High Repetition Rate (81.25MHz) FEL Project Based on cERL

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Contents

- Introduction from the view point of the previous presentation at the source workshop
- Project of High Repetition Rate (81.25MHz) MIR-FEL based on cERL (A part has been presented on IPAC2019 TUPRB107)
- Discussion about the relationship between the MIR-FEL and EUV-FEL from the view point of the accelerator technologies
- Summary

Upgrade plan of cERL for the POC as a first stage of the development on EUV-FEL high power light source

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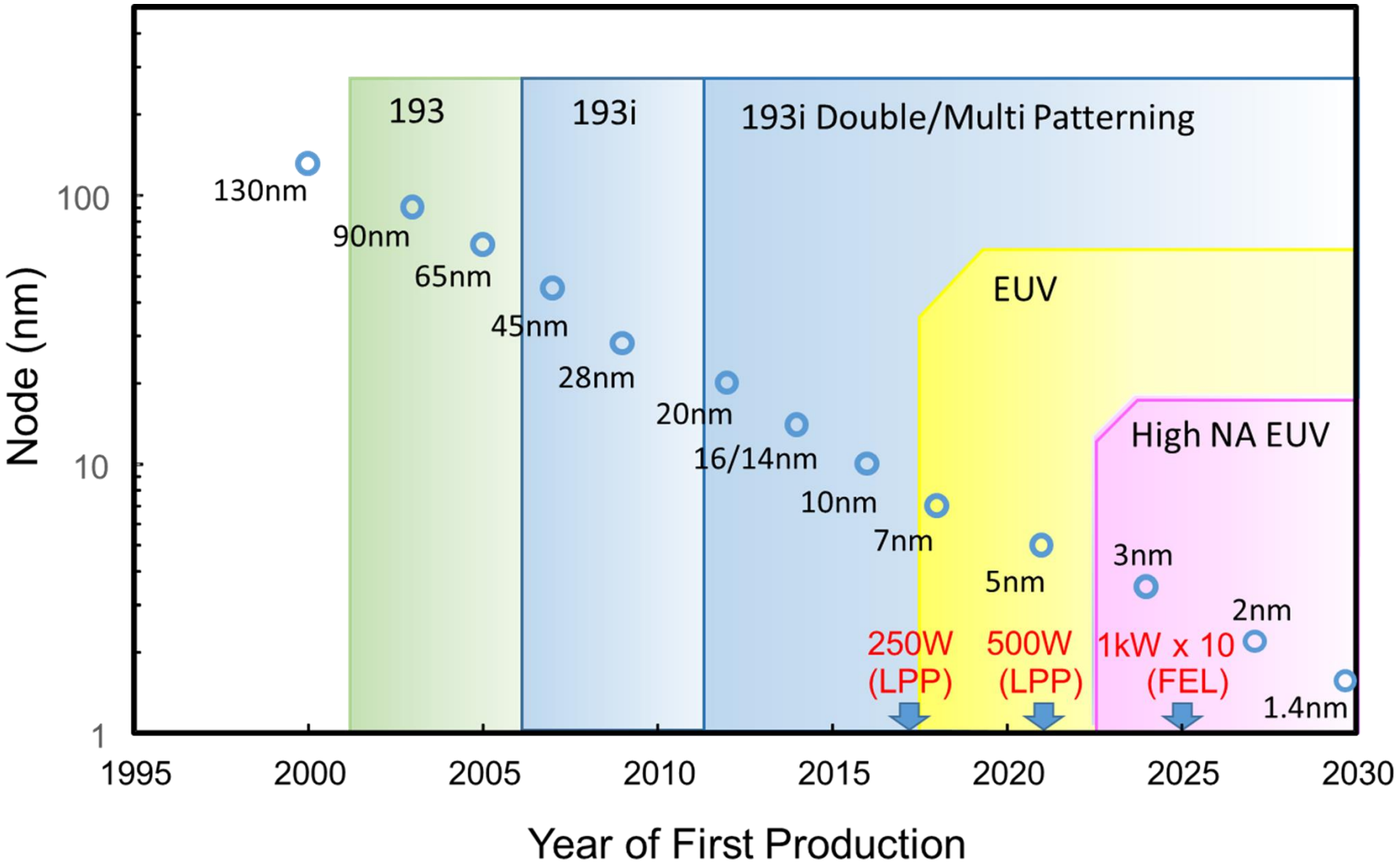
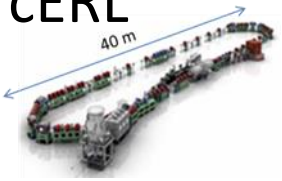
5-7/November/2018, HILASE, Prague, Czech Republic

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



Prototype design of the EUV-FEL

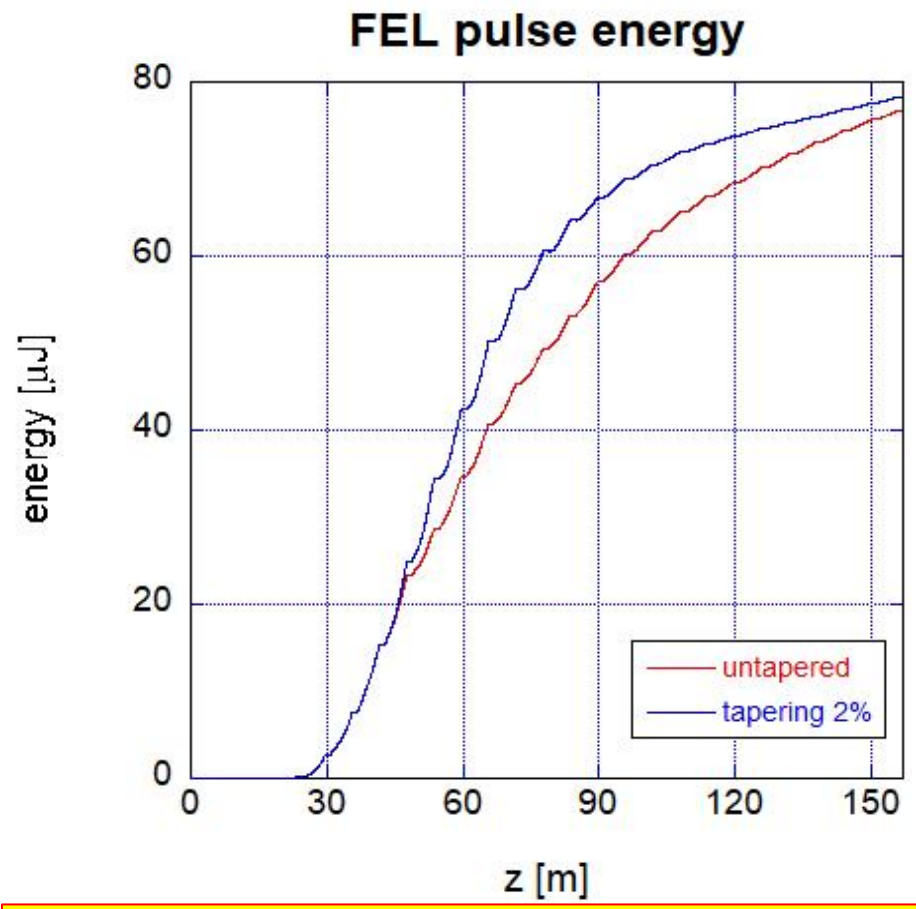
cERL

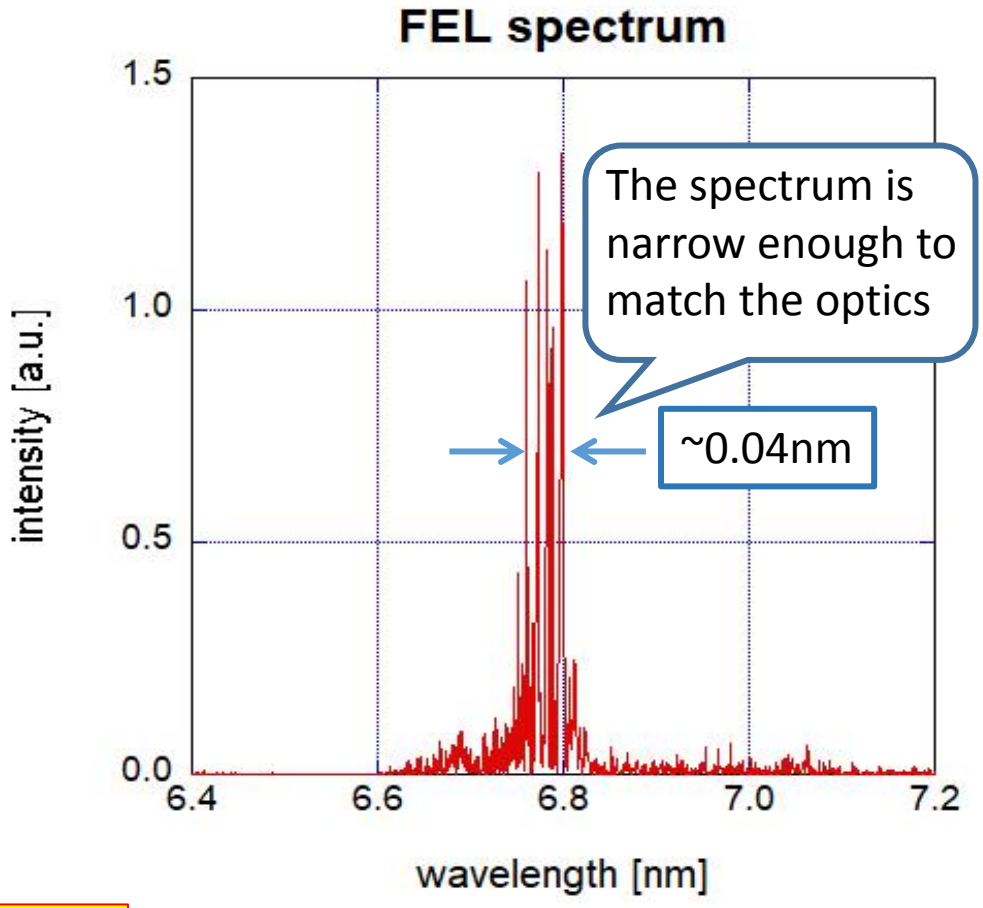


ERL test machine for developing ERL technologies

Items	Achieved values in cERL	Design Values at the EUV-FEL
Energy for injector (MeV)	2.9-6	10.5
Energy of Accelerator(MeV)	20	800
Charge /bunch (pC)	0.7-5	60
Repetition rate (MHz)	162.5-1300	162.5
Average Current (mA)	1.0	9.75
Emittance for electron beam (mm mrad)	0.3-1	~0.7
Gradient of the accelerated energy (MV/m)	8.6	12.5
Wavelength of EUV-FEL (nm)	/	13.5
Average power of EUV-FEL (kW)	/	Higher than 10 kW

Recent study about the power and spectrum at BEUV





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

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

Accelerator Parameters: $E_{acc} = 1131$ MeV $(800 \times \sqrt{2})$,
The other conditions are almost same to these of EUV-FEL

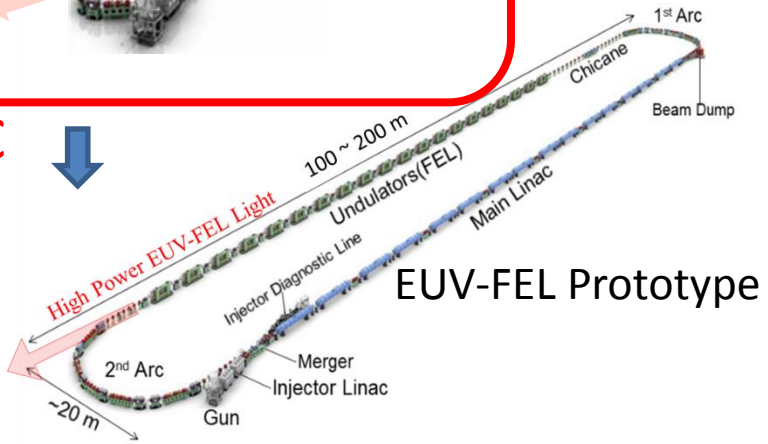
Staging to realize the EUV-FEL light source

1st stage:
Development of the feasible technologies

cERL

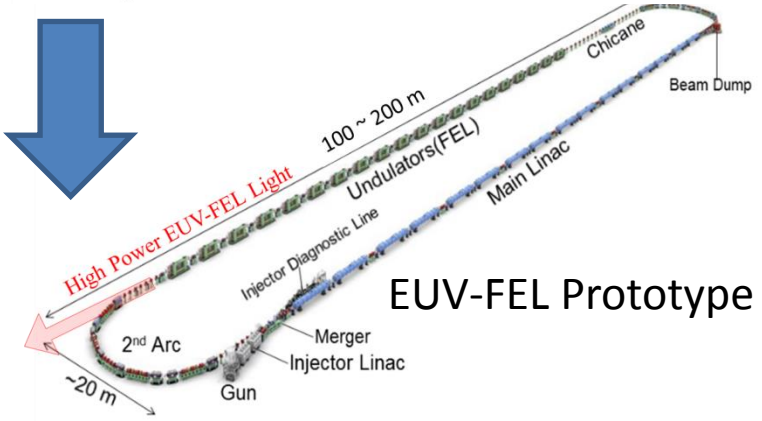
Upgrade plan of cERL for the POC

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



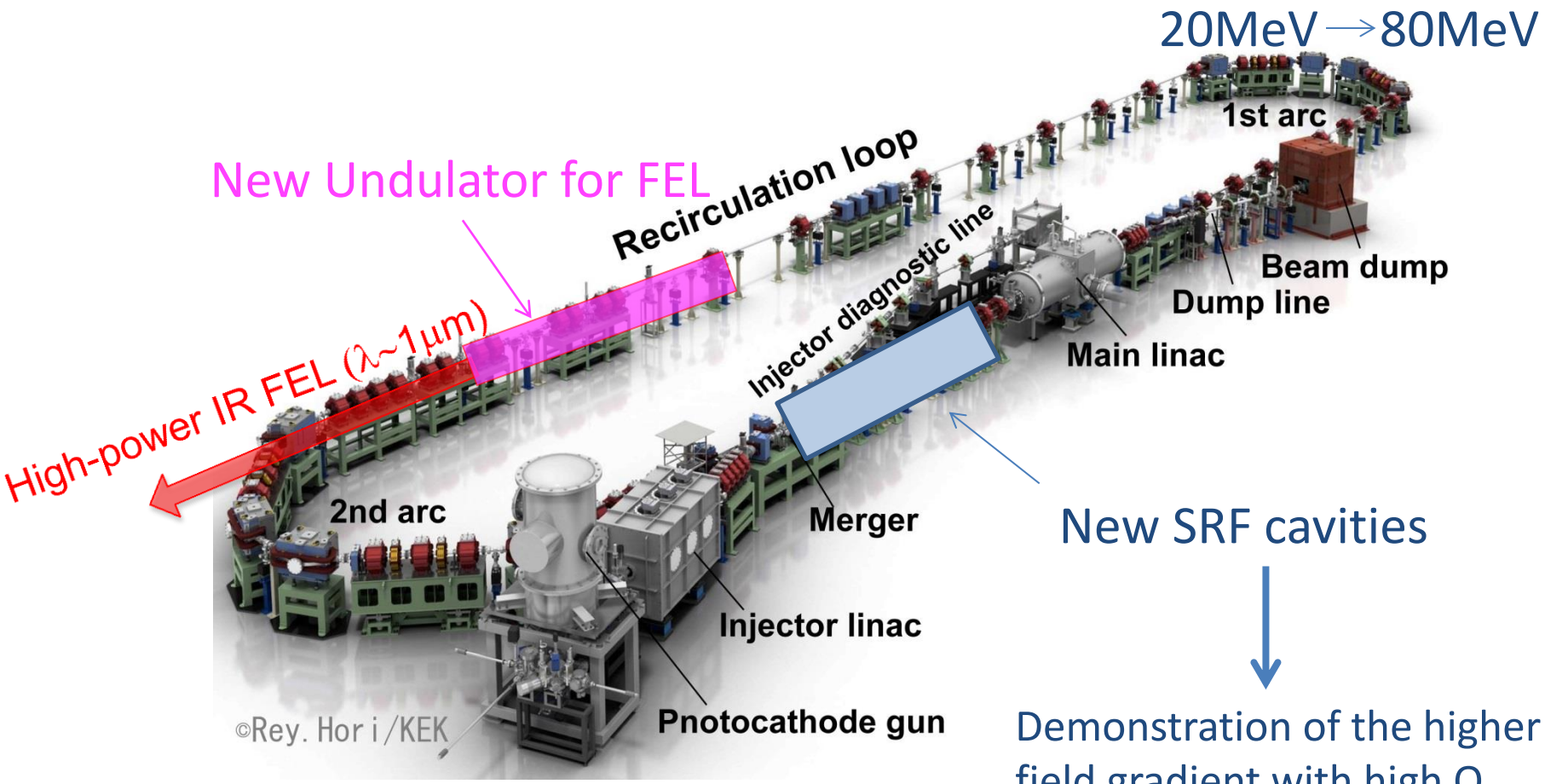
EUV-FEL Prototype

Clean room with EUV exposure system

The above concept should be important to realize the EUV-FEL high power light source for EUV Lithography.

Outline of the upgrade plan

Beam Energy: 80 MeV (5 MeV @ Injector & Dump line)

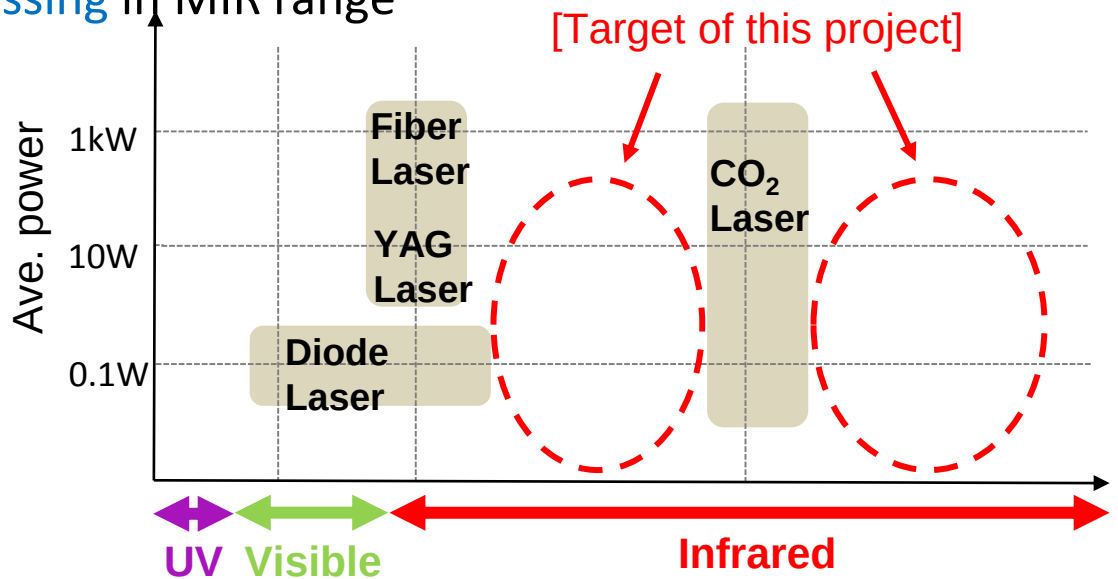


Project theme funded from NEDO: Development of mid-infrared high-power laser light source for high-efficiency machining process using molecular vibration

[Mid-infrared (MIR) region]

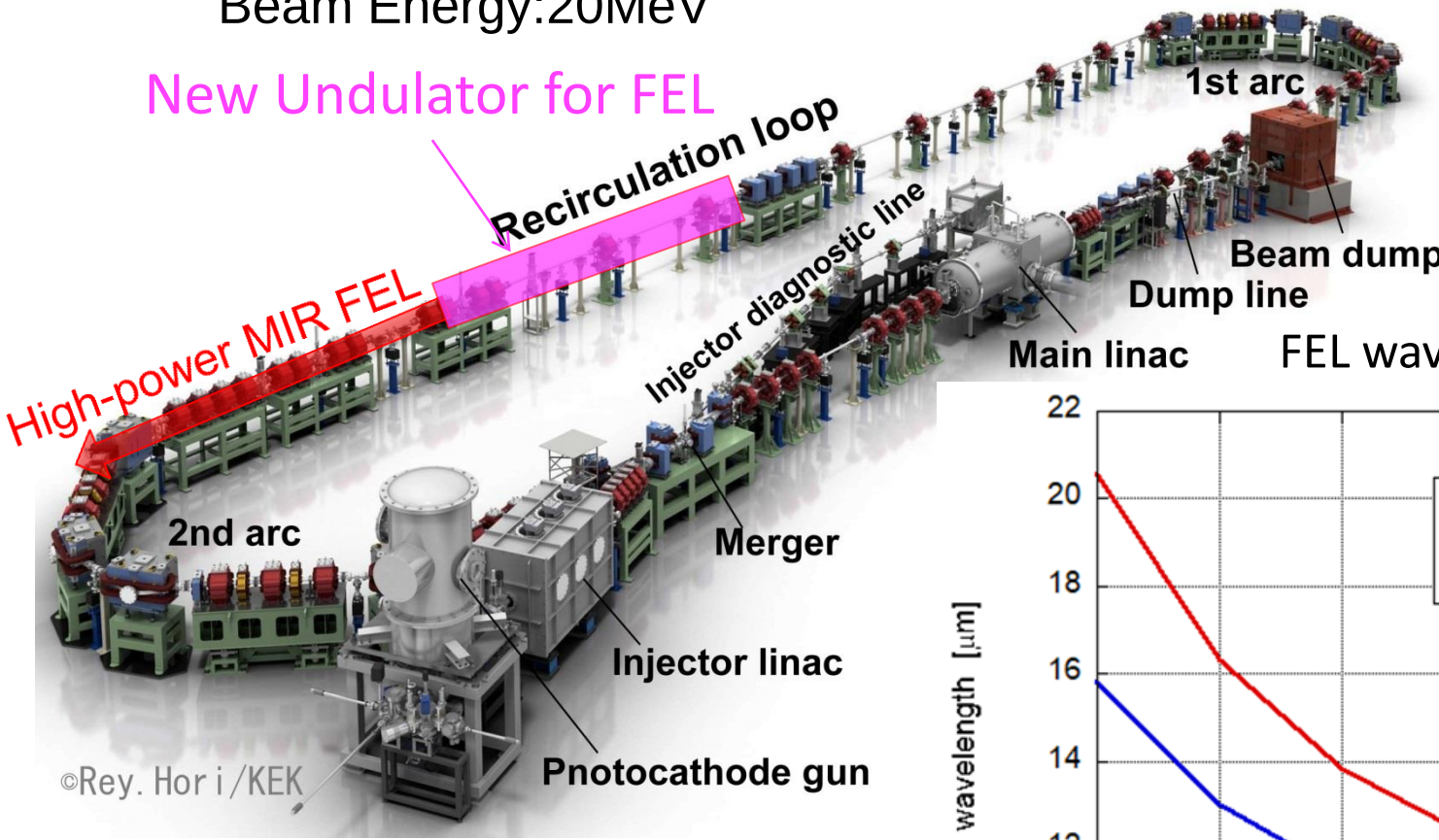
- In the wavelength region, there is vibrational absorption of organic materials whose use is expanding due to light-weight, low-cost, and high functionality.
- Considering the process of cutting and/or welding the resin, it is considered that the absorption wavelength corresponding to the vibration mode of the main chain of the molecular structure is suitable.
- There is no database of easy-to-process wavelengths and required laser power.
- Main high-power laser is CO_2 laser only → Insufficient understanding of basic phenomena required for processing in MIR range

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

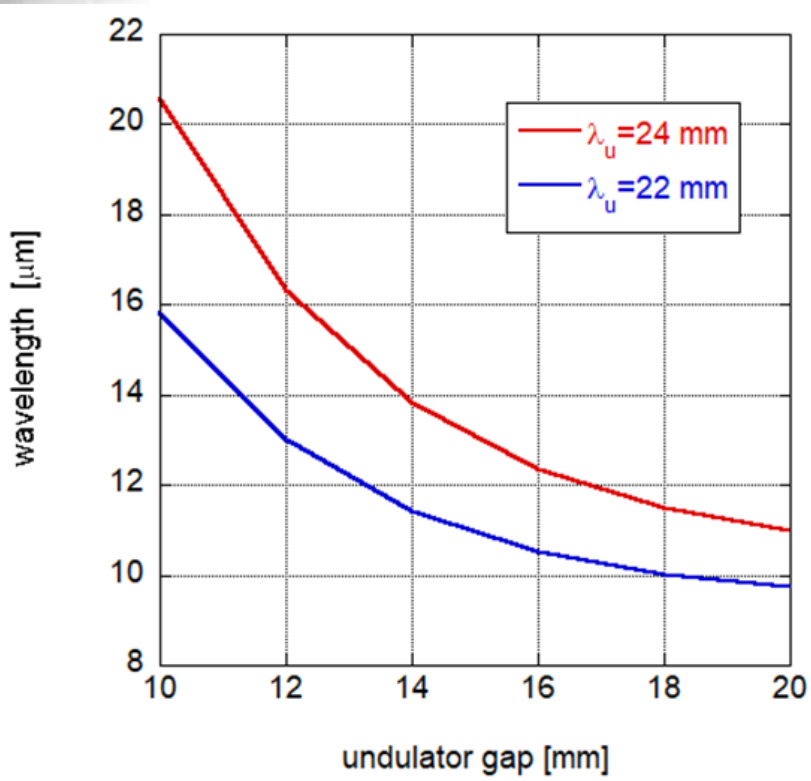


Present High repetition rate MIR FEL project

Beam Energy:20MeV



FEL wavelength



Beam Energy	17.6 MeV
Injector Energy	3.0 MeV
E-Gun Energy	500 keV
Bunch repetition	1.3 GHz
Average current	1 mA (max)
Operation mode	CW or Burst

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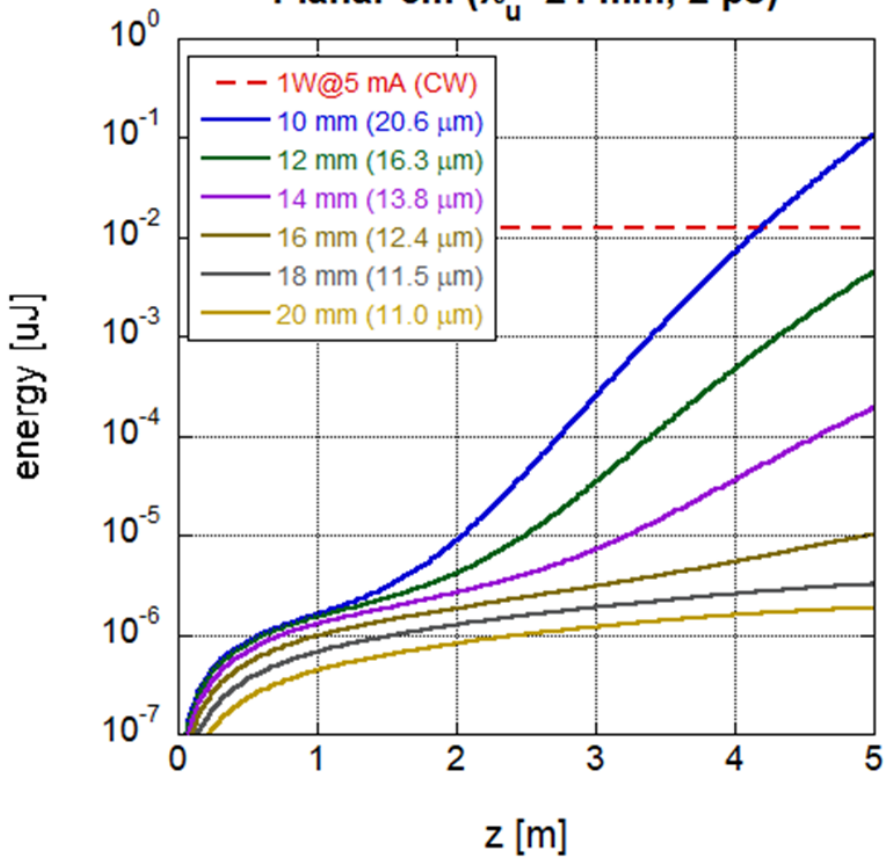
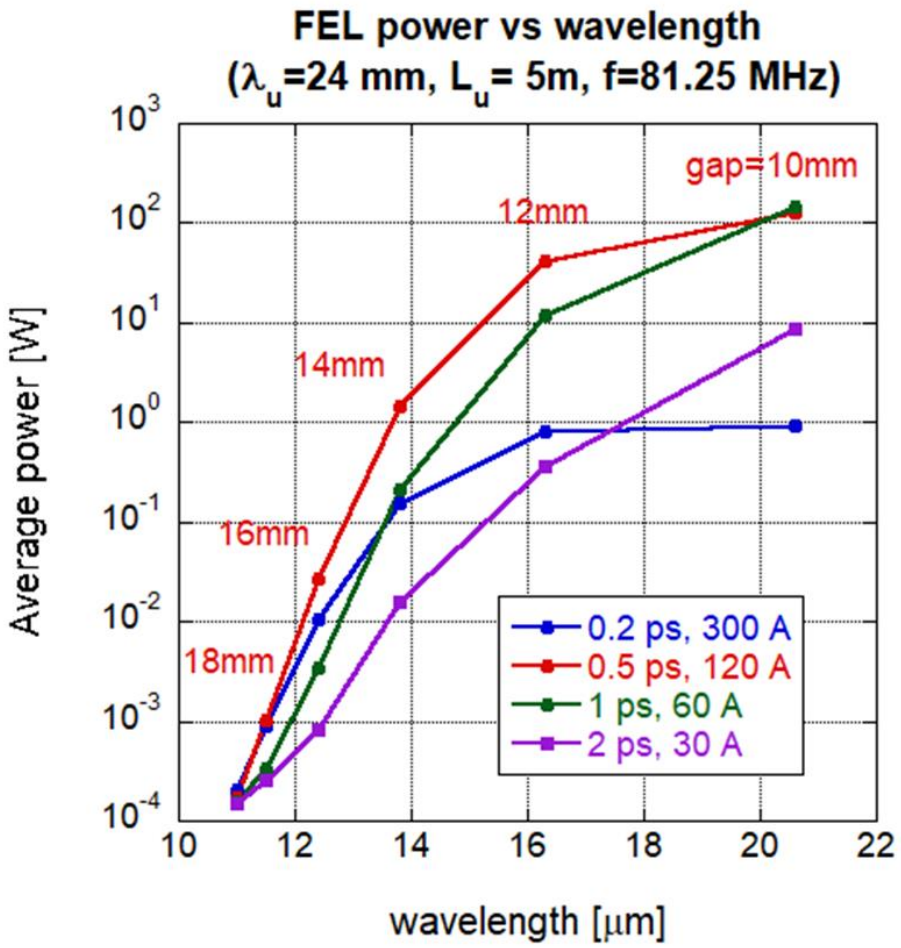
Characteristics of cERL-IR-FEL (Power)





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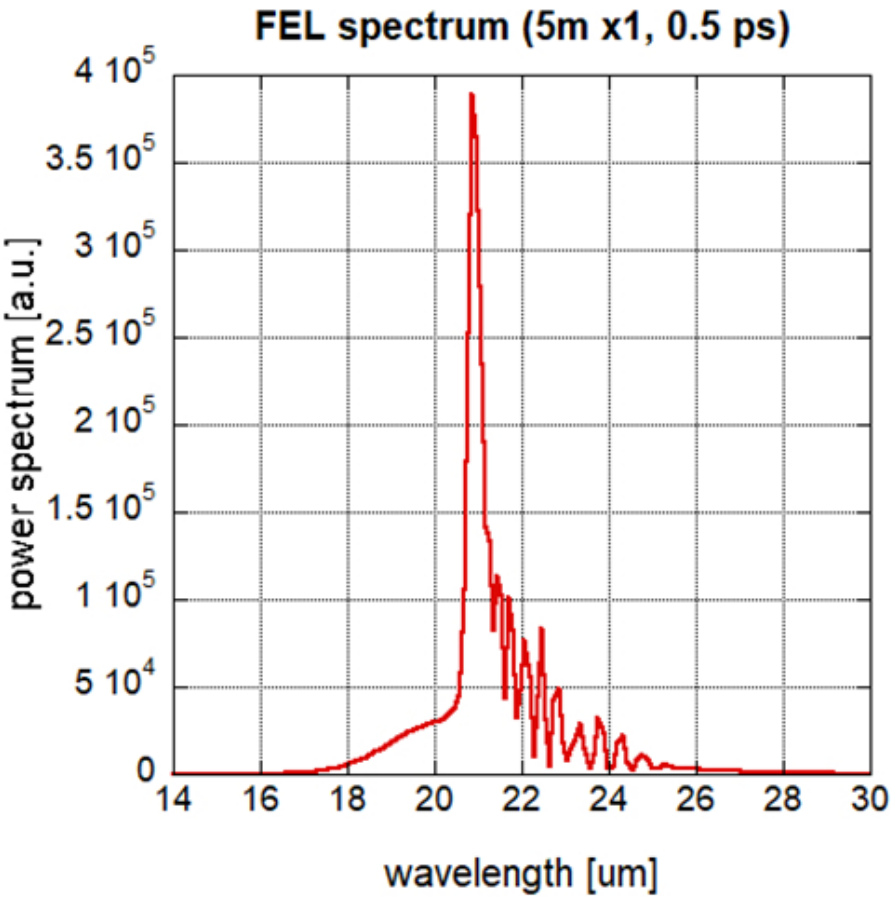
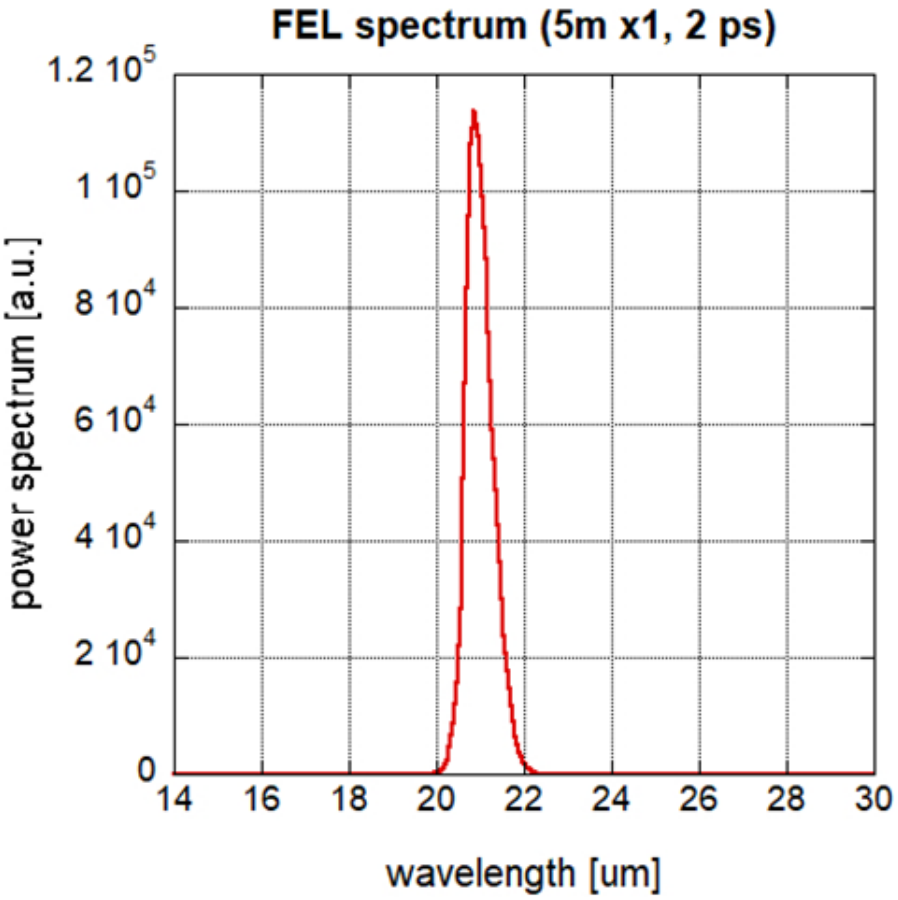
Characteristics of cERL-IR-FEL (Spectra)





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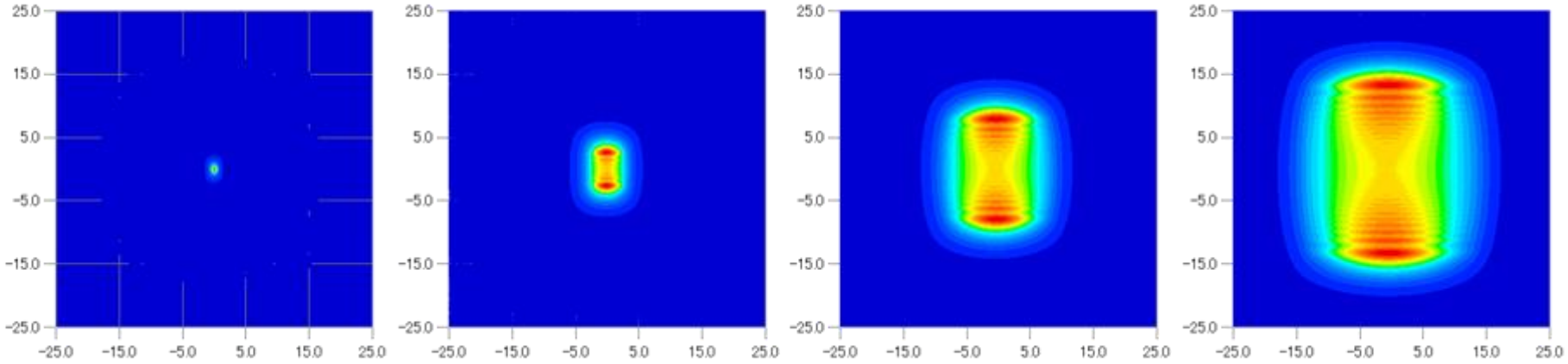
Characteristics of cERL-IR-FEL (Divergence of the FEL light)



a) z=0 m b) z=0.24 m c) z=0.72 m d) z=1.2 m

Divergence of FEL light due to diffraction effect between the undulators. z is the distance from the 1st undulator.

Discussion about the accelerator technologies between cERL-IR-FEL and of EUV-FEL (1)

Table 2 Parameters of EUV-FEL and cERL-IR-FEL		
	EUV-FEL	cERL-IR-FEL
Beam energy	800 MeV	17.5 MeV
Beam current (ave.)	10 mA	5 mA
Bunch charge	60 pC	60 pC
Bunch length（FWHM）	0.1 ps	0.5 - 2 ps
Normalized emittances	~ 0.7 π mm mrad	~ 3 π mm mrad
Energy spread	0.03 %	0.1 %
Repetition rate	162.5 MHz	81.25 MHz
Undulator type	APPLE II	Planar
Length (period x number)	5 m (28 mm × 175)	3 m (24 mm × 125)
Number of units	17	2
FEL wavelength	13.5 nm	15 - 20 μm
Output power (ave.)	> 10 kW	1 -100 W

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Discussion about the accelerator technologies between cERL-IR-FEL and of EUV-FEL (2)

What is a POC of EUV-FEL?

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

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)
- Diffraction loss of FEL light between the undulators

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Summary

- Based on the budget of NEDO project, KEK will install the undulators in the cERL south straight section and develop high average power mid-infrared FEL at the end of this fiscal year(March of 2020).
- The project will be completed at the end of next fiscal year (March of 2021).
- By the MIR-FEL in cERL, it is possible to obtain mid-infrared light with the power of 1 - 100 W in CW operation. Currently, major equipment orders have been completed and detailed design between undulators is in progress.
- The cERL-IR-FEL can be demonstrate many of the challenges for the realization of EUV-FEL.

Core members for MIR-FEL and Acknowledgement

Team leader of cERL:	Hiroshi Sakai
Head of the design team:	Ryukou Kato
Undulator design:	Kimichika Tsuchiya
Vacuum system:	Yasunori Tanimoto
FEL production:	Yosuke Honda
Beam dynamics:	Tsukasa Miyajima, Miho Shimada, Norio Nakamura

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)."

EUV-FEL Light Source Study Group for Industrialization

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Materials Magic

MITSUBISHI HEAVY INDUSTRIES MECHATRONICS SYSTEMS, LTD.

TAIYO NIPPON SANSO
The Gas Professionals

NTT AT

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

TOSHIBA

HITACHI

GIGAPHOTON

Canon
CANON ELECTRON TUBES & DEVICES CO., LTD.

TOYAMA

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Changes for the Better

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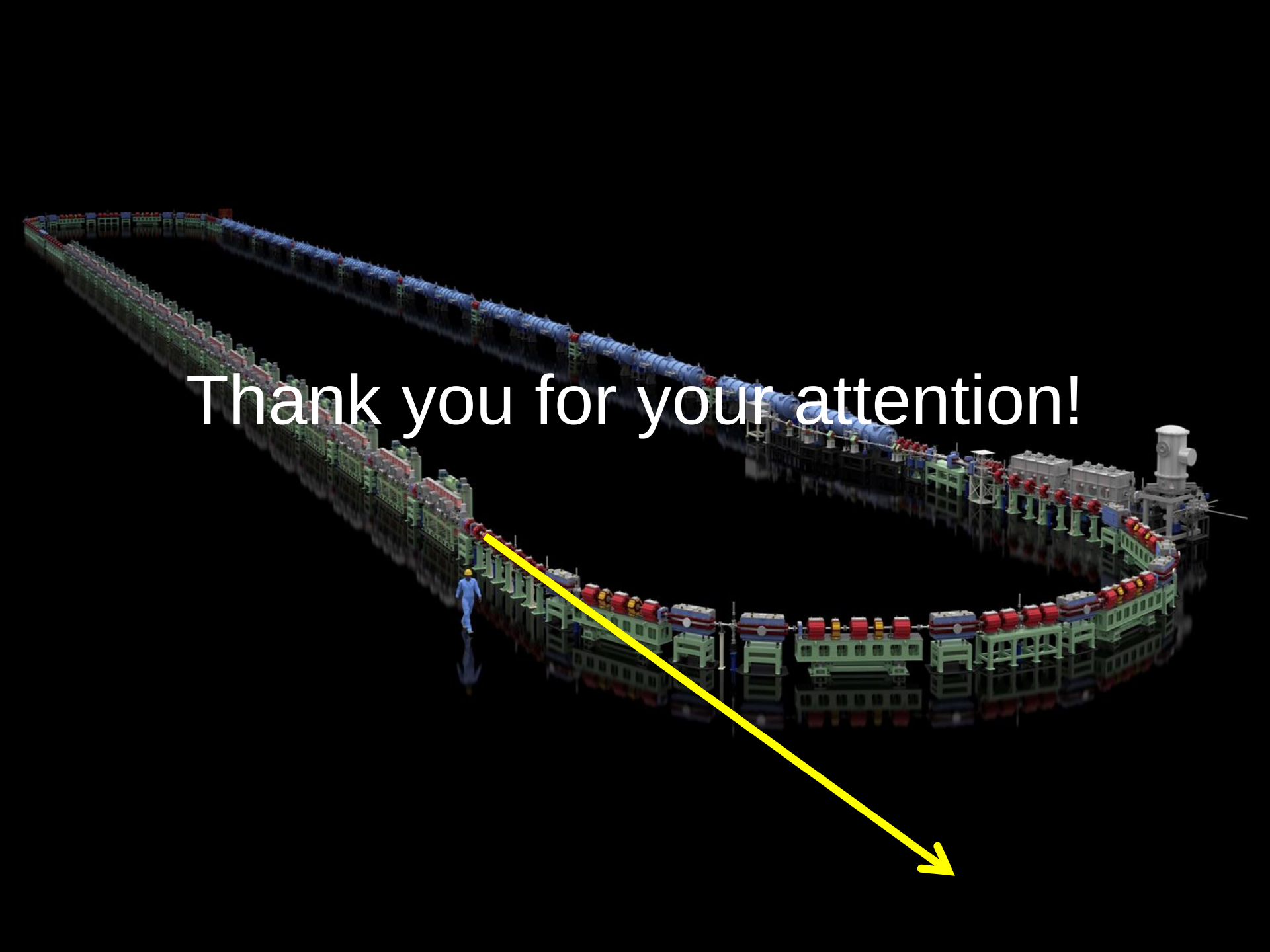
Thank you for your attention!