Industrial application of "Compact ERL (cERL)"

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(B) Applications by using cERL

(C) Summary

Hiroshi Sakai (Team leader of cERL)

Center for Applied Superconducting Accelerators (CASA), Accelerator Division

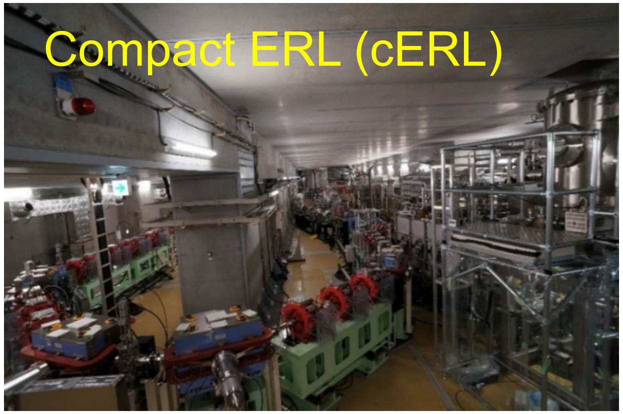
High Energy Accelerator Research Organization (KEK)

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

(25min. + 5min.) *ERL2019 @ Berlin (HZB)* (24 pages)

(A) Compact ERL (cERL) in KEK



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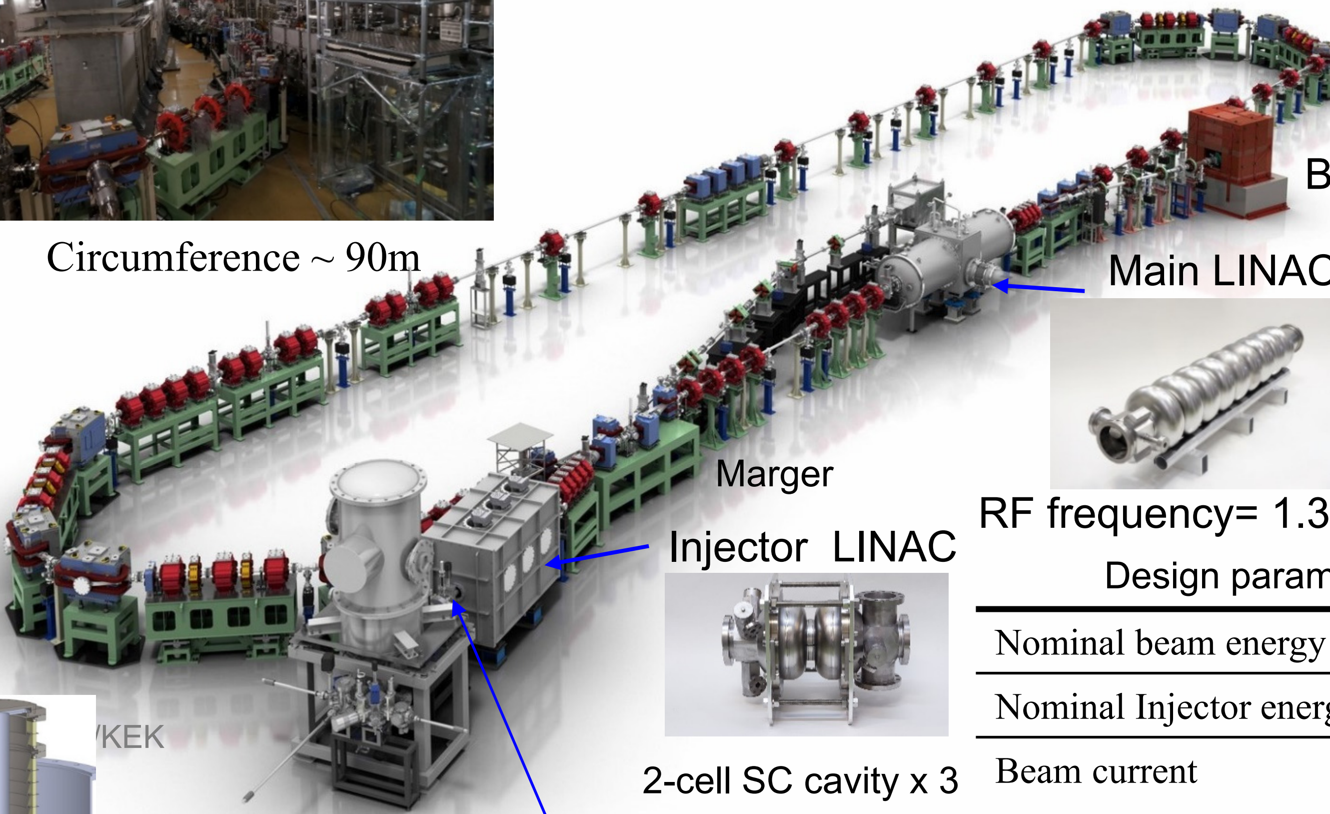
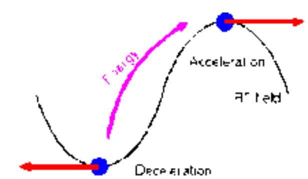
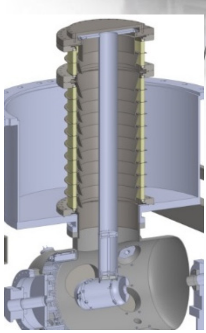




9-cell SC cavity x 2

RF frequency= 1.3 GHz

2-cell SC cavity x 3



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)

Injector & Main linac made by MHI.

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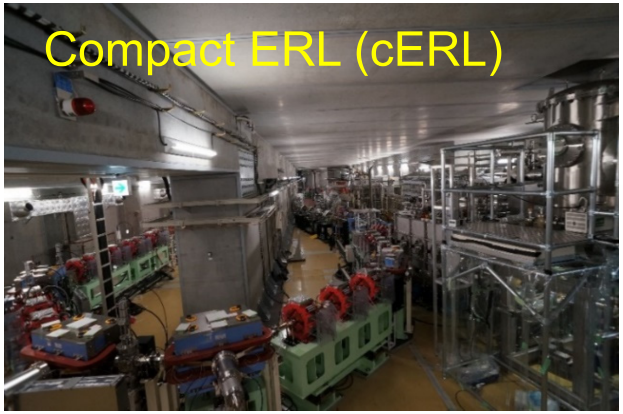

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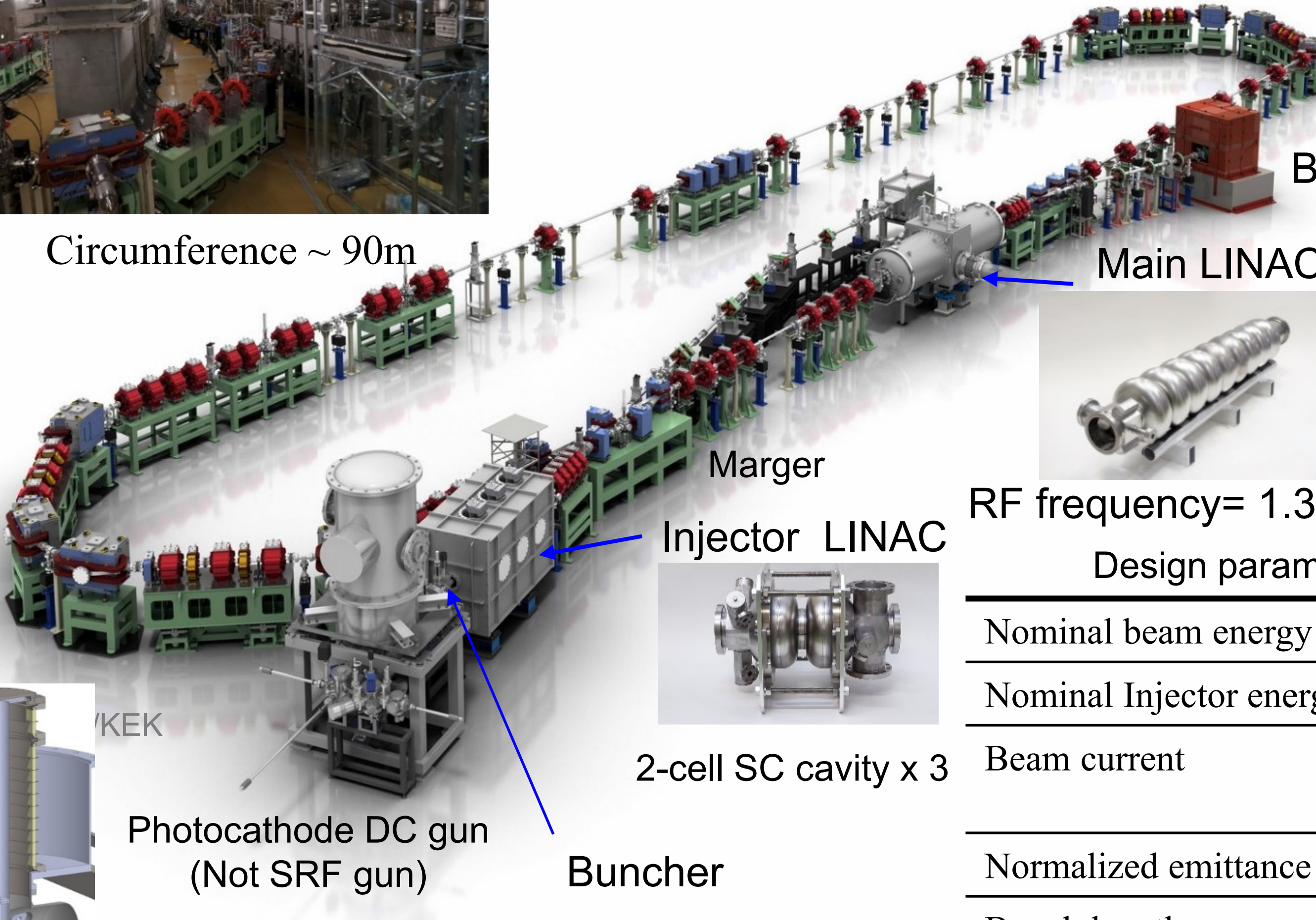

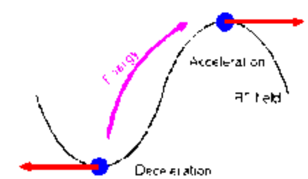

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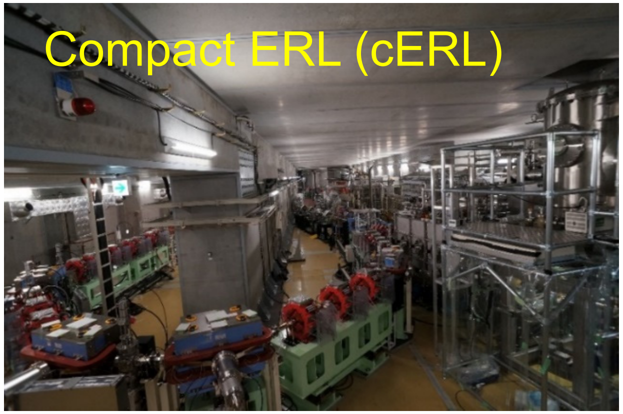

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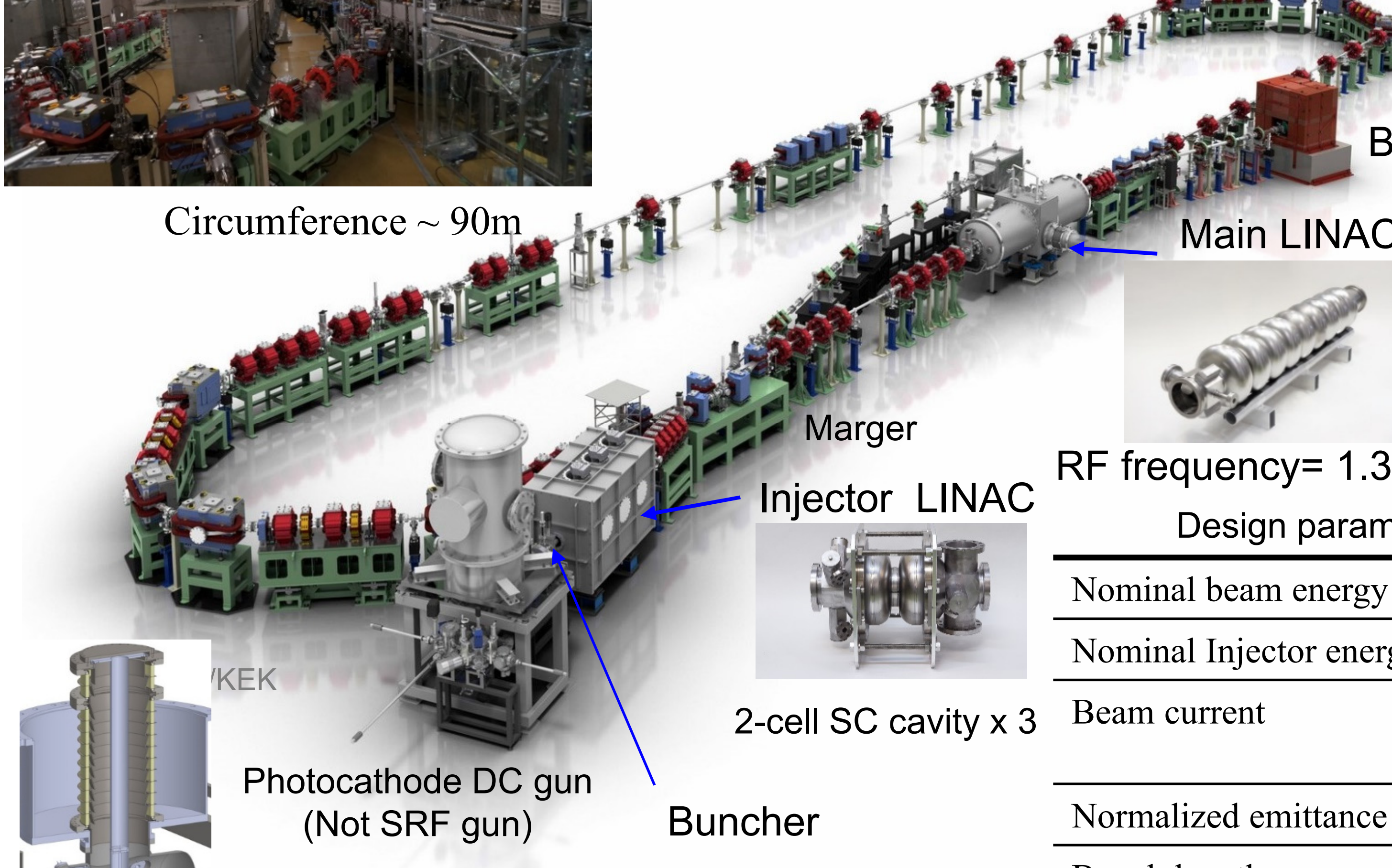
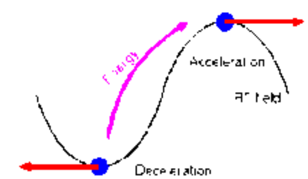
Details are talked in
- H. Sakai, “KEK ERL SRF Operation Experience” (Tue)





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The latest status of cERL from ERL2017

2013-2015 The beam commissioning started in 2013 for future 3 GeV ERL light source and achieve 1mA under energy recovery operation

2016 The future light source was shifted to the high-performance ring accelerator, so that there is no back ground to continue the ERL R&D. On the other hand, KEK directorates kept the importance of the R&D for industrial application based on ERL technologies. See the detail KEK Project Implementation Plan (KEK-PIP)

http://www.kek.jp/ja/NewsRoom/Release/20160802141100/

2017 ERL project Office was closed in KEK and "Utilization Promotion Team based on Superconductive Accelerator (SRF-application team)" was kept in Department of future Accelerator and detector technologies in KEK. (presented in ERL2017)

2018 Change the team leader of "SRF application team" from Kawata-san to me (Sakai)

Restart the beam operation by using cERL for SRF application. (2018.Mar. & Jun. (1mA))

2019 cERL was re-organized under the Center for Applied Superconducting Accelerators (CASA) in KEK to promote the industrial application by using cERL. https://www.kek.jp/casa/ja/

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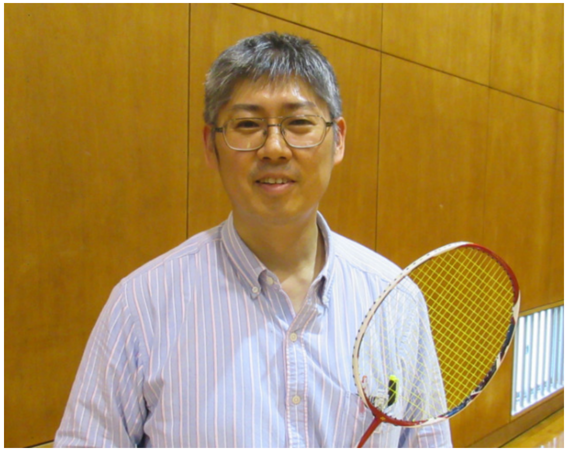
Hiroshi KAWATA (KEK)



Hiroshi SAKAI (KEK)

(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)
  – RI manufacturing facility for nuclear medical examination
  – EUV-FEL for Future Lithography for industrial application
  – Intense THz light generation

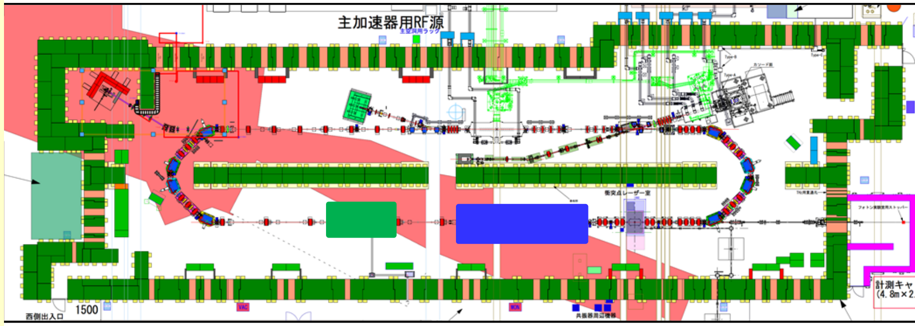
Already achieved these application by using Laser Compton Scattering (LCS) Exp. (first two items)

Next targets in a few year (last three items)

Plan of cERL beam operation (2018~2020)

- 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. (POC of EUV-FEL plan) Including high charge beam operation (~60pC).
- < 200fs bunch operation with THz generation (RCDR experiment)

cERL beam line



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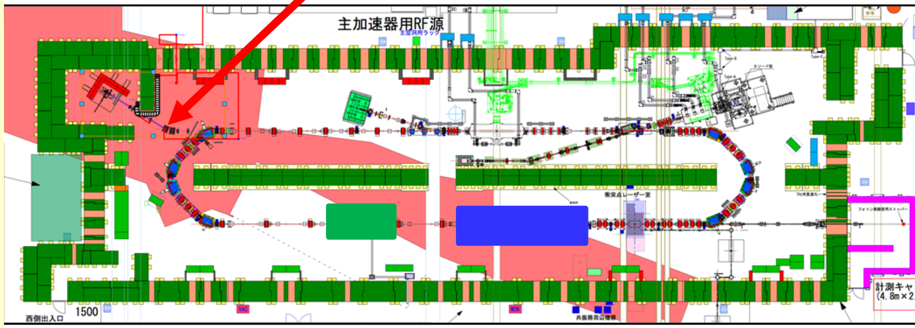

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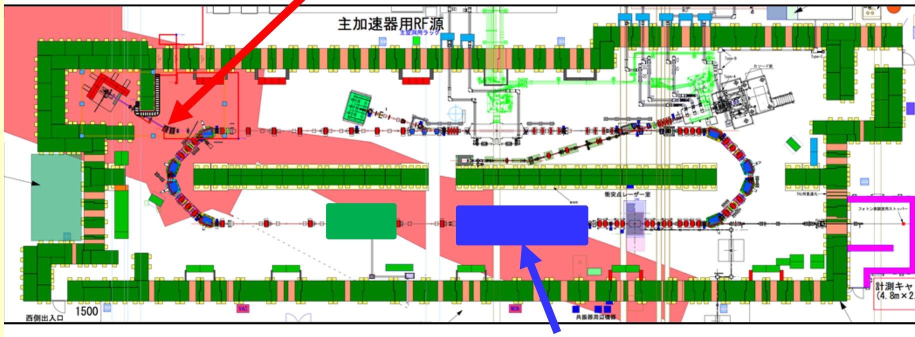

IR-FEL undulator

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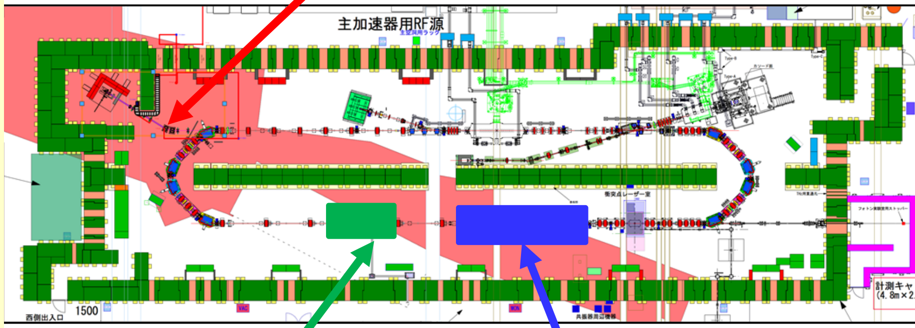


New THz beam line

IR-FEL undulator

Construction and Commissioning of cERL

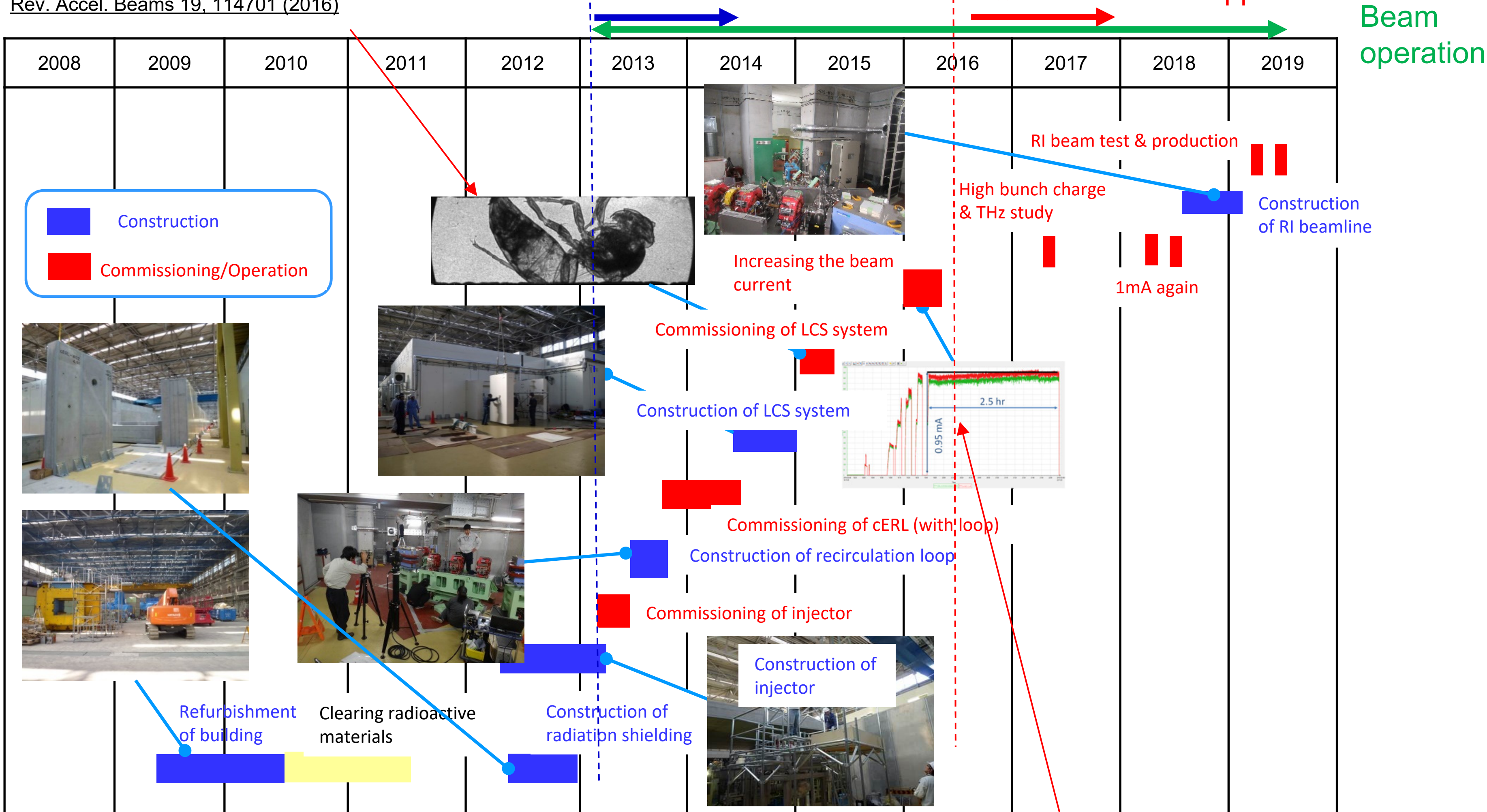
Laser Compton scattering experiment in ERL

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).

Commissioning started

R&D for Industrial application



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<u>Now we continue beam operation in 2019</u>

1mA ERL achieved

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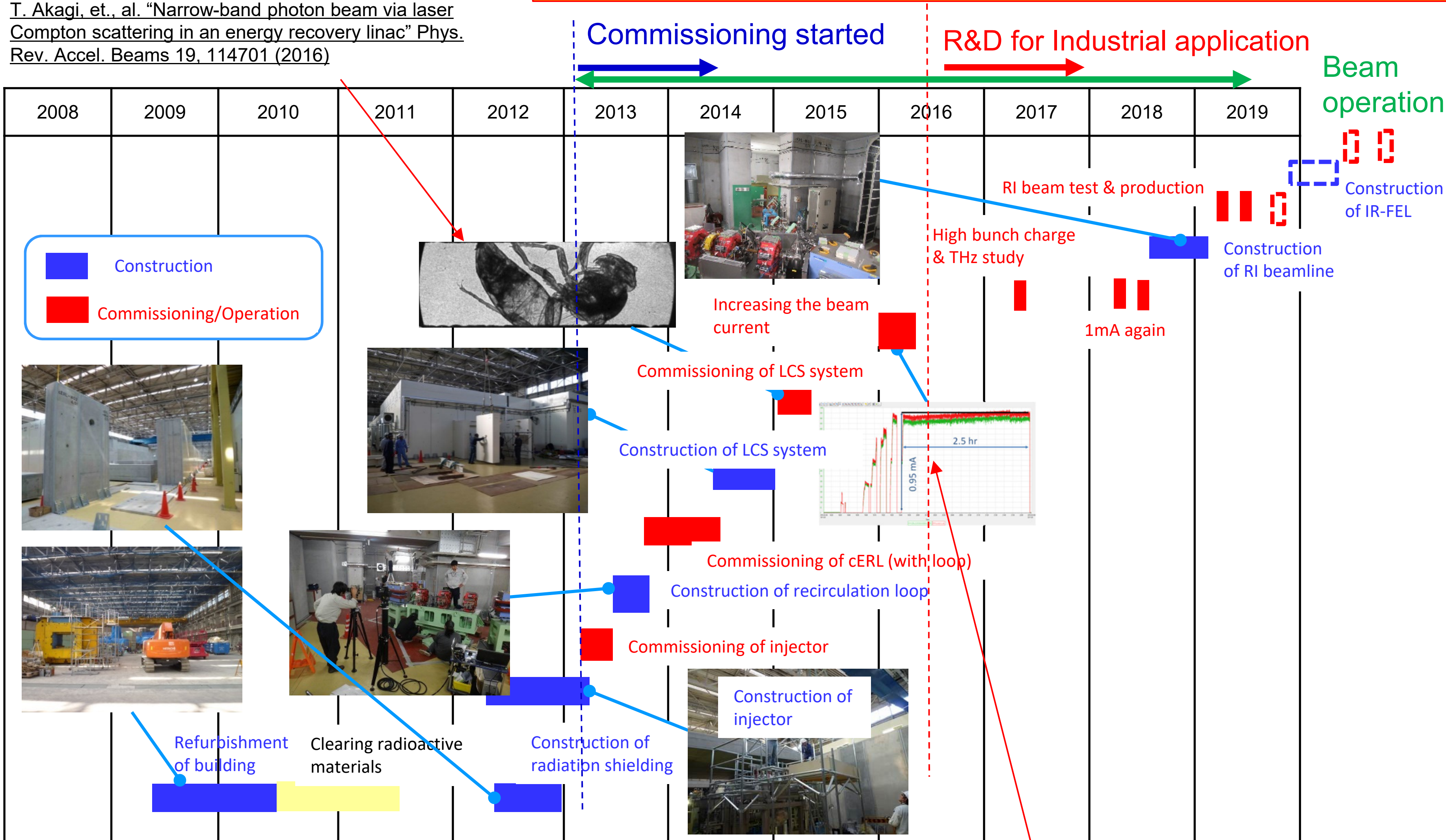

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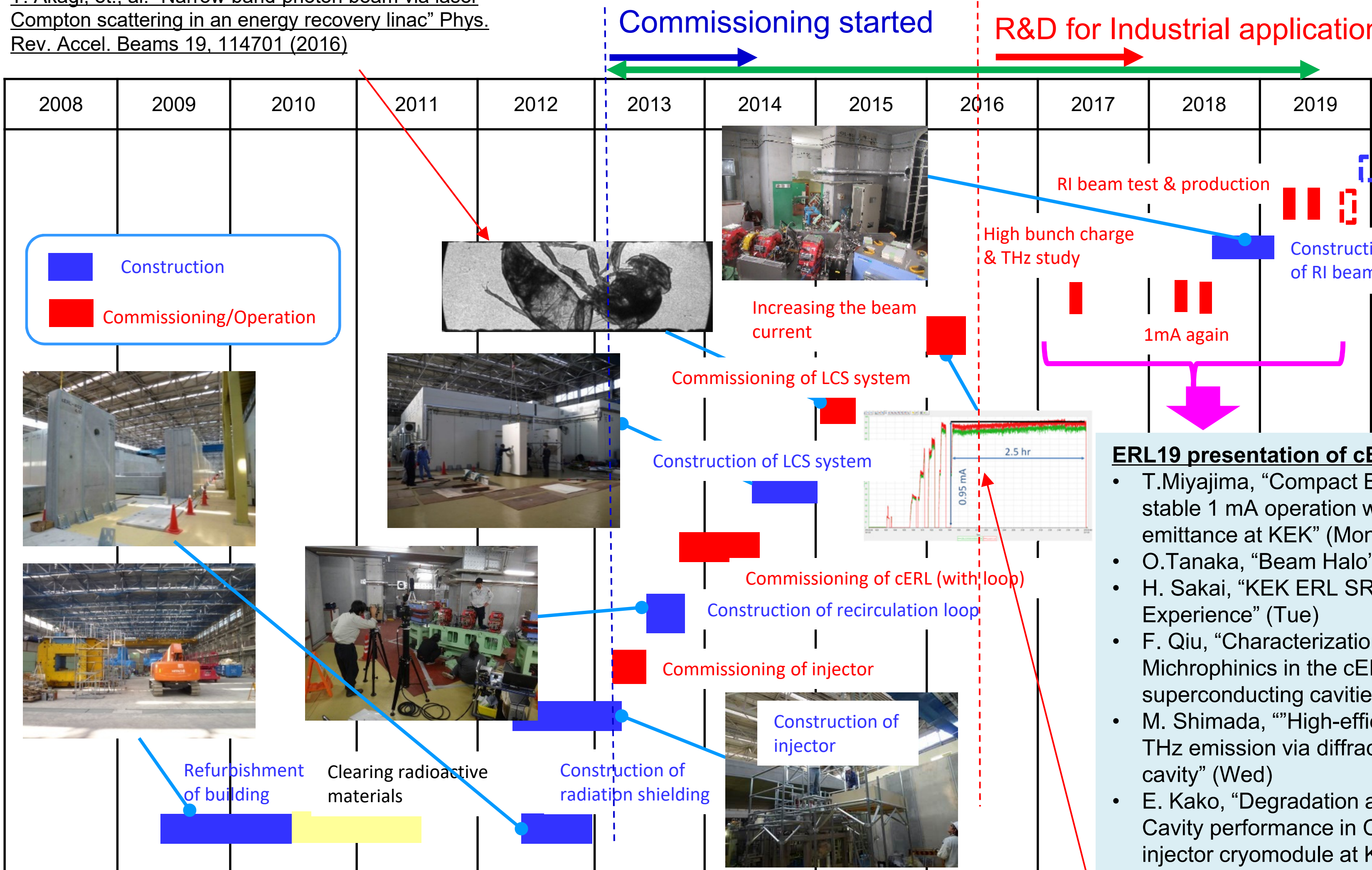

ERL19 presentation of cERL operation

- T.Miyajima, “Compact ERL(cERL), stable 1 mA operation with a small beam emittance at KEK” (Mon)
- O.Tanaka, “Beam Halo” (Tue)
- H. Sakai, “KEK ERL SRF Operation Experience” (Tue)
- F. Qiu, “Characterization of Michrophinics in the cERL main linac superconducting cavities” (Tue)
- M. Shimada, “”High-efficiency broadband THz emission via diffraction-radiation cavity” (Wed)
- E. Kako, “Degradation and Recovery of Cavity performance in Compact-ERL injector cryomodule at KEK” (Thu)

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Now we continue beam operation in 2019 → 2020

1mA ERL achieved

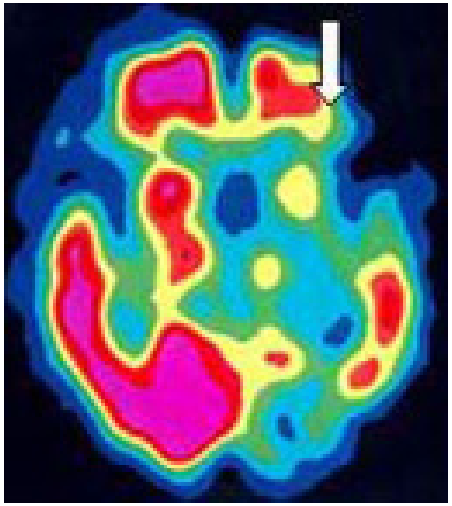
RI manufacturing facility for nuclear medical examination ($^{99}Mo/^{99m}Tc$)

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

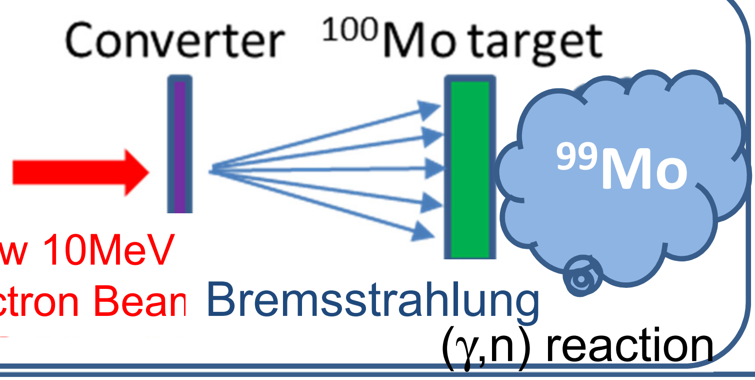
(Problem caused by volcanic eruption in the past)

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



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

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

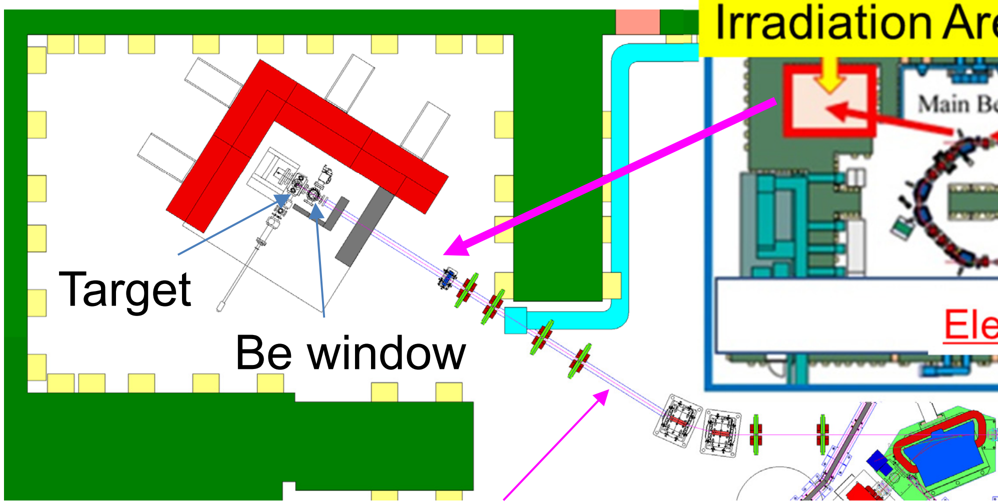


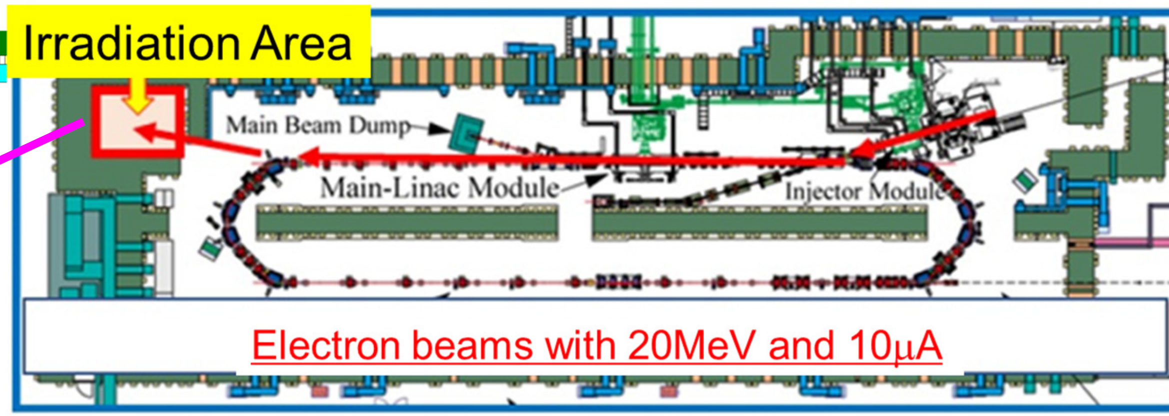
Required Specification for accelerator (final)

- 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.



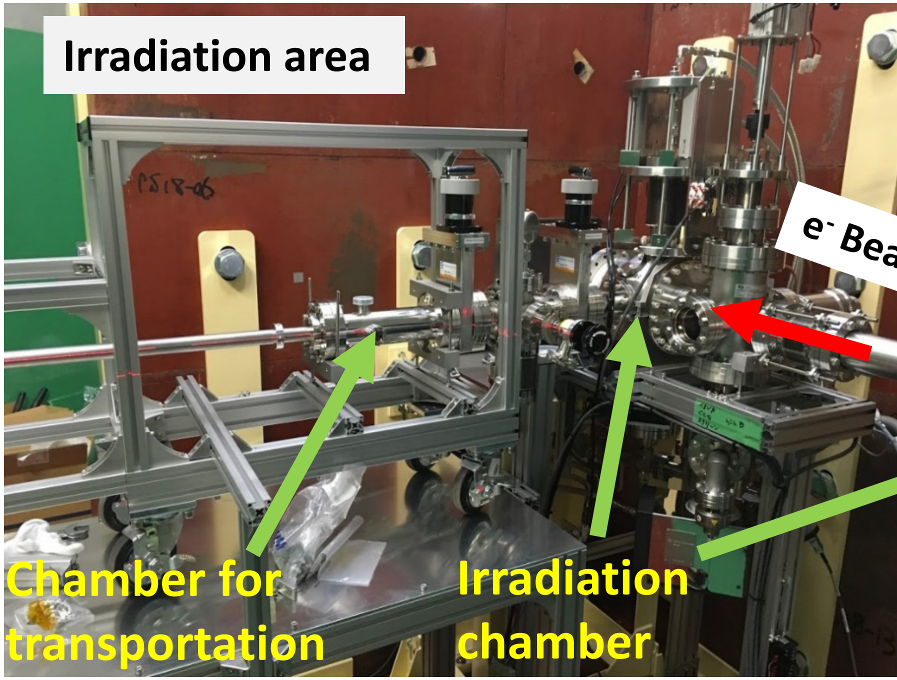


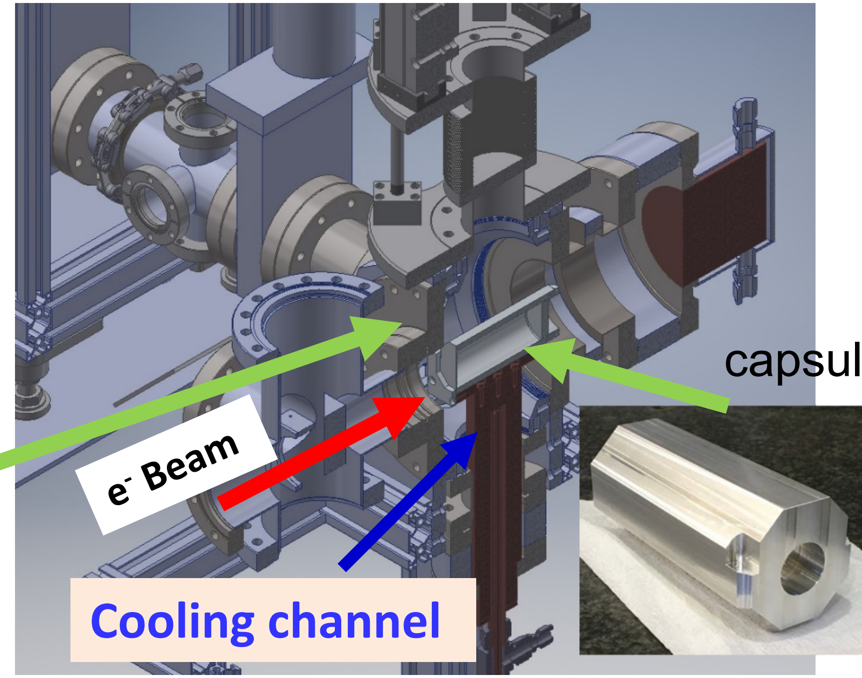
Mo 20MeV 10μA(maximum)

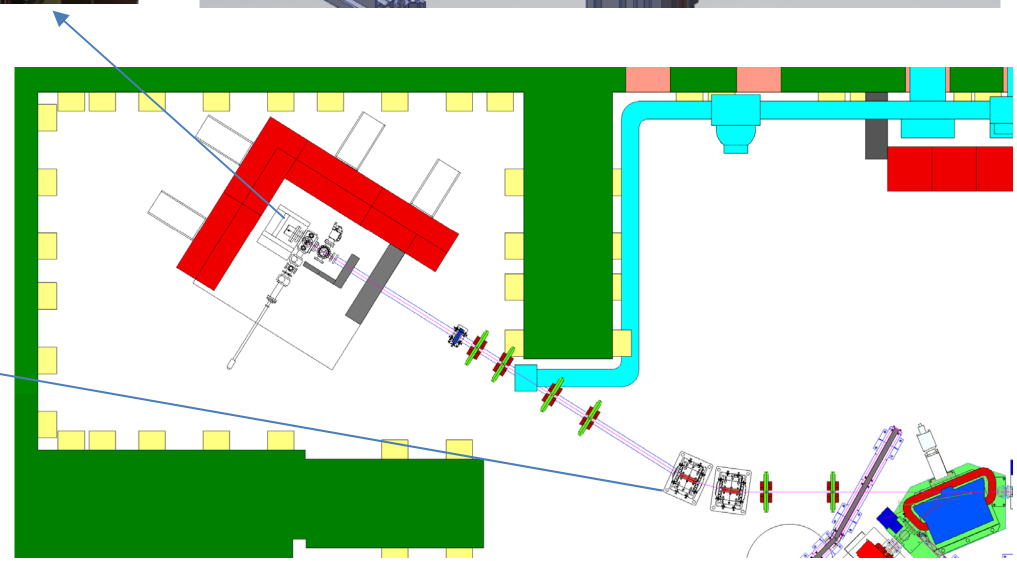
Beam line was constructed in Mar. 2019.
And beam test started in Apr.2019.

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

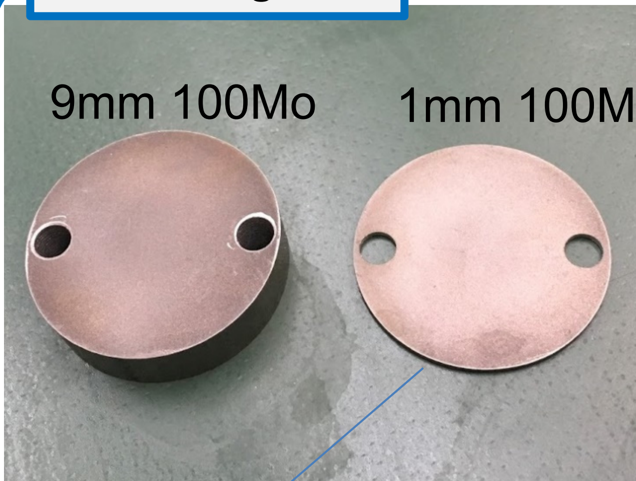


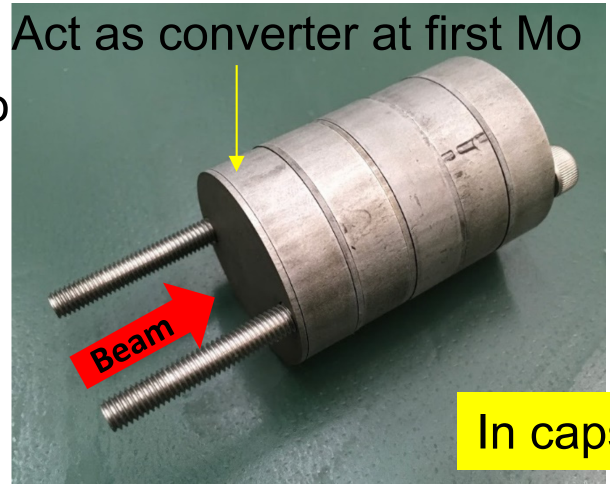




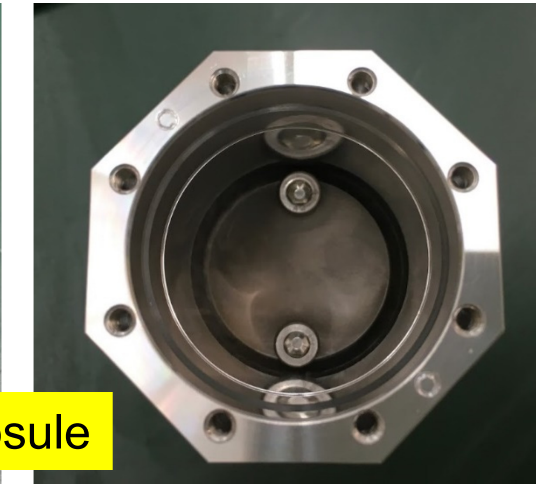
Latest results of RI production by using new beam line

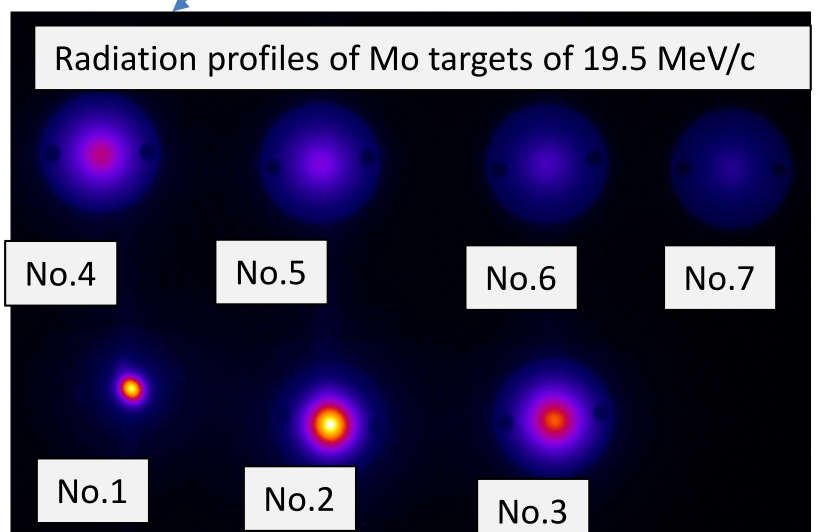
Disk targets



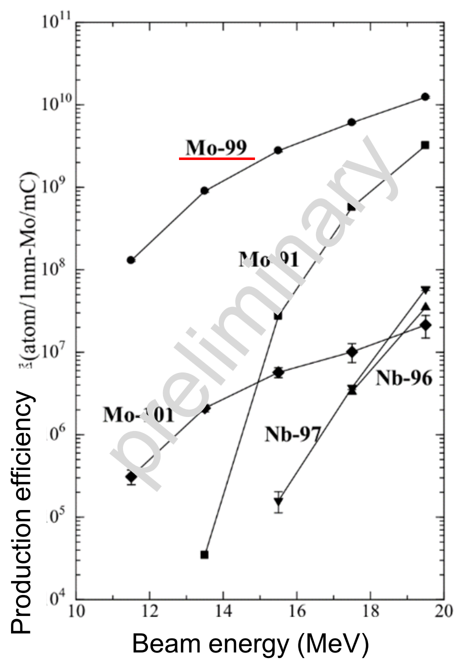


In capsule





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



- Energy dependence of ^{99}Mo production ration was obtained in Jun.2019.
- These data were consistent with simulation within 30% error and satisfied our requirements
- Next we plan to try long term production of ^{99}Mo in Oct. 2019.

Coherent Resonant Diffraction radiation THz (2018-2019)

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

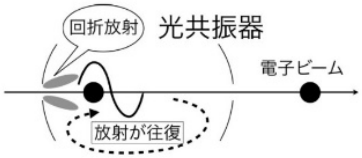
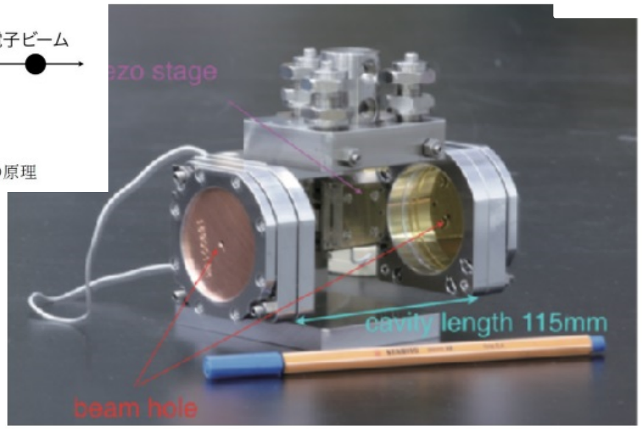
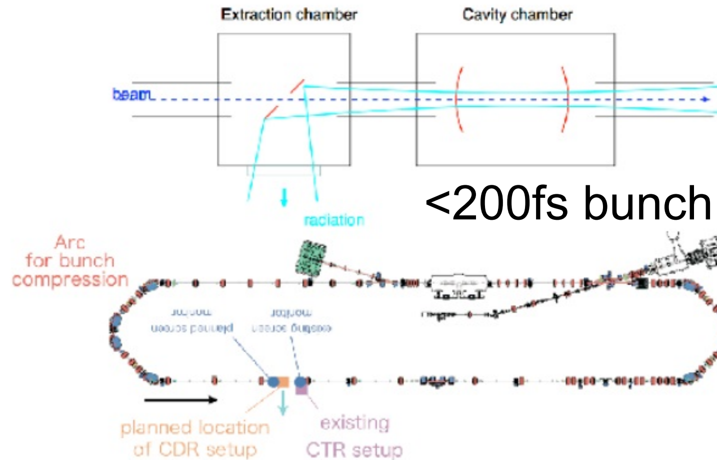


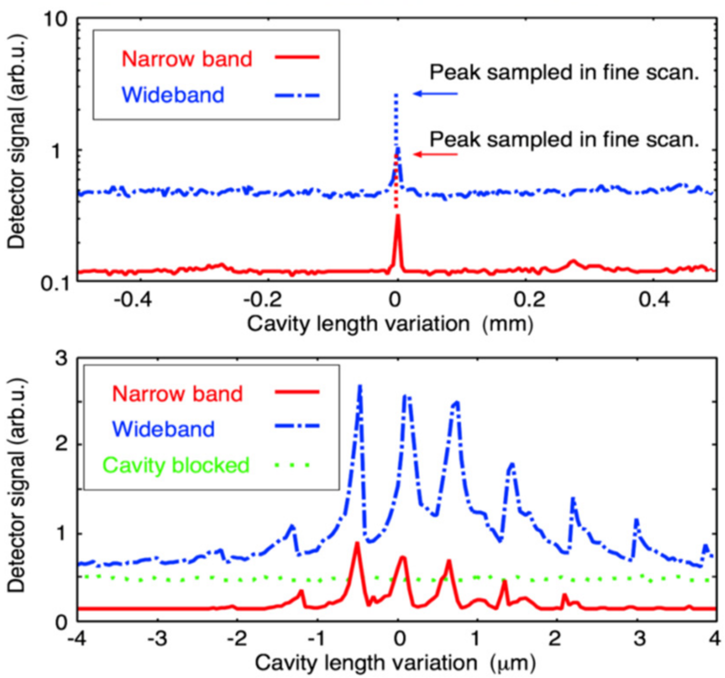
図 6: 共振器型回折放射の原理



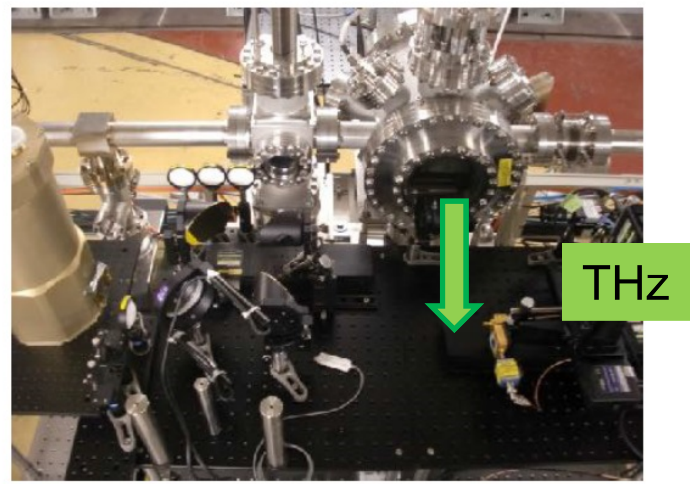


<200fs bunch length

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.

Details will be talked in the following talk in ERL2019

M. Shimada, “High-efficiency broadband THz emission via diffraction-radiation cavity” (Wed)

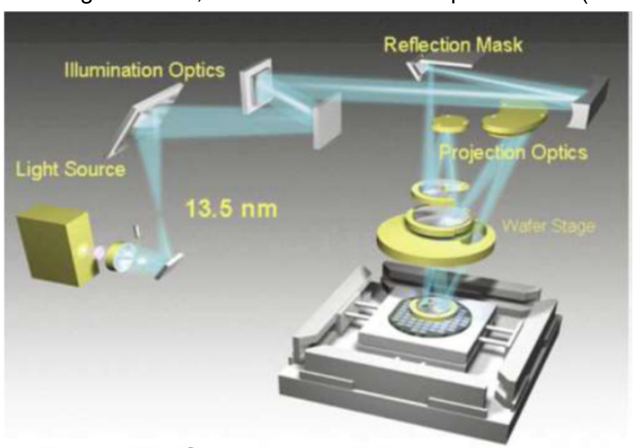
Introduction of EUV-FEL

- 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).

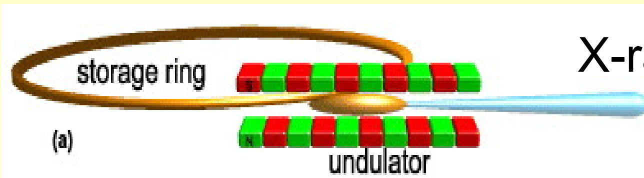
Schematic of EUV (13.5nm) exposure tool

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



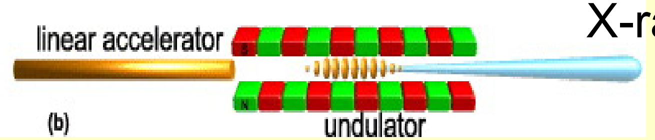
EUV of 13.5 nm by LPP (Laser produced plasma)
→ 250 W level now
(peak 400 W)
Need breakthrough for higher EUV light (>1kW)

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

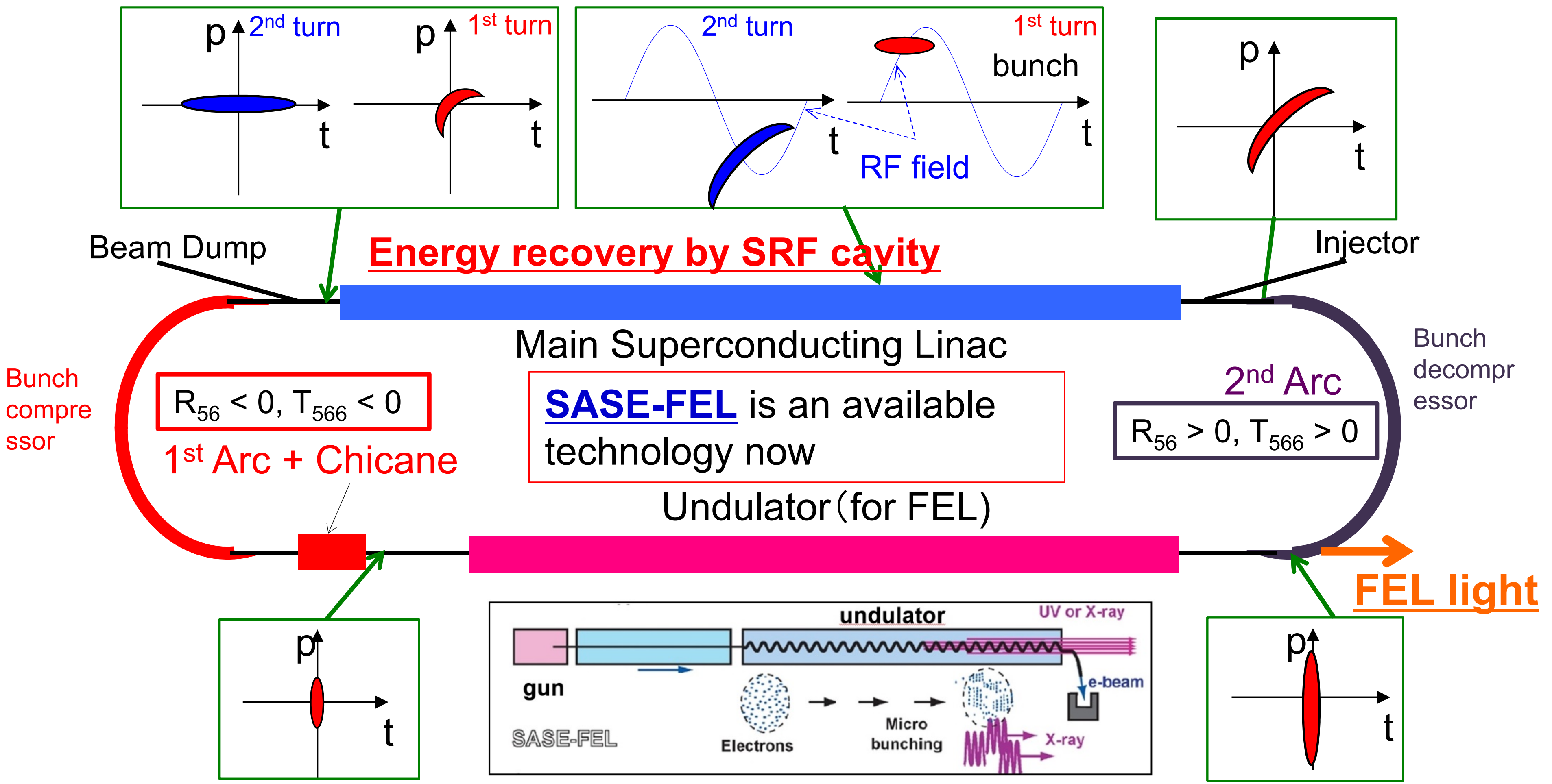
G. Dattoli et al., NIM-A (2001)

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

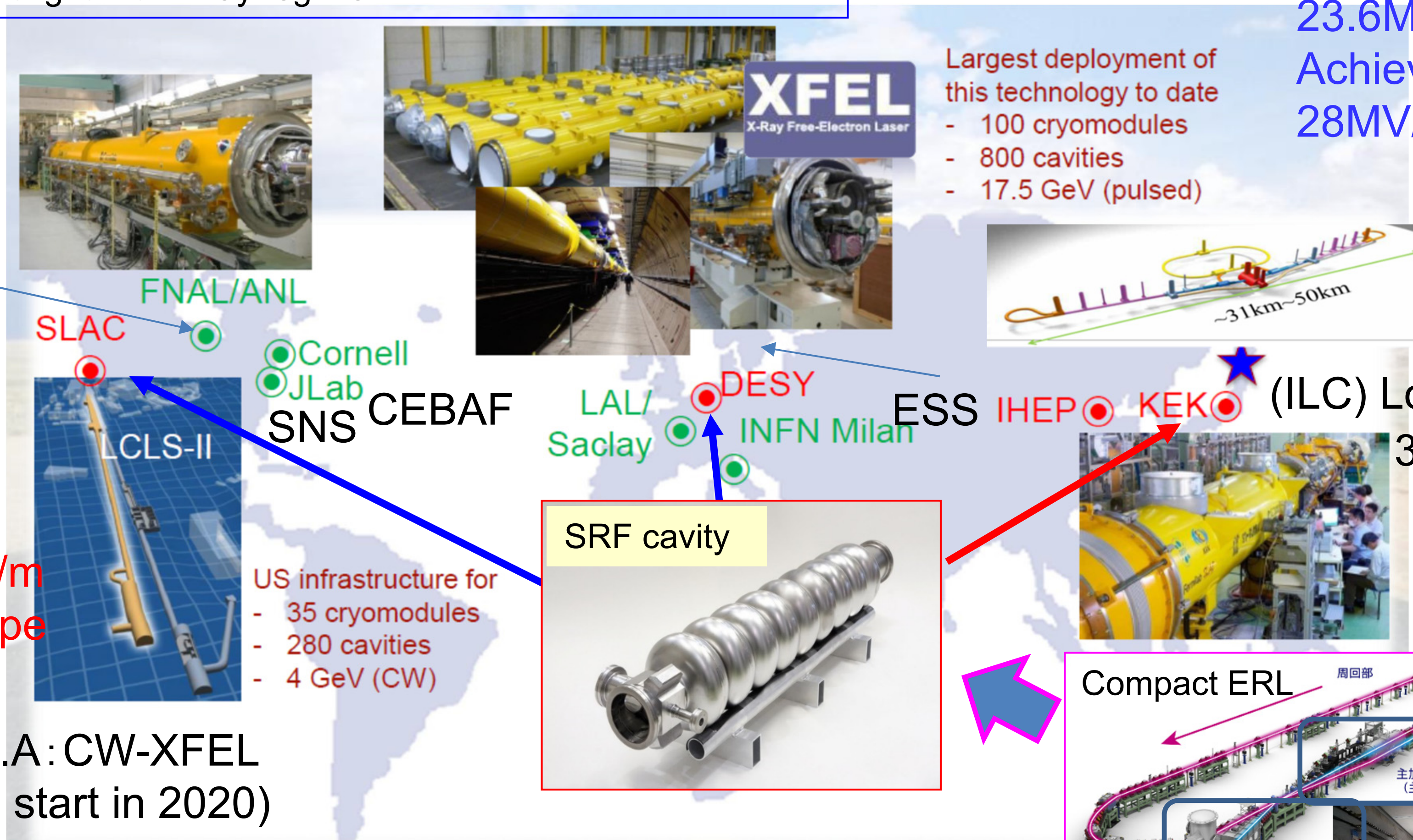
Large scale SRF facility (XFEL & ILC and more)

XFEL (X-ray Free Electron Laser):
Next generation light source makes high peak intense coherent light with X-ray regime

Europe: Germany (DESY): (start in 2017)

Long pulse
-XFEL
23.6MV/m 1ms
Achieved ave.
28MV/m

FRIB

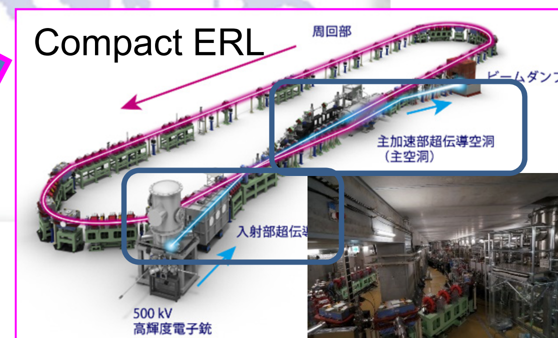


(ILC) Long pulse
31.5MV/m

CW
16MV/m
N2 dope

U.S.A: CW-XFEL
(will start in 2020)

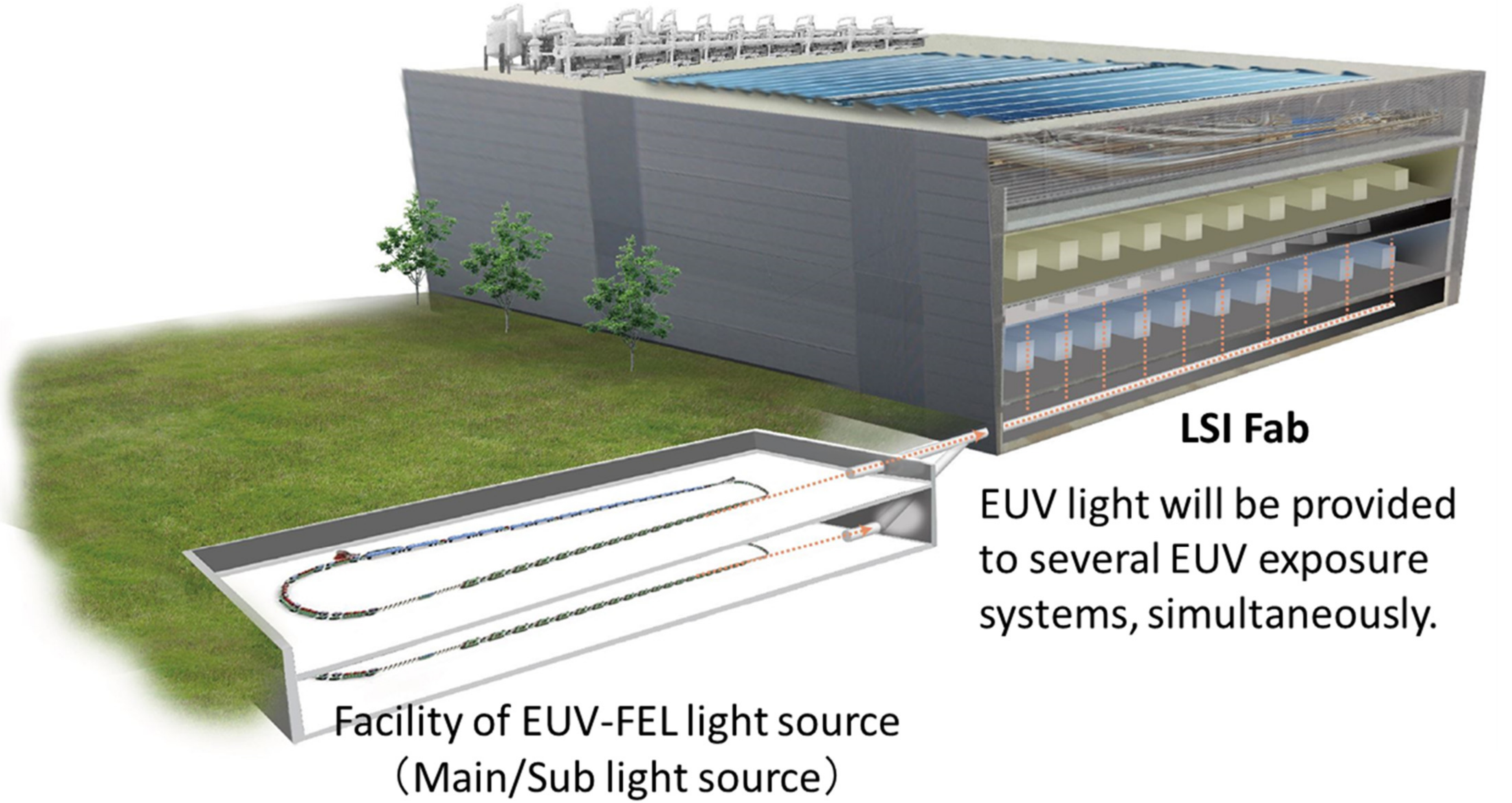
CW



Compact ERL (Test Facility of ERL in KEK) In 2013 we achieved Energy Recovery.

SRF cavity now promote new generation accelerator like X-FEL, intense proton/ion beam.

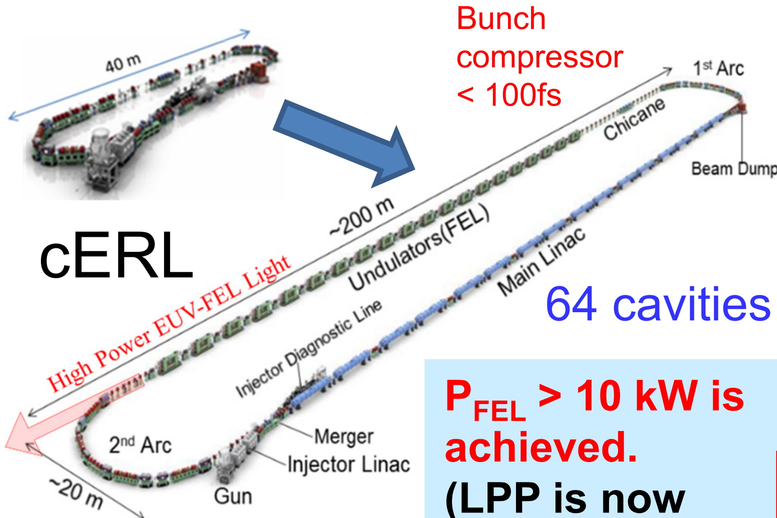
Facility Image of LSI Fab with EUV-FEL



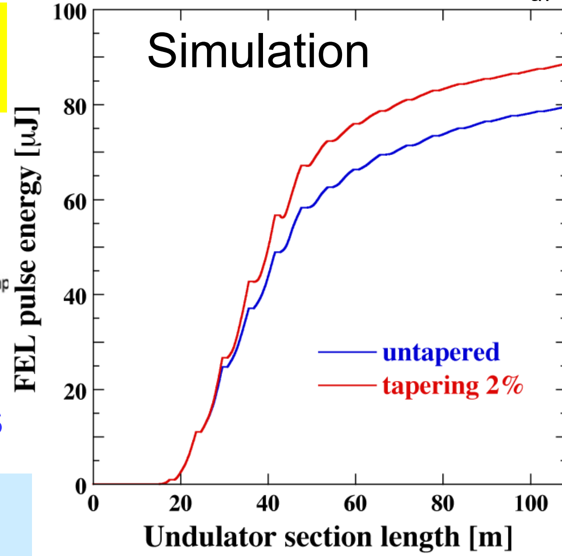
Prototype design of the EUV-FEL

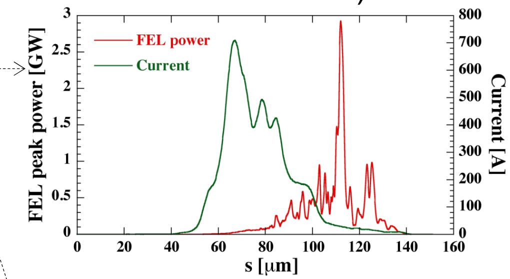
(P_{FEL}=88.5 μJ x 162.5 MHz =14.4 kW, I_{av}=60pC x 162.5 MHz= 9.75 mA)

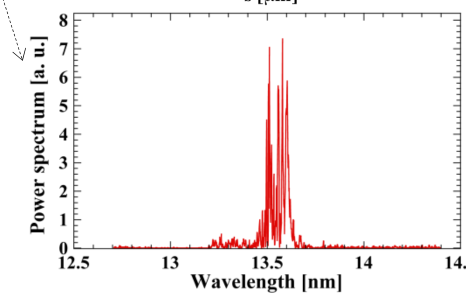
10-kW class EUV sources are required in the future for Next Generation Lithography



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

EUV/X-ray FELs

Low power → High power

	LCLS	SACLA	FLASH	Euro-XFEL	LCLSII	EUV-FEL
Type of linac	Normal conducting		Super conducting			
Operation mode	Pulse		Long pulse		CW	
Country	US	Japan	Germany	Germany	US	-------
ERL scheme	No	No	No	No	No	Yes
Repetition rate	120	30～60	<5000	<27000	1M	162.5M
Beam energy （MeV)	14300	6000～ 8000	1250	17500	4000	800
Wavelength(nm)	0.15	0.08	4.2-52	0.05	~0.3	13.5
Pulse energy(mJ)	~10	~10	<0.5	~10	~1	~0.1
Average Power （W)	~1	~1	<0.6	~100	~1000	>10000
Beam dump power（W)	~1.5k	~0.5k	~6k	~0.5M	~1M	~0.1M
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 (important in future)

Low power — EUV/X-ray FELs — High power

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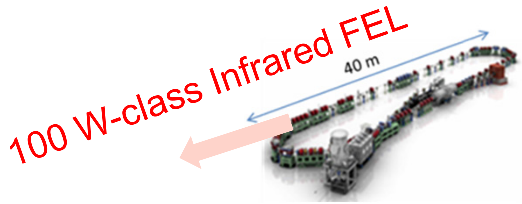
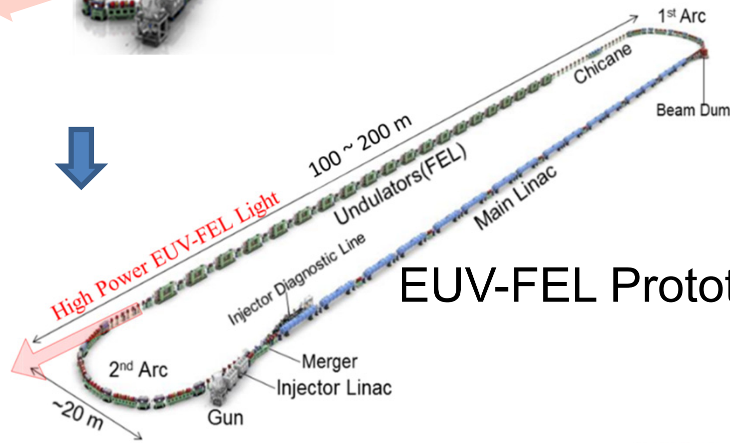
Staging to realize the EUV-FEL light source

1st stage:
Development of the feasible technologies



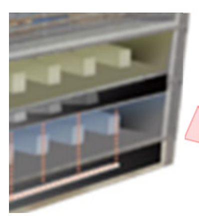
cERL

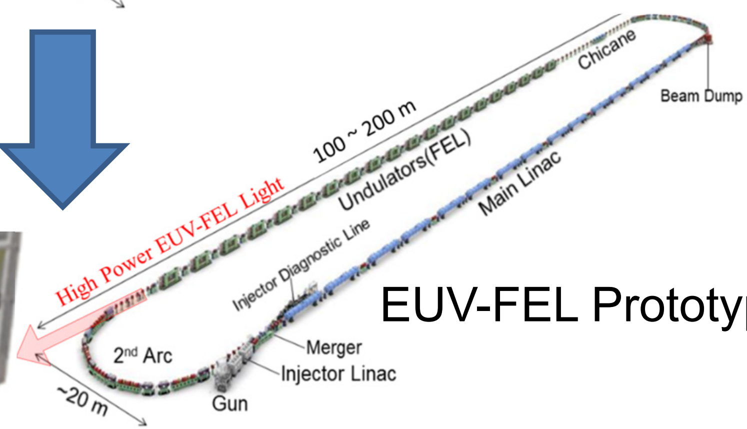
2nd stage Phase 1:
Establishment of the EUV-FEL Lithography system



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.

Staging to realize the EUV-FEL light source

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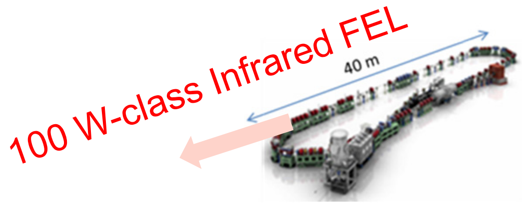
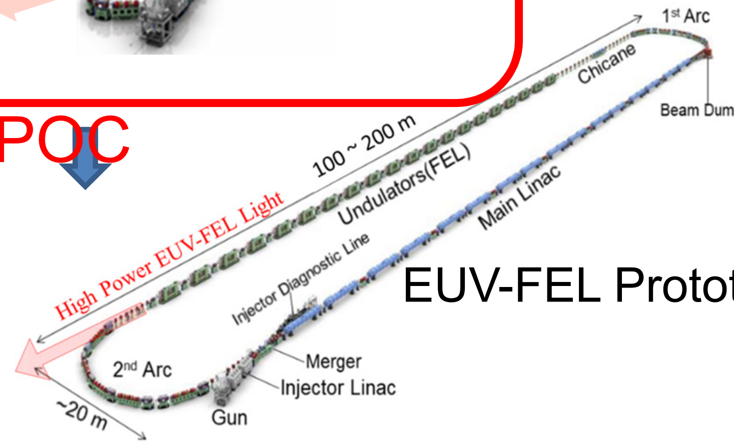


cERL

Upgrade plan of cERL for the POC

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



EUV-FEL Prototype

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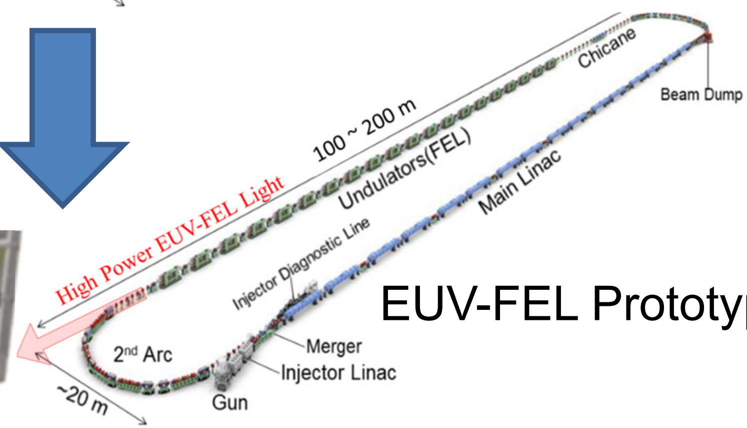

EUV-FEL Prototype

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

In recent years, the use of organic materials that are lightweight, low-cost, and highly functional has been increasing.

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!

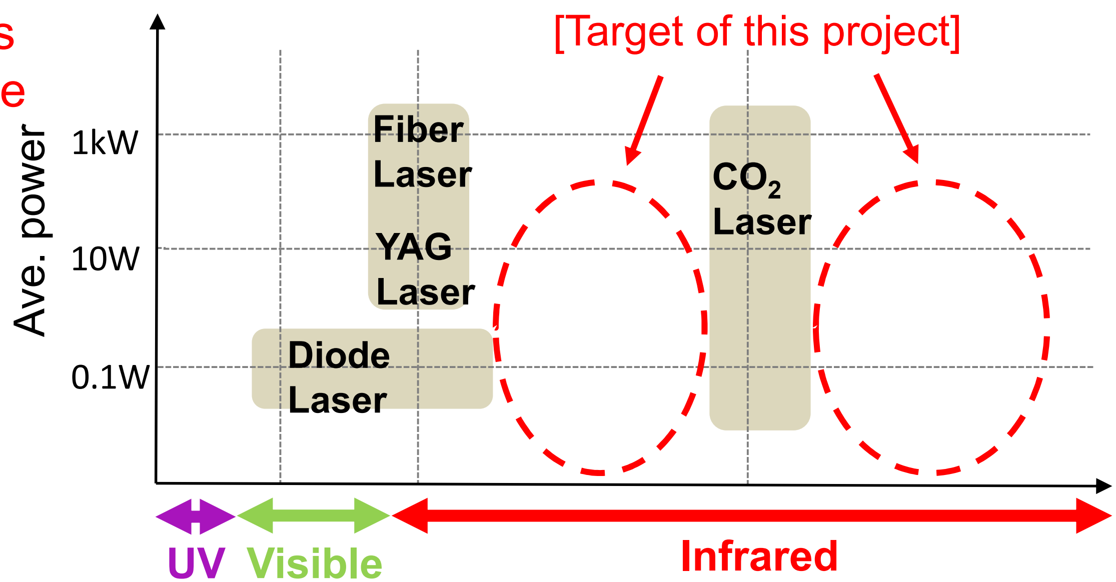

Figure: Wavelength ranges of lasers.

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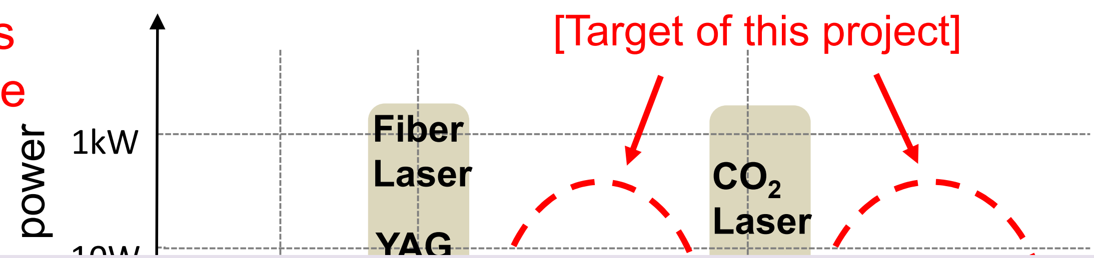
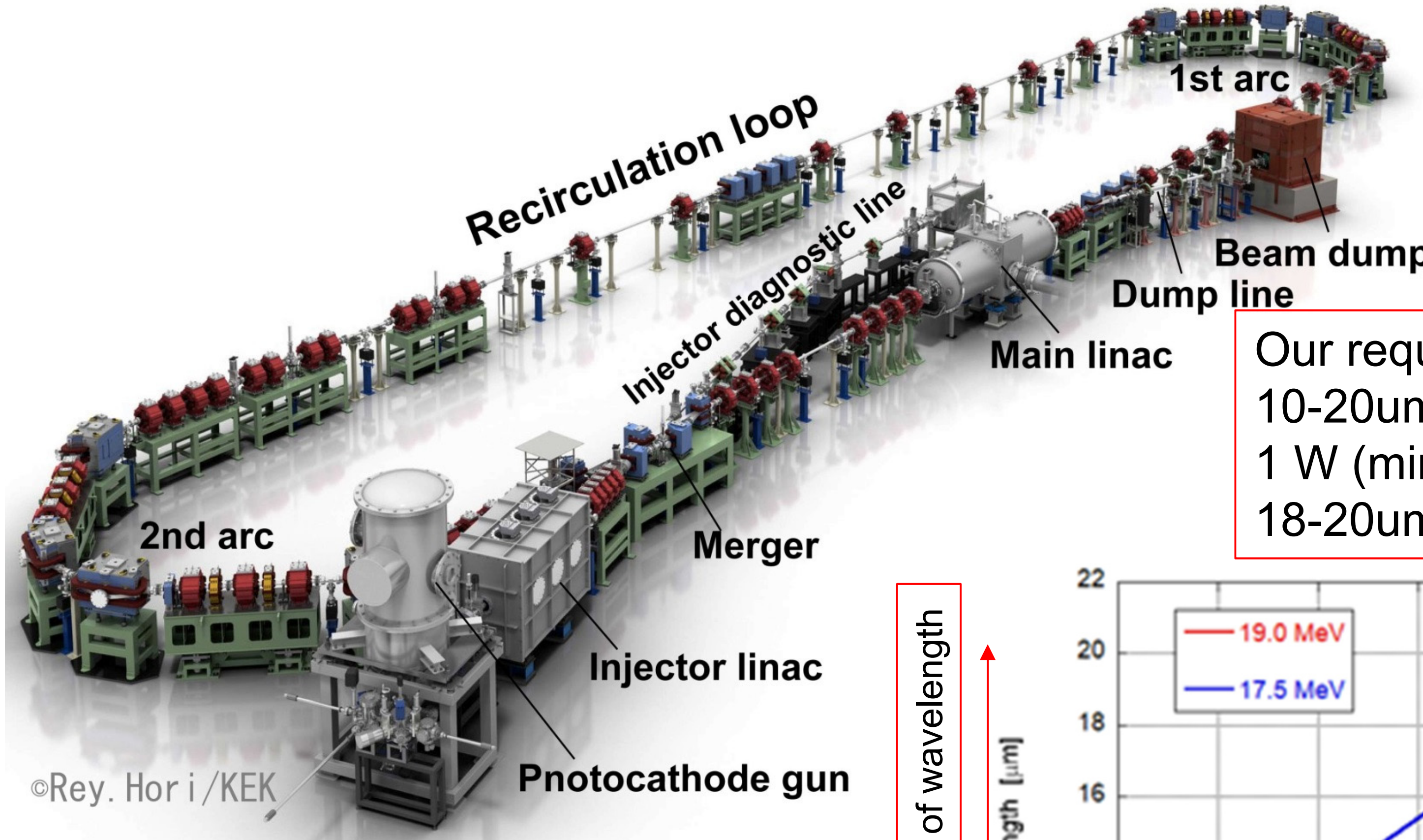


NEDO project (Ministry of Economy, Trade and Industry):
"Development of high-power mid-infrared lasers for highly-efficient laser processing utilizing photo-absorption based on molecular vibrational transitions."

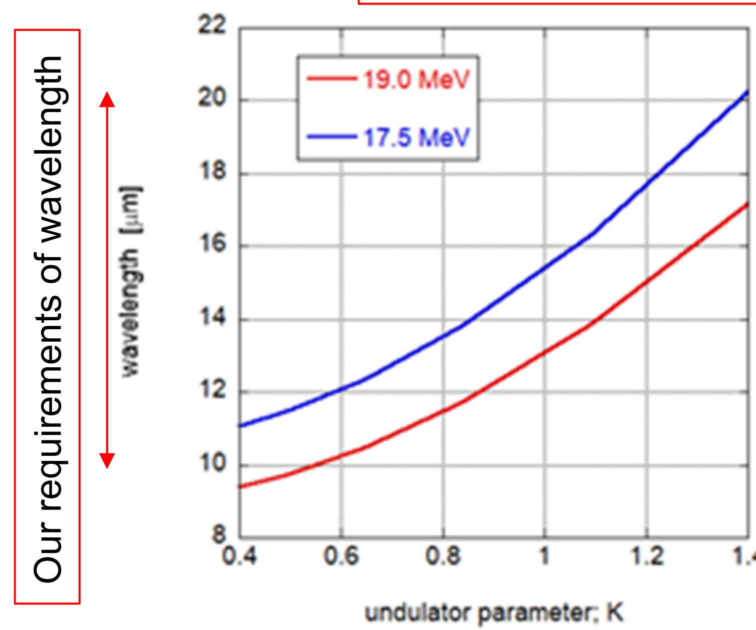
Figure: Wavelength ranges of lasers.

High average power IR-FEL Project



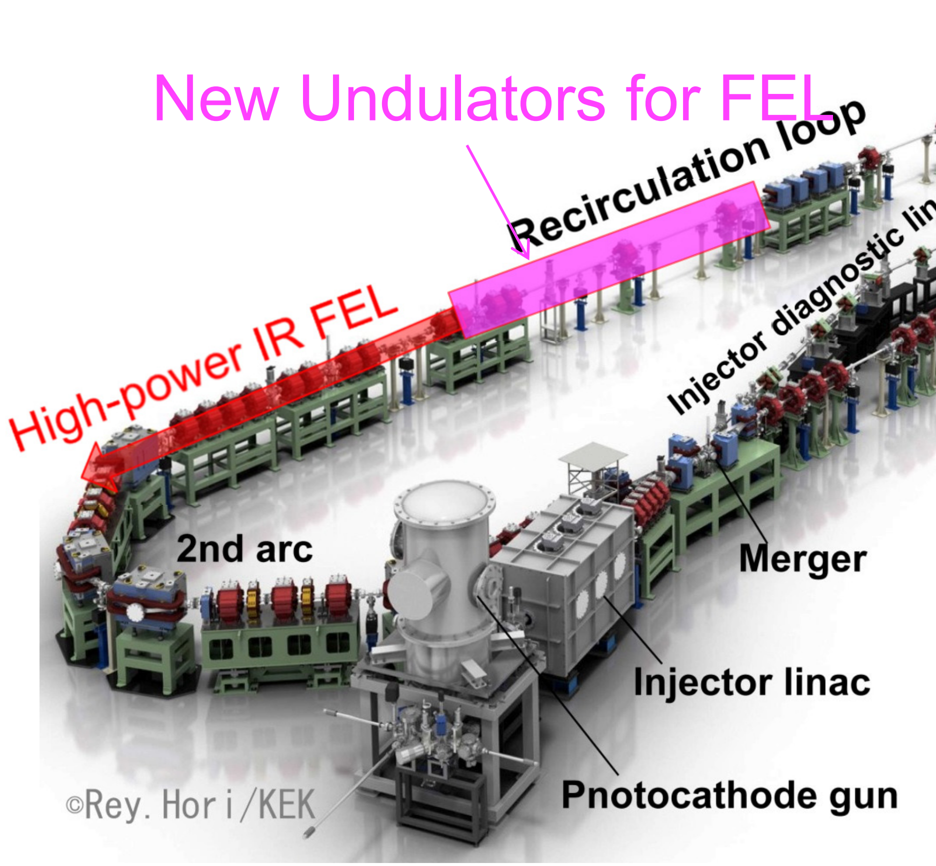
Our requirements
10-20um
1 W (minimum) @
18-20um

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



FEL wavelength

High average power IR-FEL Project



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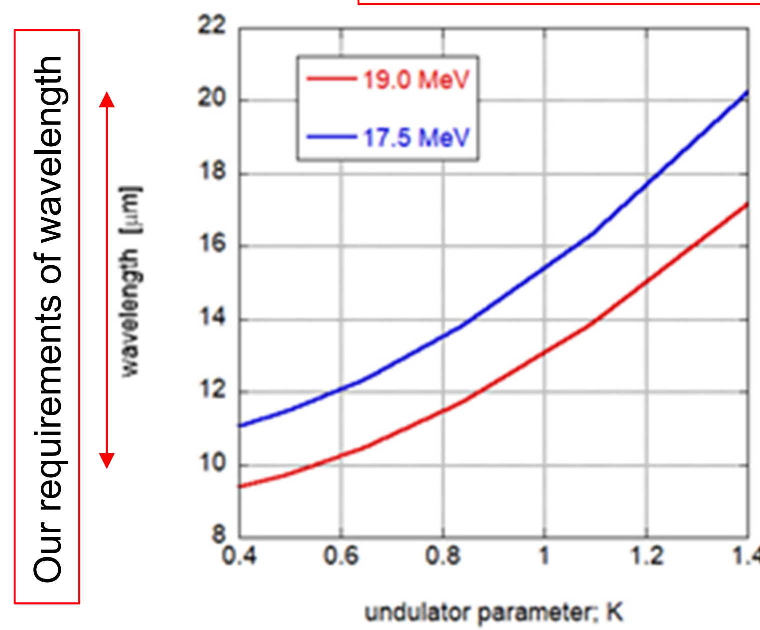
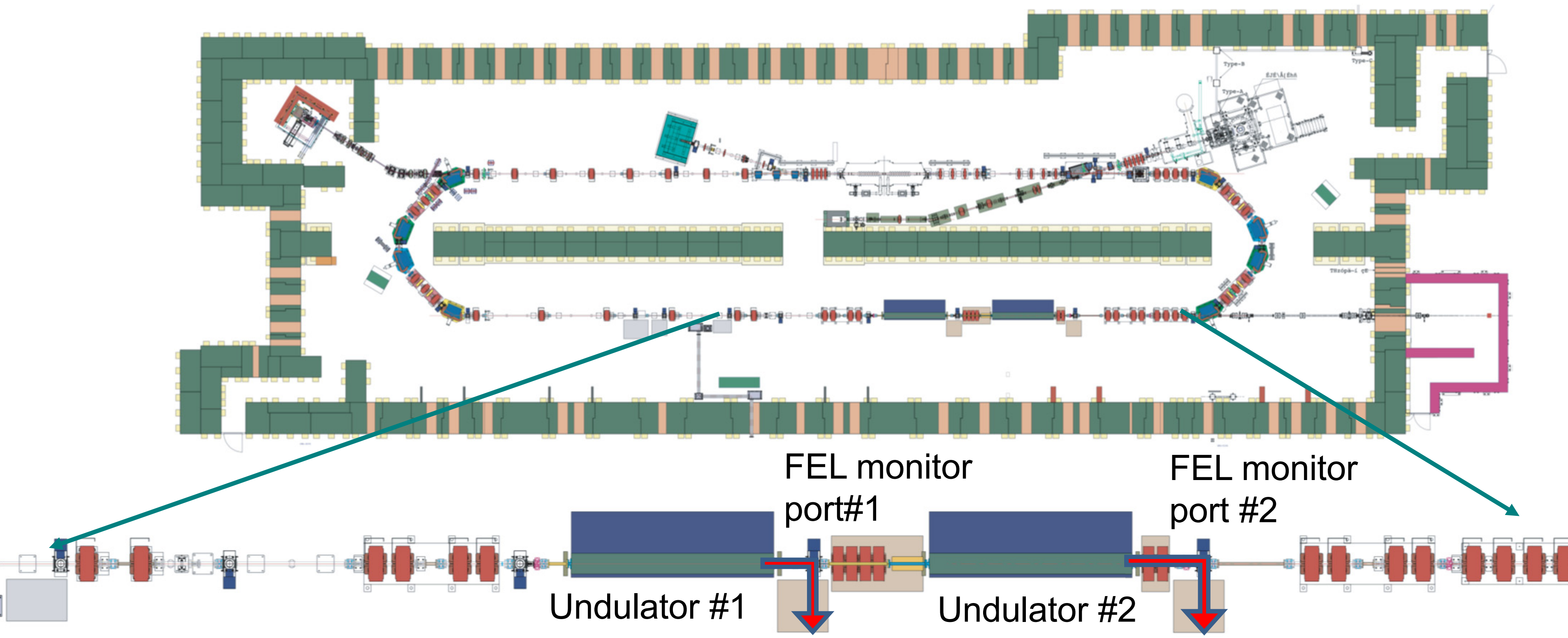


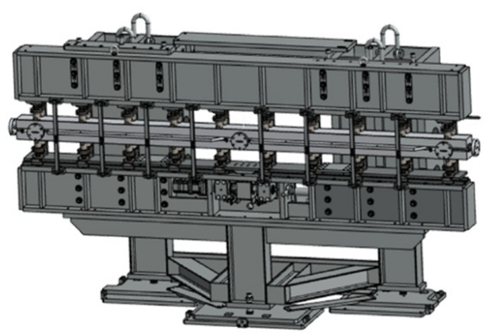
FEL wavelength

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.

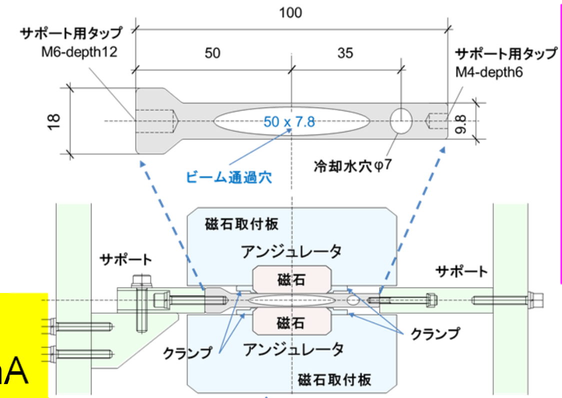
Undulator parameter

- 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.

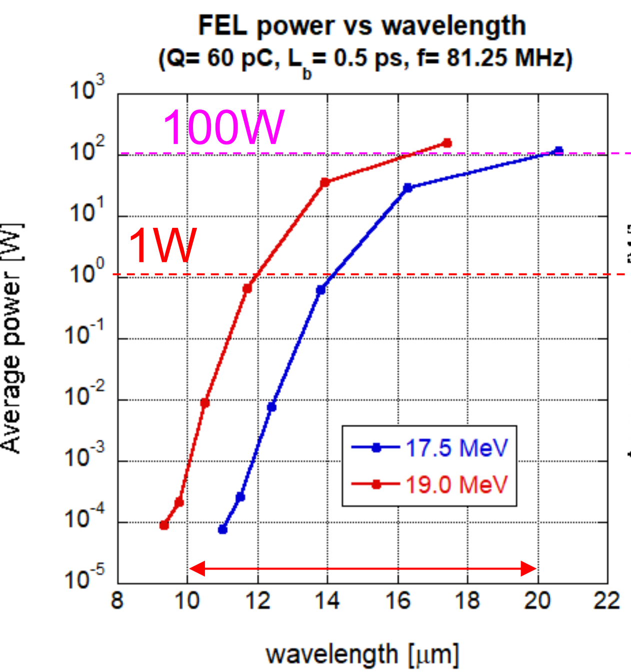
Details of cERL beam operation are talked at
- T.Miyajima, “Compact ERL(cERL), stable 1 mA operation with a small beam emittance at KEK”
- O.Tanaka, “Beam Halo”

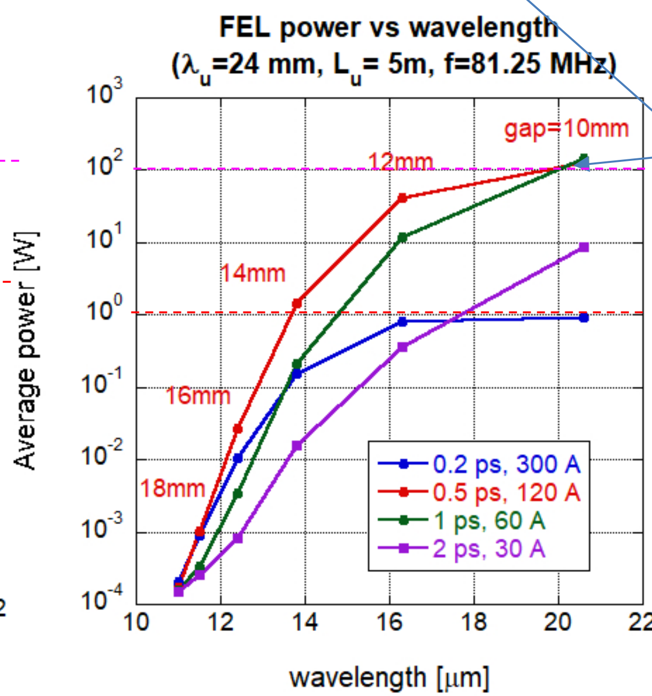


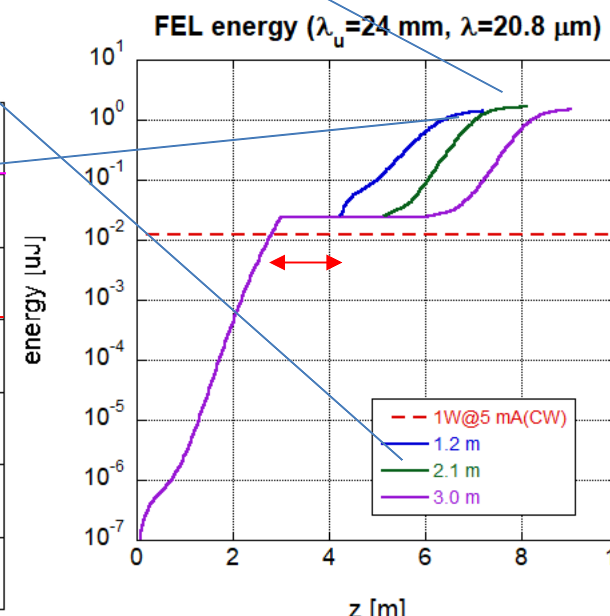
Fixed schedule by NEDO:
In FY 2019,
construct undulator
In FY 2020,
SASE IR-FEL production

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

3m undulator x 2

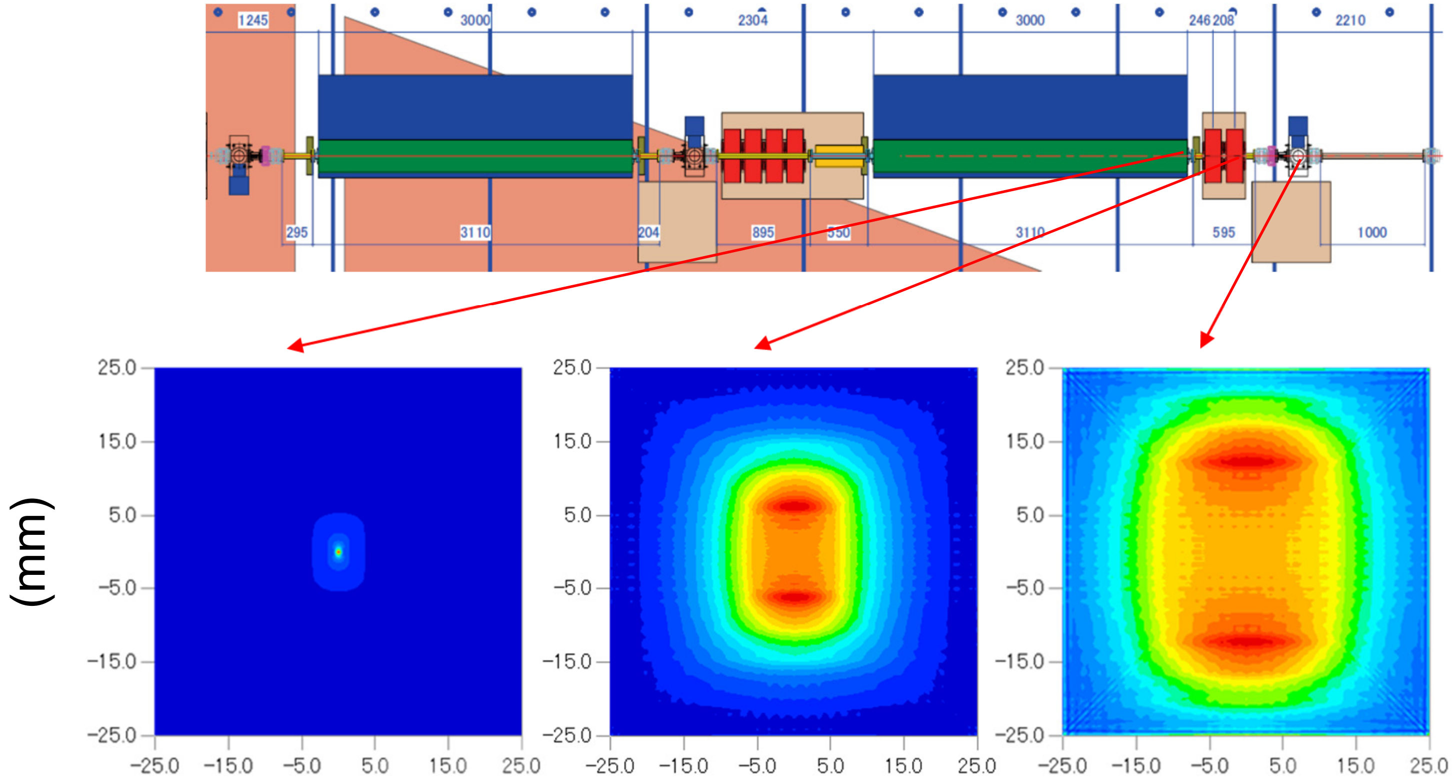






a) wavelength 20.8 μm

Divergence of IR-FEL light of cERL



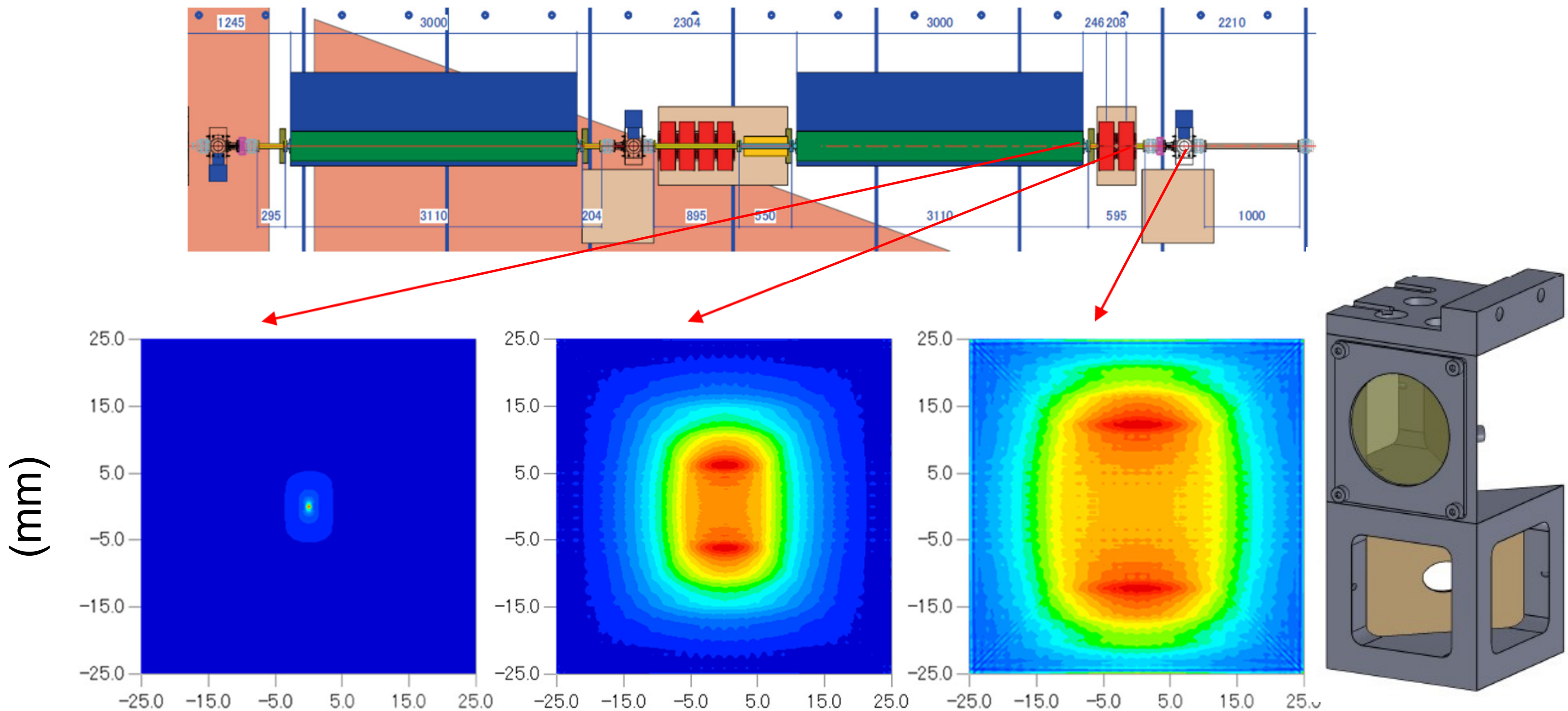
e) z=0 m

f) z=0.53 m

g) z=1.06 m

After reaching saturation, optical guiding effect decreases, so FEL light tends to spread after the 2nd undulator.
z is the distance from the 2st undulator.

Divergence of IR-FEL light of cERL



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

After reaching saturation,
tends to spread after the 2
z is the distance from the

Large optical divergence after undulator

Solution:
Light extraction using a mirror with a beam hole

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

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 → Need to be solved by cERL

What is more difficult than EUV-FEL?

- Control of low energy electron beam

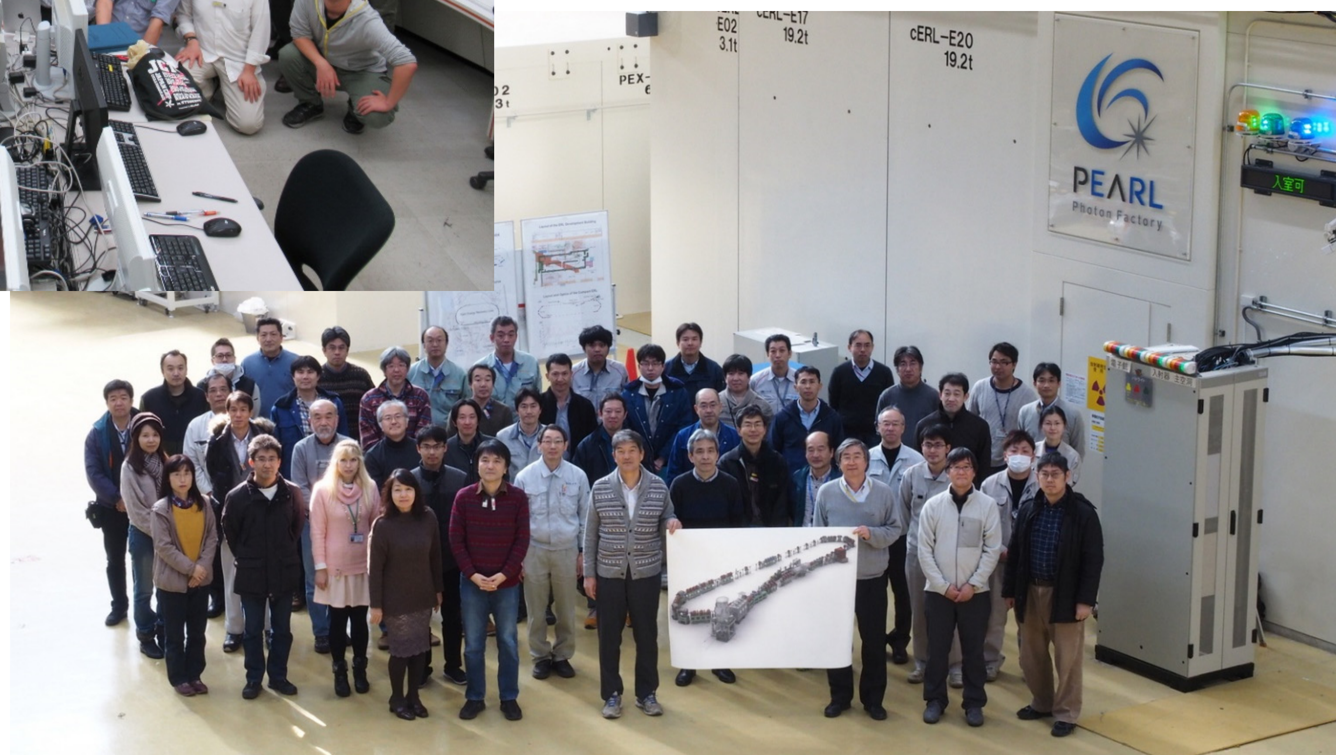
(Space charge effect, disturbances such as geomagnetic and environmental magnetic fields, error fields of the undulators)

- Long wavelength (Slippage length > Bunch Length)
- Diffraction loss of FEL light after the undulators

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.
- Diffraction radiation by Resonant cavity can give high intense THz with ERL CW beam with about 100 fs bunch.
- 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.

Thank you for your attention!



cERL Team (*)

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