Design of High-Power Free-Electron Lasers for EUV Lithography Applications

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ERL-EUV Feasibility Study Group

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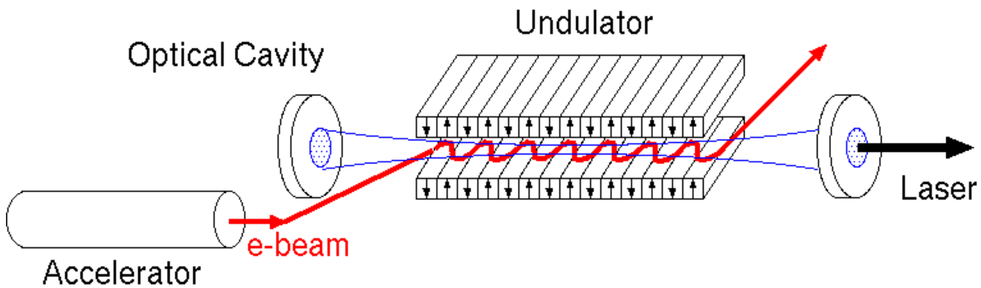
(JAEA) R. Hajima, N. Nishimori

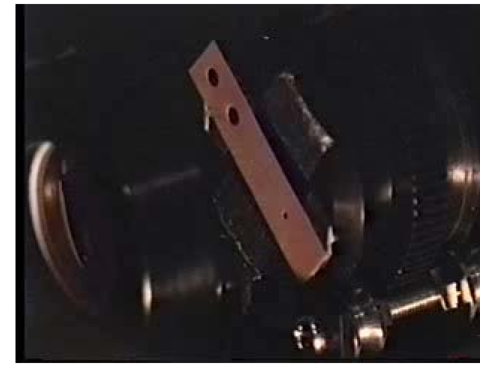
The feasibility study has been done under collaboration with a Japanese company.

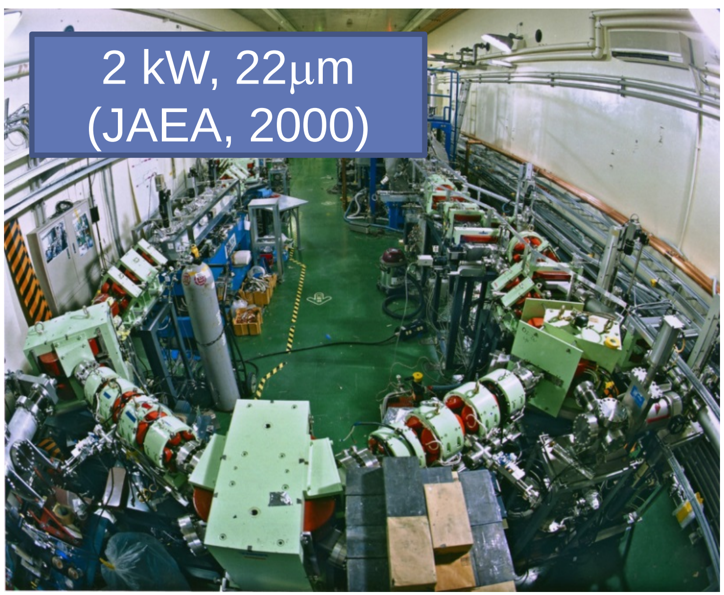
See also
E. Kako (KEK); "Development of Superconducting Accelerator with ERL for EUV-FEL" in this Workshop

High-Power FELs



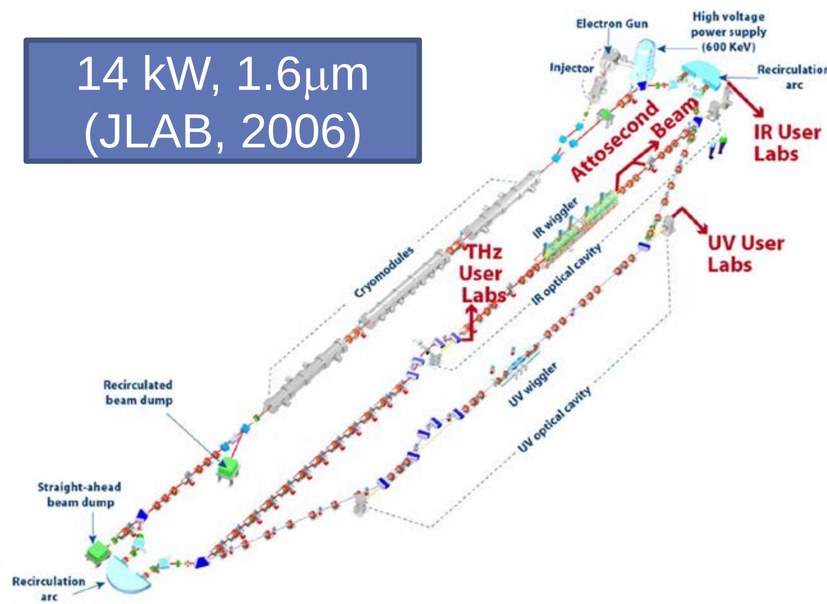
Laser Medium = Vacuum
→ free from the thermal limit



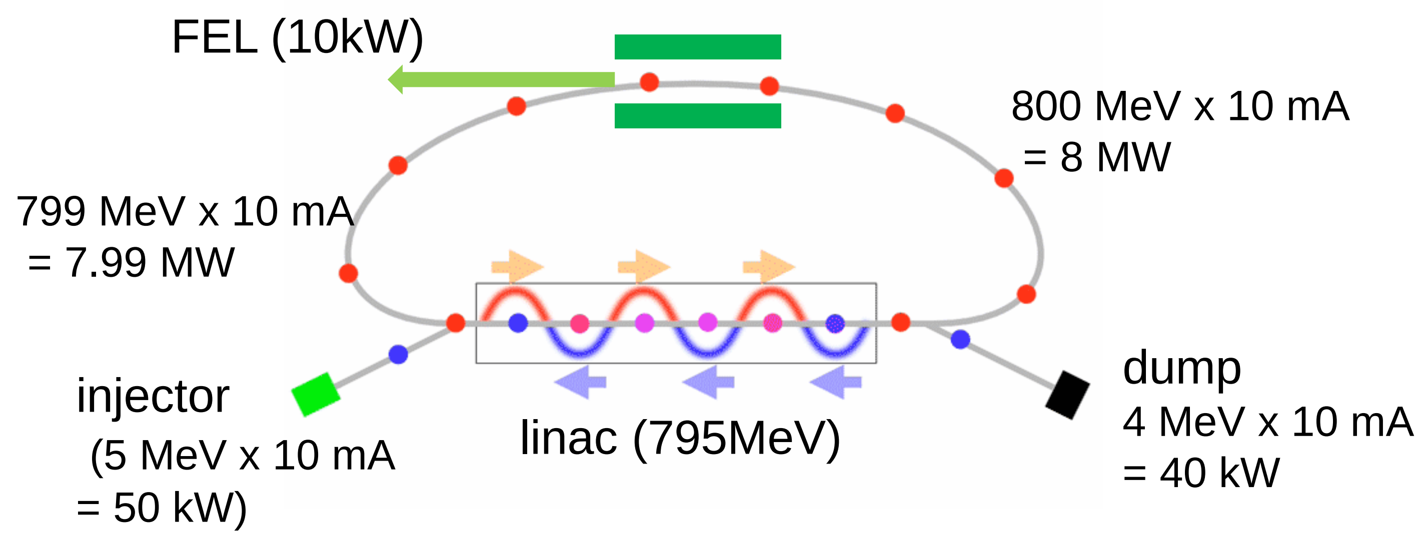


2 kW, 22μm
(JAEA, 2000)

14 kW, 1.6μm
(JLAB, 2006)



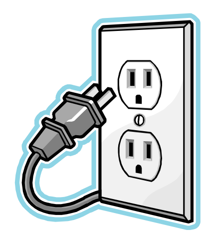
Energy Recovery Linac is a Key



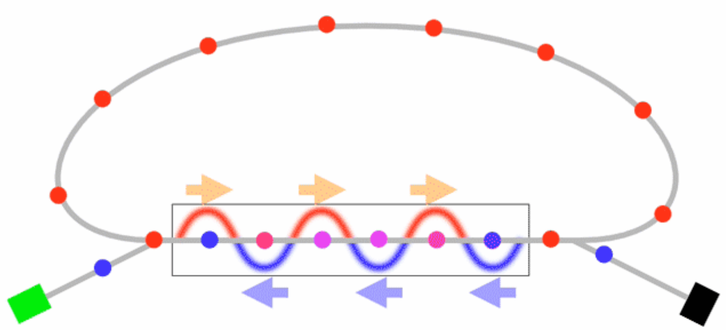
Energy Recovery Linac = ERL

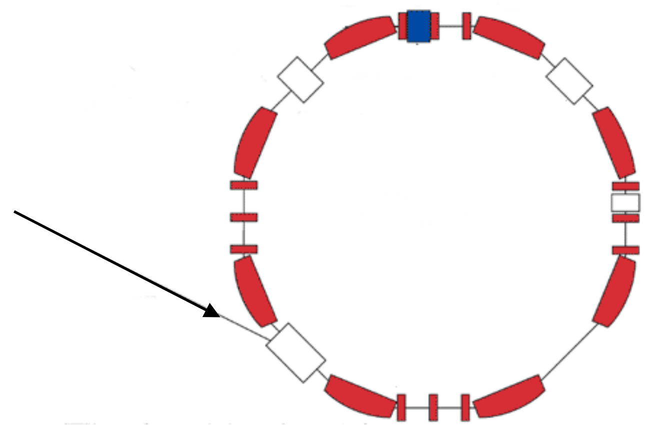
can save wall-plug power

can reduce dump energy = small radiation



ERLs are not Storage Rings





- ✓ Fresh electrons always
- ✓ Recycle energy at the linac
- ✓ Emittance is dominated by injector
- ✓ Flexible e-bunch compression

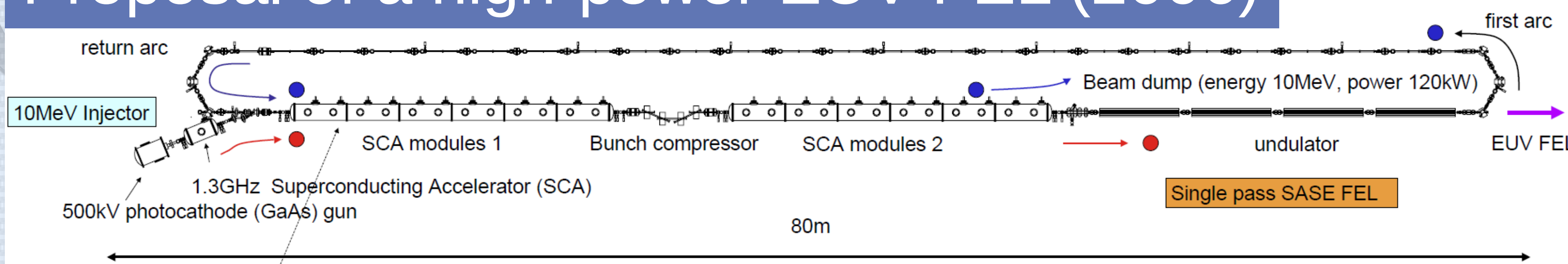
- ✓ Re-use electrons many times
- ✓ Compensate energy loss by RF
- ✓ Bunch length and emittance are dominated by ring design

Allow e-beams tailored to FEL
> 10kW for IR

FEL is limited by e-beam heating
<1 W for VUV

From IR to EUV

Proposal of a high-power EUV FEL (2006)



R. Hajima et al., EUV Source WS (2006)

$$\lambda = \lambda_u \frac{1 + a_w^2}{2\gamma^2} \qquad \gamma = \frac{E}{mc^2}$$

FEL is scalable from IR to EUV

However, several challenges exist to shorten FEL wavelength.

FEL Physics – a minimum set

FEL gain parameter

$$\rho = \left[\frac{1}{16} \frac{I_p}{I_A} \frac{K_u^2 [\mathrm{JJ}]^2}{\gamma^3 \sigma_x^2 k_u^2} \right]^{1/3}$$

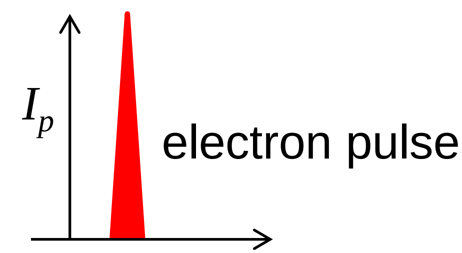
gain length

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

shorter wavelength

→ higher energy of electron

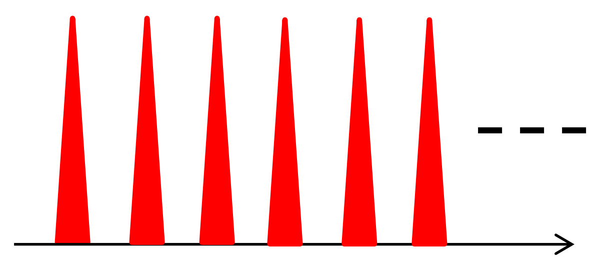
→ higher peak current



FEL power

$$P_{FEL} \approx \rho P_{electron}$$

$$P_{electron} = E \times I_{ave}$$



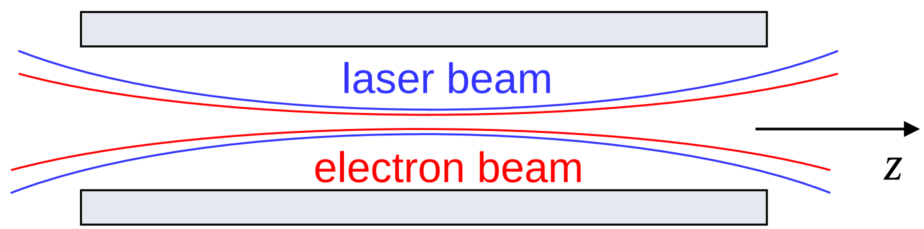
pulse train

E-beam Emittance

e-beam envelope < laser beam

$$\sigma(z) = \sigma_0 \sqrt{1 + \left(z/\beta_0\right)^2}$$
$$\sigma_0^2 = \varepsilon \beta_0$$

$$w(z) = w_0 \sqrt{1 + \left(z/Z_R\right)^2}$$
$$w_0^2 = \lambda Z_R / \pi$$

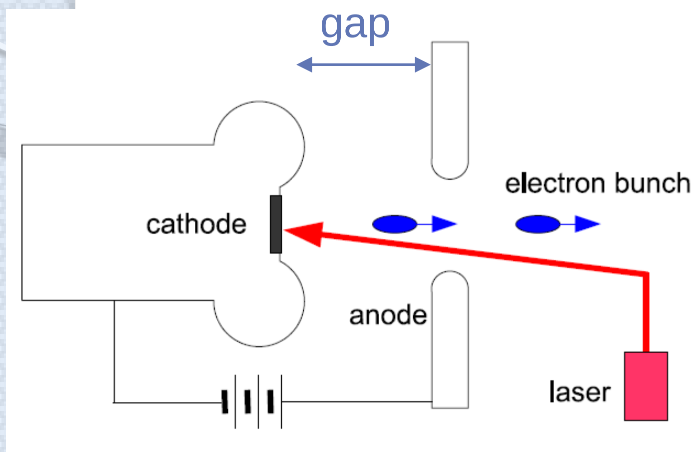


For efficient FEL interaction, an electron beam must have small emittance:

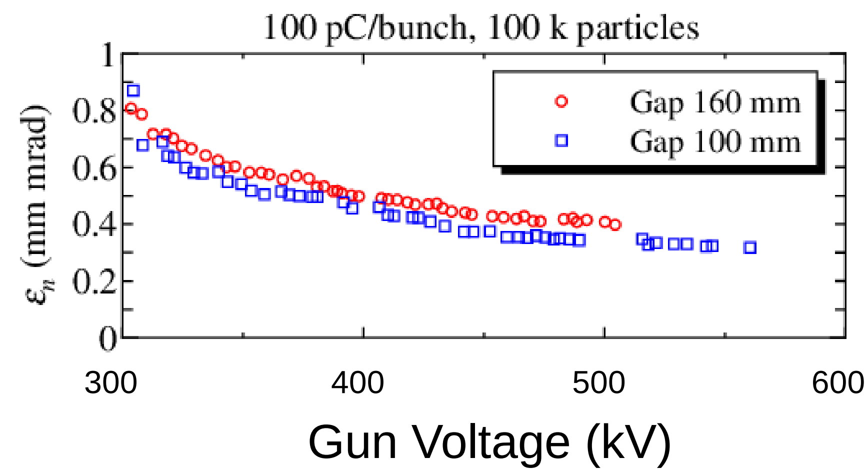
$$\varepsilon \le \frac{\lambda}{4\pi} \quad \text{or} \quad \frac{\varepsilon_n}{\gamma} \le \frac{\lambda}{4\pi}$$

Normalized emittance $\varepsilon_n \equiv \gamma \varepsilon$

Gun Voltage vs Emittance



gun voltage



T. Miyajima et al., Proc. FEL Conf. 2014.

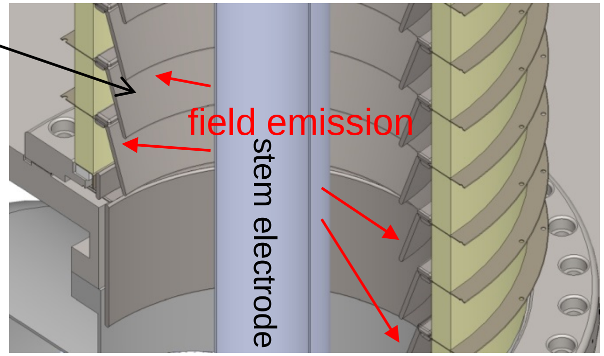
electron bunch of high density

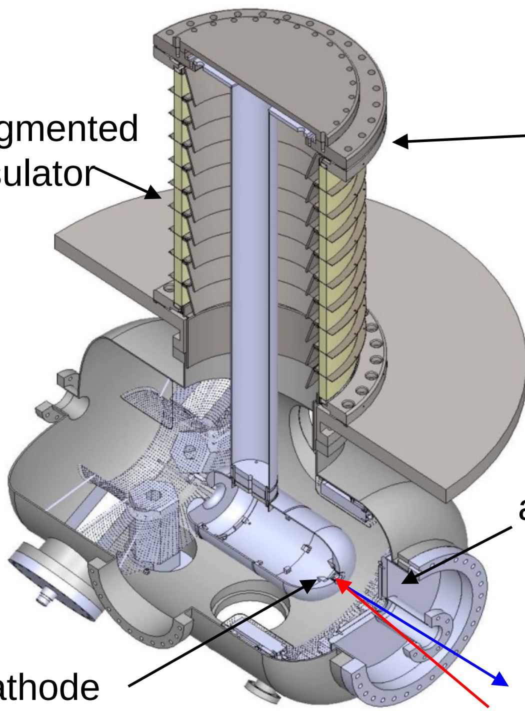
→ space charge repulsion

→ emittance growth

Gun voltage must be high enough!

Development of a 500-kV DC gun

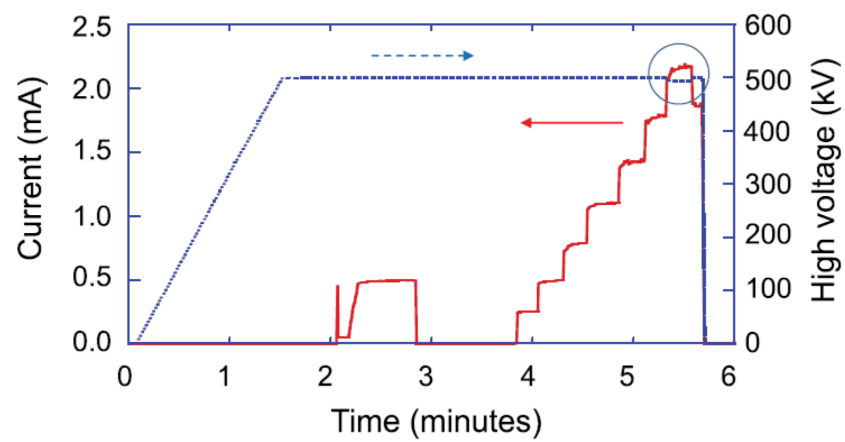




limited <350kV by damage of ceramic due to field emission

solved by segmented insulator and guard rings

generation of 500-keV beams!



N. Nishimori et al., App. Phys. Lett. (2013)

Many Trade Offs in FEL design

	small ⟵		⟶ large
E-beam energy	small foot print small FEL gain		large foot print large FEL gain
Rep. rate	more HOM's		less HOM's
Bunch charge	small emittance small current		large emittance large current
Acc. gradient	long linac small cryoplant		short linac large cryoplant
Undulator gap	small pitch more heat load		long pitch less heat load
……	…..		…..

- ✓ Consider technology readiness
- ✓ Choose parameters with analytical formulae
- ✓ Confirm parameters with numerical simulations

Examples of Parameter Set

	JAEA (2006)	JAEA/KEK (2014)-A	JAEA/KEK (2014)-B
FEL(#)	13 nm, 14 kW	13 nm, 12 kW	13 nm, 13 kW
e-beam			
energy, ave. current	580 MeV, 12 mA	800 MeV, 8 mA	1200 MeV, 8 mA
bunch charge	325 pC	100 pC	→
norm. emittance	0.8 mm-mrad	0.8 mm-mrad	0.9 mm-mrad
peak current	1300 A	1000 A	670 A
rep. rate	36 MHz	81.25 MHz	81.25 MHz
undulator			
gap	6 mm	7 mm	20 mm
pitch	20 mm	26 mm	48 mm
K	1.17	1.69	1.98
saturation length(##)	40 m	55 m	90 m

(#) including undulator tapering

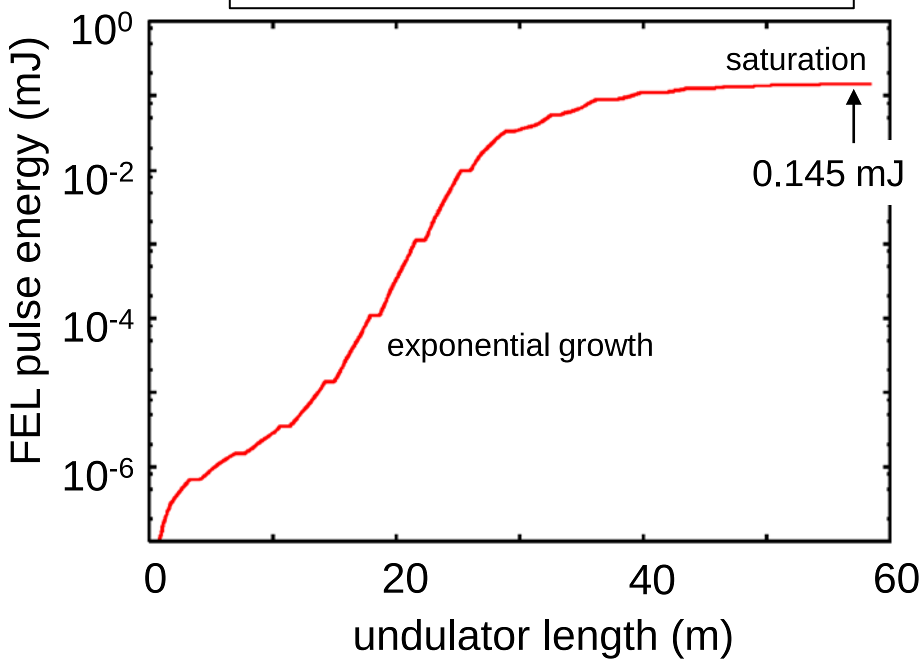
(##) including undulator intervals for quadrupole focusing

Simulation: FEL pulse evolution

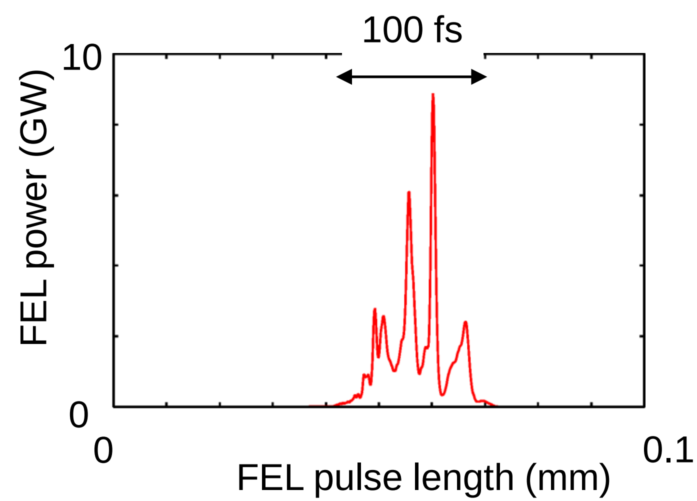
GENESIS simulations by N. Nishimori

JAEA/KEK (2014)-A:
E=800 MeV, q=100 pC, I_p=1000A, ε_n=0.8 mm-mrad,
rep.=81.25 MHz

FEL pulse energy evolution



temporal shape



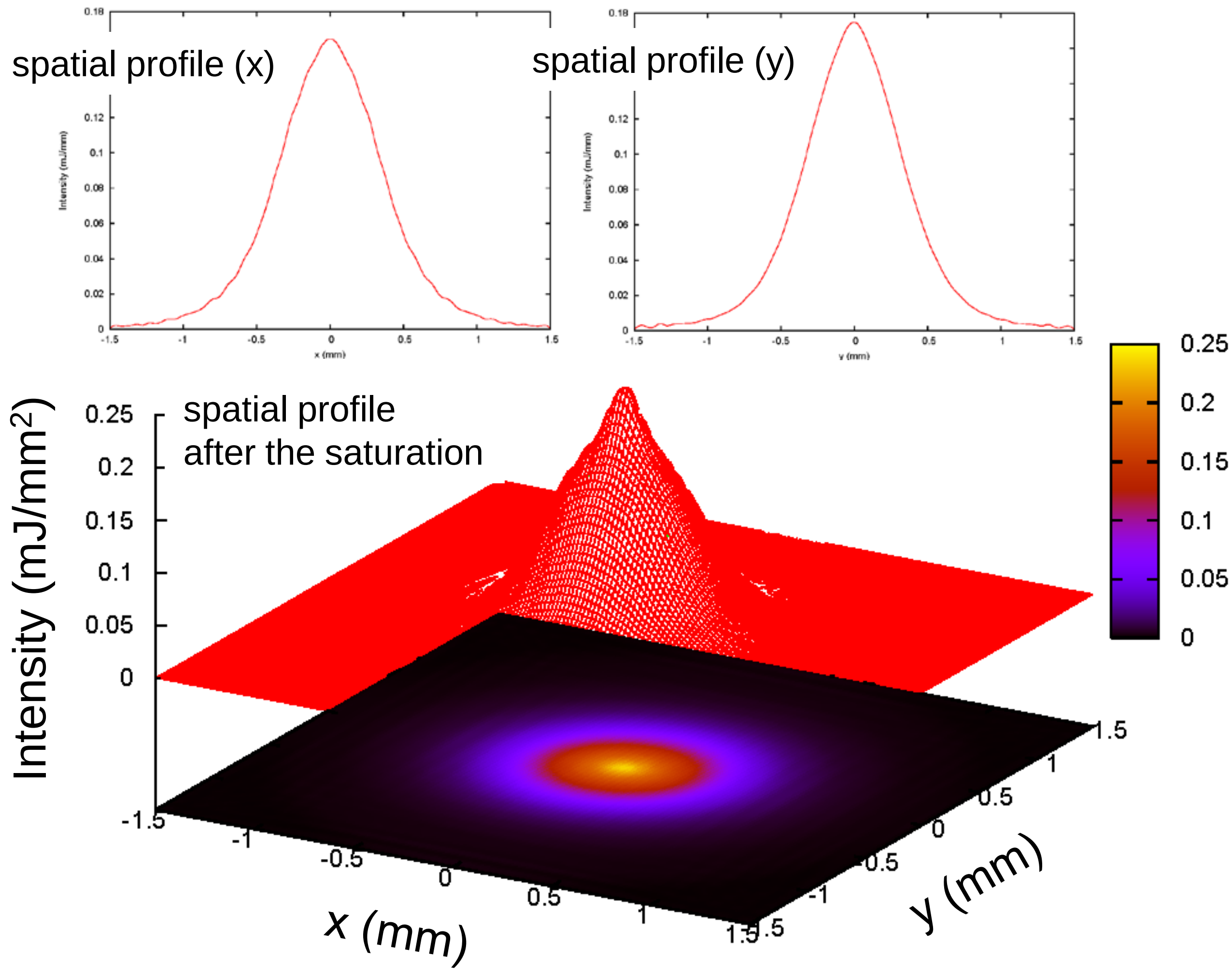
0.145 mJ x 81.25 MHz = 12 kW

Simulation: spatial pattern

JAEA/KEK (2014)-A:

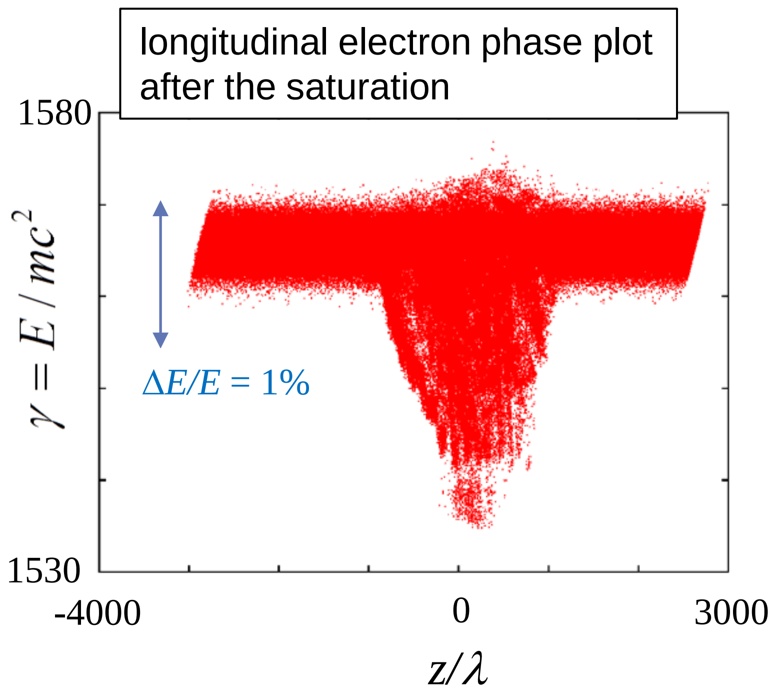
E=800 MeV, q=100 pC, I_p=1000A, ε_n=0.8 mm-mrad,

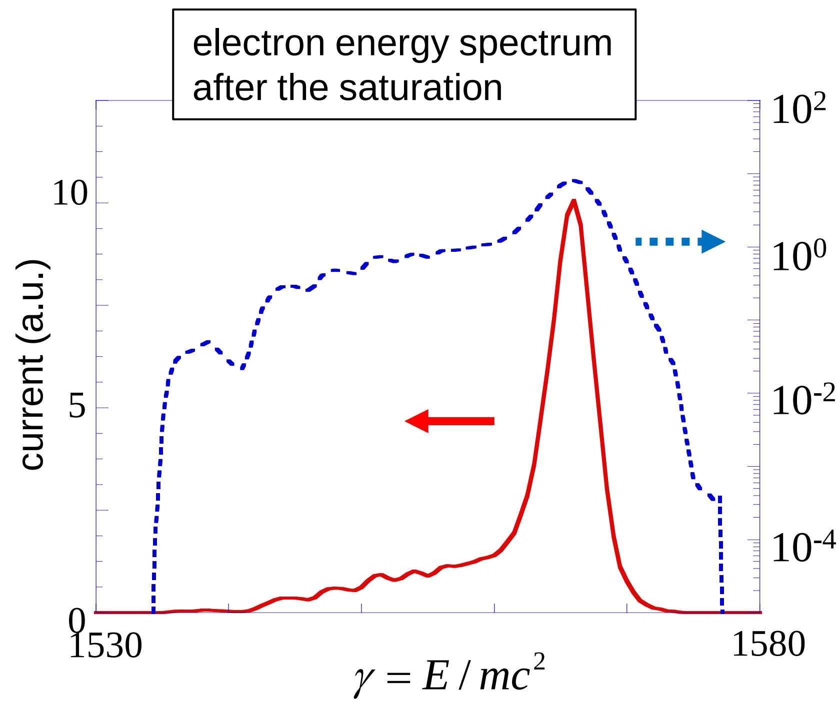
rep.=81.25 MHz



Simulation: electron energy spread

JAEA/KEK (2014)-A:
E=800 MeV, q=100 pC, I_p=1000A, ε_n=0.8 mm-mrad,
rep.=81.25 MHz



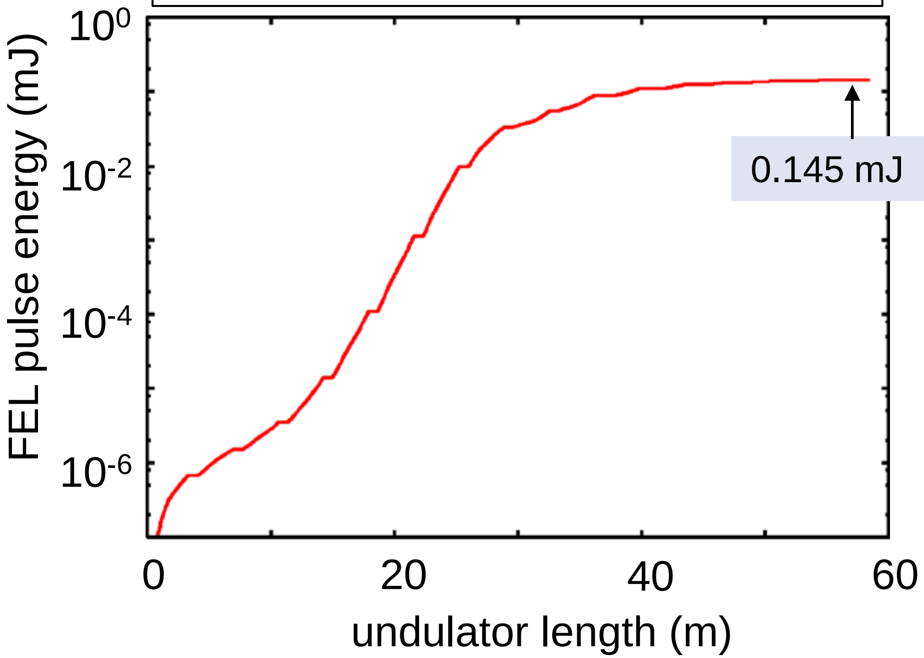


electron energy spread : 0.1%(rms) → 2.6% (full width)
conversion efficiency : 0.18% (from electron to laser)

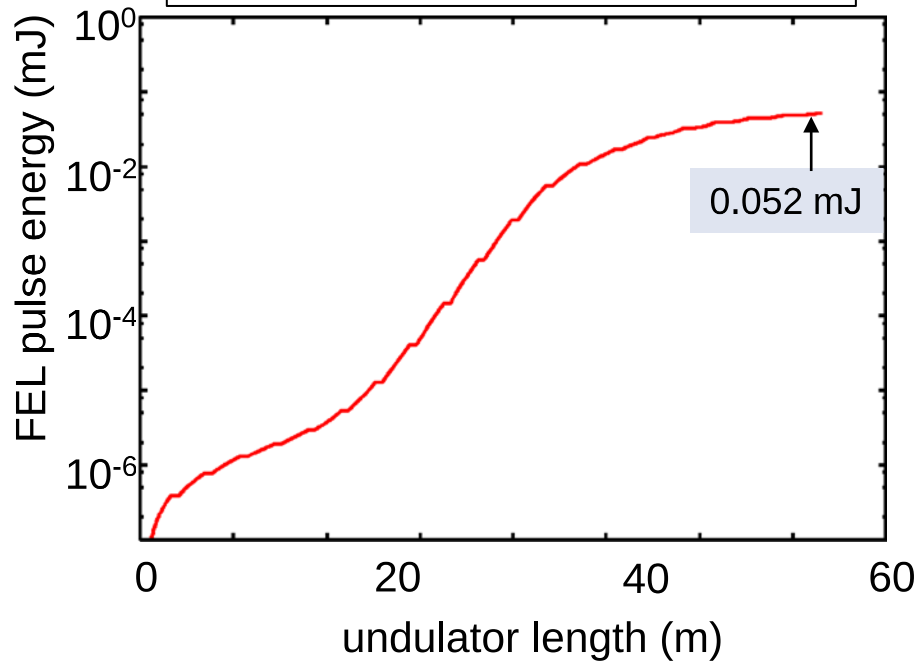
energy spread of 2.6% is manageable in ERLs

Simulation: emittance and power

norm. emittance = 0.8 mm-mrad



norm. emittance = 2 mm-mrad



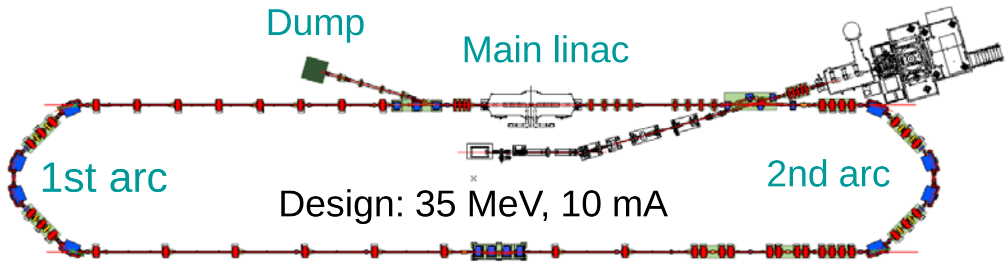
0.145 mJ x 81.25 MHz = 12 kW

0.052 mJ x 81.25 MHz = 4.2 kW

Small emittance is essential for FEL

Compact ERL – a test facility in operation at KEK

Technology Demo. for future ERL-based light sources
– X-ray, γ-ray and EUV



R&D items

- performance and reliability of components
- small emittance beam
- bunch compression to "fs"

→ Demo. of EUV-quality beam

main linac

South straight section

2^{nd} arc

Beam was successfully accelerated up to 20 MeV in the main linac, decelerated, and transported to the entrance of dump line (Dec. 16-20, 2013)

Beam energy (E)

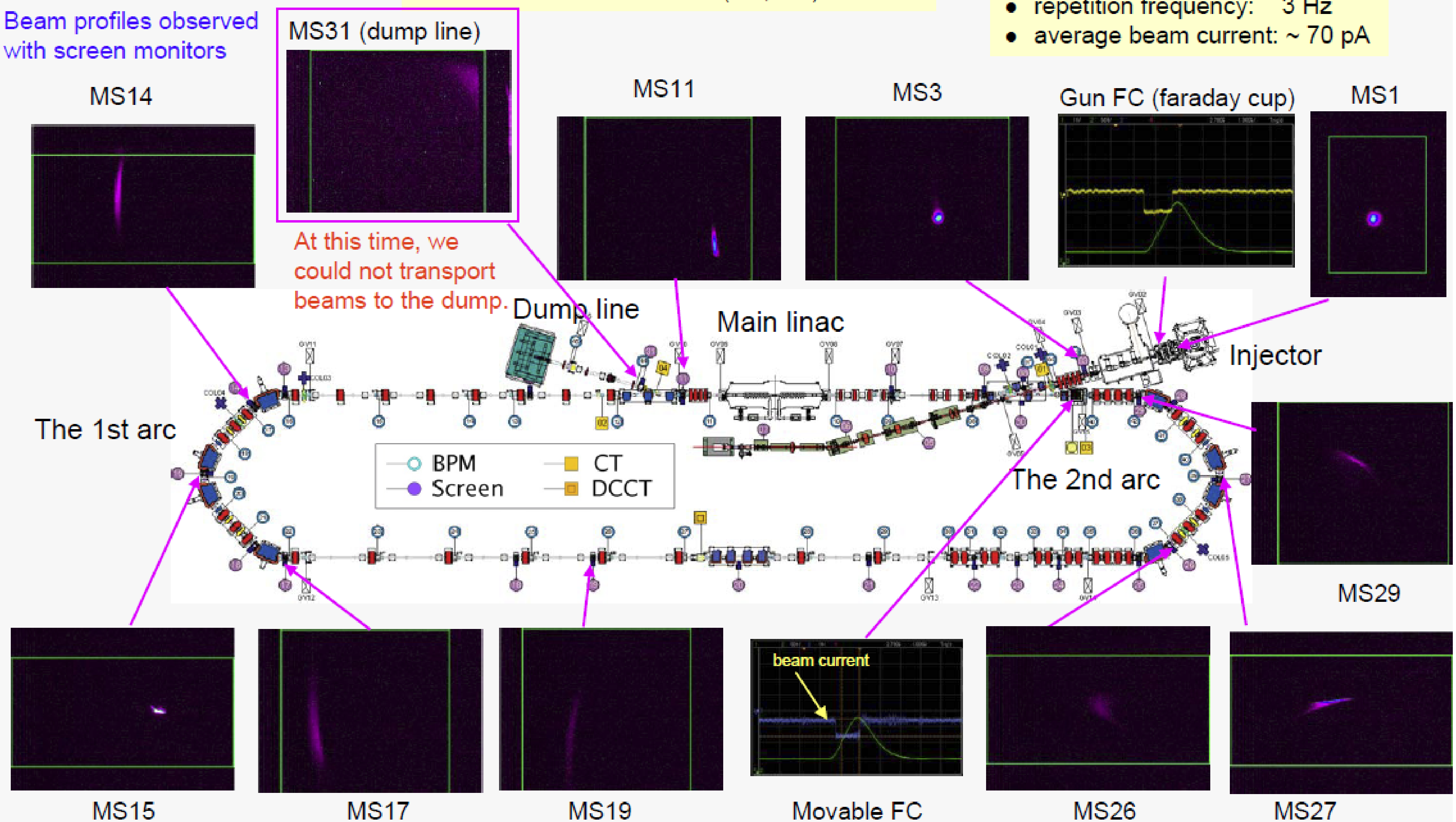
- Injector: 3.4 MeV
- Recirculation loop: 19.9 MeV

Parameters

- Gun voltage: 390 kV   Buncher: OFF
- Injector cavities: E_{acc} = (3.6, 3.6, 3.4) MV/m
- Main-Linac cavities: V_c = (8.3, 8.3) MV

Beam pulses (macropulse beams)

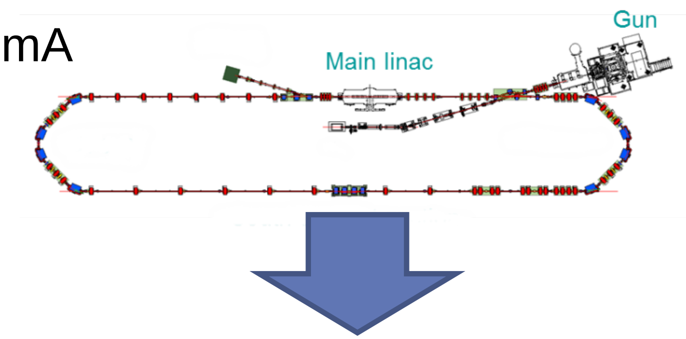
- peak current: ~20 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 3 Hz
- average beam current: ~ 70 pA



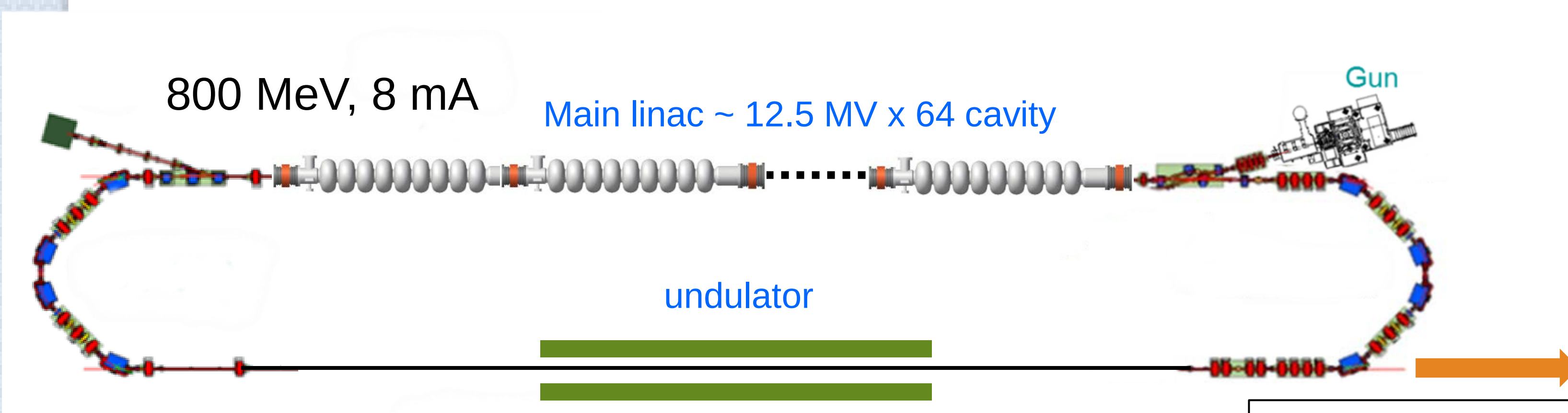
S. Sakanaka, TTC meeting (2014)

10-kW EUV for Lithography

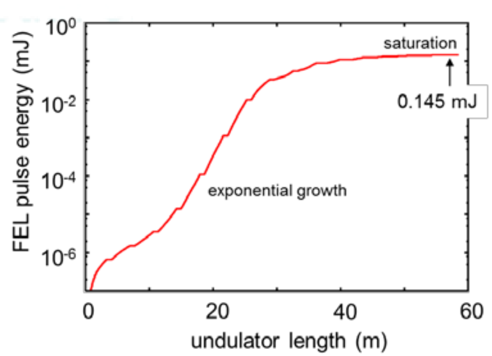
35 MeV, 10 mA

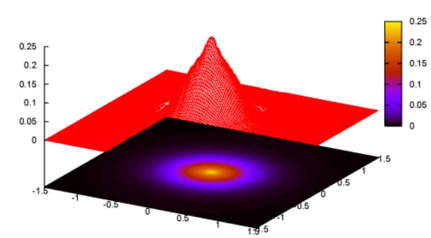


800 MeV, 8 mA

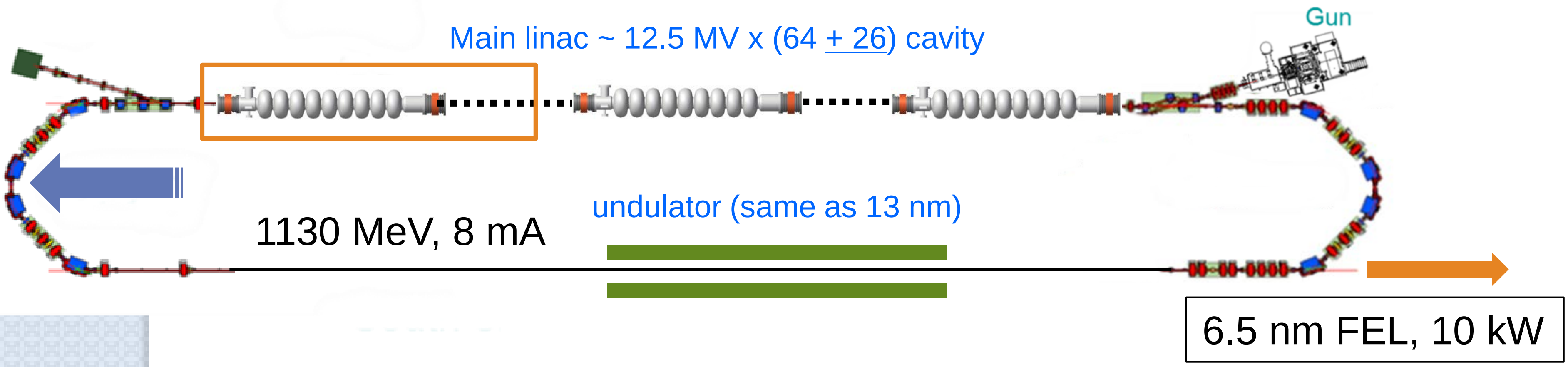


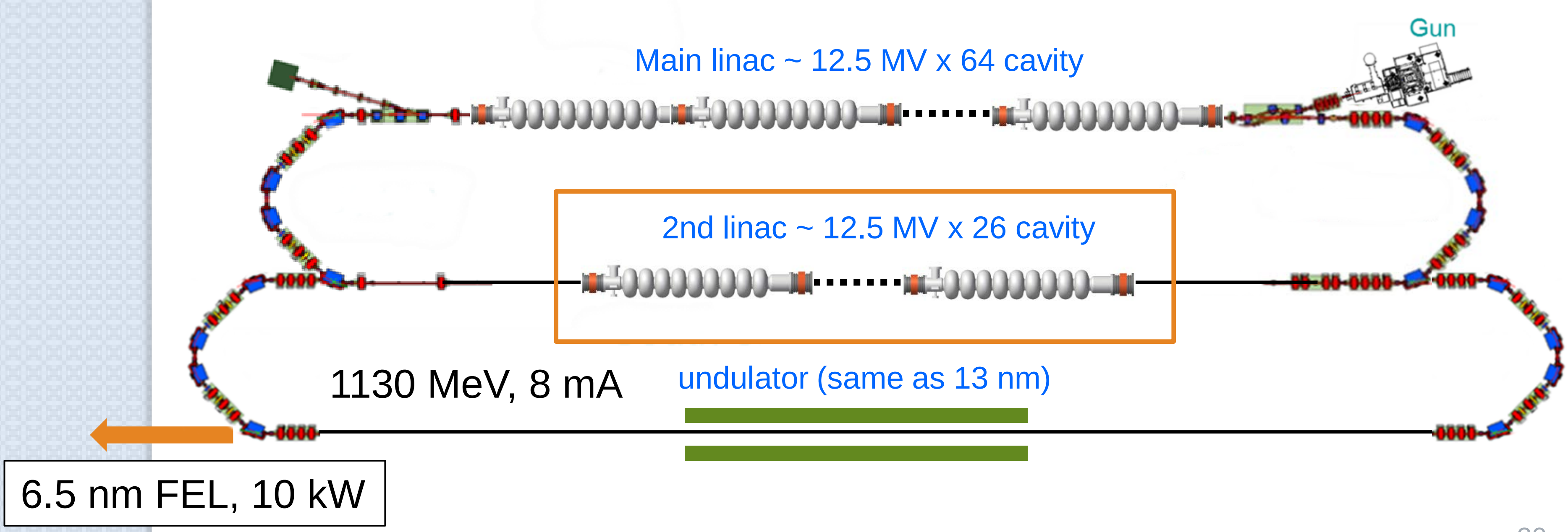
13 nm FEL, 10 kW





Possible Upgrade to 6.5 nm





Summary

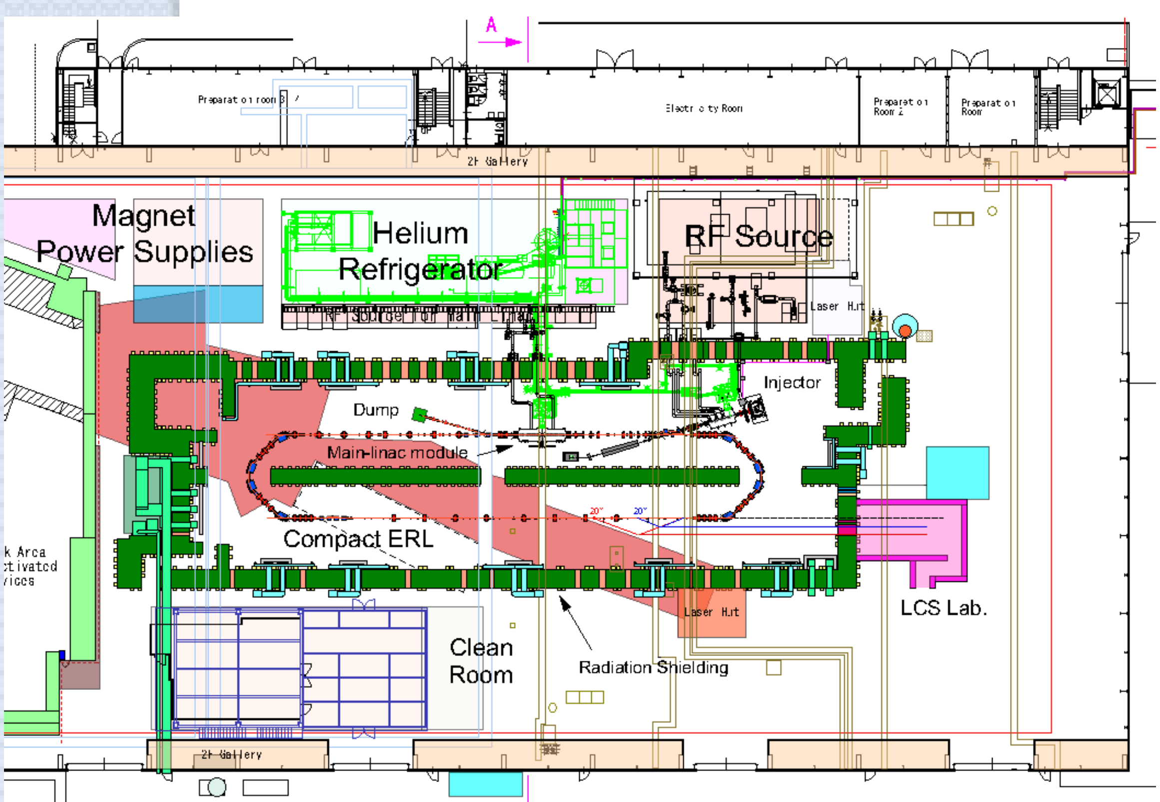
- Design of 10-kW EUV-FELs
  - employ ERL similar to 14-kW IR-FEL
  - with up-to-date technology developed at KEK/JAEA
  - 800-MeV, 8-mA ERL produces 10-kW EUV
  - future upgrade to 6.5 nm
- Demonstration at cERL is ongoing
  - Electron gun and superconducting Acc.
  - small emittance beam
  - bunch compression
  - …

Thank you !

Compact ERL

Goals of the Compact ERL

- Demonstrate reliable operations of our R&D products (guns, SRF, ...)
- Demonstrate the generation and recirculation of ultra-low emittance beams



Parameters of the Compact ERL

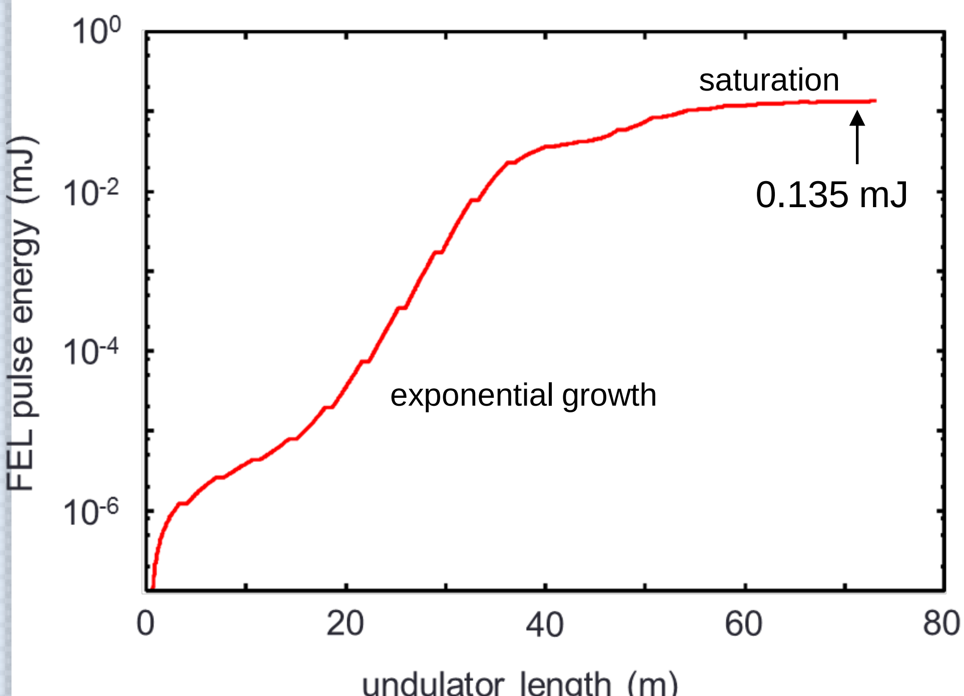
	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual) ~ 100 fs (with B.C.)
RF frequency	1.3 GHz

Simulation: FEL pulse evolution for 6.5nm

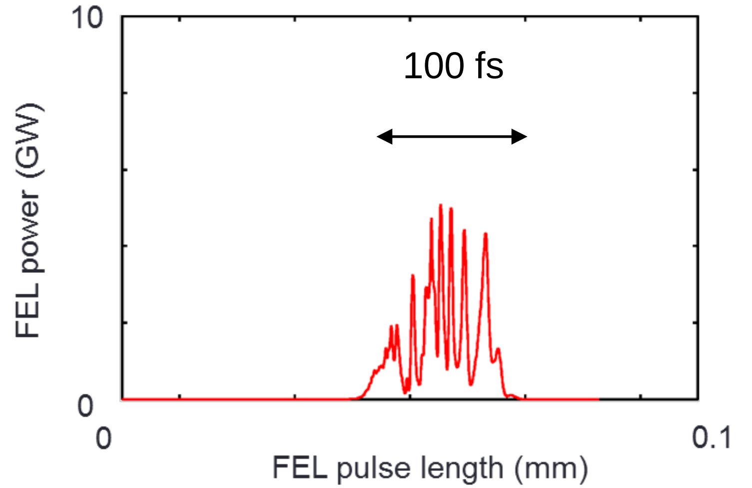
GENESIS simulations by N. Nishimori

E=1130 MeV, q=100 pC, I_p=1000A, ε_n=0.8 mm-mrad,
rep.=81.25 MHz

FEL pulse energy evolution



temporal shape



0.135 mJ x 81.25 MHz = 11 kW