Present Status and Perspectives of Long Wavelength Free Electron Lasers at Kyoto University

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Outline

- Introduction
- Present Status of MIR-FEL
- Present Status of THz-FEL
- Perspective

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- **Introduction**
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Long Wavelength FEL at Kyoto Univ.

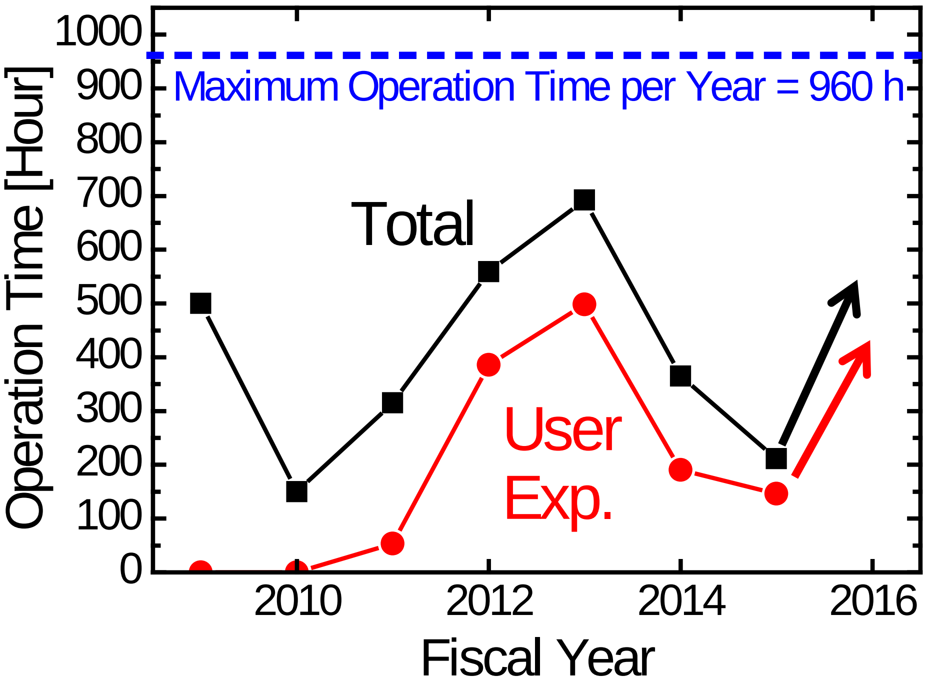
- **MIR-FEL (named as KU-FEL, 3.6 – 23 μm)**
  - FEL related research started in 1995.
  - First Lasing in 2008.
  - Opened for user experiments (2009 ~).
  - Routinely operated.
  - First Lasing with Photocathode operation (2014).

- **THz-FEL (under construction)**
  - Project started in 2008.
  - Sharing an RF source with MIR-FEL.
  - First e-Beam in 2015.
  - CTR observation in 2016.
  - First light from an undulator will be in this summer.

Facility Layout

Operation Time and User Proposals

Operation Time of MIR-FEL



Since 2014, high voltage capacitors in PFN start to break due to aging. Therefore, the total operation time can not be long in 2014 & 2015.

We got used capacitors from other institutes and purchased new capacitors.
➔ Now the trouble was solved.

User Proposals in this year

- NIR/**MIR**-Pump, **MIR**-Probe experiment of polymer film. (1 internal user)
- **MIR**-Pump, Visible-Probe experiment of solid samples. (1 internal and 2 external user)
- Investigation of **MIR** sensitivity of crayfish eyes. (1 external user)
- System development for Photoacoustic spectroscopy using **MIR-FEL**. (1 internal user)
- Investigation of scintillation properties of various crystals by high energy **single electron irradiation**. (1 external user)

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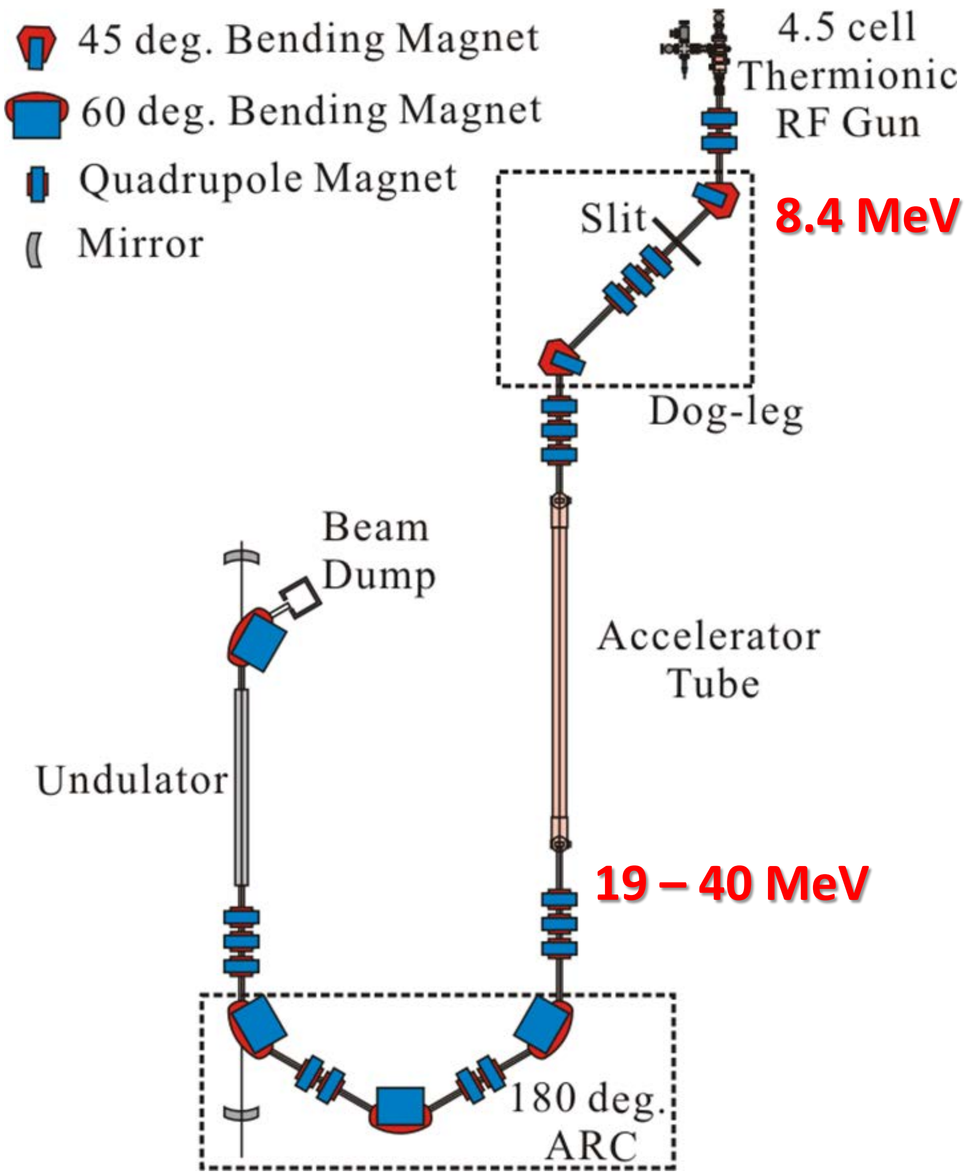
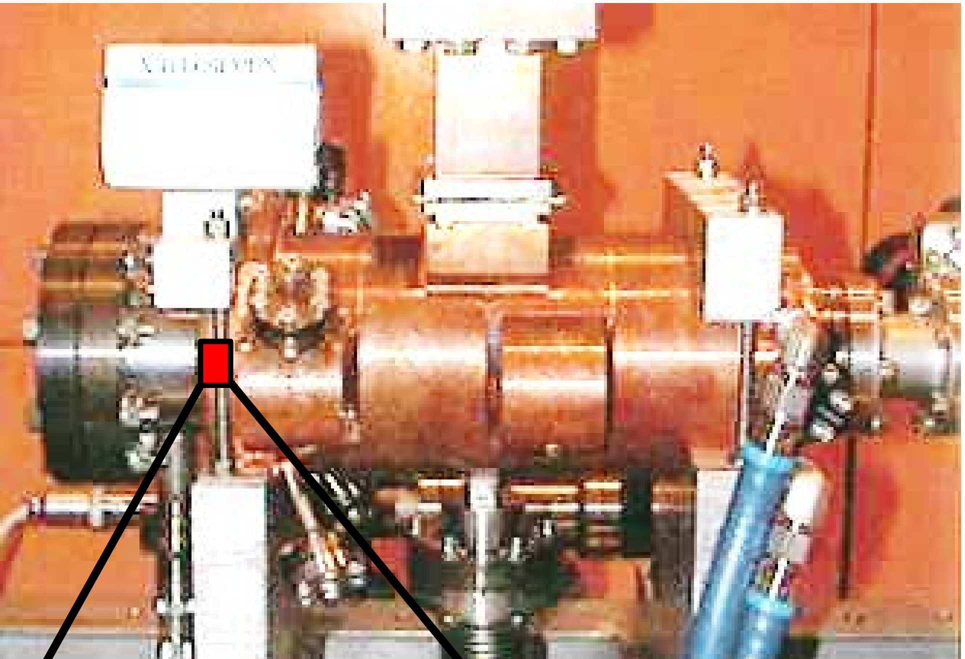
MIR-FEL in Kyoto Univ. – KU-FEL –



Unique point :

- **4.5-cell thermionic RF Gun**
  ➔ 8.4 MeV e-Beam
- **Alpha-magnet is unavailable.**
  ➔ Dog-leg for energy filter
- **Seriously strong back-bombardment effect!**
  ➔ 10-year continuous fight!
  ➔ Countermeasures developed.
- **Photocathode operation is also available.**
  ➔ **Higher peak power than thermionic operation**

Thermionic RF Gun



Main Parameters

Resonant Frequency	**~ 2856 MHz**
Coupling β	**2.8**
Q value	**12500**
Structure	**4.5-cell side couple**
Accelerating Mode	**π mode**
Cathode Material	**LaB_6 (100)**
Cathode Radius	**1 mm**
E-field on cathode	**~ 27 MV/m**

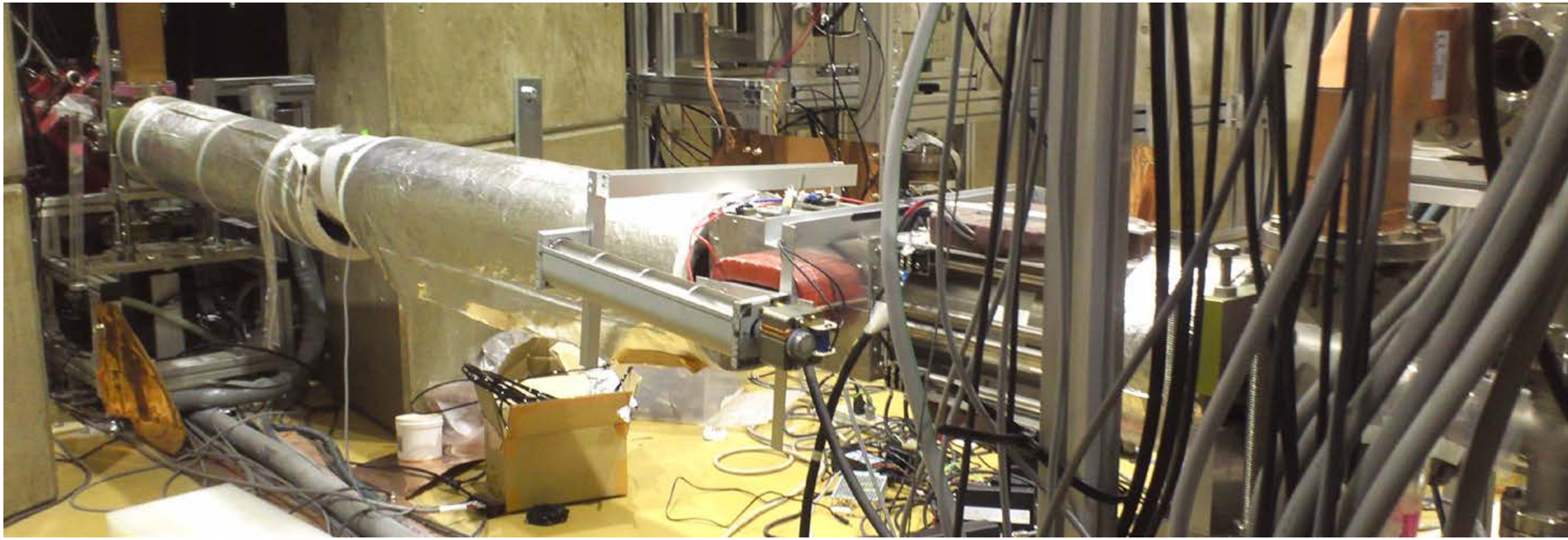
- Very compact; just 30 cm for 8.4 MeV beam.
- Cost effective
- Relatively low emittance (ε_n< 10 πmm-mrad)

- Serious Back-bombardment Effect

  → Countermeasures have been developed.

OK!

Accelerator Tube



Main Parameters

Resonant Frequency	2856 MHz
Structure	Constant Gradient Traveling Wave
Accelerating Mode	2/3 π mode
Effective Length	2.9 m

Undulator

Main Parameters

Period Length	33 mm
Number of Periods	53
Total Length	1.8 m
Maximum K-value	1.35
Structure	Planer Hybrid

- This undulator had been used for ERL-FEL in JAEA until 2009.
- Transported from JAEA to KU in 2010.
- Installed to KU-FEL in 2012.

Optical Resonator

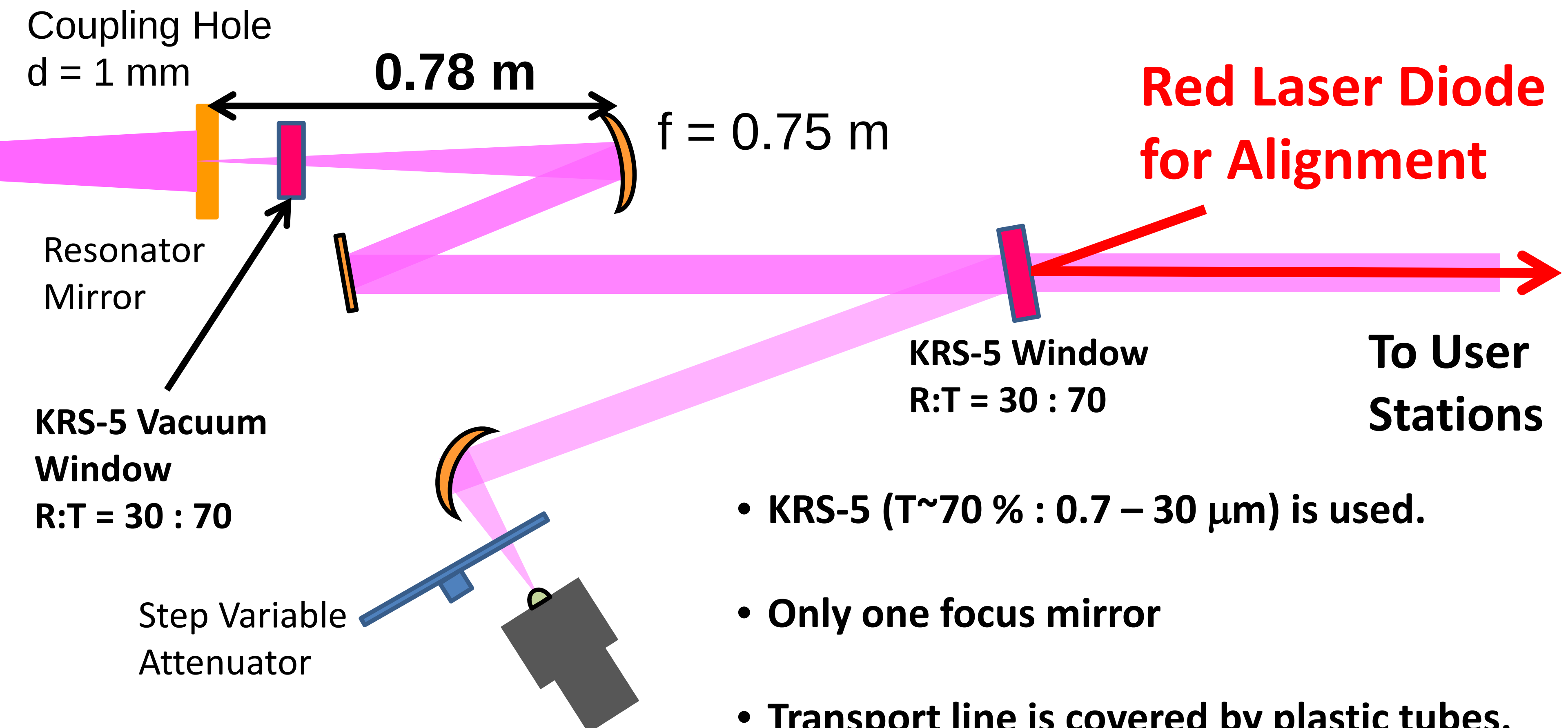
Upstream Mirror Chamber

Main Parameters

Mirror Curvature	Up: 2.946 m Down: 2.456 m
Cavity Length	5.038 m
Out-coupling way	Hole couple
Hole Diameter on Upstream Mirror	1 mm
Mirror Substrate	Copper
Mirror Coating	Gold

There is no in-vacuum mirror changer which is commonly used in rich FEL facilities.

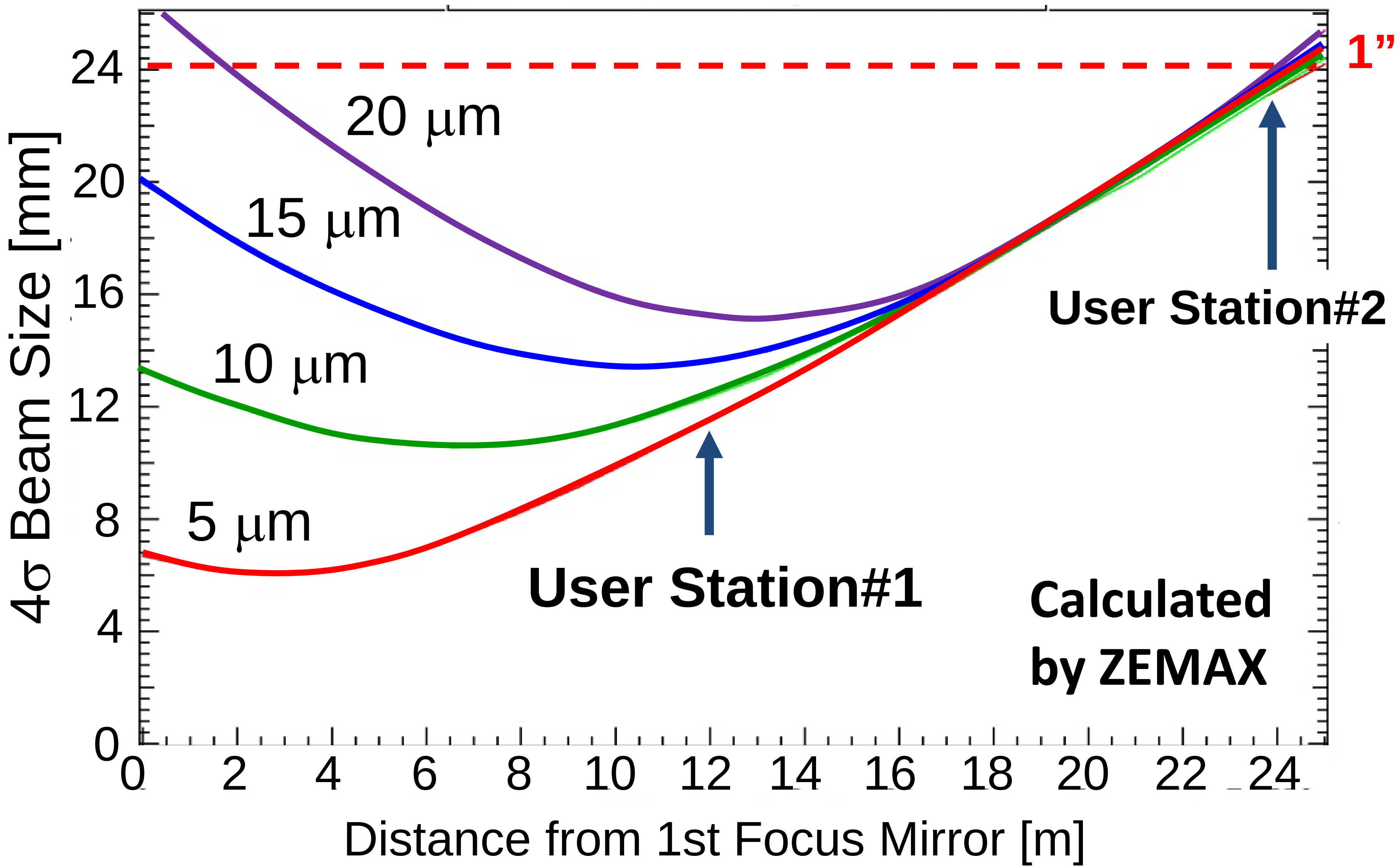
MIR Beam Transport Line



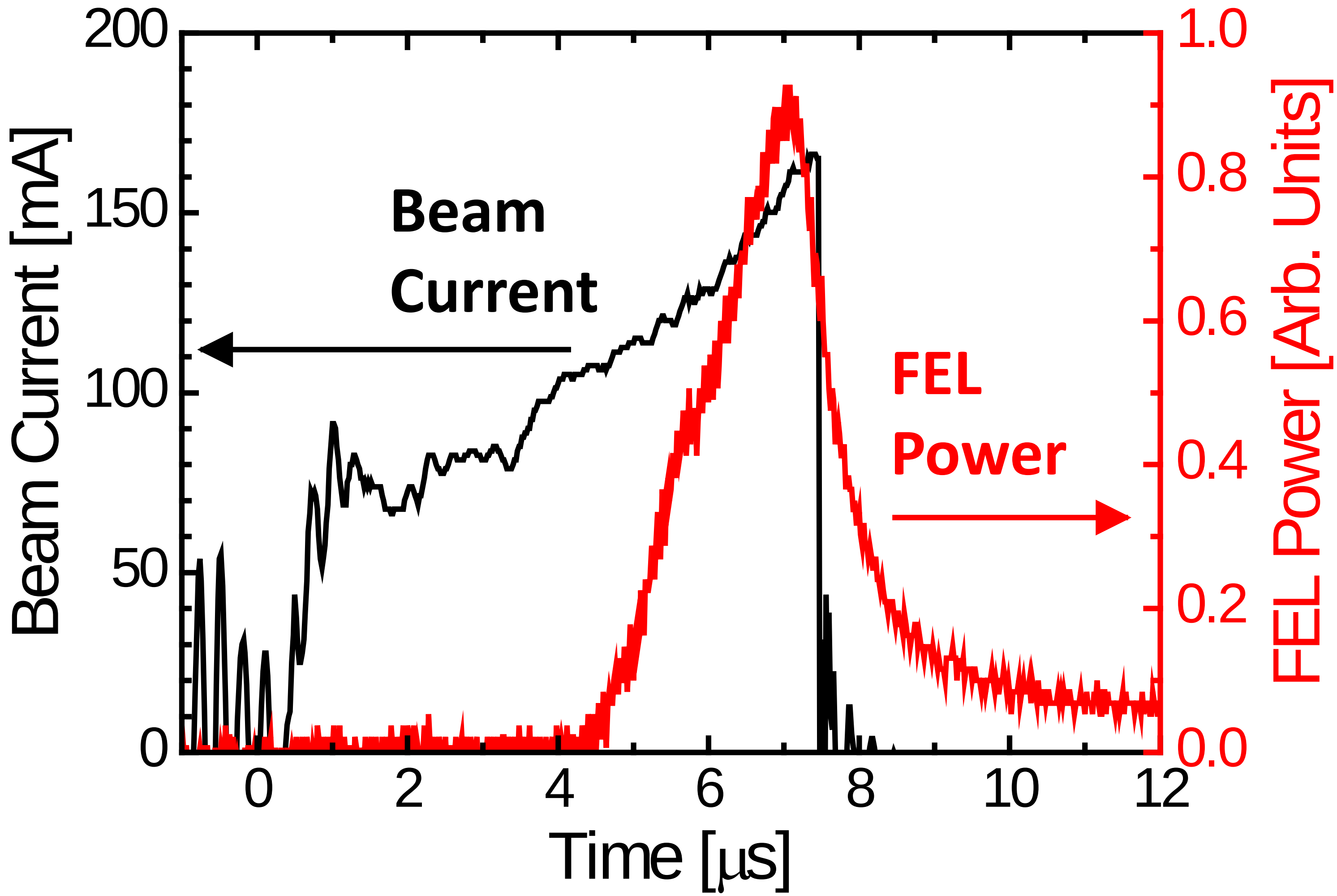
Power Evolution Monitor
Fast TE-cooled MCZT Detector
MCZT : HgCdZnTe

- **KRS-5 (T~70 % : 0.7 – 30 μm) is used.**
- **Only one focus mirror**
- **Transport line is covered by plastic tubes.**
  N_2 Gas filling ➔ Remove H_2O and CO_2.
- **Fast detector (< 1 ns) to monitor the FEL Power Evolution.**

Beam Size in Beam Transport Line



e-Beam Current Profile and FEL Power Evolution



- Beam current ramping due to the back-bombardment effect.
- Beam energy was kept constant ➔ FEL can be lased.

Time Structure of KU-FEL Pulse

Macro-pulse

Repetition rate : 1 or 2 Hz

Duration : ~ 2 μs-FWHM

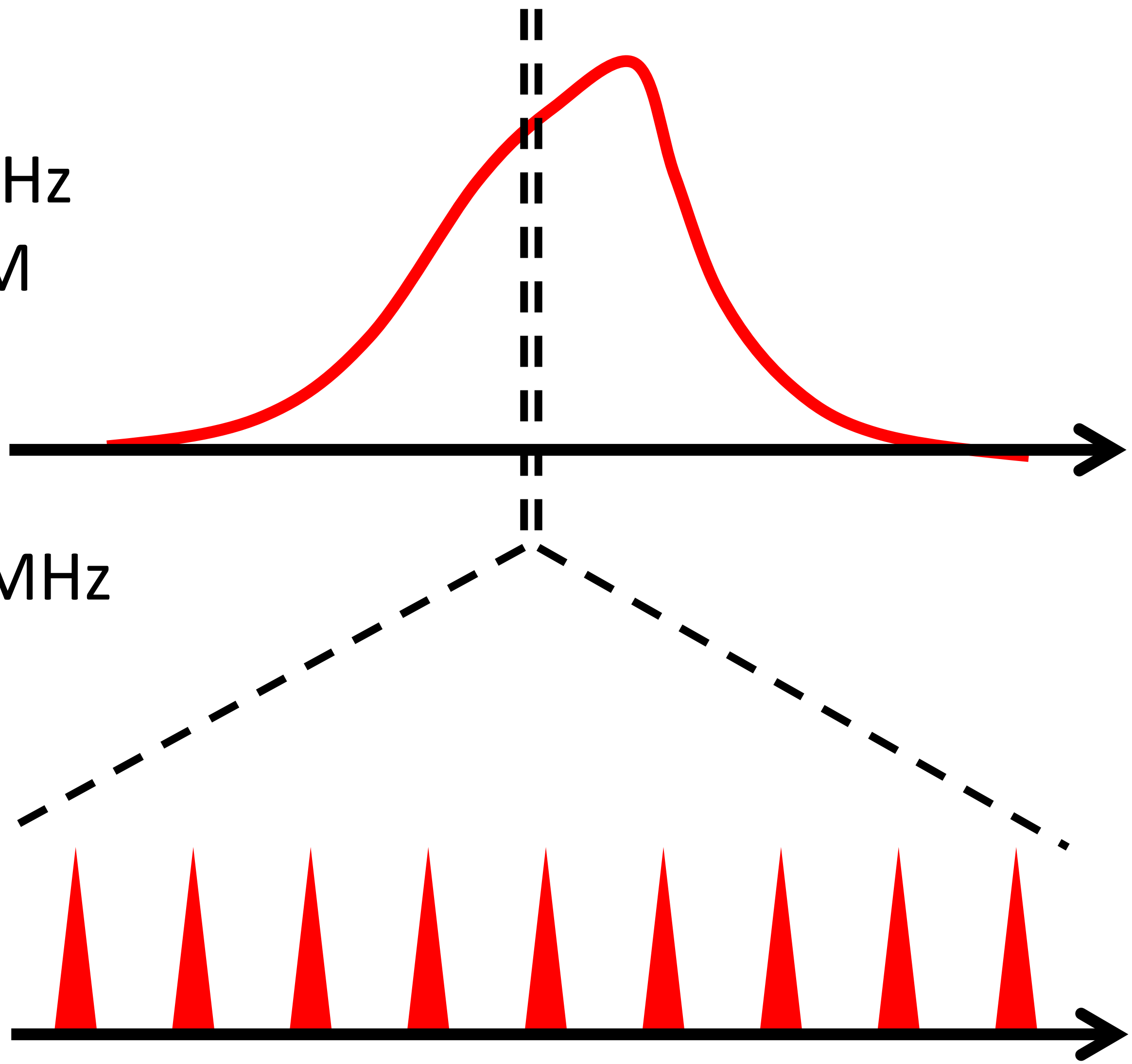
Micro-pulse

Repetition rate : 2856 MHz

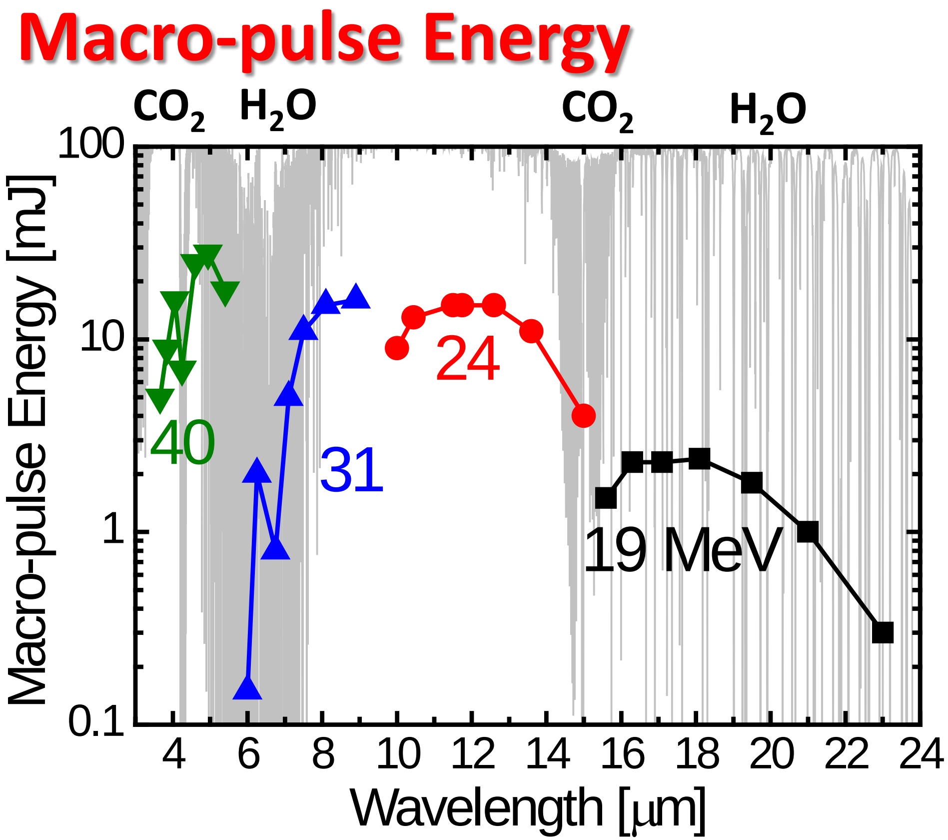
➔Interval : ~350 ps

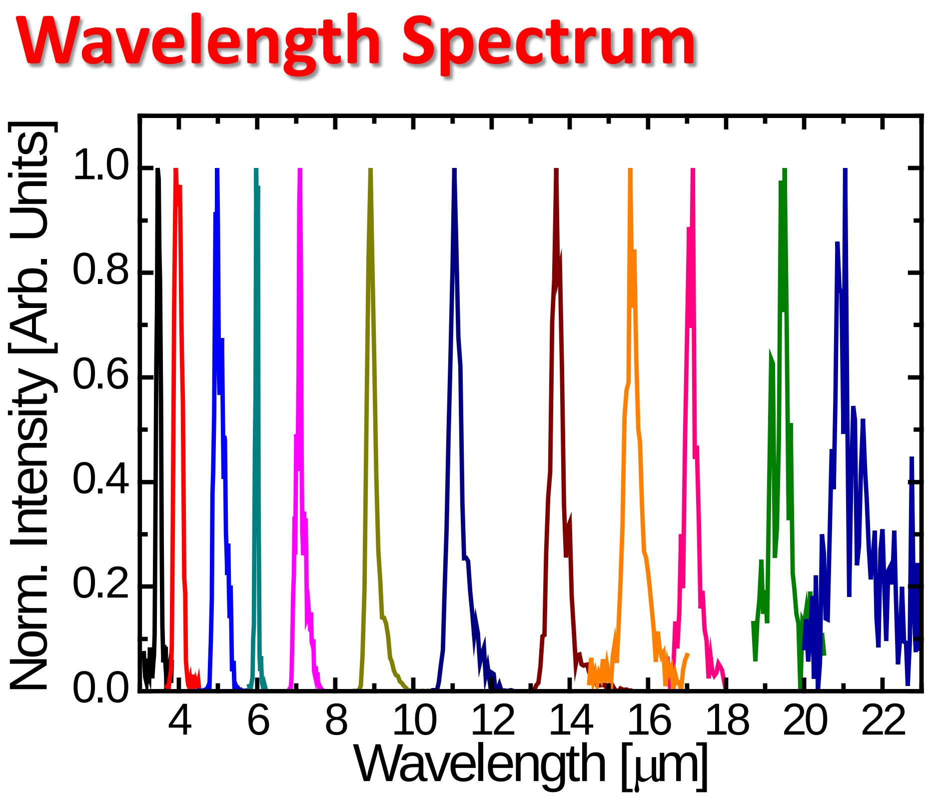
Minimum Length :

< 1 ps-FWHM



KU-FEL Performance with Thermionic Cathode





- Measurement was done @user station #1 w/o N_2 filling.
- Tunable Range was from 3.6 – 23 μm.
- Maximum Macro-pulse energy was 30 mJ/pulse @5 μm.
- Typical FEL bandwidth ~3% @Max. power optical cavity length.

Photocathode Operation of KU-FEL

LaB_6 thermionic cathode can also be used as a photocathode and Mark-III FEL succeeded in Lasing with LaB_6 photocathode.

Reference : M. Curtin, et al., NIM A296 (1990) 127-133.

The photocathode operation of LaB_6 cathode was one of a possible upgrade of KU-FEL.

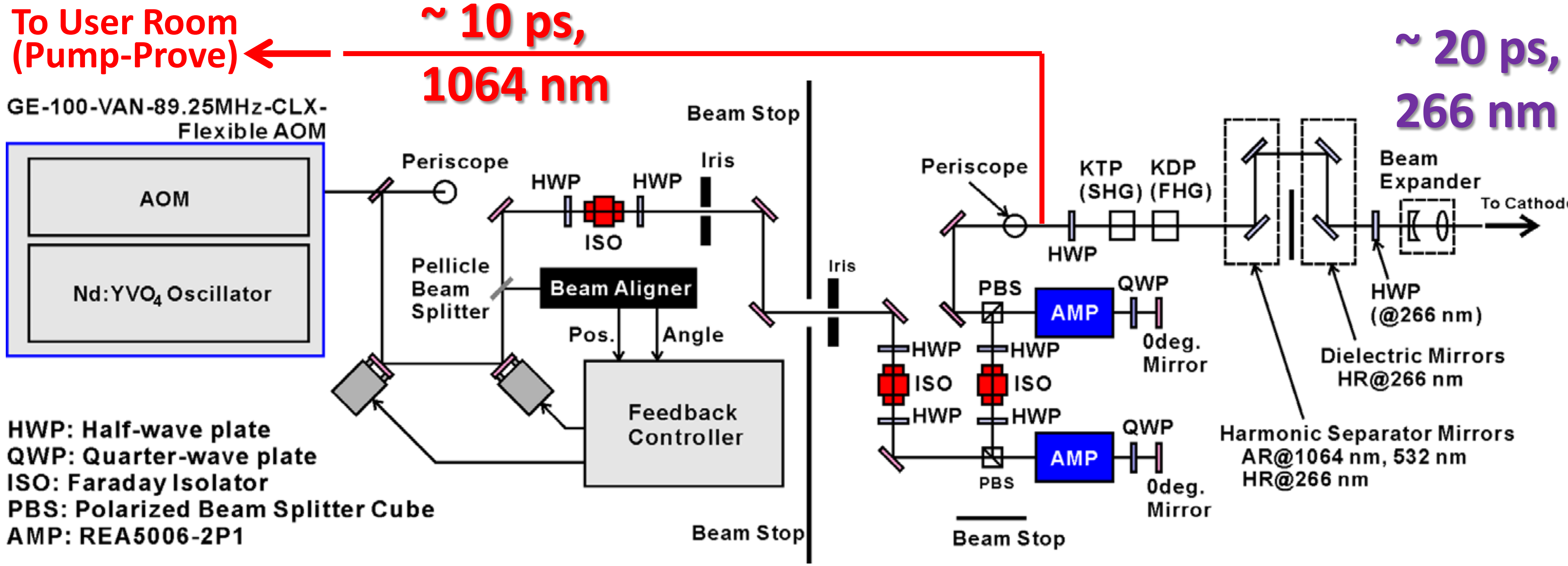
Get free from back-bombardment effect.
Electron bunch charge can be higher.

Need expensive mode-locked laser
➔ **We got budget!!**

OK!

A picosecond multi-bunch UV laser was developed.

Pico-second Multi-bunch UV Laser

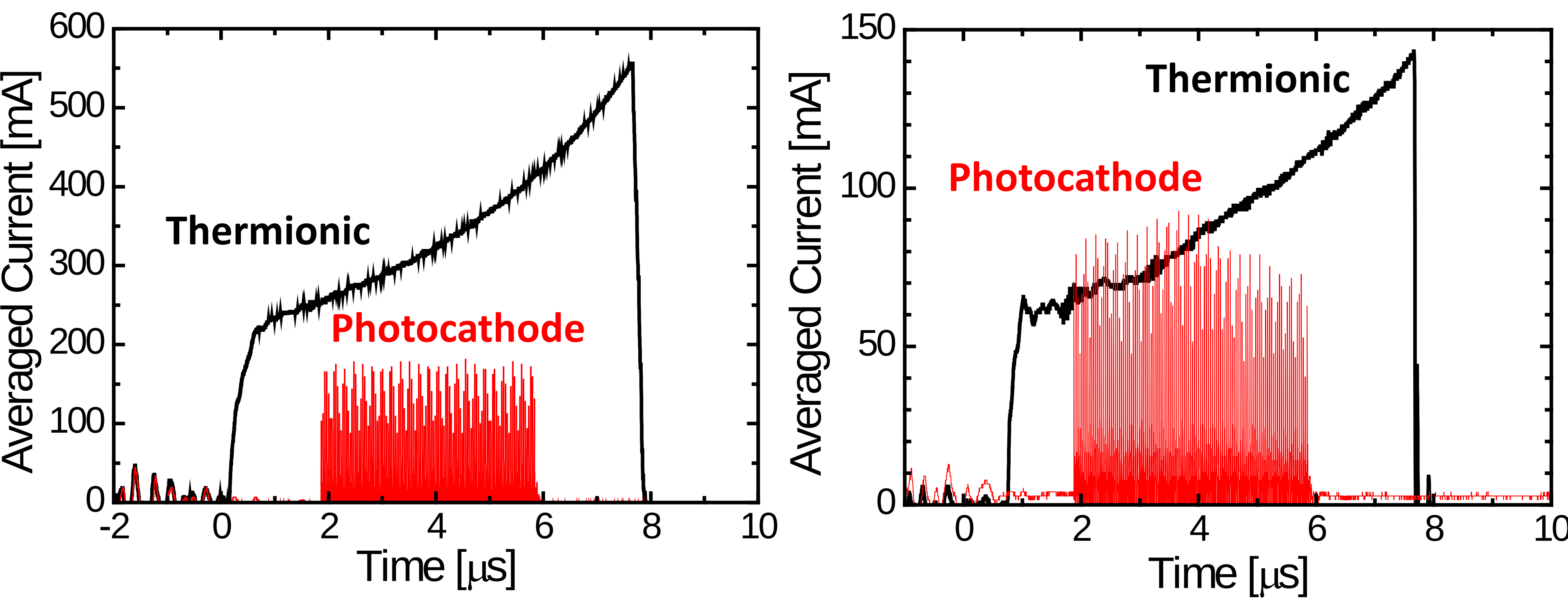


Result of Demonstration Experiment

Cathode Temperature

Thermionic : 1900 K　　Photocathode : 1400 K

Beam Current Profile @Gun Exit　　**Beam Current Profile @Undulator**



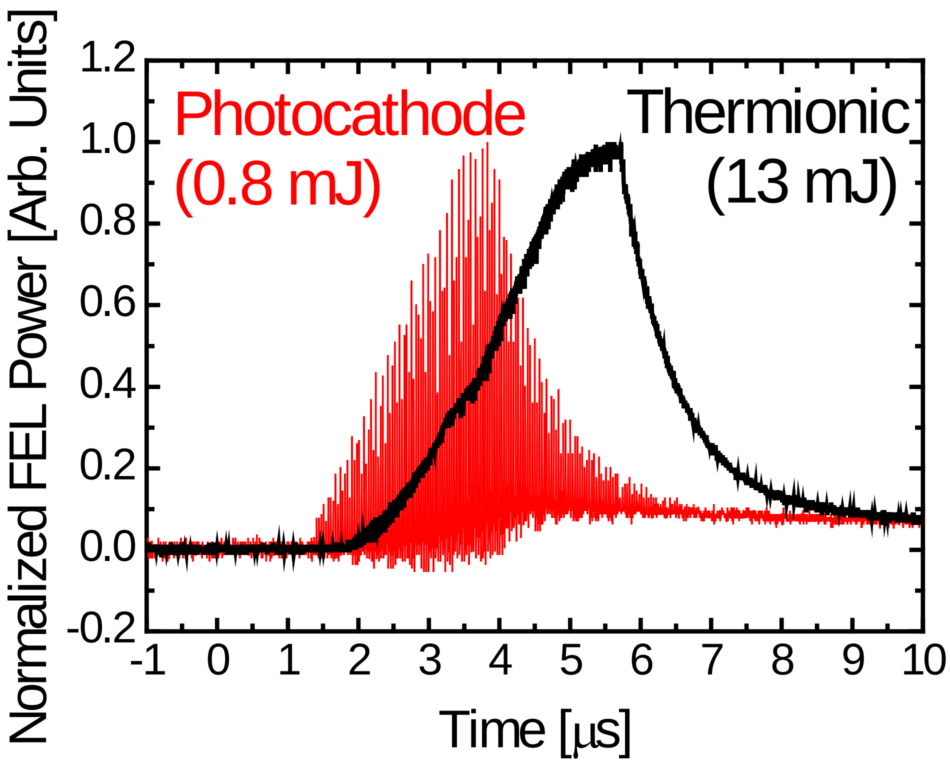
No back-bombardment effect in photocathode operation.

e-bunch repetition rate : 2856 MHz (Thermionic) ➔ 29.75 MHz (Photocathode)

Bunch charge @Undulator : 40 (Thermionic) ➔ 150 pC (Photocathode)

Macro-pulse duration @Undulator : 7 (Thermionic) ➔ 4 μs (Photocathode)

Result of Demonstration Experiment



e-Beam Energy : 23.8 MeV
Undulator Gap : 19.5 mm
FEL Wavelength : ~11.7 μm

- 6.5 times higher micro-pulse energy
- 1/16 macro-pulse energy

Good for nonlinear experiments!!

	Thermionic	Photocathode	Ratio (Ph / Th)
Repetition Rate	2856 MHz	29.75 MHz	1 / 96
FEL Macro-pulse Duration	~ 2 μs	2 μs	~1
Max. Macro-pulse Energy	13 mJ	0.8 mJ	1 / 16
Max. Micro-pulse Energy	~2 μJ	13 μJ	6.5
FOM (Micro E / Macro E)	1.5E-4	1.6E-2	~ 100

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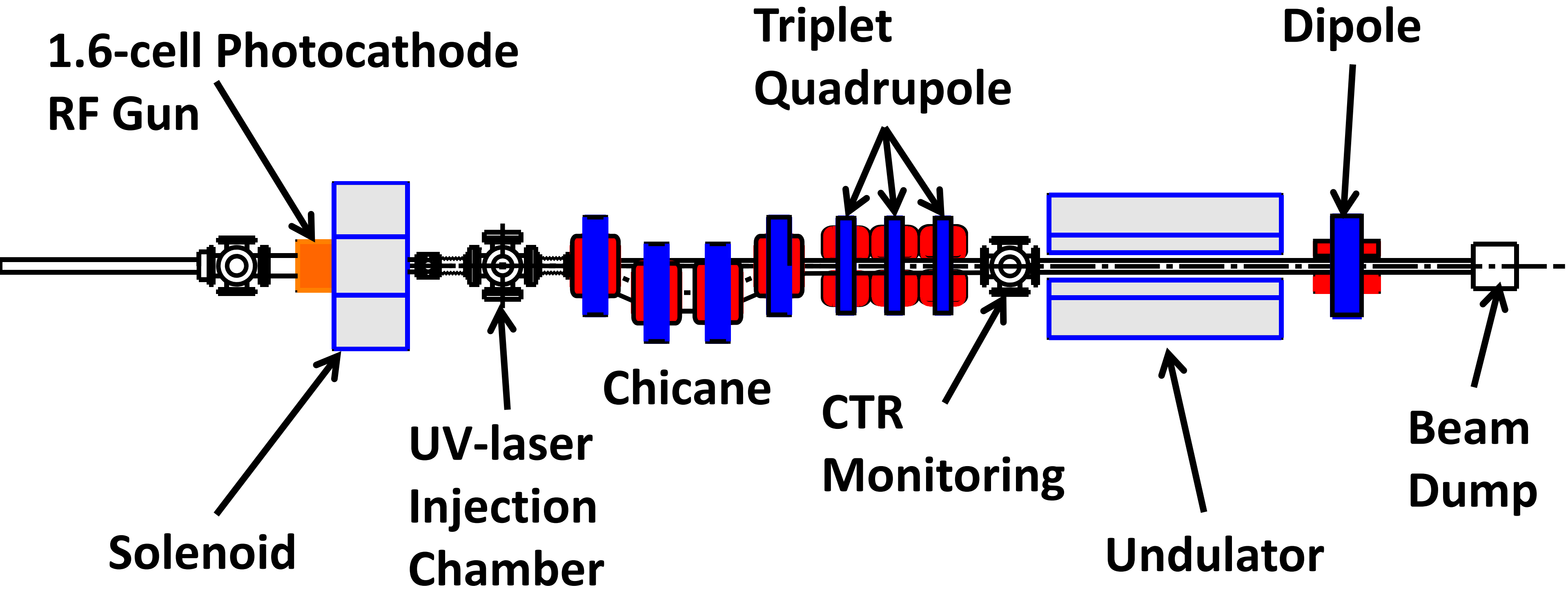
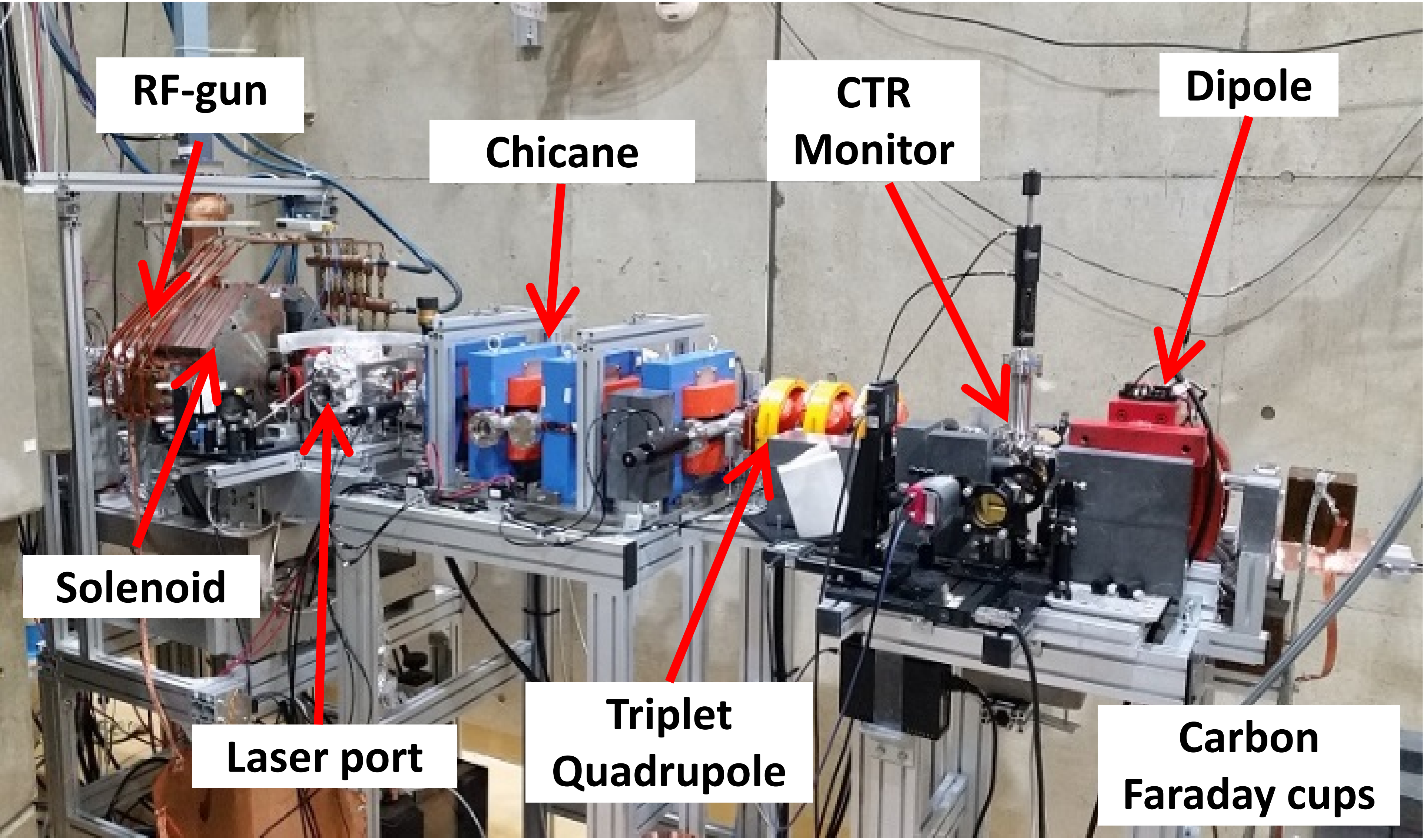
Schematic Layout



- One of the smallest configuration of THz-FEL.
- Short e-bunch is generated by RF gun and chicane bunch compressor.
- Compressed e-bunch is injected to undulator and generate THz radiation.
- Phase 1 : Measure e-beam properties. **Finished!**
- Phase 2 : Measure coherent undulator radiation. **Under Preparation**
- Phase 3 target will be determined based on phase-2 results.

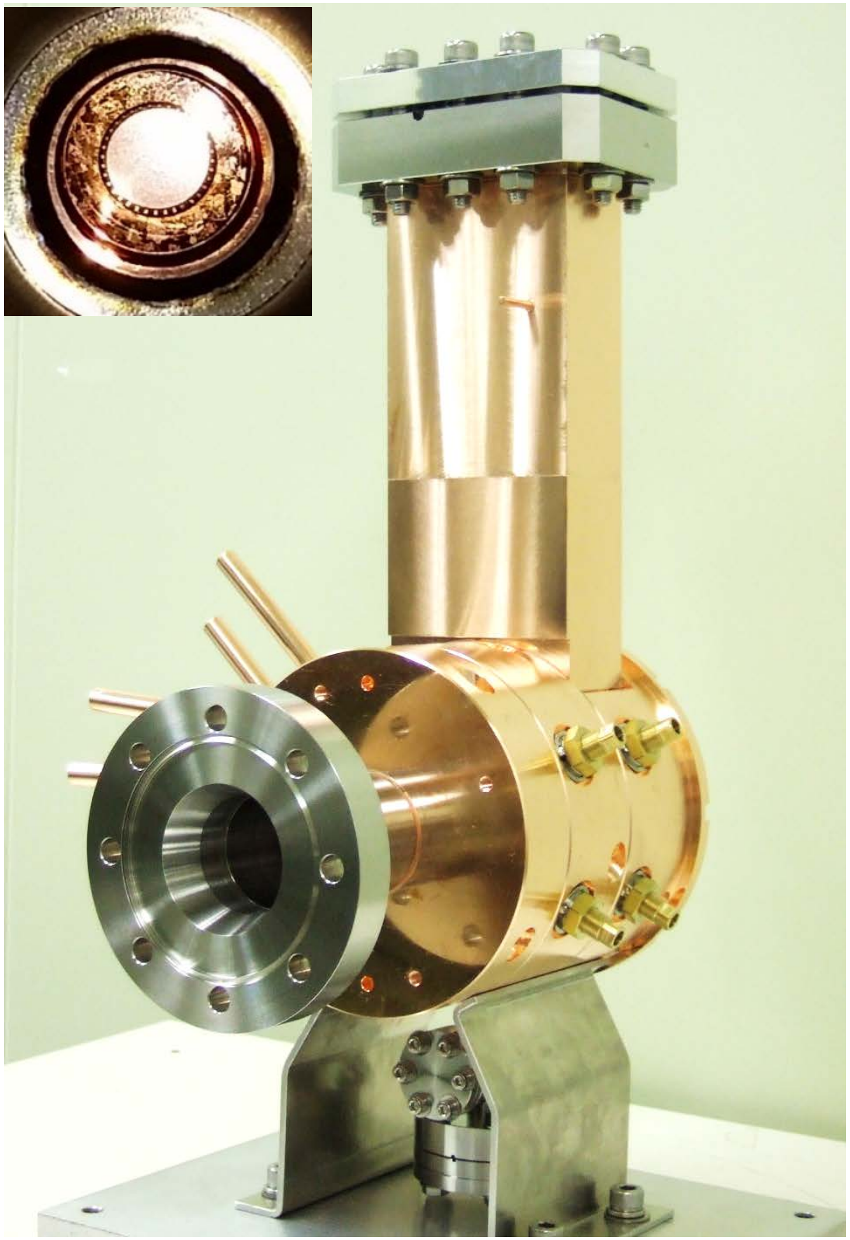
Present Condition



Undulator has not been installed yet.

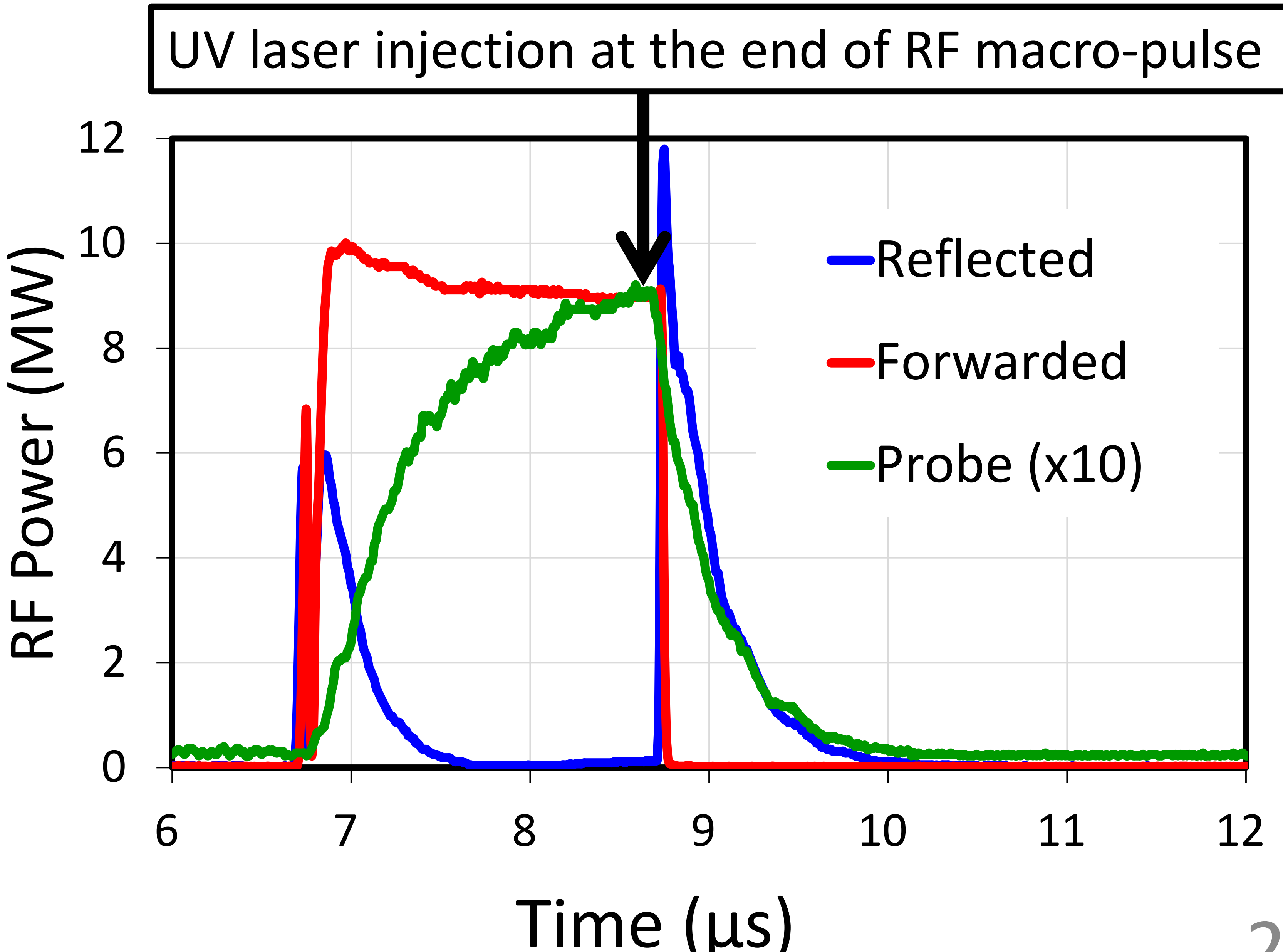
1.6-cell RF Gun

Cu Cathode



- No laser injection port
  - ➔Injection at 0-degree
- Demountable cathode
  - ➔Cu photocathode in use
- Push-pull tuner
- π-mode at 2856 MHz
- Q : ~12000, β : ~ 1.1
- Power probe in pumping port
- ps multi-bunch UV laser for photocathode excitation

Typical RF Waveforms

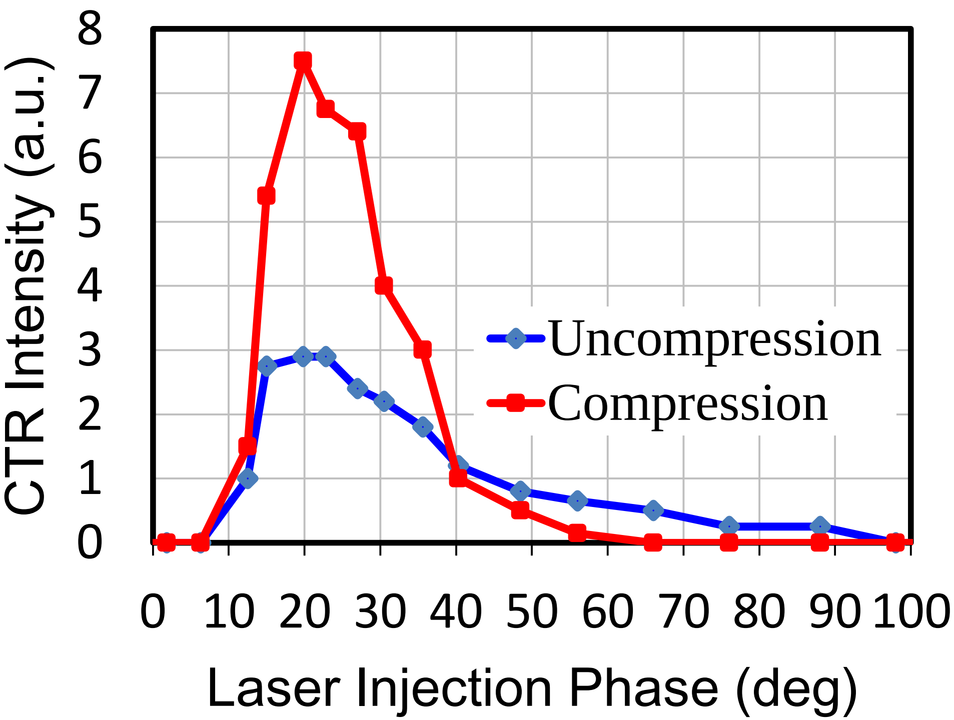


Summary of Phase 1 Experiments

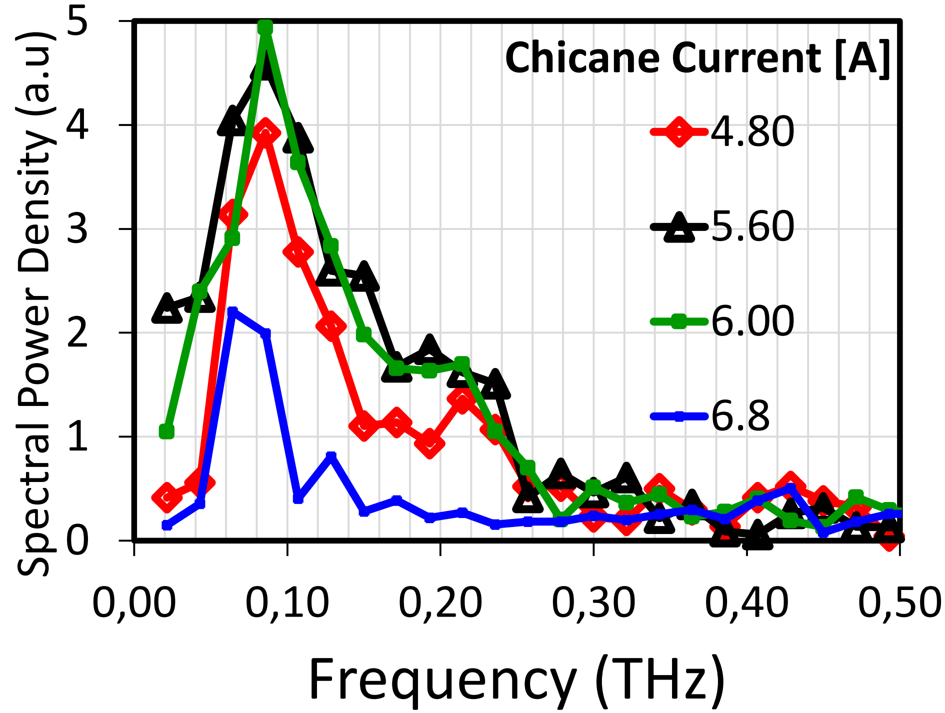
- Max. Beam Energy : 4.6 MeV
- Bunch Charge : up to 1.4 nC
- Normalized Emittance : < 10 πmm-mrad @50 pC
- CTR dependence on operation condition checked
- Observed CTR frequency up to 0.25 THz

Representative Results

CTR Intensity dependence on laser injection timing



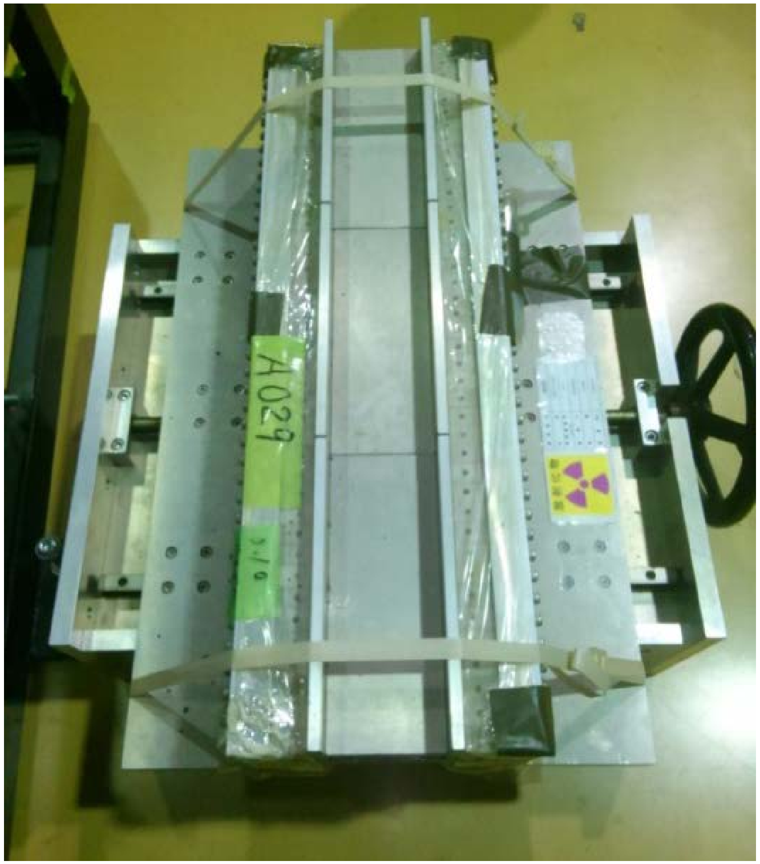
CTR Spectrum dependence on Chicane Excitation Current



- Measurement was done with 4 bunch condition to increase S/N ratio.
- A Michelson Interferometer was used for spectrum measurement.
- High sensitivity pyroelectric detector was used for this experiment.

Expectation of Phase 2 Experiment

Undulator



Number of periods : 10
Period length : 7 cm
Max. K-value : 2.7 @Gap 30 mm

Beam Energy : 4.6 MeV ➔ $\gamma = 10$

$$\boxed{\lambda_0 = (\lambda_u/2\gamma^2)\,(1+K^2/2)}$$

Longest Wavelength = 1.6 mm
Lowest Frequency = **184 GHz**

Coherent undulator radiation at **200 GHz** will be measured in Phase 2 experiment.

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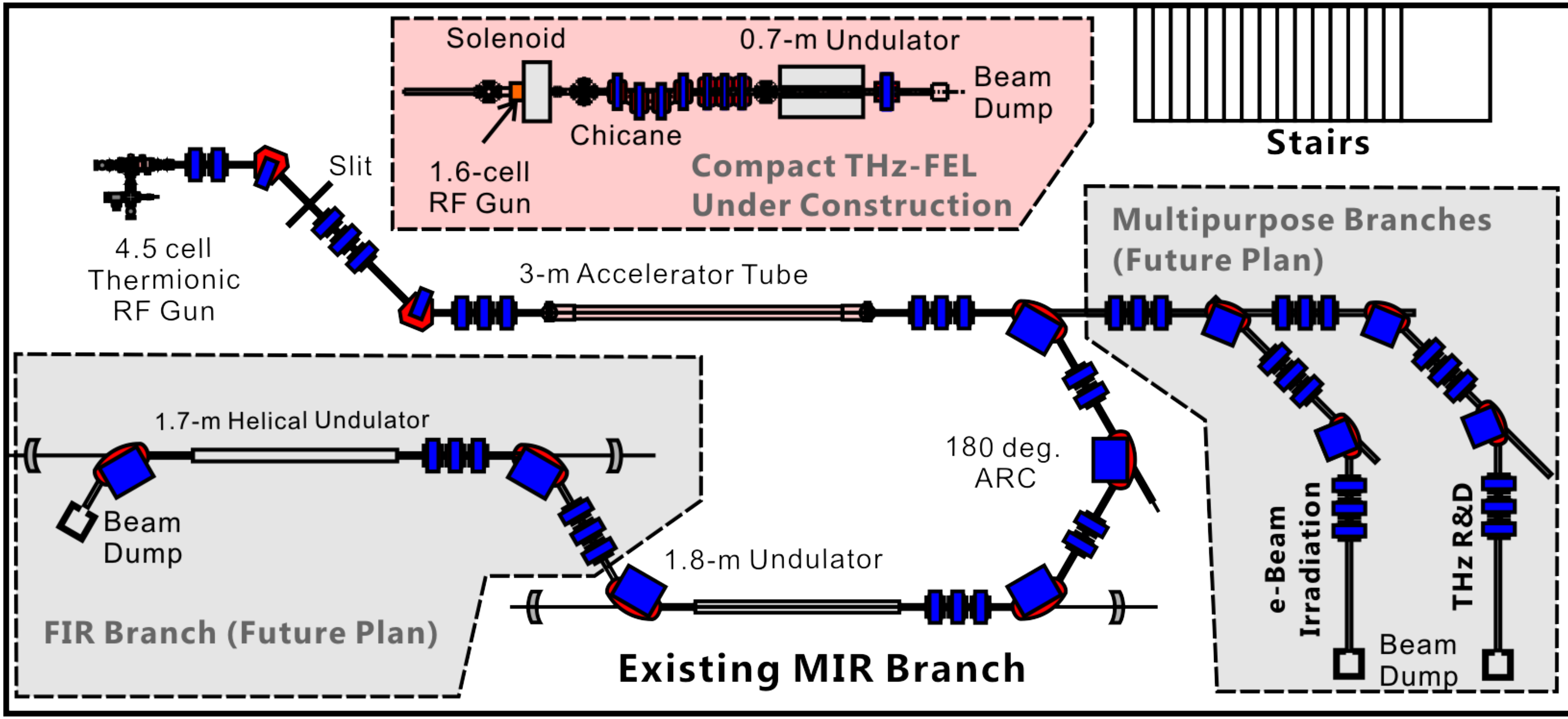
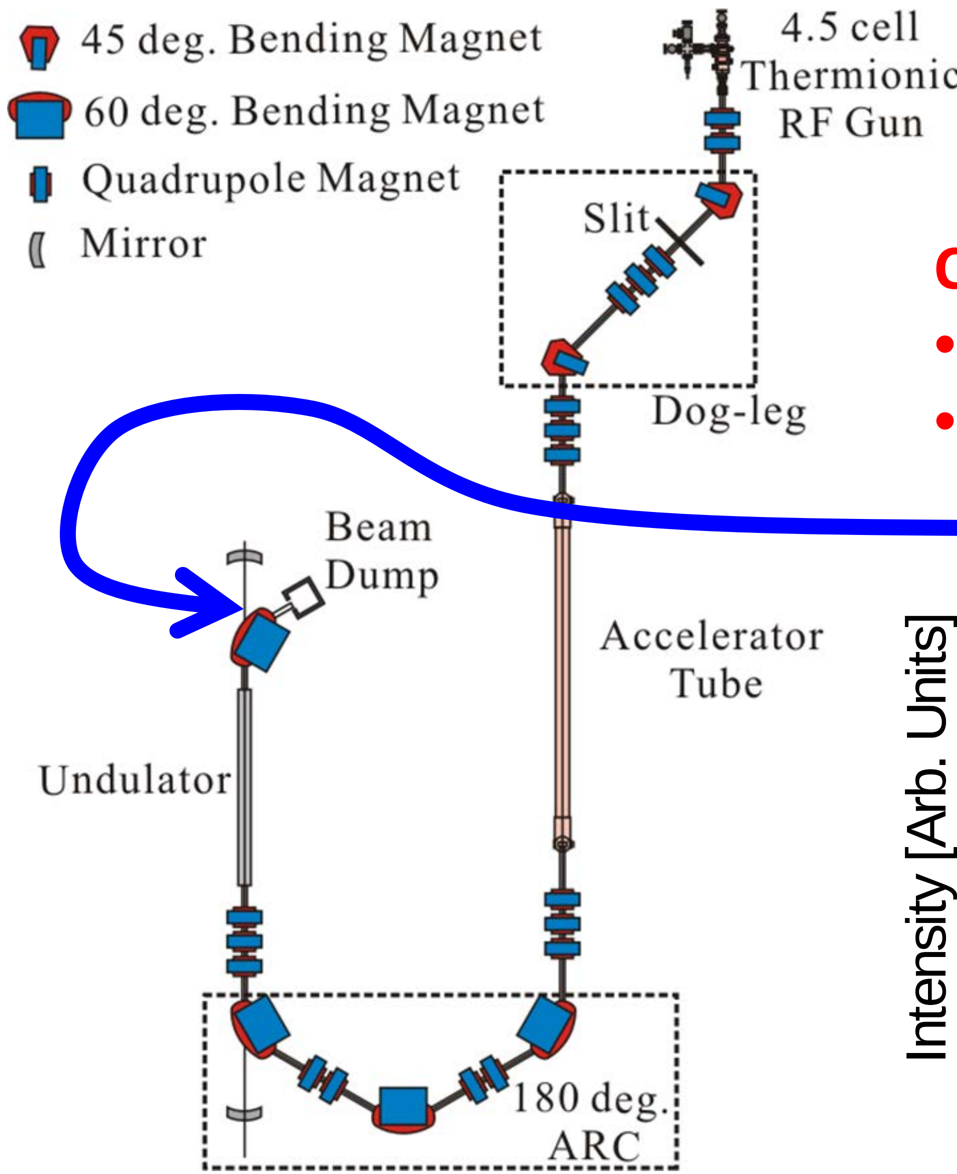
Possible Future Upgrade of Facility



- Complete the **compact THz-FEL** machine
- 2nd oscillator FEL in **longer wavelength**
- New beamlines for non-FEL application
  ➔ e-beam irradiation & **THz generation**.

Towards Longer Wavelength !!!

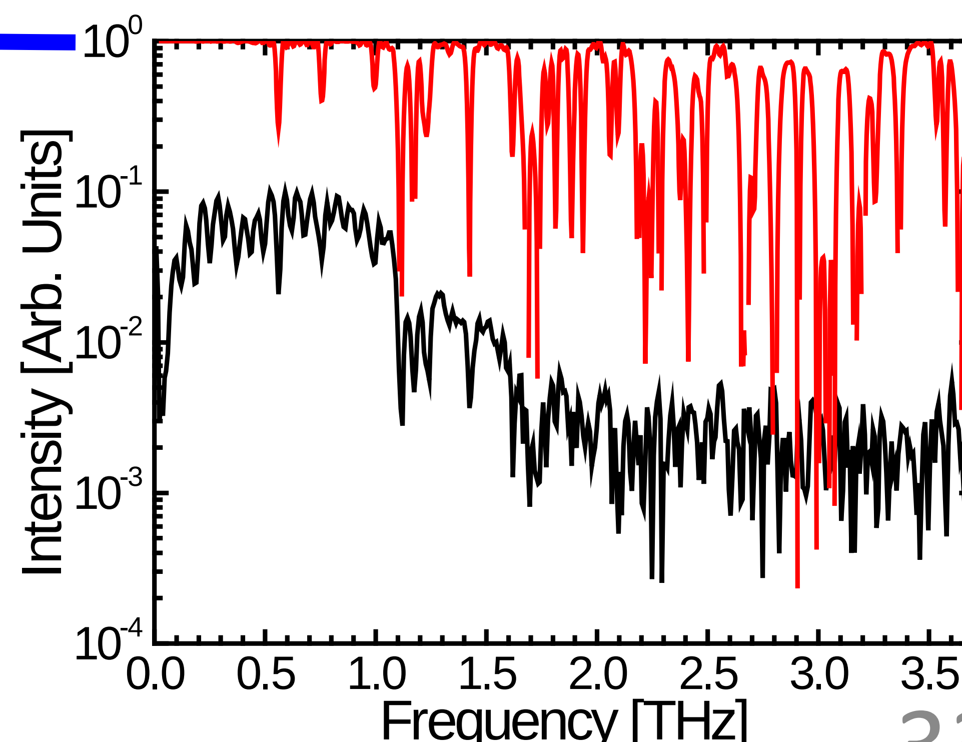
Feasibility Study of THz Generation



Edge Radiation from final bending magnet was measured @40 MeV

CER up to 2 THz was observed.

- **Pre-bunched FEL in 2nd branch?**
- **THz generation branch is feasible**



Summary

- MIR-FEL
  - Tunable range from 3.6 to 23 μm
  - Routinely operated for user experiments
  - Photocathode operation for nonlinear experiments

- THz-FEL
  - Compact configuration
  - e-beam property measurement was finished.

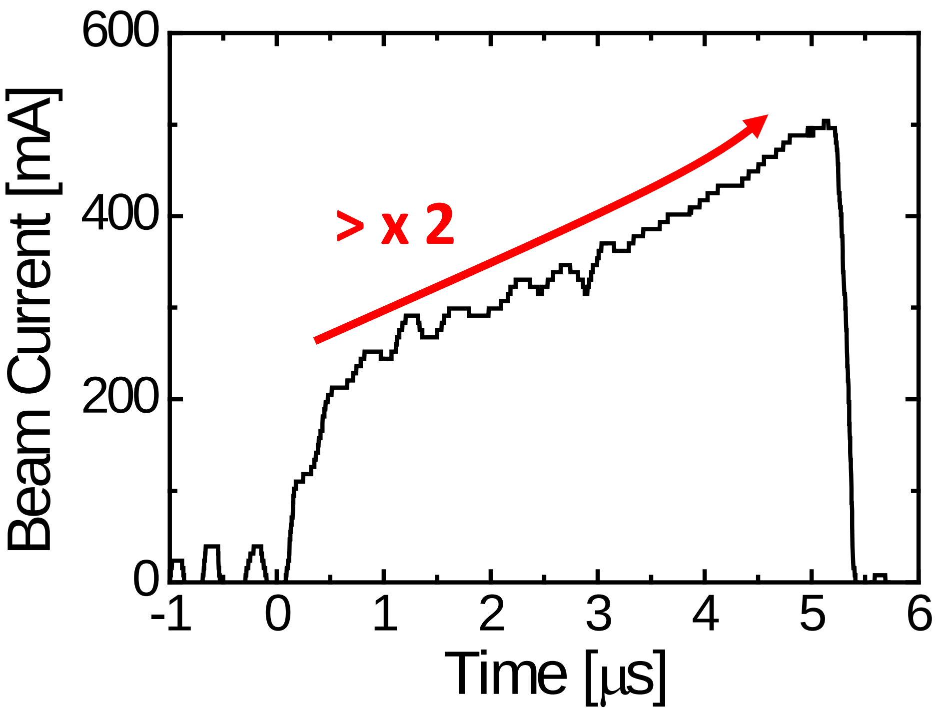
- Perspective
  - Facility will be extended to longer wavelength.

Thank you for your attention!!

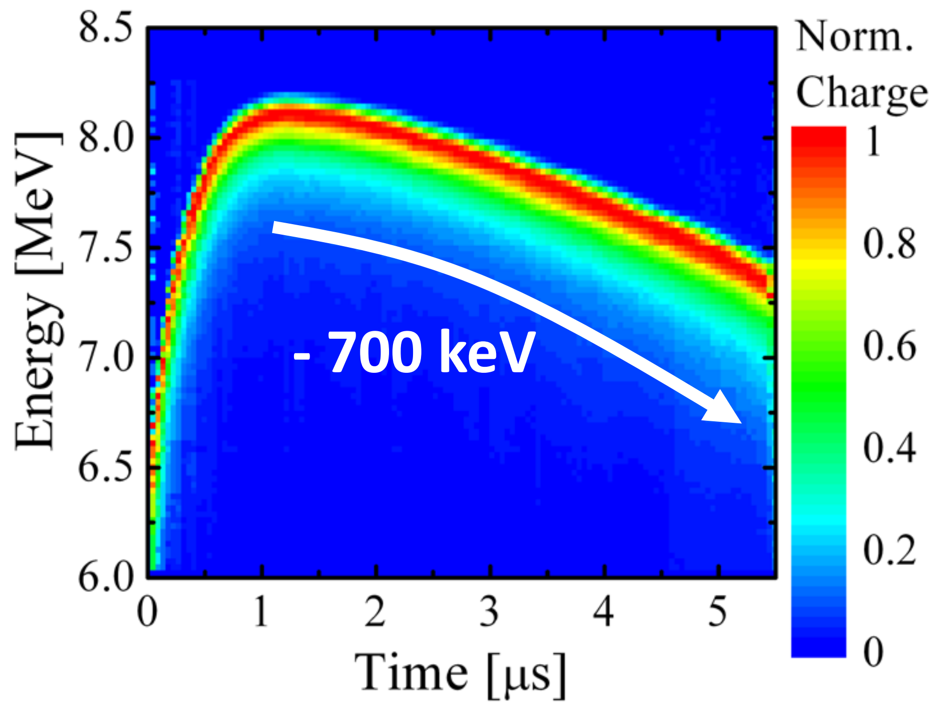
Influence of Back-bombardment Effect

Thermionic cathode supplies electron continuously.
→Some electron cannot be in acceleration phase decelerated back to the cathode.
→The energetic electron hit and heat up the cathode.
→Cathode temperature increase and beam current increase during a macro-pulse.
→Decrease of beam energy is caused by increase of beam loading.

Beam Current Profile



Beam Energy Evolution



Countermeasures against Back-bombardment

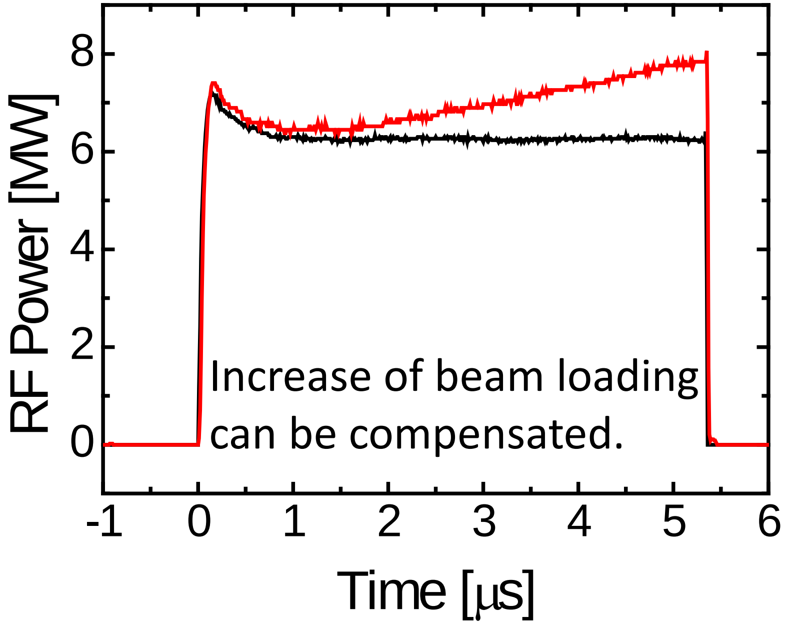
Oscillator FEL

Beam current increase in macro-pulse : **Acceptable**

Beam energy decrease in macro-pulse : **Unacceptable**

➡ We accept the beam current increase and compensated the beam energy decrease.

RF Power Ramping



RF Cavity Detuning

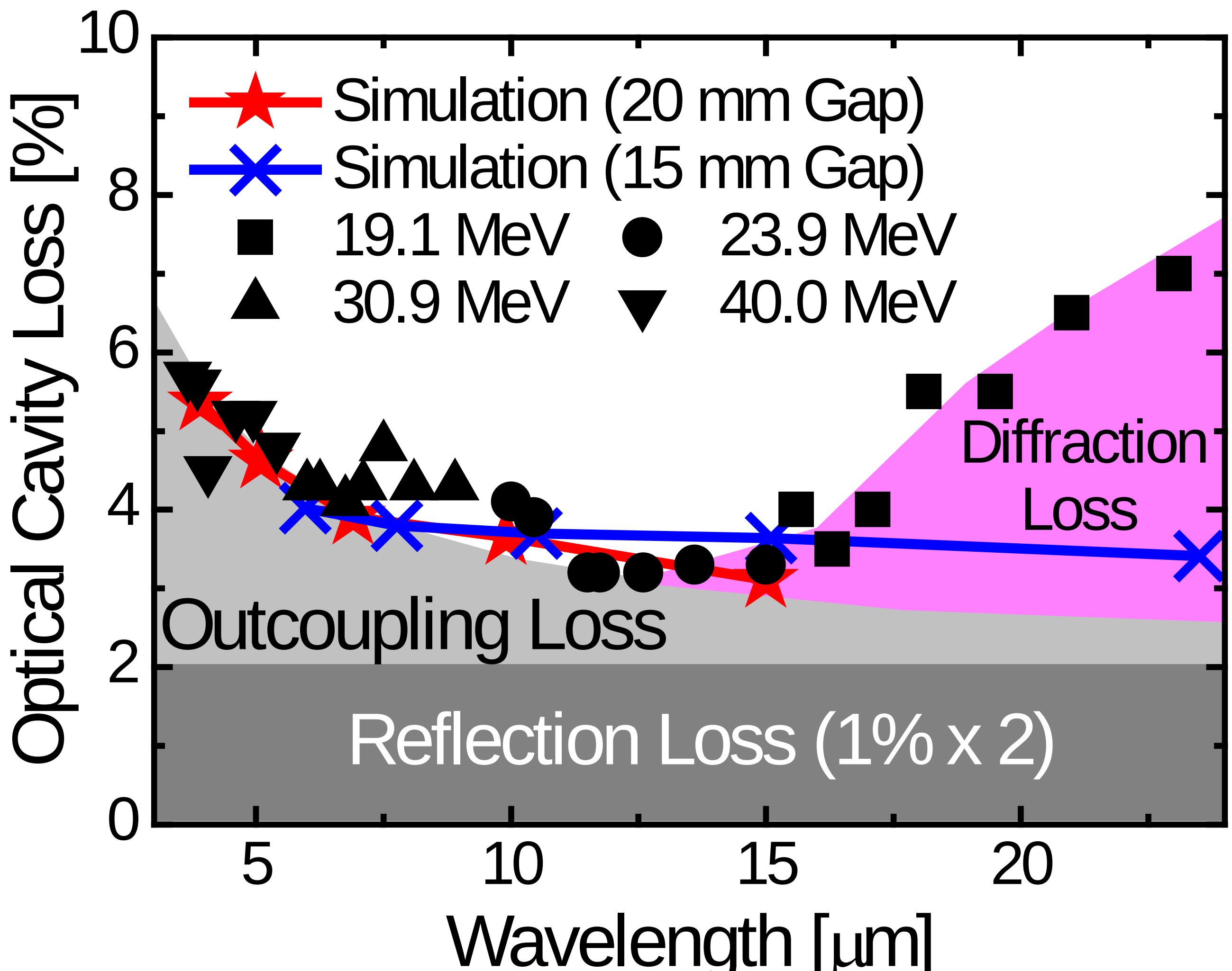
Detune the resonant frequency of RF cavity to slightly lower frequency of the feeding RF frequency.

Cavity voltage sensitivity against the change of beam current get smaller.

Ref.: H. Zen, et al., IEEE transaction on nuclear science, Vol. 56, No. 3, Pages 1487-1491 (2009).

Unexpected Increase of Optical Cavity Loss Observed in Long Wavelength Region of KU-FEL

A fast pyroelectric detector ELTEC 420-0 was used.



Machine Trouble in 2014 & 2015

Broken capacitors

New capacitor with attachment

- High voltage capacitors in the klystron modulator were broken due to aging.
- Successively more than 10 capacitors were already dead.

↓

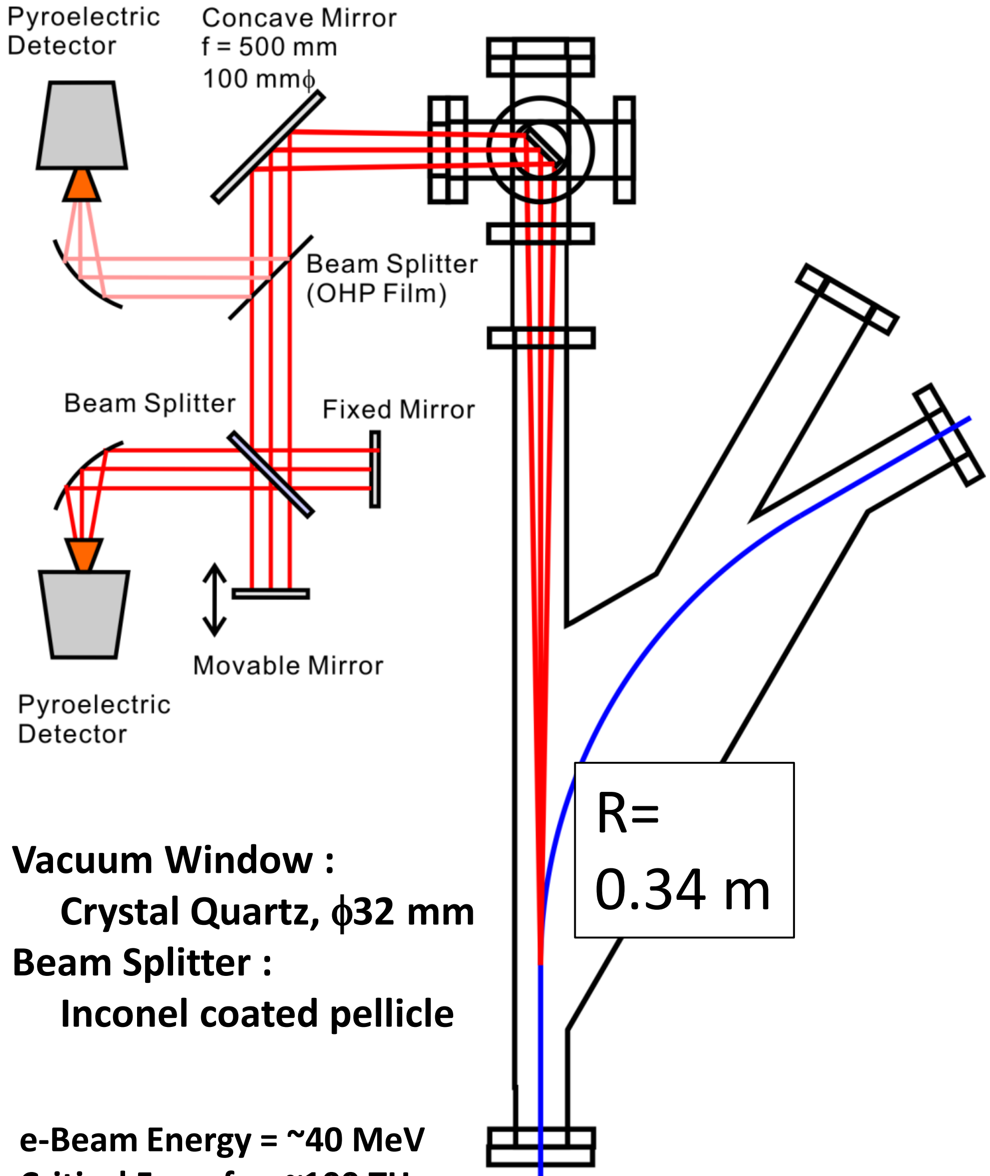
- We got some used capacitors from Waseda Univ. and AIST.
- We purchased 10 capacitors in last year and ordered another 10 in this year.

↓

- Some of new capacitors have been already installed and they have no problem for real operation.


NWL
NWL P/N: 13304 Rev: -
CAPACITANCE: 0.065 uF ±10%
VOLTAGE: 30,000 VDC peak
SERIAL NO: 49789-01-05
DANGER
THIS CAPACITOR CONTAINS NO P.C.B.'S

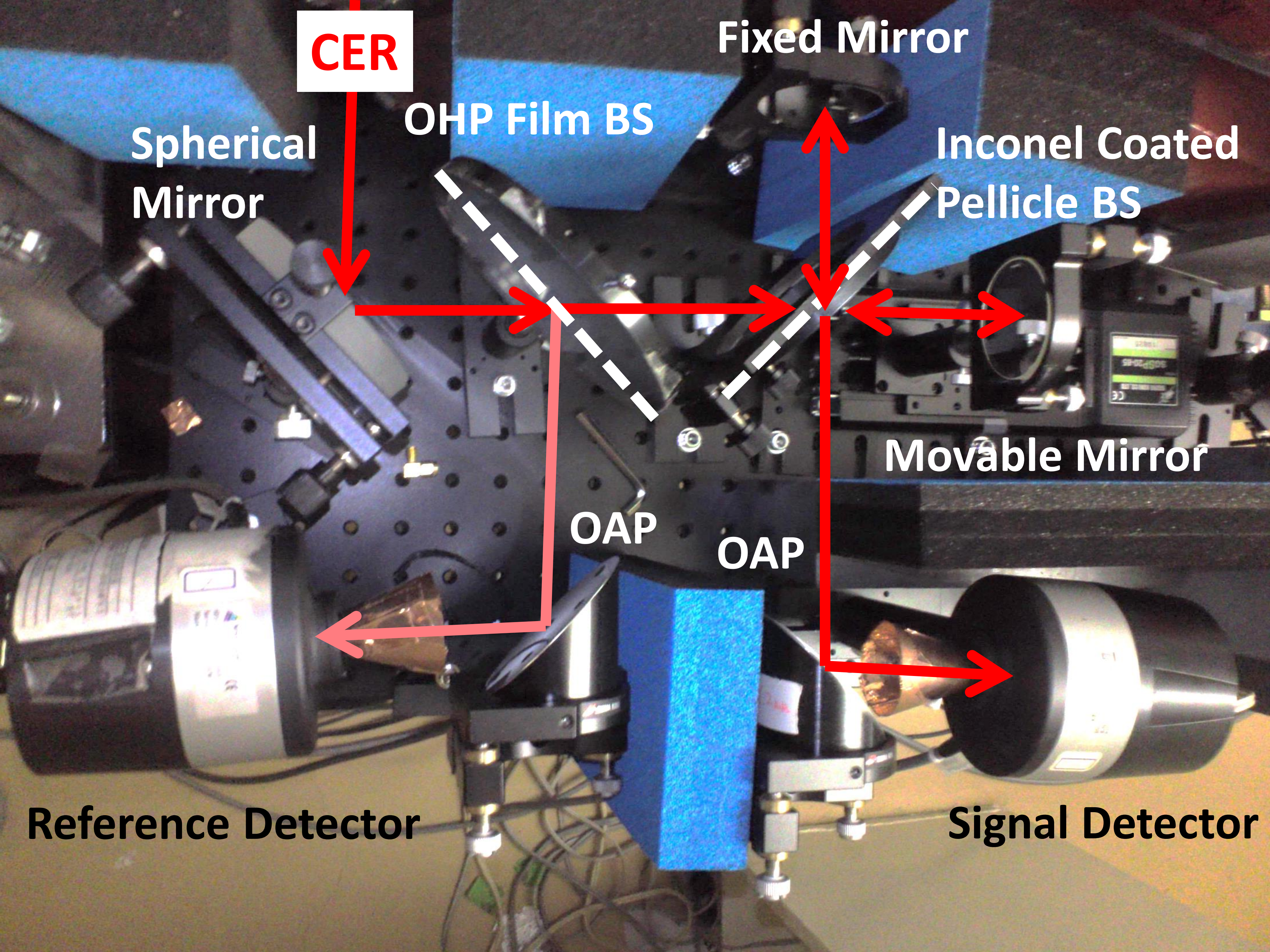
CER Measurement Setup



Vacuum Window :
Crystal Quartz, ϕ32 mm
Beam Splitter :
Inconel coated pellicle

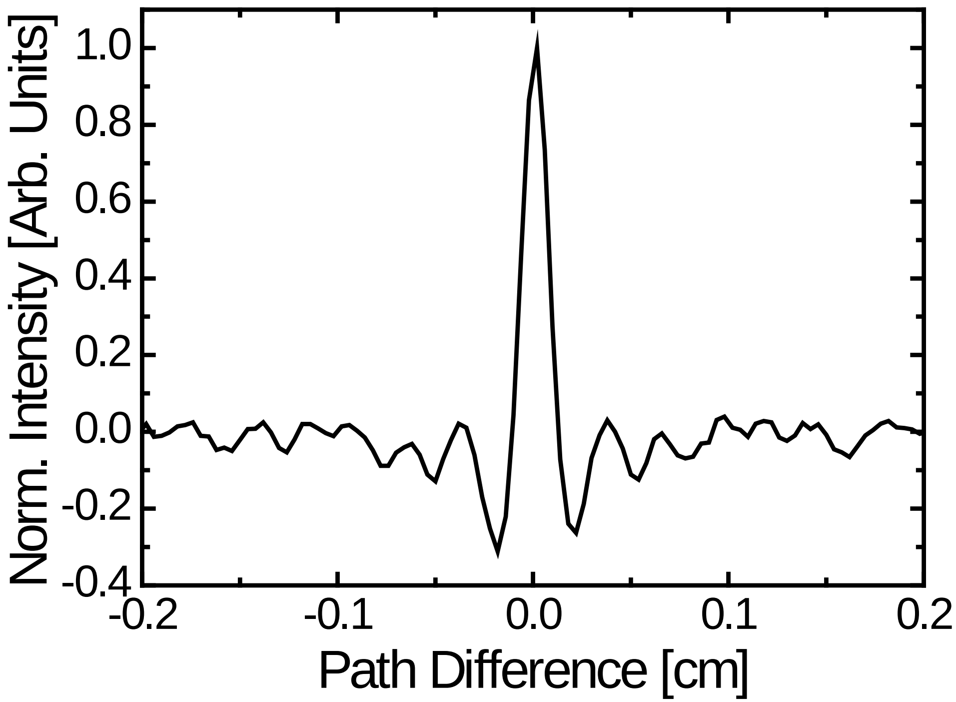
e-Beam Energy = ~40 MeV
Critical Freq. fc = ~100 THz

- Measurement was performed at the downstream of the Undulator.
- Radiation emitted on the 0-deg. line of bending magnet was reflected by a in-vacuum mirror and transported to the Michelson interferometer.
- A beam splitter made by OHP film was used to obtain the total power for normalization.
- Because the radiation intensity was enough high, low sensitivity pyroelectric detectors can be used.

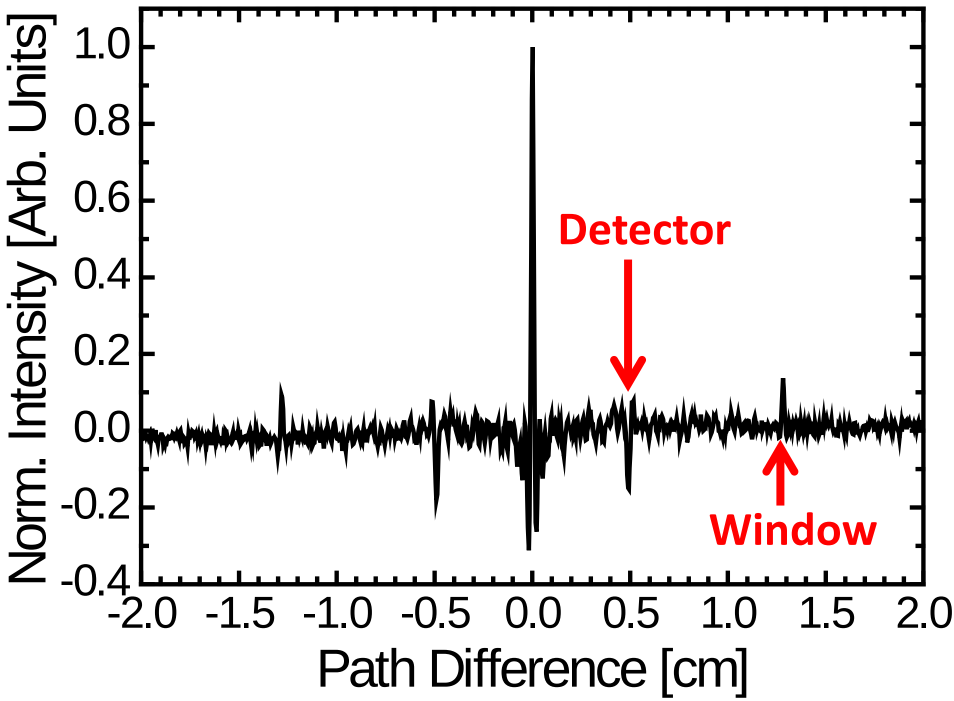

CER
Fixed Mirror
OHP Film BS
Spherical
Mirror
Inconel Coated
Pellicle BS
Movable Mirror
OAP
OAP
Reference Detector
Signal Detector

Interferogram

Around the center burst



Long Range Interferogram



- Beam Splitter of Michelson Interferometer : Inconel Coated Pellicle
- Pyroelectric Detector : QE8SP-I-BL-BNC (Gentec-EO)
- Vacuum Window : Z-cut Crystal Quartz Window (t = 4 mm)