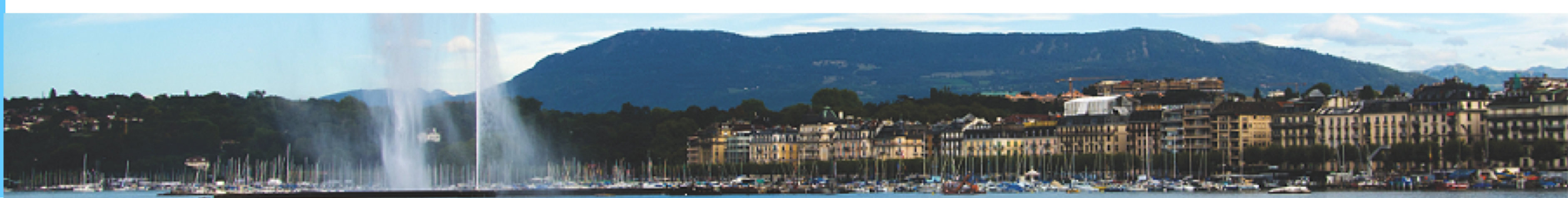
EUV ERLs for Semiconductor Integrated Circuits Lithography

Norio Nakamura

High Energy Accelerator Research Organization(KEK)

ERL17, 18-23 June 2017, CERN, Geneva, Switzerland



EUV-ERL Design Group

(KEK) T. Furuya, K. Haga, I. Hanyu, K. Harada, T. Honda, Y. Honda, E. Kako, Y. Kamiya, R. Kato, H. Kawata, Y. Kobayashi, T. Konomi, T. Kubo, S. Michizono, T. Miura, T. Miyajima, H. Nakai, N. Nakamura, T. Obina, K. Oide, H. Sakai, M. Shimada, R. Takai, Y. Tanimoto, K. Tsuchiya, K. Umemori, S. Yamaguchi, M. Yamamoto

(QST) R. Hajima

東北大学

(Tohoku Unv.) N. Nishimori

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

Outline

- Introduction
- Design of EUV ERL Source
- S2E Simulation
- Activities and Considerations for Industrialization
- Summary

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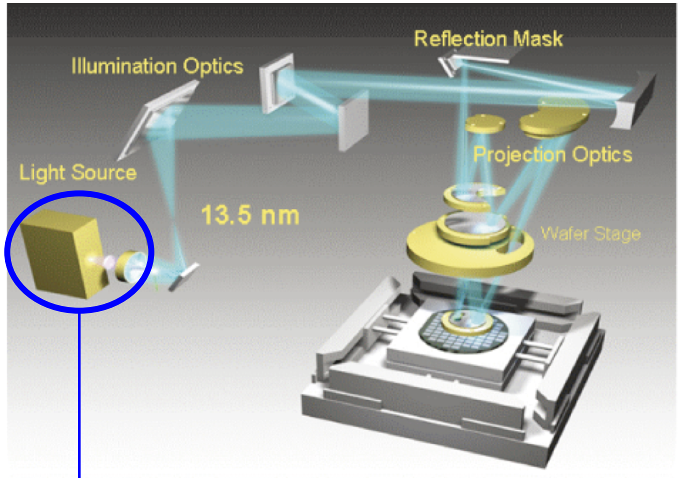
EUV Lithography

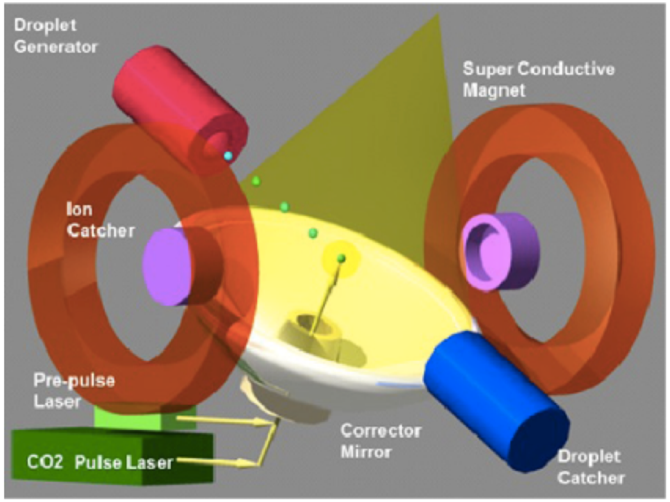
EUV Lithography :

- Next generation lithography using extreme ultraviolet light (13.5 nm)
- Allows exposure of fine circuit pattern with a half-pitch below 20 nm
- Laser-produced plasma(LPP) source is under development for ≥ 250 W



Schematic of EUV exposure tool

H. Mizoguchi et al., Komatsu Technical Report 59-166 (2013)



Concept of LPP EUV source

H. Mizoguchi et al., Proc. of SPIE 10143, 101431J (2017)

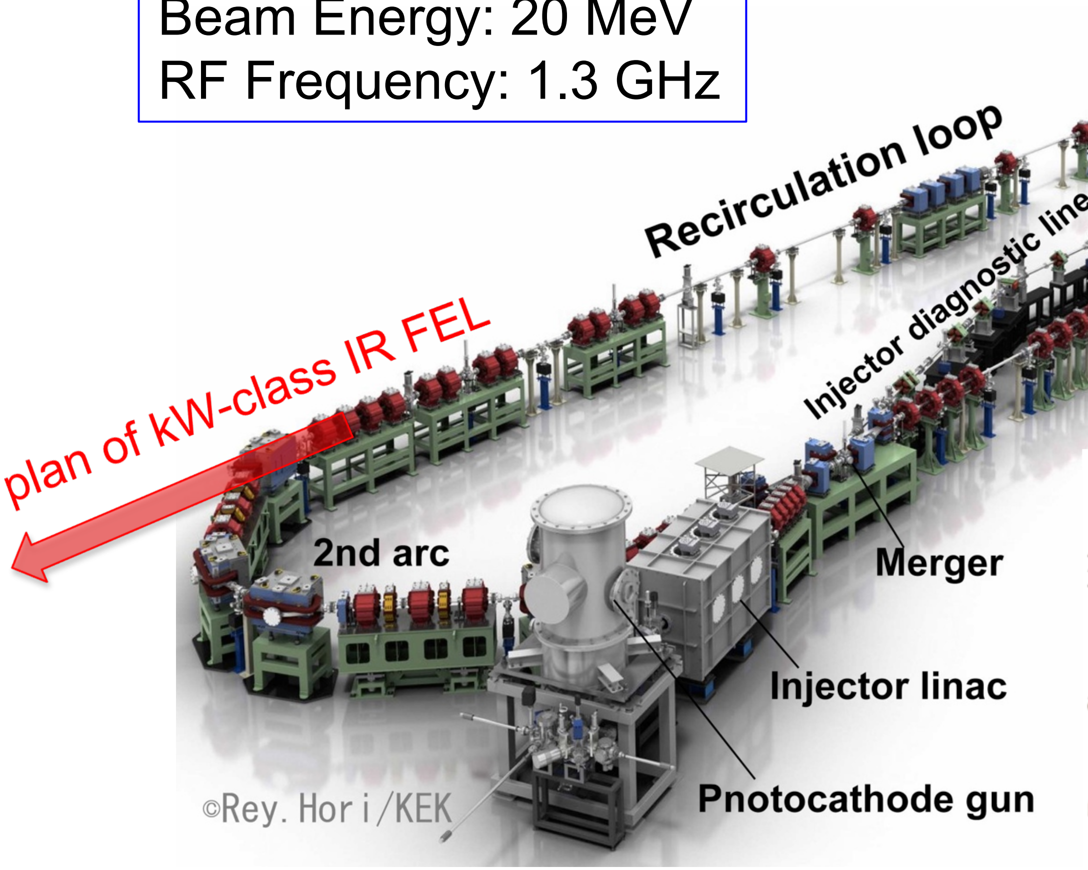
EUV ERLs (EUV FEL sources based on ERLs)

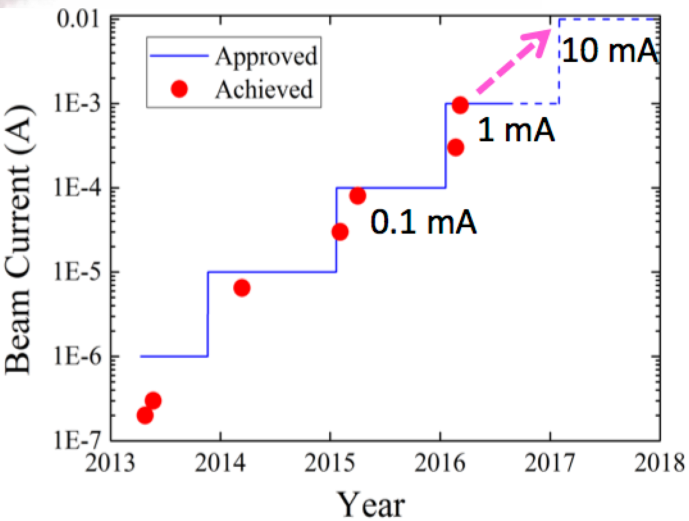
- Meet future demand for 1 kW EUV power or more
- Distribute 1-kW class power to multiple scanners → more economical
- Produce no debris contaminating the EUV optics
- Reduce dumped beam power and activation drastically

Compact ERL(cERL)

in operation at KEK since 2013

Beam Energy: 20 MeV
RF Frequency: 1.3 GHz





History of achieved beam current

cERL technologies and resources are available for EUV ERLs.

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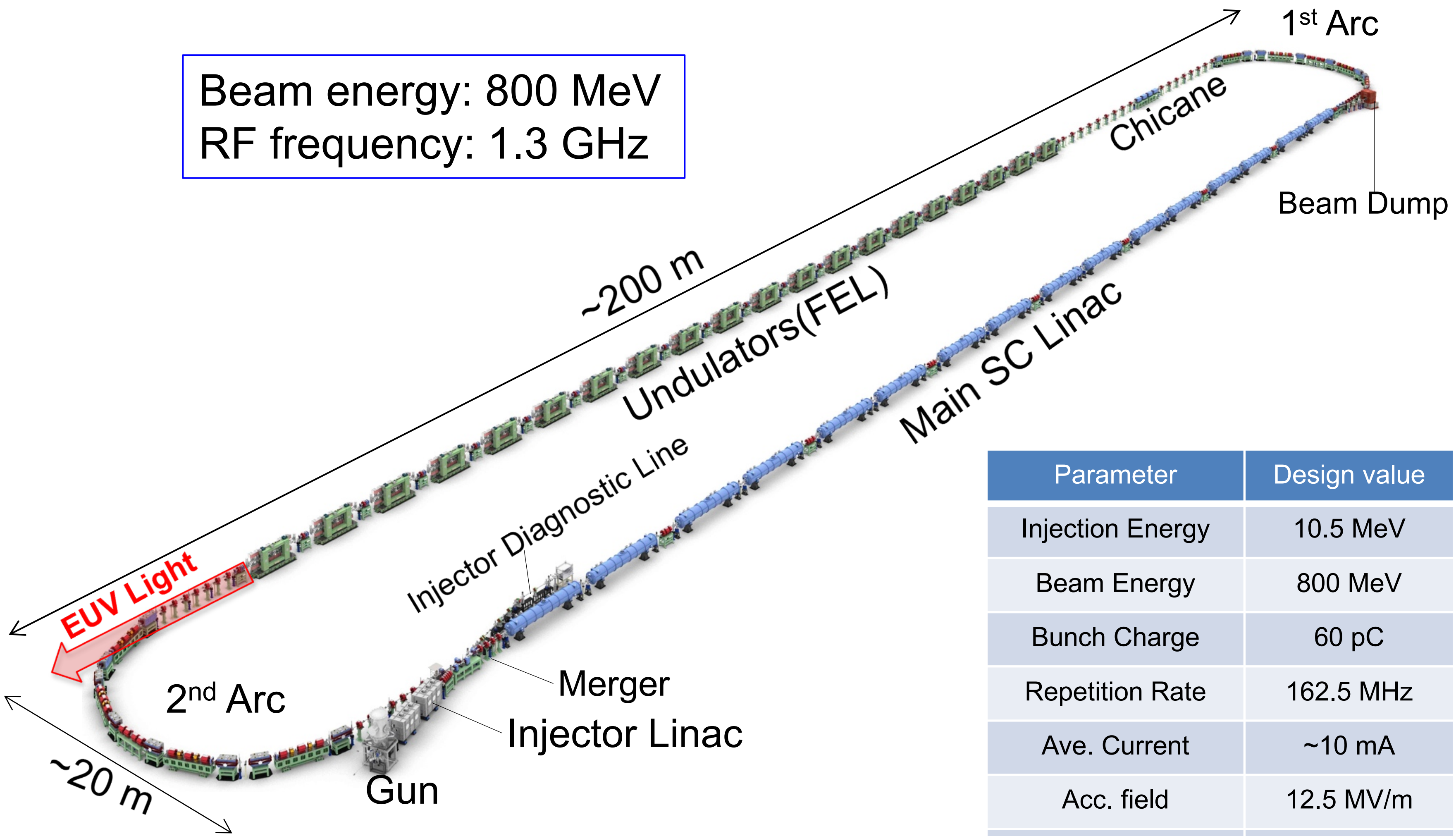
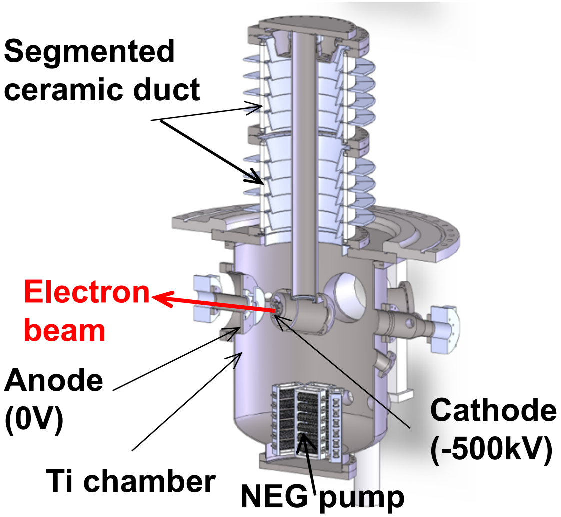
Image of EUV-ERL Source

Beam energy: 800 MeV
RF frequency: 1.3 GHz



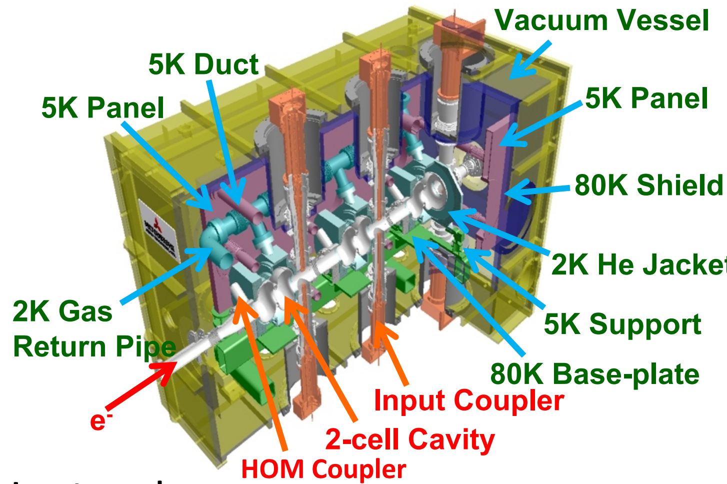
Parameter	Design value
Injection Energy	10.5 MeV
Beam Energy	800 MeV
Bunch Charge	60 pC
Repetition Rate	162.5 MHz
Ave. Current	~10 mA
Acc. field	12.5 MV/m
EUV Wavelength	13.5 nm
EUV power	> 10 kW

Injector & Merger

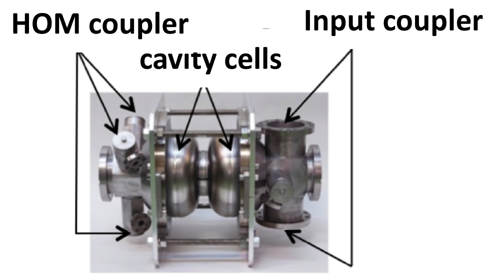


Photocathode DC gun

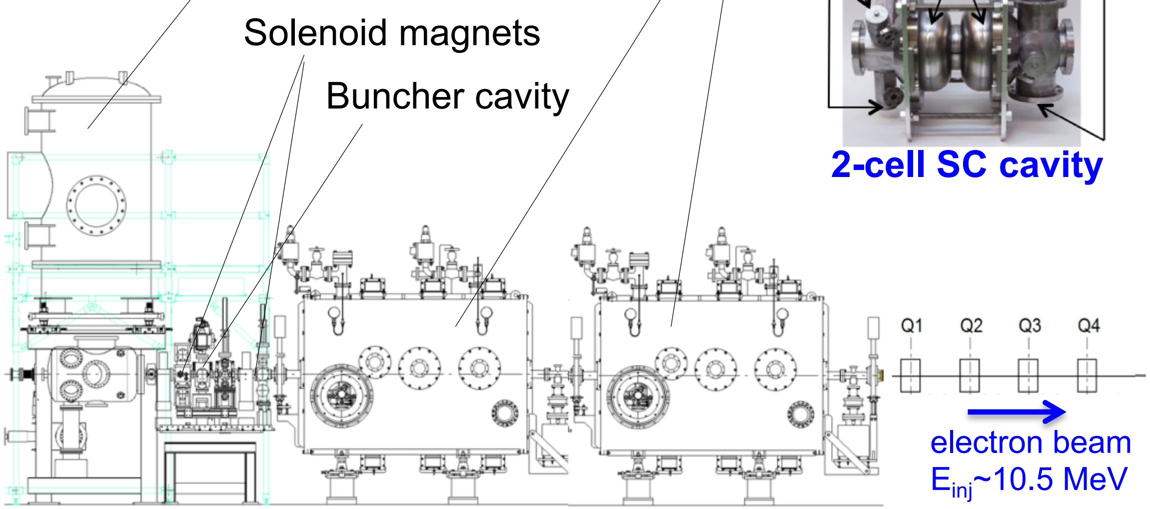
cERL Injector cryomodule



Cryomodule design

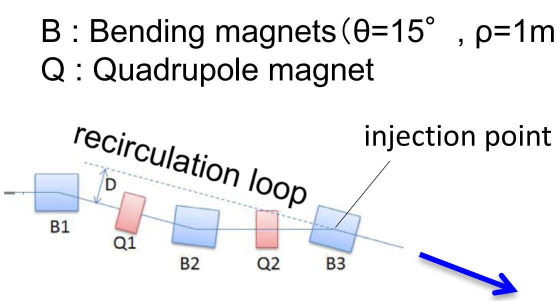


2-cell SC cavity



Injector section (side view)

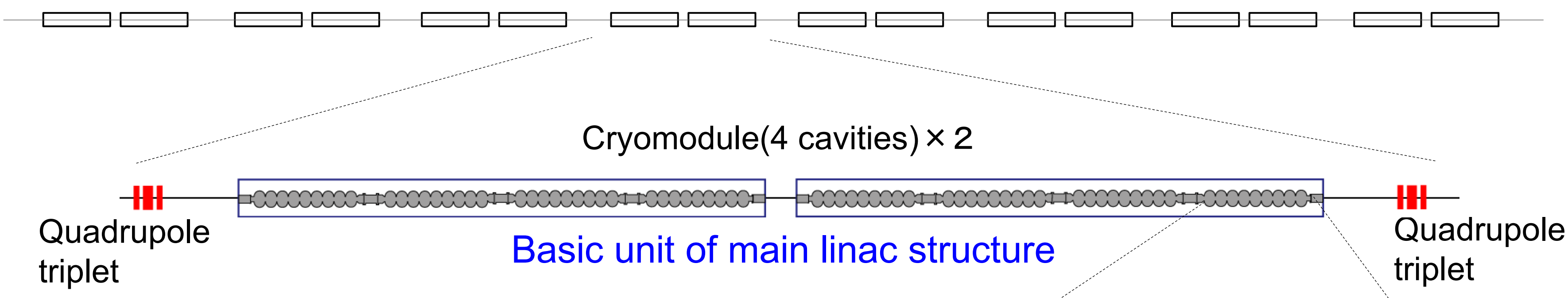
matching section



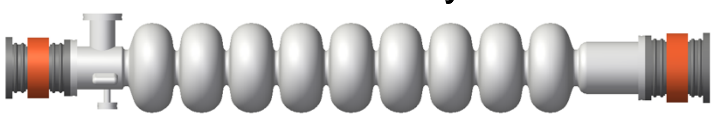
Merger section (top view)

Main Linac

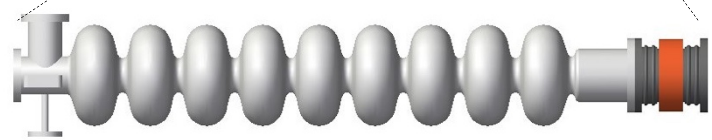
Main linac (9-cell cavities × 64 in 16 cryomodules)



cERL cavity



EUV ERL cavity



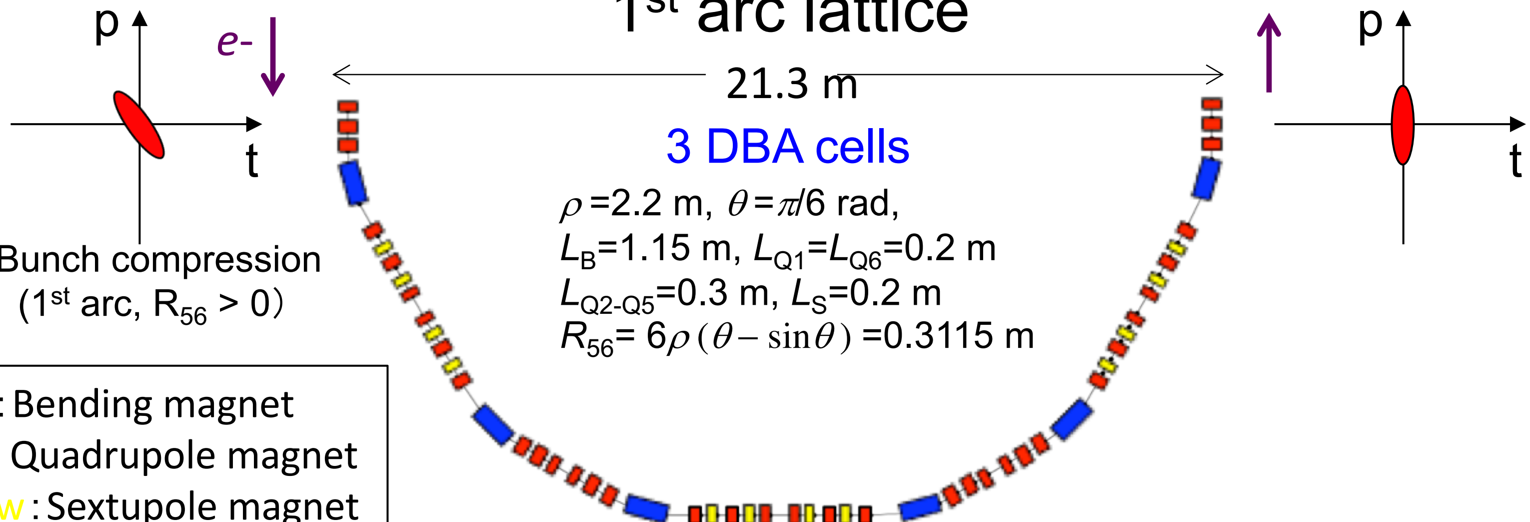
Under design. A large-aperture pipe will be also applied to the left side.

	cERL	EUV ERL		cERL	EUV ERL
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-ERL)

Arc Sections

1st arc lattice



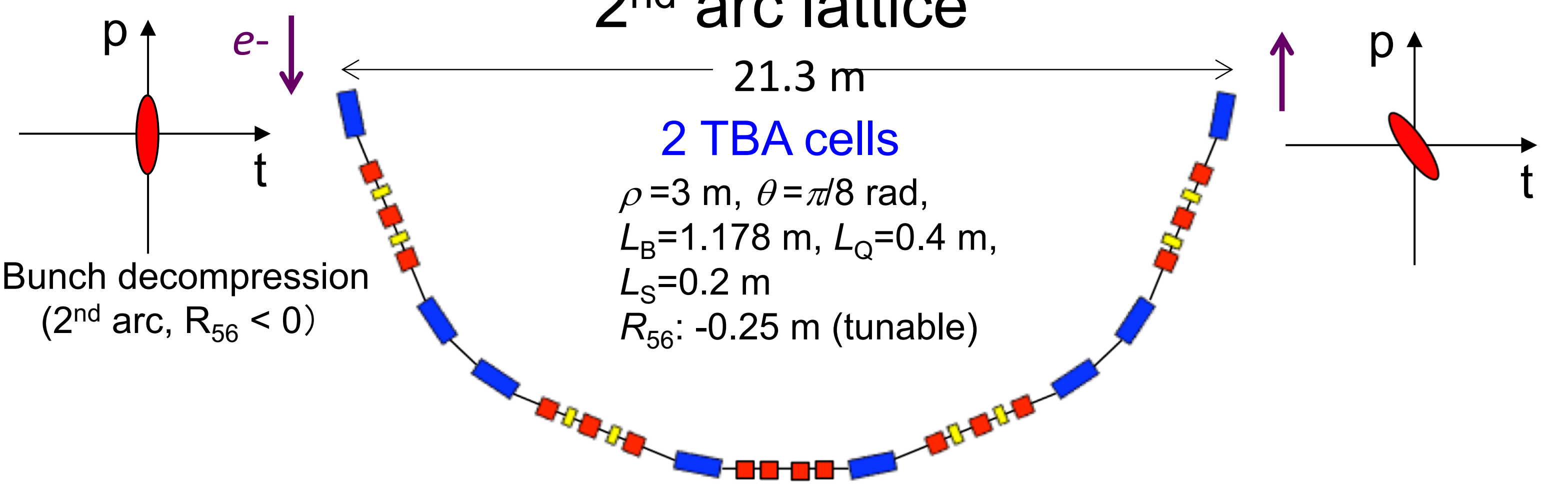
3 DBA cells

ρ =2.2 m, $\theta=\pi/6$ rad,
L_B=1.15 m, $L_{Q1}=L_{Q6}$=0.2 m
$L_{Q2\text{-}Q5}$=0.3 m, L_S=0.2 m
R_{56}= $6\rho(\theta-\sin\theta)$ =0.3115 m

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

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

2nd arc lattice



2 TBA cells

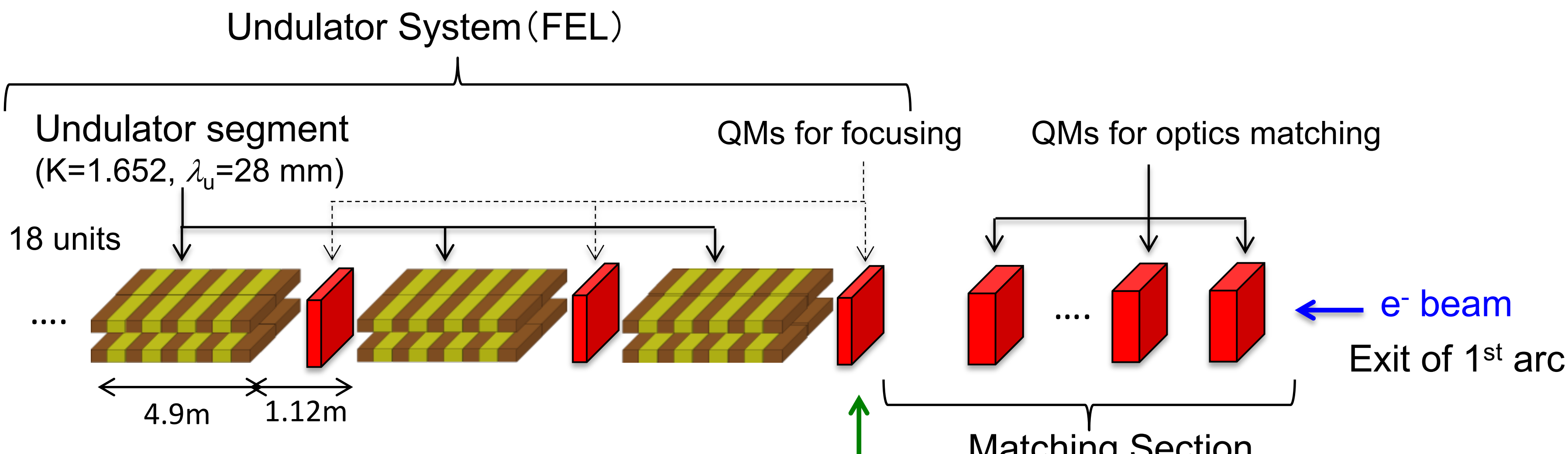
ρ =3 m, $\theta=\pi/8$ rad,
L_B=1.178 m, L_Q=0.4 m,
L_S=0.2 m
R_{56}: -0.25 m (tunable)

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

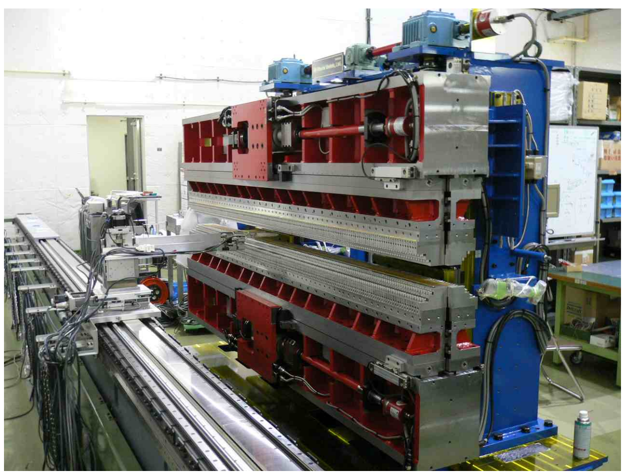
Optics are optimized for bunch compression and decompression.

Undulator System for FEL

Undulator System（including matching section）



Adjustment of Twiss parameters $\beta_{x,y}$,$\alpha_{x,y}$@ 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

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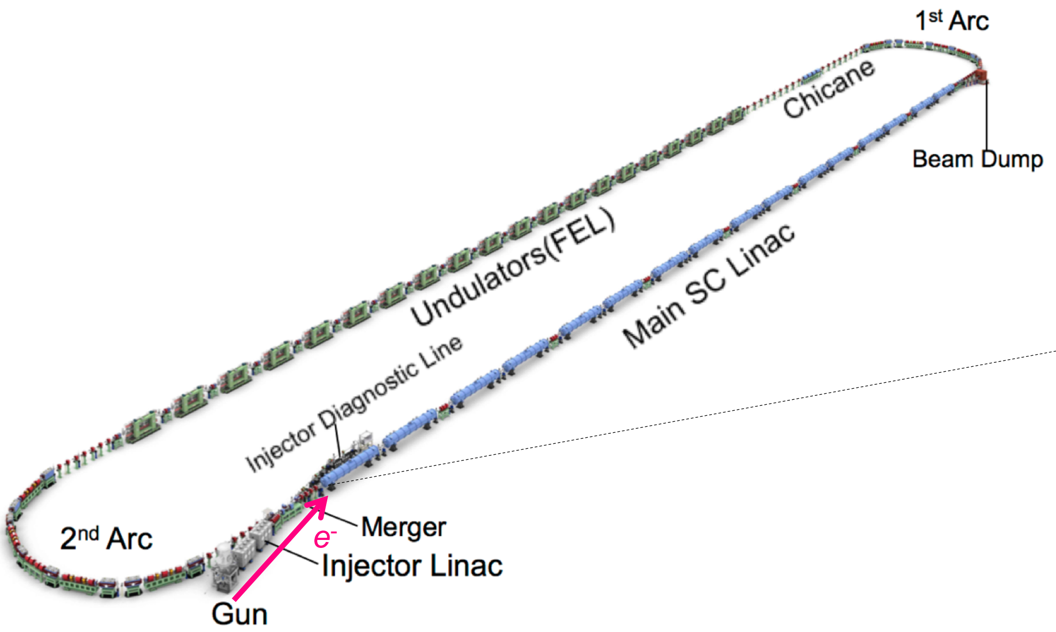
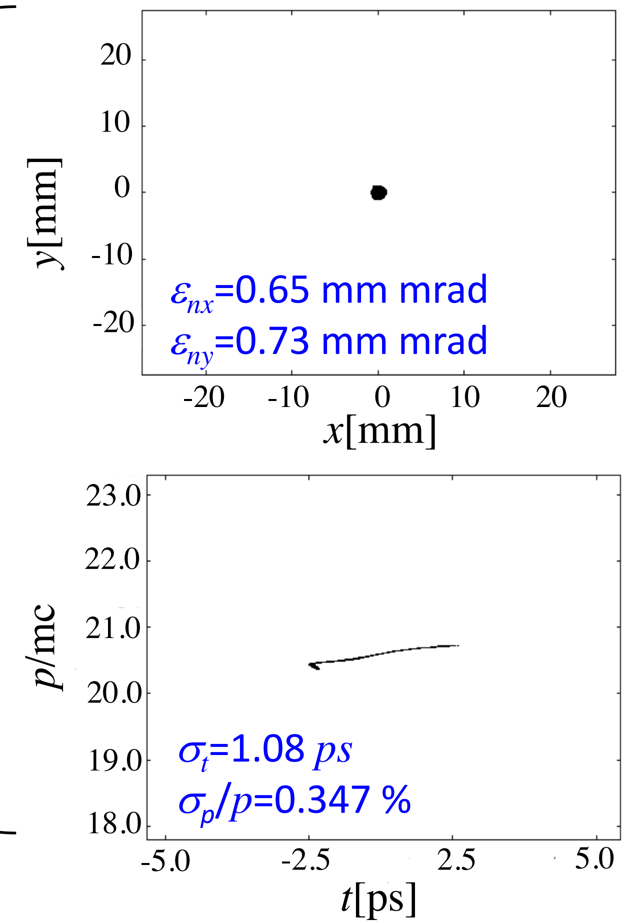
Injector & Merger

Injection beam optimization by GPT and genetic algorithm

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

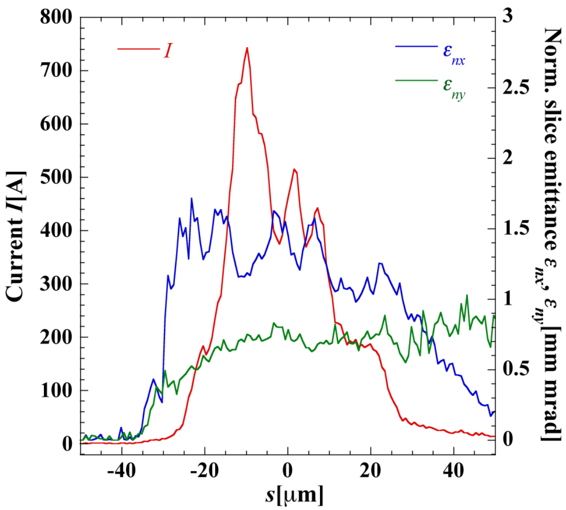


entrance of main linac

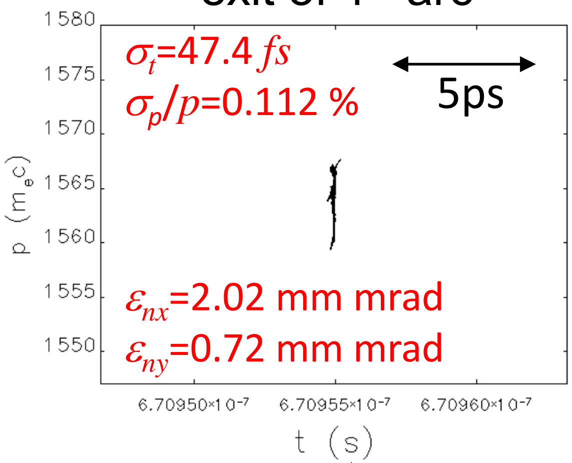


Bunch Compression

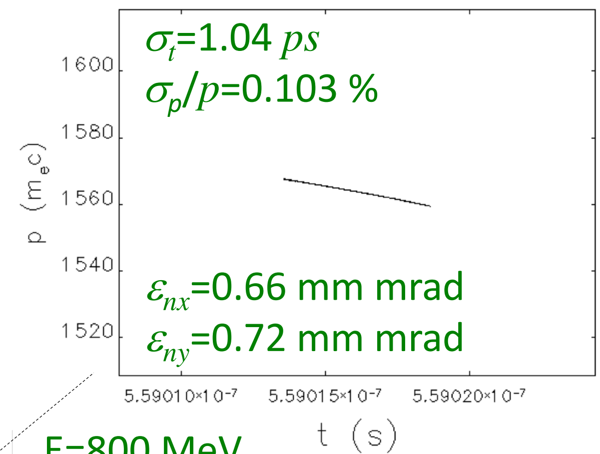
Current&slice emittance



exit of 1st arc

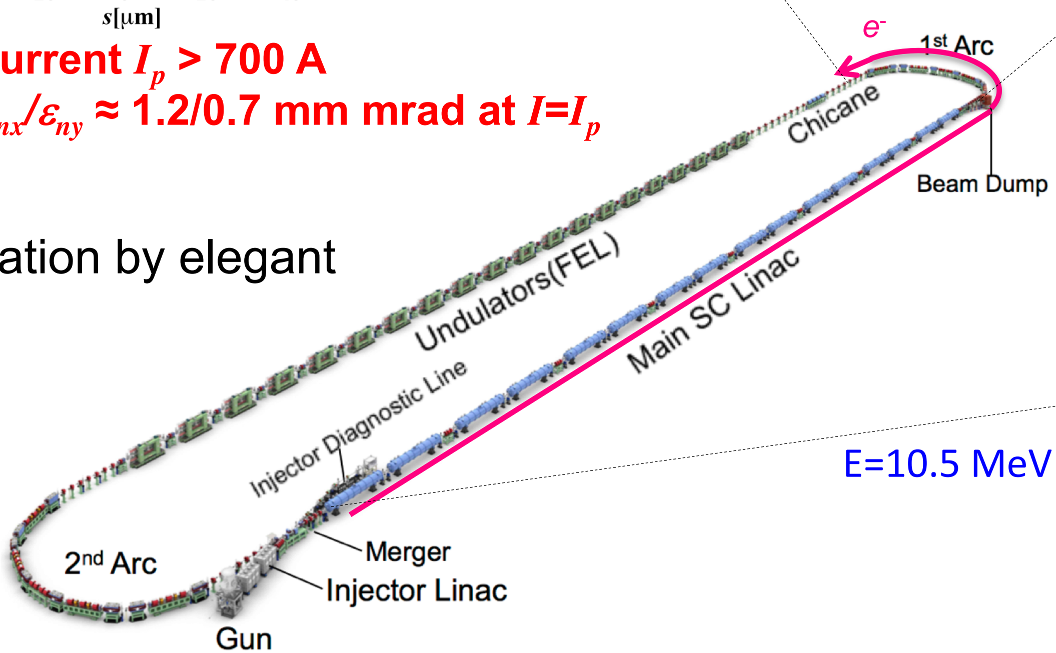


entrance of 1st arc

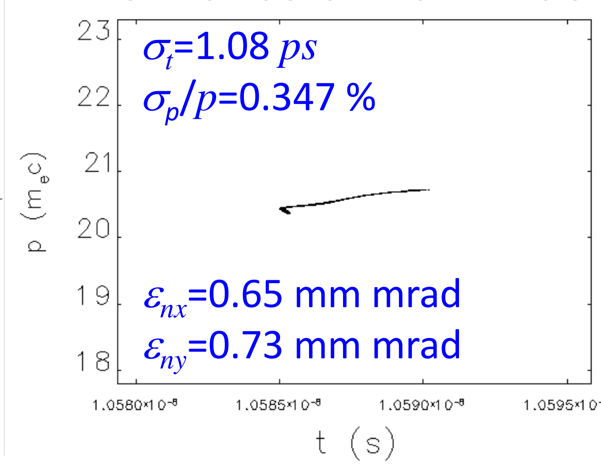


Peak current I_p > 700 A
Slice $\varepsilon_{nx}/\varepsilon_{ny}$ ≈ 1.2/0.7 mm mrad at $I=I_p$

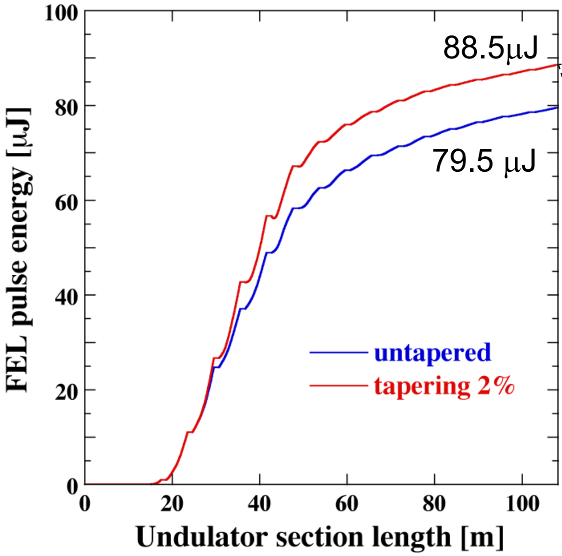
simulation by elegant

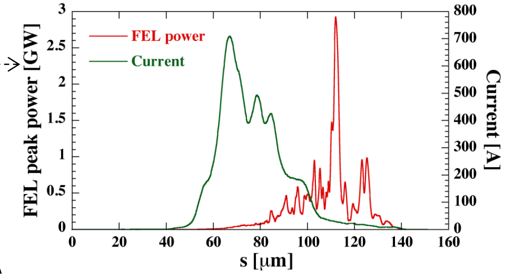


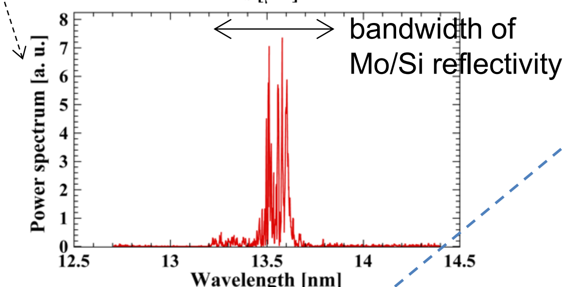
entrance of main linac

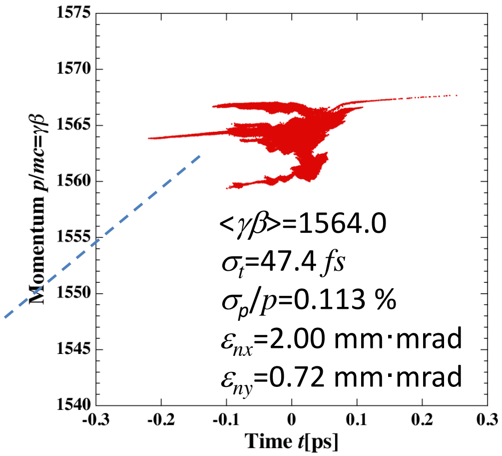


FEL









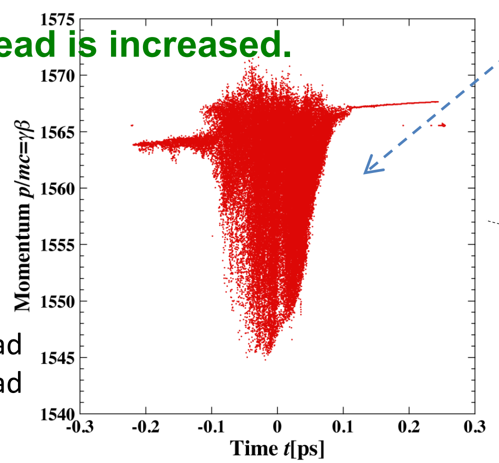
FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

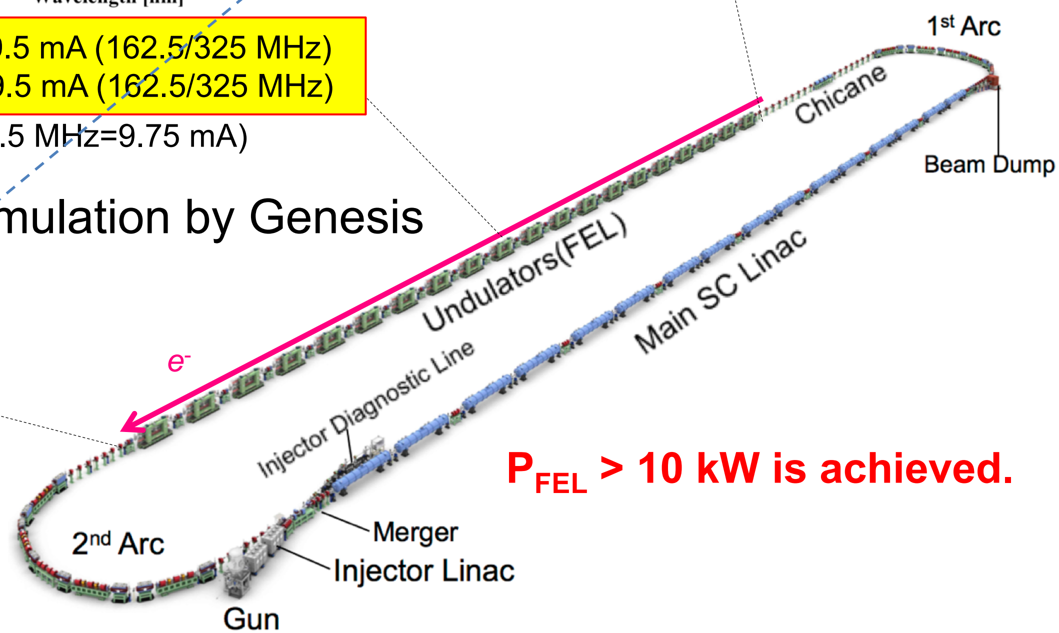
(P_{FEL}=88.5 μJ x 162.5 MHz =14.4 kW, I_{av}=60pC x 162.5 MHz=9.75 mA)

Energy spread is increased.

simulation by Genesis

$<\gamma\beta>$=1561.1
σ_t=48.5 fs
σ_p/p=0.299 %
ε_{nx}=1.98 mm·mrad
ε_{ny}=0.71 mm·mrad

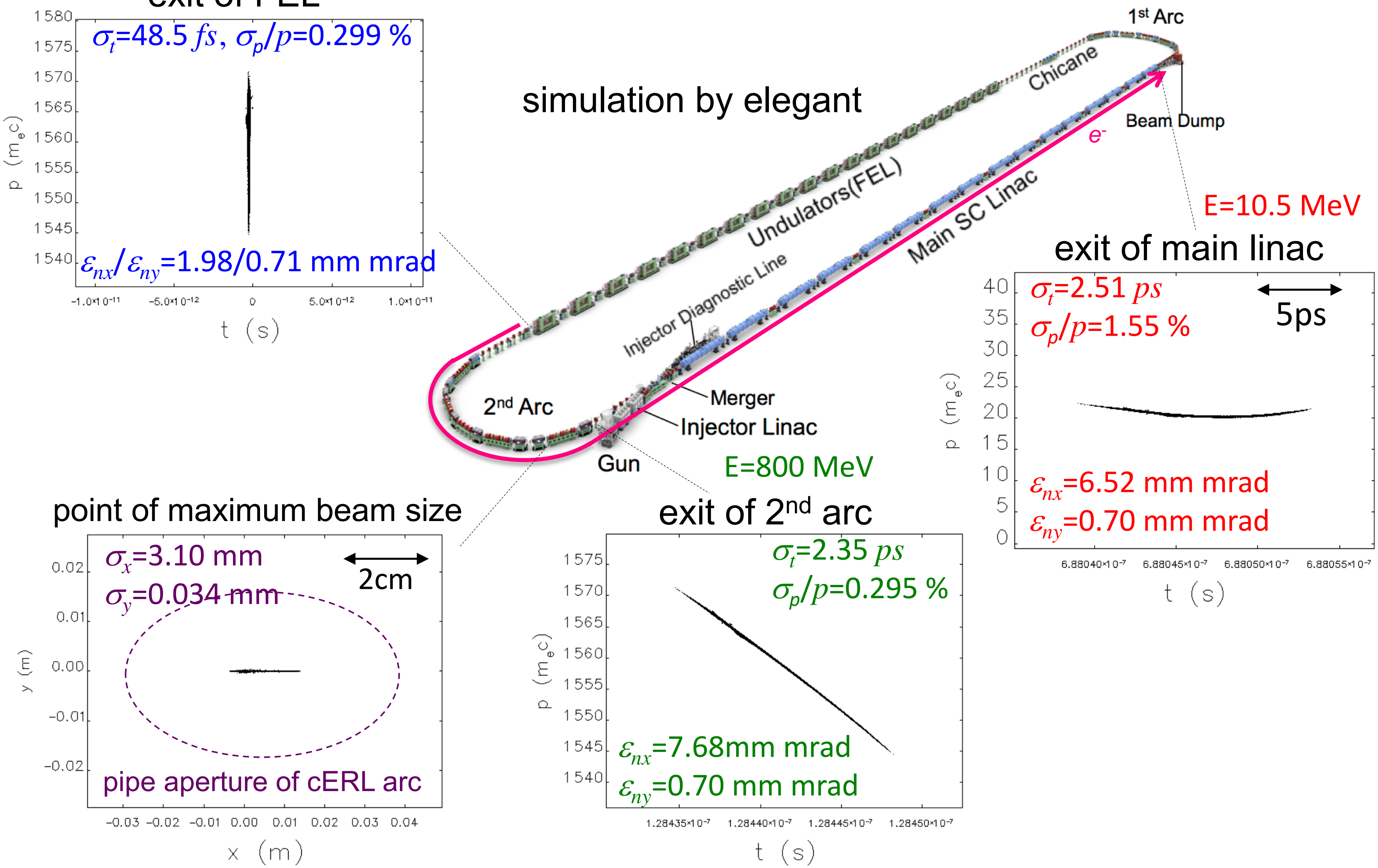




P_{FEL} > 10 kW is achieved.

Bunch Decompression

Electron beam is transported without beam loss.



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EUV-FEL Light Source Study Group for Industrialization

since 2015

THE UNIVERSITY OF TOKYO
S. Ishihara (Leader)

THE UNIVERSITY OF TOKYO
ISSP
I. Matsuda

宇都宮大学
UTSUNOMIYA UNIVERSITY
Utsunomiya Univ.
T. Higashiguchi

NewSUBARU
Univ. of Hyogo
H. Kinoshita

RISE
Waseda Univ.
M. Washio

ISIR
Osaka Univ.
T. Kozawa

Industries

TOSHIBA
Leading Innovation

MITSUBISHI HEAVY INDUSTRIES MECHATRONICS SYSTEMS, LTD.

Hitachi Metals, Ltd.
Materials Magic

GIGAPHOTON

EIDEC

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

TAIYO NIPPON SANSO
The Gas Professionals

HITACHI

TOYAMA

TOSHIBA
Leading Innovation
TOSHIBA ELECTRON TUBES & DEVICES CO.,LTD.

MITSUBISHI ELECTRIC
Changes for the Better

NTT AT

QST
R. Hajima

KEK
H. Kawata et al.

National Institute of Advanced Industrial Science and Technology
AIST
N. Sei

EUV-FEL Workshop

Date: 13 Dec 2016 10:00-17:00
Site: Akihabara UDX 4F NEXT-1
Participants : > 100
(Source group, tool and material venders, end users etc.)
URL: http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop/

Availability Issues

Required availability for industrialization: ≥ 98 %

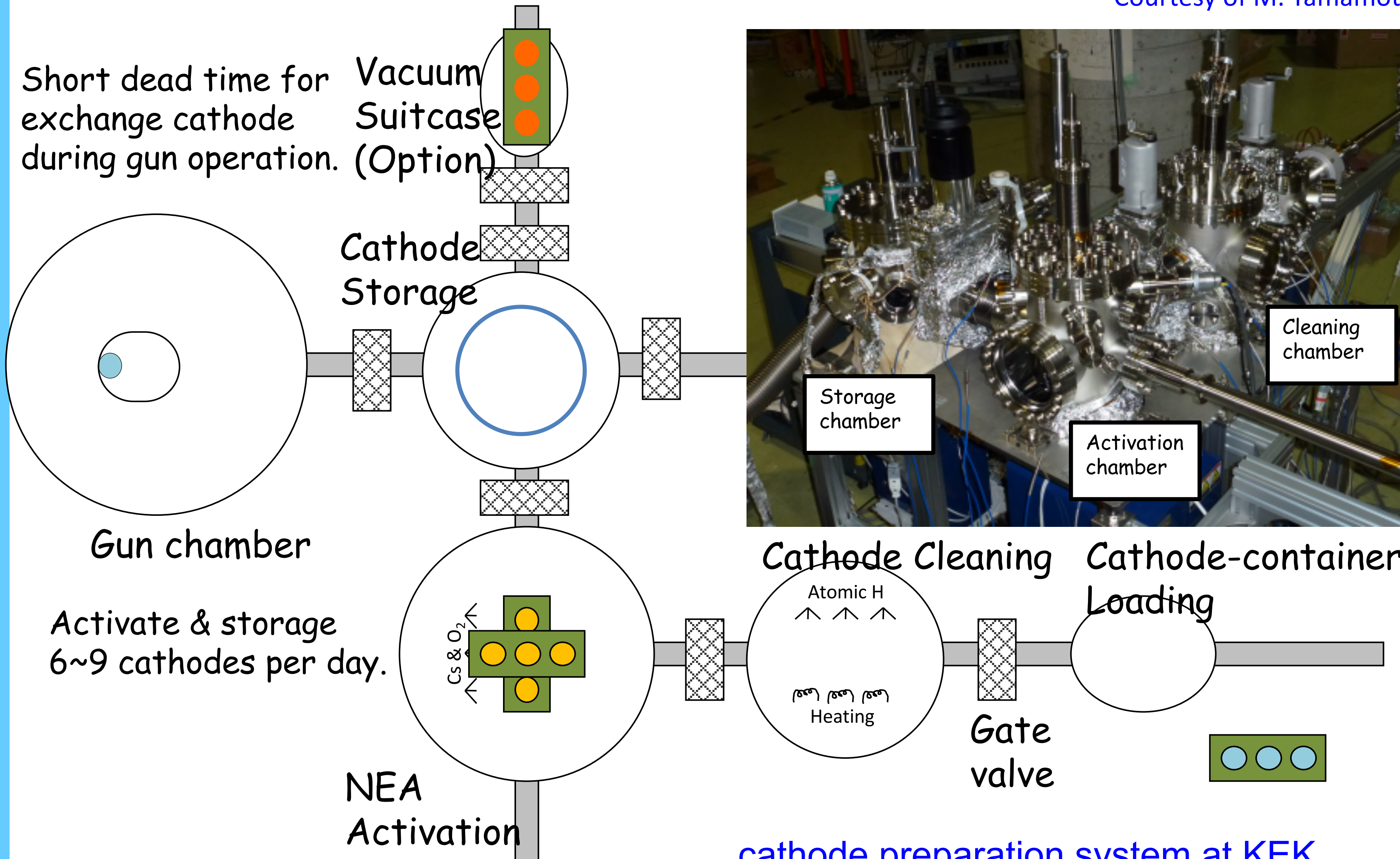
(non-operation time ≤ ~ 1 week per year)

⬇

- Electron gun
  - Short photocathode lifetime (one week for ~10 mA)
  - Remote control of photocathode exchange
- SC Cavity
  - Reduction of trip rate
  - Pulse processing time for suppression of field emission increase
- Undulator
  - Demagnetization of permanent magnets
- Cryoplant
  - High pressure gas safety law
  - Safety inspection (once per year in Japan)

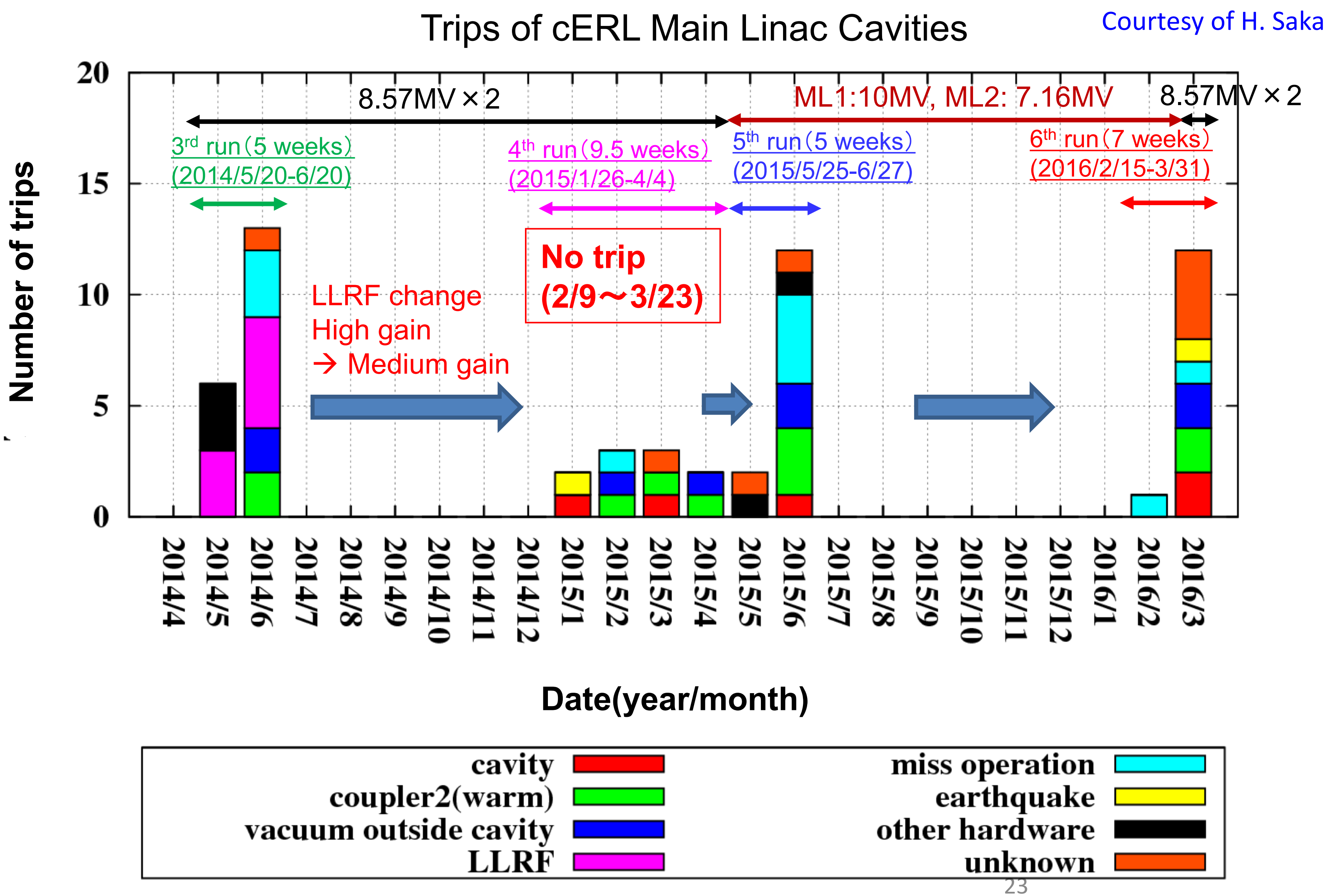
Cathode Preparation System

Courtesy of M. Yamamoto



cathode preparation system at KEK

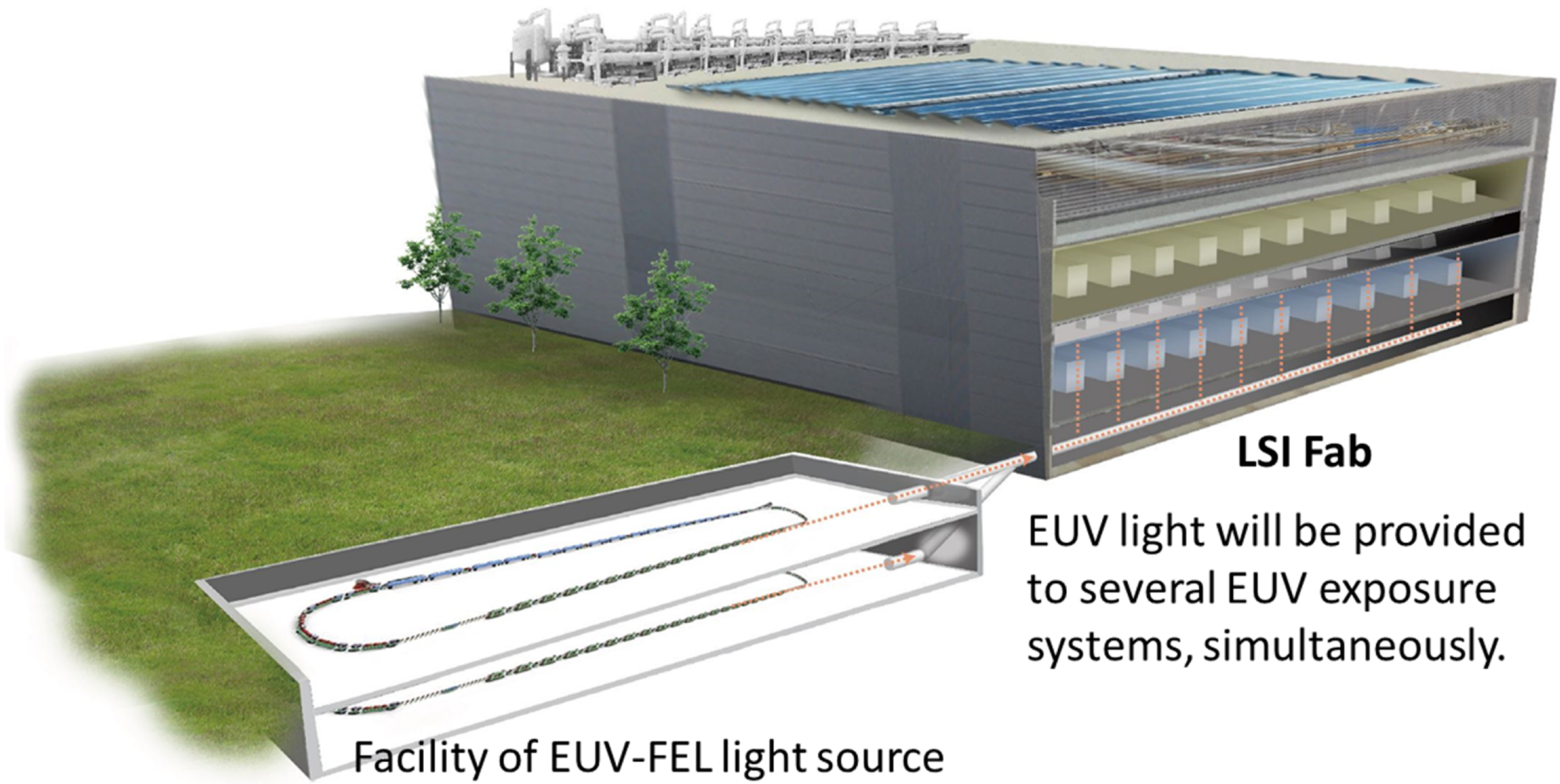
Trip of SC Cavities



Redundant System

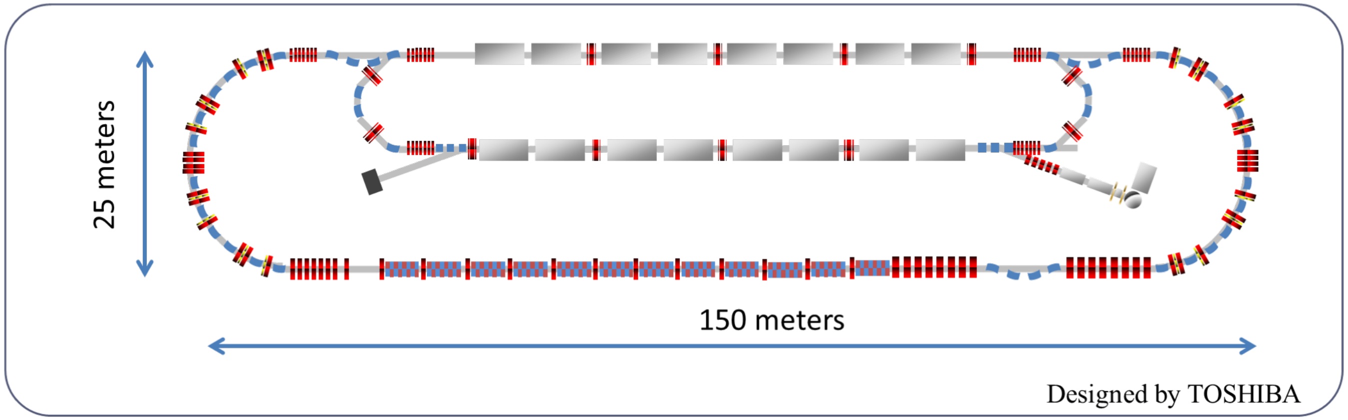
Redundant System for ensuring high availability

- Critical parts (Cryoplant, Injector, Main Linac, Undulator, …)
- Entire light source system



Reduction of Source Size

- Higher field gradient of Main SC cavities
  - Increase of power consumption $\propto E_{acc}^2/Q$
  - High-Q SC cavity (Nitrogen doping etc.)
- Lower Beam Energy
  - Shorter-period undulator with strong magnetic field
  - Increase of current or energy conversion efficiency for the same FEL power
- 2-loop/2-turn ERL
  - Optics design for CSR effect suppression
  - Increase of current for the same FEL power



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Summary

- EUV ERLs are expected to be high-power EUV sources for lithography that meet future demand.
- An EUV ERL source has been designed with available technologies and resources and its performance has been checked by S2E simulation.
  - Generation of FEL power more than 10 kW at 10 mA in the designed EUV-ERL source
  - Successful transportation of electron beams throughout the EUV-ERL source without any beam loss
- We established the source group for industrialization and organized the EUV-FEL workshop. R&D efforts are required for industrialization to achieve high availability, size reduction and so on.

Thank you for your attention!

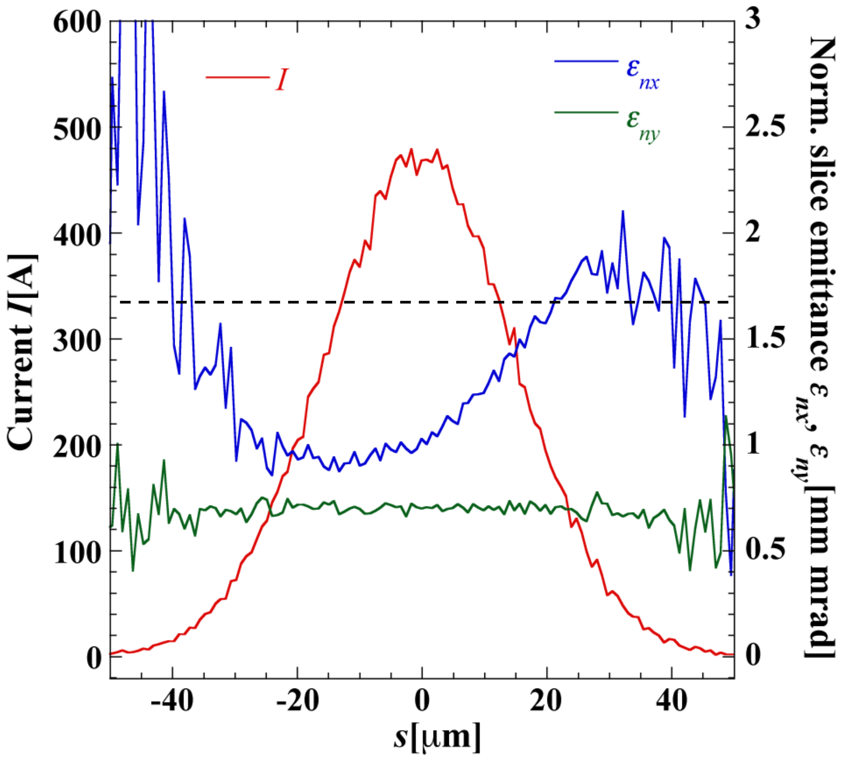
Backup Slides

Suppression of CSR effects

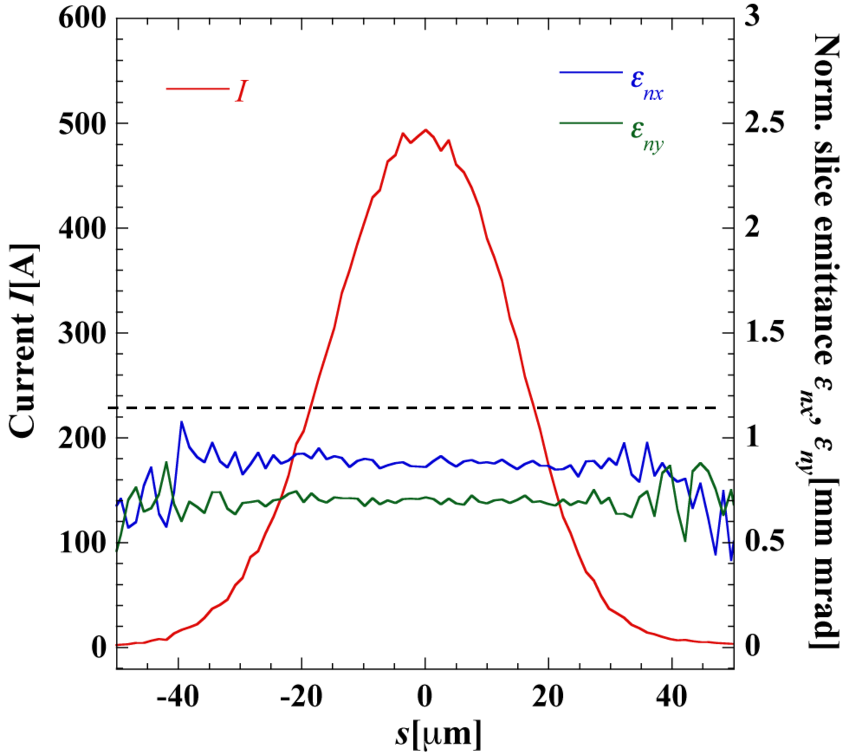
Electron distribution after bunch compression

Initial parameters: Q_b=60 pC, $\varepsilon_{nx}=\varepsilon_{ny}$= 0.7 mm mrad, σ_p/p=0.31 %, $\sigma_{t,inj}$=1 ps (Gaussian beam)

TBA arc + chicane (R_{56}=-0.15/-0.15 m)



DBA arc (R_{56}=0.31 m, β_{x2}=0.5 m, α_{x2}=1.9)

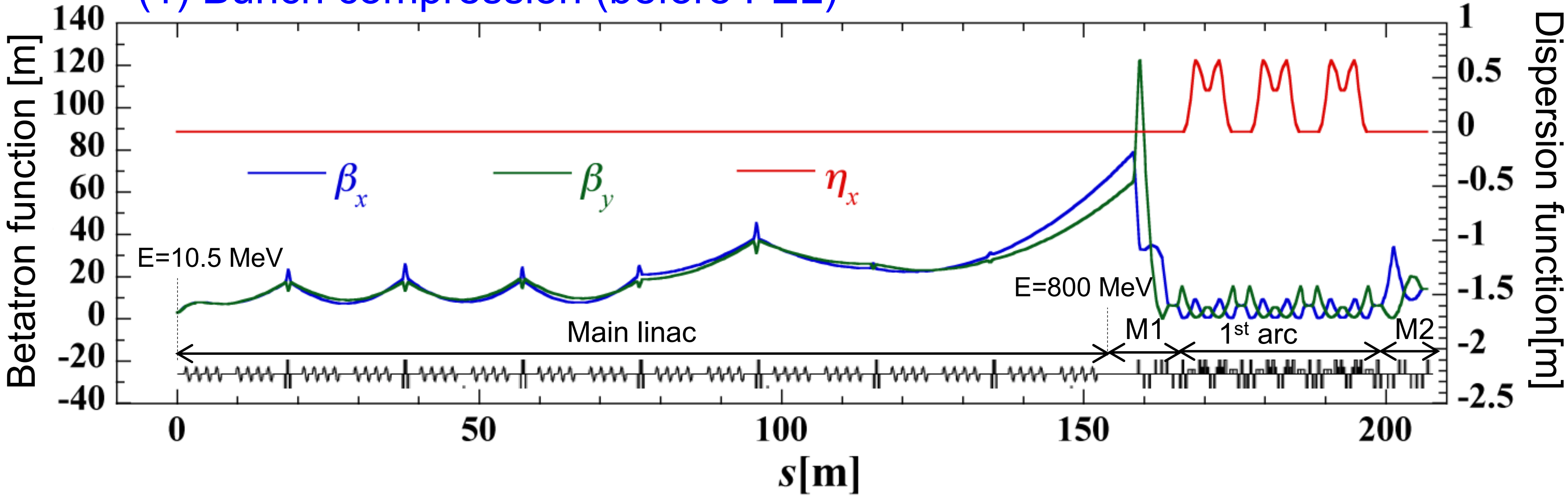


------- Projected normalized horizontal emittance

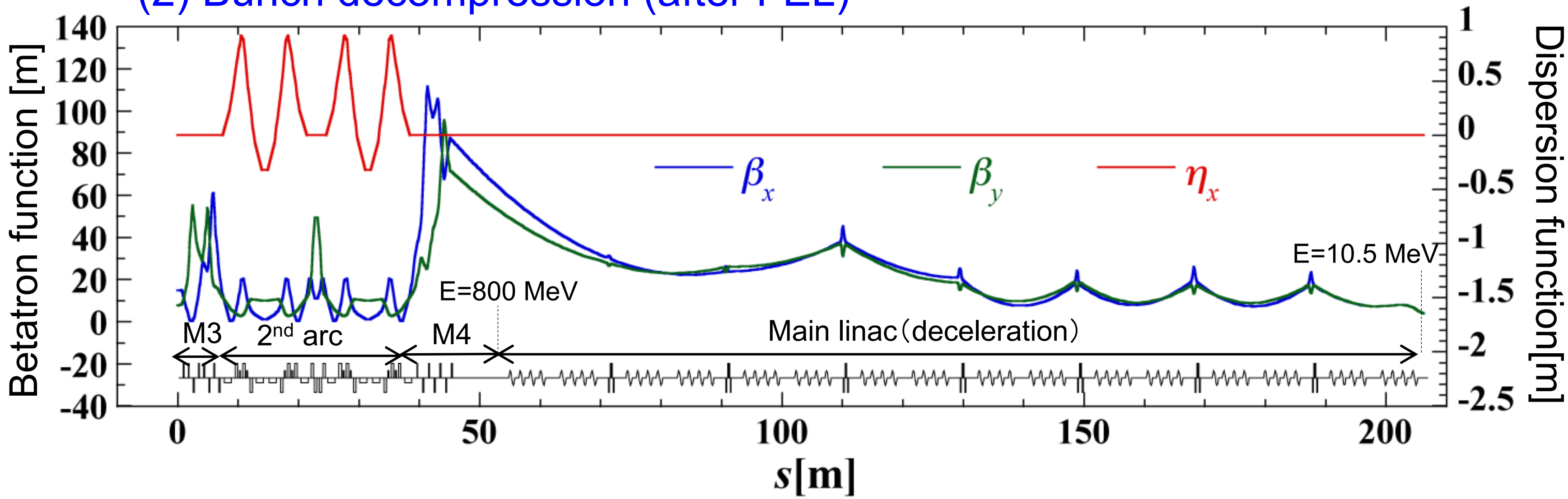
DBA lattice can well suppress CSR effects on ERL beam.

Optics of Recirculation Loop

(1) Bunch compression (before FEL)



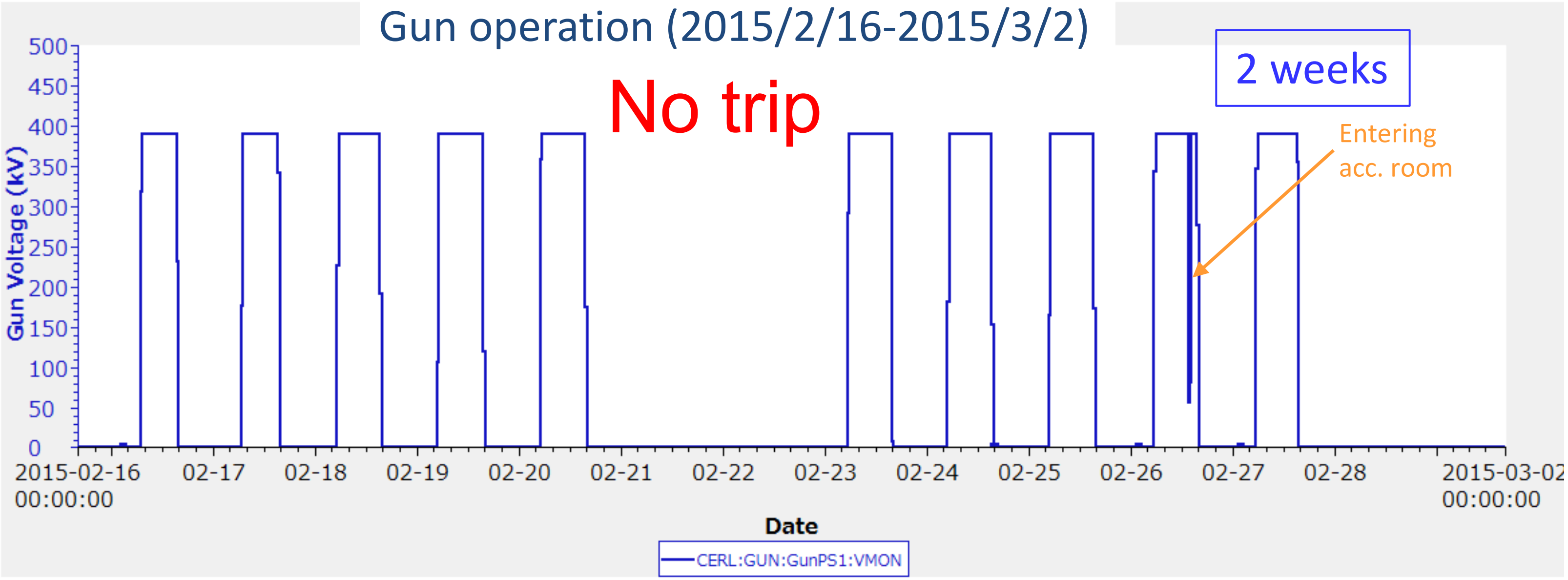
(2) Bunch decompression (after FEL)



Operation of Gun & ML Cavities

Gun

Gun voltage
(kV)



Main cavities
(ML-1, ML-2)

RF voltage
(MV)