, reducing the dimensionality of the problem and allowing the use of 1D computer codes. On the other hand, the square cross-section capillaries, which attracted significantly smaller attention, are advantageous from the point of view of plasma diagnostics and fabrication. Here we present for the first time the results of the dissipative MHD simulation of the capillary discharges with various cross sections.

We use 3D RMHD code MARPLE (KIAM, RAS) for discharge simulation in the capillaries with different section. We present the simulation results showing the plasma dynamics and the electric current and magnetic field evolution in different capillaries.

P-8

Progress on the development of single-order diffraction grating for soft x-rays

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All existing x-ray dispersive devices including crystals, multilayers and diffraction gratings generate spectra in multiple orders, whereas soft x-ray spectroscopy applications usually require only the first order spectrum. The other diffraction orders can overlap and contaminate the first order spectrum of interest. Such issue is also crucial for synchrotron beam line monochromatization. Higher-order diffractions of diffraction grating may introduce boring higher-order harmonic contamination to the beam when it is used as a monochromator. Here in this presentation the authors report their achievements and progress on the development of single-order diffraction grating for soft x-rays.

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Spectrally-Resolved Spatial Interference for Single-Shot Temporal Metrology of Ultrashort X-Ray Pulses

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Abstract: *So far, plasma-based soft X-ray lasers seeded by high harmonics have only been temporally characterized using streak cameras, with a 1-ps temporal resolution. However, theoretical and experimental studies showed that sub-ps seeded soft X-ray lasers are achievable. Existing methods do not provide enough information or require multiple shots, needing stable sources. In this work, we theoretically propose a single-shot method to characterize ultrashort soft X-ray pulses, based on spectrally-resolved spatial interference between an unknown pulse and a reference high-harmonic pulse. High harmonics have already been characterized, providing enough information to extract the unknown spectral phase from the 2D interferogram.*

P-10

Characterization of ion plumes generated by laser-driven intense extreme ultraviolet (EUV) light

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Abstracts: Material ablation caused by a laser-driven, intense extreme ultraviolet (EUV) light pulse was studied in comparison with that caused directly by laser under the same irradiance and time-duration. Ionic states and expansion energy of ablation material were measured with an ion analyzer. Ions of single ionization state were observed for the EUV ablation whereas those of multiple ionization states were for the laser ablation. The experimental results were compared with simulations made with a radiation hydrodynamic code to infer difference in density and temperature of energy deposition.

Extreme ultraviolet (EUV) light source has attracted much attention in material processing, e.g. surface modification[1] or nano-scale machining.[2] The physics of EUV material ablation followed by plasma formation are expected to be quite different from that of conventional laser ablation. It is thought that EUV light can penetrate though an expanding low-density plasma and directly deposit its energy into a dense region at the ablation front via photoionization or collision with electrons generated by the ionization because of its high photon energy ($h\nu$~100 eV) and high critical density beyond solid density (~10^{24} cm^{-3}).[3] However mechanism of material heating and plasma characteristics is not fully understood. Thus, this study aims, first at characterization of the material ablation induced by intense EUV light, and second clarifying difference of EUV ablation behavior from that with laser in order to deepen understanding the underlying physics in material heating and plasma formation.

An EUV pulse (9-25 nm in wavelength, 10 ns in duration, and 10 Hz repetition rate) emitted from laser-generated Xe plasma was focused onto the surface of a silicon plate by a total-reflection toroidal mirror overcoated with Au. EUV energy per pulse was 13 mJ, spot size was ~ϕ200 μm, and intensity on the plate was ~4×10^{9} W/cm^2. We measured ionic states and energy distributions of corresponding ions expanding from the plasma with a Thomson Parabola mass-charge analyzer. In the analyzer, magnetic and electric fields are applied perpendicular to ion trajectory. We conducted identical experiment with a Nd:YAG laser at the same irradiation parameters for comparison.

Only singly charged ions were detected in the EUV ablation whereas multiple states ranging from Z=1 to 3 were detected in the laser ablation. Plasma parameters such as pressure, temperature, density, and average charge state of ion were calculated by Star1D code [4]. Comparison of the experiments with simulations showed that electron temperature of energy deposition region tends to be lower for the EUV ablation, resulting in singly charged ions.

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P-11

Development of soft X-ray microscope in Water Window using laser produced plasma light source

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Abstracts: *A SX microscope using a laser produced plasma (LPP) light source with heavy metal targets was developed to explore the optimum conditions of the LPP light source in Water Window wavelength region and to examine observation possibility of hydrated bio-cells.*

Wavelength region from 2.3 nm to 4.5 nm is known as Water Window. The light in Water Window wavelength region is suitable to observe bio-cells because it is transparent in water and is absorbed by carbon and nitrogen atoms. Therefore, images of bio-cells show absorption contrast in Water Window wavelength region. Recently, LPP light source using heavy metal target generates broad spectral and high intense light in SX wavelength region [1]. Especially, wavelength regions of the emissions from the plasma using Au, W, Pb, and Bi metal targets are in and around Water Window. Therefore, the LPP light source using these metal targets will become one of SX light sources to observe bio-cells. The purpose of our study is that a SX microscope using the LPP light source with heavy metal targets to explore the optimum conditions of LPP light source in Water Window wavelength region and to examine observation possibility of hydrated bio-cells by the use of the SX microscope.

In this study, a contact-type microscope using a scintillator plate was developed. With the use of the scintillator plate which shows high quantum efficiency and linearity in SX region, SX images can be observed instantly by a visible (VI) microscope. As the results of these features, SX images can be directly compared with VI ones changing the irradiation light.

To demonstrate the performance of the developed microscope, polystyrene beads in water were observed changing the thickness of the water. The diameters of the polystyrene beads in water were 1 μm and 0.4 μm. The thickness of the water was gradually changed from 1.3 μm to 5 μm. The plasma was excited by Nd:YAG laser using a Bi target. The SX light from the LPP light source penetrates the water layer from 1.3 μm to 2.3 μm thick, and the diameter 1 μm of the polystyrene beads was observed.

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P-12

DNA Damage Studies with a Compact Laser Plasma Soft X-ray Source

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Abstracts: *Application of a compact laser plasma source of soft X-rays in radiobiology studies is demonstrated. The source is based on a gas puff target approach. It allows irradiation of biological samples with X-ray pulses in the "water window" spectral range in vacuum or helium atmosphere at very high-dose rates and doses exceeding the kGy level. The source has been used to study strand breaks in DNA plasmids.*

The radiation damage of biological systems with soft X-ray radiation has been routinely studied to understand the mechanism of ionizing radiation effects at the cellular and sub-cellular levels, especially in DNA. It was shown that the biological damage produced by this low energy radiation is more effective as compared with higher energy radiation. The conventional X-ray tube has been the most widely used source of soft X-rays for these studies, however, such sources deliver radiation to the sample at a low dose rate, and thus a relatively long irradiation time is needed to induce measurable biological effects. Synchrotrons, emitting radiation in the soft X-ray spectral region, are recognized as the state-of-the-art facilities for cutting-edge experiments with relatively high photon flux and therefore have become useful for radiobiology studies. However, these facilities offer limited accessibility, and have high operating and maintenance costs. Clearly, this field of study can be broadened by the availability of laboratory sources with similar characteristics for routine radiobiology experiments.

A compact laser plasma source of soft X-rays developed for radiobiology studies is presented in this report. The source is based on laser plasma produced as a result of irradiation of a double-stream gas puff target with nanosecond laser pulses from a commercially available Nd:YAG laser. The source allows irradiation of samples with soft X-ray pulses in the "water window" spectral range (wavelength: 2.3–4.4 nm; photon energy: 280–560 eV) in vacuum or helium atmosphere at very high-dose rates and doses exceeding the kGy level. Single strand breaks (SSBs) and double strand breaks (DBSs) induced in DNA plasmids pBR322 and pUC19 have been measured. The different conformations of the plasmid DNA were separated by agarose gel electrophoresis. An exponential decrease in the supercoiled form with an increase in linear and relaxed forms of the plasmids has been observed as a function of increasing photon fluence. Significant difference between SSBs and DSBs in case of wet and dry samples was observed that is connected with the production of free radicals in the wet sample by soft X-ray photons and subsequent affecting the plasmid DNA. Therefore, the new source was validated to be useful for radiobiology experiments.

P-13

Spectral Investigation of Photoionized Plasmas Induced by Nanosecond Pulses of Extreme Ultraviolet (EUV)

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Abstracts: *Investigations of plasma produced by photoionization of gases by nanosecond EUV pulses are presented. EUV radiation is generated using laser plasma sources based on a gas puff target, irradiated with nanosecond laser pulses from a Nd:YAG laser. Spectral measurements in EUV/VUV ranges have been performed. The results of the studies are presented.*

Plasma of different form is a common state of matter in Space. One of these forms is a photoionized plasma created by irradiation of interstellar gas with extreme ultraviolet (EUV) radiation. Spectral investigation of EUV photoionized plasma provides information concerning the irradiating sources. Laboratory studies of photoionized plasmas can assist with interpretation of similar plasmas existing in Space. This kind of investigation is called laboratory astrophysics and experiments concerning photoionized plasmas created in accretion discs were performed using high energy density (HED) facilities: high power Z-pinch or high power laser systems.

Similar experiments have been recently performed in our laboratory using laser plasma EUV sources. EUV beams were formed with the use of a grazing incidence axisymmetrical ellipsoidal mirror focusing radiation to a spot with a diameter of about 1 mm. Two kinds of laser plasma sources with different parameters of EUV beams were employed. First of them was based on a compact 0.8 J Nd:YAG laser allowing to obtain EUV fluence in the focal spot of approximately 50 mJ/cm^2. The second one was based on a 10 J Nd:YAG laser system and providing about 5 times higher EUV fluence. In both cases photoionized plasmas were created by irradiation of different gases injected into the focus region synchronously with the EUV pulses. Spectra in the EUV/VUV range were measured using a grazing incidence, flat-field spectrometer (McPherson Model 251), equipped with a 450 lines/mm toroidal grating. The spectra for various gases irradiated with EUV pulses at different parameters were registered. Significant differences between spectra, corresponding to the same gases, obtained for different irradiation conditions, were revealed. The atomic processes dominating in the photoionized plasmas and responsible for the spectral differences were qualitatively discussed.

P-14

Ablation of LiF and CsI by EUV Nanosecond Laser Pulse

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Abstracts: *In this paper we present results of study interaction of nanosecond EUV laser pulses at wavelength of 46.9 nm with lithium fluoride (LiF) and caesium iodide (CsI) samples. The laser beam is focused with a spherical Si/Sc multilayer coated mirror on samples. Samples was irradiated by 1, 2, 5, 10 and 20 laser shots at various fluence values. At the same time laser ablation plumes were observed. Ablation craters on the surface of the LiF and CsI samples were analysed by atomic force microscope (AFM).*

Laser ablation using nanosecond pulses have been studied extensively since 1960s. The laser-target interaction involves many processes, including heating, melting, vaporization, ejection of particles, and plasma creation and expansion. The depth of laser ablation crater over which the laser energy is absorbed, and thus the amount of material removed by a single laser pulse, depends on the material's optical properties and the laser wavelength and pulse length. Usually, plasma cloud induced by laser irradiation consists of excited or ground-state neutrals, electrons, and ions. The properties of the plume, e.g. the mass distribution, ion and atom velocity, and the angular distribution of the plume species, play an important role for applications of laser ablation in mass analysis of laser-induced plasma and in the production of thin films by pulsed laser deposition. Focused visible/IR laser pulses are absorbed in the expanding plasma plume at densities 100 - 1000 times smaller than the solid density. But, EUV laser pulses penetrate into the solid and create plasma directly at the solid density.

In this paper, we investigate an interaction of nanosecond EUV laser pulses with the LiF and CsI samples. As a source of laser radiation was used discharge plasma driver CAPEX (CAPillary EXperiment) based on high current capillary discharge in argon. The laser beam is focused with a spherical Si/Sc multilayer coated mirror on samples. Laser ablation of the samples has been performed by 1, 2, 5, 10 and 20 laser pulses at various fluence values. Subsequently, laser ablation craters were analysed by AFM microscopes. All ablation plumes from the sample surface were registered by photo camera Canon EOS 5D Mark II and macro lens Canon EF 100 mm f/2.8 Macro USM. It was found that even lower laser pulse energy is sufficient for creation of visible ablation plume on the surface of LiF and CsI samples.

P-15

Feature of soft x-ray emission from laser-produced multi-charged Pt ions

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Abstracts: *We characterized strong unresolved transition array emission in carbon window soft x-ray spectral region. Arrays resulting from n = 4–n = 4 (Δn = 0) transitions were overlaid with n = 4–n = 5 (Δn = 1) emission. The emissivity and opacity were evaluated by use of the atomic code of HULLAC, and the plasma parameters and the spectral structure were reproduced by the hydrodynamic code. We also observed the enhancement and decrease of the emissions in dual laser pulse irradiation.*

In the past decade, the development of plasma light sources has progressed rapidly, especially for lithography in the extreme ultraviolet (EUV) region predicated on the development of multilayer mirrors (MLMs) with good reflectivity at specific wavelengths. The 13.5-nm and 6.*x*-nm light sources exploit the advantage that $4p^64d^N$–$4p^64d^{N-1}4f + 4p^54d^{N+1}$ (n = 4–n = 4, Δn = 0) unresolved transition arrays (UTAs) in several charge states appear at almost same wavelength in spectra from laser-produced plasmas (LPPs) of these elements, while transitions of type $4d^{10}4f^M$–$4d^94f^{M+1}$ also make contributions to the 6.*x* nm region. In this regard, it follows that n = 4–n = 4 UTAs from LPPs of other elements could provide light sources at other wavelengths for other applications such as x-ray microscopy in the water window of 2.3–4.4 nm and the carbon window of 4.4–5 nm. We have shown that the strong resonance UTAs of Nd:YAG LPPs for elements with Z = 50–83 obey a quasi-Moseley's law [1]. A laser-produced Bi plasma is one of the candidates for a water window source, whose spectrum was analyzed using Cowan code calculations in a previous work [2]. Laser-produced Pt plasma emission spectra are considered here as a candidate for a carbon window source.

In this report, we characterized strong unresolved transition array emission in carbon window soft x-ray spectral region. Arrays resulting from n = 4–n = 4 transitions were overlaid with n = 4–n = 5 emission. The emissivity and opacity were evaluated by use of the atomic code of HULLAC, and the plasma parameters and the spectral structure were reproduced by the hydrodynamic code. The maximum electron temperature was evaluated to be 600 eV at the peak of the laser intensity of 1×10^{14} W/cm^2 at a laser wavelength of 1064 nm, which was corresponded to the ionic charged state around $q \approx 30$. The scheme would allow the effective utilization of the main laser pulse energy to heat a preplasma, which would otherwise be wasted to ionize the target material. The emission flux was enhanced 1.2 times at the pulse separation time of 8–10 ns as large as that under single laser irradiation. In addition, the flux was decreased at the pulse separation time of 40 ns, related to long electron density gradient and opacity effect. We will open various experimental results and numerical simulation.

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P-16

The observation of transient thin film structures during the femto-second laser ablation process by using the soft x-ray laser probe

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Abstracts: *We have succeeded in the observation of temporal evolution of thin film structures above the solid (or liquid) surface in the femto-second laser ablation process of metals (Au) by using the soft x-ray laser probe. The thin film was smooth and dense (a few nm roughness and near the sold density) so as to work as the soft x-ray beam splitter within 1 ns after the laser irradiation, and the spatial profile of the thin film depended on the local fluence of the femto-second laser. It implies that a possibility to create novel transient soft x-ray optics.*

The dynamical processes of the formation of the unique structures, such as the submicron scaled ripple and bubble structures [1], by the irradiation of the ultra-short pulse lasers come to attract much attention for the novel laser processing. In order to precisely control the laser ablation, the detailed observation of the laser ablation dynamics is required. In this study, we have succeeded in simultaneous observation of temporal evolution of two different surfaces by using the soft x-ray laser (SXRL) probe at the wavelength of 13.9 nm. Fig. 1 (a) shows a snap shot of the interferogram of the ablating surface (= ablation front: AF). The height of AF in the central part was measured to be only 20 nm at t = 78 ps. Fig. 1 (b) shows a reflective image at t = 607 ps. The multiple concentric rings show the Newton's rings generated between the AF and the thin film structure above AF (= expansion front: EF). The Newton's rings were observed until t ~ 1ns. The reflectivity of the soft x-ray strongly depends on the surface roughness and density gradient, therefore it implied that EF was thin (< 10 nm), dense (near a solid), and smooth (roughness < 3 nm) so as to work as the beam splitter for the soft x-ray. EF was kept until t ~ 0.8 μs and the spatial profile of EF depended on the local fluence of the femto-second laser. These results show a possibility to create novel transient soft x-ray optics.

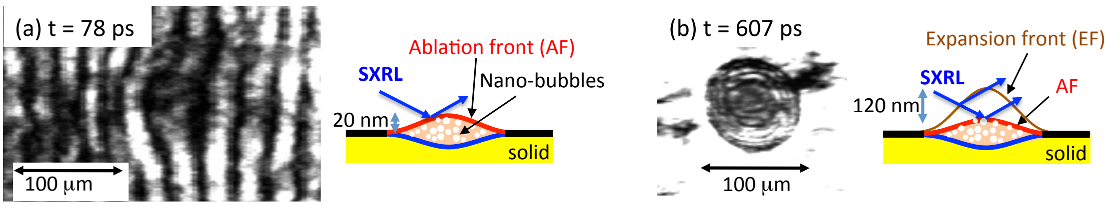

Fig. 1) Soft x-ray interferogram (a) and reflective image (b) of the fs laser ablation process of Au.

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P-17

Proposal of Hypereutectic AlSi- based Multilayer Mirrors for Wavelength between 20 nm and 25 nm

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Abstracts: *A high-thermal stable extreme ultraviolet (XUV) multilayer mirror (MLM) for wavelength region of 20–25 nm has been proposed. Calculated reflectivity of hypereutectic Al-Si based MLM have almost 40-55% in this wavelength region and they have possibility of high-thermal stabilities comparing with that of the conventional pure-Al based MLMs These new MLMs can be used for variety of applications such as high order harmonics, XUV microscopy, and XUV spectroscopy.*

A multilayer mirror (MLM) is one of typical optical device in extreme ultraviolet (XUV) region as a focusing, steering, polarization control, and spectroscopy device. It is well known that a reflectivity of MLM at XUV region is limited to 70% due to the absorption of materials. The absorption coefficient shows a local minimum at the absorption edge. Therefore, absorption edges of lower-materials are taken into account for designing a high-reflectivity MLL, such as Si (k-edge at 12.5 nm) based MLMs for wavelength region around 13-20 nm, and Mg (k edge at 25 nm) for 27–50 nm, respectively [1]. On the other hand, there are limited reports around 20–25 nm, in spite of light flax increasing at HH light source, although Al (K-edge at 15 nm) based MLMs will become the solution in this wavelength region considering the optical constants [2]. However, because of the thermal properties of Al such as crystallization and internal-diffusion, it is difficult to be practically applied for high-flax field.

Hypereutectic Al-Si alloys are one of well-known Al-based alloys on mechanical engineering field, which have high thermal conductivity, wear resistance, and good strength [3]. These properties are important not only for aerospace and electric industries requirements but also for XUV optical devices requirements. In addition, there is a possibility for high-reflectivity MLMs observation considering the absorption coefficient at wavelength region of 20–30 -nm. Figure 1 shows several calculated reflective profiles of MLMs assuming ideal conditions at wavelength around 20–25 nm, Zr/AlSi, Mo/AlSi, Y/AlSi, and C/AlSi, respectively. In the calculations, Al-30wt.%Si was assumed, which is much higher than eutectic value (12.6wt.%). These new high-reflectivity MLMs have possibility to be applied for several practical uses because of its expected higher stability comparing with that of the pure-Al based MLMs.

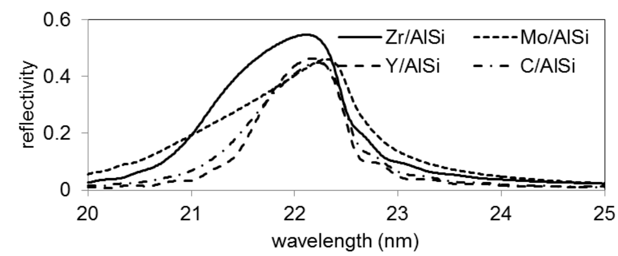

Fig. 1 Calculated reflective profiles of Zr/AlSi, Mo/AiSi, Y/AlSi, and C/AlSi, respectively. Assuming multilayer period is 11.5 nm.

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P-18

HHG beam wavefront characterization at 30 nm

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Abstracts: *For the purpose of characterization and improvement of the HHG (High-order Harmonics Generation) eXtreme Ultra-Violet (XUV) coherent beam emitting at the wavelength of 30 nm we developed an unique wavefront sensor based on the PDI (Point Diffraction Interferometer) technique. A simple self-referencing monolithic device produces interferometric patterns with encoded information about measured beam`s wavefront profile. We will describe the development, fabrication and alignment issues of the sensor as well as real results of the beam characterization measurements and evaluation outcomes.*

P-19

Resonant Betatron Hard X-rays from Ionization Injected Electrons in a Laser Plasma Accelerator

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Abstracts: A new scheme for bright hard x-ray emission via controlled ionization injection is presented. A total photon yield 8×10^8/shot and 10^8 photons with energy over 110 keV are obtained. In particular, the yield is 10 times higher than the case of self-injection mode under similar laser parameters. Simulation suggests that ionization injected electrons are quickly accelerated to the driving laser region and subsequently driven into betatron resonance. The present scheme enable the single stage betatron radiation from LWFA to be extended to bright γ-ray radiation, which is beyond the capability of the 3rd generation of synchrotrons.

Ultrafast x-ray sources have tremendous applications in time resolved x-ray diffraction and x-ray absorption spectroscopy to study the transient properties of condensed matter and biological structures, which have been realized so far mainly by use of x-ray free electron lasers (XFELs) with high brightness. However, XFELs are huge facilities accessible to limited users. With the development of femtosecond high power lasers, laser plasma x-ray sources are becoming increasingly attractive due to their compactness and natural synchronization of drive lasers and produced x-ray sources. X-ray emission from laser plasma interactions, such as Kα x-ray emission, nonlinear Thomson scattering and betatron x-ray sources, have been intensively studied. In particular, the betatron x-ray emission from electron oscillations in the laser wakefield acceleration (LWFA) is a promising source for its high spatial coherence, sound photon yield ($>10^8$/shot) and high photon energy (up to MeV).

In this report, we show the first study of bright hard x-rays based upon ionization-injected electron beams accelerated in LWFA via betatron oscillations. Highly collimated hard x-rays with a photon flux of 8×10^8/shot and with 10^8 photons over 110 keV have been produced with a pure nitrogen gas jet irradiated with 100 TW laser pulses. This yield is about 10 times higher than that obtained with helium gas under similar laser conditions, and much higher than other experiment results reported working in the self-injection mode. Two-dimensional (2D) particle-in-cell (PIC) simulations suggest that the enhanced betatron photon energy and photon flux are due to ionized early injection and effective betatron resonant oscillation in the laser fields.

The experiment was carried out using the hundred TW laser system at the Key Laboratory for Laser Plasmas in Shanghai Jiao Tong University, which delivered 40fs pulses with energy up to 3J in this experiment. The pulses were focused by an f/20 off-axis-parabola onto a 1.2mm × 10mm supersonic gas jet. The focal spot has a $1/e^2$ radius of w_0=21μm containing 50% energy. The resultant laser peak intensity was up to 1.0×10^{19} W/cm^2, corresponding to normalized vector potential a_0=2.2. A top-view system was set to monitor Thomson-scattering. The electron beams emitted from the gas jet were dispersed by a 16cm-long dipole magnet with magnetic field strength 0.98T. A combo of 4 image plates (IP) (Fuji Film SR series) covered with 12μm Al foil was set behind the magnet to record the electron and x-ray signal simultaneously. For comparison, nitrogen and helium gases had been used in the same experiment. In the presentation, we will show the details of the comparison, and the physical mechanism, which plays a critical role but has not included so far.

P-20

Multilayer-based X-ray optics for advanced light source applications

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Abstracts: *Recent developments of high efficiency X-ray multilayer optics and imaging systems in the Institute of Precision Optical Engineering in Tongji University are discussed here. Pd-based multilayers working at the wavelength region of 8-12 nm were developed with a maximum reflectance of 47% at near normal incidence. Cr/V multilayer polarizers working near the wavelength of 2.44 nm in the water window region were fabricated with a high s-polarized reflectance of 24.3%. Multilayer coated blazed grating demonstrates an almost 10 times higher efficiency than the traditional single layer grating at 2-4 keV region. Related X-ray imaging systems for plasma diagnostics will also be discussed.*

Multilayer coatings are vital optical components in the EUV and X-ray wavelength range which enable the reflection beyond the total reflection region. The multilayer mirrors and related optics have experienced significant development in the past years through the improvement of different deposition techniques, a better understanding of the layer growth physics, and the combination with two-, three-dimensional microstructures.

In this report, new developments of X-ray multilayer mirrors and gratings in the Institute of Precision Optical Engineering (IPOE) in Tongji University, China, will be discussed. Pd-based multilayers, like Pd/B_4C and Pd/Y, are ideal material combinations for the 8-12 nm region. They have been successfully fabricated which exhibit a maximum experimental reflectance of 47% at 9.9 nm under 5 degree near normal incidence. Cr/V is the most promising candidate working near the V-L edge (2.42 nm) in the water window region. A Cr/V multilayer polarizer has been demonstrated with a record reflectance of 24.3% (s-polarization) under the grazing incidence angle of 42 degree. Besides the conventional planar mirrors, the multilayer structure has also been combined with gratings, particularly the multilayer coated blazed grating, for high efficiency monochromator in the energy range of 1-4 keV. Through the collaboration with Helmholtz Zentrum Berlin (Germany) and University of Twente (the Netherlands), a high efficiency of 35% -55% was achieved from 2 keV to 4 keV, which is almost 10 times higher than the traditional single layer gratings. Based on the multilayer technology, normal incidence and grazing incidence microscopes were developed in our group for plasma diagnostics. A spatial resolution of several microns down to 100 nm can be obtained.

P-21

Irradiation damage test of Mo/Si, Ru/Si and Nb/Si multilayers using the Soft X-ray laser built at QST

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Abstracts: *The irradiation damage tests for Mo/Si, Ru/Si and Nb/Si multilayer were carried out using X-ray laser generation system built at QST. The created damages were observed by a scanning electronic microscopy and an atomic force microscopy. These observations show that the damage size of Nb/Si multilayer is smaller than the others. This result indicates that Nb/Si is superior than the other multilayers for irradiation damage and thus X-ray multilayer.*

Mo/Si multilayer is one of the most important because of their expected applications for the next generation lithography method, i.e., EUV lithography where the wavelength of 13.5 nm would be used. Recently, the 13.5nm EUV light sources, such as laser produced plasma or X-ray free electron laser, become to have higher output powers and fluences. The high power light sources are effective for high throughput of EUV lithography, but they also make serious problem for damages of Mo/Si multilayer mirrors. These damages are reducing the reflectivity or lifetime of EUV multilayer mirror, resulting in the performance deterioration of the production or measurement using these mirrors and sources. Therefore, the information of damages is important for practical use of Mo/Si multilayer and the future development of high resistance EUV multilayer mirror.

In order to reveal irradiation damage for Mo/Si multilayer, the X-ray laser irradiation system build at Japan Atomic Energy Agency was used. This experiment system has the features; (a) the short time scale for 7 pico-second, (b) narrow bandwidth of ~10^{-4}, (c) small divergence beam and (d) highly brightness. Since the system has an Ag target, 13.9nm EUV light is produced.[1] This system was already used for the observation of irradiation damages of some materials.[2, 3]

The irradiation damage test is applied to Mo/Si, Ru/Si and Nb/Si multilayer. Mo/Si multilayer is usually used around the wavelength of 13.5 nm, and the others are also candidate multilayers for same wavelength. The EUV lights that have fluences of 10-30 mJ/cm^2 are entered into these multilayers.

The damages by irradiations were studied using a scanning electronic microscopy (SEM) and an atomic force microscopy. In these observations, the irradiation damage size of Nb/Si multilayer is smaller than that of the others. This result indicates that Nb/Si multilayer has higher resistance than Mo/Si and Ru/Si multilayer for the higher fluence EUV light.

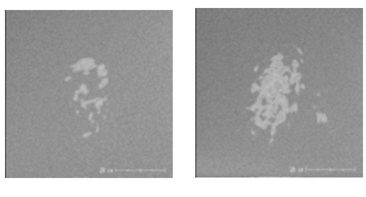

Fig. SEM image for irradiation damages of Nb/Si multilayer (left) and Mo/Si multilayer (right)

1. M. Nishikino et. al., Appl. Opt., 48, 29, 5464, 2009
2. M. Ishino et. al., J. Appl. Opt., 109, 013504, 2011
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P-22

Effects of Equation of State on fluid simulations for laser-produced plasmas

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Abstracts: *We have developed the simulation code for laser-ablation plasmas. Our code uses both HLL-HLLC Riemann solver and the upwind difference method to treat two-temperature model of ion and electron in the shock-capturing scheme. As the equation of states model for the laser-ablation, we applied BADGER model to our simulations and compared the simulation results using several equation of state models.*

In the numerical calculation of fluid dynamics for laser-ablation plasmas, it is necessary to capture the shock front and discontinuity surface and to avoid numerical oscillations. In order to overcome these numerical problems, we have used Godunov-type Riemann solver which is in the conservative form. However, for the laser-ablation we have to consider the two-temperature model for respective ion and electron because the relaxation time between ion and electron often becomes longer than the duration of laser pulses. In order to calculate numerically the two-temperature fluid model with shock capturing scheme, we have developed the new scheme. This new scheme uses both HLL-HLLC Riemann solver which is one of the conservation schemes and the upwind difference method, and we could simulate laser-ablation plasmas robust for ideal gases.

For the realistic simulation of laser-ablation, the equation of state (EOS) model is also important. We applied BADGER model to our simulations. BADGER model has three electron ionization models; 1) Thomas-Fermi model, 2) the screened hydrogenic model with *l*-splitting and 3) the individual electron accounting model. The latter two models take into account quantum effects. Also, BADGER model does not use bonding correction as used in QEOS. Figure 1(a) and (b) show SESAME and BADGER plot for electron equation of state, respectively. BADGER table has smooth and different values in the low temperature region compared to SESAME table. We simulated the laser-ablation with several equations of state models among BADGER model, QEOS and SEAME to compare the effects of equation of state on the hydrodynamics for the laser-ablation. Our simulations using of BADGER model show the realistic and robust results.

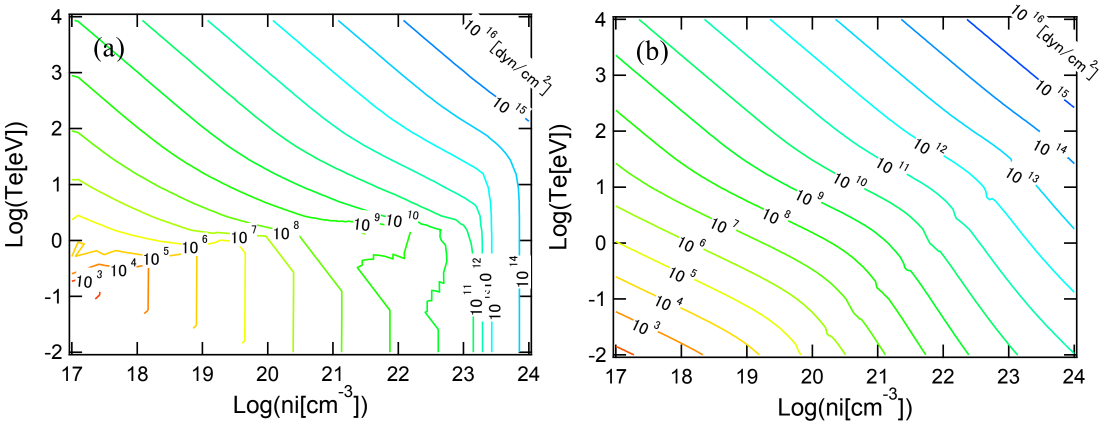

Fig.1 Electron equation of state of (a)QEOS model and (b) BADGER model

P-23

A Mo/Si Multilayer-Coated Photodiode Detector for Monitoring Soft X-Ray Laser Intensity

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A commercial X-ray photodiode detector was coated with a Mo/Si multilayer film designed for a high efficiency polarizer at soft X-ray laser (XRL) of 13.9 nm to monitor the beam intensity in real-time. Reflectivity measurements of the multilayer-coated photodiode were carried out at an angle of incidence of 45° using synchrotron radiation. The s-polarized reflectivity was evaluated to be 44% at 13.9 nm wavelength, which was detected by another photodiode detector without multilayer coating. The transmitted and absorbed light was measured as the current of the multilayer-coated photodiode detector. A very strong positive correlation of 0.999 was observed between the two photodiode detectors. Next, reflectivity measurements using the XRL were also performed, and the correlation coefficient was 0.961. The above results indicate that the multilayer-coated photodiode detector can be utilized for shot-by-shot monitoring of the fluctuating XRL beam intensity. The details of the multilayer-coated photodiode detector and its application to absolute reflectivity measurements and polarization analysis using the XRL will be reported in this conference.

P-24

Analysis of Reflection Signal from EUV Multilayer Mirror for Irradiation Induced Damage Study

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Abstracts: *The soft x-ray laser (SXRL) pulse makes damage structure on an EUV multilayer mirror. The profile of detected intensity of reflected SXRL from damaged surface is modified. In the same manner, the latter part of pulse duration in the SXRL will be affected by the damage structure, which is formed by the former part of duration, if the pulse width is longer than damage process sufficiently. In the presentation, we will discuss the analysis of SXRL pulse reflected from EUV multilayer mirror for study of laser induced damage process.*

The interactions between lasers with short pulse duration and matter are interesting in both of technological applications and theoretical studies. Lasers having short pulse widths such as pico and/or femto seconds have abilities to make ablation and/or modification structures on material surfaces accompanying the creation of unusual condition of high temperature and high pressure, so called warm dense matter (WDM). The x-ray laser is an interest laser source, because of the features of high photon energy, short duration, and highly spatial coherence. The soft x-ray laser (SXRL) pulses having a wavelength of 13.9 nm and a duration of 7 ps, which are generated from Ag plasma mediums, can make the nanometer scale ablation and/or modification structures on materials. We found that unique structures were formed on Al, Cu, Au, and Si surfaces by the irradiations of focused SXRL pulses. The mechanisms of surface modifications induced by SXRL pulses were also investigated theoretically. The atomistic model for the interaction between SXRL pulse and materials reveals that the tensile stress created in materials by SXRL pulse can produce spallative ablation of surface even for low fluence without plasma production. The theoretical model also predicted that the damage formation in irradiated surface started in a few picosecond. This time scale is comparable to the pulse width of SXRL beam.

Recently, we irradiated the focused SXRL pulses to EUV multilayer mirrors to study the ablation phenomena on optics. On multilayer mirror surfaces, we can confirm the damage structures. In this experimental series, we also observed the SXRL signals reflected from multilayer mirrors. The profiles of SXRL signals captured by an x-ray CCD camera, which were reflected from damaged mirror, were modulated, because the detected SXRL pulse was reflected on mirror surface including the damage area. This damage area was formed by the former pulse. If the pulse width of SXRL is sufficiently longer than damage time, which means degradation of periodical structure in EUV multilayer mirror, the reflection signal includes the information of damage process. In the presentation, we discuss the possibility of signal analysis reflected from EUV multilayer mirrors for irradiation induced damage study.

P-25

Numerical Calculation of Gain Coefficients of Recombination X-Ray Laser in a Cluster Plasma

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Abstracts: *For realization of the plasma X-ray laser due to charge exchange recombination process, we examined the optimal plasma condition by numerical calculation. The lasing medium is cluster plasma, where C_{60} cluster in the helium gas is irradiated with ultrashort, intense laser pulses. In this study, we focused on the charge transfer process of C^{6+} + He →C^{5+}(n=3) + He^{+}, whose cross section is ~10^{15} cm^{2}.As a result, it is found that the large gain coefficient is obtained in a specific plasma condition.*

It is expected that the soft x-ray lasers provide an innovative research method in various scientific and engineering fields, such as, solid state physics, material engineering and biomedical science. As one of the generation method of plasma x-ray laser, the recombination scheme has an advantage, because the input energy required to create the laser medium is lower than that of the transient electron excitation scheme. In addition, charge-exchange recombination process could contribute to the efficient population inversion. In this study, we performed numerical study to optimize plasma parameters for lasing of the recombination soft x-ray laser in hydrogen-like carbon (C^{5+} n=2-3 transition: 18.2 nm). Here, the lasing medium is a cluster plasma, which is generated by irradiating with a femtosecond laser pulse onto a mixture of C_{60} clusters and helium gas. Note that the cluster efficiently absorbs the laser energy due to collisional heating in solid density, while the He is still neutral. As a result, the cluster plasma is subjected to charge exchange recombination with the He atom, C^{6+} + He →C^{5+}(n=3) +He^{+}. The cross section is around ~10^{15} cm^{2} at low collision energies. The population densities of C^{6+} ion and C^{5+} levels are derived by solving the coupled rate equations, in which the effect of the charge-exchange process is incorporated. As for the optical thickness of the transition from n=1 to n=2 of C^{5+} ion, the radiative transfer equation is solved. The gain coefficient in the cluster plasma is calculated for various plasma conditions. In the presentation, details of the numerical results will be discussed.

Beam Diagnostics of X-ray Free Electron Laser by Imprinting X-ray Vortex

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Abstracts: *We here propose a method to emphasize the motion of the x-ray beam by constructing a phase sensitive system where an x-ray vortex is imprinted. We will also report on our successful demonstration to retrieve the wave front at the focused x-ray vortex beam by analyzing one interferogram obtained in two-beam interferometry.*

XFEL radiation is formed by the Self Amplified Spontaneous Emission (SASE). To improve the x-ray beam stability for precise scientific measurements, the development of x-ray beam diagnostics is an urgent issue. SACLA facility already provides efficient diagnostic tag database on x-ray energy, position, and total energy of pulse. The remaining issue is to improve the stability of the x-ray beam by clarifying the nature of its oscillation. We here propose a method to sensitively monitor the x-ray beam motion by generating a focused x-ray beam with a vortex and use a pinhole as a spatial filter. The center of the optical vortex is characterized by a zero-intensity dark spot and the spiral phase structure with a jump equaling multiples of 2π.

We devised a diagnostic method where we set a spatial filter, a pinhole, at the focal plane of Spiral Fresnel Zone Plate (SFZP, Fig. 1, [1]). We designed a SFZP having a zone with a depth for the phase shift of π and the destructive interference. By recording the diffraction pattern of the pinhole by a downstream x-ray image sensor, the motion of the x-ray beam position and tilt is extracted. During the beam oscillation, the dark spot inside the diffraction pattern shifts by a significant amount due to the eccentricity of the vortex core from the center of pinhole. We will show how effectively the x-ray beam is diagnosed using simulations and experiment at SACLA.

As the next topic, we demonstrate that the wave front at the focal plane of SFZP is retrievable by analyzing one interferogram obtained in two–beam x-ray interferometry at SPring-8 undulator beamline. Using the Fourier-transform method on one x-ray interferometric pattern, we observed a spiral phase structure with a 2π jump at the focal plane. This proves that x-ray interferometry would be powerful in XFEL studies.

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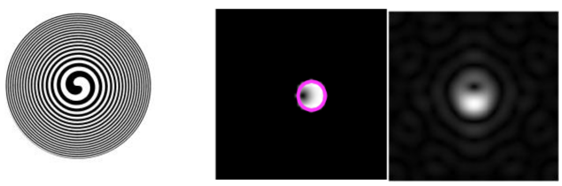

(a) (b) (c)

Fig.1. (a)Schematic diagram of SFZP. (b) The transmitted amplitude distribution through a pinhole. (c) The simulated diffraction pattern at the detector plane.

P-27

Evaluation of a flat-field grazing incidence spectrometer for highly charged ion plasma emission in 1−10 nm

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Abstracts: *A flat-field grazing incident spectrometer was built to investigate soft x-ray spectral structure and photon flux emitted from highly charged ion (HCI) plasmas in the spectral region from 1 to 10 nm. It consists of a flat-filed grating with 2400 lines/mm as a dispersing element and an x-ray charged coupled device (CCD) camera as the detector. In order to produce accurate intensity calibrated spectra of the HCI plasmas, the diffraction efficiency of the grating and the sensitivity of the CCD camera were directly measured by use of the reflectometer installed at the BL-11D of the Photon Factory (PF).*

Interest in highly charged ion (HCI) spectroscopy has increased in the last decade due in part to the development of efficient and powerful extreme ultraviolet (EUV) and soft x-ray (SXR) sources for applications. Laser-produced HCI plasmas, are potentially suitable as laboratory scale high power sources, in which the use of intense unresolved transition arrays (UTAs), instead of discrete line emission, with reflective rather than transmission optics has been proposed. Ideally the UTA emission should lie within the reflectance bandwidth of a multilayer mirror. The in-band high-energy emission is attributable, in some cases, to hundreds of thousands of near-degenerate resonance lines lying within a narrow wavelength range. Despite the fact that ideally UTA emission cannot be resolved by a spectrometer, their spectroscopy plays an important role for further understanding of the processes occurring and the physics of high temperature and high energy density plasmas.

In the following article we measure the diffraction efficiency of the holographic fabricated grating with 2400 lines/mm for use in wavelength range from 1 to 10 nm. A flat-field grazing incidence spectrometer (GIS) is built for investigating the SXR emission from laser-produced HCI plasmas. The diffraction efficiency of the 2400 lines/mm grating and a thermoelectrically cooled back-illuminated x-ray charge coupled device (CCD) camera were measured by using the soft x-ray reflectometer installed at the BL-11D beamline of the Photon Factory (PF) at the KEK in Japan. The incident beam with a divergent angle less than 0.1° and a full width at half maximum (FWHM) diameter of approximately 200 μm was incident on the gating located at the center of the reflectometer chamber. The angular profiles of the incident and diffracted beams were scanned by a detector, which consisted of an x-ray diode and a slit with a width of 100 μm. The distance from the grating to the detector was about 225 mm and was fixed due to the configuration of the reflectometer. This allows for highly accurate spectroscopy of HCI plasmas. We also studied the calibrated spectra of Gd HCI plasmas which were produced by a 10-ns Nd:YAG laser. A maximum energy conversion efficiency of 0.6% was observed at a laser intensity of 3×10^{12} W/cm^2 by use of a calibrated GIS.

P-28

Development of time-resolved small-angle X-ray scattering system using soft-X-ray laser

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Abstracts: *We are developing time-resolved grazing-incidence small-angle scattering (GI-SAXS) system using a soft X-ray laser. As a first step, we carried out GI-SAXS measurements of optical grating and craters on gold surface produced by femtosecond laser ablation. We succeeded in observing the diffraction spots from the grating as expected, but the diffuse scattering from the craters was hidden in thermal noises of a soft X-ray CCD camera.*

The non-thermal (pressure) effect on femtosecond laser ablation has been focused on for development of high-precision micromachining technique with small thermal effect. Since the pressure is always zero at the surface due to boundary condition, the maximum tensile stress is generated not at the surface but around the center depth in the photo-excited volume. The upper part of the photo-excited volume is separated as a thin-layer by merging voids which are generated by aid of the tensile stress. The ablation phenomena is usually called by the spallation in the femtosecond laser ablation dynamics. The spallation dynamics has been studied using time-resolved X-ray microscopy. Nishikino et al. [1] have observed time-resolved X-ray microscopic images and shadowgraphs of the separated thin-layers, and discussed the ablation dynamics in the viewpoints of thermodynamics and thermomechanics so far. Recently, we newly focused on a time-resolved grazing-incidence small-angle X-ray scattering (GI-SAXS) measurement on the femtosecond laser ablation. In principle, the GI-SAXS can measure time-evolution of the morphology of the voids, which would be stretched in normal to the sample surface by the tensile stress, whereas bubbles would be formed when the ablation is dominated purely by the thermal effect. We can quantitatively evaluate the contribution of the tensile stress on the femtosecond laser ablation from the asymmetric morphology of the voids. In this presentation, we report the result of the GI-SAXS measurement, and discuss the possibility and problem on the development of the time-resolved GI-SAXS system.

Figure 1 shows the experimental setup, which was slightly modified from X-ray imaging [1].

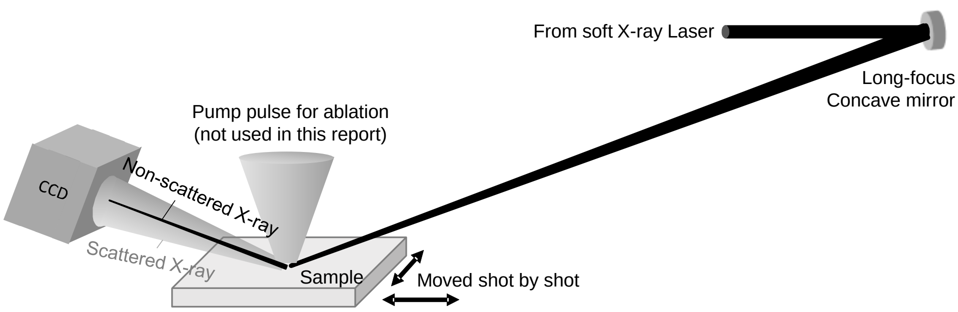

Figure 1 Experimental setup

A soft X-ray pulse with a wavelength λ = 13.9 nm, dispersion $\Delta\lambda/\lambda = 10^{-4}$, and time-duration of 1 ps from the soft X-ray laser in KPSI was guided through a 2-5 mm-thick zirconium filter and a concave mirror with a curvature radius of 3 m to a sample at an incident angle of 19.2° from the surface. The reflected pulse from the sample surface was detected using a soft X-ray charge coupled device (CCD) camera (Princeton, PI-MTE: 2048B) with the sample-to-camera distance of 124 mm. The X-ray pulse was focused to a diameter of approximately 50 μm on the CCD camera, whereas the beam diameters of an ellipsoidal spot at the sample surface was approximately 400 and 100 μm in the major and minor axes, respectively. We used the gold-deposited optical grating for visible and infrared wavelengths (1740 lines / mm) as a standard sample.

Figures 2(a) and (b) show the GI-SAXS profiles of the grating whose groove directions are parallel and perpendicular to the plane of incidence, respectively. The diffraction spots with the number *n* in the figures are attributed to the *n*-order diffraction peaks. Their positions are consistent with theoretical predictions (not shown). The full widths at half maximum of the diffraction spots are determined by the width of the 0-order diffraction pulse focused on the CCD camera, giving the minimum magnitude of the scattering vector q of the order of 10^{-4} nm^{-1}.

We tried to observe a GI-SAXS profile of an ablated crater on a femtosecond-laser-irradiated gold, but resulted in unsuccessful. As shown in Figure 2, thermal noise with dozens of counts remains per each pixel even after background signal is subtracted. This level is too large to pick up dispersed scattering signal from disordered system such as the crater. Since structural information is obtained from power-law scattering of intensity against scattering angle, much wider dynamic range of the scattering signal has to be obtained by decreasing the background signal.

References
[1] N. Hasegawa, M. Nishikino, T. Tomita, N. Ohnishi, A. M. Ito, et al.,Proceedings of SPIE 9589, 95890A-1-8 (2015).

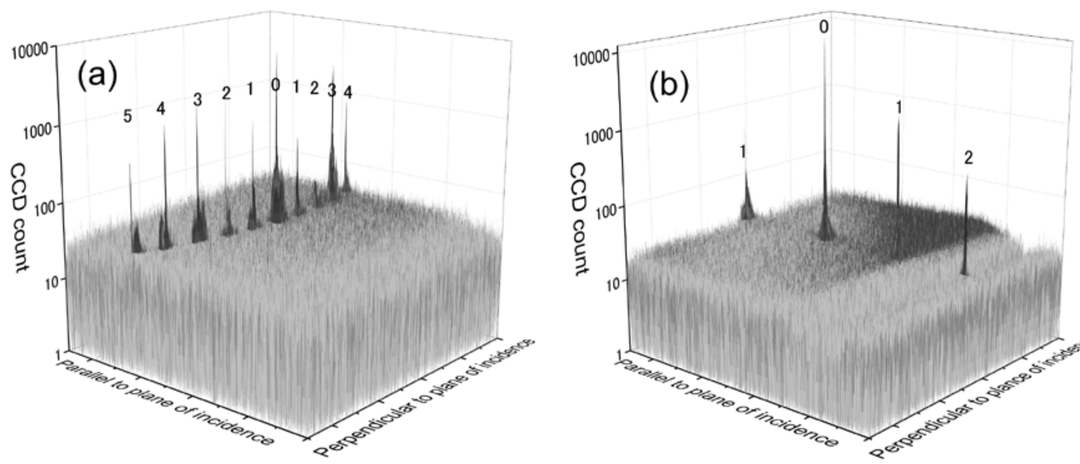

Figure 2 GI-SAXS profiles of the optical grating aligned in (a) parallel and (b) perpendicular to the plane of incidence. The image area is 27.6 x 27.6 mm.

P-29

Hard X-ray emission lasers from neon like selenium Se^{+21}

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Hard X-ray emission from neon like selenium were Predicted to be emitted. The atomic data were relativistically calculated. A 457 energy levels were considered with four possible transition types (E1, E2, M1 and M2). Electron impact excitation were calculated using the effective collision strengths through the distorted wave approximation technique. All laser lines with gain coefficients ≥ 1 were determined. Population inversions, Doppler broadening are calculated for the highest gain transitions.

X-ray lasers are a class of lasers that have a wavelength ranges from 2 nm to 50 nm. Producing such lasers faces the problem of getting a high power excitation energy for the atoms to produce the population inversion. X-ray lasers need a special set up for getting such power energy. X-ray laser wavelengths are not affected by dense plasmas either by reflection or diffractions, which makes these lasers as a good tools in studying such plasmas, that improves our knowledge in the nuclear fusion or in astrophysics.

Since 1960 lasers become an essential tools in our life. Lasers can be used in surgery, industry and in lots of applications like laser printers. Lasers have a monochromatic and collimated beams of light.

In X-ray lasers, atoms with high number of electrons was suggested by Peter L. Hagelstein. Hagelstein suggested using a thin foil of selenium or molybdenum. The proposed model was as the following, when a high energetic beam of radiation falls on a thin foil of a material such as selenium, then the outer shell electrons can easily collide with the selenium plasma which are now Ne-like (Se^{+24}) and then an inner electron is excited to a higher energy level. These type of excitation is called collisional excitation.

In 1972, the first X-ray laser experiment was proved. In that experiment a Q-switched Nd:glass laser with 1.06 μm wavelength, 20 nm pulse duration and 30 Joules per pulse was used. The target was aqueous copper sulfate ($CuSo_4$) gel with different concentrations of copper. When the laser beams falls on the copper target a collimated radiation was detected by a photographic plates, like the medical X-ray films. These photographic plates were wrapped by one to four layers of Aluminum with 13 μm thickness to prevent soft X-ray radiation from detection. It was found that by placing the photographic film at 30 cm and 110 cm, the spot size of the emitted radiation remains the same 0.01 cm in radius which means that the output radiation is collimated hard X-rays. In that experiment, the wavelength was not measured and no one could get the same results. In 1975, a seminal review paper about X-ray lasers predicts that the population inversion density should exceed 10^{18} cm^{-3}. In order to use lasers as a pump power to get shorter wavelengths (≤ 1 nm) we should focus the laser of power (> 10^{12} W) into a very small spot with diameter (< 30 μm). It was also shown that the main dominant process is the spontaneous emission in producing the X-ray lasers this emission is called amplified spontaneous emission

(ASE). In 1985, It was first experimentally proved that emission of two bright lines from selenium with wavelengths 20.63 and 20.96 nm with gain coefficient 5.5 cm^{-1}.

In 1998, a new technique for the pumping was checked, by using two laser pulses one with 5 J every 800 ps which ionizes the plasma and other laser has 5 J every 1.1 ps which excites the produced ions. Using that it becomes possible to get high gain coefficient 35 cm^{-1} from Nickel-like Palladium from 4d $\rightarrow$ 4p transition with a wavelength 14.7 nm.

Recently a laser transitions from Ne-like Ti, V, Cr, Fe and Co were detected. Using a laser pulses with a delay time, we could detect a 3p $\rightarrow$ 3s transition and the emitted wavelength from Ne-like Ti was 30.1 nm. Also inner shell X-ray lasers were proved from neon gases by 960 eV photon energy emitting 1.46 nm wavelength with gain coefficients of 61−70 cm^{-1} . Short laser wavelengths ($\approx$ 6.85) nm were also detected in Ni-like samarium.

In this report we try to obtain a short wavelengths from neon like selenium at different electron energies. The data are compared with the experimental results.

P-30

Study on surface excitation of SiC by double pulse femtosecond laser process —Investigation of surface irradiation—

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Abstracts: *Femtosecond laser irradiation excites semiconductor electron. Excited electron in the conduction band makes semiconductor absorb light more easily. We divided the one pulse to the two, and use one pulse for the semiconductor of excitation , using another for processing. This double pulse femtosecond laser process can be processed at lower laser intensity and processed with less damage. Pulse interval of 400 fs showed lowest processing threshold and after 10 ps, processing threshold was gradually increased.*

Silicon carbide (SiC) is known as a very useful semiconductor for high power, high breakdown voltage and high temperature devices. Because of such characteristics, it is difficult to process SiC by machining, chemical machining, laser machining and so on. Femtosecond laser to cause multi photon absorption, however, can be processed SiC.

We propose a new SiC processing method, double pulse femtosecond laser process. When the laser is irradiated to the semiconductor, electrons in the valence band are excited to the conduction band by absorbing photon energy ($E = h\nu$). This excitation is continued for about 10 pico second and electrons in the conduction band behave like free electrons , resulting in light absorption rate of the semiconductor increases. Thereby, we expect that semiconductor of the excited state can be processed at lower laser intensity and processed with less damage. In this report, by measuring the machining threshold while changing pulse interval of the double pulse, consider the validity of the proposed method.

Experimental apparatus was created based on Michelson interferometer with a Ti:Sapphire laser with the duration of 64 fs at a wavelength of 794 nm and pulse interval can be set up 0 s to 400 ps by electric stage. The sample was 4H-SiC(0001) polished surface, and the polarization direction of the laser was set at (11-20) surface. Each pulse fluence (peak fluence) was nearly 800 mJ/cm^2 which is less than machining threshold by single pulse process. In the experiment, We set the pulse interval of 400 fs, 1 ps, 4 ps, 10 ps, 40 ps, 100 ps and 400 ps, and conducted once irradiation with double pulse. After that, the processing marks were observed with a Scanning Electron Microscope(SEM) to derive the processed threshold.

Experimental results , processing threshold in a double pulse processing was reduced up to 48 % compared to that of a single pulse. Pulse interval of 400 fs showed lowest processing threshold, and after 10 ps, processing threshold was gradually increased. In the presentation, we will show the details of the experiment data, and the processing mechanism.

P-31

Development of High-Repetition-Rate and High-Pulse-Energy Nd:YAG MOPA Laser System

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Abstracts: *High-pulse-energy laser systems as pump source for Ti:Sapphire laser in a laser-driven plasma soft x-ray laser systems are required for operation with high-repetition-rate. A Nd:YAG laser system which the size was about 4 m×0.8 m was developed by master oscillator power amplifier (MOPA) platform. A laser beam of the master oscillator was amplified by the two Nd:YAG rods and the designed values of pulse energy and repetition rate were 5 J and 50 Hz with fundamental wavelength, respectively. The amplified spontaneous emission that is a significant problem in high energy laser development was almost neglected.*

High-pulse-energy Nd:YAG laser systems are required as typical pump source of Ti:Sapphire laser systems. Ti:Sapphire laser systems having high-pulse-energy would be applied into a laser-driven plasma soft x-ray laser (SXRL) system and the repetition rate determines that of the SXRL. At the Japan Atomic Energy Agency (JAEA), we developed a fully spatial coherent SXRL named TOPAZ (Twin OPtical Amplifiers using Zigzag slab) and the TOPAZ is operating with 0.1 Hz pumped by two 10 J picosecond lasers [1,2]. A high-repetition-rate SXRL was already demonstrated with frequency 5 Hz pumped by 1 J picosecond laser [3]. In this study, a new high-repetition-rate tabletop Nd:YAG laser system was developed which utilizes master oscillator power amplifier (MOPA) platform for pump source of a Ti:Sapphire laser system in SXRL. Designed values of the pulse energy and the repetition rate were 5 J and 50 Hz with fundamental wavelength, respectively. The 5-J 50-Hz laser beam will be generated second harmonics by BBO crystal and the expected output specifications of a Ti:Sapphire laser pumped by the developed laser system is over 1 J with 50 Hz.

A commercial Q-switched Nd:YAG laser system (wavelength 1064 nm, repetition rate 50 Hz, pulse width 14 ns) was combined as the master oscillator and the maximum output energy was about 400 mJ at in front of the exposure port. Two 1.1 at% Nd:YAG rods were installed in the amplifier and the seed laser beam was amplified through a double-pass in the first rod and through a single-pass in the second rod (total 3-passes). The laser system was constructed on an optical table that the size was 4.0 m×0.8 m. The Nd:YAG rods were excited by two flush lamps for each laser rod. The small signal gain coefficient and the stored energy of the installed Nd:YAG rod were 0.33 cm^{-1} and 2.4 J when each lamp energy was 50 J. The focusing length of the thermal lens effect was about 2 m and was slightly different with each direction. However, the difference could be corrected with a single lens on a ray-trace calculation and the real system. Amplified spontaneous emission (ASE) was a significant problem in high energy laser development. In this laser system, the ASE was monitored by free-running and its energy was able to almost neglect (about 5 mJ).

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P-32

Laser-Induced Damage on Silica Glasses by Irradiation of Soft X-Ray Laser Pulses

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Abstracts: *Laser-induced damage thresholds (LIDT) on silica glasses were measured by pulse irradiation of soft X-ray laser (SXRL). Silica glasses are one of the typical materials in the field of near-infrared and visible laser systems, and output energy of the systems is limited by material's LIDTs. High-photon energy of the SXRL would have great potential to study with simple discussion for the laser-induced damage mechanisms. The LIDTs on silica glasses measured by 7-ps SXRL pulses are several dozen of mJ/cm^2 as the experimental results and the LIDTs will be discussed by a simple calculations.*

Output energies of the laser systems were limited by laser-induced damage thresholds (LIDTs) of the materials. Laser-induced damage mechanisms (LIDMs) of the materials are studying with various experimental and theoretical approaches to develop high-LIDT optics. However, the wide-bandgap of the materials is leading an extremely complex LIDM and there are a lot of suggested models [1]. In this study, LIDTs on silica glasses were measured by irradiation of soft X-ray laser (SXRL) pulses. Silica glasses are one of the typical materials in the field of near-infrared- and visible-laser systems. High-photon energy of the SXRL would have great potential to study with simple discussion for the LIDMs, in particular, a process of the initial free-electron generation is confined to only single-photon absorption.

As damage-testing laser, we used a fully spatial coherent SXRL generated by TOPAZ (Twin OPtical Amplifiers using Zigzag slab) laser system and the TOPAZ is operating with 0.1 Hz pumped by two 10 J, picosecond lasers [2,3]. The wavelength and pulse width of SXRL generated by TOPAZ were 13.9 nm and 7 ps, respectively. Optical polished fused- and synthetic-silica glasses were prepared as experimental sample and the contaminations including these glasses were greatly differing each other. The LIDTs were measured by 1-on-1, 5-on-1, and 10-on-1 damage testing methods.

The measured LIDTs on fused- and synthetic- silica glasses were several dozen mJ/cm^2 and the LIDTs of the synthetic silica glass was higher than that of the fused silica glass. In the case of the fused-silica sample, the LIDTs at 1-on-1, 5-on-1, and 10-on-1 damage testing were the same value but the damage probability was clearly different. The damage morphology of the fused silica glass was dotted with SXRL irradiation spot. The experimental results of the synthetic-silica glass was used to evaluate effects of the contaminations with comparing that of the fused-silica glass. Additionally, we calculated the LIDT with a simple model. The suggested model is including single-photon absorption and impact ionization processes.

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[2] M. Nishikino *et al.*, Appl. Opt. **47** (2008) 1129
[3] Y. Ochi *et al.*, Jap. J. Appl. Phys. **48** (2009) 120212

P-33

Development of a fast zinc oxide scintillator for the short wavelength region using soft X-ray laser

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Abstracts: *Zinc oxide (ZnO) is a prominent scintillator material because of its improved growth technology and excellent optical properties. Large and high-quality ZnO single crystals have been prepared by the hydrothermal growth method. Moreover, hydrothermal-grown bulk ZnO crystals exhibit fast decay times related to ZnO's free excitonic emission. In this regard, ZnO is investigated as a scintillator using a Ni-like Ag-ion plasma soft X-ray laser. A ZnO crystal has a nanosecond temporal resolution and a sub-micron spatial resolution suitable for short wavelength applications. Improvement of ZnO as a scintillator using novel methods is then anticipated in the future.*

The application of light sources in the short wavelength region has been expected to aid in the development of various fields of science, medicine, and industry. Efficient and fast imaging scintillator devices with sufficient sizes are particularly needed because they are key elements for short wavelength applications. Zinc oxide (ZnO) is a prominent scintillator material because of its improved growth technology and excellent optical properties. A large, high-quality single crystal has been prepared with reasonable cost by the hydrothermal growth method. In the past, we have been investigating the various optical properties of ZnO materials. A hydrothermal-grown bulk crystal exhibit fast decay times regardless of the incident optical excitation. In this report, we summarize the development of a fast ZnO scintillator for the short wavelength region using the soft X-ray laser of the Japan Atomic Energy Agency (JAEA).

The Ni-like Ag-ion plasma soft X-ray laser was employed as the excitation source because its properties are appropriate for our desired experiment. The soft X-ray laser had an output wavelength of 13.9 nm with a picosecond duration and a microjoule energy. The sample used was a high-purity ZnO single crystal grown by hydrothermal method. The emission decay time of the sample at around 380 nm is determined to be 1 ns using a streak camera system. The response time is sufficiently short for lithography light sources since these sources have a few nanosecond duration. In addition, we are able to demonstrate that the emission wavelength and decay time is independent of the excitation wavelength by comparing it with the results using other short wavelength light sources. We have also demonstrated the evaluation of the beam profile of a soft X-ray laser focused by a spherical mirror or a Fresnel zone plate. The evolution of the beam radius around the focal point is monitored by observing the emission patterns of ZnO at each position. The measured spatial resolution with magnification optics and with a telescope for imaging is 5 μm. It is then estimated that ZnO has a sub-micron spatial resolution because the measurement from the optical configuration was estimated to be 4 μm. These high temporal and spatial resolutions indicate that ZnO is suitable to characterize lithography light sources. Since a short decay time leads to improved spatial resolution, we are currently exploring methods such as impurity doping or quantum beam irradiation. By using these doped and ion-implanted ZnO crystals, the performance of ZnO as scintillator might be improved.

P-34

Femtosecond structure determination of molecules in an alignment laser by photoelectron diffraction with a XFEL

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Abstracts: *We have successfully measured the X-ray photoelectron diffraction (XPD) of laser-aligned iodine molecules by using X-ray free electron laser pulses. Thanks to a higher degree of alignment of sample molecules, we have obtained the XPD image having structural information. The experimental XPD image is analyzed with the help of the XPD theory to obtain the structure of molecules in an intense laser field.*

In the last two decades, laser-induced alignment and orientation techniques of molecules are well developed and successfully applied to high-order harmonic spectroscopy [1], photochemical reaction controls [2], and so on. However, a fundamental aspect of the technique was not scrutinized so far; the intense field of the alignment pulse may modify the ground-state structure of the molecules, especially in the case of the adiabatic alignment technique. Here we report our recent results on the structure determination of iodine molecules, I_2, in an intense laser field by the X-ray photoelectron diffraction (XPD) using ultrafast X-ray Free Electron Laser (XFEL) pulses [3,4].

The experiment was performed at BL3 of the SACLA facility with the photon energy of 4.7 keV. The momentum images of both electrons and ions produced by the XFEL pulses have been measured simultaneously with double velocity-map imaging spectrometers [3]. The sample I_2 molecules are aligned parallel to the polarization direction of XFEL by the Nd:YAG laser pulses. The degree of alignment was estimated to be ~0.73 from the obtained fragment-ion images.

The measured electron image consists of the central part for low-energy electrons due to Auger cascades and the outer ring of I 2*p* photoelectrons with kinetic energy of 140eV, i.e., the XPD image. Thanks to the higher degree of alignment compared to that in [3], we have observed intensity minima in the XPD as shown in Fig. 1, though interference structures could not be resolved. To determine the molecular structure, i.e., the bond length of the I_2 molecules in the Nd:YAG laser field of ~1×10^{12} W/cm^2, we have applied our molecular-structure-determination methodology [4] to the measured XPD data. Thus, we have found that the bond length in the laser is longer by 0.5Å than the equilibrium nuclear distance. The details of the present work will be discussed in the presentation.

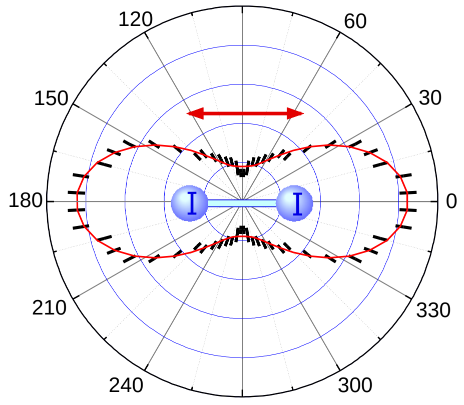

Fig. 1: Angular distributions of I 2*p* photoelectrons. The arrow shows the polarization direction of XFEL pulses.

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P-35

Aiming to measure cluster DNA damage, proposal for experiment systems using XFEL and laser driven ion beams

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Abstracts: We propose some experiment systems to measure cluster DNA damage created from the heavy ion irradiation. In our proposal, the combination of XFEL and laser driven ion beams is employed. This combination may allow us to analyze the cluster DNA damage with high time and space resolution.

Heavy ions are a good research tool in the field of bio-physics, material science, medical science. For example, in bio-physics, the important phenomenon of relative biological effectiveness (RBE) has been not yet fully understood. The understanding of RBE is directly connected to understand why heavy ion beam cancer therapy has higher efficiency than the other radiation cancer therapy. This phenomenon (RBE) may come from the fact that carbon ions produce larger number of clustered DNA damages that are defined as multiply damaged sites within a region of several nm length of DNA. Although evidence on the biological significance of clustered DNA damage has been accumulated, it remains largely unknown how clustered DNA damage is generated after irradiation.

In this report, we propose some experiment systems to apply the combination of XFEL and laser driven ion beams to study the physical phenomena caused from the ion irradiation. We utilize advantages of this combination: (i) all sources can become short pulse (ps - ns) and (ii) XFEL has very high brightness. Therefore, pump-probe methods may allow us to measure the structure of cluster DNA damage with high time and space resolutions.

Fig.1 shows an example of our proposal for an experiment system. We may measure from experiments that we propose as follows: (1) the track structure of the incident ion, (2) the relationship between the production points of cluster DNA damage and (3) the incident ion path, and the different mechanisms of DNA damage between the irradiation of heavy ions and protons or x-rays.

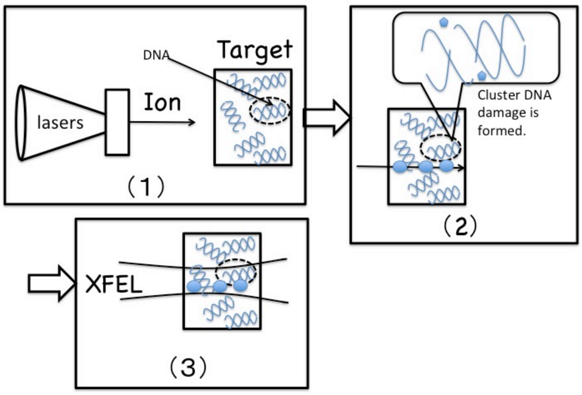

Fig.1 An example of our proposal for the experiment system: (1) DNA target is arranged and high intensity lasers drives ion beams, (2) this ion beam irradiates the target and cluster DNA damage is created, and (3) the structure of the cluster DNA damage is measured by XFELs.

P-36

Coherent plasma x-ray laser by injection of a parametrically amplified high-order harmonic light

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Abstracts: *The injection of high-order harmonics light into plasma laser medium (x-ray amplifier) is one of the attractive means to improve the beam quality. The lasing wavelength we focus on is 13.9 nm (Transient Collisional Excitation scheme of Ni-like Silver) and the plasma amplifier is created by a grazing incidence pump of the target. The seed harmonic light tuned at the laser transition is generated by parametric amplification. By using the seed-amplifier scheme, we are to demonstrate a spatial and temporal coherent plasma x-ray laser with a repetition rate of 10 Hz.*

Conventional plasma x-ray lasers have the characteristics of spatial coherence, while less temporal one. In order to realize fully coherent plasma x-ray lasers, we have employed a seed-amplifier scheme [1]. In this setup, a high-order harmonics light as the seeder is injected into an amplifier plasma medium. As a result, the harmonics is amplified while maintaining its original coherencies [2,3].

In this study, for generation of a narrow beam divergence and intense high-order harmonics, we focus on the x-ray parametric amplification [4]. The high-order harmonics generated in neon gas are further amplified due to high-order parametric interaction in helium gas. During the amplification, the quality of the harmonic pulses are improved by means of the harmonic lines became narrower and the divergence of the harmonic beam dramatically decreases, making the seed beam much suitable for efficient seeding of the x-ray lasers. On the other hand, the plasma amplifier is created by using a Ti:Sapphire laser (~80 fs, ~1 J) by means of a grazing incident pumping. Here a beam splitter divides the incoming beam into two branches: one of the beams is used to generate the harmonics, while the other is for the plasma amplifier. To meet the requirements on the spatial and spectral coupling between both beams is essential to achieve the efficient amplification. Therefore, the central wavelength of the Ti: Sapphire laser is tuned at 792.3 nm, by which the lasing transition (13.9 nm) matches the wavelength of 57th order harmonics. As for the spatial overlap, we compensate the effect of x-ray refraction of the harmonic light in dense plasma medium by slightly tilting the target surface.

In the presentation, we will show the preliminary results of the parametric amplification of the harmonics and the injection of the seed beam in the plasma amplifier conducted at the JEAE.

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P-37

1 kHz repetition picosecond pulse laser system

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Abstracts: *We have been developed a 1 kHz repetition picosecond pulse laser system based on the chirped pulse amplification (CPA) technology. The main amplifier is a regenerative amplifier using Yb:YAG or Yb:Y_2O_3 thin-disk. Present status of the output pulse is 10 mJ/1.3 ps and 2 mJ/0.9 ps by using Yb:YAG and Yb:Y_2O_3 regenerative amplifiers, respectively. The pulses are mainly used for terahertz pulse generation based on an optical rectification in a nonlinear crystal.*

The laser system, which is named "*QUADRA-T*", consists of a master oscillator, a pulse stretcher, a fiber pre-amplifier, a regenerative amplifier using a Yb:YAG thin-disk [1] or Yb:Y_2O_3 thin-disk [2], and a pulse compressor, shown in Fig. 1. The master oscillator is a mode-locked Ti:Sapphire laser operating at the central wavelength of 1030 nm with band width of 6 nm. The laser frequency is 80 MHz and the power is 150 mW. The pulse stretcher with a reflection grating gives the chirp of 400 ps/nm to each pulses. The throughput power from the pulse stretcher is 30 mW. The pulse energy is amplified up to 2 W in a laser diode pump Yb-doped fiber amplifier. Then 1 kHz pulses picked up by a pulse picker 1 and 2 are inserted into Yb:YAG and Yb:Y_2O_3 thin-disk regenerative amplifiers respectively. The thin-disk geometry is preferable for high average power operation because this geometry affords good cooling efficiency by facilitating volume heat transfer through the contacted disk surface. In this system ceramic Yb:YAG and Yb:Y_2O_3 thin-disks with 10 mm in the diameter and 0.2 mm in the thickness are used. Yb dopant ratios are 7at% for YAG and 5at% for Y_2O_3. In general, Yb:YAG is preferable for high power operation due to higher emission cross section than Yb:Y_2O_3. While Yb:Y_2O_3 has wider emission bandwidth, therefore it can provide shorter duration pulses. The output pulse energy and the spectral bandwidth are 12 mJ and 1.2 nm by the Yb:YAG regenerative amplifier and 2 mJ and 1.8 nm by the Yb:Y_2O_3 regenerative amplifier, respectively. Those pulses are compressed to 1.3 ps (YAG) and 0.9 ps (Y_2O_3) by pulse compressors with a pair of gold coated gratings of 1740 grooves/mm. Now we are developing Yb:YAG thin-disk multi-pass amplifier after the Yb:YAG regenerative amplifier to increase the pulse energy for a few tens mJ.

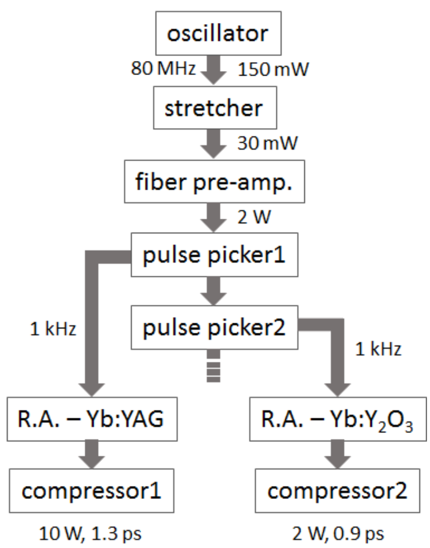

Fig.1 System configuration of QUADRA-T.
(R.A.: regenerative amplifier)

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P-38

Sub-cycle ultrafast modulation of the optical properties of the dielectrics by an intense laser field

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Abstracts: *We found the subcyle change of the optical properties of the diamond under an intense laser field employing the first-principle calculation. The ultrafast modulation is caused by the interference between the dressed states.*

Intense ultrashort pulse laser has been widely used for the ultrafast phenomena in solid states and/or the non-thermal laser processing. In such highly nonlinear and fast processes, new theoretical approach, real-time description including nonlinear and/or non-perturbative, is indispensable.

We developed the first-principle real-time approach by solving the time-dependent Kohn-Sham equation [1]. Recently, we predict the unknown laser induced sub-cycle change of the optical properties, time-resolved dynamical Franz-Keldysh effect (Tr-DFKE)[2], by employing the first-principle calculation and analytical formulation. We found that the Tr-DFKE shows the interesting phase shift with respect to the pump light electric field. This phase shift is owing to the interference between many different paths in dressed states induced by the pump light. Since the phase of the wavefunctions of the dressed states is locked, the phase difference between them causes the time-evolution of the optical responses.

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P-39

Modeling of ablation of the target material for the plasma for coherent and incoherent EUV sources

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Abstracts: *Initial interaction between the target and laser pulse for the excitation of plasma x-ray lasers and EUV sources is investigated using a hydrodynamics model, which takes liquid gas phase transition and particle emission from the ablation of the target material into account. Investigations are carried out for the irradiation of relatively weak pre-pulse laser pulse, which produces particles and decides further heating by the main laser pulse and EUV emission.*

For the excitation of plasma x-ray lasers and EUV sources the metal target is irradiated by intense laser pulses, and multiple charged ions are produced in hot plasmas. By the irradiation of relatively weak pre-pulse laser, it is expected that pre-formed plasmas is produced, however, sometimes particles are produced from the target. Particles may be useful for the efficient EUV emission because the absorption of the energy of the main pulse laser is enhanced, however, they also cause a non-uniform density profile in the plasma, which have detrimental effects of the amplification of x-ray laser light.

We develop a hydrodynamics model to investigate instabilities and particle emission during the melting and evaporation processes of the target material after the laser irradiation. The model is based on the two-dimensional Lagrange hydrodynamics, which includes mesh reorganization algorithms to calculate dynamics of small liquid particles in gas phase as well as gas bubbles in the liquid phase. Production of particles and bubbles are calculated using a phase transition model based on the Van-der-waals equation of state of Sn that will be used for the light source at λ=13.5nm for the EUV lithography.

A test calculation is carried out for the expansion of an initially hot (T=3,000K) liquid Sn cylinder with a radius of 10μm, which shows that although initially particles are formed, all materials are evaporated in a short time (<100ns). Conditions to obtain a shell structure of particles, which is observed in the experiments, are investigated.

This work is supported by JSPS grant (26610195) and NEDO.

P-40

Spatial Profiles of Electron Density and Electron Temperature of Laser-Produced Sn Plasmas for EUV Lithography

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Abstracts: *Spatial profiles of electron density (n_e) and electron temperature (T_e) of laser-produced Sn plasmas for EUV lithography were measured using a collective Thomson scattering technique. Under a condition of high conversion efficiency (CE) (>4.0%), n_e and T_e were in the range of10^{24}-10^{25} m^{-3}, and 30-40 eV, respectively. These values are adequate to the values predicted by simulations for optimum EUV light source plasmas. Comparison with other plasma conditions, whose CE were less than 4.0 %, mentions that control of laser absorption length is important to realize the high CE.*

EUV lithography (EUVL) is a most promising candidate for next generation lithography system. As a light source for the EUVL, laser-produced Sn plasmas with moderate temperature and density has been used. As the practical use, improvement of conversion efficiency (CE) of the EUV light source corresponding to the CO_2 laser, which is used as the driving laser to produce the plasma, is one of the biggest problem to be solved. For this purpose, importance of controlling and understanding of the Sn plasma has been mentioned, because EUV emission is strongly depend on the ionic charge of the Sn plasma. In addition, opacity is not negligible when plasma density becomes too high. Optimum T_e, n_e, and Z to realize high-power EUV light source with excellent CE are predicted as 30-50 eV, 10^{24}-10^{25} m^{-3}, and 10-13, respectively. However, direct measurements of these plasma parameters of the laser-produced EUV plasma having high CE have never been performed yet.

So far, we have been developing collective Thomson scattering system to realize a simultaneous measurements of n_e, T_e, and Z of the EUV plasmas [1, 2]. The previous study shows that ion feature from laser-produced Sn plasma is detectable for the EUV light source.

The important points of this report are as follows:

(a) Thomson scattering has been performed to measure one-dimensional spatial profiles of laser-produces Sn plasmas for EUVL, whose CE range is 2.5-4.0%.

(b) It was confirmed that n_e and T_e of the Sn plasmas were in ranges of 20-50 eV, and 10^{24}-10^{25} m^{-3}, respectively.

(c) Although the condition of driving laser (CO_2 laser) was same, spatial profiles of n_e and T_e were clearly different when the initial shape of Sn droplet target was different.

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P-41

Scaling EUV and X-ray Thomson Sources to Optical Free-Electron Laser Operation with Traveling-Wave Thomson-Scattering

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Traveling-Wave Thomson-Scattering (TWTS) is a novel Thomson scattering geometry which allows for orders of magnitude higher photon yields than classic head-on Thomson sources. TWTS thereby remains compact and provides narrowband and ultra-short ultraviolet to γ-ray radiation pulses just as classic Thomson sources. Even the realization of optical free-electron lasers is possible with the TWTS geometry since it provides both optical undulators with thousands of periods needed to microbunch the electron beam and a reduction of electron beam quality requirements compared to classic Thomson scattering to a level technically feasible today.

TWTS employs a side-scattering geometry depicted in fig. 1. Laser and electron propagation direction of motion enclose the interaction angle ϕ. Tilting the laser pulse front with respect to the wave front by half the interaction angle ensures continuous overlap of electrons and laser pulse over the whole laser pulse width while the laser pulse crosses the electron beam trajectory. In this way the interaction length becomes controllable by the laser pulse width and independent of the laser pulse duration. Utilizing wide, petawatt class laser pulses for TWTS allows to realize thousands of optical undulator periods.

The variability of TWTS with respect to the interaction angle can be used to control the radiation wavelength even for electron sources with fixed energy. For a fixed target wavelength on the other hand, the free choice of interaction angle enables control over electron beam quality requirements. Small interaction angle scenarios ($\phi \sim 10°$) typically yield the best trade-off between requirements on electron beam quality, laser power and laser intensity stability.

In the talk we will show that TWTS OFELs emitting extreme ultraviolet radiation are realizable today with existing technology for electron accelerators and laser systems. We detail an experimental setup to generate the tilted TWTS laser pulses which aims at compactness and provides focusing of these high-power pulses and compensation of dispersion accompanying pulse-front tilts. The method presented for dispersion compensation is especially relevant when building high yield X- and γ-ray sources in large interaction angle setups of TWTS.

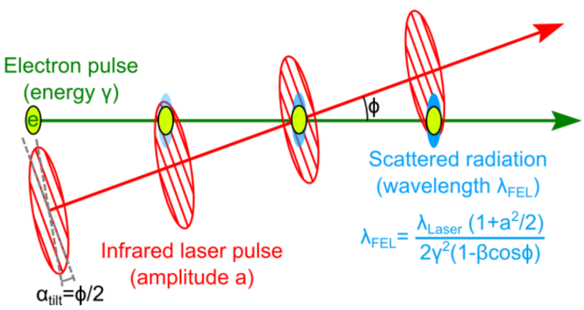

Fig. 1

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P-42

Theory of Ellipticity of High Harmonics Generated in Noble Gases Irradiated by Two-Color Laser Fields Having Orthogonal Linear Polarizations

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Abstracts: *Here we present theoretical explanations of the observation [G. Lambert et al, Nature Comm., 6:6167 (2015)] of elliptically-polarized high harmonics as a result of interaction of two-color laser beams having orthogonal linear polarizations in a noble gas. Numerical calculations based on the non-perturbative light-atom interaction theory reproduce well the experimental data. In addition, the degree of polarization is analyzed for different harmonic orders and found to be high. Through a simplified theoretical model it is shown that the degree of harmonic ellipticity depends mainly on the population of atomic states sublevels with different angular momentum projections.*

Recently, several techniques demonstrated the production of elliptically-polarized high harmonics [1-3], thus increasing the number of possible applications of the HHG for the investigation of polarization sensitive phenomena, such as the X-ray magnetic circular dichroism (XMCD). One of these techniques is based on a two-color laser field in the cross-polarized configuration [3]. Within this scheme, the study of the XMCD in Ni (around 67 eV) brought the proof that the harmonics were highly elliptically polarized and with a non negligible degree of polarization, but up to now no real evaluation of this latter was done. Also, the origin of the observed phenomena was not clear.

For that, we developed a numerical model of the single atom, based on the non-perturbative theory [4], and which takes into account the dynamics of not only the ground states by also of the finite number of excited states. To make a reliable comparison with the experimentally measured spectra, the transmission effects and the material dispersion have been taken into account for calculating the phase-matching effects for the harmonics. The numerical model was preliminarily tested at the demonstration of some typical behavior of the HHG in standard conditions: the generation of elliptically polarized harmonics by elliptically polarized laser radiation and the generation of linearly polarized harmonics in a two-color linearly polarized relatively weak laser field [5].

First, in this report, we show that our numerical results represent nicely the experimentally measured polarization characteristics of the harmonics spectra previously observed [3]. In addition, the degree of polarization of the spatial and temporal behavior of harmonics was evaluated and was demonstrated to be high. Finally, the origin of the high value of harmonics' ellipticity was studied analytically, and leads to the conclusion that this phenomenon results from the population of sublevels with different projections of the orbital quantum numbers of the atomic states.

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P-43

Fabrication of High Precision, Multilayer Based Polarimeter Designed for Wide Energy Range in EUV

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Abstracts: *We designed and fabricated a high precision five-axis polarimeter for wide energy range in EUV using transmission and reflection multilayers. This polarimeter is supported on a hexapod so that it can be transferred easily between different EUV beamlines.*

A polarimeter with multilayers has been used to characterize the state of polarization of the EUV beam such as synchrotron radiation, and the optical properties of the multilayers can be determined simultaneously [1-3]. A high precision five-axis EUV polarimeter using transmission multilayers as polarizers or phase shifters, and reflection multilayers as analyzers have been designed and fabricated (Fig.1). Using this instrument, a set of Mo/Si, Cr/C, Sc/Cr, W/B_4C multilayers for reflection and transmission (Fig.2) have also been developed. Reflection multilayers were fabricated using magnetron sputtering and transmission multilayers were fabricated using CVD deposition, magnetron sputtering and chemically etching process [4, 5]. A multilayer holder can store five sets of transmission and reflection multilayers [2], and the multilayers can be directly transferred from the holder, mounted and aligned in situ to the measuring position by wobble-stick mechanism. This polarimeter is supported on a hexapod to simplify the alignment [6]. The whole machine is designed to be transferred easily between different EUV beamlines at synchrotron facilities.

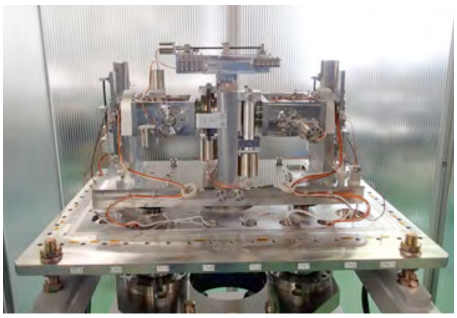

Fig. 1: *Fabricated polarimeter.*

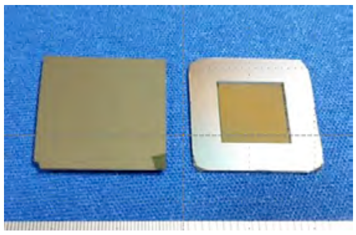

Fig. 2: *Example of transmission multilayers*

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P-44

Surface layer modification of metal nanoparticle supported polymer by irradiation of laser driven extreme ultraviolet light

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Abstracts: *We have studied irradiation effects of extreme ultraviolet (EUV) radiation on surface structure and interfacial properties of AuPd nanoparticle supported Polydimethylsiloxane to show the feasibility of EUV use for creation of functional materials by non-thermal interaction. Irradiation of ns high-energy EUV pulse on large area was successfully performed. Change in sample surface structure and creation of metal-polymer mixed layer were confirmed.*

Recent progress in intense extreme ultraviolet (EUV) light source for photolithography has been attracting much attention from many other research fields not only industry but also applied physics and fundamental physics. EUV-matter interaction and conventional laser-matter interaction, especially in energy transfer, are expected be fundamentally different. Due to its high photon energy ~100 eV, EUV photons directly ionize atoms by photoionization or break the chemical bonds without lattice vibration. Thus, it is expected that EUV radiation can change physical and chemical properties of material surface without or less thermal process. Polydimethylsiloxane (PDMS) is a polymer material widely used in industry. Creation of interfacial structure between PDMS and metal nanoparticles in discharge plasma has been confirmed. Although such structure allows us to create of functional materials [1], thermal effect is large and thermal/particle damage is one of the biggest concerns in discharge plasma. To avoid those negative effects on materials, EUV light would be suitable energy source for modification of material surface. This study aims at showing the feasibility of EUV use for modification of surface structure and interfacial properties.

The samples were prepared by using a DC sputter device. AuPd (Au97Pd3 wt%) layer with thickness of 10 and 20 nm were formed on the PDMS surface. Besides those samples, PDMS sample without nanoparticle layer was also irradiated by EUV radiation for comparison. Laser driven xenon plasma EUV source was used for the irradiation experiment. EUV light was collected on the samples by an Au coated elliptical toroidal mirror [2]. The broad wavelength spectrum ranged form 11 to 20 nm, pulse length was 10 ns, EUV energy was 13 mJ, and the spot size on the sample was 7 mmϕ. The surface structure and the chemical bound were analyzed using atomic force microscopy (AFM) and x-ray photoelectron spectroscopy (XPS) respectively. The original samples were also analyzed for comparison.

The color of irradiated area changed from transparent dark gray to transparent dark red indicating change in surface structure. The Original surface had ~10 nm nanoparticles distributing on the smooth PDMS, and depth profile of XPS result showed AuPd layer on PDMS bulk. On the other hand, growth of bumps (~50 nm) was confirmed, and both Si and Au peaks were detected in the most surface layer by XPS analysis. These change appeared in both 10 and 20 nm samples, but PDMS sample did not have such changes. Detailed discussion will be presented in the paper.

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P-45

Supersonic Three-dimensional Sapphire Micronozzles for Laser-Plasma Wakefield Accelerators

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Abstracts: *Analysis of supersonic three-dimensional micronozzles laser-machined in a sapphire block with ultrashort femtosecond laser pulses for tailored electron beam injection into Laser Plasma Wakefield accelerators is presented. The designed sub-millimeter 3D structures are inscribed inside the transparent sapphire plate and etched with hydrofluoric acid to remove the modified material. Micronozzles will be used for investigation of the critical flow parameters like pressure, temperature and tailored longitudinal density profile formation of the gas target.*

Laser plasma wakefield particle acceleration provides a significant reduction of the accelerator length, compared to conventional RF accelerators however due to the lack of proper control over the injection of electrons into the wakefield it is difficult to produce monoenergetic accelerated electron bunches [1]. Micro-sized components in the order of tens to few hundred micrometers to control the plasma density gradient are required. The behavior of fluid flow in supersonic micronozzles of sub-millimeter-scale significantly differs from classical nozzles due to the relative importance of the viscous forces.

In this report, the analysis of several configurations of supersonic 3D converging-diverging micronozzles in the range of throat size between 30 μm and 500 μm laser-machined in a sapphire block for the controlled electron beam injection into laser plasma wakefield accelerators is presented. Based on numeric flow simulation, the critical flow parameters like density, pressure, temperature, velocity and divergence are optimized for longitudinal density profile formation of the gas target. Tailored microjets of supersonic helium and/or hydrogen gas jet will be used for the formation of a plasma channel and laser plasma wakefield electron acceleration by few-cycle femtosecond 800 nm and 1030 nm laser allowing the amplification of pulses to multi-TW power with intensity of 10^{19} W/cm^2 and propagating through the plasma with an electron density of 10^{19} cm^{-3}.

The designed sub-millimeter 3D structures are inscribed inside the transparent sapphire plate. Special kind of modification, nanogratings are formed inside sapphire due to nonlinear interaction with the laser beam. That facilitates in different etching rates between the laser-modified and the unmodified material of more than 10,000:1 in sapphire. The samples are selectively etched with hydrofluoric acid to remove the modified material, expose microchannels and hollow structures.

Proposed micronozzles are integrated with Lab-on-Chip capillary-waveguides for gas supply and control, formation of double gas jets, implementation of shocks for sharper transition in density of injected electrons into the wakefield and design of thrusters for nano-satellite applications.

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P-46

Micrometer-scale photo direct machining of polydimethylsiloxane using laser plasma EUV radiations

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Abstracts: *We have investigated micromachining of PDMS sheets using laser plasma EUV radiations. We found that submicrometer structures can be fabricated by direct EUV irradiation through contact masks. X-ray photoelectron spectroscopy has revealed that there is no chemical modification induced by the EUV irradiation. All these properties are suitable for micromachining of PDMS elastomers at high aspect ratios*

Polydimethylsiloxane (PDMS) is a material used for micro total analysis systems / lab-on-chips due to its flexibility, chemical / thermo-dynamic stability, bio-compatibility and mold ability. For further development, it is inevitable to develop a technique to fabricate three dimensional structures in micrometer-scale at high aspect ratio. In the present work, we have investigated a technique for micromachining of PDMS by means of photo direct machining using laser plasma EUV light. Figure 3 shows the experimental setup for the EUV micromachining. The EUV radiations were generated by irradiation of Ta with Nd:YAG (10 ns) light. The generated EUV light around 100 eV (10 nm) were focused on PDMS surfaces at power densities up to 1×10^{8} W/cm^{2}, using an ellipsoidal mirror. Contact masks were placed on top of PDMS sheets to fabricate designed microstructures. Figure 1 shows fabricated square holes. It is remarkable that the edge have steep walls as shown by Fig. 2. We found that ablation depth is governed by power density of EUV light on PDMS surfaces. At power densities sufficiently higher than the threshold, the surfaces are ablated at a rate up to 200 nm/shot. X-ray photoelectron spectroscopy has revealed that there is no chemical modification induced by the EUV irradiation. All these properties are suitable for micromachining of PDMS elastomers at high aspect ratios.

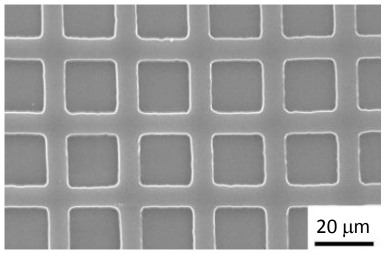

Figure 2: SEM image of microstructures fabricated by EUV irradiation on a PDMS sheet.

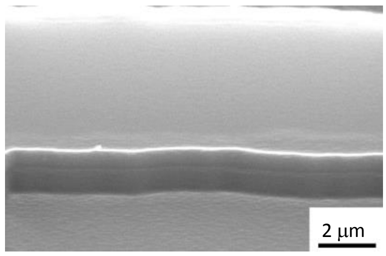

Figure 3: SEM image of edge of the structure observed at 45°.

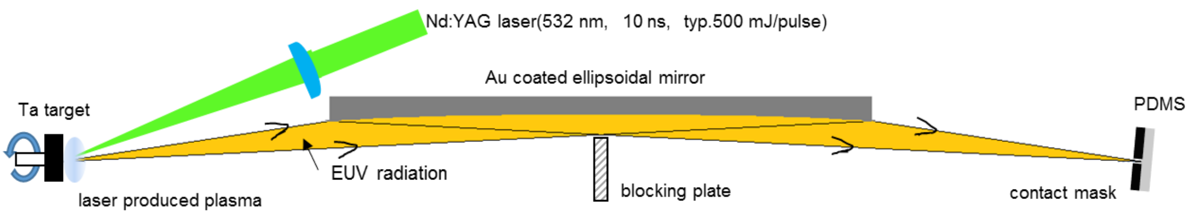

Figure 1: Experimental set up for EUV irradiation.

P-47

Possible Way of Tandem Free Electron Laser Realization on Channeling Relativistic Particles

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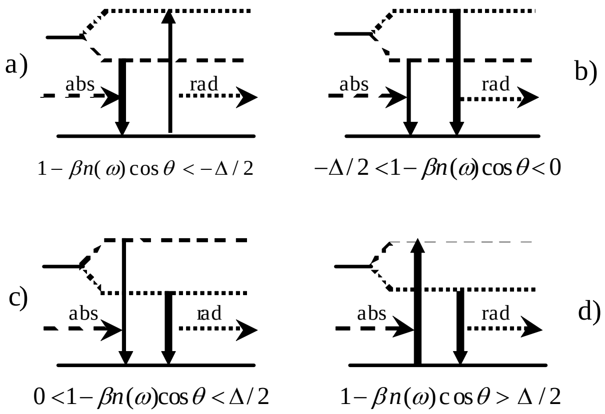
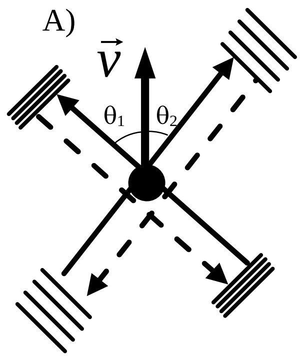
Abstracts: *In the report the possibilities of X-Ray FEL optimization and creation of tandem multiphoton inversionless X-Ray (gamma-Ray) laser are considered.*

One of the optimal ways of generation of coherent hard radiation is connected with Free Electron Laser on relativistic particles. Unfortunately, the effectiveness of "usual" FEL is very low (*dN/dn<0.001* quanta/particle). The possibilities of optimization of FEL and creation of tandem (multiphoton) short wave laser with extremely high efficiency (*dN/dn>>1* quanta/particle) are discussed. The main role in such system plays the full Doppler effect in extreme area of Cherenkov parameters $\beta n(\omega)\cos\theta\approx 1$ (see Fig. a)-d)) that was investigated for the first time in 2006 [1].





For such laser (see Fig. A)) the very effective process of consecutive generation of two types of photons with different frequencies $\omega_{1,2}$ on the same radiating transition is possible and this double photon generation leads to the restoration of the initial state of quantum system. This effect allows predicting the possibility of multiple repeat of radiation cycle on the same pair of energy levels $\varepsilon_2\to\varepsilon_1+h\omega_1\to\varepsilon_2+h\omega_1+h\omega_2\to\varepsilon_1+2h\omega_1+h\omega_2\to\varepsilon_2+2h\omega_1+2h\omega_2\to\ldots\to\varepsilon_2+Nh\omega_1+Nh\omega_2\to\ldots$ This closed loop can be repeated many times, leading to the possibility of multiphoton generation at two-level transition of the same particle [2]. The pumping source for such laser is the kinetic energy of moving particles. In tandem FEL there is no need for inversion and absorption on radiation frequency is totally absent. The main problem of realization of tandem FEL is connected with the need of mediums with positive susceptibility in high frequency range, possible ways to solve this problem are also regarded.

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P-48

Features of resonant absorption and X-Ray (gamma-Ray) laser amplification in realistic (inhomogeneous) media

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Abstracts: *In the work the problem of influence of space distribution of electron, atoms and molecules in any realistic material target on effective susceptibility and permittivity and on the threshold conditions for short-wave laser generation is discussed.*

The influence of microstructure of material medium (including features the spatial distribution of electrons, atoms or molecules) on its effective electromagnetic characteristics (susceptibility, sensitivity and permittivity) are discussed and investigated. Such influence previously has been considered only for short-wave diffraction effects and it was not taken into account during the propagation and interaction of electromagnetic waves in realistic medium [1]. The wave equation, which takes into account this influence, and some of its solutions are found.

It is shown for the first time that the features of the propagation of electromagnetic waves depend not only on the average values of these parameters (sensitivity and permittivity), but also on their spatial distribution on nanolevel. This effect is of great importance in the X-ray and gamma-Ray region but is not essential for microwave, visual and ultraviolet regions and don't change previously well known optical laws! It is shown that the presence of these features leads to a strong mutual influence of the real and imaginary parts of the susceptibility in realistic linear mediums. It was shown also that coefficient of resonant X-Ray and gamma-Ray amplification for realistic (atomic inhomogeneous) medium

$$G_{realistic} = \frac{\omega}{c}\bar{\chi}_n''(\omega)\{1-2(\bar{\chi}_n'(\omega)+\bar{\chi}_e'(\omega))K_3\} \approx$$

$$\frac{<\Delta n_n^{(2\leftrightarrow 1)}(\boldsymbol{r})>\sigma_0\Gamma^2}{(\omega_0-\omega)^2+\Gamma^2}\left\{1+\left(4\frac{<n_n(\boldsymbol{r})>c\sigma_0(\omega-\omega_0)}{\omega_0\Gamma\{1+[2(\omega_0-\omega)/\Gamma]^2\}}+2\frac{\omega_p^2}{\omega^2}\right)K_3\right\}, K_3>>1$$

differs significantly from the similar coefficients for homogeneous medium

$$G_{homog} = \frac{<\Delta n_n^{(2\leftrightarrow 1)}(\boldsymbol{r})>\sigma_0\Gamma^2}{(\omega_0-\omega)^2+\Gamma^2}$$

Applied aspects of these results to optimize the problem of creating X-Ray and gamma-Ray laser are discussed.

1. Vysotskii V.I., Vysotskyy M.V. *Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques #* **7**, 51 (2013).
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P-49

X-ray phase imaging with grating interferometer using inverse Compton scattering compact X-ray source

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Abstracts: *The inverse Compton scattering compact X-ray source is suitable for X-ray phase imaging with an X-ray grating interferometer since the spectrum of the source (about 10%) is compatible with the interferometer. Here we report the first results of X-ray phase imaging with a Talbot interferometer using the inverse Compton scattering compact X-ray source (LUCX) at KEK, which was operated at a 9 keV X-ray mean energy.*

Since an X-ray Talbot interferometer functions with cone beam of a broad energy band width, the combination with various X-ray sources is flexible for phase imaging applications to samples consisting of low-Z elements. The property of inverse Compton scattering X-ray beam is preferable for Talbot interferometry from viewpoints of spectrum and beam size. Inverse Compton scattering compact X-ray sources are formed by the collision between an electron beam and a high power pulsed laser beam, and the spectrum is quasi-monochromatic having a bandwidth of 10%. Since a grating interferometer can be operated for such a bandwidth with a performance similar to that in the case of monochromatic beam, an inverse Compton scattering X-ray beam can be used effectively as it is without any spectrum filtering for X-ray phase imaging.

Here we report the first results of X-ray Talbot interferometry using the inverse Compton scattering compact X-ray source (LUCX) at KEK, where mean energy of X-rays was 9 keV. The Talbot interferometer consisted of a $\pi/2$ phase grating and an amplitude grating 6 µm in period. The spatial coherence required for the Talbot interferometer was ensured by the source size of 120 µm (FWHM) and the distance (about 6 m) from the source to the interferometer.

The obtained moiré fringes in a 2×2 cm^2 field of view of the X-ray Talbot interferometer were recorded by a photon-counting image detector (HyPix-3000, Rigaku), whose pixel size was 100 µm. A five-step fringe-scanning method was applied with an exposure time of 30 minutes/step. The visibility of the moiré fringes was about 33%. X-ray phase imaging was successfully performed for insect samples. However, since there was artifact due to mechanical drift of gratings and the beam intensity instability during the long fringe scan time, the resultant images were not satisfactory. The drift problem will be relaxed in the near future by the increase in the beam intensity by improving the LUCX system. Then, the practical application of the combination of an inverse Compton scattering source and an X-ray Talbot interferometer will be explored extensively for X-ray phase imaging.

P-50

A Concept Design of A Monochromator Based on Linear Varying Plane Grating

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Abstracts: *Based on a linear varying plane grating (LVG), a novel monochromator is designed and verified by the optical designing and simulation software X-LAB. The designed monochromator is composed of three optical elements: two spherical mirrors and one LVG. The monochromator offers high spectral resolving power at 12.4 nm~124 nm wavelength range. The grating periods of the LVG along the ruling direction are no longer constant but linear varying along the ruling direction. The LVG has two key parameters: the center grating period and the varying rate along the ruling direction.*

The developments of soft X-ray, especially for synchrotron radiation, free-electron-laser and even the laser-plasma sources, have opened up a fundamentally new research area. Also, the monochromators for soft X-ray are necessary for experiments requiring a high spectral resolution. Many kinds of monochromator with high spectral resolution have been proposed based on plane grating with in-plane or off-plane mount and varied-line-spacing plane grating.

However, all of these monochromators have their own disadvantages, such as requiring at least four X-ray optical elements, not easy for alignment or optical design. In this report, a concept design of a monochromator based on linear varying plane grating (LVG) was designed for 4B7B beamline in Beijing Synchrotron Radiation Facility and this design was verified by X-LAB which is developed for optical system design and simulation by Research Center of Laser Fusion. This monochromator offers high spectral resolving power at 12.4nm ~ 124nm wavelength ranges and the desirable wavelength is tunable just through pushing the VLG along the ruling direction to change the illustrated grating period. Only the X-LAB has the LVG optical element design library with two key parameters which are the center grating period and the varying rate. The proposed monochromator in this report is much easier in operation, mechanical fabrication, and cheaper in the cost than the traditional type. With the development of the micro-fabrication technology, this novel monochromator may become a popular and useful kind.

In the presentation, we will show the details of the design of the novel monochromator and simulation using X-LAB.

P-51

Generating ultrahigh brilliance quasi-monochromatic MeV γ-rays with high-quality LWFA electron beams

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Abstracts: *By designing a special cascaded laser-wakefield accelerator to generate high-quality monoenergetic e-beams, which were bound to head-on collide with the intense driving laser pulse via the reflection of a 20-um-thick Ti foil, as using a self-synchronized all-optical Compton scattering scheme, we has produced tunable quasi-monochromatic ultrahigh brilliance MeV γ-rays. This robust and compact ultrahigh brilliance γ-ray source may pave the way towards a variety of practical and research applications in x-ray radiology and photonuclear fields.*

Laser wakefield accelerators (LWFA) have achieved significant progress recently owing to the sophisticated injections, cascade and guiding technologies, and they can produce monoenergetic, energy tunable, GeV-class femtosecond e-beams with tens of pC charge over a distance of centimeter-scale, which hold the potential of becoming compact alternatives to conventional accelerators. The properties of the e-beams qualify them as a unique driver for the generation of compact, well-collimated, near-monochromatic, tunable, ultra-short and high peak brilliant x- and γ-ray sources up to a few MeV.

In this report, a cascaded laser accelerator (0.8mm+3mm) is designed to generate high-quality e-beams (~ 1% rms energy spread, ~ 50 pC at the peak energy, tunable from 200 to 500 MeV, < 0.4 mrad rms divergence). In order to reduce the difficulty of laser-electron temporal and spatial synchronization, we employed a self-synchronized all-optical Compton scattering scheme, in which the reproducible e-beams collide with the intense driving laser pulse via the reflection of a thin foil (20um Ti or 30um Al) in the naturally overlapped region. With the perfect combination of a cascaded laser-plasma accelerator and a plasma mirror, the photon yield was improved up to ~ 5×10^7 per shot and quasi-monochromatic γ-rays (tunable from 0.3 to 2 MeV) with a narrow bandwidth of ~ 14% (rms) have been achieved, corresponding to an ultrahigh brilliance of ~ 3.1×10^{22} photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% BW, which is one order of magnitude higher than ever reported value in MeV regime to the best of our knowledge.

The experiments were carried out at the SIOM 200TW laser system based on the chirped-pulse amplification (CPA) Ti:sapphire @ 1-Hz repetition rate with a duration of 33*f*s at a wavelength of 800nm. With careful design and sophisticated measurements, the e-beams and γ-rays were detected and analyzed respectively. Moreover, relevant particle-in-cell and Monte Carlo simulations showed good agreements with the experimental results and theoretical analysis. We anticipate that this ultrahigh brilliance and quasi-monochromatic MeV γ-rays enable many practical applications.

P-52

High order harmonic generation with Mid-infrared laser pulse

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Abstracts: *As one of the most important physical processes of strong-field laser-matter interaction, laser-driven electron-ion recollision is the fundamental process during high-order harmonic generation (HHG). For a multicycle laser field, the recollision process repeats itself every half-cycle of the laser field. Thus, many electronic trajectories would interfere constructively and the well-resolved discrete harmonic peaks can be generated. As we known, the well-known three-step model of HHG predicts that the cutoff law obeys Ecutoff = Ip + 3.17Up (Ip is the ionization potential; Up∞Iλ2 is the ponderomotive energy), implying that the cutoff energy of HHG can be extended by increasing the driving wavelength. The rapid development in ultrafast laser technology has enabled the construction of high-power femtosecond optical parametric amplifiers, which can offer a carrier-envelope-phase (CEP) -stabilized few-cycle pulse at midinfrared wavelengths. With the longer wavelength mid-infrared laser pulse, it is easy for the pondermotive energy of the returning electron to be very large. Only a few recollisions occur in a multicycle 1800/900 nm OTC laser field. KeV harmonics/fluorescence can be generated.*

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軟X線領域用ラミナーレプリカ回折格子

- 軟X線領域用の収差補正型フラットフィールドポリクロメータ用凹面ラミナー型レプリカ回折格子です。
- アレイ型検出器と組み合わせることにより、簡単に分光器としてお使いいただけます。

標準仕様

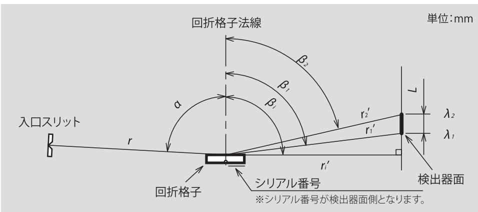
種別	不等間隔曲線溝ラミナーレプリカ回折格子※1	中心厚許容差 (mm)	±0.5 (T)
		有効領域 (mm)	外形の周囲5mmを除く全面
ブランク材質	BK7相当品	溝本数許容差	±0.5%
外形寸法許容差 (mm)	±0.2 (W) ×±0.2 (H)	キズ	80-50 (MIL-O-13830A準拠)

※1 格子溝は樹脂にて形成されています。

標準品リスト

コード番号	溝本数	波長範囲	検出器長	設計マウントパラメータ								外形寸法	コーティング
	N (本/mm)	$\lambda_1 \sim \lambda_2$ (nm)	L (mm)	r (mm)	α (deg.)	r_1' (mm)	β_1 (deg.)	r_2' (mm)	β_2 (deg.)	r_i' (mm)	β_i (deg.)	W × H × T (mm)	材質
30-001	2400	1 ~ 6	23.5	237.0	88.65	235.6	85.81	238.5	80.17	235.0	90.0	50 × 30 × 10	Au
30-002	1200	5 ~ 20	25.3	237.0	87.0	236.7	83.0	241.1	77.1	235.0	90.0	50 × 30 × 10	Au
30-003	2400	1 ~ 7	26.8	236.7	88.6	235.8	85.8	239.5	79.4	235.0	90.5	50 × 30 × 10	Au
30-004	2400	0.6 ~ 4	19.4	236.8	88.65	233.9	86.64	235.8	81.94	233.5	90.0	50 × 30 × 10	Au
30-005	1200	3.5 ~ 8.5	11.1	237.0	87.07	234.8	83.98	236.2	81.30	233.5	90.0	50 × 30 × 10	Ni
30-006	300	20 ~ 80	25.3	237.0	87.00	236.7	83.04	241.1	77.07	235.0	90.0	50 × 30 × 10	Au

分光系配置図

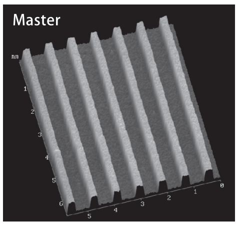


特長

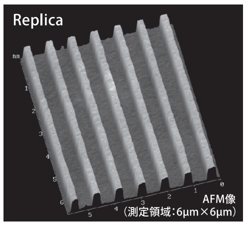
- 高効率
- 低迷光
- 高次光が少ない
- 高分解能

溝形状

- マスターとレプリカの形状比較



面精度※2 ：0.12 λ
面粗さ※3 ：0.33nmRMS



面精度※2 ：0.13 λ
面粗さ※3 ：0.37nmRMS

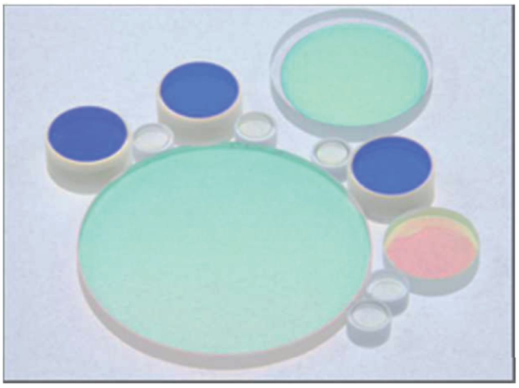
※2 測定領域：46mm (W) ×26mm (H)　※3 測定領域：0.2mm×0.22mm

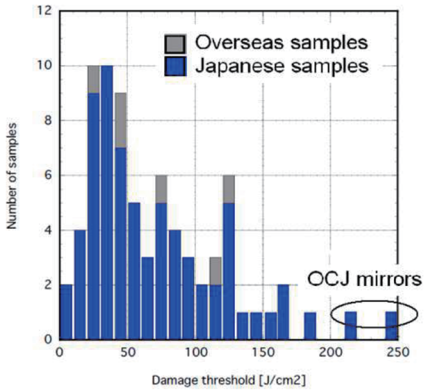
放射光用ラミナー回折格子 (VLSG) も特注で製作しておりますのでお問い合わせ頂ければ対応可能です。

株式会社 島津製作所　デバイス部　〒101-8448 東京都千代田区神田錦町1丁目3番
TEL：(03) 3219-5797　FAX：(03) 3219-5567
E-mail：sensor@group.shimadzu.co.jp　URL：http://www.shimadzu.co.jp/opt/　最新情報はWebにてご確認ください。

Laser mirror

532nm 45deg type





Standard spectrum specification :

R 532nm≧ 99%（p-polarization）　　θ=45 deg.

Advantage :

The damage threshold of this filter was found to be more than 200 J/cm²
under the test condition of pulse width 8ns in a Japanese laser damage competition in 2009. This competition result also showed ***OCJ coatings were No.1 and No.2 in 75 samples from 25 companies.***

The filters were evaluated by the Institute for Laser Technology in Japan on 18th November 2009.

Application field :

Nd:YAG 532nm laser optics

OCJ/Optical Coatings Japan

Head office : Tokyo, Japan

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NTT AT

ICXRL 2016 Schedule

Sunday 22	Monday 23	Tuesday 24	Wednesday 25	Thursday 26	Friday 27
	8:30-9:25 **Registration** 9:25-9:45 **Opening** **Chair: T. Kawachi** 09:45-11:00 **Session 1: Prospect of coherent x-ray source-1** **Chair: S. Bulanov** (Invited) G. Korn (Invited) T. Ishikawa (Invited) W. Leemans	09:00-10:35 **Session 5: Laser plasma physics and intense x-ray** **Chair: G. Tallent** (Invited) H. Nishimura (Invited) L. Fletcher (Invited) A. Faenov V. Vysotskii	09:00-10:15 **Session 9: Novel x-ray source and the applications** **Chair: J. Nilsen** (Invited) G. Mourou (Invited) C. Barty (Invited) M. Kando	09:00-10:30 **Session 11: Laser-driven x-ray lasers-2** **Chair: C.-H. Nam** (Invited) G. Tallents (Invited) M. Kozlova M. Nishikino E. Oliva	09:00-10:15 **Session 15: Novel x-ray source and applications using LWFA electron beams-2** **Chair: L. Chen** (Invited) E. Esarey (Invited) H.-T. Kim (Invited) J. Liu
	11:00-11:15 **Coffee break**	10:35-10:50 **Coffee break**	10:15-10:30 **Coffee break**	10:30-10:45 **Coffee break**	10:15-10:30 **Coffee break**
	11:15-12:30 **Session 2: Prospect of coherent x-ray source-2** **Chair: K. Kondo** (Invited) K. Midorikawa (Invited) J. Rocca (Invited) V. Malka	10:50-12:20 **Session 6: Ultrafast coherent x-ray source and application** **Chair: A. Klisnick** (Invited) B. Vodungbo (Invited) D.-E. Kim R. Itakura S. Miyamoto	10:30-11:55 **Session 10: Novel x-ray source and applications using LWFA electron beams-1** **Chair: W.Leemans** (Invited) L. Chen M. Hadj-Bachir K. Hu M. Toyoda	10:45-12:00 **Session 12: EUV light source and EUV lithography** **Chair: A. Sasaki** (Invited) S. Okazaki (Invited) E. Hosler (Invited) M. Marconi	10:30-11:30 **Session 16: Novel x-ray source and applications using LWFA electron beams-3** **Chair: H. Daido** C. Schroeder S. Rykovanov J. Koga
	12:30-13:50 **Lunch break**	12:20-13:45 **Lunch break** (International advisory board meeting)	**Excursion**, Kyoto, Hozugawa river boat ride	12:00-13:20 **Lunch break**	11:30-12:00 **Closing: ICXRL-2016** **S. Bulanov & T. Kawachi**
	13:50-15:30 **Session 3: Laser-driven X-ray Laser-1** **Chair: J. Rocca** (Invited) A. Klisnick (Invited) S. Sebban (Invited) J. Nejdl (Invited) D. Bleiner	13:45-15:50 **Session 7: High order harmonic generation** **Chair: S. Sebban** (Invited) C.-H. Nam (Invited) A. Pirozhkov (Invited) C. Bourassin-Bouchet (Invited) D. Villeneuve L. Dao		13:20-14:50 **Session 13: Capillary discharge plasma x-ray lasers** **Chair: H.-T. Kim** (Invited) P. Sasorov (Invited) A. Jancarek H. Cui V. Antonov	**Laboratory Tour**
	15:30-15:55 **Coffee break and Conference photograph**	15:50-16:05 **Coffee break**		14:50-15:05 **Coffee break**	
	15:55-18:20 **Session 4: X-ray imaging-1** **Chair: A. Vinogradov** (Invited) C. Menoni (Invited) A. Momose (Invited) M. Zuerch (Invited) Y. Takahashi (Invited) N. Popov N. Inogamov	16:05-18:00 **Session 8: X-FEL and synchrotron radiation** **Chair: T. Ishikawa** (Invited) J. Nilsen (Invited) H. Yoneda (Invited) Y. Inubushi J. Harries L. Wei		15:05-00:00 **Session 14a: X-ray imaging-2** **Chair: M. Kozlova** (Invited) H. Fiedorowicz H. Daido (Invited) S. Witte 16:15-17:40 **Session 14b: X-ray imaging-3** **Chair: A. Momose** (Invited) H. Stiel E. Ragozin T. Pikuz A. Kosuge	
18:00-20:00 **Registration and Welcome reception** at the garden, Nara Kasugano International Forum, Iraka		18:00-20:00 **Poster Session** (with light meal and refreshments) **Chair: M. Nishikino**		19:00-21:00 **Conferene Dinner** (" Half Time" Museum Restaurant)	