The 4h EUV-FEL Workshop
Akihabara UDX, Tokyo,
10 Dec 2019

# Demonstration of high-repetition FEL using cERL and beyond EUV-FEL

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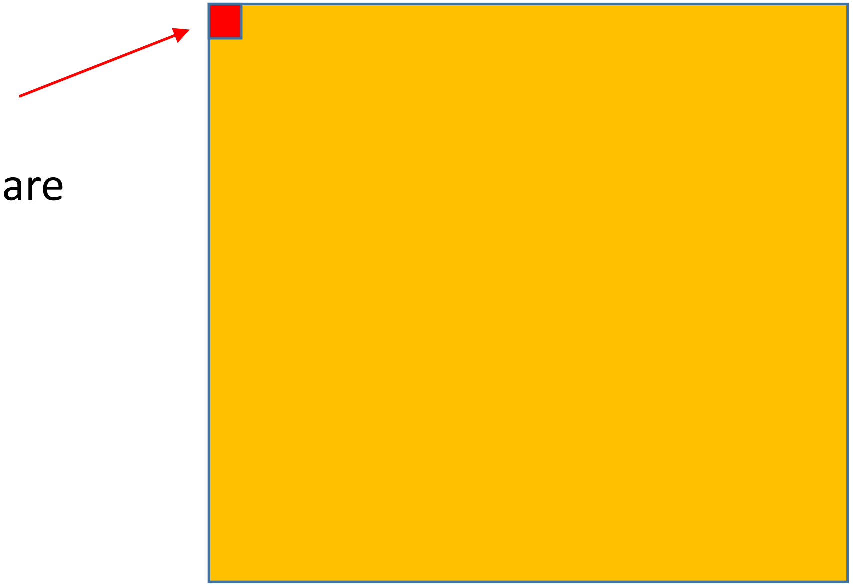
- Why is Energy Recovery required?
- Project of IR-FEL based on the cERL
  - Demonstration of high-repetition FEL -
- Is it possible to obtain a wavelength of several nm from EUV-FEL?
- Summary

## Part 1:

# Why is Energy Recovery required?

# Efficiency of FEL

- Assuming this square area is the power of the electron beam, how much area is converted to light by FEL?

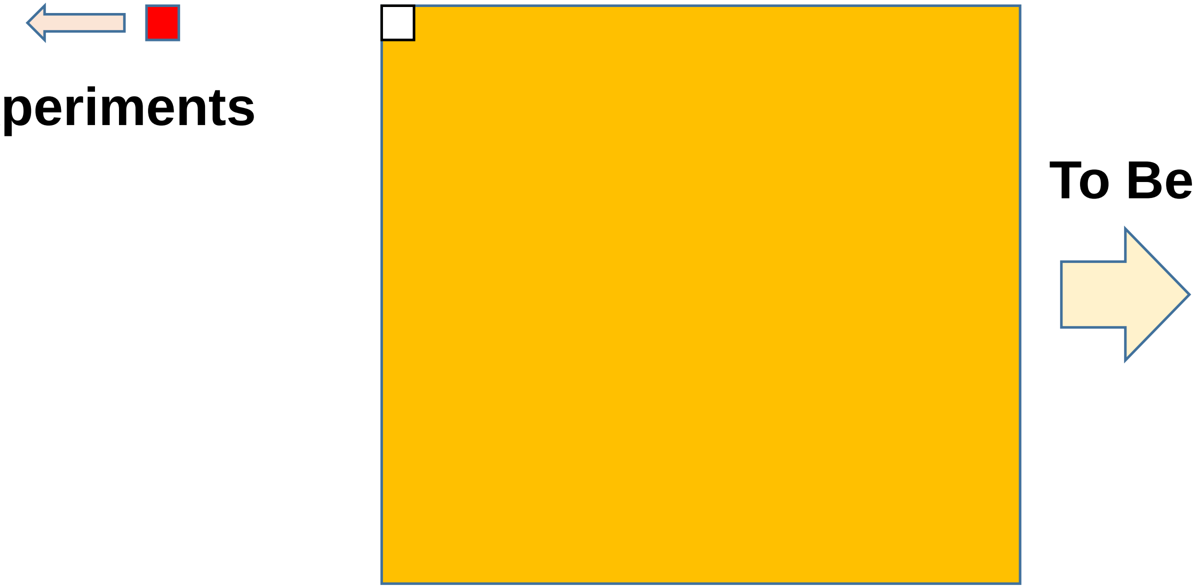


Maybe …
this red square

- FEL conversion efficiency is ~ $10^{-2}$ in the infrared region and $10^{-3}$ to $10^{-4}$ in the EUV/X-ray region

# Efficiency of FEL

- Assuming this square area is the power of the electron beam, how much area is converted to light by FEL?



**To User Experiments**

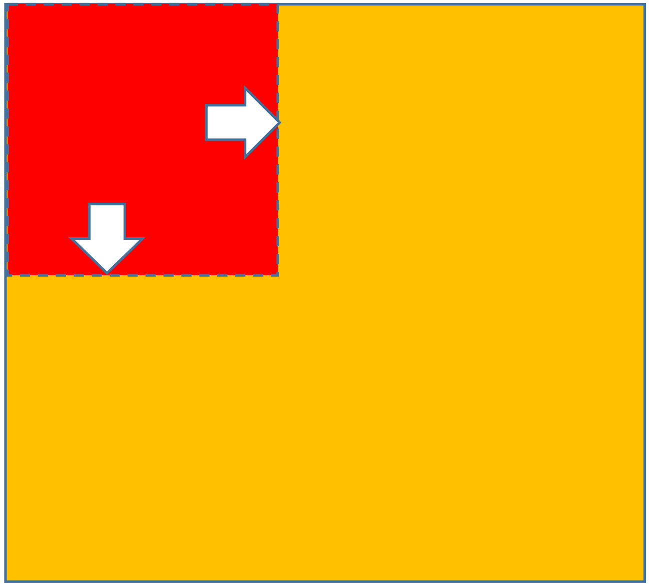
**To Beam Dump**

- Low conversion efficiency of FEL is not a serious problem for academic use.
- However, for industrial use ... we need improvement!

# To make the efficiency better

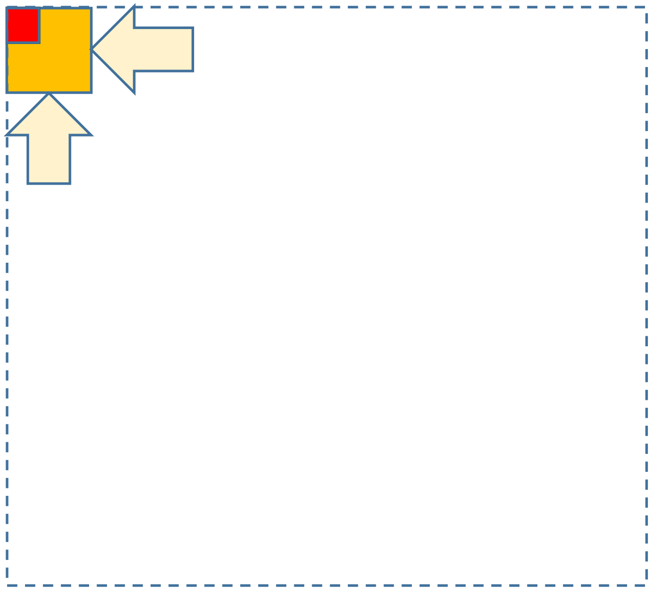
- There are 2 ways to improve conversion efficiency

**(1) Increase efficiency itself**



**Tapered FEL, TESSA*, …**

**(2) Reduce dump power**

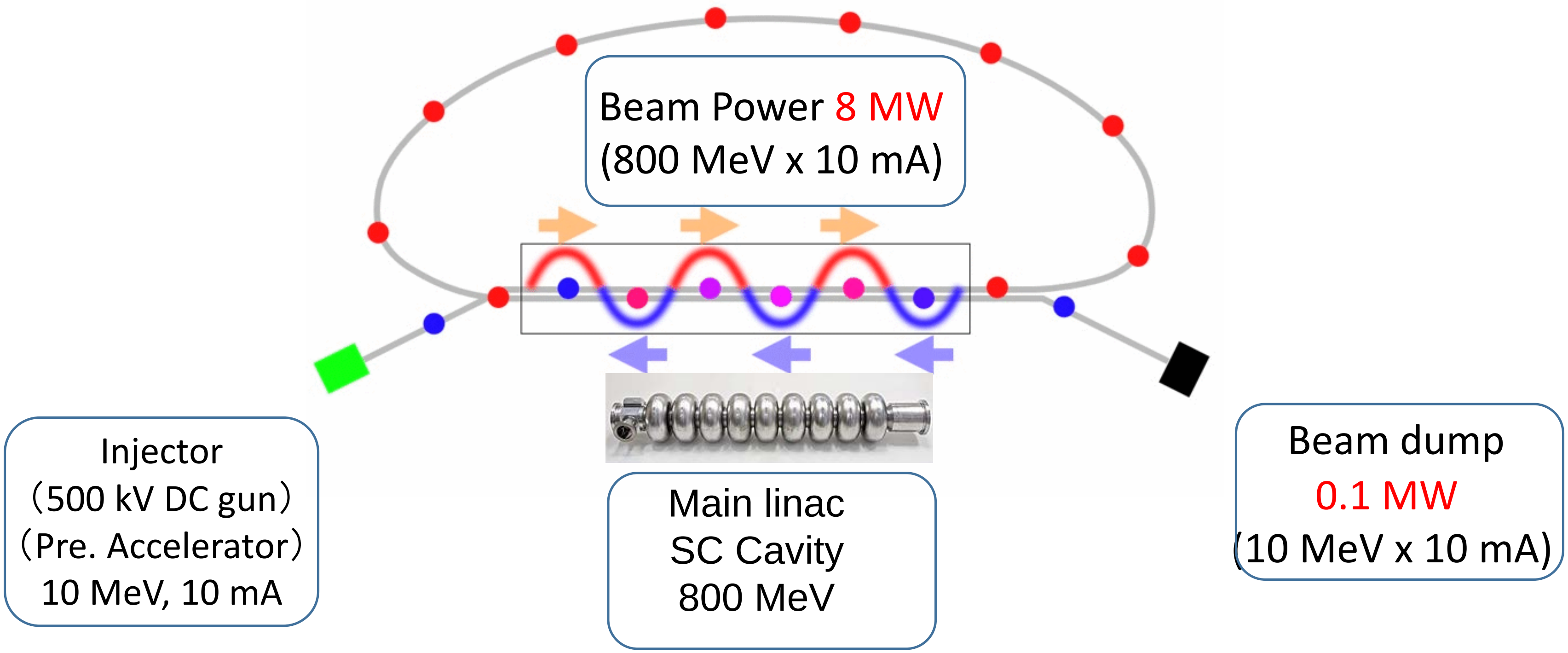


**Energy Recovery**

*Alex Murokh, EUVL workshop, LBNL, June 15 - 2016, P44

# Energy Recovery Linac

Energy exchanged between fresh bunches (from injector) and old bunches (from circulation) in the main SC Cavities.



Beam Power 8 MW
(800 MeV x 10 mA)

Injector
（500 kV DC gun）
（Pre. Accelerator）
10 MeV, 10 mA

Main linac
SC Cavity
800 MeV

Beam dump
0.1 MW
(10 MeV x 10 mA)

- Increase average beam power
- Reduce dump power (small radiation)

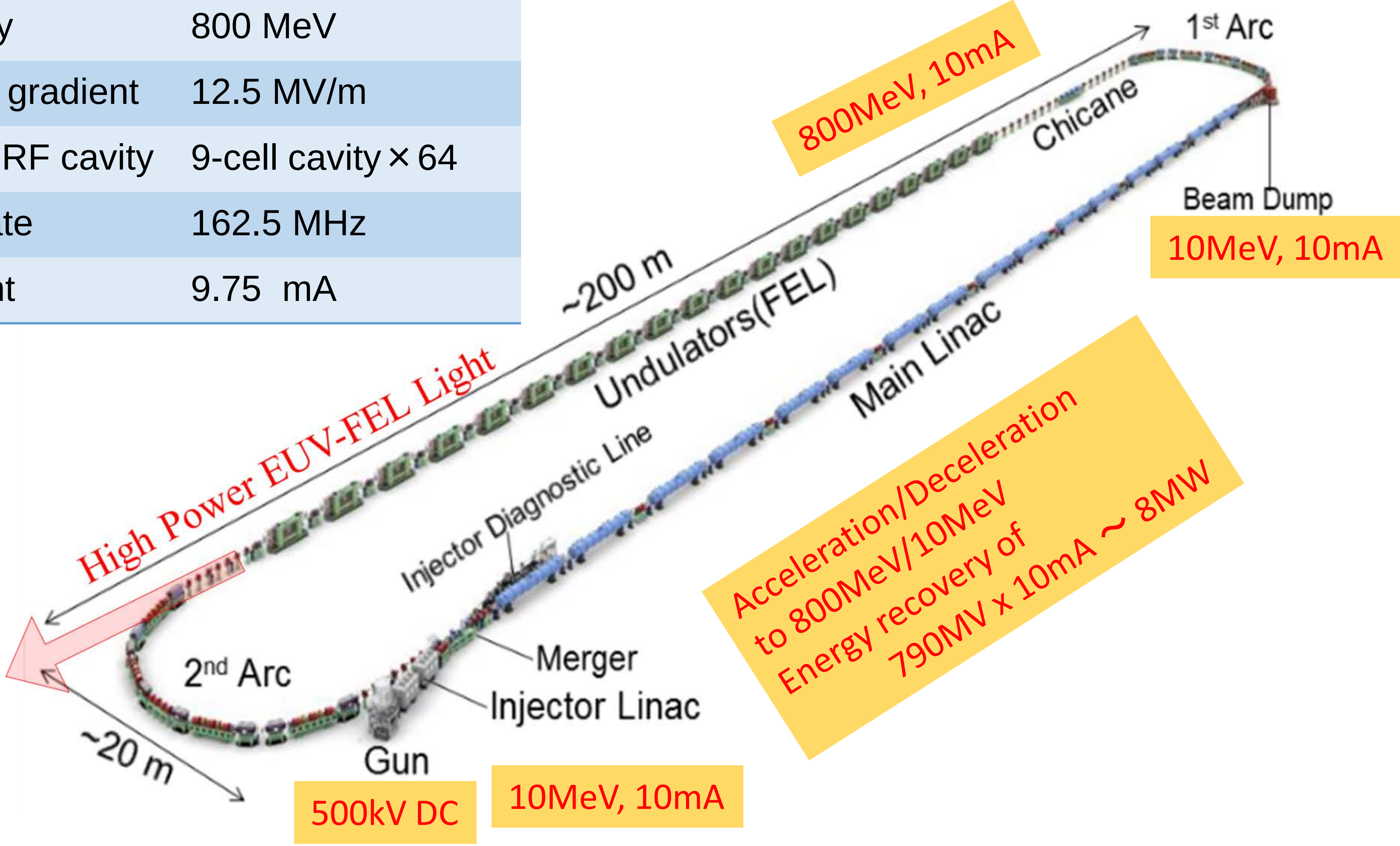
# EUV/X-Ray FELs

| | LCLS | SACLA | FLASH | Euro-XFEL | LCLS II | EUV-FEL |
|---|---|---|---|---|---|---|
| Type | Normal conducting | | Super conducting | | | |
| Configuration | Linac | | Linac | | | ERL |
| Operation Mode | Pulse | | Long-pulse | | CW | |
| Country | US | Japan | Germany | EU | US | --- |
| Repetition rate (pulse/sec) | 120 | 60 | <5000 | <27000 | 1M | 162.5M |
| Beam energy （GeV) | 14.3 | 6〜8 | 1.25 | 17.5 | 4 | 0.8 |
| Wavelength (nm) | 0.15 | 0.08 | 4.2-52 | 0.05 | ~0.3 | 13.5 |
| FEL Pulse energy (mJ) | ~10 | ~10 | <0.5 | ~10 | ~1 | ~0.1 |
| Average FEL power (W) | ~1 | ~1 | <0.6 | ~100 | ~1k | >10k |
| Beam dump power (W) | ~1.5k | ~0.5k | ~6k | ~0.5M | ~1M | ~0.1M |
| FEL / Dump (%) | 0.07 | 0.2 | 0.01 | 0.02 | 0.1 | 10 |
| Status | Operation 2009 | Operation 2011 | Operation 2004 | Operation 2017 | Construction 2020 | Planning |

**ERL helps to make high-power CW FEL and reduce the beam dump power.**

# Prototype design of the EUV-FEL

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



800MeV, 10mA

10MeV, 10mA

Acceleration/Deceleration to 800MeV/10MeV
Energy recovery of 790MV x 10mA ~ 8MW

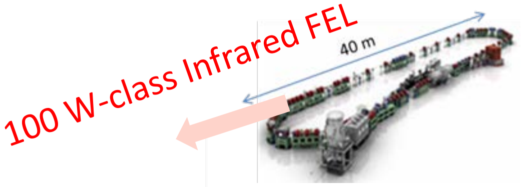
10kW FEL output

500kV DC

10MeV, 10mA

# Staging to realize the EUV-FEL light source

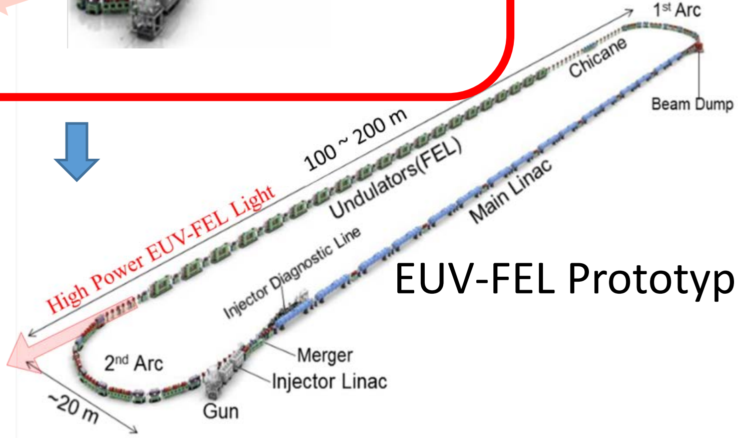
**1st stage:**
**Development of the feasible technologies**



cERL

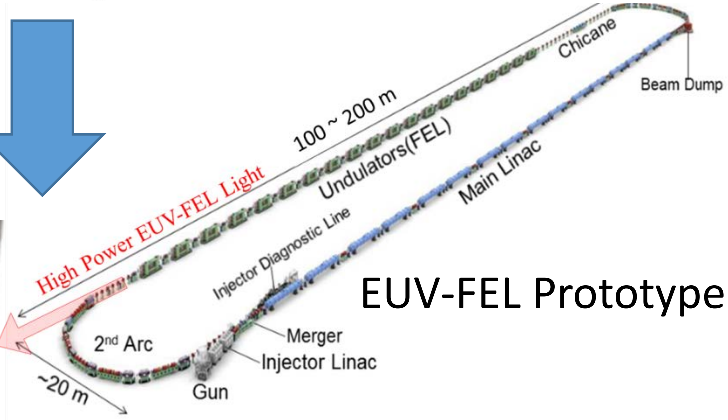
Upgrade plan of cERL for the PoC

**2nd stage Phase 1:**
**Establishment of the EUV-FEL Lithography system**



EUV-FEL Prototype

**2nd stage Phase 2:**
**International Development Center on the processing of EUV-FEL lithography**



EUV-FEL Prototype

Clean room with EUV exposure system

IR-FEL project as a PoC is important to realize the EUV-FEL light source for future EUV Lithography.

## Part 2:

# Project of IR-FEL based on the cERL

## - Demonstration of high-repetition FEL -

# Background of IR-FEL Project (1)

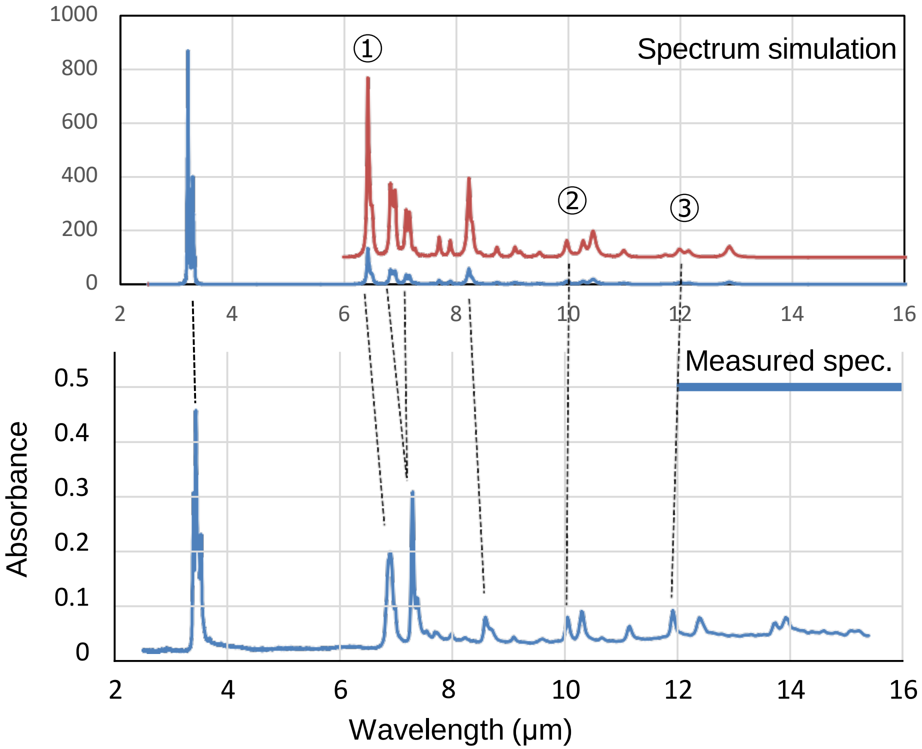
Organic materials (Resin, Engineering plastic) : light-weight, low-cost, high-functional

Recently, the use of organic materials has been increasing.

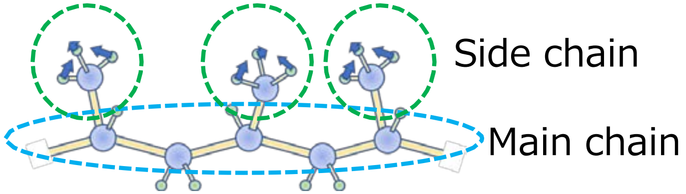
Processing methods : Machining, Molding, Laser processing ($CO_2$, Fiber)

These organic materials have vibration absorption in the mid-infrared region

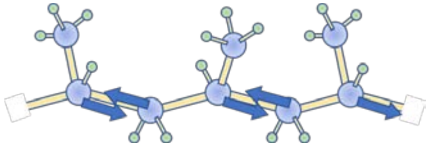
Absorption spectrum of polypropylene



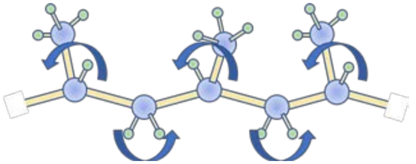
Peak①: δ declination of side chain methyl group



Peak②: Stretch vibration of main chain C-C bond



Peak③: Twist of main chain C-C bond



Considering the process of cutting the resin, the absorption wavelength of ② and ③ seem to be more suitable than ①,

However, there is no database of easy-to-process wavelengths and required laser power.

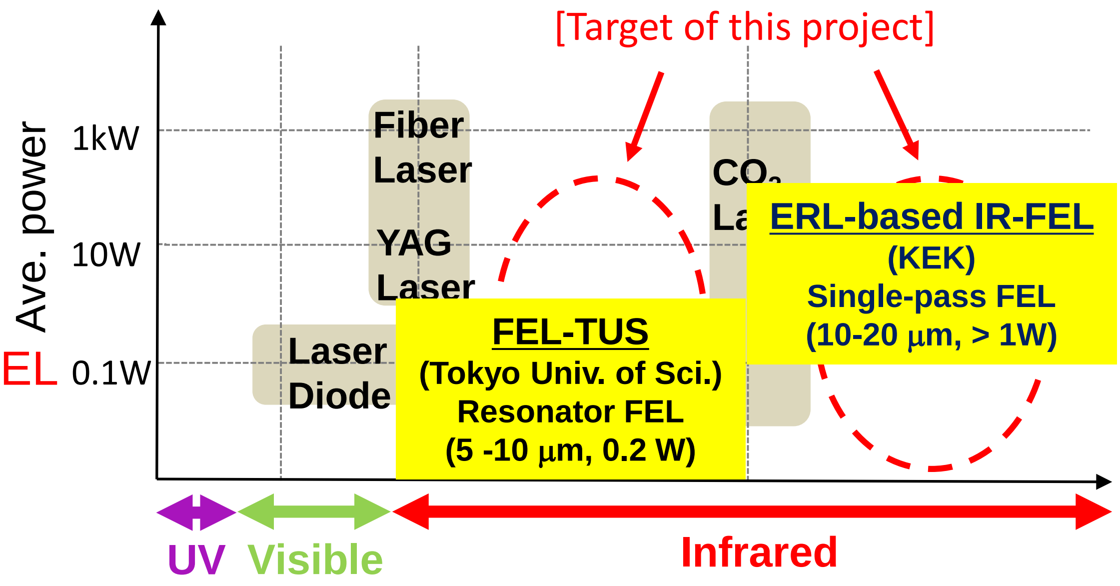
# Background of IR-FEL Project (2)

Main high-power laser in MIR range is $CO_2$ laser only
→ Insufficient understanding of basic phenomena required for processing

A tunable high-power laser is required to create a database for processing!

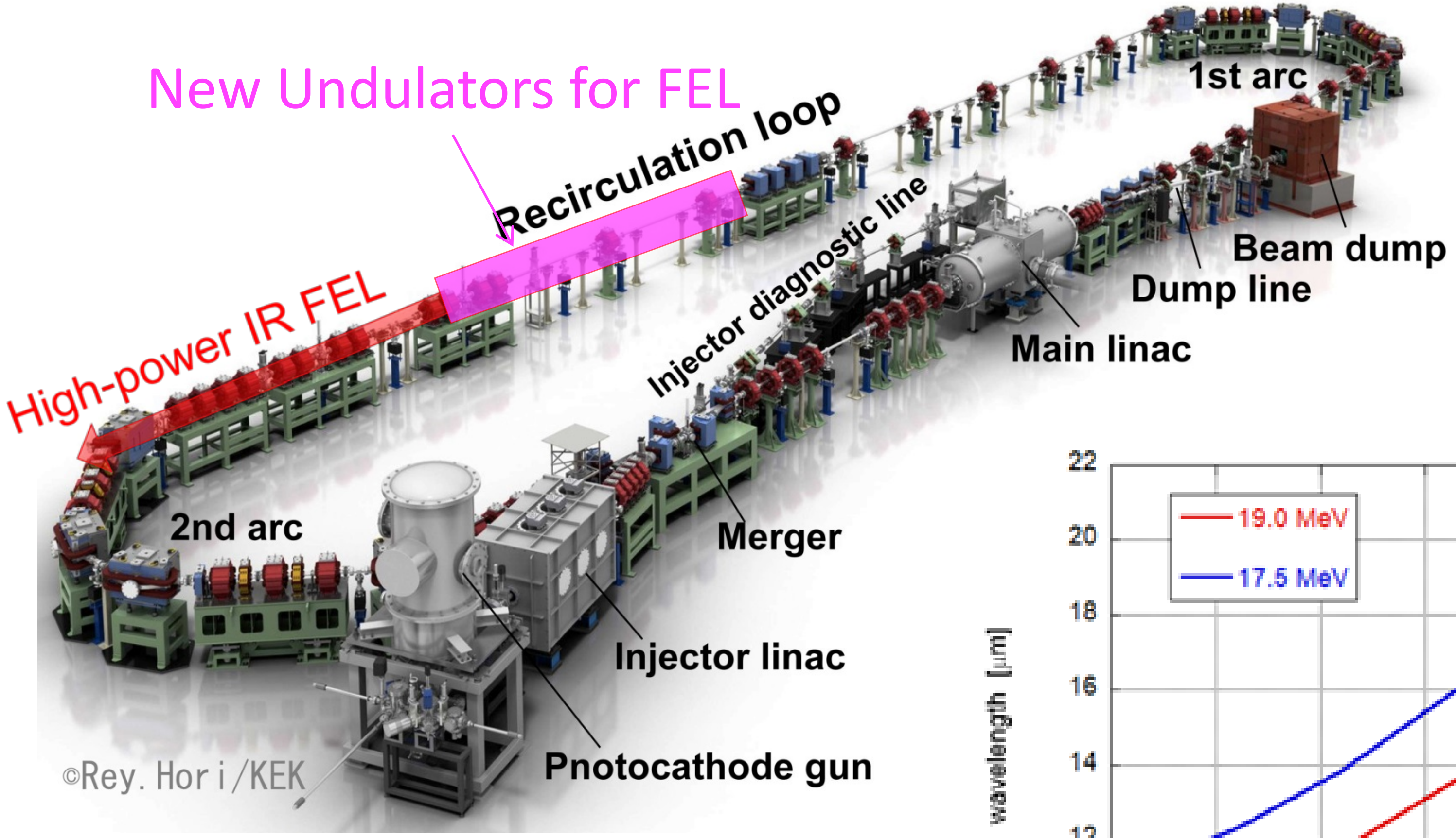
Project theme founded by NEDO (Ministry of Economy, Trade and Industry)
"Development of high-power mid-infrared lasers for high-efficiency laser processing utilizing photo-absorption based on molecular vibrational transitions."

KEK's mission
1. Development of high-power IR-FEL
2. Creation of processing database
3. Processing demonstration

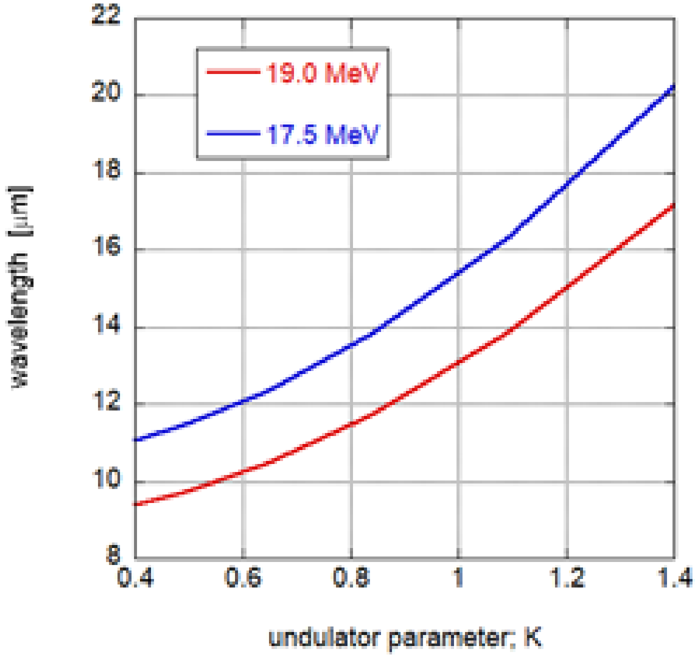


Wavelength ranges of lasers.

# High average power IR-FEL Project

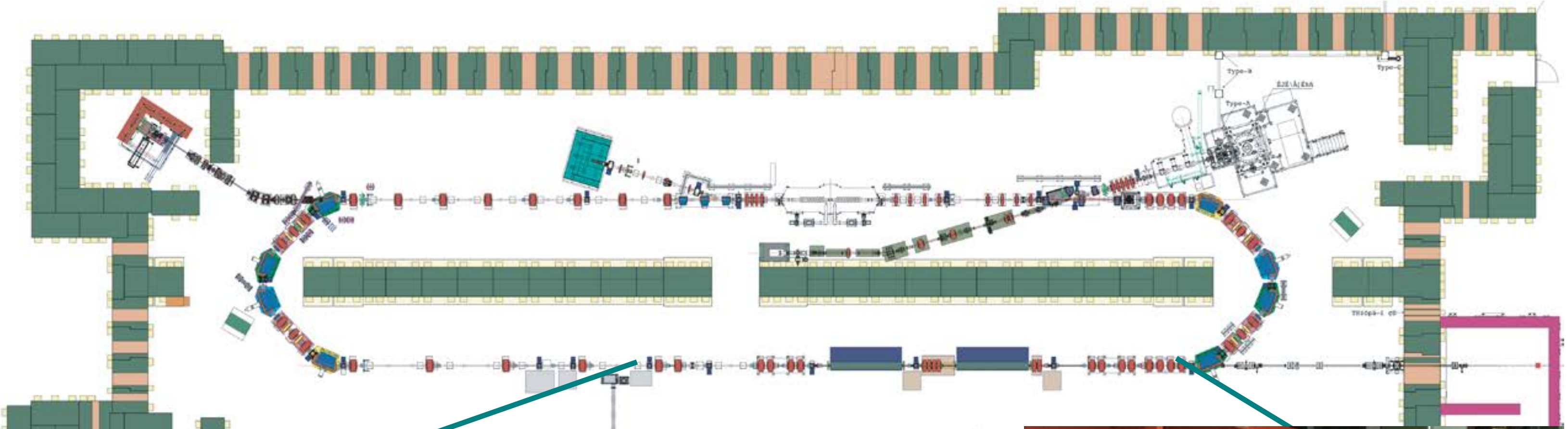


| | |
|---|---|
| **Beam Energy** | 17.5 - 19.0 MeV |
| **Injector Energy** | 3.0  - 4.0 MeV |
| **E-Gun Energy** | 500 keV |
| **Bunch repetition** | 1.3 GHz → 81.25 MHz |
| **Average current** | 1 mA (→ 5 mA ) |
| **Operation mode** | CW or Burst |



FEL wavelength

# Layout and parameters of IR-FEL



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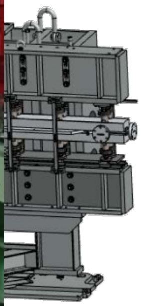
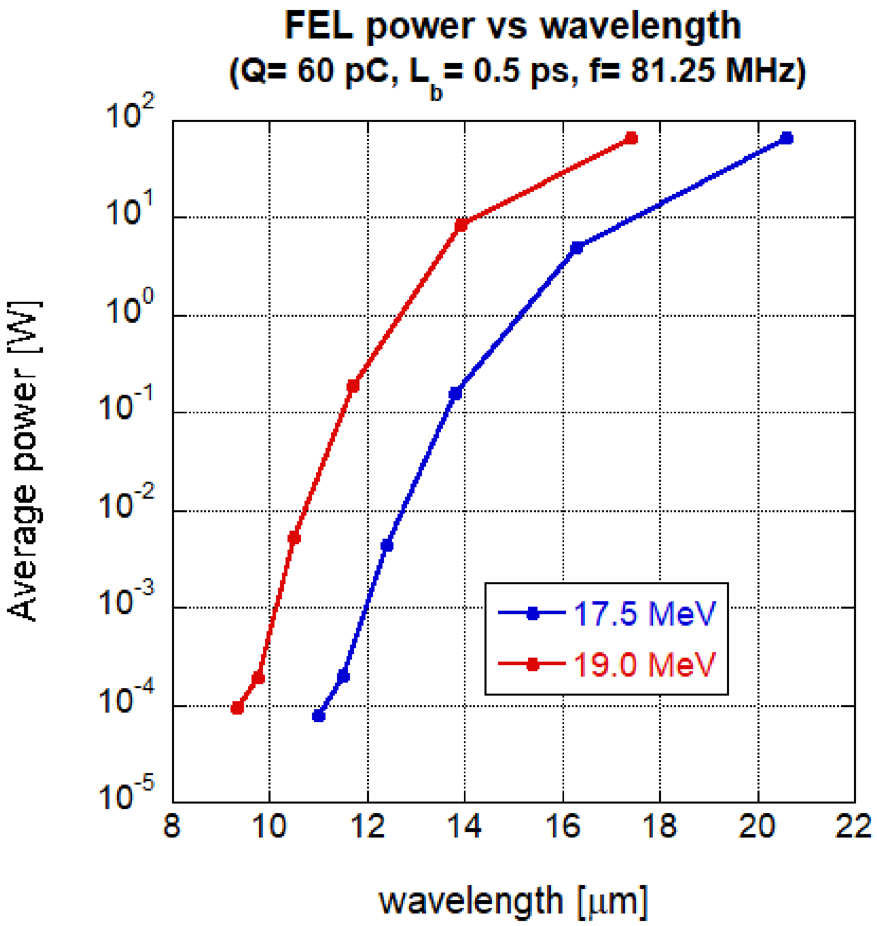
Undula

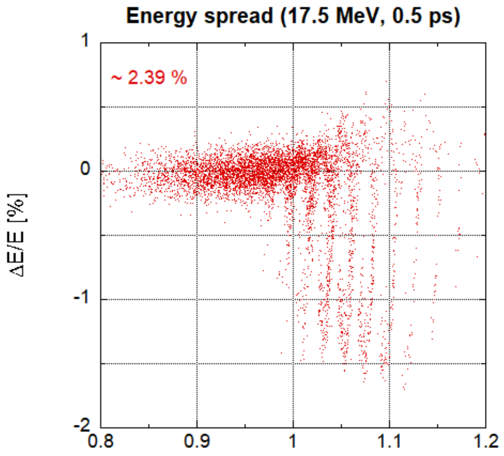


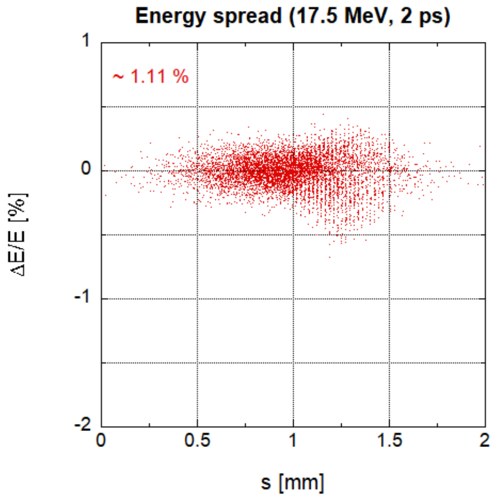
Design of undulators.

# Ave. Power of IR-FEL and energy spread

By changing the energy, average power exceeding 1 W can be obtained in the range of 13 – 20 μm.
A large density modulation is formed in front of the electronic bunch due to the slippage effect.


FEL power vs wavelength
(Q= 60 pC, $L_b$ = 0.5 ps, f= 81.25 MHz)


Energy spread (17.5 MeV, 0.5 ps)

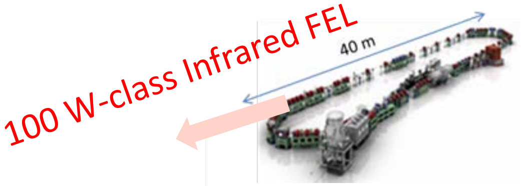

Energy spread (17.5 MeV, 2 ps)

# Items to be consider for cERL-FEL from the view points of beam operation

1. Operation of high current beam
   - Average current of 5 mA (10 mA @ EUV-FEL)
   - Bunch charge of 60 pC with low emittances
   - Bunch repetition rate of 81.25 MHz (162.5 MHz @ EUV-FEL)
2. Beam transportation after FEL
   - Large energy spread due to FEL lasing
   - Beam loss in the dispersion sections (dump line, 2nd arc)
3. Bunch compression & decompression
   - Essential to EUV-FELs
   - Increased peak currents for FEL
   - Reduced energy spread after deceleration

# Staging to realize the EUV-FEL light source

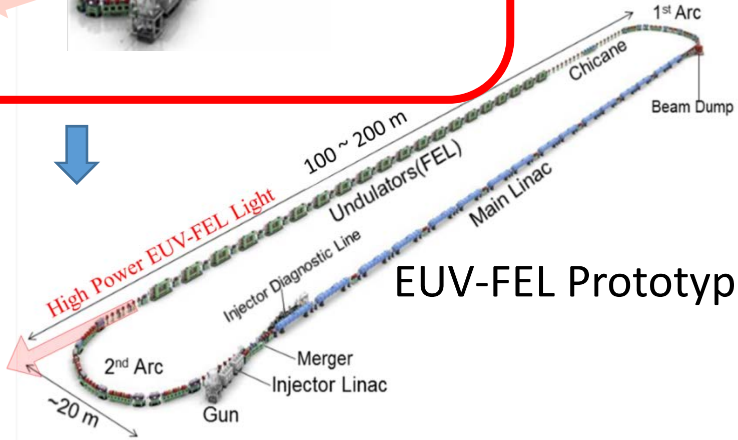
**1st stage:**
**Development of the feasible technologies**



cERL

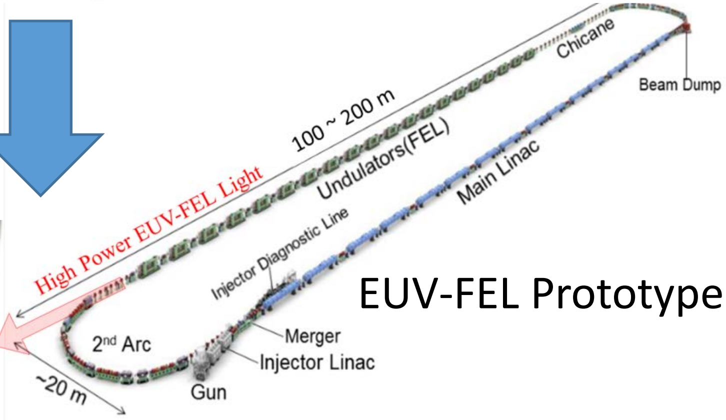
Upgrade plan of cERL for the PoC

**2nd stage Phase 1:**
**Establishment of the EUV-FEL Lithography system**



EUV-FEL Prototype

**2nd stage Phase 2:**
**International Development Center on the processing of EUV-FEL lithography**

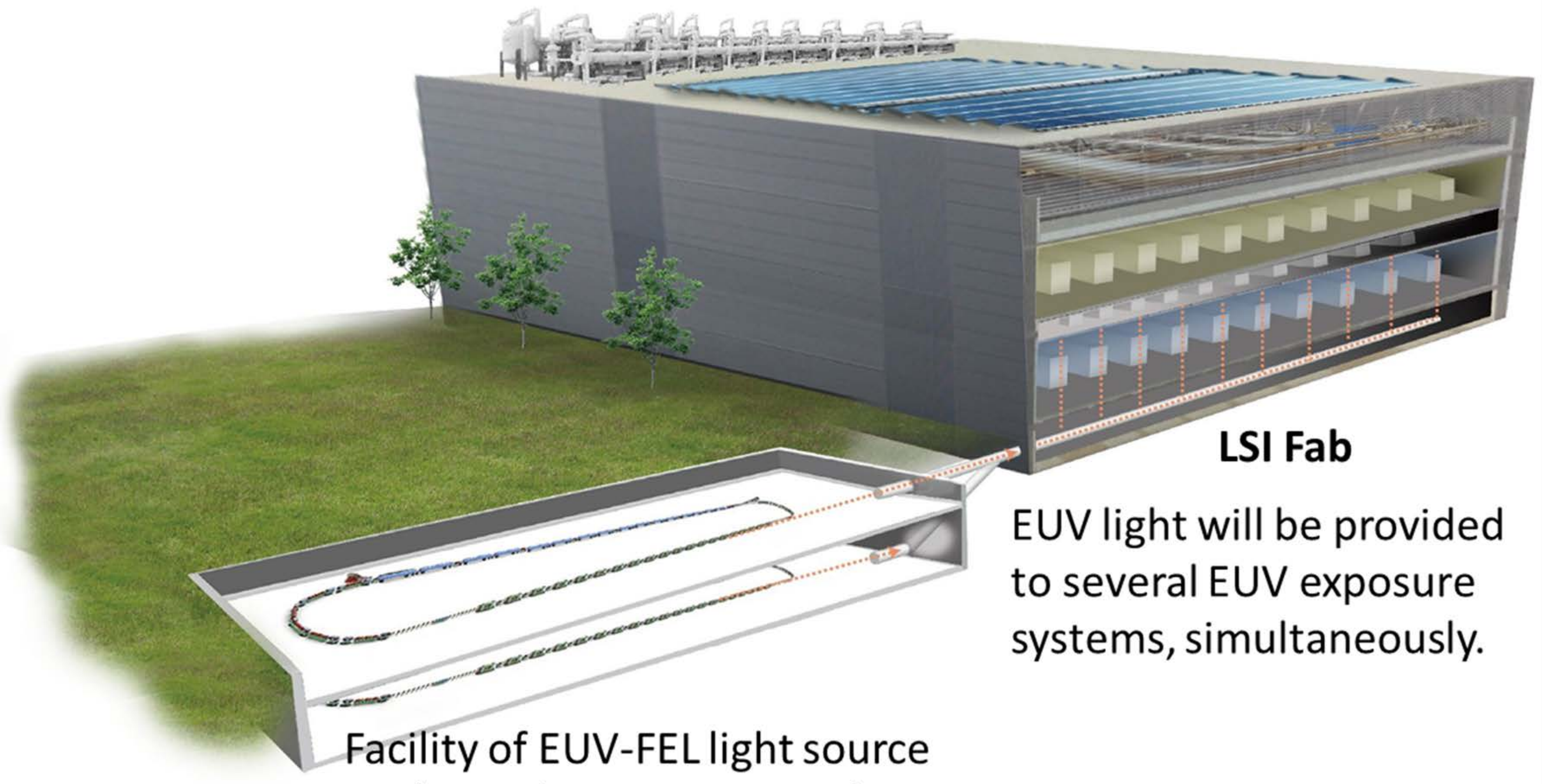


EUV-FEL Prototype

Clean room with EUV exposure system

IR-FEL project as a PoC is important to realize the EUV-FEL light source for future EUV Lithography.

# Expected LSI Fab with EUV-FEL



**LSI Fab**

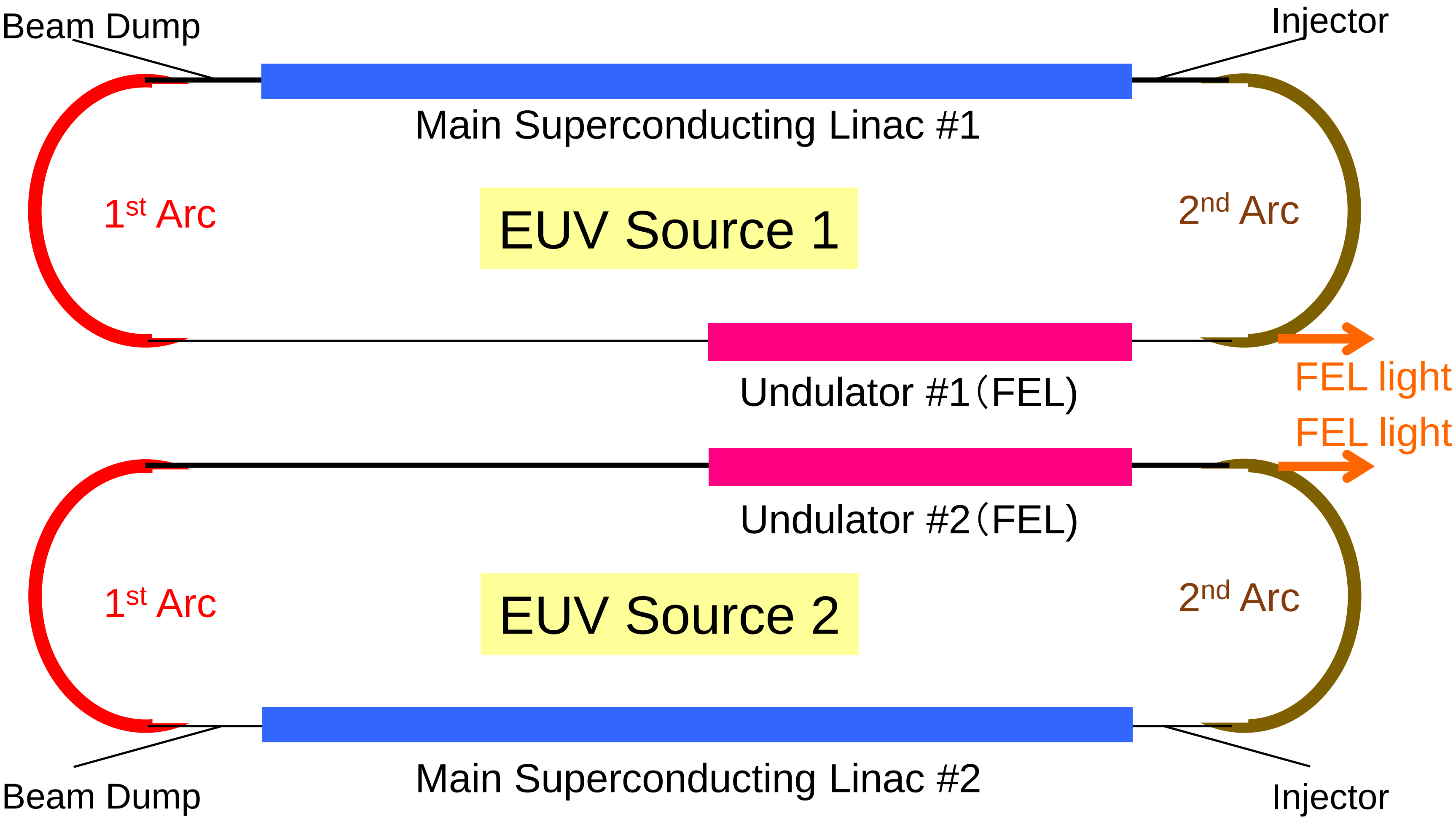
EUV light will be provided to several EUV exposure systems, simultaneously.

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

# Part 3:

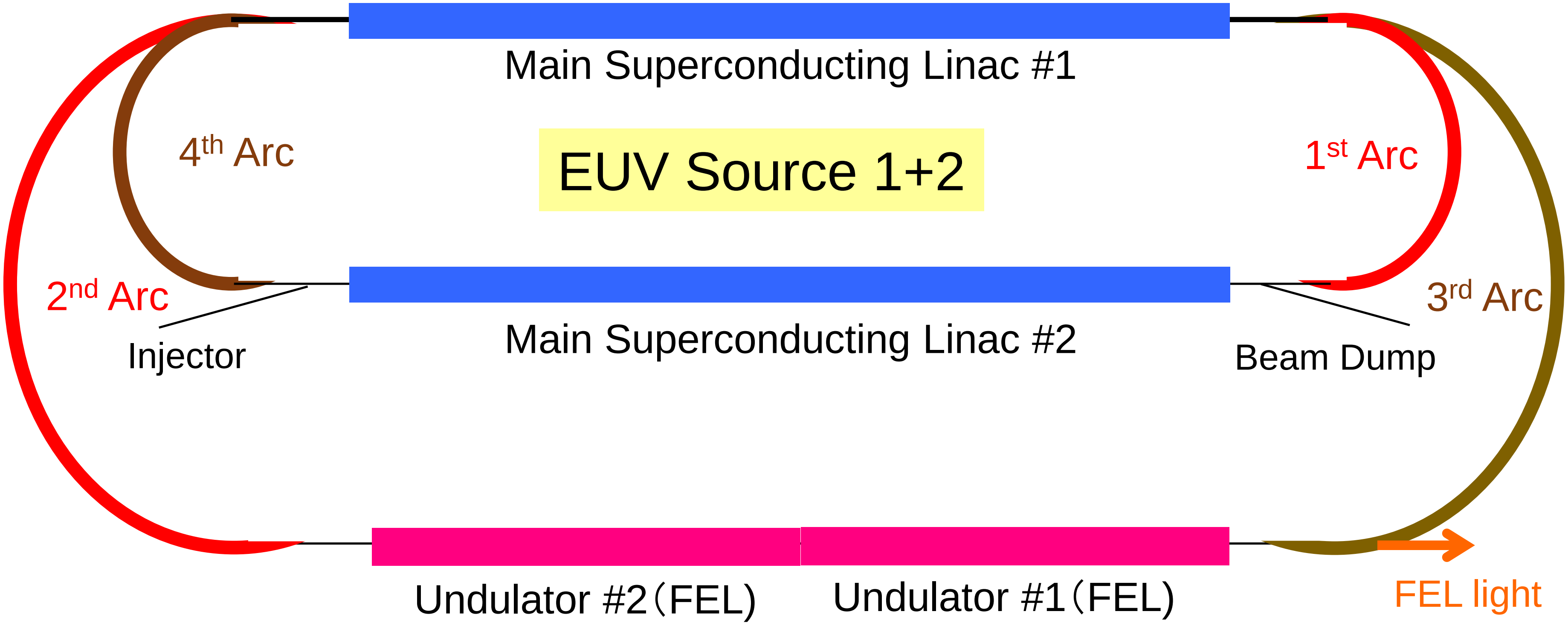
# Is it possible to obtain a wavelength of several nm from EUV-FEL?

# Redundancy of EUV-FEL (13.5 nm)



FEL output power : 10 kW x 2 (13.5 nm, redundant)

# Rearrangement of EUV-FEL (3.4 nm)



FEL output power : ~10 kW (3.4 nm)

# SASE-FEL formula (1D model)

- **FEL wavelength**

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

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

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

- **FEL parameter (1D)**

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

- **Gain Length (1D)**

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

- **Saturation Length**

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

- **FEL power**

$$P_{FEL} = \rho P_{beam} = \rho E I_{beam}$$

| | 13.5 nm | 6.7 nm | 3.4 nm |
|---|---|---|---|
| Wavelength | $\lambda$ | $\lambda/2$ | $\lambda/4$ |
| Beam Energy | $\gamma$ | $\sqrt{2}\gamma$ | $2\gamma$ |
| FEL Parameter (1D) | $\rho$ | $\rho/\sqrt{2}$ | $\rho/2$ |
| Gain Length (1D) | $L_{gain}$ | $\sqrt{2}L_{gain}$ | $2L_{gain}$ |
| Saturation Length | $L_{sat}$ | $\sqrt{2}L_{sat}$ | $2L_{sat}$ |
| Beam Power | $P_{beam}$ | $\sqrt{2}P_{beam}$ | $2P_{beam}$ |
| FEL Power | $\rho P_{beam}$ | $\rho P_{beam}$ | $\rho P_{beam}$ |

# Issues beyond the EUV-FEL

- Stochastic effect
- Low reflectivity of multilayer mirror
- Narrow bandwidth of multilayer mirror

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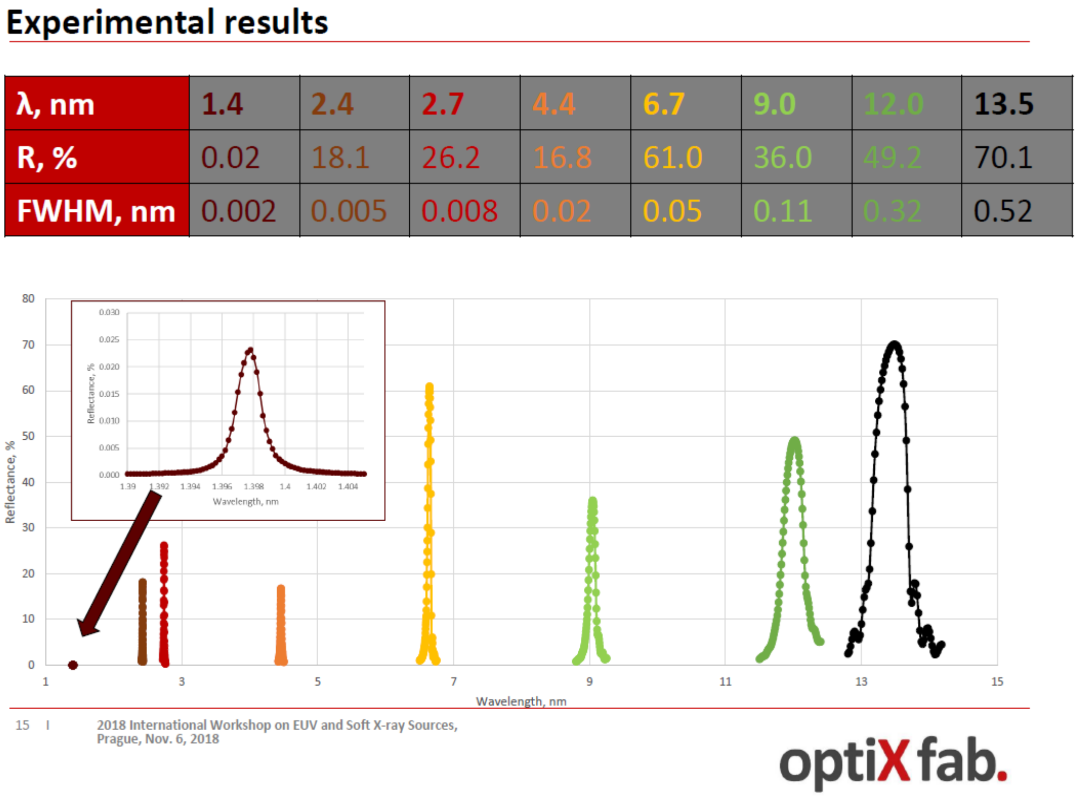
Low reflectivity & Narrow bandwidth of multilayer mirrors were shown at 2018&2019 Source Workshop from optiX fab.



**Experimental results**

| **λ, nm** | **1.4** | **2.4** | **2.7** | **4.4** | **6.7** | **9.0** | **12.0** | **13.5** |
|---|---|---|---|---|---|---|---|---|
| **R, %** | 0.02 | 18.1 | 26.2 | 16.8 | 61.0 | 36.0 | 49.2 | 70.1 |
| **FWHM, nm** | 0.002 | 0.005 | 0.008 | 0.02 | 0.05 | 0.11 | 0.32 | 0.52 |

15 | 2018 International Workshop on EUV and Soft X-ray Sources, Prague, Nov. 6, 2018

optiX fab.

https://www.euvlitho.com/2018/S18.pdf

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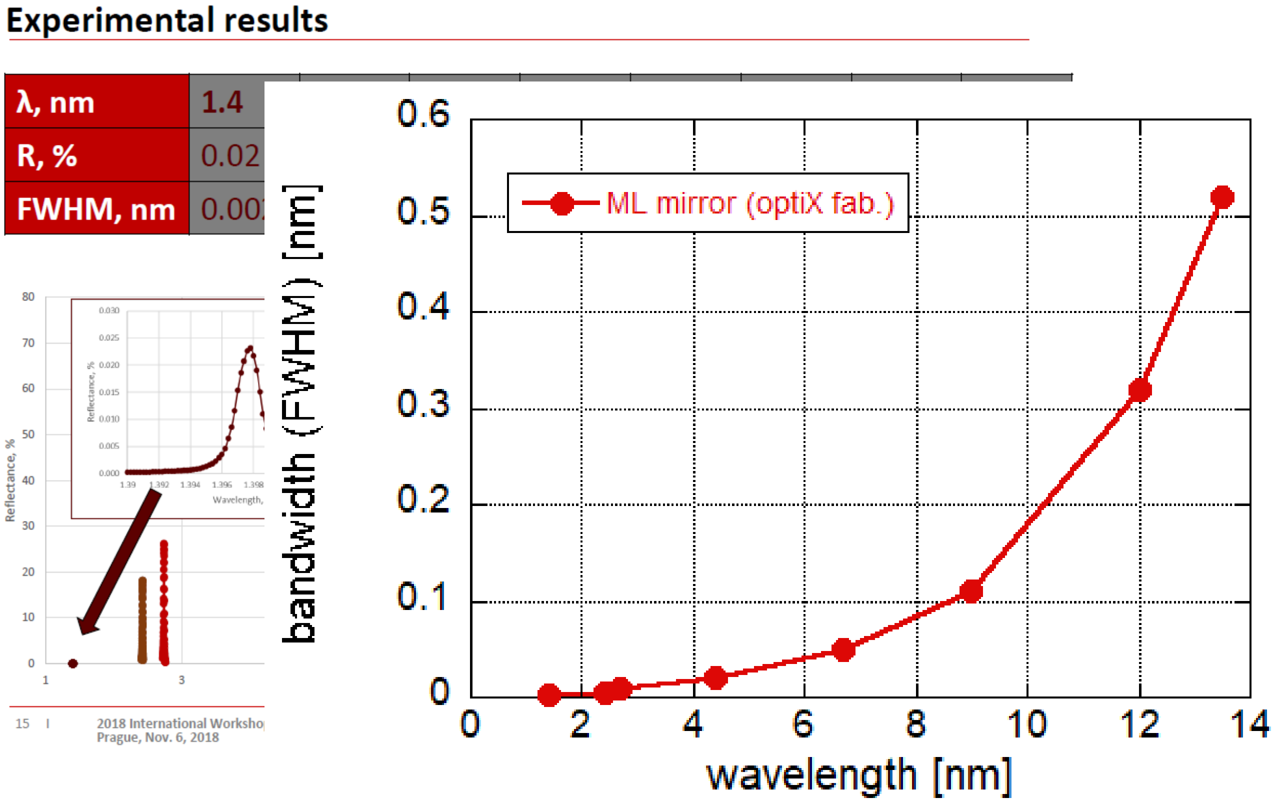

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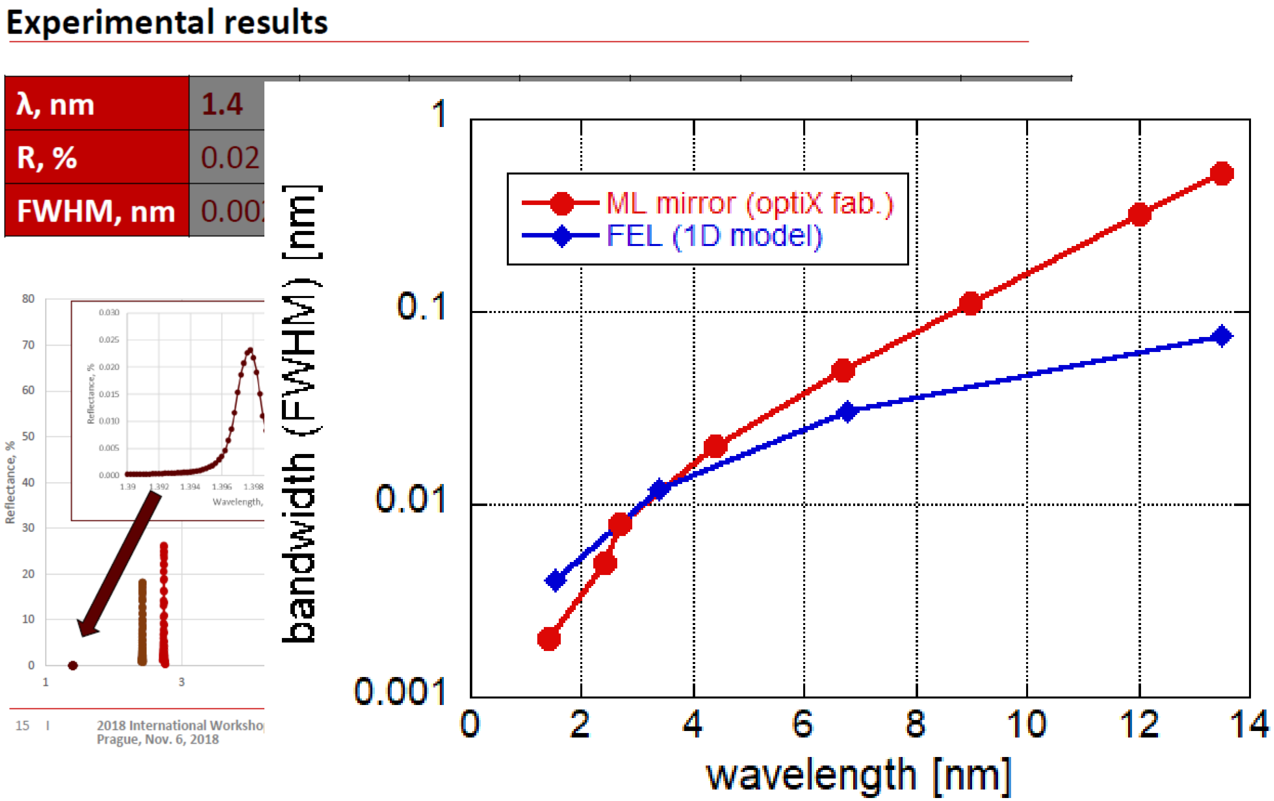

**Experimental results**

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15 | 2018 International Worksho
Prague, Nov. 6, 2018

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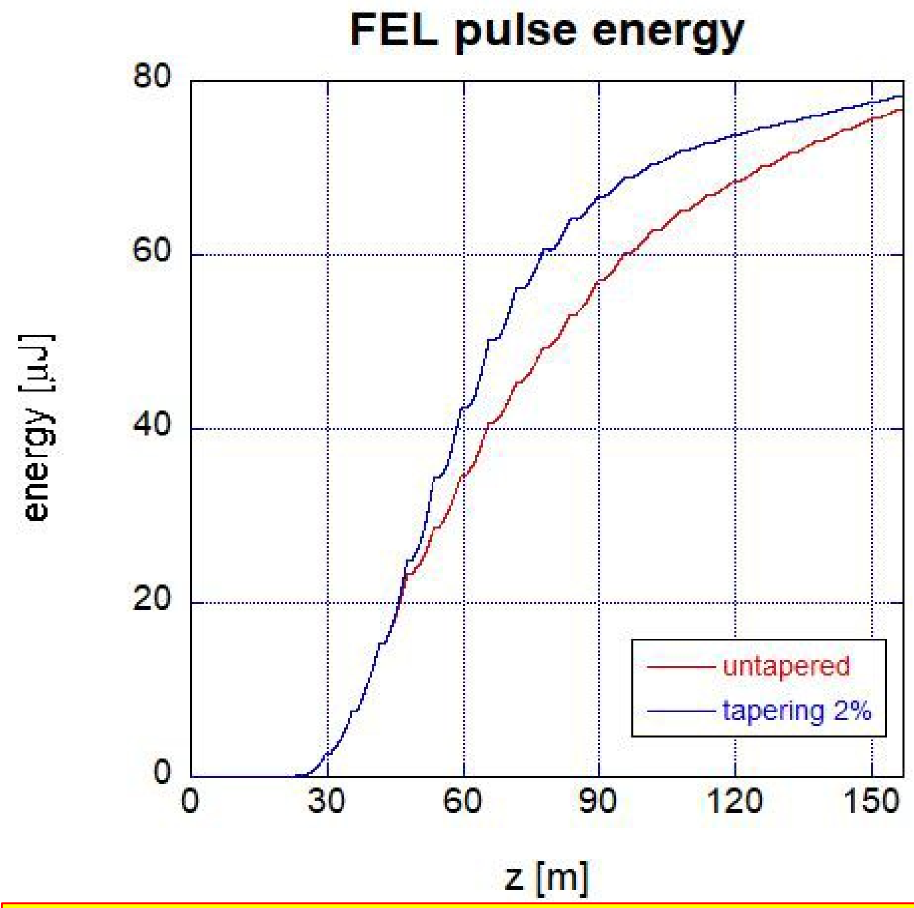
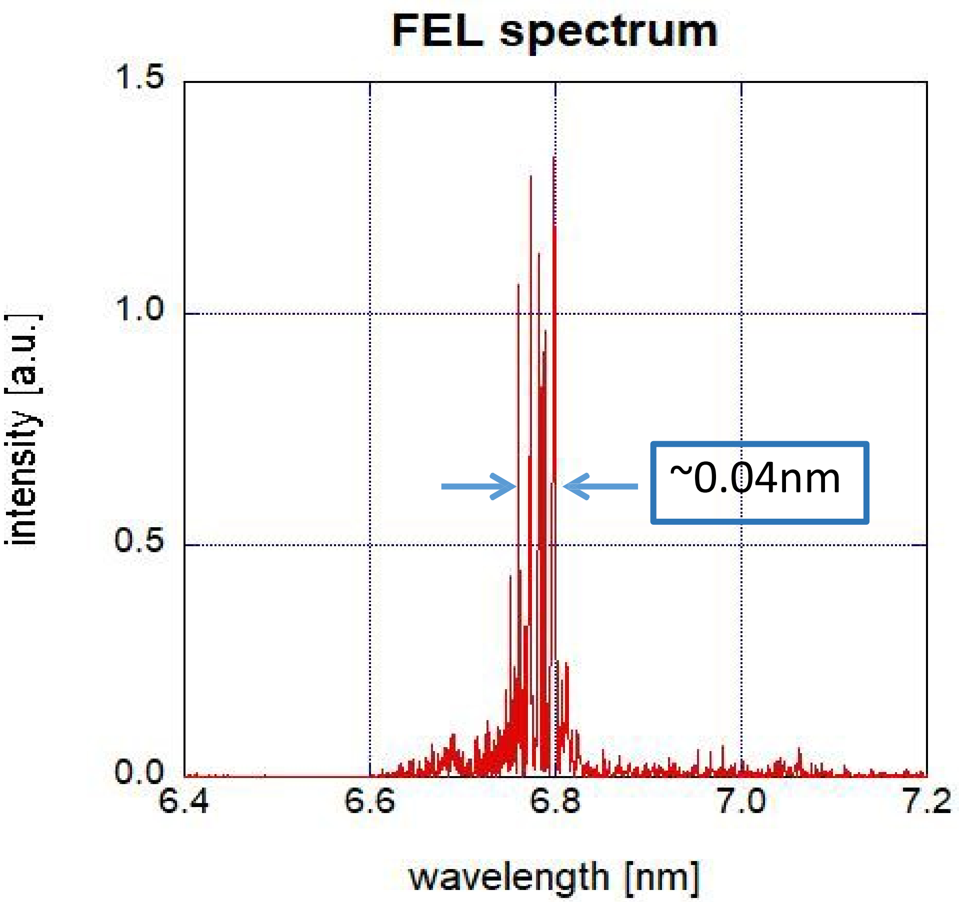
# Recent study about the power and spectrum





FEL power with 2% tapering:
12.7/25.4 kW @ 9.75/19.5 mA (162.5/325 MHz)

$\Delta\lambda/\lambda = 6 \times 10^{-3}$

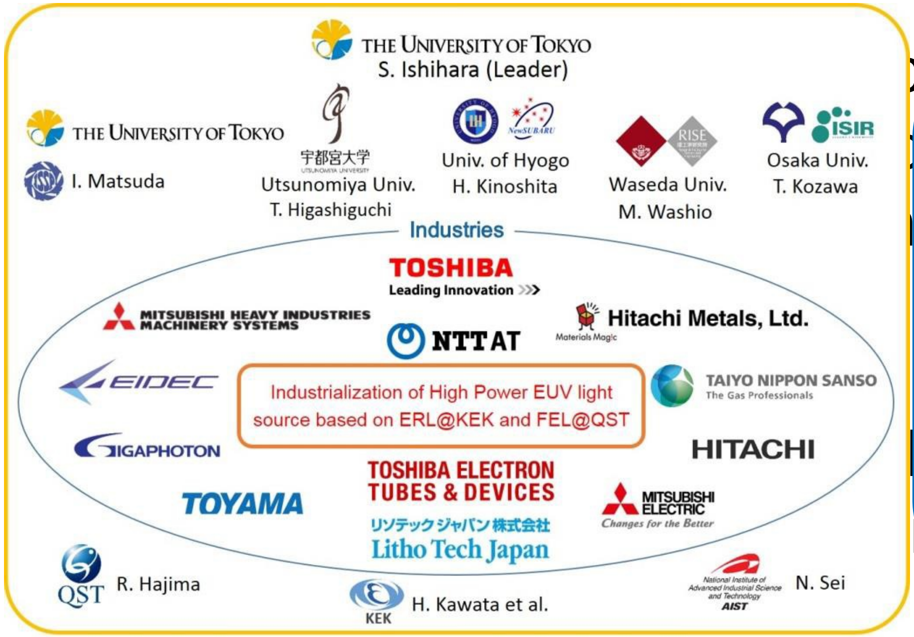
Beam energy : E = 1131 MeV ($800 \times \sqrt{2}$),
The other parameters are almost same to these of EUV-FEL

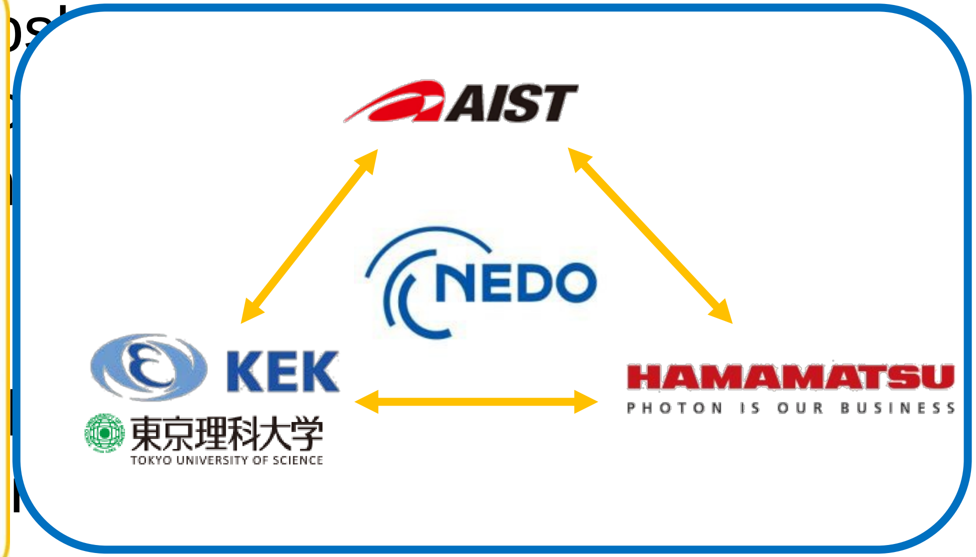
# Summary

# Summary

- By using ERL technology, FEL can be operated in high repeat rate, and the beam dump power can be reduced.
- KEK will install two undulators in the cERL and develop an infrared FEL with high average power. With the IR-FEL, mid-infrared light can be obtained average power exceeding 1 W  in CW operation.
- IR-FEL can demonstrate many of the challenges for the realization of EUV-FEL.
- From the viewpoint of compatibility with the bandwidth of multilayer mirrors, the EUV-FEL's critical wavelength is expected to be about 3.5 nm.
- In the 6.7 nm wavelength range, the FEL spectrum is well within the bandwidth of the multilayer mirror, and an output of 10 kW or more can be expected.

# Core members for IR-FEL and Acknowledgement





This presentation is based on results obtained from NEDO project "Development of advanced laser processing with intelligence based high-brightness and high-efficiency laser technologies (TACMI project)."

Thank you for your attention!