EUV-FEL Light Source for Lithography

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Outline

- Introduction
- Design and Performance
- Considerations and Developments for Industrialization
    - Availability
    - Size Reduction
- Summary

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Status & Prospect of EUV Lithography

Present Status

- EUV Lithography system based on 200-W-class LPP source is progressing and at starting point of HVM.

Future Requirement

- 1-kW-class EUV light sources will be required to realize the production for less than 3-nm node.

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It is important to develop a new-type light source such as an ERL(energy recovery linac)-based EUV FEL, which has a potential of providing 1-kW-class EUV power, even to multiple scanners simultaneously.

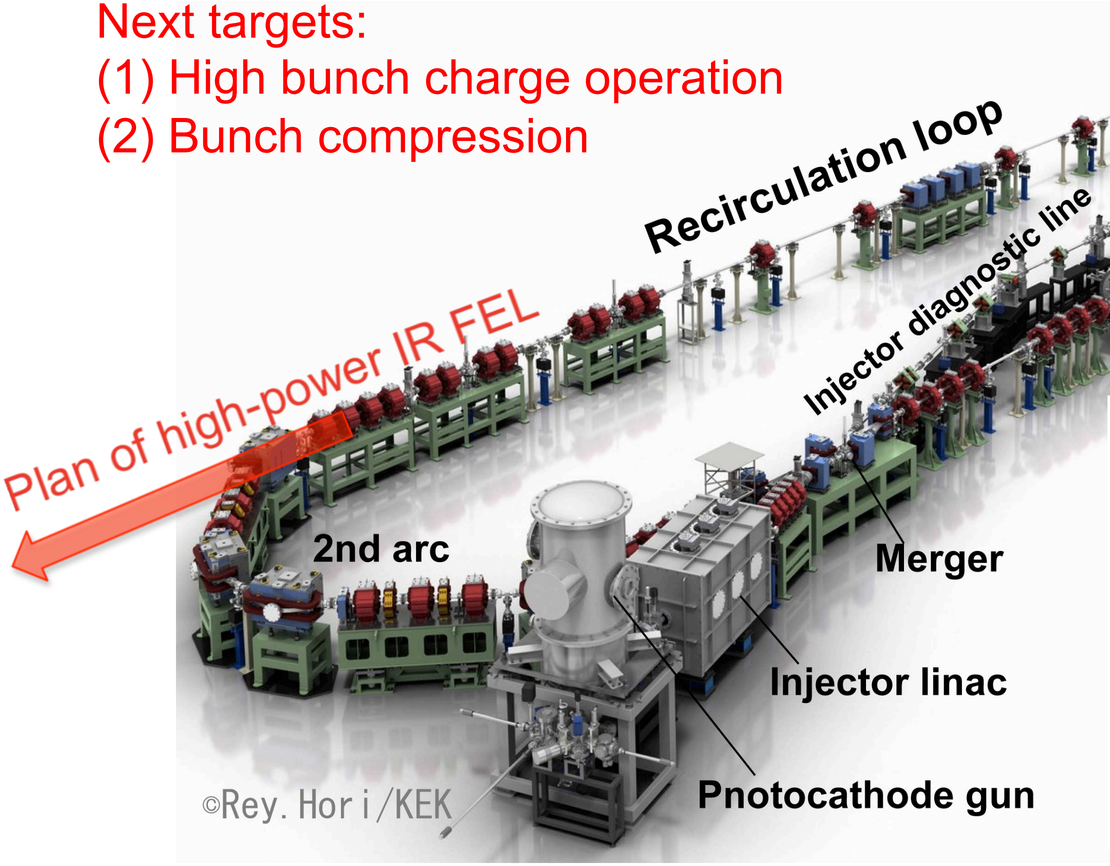
Compact ERL(cERL)

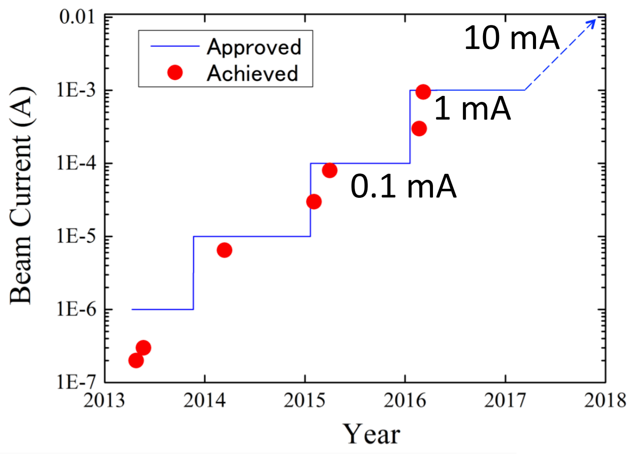
Test machine for developing ERL technologies

in operation at KEK since 2013

Beam Energy: 20 MeV
RF Frequency: 1.3 GHz
Acceleration field(ML) : 8.3 MV/m

Next targets:
(1) High bunch charge operation
(2) Bunch compression





History of achieved beam current

cERL technologies and resources are available for EUV-FEL light sources.

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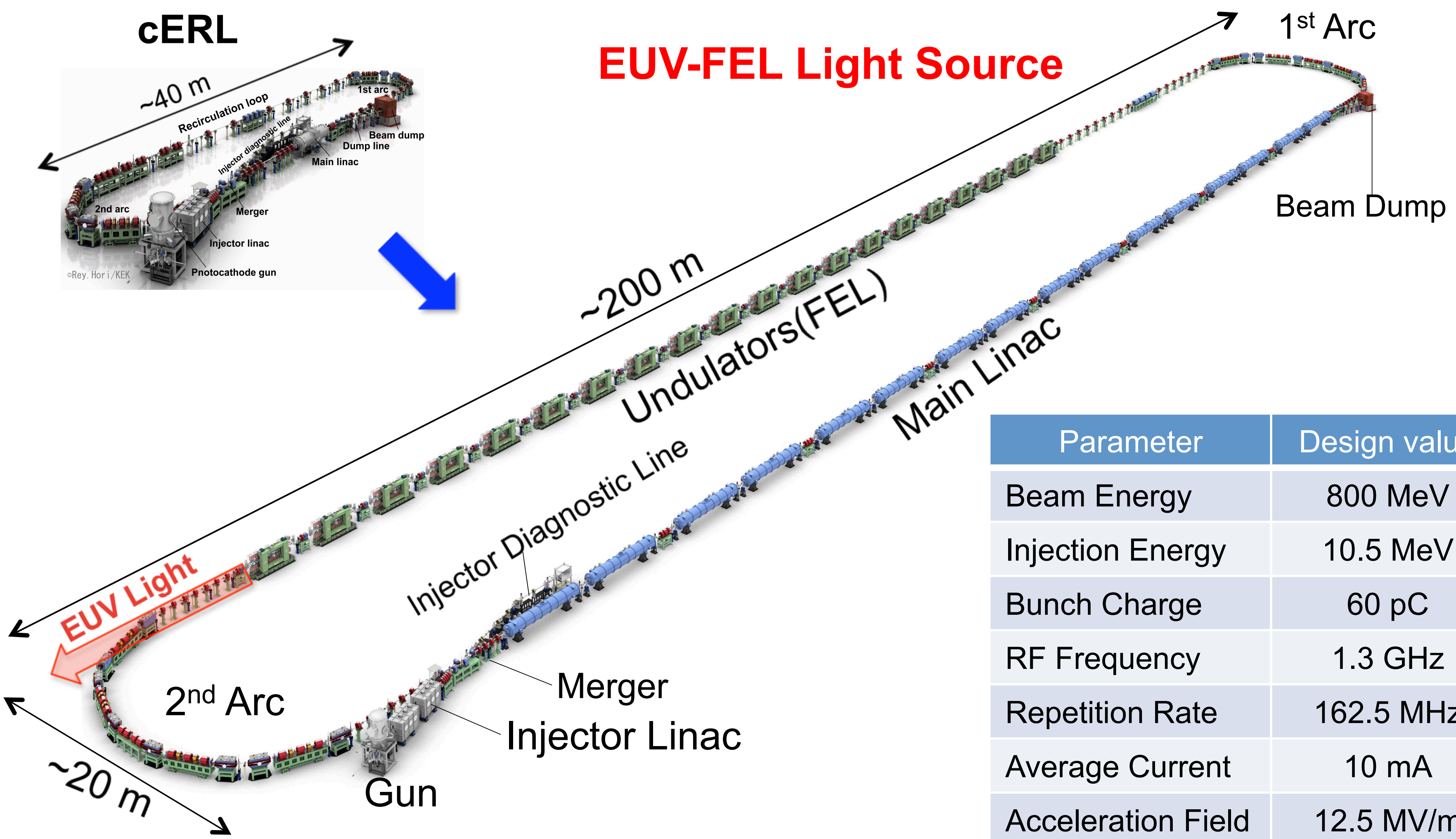
Design of EUV-FEL Light Source



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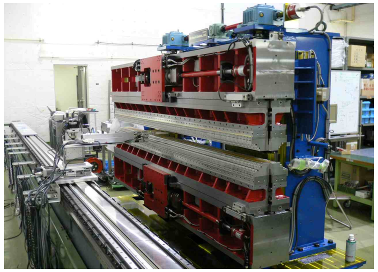
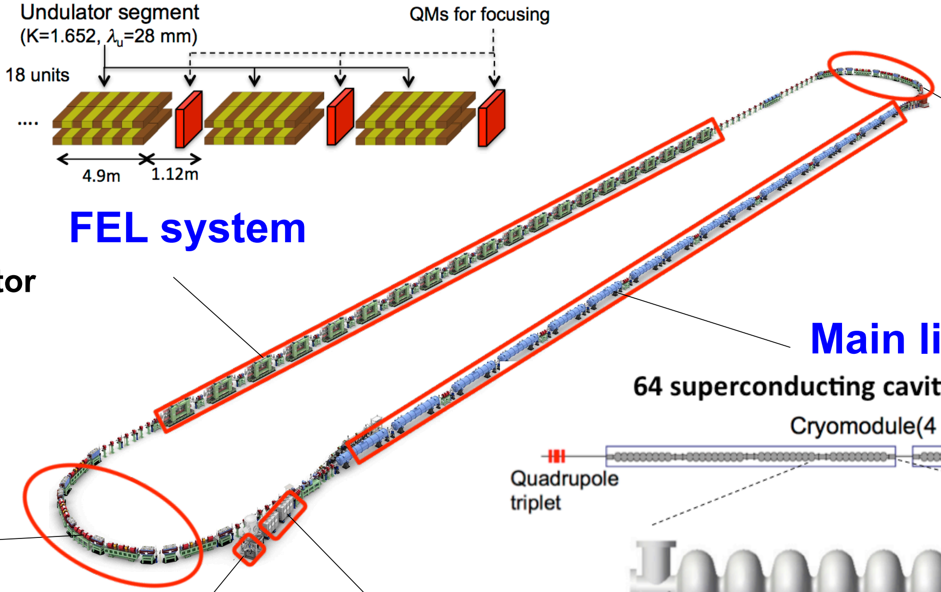
Parameter	Design value
Beam Energy	800 MeV
Injection Energy	10.5 MeV
Bunch Charge	60 pC
RF Frequency	1.3 GHz
Repetition Rate	162.5 MHz
Average Current	10 mA
Acceleration Field	12.5 MV/m
EUV Wavelength	13.5 nm
EUV Power	> 10 kW

Light Source Components



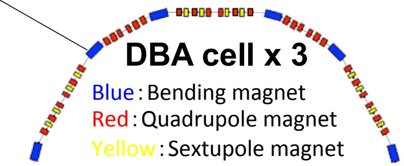
Circularly-polarizing undulator developed at KEK-PF



FEL system

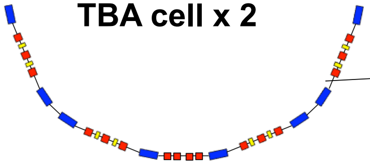
1st arc (new design)

bunch compression



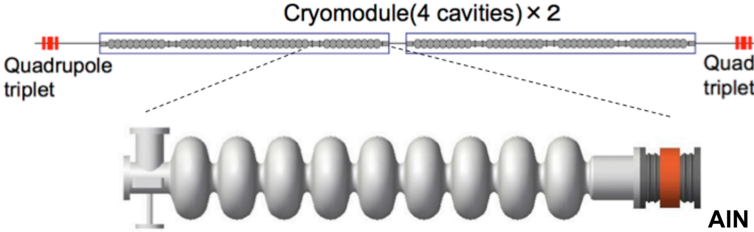
2nd arc

bunch decompression



Main linac

64 superconducting cavities in 16 cryomodules



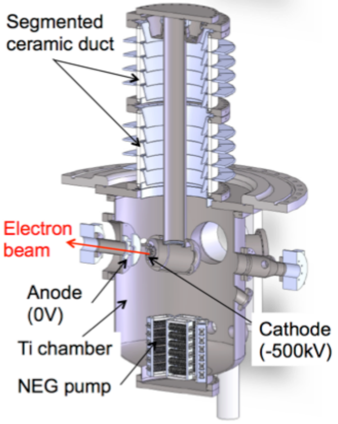
AlN HOM absorber

Main cavity – TESLA-type 9-cell cavity + 108ϕ beam pipe

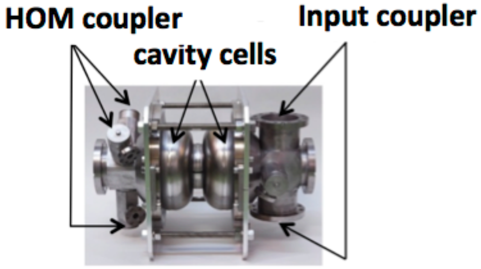
Under design. A large-aperture beam pipe will be also applied to the left side.

stable operation at E_{acc}=12.5 MV/m

Photocathode DC gun



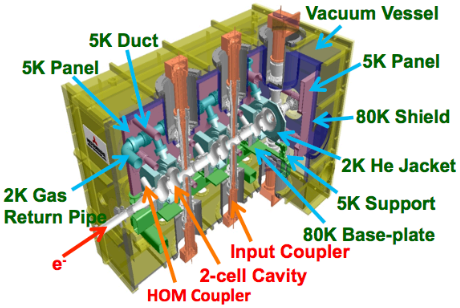
2nd DC gun developed for cERL



2-cell SRF cavity for cERL

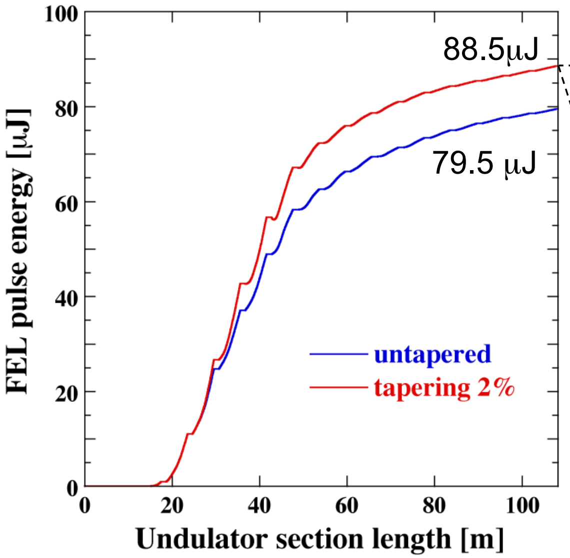
Injector linac

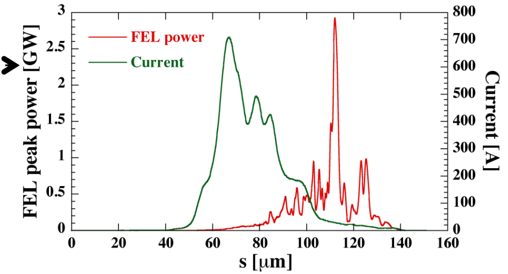
cERL injector cryomodule

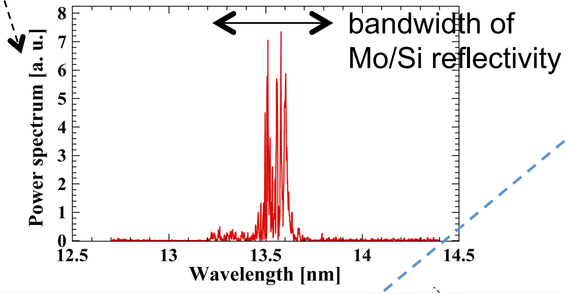


cERL cryomodule structure

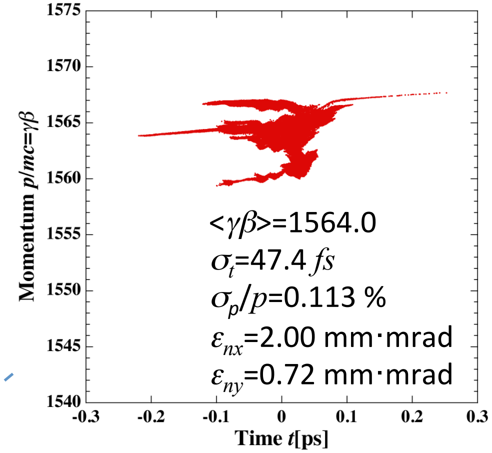
Simulation Study







bandwidth of Mo/Si reflectivity

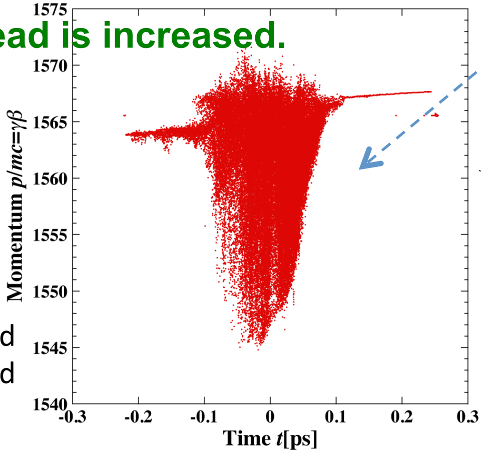


$<\gamma\beta>=1564.0$
$\sigma_t=47.4\ fs$
$\sigma_p/p=0.113$ %
$\varepsilon_{nx}=2.00$ mm·mrad
$\varepsilon_{ny}=0.72$ mm·mrad

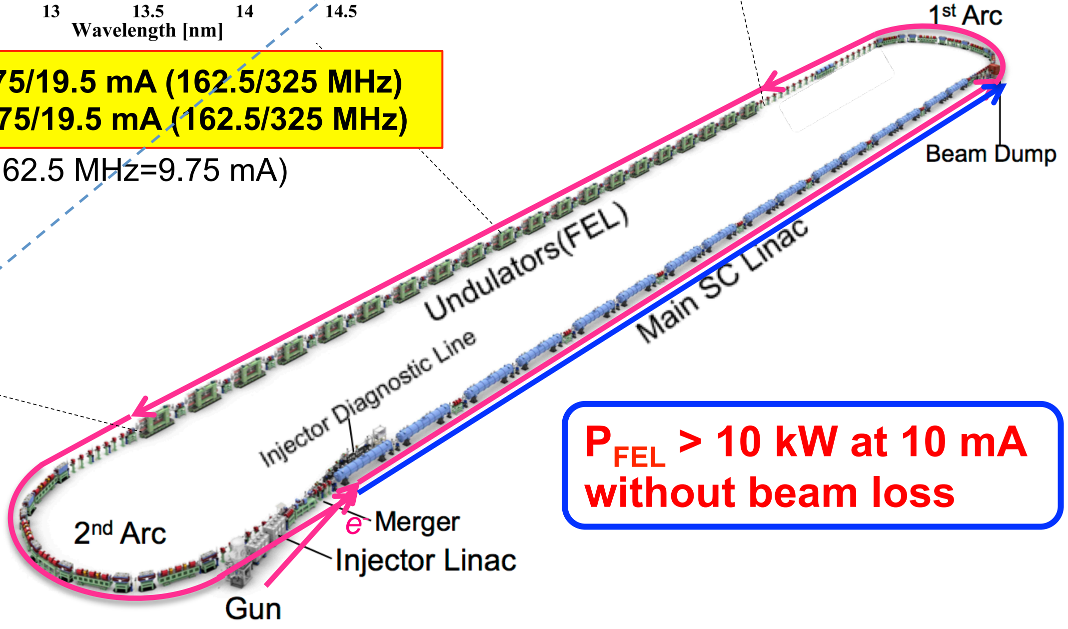
FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

(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.



$<\gamma\beta>=1561.1$
$\sigma_t=48.5\ fs$
$\sigma_p/p=0.299$ %
$\varepsilon_{nx}=1.98$ mm·mrad
$\varepsilon_{ny}=0.71$ mm·mrad



P_{FEL} > 10 kW at 10 mA without beam loss

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Availability Issues

Required availability for industrialization: ≥ 98 %

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

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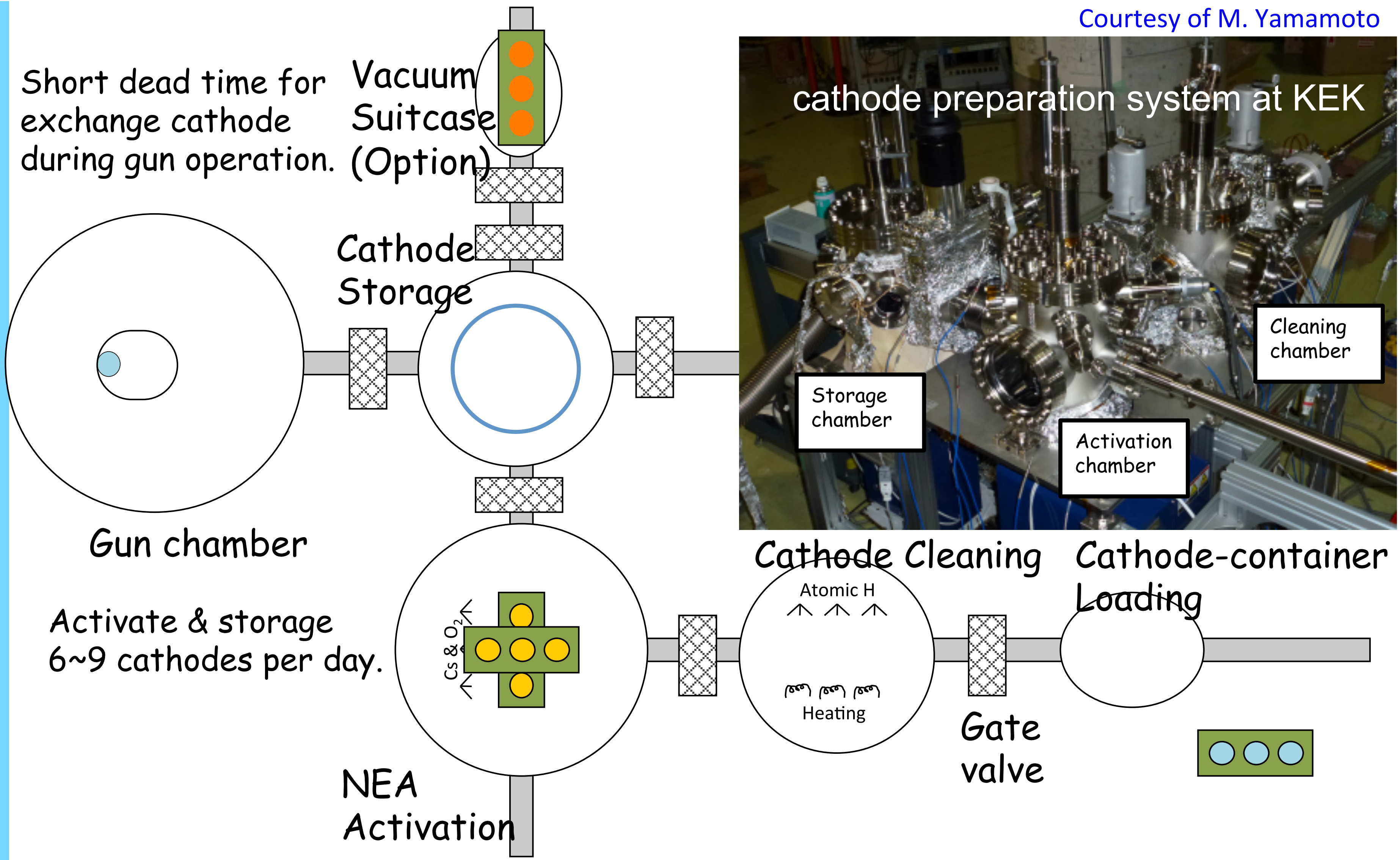
- Electron Gun
  - Photocathode exchange/preparation time
- SRF Cavity
  - Trip rate
  - Increase of field emission in long-term operation
- Cryoplant
  - High pressure gas safety law
  - Safety inspection (once a year in Japan)

Cathode Preparation System

Courtesy of M. Yamamoto



Short dead time for exchange cathode during gun operation.

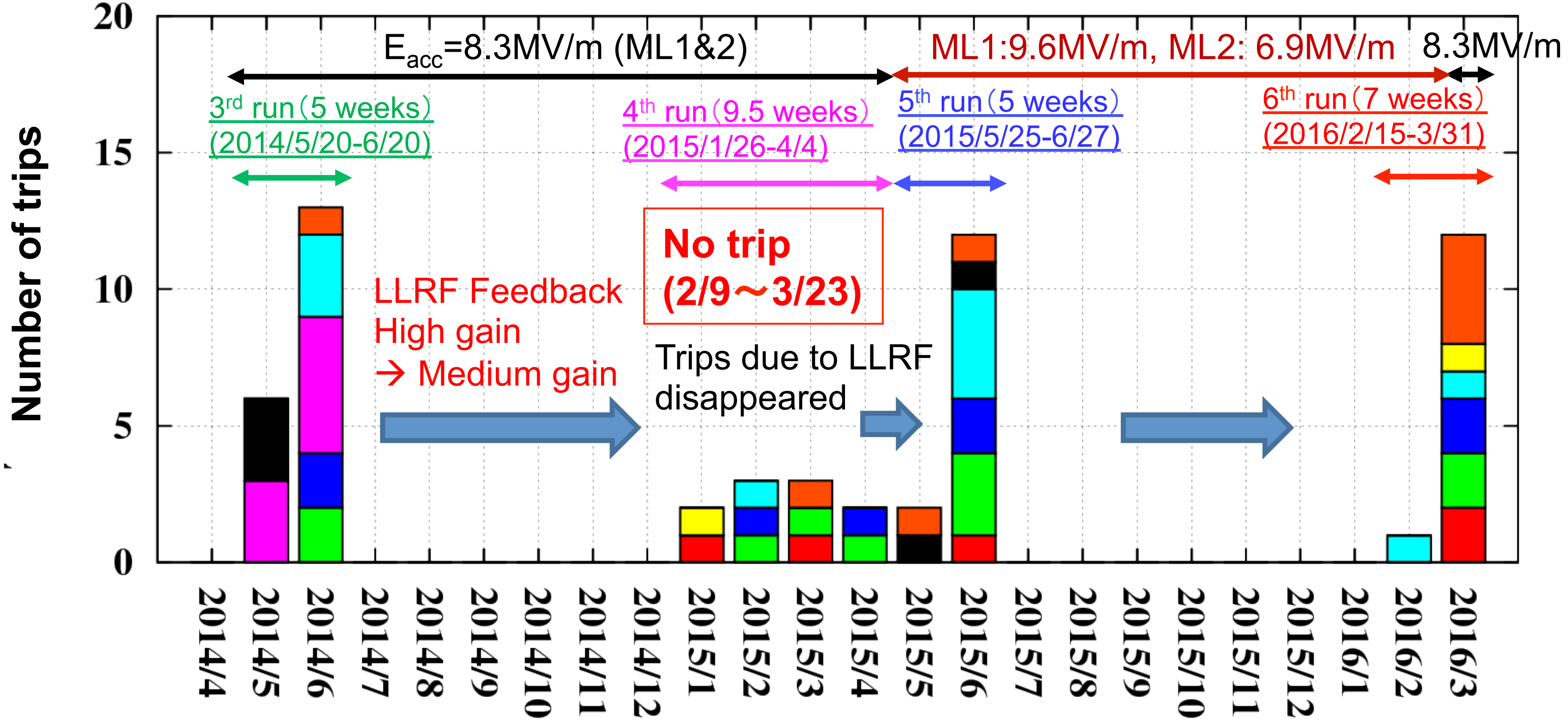
Activate & storage 6~9 cathodes per day.

Cathode preparation system should and can be remote-controlled.

Trip of SRF Cavities

Courtesy of H. Sakai

Trip statistics of two cERL Main Linac Cavities



E_{acc}=8.3MV/m (ML1&2)

ML1:9.6MV/m, ML2: 6.9MV/m

8.3MV/m

3rd run（5 weeks）
(2014/5/20-6/20)

4th run（9.5 weeks）
(2015/1/26-4/4)

5th run（5 weeks）
(2015/5/25-6/27)

6th run（7 weeks）
(2016/2/15-3/31)

LLRF Feedback
High gain
→ Medium gain

No trip
(2/9～3/23)

Trips due to LLRF disappeared

Trip rate of SRF cavities is very low and not a serious problem.

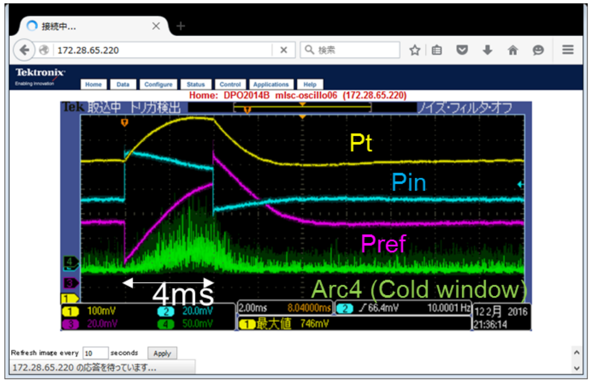
cavity 🟥
coupler2(warm) 🟩
vacuum outside cavity 🟦
LLRF 🟪
miss operation 🟦
earthquake 🟨
other hardware ⬛
unknown 🟧

Pulse Processing of SRF Cavities

Field emission(FE) of the cERL cavities increased in the long-time operation.

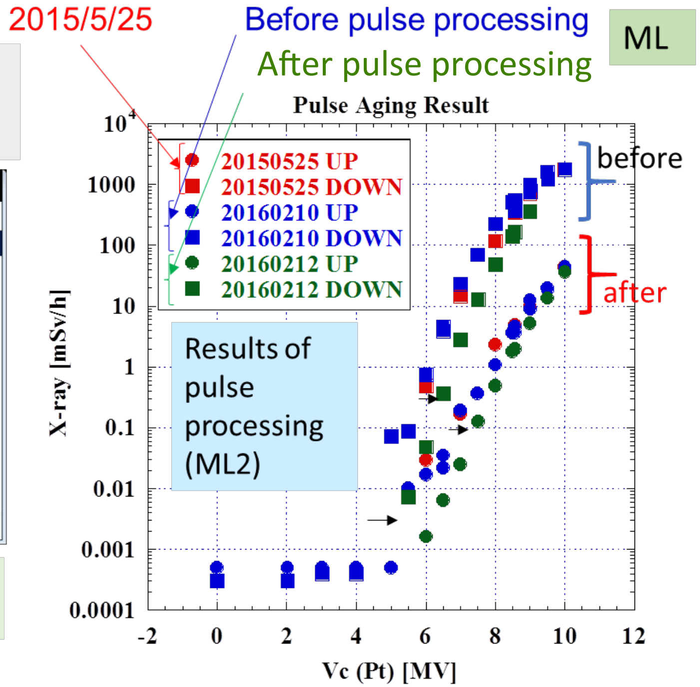
High peak pulse RF power is input to the cavities to reduce FE.

ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
:40min pulse aging was done.

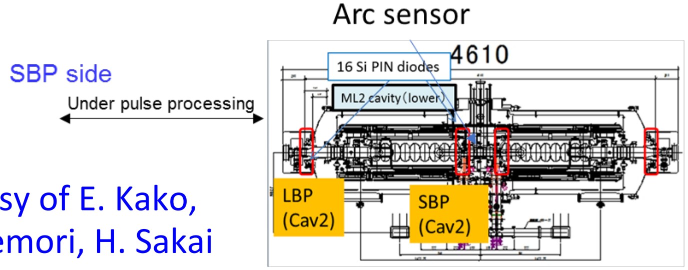


History of pulse processing: In ML, we were processing by monitoring side 32 PIN diodes

ML



ML2 Vc vs ALOKA monitor



Courtesy of E. Kako,
K. Umemori, H. Sakai

- Onset moved up 0.5 MV.
- Radiation reduced half on same acc. field.

→Pulse processing works well.

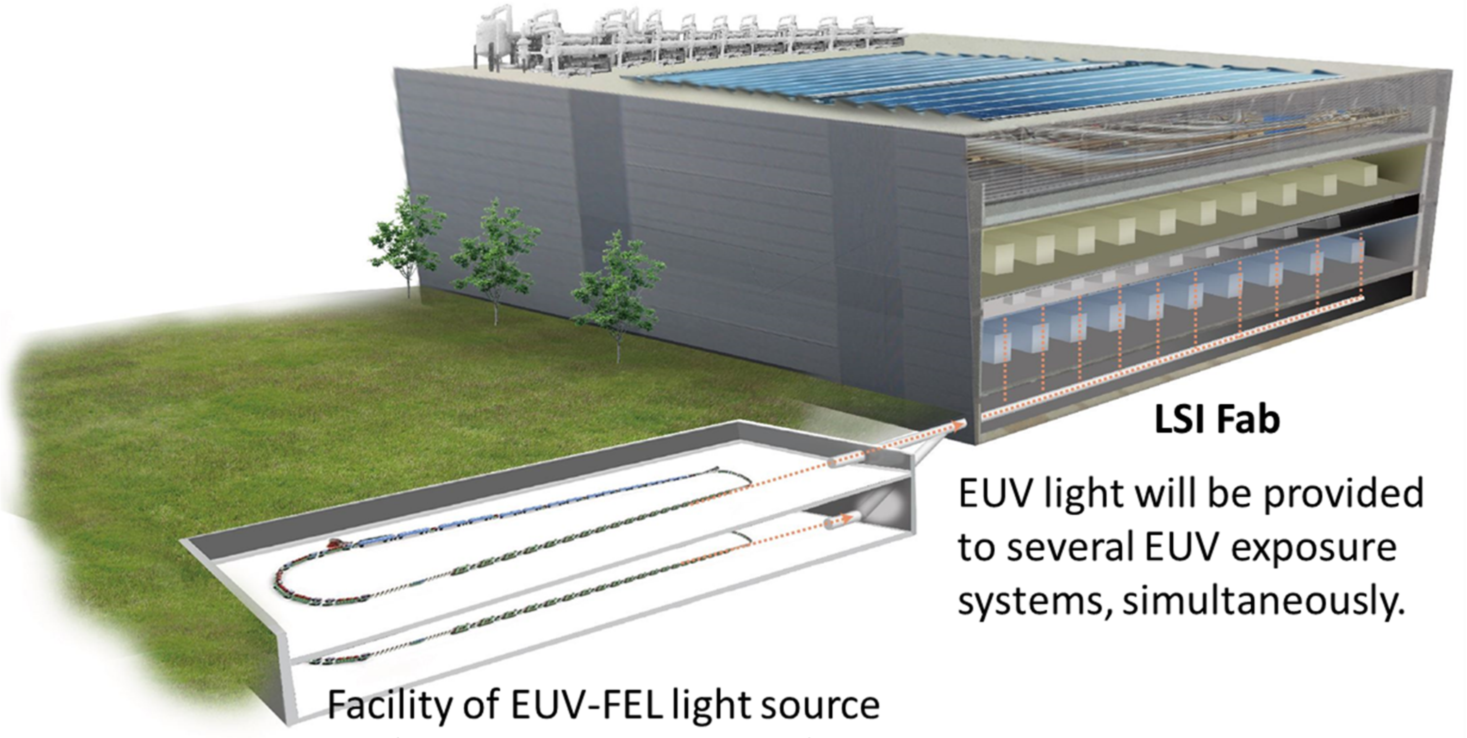
Short-time pulse processing can recover the degraded performance.

Other in-situ processing methods are also studied to reduce FE.

Redundant System

Redundant System for ensuring high availability

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



EUV light will be provided to several EUV exposure systems, simultaneously.

Facility of EUV-FEL light source
（Main/Sub light source）

Redundant system configuration should be designed.

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Reduction of Light Source Size

The present size is mainly decided by the main linac length.

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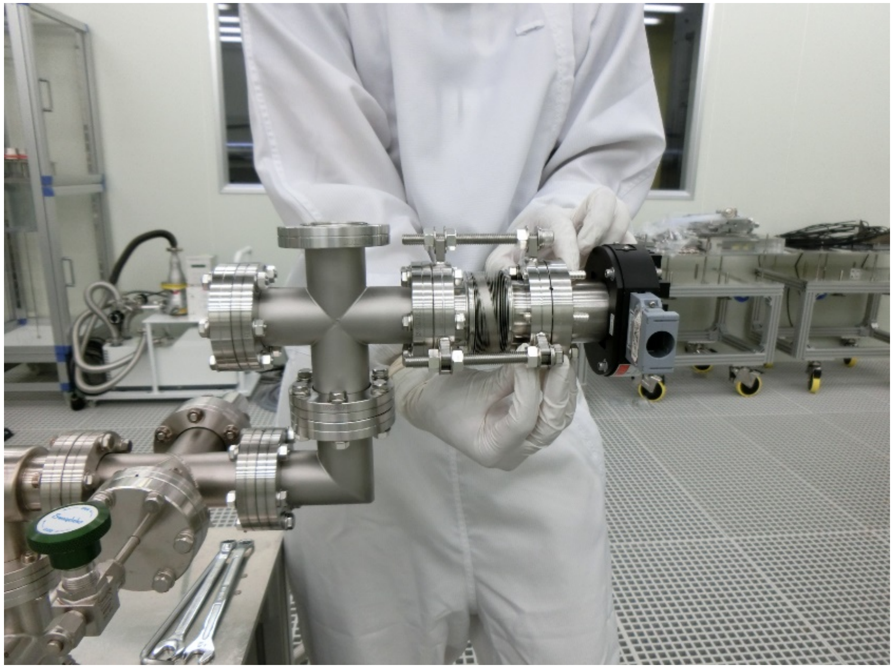
Possible solutions of reducing the main-linac length

- Higher acceleration field of main linac
  - Suppression of field emission
  - Higher-Q SRF cavity
- Lower beam energy
  - Shorter-period undulators with stronger magnetic field
    - In-vacuum undulators
    - Cryogenic permanent magnet undulators
- Double-loop configuration
  - Two-times acceleration with half the main linac
  - Division of the main linac into two parts

Suppression of Field Emission

Suppression of field emission is a key issue for higher acceleration field of main-linac SRF cavities in CW operation.

Improvement for clean environments with dust free during assembly work



Introduction of a particle measurement system in vacuum and a slow pumping and venting system for suppression of particle movement

Test bench to confirm the higher field performance of cavities

Horizontal cryostat to check cavity performance after assembly work

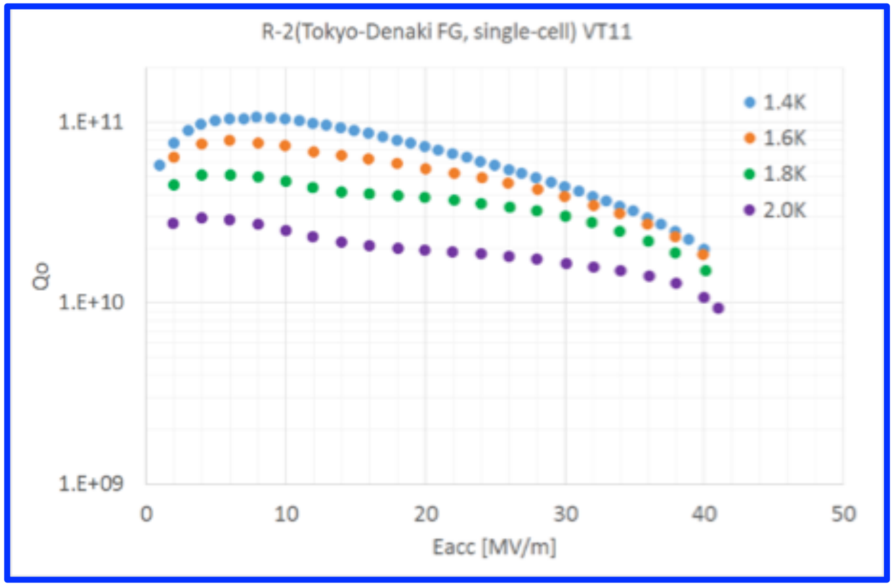
Courtesy of E. Kako, K. Umemori, H. Sakai

Higher-Q SRF Cavities

Power loss in SRF cavity: $P_{loss} \propto E_{acc}^2/Q$

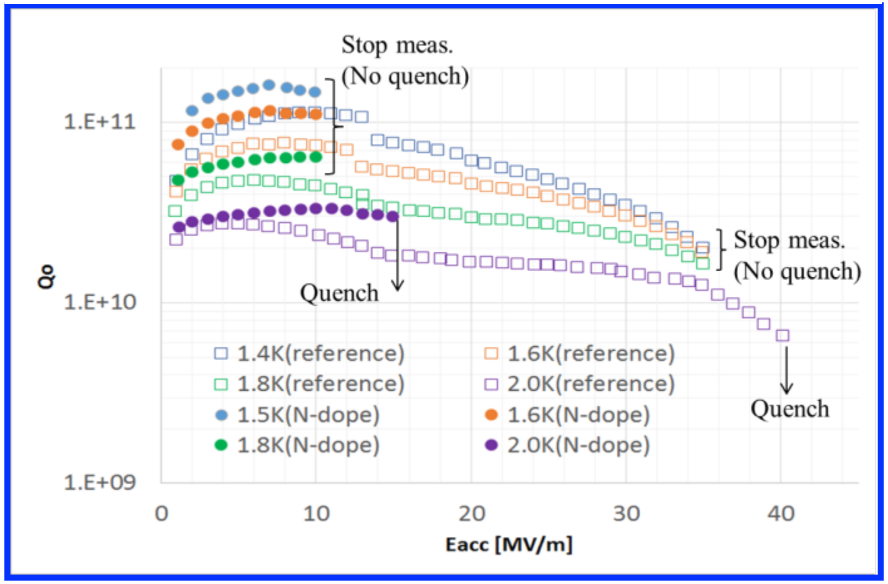
Methods of achieving higher Q values
(1) Reduction of residual magnetic field by a solenoid magnet and so on
(2) Introduction of nitrogen(N_2) doping treatment

$Q = \sim 1 \times 10^{10} \rightarrow 2 \times 10^{10}$ @ E_{acc}=15 MV/m, 2K



Cancellation of the residual magnetic field by a solenoid coil

$Q = 2 \times 10^{10} \rightarrow 3 \times 10^{10}$ @ E_{acc}=15 MV/m, 2K



Improvement of Q values by nitrogen doping treatment

Courtesy of E. Kako, K. Umemori, H. Sakai

Further study on N_2 doping is necessary for more optimum condition.

Shorter Period Undulators (1)

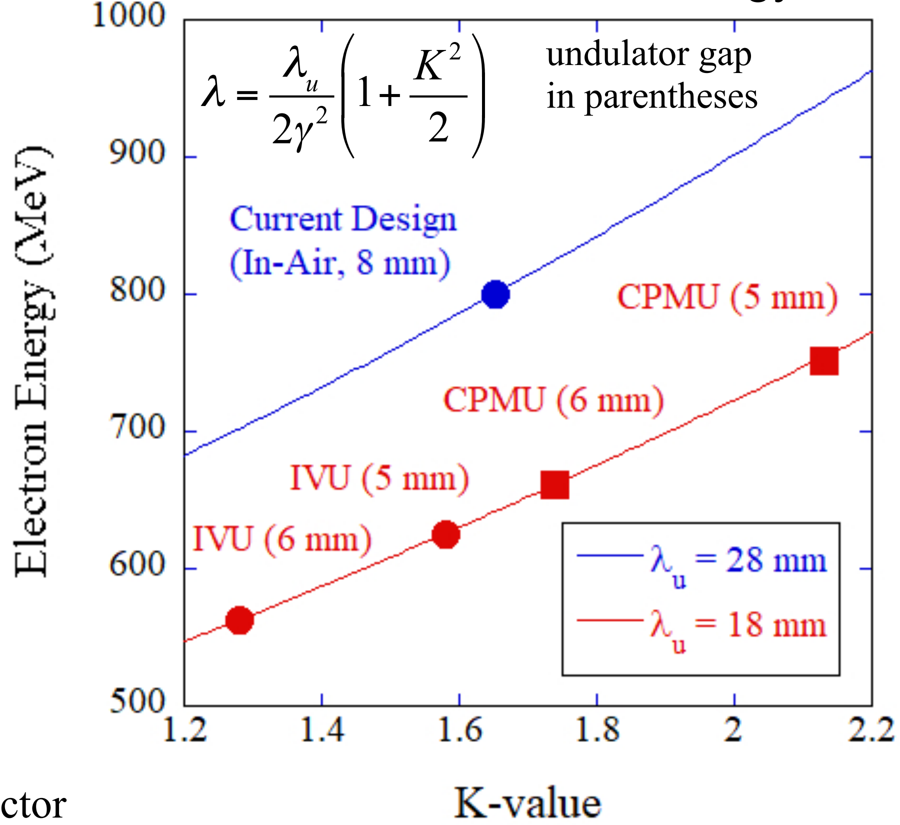
Shorter period undulators for reducing beam energy
(1) In-vacuum undulators (IVUs)
(2) Cryogenic permanent magnet undulators (CPMUs)

Beam parameters assumed in the calculation

Energy spread	0.1 %
Charge	60 pC/bunch
Bunch length	100 fs
Peak current I_p	600 A
Average current	9.75 mA
Normalized emittance ($\varepsilon_x = \varepsilon_y$)	1 mm mrad
Beta func. ($\beta_x = \beta_y$)	5 m
Repetition frequency	162.5 MHz

λ : radiation wavelength(13.5 nm)
λ_u : undulator period
K : K-value of undulator γ : Lorentz factor

Reduction of beam energy



Courtesy of R. Kato

Shorter Period Undulators (2)

FEL Output Power

$$P_{FEL}=\eta P_b \quad (P_b=E_b I_b)$$

$$\eta=1.6\,\rho/(1+\Lambda)^2$$

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

P_{FEL}: FEL output power P_b: beam power

E_b: beam energy I_b: average beam current

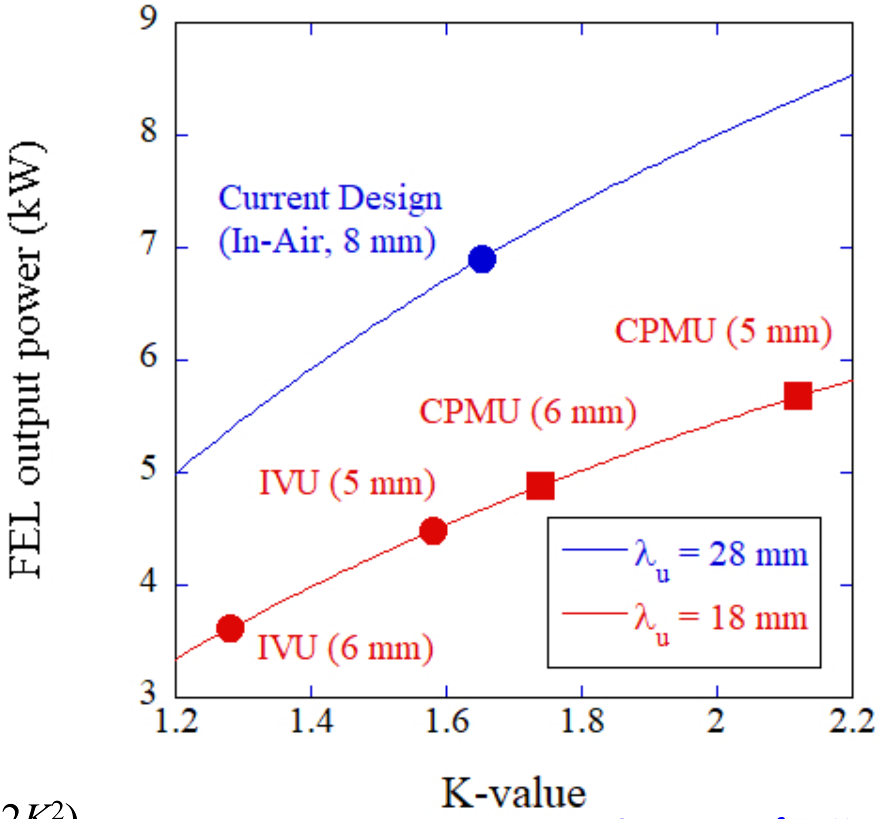
η: energy conversion efficiency

ρ : one-dimensional FEL parameter

Λ : correction term for three-dimensional effects

I_p : peak current, I_A : Alfven current

r_b: transverse beam size JJ: $J_0(\xi)$-$J_1(\xi)$, $\xi=K^2/(4+2K^2)$



Courtesy of R. Kato

Conclusions:

(1) The beam energy and the main-linac length are reduced.

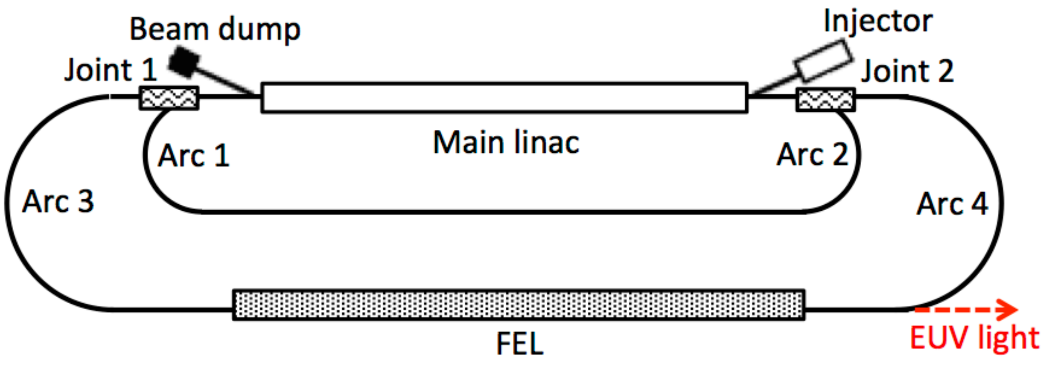
(2) The FEL output power is also decreased (without current increase).

Double-Loop Configuration

Type A:

Beam is accelerated twice by the same main-inac(ML) cavities and the ML length is reduced by half.

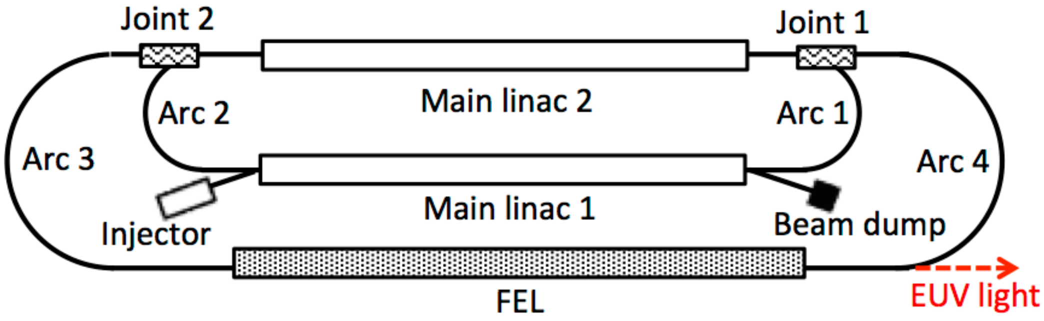
The beam current and the higher-order-mode(HOM) power in ML become double.



Type B:

Main linac(ML) is divided into two and each ML length becomes half. The beam current and the HOM power in ML are the same.

The number of the ML cavities is doubly larger than that of Type-A configuration.



Joint 1 & 2 consist mainly of bending magnets.

- Light source size is significantly reduced.
- Design study is needed to keep the same EUV output power.

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Summary

- ERL-based EUV-FEL light sources have a potential of providing high-power EUV light that meets future demand for lithography.
- It is demonstrated in simulation that our designed EUV-FEL light source can generate EUV power of more than 10 kW at 10 mA without serious beam loss.
- High availability required for lithography can be achieved without too much technology development and with a redundant system.
- Reduction of the light source size is also possible and requires further R&D and design work.

EUV-FEL Light Source Study Group for Industrialization

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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

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

Thank you for your attention!