AFAD-2021 WG-1

Activities of small-accelerator-based ultrafast-electron diffraction and free-electron laser in KAERI

Young Uk JEONG 2021. 3. 16

WCI
WORLD CLASS INSTITUTE

COLLECTIVE INTELLIGENCE
Radiation Center for Ultrafast Science
circus

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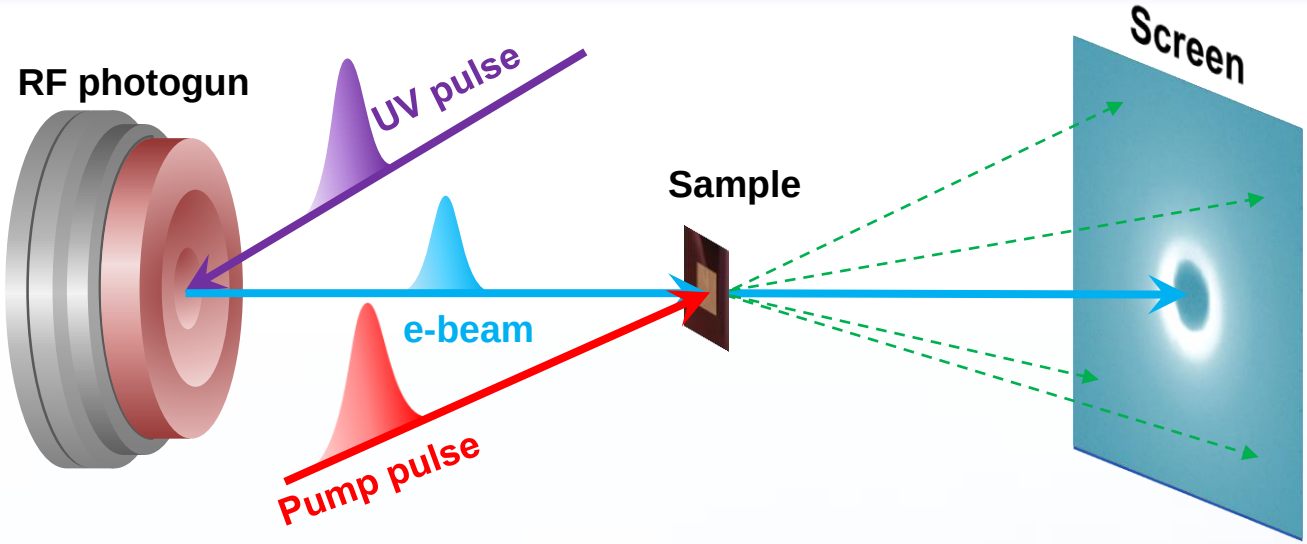
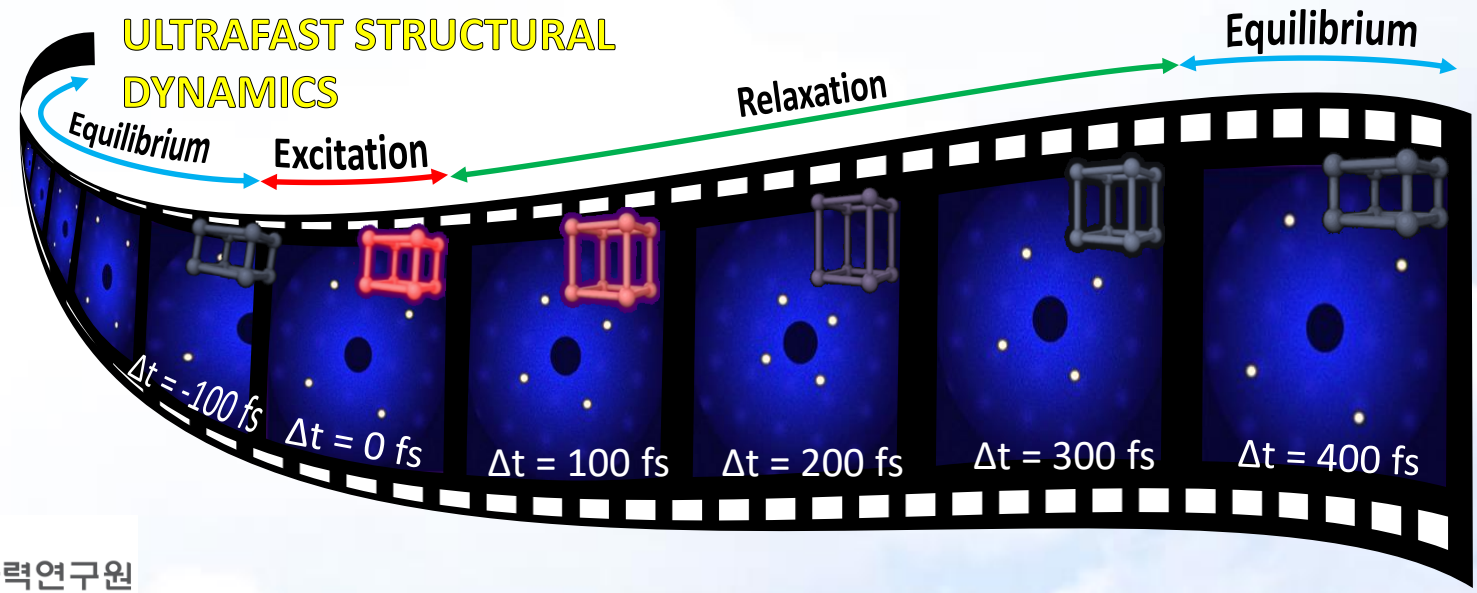
I. Ultrafast Electron Diffraction

Ultrafast Electron Diffraction (UED)

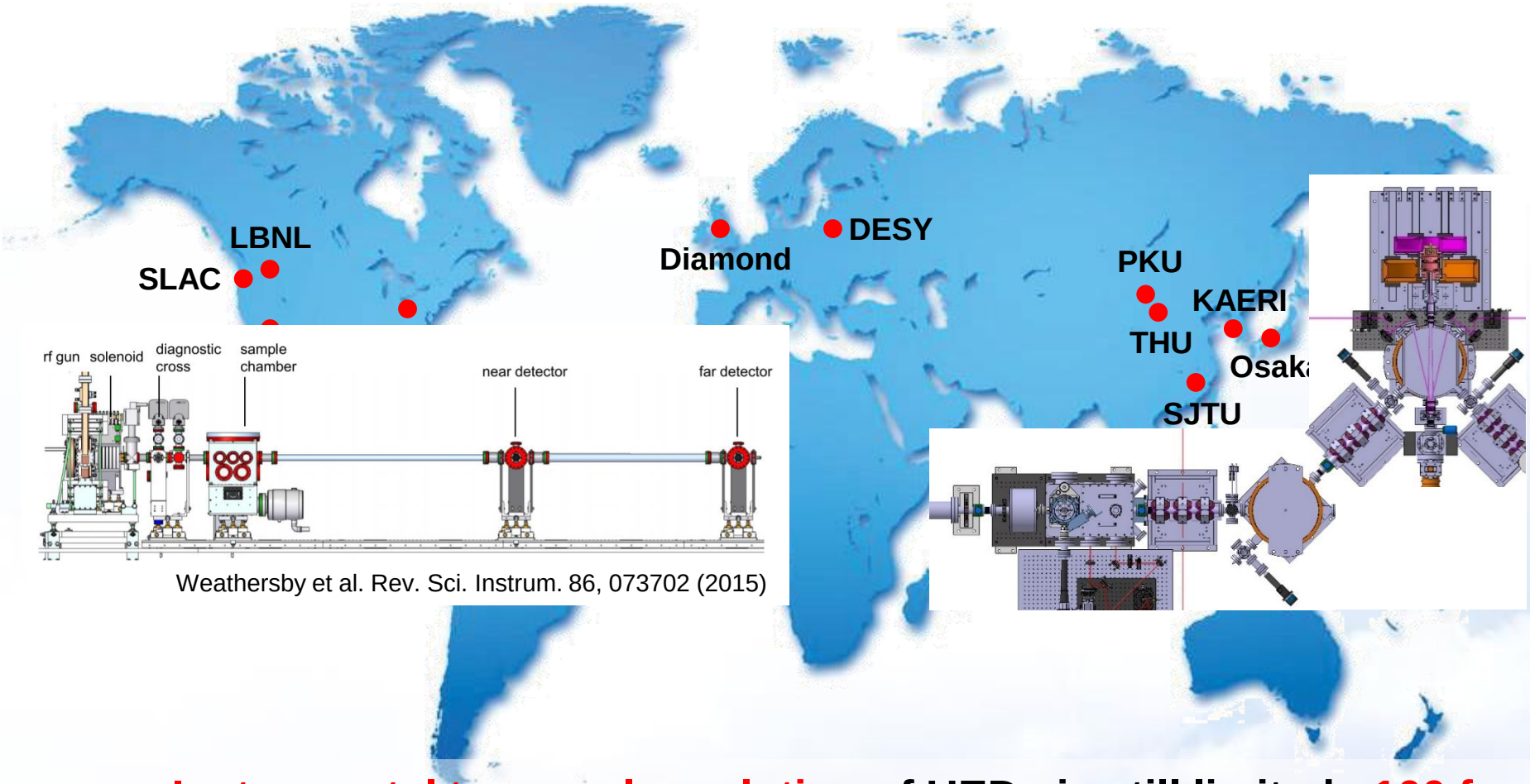




World-wide efforts for MeV UED

Instrumental temporal resolution of UEDs is still limited >100 fs.

World-wide efforts for MeV UED

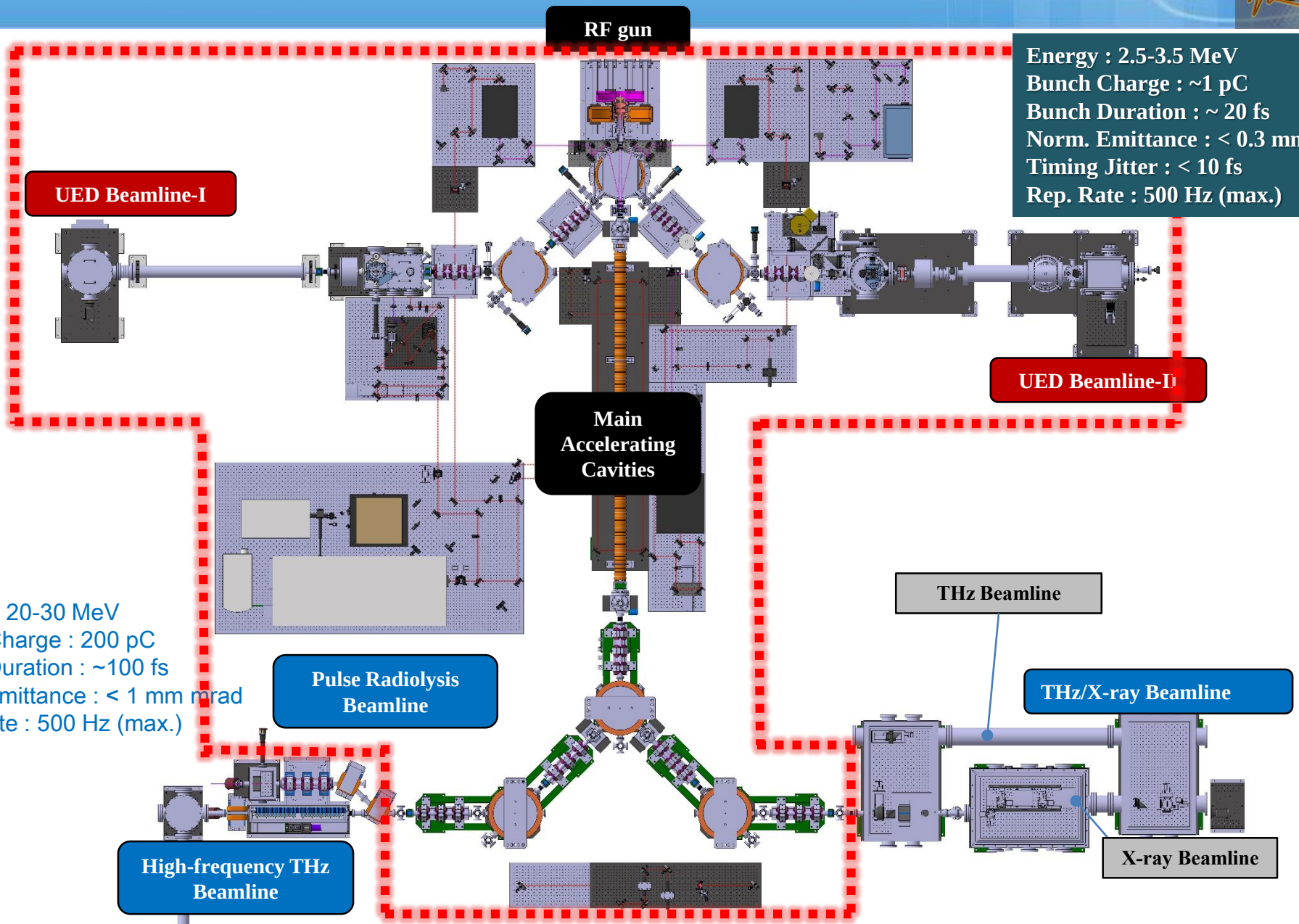


Weathersby et al. Rev. Sci. Instrum. 86, 073702 (2015)

Instrumental temporal resolution of UEDs is still limited >100 fs.

Facility Bird-eye View

시설 개관

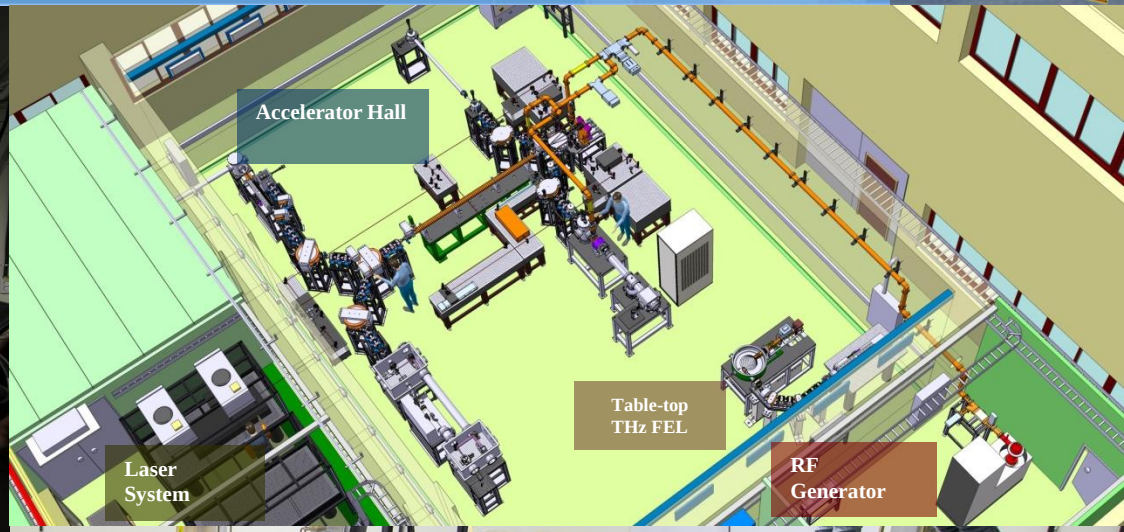


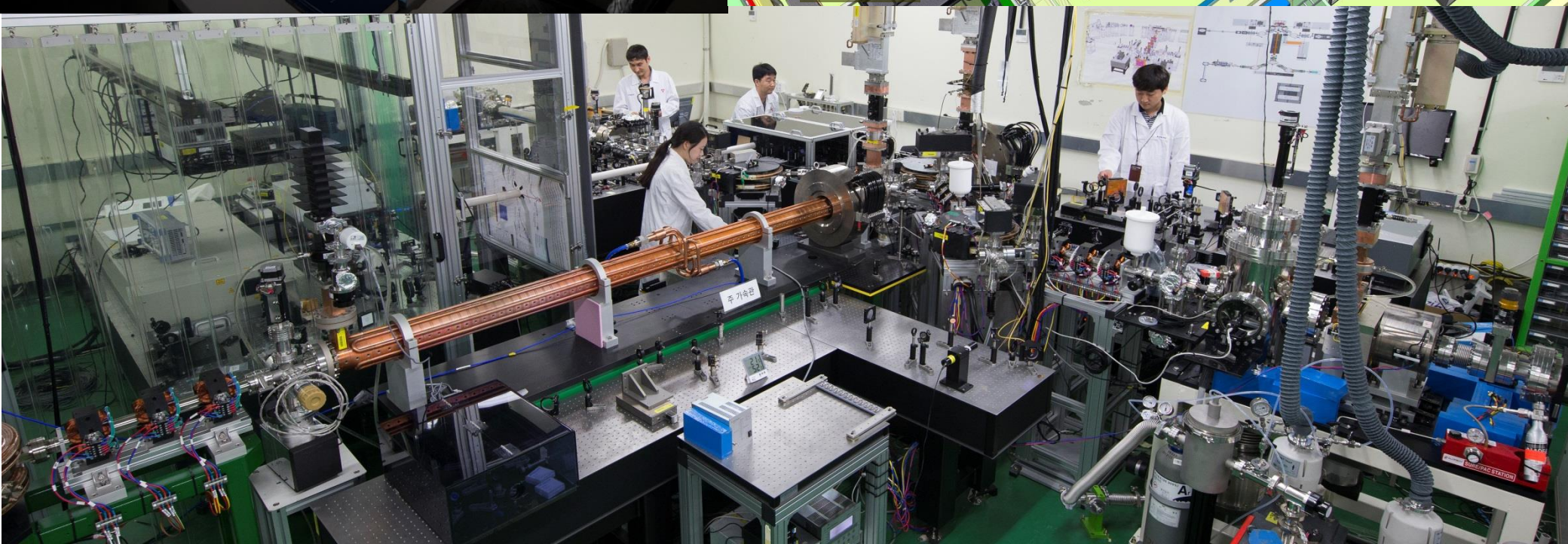
Energy : 2.5-3.5 MeV
Bunch Charge : ~1 pC
Bunch Duration : ~ 20 fs
Norm. Emittance : < 0.3 mm mrad
Timing Jitter : < 10 fs
Rep. Rate : 500 Hz (max.)

Energy : 20-30 MeV
Bunch Charge : 200 pC
Bunch Duration : ~100 fs
Norm. Emittance : < 1 mm mrad
Rep. Rate : 500 Hz (max.)

Facility Appearance

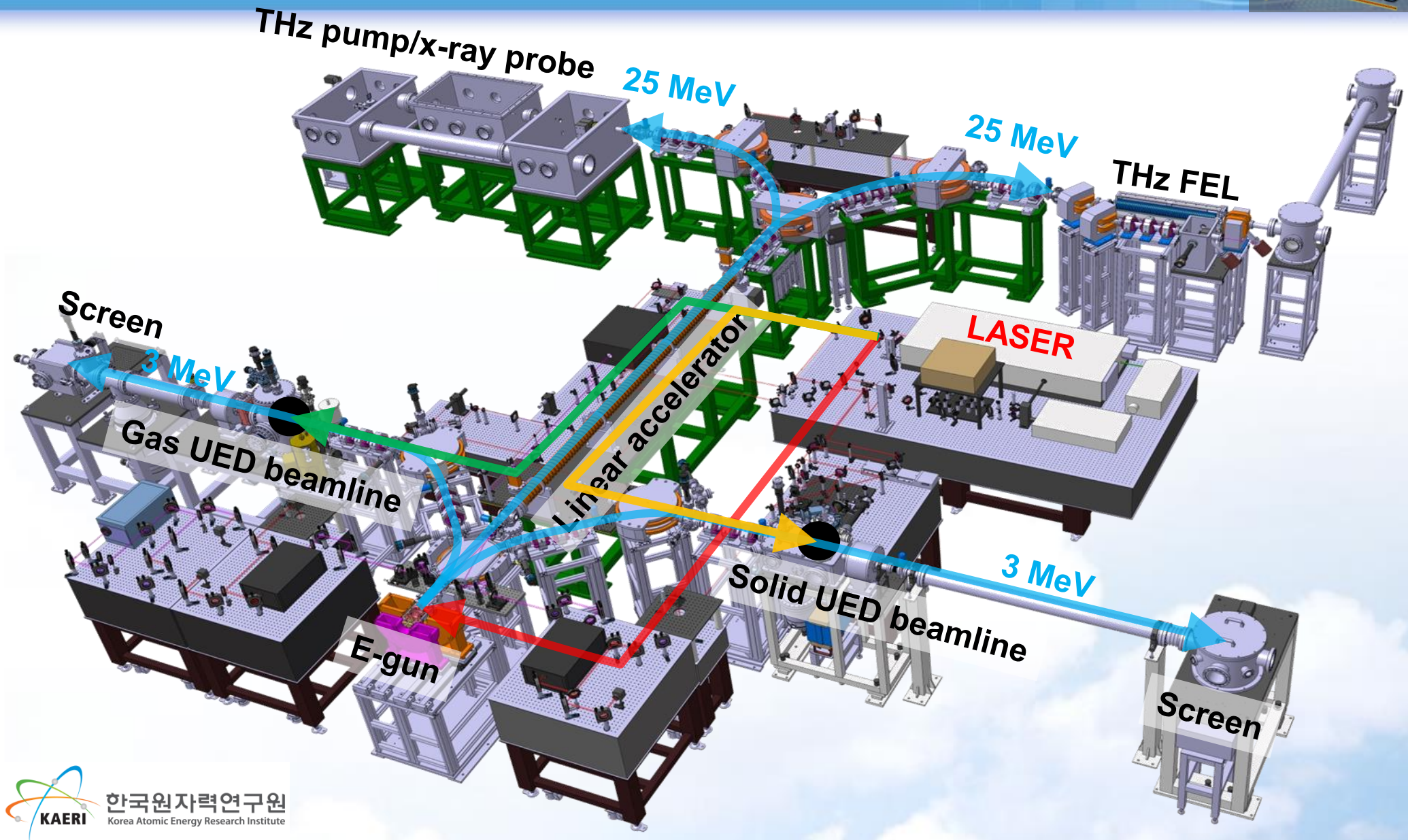
시설 개관





Facility Overview

시설 개관



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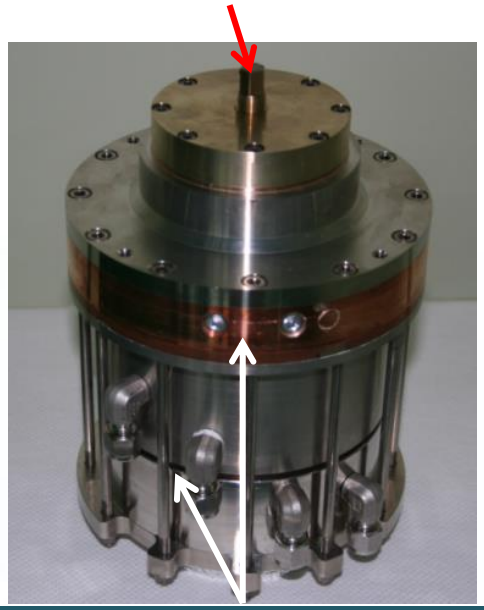
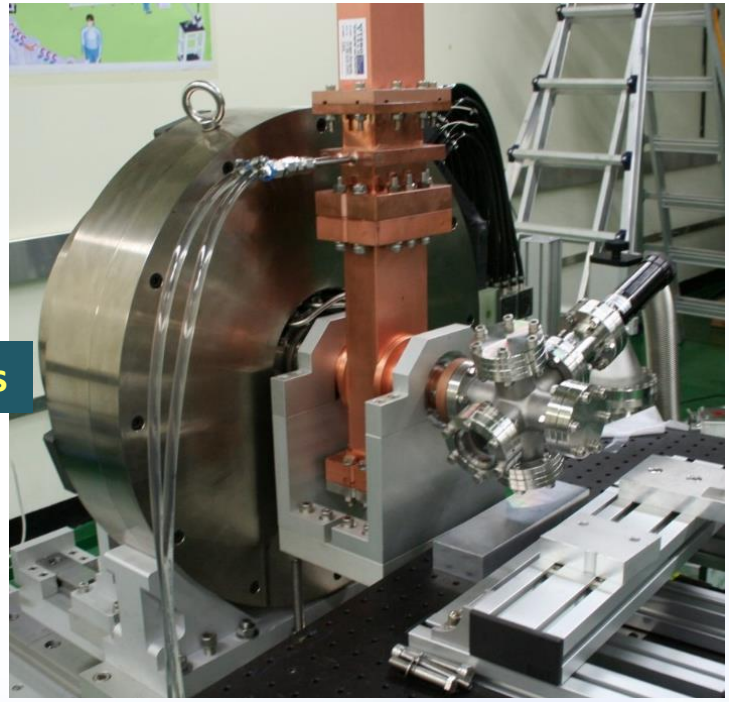
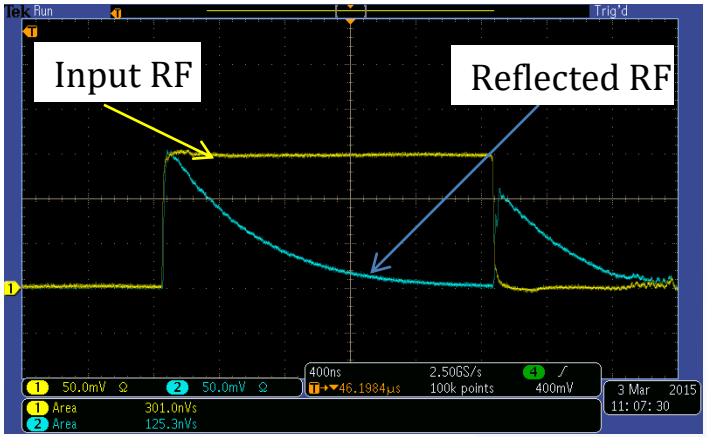
Coaxial-type Indium-sealed RF Photogun

Frequency Tuning Mechanics



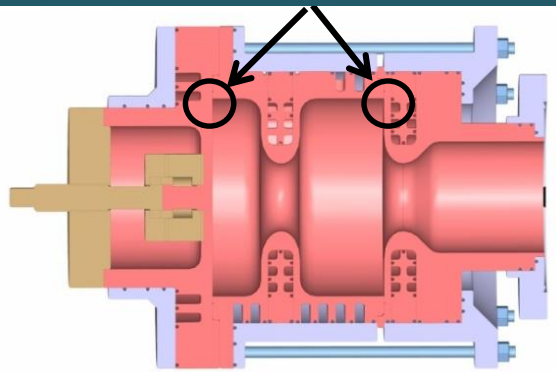
Frequency : 2.856 GHz
Repetition Rate : 1-500 Hz
Axial Symmetry with a Coaxial Coupler

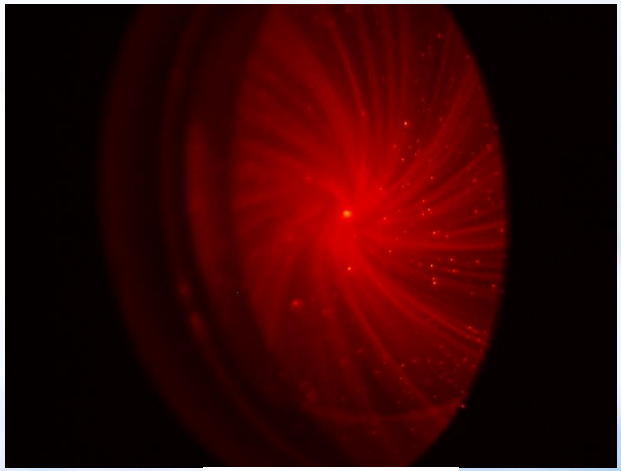




High power test

Vacuum sealed with Indium wires





Dark current

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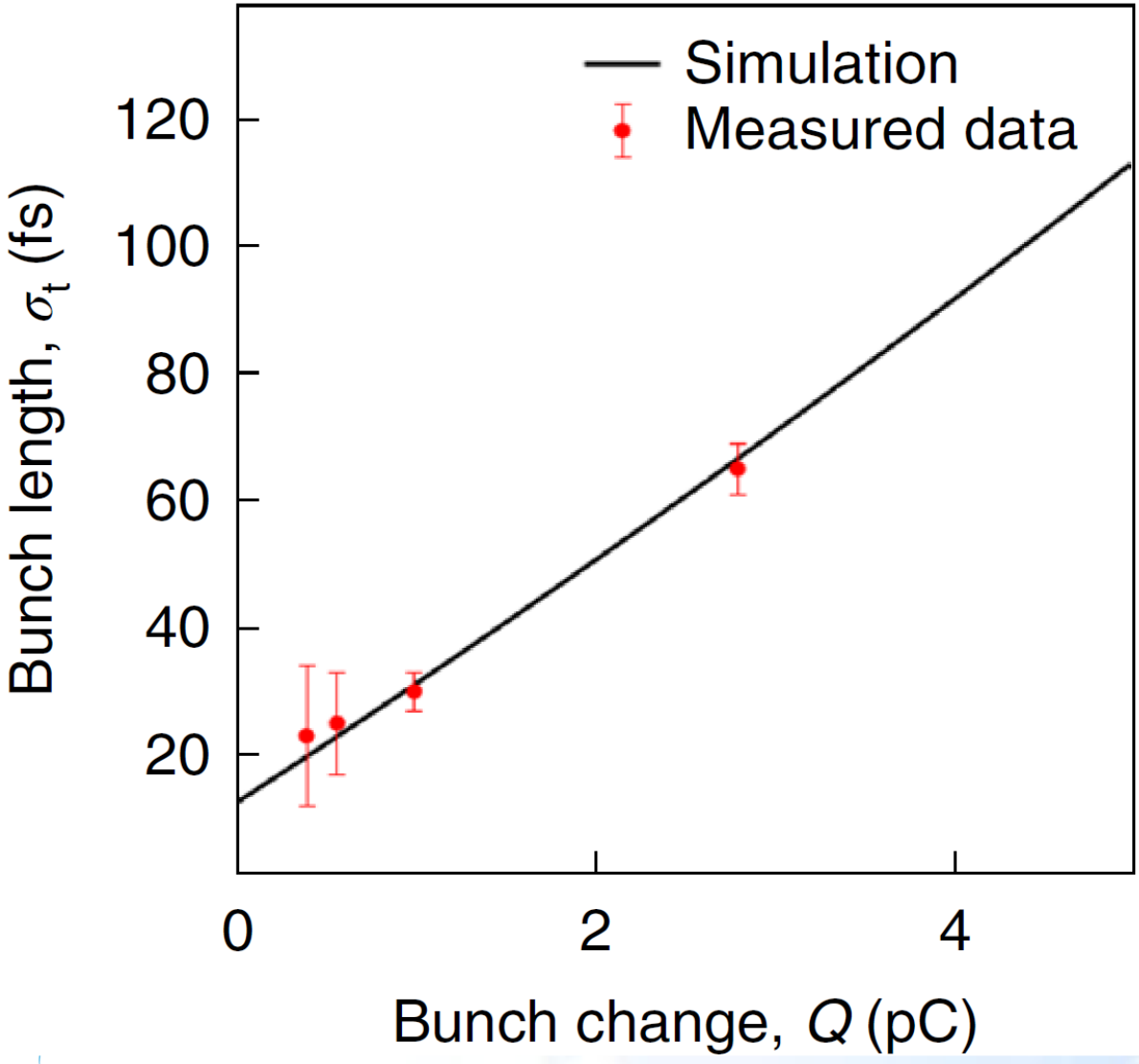
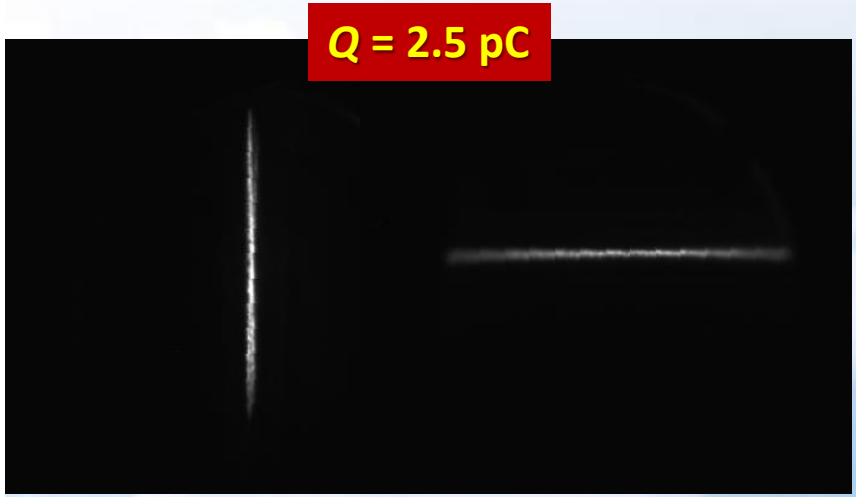
H. W. Kim et al., J. Kor. Phys. Soc., 74, 24 (2019)

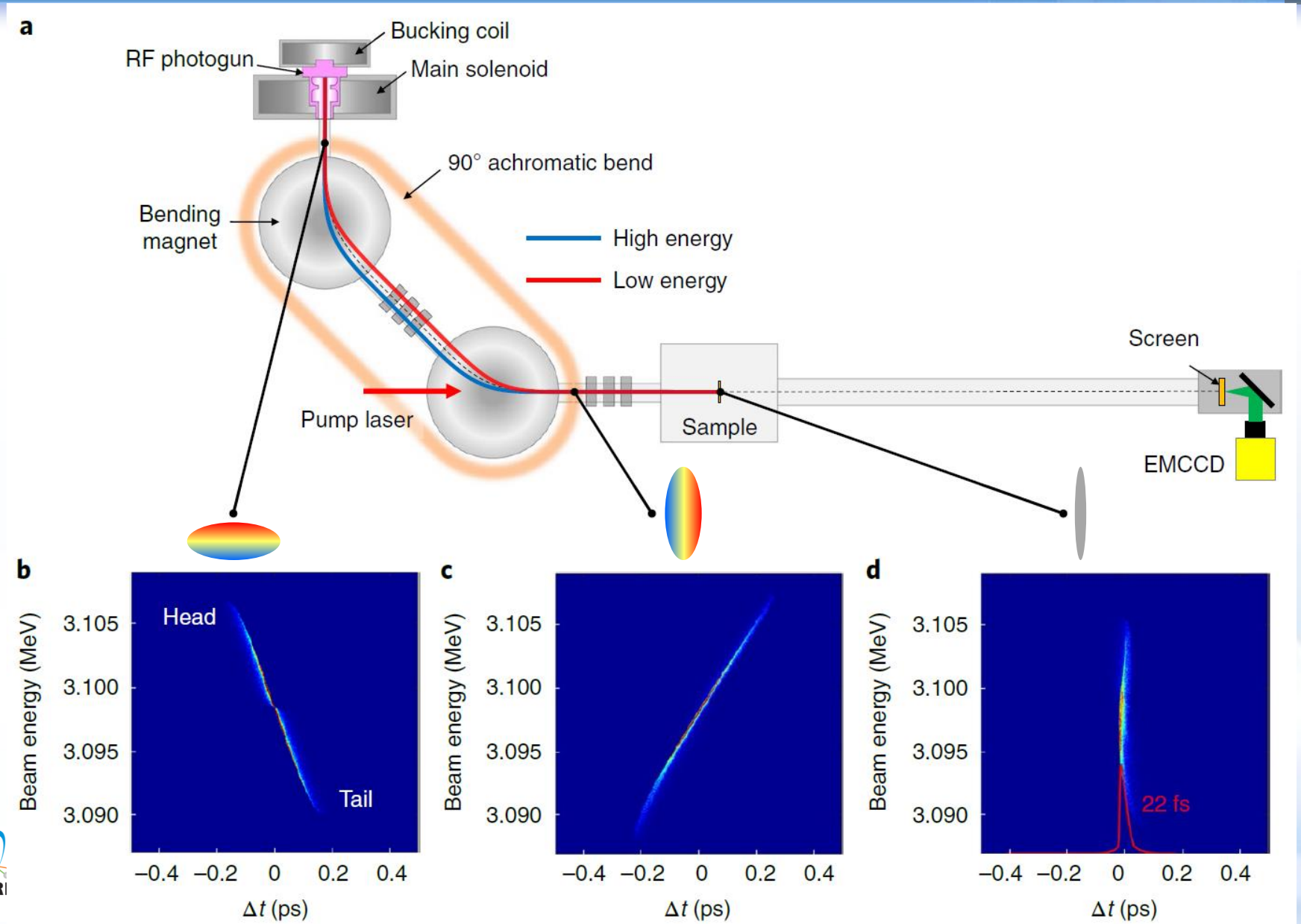
Emittance Measurement



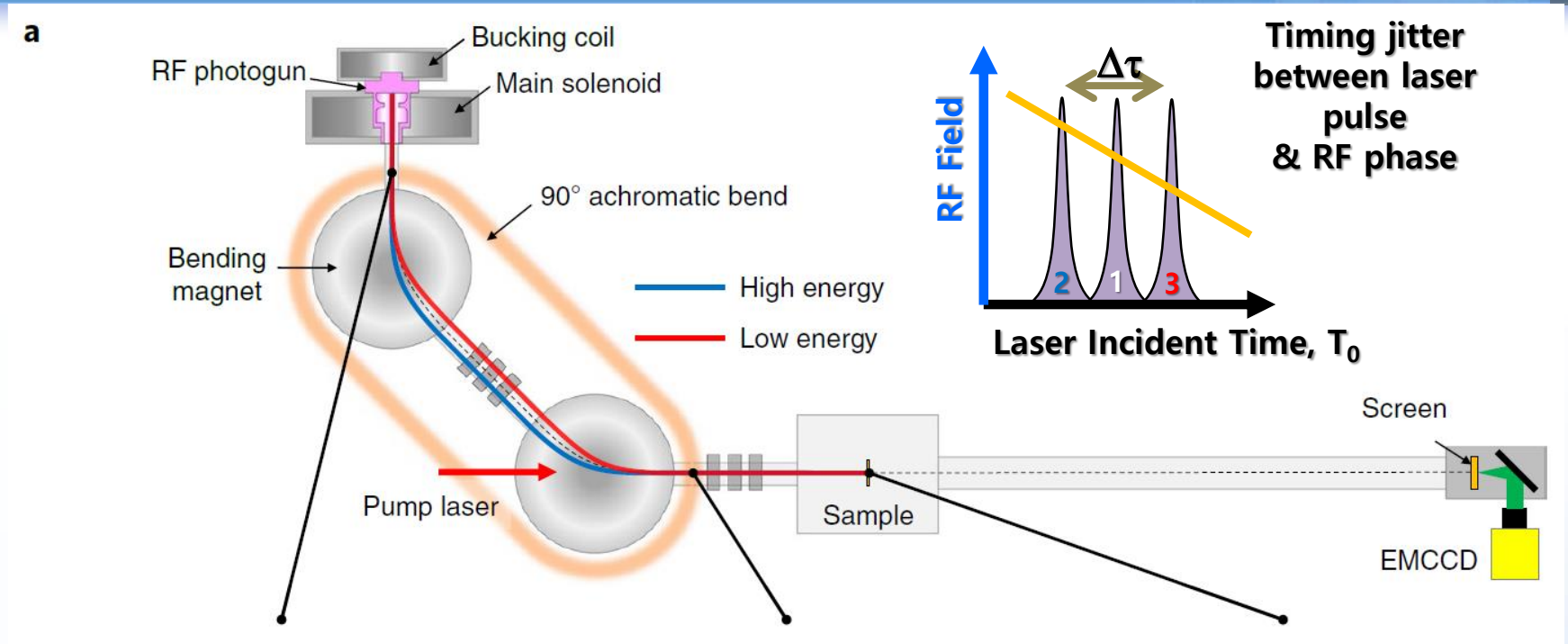
Parameters	
Laser spot size @cathode	200 μm FWHM
Bunch charge	0.4 – 11.3 pC
Beam energy	3 MeV
ε_{norm_x}	0.23 – 1.45 mm-mrad
ε_{norm_y}	0.25 - 1.40 mm-mrad

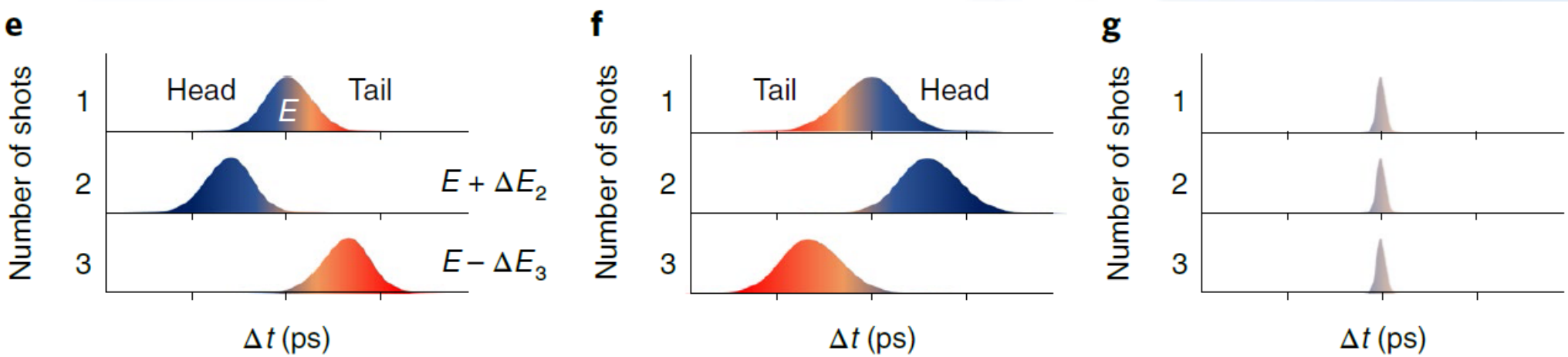


KAERI UED: Bunch Compression



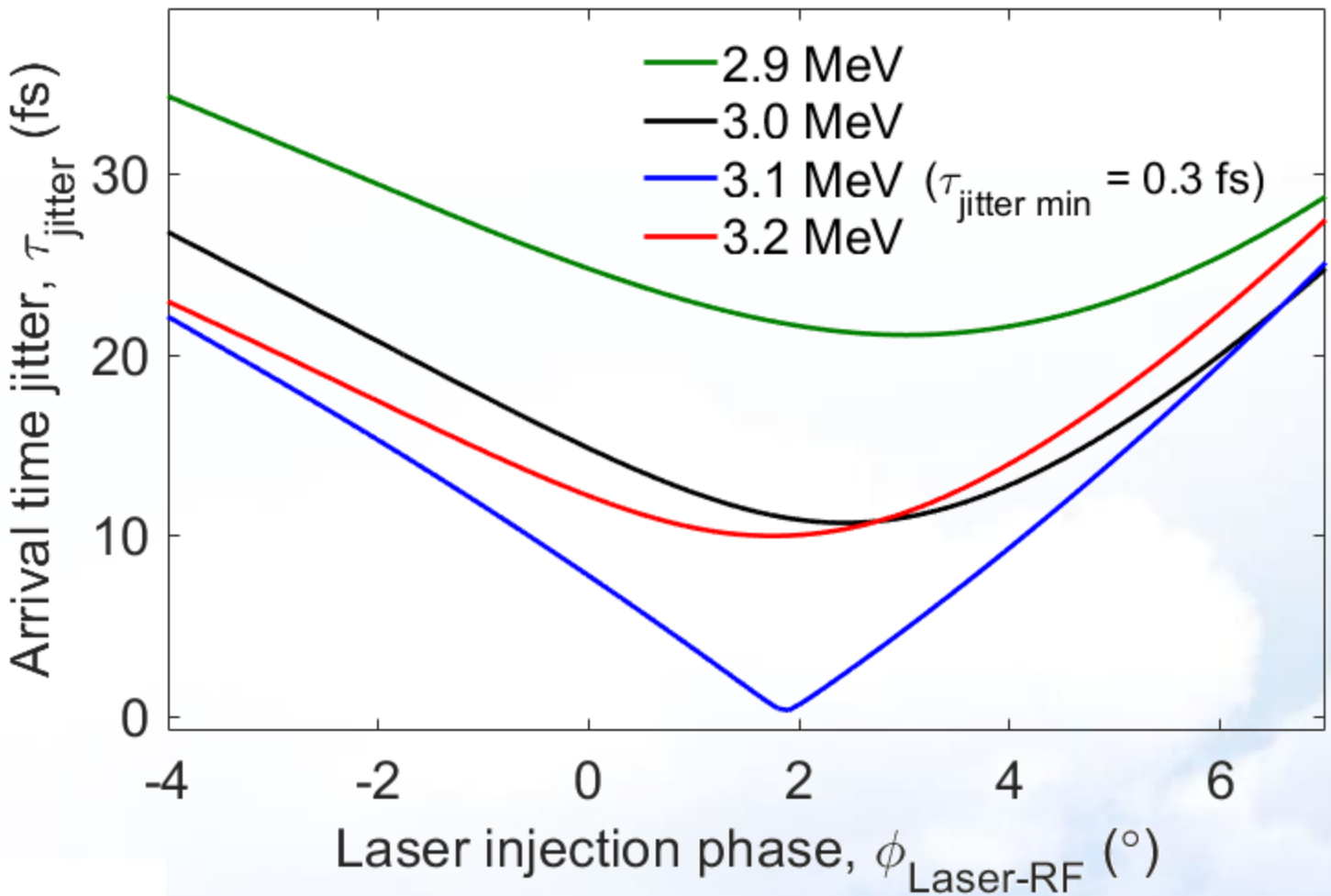
KAERI UED: Jitter Compression





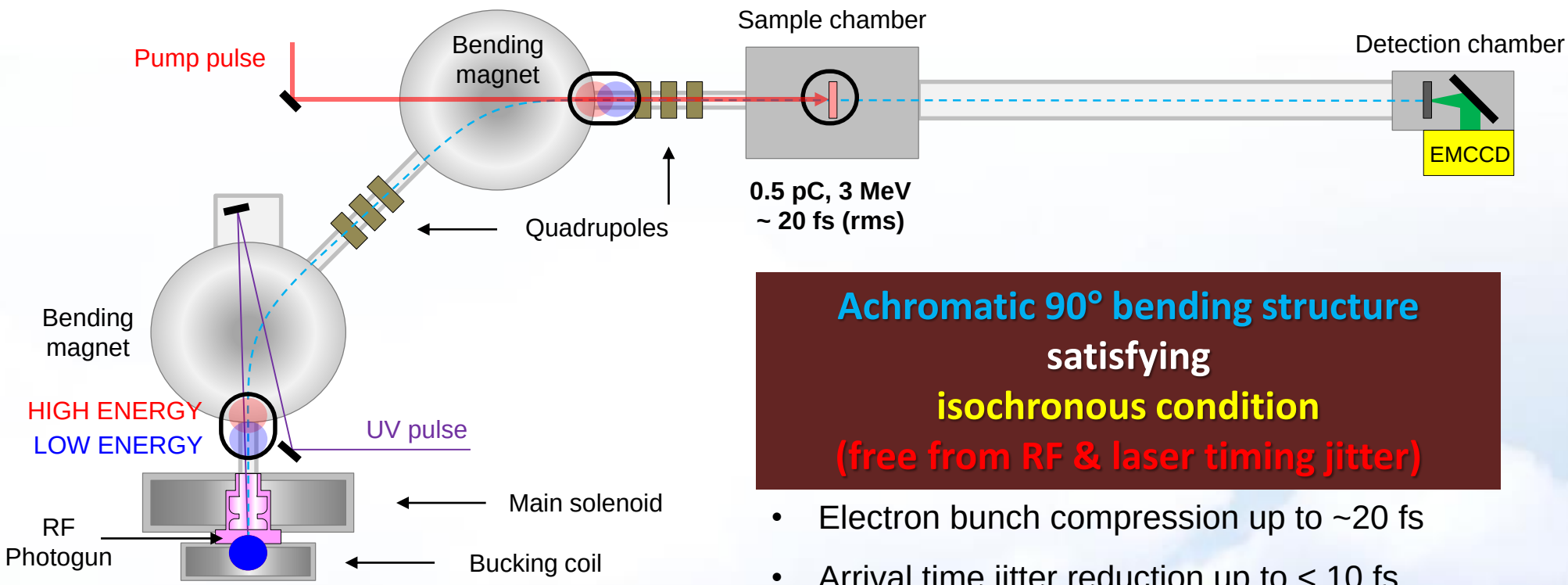
Arrival time jitter due to RF amplitude & phase

$\Delta E/E$ = 0.07%
$\Delta \Phi_{\text{Laser-RF}}$ = 40 fs



Toward the fastest Electron Camera

$$\tau_{Inst.res.} = \sqrt{\tau^2_{pump\ laser} + \tau^2_{e-bunch} + \tau^2_{jitter} + \tau^2_{velocity-mismatching}}$$



Achromatic 90° bending structure satisfying isochronous condition (free from RF & laser timing jitter)

- Electron bunch compression up to ~20 fs
- Arrival time jitter reduction up to < 10 fs
- Velocity mismatching-free scheme
- Multiple beamlines

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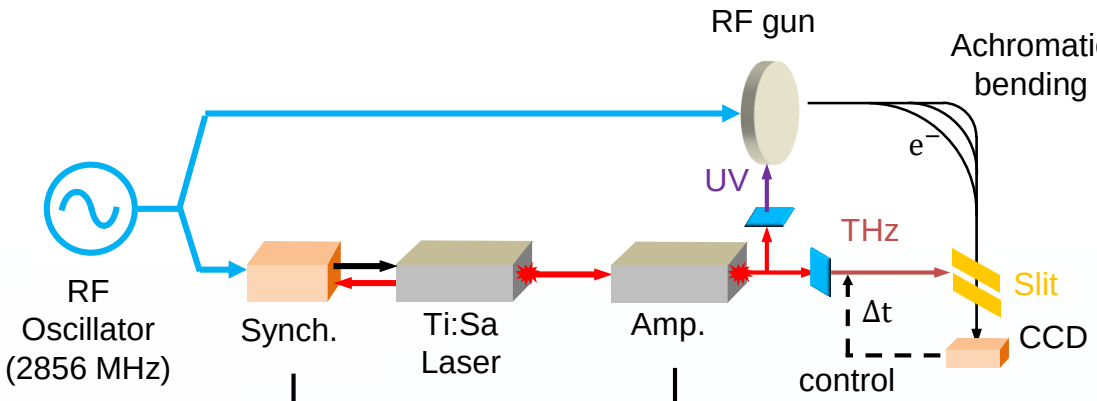
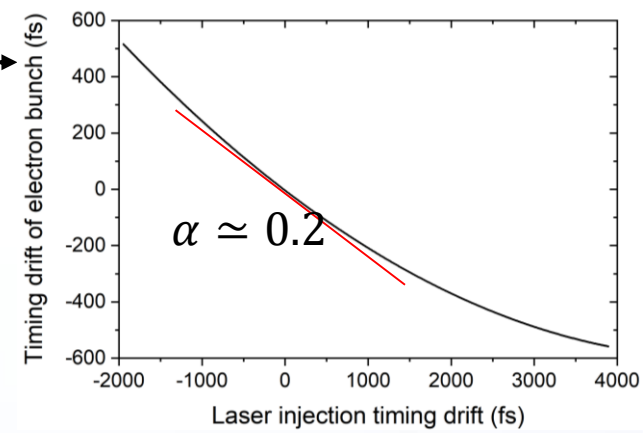
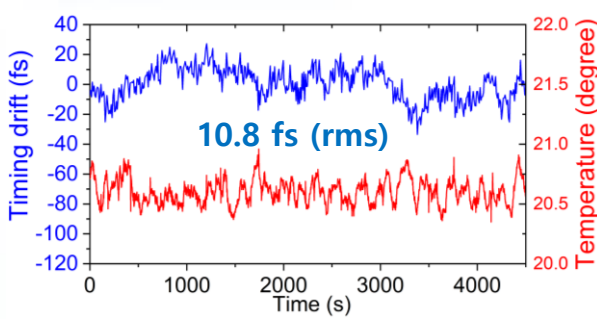
Timing Stabilization between Laser & RF



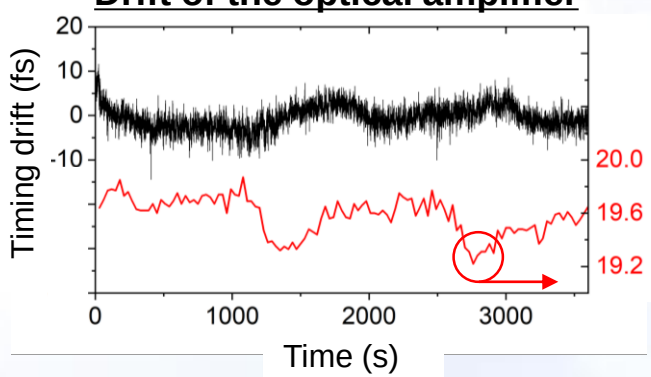
Simulated drift suppression ratio



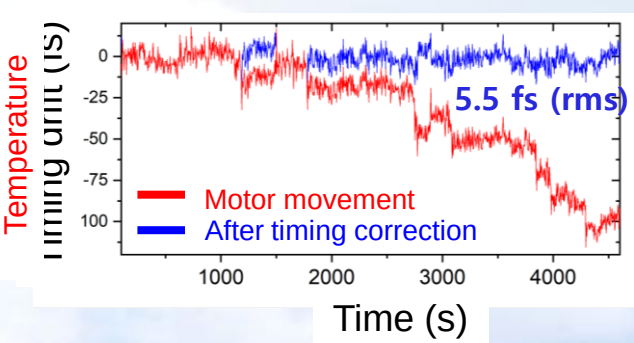
Drift of the RF-to-laser synch.



Drift of the optical amplifier



Timing drift of electron beam



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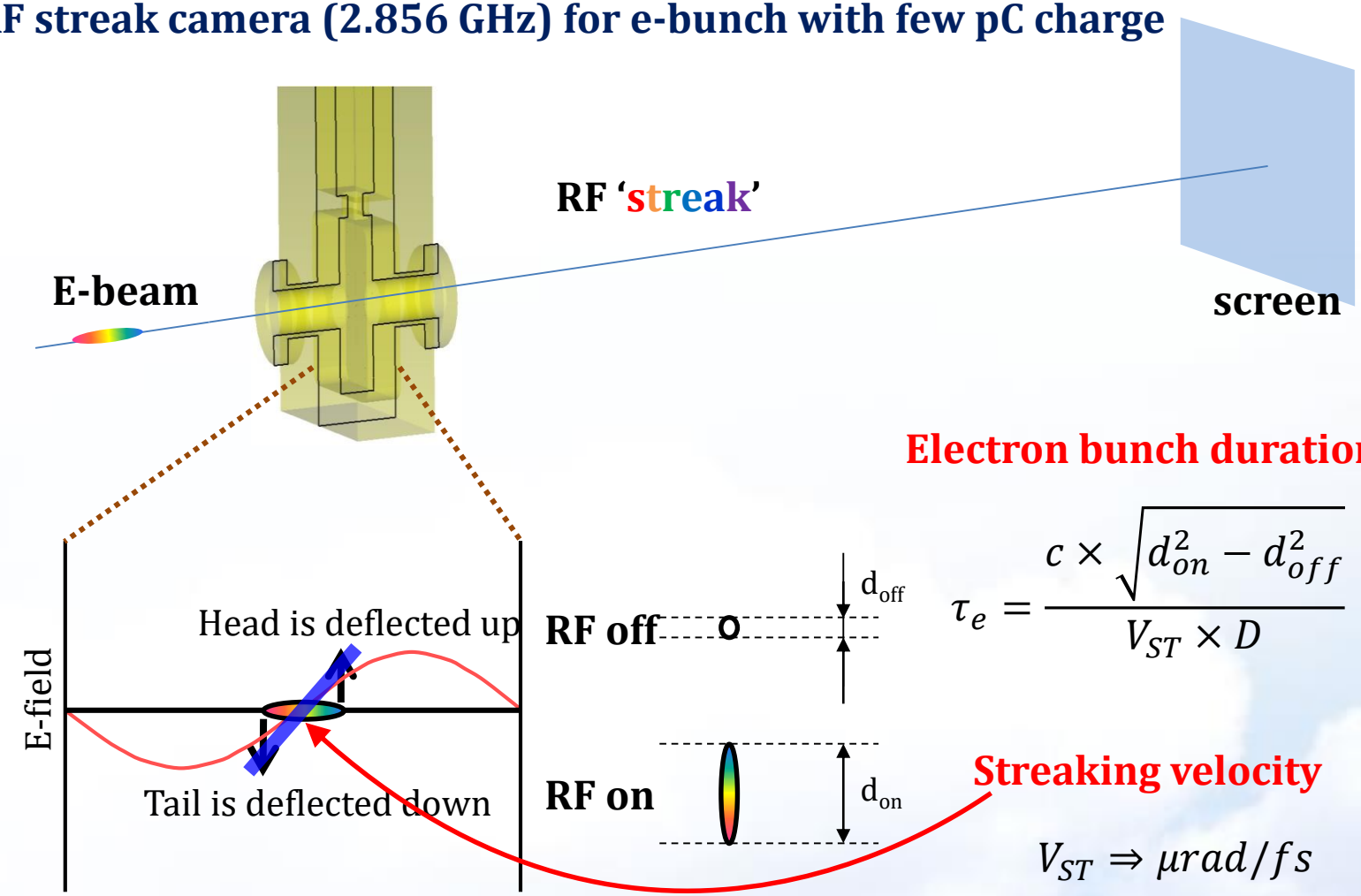
J. Shin et al., Laser Photon. Rev. 15, 200326 (2021).

Conventional Characterization of Electron Bunch

RF streak camera (2.856 GHz) for e-bunch with few pC charge



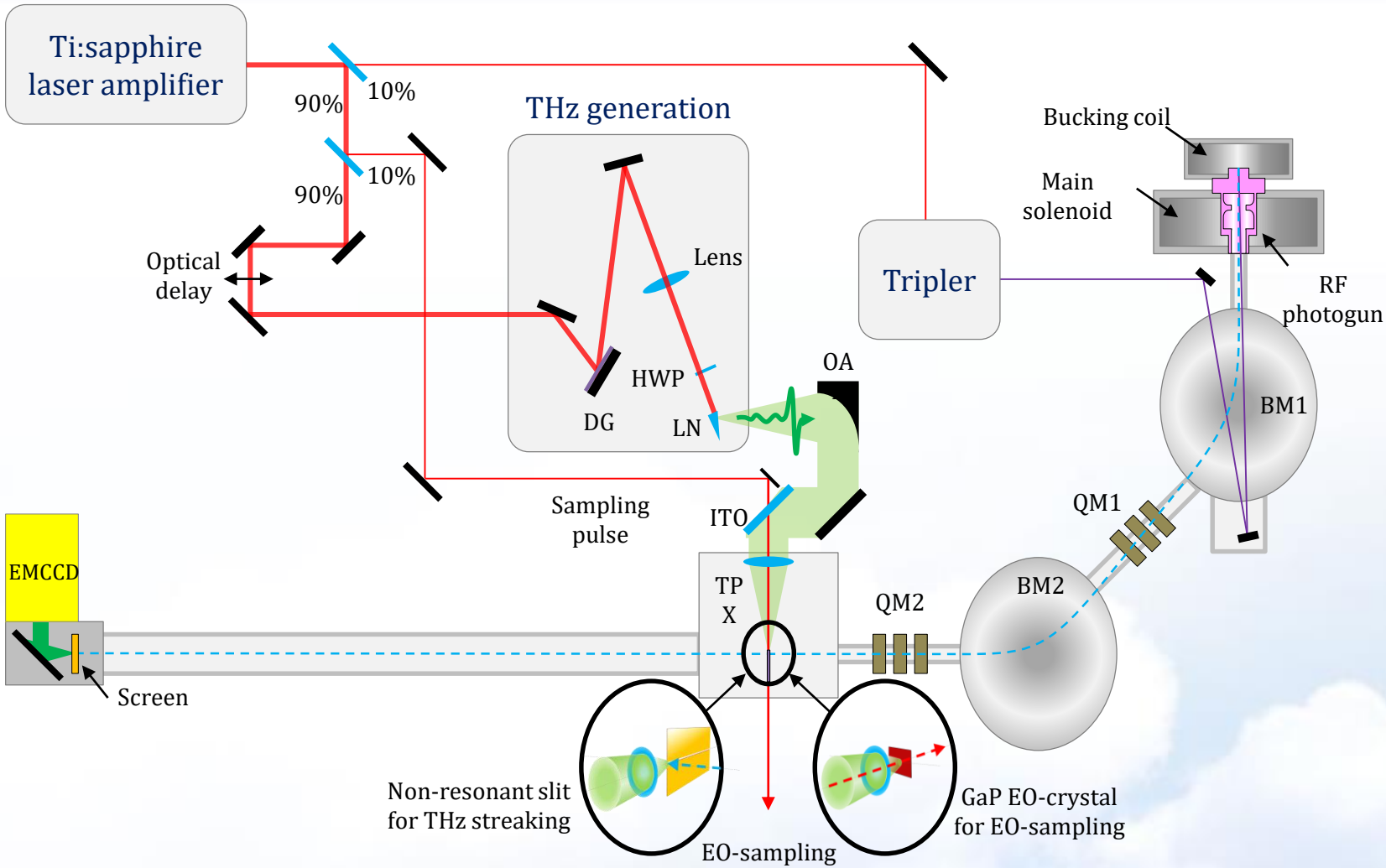
Electron bunch duration

$$\tau_e = \frac{c \times \sqrt{d_{on}^2 - d_{off}^2}}{V_{ST} \times D}$$

Streaking velocity

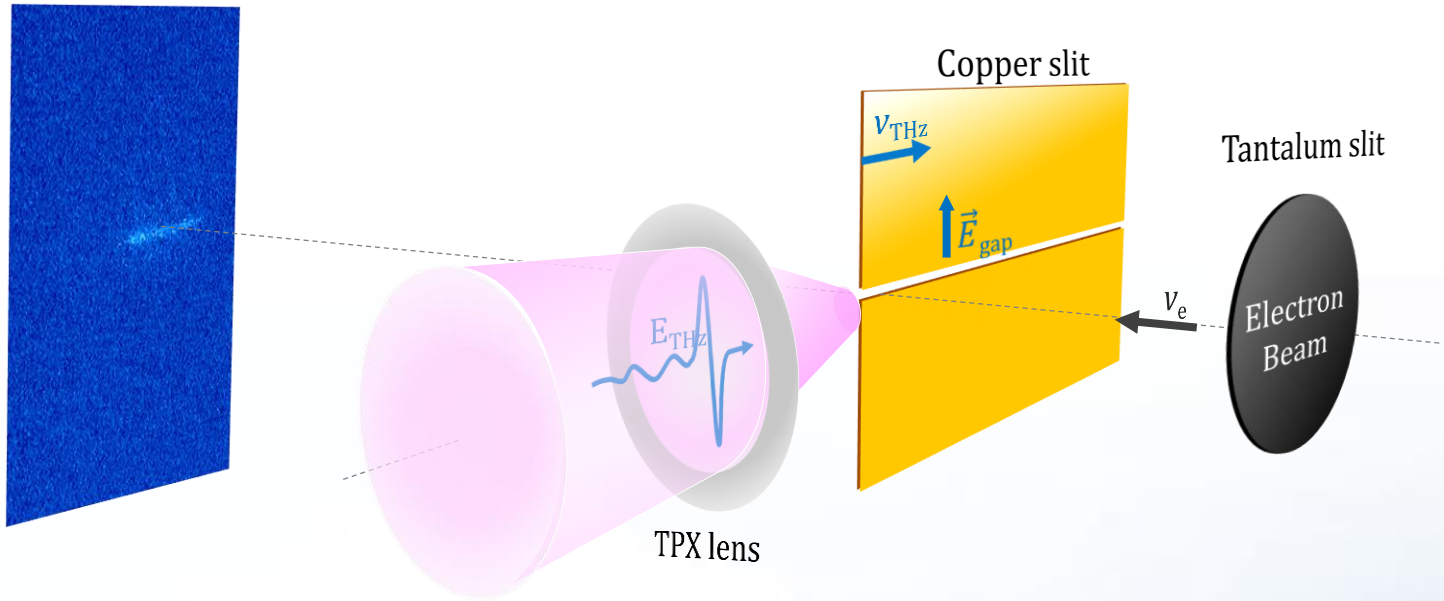
$$V_{ST} \Rightarrow \mu rad/fs$$

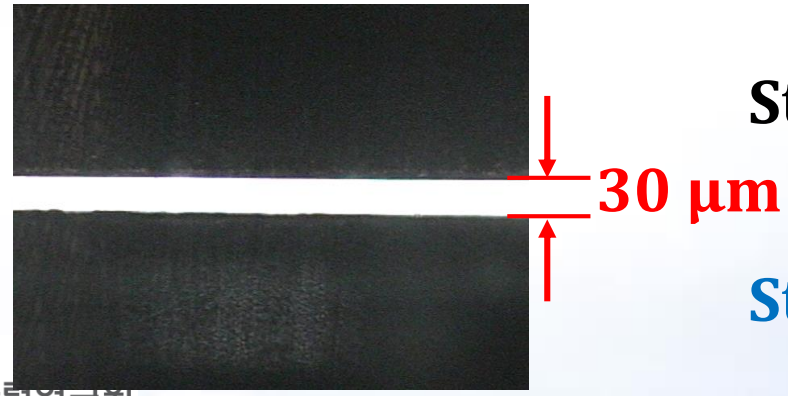
Setup of Terahertz (THz) Streak Camera



Kim et al., Nat. Photon. **14**, 245-249 (2020).

THz Streak Camera with Non-resonant Slit

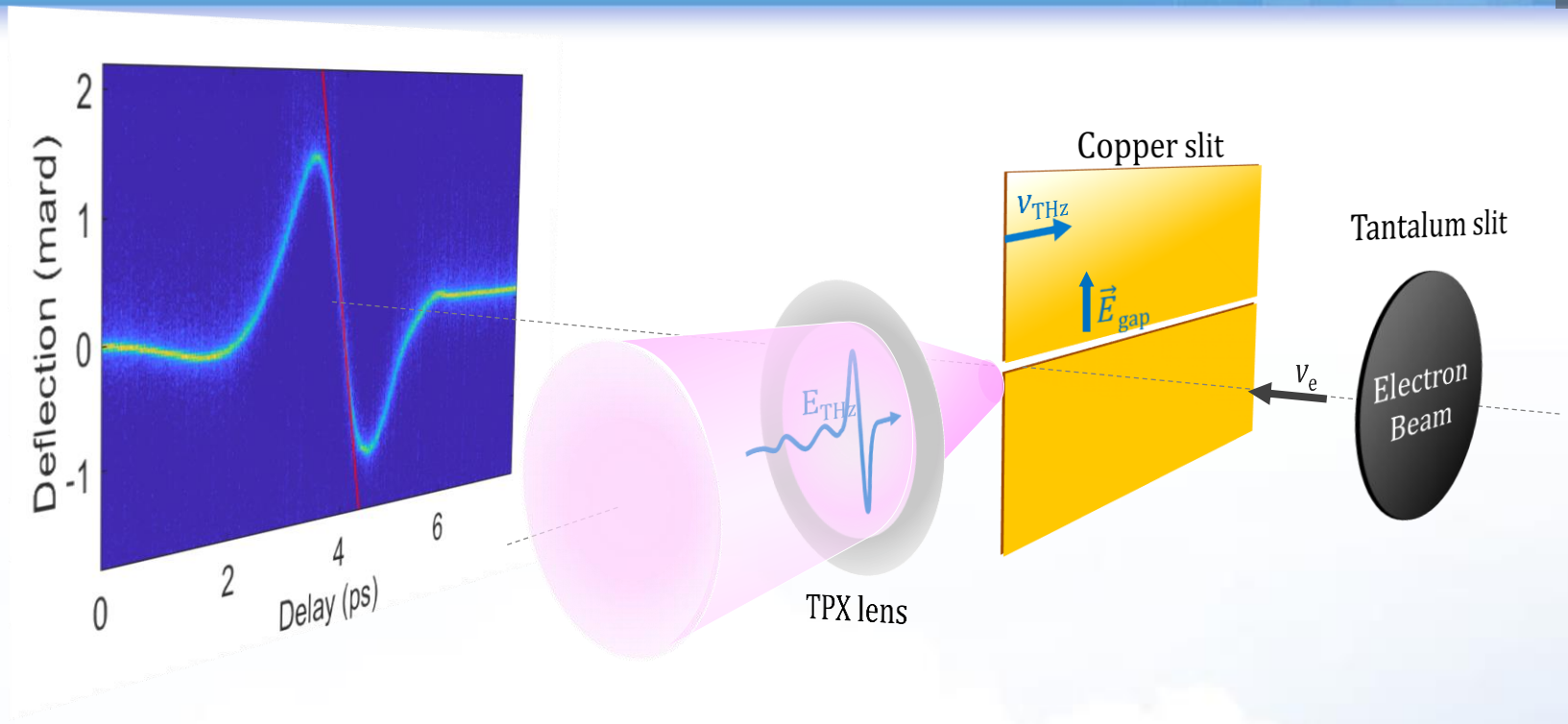


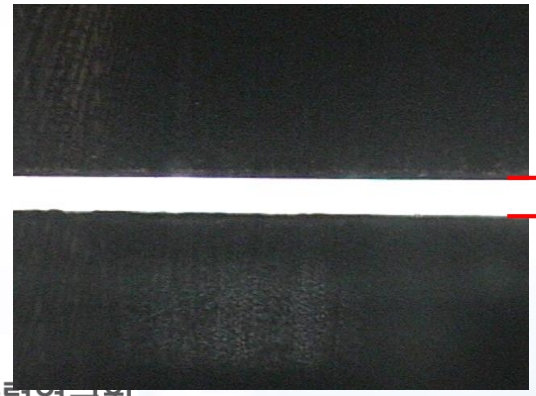


Streaking velocity = 4.8 μrad/fs

Streaking resolution = 3.8 fs

THz Streak Camera with Non-resonant Slit



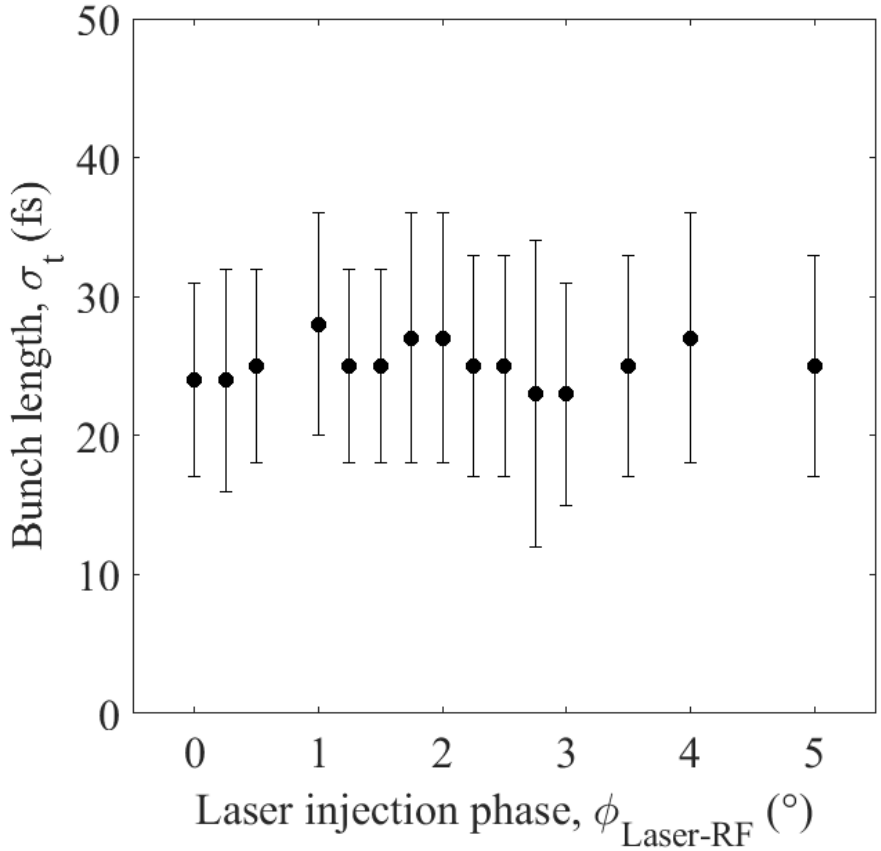


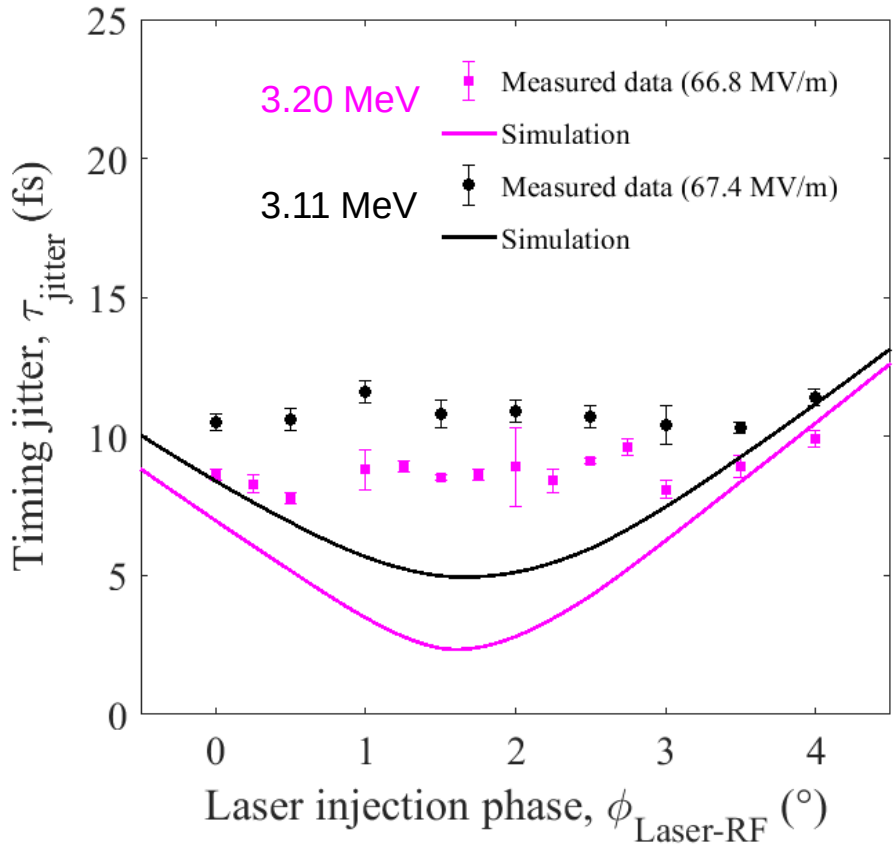
30 μm

Streaking velocity = 4.8 μrad/fs

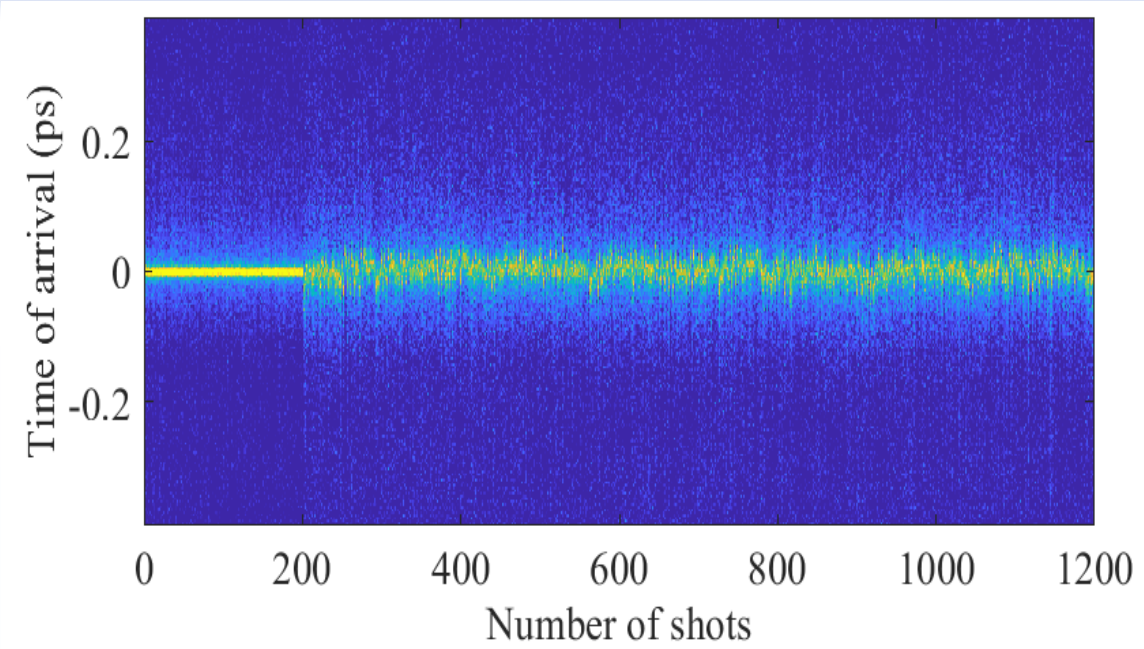
Streaking resolution = 3.8 fs

Experimental Results on THz Streaking





Experimental Results on THz Streaking



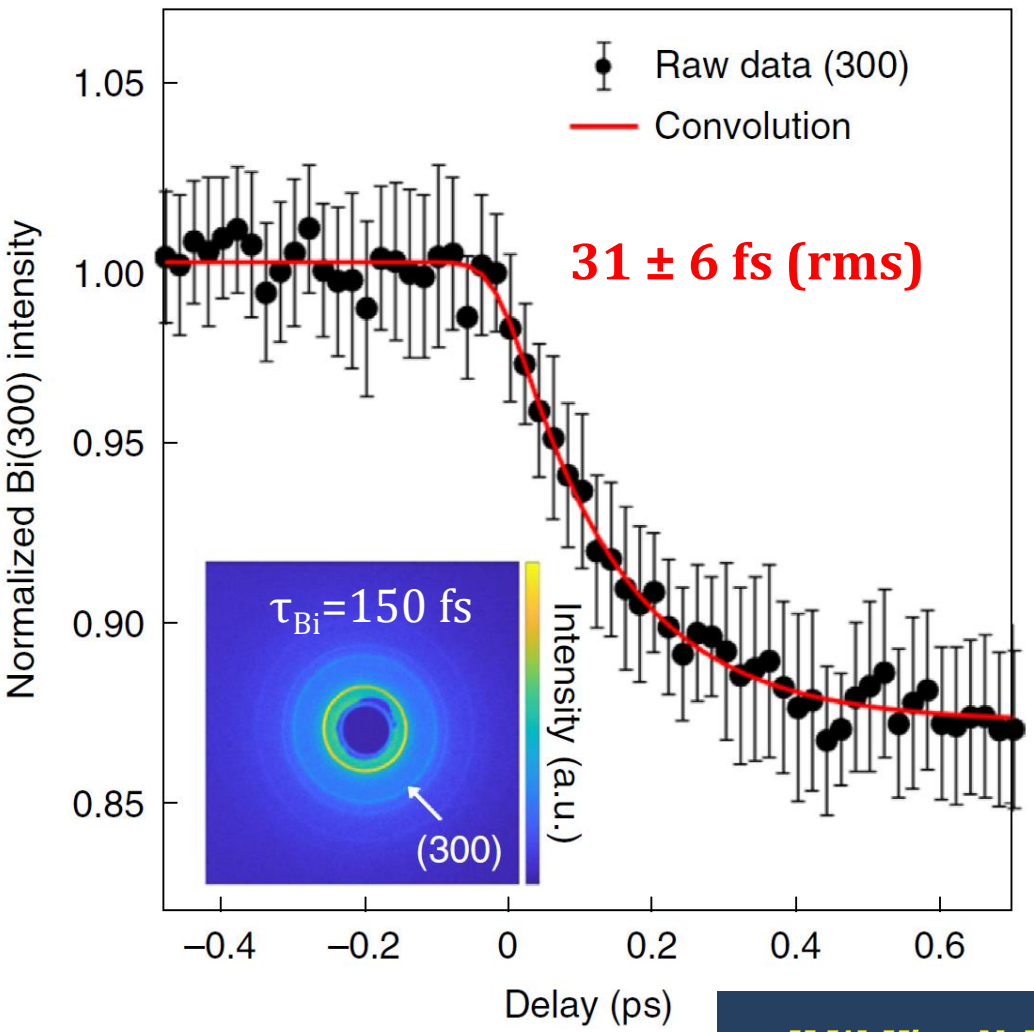
Bunch duration = **25 ± 8 fs (rms)** @ 0.57 pC, 3.11 MeV

Arrival time jitter b/w THz pulse & electron bunch = **8 fs (rms)**

$$\tau_{IRF} = \sqrt{\tau_{pump\ laser}^2 + \tau_{electron}^2 + \tau_{jitter}^2 + \tau_{drift}^2}$$

τ_{IRF}	$\tau_{pump\ laser}$	$\tau_{electron}$	τ_{jitter}	τ_{drift}
32 fs	19 fs	25 fs	8 fs	0

Dynamics of Polycrystalline Bismuth Film



$$\tau_{IRF} = \sqrt{\tau_{pump\ laser}^2 + \tau_{electron}^2 + \tau_{jitter}^2 + \tau_{drift}^2}$$

τ_{IRF}	$\tau_{pump\ laser}$	$\tau_{electron}$	τ_{jitter}	τ_{drift}
32 fs	19 fs	25 fs	8 fs	0

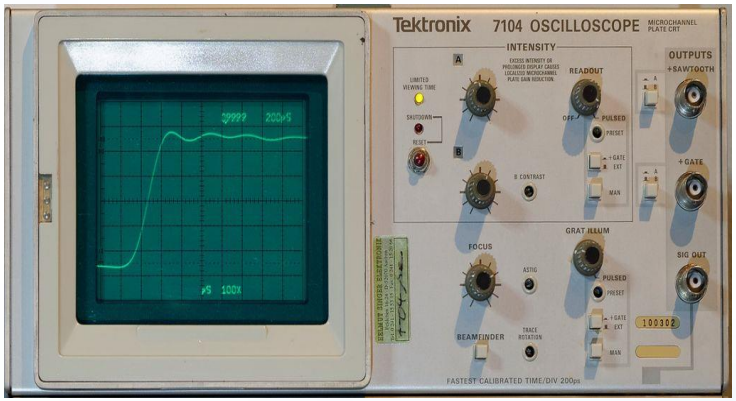
H.W. Kim, N. Vinokurov, et al., Nat. Photon. 14, 245-249 (2020).

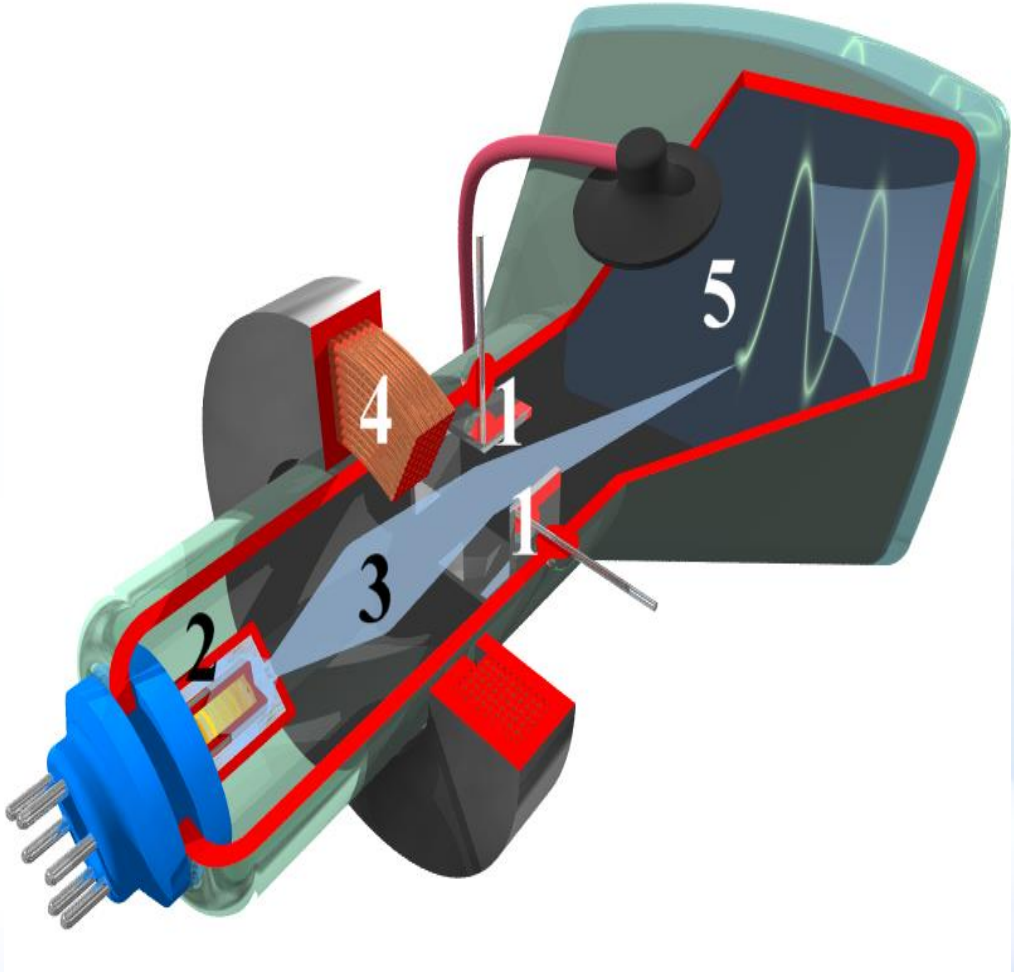
Electron is the most trustful probe of EM-field

The first cathode-ray oscilloscope (1897)

K. F. Braun

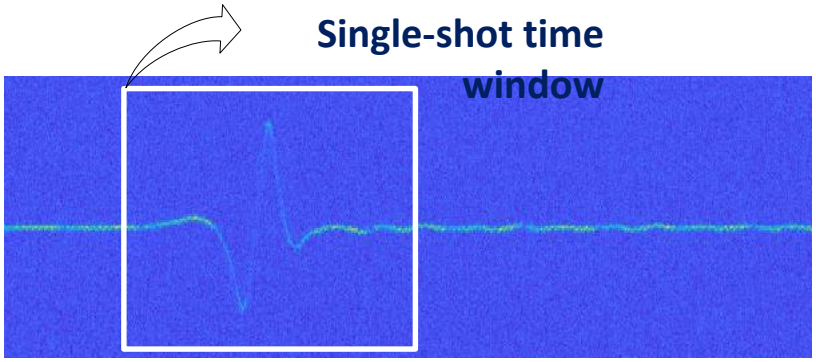
1 GHz at 10 mV analog oscilloscope (1979)

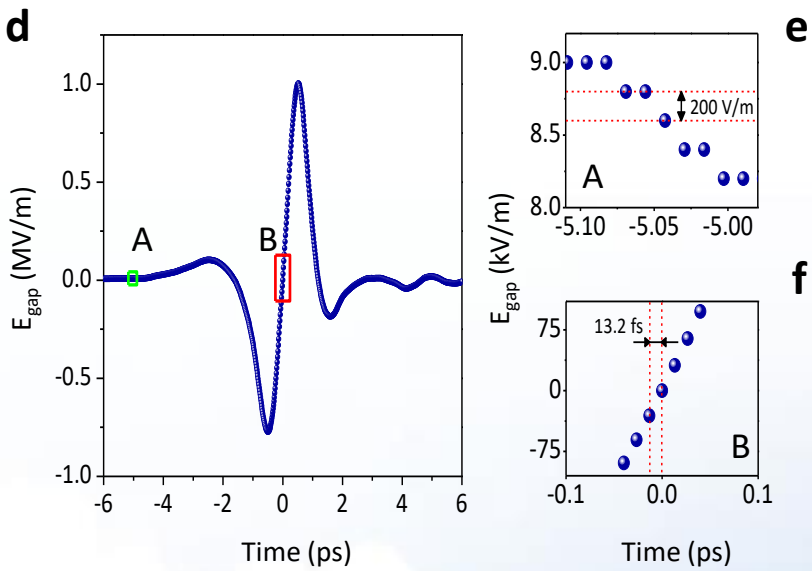




https://upload.wikimedia.org/wikipedia/commons/9/98/CRT_oscilloscope.png

Recorded THz waveform

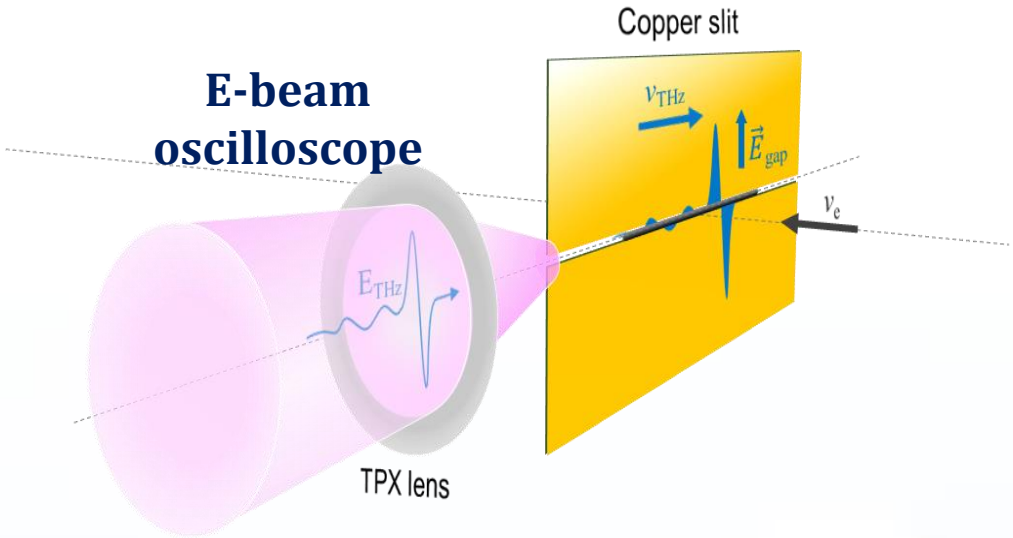


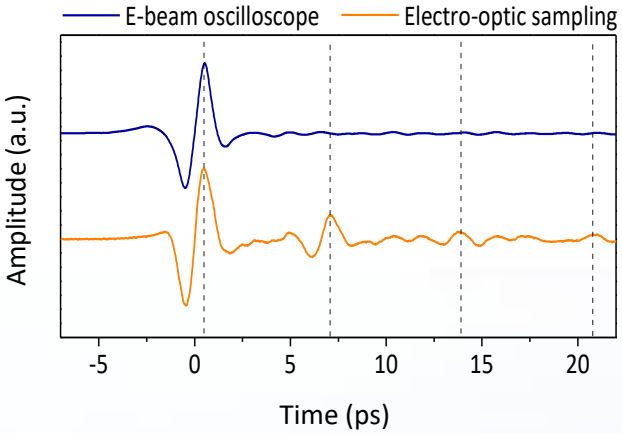


- Horizontal beam size @ slit = 3.7 mm
- Single-shot time window = 12.3 ps
- ~100 electrons/pixel for single-shot image
- Electron bunch : 0.5 pC, 3.101 MeV @ 50 Hz
- Time resolution per pixel = 13.2 fs (Sampling rate ~ 75.7 TS/s)
- Resolution of E-field amplitude = 200 V/m

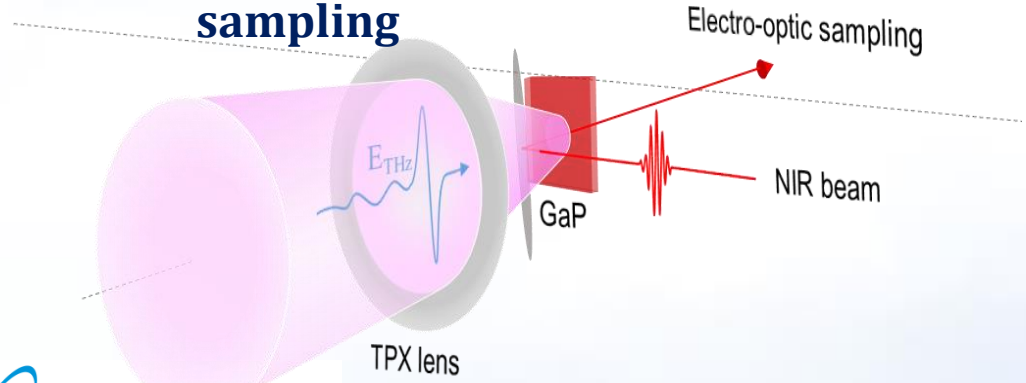
Signal integrity

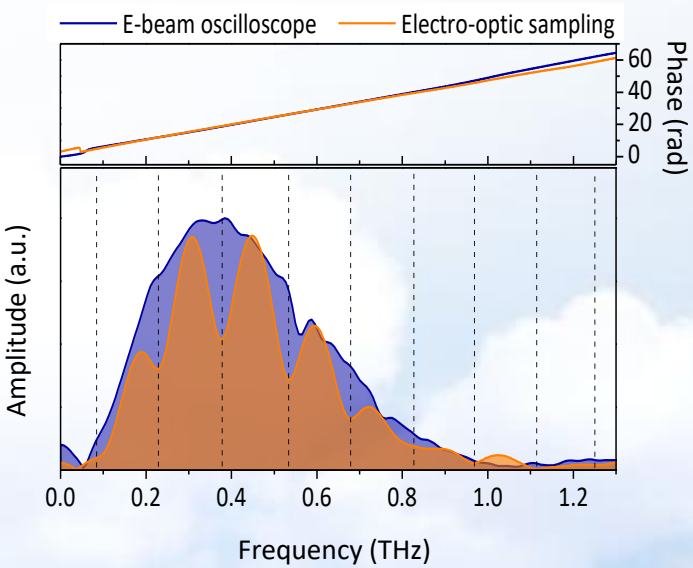
E-beam oscilloscope



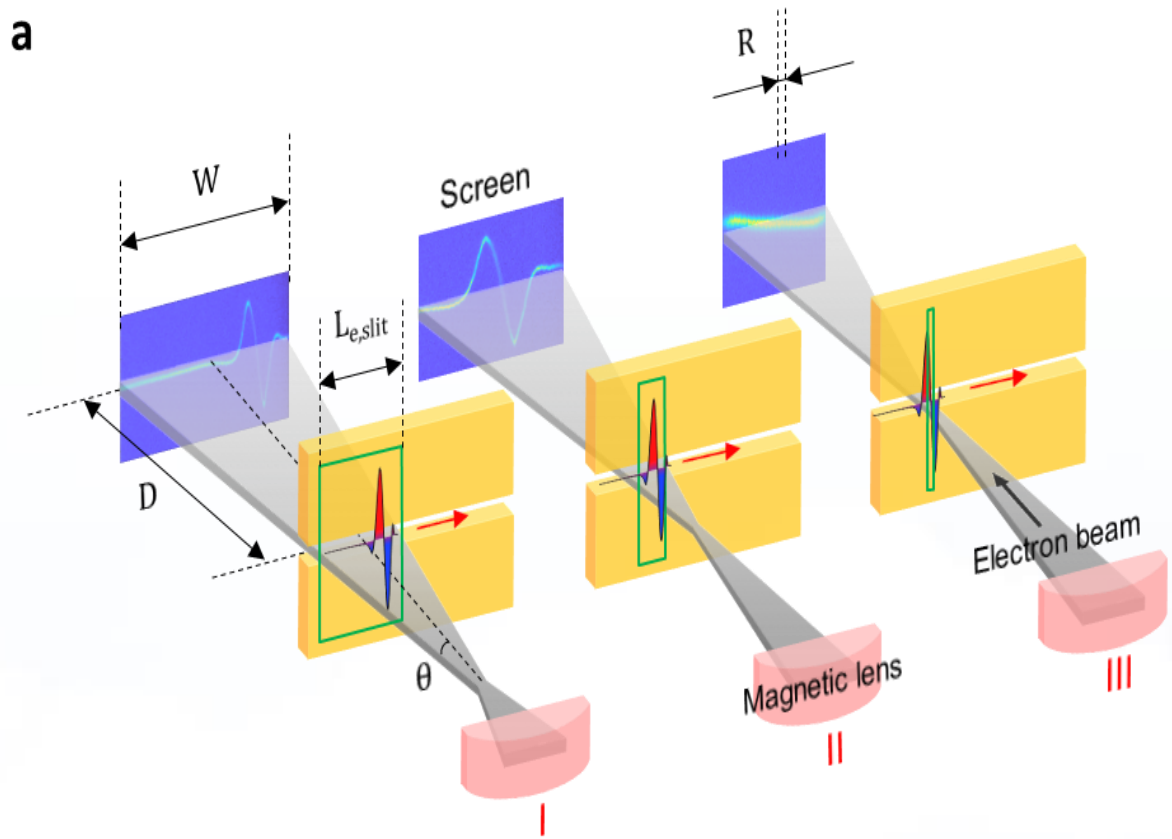


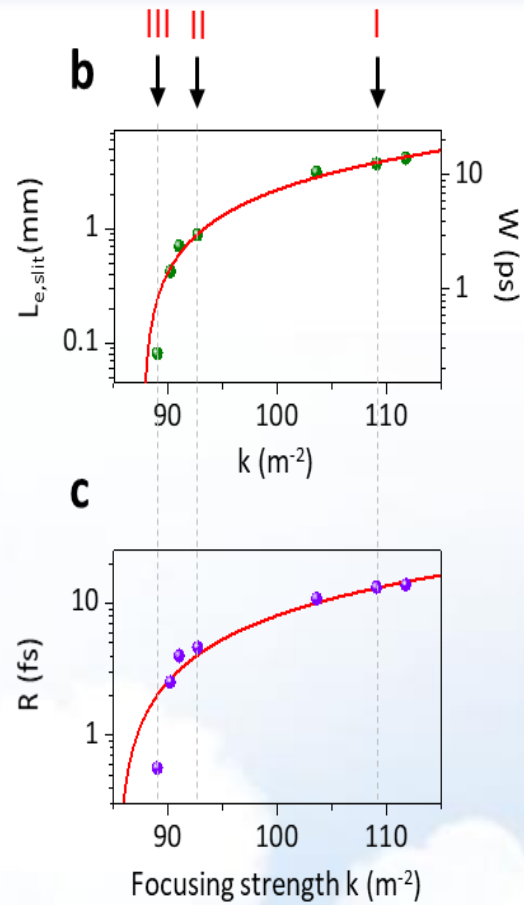
Electro-optic sampling





Feasibility of real-time PHz oscilloscope





For 800 nm pulse visualization,

1. Electron pulse duration should be 170 as.

2. Thickness of metal slit should be 53 nm.

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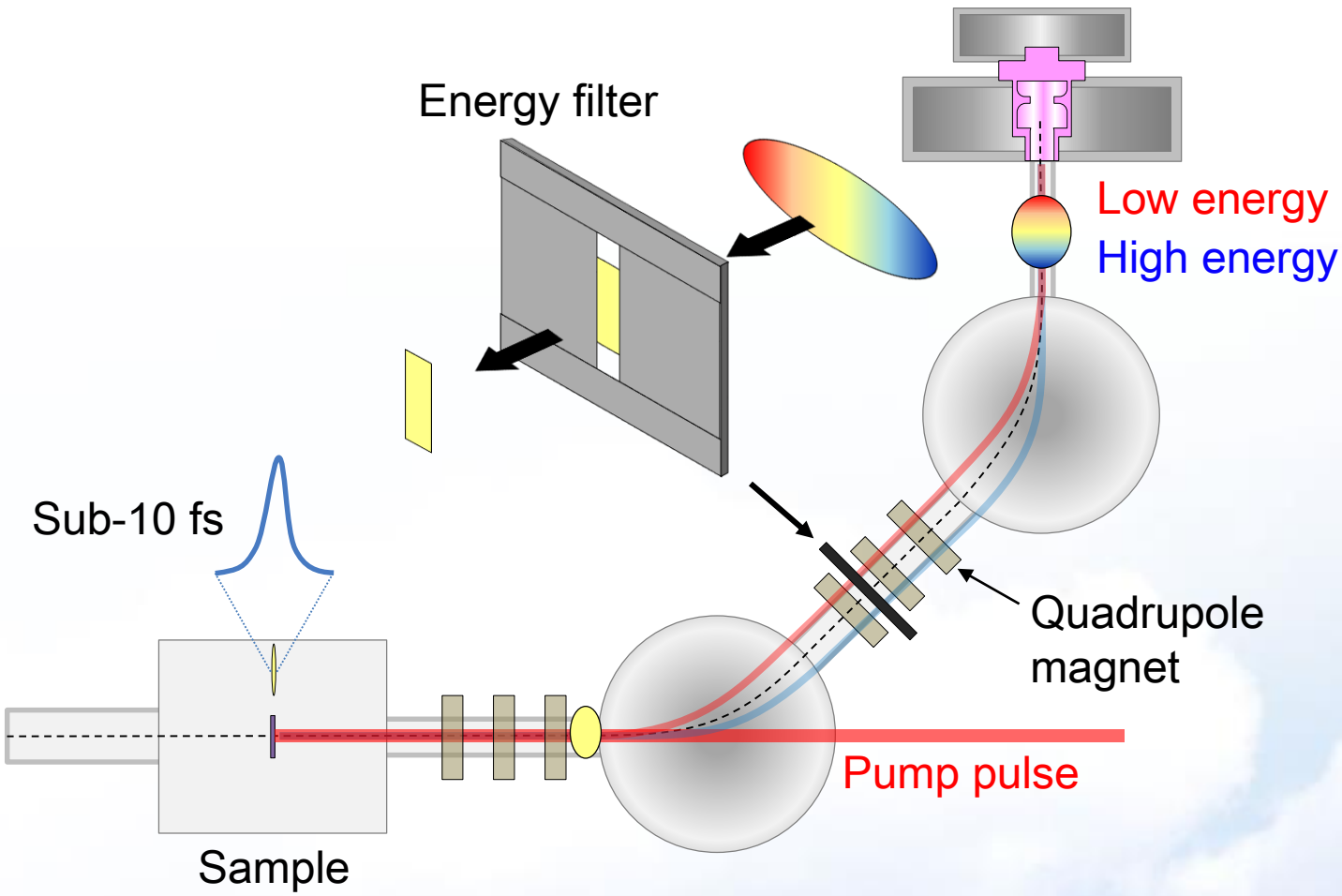
Manuscript under review.

Sub-10 fs UED by using an Energy Filter



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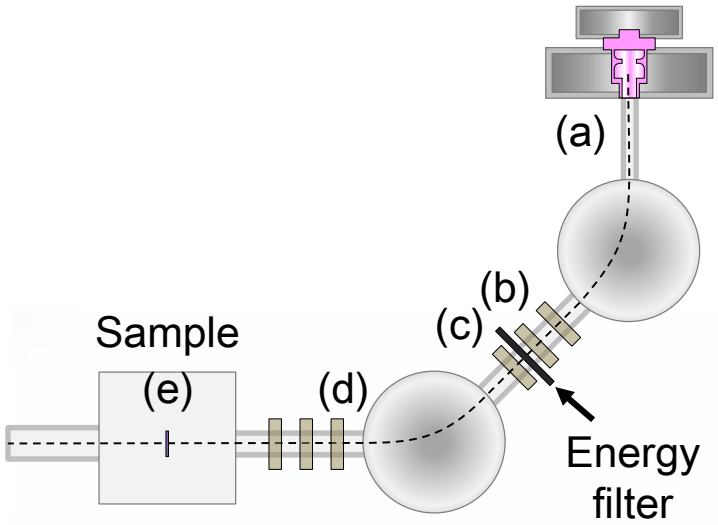
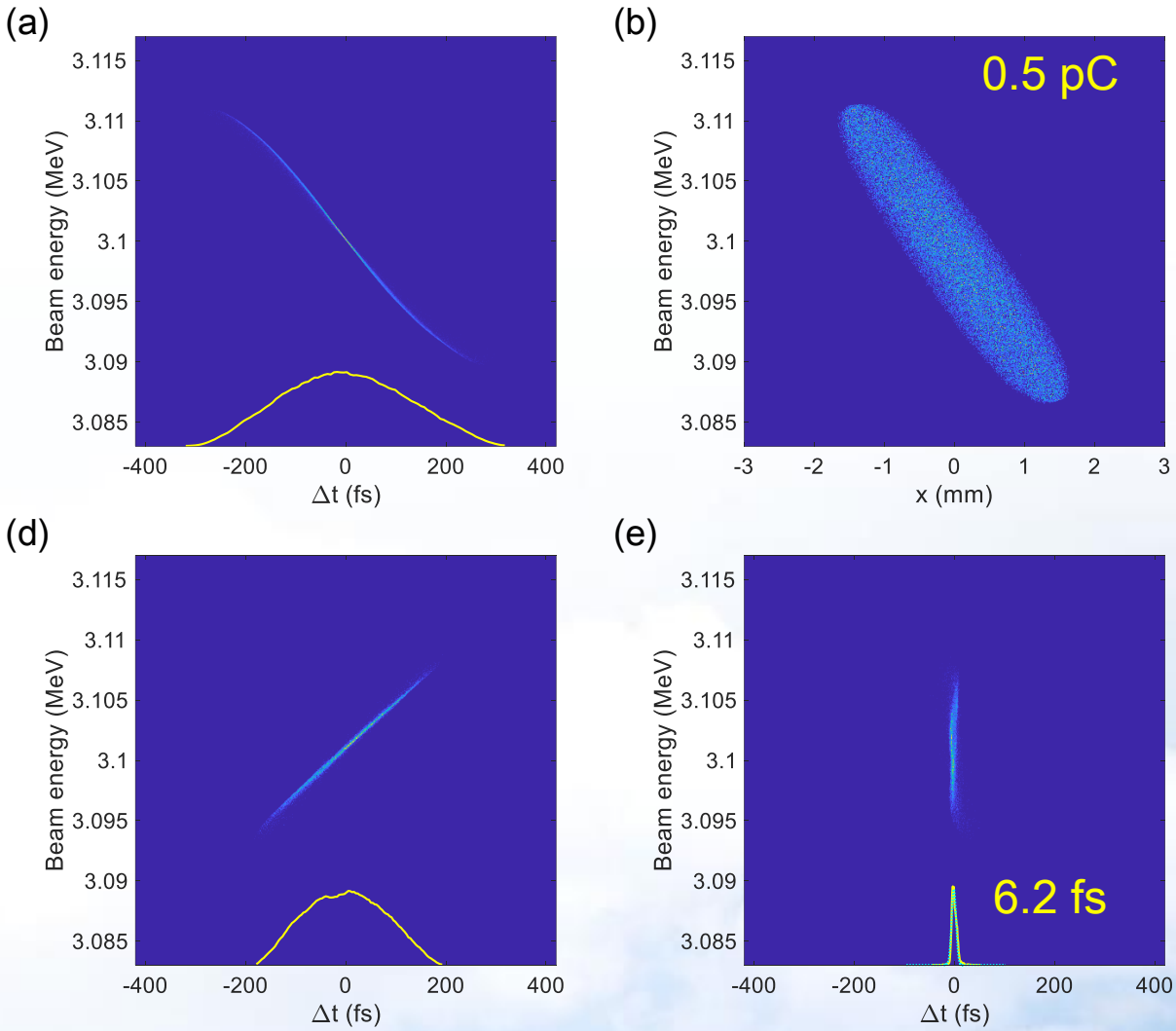
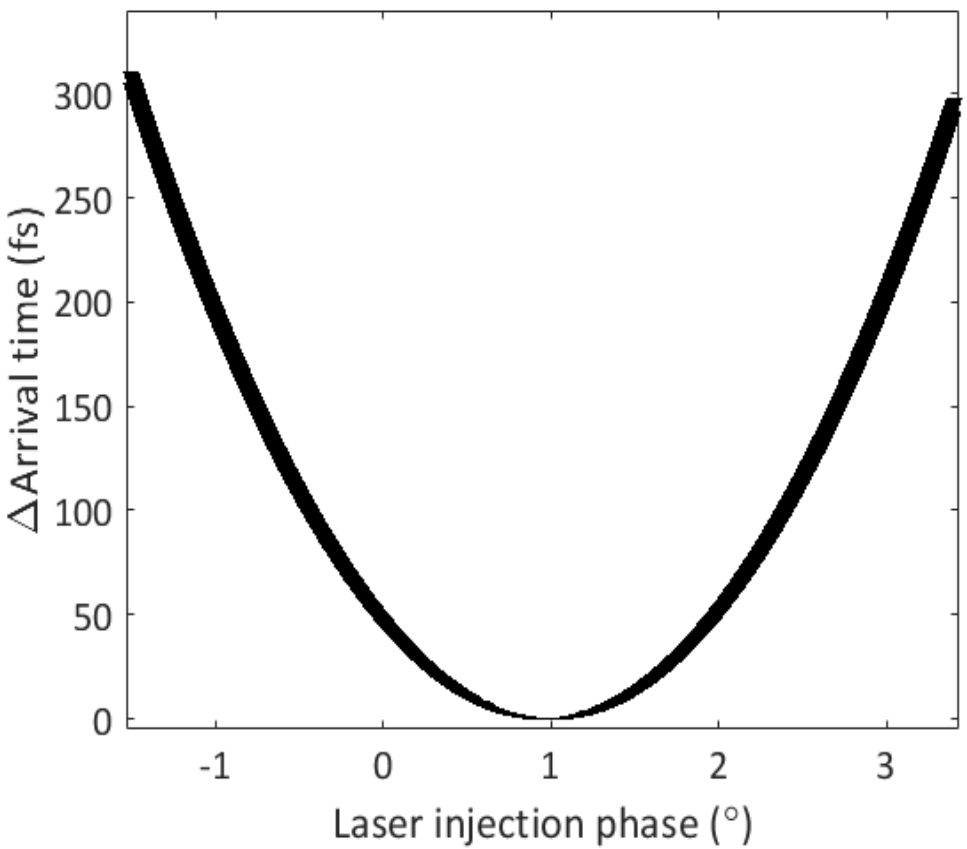
H. W. Kim et al., Structural Dynamics, 7, 034301 (2020).

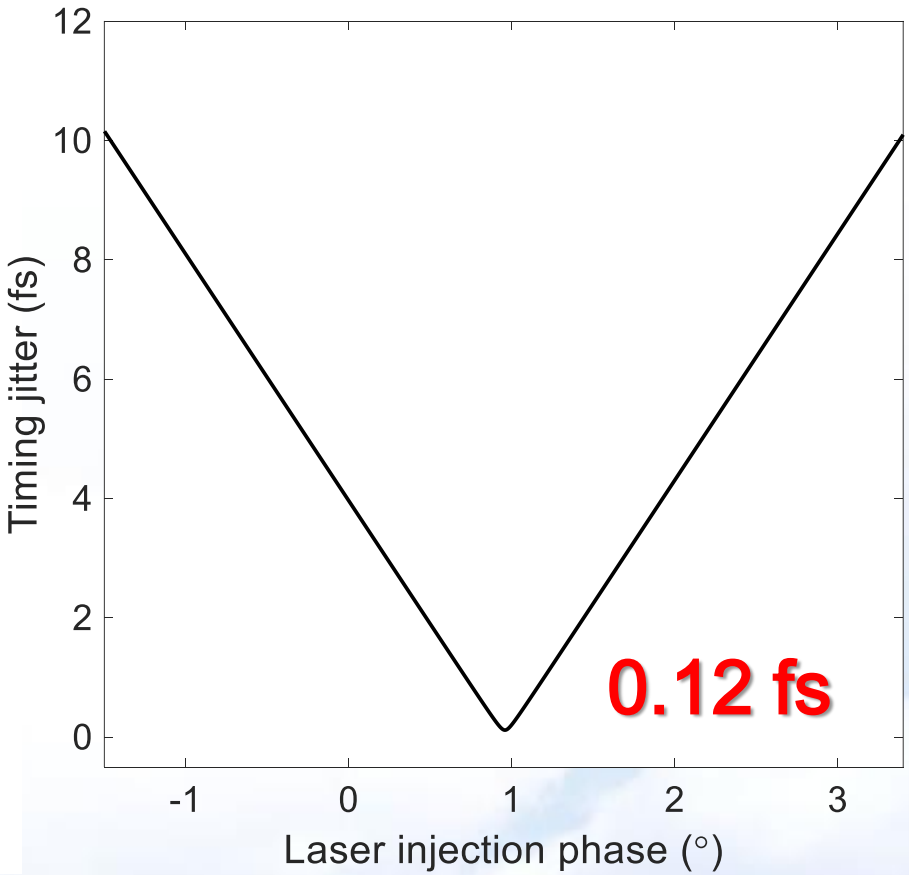
Sub-10 fs UED by using an Energy Filter



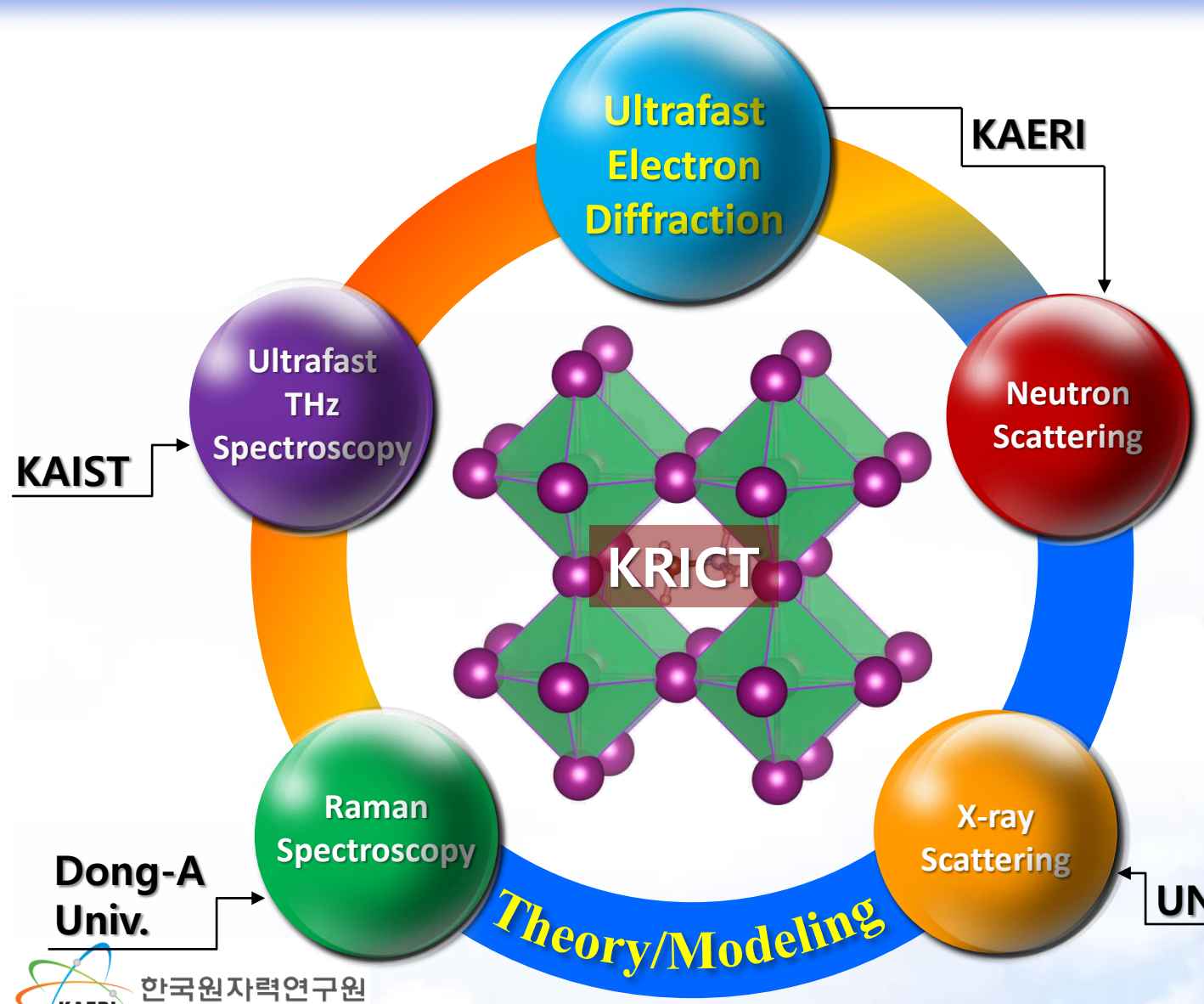


Sub-10 fs UED by using an Energy Filter





Collaboration for New Understanding



Unknown physics of metal halide perovskites

- ✓ Long Charge-carrier Lifetime
- ✓ Benign Defects
- ✓ Role of the Organic Cation
- ✓ Ion Migration
- ✓ Ferroelectricity
- ✓ Soft Lattice & Dynamic Disorder

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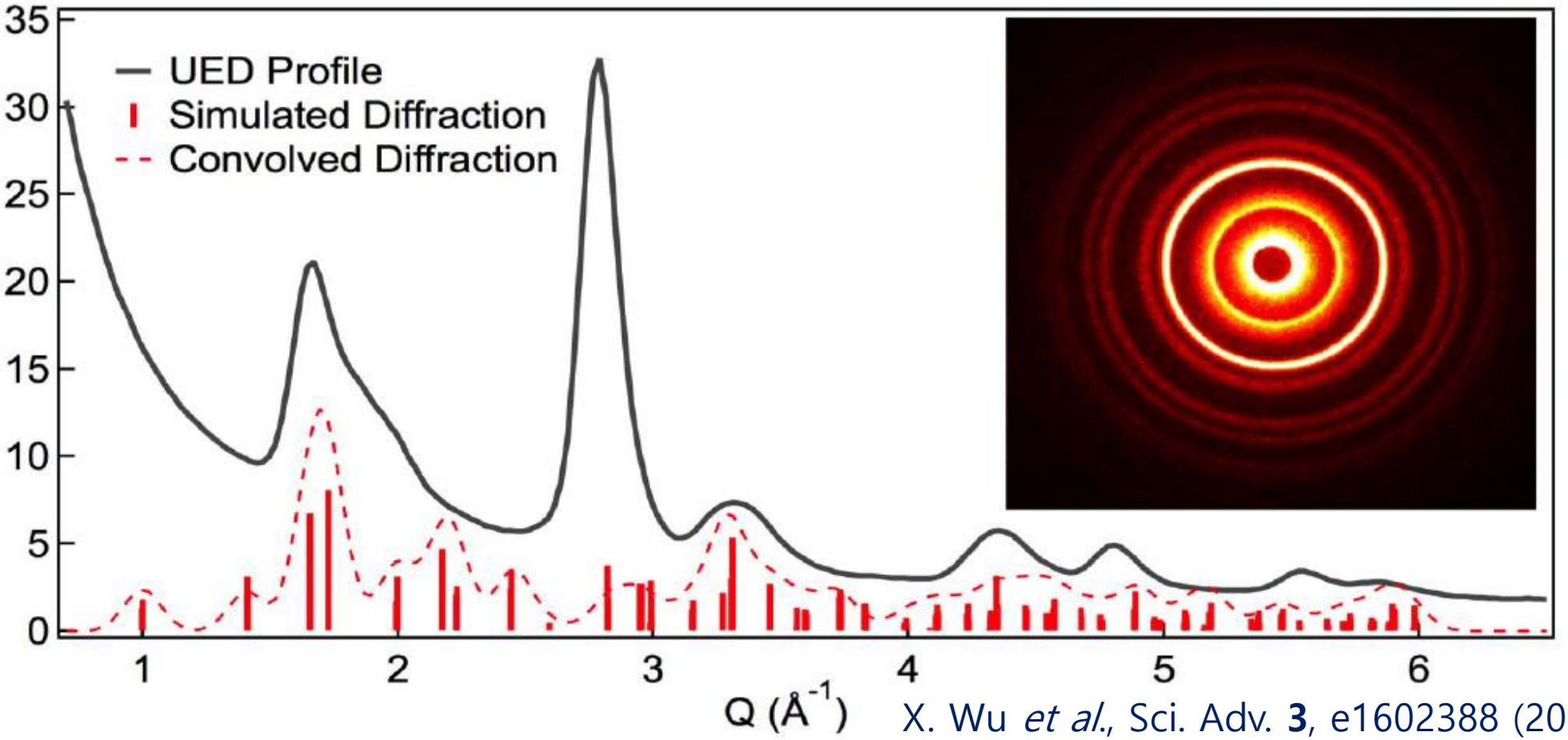
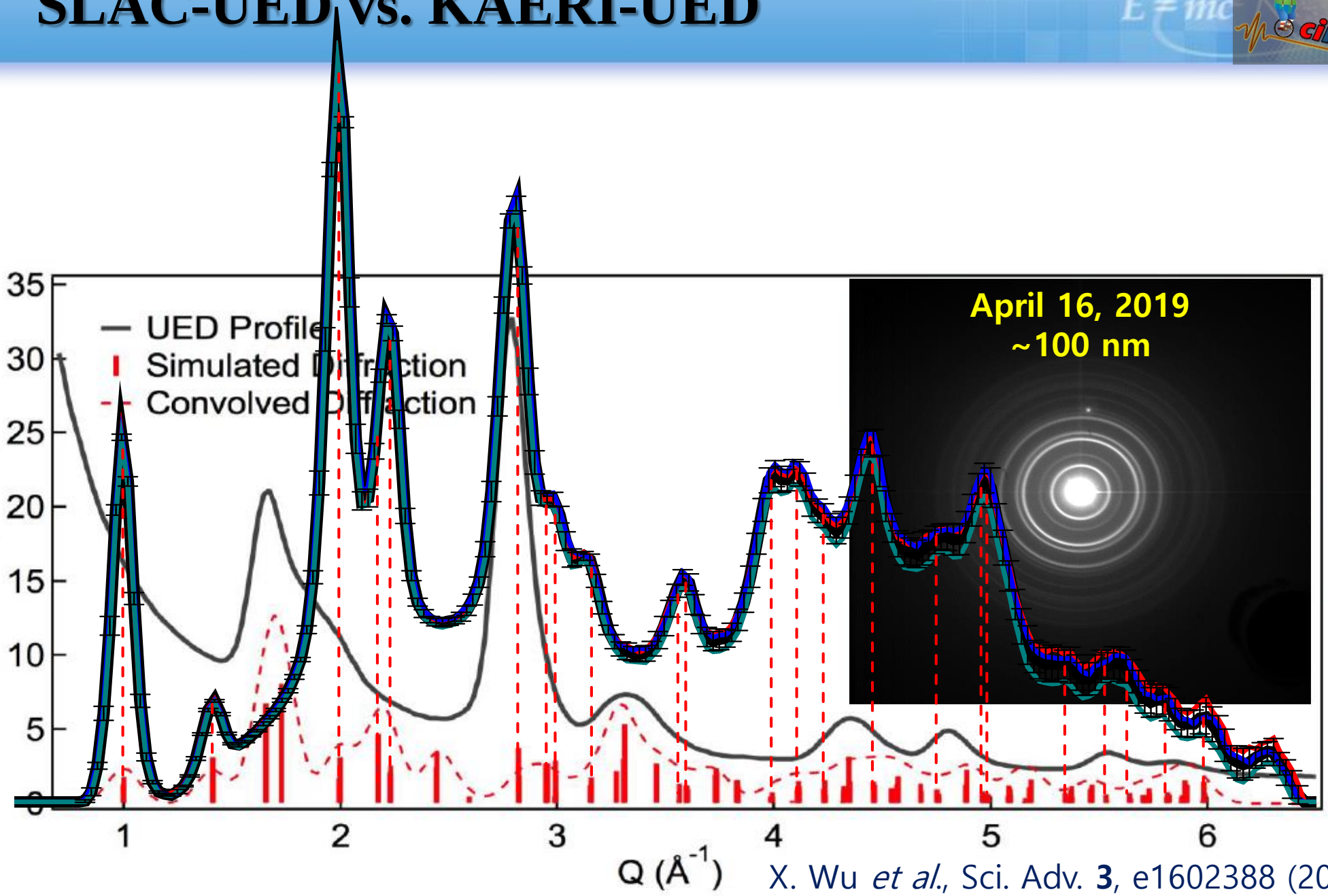
SLAC-UED vs. KAERI-UED

Perovskite Diffractions measured by SLAC-UED



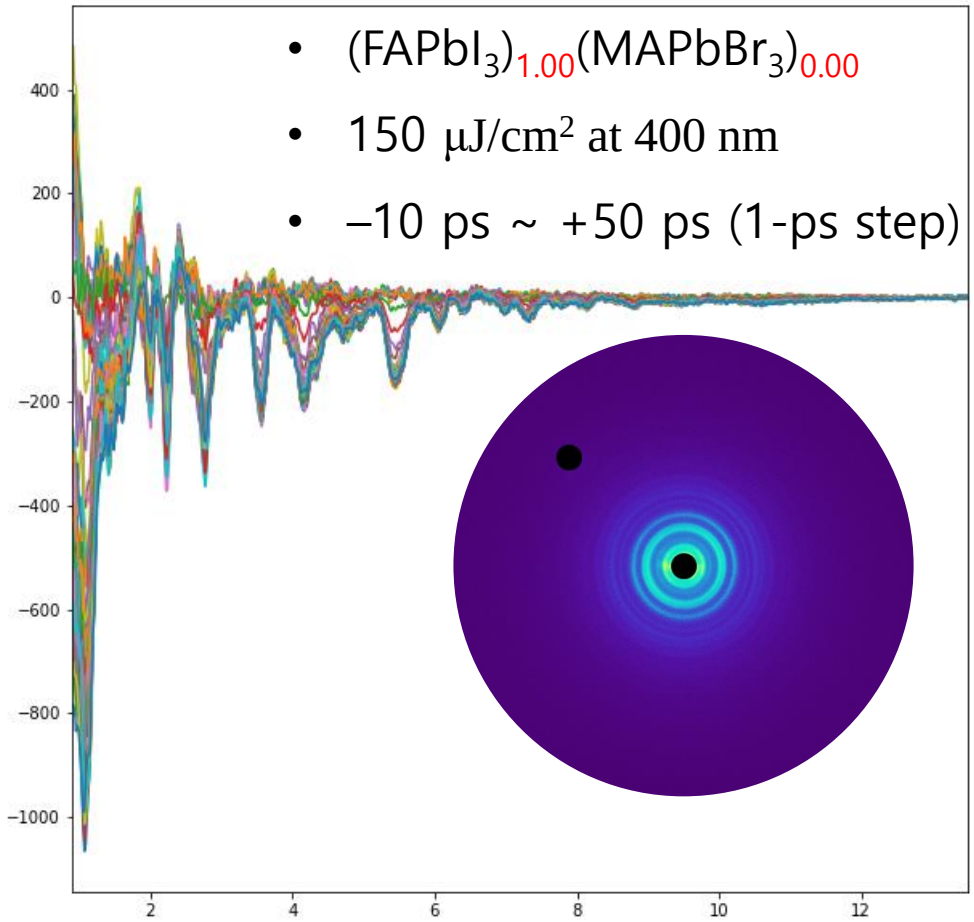
X. Wu *et al.*, Sci. Adv. **3**, e1602388 (2017)

SLAC-UED vs. KAERI-UED

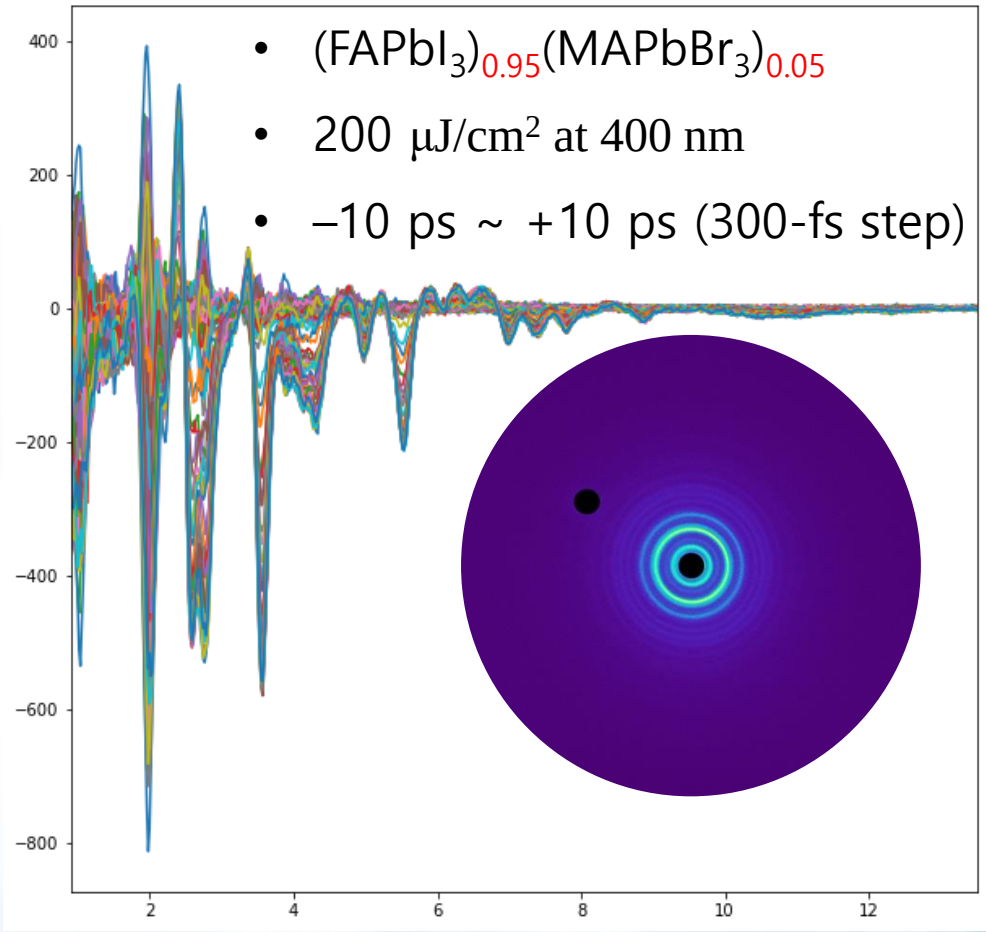


X. Wu *et al.*, Sci. Adv. **3**, e1602388 (2017)

Overall 1D difference curves; $\Delta I(q,t) = I(q,t) - I(q,t_{ref})$



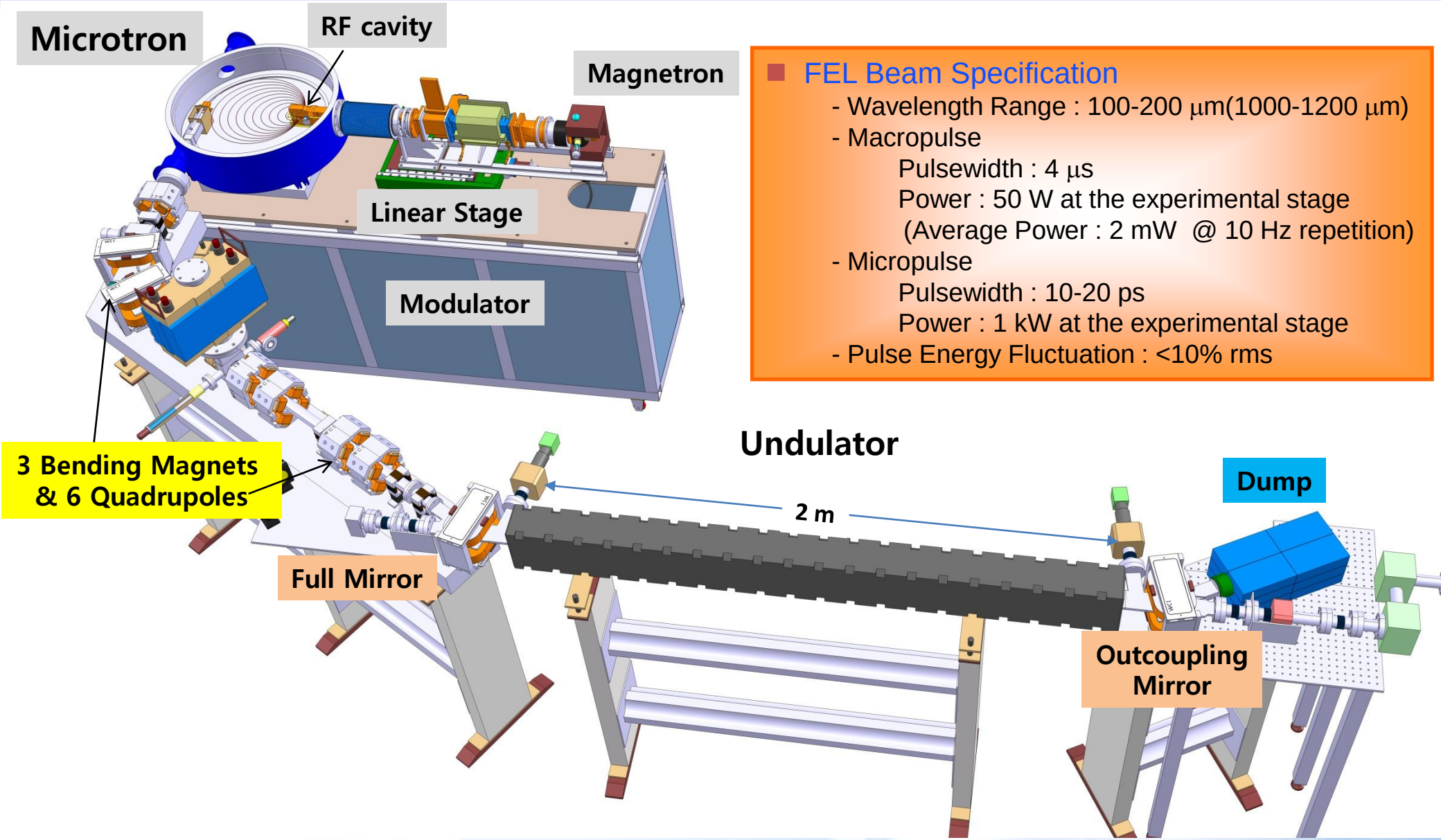
q (Å^{-1})



q (Å^{-1})

II. Terahertz Free Electron Laser

Terahertz FEL (1995-present)



- FEL Beam Specification
  - Wavelength Range : 100-200 μm(1000-1200 μm)
  - Macropulse
    - Pulsewidth : 4 μs
    - Power : 50 W at the experimental stage
    - (Average Power : 2 mW @ 10 Hz repetition)
  - Micropulse
    - Pulsewidth : 10-20 ps
    - Power : 1 kW at the experimental stage
  - Pulse Energy Fluctuation : <10% rms

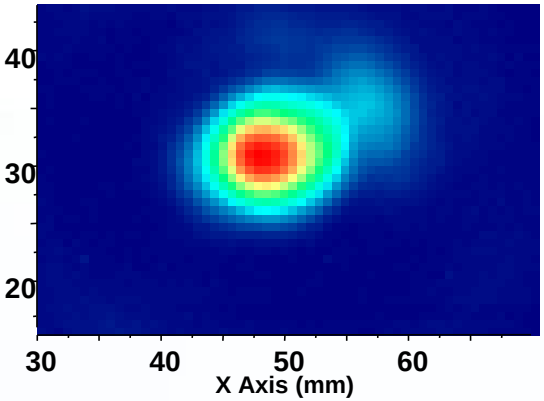
FEL Beam Characteristics

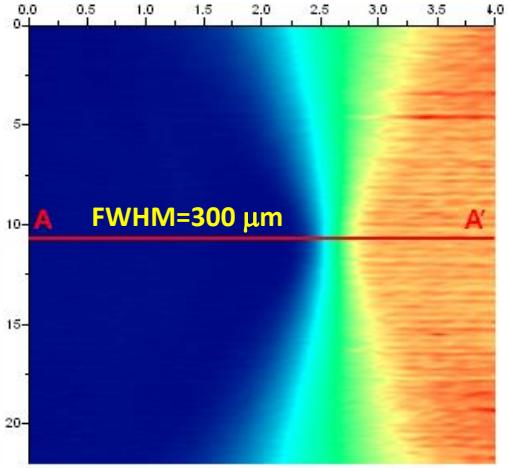
"First Lasing of the KAERI Compact Far-Infrared Free-Electron Laser Driven by a Magnetron-Based Microtron", Y.U.Jeong, et al., Nucl. Instr. and Meth. in Phys. Research A 475, 47(2001).

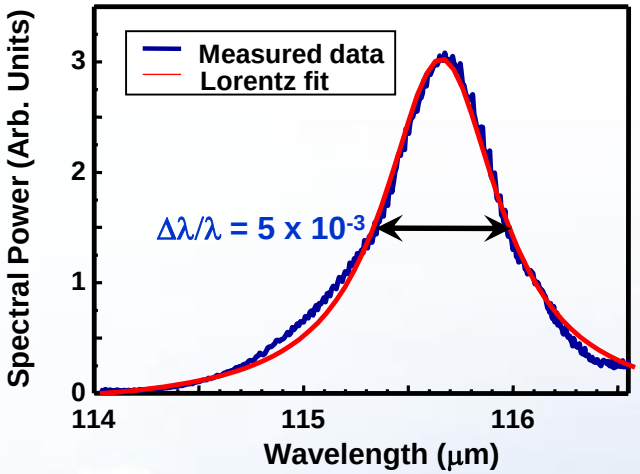
Diffraction-limited Beam

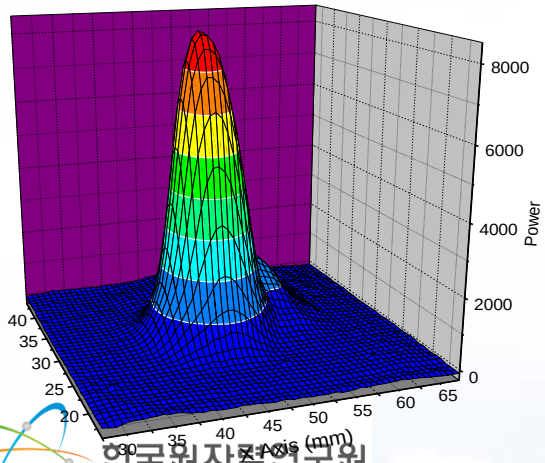
Fourier-transform Limited Beam

Focusing by a Mirror of f/#=0.26



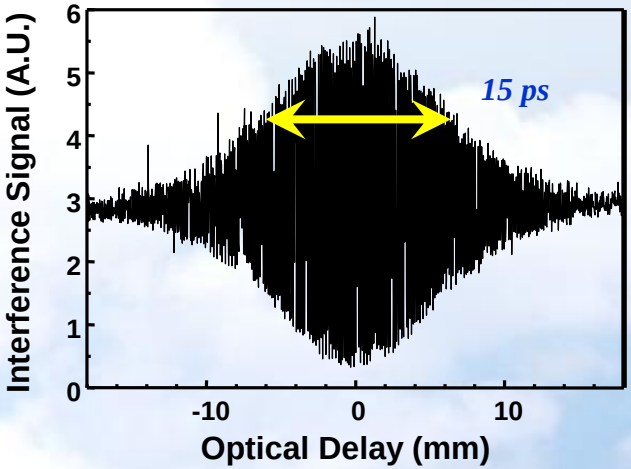






Low Beam Energy

THz Macropulse Energy : 0.3 mJ
THz Micropulse Energy : 20 nJ
Max. Average Power : 3 mW (@ 10 Hz)



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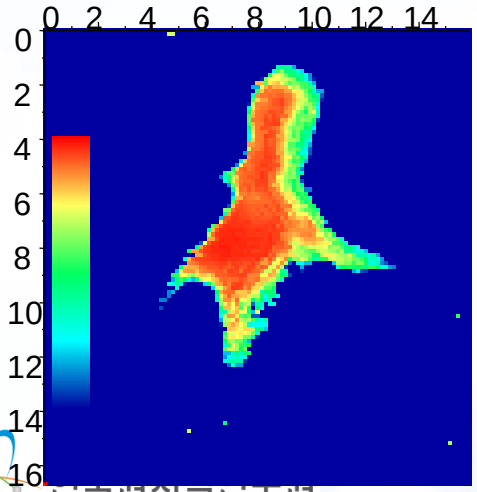
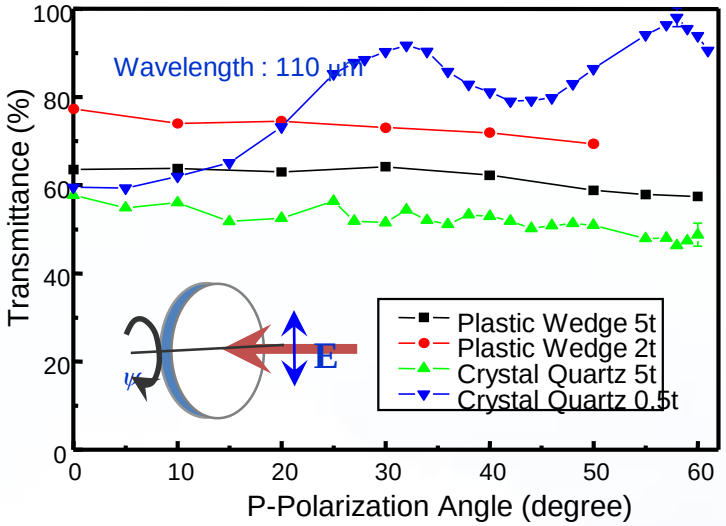
KAERI Activities on THz FEL Applications

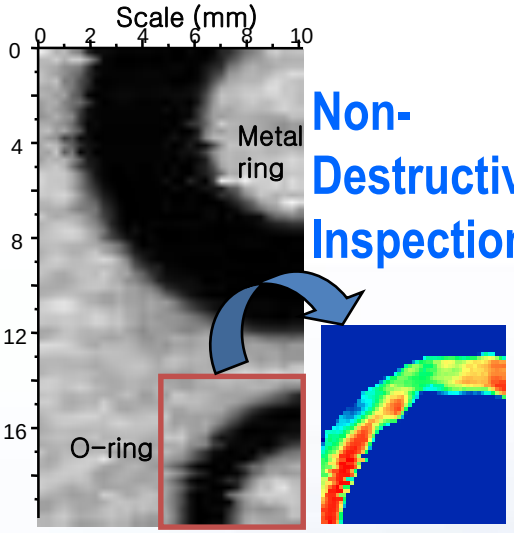
THz Imaging



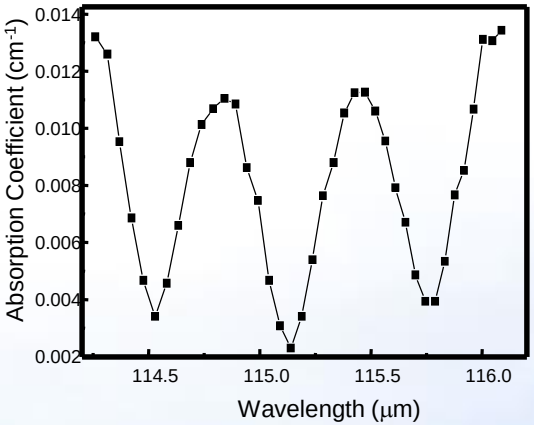
Material Study



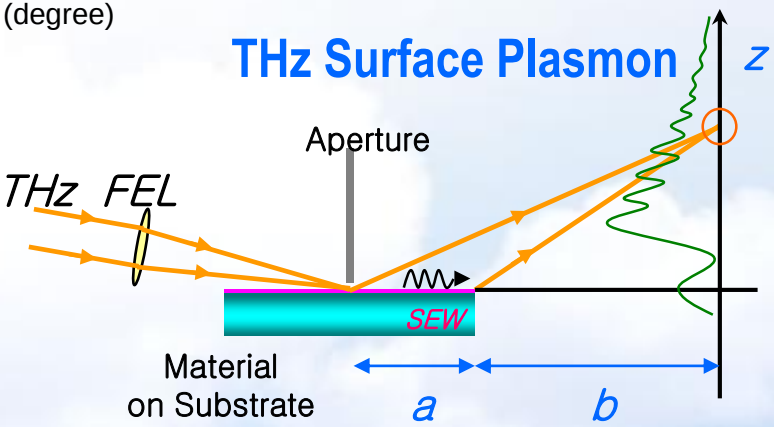
Non-Destructive Inspection



Spectroscopy



THz Surface Plasmon



$$Re\,\Omega \cdot a + \sqrt{b^2 + z^2} + \Delta\varphi \cdot \lambda - \sqrt{(b+a)^2 + z^2} = m\lambda$$

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Table-top THz FEL for Security Inspection

- Wavelength : 300-600 μm
- THz Power : 0.1-1 W
- Target System Size : Table-top or Rack Type

↓

Microtron-based FEL
with a Short & Strong Hybrid EM Undulator
- a Low-loss LIPS Waveguide & Mesh Mirrors

Laboratory-scale THz FEL

3.0 x 5.0 m^2

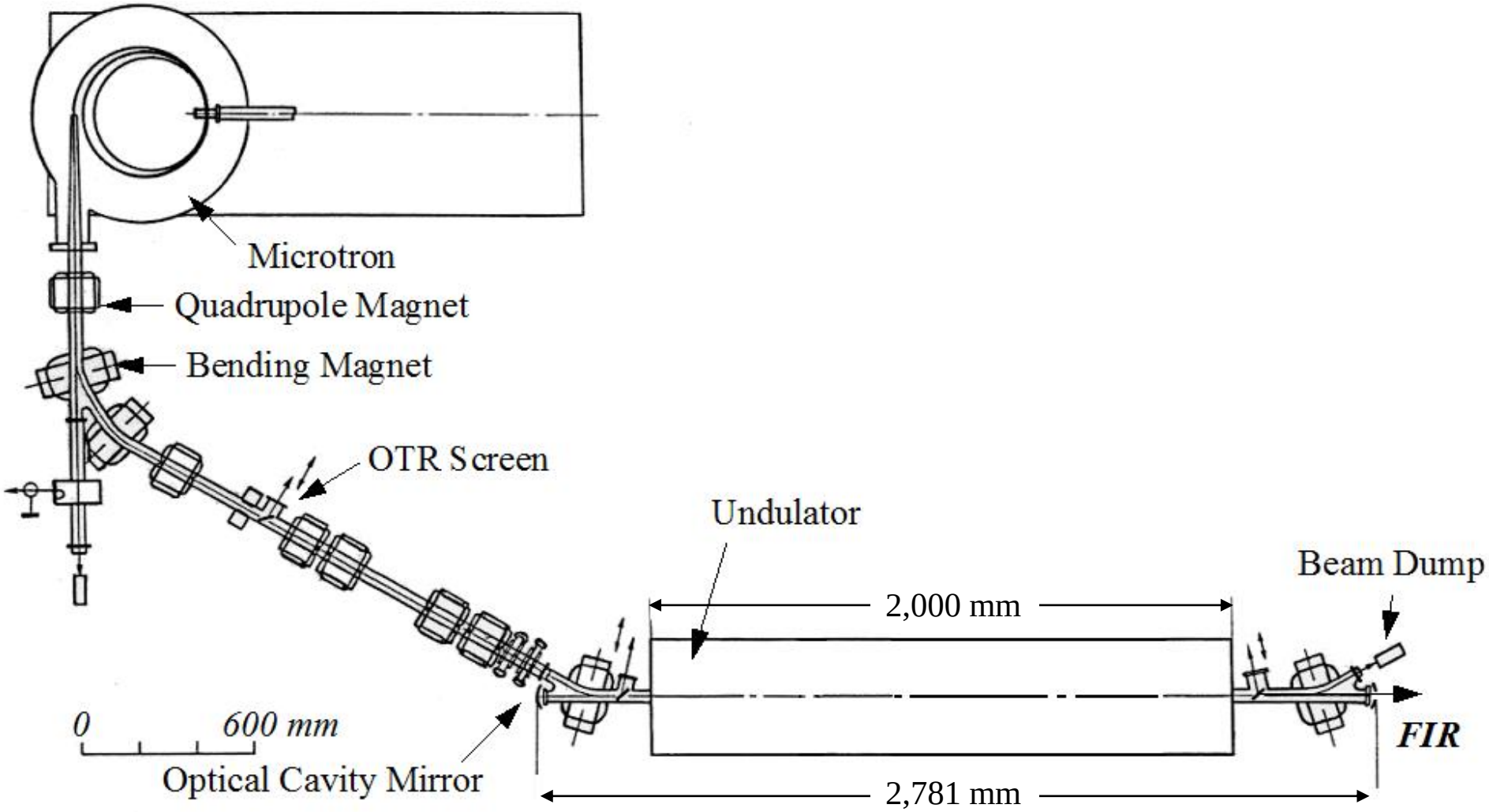

Table-top THz FEL

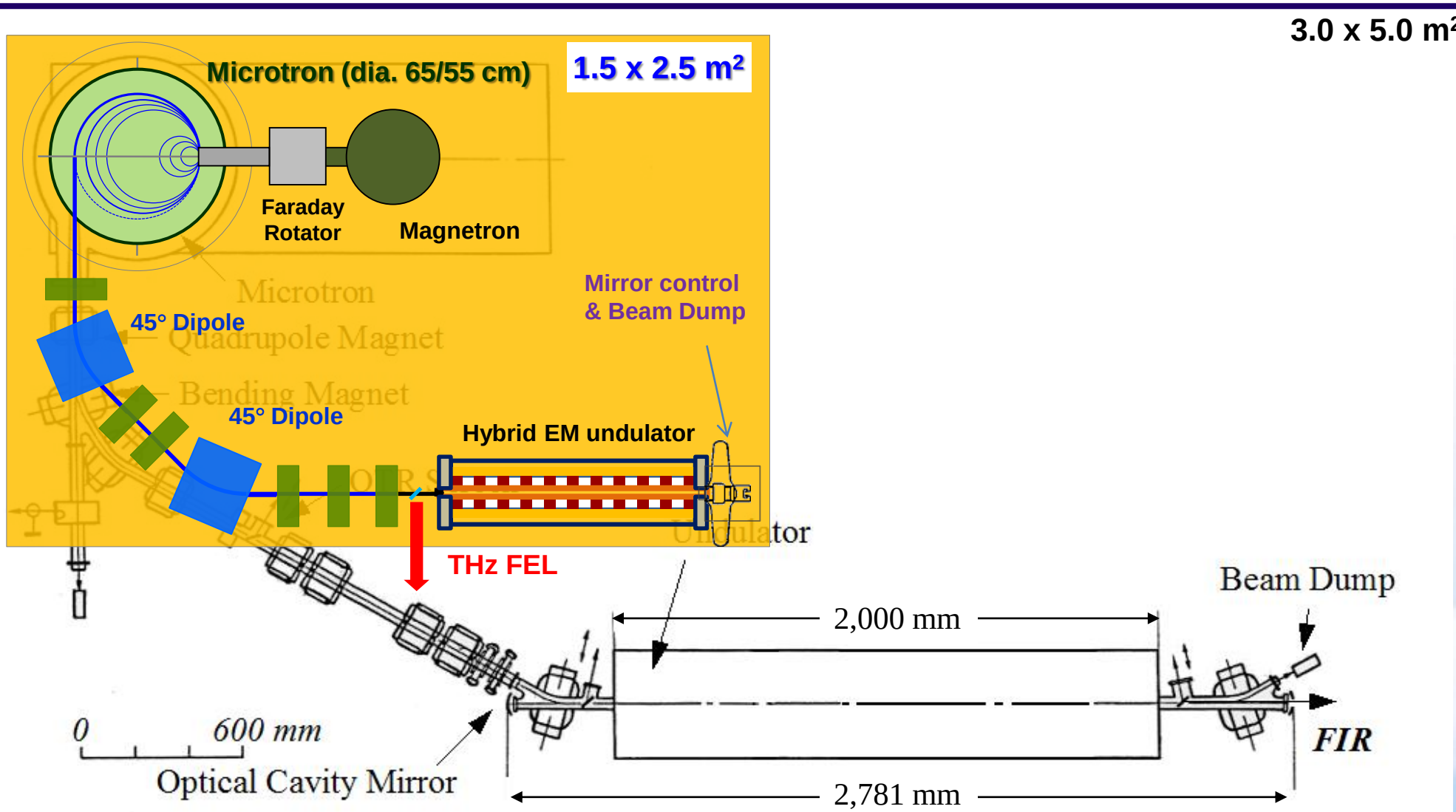

Table-top THz FEL

"Waveguide-Mode Terahertz Free Electron Lasers Driven by Magnetron-Based Microtrons",
Y. U. Jeong, et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, 898, 2016

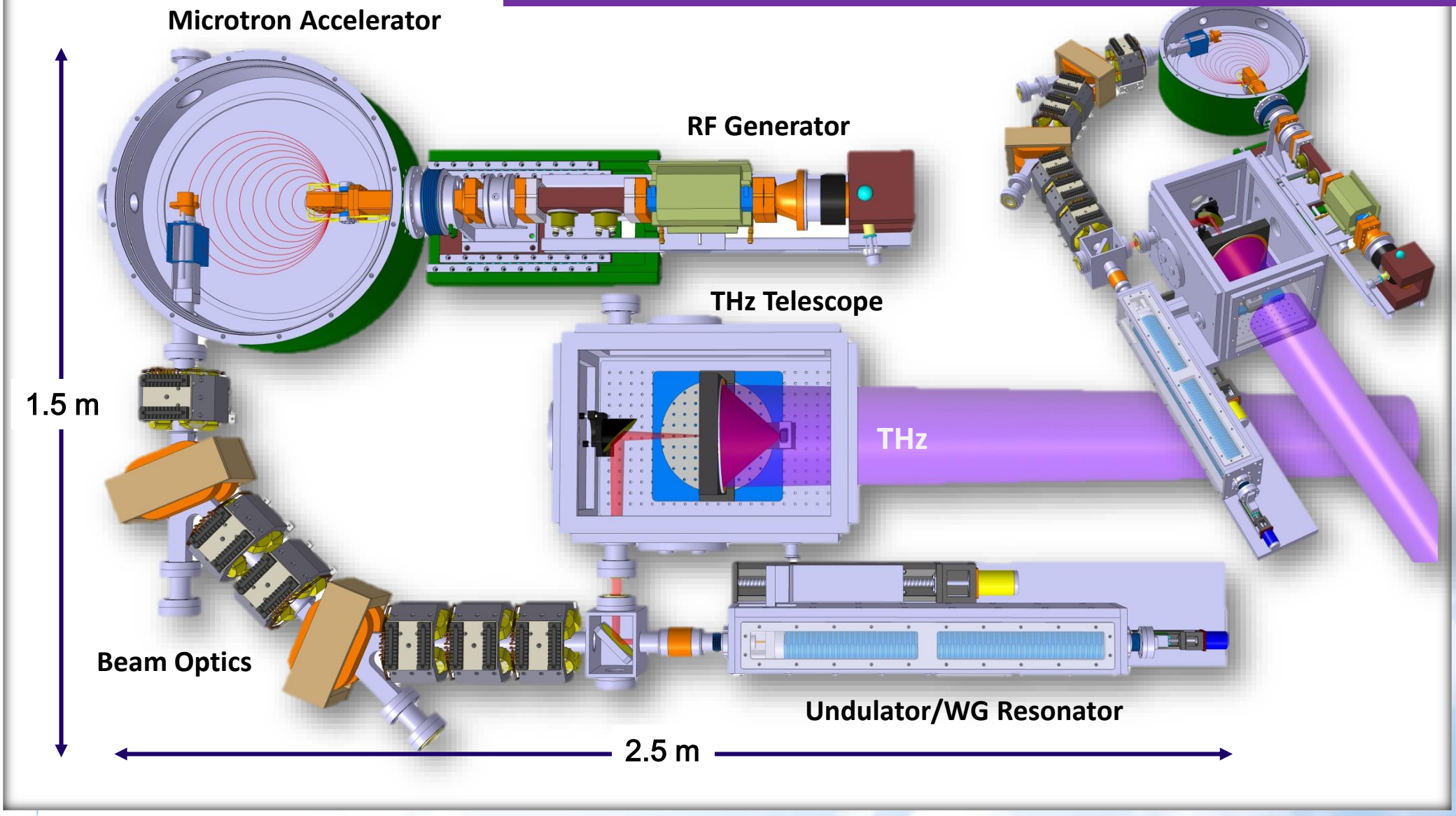

Table-top THz FEL

S. Bae, *et al.*, *J. Kor. Phys. Soc.*, under review

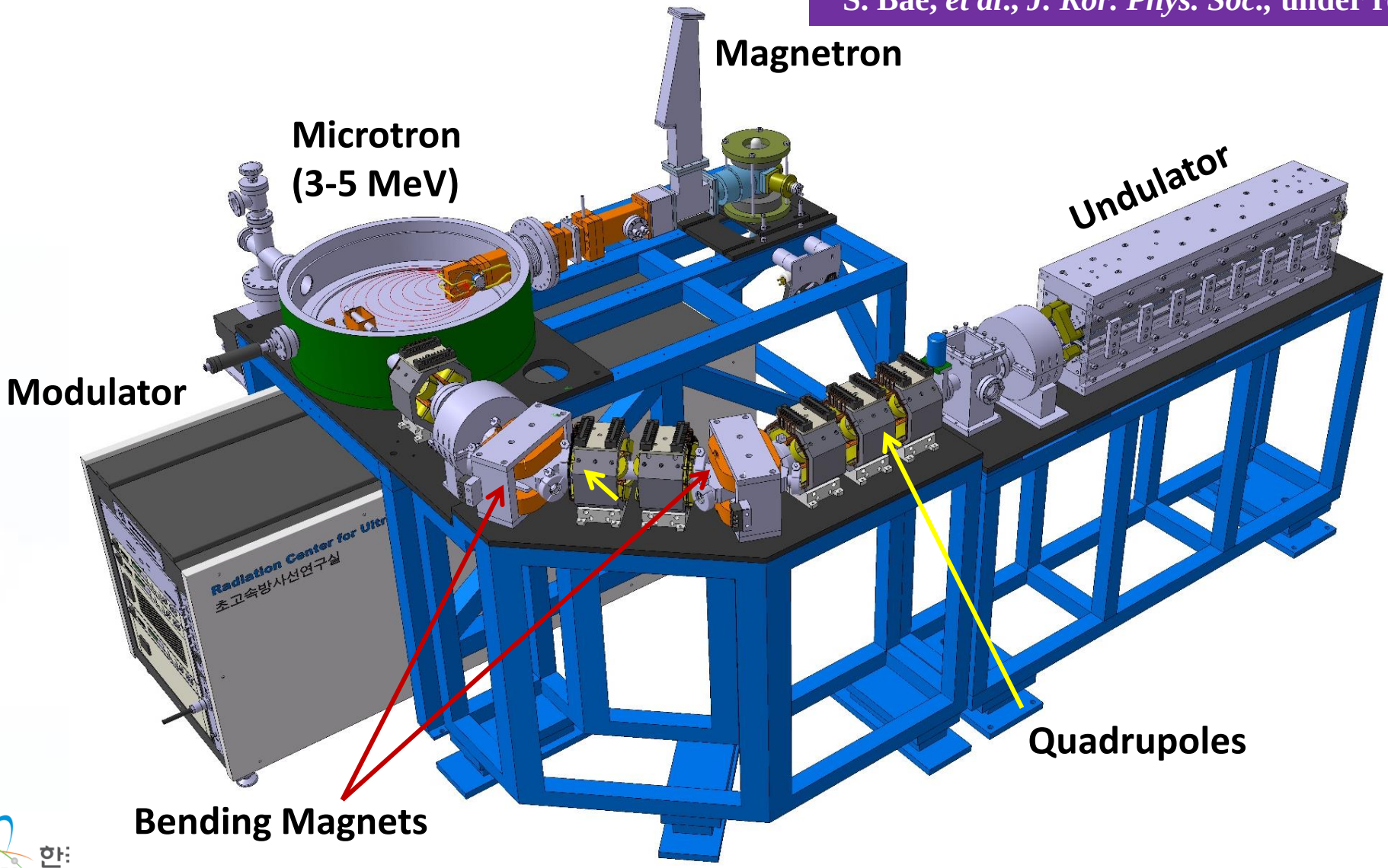

Table-top THz FEL

S. Bae, *et al.*, *J. Kor. Phys. Soc.*, under review

Parameters	OLD FEL (FEL-1)	NEW FEL (FEL-2)	NEW FEL (FEL-3)
Electron Kinetic Energy	6.5 MeV	5 MeV	3.5 MeV
Electron Micropulse Duration	20 ps	20 ps	20 ps
Electron Macropulse Duration	5 μs	5 μs	5 μs
Electron Micropulse Current	1 A	1 A	1.2 A
Electron Macropulse Current	40 mA	40 mA	50 mA
Undulator Magnetic Field	4.5-6.8 kG	7-11 kG	4.5-7.0 kG
Undulator Period	2.5 cm	2.5 cm	2.5 cm
Number of Undulator Period	80	40	20/30
Undulator K-parameter	1.0-1.6	1.9-2.6	1.0-1.6
FEL Wavelength	100-200 μm	300-600 μm	300-600 μm
Resonator Type	Parallel-plate Waveguide & Confocal Free-space Mode	Waveguide Mode	Waveguide Mode
Mode Cross Section Size (vertical x horizontal)	1.0 mm x 10.7 mm	1.5 mm x 3.4 mm	1.5 mm x 3.4 mm

Acknowledgements

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The late Boris Gudkov

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Prof. Jungwon Kim

THz wave generation
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Ms. Mozhgan Hayati,
Prof. Thomas Feurer

RF deflector
Prof. Seong Hee Park

Sample preparation
Prof. Sunglae Cho

Thank you and my dear friends!!

The Late Boris Gudkov
(Nov. 1947-Dec. 2019)

The Late Sergey Miginsky
(May 1961-Jan. 2021)