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IR-FEL Project at the cERL and Future EUV-FEL Lithography

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High Energy Accelerator Research Organization (KEK)

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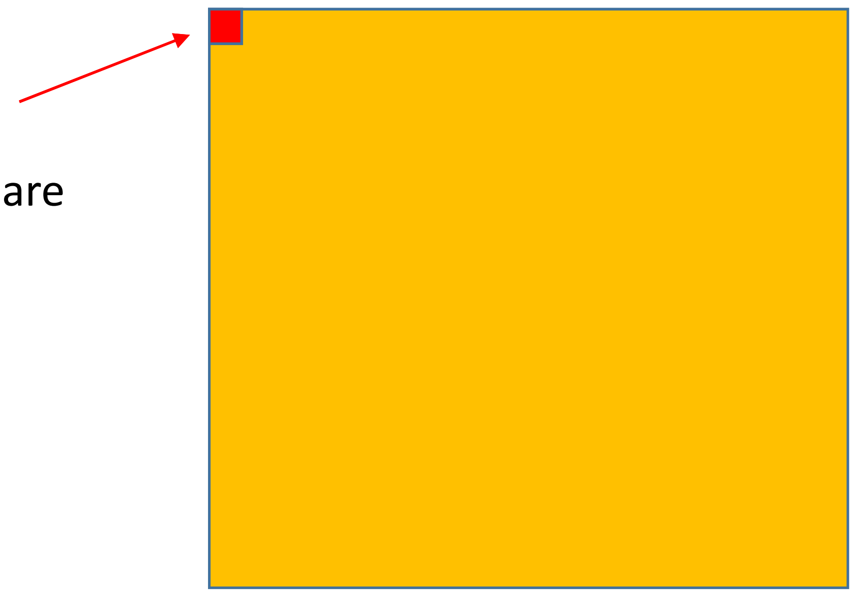
Part 1:

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?

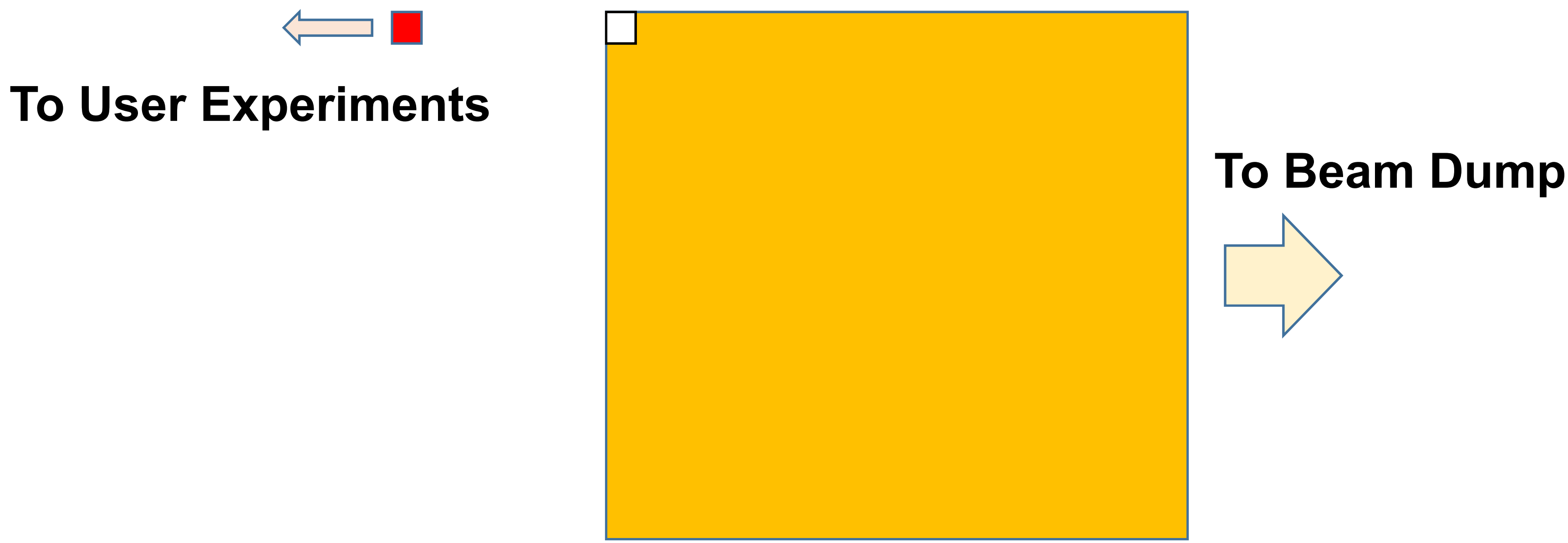


Maybe …
this red square

- FEL conversion efficiency is ~ 10^{-2} in the infrared region and 10^{-3} to 10^{-4} in the 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?

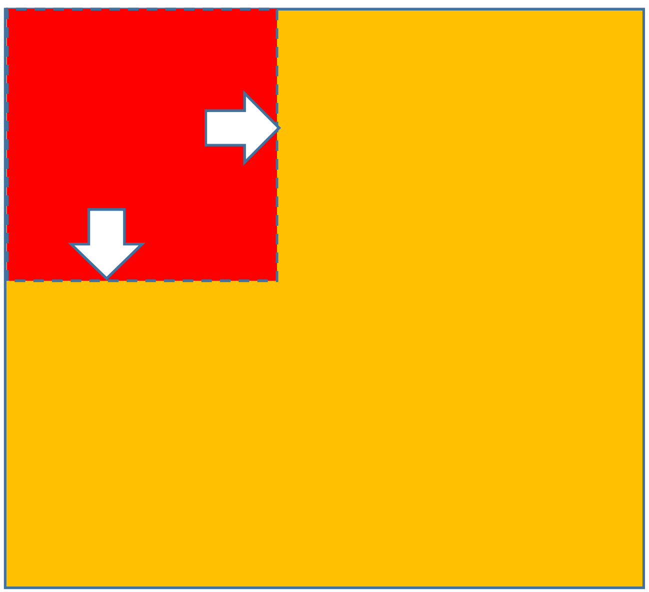


- Low conversion efficiency of FEL is not a serious problem for academic use.
- However, for industrial use ... we need improvement!

To make the efficiency better

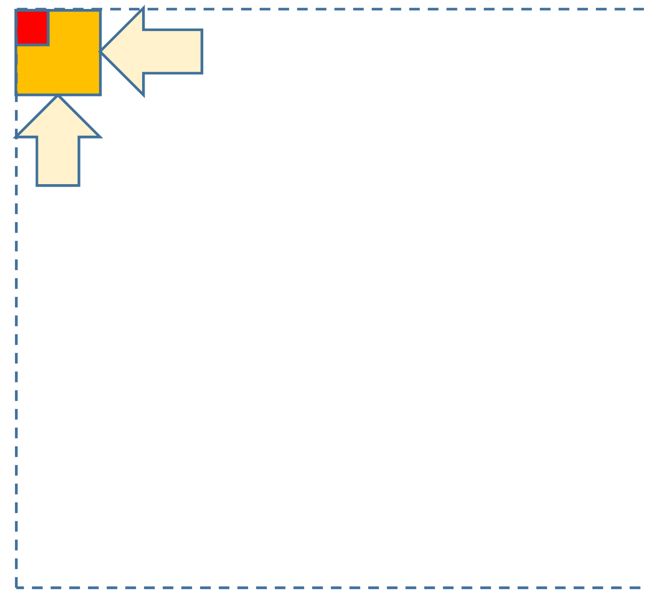
- There are 2 ways to improve conversion efficiency

(1) Increase efficiency itself



Tapered FEL, TESSA*, …

(2) Reduce dump power

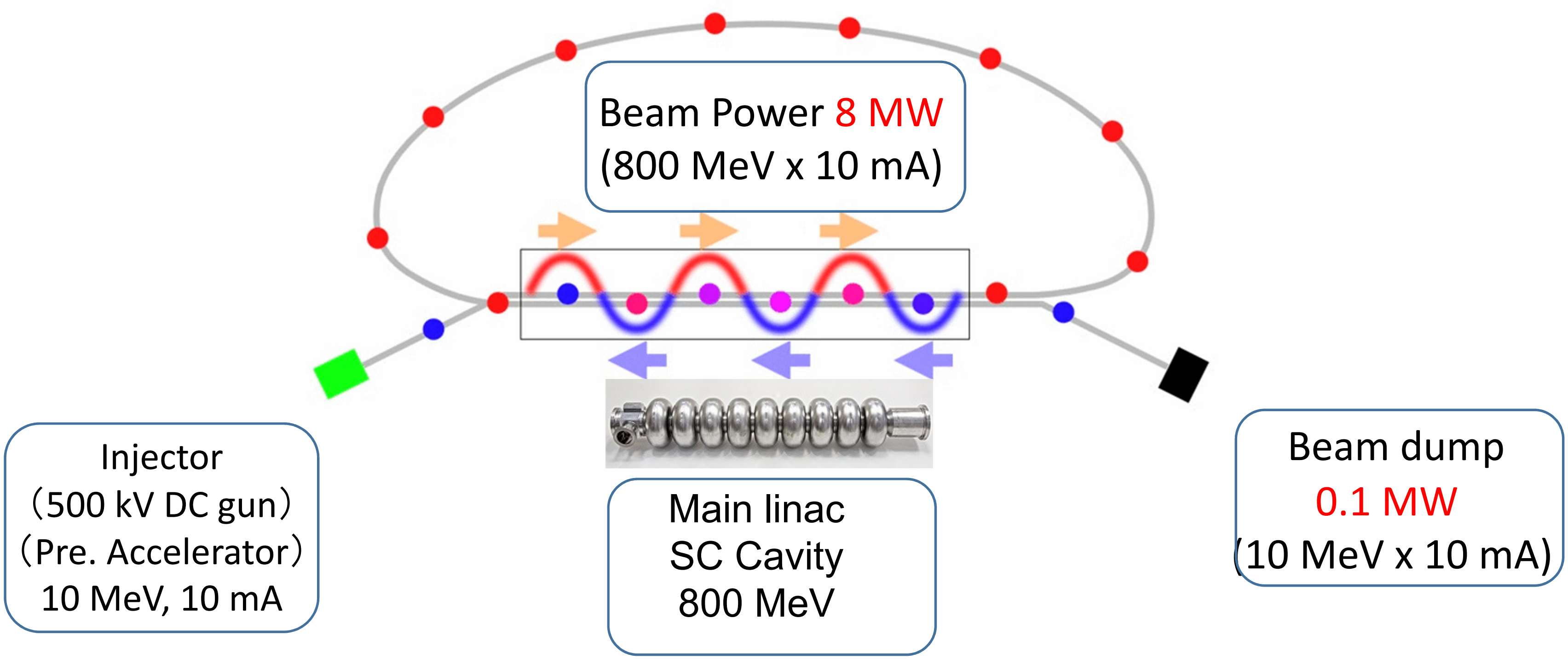


Energy Recovery

*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.



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

EUV/X-Ray FELs

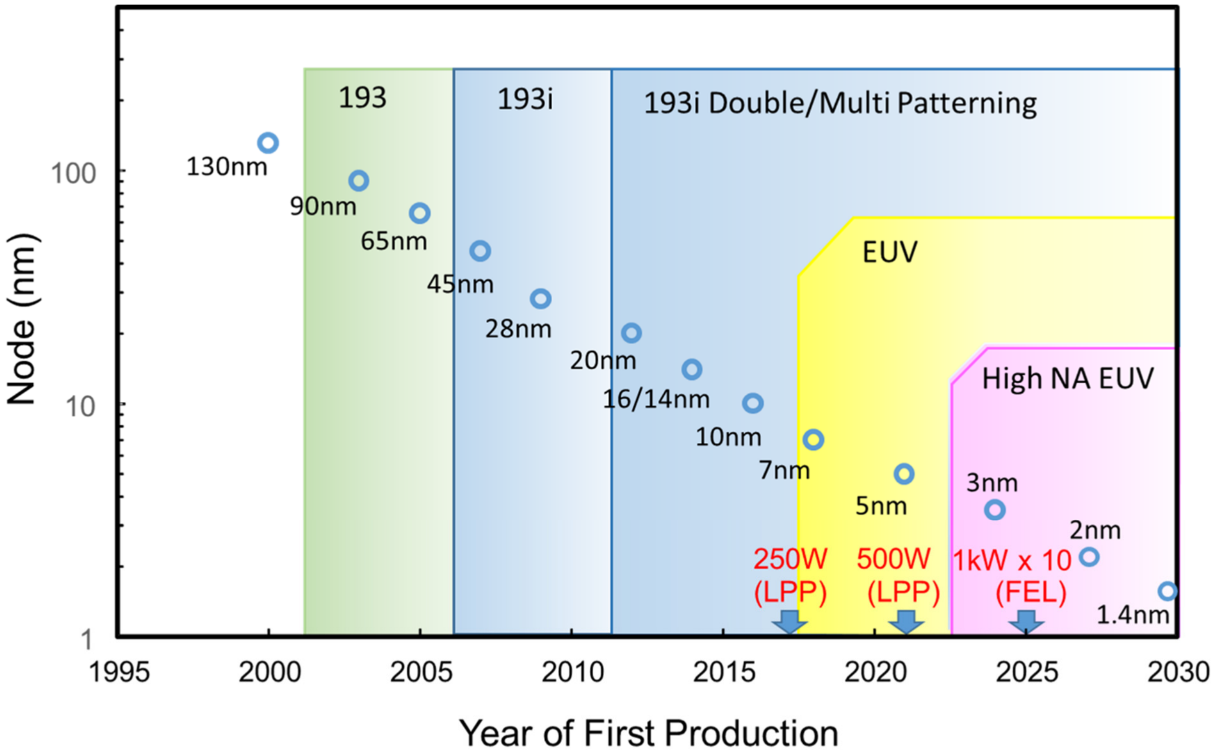
	LCLS	SACLA	FLASH	Euro-XFEL	LCLS II	EUV-FEL
Type	Normal conducting		Super conducting			
Configuration	Linac		Linac			ERL
Operation Mode	Pulse		Long-pulse		CW	
Country	US	Japan	Germany	EU	US	---
Repetition rate (pulse/sec)	120	60	<5000	<27000	1M	162.5M
Beam energy (GeV)	14.3	6～8	1.25	17.5	4	0.8
Wavelength (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

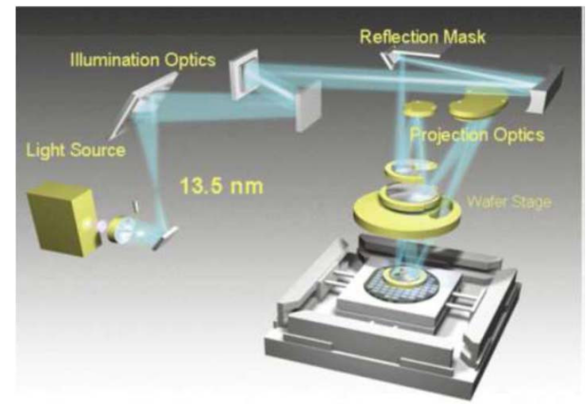
ERL helps to make high-power CW FEL and reduce the beam dump power.

Part 2:

EUV-FEL Light Source for Future Lithography

Technology node trend of Logic LSI and expected power on EUV light source





LPP (Laser Produced Plasma) of 13.5nm
→ 250W level now

Emission from Sn Plasma
CE(CO_2 to EUV):5.5 %
CO_2 Laser: : 5 kW

For 1-kW EUV LS
CO_2 laser :20 kW
CE (Plug to CO_2) : 10%

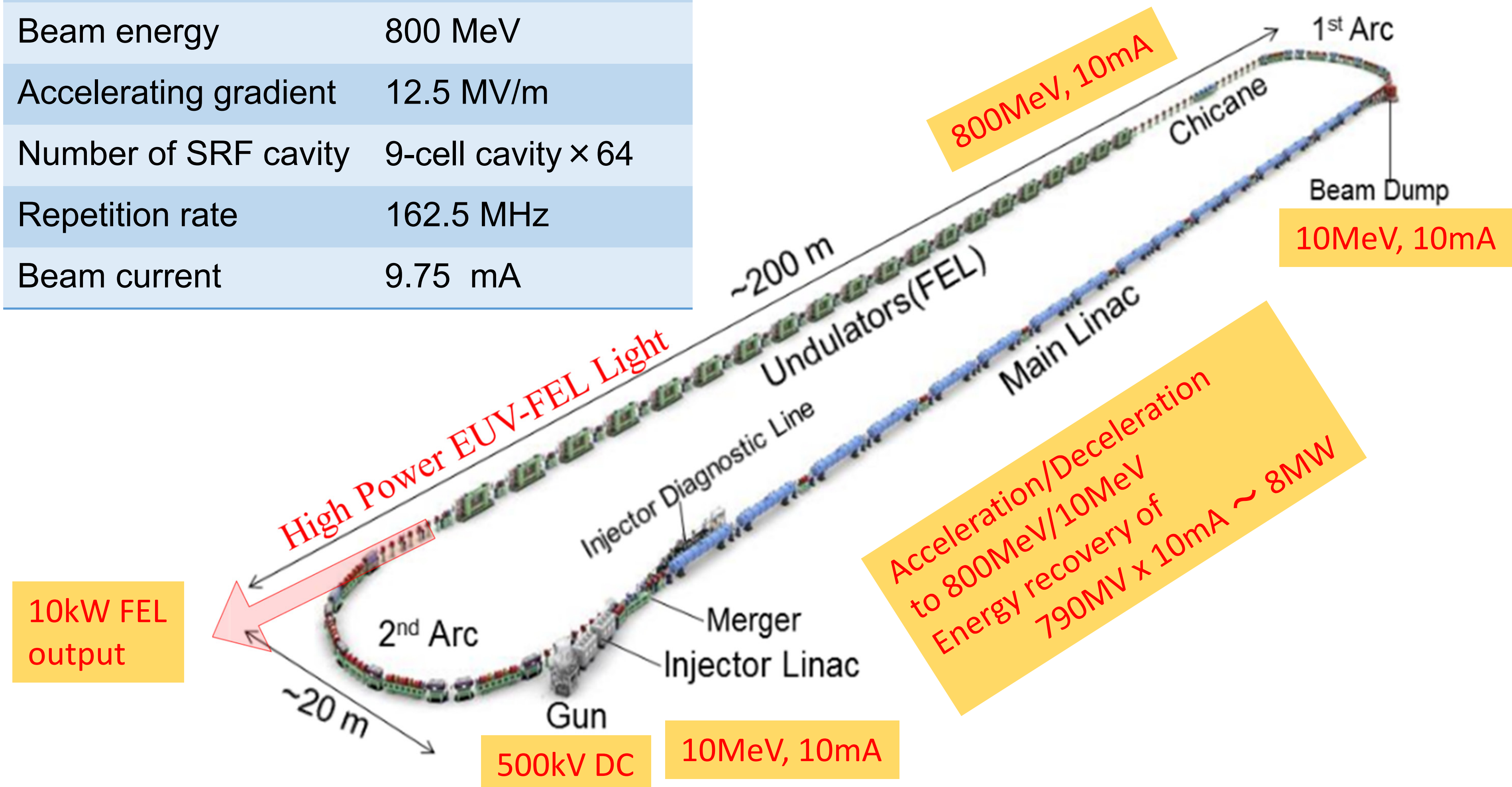
Need breakthrough for 1kW EUV LS

In the future, 1-kW class EUV sources are required for High NA (Numerical Aperture) Lithography

So we have proposed ERL-based FEL (EUV-FEL) that can supply 1 kW power to 10 exposure systems .

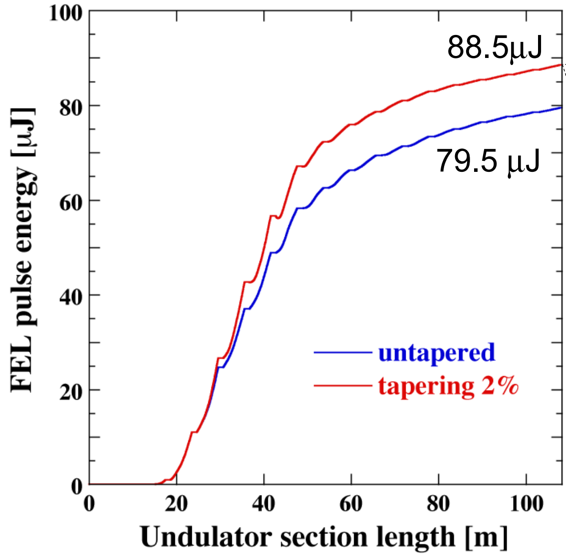
Prototype design of the EUV-FEL

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

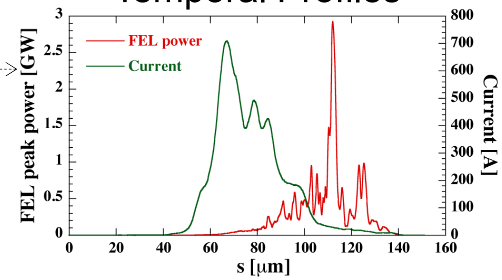


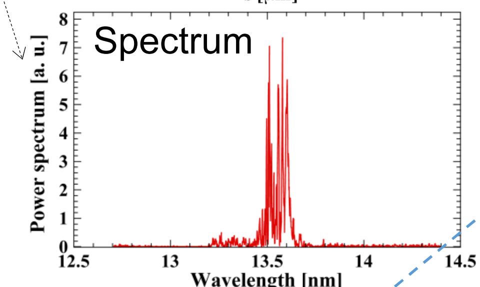
FEL Performance

FEL pulse energy evolution

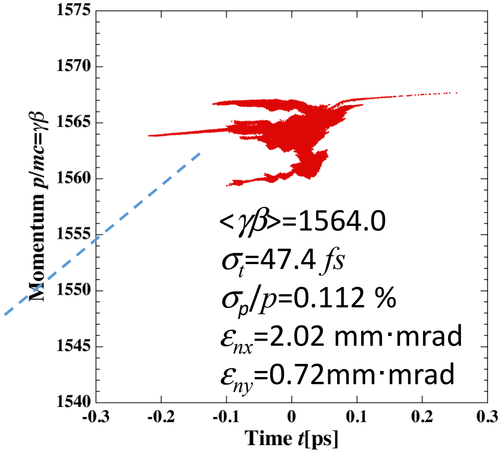


Temporal Profiles





e$^-$ dist. before FEL

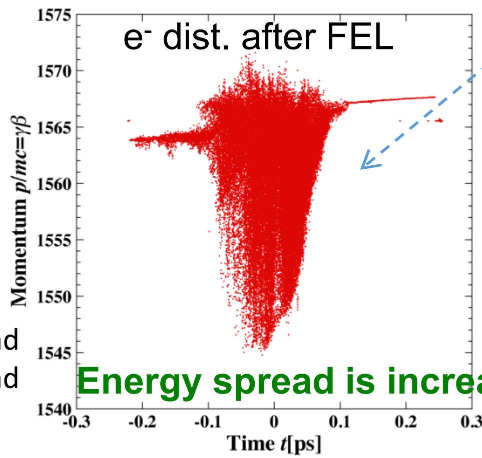


$<\gamma\beta>$=1564.0
σ_t=47.4 *fs*
σ_p/p=0.112 %
ε_{nx}=2.02 mm·mrad
ε_{ny}=0.72mm·mrad

FEL power without tapering: 12.9 kW @ 9.75 mA (162.5 MHz)
FEL power with 2% tapering: 14.4 kW @ 9.75 mA (162.5 MHz)

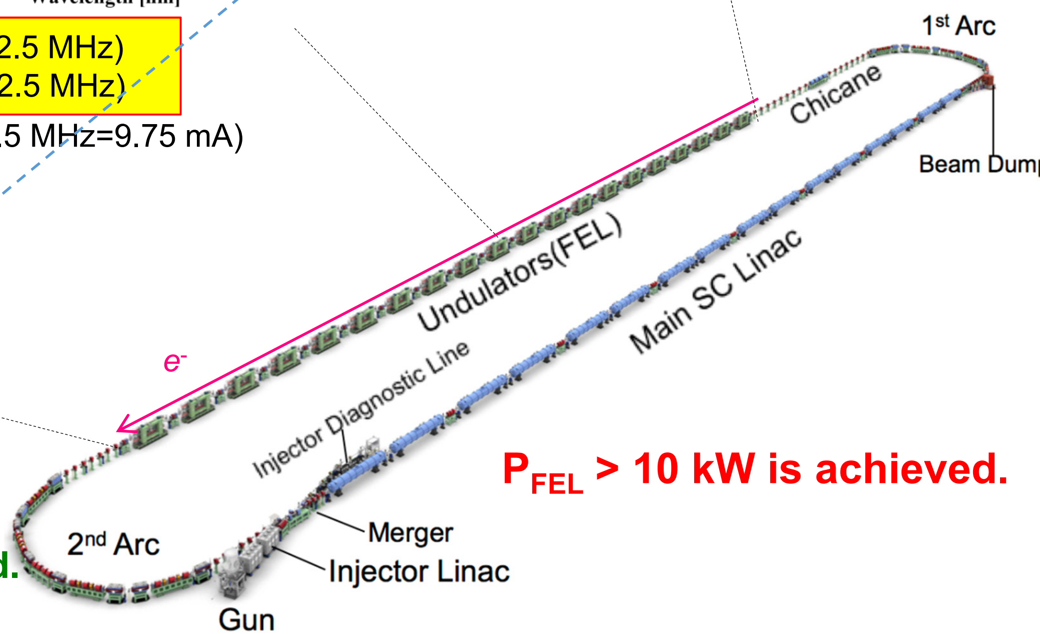
(P_{FEL}=88.5 μJ x 162.5 MHz =14.4 kW, I_{av}=60pC x 162.5 MHz=9.75 mA)

e$^-$ dist. after FEL



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

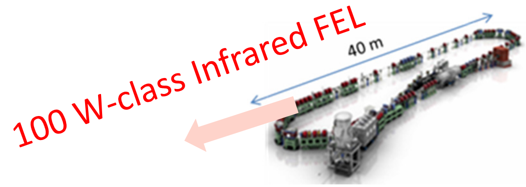
Energy spread is increased.



P_{FEL} > 10 kW is achieved.

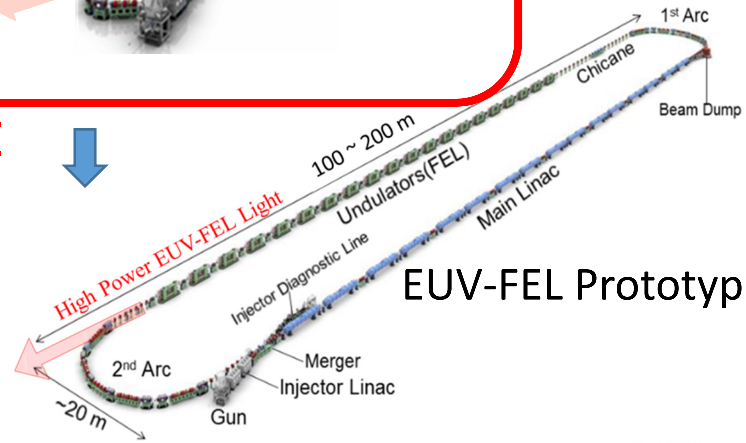
Staging to realize the EUV-FEL light source

1st stage:
Development of the feasible technologies

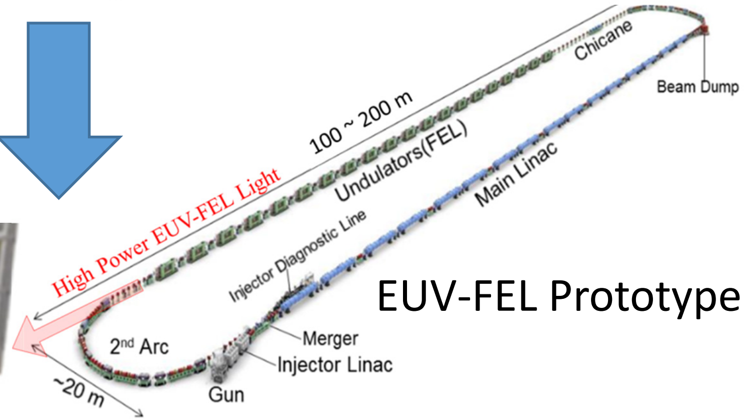


Upgrade plan of cERL for the PoC

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



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



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 3:

Project of IR-FEL based on the cERL

Background of IR-FEL Project (1)

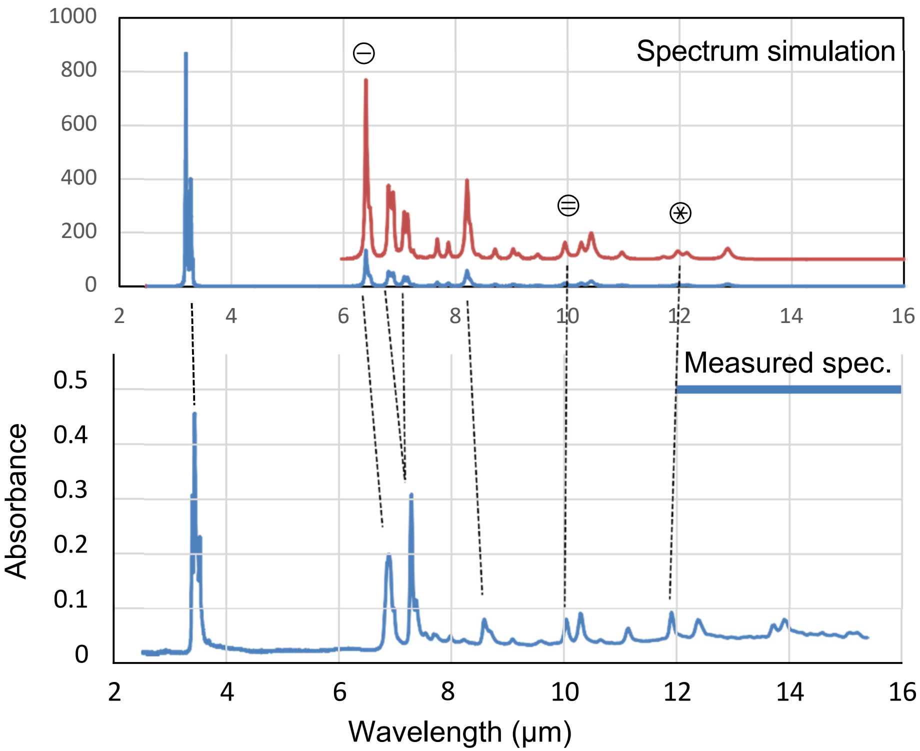
Organic materials (Resin, Engineering plastic) : light-weight, low-cost, high-functional

Recently, the use of organic materials has been increasing.

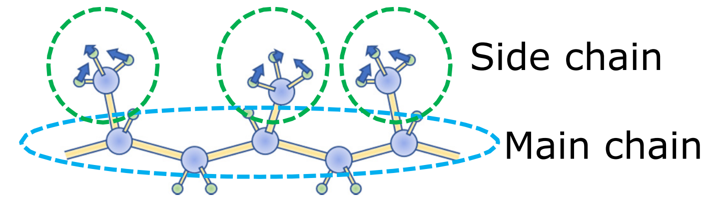
Processing methods : Machining, Molding, Laser processing (CO_2, Fiber)

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

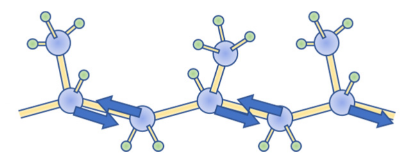
Absorption spectrum of polypropylene



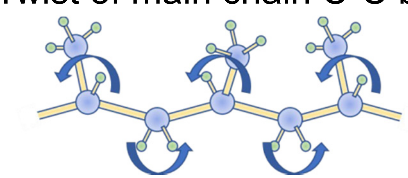
Peak①: δ declination of side chain methyl group



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,

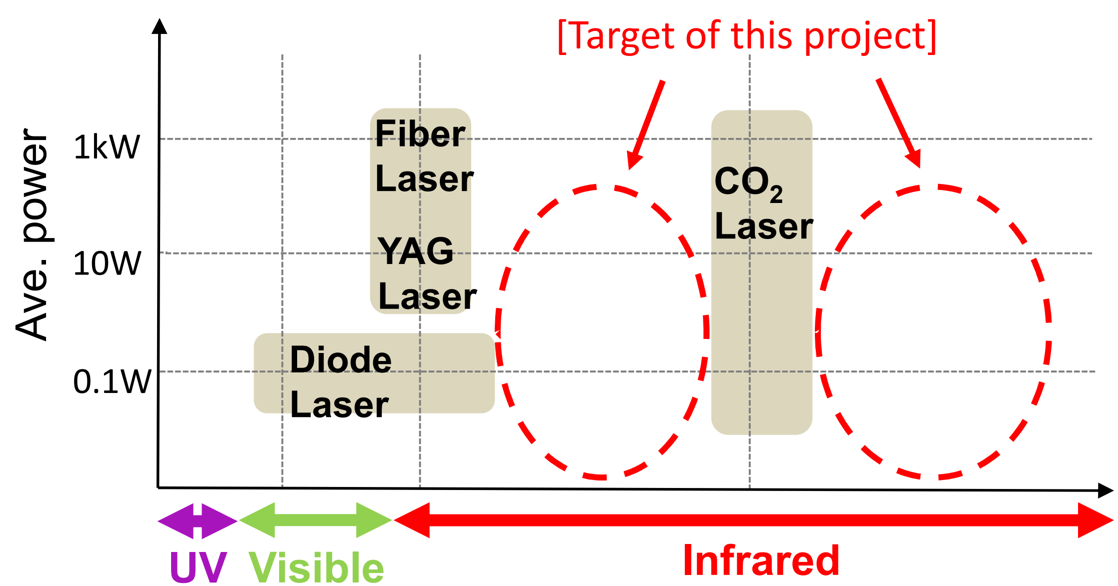
However, there is no database of easy-to-process wavelengths and required laser power.

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."



Wavelength ranges of lasers.

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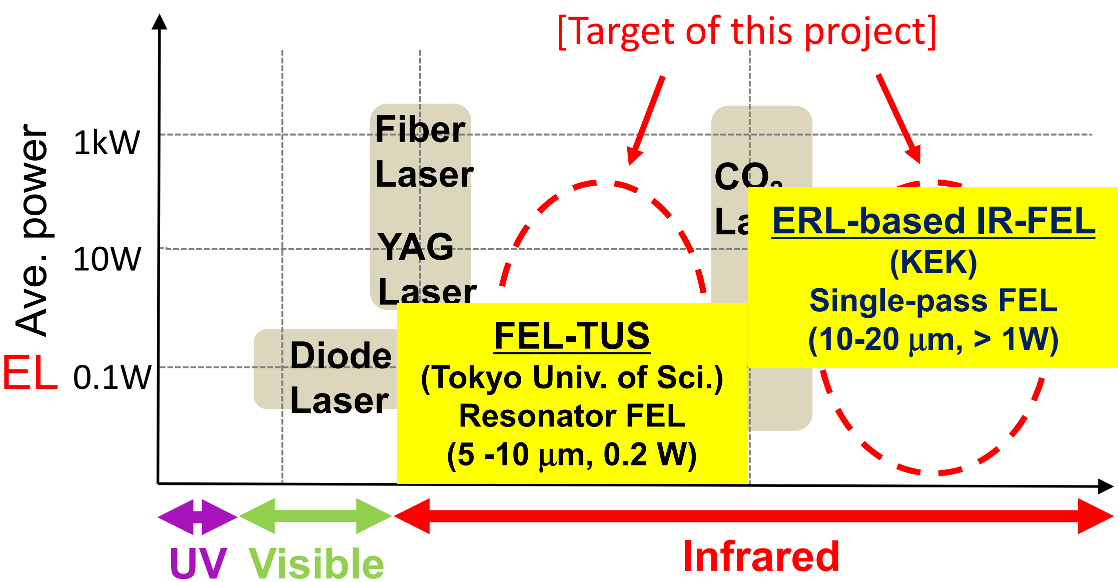
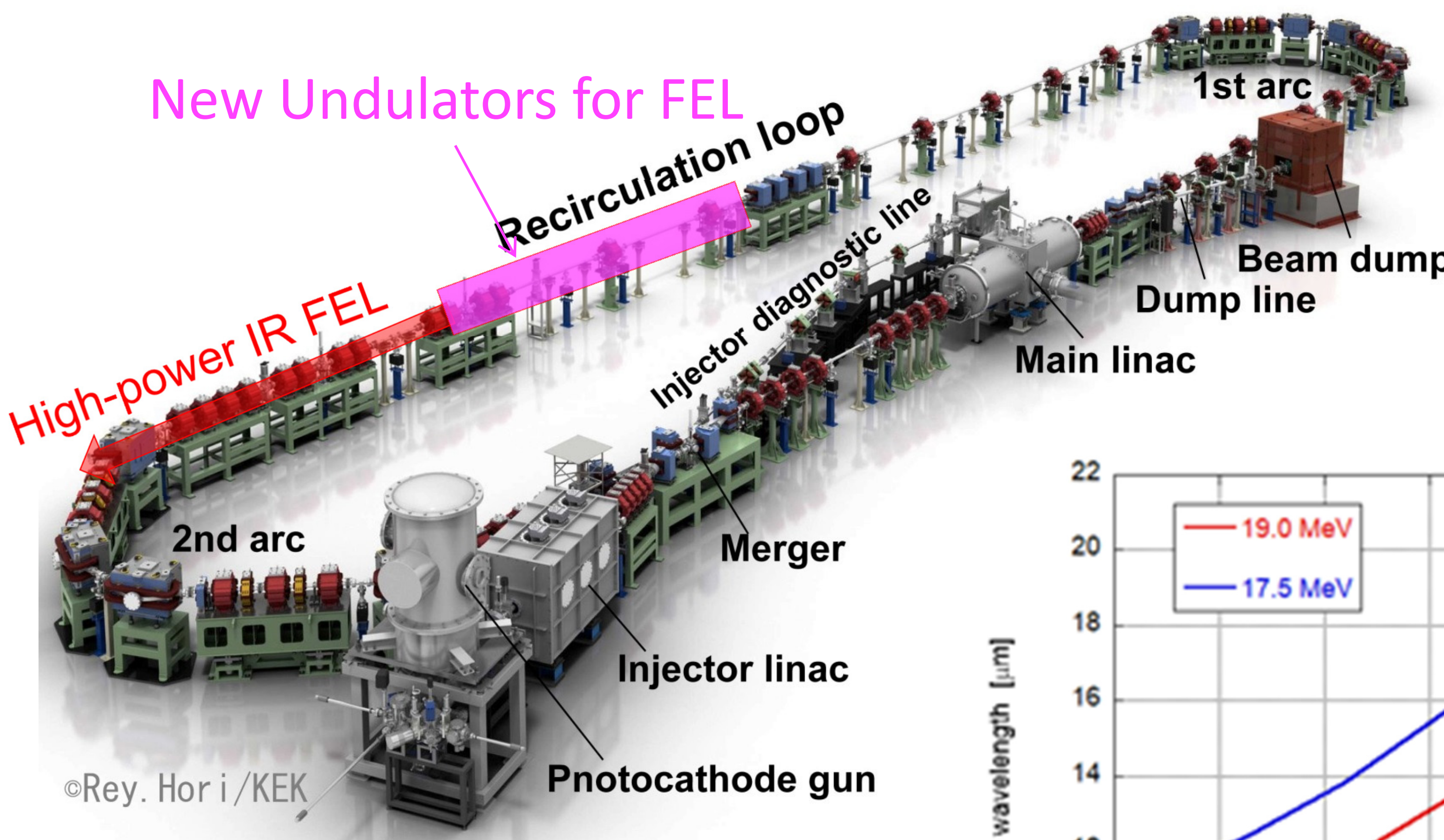
“Development of high-power mid-infrared lasers for high-efficiency laser processing utilizing photo-absorption based on molecular vibrational transitions.”

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

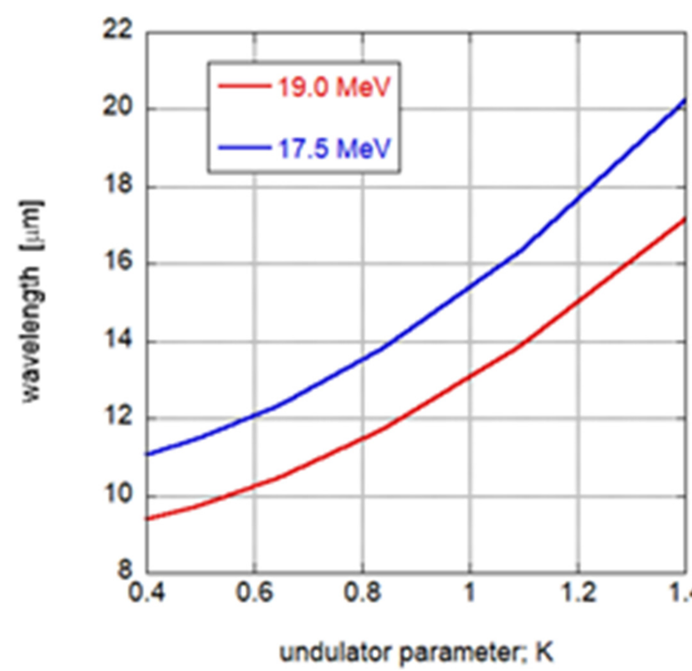


Wavelength ranges of lasers.

High average power IR-FEL Project

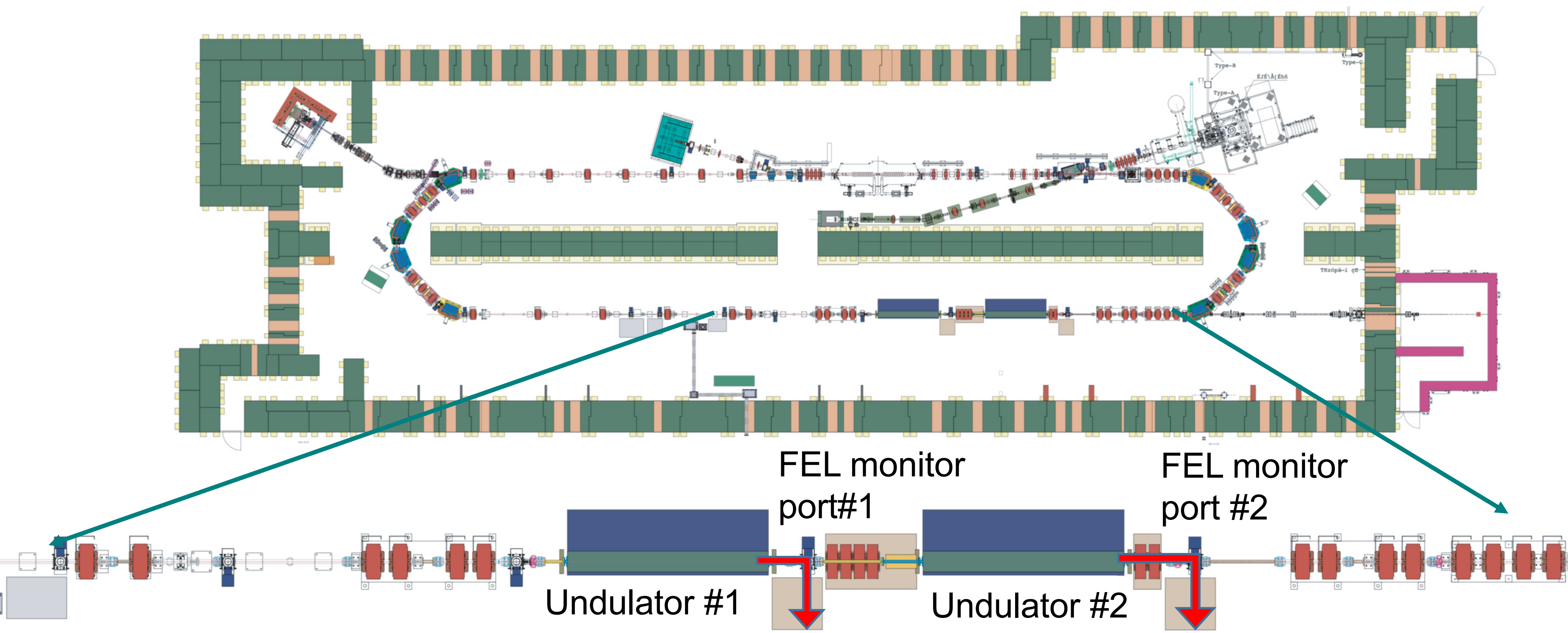


Beam Energy	17.5 - 19.0 MeV
Injector Energy	3.0 - 4.0 MeV
E-Gun Energy	500 keV
Bunch repetition	1.3 GHz → 81.25 MHz
Average current	1 mA (→ 5 mA)
Operation mode	CW or Burst



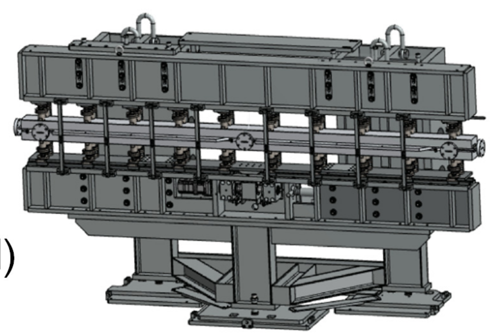
FEL wavelength

Layout and parameters of IR-FEL



Beam parameter

- Energy : 17.5 – 19.0 MeV
- Bunch charge : 60 pC
- Repetition : 81.25 MHz
- Bunch length : 0.5 – 2 ps (FWHM)
- Energy spread : 0.1%
- Norm. emittance : 3 π mm mrad



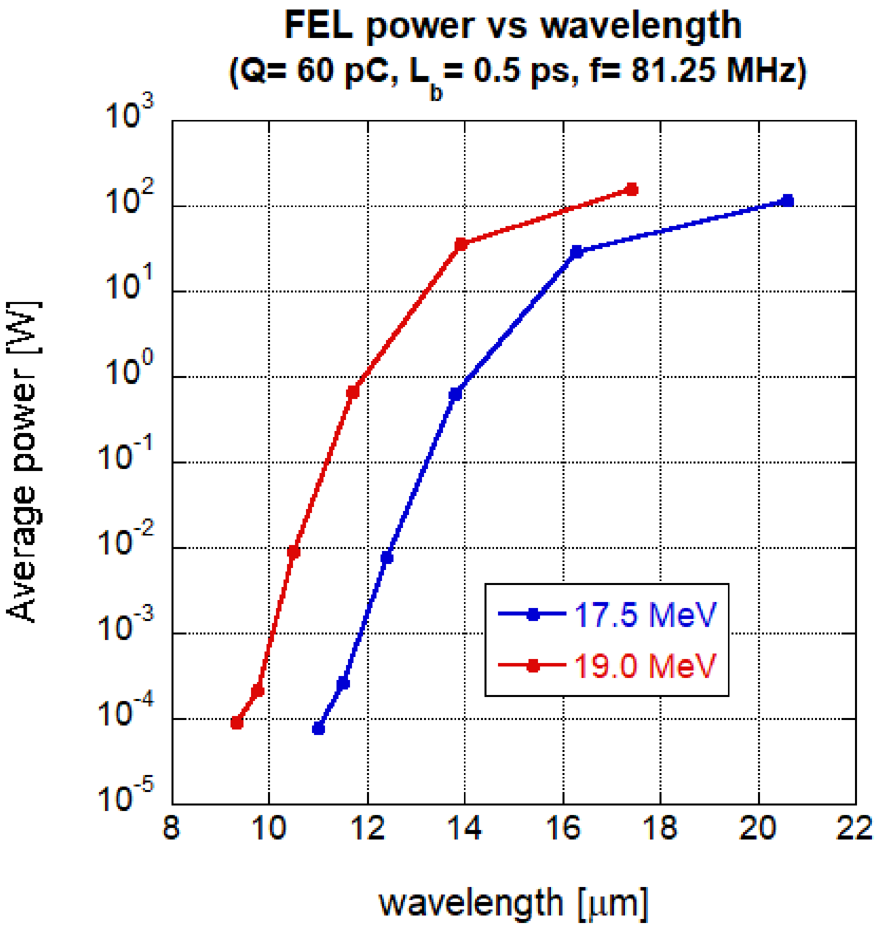
Design of undulators.

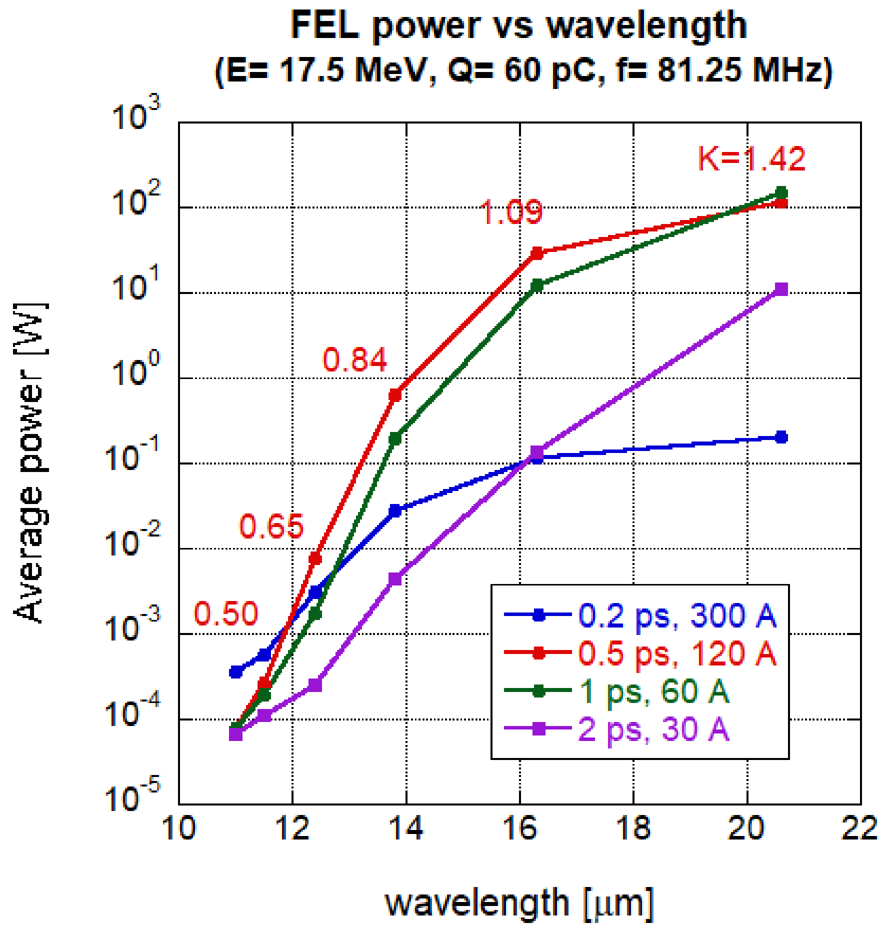
Undulator parameter

- Type: APU (Planar)
- Gap: 10 mm (Fixed)
- K: 1.42
- Period λu : 24 mm
- Total length : 3 m
- No. of Undulator : 2

Wavelengths & Ave. Power of IR-FEL

By changing the energy, an average power of 1 - 100 W can be obtained in the range of 12 – 20 μm. (Left)
FEL power depends on bunch length, but it decreases if bunch length is too short.

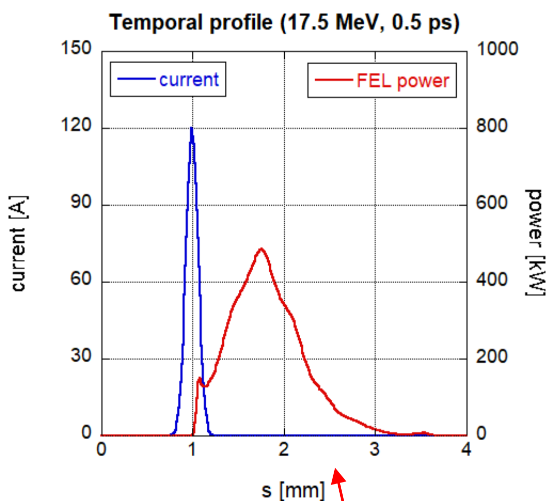


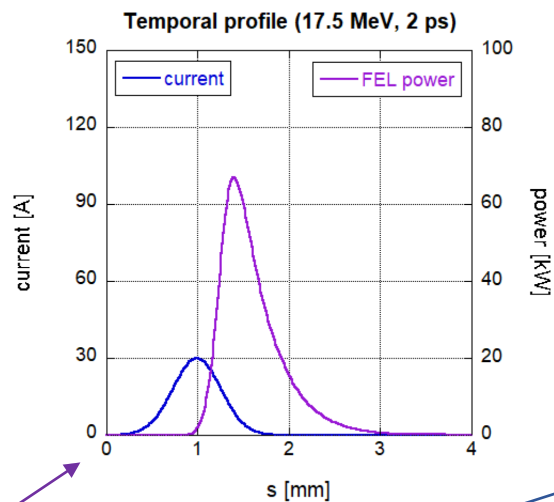


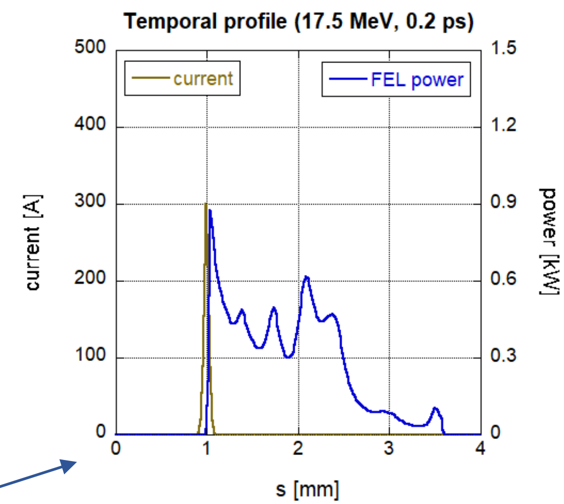
Temporal Profile of IR-FEL

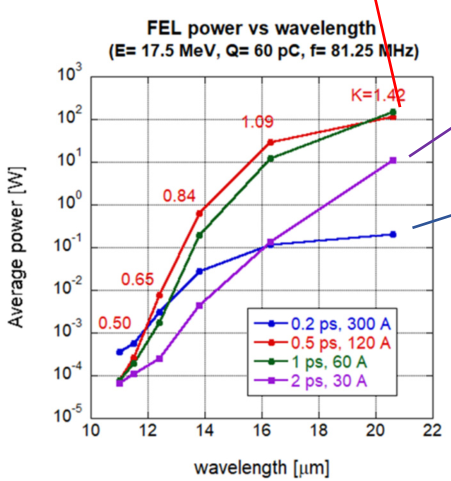
This IR-FEL is a high-gain, short pulse FEL in the MIR region.

Bunch length (0.2 – 2 ps) < Slipage (20 μm x 124 x 2 ~ 16 ps)









Proper bunch compression increases FEL output, but output power is significantly reduced if the bunch length is too short. [Issue 1]

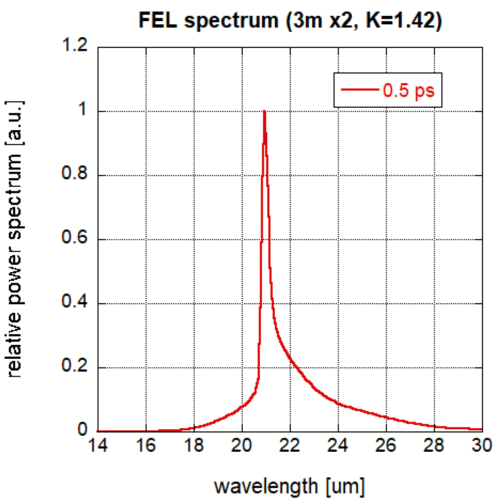
Requires precise control of bunch compression

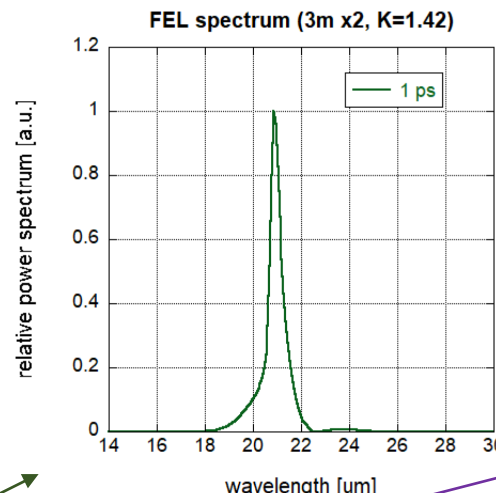
Spectrum of IR-FEL

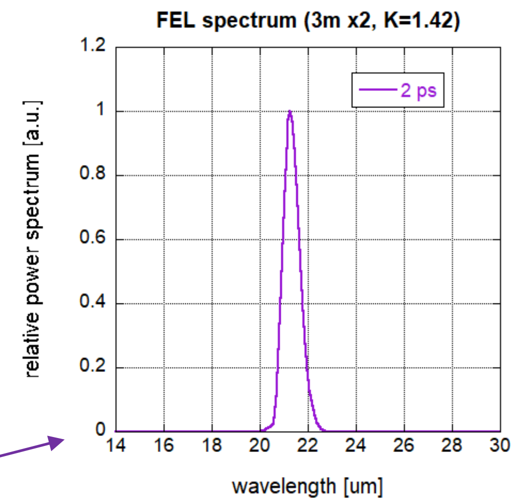
Spectral width of IR-FEL : 3 – 7 % (FHWM)

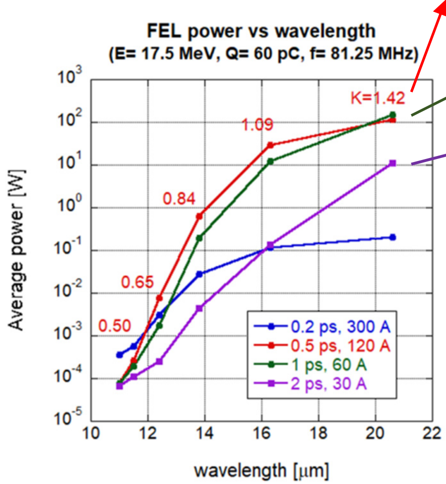
The absorption width of the resin in the 15-20 μm region is a little wider.

This level of wavelength spectral width is considered acceptable.









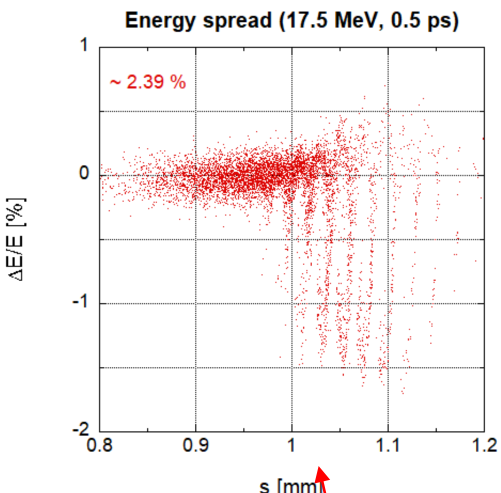
For the bunch length of 0.5 ps, a long tail appears on the long wavelength side. [Issue 2]

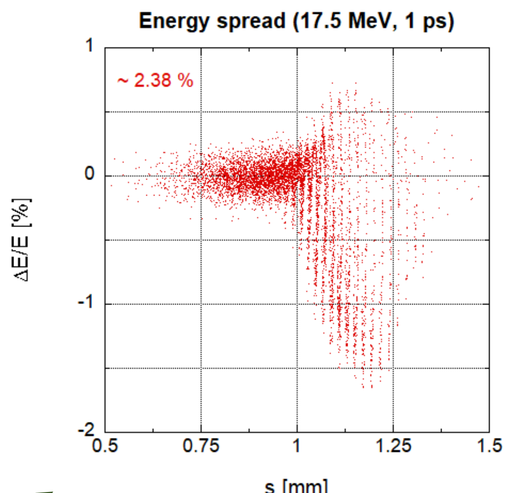
Trade-off between FEL power and spectral width

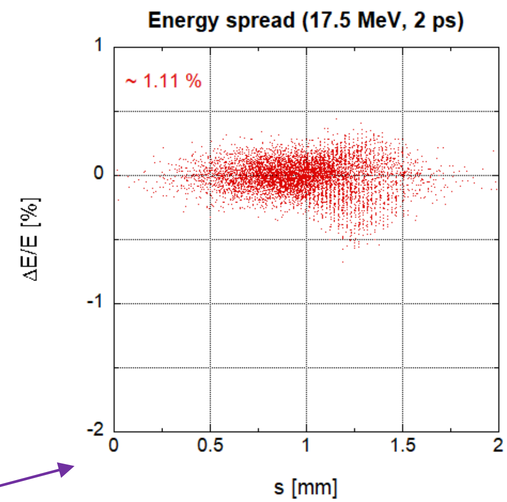
ΔE/E of e-beam after FEL

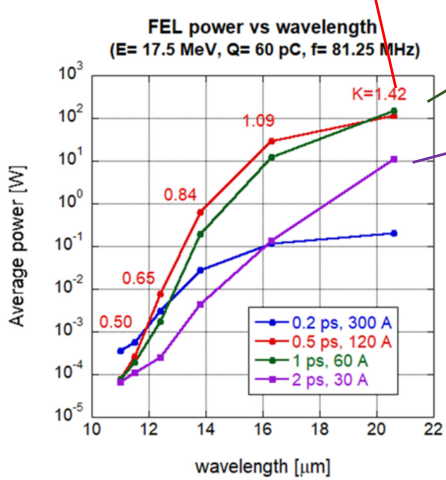
A large density modulation is formed in front of the electronic bunch due to the slippage effect.

All electrons need to be decelerated for energy recovery operation.









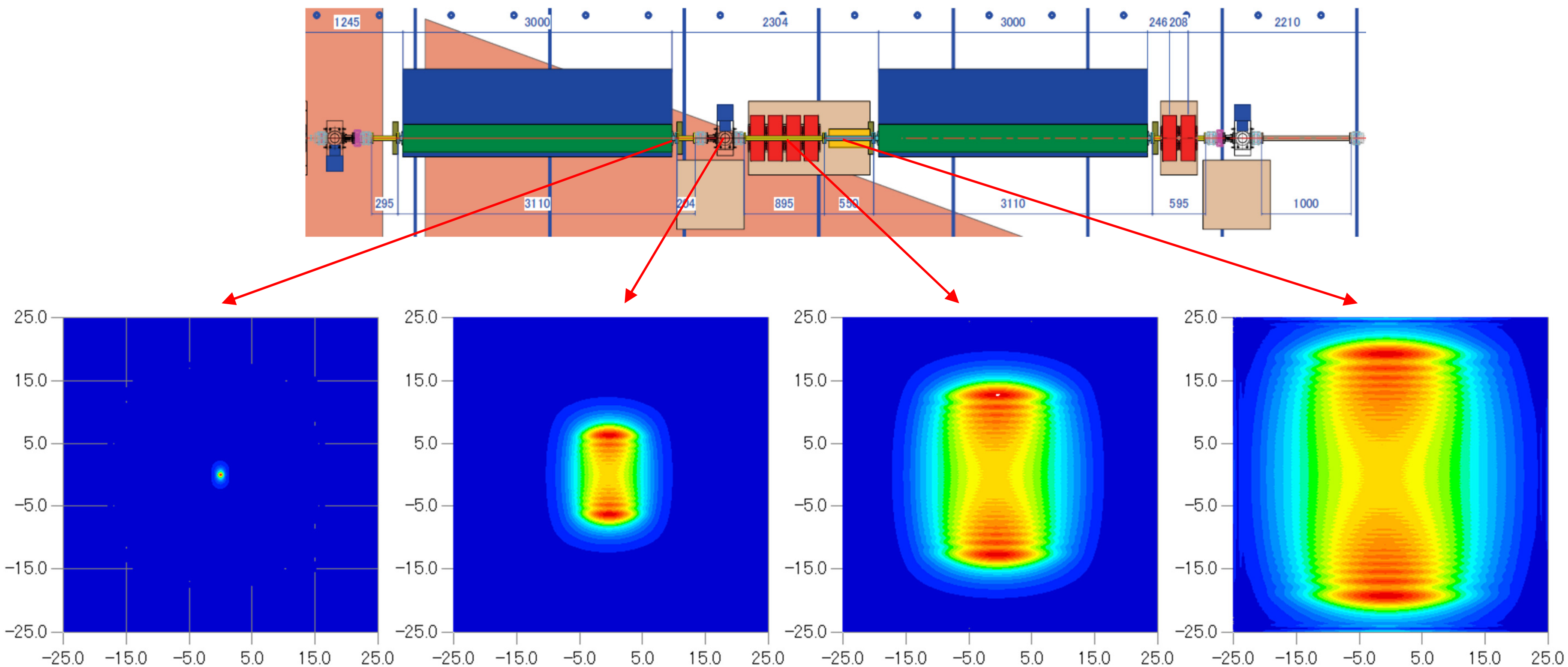
Acceptance of 2nd Arc ~ 2.5 %

Acceptance of Dump line (DL) ~ 1.7 % [Issue 3]

Energy compression & improvement of acceptance at DL

Divergence of FEL light (1)

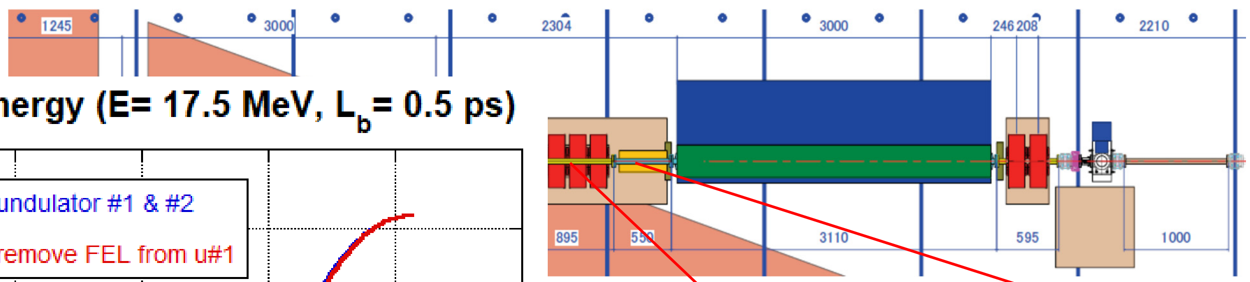
Vertical beam size is about 100μm,FEL becomes diffraction limited light
When optical guiding disappears, it spreads rapidly.

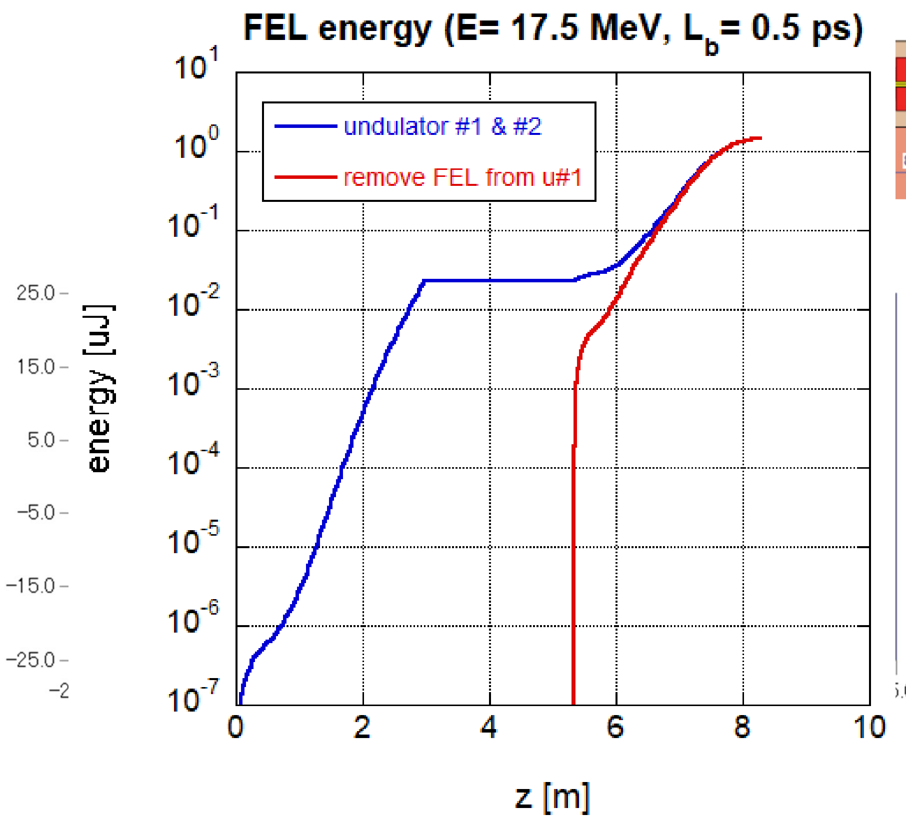


a) z=0 m b) z=0.57 m c) z=1.15 m d) z=1.73 m

Divergence of FEL light (1)

Vertical beam size is about 100μm,FEL becomes diffraction limited light
When optical guiding disappears, it spreads rapidly.





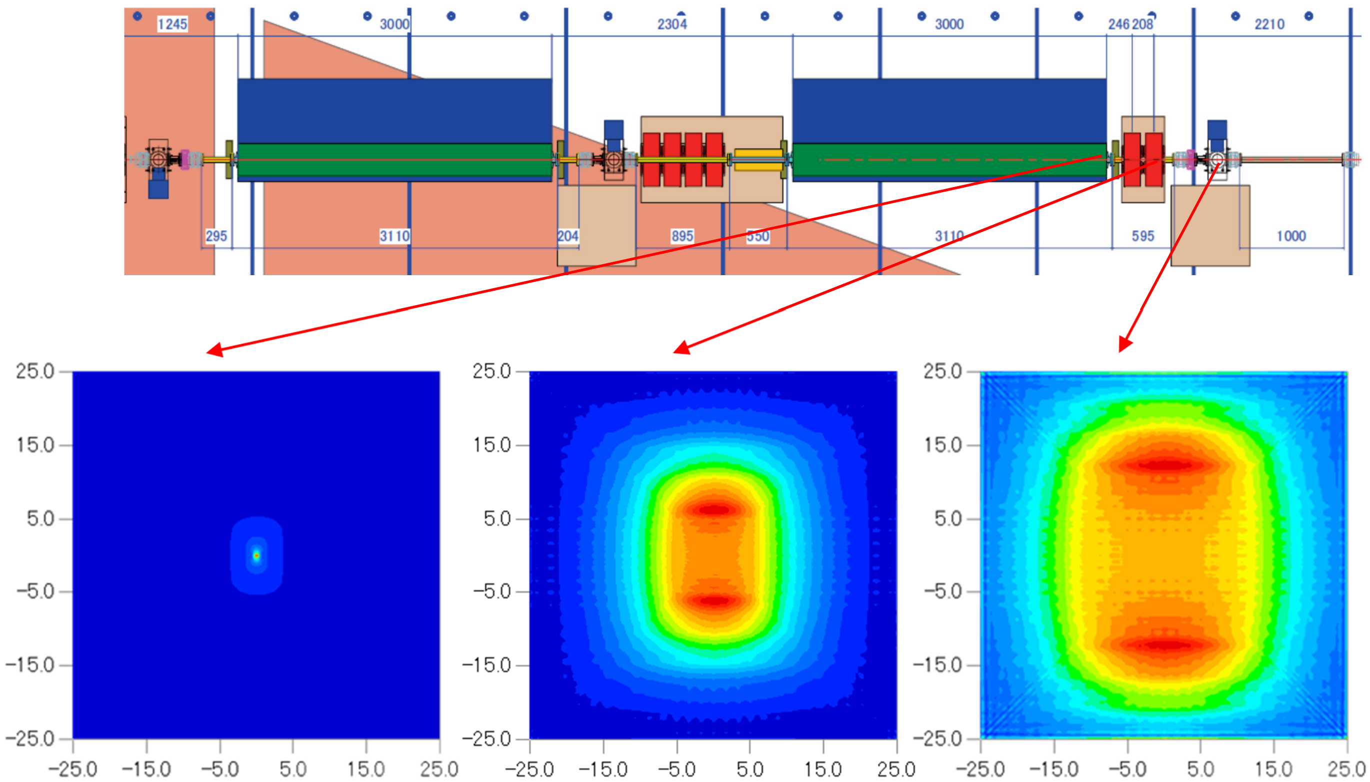
FEL light from 1st undulator is almost lost.
[Issue 4]

Even if all the FEL light from 1st undulator is removed, the FEL output does not change (red line in Figure).

Micro-bunched electron beam is important in this IR-FEL.

Divergence of FEL light (2)

FEL light after 2nd undulator is also rapidly diverging.
Needed to separate electron beam and FEL light



e) z=0 m f) z=0.53 m g) z=1.06 m

Divergence of FEL light (2)

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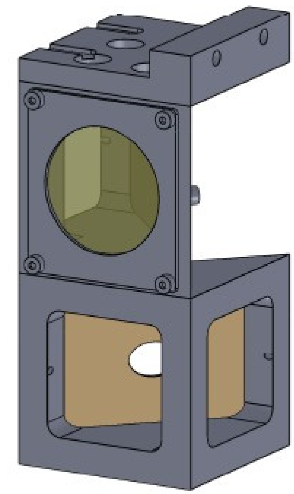
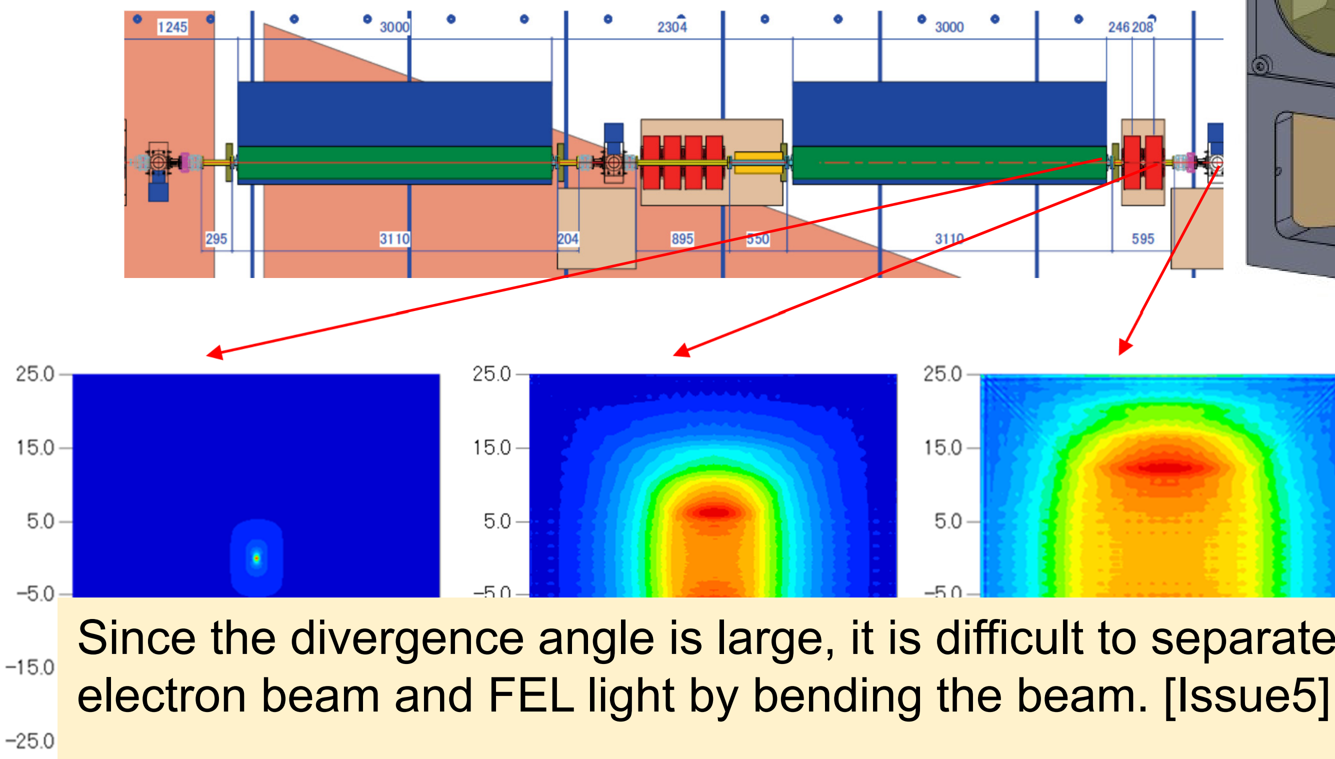
Needed to separate electron beam and FEL light





Since the divergence angle is large, it is difficult to separate electron beam and FEL light by bending the beam. [Issue5]

Using a mirror with a hole, let the electron beam pass and extract only the FEL light in the 90 degree direction.

Discussion and Summary

Discussion about the accelerator technologies between IR-FEL and EUV-FEL

What is a PoC of EUV-FEL?

1. ERL operation with a high bunch charge at a high-repetition
2. Realization of local high peak current by bunch compression and decompression of electron beam
3. Realization of a high-gain, high-repetition, single-pass FEL in ERL
4. Energy recovery of electron beam with large energy spread increased by FEL interaction [Issue 3]

What is more difficult than EUV-FEL?

- Control of low energy electron beam

(Space charge effect, disturbances such as geomagnetic and environmental magnetic fields, error fields of the undulators)

- Long wavelength (Slippage length > Bunch Length) [Issue 1]
- Diffraction loss of FEL light after the undulators [Issue 4] [Issue 5]

Summary

- By using ERL technology, FEL can be operated in high repeat rate, and the beam dump power can be reduced.

- We are proposing ERL-based FEL as a future light source in the EUV region.

- KEK will install two undulators in the cERL southern straight section and develop a mid-infrared FEL with high average power.

- With the IR-FEL, mid-infrared light can be obtained with a power of 1 to 100 W in CW operation. Orders for major equipment are now complete, construction will begin in November, and the first FEL experiment will be conducted in March 2020.

- IR-FEL can demonstrate many of the challenges for the realization of EUV-FEL.

Core members for IR-FEL and Acknowledgement

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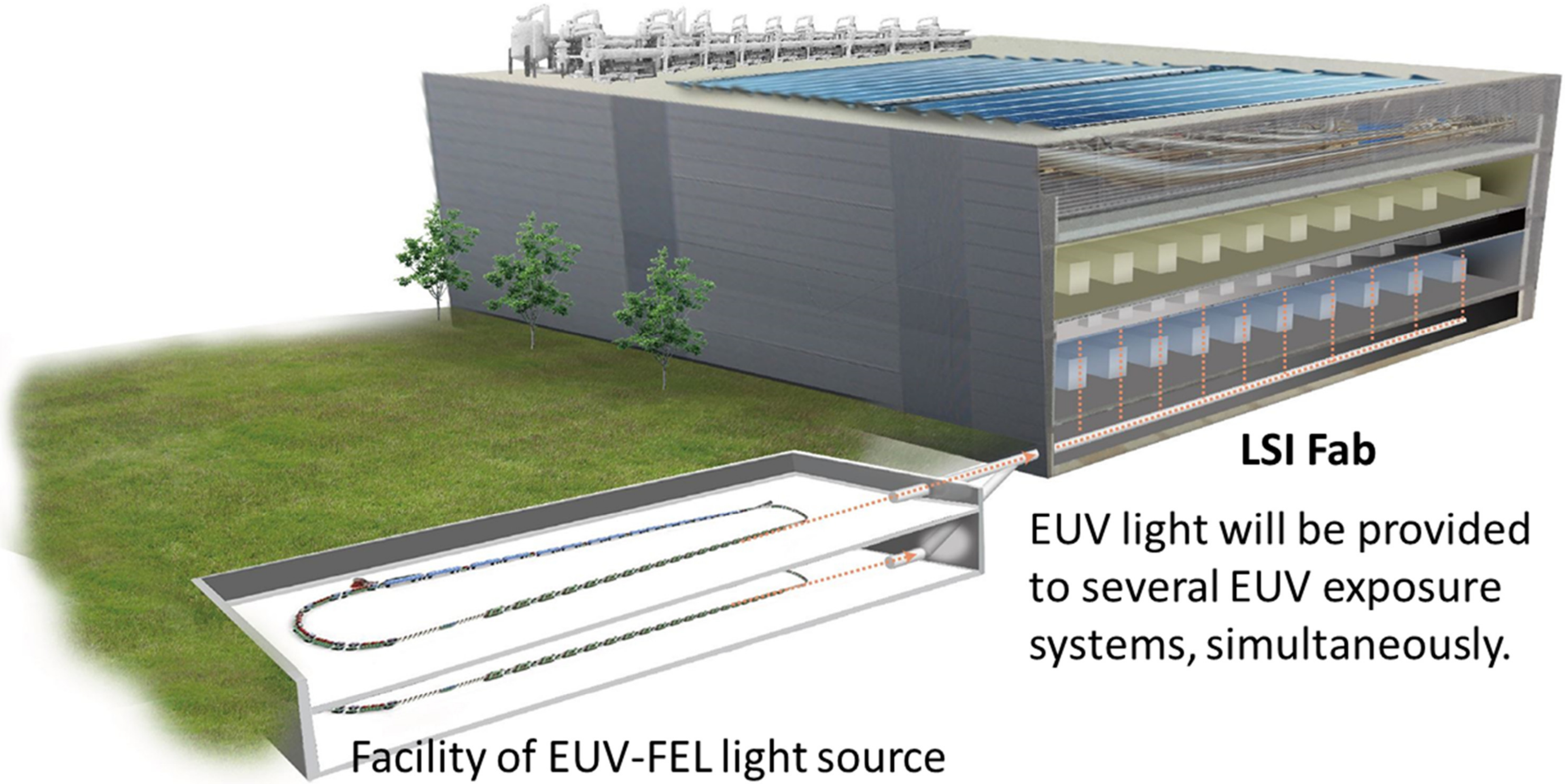
This presentation is based on results obtained from NEDO project "Development of advanced laser processing with intelligence based high-brightness and high-efficiency laser technologies (TACMI project)."

Thank you for your attention!



Facility Image of LSI Fab with EUV-FEL