ERL-Based High-Power EUV-FEL Source
（ERLを用いた高出力EUV-FEL光源）

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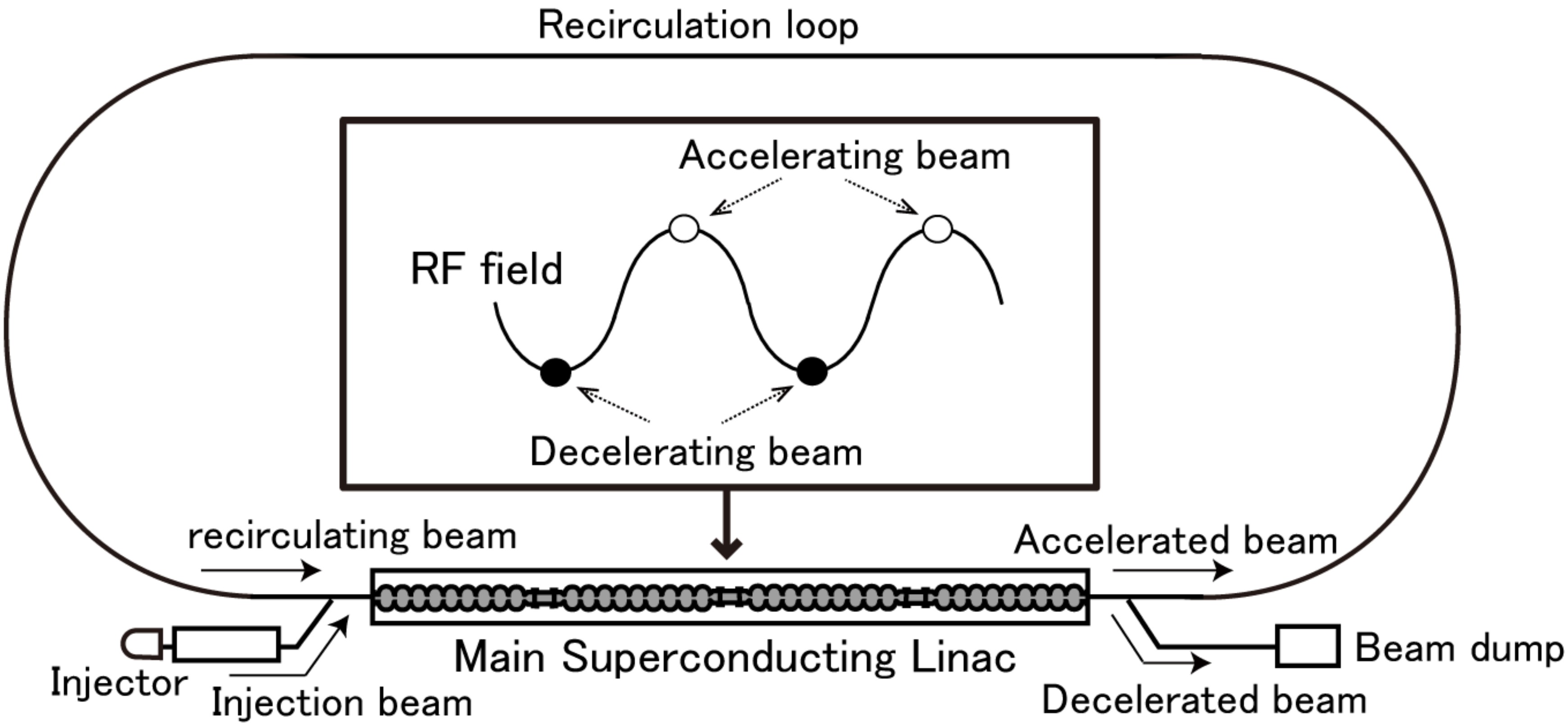
Outline

- Introduction
- Energy Recovery Linac(ERL)
- Design of EUV-FEL Source
- Simulation
- Conclusions

Energy Recovery Linac (ERL)

Energy Recovery Linac(ERL)



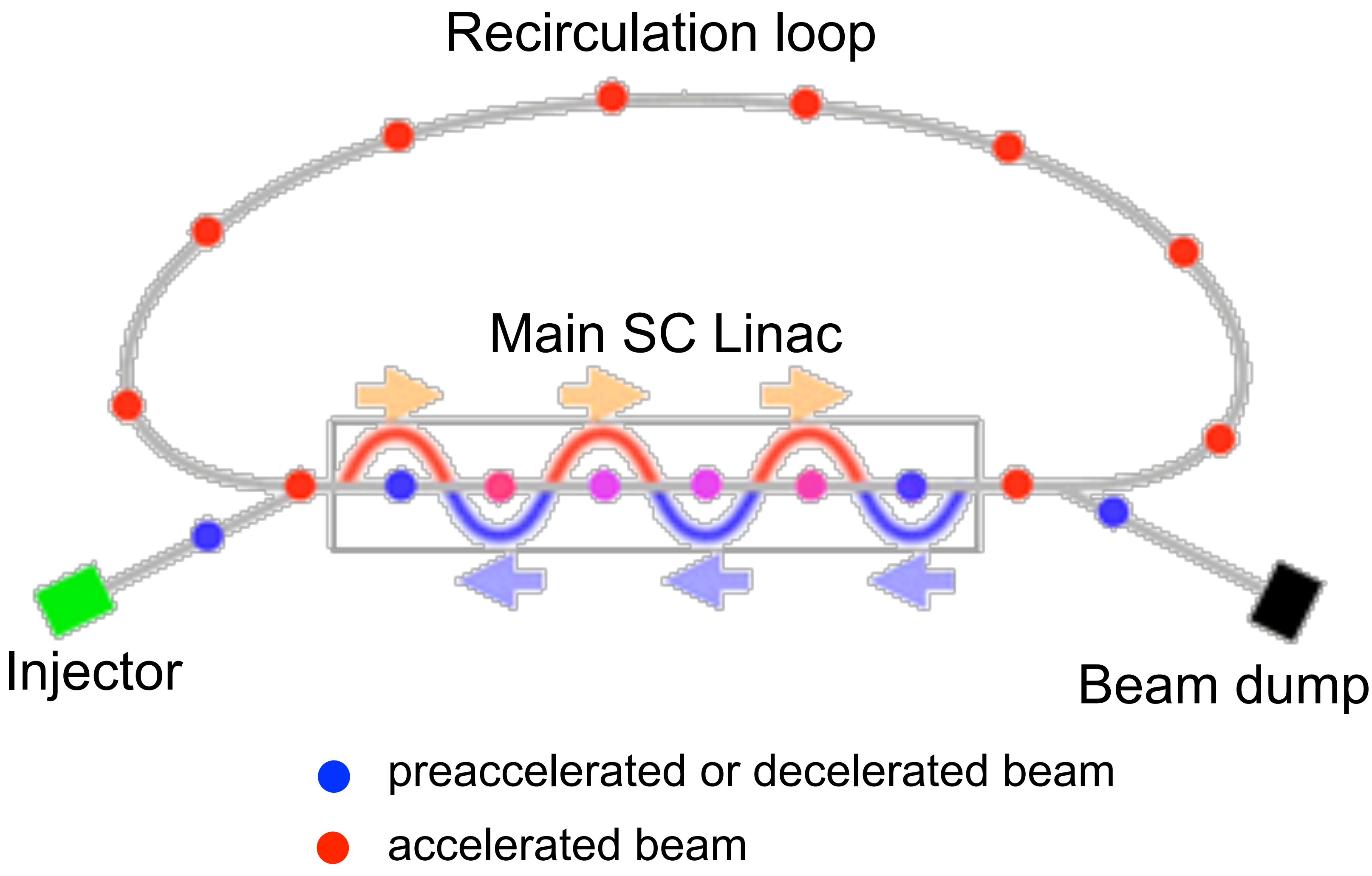
Energy Recovery Linac (ERL)

Merits of ERLs

- **Acceleration energy is almost recovered.**
- **Dumped beam power and activation are drastically reduced.**

→ High average current (high beam power) can be achieved more easily.

Energy Recovery Linac(ERL)

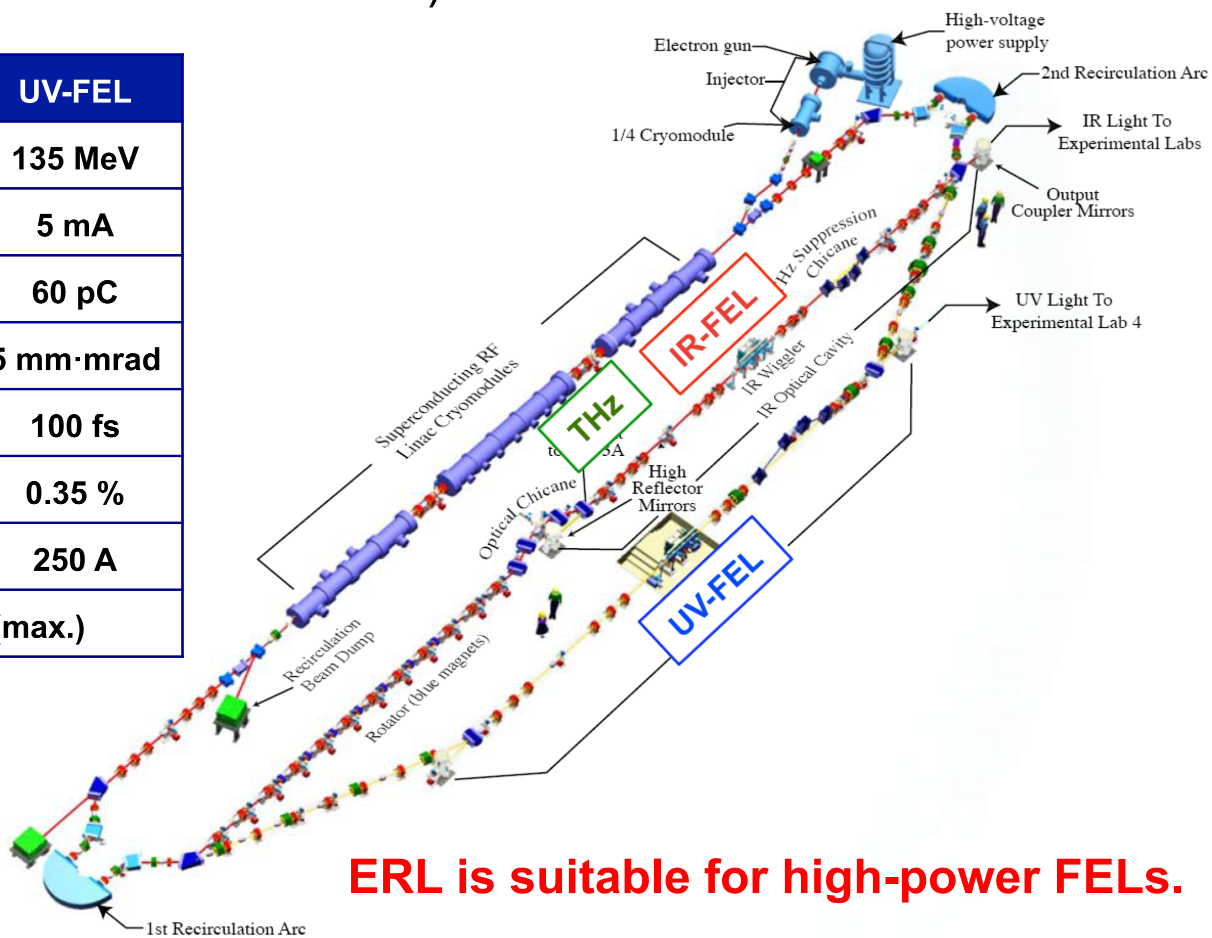


JLab ERL-FEL

ERL FEL at Thomas Jefferson Laboratory（US）

- First kW-class FEL in the world, average current up to 10 mA
- IR-FEL: 1.7 kW@3.1 μm(1999）,14.3 kW@1.6 μm (2006) with oscillator
- UV-FEL: 124 nm (3rd harminics of 372 nm) with oscillator

Parameter	IR-FEL	UV-FEL
Beam Energy	88 – 165 MeV	135 MeV
Average Current	9.1 mA	5 mA
Bunch Charge	135 pC	60 pC
Norm. Emittance	8 mm·mrad	5 mm·mrad
Bunch Length	125 fs	100 fs
Energy Spread	0.4 %	0.35 %
Peak Current	400 A	250 A
Bunch Frequency	74.85 MHz (max.)	



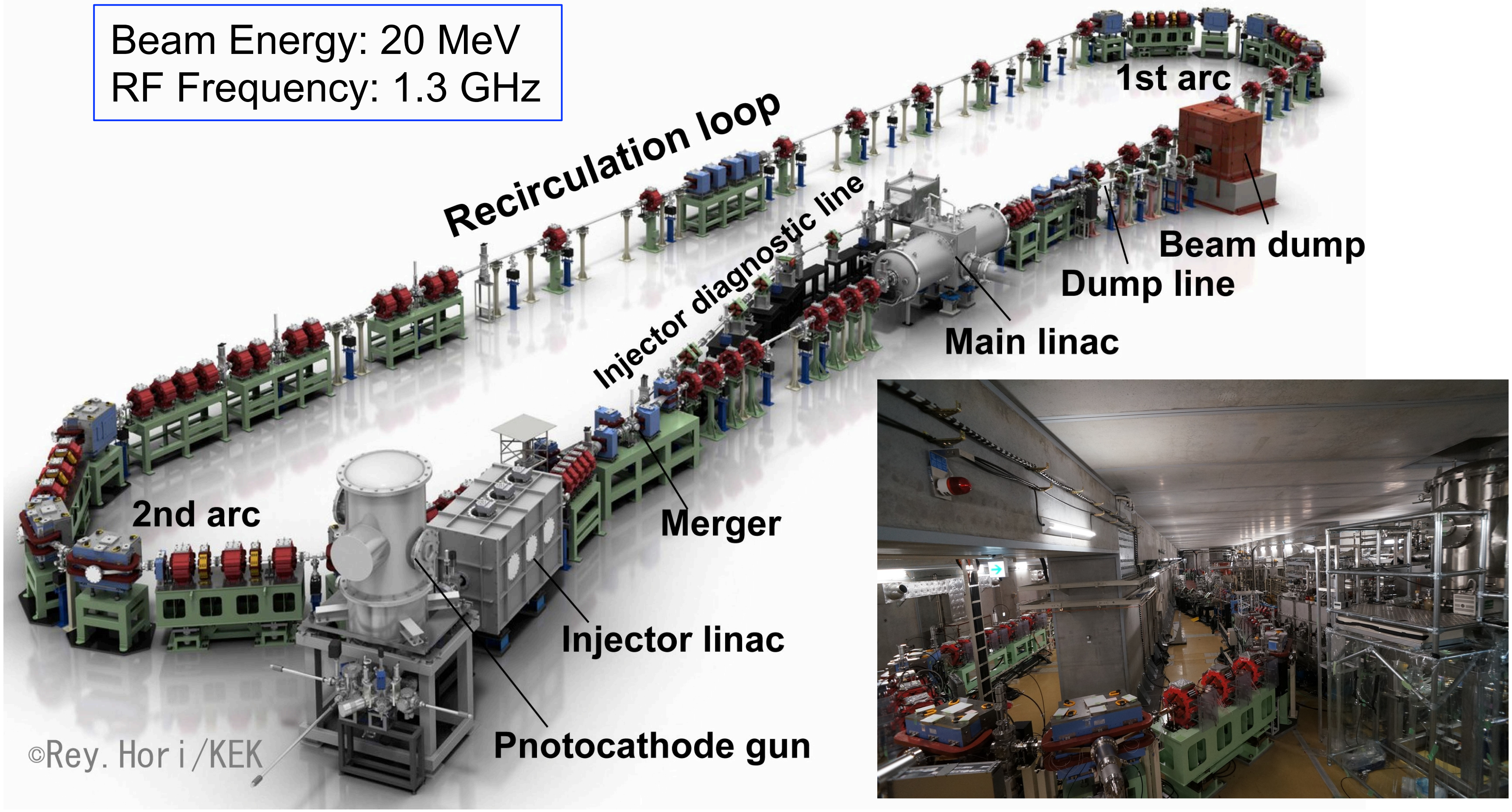
ERL is suitable for high-power FELs.

Compact ERL(cERL) at KEK

- Demonstration of ERL potentials for future light sources
- Development of key technologies (photocathode gun, CW SC cavities, …)

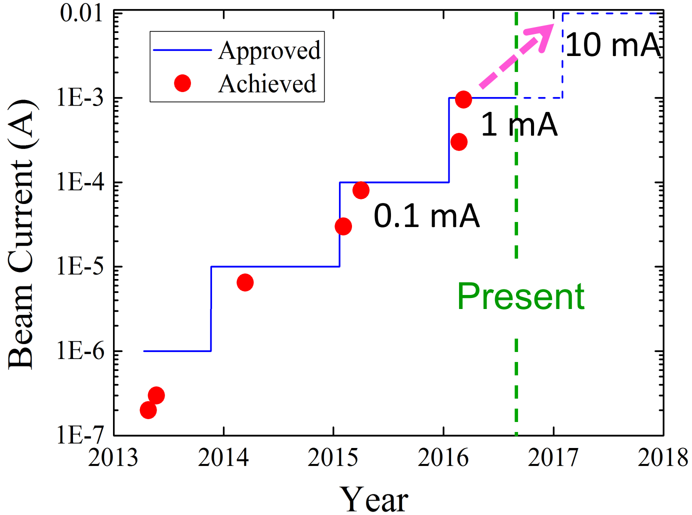
in operation since 2013

Beam Energy: 20 MeV
RF Frequency: 1.3 GHz

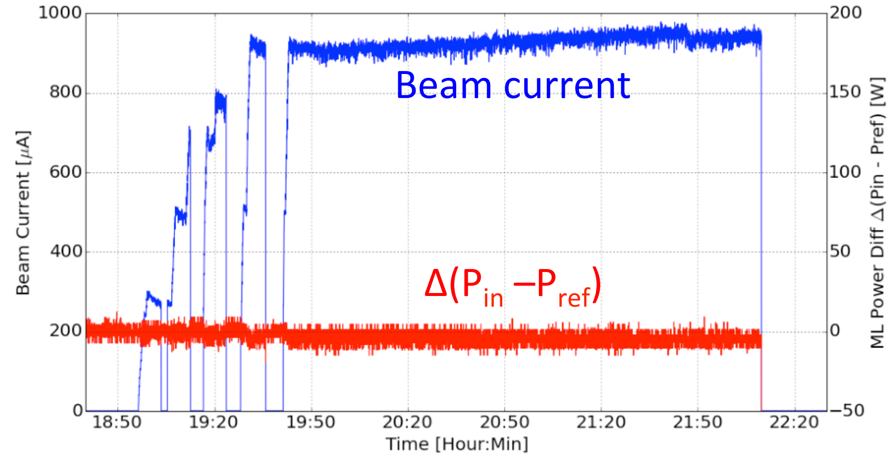


Recent Progress of cERL

(1) High average current & efficient energy recovery

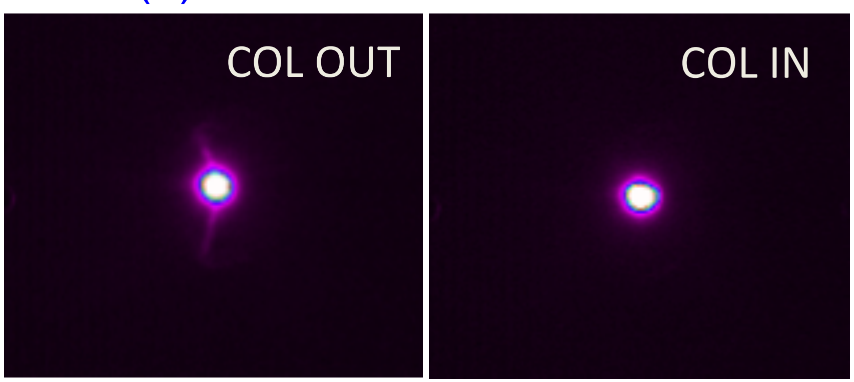


History of achieved beam current



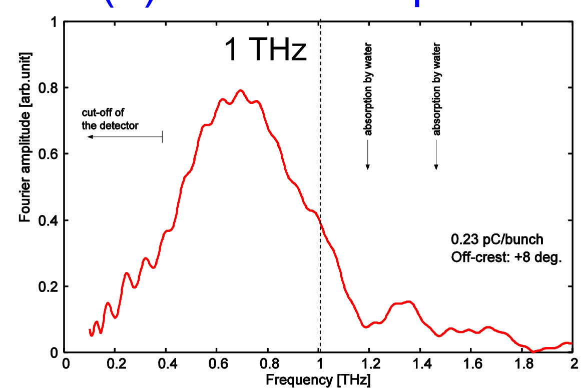
Achievement of high beam current (~1 mA) with efficient energy recovery (~99.97 %)

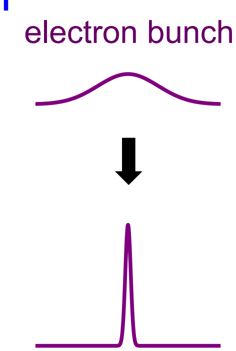
(2) Beam loss reduction



Mitigation of beam halo by collimators at injector

(3) Bunch compression





Coherent radiation spectrum up to THz by bunch compression in 1^{st} arc

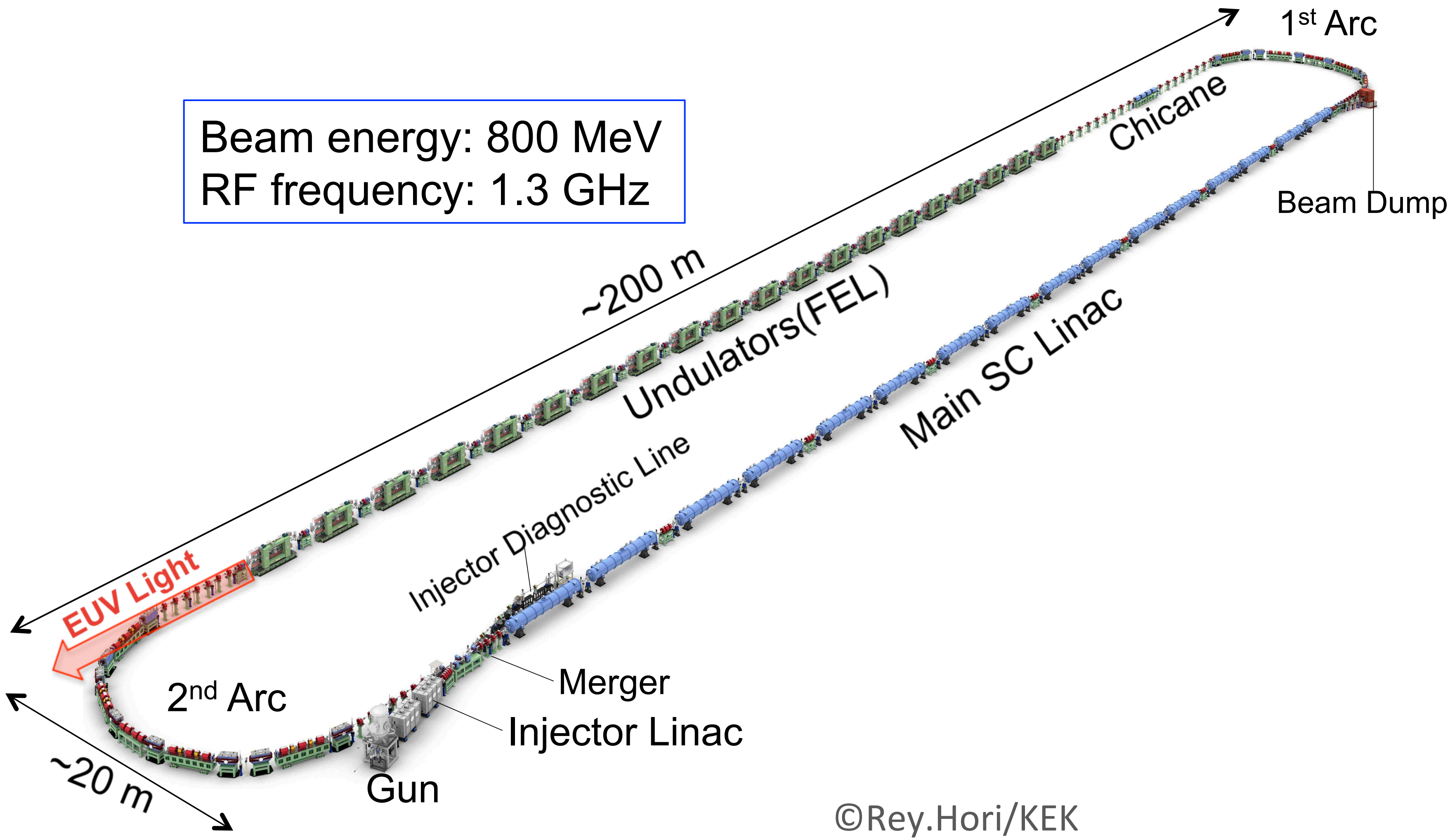
Design of EUV-FEL Source

Design Concept

- Target : 10kW power @ 13.5 nm, 800 MeV
- Use available technology without too much development
- Make the most of the cERL designs, technologies and operational experiences

Image of EUV-FEL Source

Beam energy: 800 MeV
RF frequency: 1.3 GHz



FEL Parameters

FEL average power

$$P_{FEL} \approx \rho_{FEL} P_{electron}, \quad P_{electron} = EI_{av}$$

average current

Pierce parameter

$$\rho_{FEL} = \left[\frac{1}{16} \frac{I_p}{I_A} \frac{K^2 [JJ]^2 \lambda_u^2}{\gamma^3 \sigma_x \sigma_y (2\pi)^2} \right]^{1/3} \qquad \left(\rho_{FEL} > \sigma_p / p \right)$$

momentum spread

$$I_p = \frac{Q_b}{\sqrt{2\pi}\sigma_t}, \quad I_A = 17kA \quad \sigma_x = \sqrt{\varepsilon_{nx} \beta_x / \gamma}, \quad \sigma_y = \sqrt{\varepsilon_{ny} \beta_y / \gamma} \quad K = \frac{eB_0 \lambda_u}{2\pi mc}$$

peak current

normalized emittance

undulator field/period

$[JJ] = J_0(\xi) - J_1(\xi), \quad \xi = K^2 / (4 + 2K^2)$ Linear-polarizing undulator

$[JJ] = 1$ Circular-poliarizing undulator

FEL wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

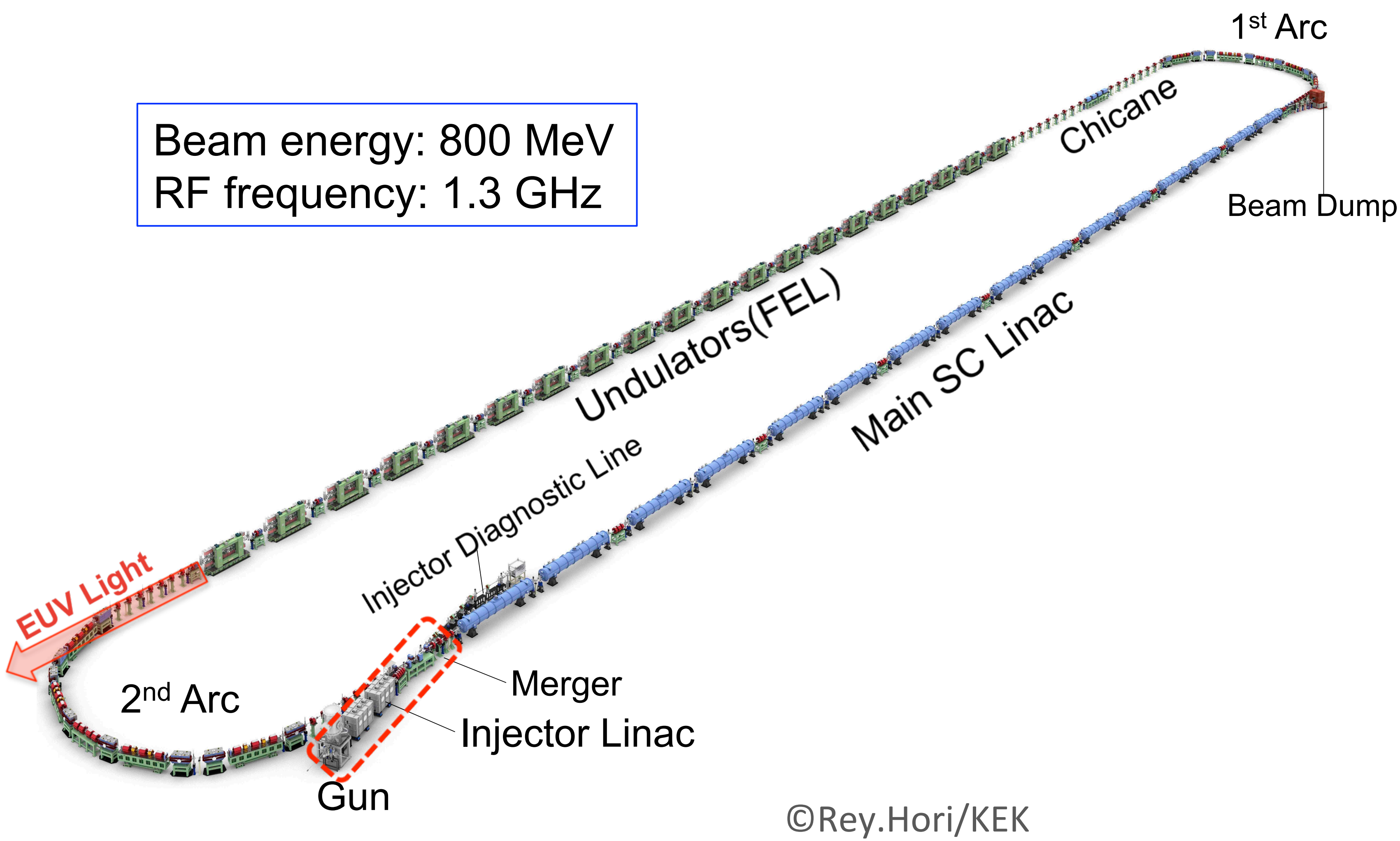
$K = K_y$ Linear-polarizing undulator

$K = \sqrt{2} K_x = \sqrt{2} K_y$ Circular-polarizing undulator

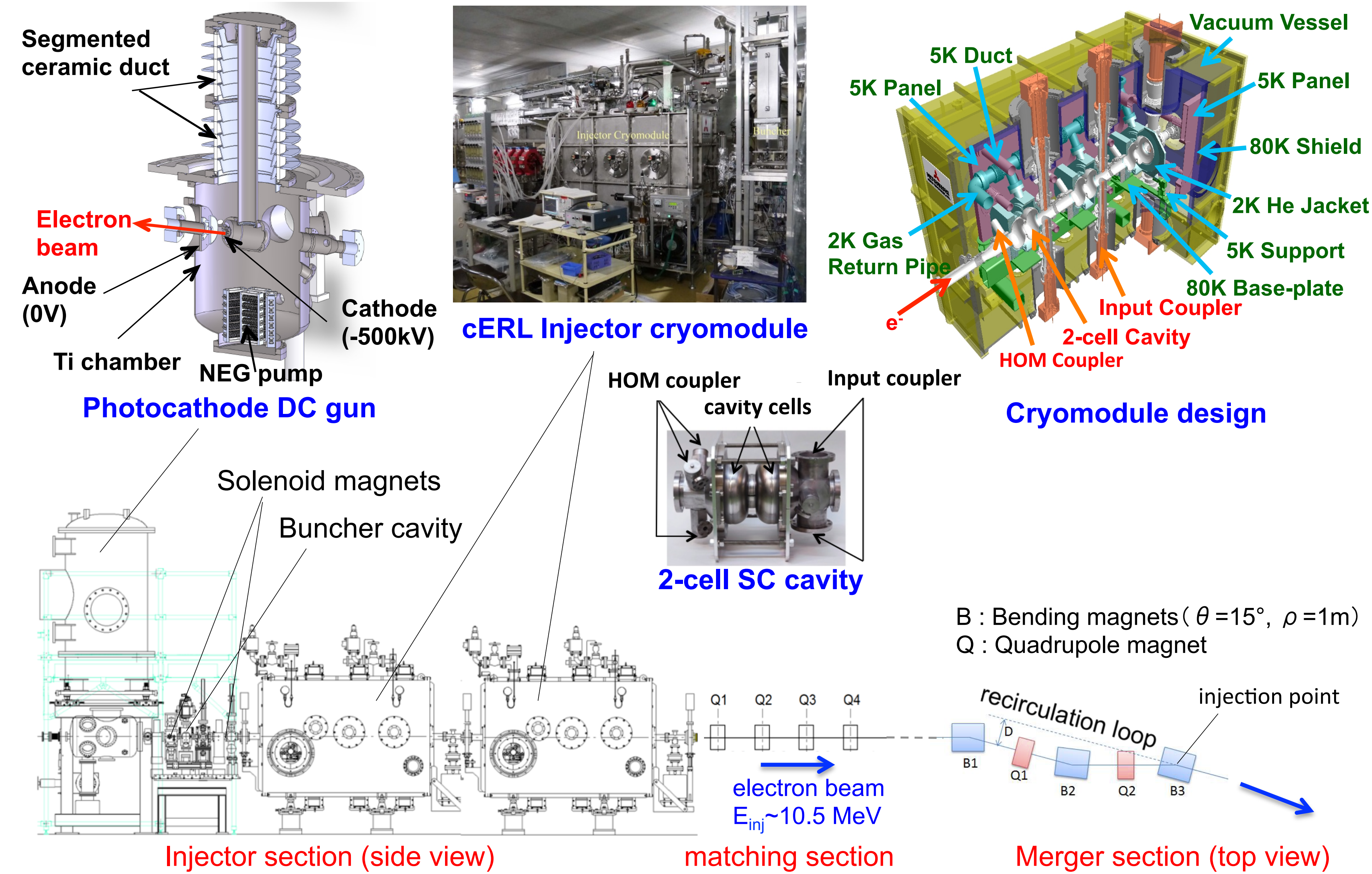
High average current, high peak current and low emittance are important.
(Lower momentum spread is also required.)

Injector & Merger

Beam energy: 800 MeV
RF frequency: 1.3 GHz

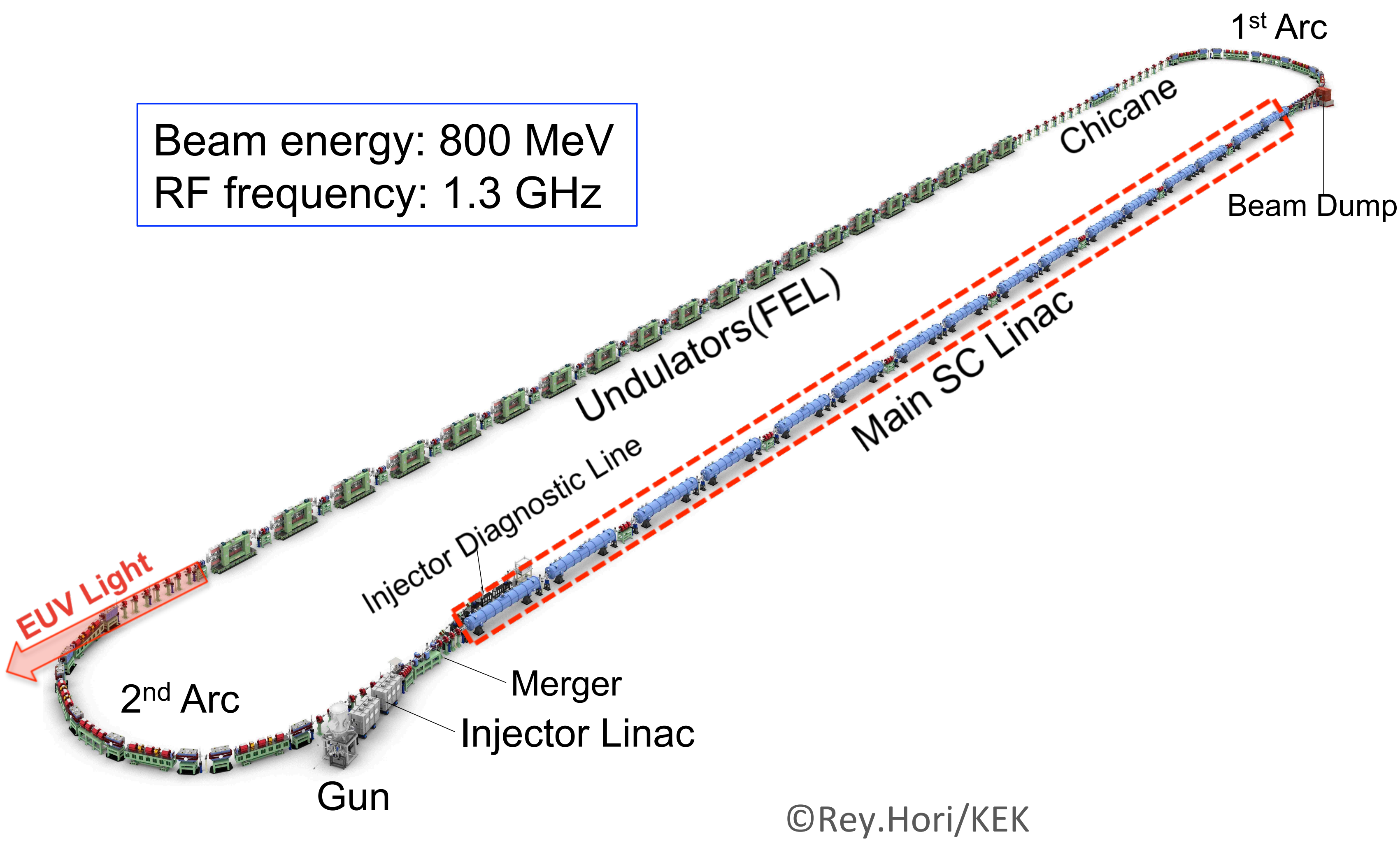


Injector & Merger Design



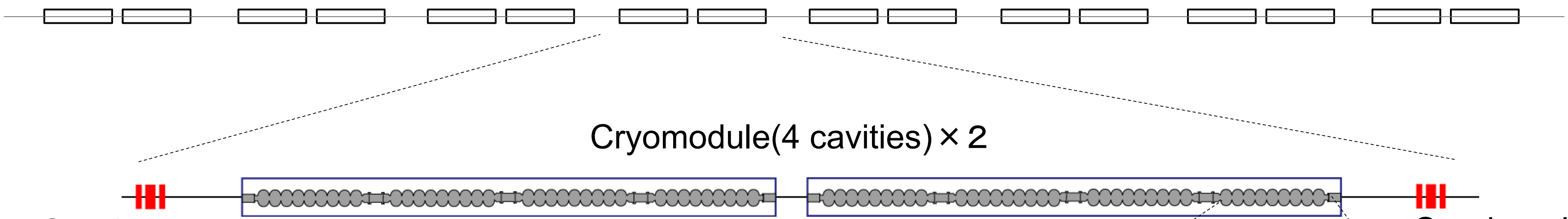
Main Linac

Beam energy: 800 MeV
RF frequency: 1.3 GHz



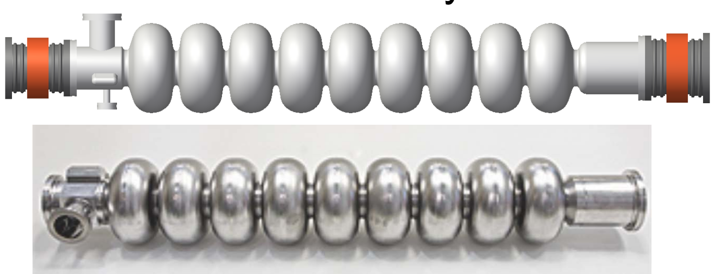
Main Linac Design

Main linac (9-cell cavities × 64 in 16 cryomodules)

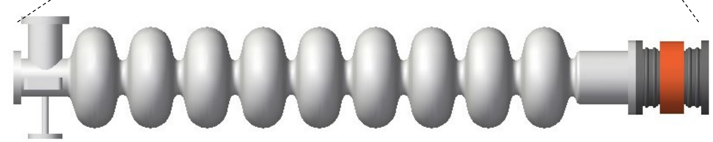


Basic unit of main linac structure

cERL cavity



EUV FEL cavity



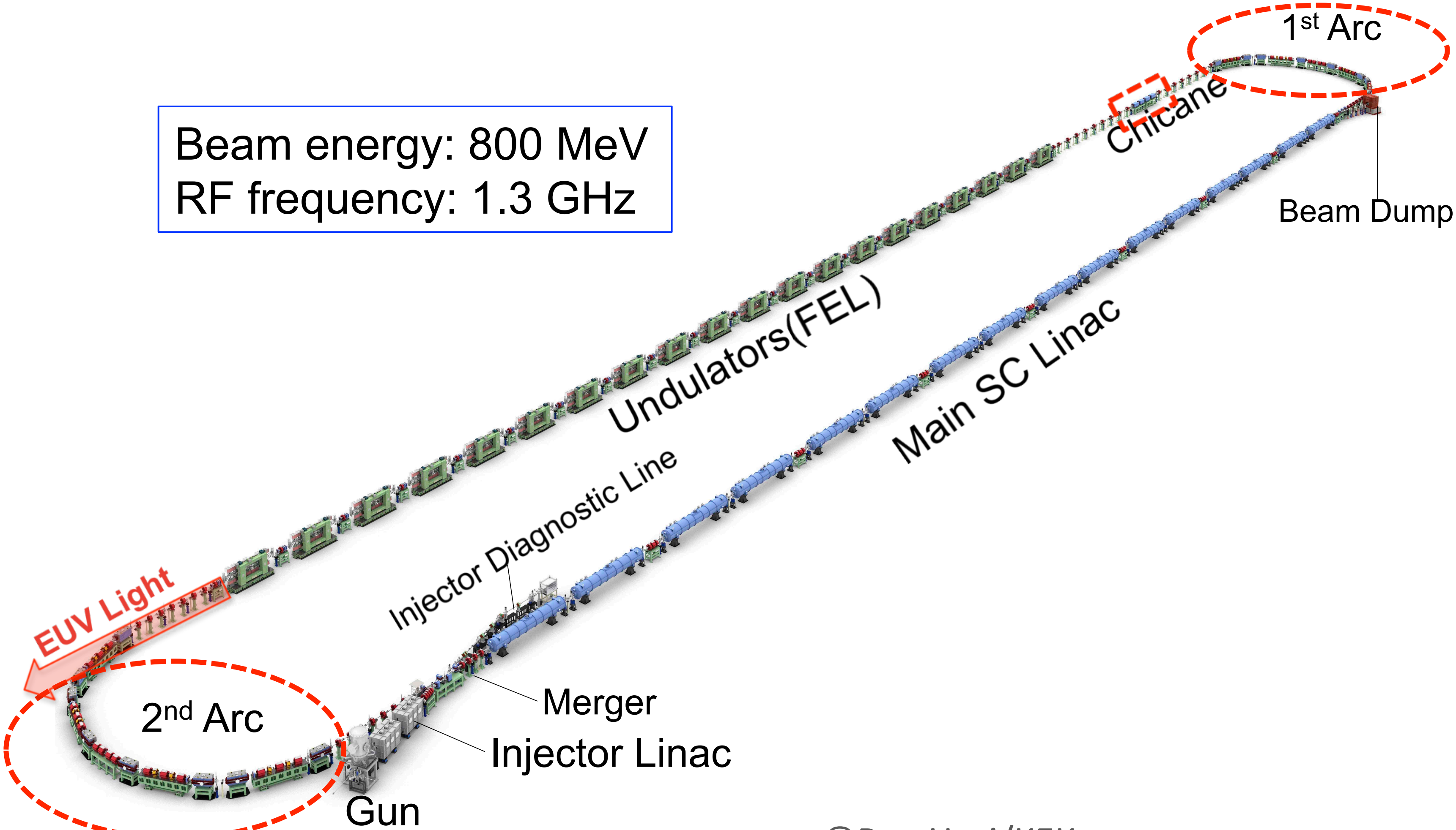
Under design. A large-aperture pipe will be also applied to the left side.

	cERL	EUV FEL		cERL	EUV FEL
Frequency	1.3 GHz	1.3 GHz	Iris diameter	80 mm	70 mm
R_{sh}/Q	897 Ω	1007 Ω	$Q_o \times R_s$	289 Ω	272 Ω
E_p/E_{acc}	3.0 ➔	**2.0**	H_p/E_{acc}	42.5 Oe/(MV/m)	42.0 Oe/(MV/m)

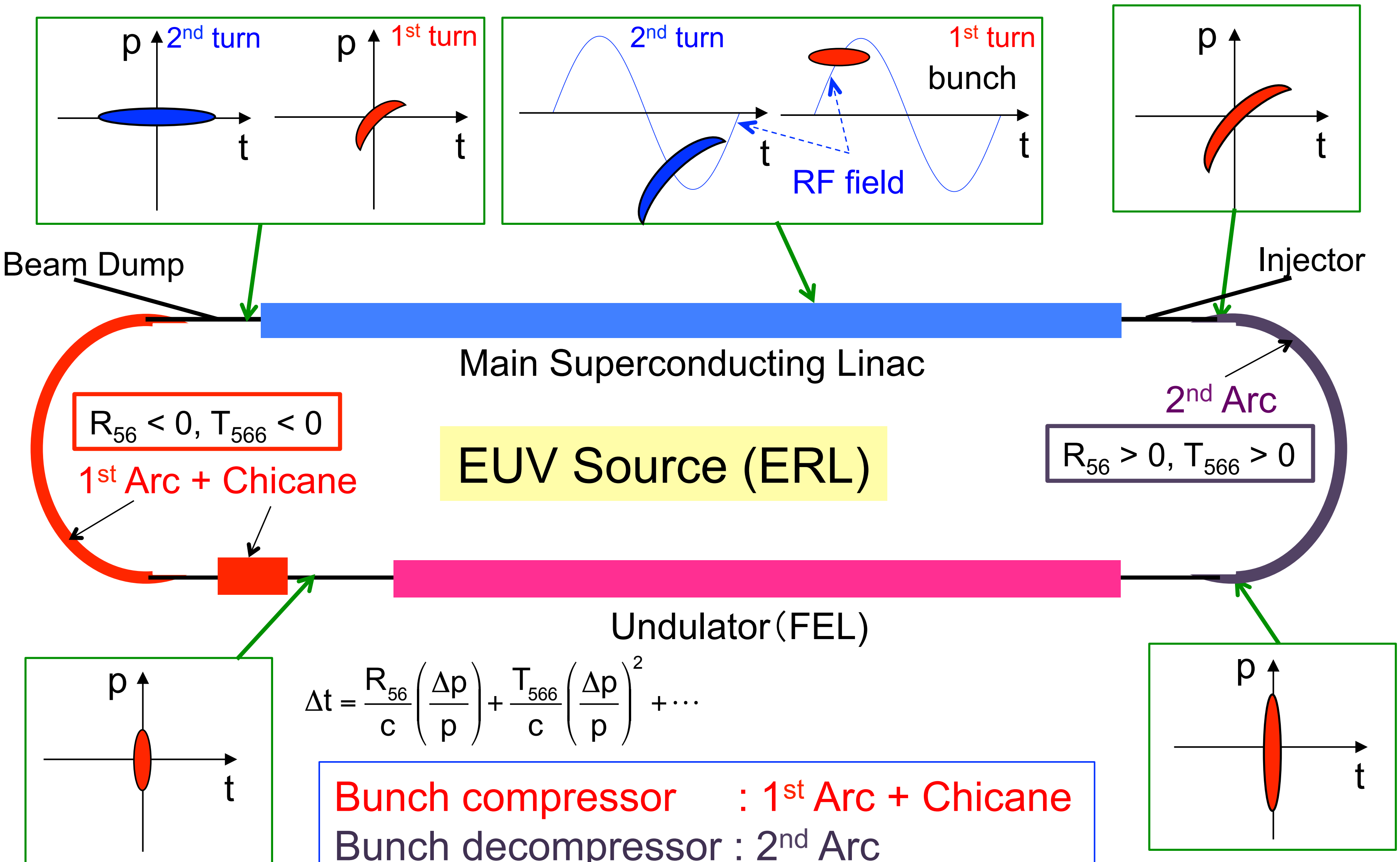
Stable operation at 8.5 MV/m (cERL) ➔ 12.5 MV/m (EUV-FEL)

Arc Sections & Chicane

Beam energy: 800 MeV
RF frequency: 1.3 GHz



Bunch Compression and Decompression Scheme



$$\Delta t = \frac{R_{56}}{c}\left(\frac{\Delta p}{p}\right) + \frac{T_{566}}{c}\left(\frac{\Delta p}{p}\right)^2 + \cdots$$

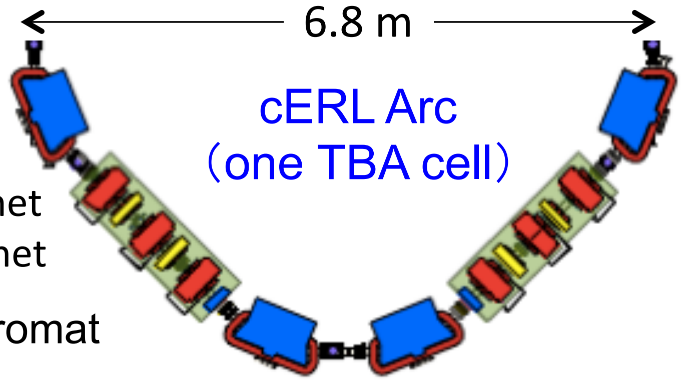
Bunch compressor : 1^{st} Arc + Chicane

Bunch decompressor : 2^{nd} Arc

Design of Arc Sections

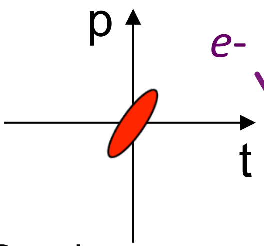
Blue : Bending magnet
Red : Quadrupole magnet
Yellow : Sextupole magnet

TBA: Triple-bend achromat

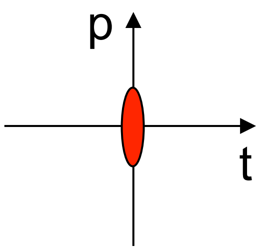


cERL arc (photograph)

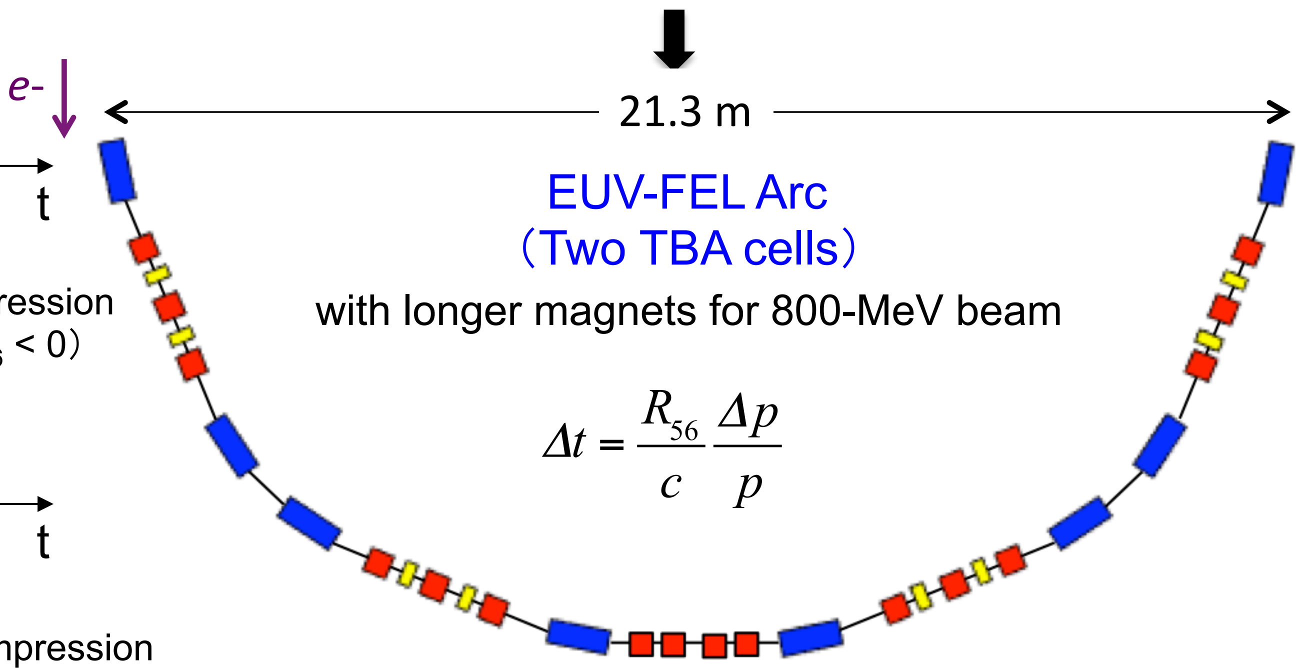
Same configuration with different R_{56} signs → Bunch compression & decompression



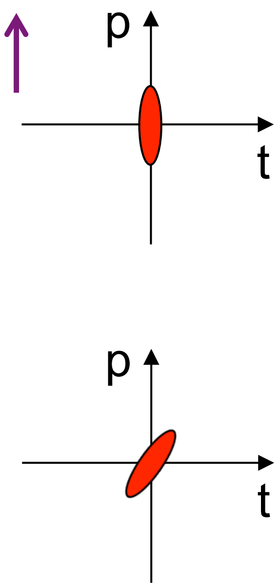
Bunch compression
(1^{st} arc, $R_{56} < 0$)



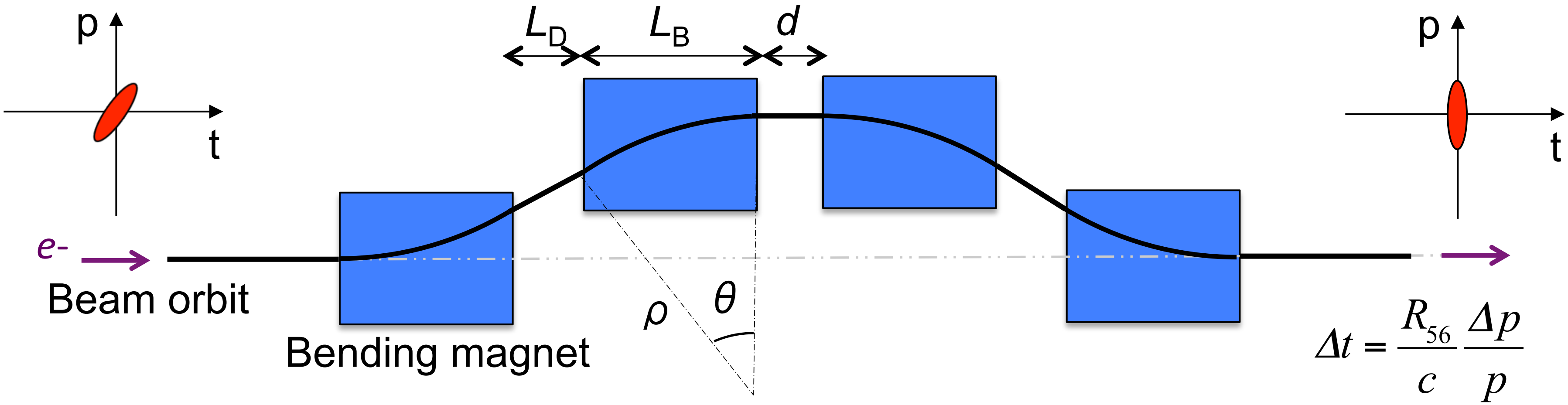
Bunch decompression
(2^{nd} arc, $R_{56} > 0$)



$$\Delta t = \frac{R_{56}}{c} \frac{\Delta p}{p}$$



Design of Chicane



$$\Delta t = \frac{R_{56}}{c}\frac{\Delta p}{p}$$

Four-magnet chicane for bunch compression

cERL chicane for path-length control

$$R_{56} = -\frac{4L_B}{\cos\theta} - \frac{4L_B^2 L_D}{\rho^2\cos^3\theta} + 4\rho\theta$$

L_B=1m and L_D=d=0.51m

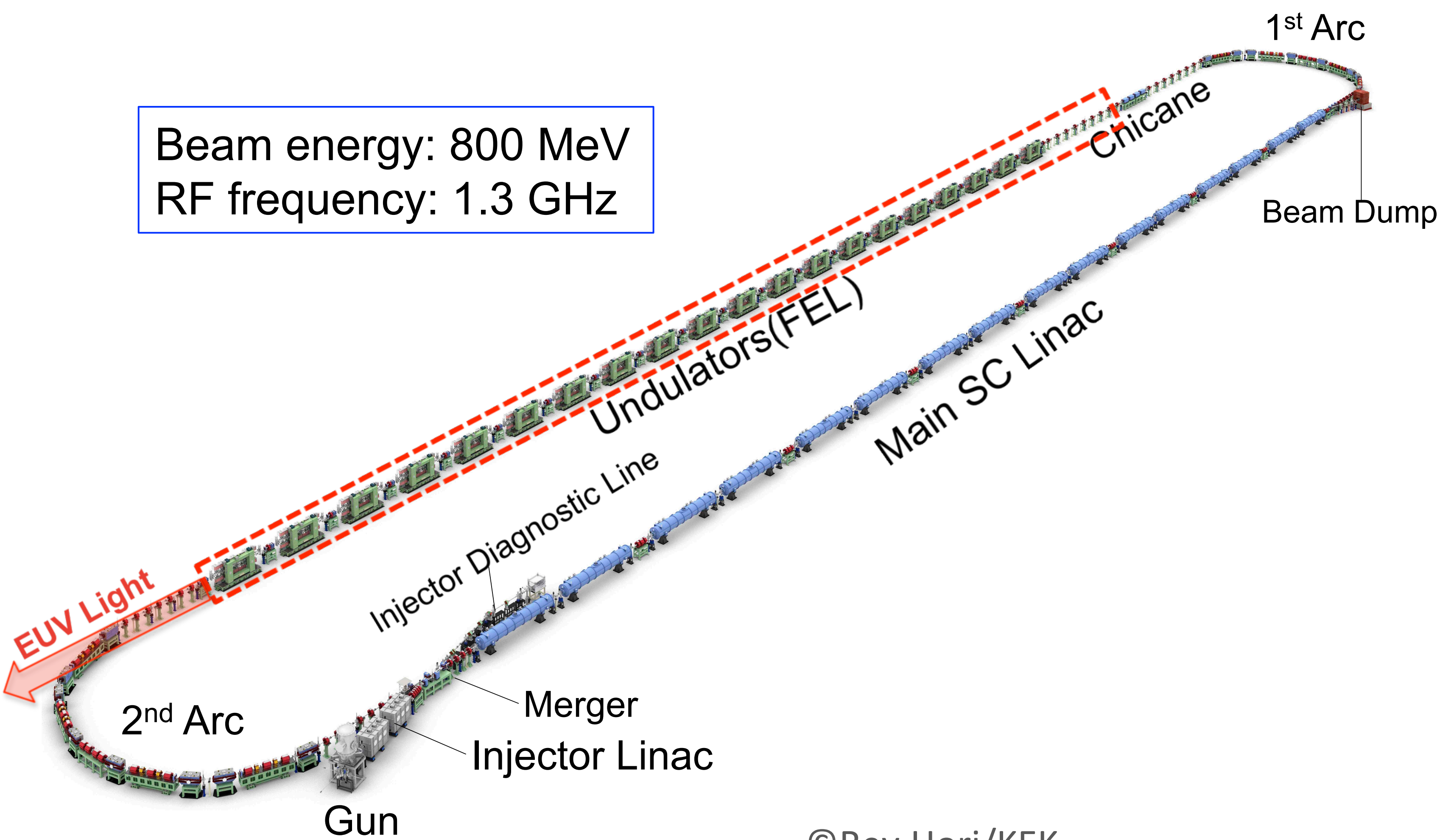
⬇

R_{56}=-0.15 m → ρ=4.1 m, θ=0.246 rad

R_{56}=-0.30 m → ρ=3.0 m, θ=0.340 rad

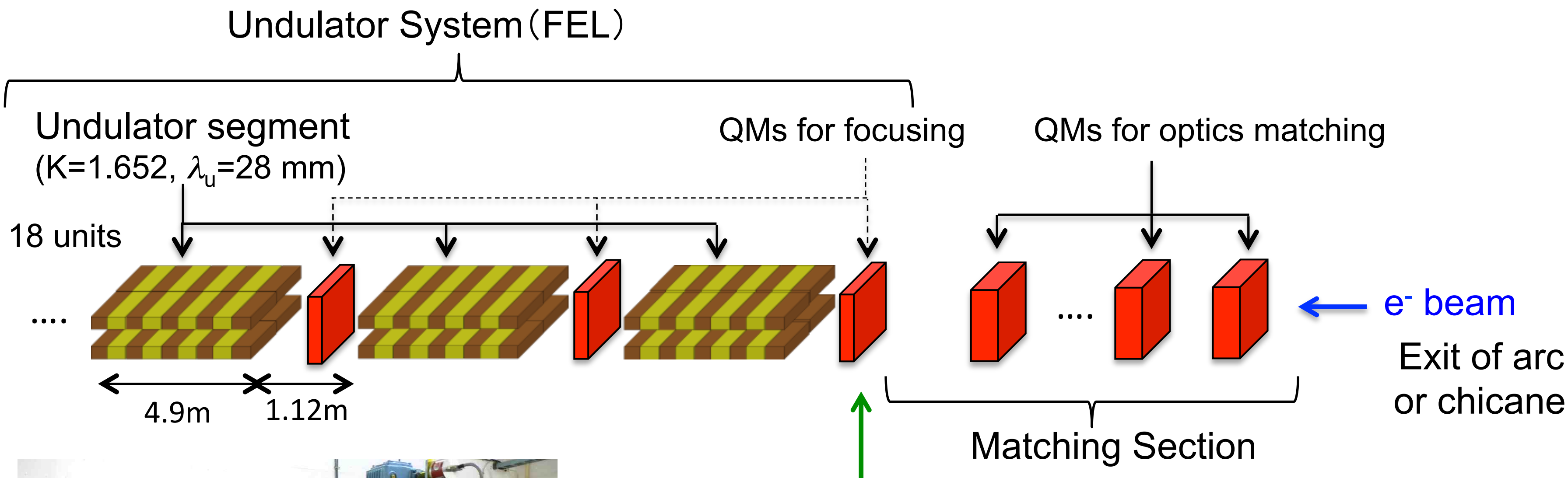
Undulator(FEL) Section

Beam energy: 800 MeV
RF frequency: 1.3 GHz

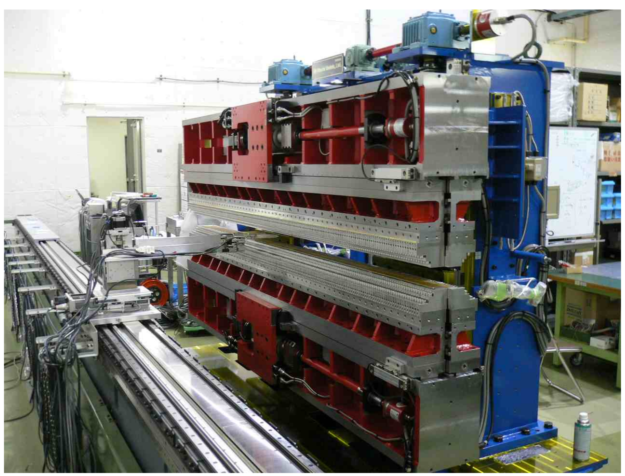


Undulator System for FEL

Undulator System (including matching section)



Adjustment of twiss parameter $\beta_{x,y}$,$\alpha_{x,y}$@ FEL entrance for maximizing FEL output power



Circularly-polarizing undulator developed at KEK

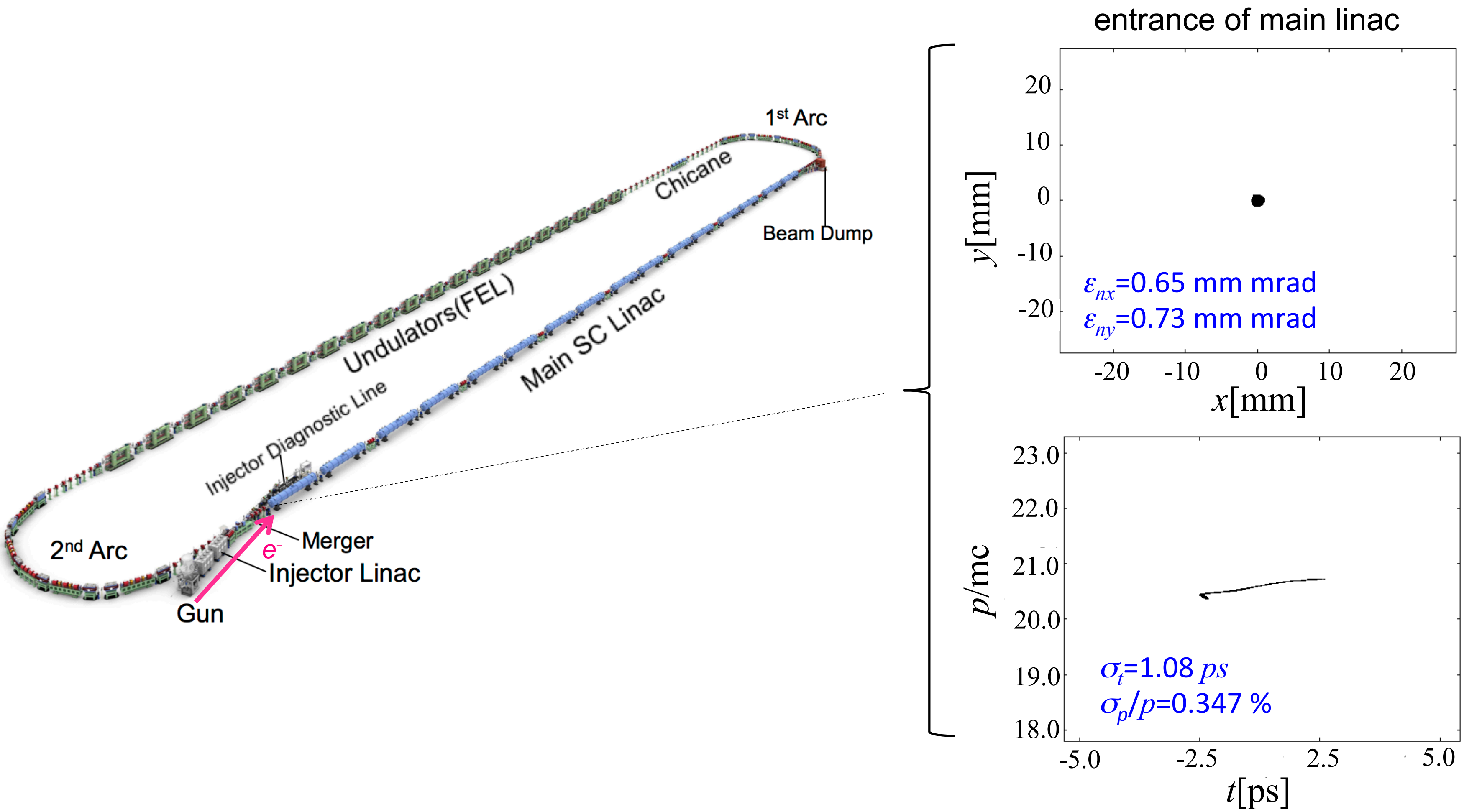
Parameters of undulator system to be optimized
(1) Undulator period and K-value (magnetic gap)
(2) Segment length and gap between segments
(3) Magnetic strength of QMs for focusing
(4) Undulator tapering

Simulation

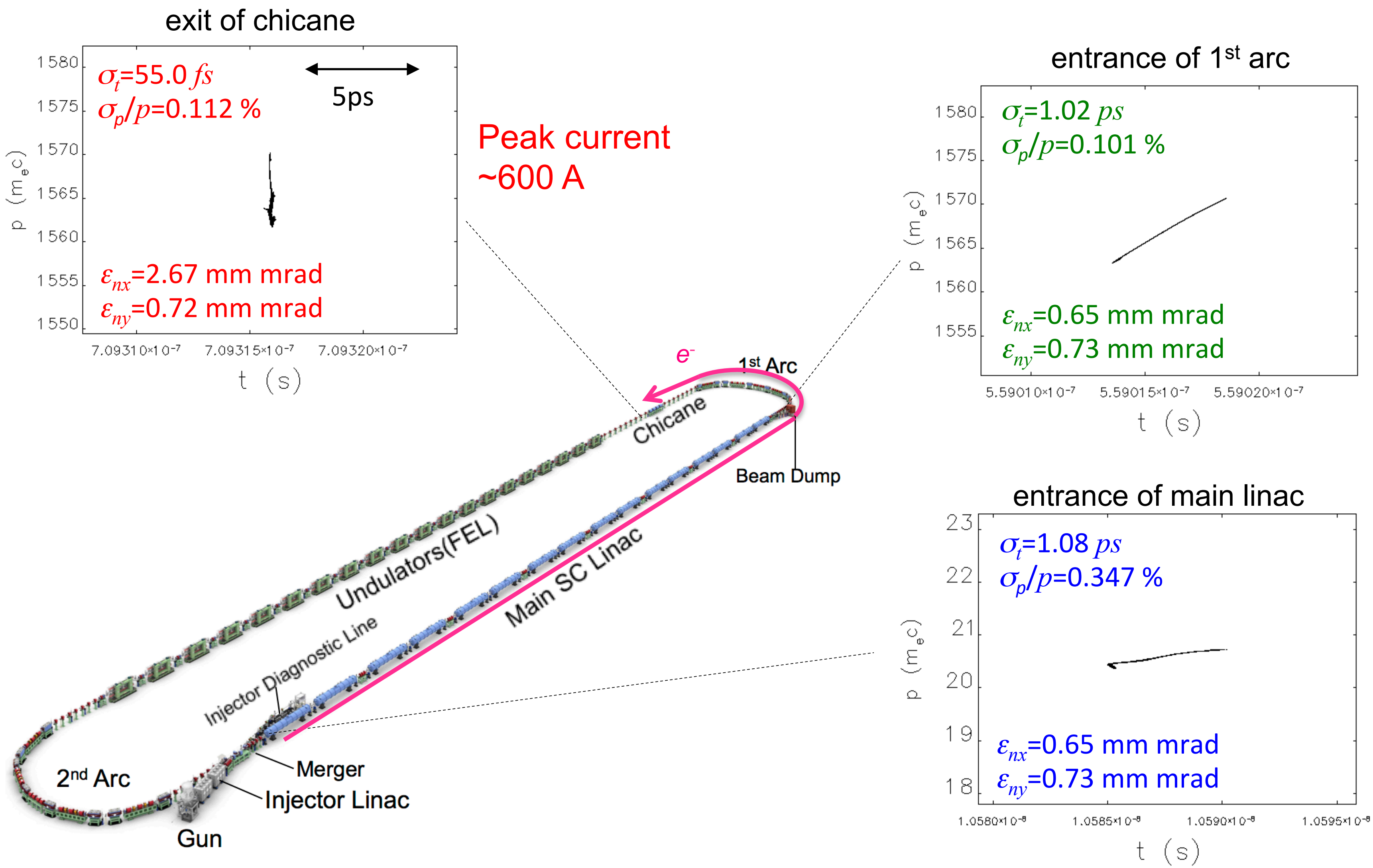
Injector & Merger

Optimization of Injection beam by simulation

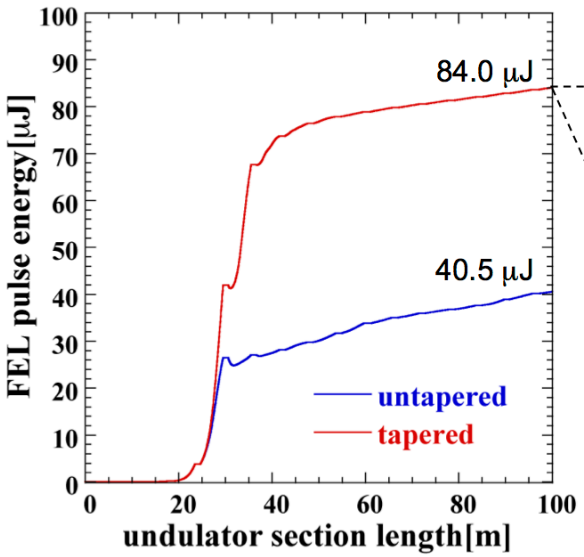
Bunch charge: Q_b=60pC, Injection energy: E_{inj}=10.5 MeV, Bunch length: σ_t ~ 1ps

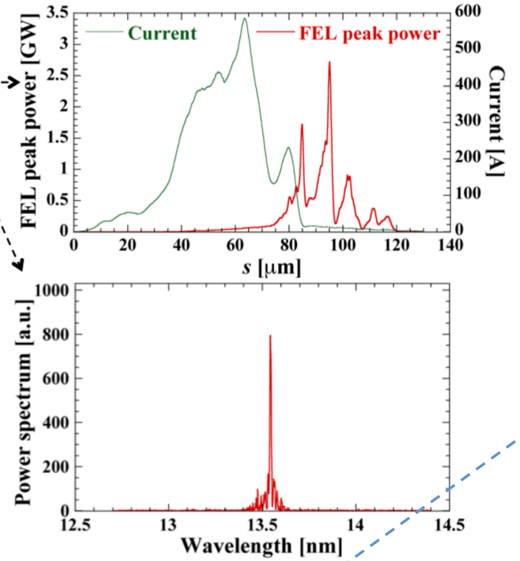


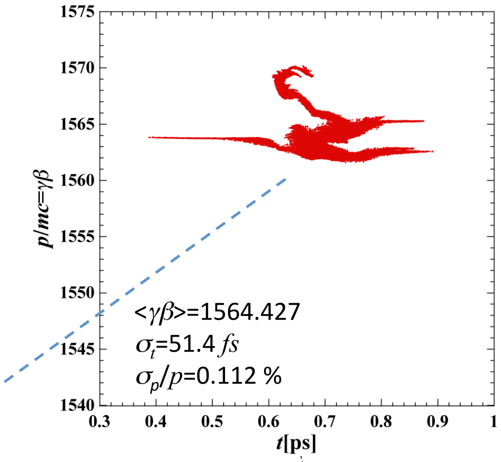
Bunch Compression



FEL Performance

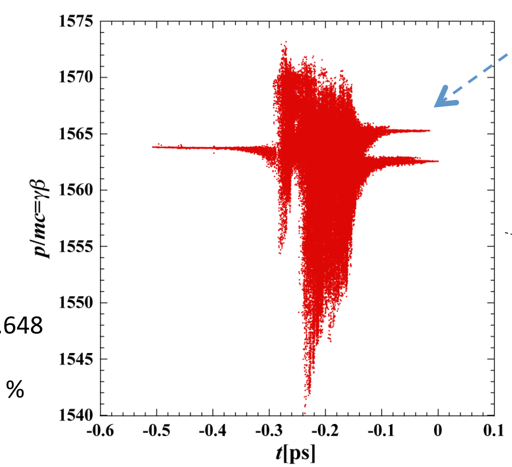




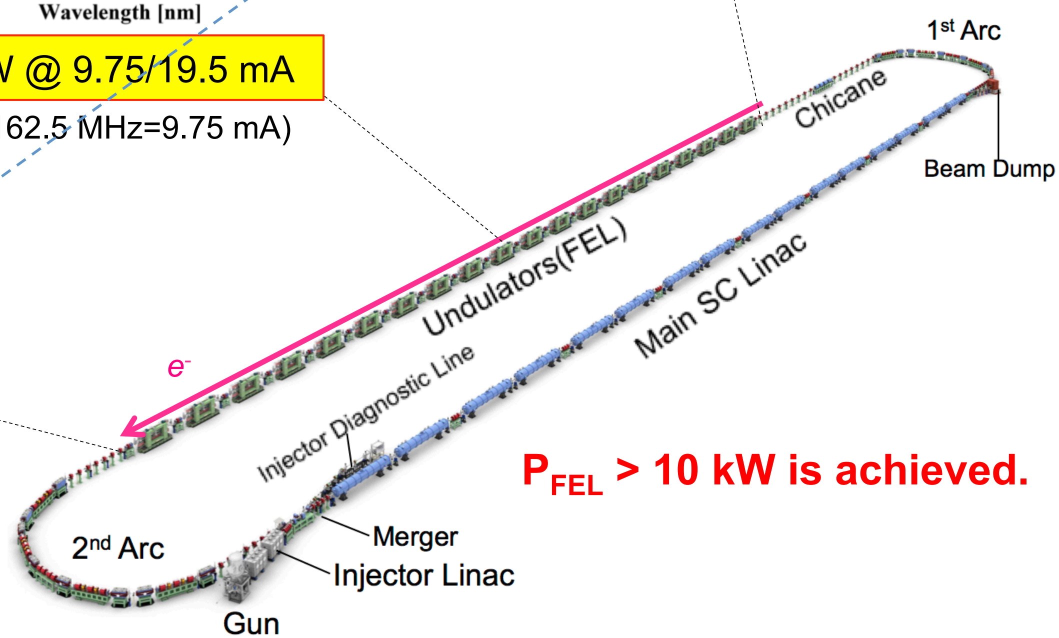


FEL power with 6% tapering: 13.7/27.3 kW @ 9.75/19.5 mA

(P_{FEL}=84 μJ x 162.5 MHz =13.7 kW, I_{av}=60pC x 162.5 MHz=9.75 mA)



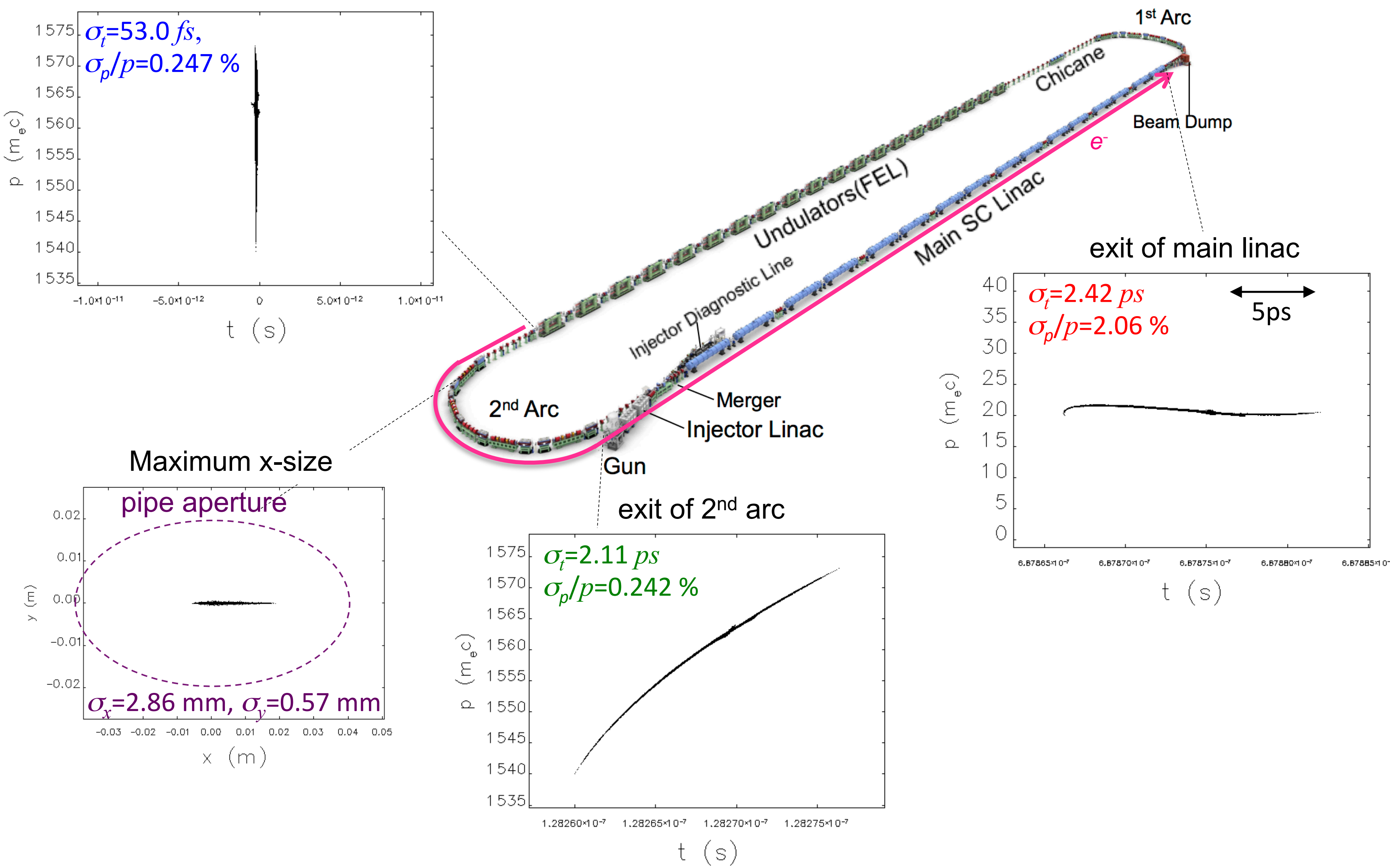
<γβ>=1562.648
σ_t=53.0 fs
σ_p/p=0.247 %



P_{FEL} > 10 kW is achieved.

Bunch Decompression

Bunch decompression is achieved without beam loss.



Conclusions

- ERL is a suitable accelerator for high-power FELs.
- ERL-based EUV-FEL source has been designed with available technologies and its performance has been checked by computer simulation.
  - Generation of FEL power more than 10 kW at 10 mA in the designed EUV-FEL source
  - Successful transportation of electron beams throughout the EUV-FEL source without any beam loss
- Further design work and R&D will improve the source performance and enhance feasibility of the EUV-FEL source for lithography.

EUV-FEL Design Group

(KEK) T. Furuya, K. Haga, I. Hanyu, K. Harada,
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H. Kawata, Y. Kobayashi, T. Konomi, T. Kubo,
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(QST) R. Hajima

(Tohoku Unv.) N. Nishimori

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

EUV-FEL Light Source Study Group for Industrialization

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Materials Mag!c

GIGAPHOTON

EIDEC

Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST

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Changes for the Better

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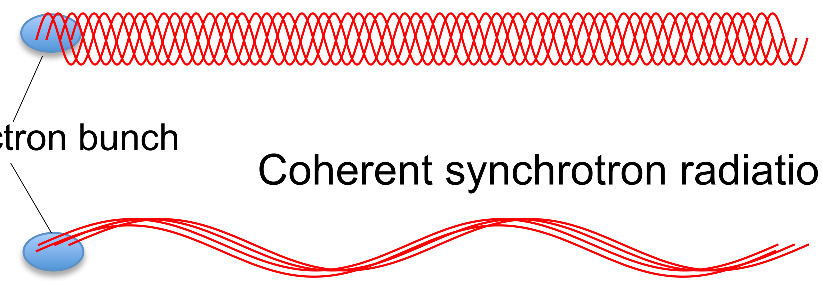
Thank you for your attention!

Backup Slides

Effects of CSR

Generation of coherent synchrotron radiation(CSR) in bending sections

Incoherent synchrotron radiation(ISR)



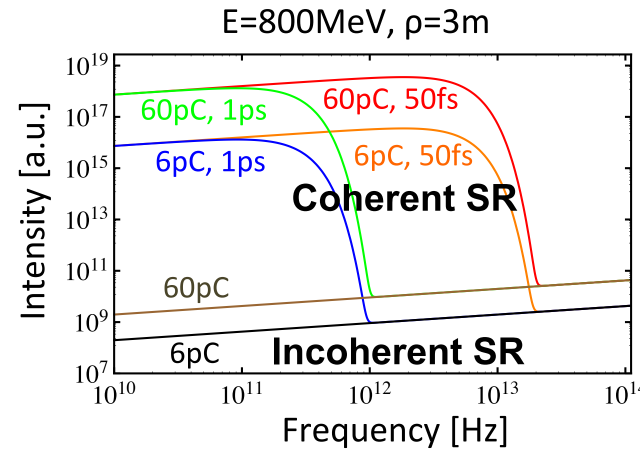
$N_{ph} \propto N_e$

Electron bunch

Coherent synchrotron radiation(CSR)

$N_{ph} \propto N_e^2$

in Bending magnet

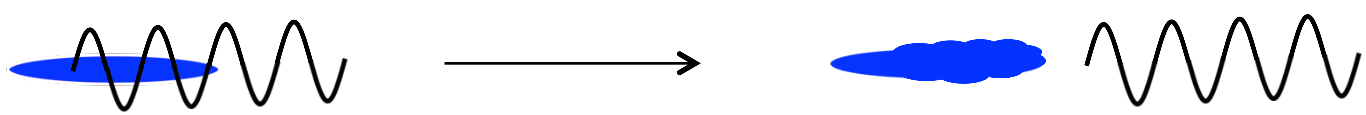


CSR field becomes strong for higher bunch charge and shorter bunch length

Strong CSR field from the back part of bunch affects front part

CSR

Electron bunch



in Bending magnet

→ Degrade of beam quality
→ Reduction of FEL power

Arc sections/chicane should be designed so as to suppress CSR effects.

EUV/X-ray FELs

	LCLS	SACLA	FLASH	Euro-XFEL	LCLSII	EUV-FEL
Type of linac	Normal conducting		Super conducting			
Operation mode	Pulse		Long pulse		CW	
Country	US	Japan	Germany	Germany	US	-------
ERL scheme	No	No	No	No	No	**Yes**
Repetition rate	120	30～60	<5000	<27000	1M	**162.5M**
Beam energy (MeV)	14300	6000～8000	1250	17500	4000	**800**
Wavelength(nm)	0.15	0.08	4.2-52	0.05	~0.3	13.5
Pulse energy(mJ)	~10	~10	<0.5	~10	~1	~0.1
Average Power (W)	~1	~1	<0.6	~100	~1000	**>10000**
Beam dump power (W)	~1.5k	~0.5k	~6k	~0.5M	~1M	**~0.1M**
Status	Operation 2009	Operation 2011	Operation 2004	Construction 2017	Construction 2020	Planning