統合シミュレーションコードによる高速点火実験解析

大阪大学レーザーエネルギー学研究センター　中村　龍史

概要

高速点火核融合ではターゲット爆縮から追加熱用レーザーによる高速電子発生まで時間・空間スケールにおいて非常に広範な領域の現象を理解する必要がある。そこで本プロジェクトでは輻射流体コード、粒子コード、Fokker-Planckコード、の開発が進められており、これらのコードをネットワークを介して結合することで統合コードの構築を目指している。具体的には、１）爆縮レーザーと燃料プラズマとの相互作用による流体運動、２）点火レーザーと金ターゲットとの相互作用による高速電子発生、３）高速電子と爆縮プラズマとの相互作用によるエネルギー緩和及び原子核反応過程、をそれぞれの流体、粒子、フォッカープランクコードを用いて解析する。各コードで得られた結果を必要に応じて互いにデータ交換することで、高速点火実験の再現を目指している。

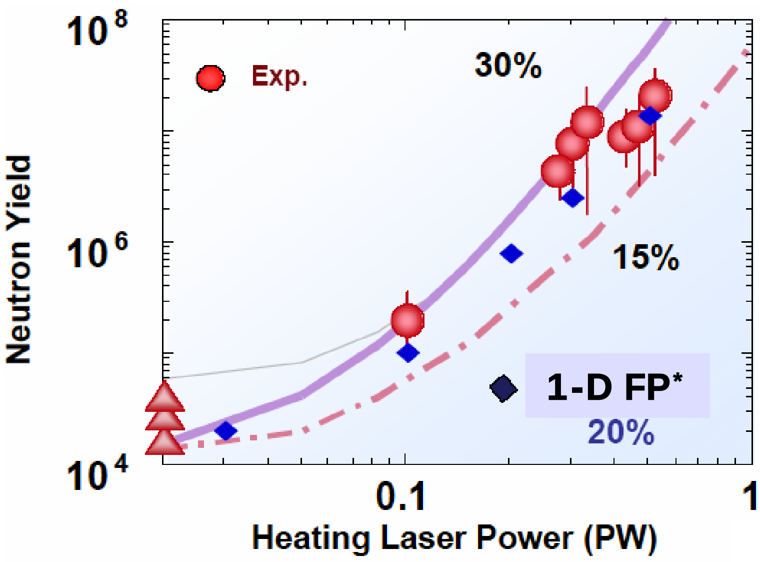
Background : Necessity of Integrated Simulation

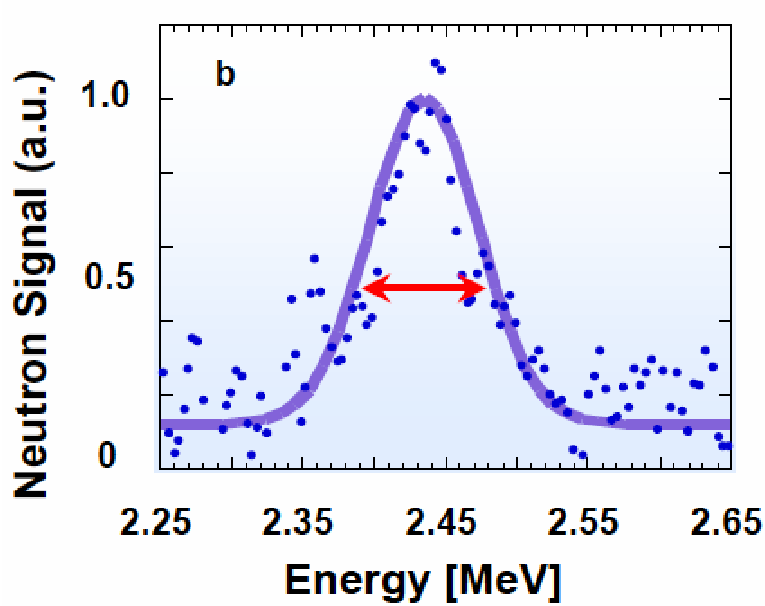
Fast Heating of Cone-Guided CD Targets with GEKKO PW Laser at ILE

R. Kodama, et al., Nature 418, 933 (2002)

Neutron yield was enhanced by 3 orders of magnitude.

Core temperature reached ~ 800eV.

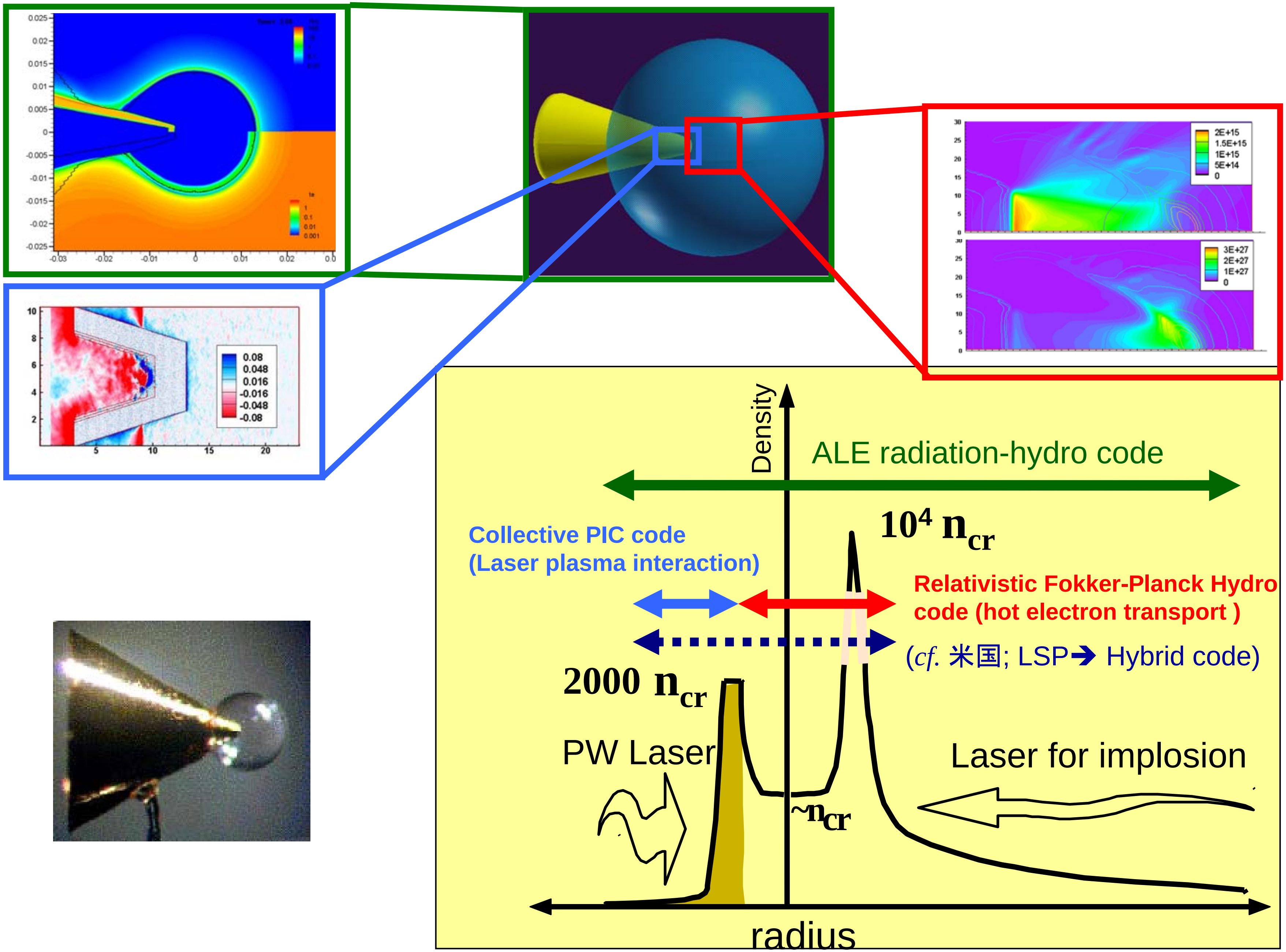




*) 1-D Fokker-Planck simulations using assumed profiles of a) imploded core, and b) fast electrons entering the core

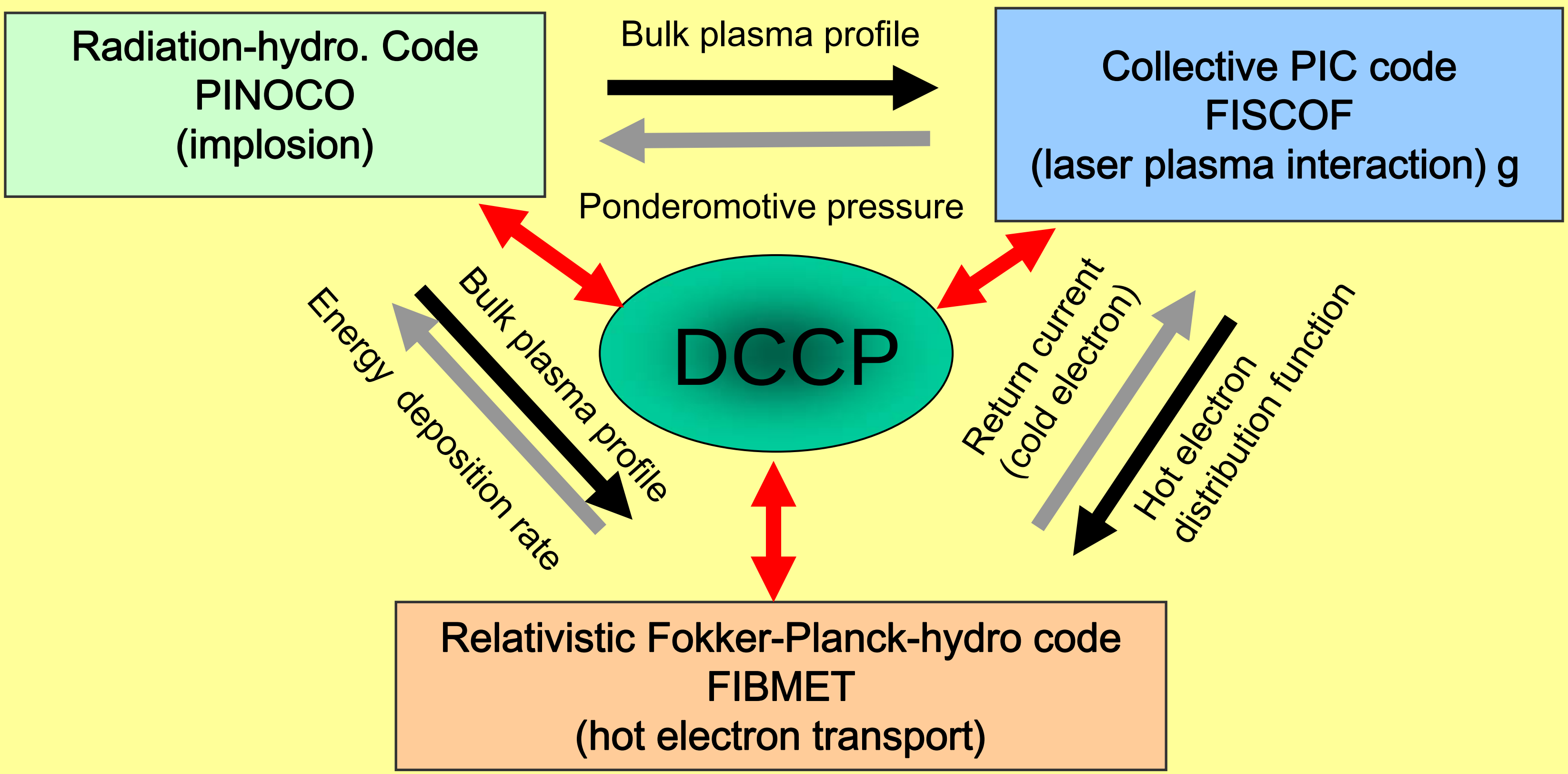
For understanding the core heating properties and estimating ignition and burn characteristics of FI, multidimensional overall calculation, which includes the implosion dynamics, generation of fast electrons, and core heating, is indispensable.

レーザープラズマ統合コード(FI3)



FI^3 project

Fast Ignition Integrated Interconnecting code project



Data flow in FI^3 system. (Black arrows are already executable data flows, and gray arrows are next plan to be considered.)

Numerical simulation of cone-guided implosion using 2D radiation-hydro simulation code "PINOCO"

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PINOCO

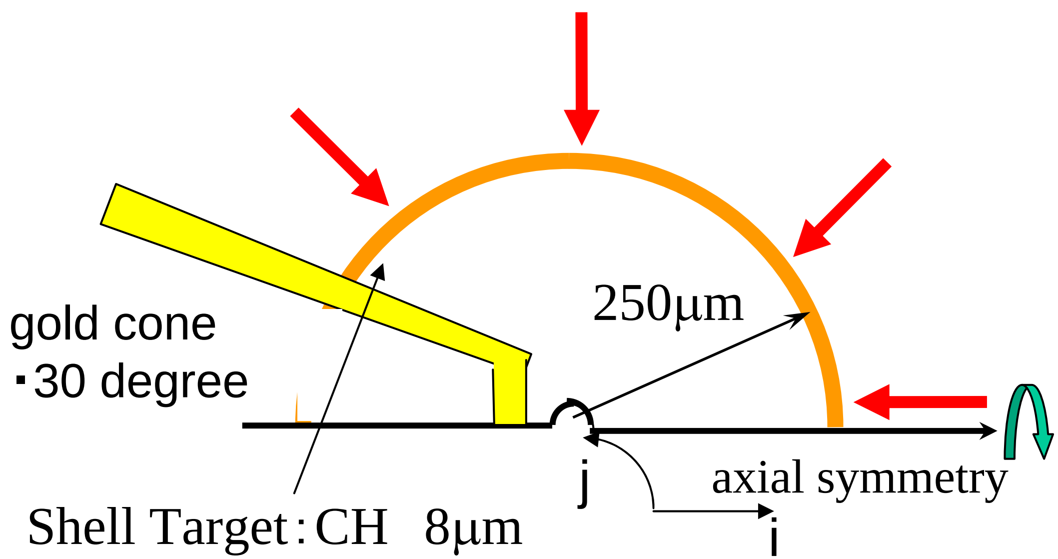
- 2 temperature plasma
  - Hydro ALE-CIP method
- Thermal transport
  - flux limited type Spiter-Harm
  - Implicit (9 point-ILUBCG)
- Radiation transport
  - multi-group diffusion approximation
  - Implicit (9 point-ILUBCG)
  - Opacity, Emissivity (LTE, CRE)
- Laser energy
  - 1-D ray-trace
- EOS
  - Tomas-Fermi
  - Cowan

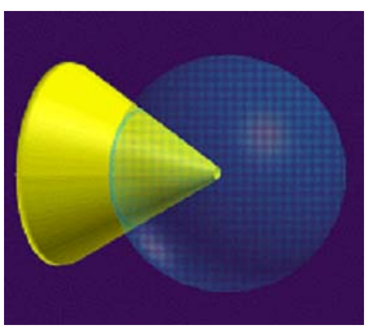
Implosion Laser condition

・Wavelength：0.53μm

・Energy ： 4.5 kJ (Gaussian, on target, center focused)

・Ray-trace : 1 - D (radial direction)





computational grids：300（i- direction)x280（j - direction）

Imploded core plasma ρR is higher for cone target than for spherical target in PINOCO-2D simulations

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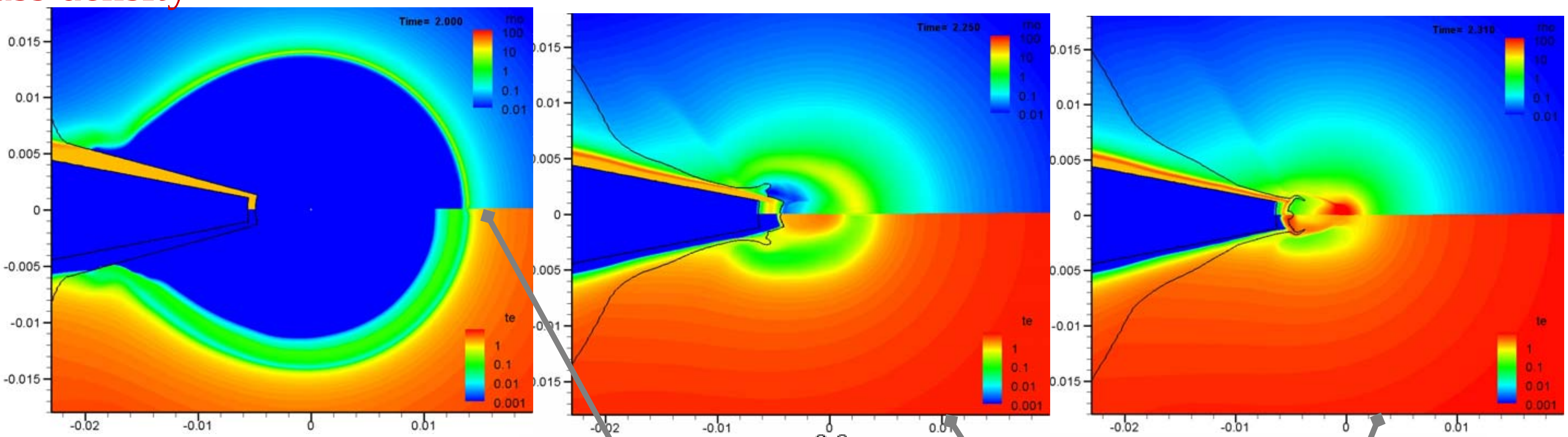
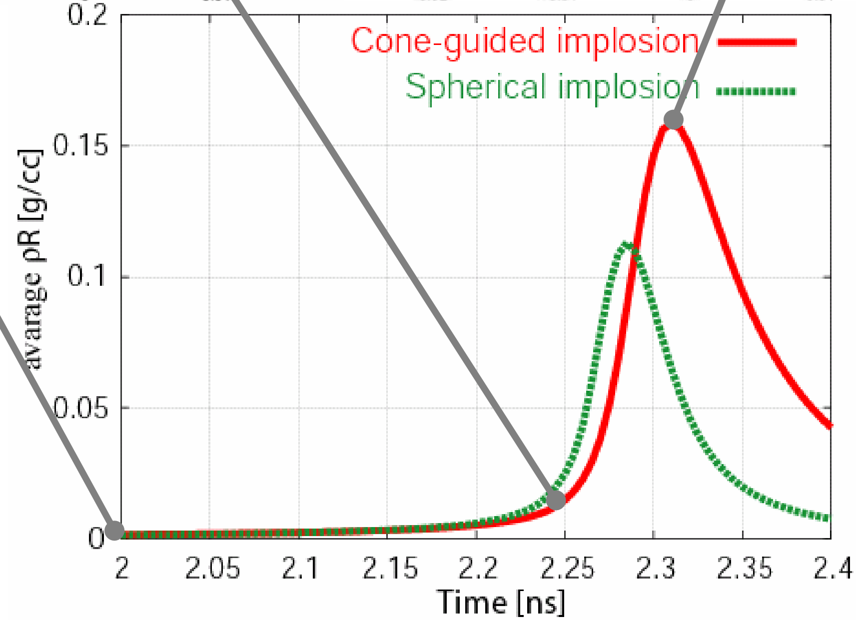
mass density



electron temperature



time dependence of angular average ρR in gold cone-guided implosion (GXII scale CH target)

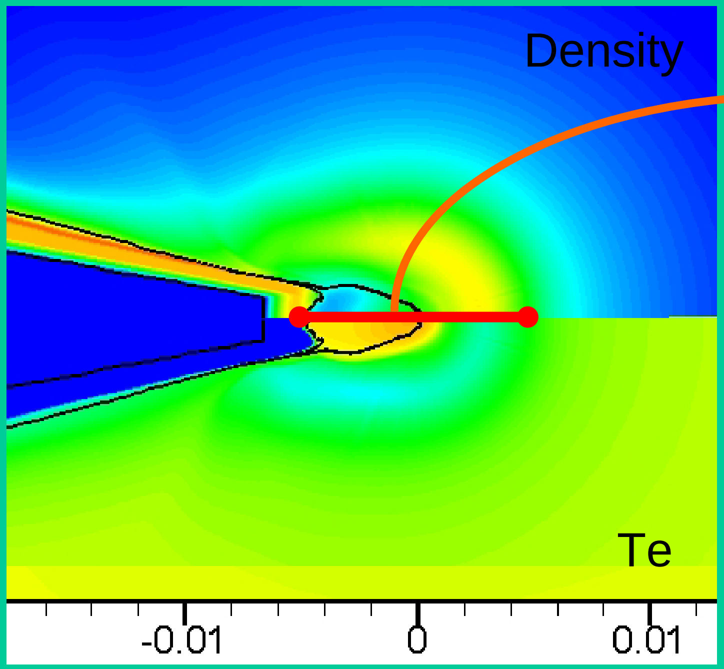
In the spherical implosion, the shell target reach the maximum compression at 2.285 ns.
In non-spherical implosion case, the shell continued to be compressed since a hot spot is not formed and an average ρR reached a higher value (0.15 g/cm^2).

H. Nagatomo *et al.*, IAEA/FEC-IF/P7-29

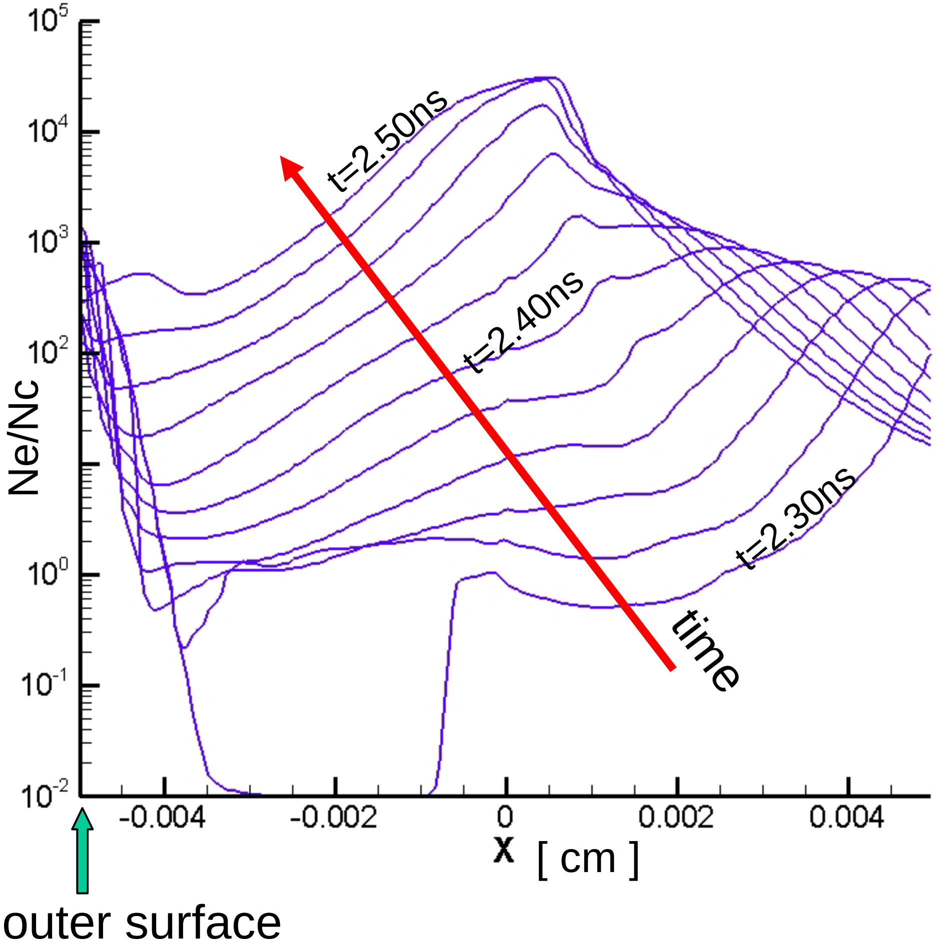
In the cone-guided implosion simulation by PINOCO-2D, there is low density (=<10Nc) spot between gold cone and imploded core plasma.

Implosion simulation (PINOCO-2D)

Laser : 2.5kJ 2ω
Target : CH (r=250μm, t=8μm)
Cone : 30 degree, gold

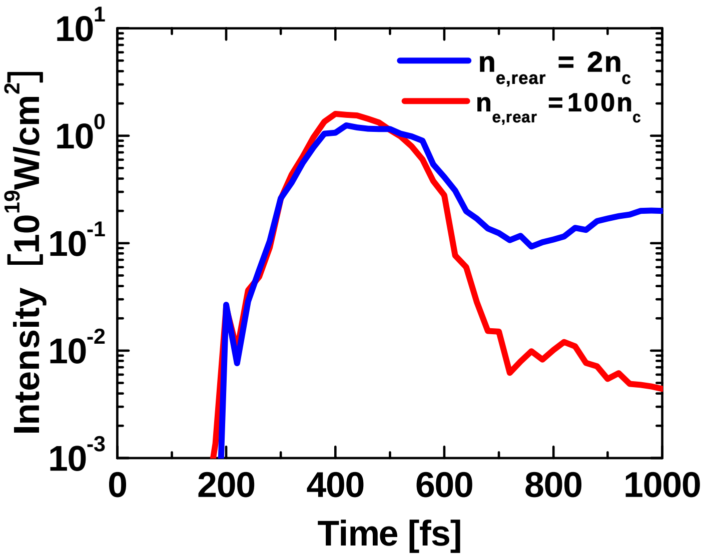


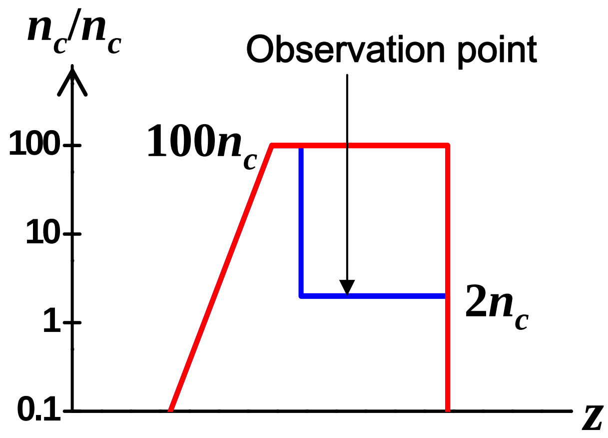
Time history of electron number density distribution on the x-axis



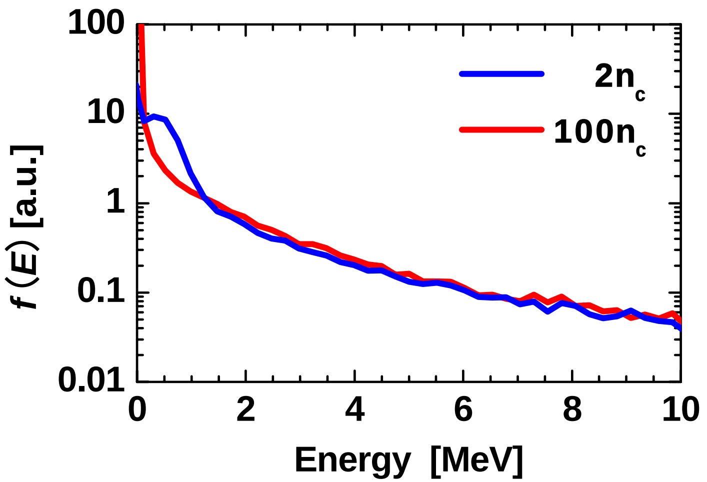
1D PIC simulation results ; conversion efficiency ~ 20 %

Time-dependent beam intensity I_{fe}





Time-averaged energy distribution



- In the $n_{e,rear}=2n_c$ case, I_{fe} dose not drop off even after finishing laser irradiation.
- Sub-MeV electrons, which are favorable for core heating, are observed more in $2n_c$ case than in $100n_c$ case (w/o density gap).
- **Conversion efficiency from laser to hot electron is about 20 percent.**

Fokker-Planck Simulation Model

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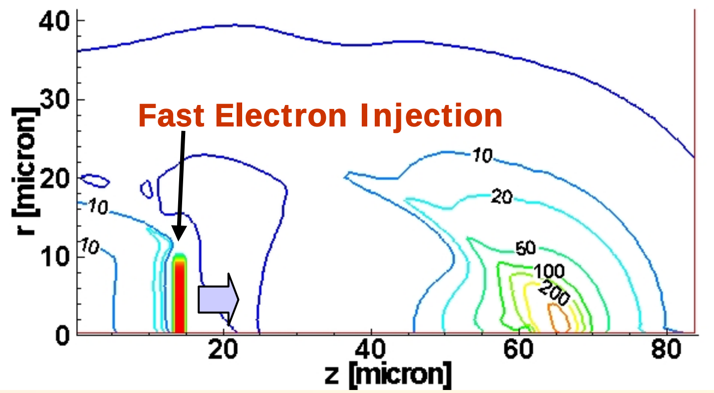
Fast Electron Profiles
(PIC Code)

Fast electrons were injected at inner or outer surface of a gold cone.



Imploded Core Profiles
(ALE Rad-Hydro Code)

Fast Electron Transport

Relativistic Fokker-Planck transport
Electromagnetic Fields

(x,y) – CIP (80x160 mesh)
(p) – Discontinuous Linear FEM (30 groups)
(μ, ϕ) – 2D Discrete Ordinate Sn method (144 directions)

ρ, T ↑ ↓ **Energy deposition rate**

Radiation-Hydrodynamics

Bulk Plasma
・1-fluid 2-temp. CIP code

Radiation
・ Flux-limited diffusion

Fast Electron Heating Profile ($n_{e,rear}$ = $2n_c$)

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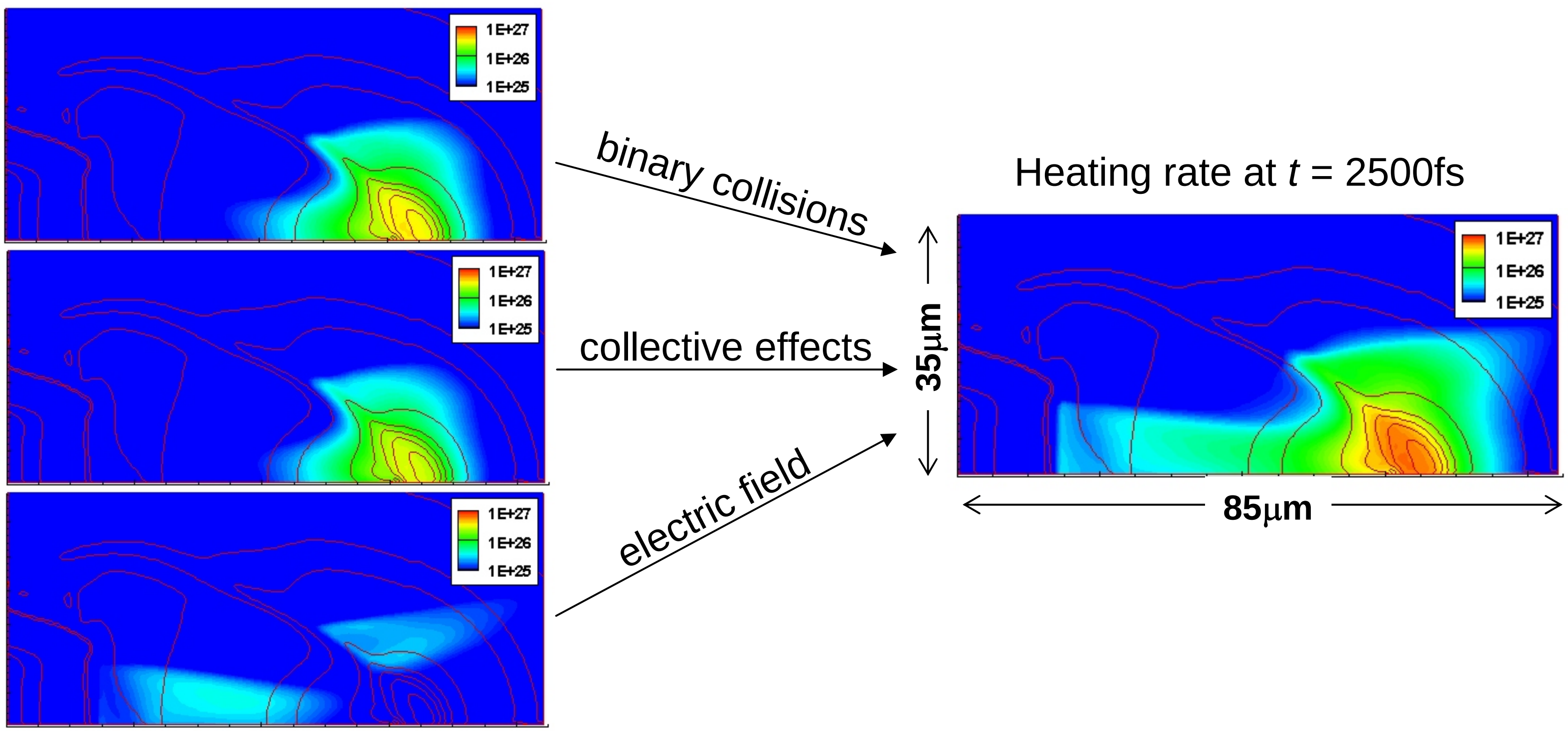

Injected fast electron energy = 80J →

	Core (ρ > 50g/cc)	Other	Total
Deposited [J]	20	20	40
Binary [%]	56	50	53
Collective [%]	42	34	38
E-field [%]	0.17	15	8.7

Core Heating rate & Temperature (ρ > 50g/cc)

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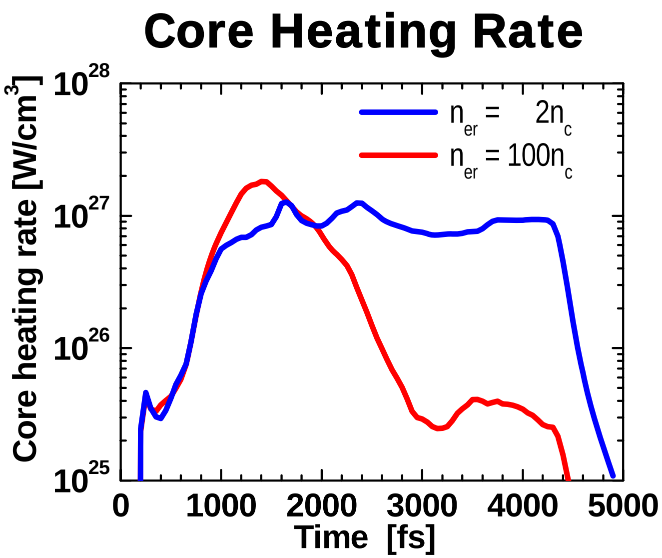
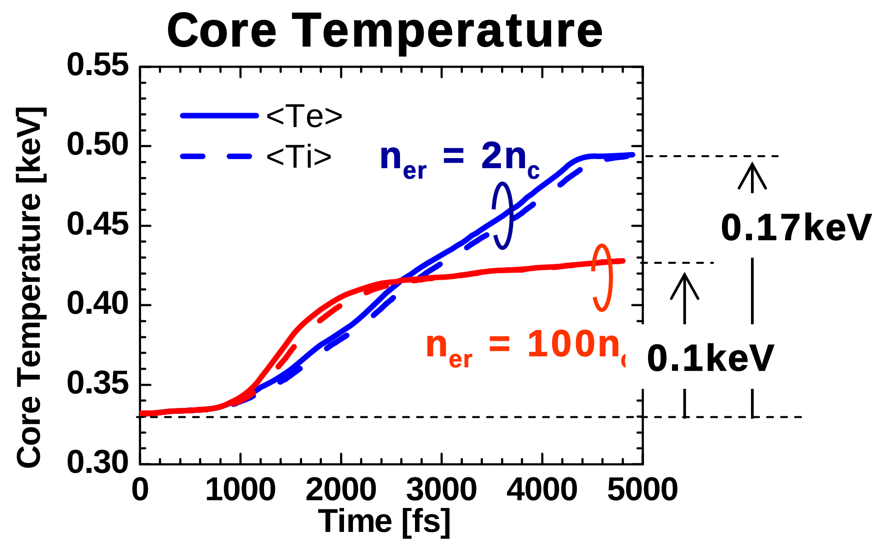




In the early stage (t <2000fs), P_{dep} is lower in 2n_c case (with density gap) than in 100n_c case (w/o gap); Temperatures rises more slowly in 2n_c case.

Core heating duration is longer in 2n_c case, because fast electrons are constantly delivered to the core even after finishing laser irradiation.

	n_{er} = 100n_c	n_{er} = 2n_c
Core temp., <Ti>	0.43keV	0.50keV
Increment, Δ<Ti>	0.10keV	0.17keV (~70% ↑)

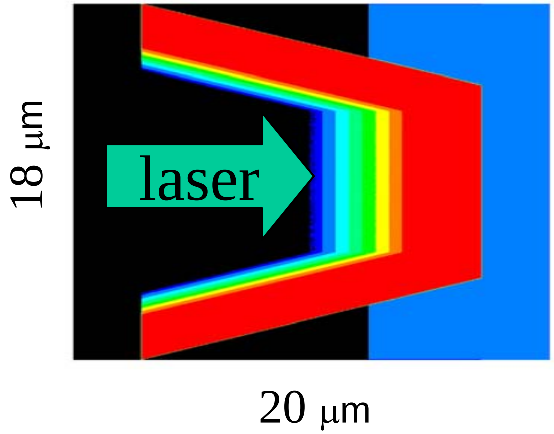
Coupling efficiency in 2n_c case

$\eta_{L\rightarrow e}$ = 21%, $\eta_{e\rightarrow core}$ = 25% ⇒ $\eta_{L\rightarrow core}$ = 5.4%.

experiments ~ 0.8keV

Cone – laser interaction by 2D PIC

- Electron spectrum propagating out from cone target
- Hot electron generation process, i.e.,
    1. Hot electron generation and transport
    2. Electron acceleration at cone tip
    3. Beam propagation at steep density gap



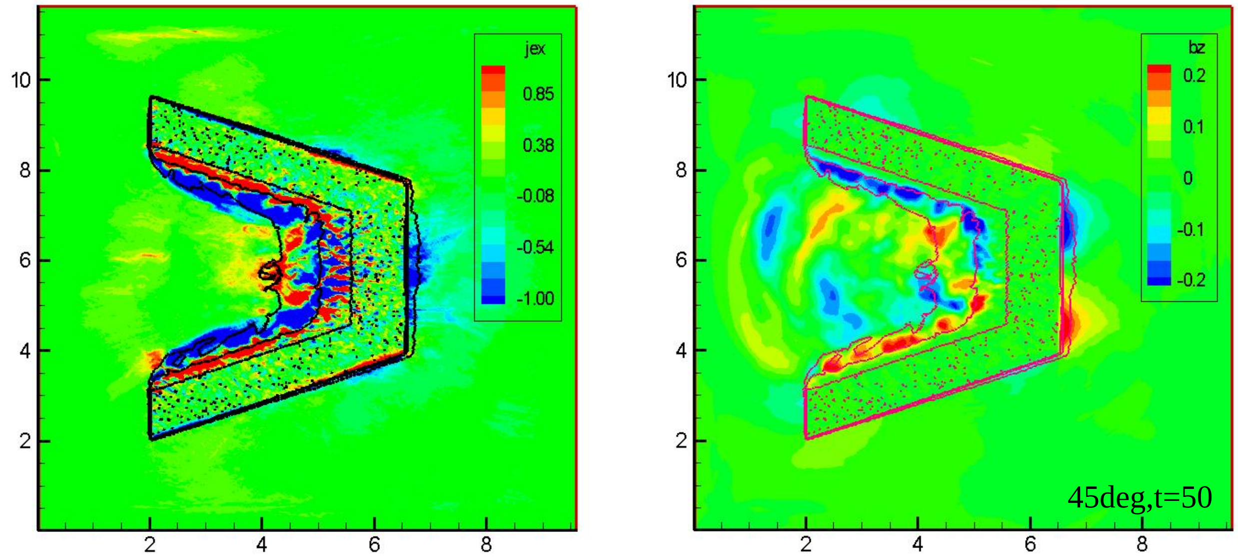
<u>Plasma condition</u>
100Nc cone target with 2 μm scale Length preplasma. Rear side plasma Density is 2 Nc.

<u>Laser Condition</u>
Wavelength : 1 μm
Peak Intensity : 2.5 *10^{19} w/cm^2
Spot size : 5.0 μm
Pulse duration : 150 fs

<u>System condition</u>
Simulation box : 1366 × 1144
Particles for Nc : 8
Maximum particles : 12

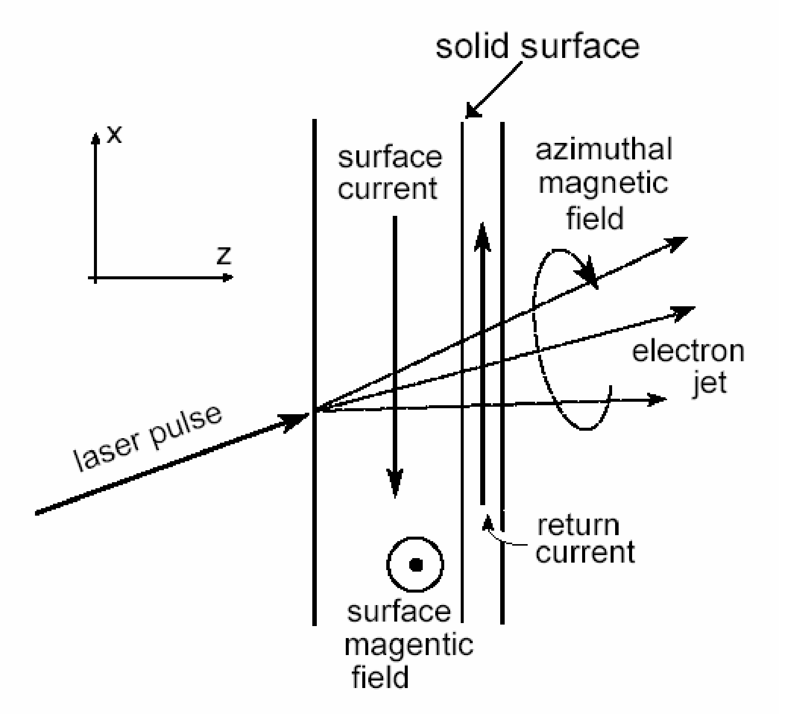
Electron transport along cone surface

Profile of current density and static magnetic field

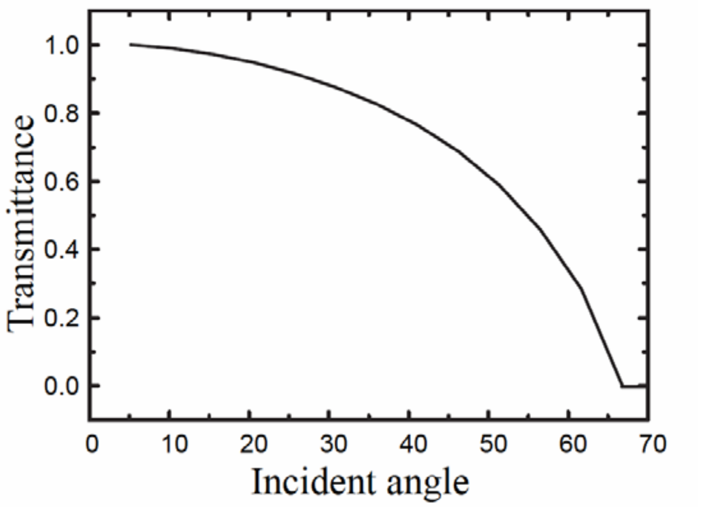


Fast electrons flows inside of the effective critical surface (~ Ncr / a, for a >> 1). They are confined by static magnetic field and guided towards the cone tip.

Surface magnetic field and current layer formation



Transmittance strongly depend on the laser incident angle.

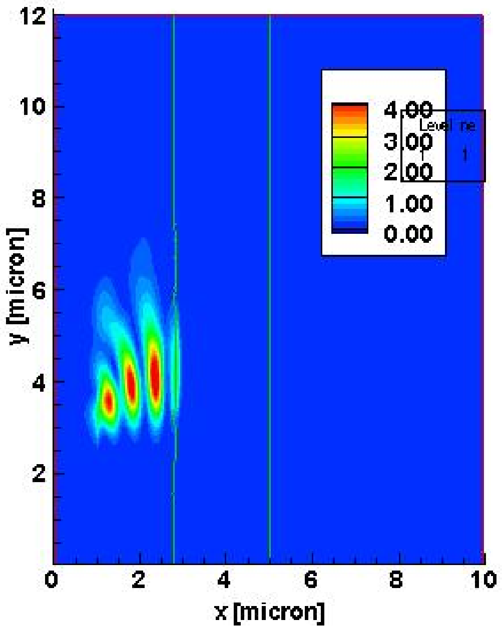


Fast electrons produced by obliquely incident laser pulse flows along the solid surface guided by static magnetic and electric field.

PRL.**93**,265002(2004)

Energy transport along the target surface

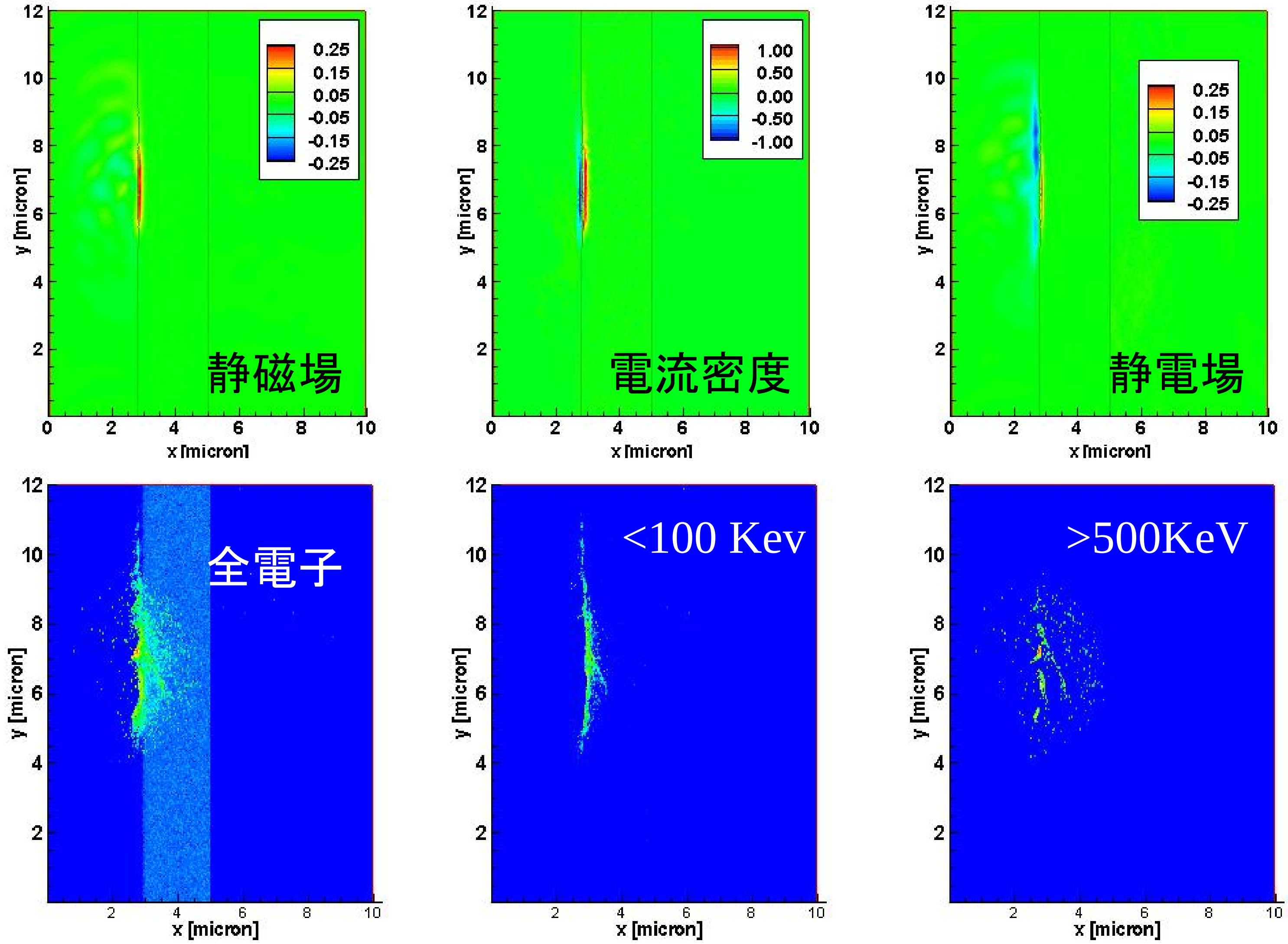
Fast electrons are dominantly transported along the solid surface by oblique incident laser pulse. (Univ. Michigan, Univ. Texas)



Simulation condition

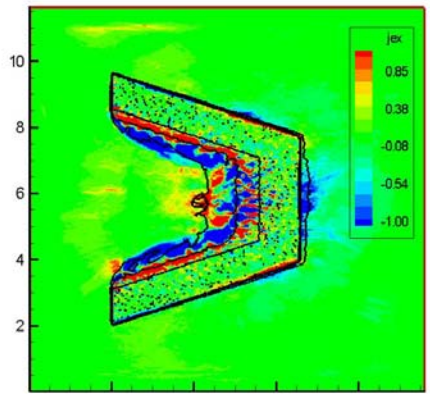
- Plasma : Density of 10 Nc, 2 micron width, initial temperature of 500 eV .
- Laser : a =1 , spot size is 1 micron. Pulse duration of 25 fs
- Geometry: Obliquely incident on target with 30, 45, and 70 degree

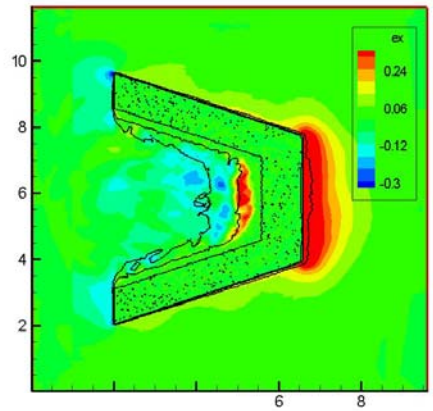
Electrons with moderate energy flows in lateral direction

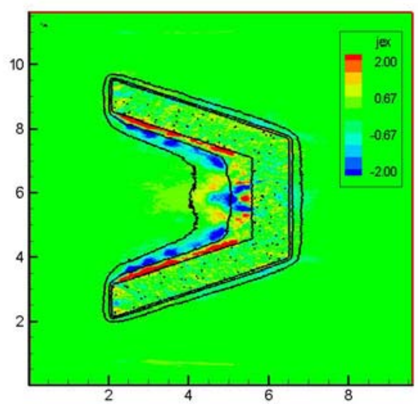


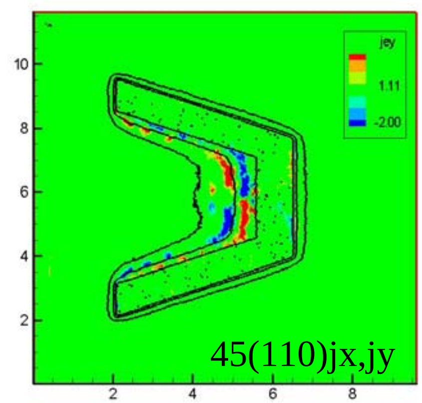
Density gap prevents electron beam flow

Electron beams do not propagate through density gap smoothly since strong electro-static field is induced via Weibel instability.





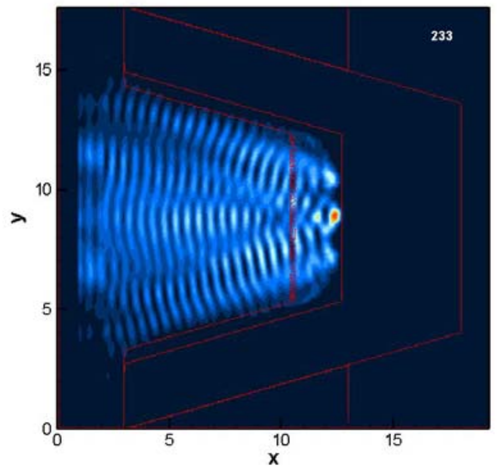




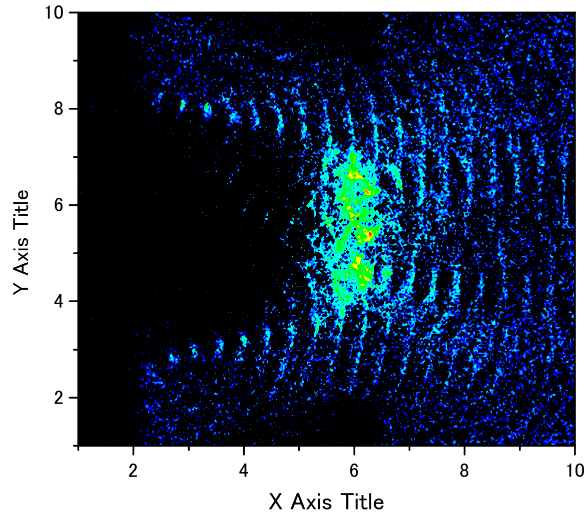
Hot electrons are reflected back at the effective critical surface.

Accumulated electrons are pushed by the laser fields at the cone tip

Intensity pattern of laser field focused by the cone target

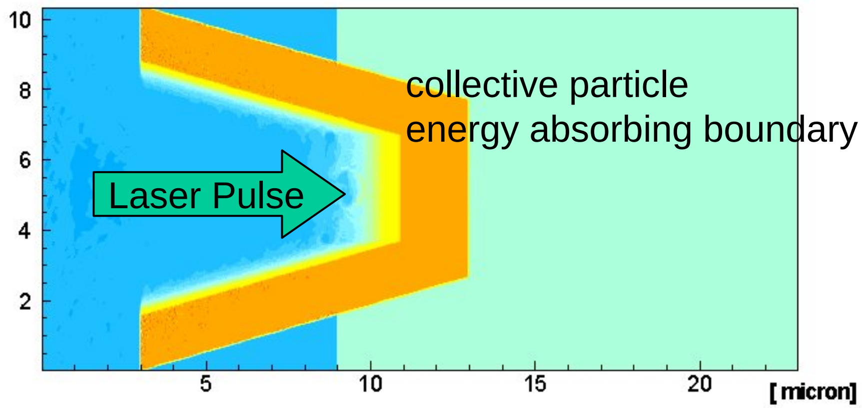


Snap shot of hot electron distribution



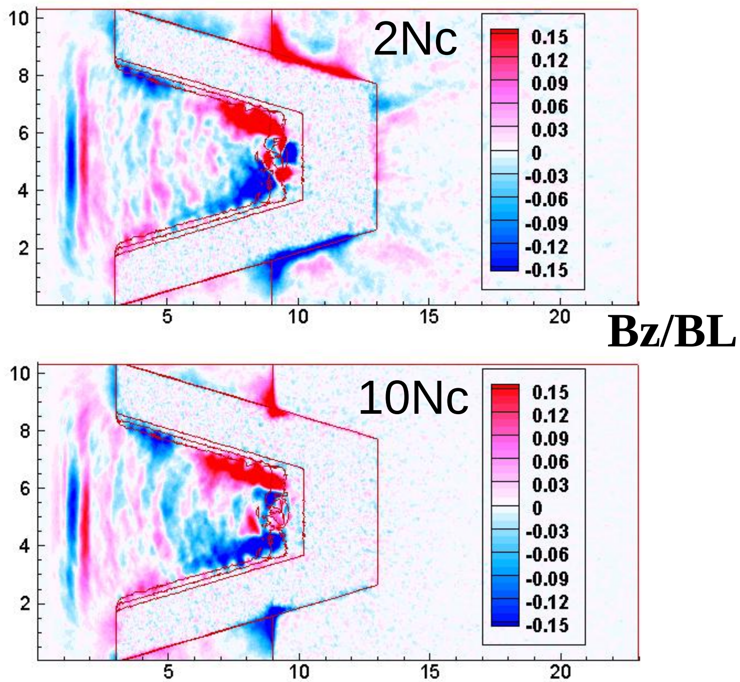
Electrons are strongly pushed forward at the cone tip. Its distribution is determined by the laser intensity pattern.

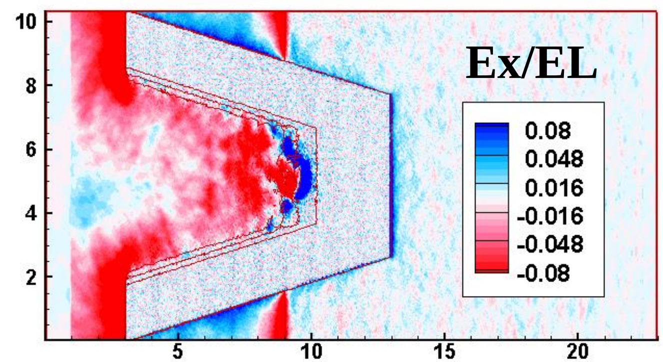
Strong static field is induced at boundary to decelerate electrons



<u>Laser Condition</u>
Wavelength : 1 micron
Peak Intensity : 2.5 *10^{19} w/cm^2
Spot size : 2.5 micron
Pulse duration : 100 fs

<u>Plasma condition</u>
30Nc cone target with rear side plasma, density of
a) 2Nc (1/15) , b) 10 Nc (1/3).

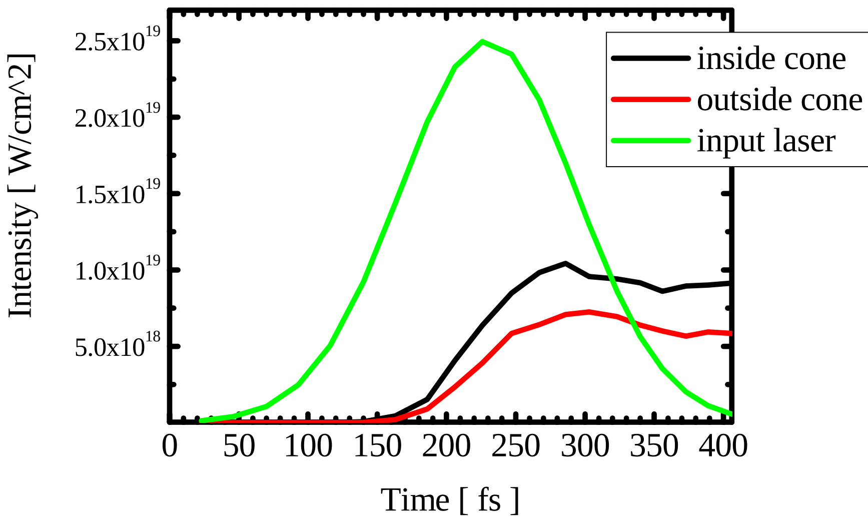


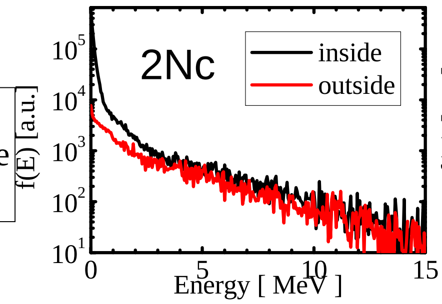


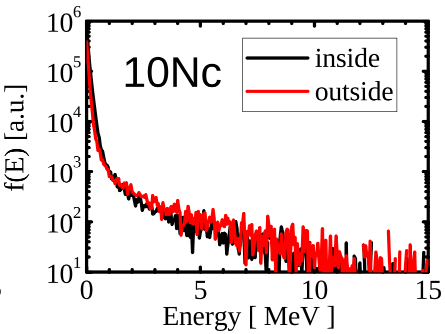
Weibel instability occurs in 2Nc case, resulting electro-static field at the boundary.

Conversion efficiency is over 30 percent in 2D case, expecting higher core temperature

Conversion efficiency is 30 percent

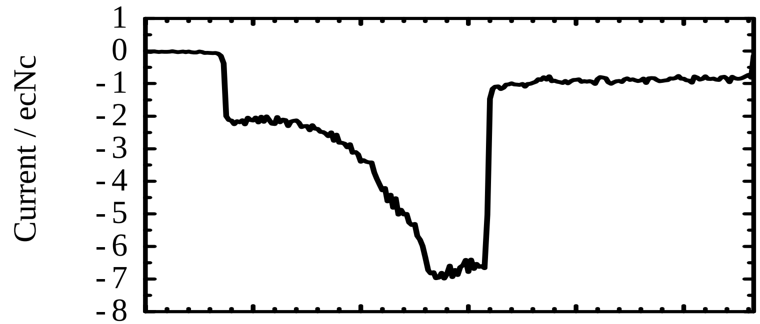






Energy spectrum observed inside and outside the cone for 10Nc(upper) and 2Nc(lower).

Target: 100 Nc attached with 2 Ne rear side plasma. 20 micron size.



Laser: 150 fs (FWHM), Intensity of 2.5 * 10^{19} w/cm^2.

まとめと今後の課題１

- 輻射流体コード(**PINOCO**), 超高強度レーザープラズマ相互作用(**FISCOF1**), フォッカープランク一流体コード(**FIBMET**)を用いて、高速点火レーザー核融合に関連した物理の解明が進められている。

- これら３つのシミュレーションコードを結合するために、遠隔にある異機種間のコンピュータシステム間を通信するプロトコル(**DCCP**)を開発した。これにより高速点火の統合シミュレーションが可能となった(**FI^3 code system**) .
  - 各コードで記述できるパラメーター領域をできる限り精度よく
  - 各コードに最適な計算機を用いて
  - 各コード間のデータ交換を最小限の手続きで(**DCCP**)

- **FI^3 code system**によって初めて実験スケールの比較が現実的になった.

まとめと今後の課題2

Including the density gap effect, we performed integrated simulation for recent core heating experiment with cone-guided targets.

- **Core temperature reached 0.5keV, ～70％ higher increment than in the case neglecting the density gap effect.**
- **Even with this effect, however, we could not get core heating as observed (～0.8keV) in the experiments.**

Each of the codes is required to improve simulation model to fit more realistic situations

- **neutron yield / core temperature estimation based on neutron spectrum・・・ Hydro**
- **Geometrical effects in the fast electron generation・・・ PIC**
- **Re-circulation of fast electrons due to sheath field generated around the core・・・ Fokker-Planck**
- **Effect of magnetic field generated during implosion**
- **・・・・・**

Summary

- Hot electrons are generated at the critical surface and guided by surface field towards the cone tip.
- Huge electro-static field is induced at the density gap to prevent electrons flow.
- Electrons are pushed by the laser field at the cone tip. Cone geometry determines laser focus pattern which might be important for determining electron spectrum.