The Design and Development of a 10-kW Class EUV-FEL Project in Japan

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Part One:

Challenging Issue and recent progress of compact ERL

SASE-FEL formula

- FEL wavelength

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

- FEL parameter ρ

beam current　　undulator

$$\rho = \frac{1}{\gamma}\left\{\frac{1}{64\pi^2}\frac{I_P}{I_A}\frac{K^2\lambda_u^2[JJ]^2}{\sigma_x\sigma_y}\right\}^{\frac{1}{3}}$$

beam energy　　beam sizes

- Gain Length

$$L_{gain} = \lambda_u / 4\sqrt{3}\pi\rho$$

$$[JJ] = J_0(\xi) - J_1(\xi)$$

- Saturation Length

$$L_{sat} \approx 20 \times L_{gain}$$

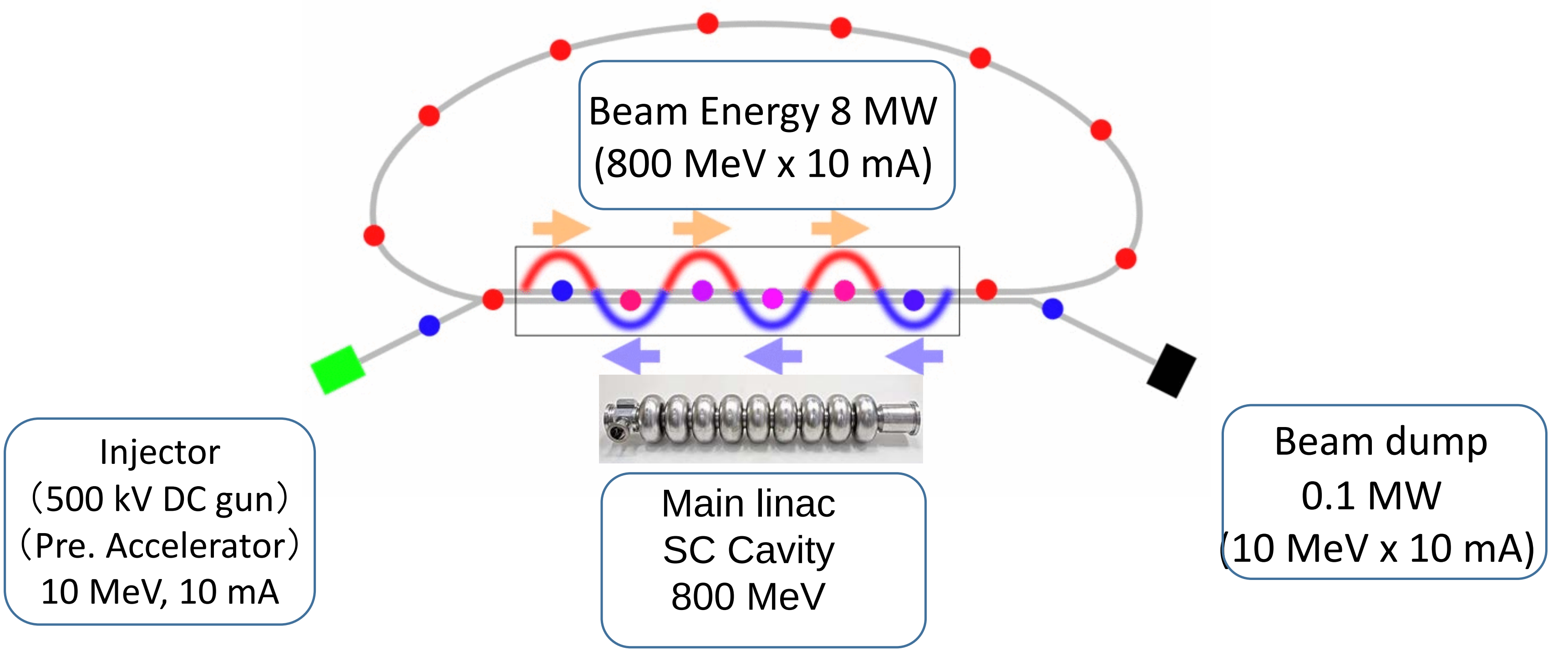
$$\xi = \frac{(K/2)^2}{2\left(1 + (K/2)^2\right)}$$

- FEL power

$$\langle P_{FEL}\rangle = \rho\langle P_{beam}\rangle = \rho E \times \langle I_{beam}\rangle$$

Energy Recovery Linac

Energy exchanged between new bunches (from injector) and old bunches (to dump) at the main linac



- <u>Increase average beam current</u>
- <u>Reduce dump energy (small radiation)</u>

What's challenging in ERL?

1. High average current operation over 10 mA!

   J-lab demonstrated up to 10 mA

2. Small beam loss operation

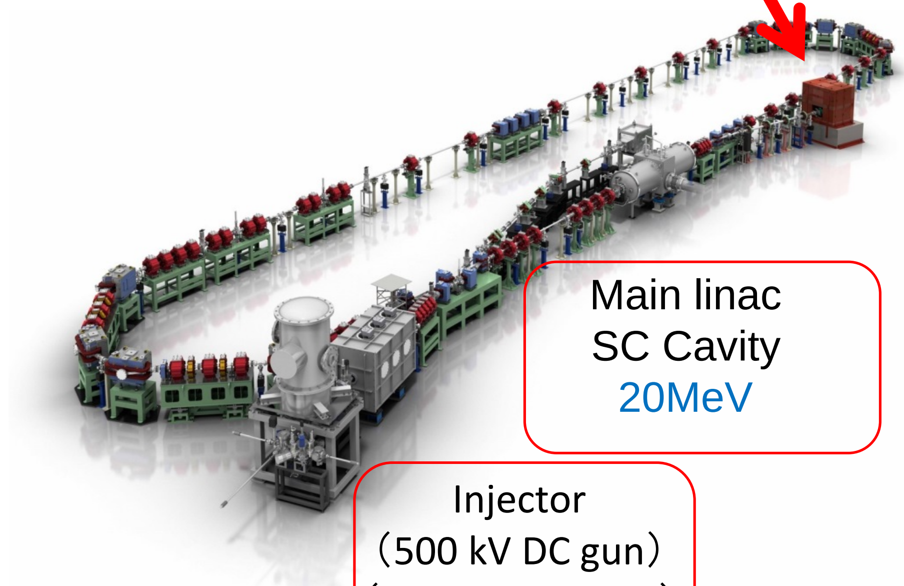
   ERL has higher duty

   (x100 ~ x1000) than non-ERL

   Reduction of beam loss is needed!

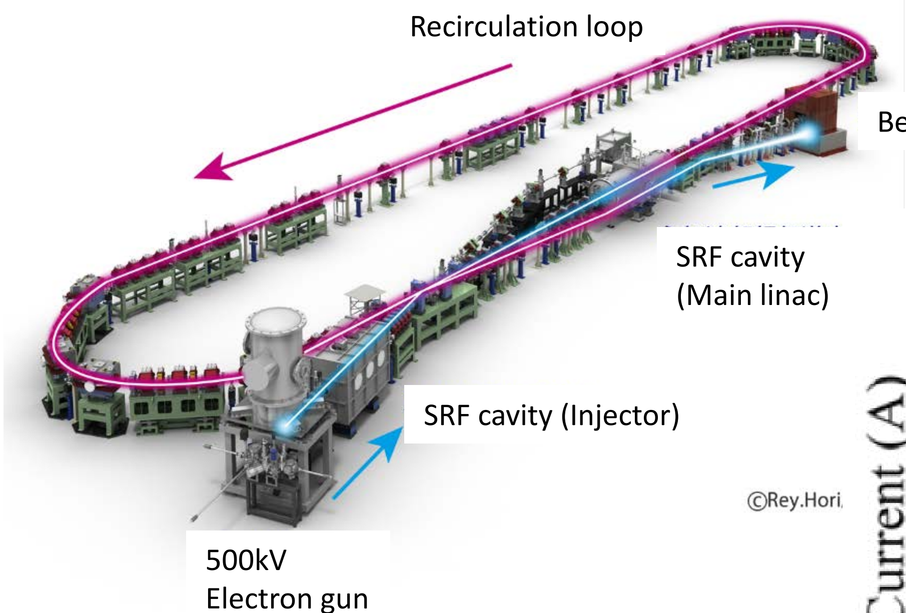
3. Energy Recovery after FEL process

   ER after single pass FEL (SASE) not demonstrated!



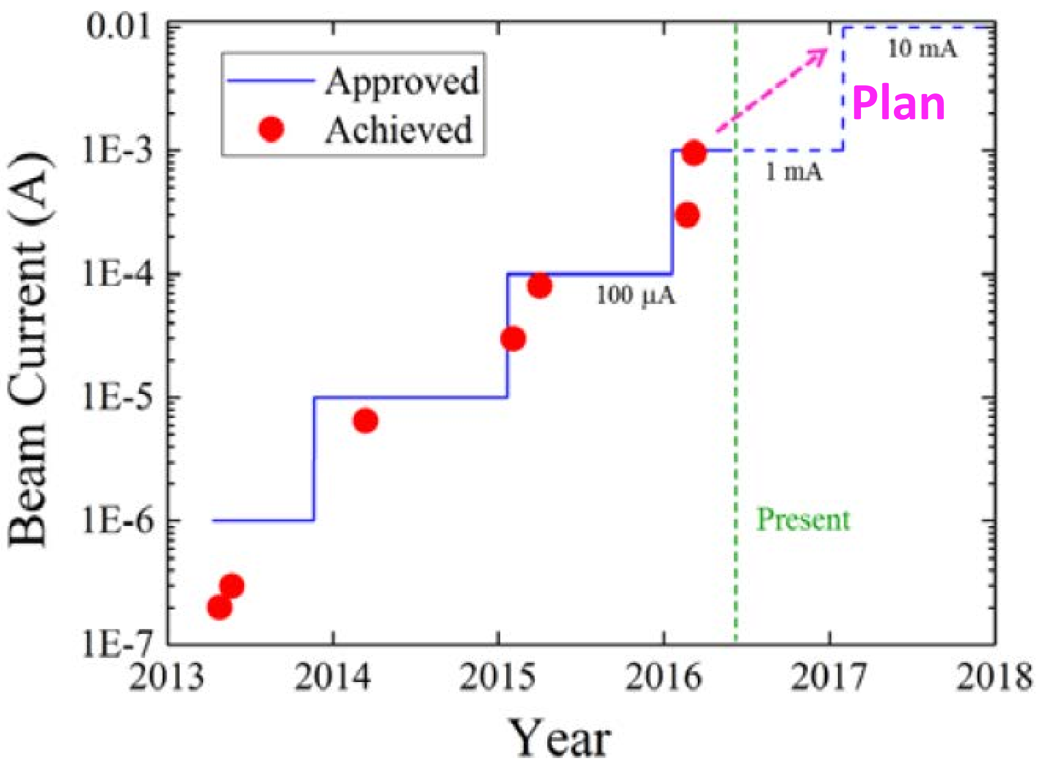
Compact ERL @ KEK

1 mA operation of cERL



Energy recovery successful.
20 MeV, 1 mA at present

Upgrade of beam current
(T. Obina, IPAC16, TUPOW036)

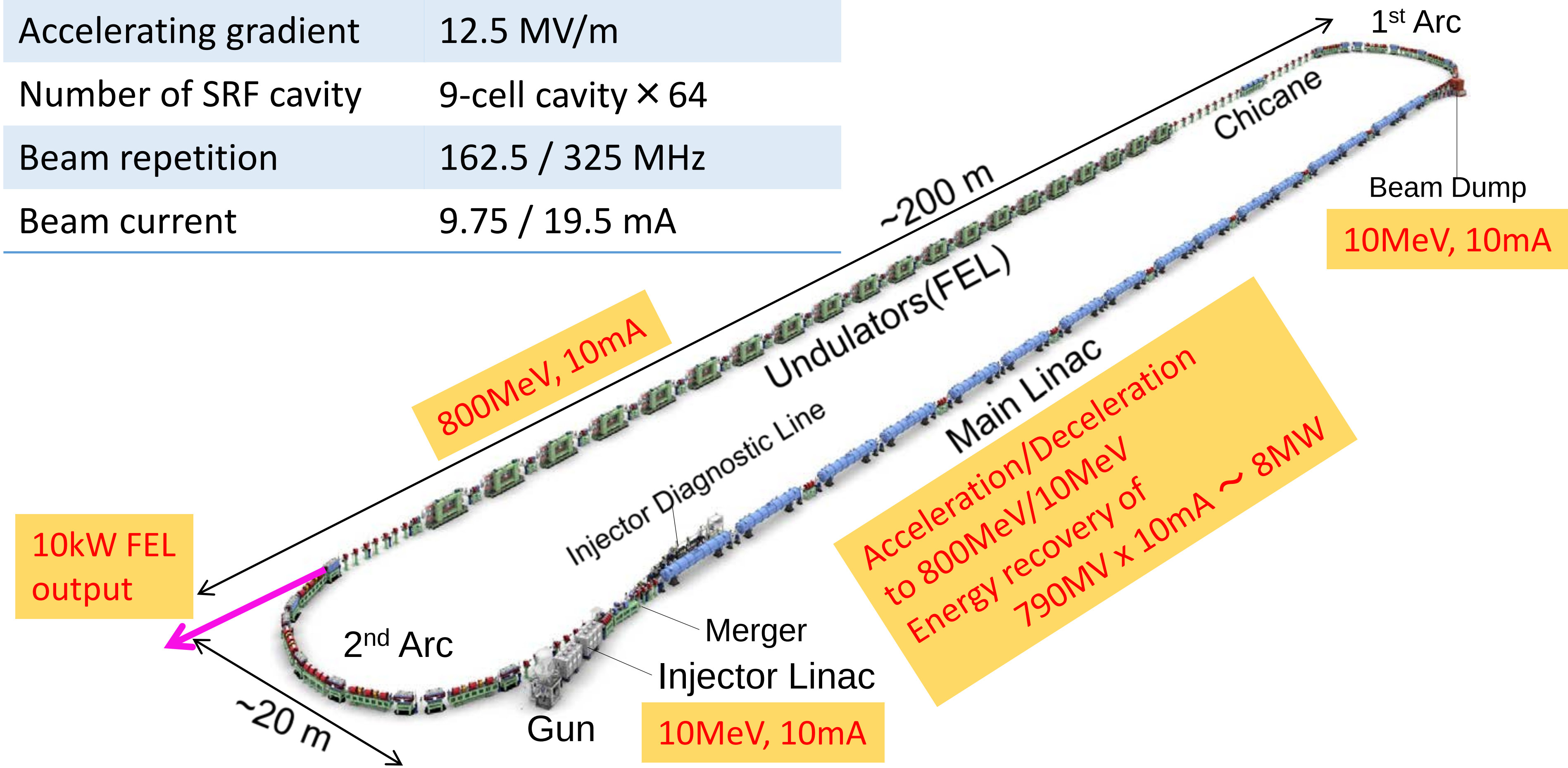


Part Two:

FEL and Energy Recover Simulation

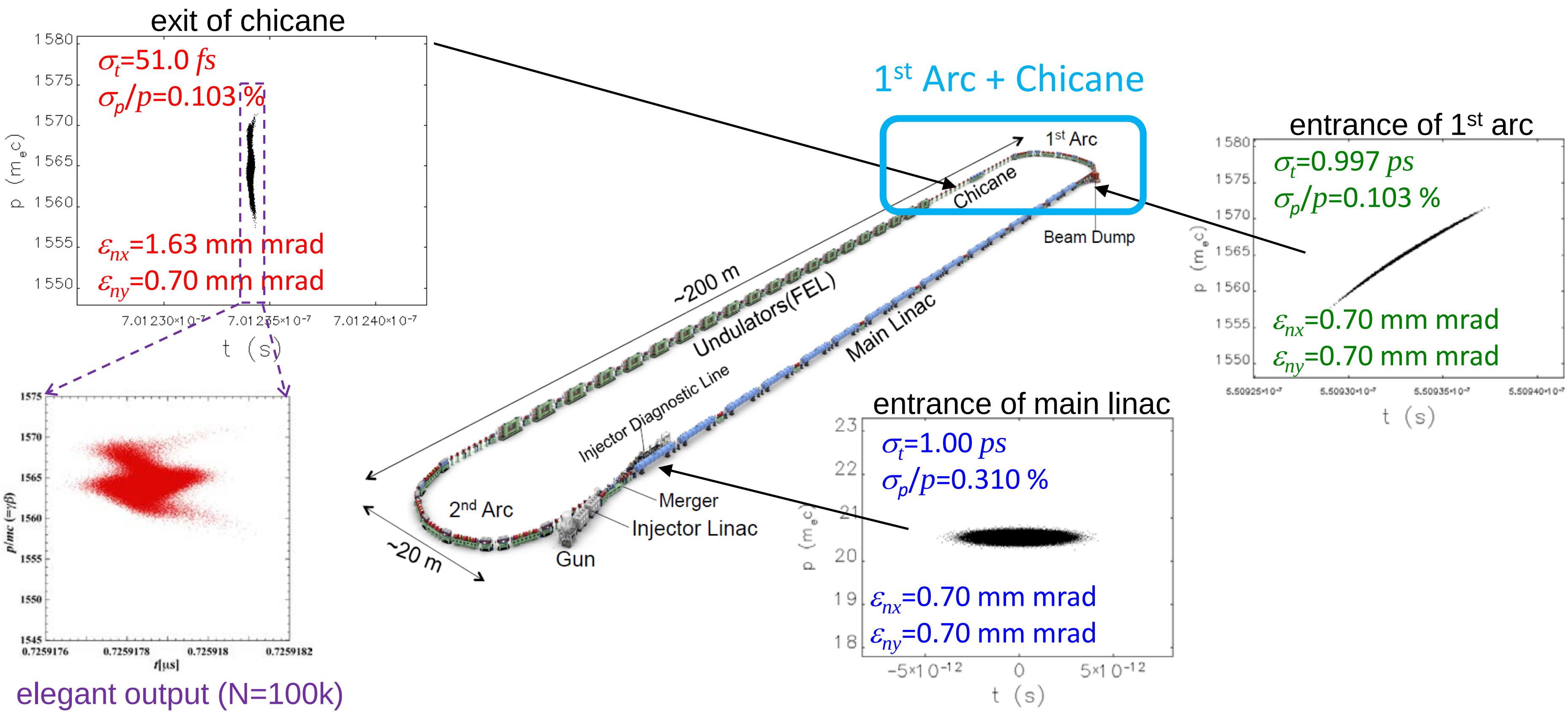
Design & Spec.

Parameter	Specification
Wavelength	13.5 nm
Output power	> 10 / 20 kW
Bunch charge	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 / 325 MHz
Beam current	9.75 / 19.5 mA



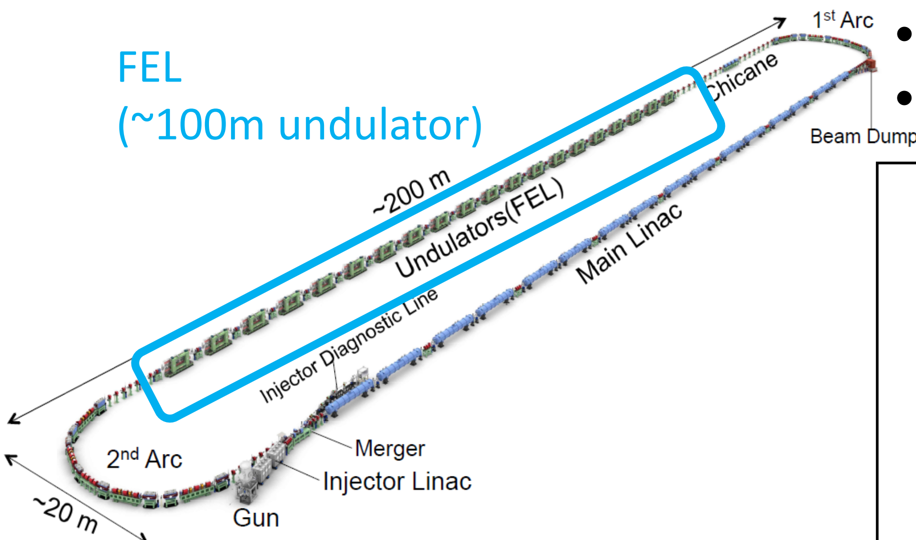
Bunch Compression before FEL (elegant)

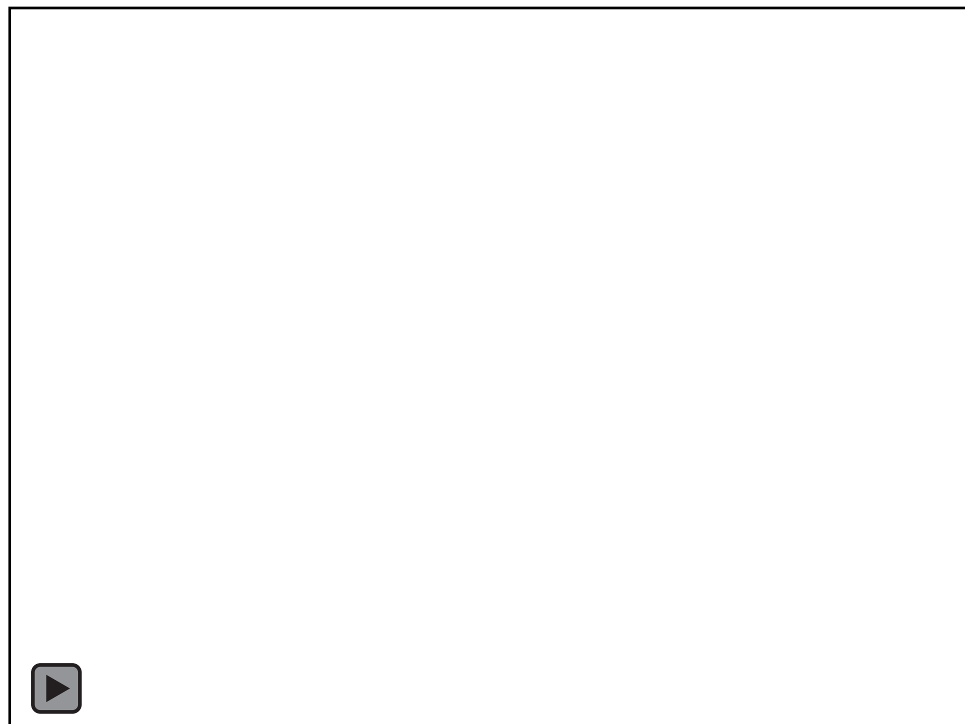
Bunch compression by 1st Arc (R56=-0.15 m) + Chicane (R56=-0.15 m)



FEL Simulation (Genesis)

- 800 MeV, 60 pC, Freq.=162.5 / 325 MHz
- Und. entrance: $\alpha x=\alpha y=0$, $\beta x=4$ m, $\beta y=6$ m
- Und. K=1.652, λ_u=28 mm, L_u=2.8 m (x 35)
- Und #1-#7 Normal type
- Und #8-End Tapered (2% Linear)





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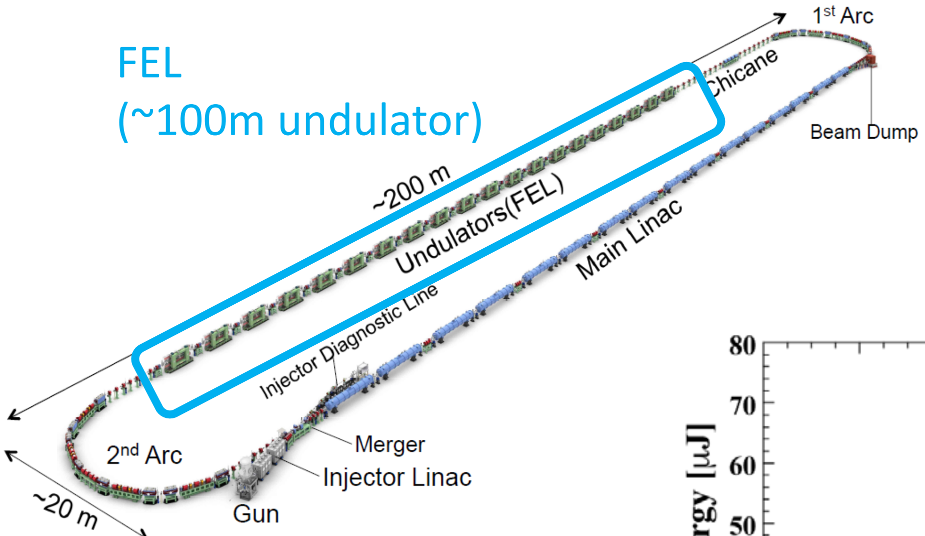
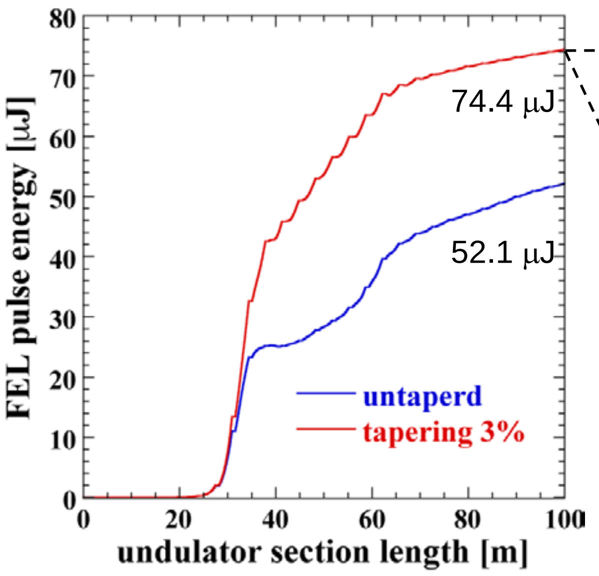
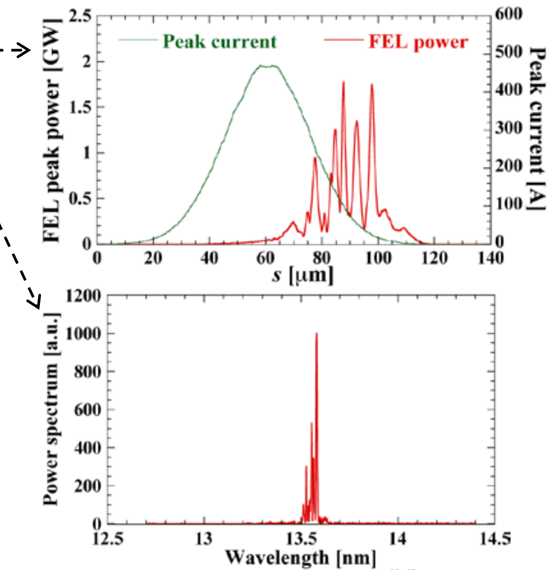
FEL Performance

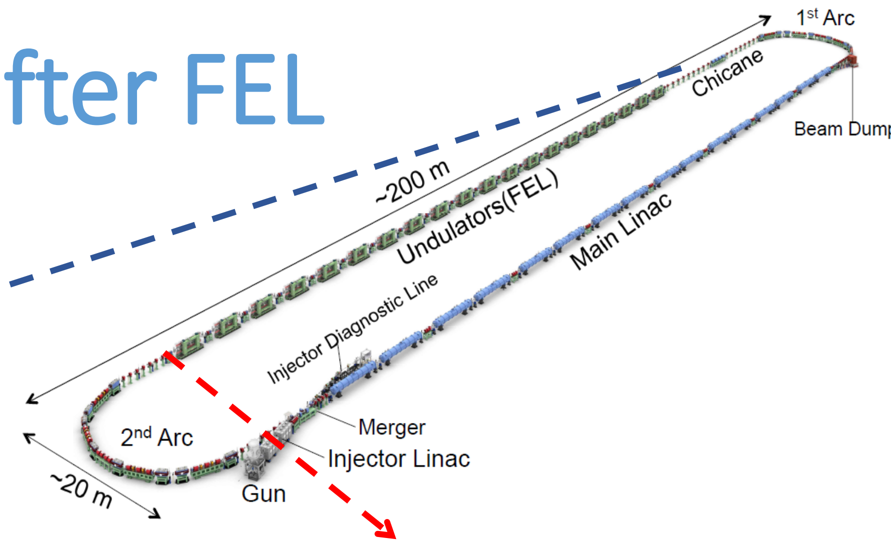
- 800 MeV, 60 pC, Freq.=162.5 / 325 MHz
- FEL power with 2% tapering:
  12.1 / 24.2 kW @ 9.75 / 19.5 mA



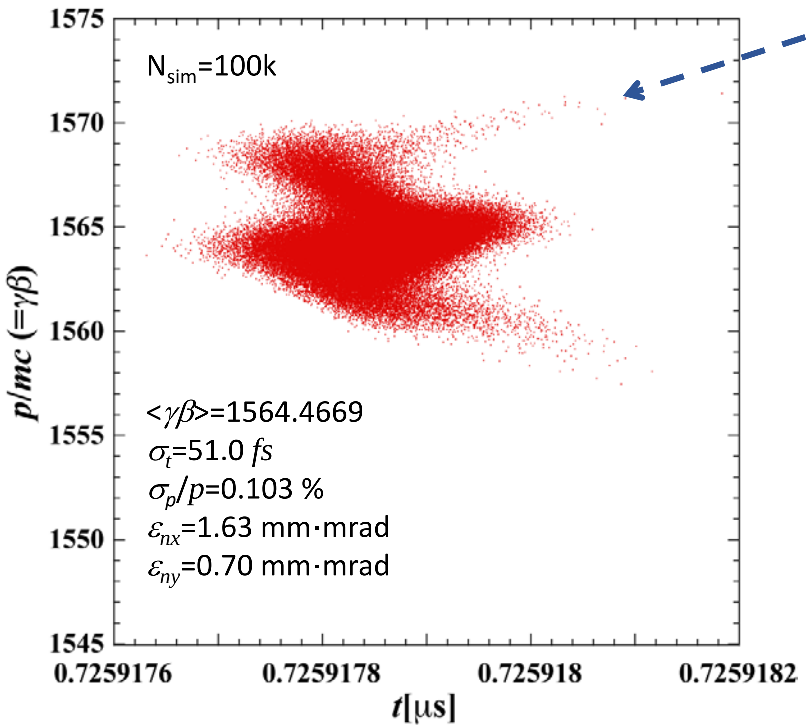




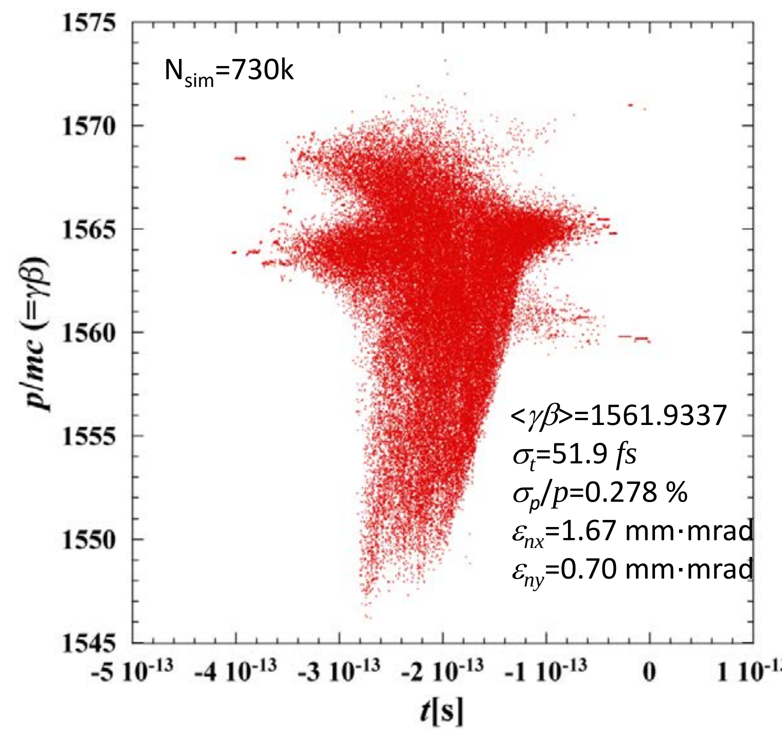
Momentum Spread after FEL



Before FEL（elegant output）

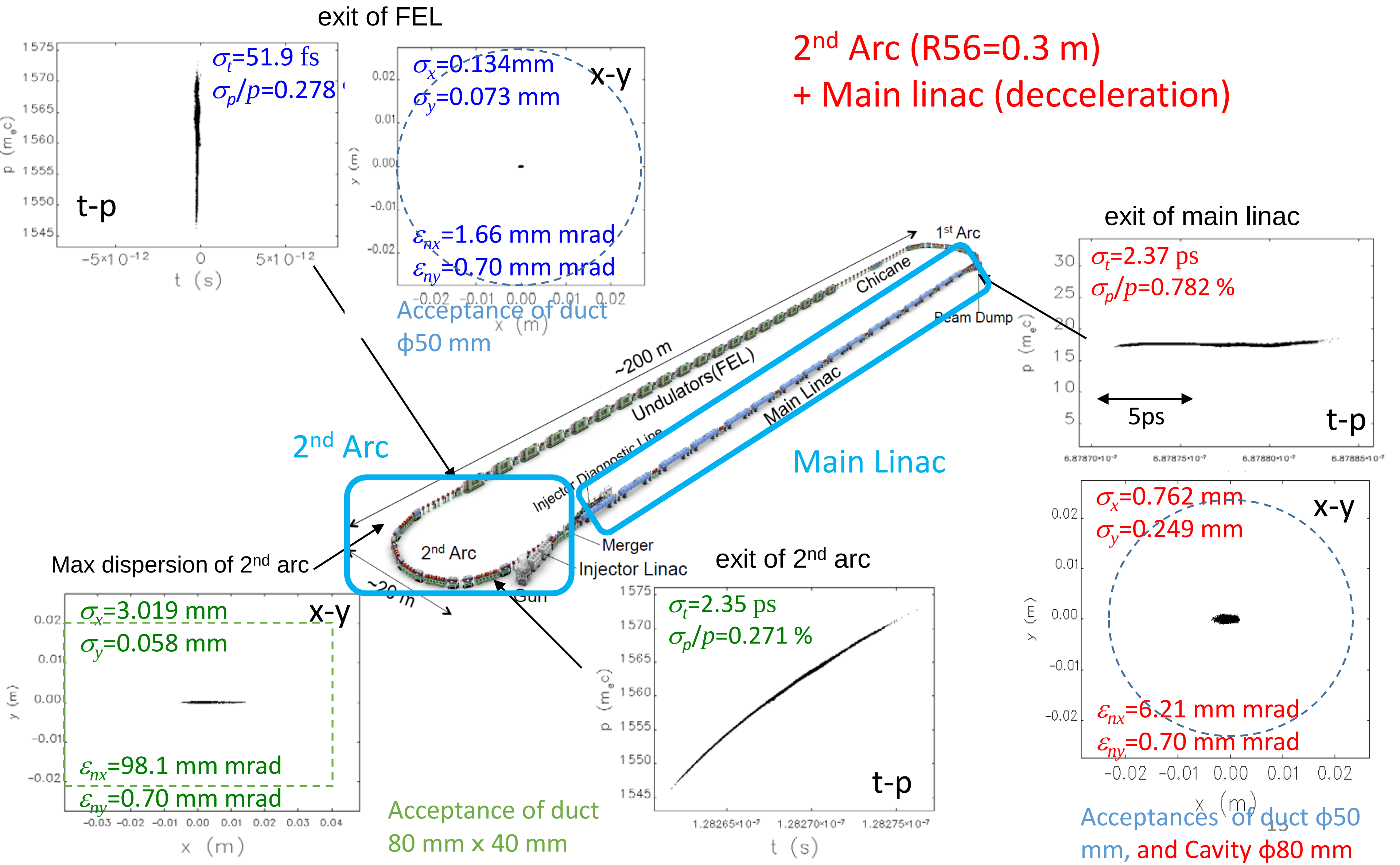


After FEL（Genesis output）



e- Distribution in Longitudinal Phase Space

Bunch Decomp. and ER after FEL (elegant)



Part Three

Startup of the EUV-FEL Light Source Study Group for Industrialization

EUV-FEL Light Source Study Group for Industrialization
- History and Activity

<Back ground>

2012	ASML indicated the possibility of FEL as an EUV light source in EUV Source Workshop
2014.2	HZB and Carl Zeiss group presented the feasibility study on various types of FEL for EUV Lithography at SPIE Advanced Lithography
2014.2~	KEK and a Japanese company started the feasibility study on EUV-FEL source by ERL-FEL from the view point of accelerator technologies Another Japanese company started the feasibility study on EUV-FEL source from the view point of lithography application

<Activity>

2015.6	Planning to establish the **EUV-FEL Study Group for Industrialization** to combine these activities
2015.8	Kick off meeting of the EUV-FEL Light Source Study Group for Industrialization (6 companies, 1 consortia, 6 universities .etc.)
2016.1	Establish the source working group to make a planning of the research and development project (8 companies, KEK, QST and Universities)
~Present	10 companies, 1 consortia, 7 Universities, Research Laboratories Meeting: almost once a month

EUV-FEL Light Source Study Group for Industrialization - since Aug. 2015 -

Leader : The Univ. Tokyo S. Ishihara

Utsunomiya Univ.
T. Higashiguchi

Waseda Univ.
M. Washio

Hyogo Pref. Univ.
H. Kinoshita

Osaka Univ.
T. Kozawa

Industries

Mitsubishi Heavy Industries Mechatronics Systems

Toshiba

Hitachi Metals

Gigaphoton

EIDEC

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

Taiyo Nippon Sanso

Hitachi

NTT Advance Technology

Toshiba Electron Tube & Devices

Mitsubishi Electric

QST
R. Hajima

AIST N. Sei

KEK
H. Kawata et al.

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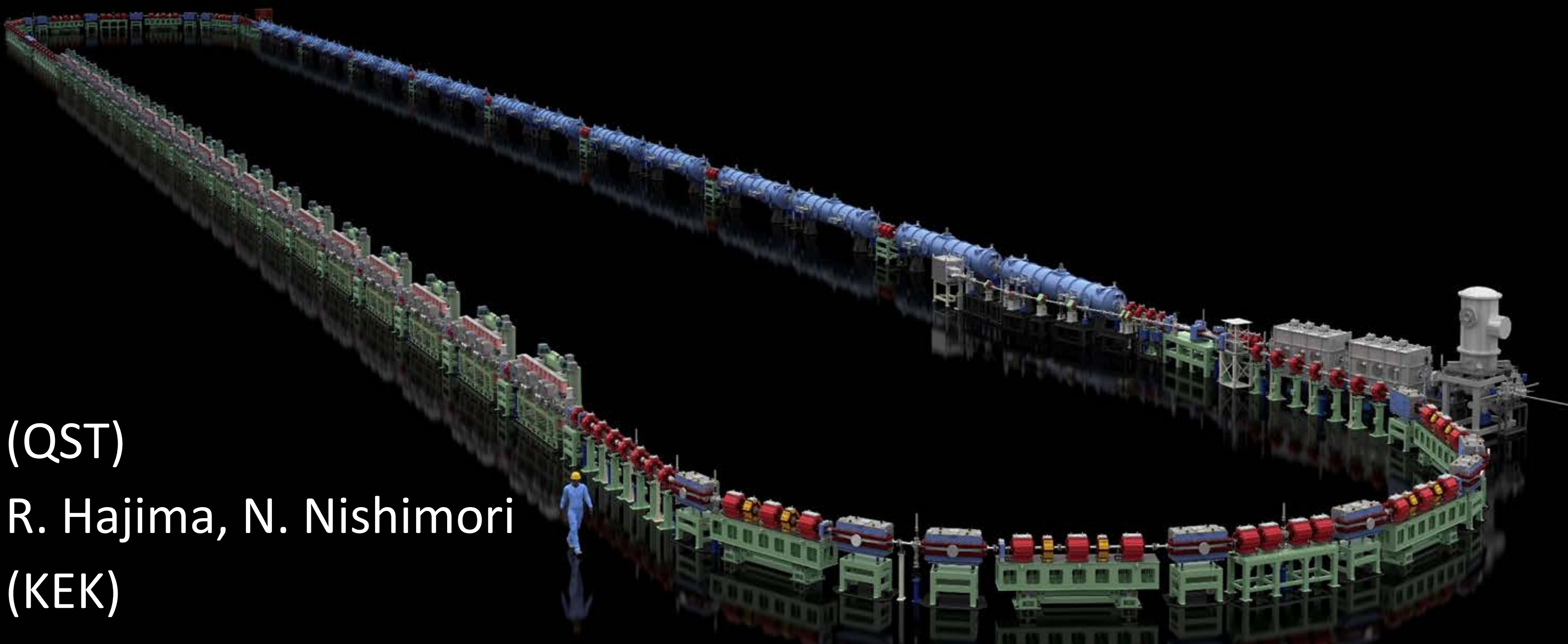
Summary

- Development of compact ERL
  - Energy of 20 MeV, 1 mA electron beam is successfully recovered
  - Small beam loss operation is achieved
- Performance of the designed EUV-FEL
  - 12.1 / 24.2 kW output obtained at 9.75 / 19.5 mA with tapering
  - Energy recovery after 12 kW lasing seems to be possible
- EUV-FEL Study Group for Industrialization is established
  - 10 companies, 1 consortia, 7 Universities, Research Laboratories

EUV-FEL Design Group



(QST)

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