Present status of cERL-FEL as a Proof of Concept on the EUV-FEL high power light source for future lithography

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- Staging to realize the EUV-FEL light source step by step
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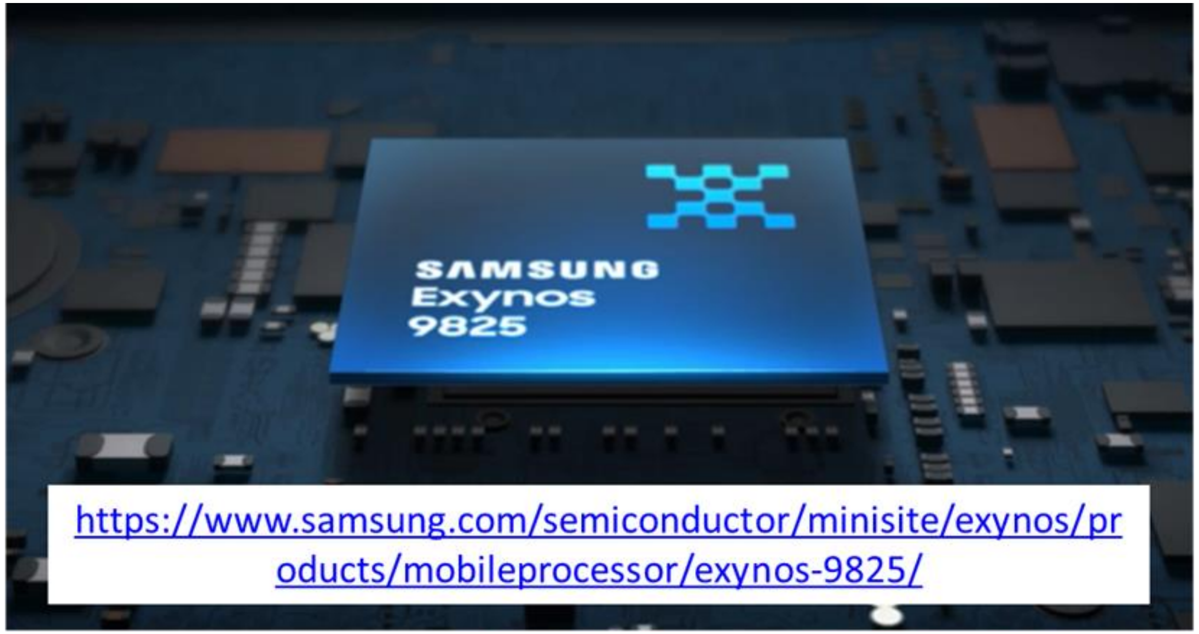
- Construction of the MIR-FEL and present performance at preliminary commissioning phase
- Summary

EUVL has became as a daily tool



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

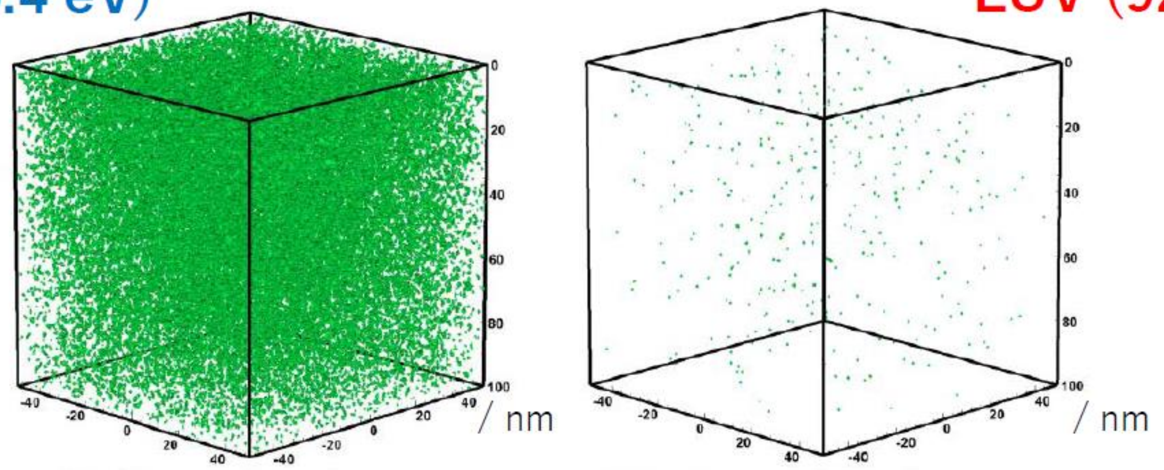
https://consumer.huawei.com/en/campaign/kirin-990-series/

TSMC's N7+ Technology is First EUV Process Delivering Customer Products to Market in High Volume
https://www.tsmc.com/tsmcdotcom/PRListingNewsArchivesAction.do?action=detail&newsid=THHIHIPGTH&language=E

One of the big issues is "Stochastic noise" for future fine patterning like 3nm and 2nm node

Absorbed photon distribution

ArF (6.4 eV) | EUV (92.5 eV)



ArF (6.4 eV):
Dose=10 mJ/ cm^2
$\alpha = 4$ /µm
$n_{absorbed}$: 366528
$E_{absorbed}$: 2354 keV

EUV (92.5 eV):
Dose=10 mJ/ cm^2
$\alpha = 4$ /µm
$n_{absorbed}$: 25328
$E_{absorbed}$: 2326 keV

Biafore et al., *Proc. SPIE* 7273 (2009) 727343. 7

This challenge is being addressed by <u>more powerful EUV sources</u>, improved resist processes, advanced etches and other LER smoothing processes.

By Harry J Levinson at PLENARY PRESENTATIONS on PHOTOMASK TECHNOLOGY AND EXTREME ULTRAVIOLET LITHOGRAPHY 2018

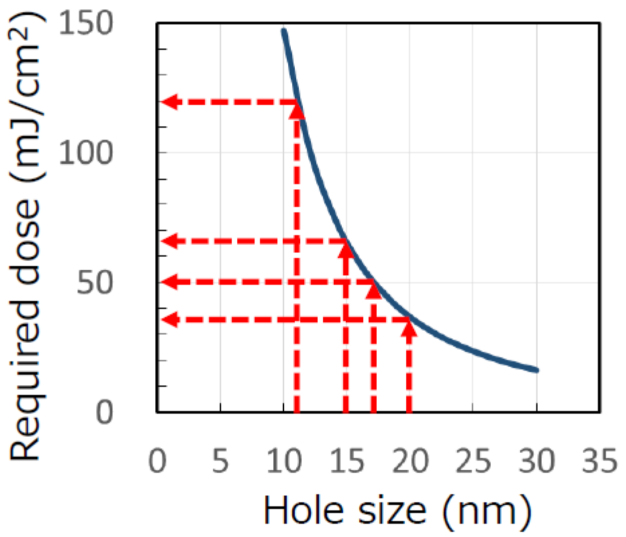
Estimated source power for Maximum throughput

Presented by Soichi Inoue (KIOXIA) @ 4th EUV-FEL Workshop 2019

https://conference-indico.kek.jp/event/93/timetable/#20191210

EUVL: Resist Sensitivity for Mitigating Photon Shot Noise Effect

- Photon energy of EUV light: **14.7 E-18 J**
- CD error due to shot noise: < **3 %**
- Requirement of photon number (hole): > **10,000**
- Required dose based on shot noise (by calculation):



20 nm hole (N7): **36 mJ / cm²**
17 nm hole (N5): **50 mJ / cm²**
15 nm hole (N3): **65 mJ / cm²**
11 nm hole (N2): **120 mJ / cm²**

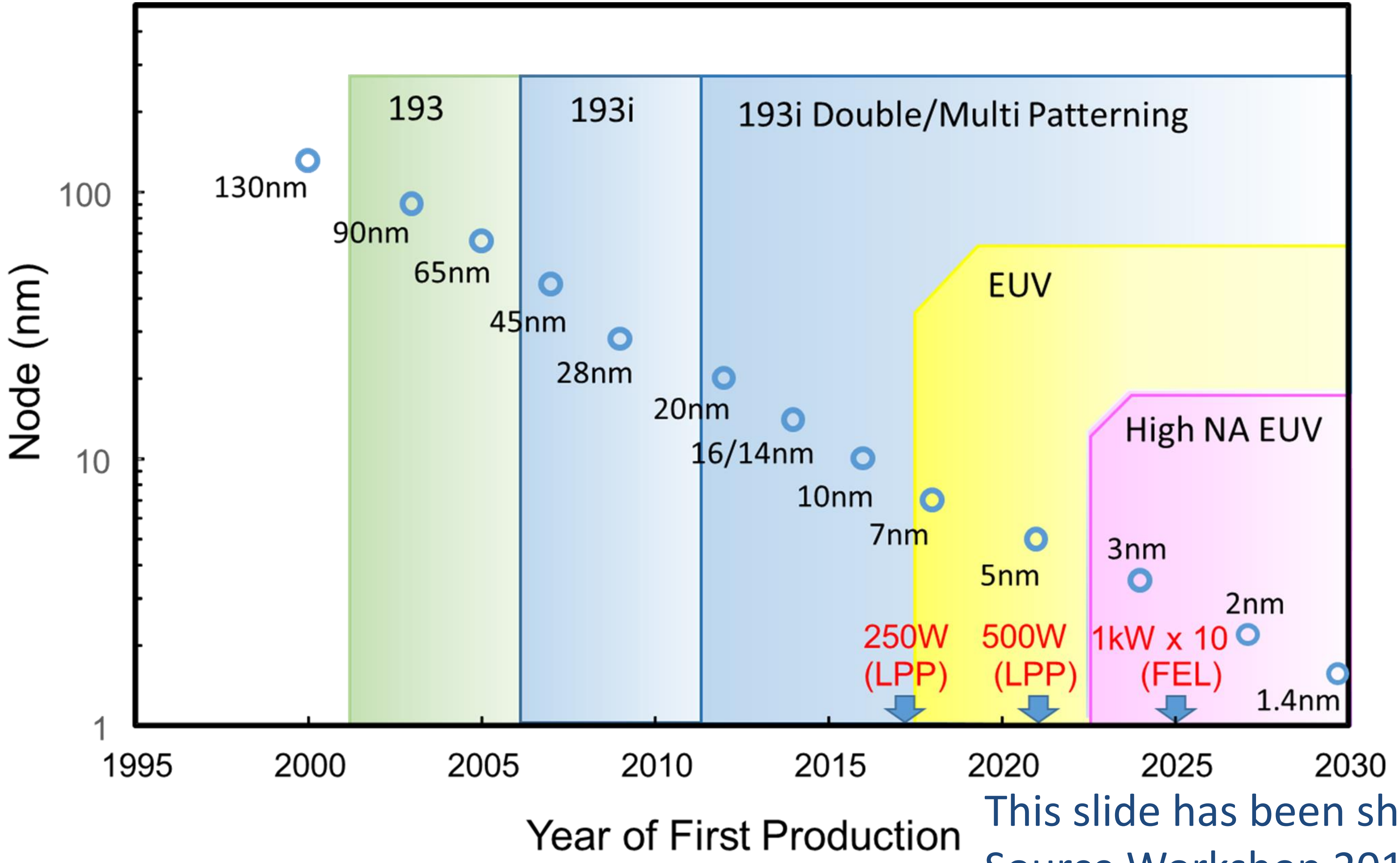
KIOXIA 第4回EUV-FELワークショップ

Required Source power for Maximum Throughput

N3 -> 1.5kW

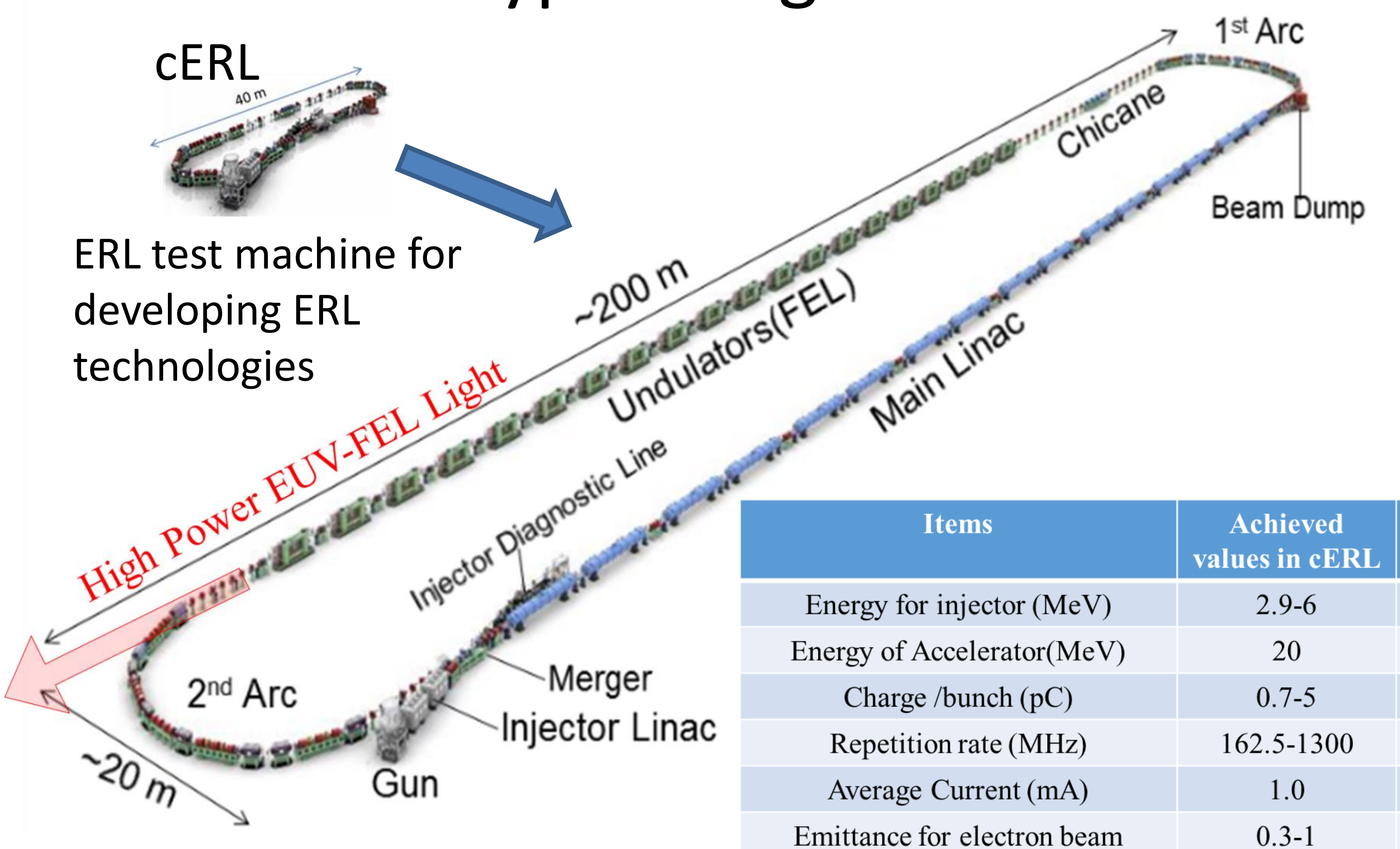
N2 -> 2.8kW

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



This slide has been shown from the Source Workshop 2016 (Amsteldum)

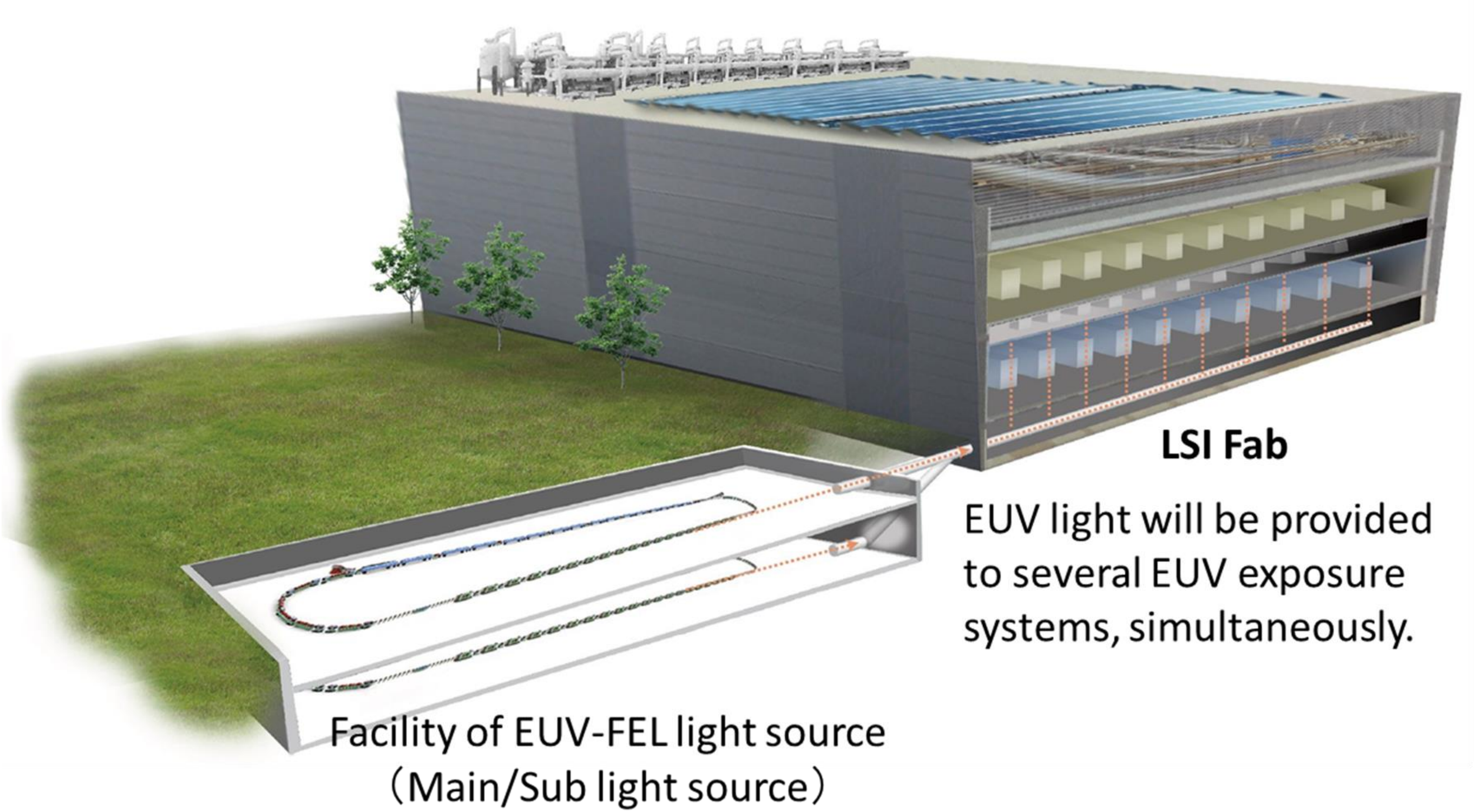
Prototype design of the EUV-FEL



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

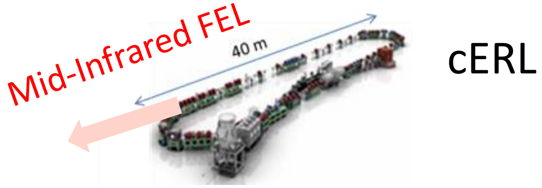
This slide has been shown from the Source Workshop 2016 (Amsteldum)

Expected LSI Fab with EUV-FEL



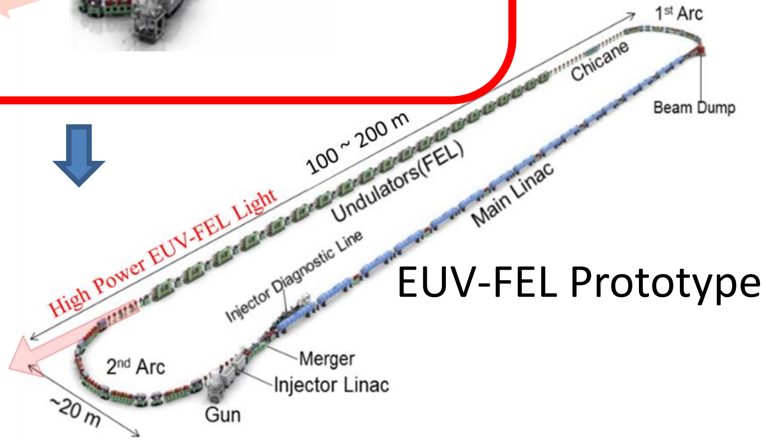
Staging to realize the EUV-FEL light source

1st stage:
Development of the feasible technologies

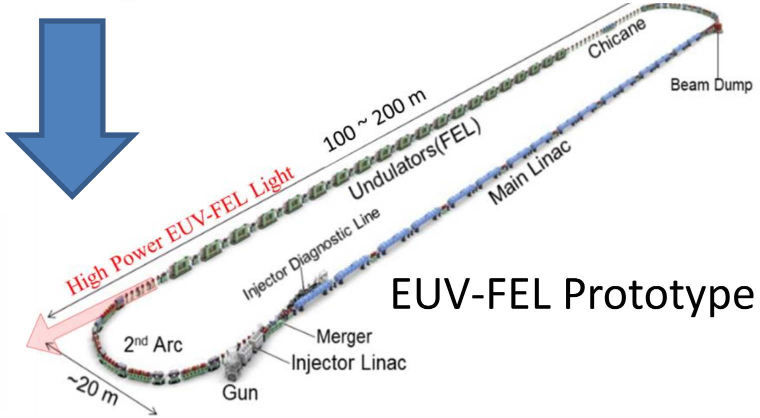


Upgrade plan of cERL for the PoC

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



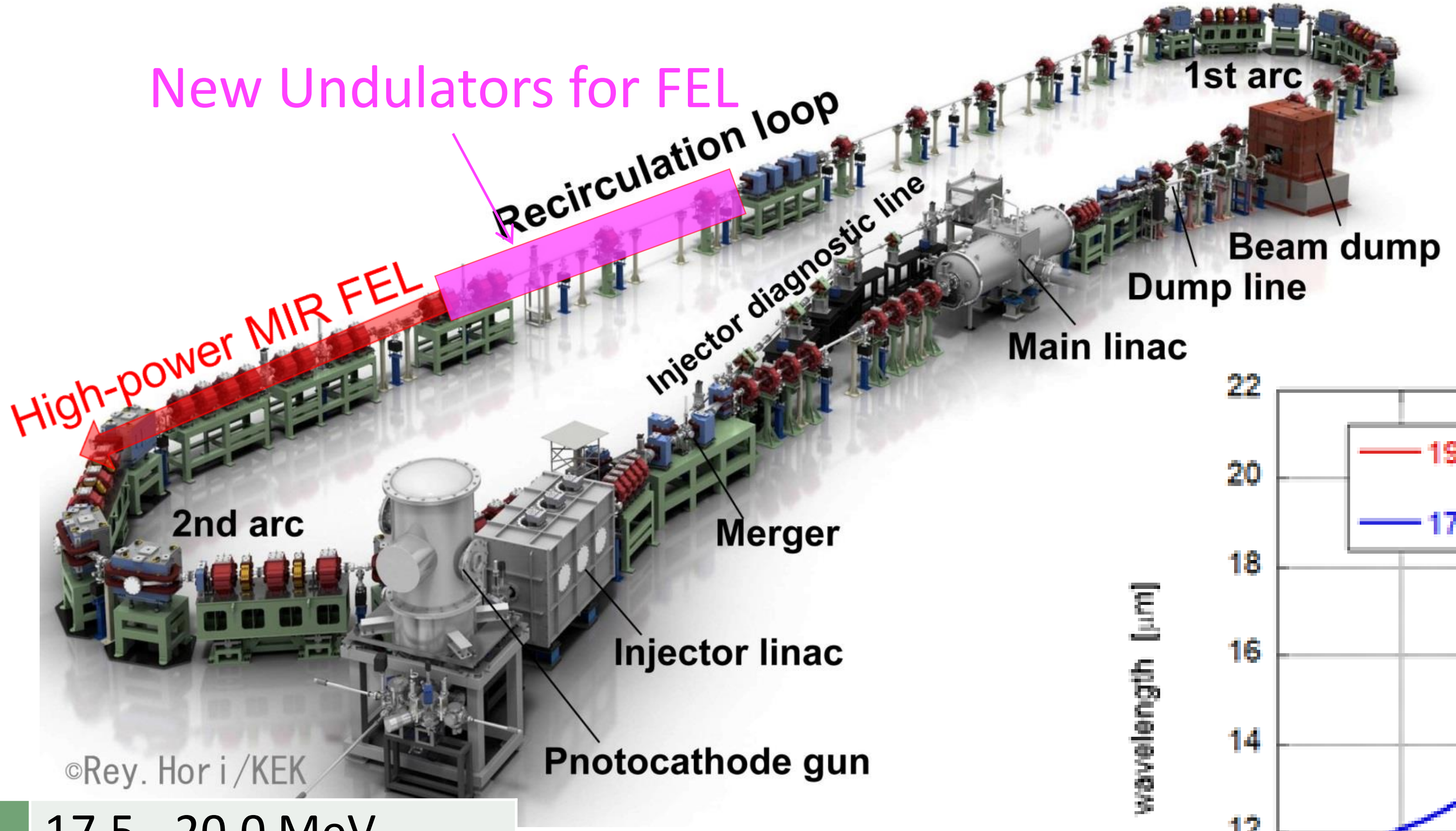
2nd stage Phase 2:
International Development Center on the processing of EUV-FEL lithography



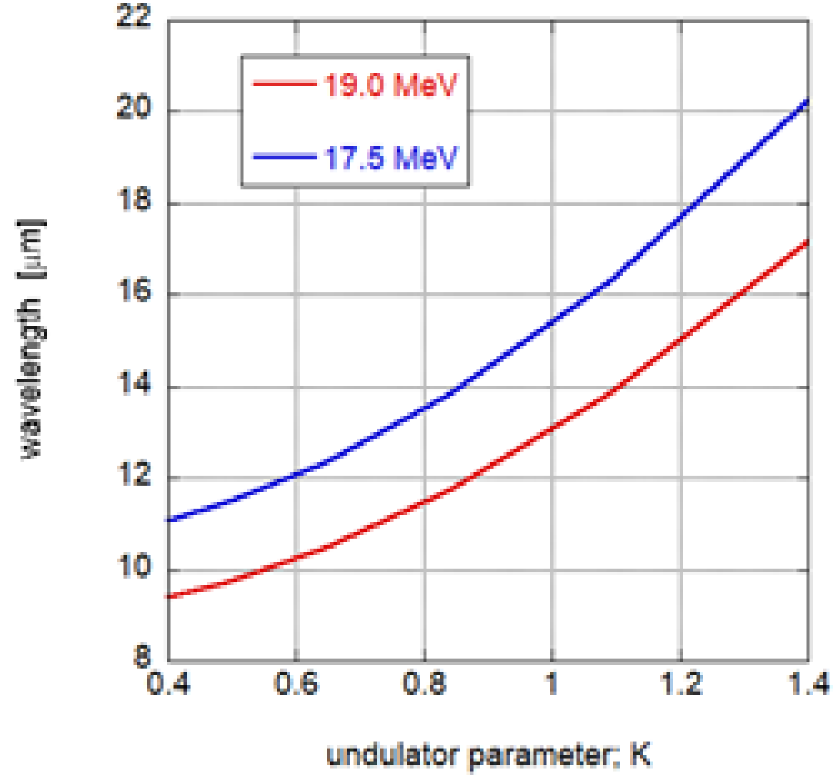
Clean room with EUV exposure system

This slide has been shown from the EUVL symposium 2017 (Monterey)

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



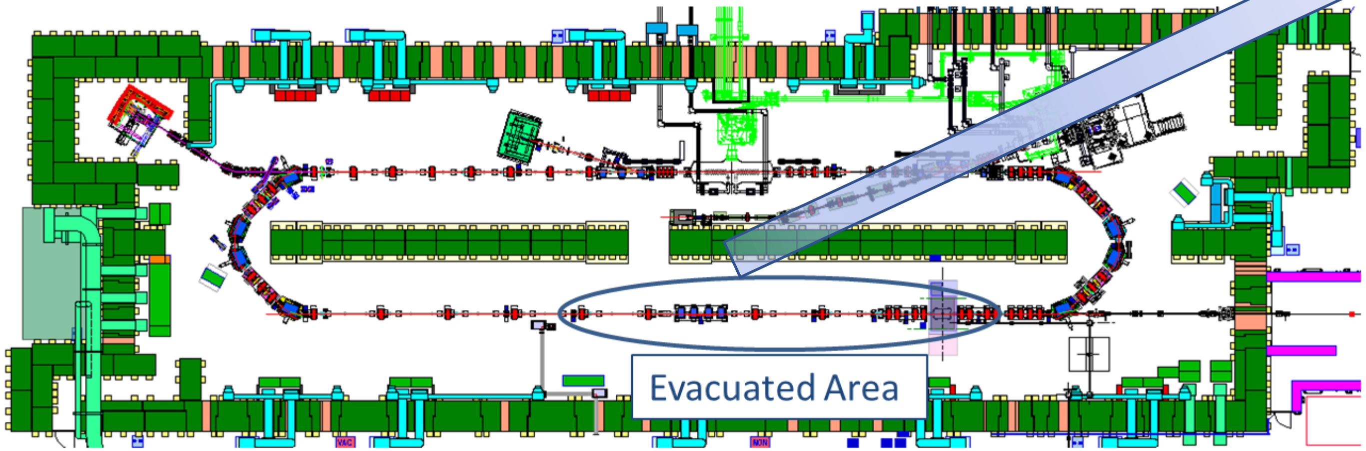
Beam Energy	17.5 - 20.0 MeV
Injector Energy	3.0 - 5.0 MeV
E-Gun Energy	500 keV
Bunch repetition	1.3 GHz → 81.25 MHz
Average current	1 mA (→ 5 mA)
Operation mode	CW or Burst



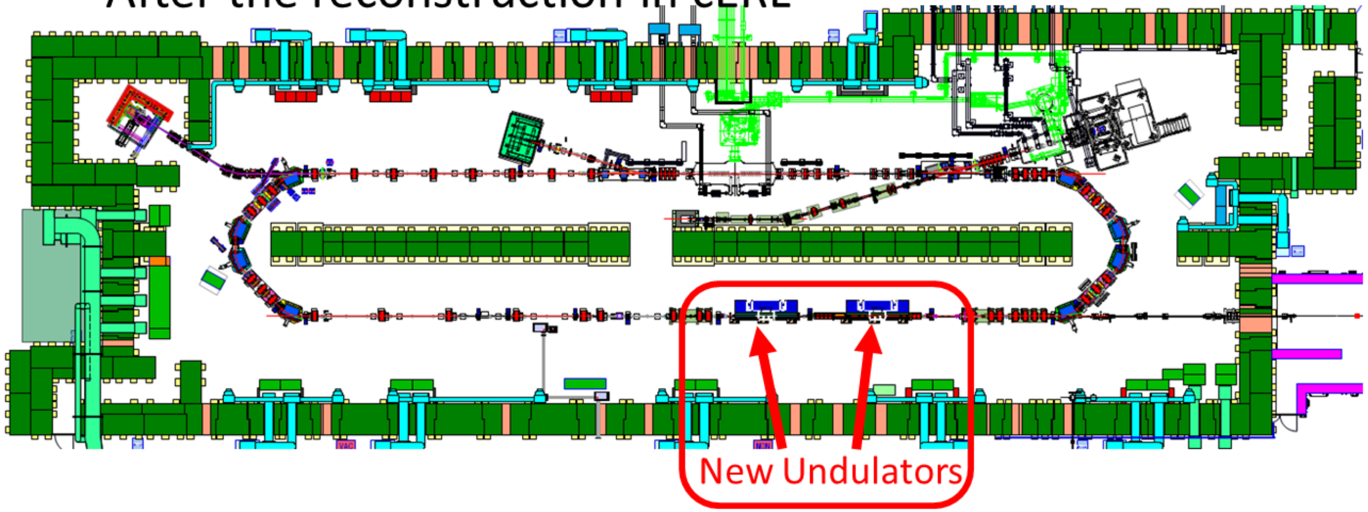
FEL wavelength

Construction of the MIR-FEL in cERL (1)

Before the reconstruction in cERL to install two Undulators

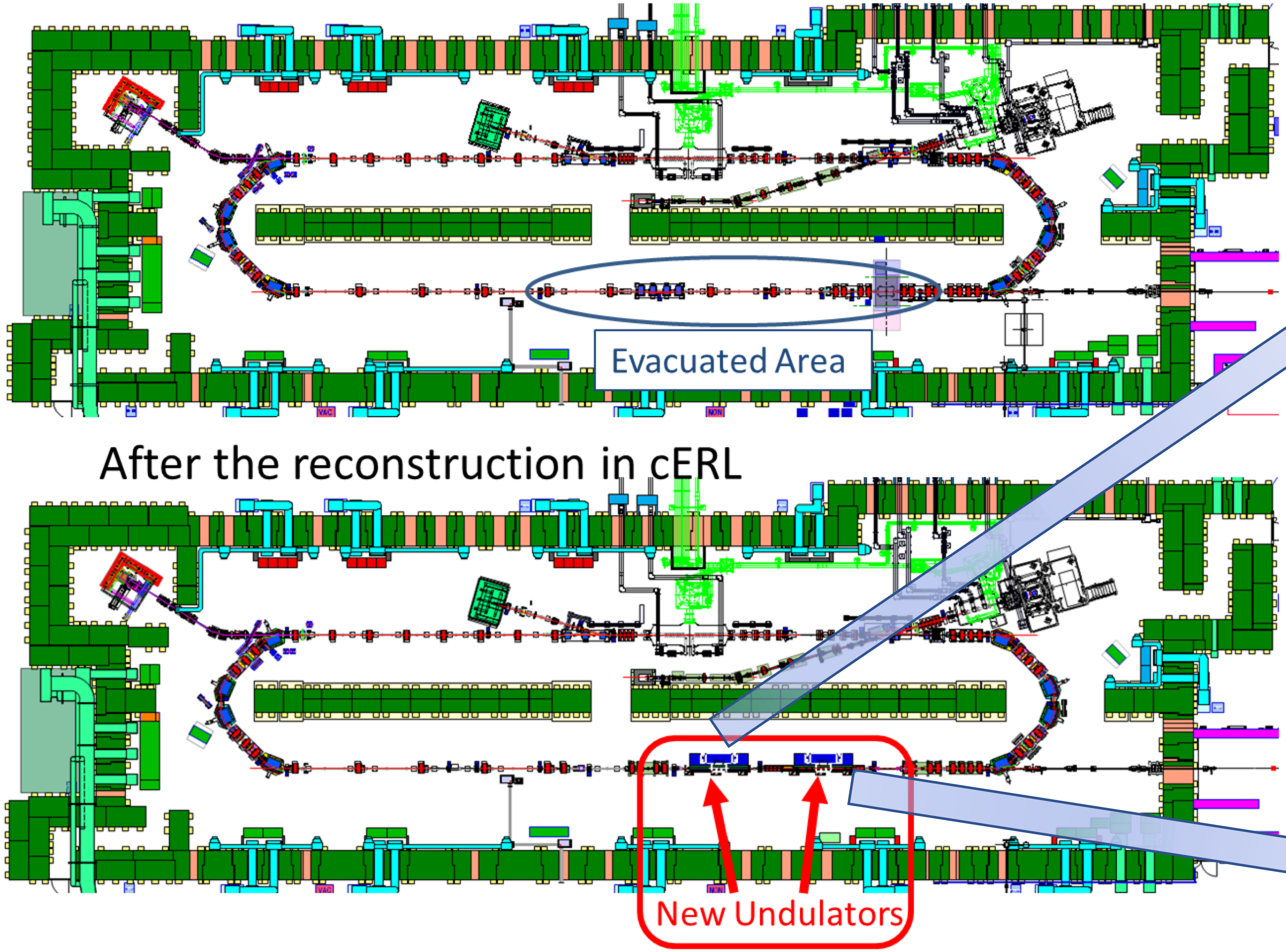


After the reconstruction in cERL



Construction of the MIR-FEL in cERL (2)

Before the reconstruction in cERL to install two Undulators

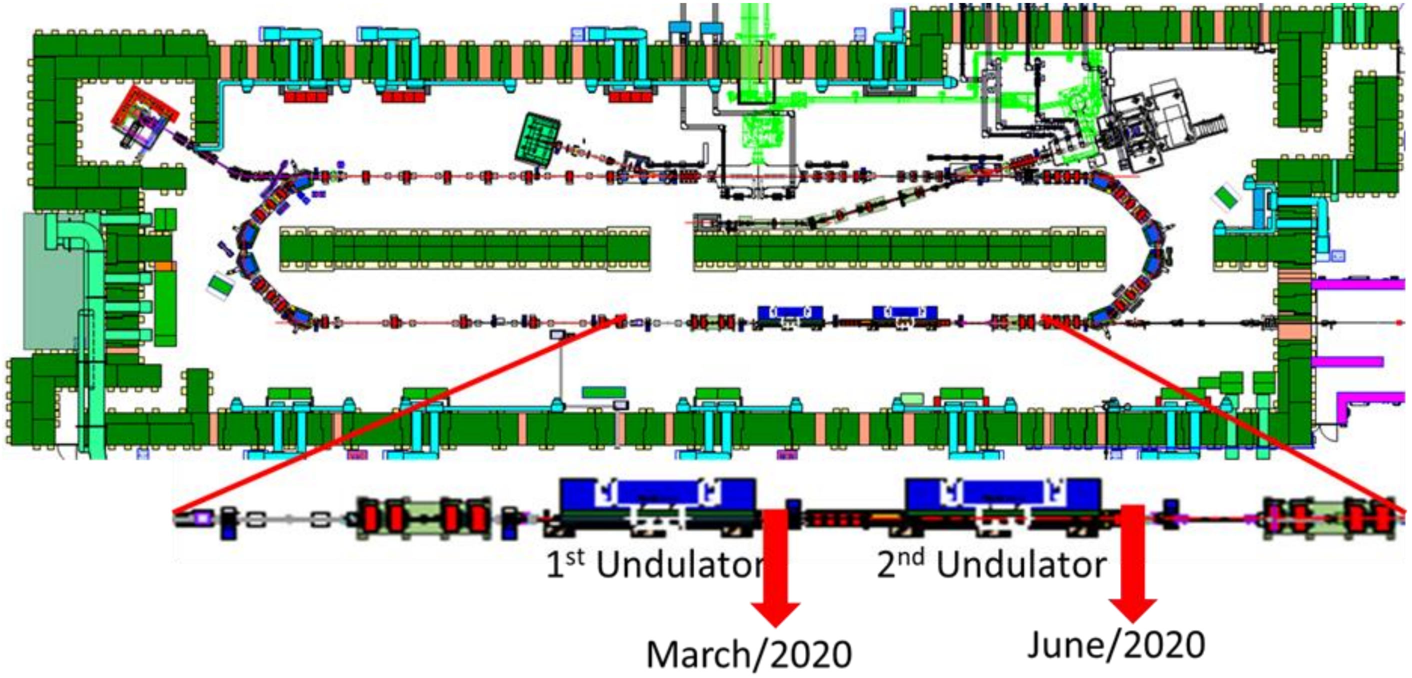


Middle of Jan./2020 Installation of 1st Undulator

End of April/2020 Installation of 2nd Undulator

Time schedule of the commissioning

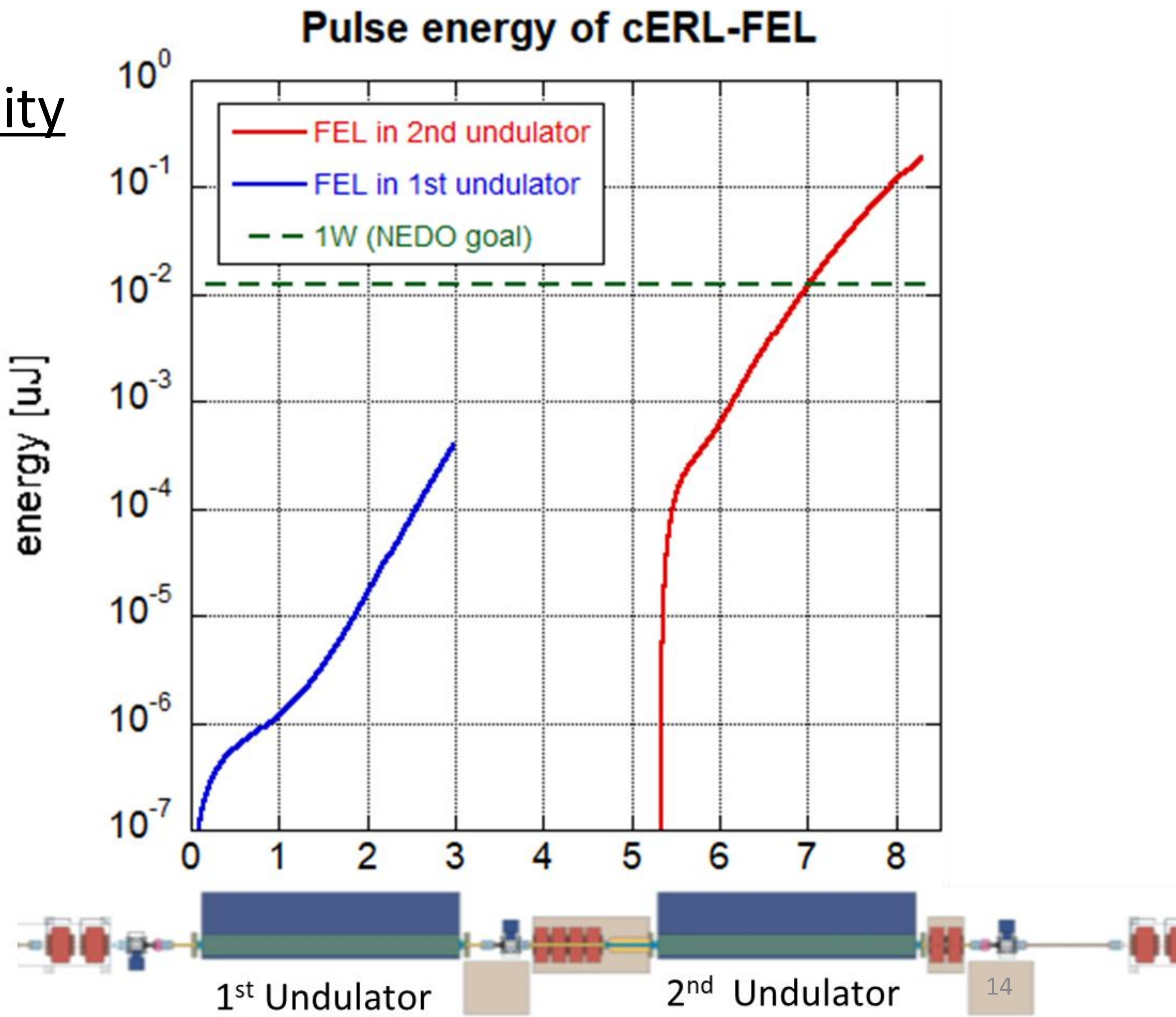
- **March/2020:** Beam operation and First FEL light production from the 1st undulator in burst mode.
- **April-May/2020:** Installation of the 2nd undulator.
- **June/2020:** FEL light observation from the 2nd undulator in burst mode.
- **December/2020:** Fine tuning of the beam development for higher power FEL light and also topical demonstration on laser processing.
- **February/2021:** Several applications on laser processing



Expected intensity of FEL light in this project

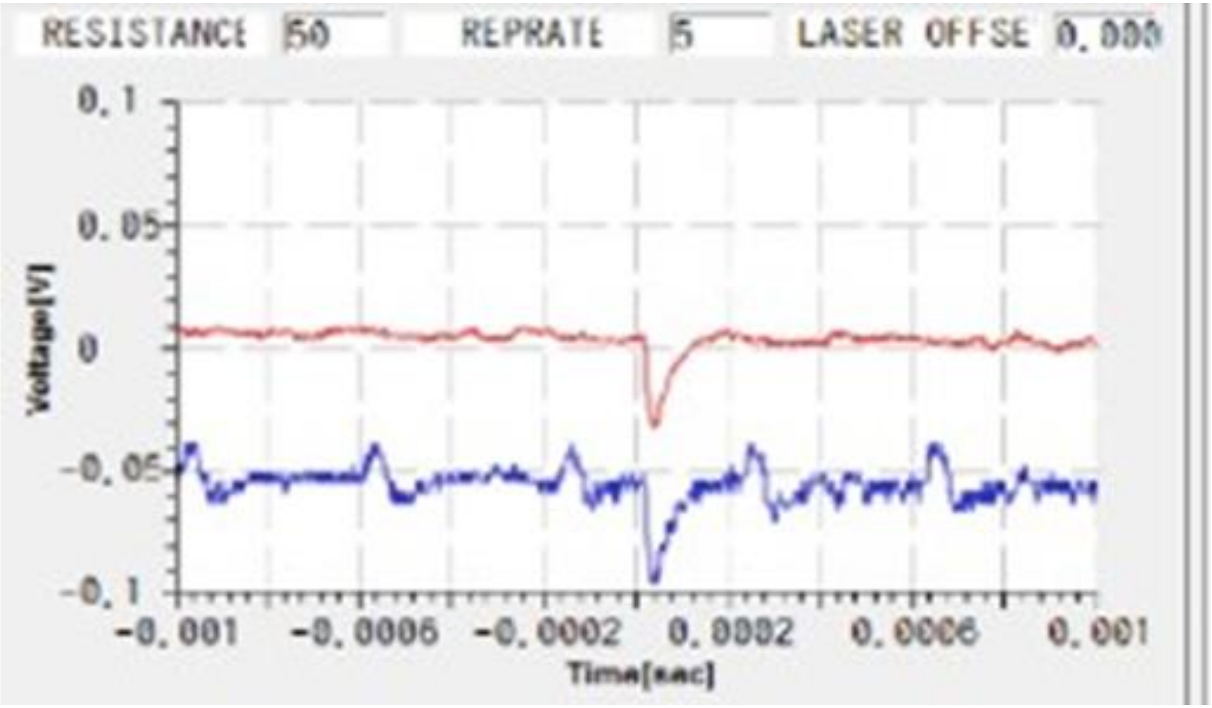
Expected development of the intensity

- Micro-bunching, which is produced by the correlation effect between the undulator light and electron bunch, produces the development of the intensity.
- There is no correlation effect between the 1st and 2nd Undulator.
- At the 2nd undulator, the micro-bunching, which is produced by the 1st undulator, again produces the development of the intensity.

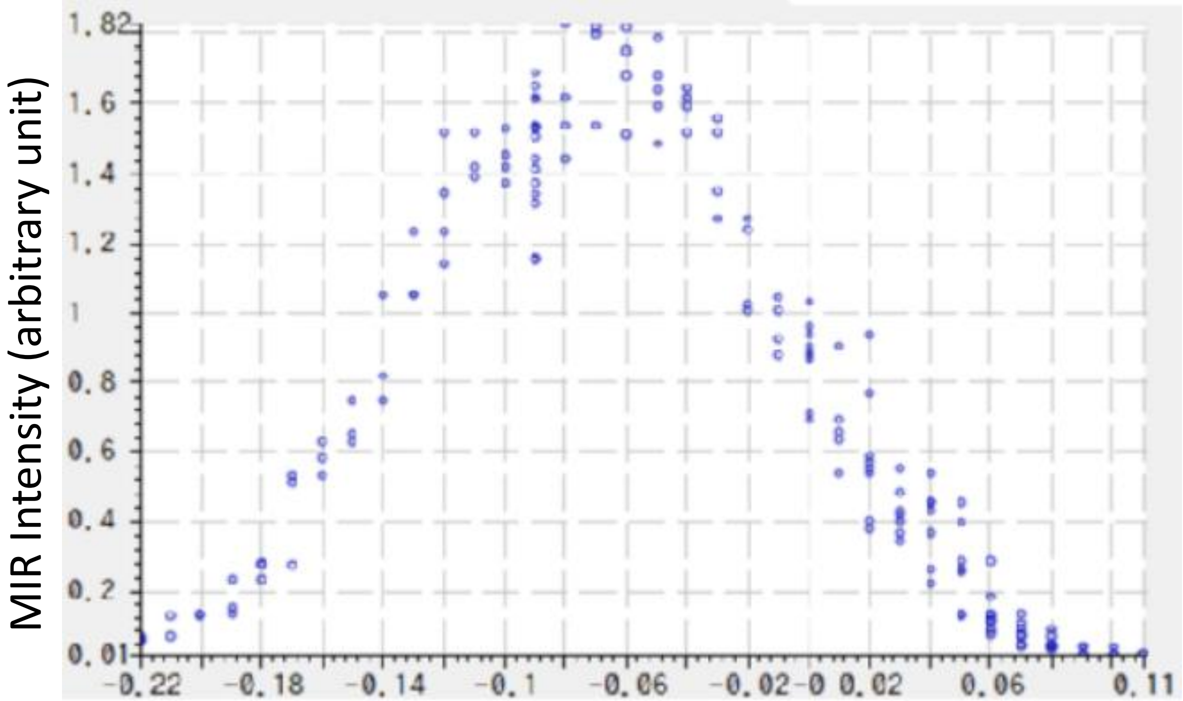


Results of the commissioning (1)

- Observation of the MIR radiation from the 1st Undulator. The large enhancement on the bunch compression indicates that the radiation is NOT a normal spontaneous emission.



MIR photon signal could be clearly seen by a HgCdTe detector (MCT) under the suitable bunch compressed condition.



R56 parameter which corresponds to the bunch compression

Bunch compression dependence on the MIR intensity. The horizontal axis corresponds to the accelerator parameter on bunch compression.

Results of the commissioning (2)

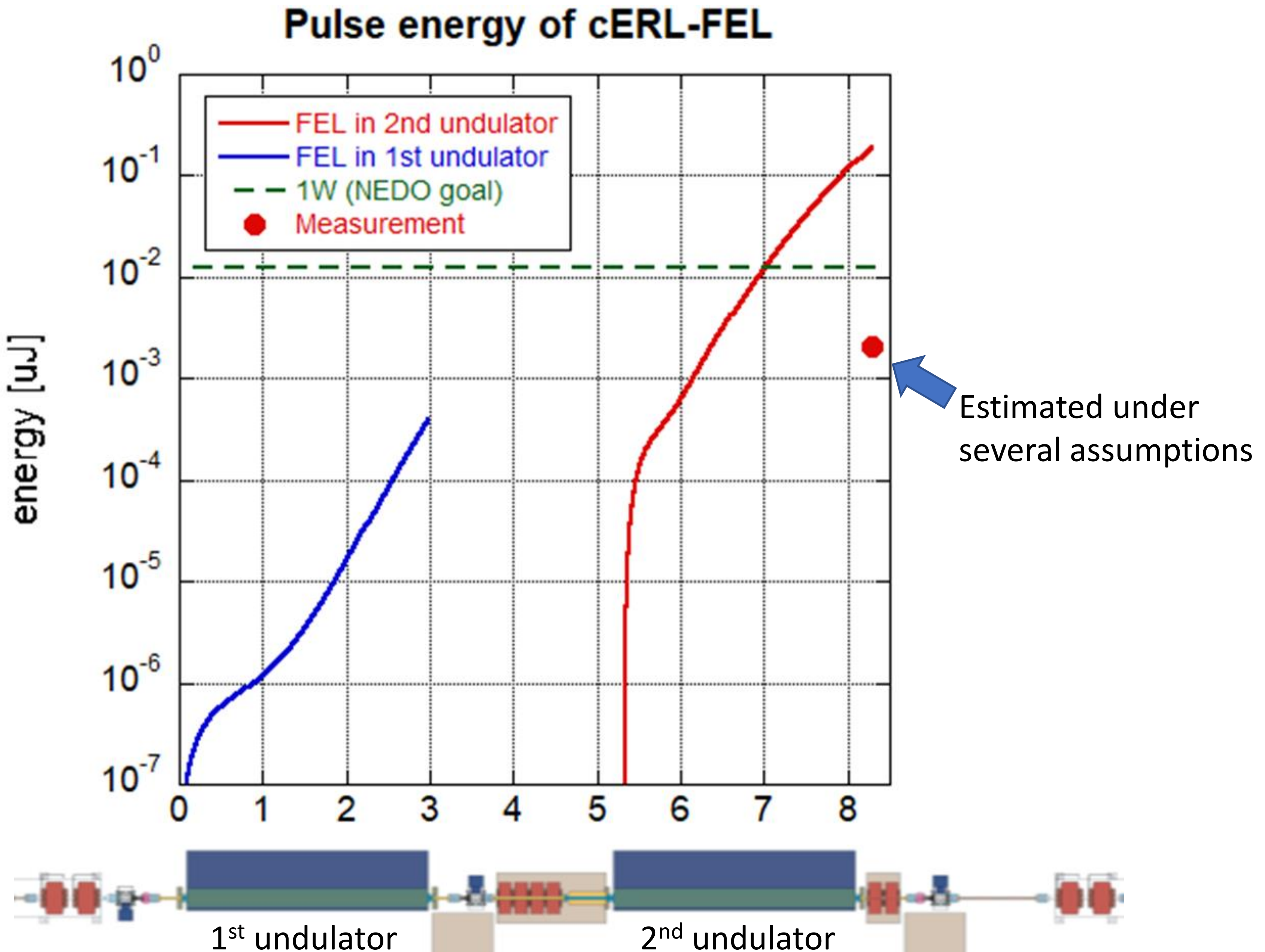
- It was confirmed that the wavelength of the MIR radiation could be tuned from 11 μm to 20 μm by means of changing the magnetic field of the undulator.

- The radiation has a horizontal polarization as expected as FEL Radiation.

- The intensity of the MIR radiation was several-ten mW *). The target value of the intensity is about 1W, so that the careful development of the electron beam quality and other efforts will be done at the next machine time of Dec./2020 to achieve much higher intensity.

*) The value is estimated under several assumptions

Preliminary results of the commissioning



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

Parameters of EUV-FEL and cERL-MIR-FEL			
	EUV-FEL	cERL-MIR-FEL (Target)	cERL-MIR-FEL (Present preliminary result)
Beam energy	800 MeV	17.5-20.0 MeV	17.5-20.0 MeV
Beam current (ave.)	10 mA	5 mA	Burst mode
Bunch charge	60 pC	60 pC	60 pC
Bunch length (FWHM)	0.1 ps	0.5-2 ps	3-5 ps
Normalized emittances	~0.7 π mm mrad	~3 π mm mrad	3-10 π mm mrad
Energy spread	0.03%	0.1%	~0.3 %
Repetition rate	162.5 MHz	81.25 MHz	81.25 MHz
Undulator type	APPLE II	Planar	Planar
Length (period x number)	5m (28 mm x 175)	3 m (24mm x 124)	3 m (24mm x 124)
Number of units	17	2	2
FEL wavelength	13.5 nm	15-20 μm	11-20 μm
Output power (ave.)	>10 kW	1 W	several-ten mW *)

*) The value is estimated under several assumptions

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

This slide was presented at the previous EUVL conference 2019, Monterey

1. Partially OK
2. Partially OK
3. To be examined
4. Next target

- Space charge effect is very serious -> Still on going to be solved
- OK

Summary

- We are proposing ERL-based FEL as a future light source in the EUV region for future lithography such as 3nm and 2nm node.
- KEK installed two undulators in the cERL southern straight section and develop a mid-infrared (MIR) FEL with high average power for NEDO project.
- We have already got a first MIR radiation from the installed undulator, which has a strong enhancement of the intensity according to the bunch compression.
- Fine tuning of the beam development for higher power FEL light will be done at the next machine time of Dec. 2020 and Feb. 2021.
- MIR-FEL can demonstrate many of the challenges for the realization of EUV-FEL.

Core members for this work 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)."

5th EUV-FEL Workshop 22/ January 2021

We will organize 5th EUV-FEL Workshop with source group, tool and material venders, and end users as an online workshop (Zoom).

Date: 22/ January/2021 12:30 – 17:00
Registration fee: Free
Capacity: Less than 300
Language: English

Key note lecturer: Takeo Watanabe (Univ. of Hyogo)
Invited speaker: Jack Kasahara (Lyncean Technologies, Inc.)
Invited speaker: Geert Vandenberghe (IMEC)
Invited speaker: Jan van Schoot (ASML)
Invited speaker: Norio Nakamura (KEK)
Invited speaker: Kentaro Harada (KEK)
Invited speaker: TBA