Development to realize the EUV-FEL high power light source for future lithography

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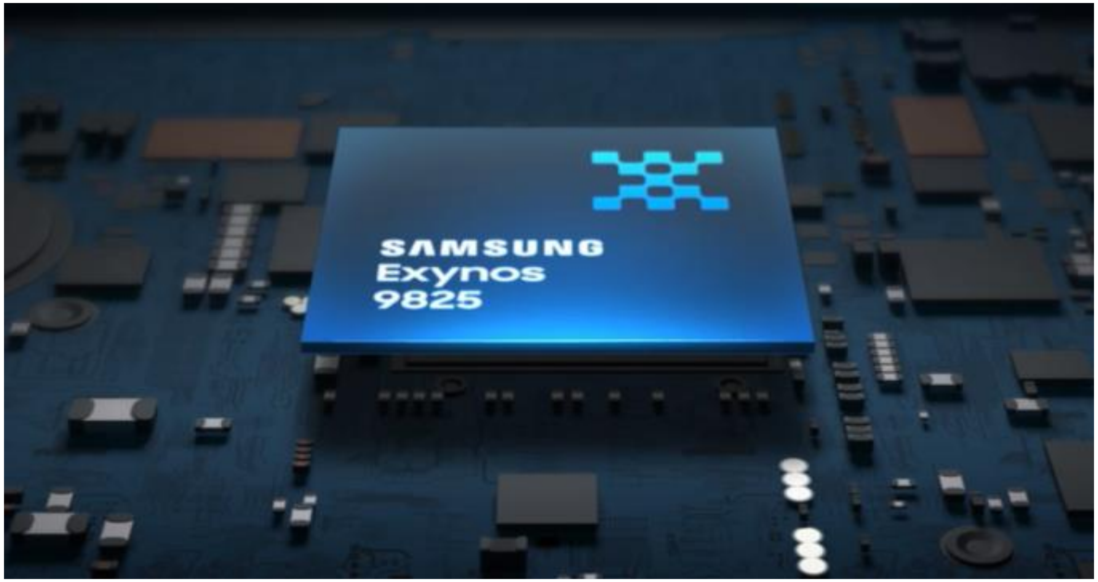
Contents

- Introduction about the present work from the view point of the development of higher power EUV light source
- Project of High Repetition Rate (81.25MHz) MIR-FEL based on cERL (A part has been presented on IPAC2019 TUPRB107 and FEL2019 THA03 Presented by R. Kato "IR-FEL Project at the cERL and Future EUV-FEL Lithography ")
- Present status about the beam development on the high charge bunch condition
- Discussion about the relationship between the MIR-FEL and EUV-FEL from the view point of the accelerator technologies
- A preliminary design concept for optical beamline from FEL to multi-scanners
- Summary

EUVL Status today – Samsung Starts HVM!

https://www.samsung.com/semiconductor/minisite/exynos/products/mobileprocessor/exynos-9825/

Power efficiency and performance come first with the Exynos 9825, the industry’s first mobile processor built with 7nm EUV processing technology. EUV, or extreme ultraviolet lithography, allows Samsung to leverage extreme ultraviolet wavelengths to print finer circuits and develop a faster and more power efficient processor.



PLENARY PRESENTATIONS

9:00 to 9:40 am

International Conference on Extreme Ultraviolet Lithography 2018

Timothy A. Brunner
GLOBALFOUNDRIES Inc. (USA)

↓

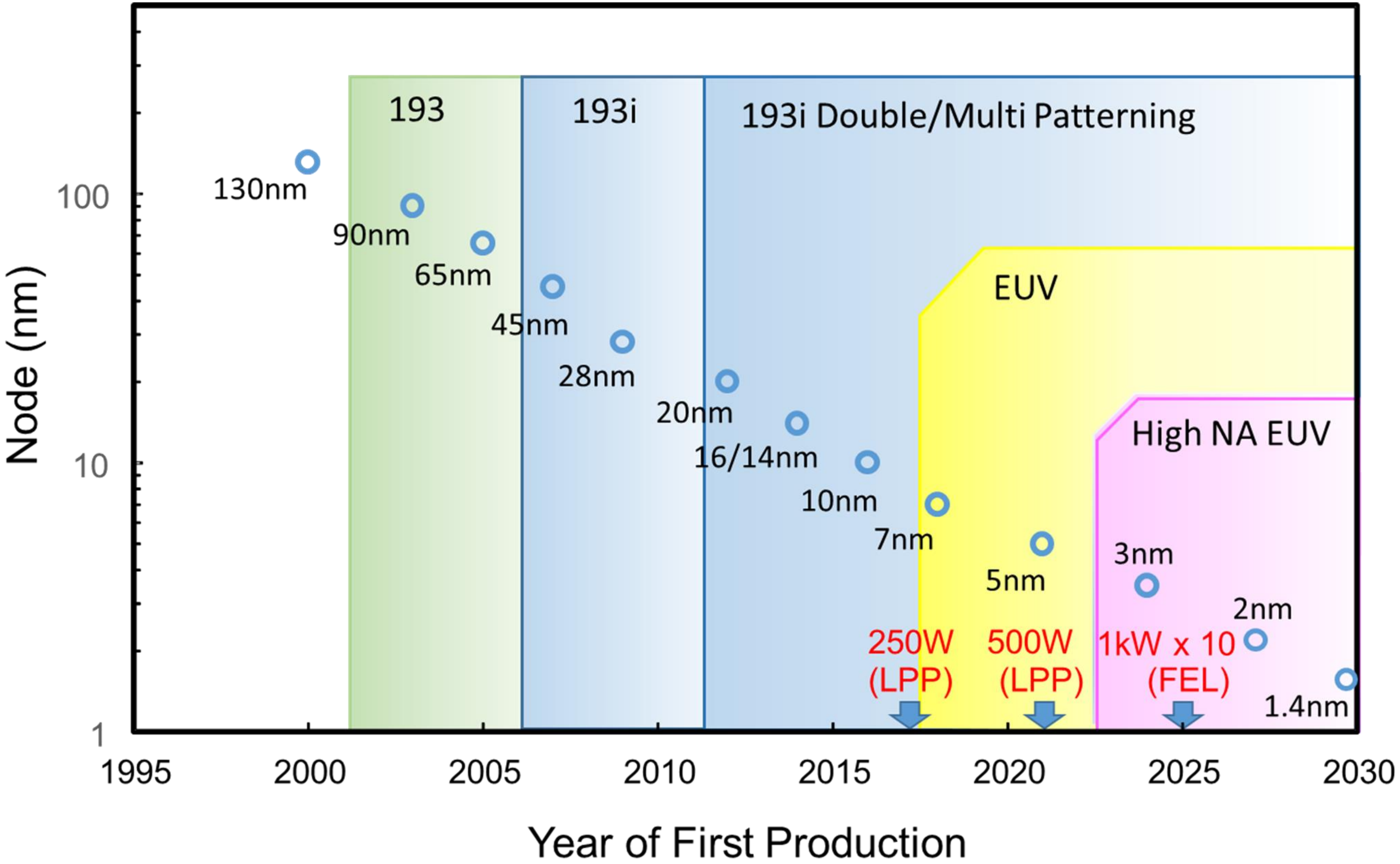
Harry J Levinson HJL Lithography

Current Challenges and Opportunities for EUV Lithography

Harry J Levinson
HJL Lithography

Thirty years ago, the first glimmers of "Soft X-ray Projection Lithography" were achieved by ambitious and far-sighted researchers. Steady progress has overcome many difficult barriers, and the renamed "Extreme Ultra-Violet (EUV) Lithography" is on the brink of High Volume Manufacturing (HVM) applications. This presentation will consider some of the remaining challenges for the next several years. Since an EUV image has only 1/14th as many photons of a 193 image with the same power, stochastic noise is a fundamental EUV concern. This challenge is being addressed by more powerful EUV sources, improved resist processes, advanced etches and other LER smoothing processes. Edge Placement Errors must be reduced to nm levels, which will require advanced data-prep methods to overcome asymmetric 3D mask effects and lens aberrations. Mask defects remain a worrisome issue, and EUV pellicles are highly desired to protect against particles which might fall onto the mask pattern. ....

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

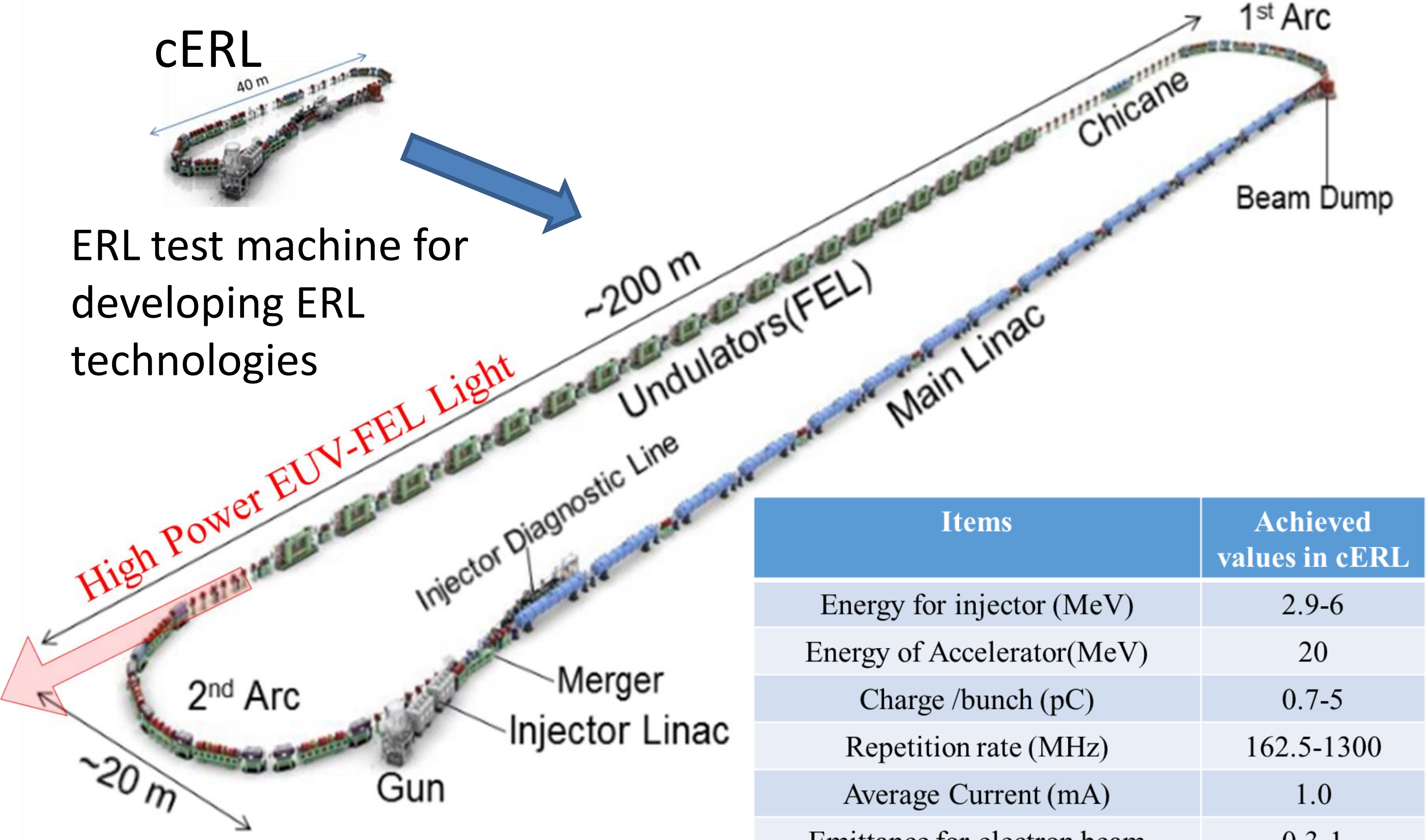


This slide has been shown from the Source workshop 2016 (Amsterdam)

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

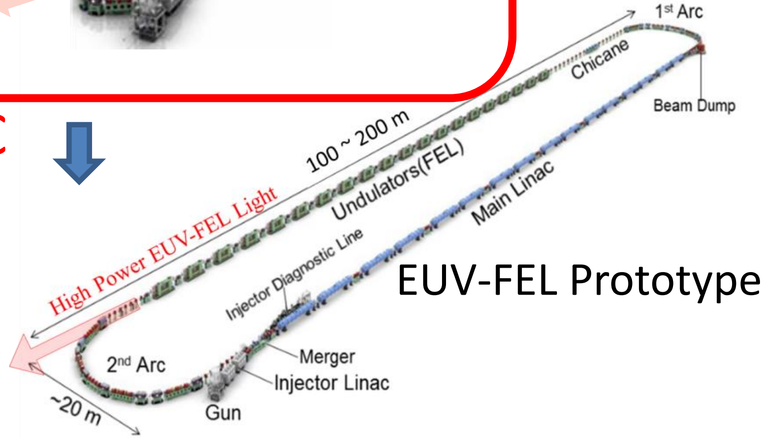
Staging to realize the EUV-FEL light source

1st stage:
Development of the
feasible technologies

cERL

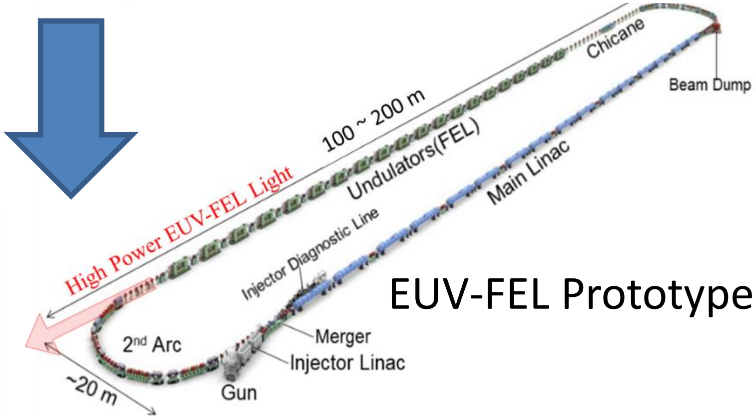
Upgrade plan of cERL for the POC

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

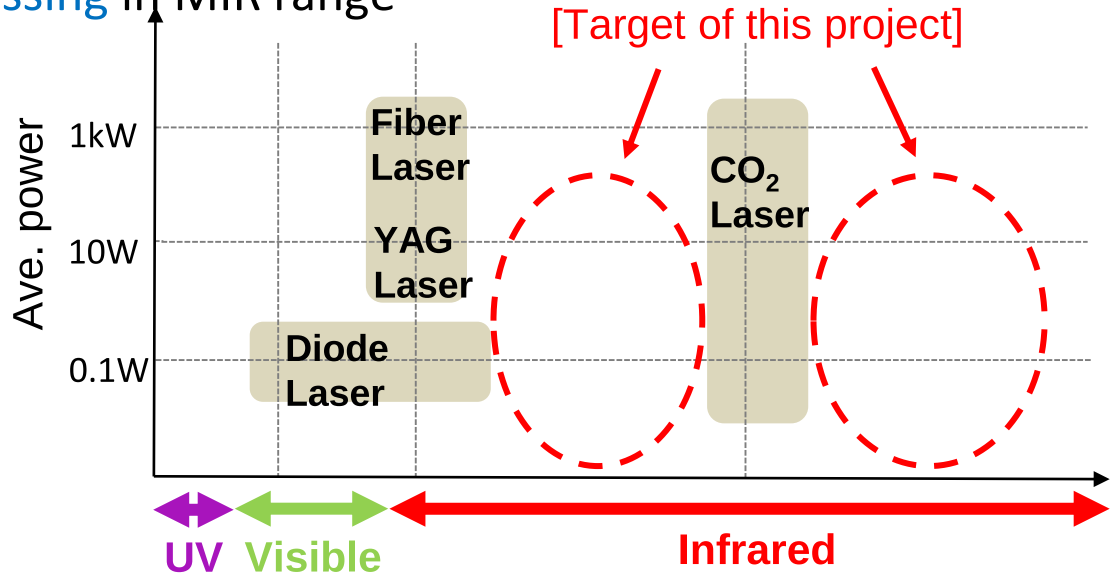
This slide has been shown from the EUVL workshop 2017 (Berkley)

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]

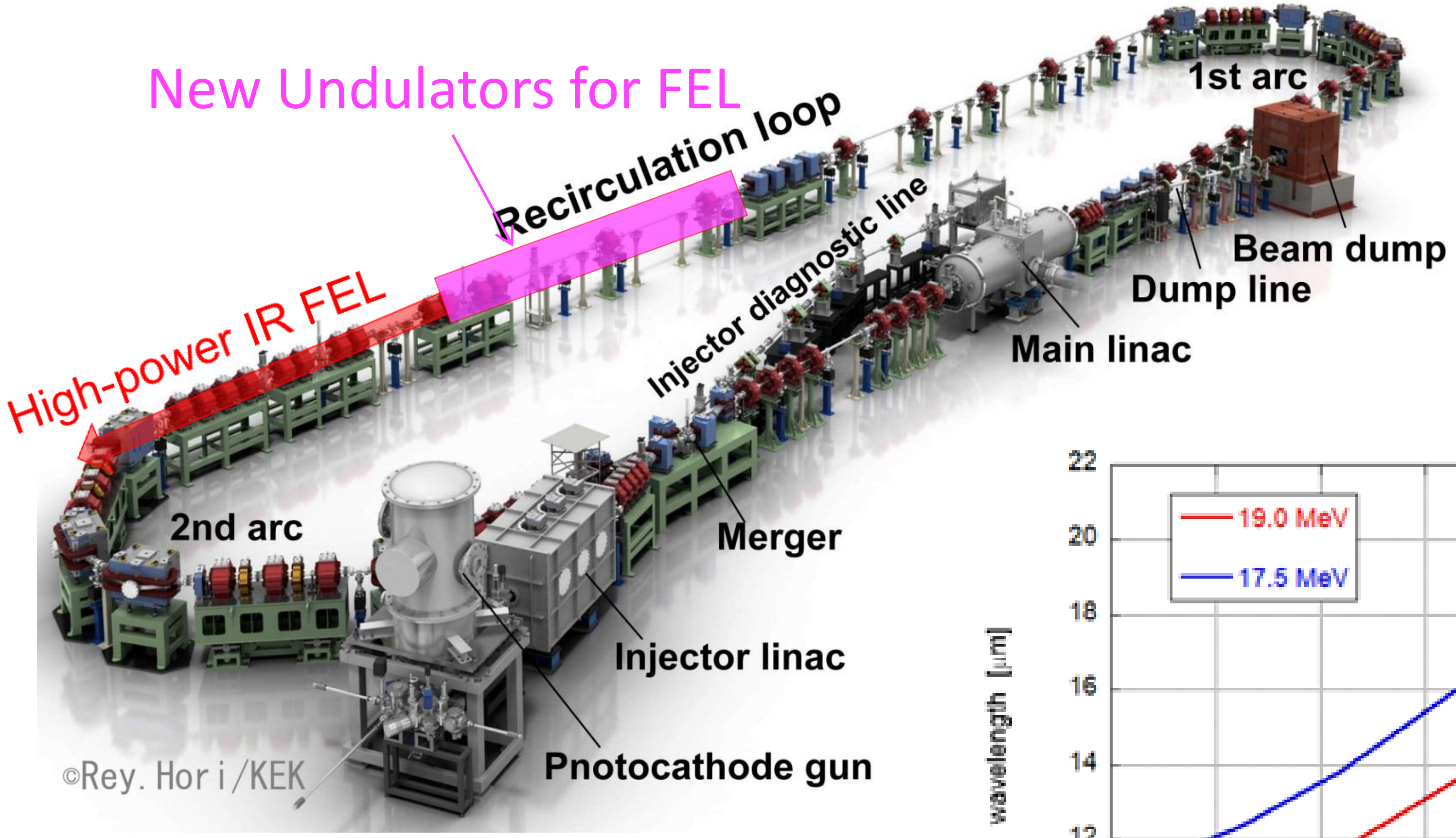
- In the wavelength region, there is vibrational absorption of organic materials whose use is expanding due to light-weight, low-cost, and high functionality.
- Considering the process of cutting and/or welding the resin, it is considered that the absorption wavelength corresponding to the vibration 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!

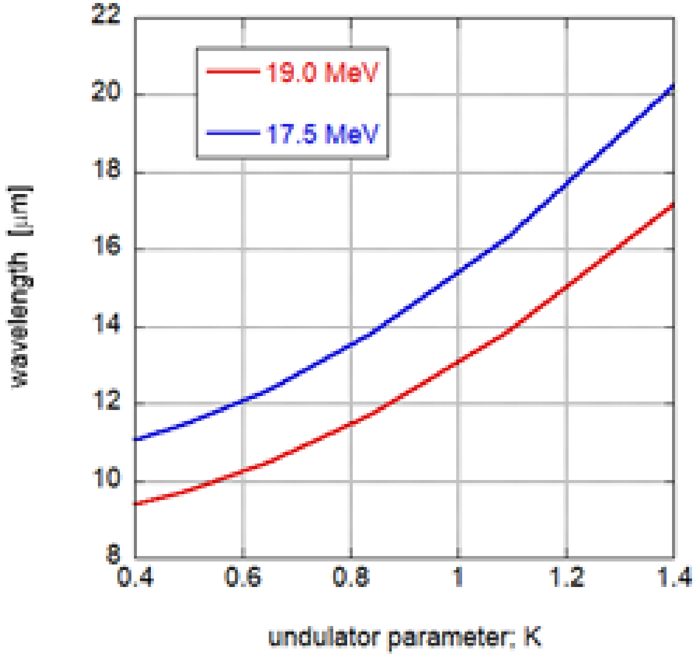


IPAC2019 TUPRB107

High average power IR-FEL Project



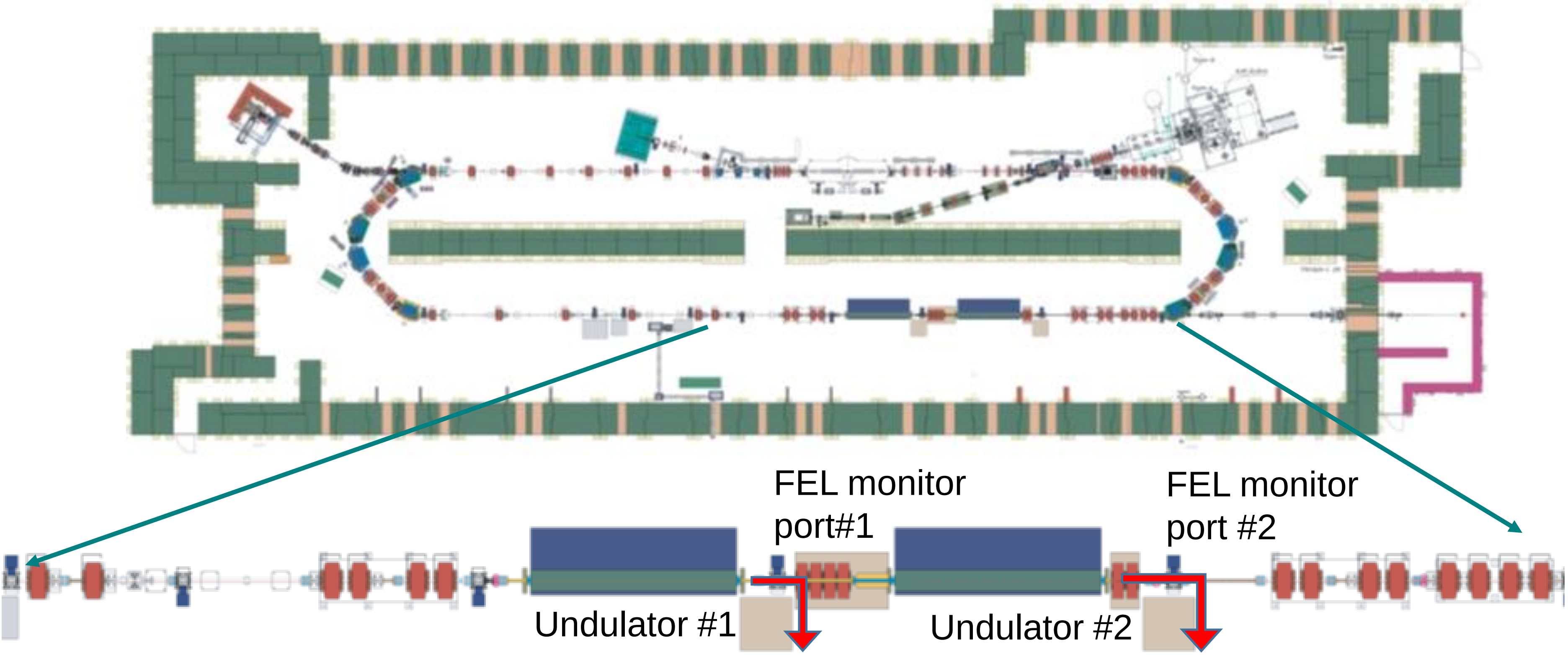
Beam Energy	17.5 - 19.0 MeV
Injector Energy	3.0 - 4.0 MeV
E-Gun Energy	500 keV
Bunch repetition	1.3 GHz → 81.25 MHz
Average current	1 mA (→ 5 mA)
Operation mode	CW or Burst



FEL wavelength

FEL2019 THA03

Layout and parameters of IR-FEL



FEL monitor port#1

FEL monitor port #2

Undulator #1

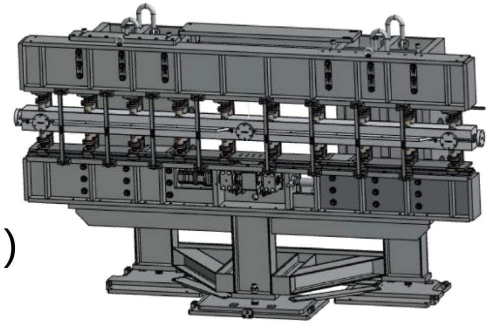
Undulator #2

March/2020

June/2020

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.

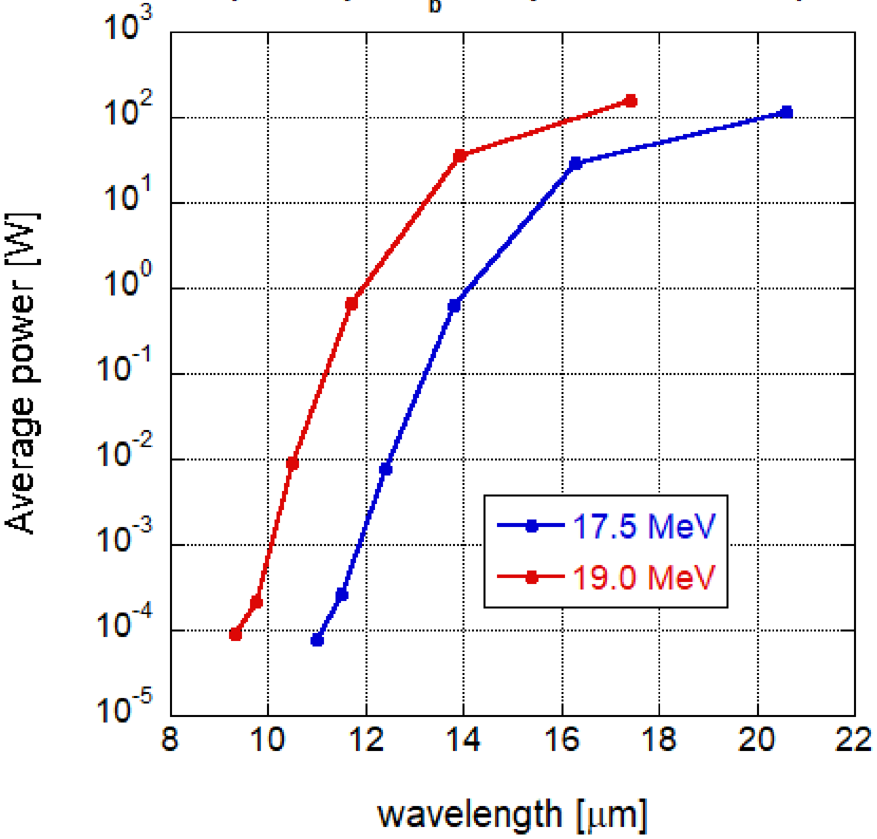
Undulator parameter

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

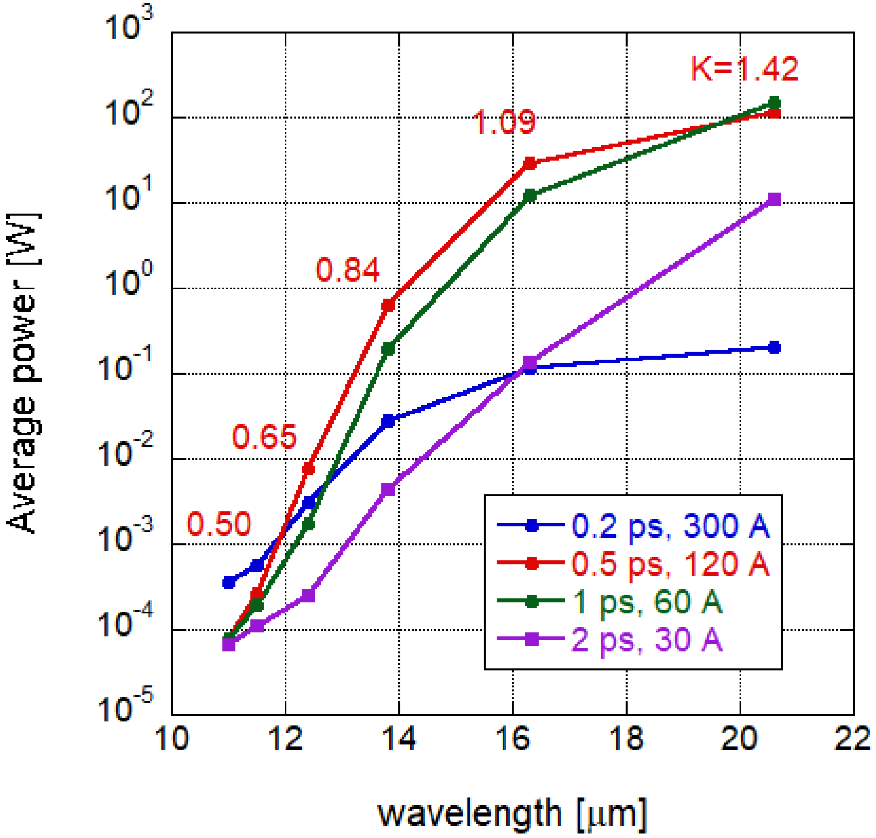
FEL2019 THA03

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.



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



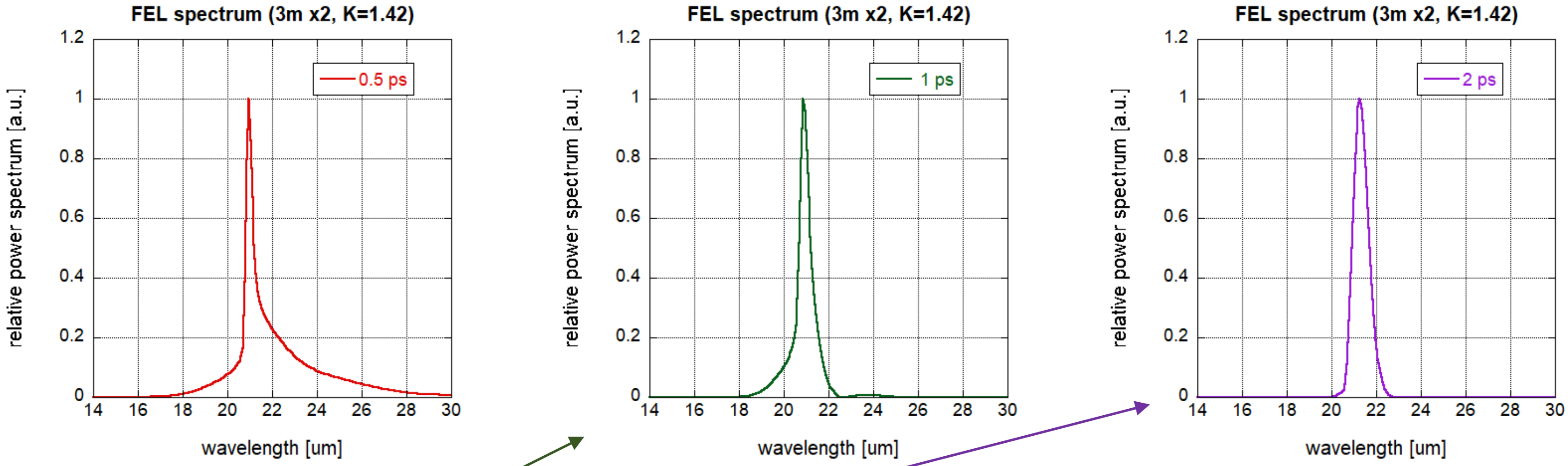
FEL power vs wavelength
(E= 17.5 MeV, Q= 60 pC, f= 81.25 MHz)

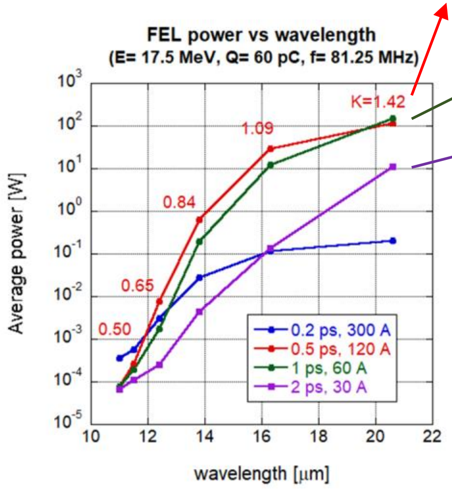
Spectrum of IR-FEL

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.





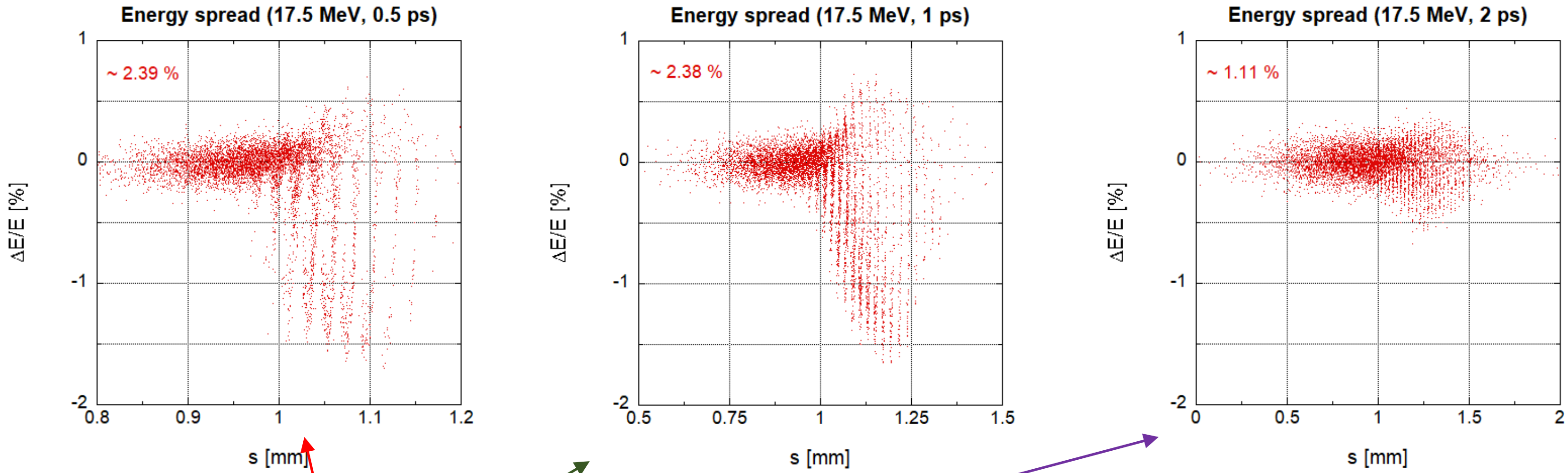
For the bunch length of 0.5 ps, a long tail appears on the long wavelength side.

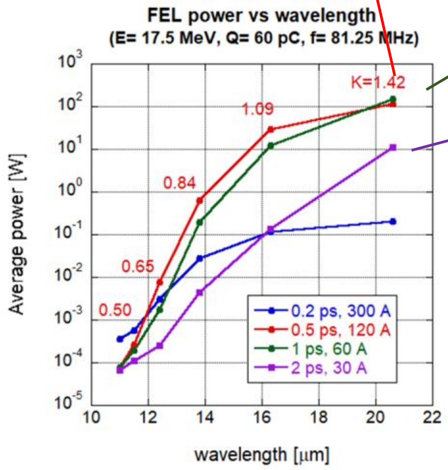
Trade-off between FEL power and spectral width

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.





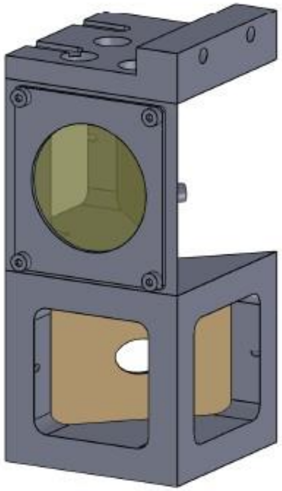
Acceptance of 2nd Arc ~ 2.5 %

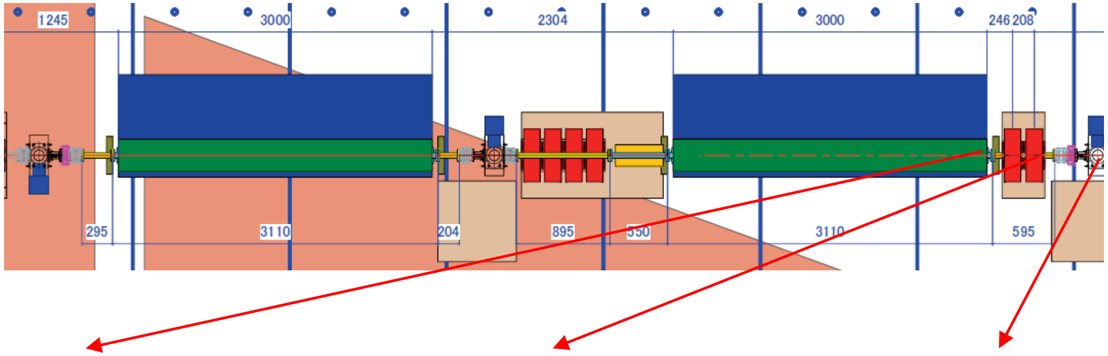
Acceptance of Dump line (DL) ~ 1.7 %

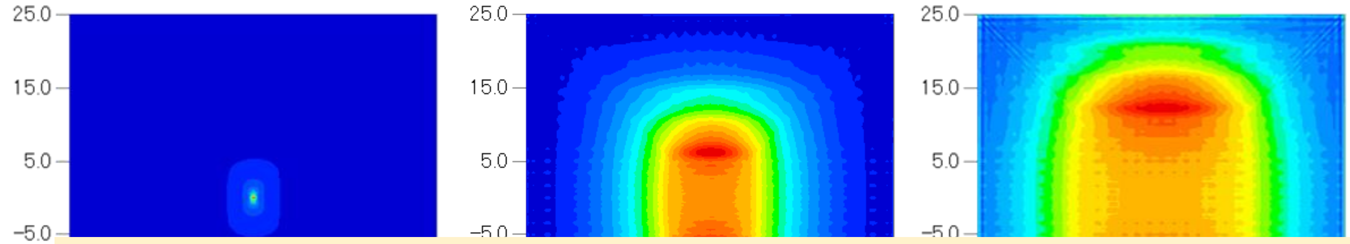
Energy compression & improvement of acceptance at DL

Divergence of FEL light

FEL light after 2nd undulator is also rapidly diverging.
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.
Using a mirror with a hole, let the electron beam pass and extract only the FEL light in the 90 degree direction.

Present status about the beam development on the high charge bunch condition

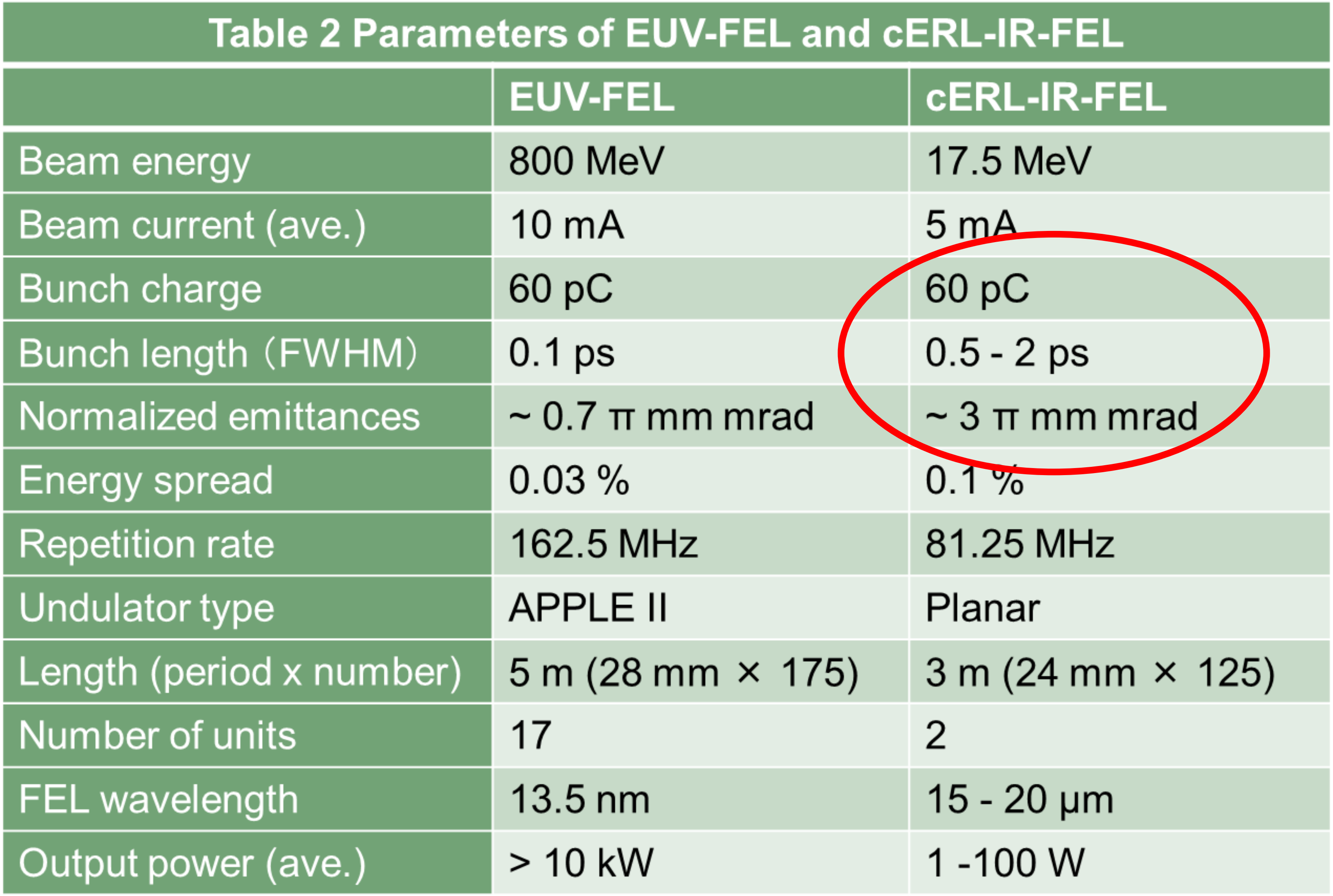


Table 2 Parameters of EUV-FEL and cERL-IR-FEL

	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

Present status about the beam development on the high charge bunch condition (1)

PASL2019 FRPI025 *O. Tanaka et. al.*

“HIGH BUNCH CHARGE INJECTOR OPERATION OF CERL FOR INFRARED FREE ELECTRON LASER TEST”

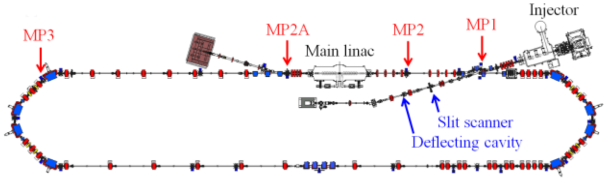


Table 1: Normalized RMS Emittance at Slit Scanner

	Design	Analysis 1	Analysis 2
ε_{nx} (πmm · mrad)	1.42	1.87	1.937 ±0.286
ε_{ny} (πmm · mrad)	1.48	0.88	0.826 ±0.018

Injector characterization beamline

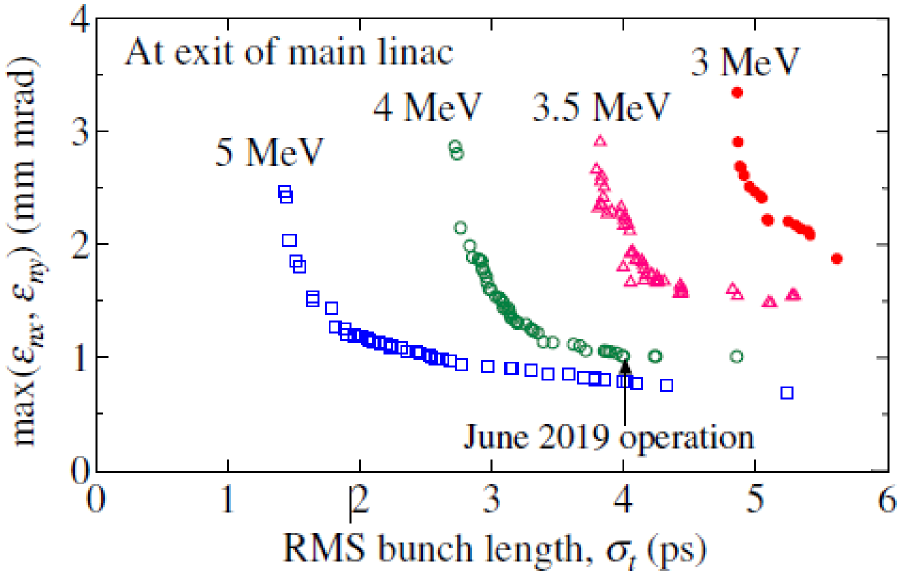
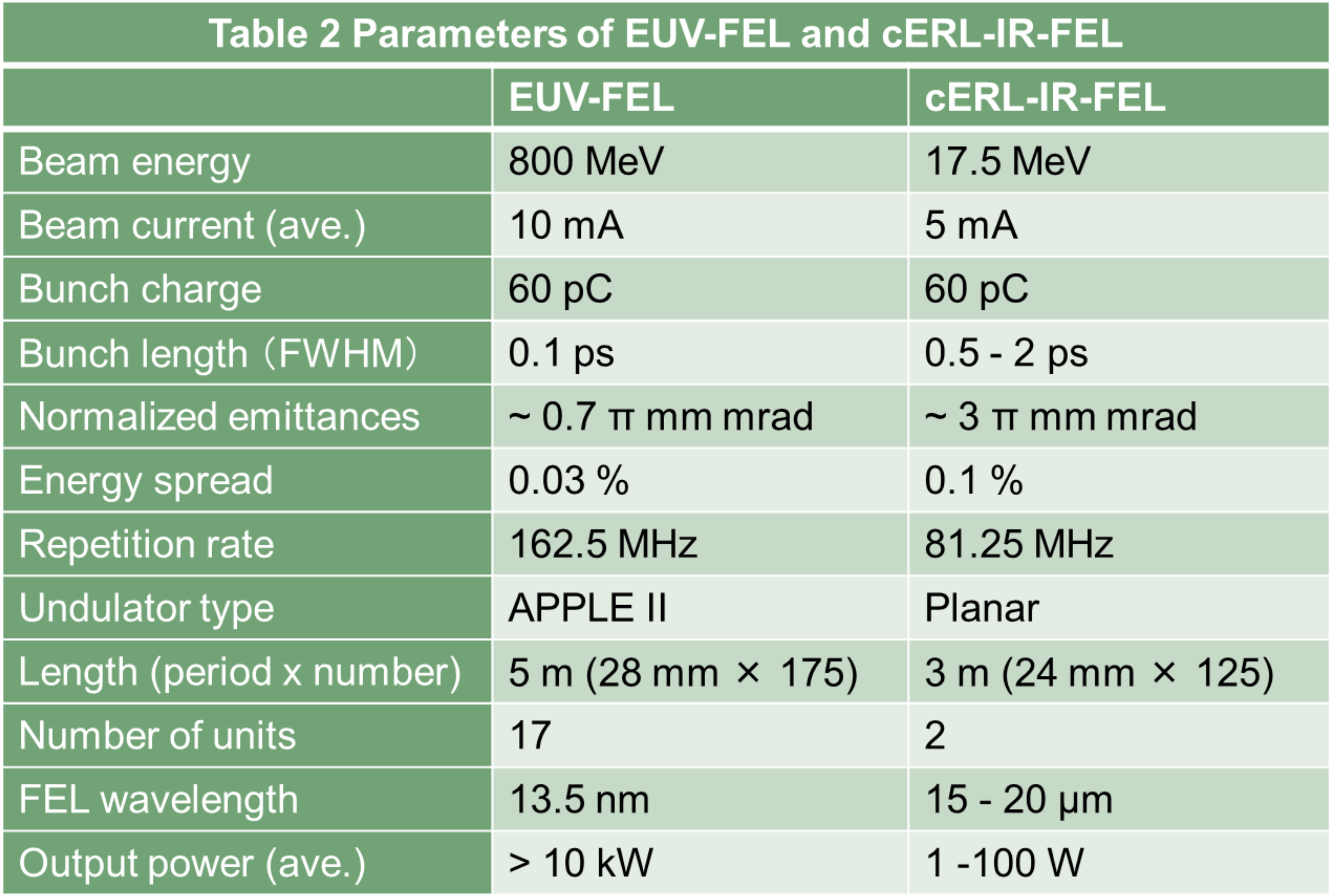


Figure 2: Optimization results for 3, 3.5, 4, and 5 MeV injection energies. Both bunch length and normalized emittance were minimized at the exit of main linac.

4 MeV was selected at the injection energy, so that the reasonable small emittance values were realized.

The emittance values were obtained as the design values at the injector line, and were observed less than 3 πmm mrad at the recirculation loop

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



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Norn

IPAC2019 TUPRB107

Discussion about the accelerator technologies between MIR-FEL and EUV-FEL (2)

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

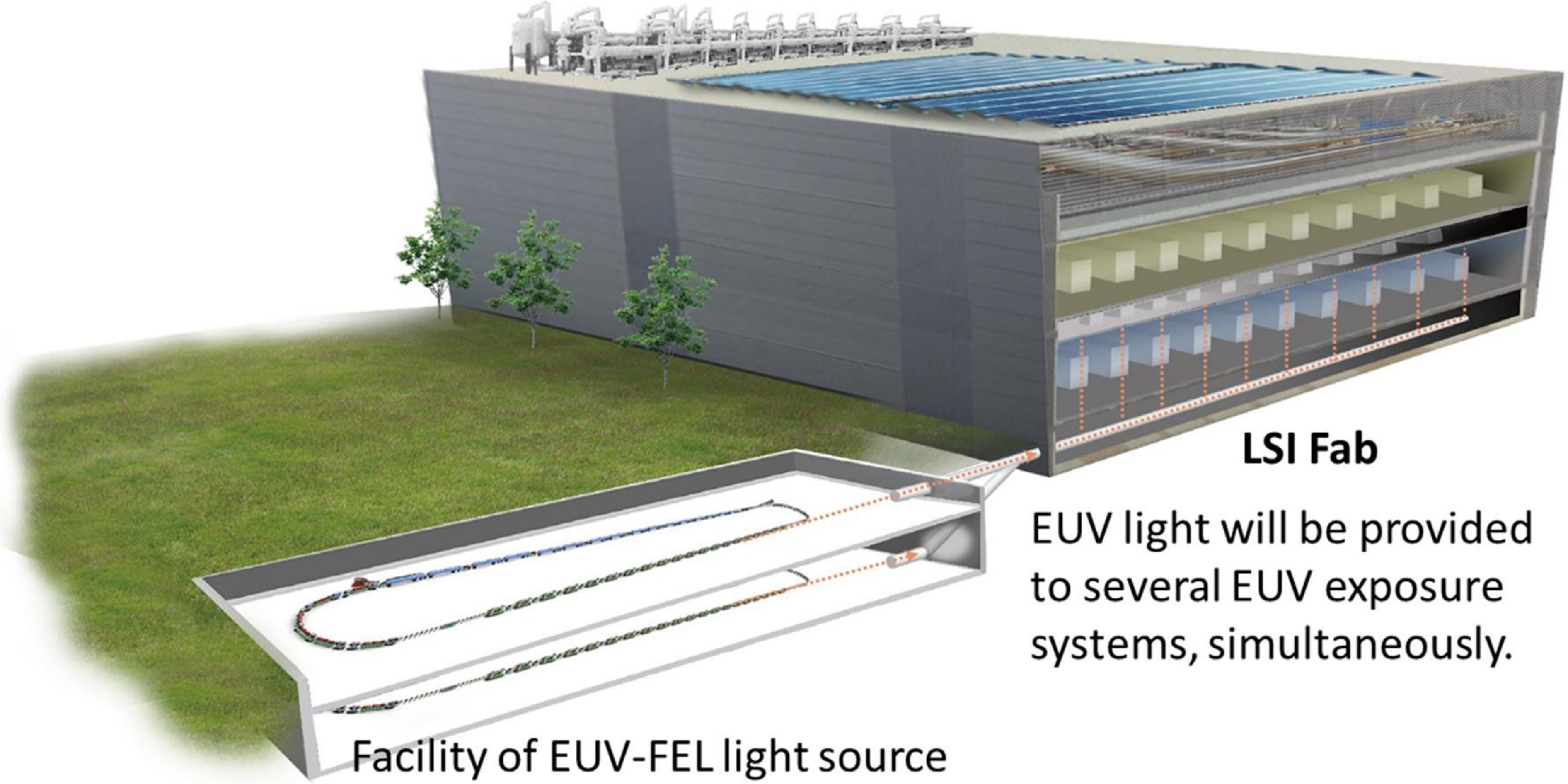
What is more difficult than EUV-FEL?

- Control of low energy electron beam

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

- Long wavelength
- Diffraction loss of FEL light after the undulators

Expected LSI Fab with EUV-FEL



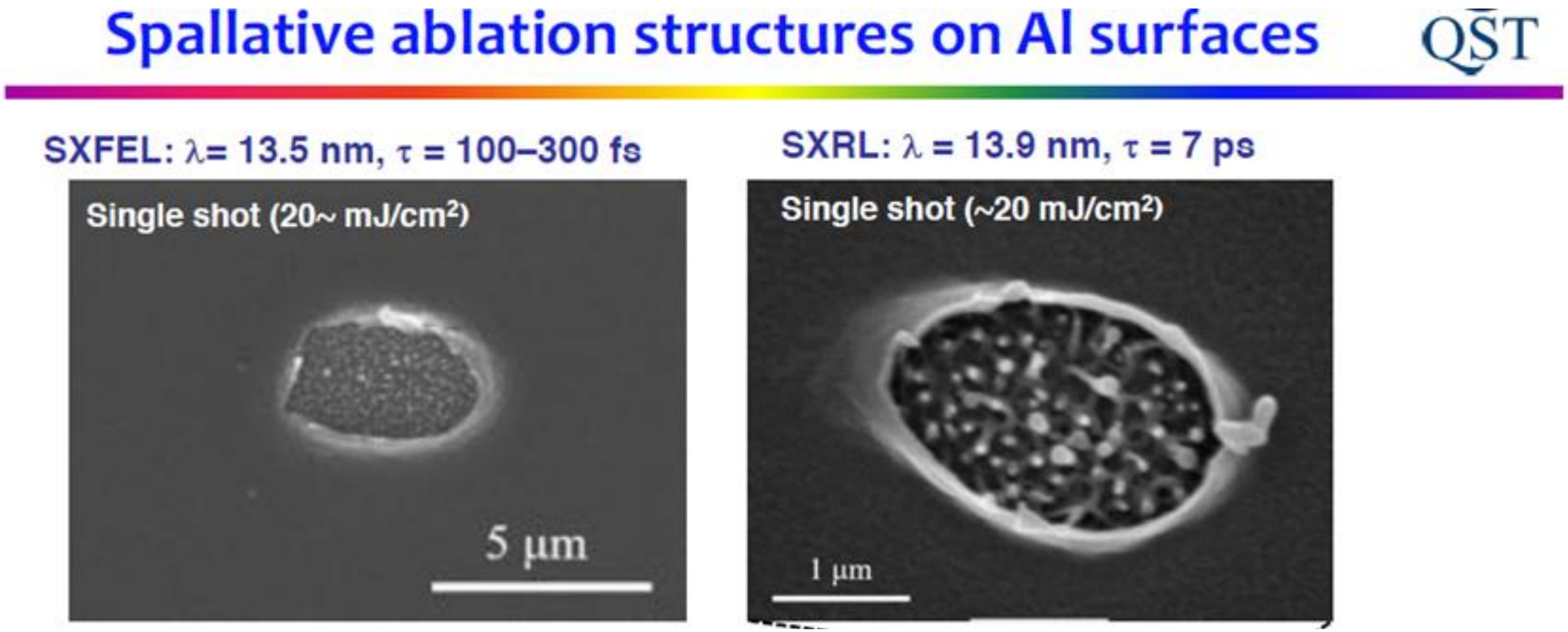
LSI Fab

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

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

A preliminary design concept for optical beamline from FEL to multi-scanners

Many people ask us " Is it possible to withstand the optical component from the high peak power irradiation on the EUV-FEL?" .



Spallative ablation structures on Al surfaces

SXFEL: λ= 13.5 nm, τ = 100–300 fs

Single shot (20~ mJ/cm²)

SXRL: λ = 13.9 nm, τ = 7 ps

Single shot (~20 mJ/cm²)

Presented by Nishikino: 2nd EUV-FEL Workshop 12 Dec. 2017 Tokyo

A preliminary design concept for optical beamline from FEL to multi-scanners (1)

Important results of Nishikino’s presentation

1) Ablation threshold on Al and Mo/Si Mirror is about 20mJ/cm^2/pulse

2) The threshold is not depend on a peak power, when the peak width is less than 10 psec.

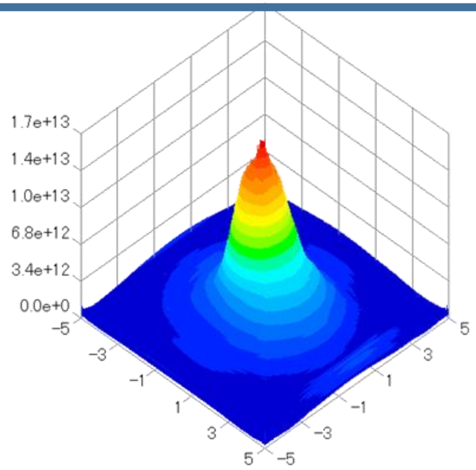
3)Total reflection mirror (glancing angle ~ 3degree) has no ablation damage at the FEL light irradiation.

Characteristics of the EUV-FEL Light

1) One shot power is about 100μJ/pulse

2) Typical beam size at the first optics (3m far from the undulator) is ~1mm ϕ

3) Typical power density of the normal incidence is ~10mJ/cm^2/pulse

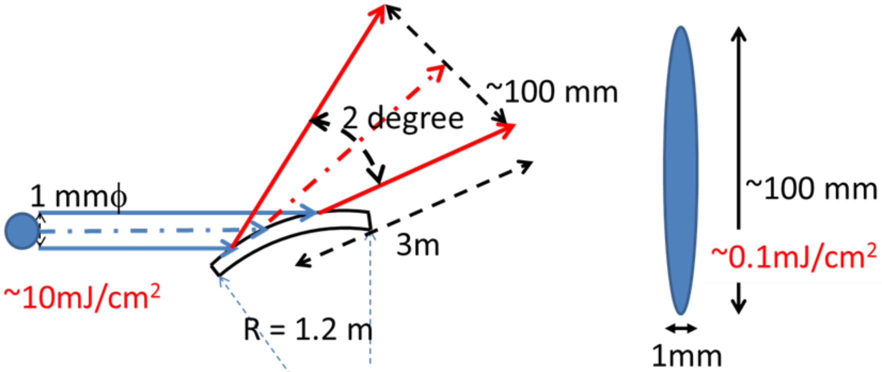


Power distribution at the position of 3m far from undulator

A preliminary design concept for optical beamline from FEL to multi-scanners (2)

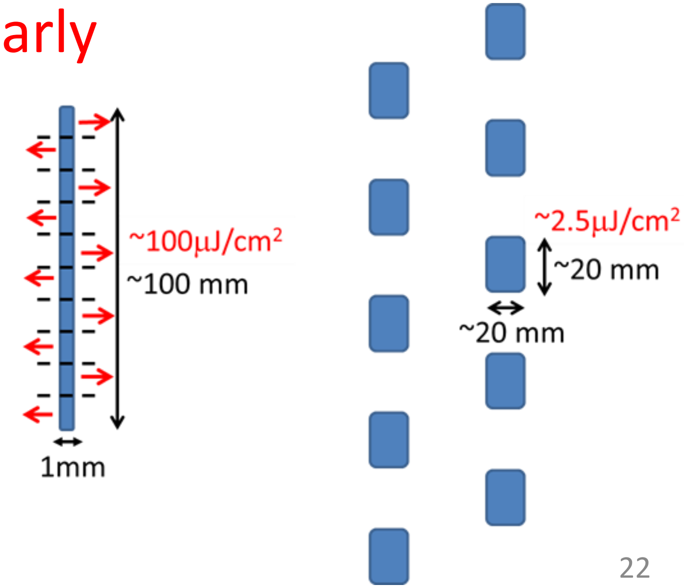
1) Vertical beam expanding by using curved glancing mirror

For example, when the curved mirror, whose bending radius is about 1.2 m, is set as the central glancing angle is 2.5 degree, it is possible to expand the FEL light up to ~100mm at the position after 3m far from the mirror.



2) Horizontal beam separation and beam expanding by using segmented multi-curved mirrors, similarly

3) Collimation mirror systems for both directions to keep the beam size



The power density for 1st ML mirror to introduce the FEL light to the scanner is about 2.5 μJ/cm^2/pulse

Summary

- We are proposing ERL-based FEL as a future light source in the EUV region for future lithography.
- KEK will install two undulators in the cERL southern straight section and develop a mid-infrared FEL with high average power.
- With the MIR-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.
- MIR-FEL can demonstrate many of the challenges for the realization of EUV-FEL.
- Beam development also progressed, and we could realize the beam performance in order to produce MIR-SASE-FEL.
- Preliminary design concept of the beamline to lead the FEL light to multi-scanners is presented.

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)."

3rd EUV-FEL Workshop

http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop3/program_eng.html

Invited Talk

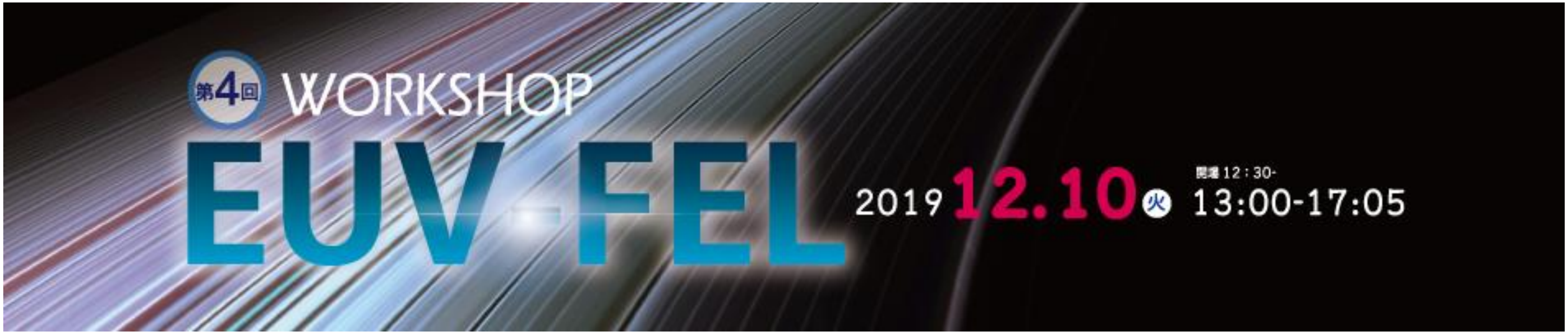
1) Prof. Hiroo Kinoshita

Aiming at the mass production by EUVL
~From the beginning to the future prospect~

2) Prof. Hiroshi Sakai

Development of "Compact ERL (cERL)" accelerator based on Superconducting cavity technology and its application by using cERL

4th EUV-FEL Workshop 10/ Dec. 2019



https://conference-indico.kek.jp/indico/event/93/

We will organize 4th EUV-FEL Workshop with source group, tool and material venders, and end users.

Date: 10/ Dec. /2019 13:00-17:05
Site: UDX NEXT1 Akihabara, TOKYO
Registration fee: Free

Thank you for your attention!