Industrial application of "Compact ERL (cERL)"

Contents

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High Energy Accelerator Research Organization (KEK)

Center for Applied Superconducting Accelerators (CASA)
was newly organized in 2019 in Accelerator Division of KEK.
Its aim is to promote the industrial application by using Superconducting accelerator technologies.
https://www.kek.jp/casa/ja/

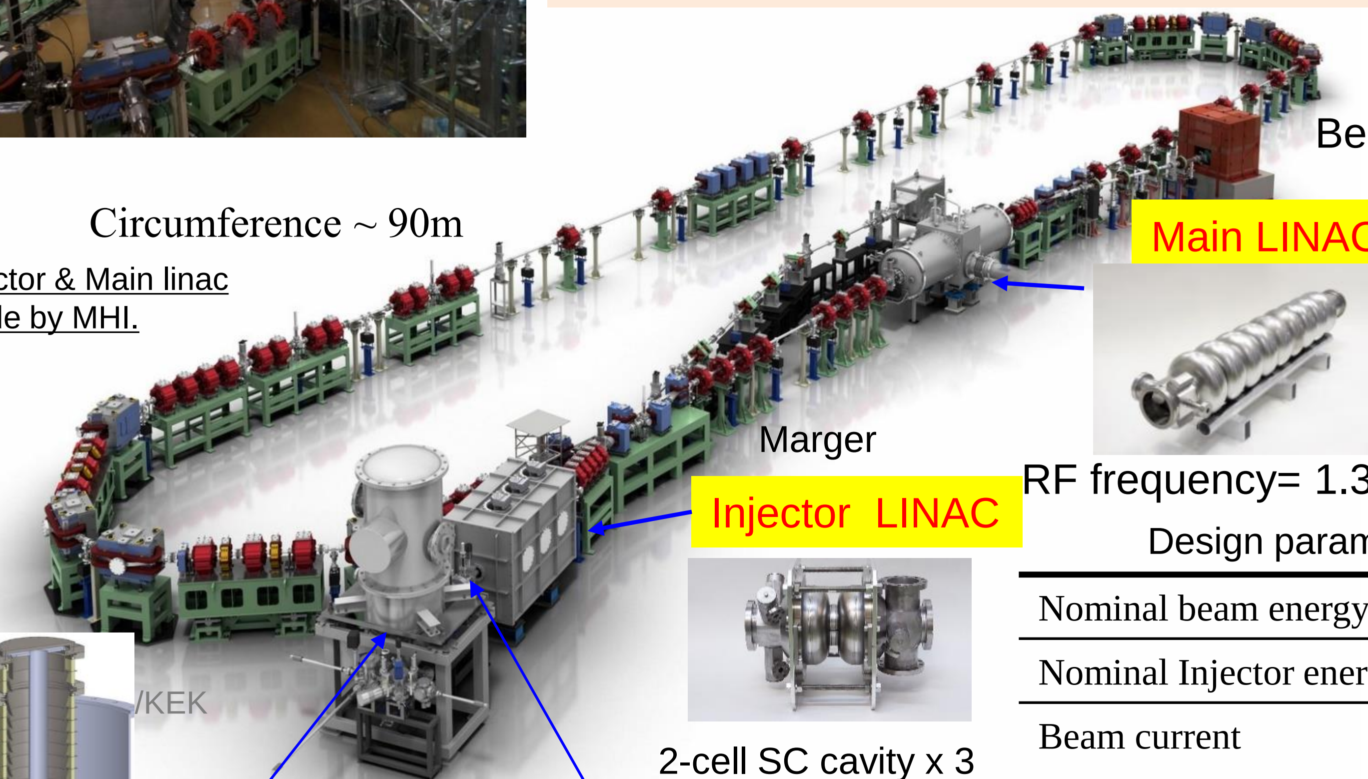
CASA Center for Applied Superconducting Accelerator 応用超伝導加速器センター

(15min.) *LCWS2019 @Sendai (2019.Oct.29)* (14 pages)

(A) Compact ERL (cERL) in KEK

Compact ERL (**cERL**) has been constructed in 2013 at KEK to demonstrate energy recovery with low-emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL with SRF cavities.

2019: cERL was re-organized under the (CASA) in KEK to promote the industrial application by using cERL.

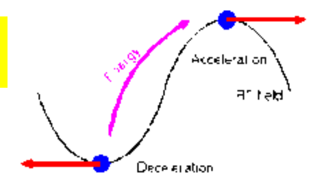


Beam Dump

Circumference ~ 90m

Injector & Main linac made by MHI.

Main LINAC



9-cell SC cavity x 2

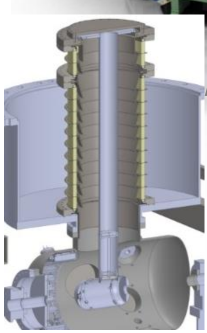
Marger

RF frequency= 1.3 GHz

17.5 MeV & 19MeV

Injector LINAC

2-cell SC cavity x 3



/KEK

Photocathode DC gun (Not SRF gun)

500kV DC Gun

Buncher

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

DC gun & SRF linac are based on linear collider technologies → **cERL is a real LC application.**

(B) Applications by using cERL

- Super conducting accelerator with ERL scheme gives us high current linac-based electron beam (~10mA) with high quality of the electron beam such as small emittance, Short pulses.
- The unique performance gives us several important industrial applications as follows.
  - High resolution X-ray imaging device for medical use
  - Nuclear security system (gamma-ray by LCS)
  - (1) RI manufacturing facility for nuclear medical examination
  - (2) EUV-FEL for Future Lithography for industrial application
  - (3) Intense THz light generation

Already achieved these application by using Laser Compton Scattering (LCS) Exp.

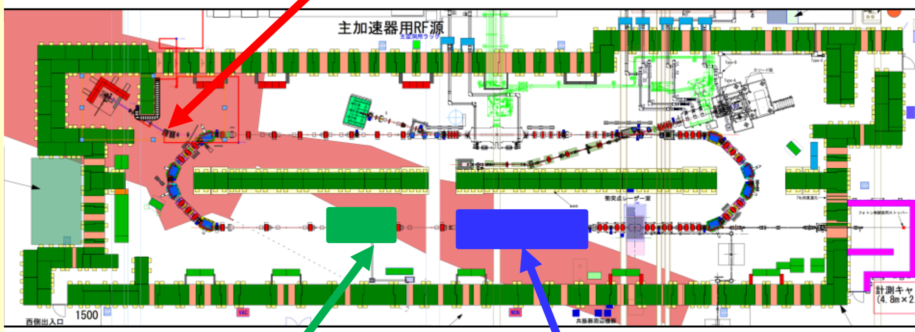
Next targets in a few year

<u>Plan of cERL beam operation (2018~2020)</u>

- New beam line for 99Mo RI production & material irradiation in cERL. (from 2019)
- We will produce FEL with this high current beam in the IR-FEL regime. (<u>POC of EUV-FEL plan</u>) Including high charge beam operation (~60pC).
- < 200fs bunch operation with THz generation (RCDR experiment)

cERL beam line

New beam line for 99Mo & material irradiation



New THz beam line

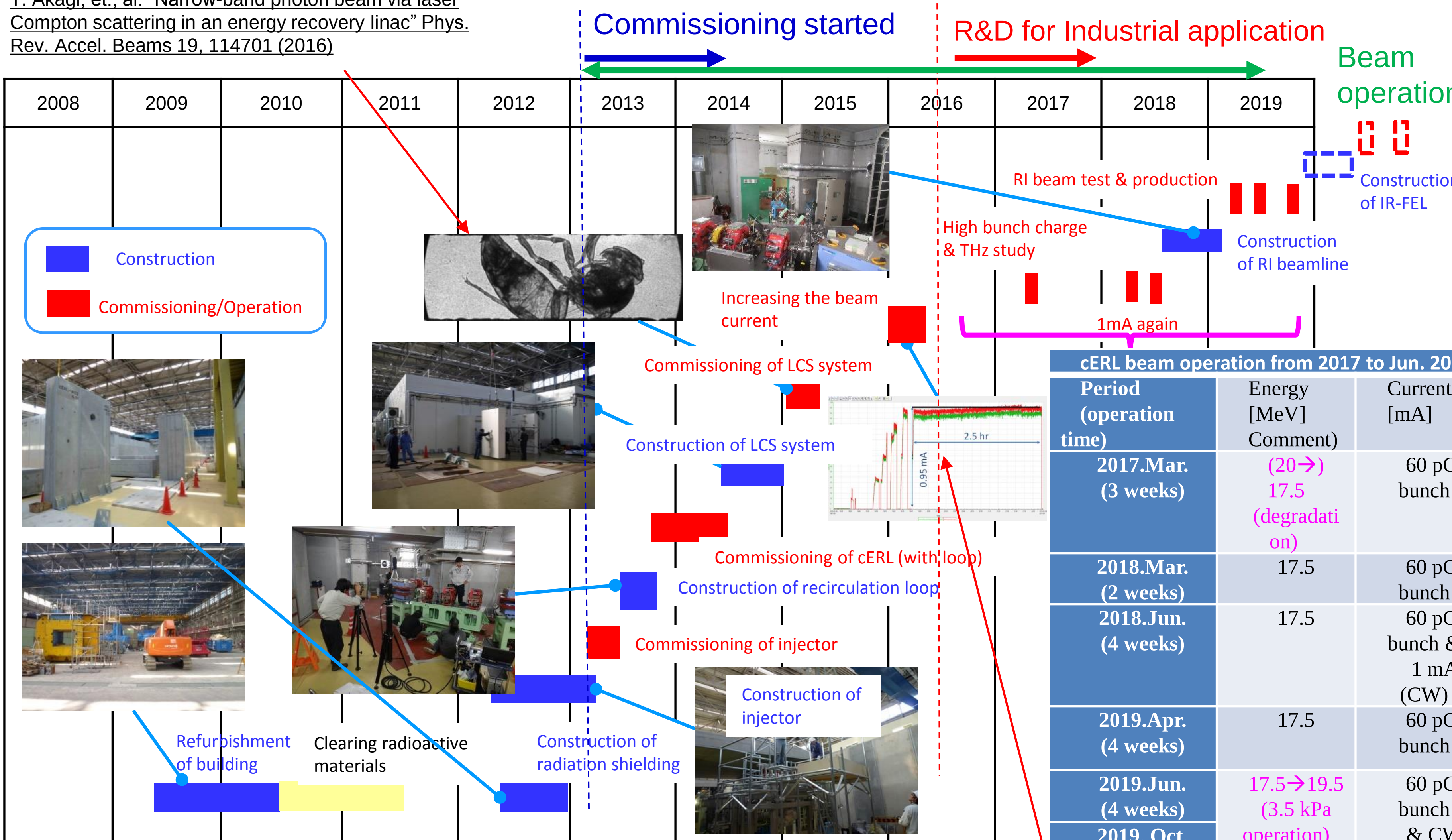
IR-FEL undulator

Construction and Commissioning of cERL

Laser Compton scattering experiment in ERL

T. Akagi, et., al. "Narrow-band photon beam via laser Compton scattering in an energy recovery linac" Phys. Rev. Accel. Beams 19, 114701 (2016)

(Published) M. Akemoto *et al.*, "Construction and commissioning of the compact energy-recovery linac at KEK" Nucl. Instrum. Method A 877 p.197-219 (2018).



cERL beam operation from 2017 to Jun. 2019

Period (operation time)	Energy [MeV] Comment)	Current [mA]
2017.Mar. (3 weeks)	(20→) 17.5 (degradation)	60 pC/ bunch
2018.Mar. (2 weeks)	17.5	60 pC/ bunch
2018.Jun. (4 weeks)	17.5	60 pC/ bunch & 1 mA (CW)
2019.Apr. (4 weeks)	17.5	60 pC/ bunch
2019.Jun. (4 weeks) 2019. Oct. (4 weeks)	17.5→19.5 (3.5 kPa operation)	60 pC/ bunch & CW beam (<10μA)

1mA ERL achieved

Construction started in 2009 and commissioning start in 2013.

Now we continue beam operation in 2019 → 2020

(1) RI manufacturing facility for nuclear medical examination ($^{99}Mo/^{99m}Tc$)

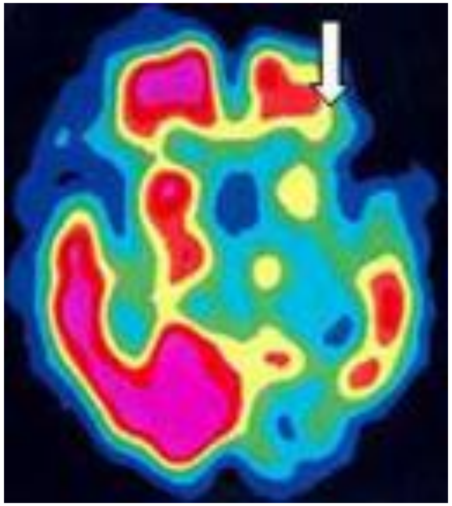
Concern about the stable supply of ^{99}Mo / ^{99m}Tc

- ^{99}Mo is almost 100% imported, even though the largest number of applications in nuclear medicine diagnosis
- Problem of the stable air transportation

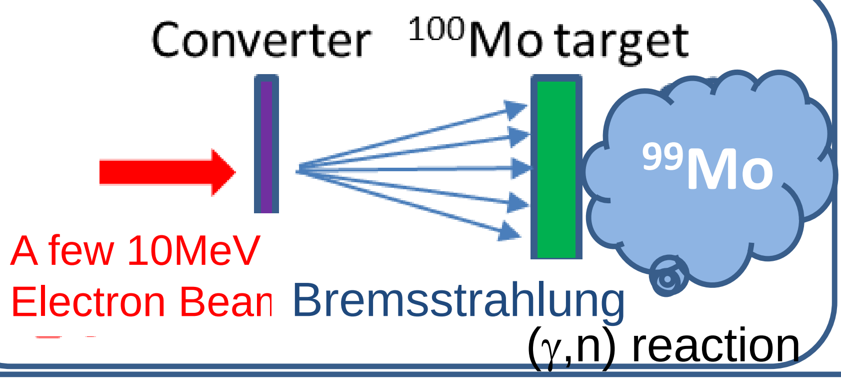
(Problem caused by volcanic eruption in the past)

- Most ^{99}Mo is manufactured in nuclear reactor
- Due to the aging of nuclear reactors, stable supply in the future is a big issue

Development of RI manufacturing (^{99}Mo / ^{99m}Tc) by using accelerator for stable supply



A state of brain blood flow revealed by nuclear medicine diagnosis by ^{99m}Tc

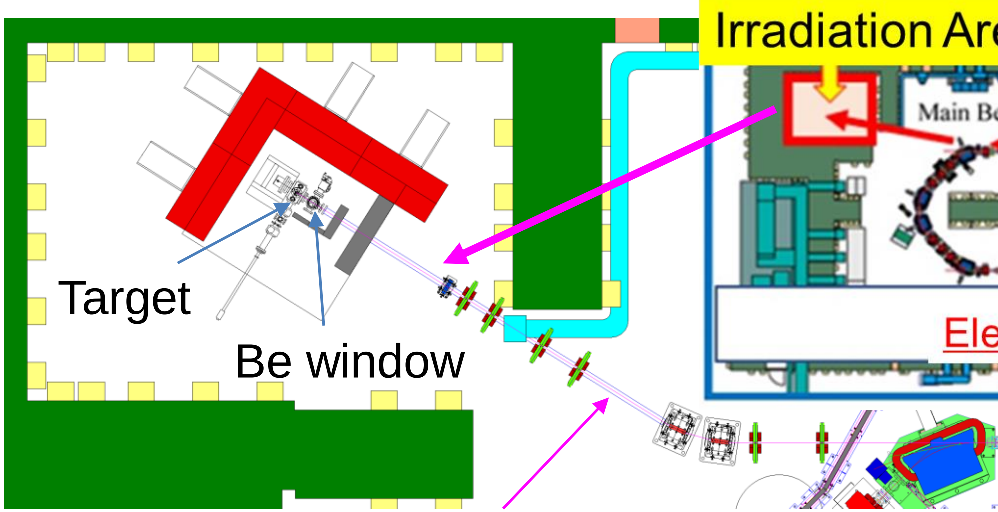


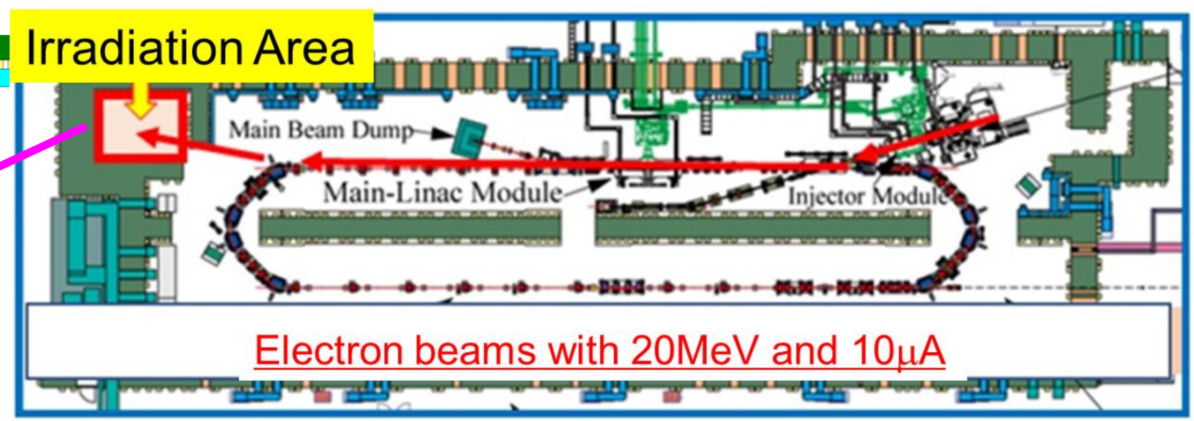
Required Specification for accelerator (final)

- 20 ~ 50 MeV electron beam
- Several mA to 10 mA

Test Experiment to produce ^{99}Mo in cERL is preparing

- The test irradiation of electron beams to a multiple molybdenum target will be done at this fiscal year to produce ^{99}Mo and check the yield of the production in order to realize a real machine with large electron beam power. → start 10uA with 20 MeV (max) electron CW beam
- It is necessary to get several knowledge to design a target system for large irradiation power such as a practical technique for ^{99}Mo production, target thermal design, shielding radiation design and legal procedures, etc. It is the final objective of this project.





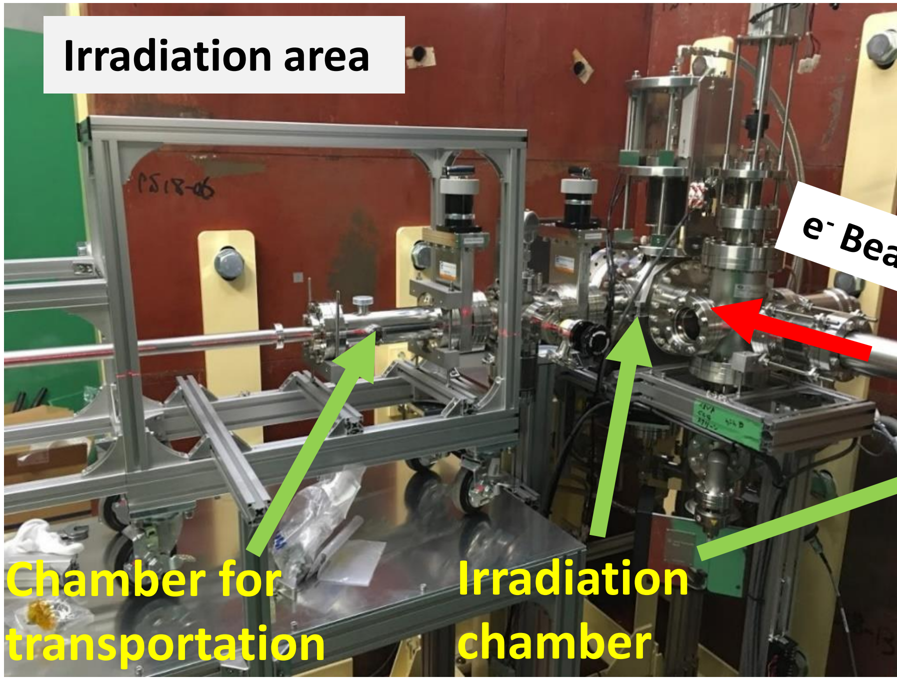
Beam line was constructed in Mar. 2019. And beam test started in Apr.2019.

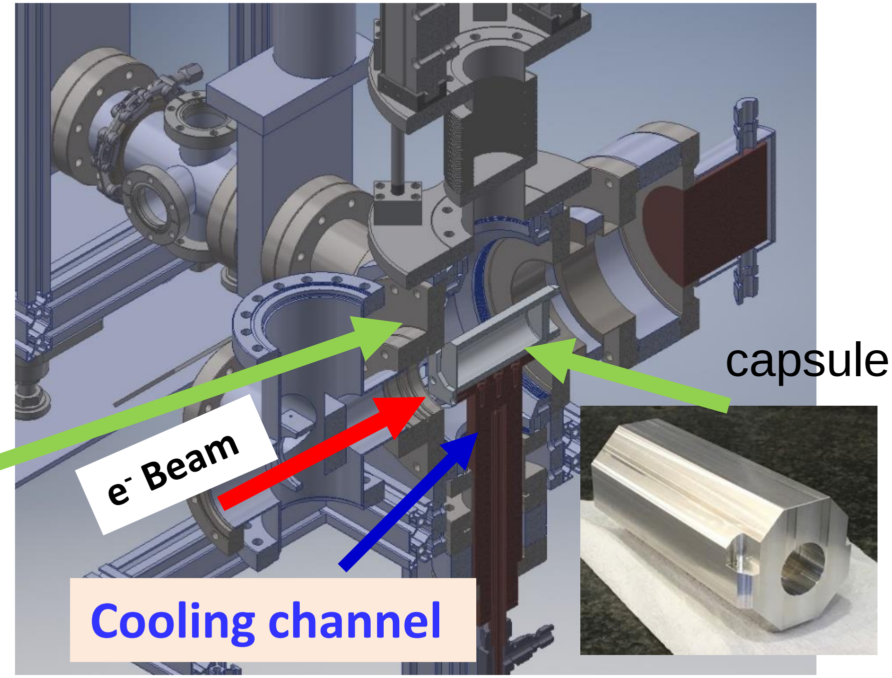
Mo 20MeV 10μA(maximum)

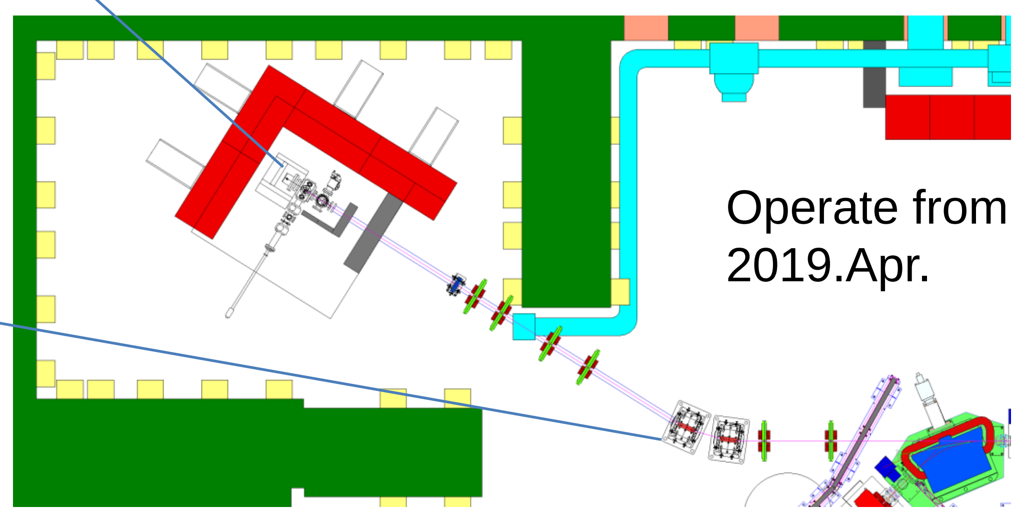
We are engaged in R & D on utilization of accelerator beams for radioisotope generation and reforming of organic matter under research contract with "Accelerator Inc." https://www.accelerator-inc.com/

Picture of cERL 99Mo beam line

Courtesy of Y.Morikawa, N.Higashi, K.Harada, M. Yamamoto, H.Matsumura and A. Toyoda

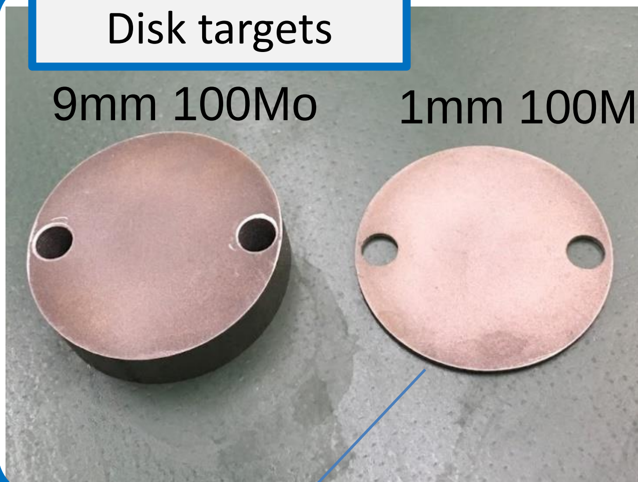


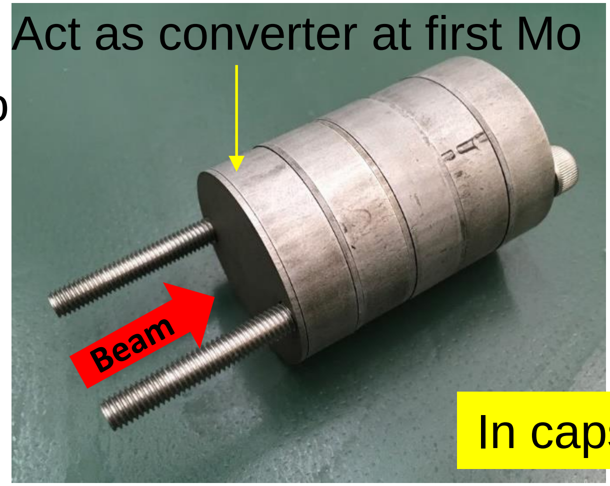


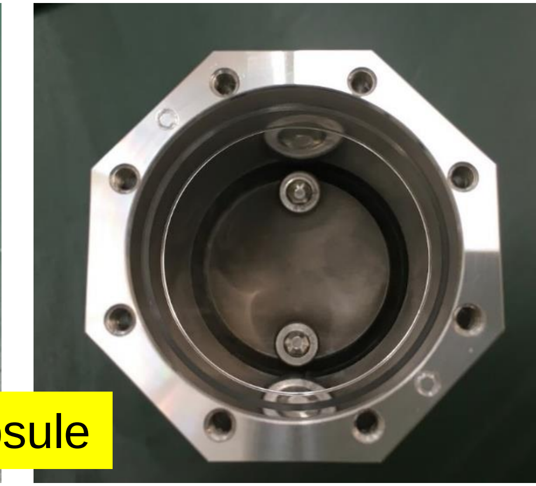


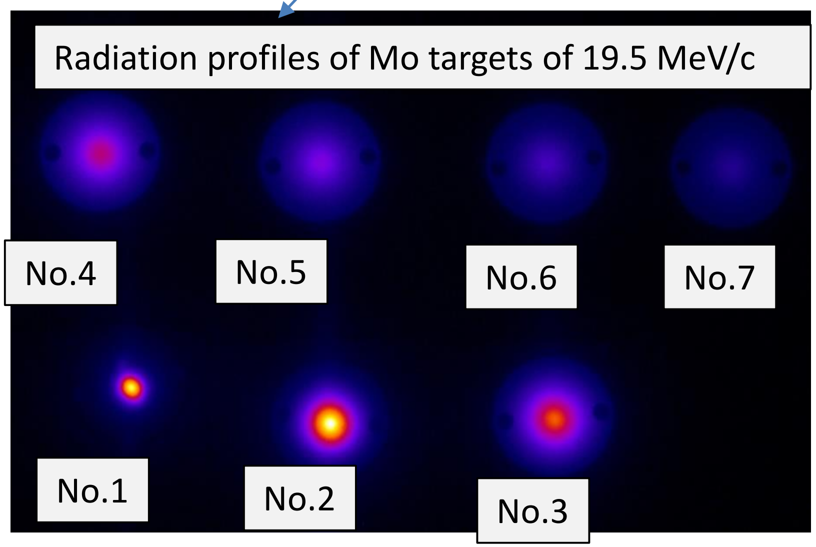
Latest results of RI production by using new beam line

Courtesy of Y.Morikawa, N.Higashi, K.Harada, M. Yamamoto, H.Matsumura and A. Toyoda

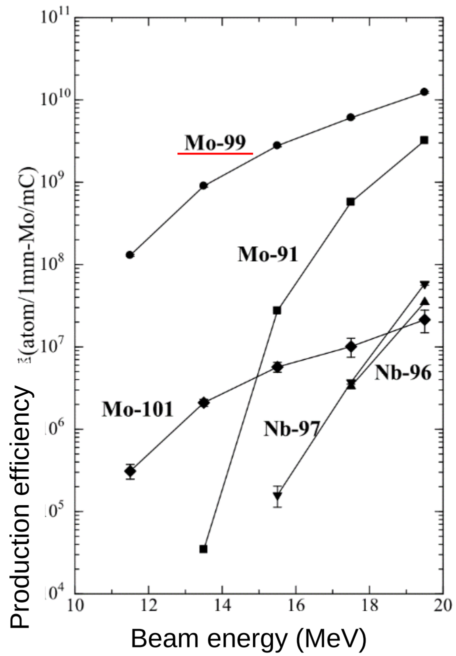








Obtain clear beam profile in Jun.2019 in each Mo target @19.5 MeV/c



- Energy dependence of ^{99}Mo production ratio was obtained in Jun. and Oct. 2019.
- These data almost agree with simulation and satisfied our requirements

Press release (2019.Oct.18) : https://www.kek.jp/ja/newsroom/2019/10/18/1400/

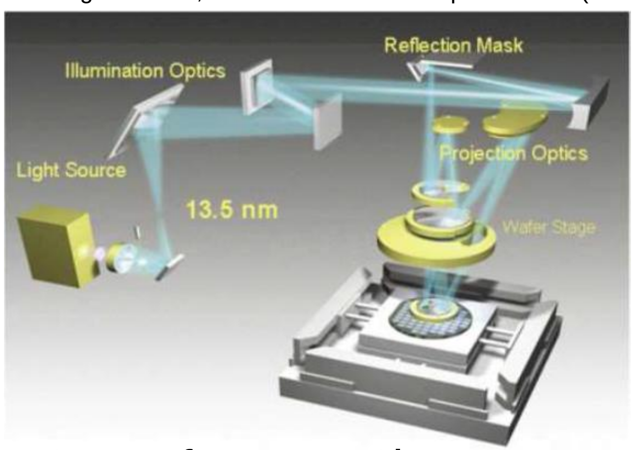
(2) Introduction of EUV-FEL

- 10-kW class EUV sources are required in the future for Next Generation Lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate (≦1.3 GHz) and high current linac system).

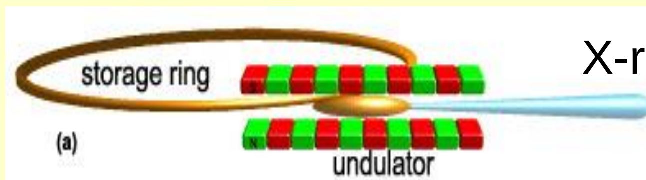
Schematic of EUV (13.5nm) exposure tool

H. Mizoguchi et al., Komatsu Technical Report 59-166 (2013)



EUV of 13.5 nm by LPP (Laser produced plasma)
→ 250 W level now
(peak 400 W)
Need breakthrough for higher EUV light (>1kW)

Breakthrough for EUV light by using FEL (with ERL)



X-ray pulse duration ~ 50 ps

Micro-bunching -> SASE lasing → high peak power

X-ray pulse duration ~ 10 fs

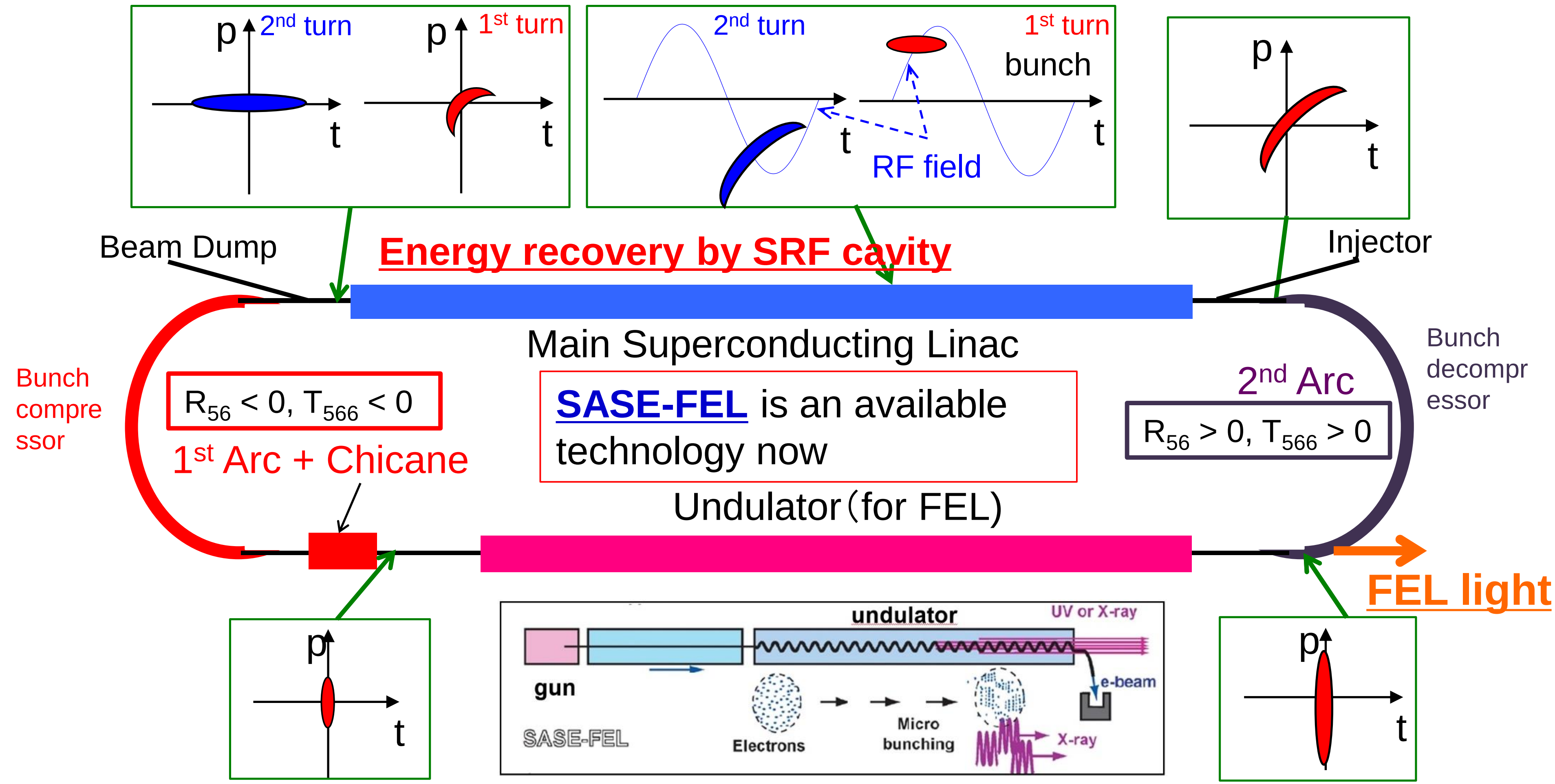
G. Dattoli et al., NIM-A (2001)

In case of normal conducting accelerator,
The repetition rate of FEL is less than 100Hz
→ High repetition with SC cavity is needed for kW laser

Design Concept for high repetition high current EUV-FEL

EUV Source (ERL)

- Target : 10kW power @ 13.5 nm, (800 MeV, 10mA)
- Use available technology (based on SASE-FEL) without too much development
- Make ERL scheme by cERL designs, technologies and operational experiences



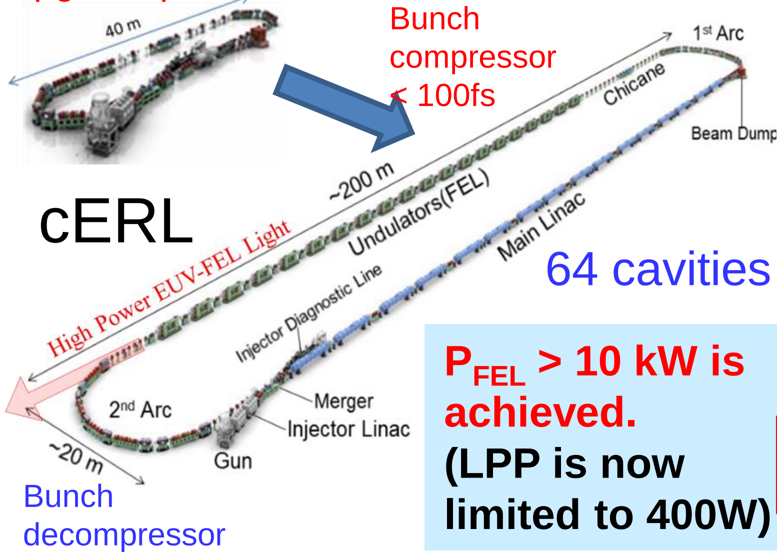
Energy recovery is needed for accelerating more than 10 mA to reduce beam dump and save RF power.
This operational experience with high current is studied in Compact ERL (cERL) at KEK

Prototype design of the EUV-FEL

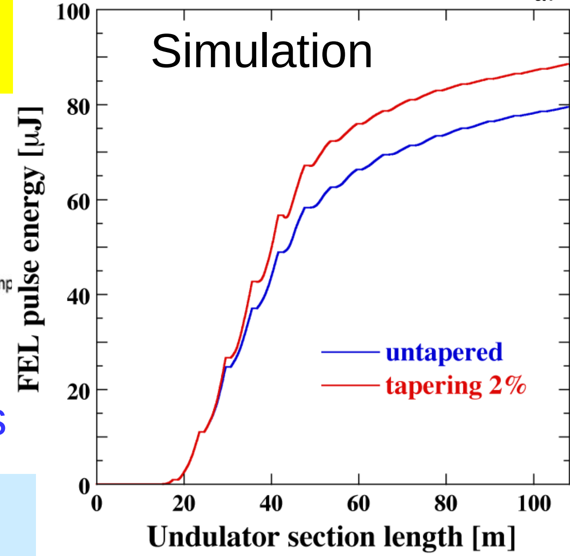
(P_{FEL}=88.5 μJ x 162.5 MHz =14.4 kW,
I_{av}=60pC x 162.5 MHz= 9.75 mA)

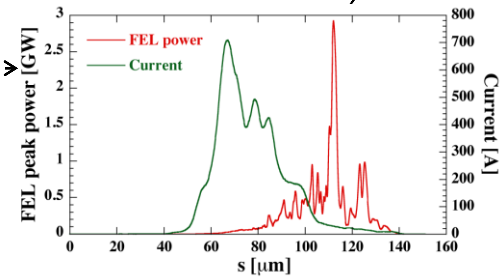
10-kW class EUV sources are required in the future for Next Generation Lithography

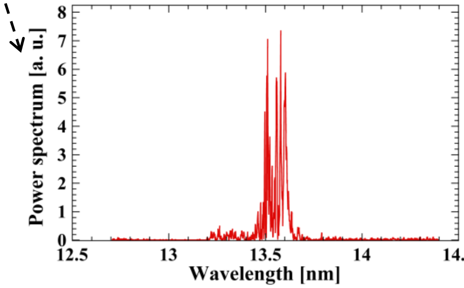
Upgrade plan of cERL for the POC



P_{FEL} > 10 kW is achieved.
(LPP is now limited to 400W)







FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

ERL technologies will help to make high intense EUV light based on FEL scheme. Further R&D test is needed on cERL.

Presented by Norio NAKAMURA
ERL2017（https://indico.cern.ch/event/470407/ ）

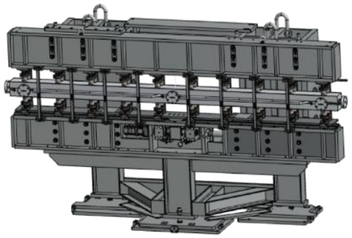
Design strategy (main linac)
Epeak/Eacc is 1.5 times reduced from cERL cavity to overcome field emission.
8.3 MV/m → 12.5MV/m

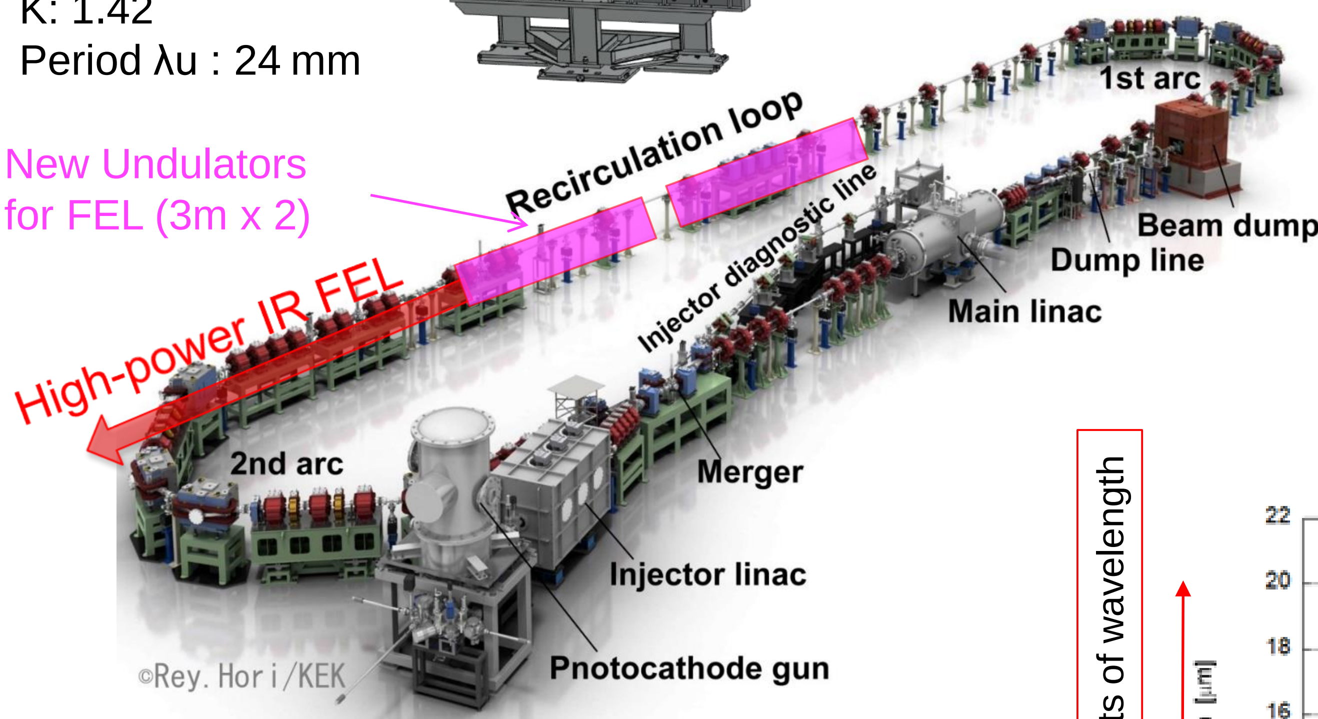
Items	Achieved values in cERL	Design at the EUV-FEL
Energy for injector (MeV)	2.9-6	10.5
Energy of Accelerator(MeV)	17.7	800
Charge /bunch (pC)	0.7-60	60
Repetition rate (MHz)	162.5-1300	162.5
Average Current (mA)	1.0	9.75
Emittance for electron beam (mm mrad)	0.3-1	~0.7
Gradient of the main linac (MV/m)	8.3	12.5
Wavelength of EUV-FEL (nm)	/	13.5
Average power of EUV-FEL (kW)	/	>10 kW

High average power IR-FEL Project in cERL

NEDO project (Ministry of Economy, Trade and Industry): "Development of high-power mid-infrared lasers for highly- efficient laser processing utilizing photo-absorption based on molecular vibrational transitions." starts to making SASE-IR-FEL with ERL.

- Type: APU (Planar)
- Gap: 10 mm (Fixed)
- K: 1.42
- Period λu : 24 mm

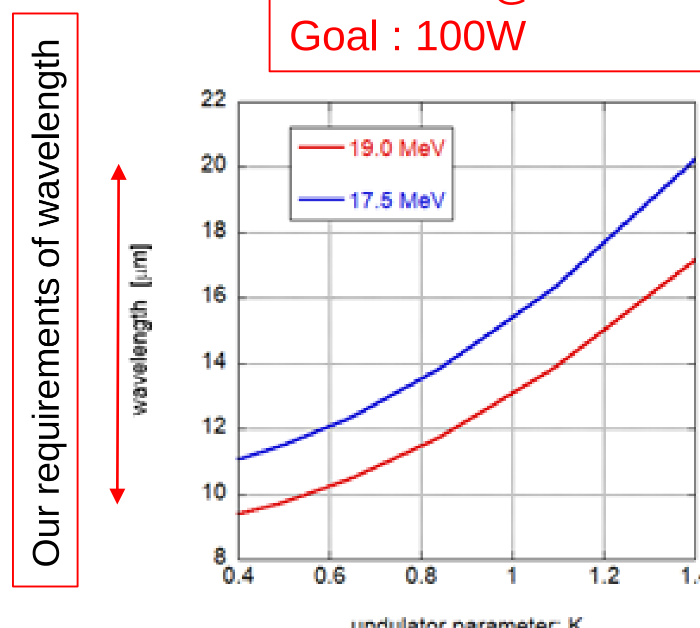




Fixed schedule by NEDO:
In FY 2019,
construct undulator
In FY 2020,
SASE IR-FEL production

Our requirements
10-20um
Start 1 W @ 18-20um
Goal : 100W

Beam Energy	17.6 MeV (19.0MeV)
Injector Energy	3.0 MeV (4.0 MeV)
E-Gun Energy	500 keV
Bunch repetition	1.3 GHz → 81.25 MHz
Average current	1 mA (max)
Operation mode	CW or Burst



Done by R.Kato FEL wavelength

(3) Coherent Resonant Diffraction radiation THz (2018-2019) Courtesy of Y.Honda

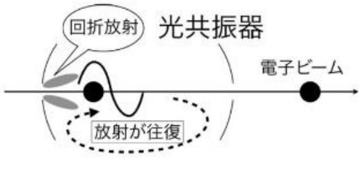
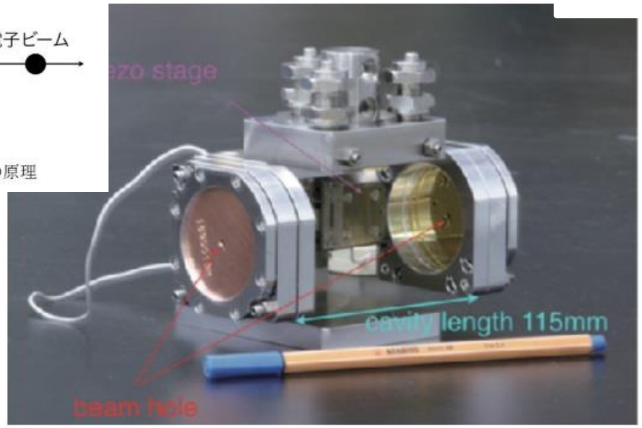
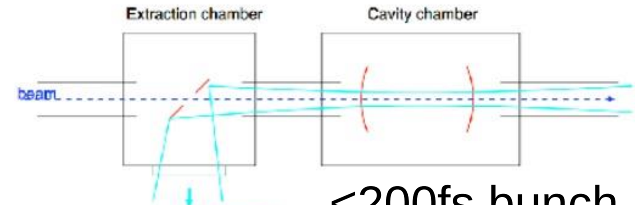
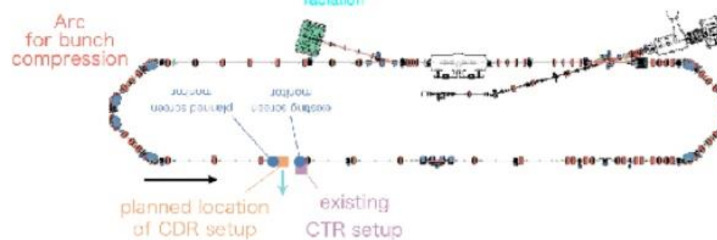


図 6: 共振器型回折放射の原理

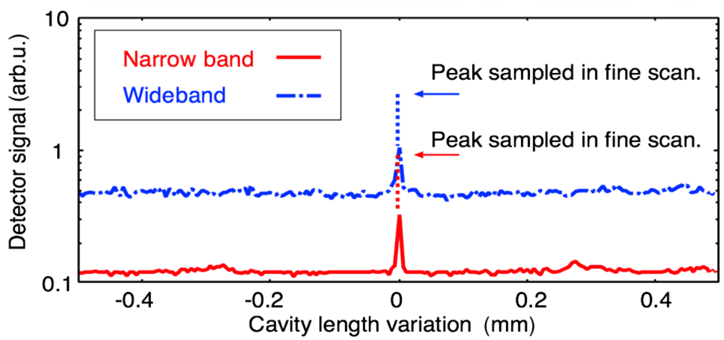


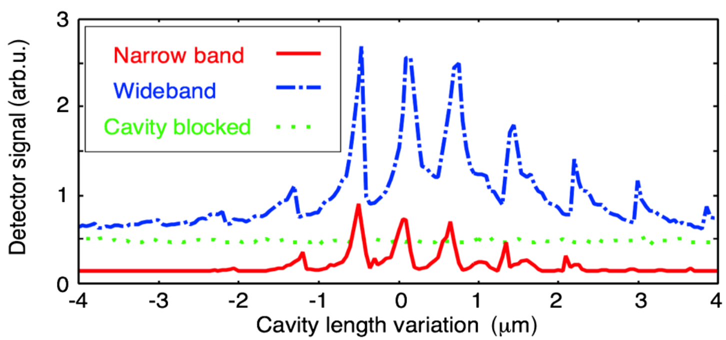


<200fs bunch length

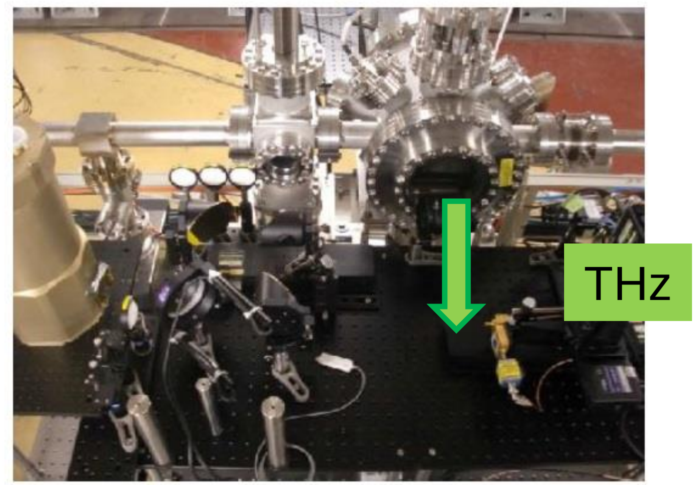


Intensity of THz from Resonant cavity





Cavity length scan results.



New idea to obtain the intense THz.

ERL beam suitable to generate shorter bunch and high intense THz light.

In 2019, THz beam line was also prepared.

Y.Honda, et. al., "High-efficiency broadband THz emission via diffraction-radiation cavity", Phys. Rev. Accel. Beams **22**, 040703 (2019)

Summary

- Show our status of cERL at KEK . High current beam operation of 1mA was achieved at cERL. → plan to increase 10 mA.
- cERL now move to use for the industrial application by using SCRF technology. ^{99}Mo beam line was built for RI production with CW intense beam with 10uA and successfully produce ^{99}Mo under the contract business with the company.
- Conceptual design study for EUV-ERL-FEL based on SASE scheme was carried out to open the era of more higher light source of EUV-lithography, 10 kW class high power EUV light source is NOT just a dream from the experience of cERL in KEK with 10mA beam.
- In order to demonstrate ERL-SASE-FEL scheme, IR-FEL production started in cERL. 100 W IR-FEL with SASE scheme will be produced by constructing 2 x 3 m undulators in cERL beam line in 2020 based on the budget of NEDO project in Japan.
- Diffraction radiation by Resonant cavity can give high intense THz with ERL CW beam with about 100 fs bunch.

Thank you for your attention!

cERL Team (*)

High Energy Accelerator Research Organization (KEK)
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Hiroshima University
M. Kuriki, Lei Guo[on leave]

The Graduate University for Advanced Studies (Sokendai)
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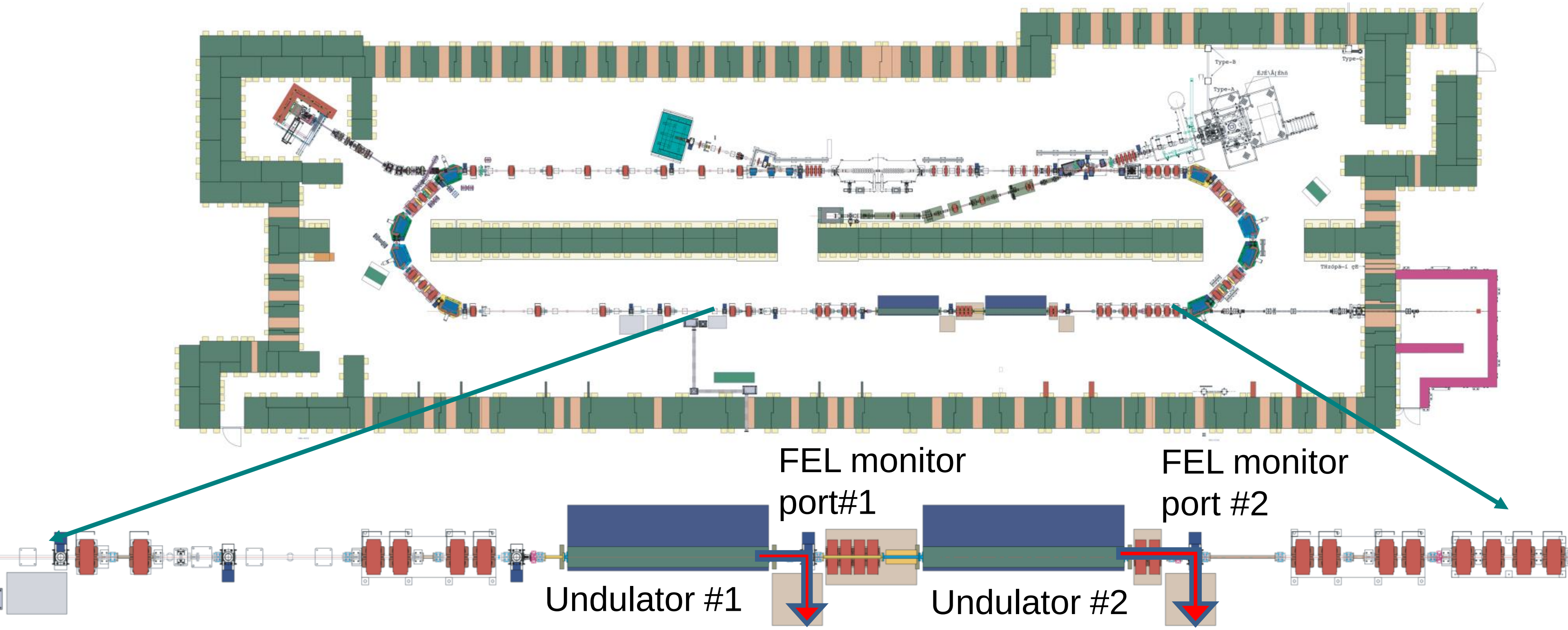
SLAC
N. Nora

2019.Sep.

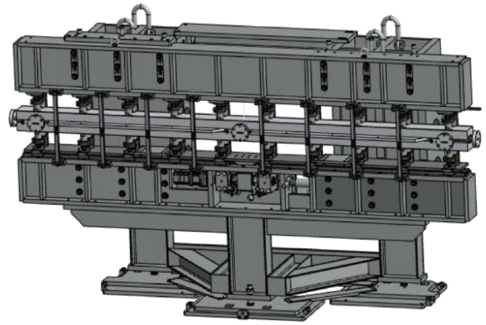
INSTITUTE OF MODERN PHYSICS, CHINESE ACADEMY OF SCIENCES
ZONG Yang

Layout and parameters of IR-FEL



Beam parameter

- Energy : 17.5 MeV→19MeV
- Bunch charge : 60 pC
- Repetition : 81.25 MHz
- Bunch length : 2ps (0.5ps)
- Energy spread : 0.1%
- Beam emittance : 3π mm mrad



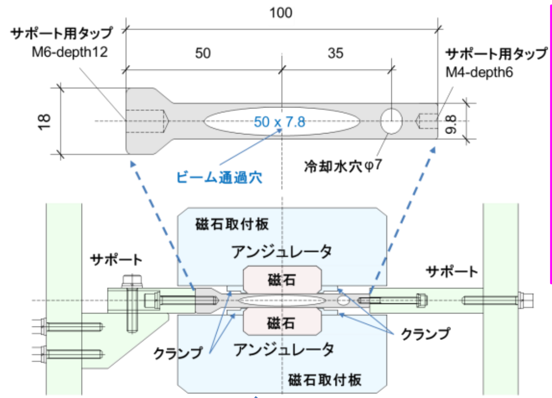
Design of APU-type undulators.

Undulator parameter

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

Present status of IR-FEL construction in cERL

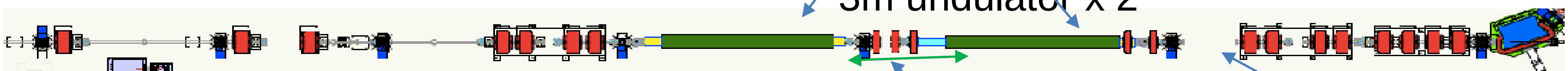
Beam operation was done in Apr. and Jun. 2019 to optimize the bunch length (<250 fs), energy spread (0.3%) and normalized emittance (3π mm mrad) to meet our requirements.

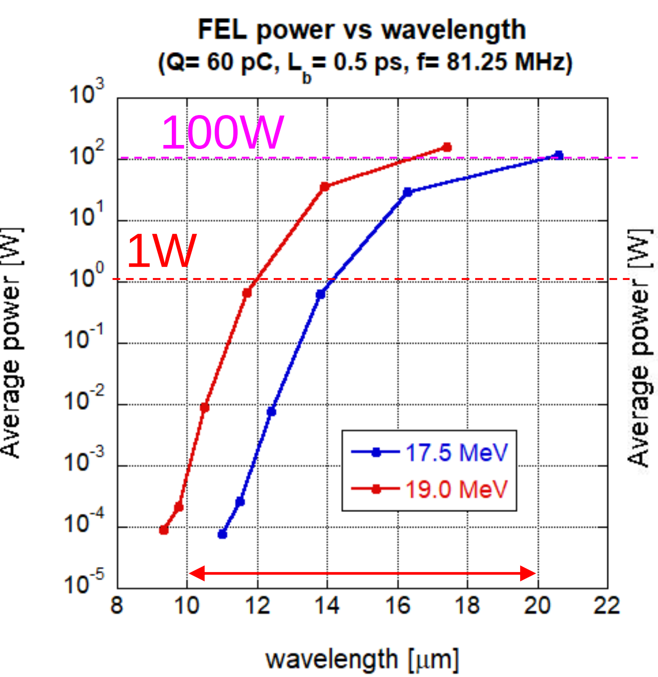


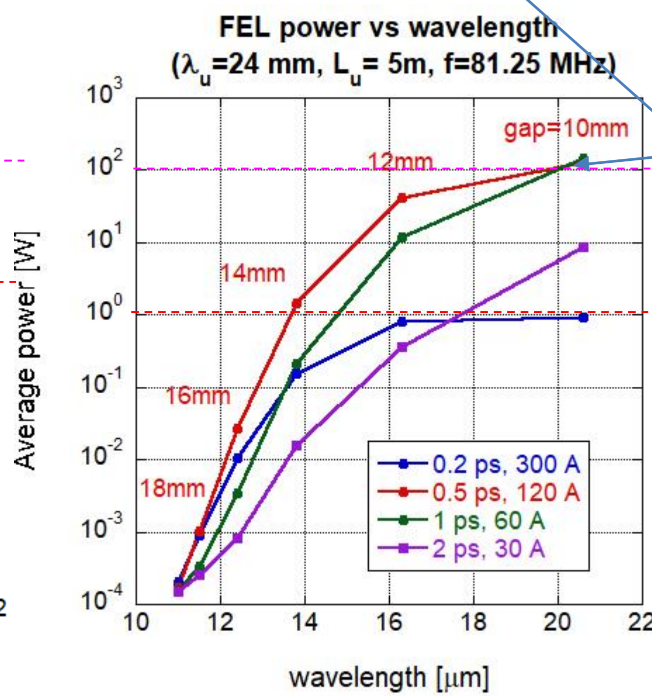
Fixed schedule by NEDO:
In FY 2019,
construct undulator
In FY 2020,
SASE IR-FEL production

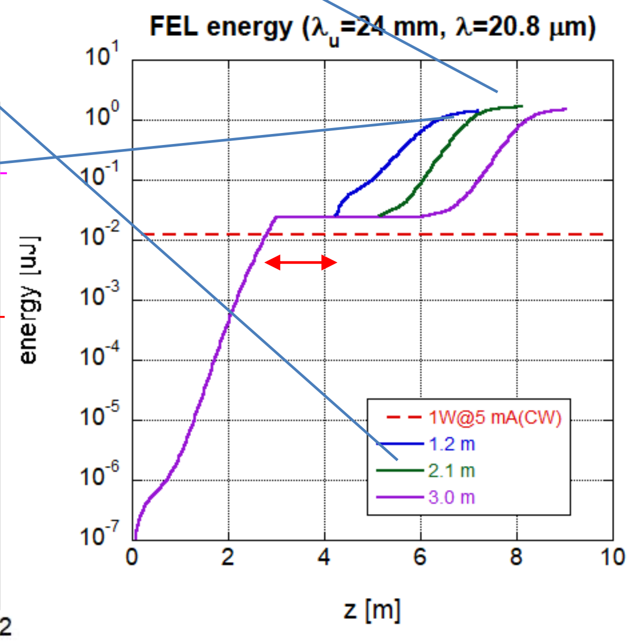
Finally we'd like to 5 mA CW beam → and try to increase >10mA

3m undulator x 2









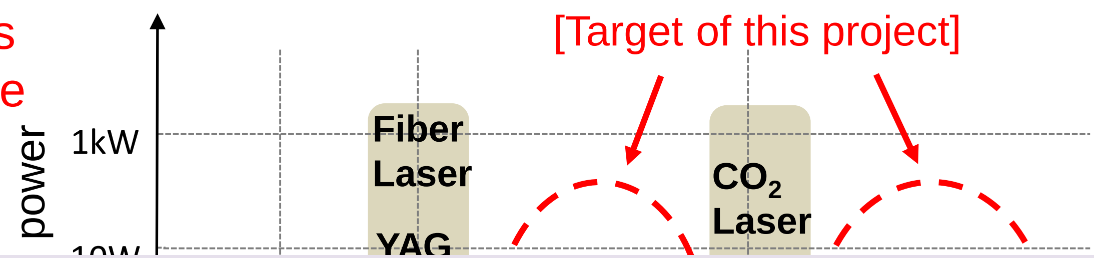
a) wavelength 20.8 μm

Project of IR-FEL based on the cERL
(Background of IR-FEL Project)

The mid-infrared wavelength region is the wavelength region with vibration absorption of these organic materials. →
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.

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



NEDO project (Ministry of Economy, Trade and Industry):
"Development of high-power mid-infrared lasers for highly-efficient laser processing utilizing photo-absorption based on molecular vibrational transitions."

Figure: Wavelength ranges of lasers.