Overview of Compact ERL (cERL)

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21 pages

A) Introduction
B) 1 mA energy recovery operation with low emittance beam
C) Applications by using cERL

15min

E-linac reliability workshop (2022.May.9-10)

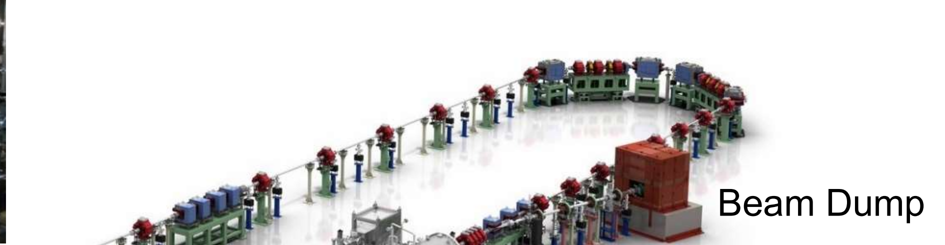
A) Introduction

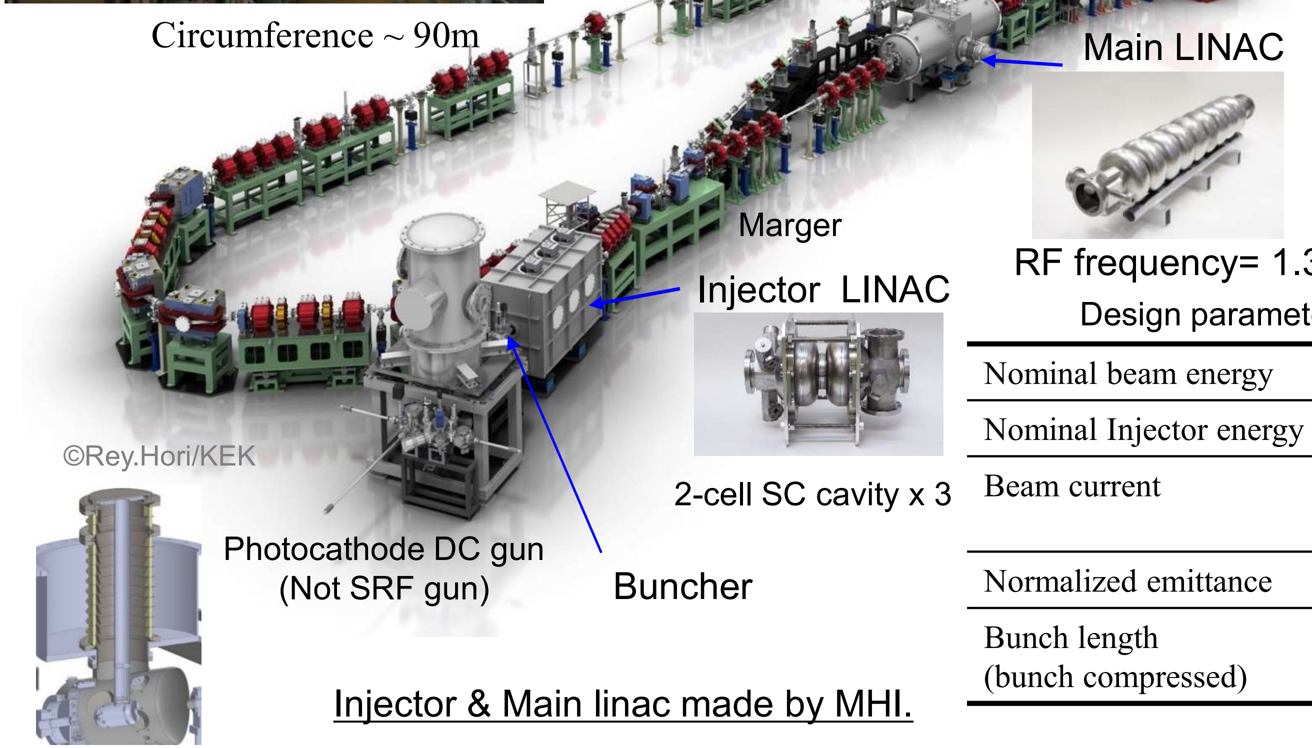
B) 1 mA energy recovery operation with low emittance beam

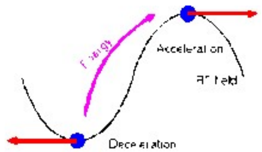
C) Applications by using cERL

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.







9-cell SC cavity x 2

RF frequency= 1.3 GHz

17.7 MeV

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)

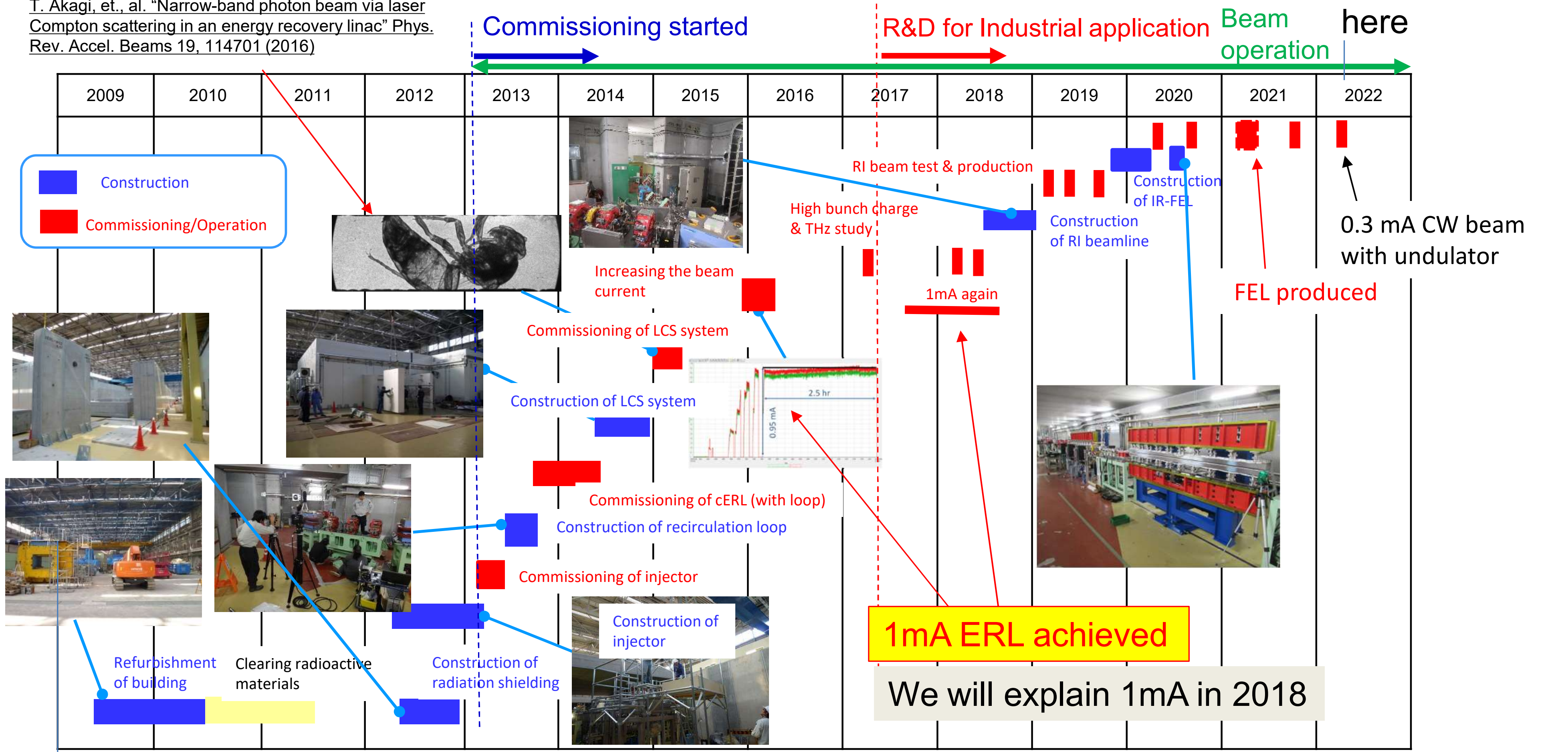
Injector & Main linac made by MHI.

Construction and Commissioning of cERL

Laser Compton scattering experiment in ERL

(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).

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



Construction started in 2009 and commissioning start in 2013.

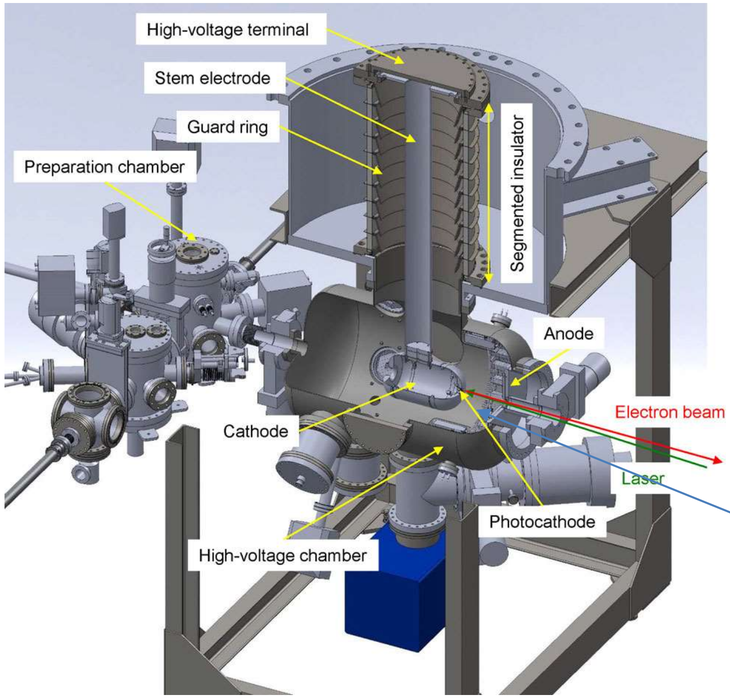
<u>Now we continue beam operation in 2022</u>

A) Introduction

B) 1 mA energy recovery operation with low emittance beam

C) Applications by using cERL

1mA CW ERL stable beam operation (DC Gun)

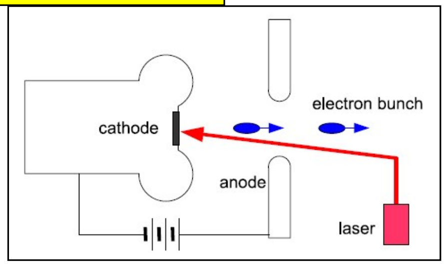


DOI: 10.1103/PhysRevAccelBeams.22.053402

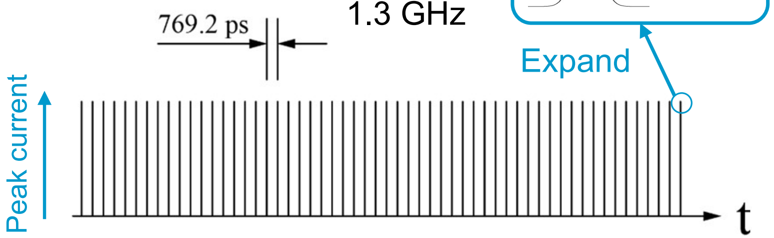
Operates with GaAs photocathodes

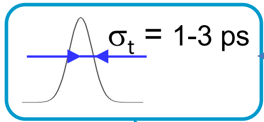
Parameter	Units	Value
Operation voltage	kV	350 - **500**
Average current	mA	1 mA
Vacuum level	Pa	~ 10^{-10}

Photocathode DC gun



CW beam





Bunch charge: 7.7 pC → average current: 10 mA

Initial conditions are determined by the gun-drive laser (green laser).

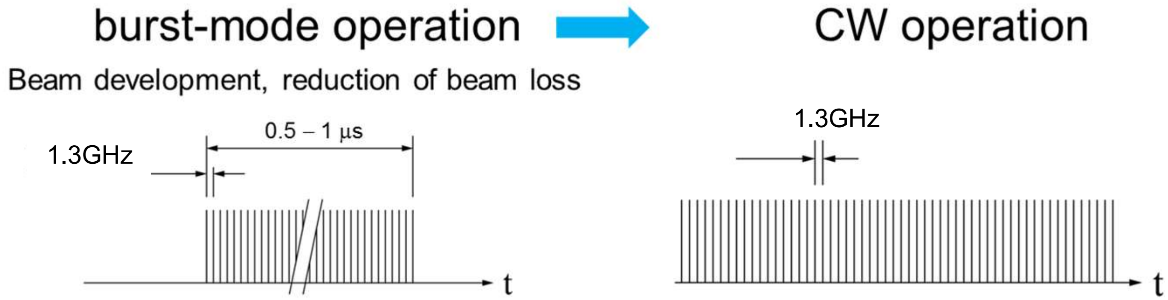
0.77pC : 1.3 GHz = 1mA

We successfully extract 500 keV electron from gun to dump (previous 390keV)
→ Highest DC field achieved in the world .

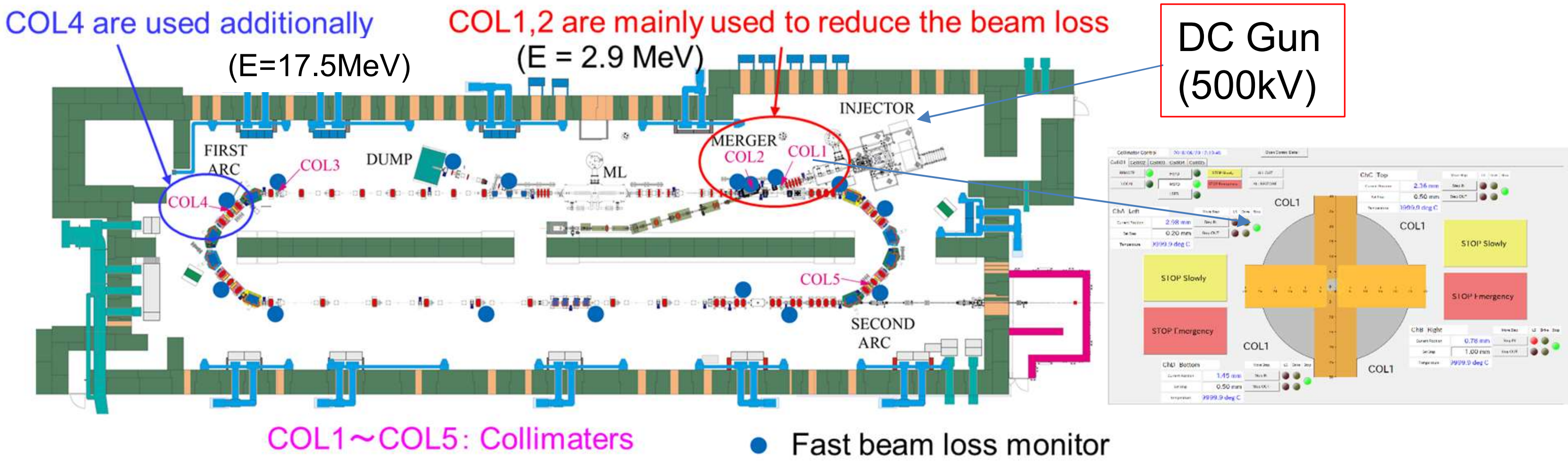
To realize 1mA stable operation

Beam handling system

- Careful optics matching and orbital optimization
- Beam development with the burst-mode operation



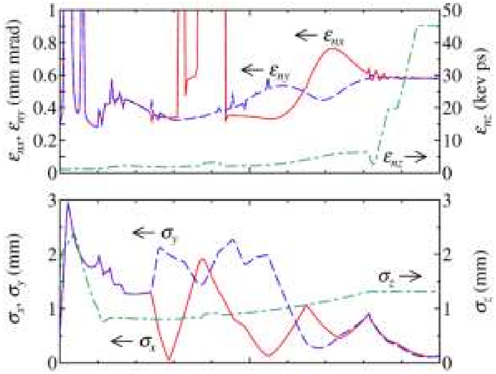
- Adjustment of the beam collimator to avoid beam loss



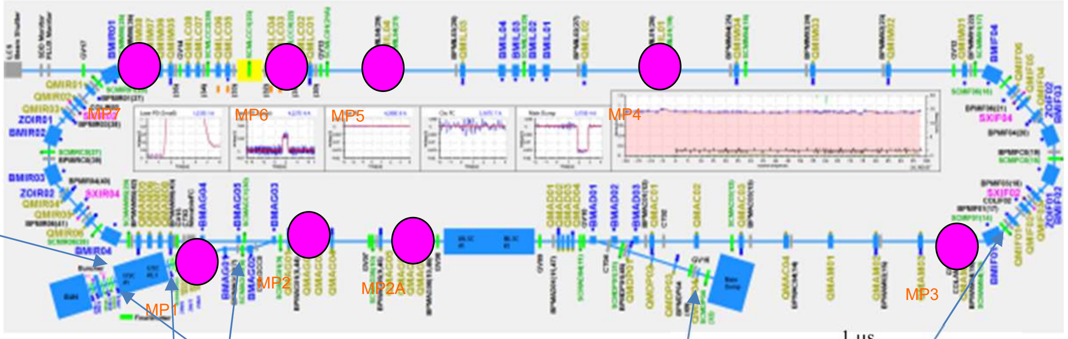
Matching of beam profile and measured emittance with high charge

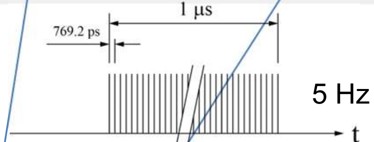
T. Miyajima, Proc IPAC'15

Calc. of injector parts :
390 keV Gun, 7.7 pC/bunch, laser 3 ps/8 pulse stack



Add new matching point not to make beam loss by using burst mode





collimator

Matching Example (0.5 pC/bunch)

Small beam profile was achieved by matching and collimator

Measured emittance

Bunch Charge	Normlized Emittance at arc Horiz/Vert [mm.mrad]
0.02 pC	0.14 / 0.14
0.5 pC	0.27 / 0.17
7.7 pC	1.5 / 1.1 (Tentative)

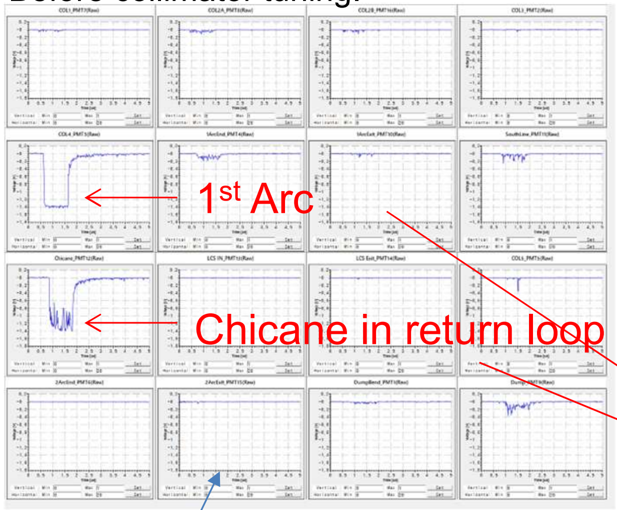
After sophisticated matching, beam profile became good and measured emittance was almost reached our requirements of 1 mm mrad normalized emittance at 7.7pC (equal = 10mA@1.3GHz)
(previous 5mm mrad@7.7pC before 2015)

Collimator tuning for CW 1 mA operation

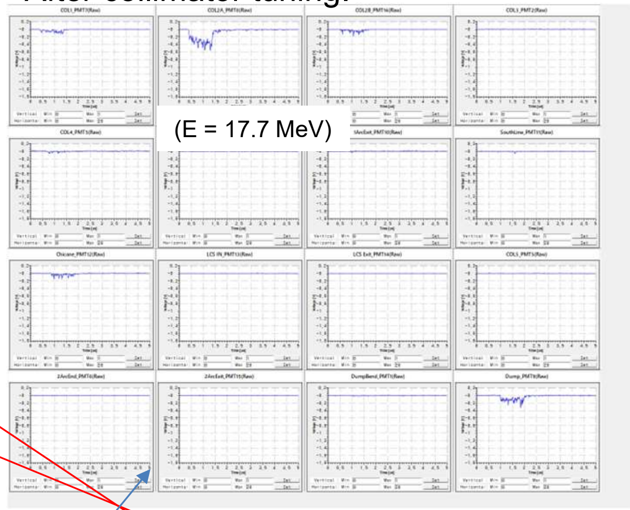
Los monitor signals 0.7pC/bunch

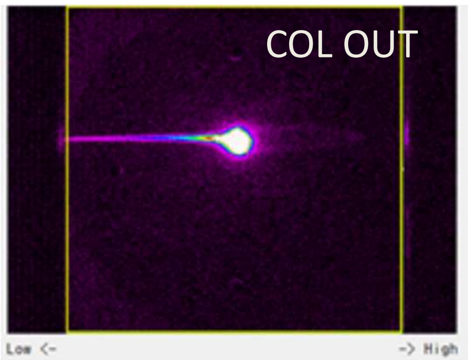
Courtesy of T. Obina

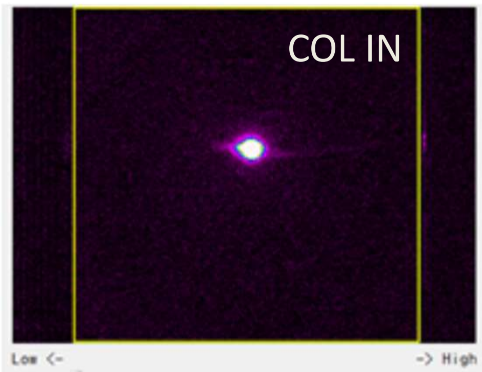
Before collimator tuning.

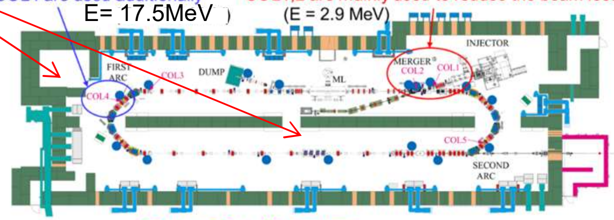


After collimator tuning.









* Design (after main linac)

enx = 0.34 mm mrad

eny = 0.24 mm mrad

* Measurement（Q-scan method）

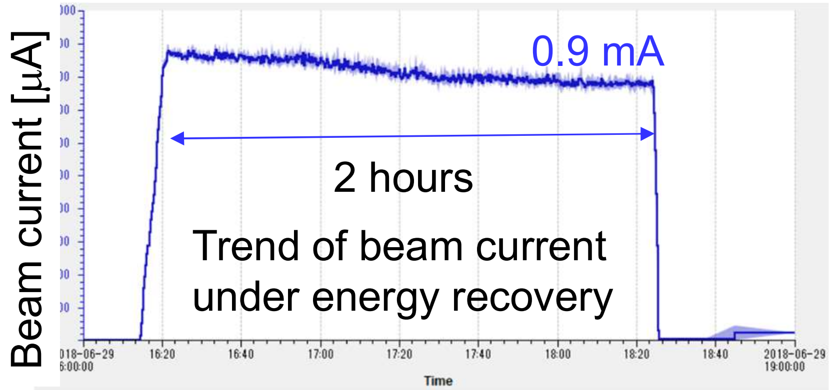
（x, y）= (0.42, 0.26) mm mrad

Low emittance beam in ERL was achieved in high current beam.

High charge operation of 60 pC/bunch with low emittance under ERL is next issue

Successful ~ 1mA CW beam operation with energy recovery

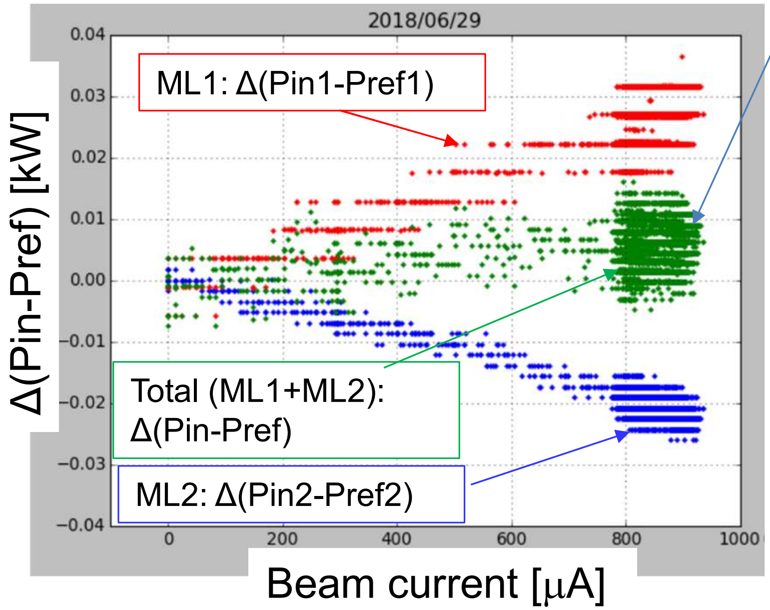
Change CW mode and increase the beam current :Reach 0.9 mA after the 1mA approval from the government on Jun/2018. Without HOM-BBU instability

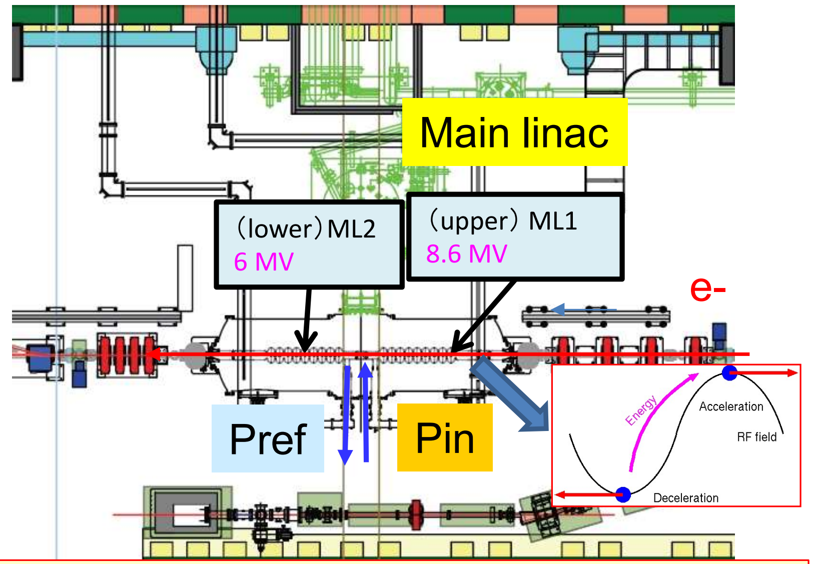


Required power without recovery is :
14.6 MV x 900 uA = 13.1 kW

Energy recovery was successfully done with 100.00 +- 0.03 %

Feed power : less than 10W !! (r.m.s 4 W)





RF stability : **ΔA/A = 0.01%, Δϕ = 0.01deg**

Stable energy recovery of about 1 mA was successfully done without beam loss.

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C) Applications by using cERL

cERL beam operation for Applications

- Superconducting 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 (high current, low emittance, short bunch with ERL) 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) IR-FEL experiment with high current ERL beam
  - (3) Intense THz light generation with ERL

This talk [(1)–(2)]

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

Already achieved these application by using Laser Compton Scattering (LCS) Exp. In 2015

Our targets in a few year (2018-2020)

Plan of cERL beam operation (2018~2020)

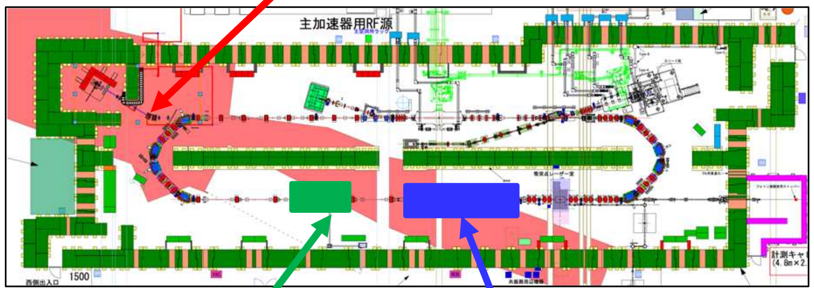
- New beam line for 99Mo RI production & material irradiation in cERL. (from 2019)
- We will produce FEL with this high current beam in the IR-FEL regime. (POC of EUV-FEL plan) Including high charge beam operation (~60pC).
- < 200fs bunch operation with THz generation (RCDR experiment)

See detail for THz operation

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

cERL beam line

New beam line for 99Mo & material irradiation (nanocellulose)



New THz beam line

IR-FEL undulator

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

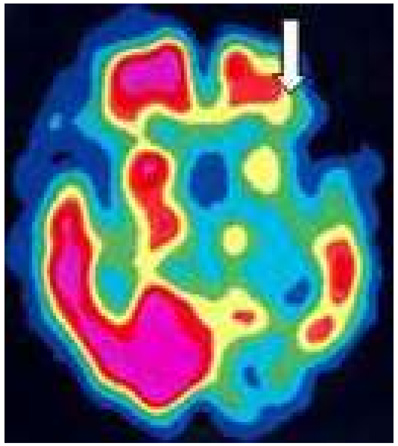
Concern about the stable supply of ^{99}Mo / ^{99m}Tc

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

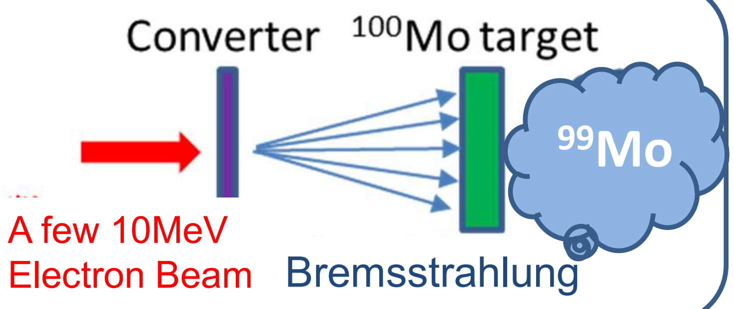
(Problem caused by volcanic eruption in the past)

- 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 99 ^{m}Tc



Required Specification for accelerator (final)

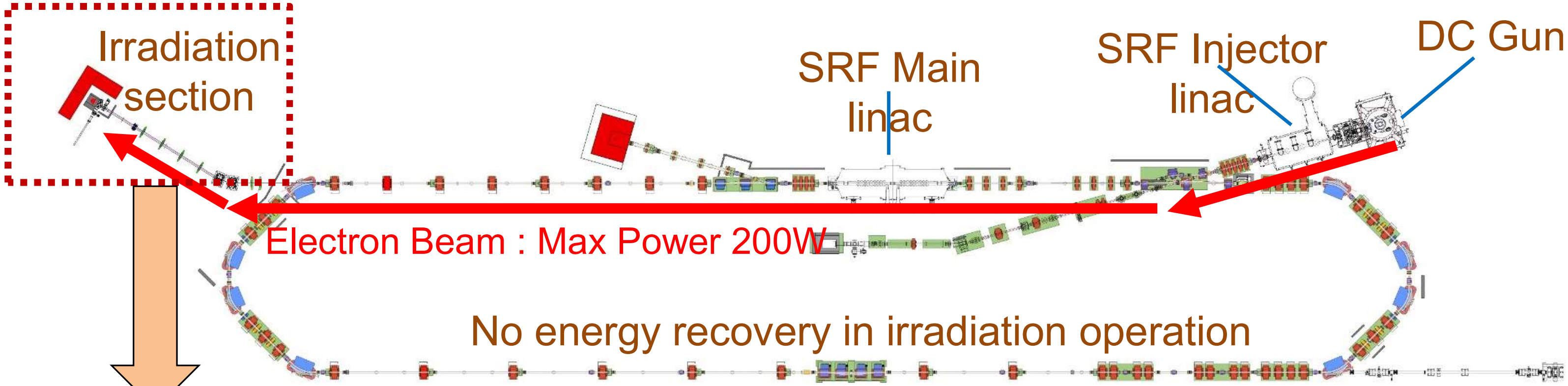
- 20 ~ 50 MeV electron beam
- Several mA to 10 mA (final)

- The test irradiation of electron beams to a multiple molybdenum target will be done from 2018 to 2020 produce ^{99}Mo and <u>check the yield of the production</u> in order to realize a real machine with large electron beam power.
- → <u>**start 10uA with 20 MeV (max) electron CW beam**</u>
- This project was done under research contract with <u>"Accelerator Inc."</u> https://www.accelerator-inc.com/

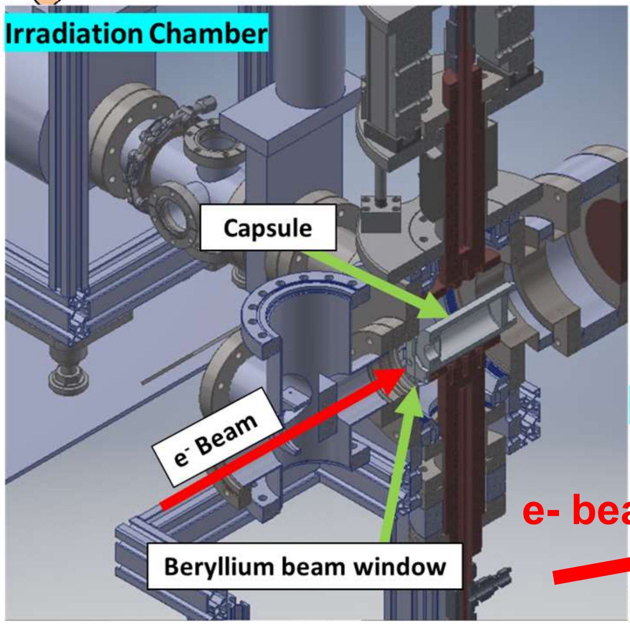
<u>Motivation</u>: get several knowledges to design a target system for large irradiation power such as a practical technique for ^{99}Mo production, target thermal design, extraction method of

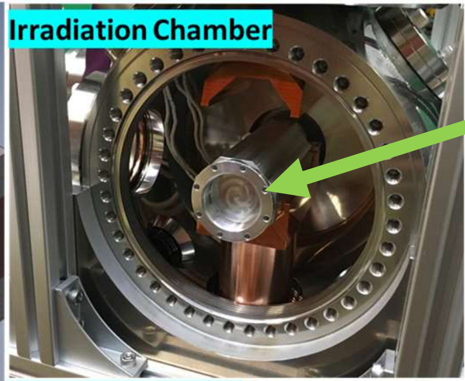
cERL – irradiation beam line

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

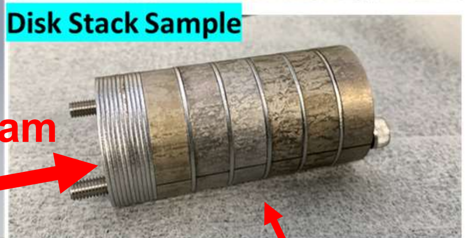


Available beam	
Beam repetition	Continuous Wave
Max energy (MeV)	21
Max current (μA)	10
Max power (W)	200
Energy spread (measured)	5×10^{-4}
beam size at Target (measured)	σ ~1.5 mm



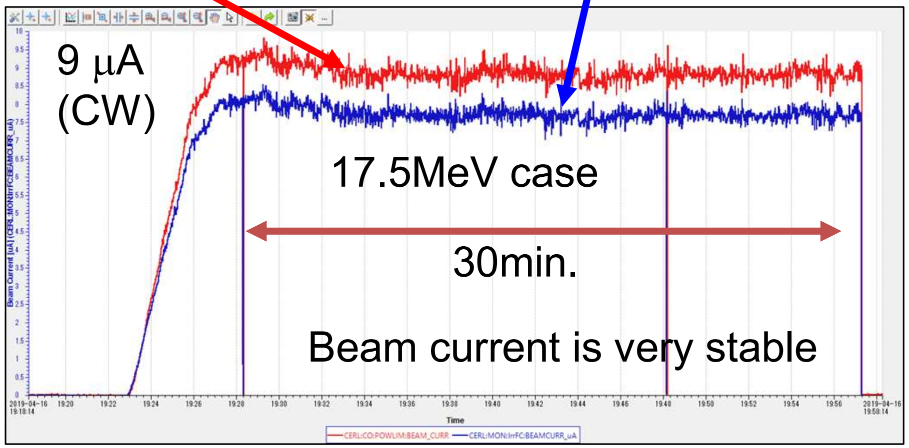


Aluminum capsule target holder



Typical trend of beam current (faraday cup set on the same position of target)

Gun current



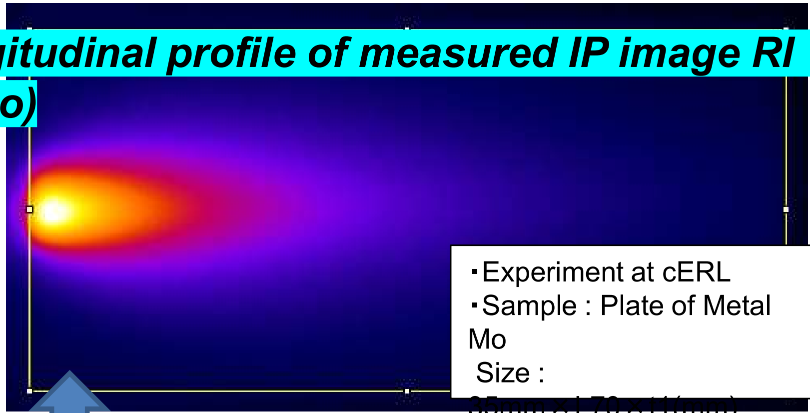
100Mo targets with 1mm disks and 9mm disks in target folder

Y. Morikawa, *et al.*, "New Industrial Application Beamline for the cERL in KEK", Proc. of IPAC2019, (Melbourne, Australia) p3475-3477, (2019)

Results of RI production of ^{99}Mo

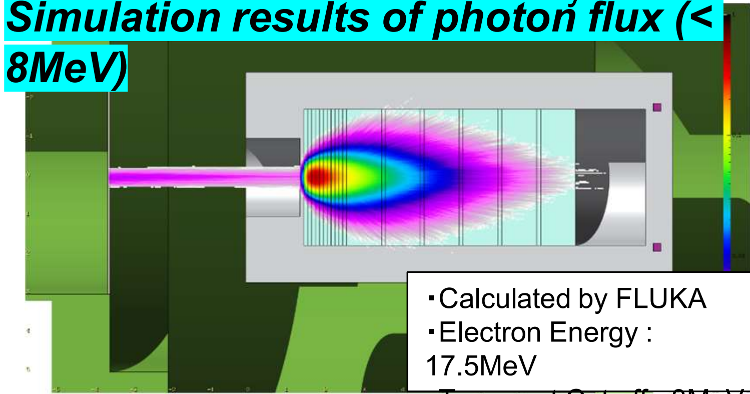
Courtesy of Y.Morikawa, N.Higashi, K.Harada, M. Yamamoto, H.Matsumura and A. Toyoda

Longitudinal profile of measured IP image RI (99Mo)



・Experiment at cERL
・Sample : Plate of Metal Mo
Size :
・Electron Energy :
17.5MeV

Simulation results of photon flux (< 8MeV)



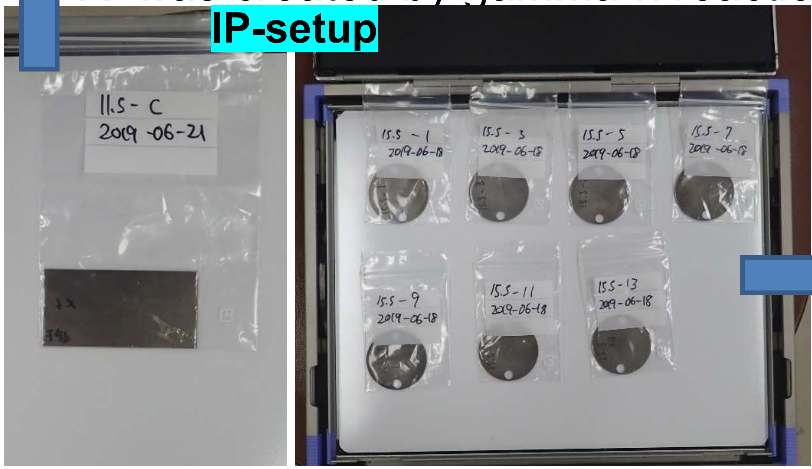
・Calculated by FLUKA
・Electron Energy : 17.5MeV
・Transport Cut off : 8MeV

Profile was almost consistent with simulation

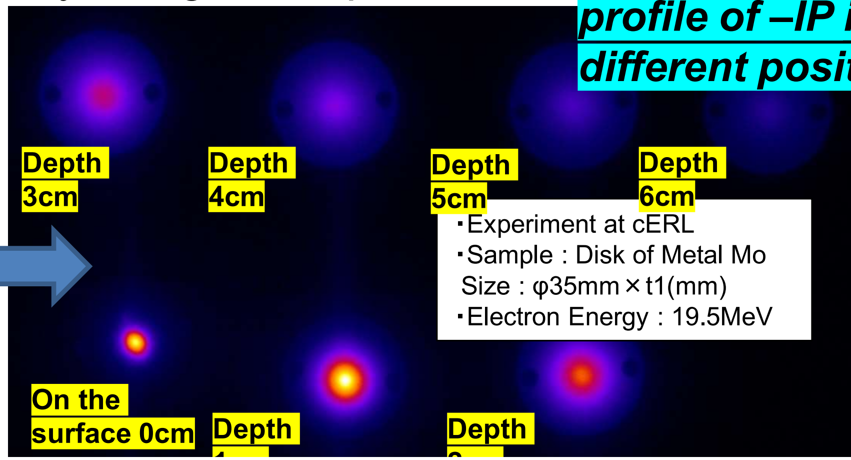
Photon was created by bremsstrahlung of target.
RI was created by gamma-n reaction by using these photons.

IP-setup

Irradiated targets in capsule under cERL beam



Meaasured transvers profile of –IP image of different positions



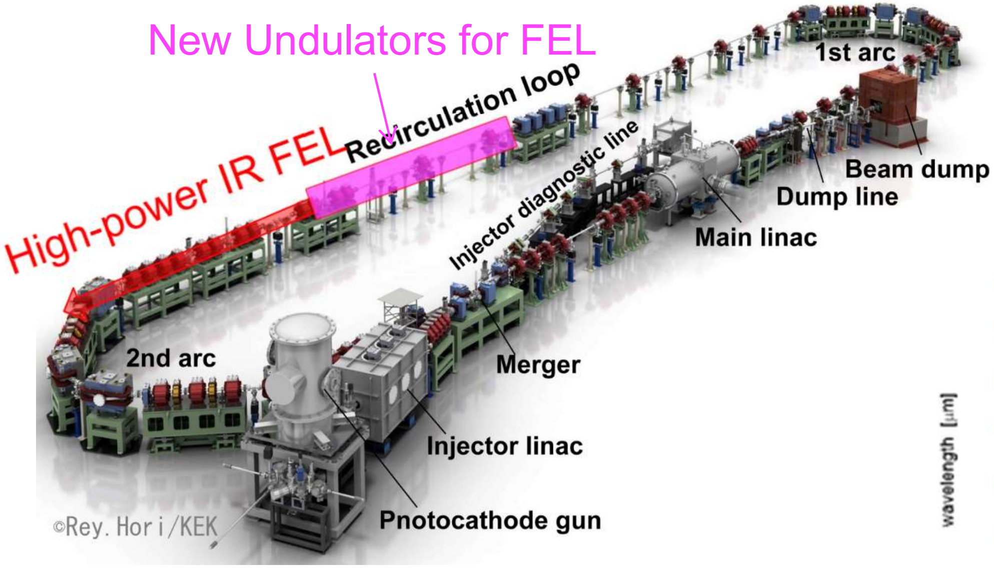
・Experiment at cERL
・Sample : Disk of Metal Mo
Size : φ35mm×t1(mm)
・Electron Energy : 19.5MeV

Clear beam profiles were obtained by using stable cERL beam.

By using stable cERL CW beam, we could clear RI image and this profile are almost consistent with our simulation.
First data was summarized in Press release (2019.Oct.18) : https://www.kek.jp/ja/newsroom/2019/10/18/1400/
and detailed analysis will be published in a peer review journal.

cERL FEL layout & operation

NEDO Project (Dec. 2018 – Mar. 2021) : “Development of high-power mid-infrared lasers for high-efficiency laser processing utilizing photo-absorption based on molecular vibrational transitions.”

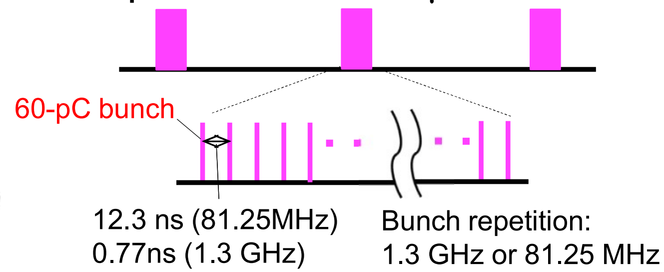


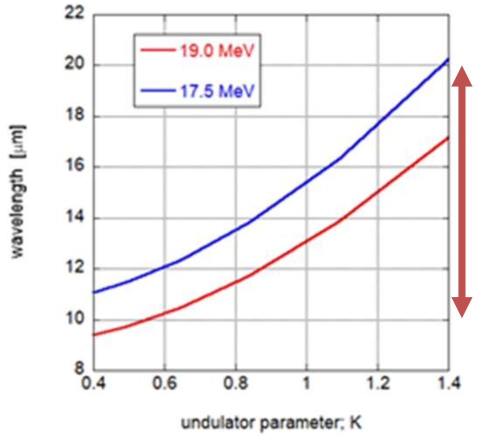
Beam Energy	17.5 - 19.0 MeV
Injector Energy	3.0 - 5.0 MeV
E-Gun Energy	500 keV (or 480 keV)
Bunch repetition	1.3 GHz (or 81.25 MHz)
Average current	1 mA (or 5 mA) in CW
Operation mode	CW or Burst

During FEL optimization, we operate Burst mode

Burst mode (FEL&e-beam tuning)

Macro pulse of 0.1 ~1 μs at 1 - 5 Hz





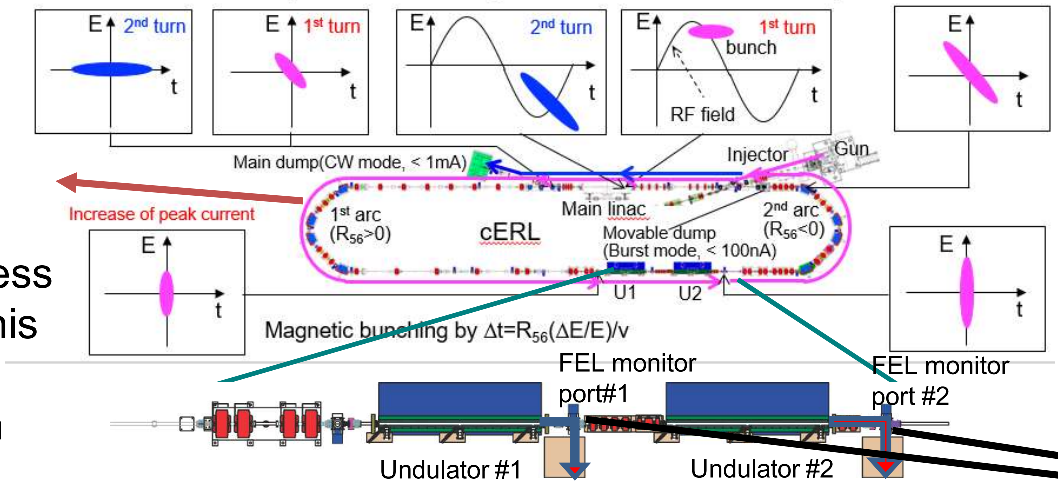
Requirement of the wavelength range of IR-FEL (10 ～20um)

Our target:
1W level IR-FEL
(81.25 MHz)
~12nJ/pulse

Setup of cERL-FEL

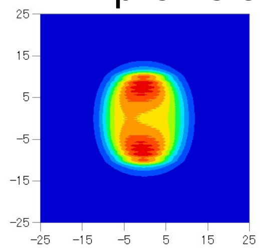
Operation was done by burst mode

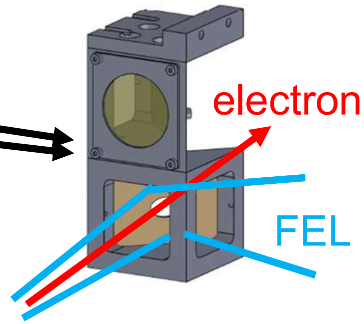
Bunch compression & decompression scheme for the FEL operation



Bunch length compressed in this arc section

FEL profile at mirror





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

Undulator parameter

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

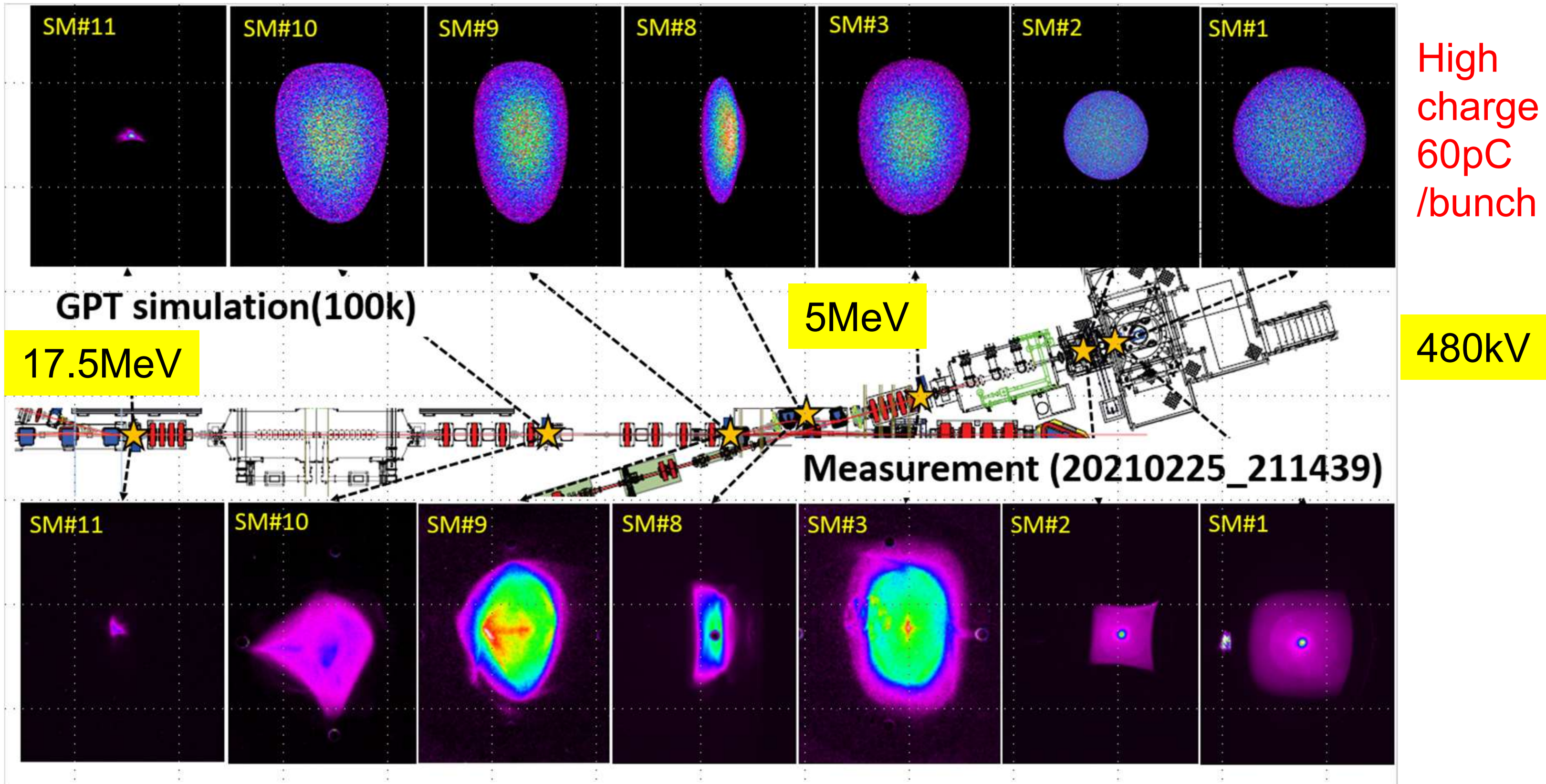
Two 3m undulators

Only FEL was reflected and electron went through the hole

Demonstration of PoC of the EUV-FEL First ERL-based SASE-FEL in the world(explained later)

Optics tuning of high charge operation (2021)

O.Tanaka **High charge operation is very difficult to keep small emittance to suppress space charge effect.**



Meausment results of emittances at the exit of main linac

Design (60pC/bunch):

1.74 π mm mrad (x) / 1.92 π mm mrad (y).

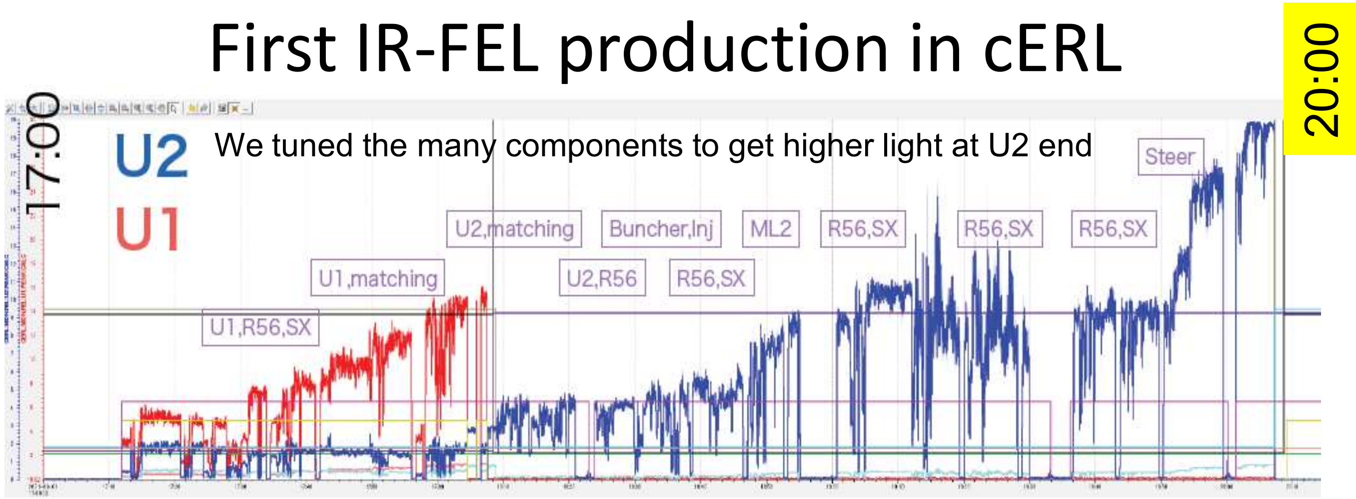
Measurement (60pC/bunch) :

2.87 ± 0.03 π mm mrad (x) /

1.57 ± 0.02 π mm mrad (y)

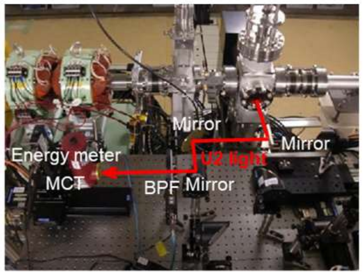
- Good agreement between simulation and measurement including space charge effect.
- We satiflied the requirements for FEL operation.

First IR-FEL production in cERL

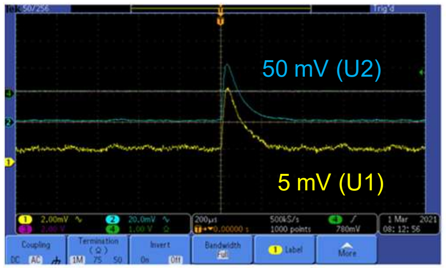


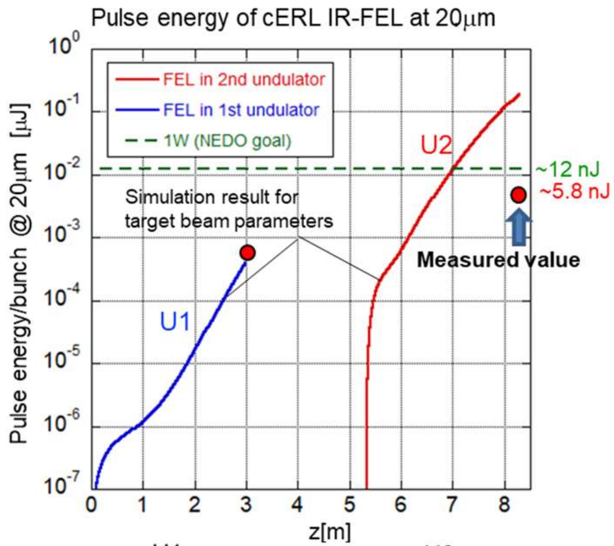
Commissioning of MIR FEL

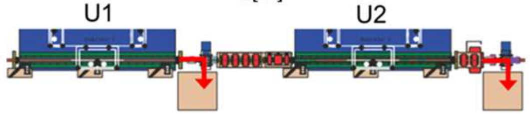
- By using FEL optimization by using AI under stable cERL beam condition, we successfully obtained 5~10 times higher light signal from U2 than that from U1.
- →FEL was produced. And the light intensity almost satisfied our requirements.
- Next target is CW ERL-SASE-FEL (for EUV-FEL)



FEL monitor port #2 for the U2 light







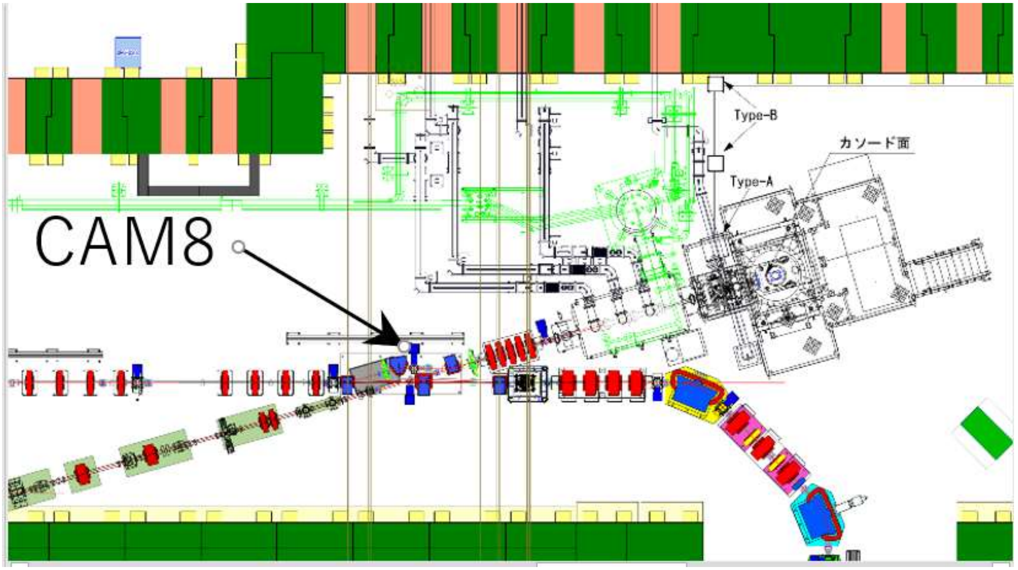
FEL monitor port #1 FEL monitor port #2

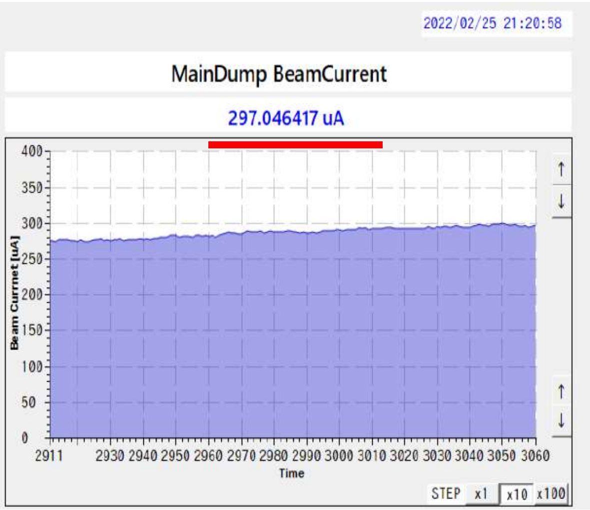
Y. Honda et al. *"Construction and Commissioning of Mid-Infrared SASE FEL at cERL"* https://doi.org/10.1063/5.0072511 is published in "Review of Scientific Instruments, (11) Vol.92

Latest operation status (2022.Feb-Mar.)

We operate CW beam with undulator for ERL-FEL.
Successfully operate with 0.3 mA beam in Feb. 2022.
There are few radiation outside concrete shield. → it is possible to increase more beam current.
Next target is ERL with CW beam with high charge (more than 60 pC) for ERL-FEL operation

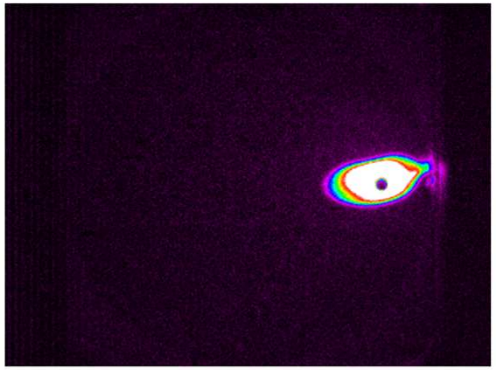
During operation, we met hardware trouble (broke screen monitor) beam was stopped by vacuum ITL.→ it is our discussion items in this workshop for reliable beam operation.





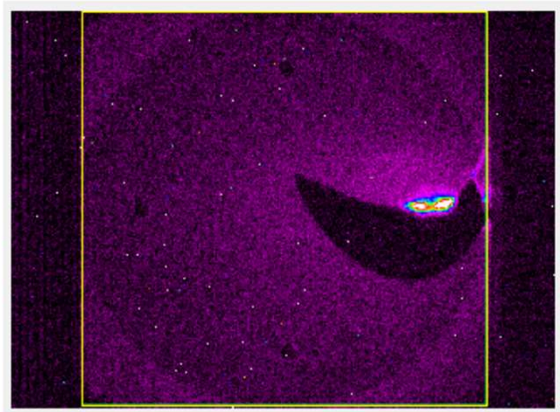
CW beam current in the main dump

Before break (CAM 8 beam profile)



20220228_202757_cam8.png

After break CAM 8

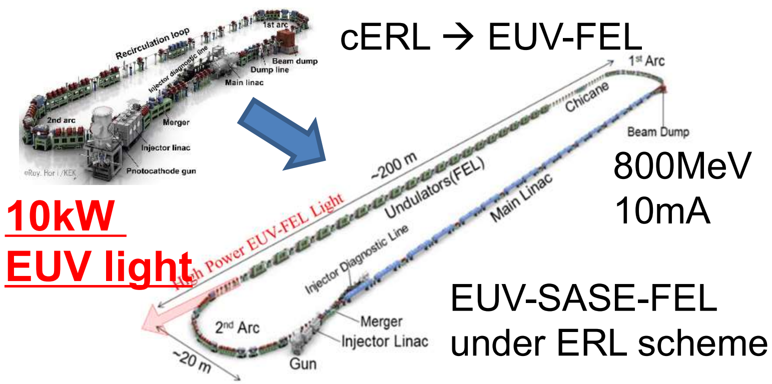


No beam profile observed.

Summary

- Show our status of cERL at KEK . High current beam operation of 1mA was achieved at cERL. → plan to increase 10 mA.
- We made efforts for keeping stable beam operation.
- cERL now move to use for the industrial application by using SCRF technology. ^{99}Mo beam line was built for RI production with CW beam of 10uA and successfully produce ^{99}Mo.
- In order to demonstrate ERL-SASE-FEL scheme, IR-FEL production started in cERL. High power IR-FEL with SASE scheme was produced by constructing 2 x 3 m undulators in cERL beam line based on the budget of NEDO project in Japan.
- It is important for reliable CW high current beam operation to make many ITL system
- → To be discussed in this workshop

Our SRF technology will promote high power irradiation beam production with high energy such as RI production. Furthermore, for 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.



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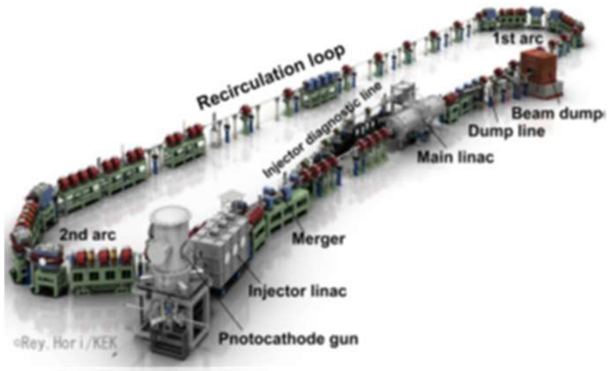
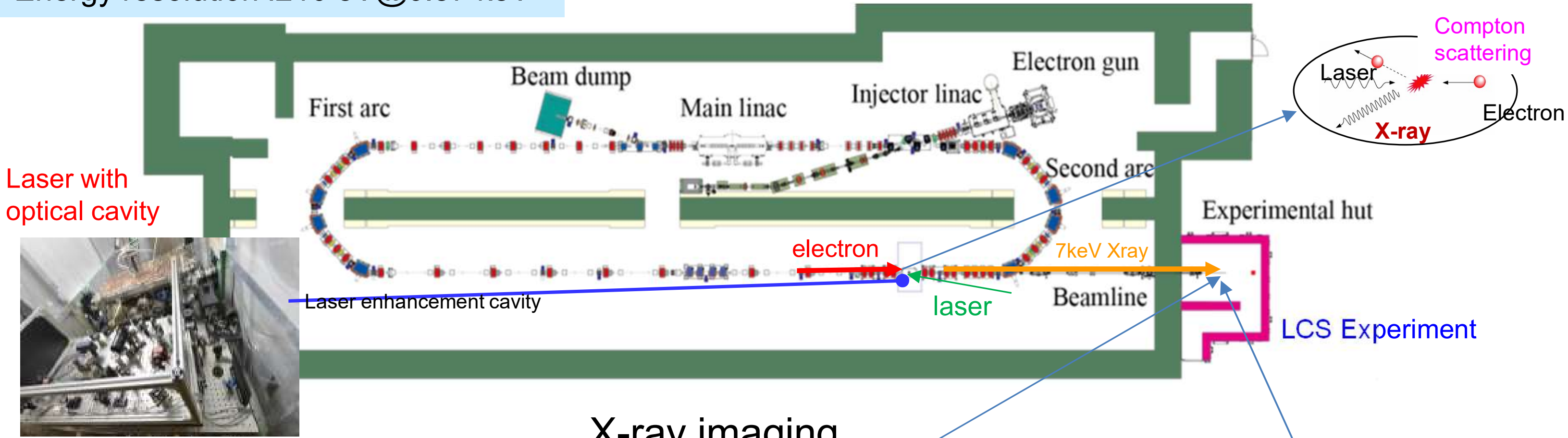


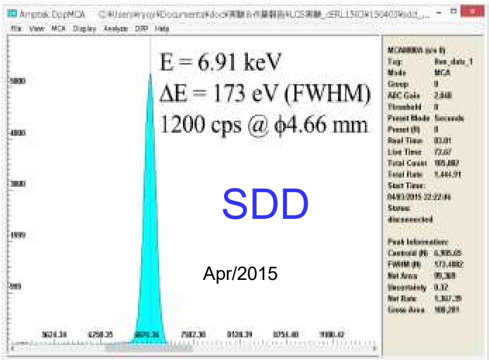
backup

Production of high intensity X-ray From Laser Compton Scattering (LCS)

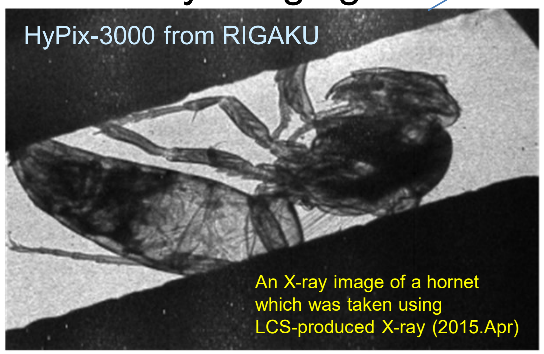
Parameters in Mar/2016:
Beam : 5.5 pC/bunch, 162.5 MHz CW
Laser : 1064 nm, 39.4 μJ/pulse
Energy resolution :210 eV@6.87 keV

In 2016, we tried to make more brighter X-ray LCS beam by using 0.9 mA with low emittance beam.





X-ray imaging



In Mar. 2016, intensity of the X-ray has been increased 6 times higher than the experiment in April 2015. Time duration for LCS is limited only for 2 days. Further improvement of laser system is anticipated.

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

Coherent Resonant Diffraction radiation THz (2018-2021)

Courtesy of Y.Honda

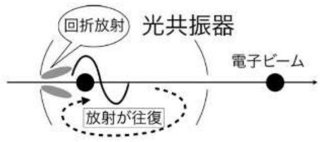
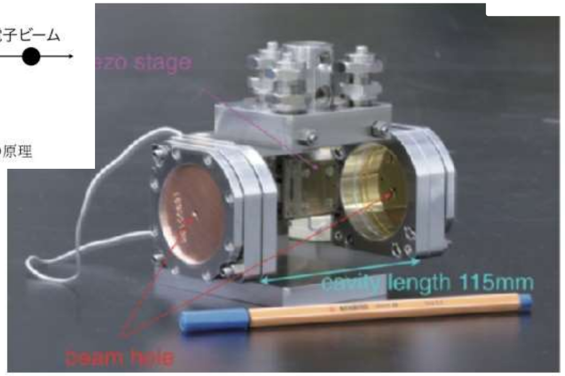
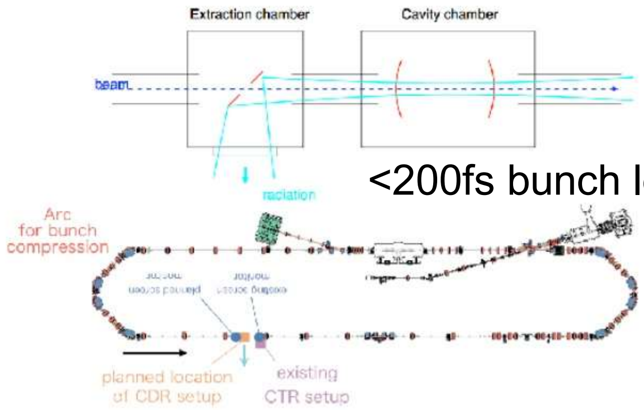


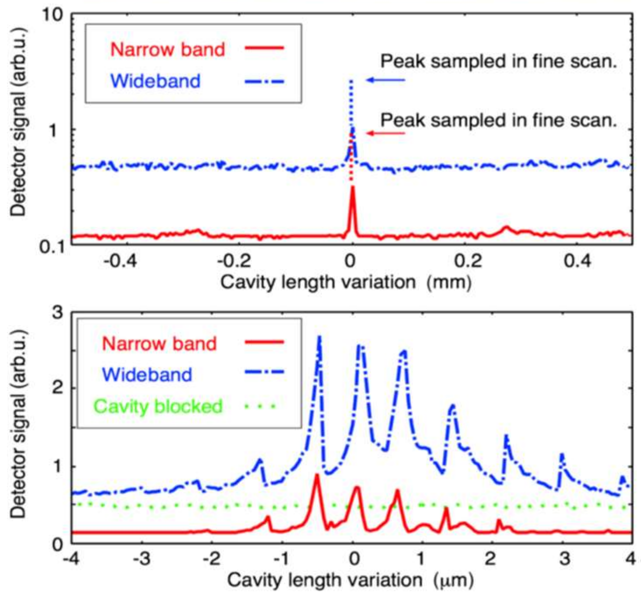
図 6: 共振器型回折放射の原理



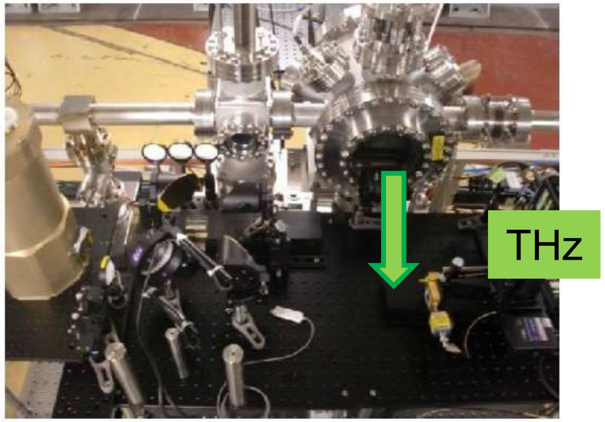


<200fs bunch length

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)