FEL 2014, Basel, Swiss

세계수준의 연구센터
World Class Institute

Small-scale Accelerator-based Radiation Sources & Their Applications

24 Aug., 2014

Young Uk Jeong

WCI Center for Quantum-Beam-based Radiation Research

Korea Atomic Energy Research Institute

한국원자력연구원
KAERI
Korea Atomic Energy Research Institute

2RC
THz Pump
X-ray Probe

Co-Authors

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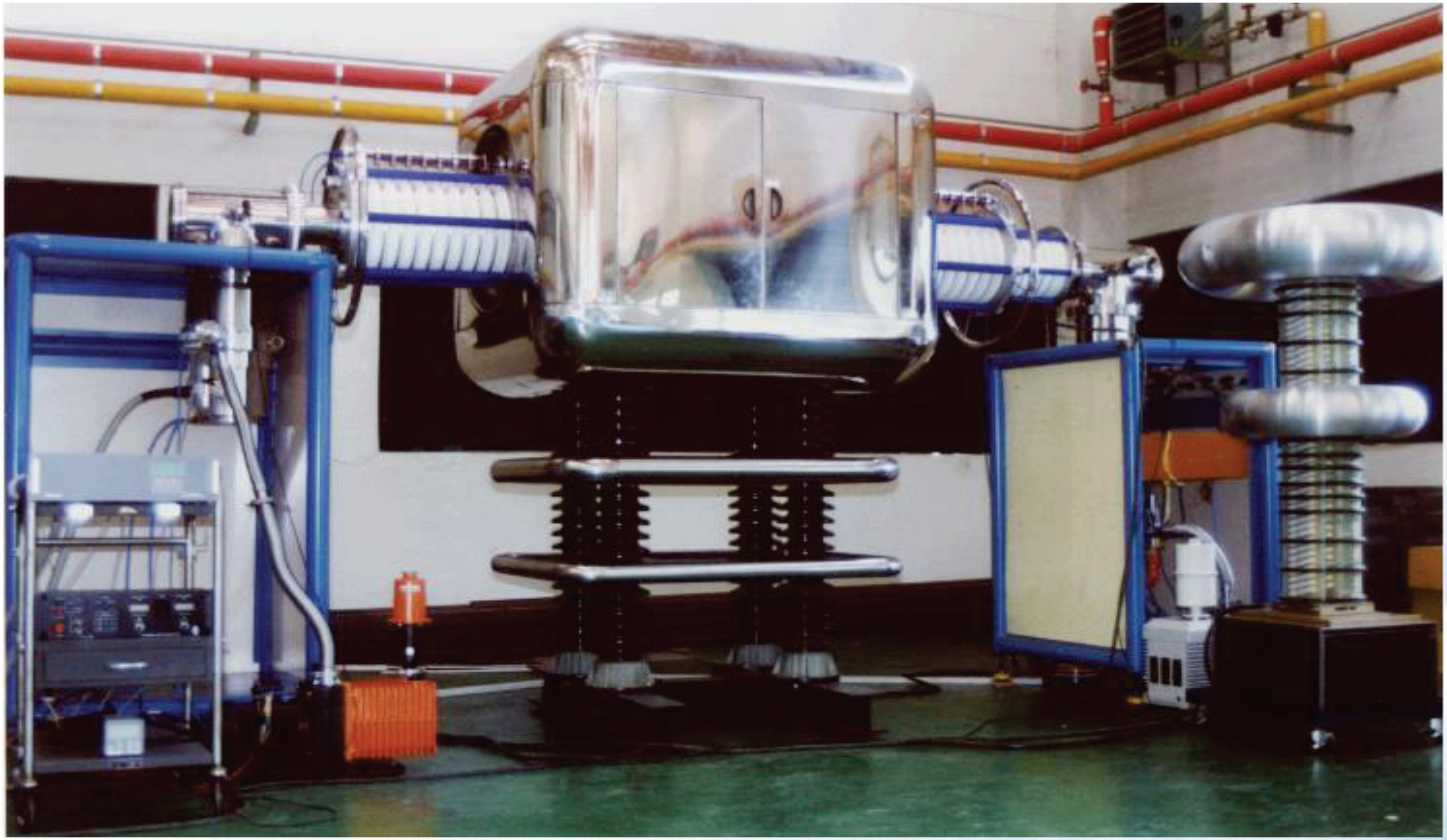
Contents

I. Millimeter-wave FEL

Millimeter-wave FEL (1992-1995)

Millimeter-wave FEL driven by a tandem-type Electrostatic Energy-Recovery Accelerator



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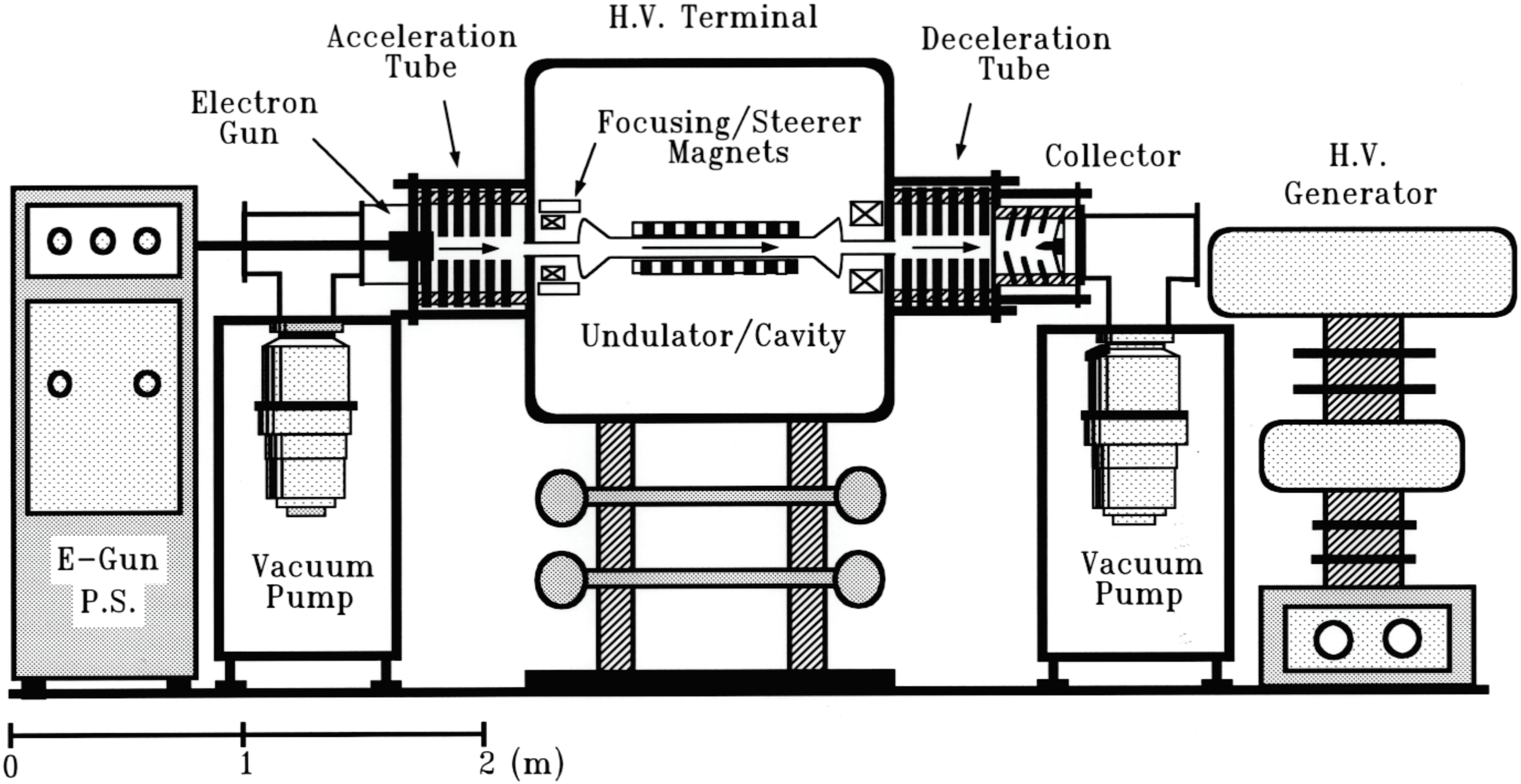
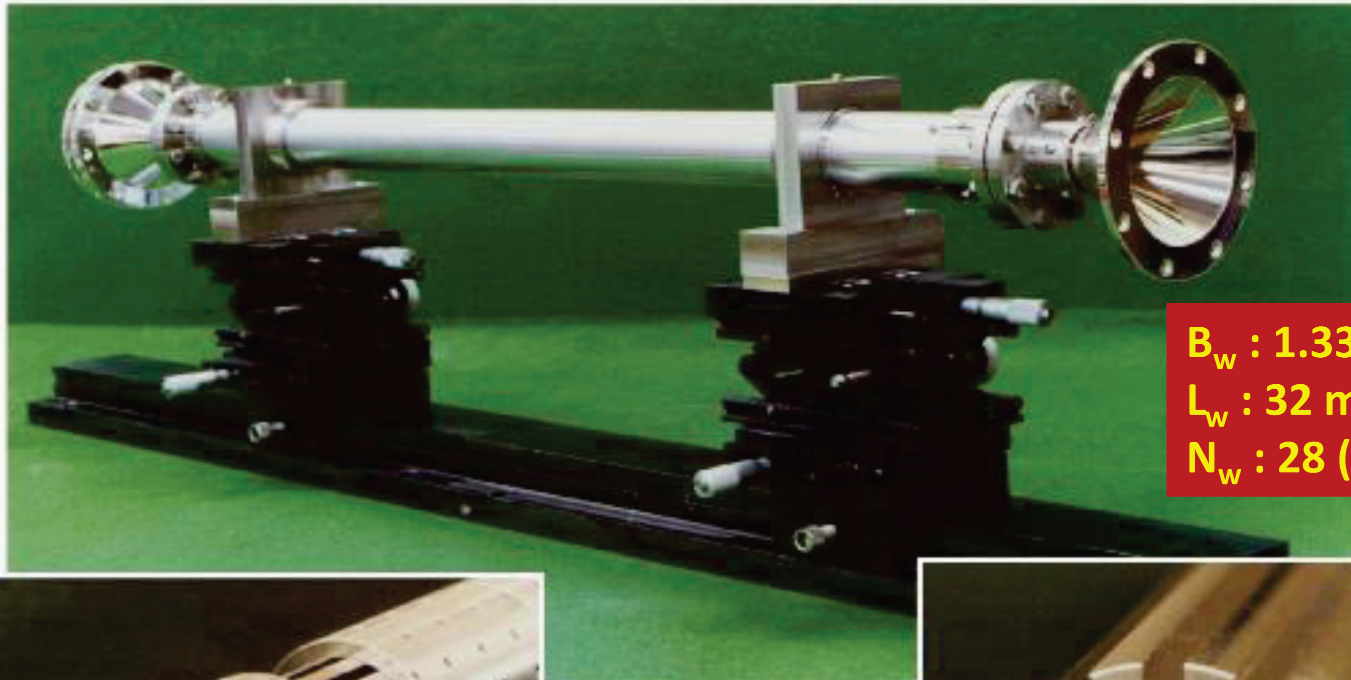
Millimeter-wave FEL (1992-1995)

Millimeter-wave FEL driven by a tandem-type Electrostatic Energy-Recovery Accelerator

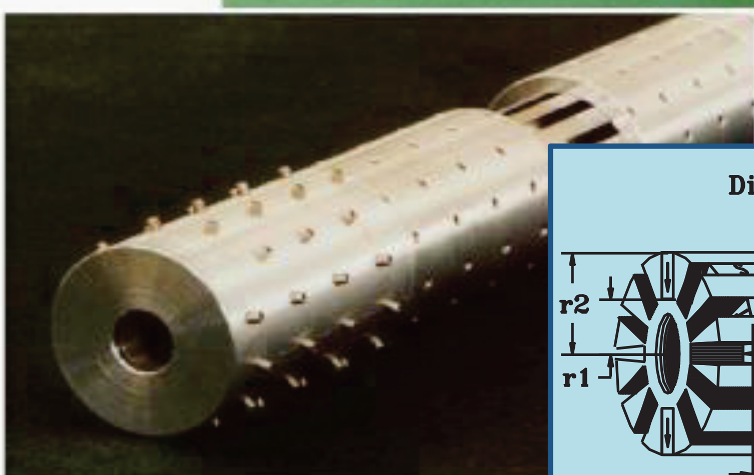


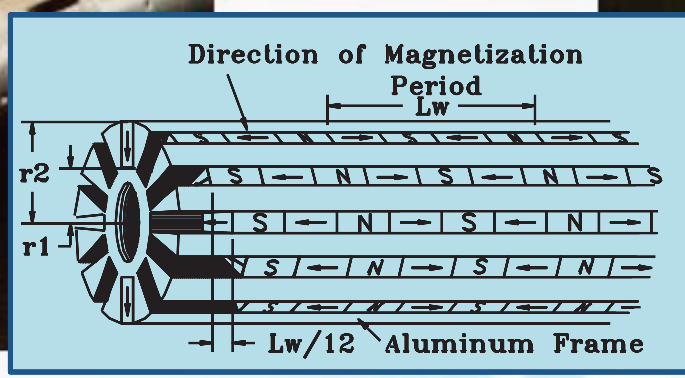
Millimeter-wave FEL (1992-1995)

Bifilar-type Permanent-magnet Helical Undulator & Circular Waveguide Resonator



- B_w : 1.33 kG (+/- 0.7%)
- L_w : 32 mm
- N_w : 28 (3+22+3)





II. Compact THz FELs

Terahertz FEL (1995-present)

1. FIR FEL Development (1995-1998)

- Target wavelength of 30-40 μm with a 12.5-mm-period undulator
- Failed in FEL lasing

2. THz FEL Development (1998-2003)

- Target wavelength of 100-300 μm with a 25-mm-period period
- First lasing at the end of 1999 (λ=100-170 μm)
- FEL & beam dynamics study
- System stabilization & upgrade (λ=100-300 μm)

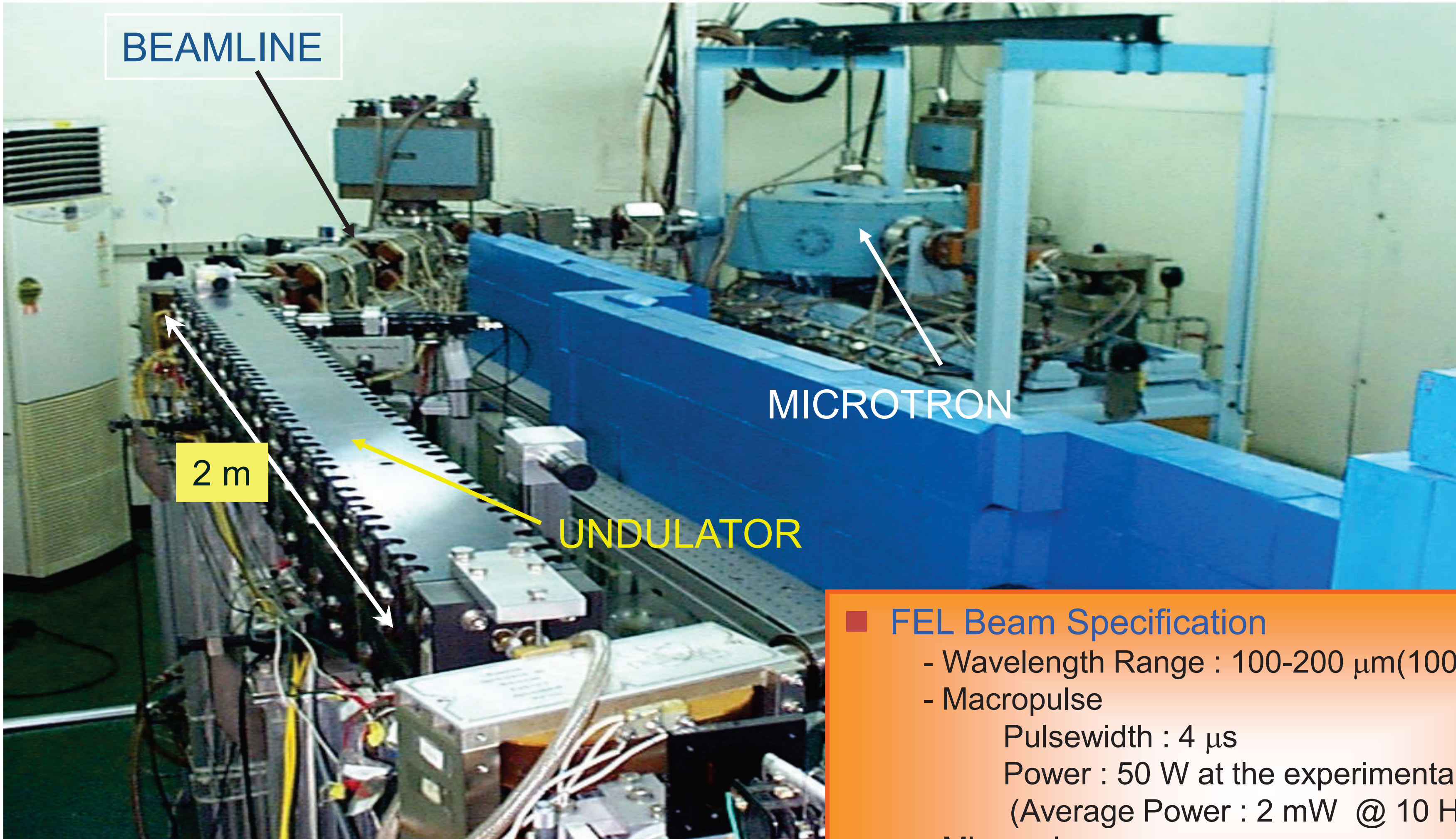
3. THz Applications (2004-present)

- THz imaging, spectroscopy, meta-material study, THz-bio interaction, & so on

4. Table-top THz FEL Development (2008-present)

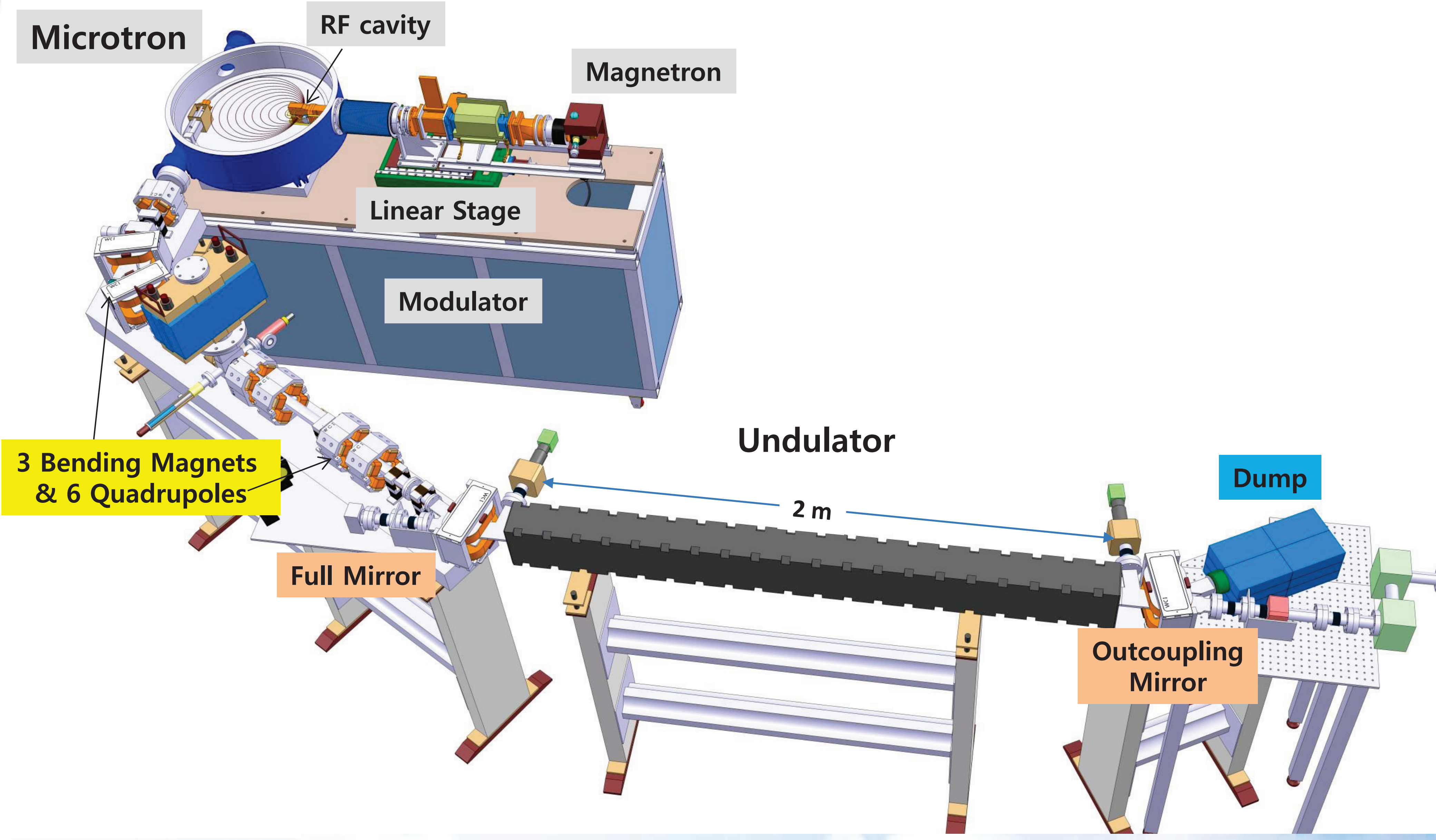
- Rack-type FEL for security inspection (dimensions of 1.5 x 2.5 m^2)
- Target wavelength of 300-600 μm with the average power of 0.1-1 W

Terahertz FEL (1995-present)

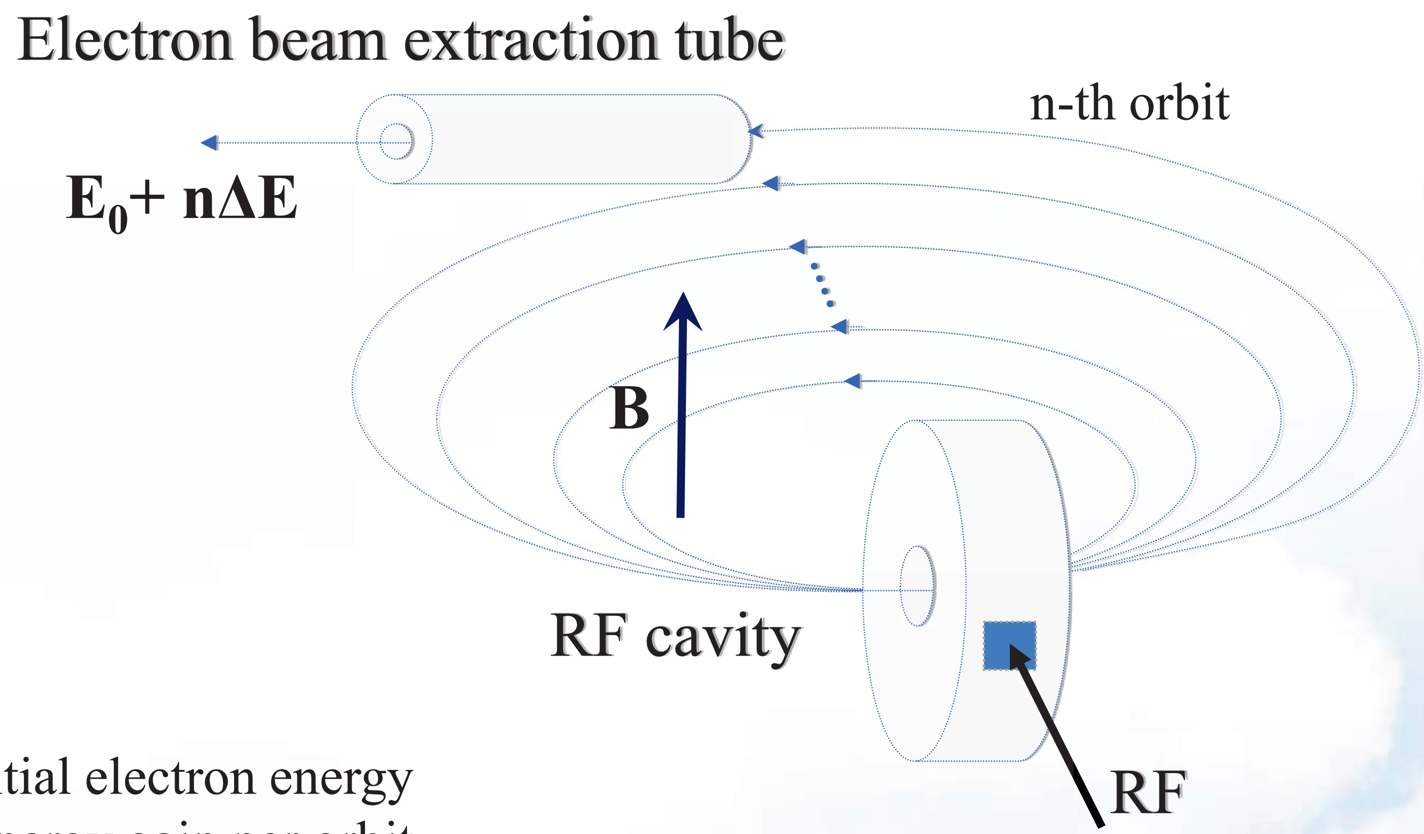


- FEL Beam Specification
  - Wavelength Range : 100-200 μm(1000-1200 μm)
  - Macropulse
    - Pulsewidth : 4 μs
    - Power : 50 W at the experimental stage
    - (Average Power : 2 mW @ 10 Hz repetition)
  - Micropulse
    - Pulsewidth : 10-20 ps
    - Power : 1 kW at the experimental stage
  - Pulse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

Terahertz FEL (1995-present)



Classical Microtron

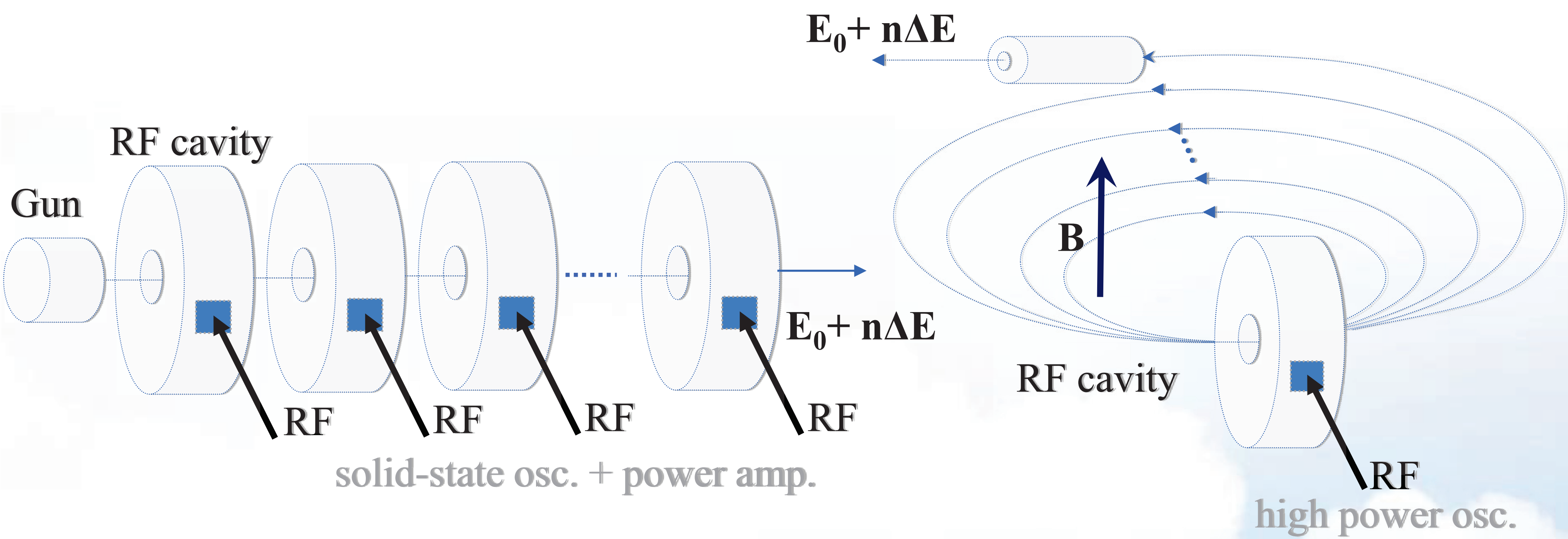


E_0 : initial electron energy
ΔE : energy gain per orbit

Linear Accelerator & Microtron

Linear Accelerator

Microtron



Microtron,

same electron energy but less current

Microtron for Compact THz FEL

Microtron-based FELs

- ~1980s : Bell Lab., Microtron FEL driven by a Klystron

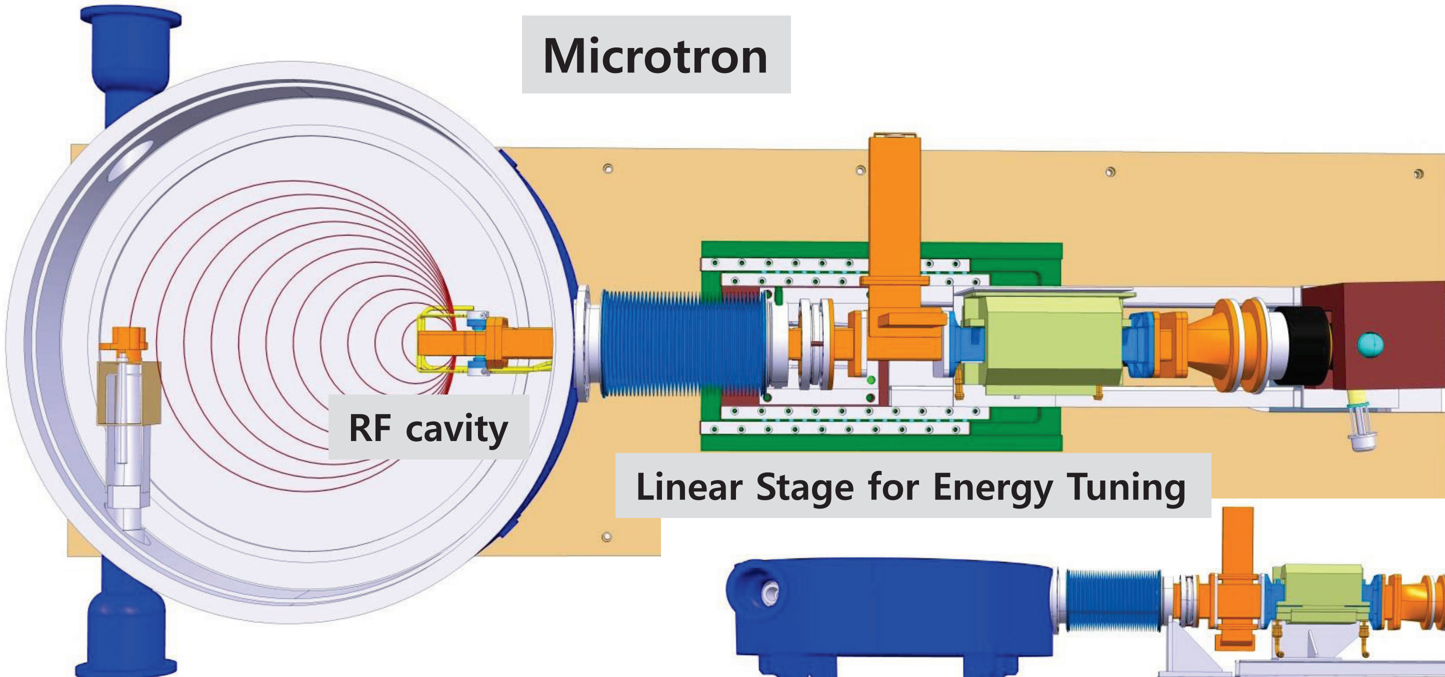
- 1992 : ENEA-Frascati, millimeter-wave Microtron FEL, λ=2~3.3 mm

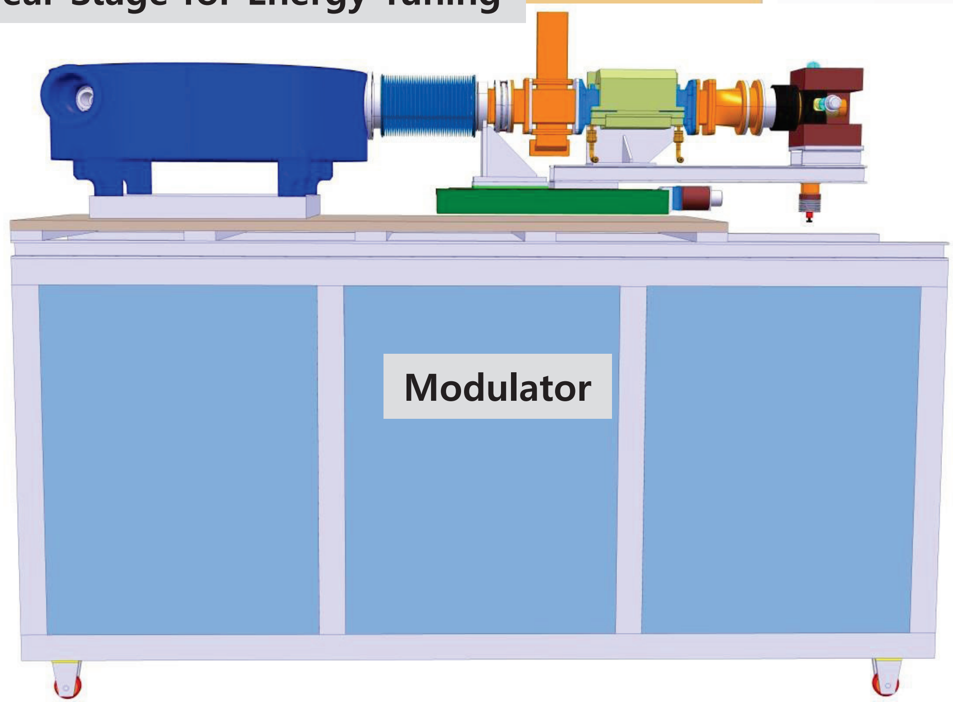
*“**Operation of a compact free-electron laser in the millimeter wave region with a bunched electron beam**” F. Ciocci, R. Bartolini, A. Doria, G. P. Gallerano, E. Giovenale, M. F. Kimmitt, Messina, A.Renieri. Phys. Rev. Lett. **70**, 928-931 (1993)*

- 1999 : KAERI, THz Microtron FEL, λ=100~150 μm

*“**First Lasing of the KAERI Compact Far-Infrared Free-Electron Laser Driven by a Magnetron-Based Microtron**”, Y.U. Jeong, B.C. Lee, S.K. Kim, S.O. Cho, B.H. Cha, J. Lee, G.M. Kazakevitch, P.D. Vobly, N.G. Gavrilov, V.V. Kubarev, and G.N. Kulipanov, Nucl. Instr. and Meth. in Phys. Research A 475, 47 (2001).*

Magnetron-driven Microtron





- Beam Energy : 4.4-6.5 MeV
- Energy Spread : 0.3-0.5%
- Emittance (hor./ver.) : 1.07/0.45 μrad
- Micropulse
  - Repetition Rate : 2.8 GHz
  - Charge : 14 pC
  - Pulse Duration : ~20 ps
- Macropulse
  - Repetition Rate : 1-10 Hz
  - Pulse Duration : 5 μs

Magnetron-driven Microtron

1. High-quality but Low-current Electron Beam

Beam Energy : 4.4-6.5 MeV
Energy Spread : 0.3-0.5%
Emittance (hor./ver.) : 1.07/0.45 μrad
Micropulse
- Repetition Rate : 2.8 GHz
- Charge : 14 pC
- Pulse Duration : ~20 ps

Macropulse
- Repetition Rate : 1-10 Hz
- Pulse Duration : 5 μs

Accelerator for Compact, Simple, & Inexpensive FEL

Low Gain & RF Instability

2. High-power RF Oscillator, Magnetron

Operating Frequency Range : 2792-2802 MHz
- Δf/A : 200-300 kHz/A

Pulsed Output Power : > 2500 kW
Anode Voltage : < 50 kV
Anode Current : 100 A
Duty Factor : < 0.0015
Weight : < 10 kg
MTBF : > 3000 h

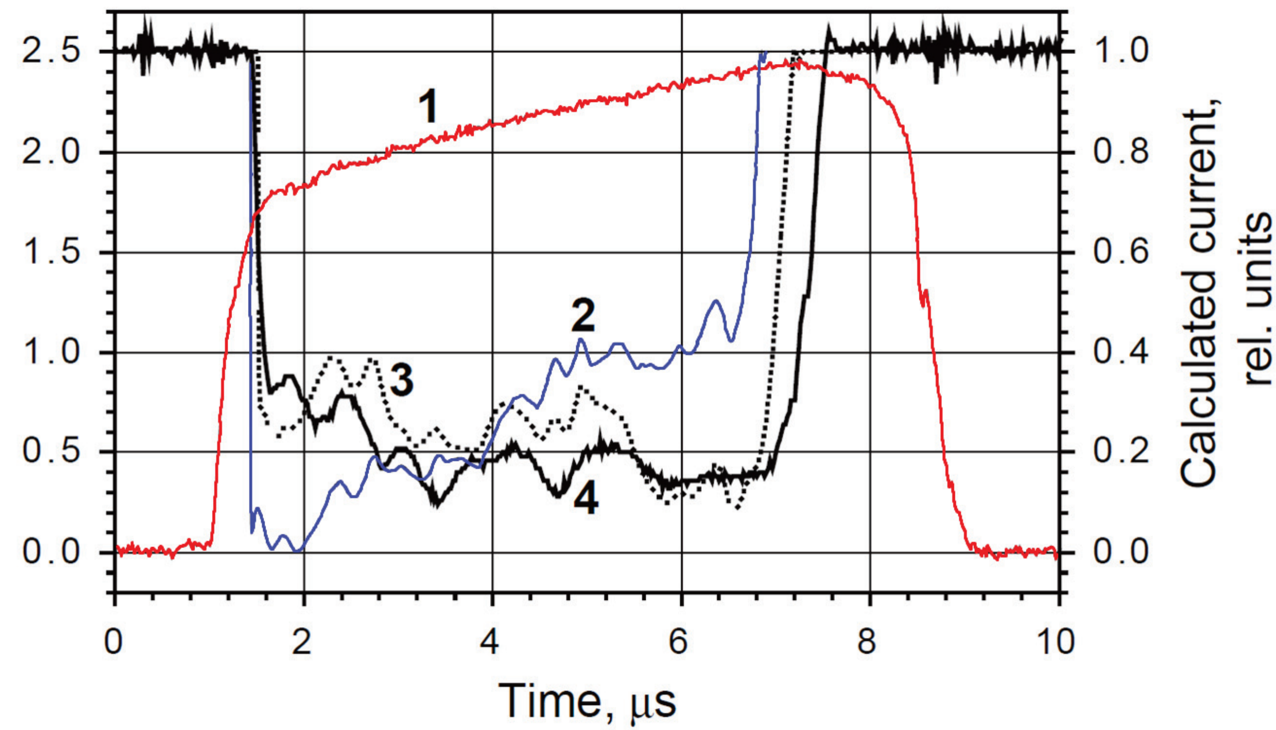
Magnetron-driven Microtron

1. **Incremental Emission Current from a Cathode in the Microtron Cavity**
   - Due to Cathode Heating by Back-bombarding Electrons during Macropulse

2. **Decreasing Accelerated Beam Current of the Microtron**
   - Due to Cavity Loading by Incremental Emission Current

3. **Keeping Constant Beam Current by Incremental RF Pulse**
   - 10% Increasing Magnetron Anode Current during 6 μs Pulse while Keeping Voltage

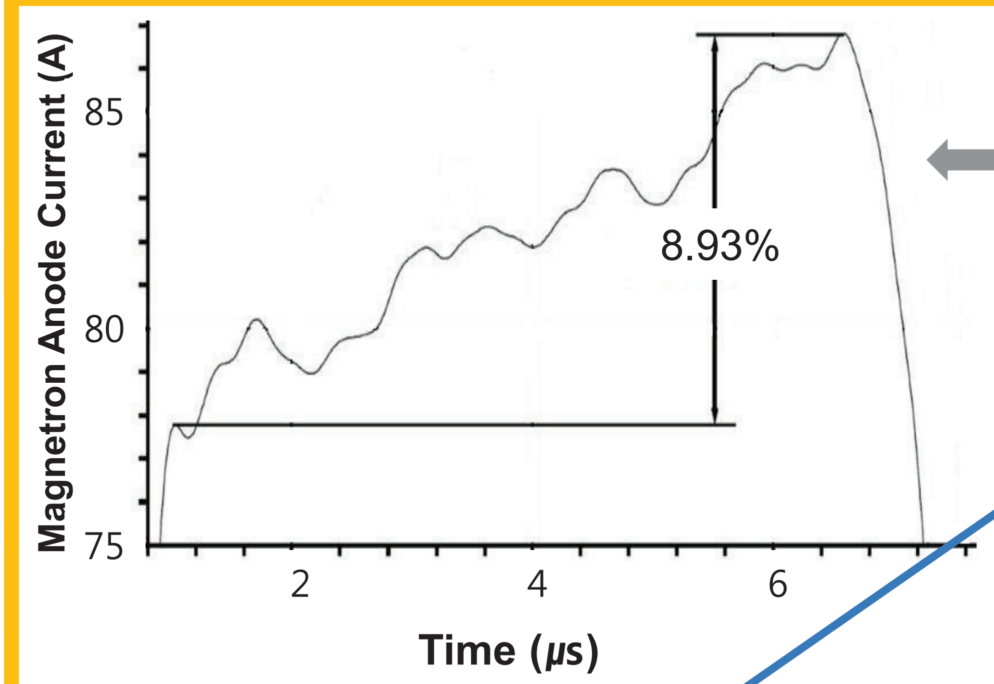
4. **Measured Beam Current**



Magnetron-driven Microtron

3. Keeping Constant Beam Current by Incremental RF Pulse

- 8.9% Increasing Magnetron Anode Current during 6 μs Pulse while Keeping Voltage



Magnetron Current

~10 A Increasing during a Pulse

Max. 2-3 MHz Change of RF Frequency

Operating Frequency Range : 2792-2802 MHz
- Δf/A : 200-300 kHz/A
Pulsed output power : > 2500 kW
Anode voltage : < 50 kV
Anode current : 100 A
Duty factor : < 0.0015
Weight : < 10 kg
MTBF : > 3000 h

- **Required RF Frequency Deviation**

  for overlapping e-beam and optical beam

$$\Delta f \leq 4\frac{\Delta l}{c\tau} f_0 = 100kHz$$

τ : Pulse duration of e-beam macropulse

Δ*l* : Pulse length of optical micropulse

Magnetron Based Microtron as a Driver of FEL

Frequency Pulling Effect

Coupling the magnetron with an accelerating cavity by permitting some ratio of the reflected wave from the cavity

$$\left\{\frac{\mathrm{d}}{\mathrm{d}\tau}+\left[1-\mathrm{i}\frac{Q_0}{1+\beta_C}\left(\frac{\omega_0}{\omega}-\frac{\omega}{\omega_0}\right)\right]\right\}\tilde{V}_C=\frac{2\beta_C}{1+\beta_C}\tilde{V}_{FC}-\frac{R_{sh}}{2(1+\beta_C)}\tilde{J}_C\cdot\exp(\mathrm{i}\varphi_C)$$

$\tau = t/\tau_{C0}$, τ_{C0} is the fill-time of the cavity,

Q_0 is the wall quality factor,

ω_0 is the circular eigen frequency of the cavity,

β_C is the cavity coupling coefficient,

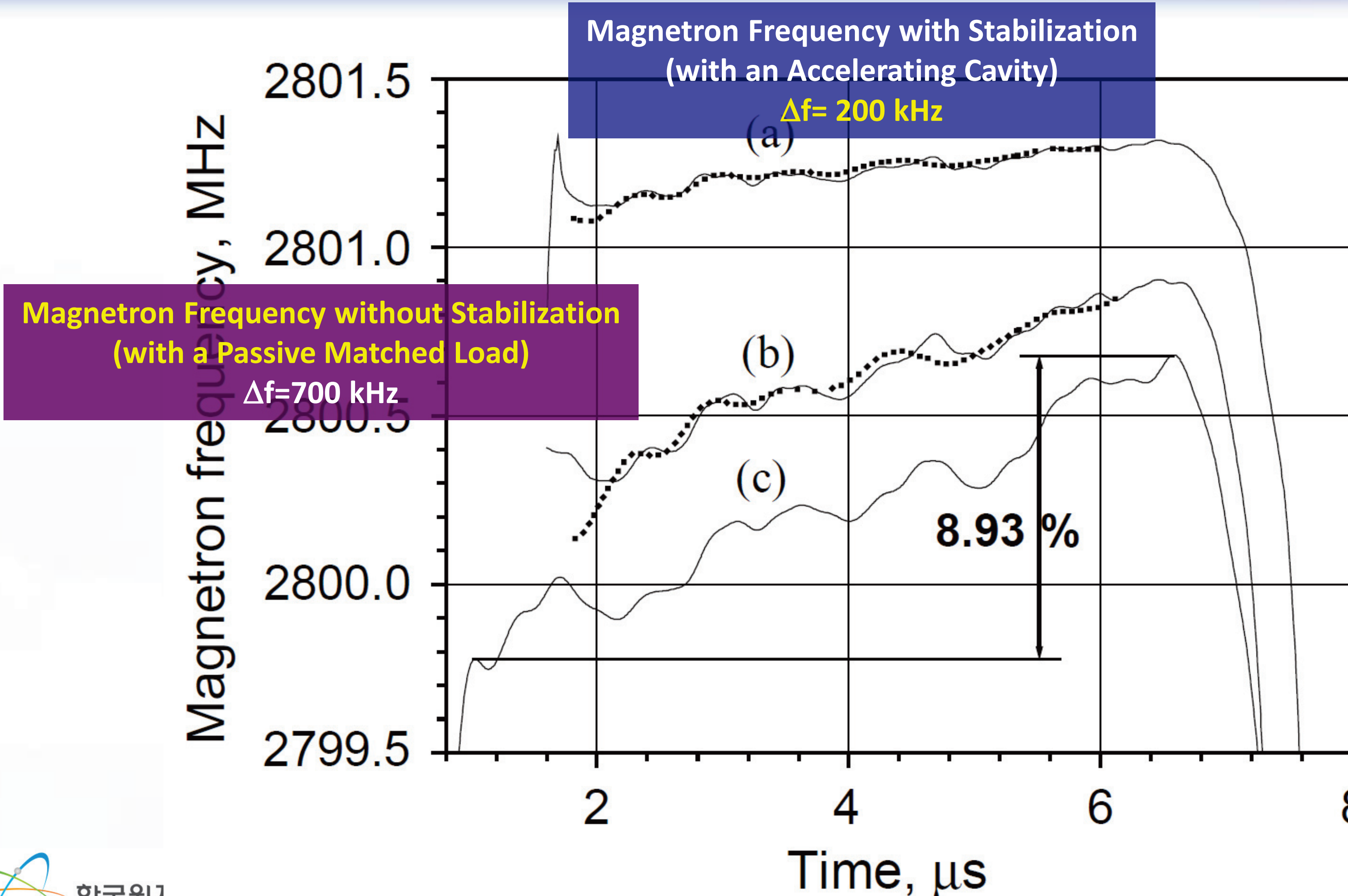
$\tilde{V}_C$ and $\tilde{V}_{FC}$ are complex amplitudes of the oscillation in the cavity and in the forward wave, respectively,

R_{Sh} is the shunt impedance of the cavity,

$\tilde{J}_C$ is the complex amplitude of the first-time harmonic of the loading current,

and φ_C is the phase of the complex amplitude of $\tilde{V}_C(t)$.

Stabilization of Magnetron



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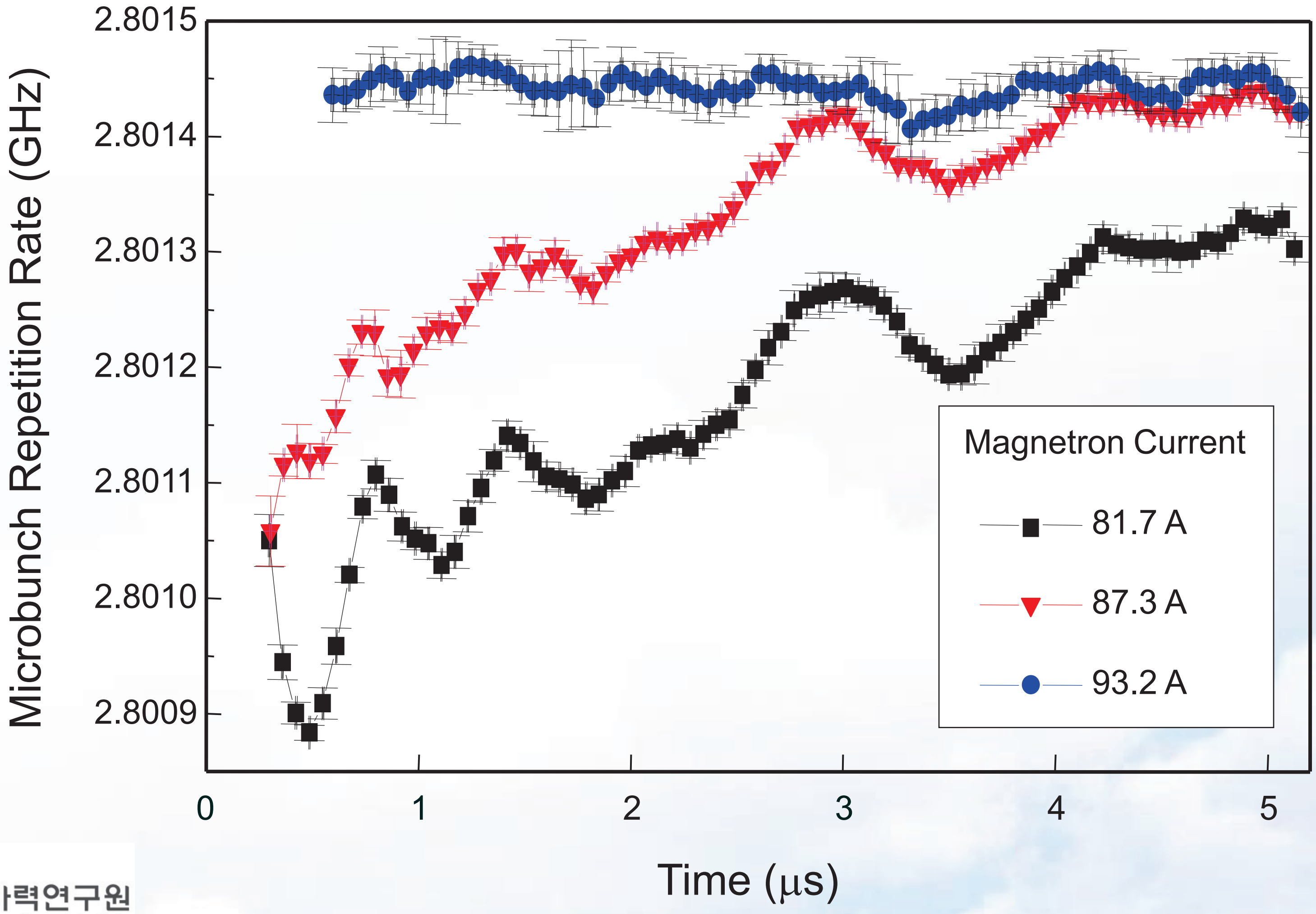
Electron Bunch Repetition Rate

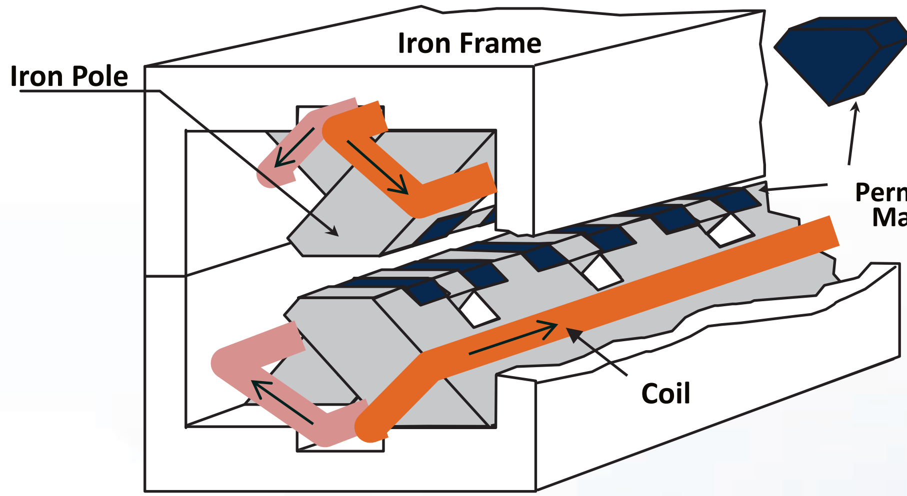
Beam Instability vs. Magnetron Power



FEL Operation by the Microtron

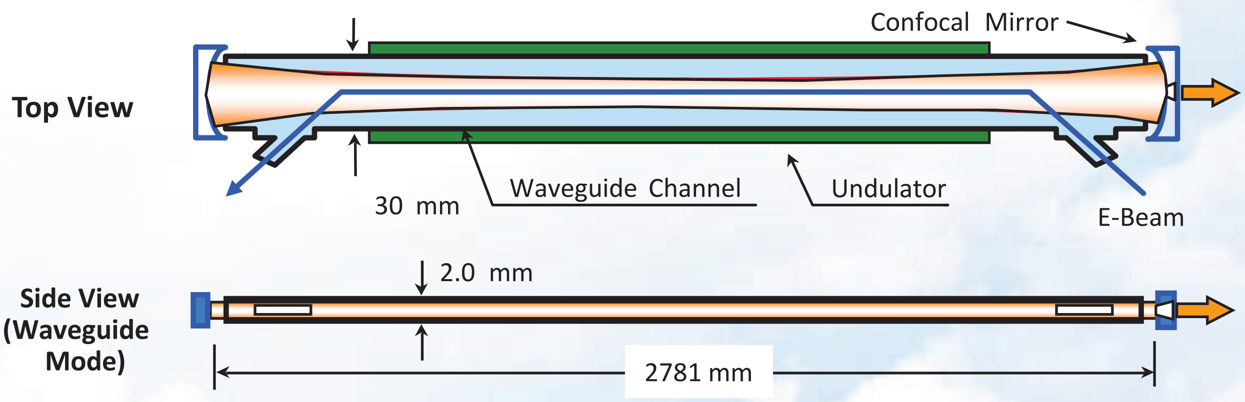
1. High-performance Undulator (Halbach EM Undulator)

- PM-assisted EM Undulator
- N_w=80
- λ_W=25 mm
- B_w=4.5-6.8 kG (+0.01%)



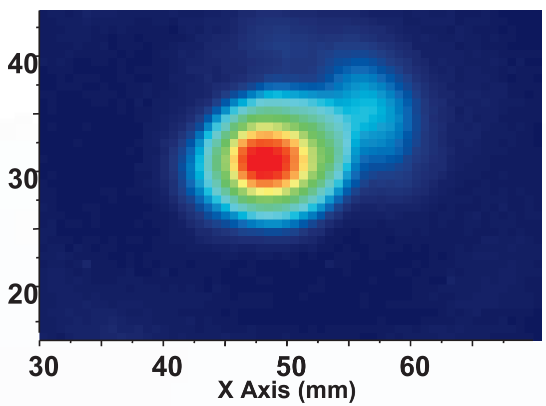
2. Narrow-gap Parallel-plate Waveguide Resonator

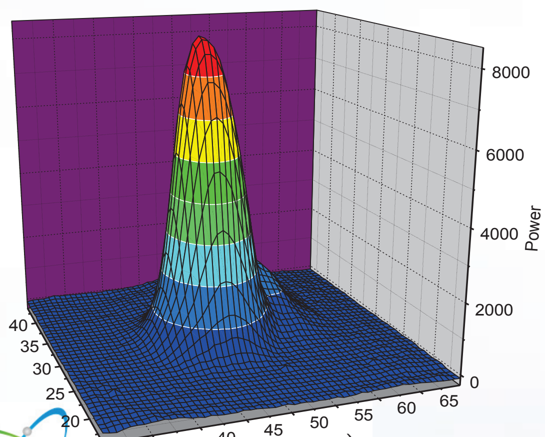
- Gap=2 mm, L=2800 mm, Hole Coupling by Cylindrical Mirror



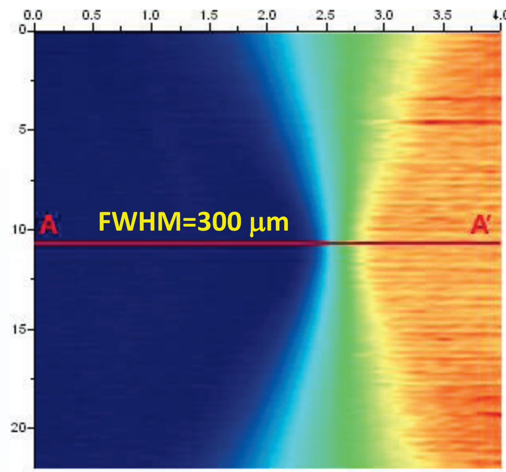
FEL Beam Characteristics

Diffraction-limited Beam





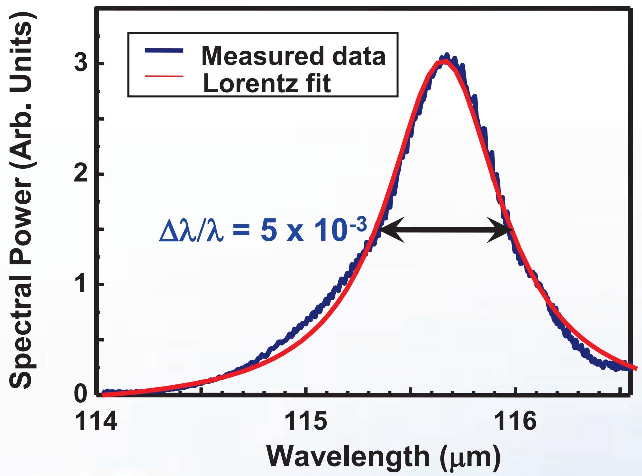
Focusing by a Mirror of f/#=0.26

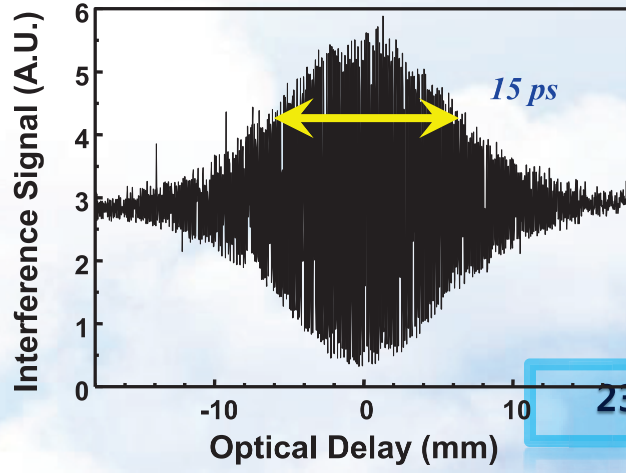


Low Beam Energy

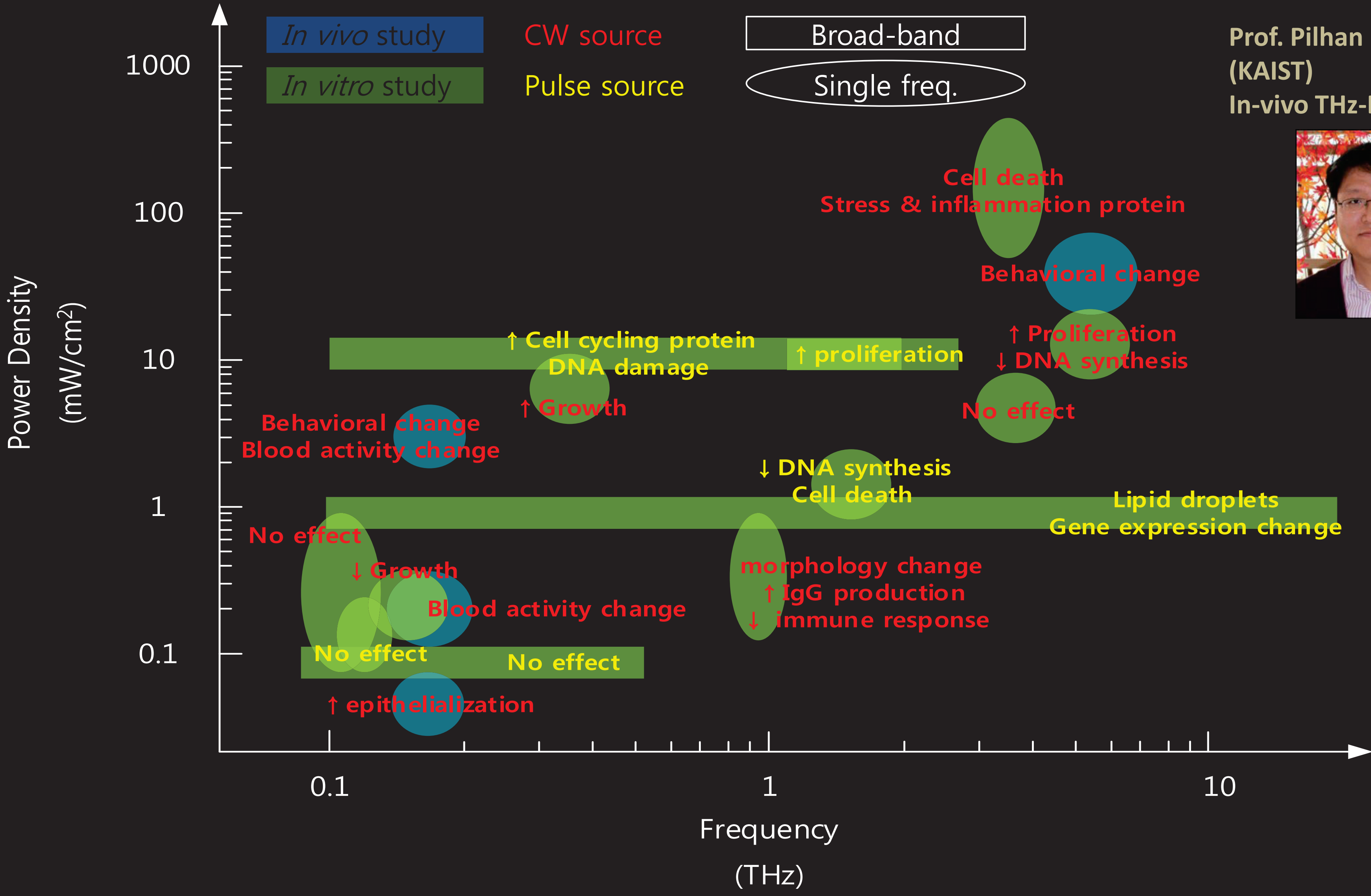
THz Macropulse Energy : 0.3 mJ
THz Micropulse Energy : 20 nJ
Max. Average Power : 3 mW (@ 10 Hz)

Fourier-transform Limited Beam





Summary of THz-Bio Studies



Prof. Pilhan Kim
(KAIST)
In-vivo THz-Bio Imaging

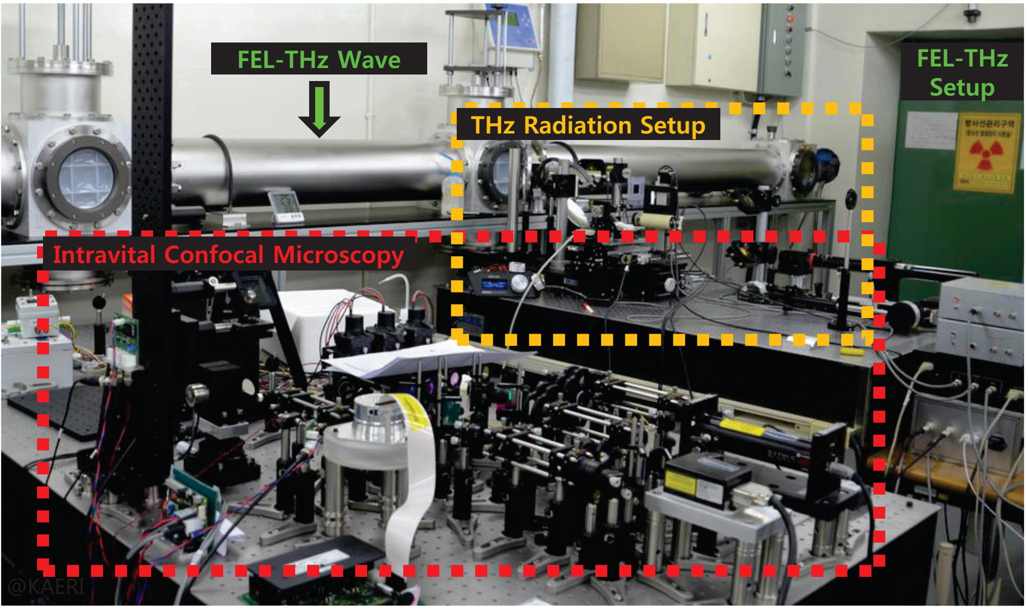
Motivation of in-vivo THz-Bio Study

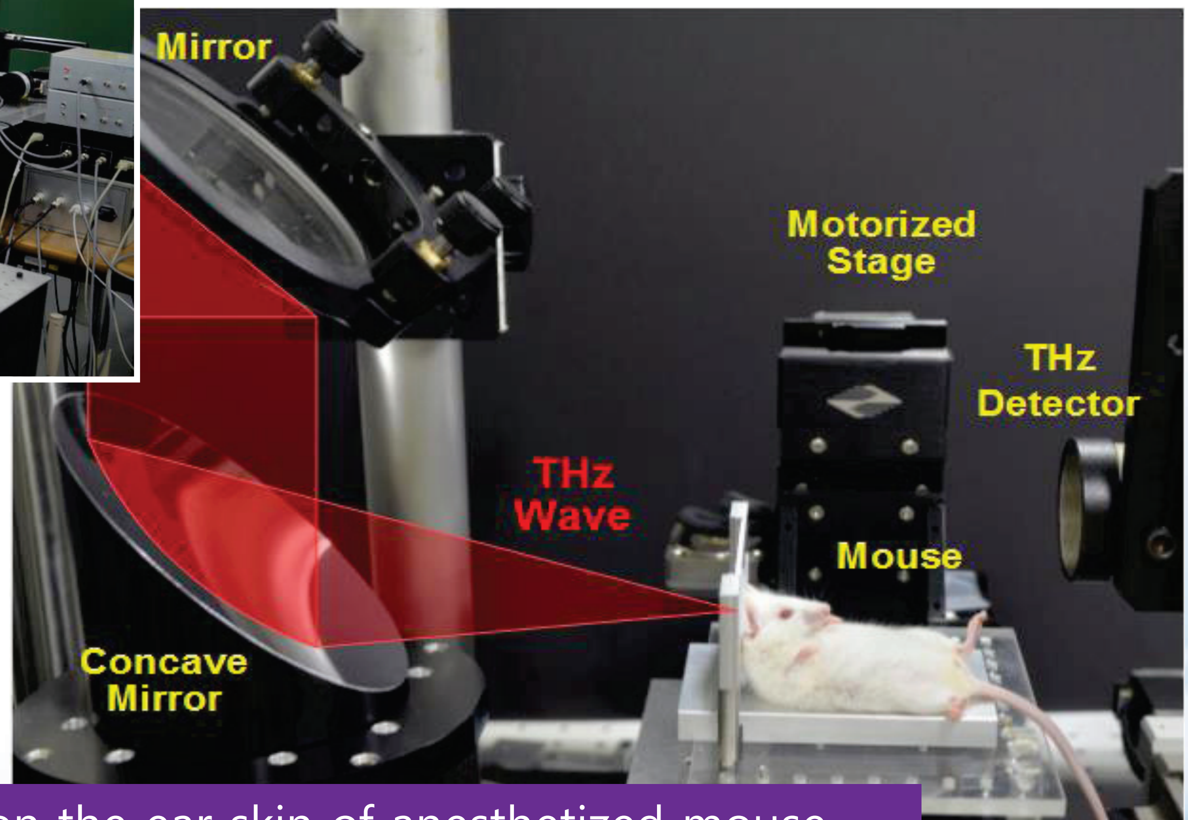
Yet, despite their critical significance in implementing THz-wave based biomedical application, short- and long-term **cellular-level effects** of single or multiple **THz irradiations live animal *in vivo*** were mostly unknown.

↓

In vivo laser-scanning microscopy with THz radiation setup
- Apparatus to radiate THz wave at imaging focal plane
Monitoring of cellular response under THz wave **in vivo**

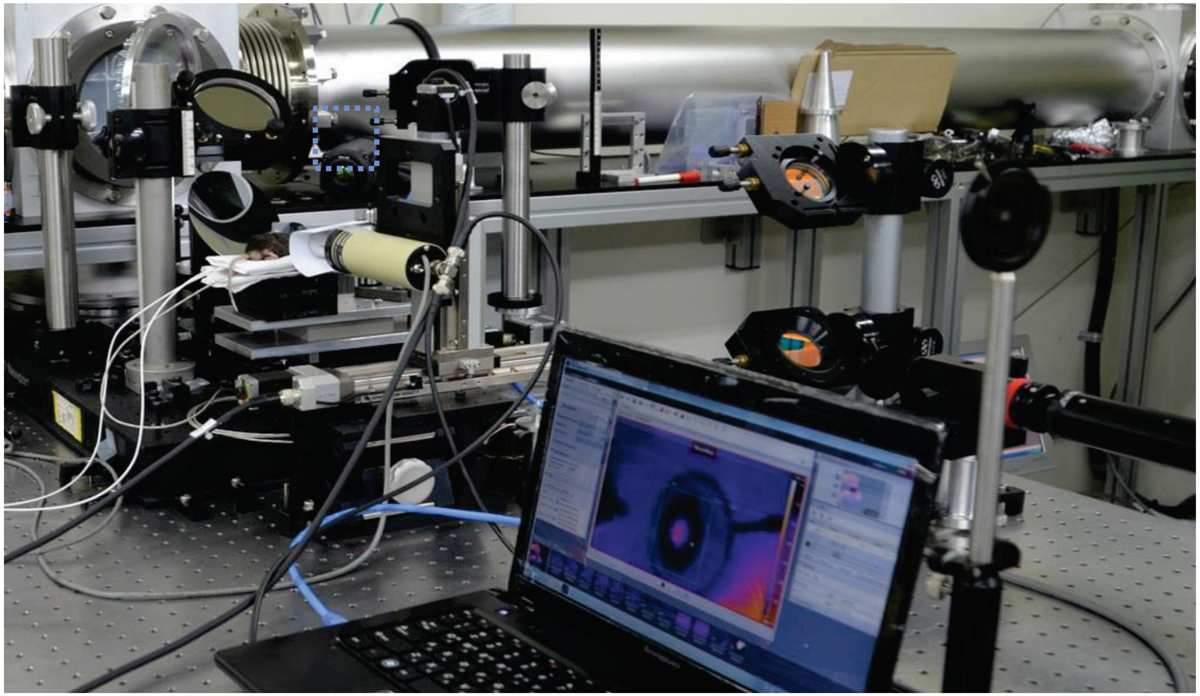
In Vivo Study of THz Radiation to Mouse Model

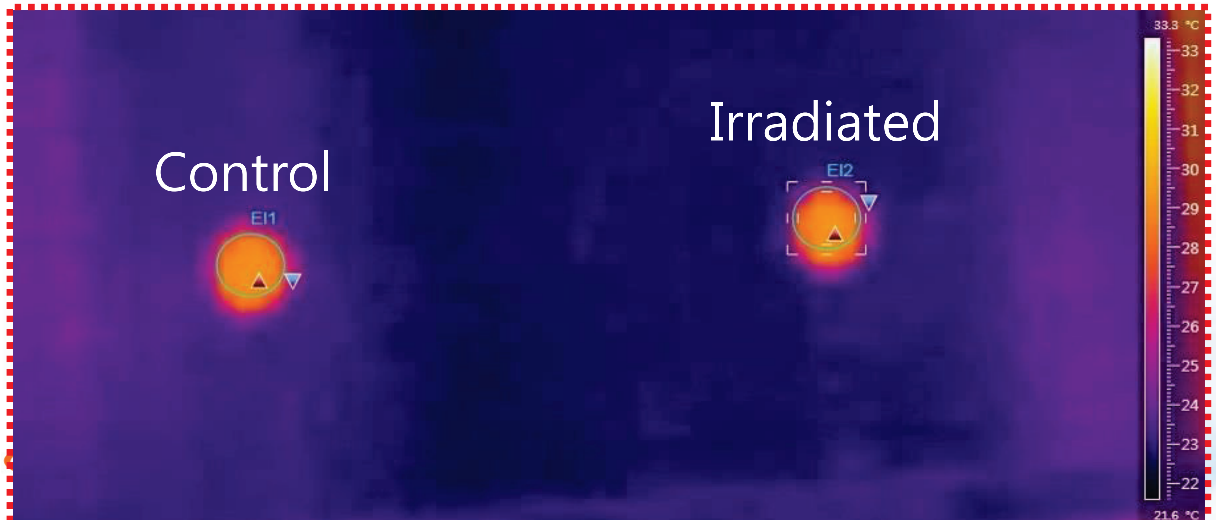




- **Focused THz wave** on the ear skin of anesthetized mouse
  - 300 μm diameter, Visible laser colocalization for alignment
  - Heated plate to keep body temperature

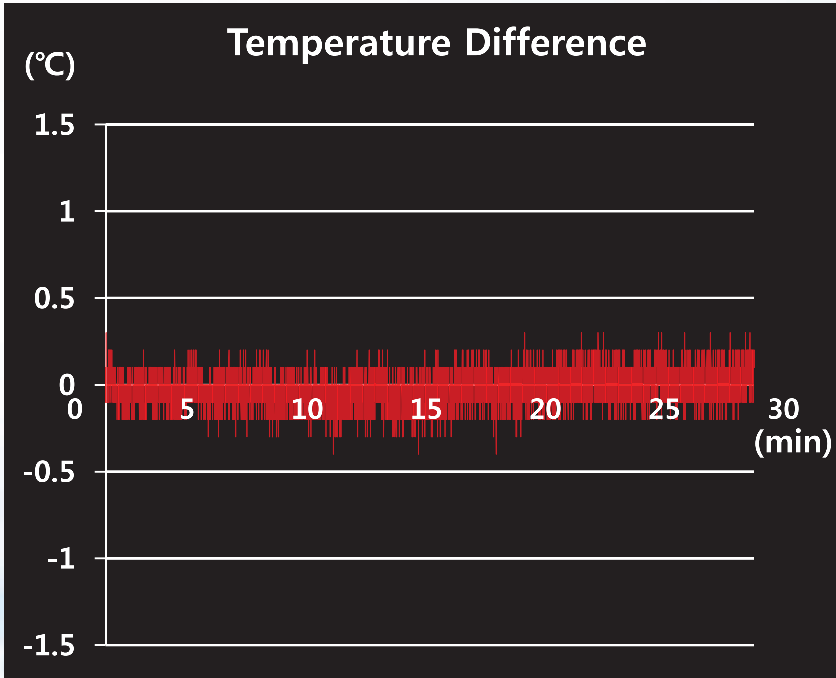
Temperature Monitoring



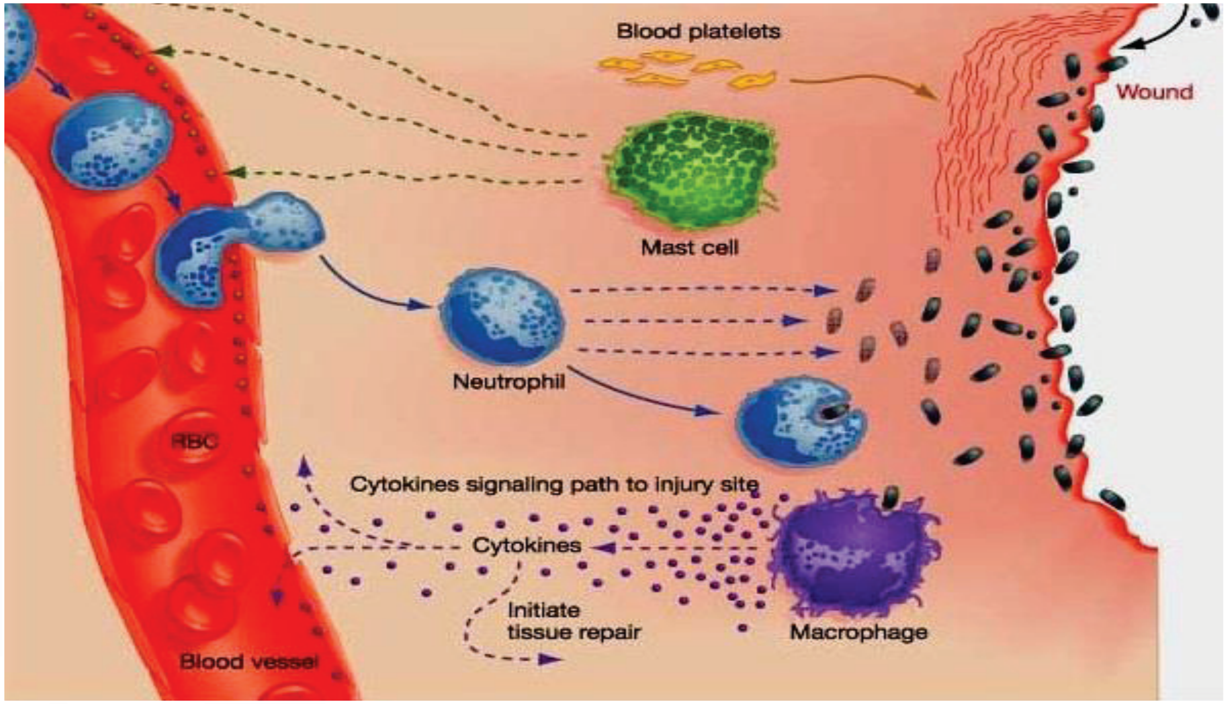


FLIR A-series Infrared Camera

Monitor the temperature of the area radiated by THz wave

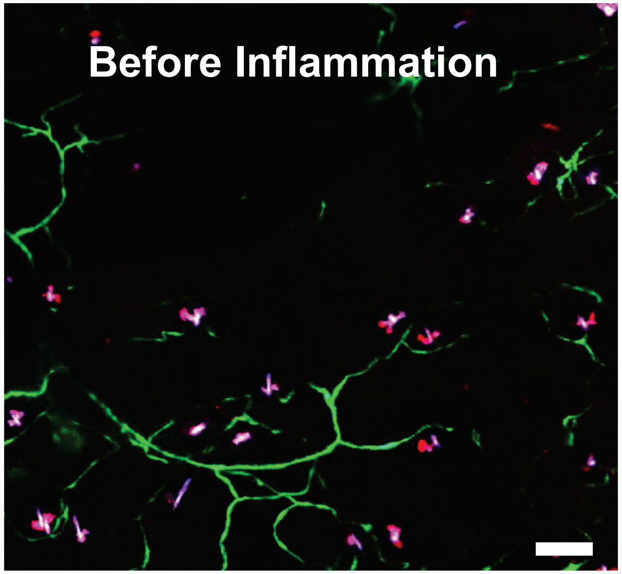


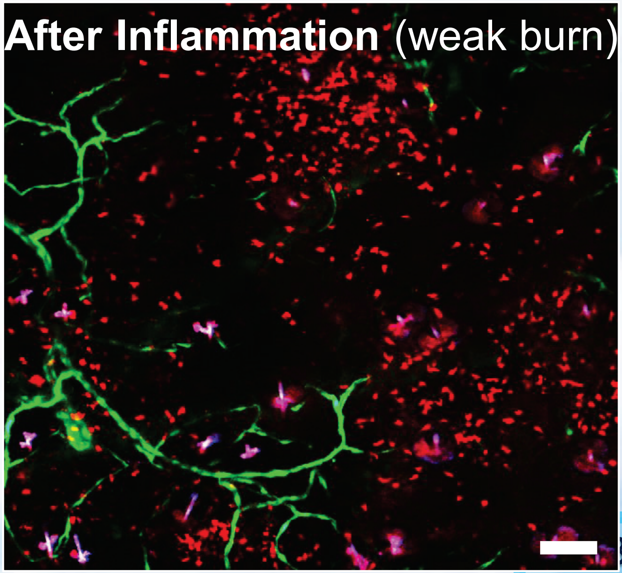
Inflammation



- biological response to harmful stimuli
  (pathogens, damaged cells, irritants)
- redness, swelling, heat, pain,loss of function

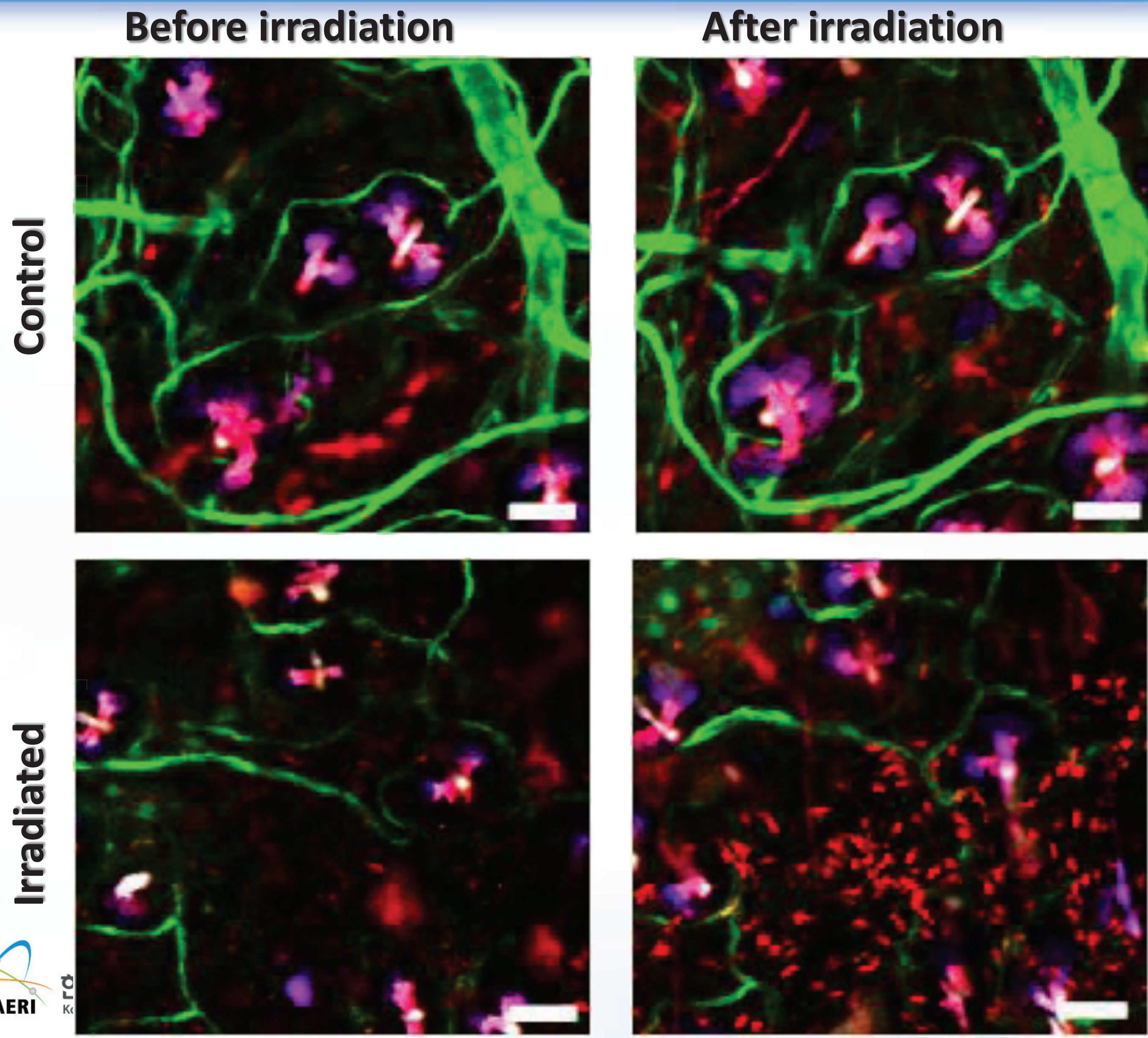
- Neutrophils can be an indicator for inflammatory response





Tie2-GFP Gr-1- Alexa647 Autofluorescence

In vivo monitoring



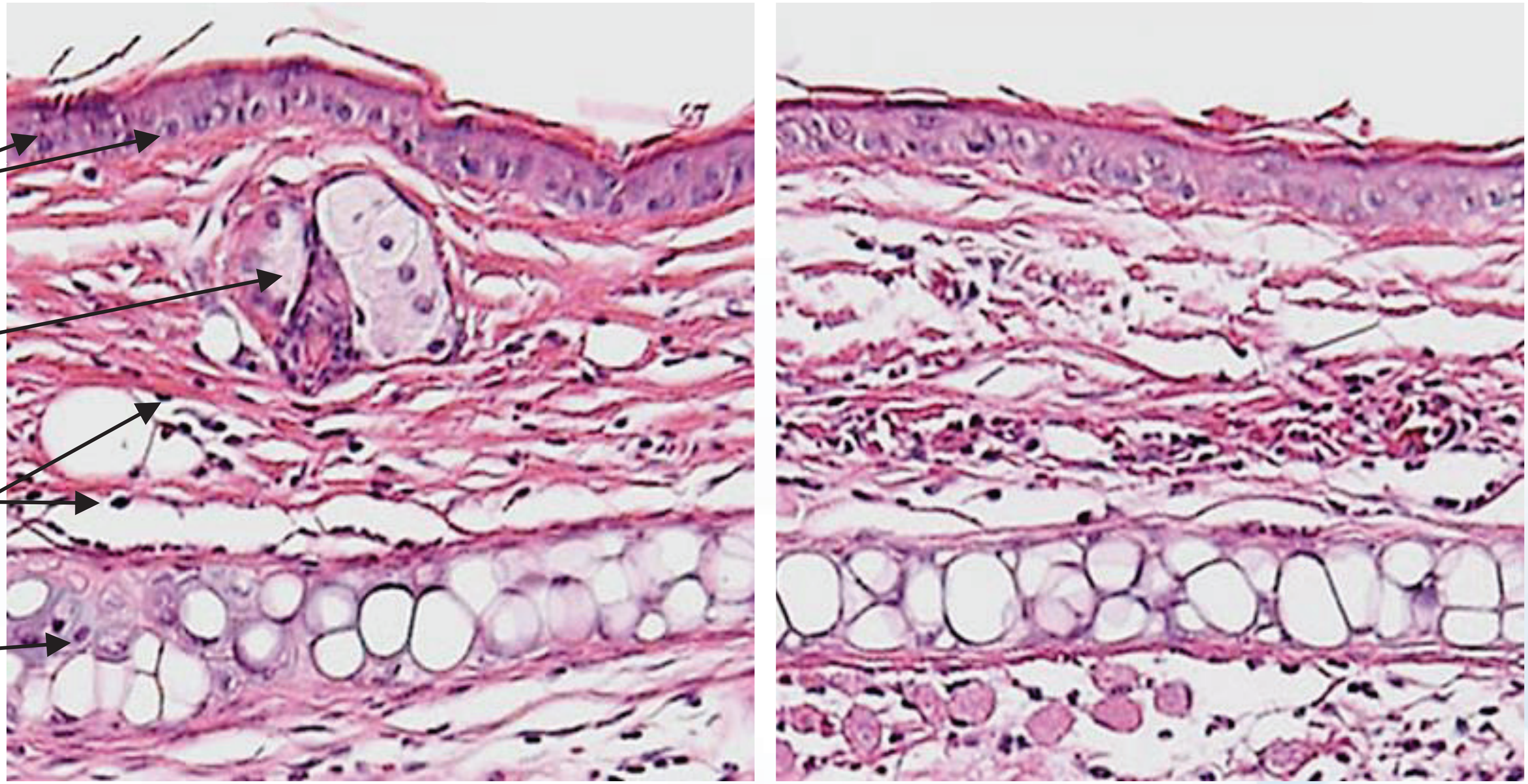
Tie2-GFP
Gr-1- Alexa647
Autofluorescence

Scale bar: 250 µm

I_{THz}=260 mW/cm^2

Histological Analysis

Control | **THz Radiated Skin**



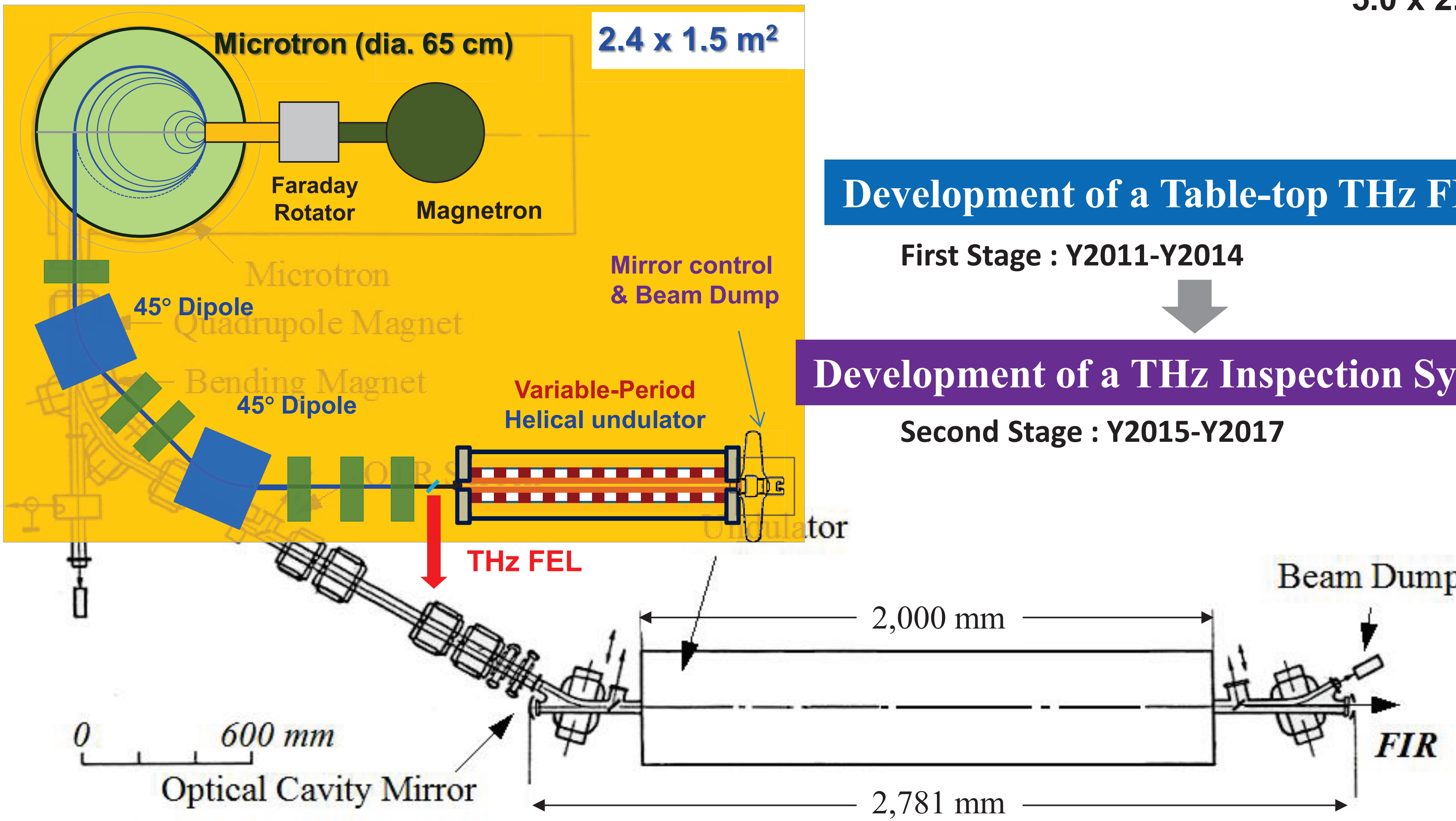
Slightly increased number of inflammatory cells (염증세포) in dermis (진피층)

No definite damaged cell or atypical keratinocytes (각질세포) in epidermis (표피층)

No difference in sebaceous gland (피지샘) and auricular cartilage (이개연골)

Table-top Terahertz FEL (2011-present)

5.0 x 2.7 m^2



Development of a Table-top THz FEL

First Stage : Y2011-Y2014

Development of a THz Inspection System

Second Stage : Y2015-Y2017

Table-top THHz FEL for Security Inspection

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

Microtron-based FEL
with a Short & Strong PM Helical Undulator
- a Low-loss Circular Waveguide & Mesh Mirrors

Why PM Helical Undulator?

- Compactness : < 200 x 200 x 1,000 mm^3
- Strong Field : 1 T
- Low THz Loss in a Circular WG : HE_{11} Mode

↓

But, how to Control FEL Wavelength?

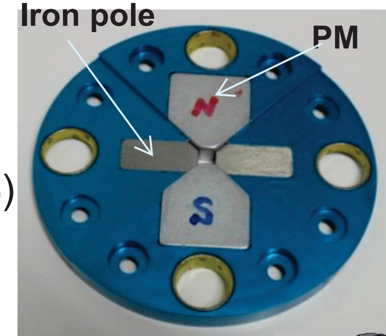
Super Conducting?
Or return to Planar Type?

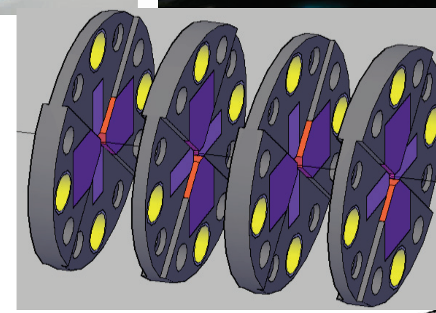
↓

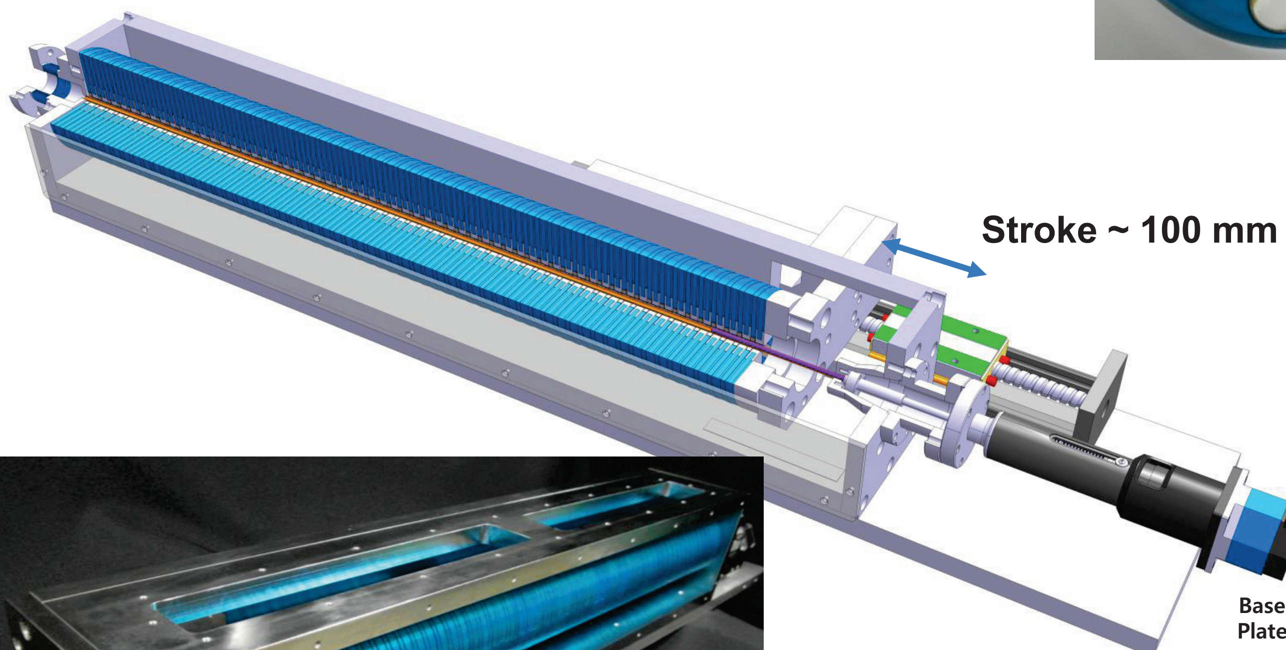
Variable-period PM Helical Undulator

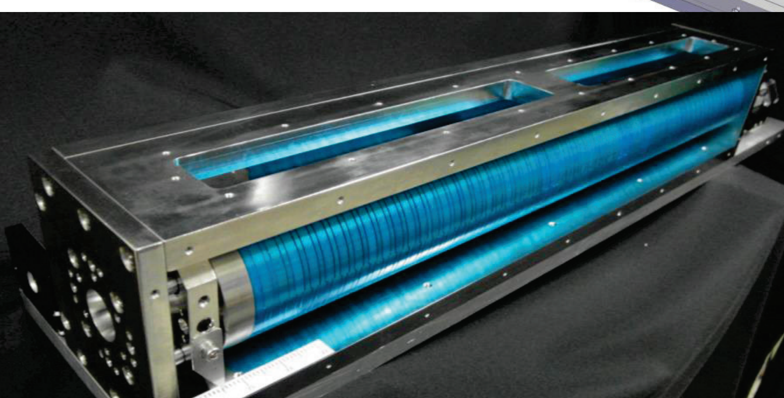
Variable-period PM Helical Undulator

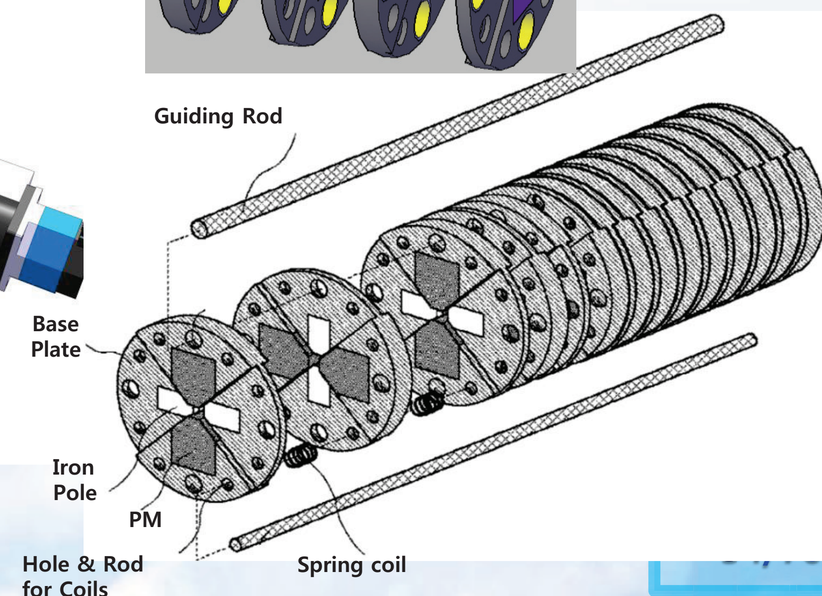
- Permanent-Magnet Variable-Period Helical Undulator
- **Variable Period : λ_w = 23~26 mm** with N_w = 30 (28+2)
- Total Length : 70~80 cm; Gap Diameter : 5 mm
- **Magnetic Field Strength on Axis : 1 T** (K-value : **2.1-2.4**)
- Cross-sectional Size of Undulator : 140 mm x 160 mm





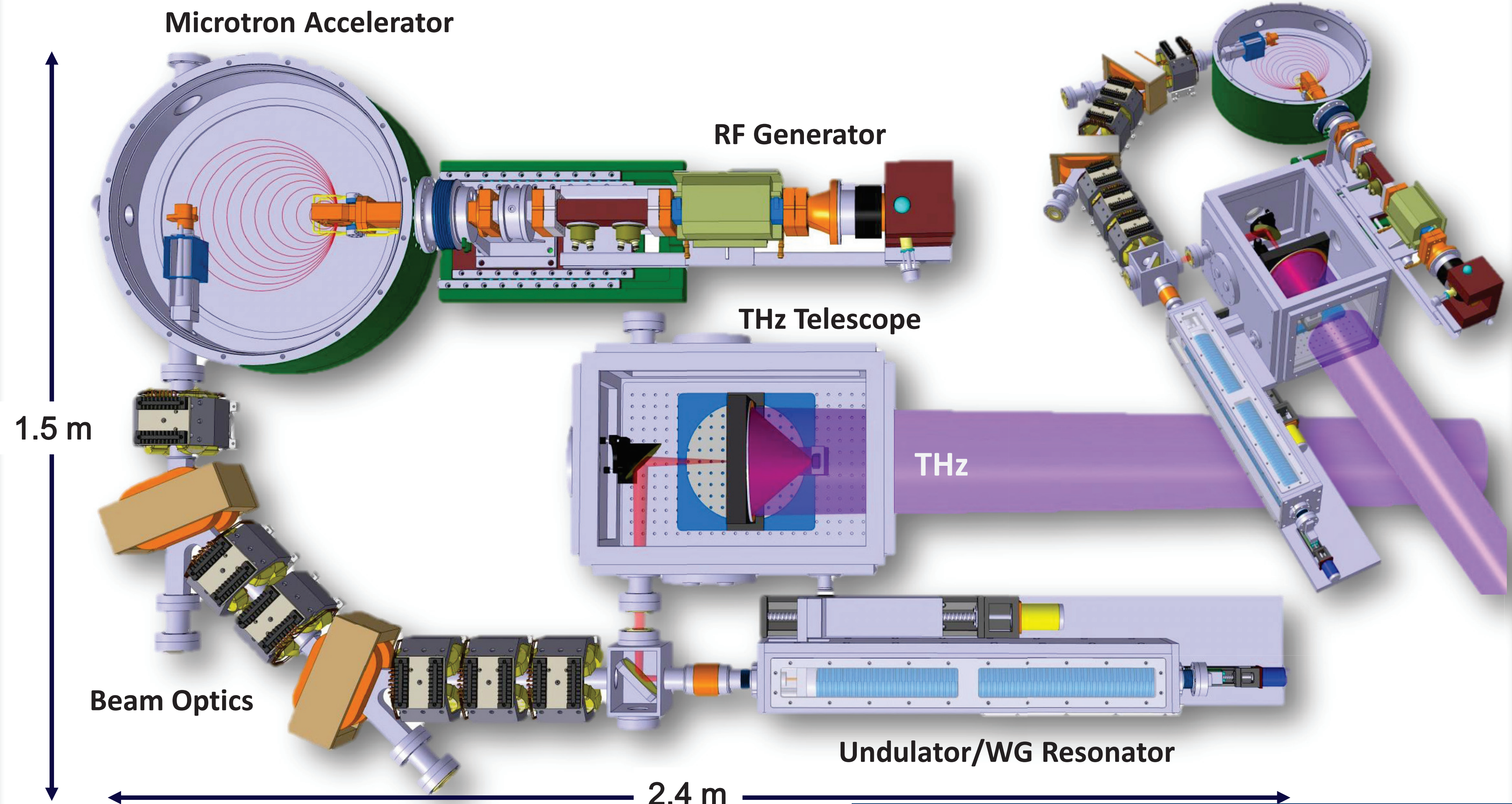




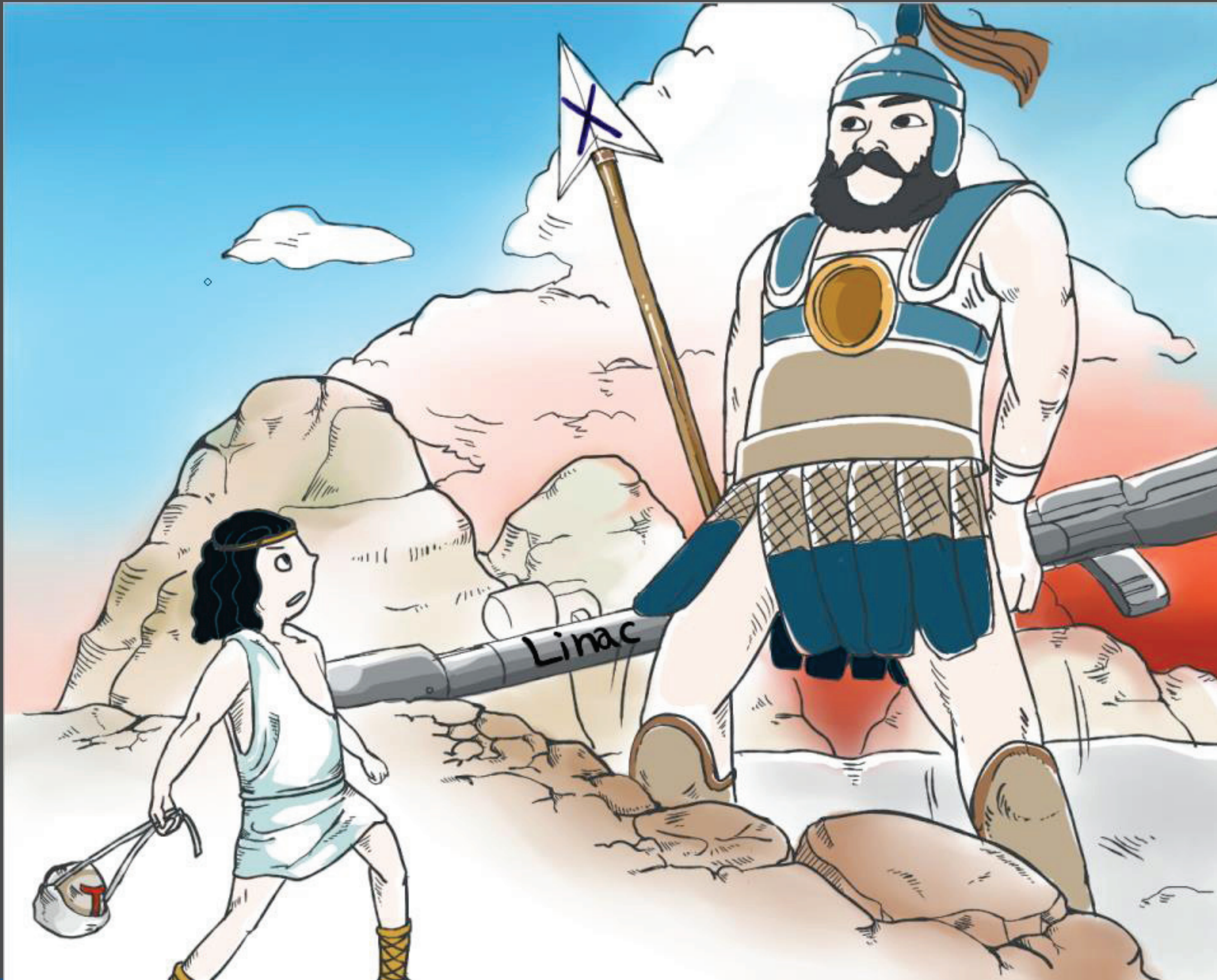


MOP030 Jungho Mun, "Performance Analysis of Variable-Period Helical Undulator…"

Table-top THz FEL (2011-present)



THP096 SeonYeong Noh,
"Development of an S-band Cavity-type Beam Position Monitor"


Linac


Linac


Linac


?
Linac

III. Relativistic UED* Facilities

*UED: Ultrafast Electron Diffraction

X-ray Diffraction

The Nobel Prize in Physics 1915

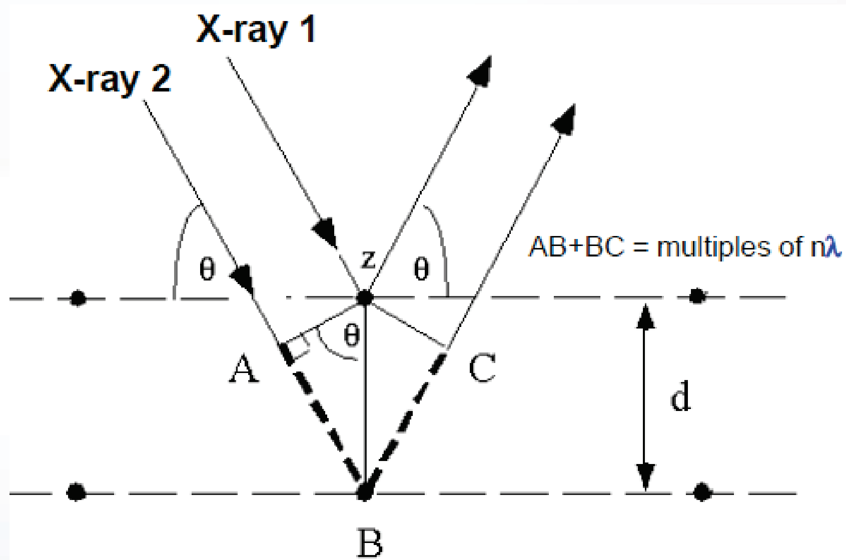
Sir William Henry Bragg

William Lawrence Bragg

The Braggs were awarded the Nobel Prize in physics in 1915 for their work in determining crystal structures beginning with NaCl, ZnS and diamond.

Bragg's Law

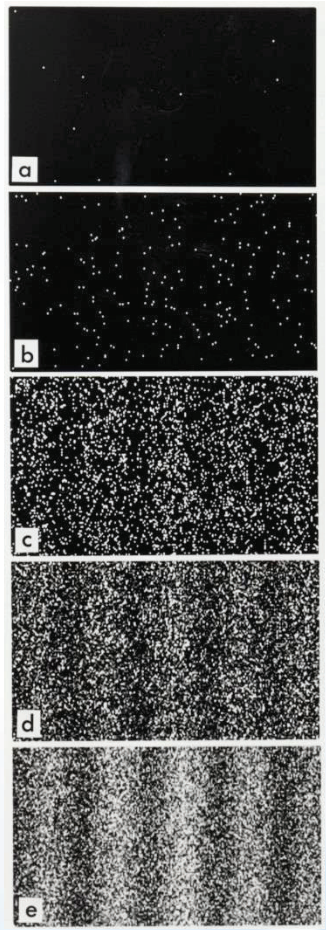
$$n\lambda = 2d\sin\theta$$



Electron Diffraction

- Matter wave, de Broglie equation

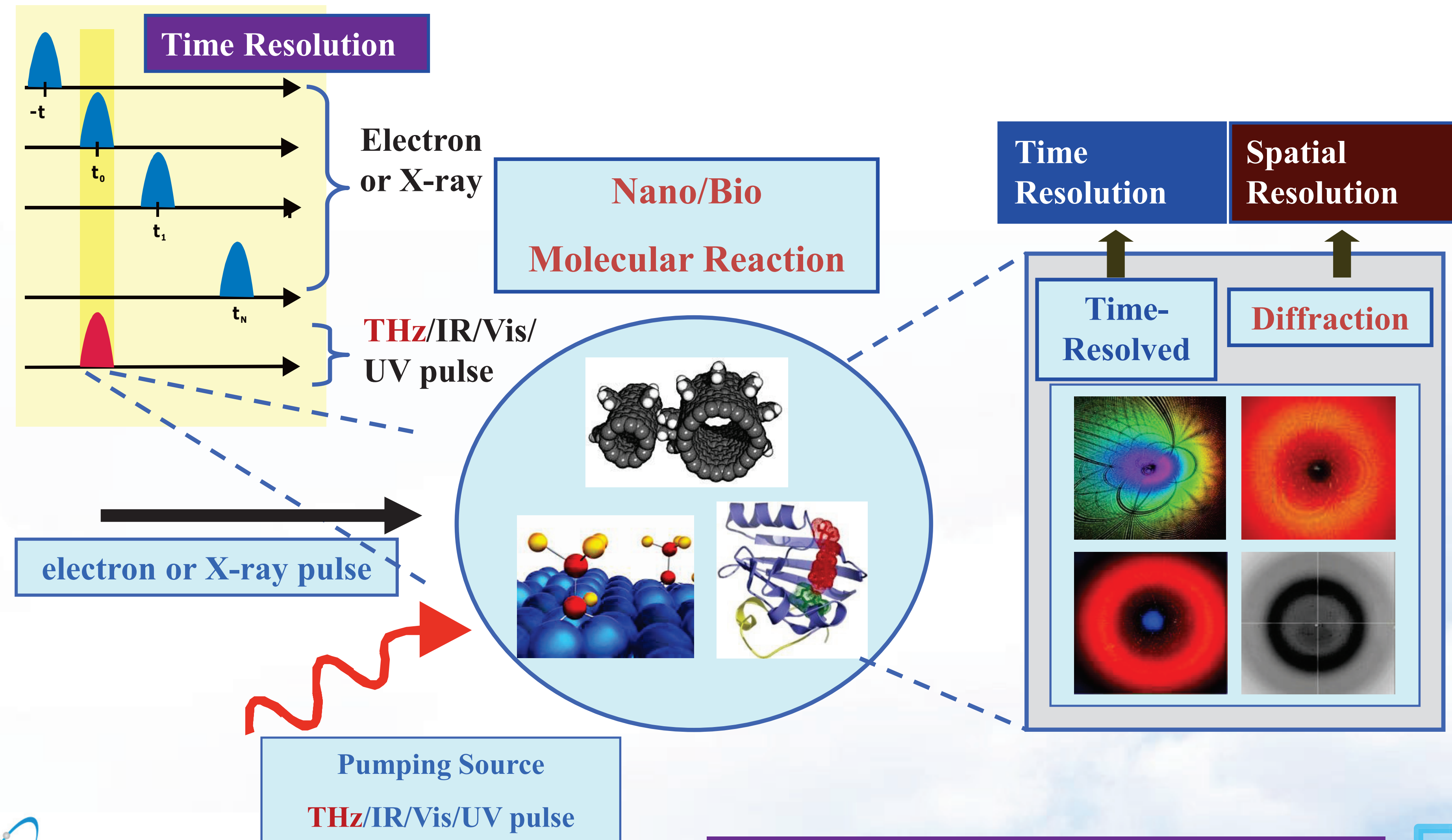
$$\lambda = \frac{h}{p} = \frac{h}{mv} \sim 0.4\,pm$$ for 2.5 MeV electron beam



Electron diffraction by double slit

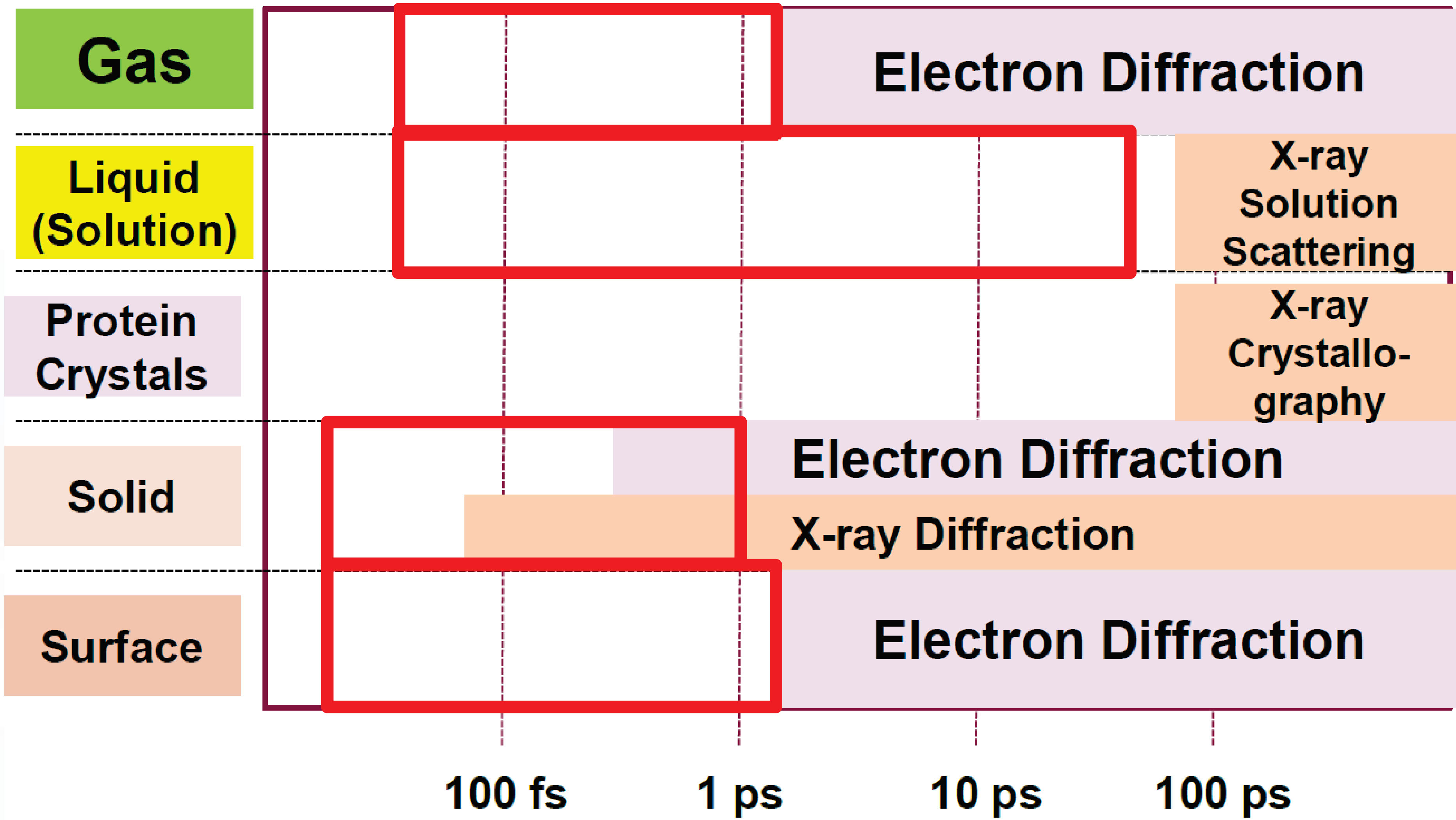
from Wikipedia

Time-resolved Diffraction



Courtesy : Prof. H. Ihee (KAIST/IBS)

Time Resolution achieved by Time Resolved Diffraction



한국원자력연구원 Korea Atomic Energy Research Institute

Courtesy : Prof. H. Ihee (KAIST/IBS)

Relativistic UEDs

Non-relativistic UEDs

- Using 10-100 keV Electrostatic Photoguns
- Larger Scattering Cross-section than X-ray
- Observation of ~100 fs Dynamics with Atomic-scale Resolution
- Limited Number of Electrons (<10^4) due to Space Charge
- Impossible to Perform Single-shot Measurement

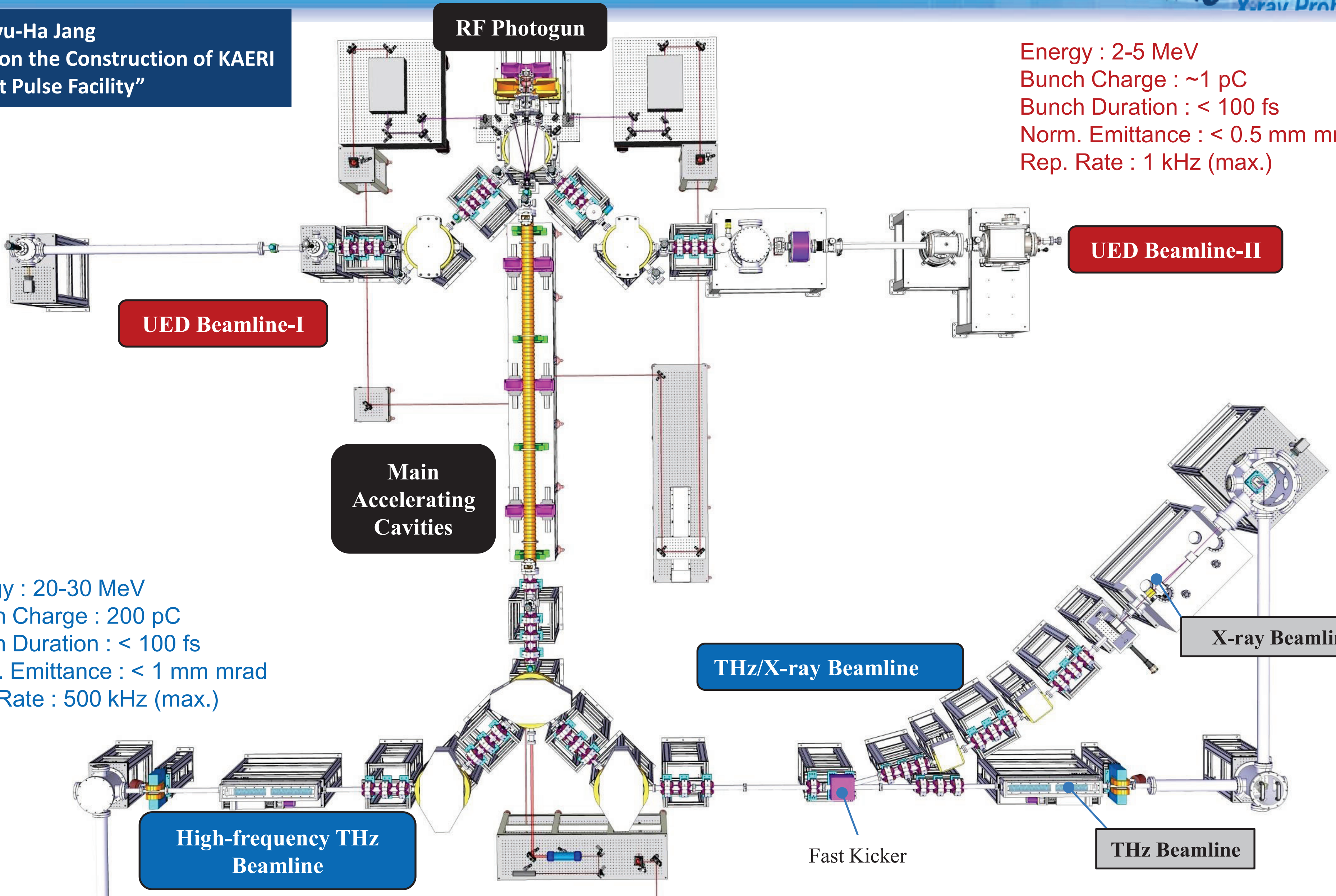
Relativistic UEDs

- 2-5 MeV RF Photoguns
- Suppressing Space Charge Forces with High-gradient Acceleration
- Sub-100 fs Timing Accuracy with > 10^6 Electrons
- Single-event Measurement

Scheme of the KAERI Ultra-short Accelerator

THP038 Kyu-Ha Jang
"Progress on the Construction of KAERI Ultra-short Pulse Facility"

Energy : 2-5 MeV
Bunch Charge : ~1 pC
Bunch Duration : < 100 fs
Norm. Emittance : < 0.5 mm mrad
Rep. Rate : 1 kHz (max.)



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

Main Concept of the Accelerator

1. Two Beamlines for Ultrafast Electron Diffraction

- Single-shot Measurement* with < 100 fs Resolution
- Two Beamlines for Gases & Solid-states
- Pumping Sources of IR-UV & THz Pulses
- Probing Sources of ~3 MeV Electron Bunches (< 100 fs, 1 pC)

2. Beamline for THz pump & X-ray probe

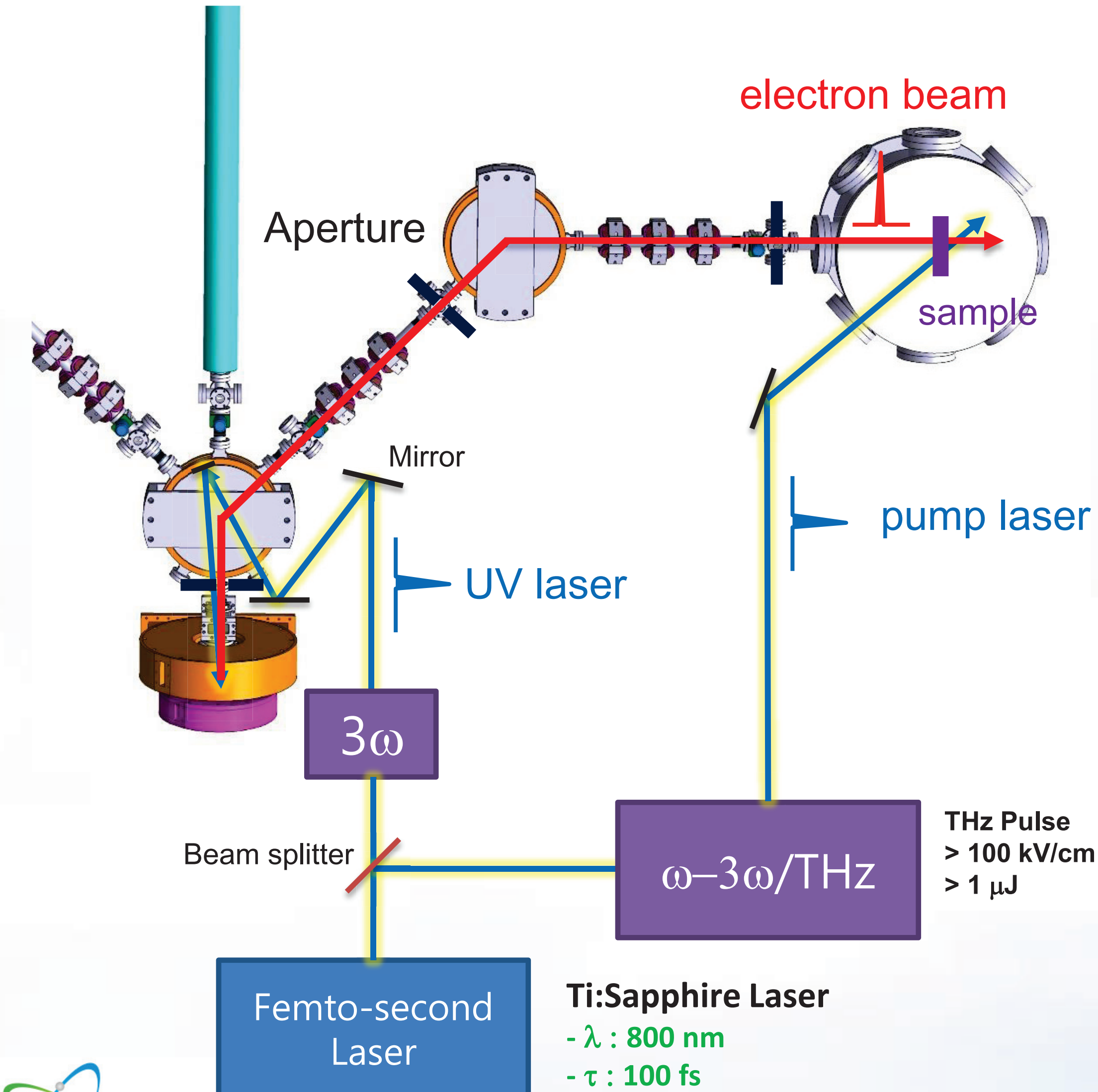
- Multi-shot Measurement with ~100 fs Resolution
- Synchronized Two Electron Bunches (~25 MeV, 200 pC) for Generating Pump/Probe Radiations
- Pumping Sources of Wide-band & Narrow-band Intense THz Pulses
- Probing Sources of Bremsstrahlung X-ray Pulse with Crystals

3. High-accuracy Synch. and Timing for Pump & Probe (< 50 fs)

4. High-repetition Operation (500 Hz Hz)

* Single-event measurement needs > 10^6 electrons, 1 pC : ~6 x 10^6 electrons/bunch

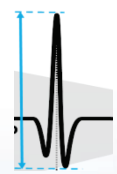
Scheme of the UED Beamline



Ti:Sapphire Laser
- λ : 800 nm
- τ : 100 fs
- Pulse Energy : 5 mJ
- Rep. Rate : 1 kHz

RF gun Parameters	Value	unit
Bunch charge	1	pC
Peak field at cathode	60	MV/m
Phase from 0-crossing	29.5	deg
Thermal emittance	0.3858	mm mrad
Photo emission efficiency	0.001	%

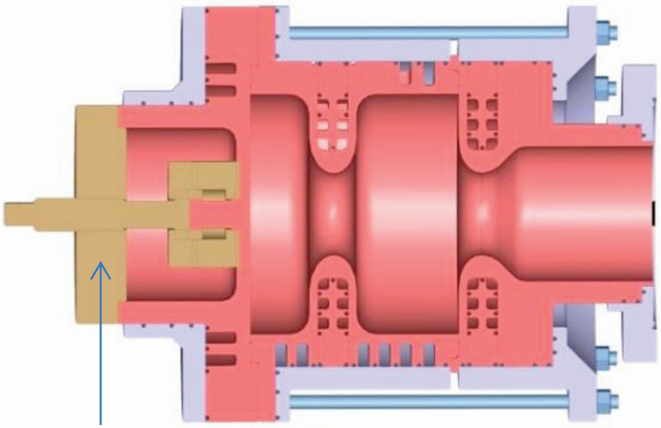
Laser Parameters	Value	unit
Laser energy	0.5	μJ
Wavelength of laser	266	nm
Laser spot size (FWHM)	1	mm
Laser pulse width (FWHM)	100	fs



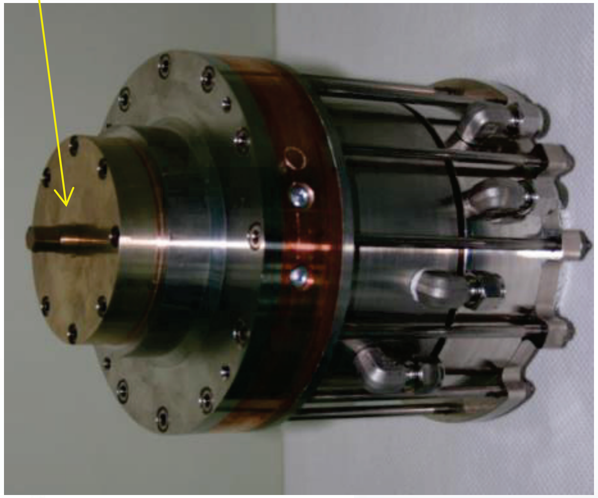
KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

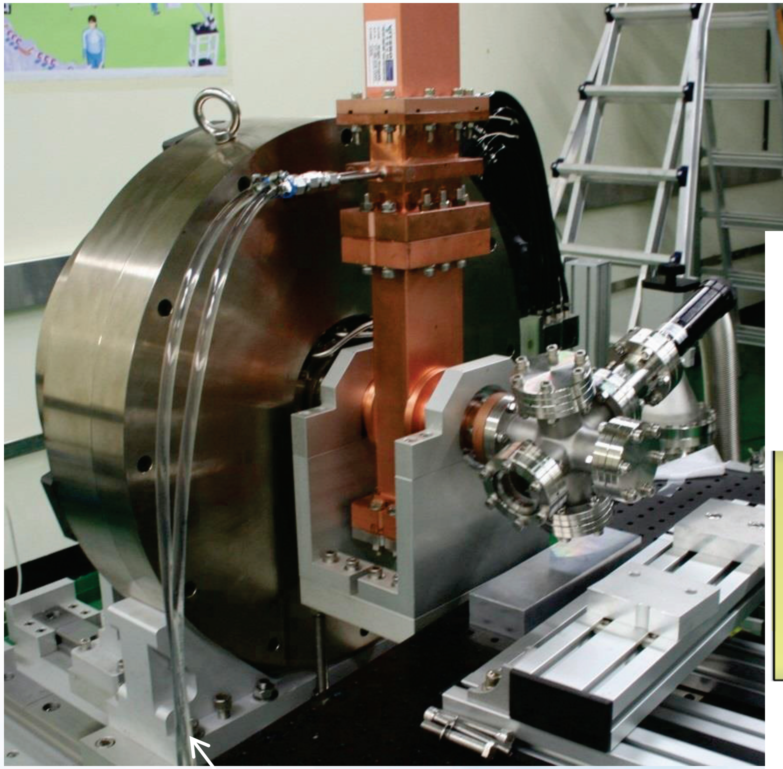
Coaxial-type RF Photogun

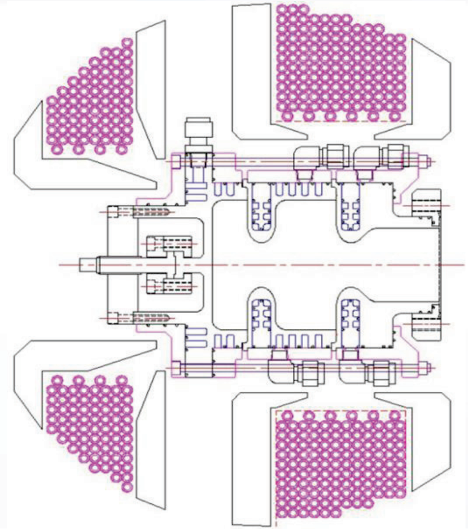
Frequency : 2.856 GHz
Repetition Rate : 1-500 Hz
Axial Symmetry with a Coaxial Coupler
Original Design by J.-H. Han (PAL)



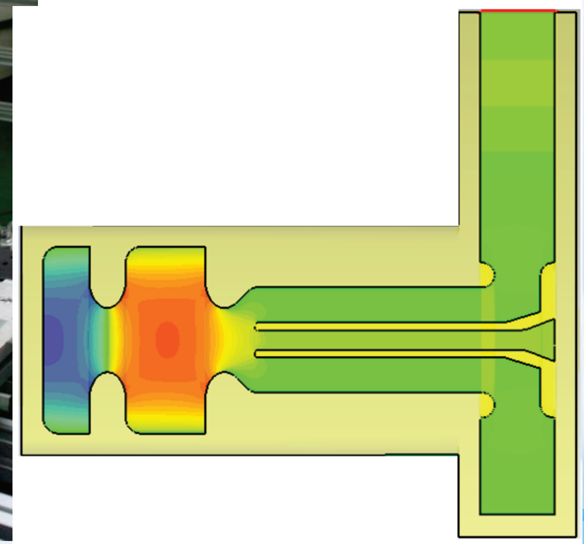
Frequency Tuning Mechanics







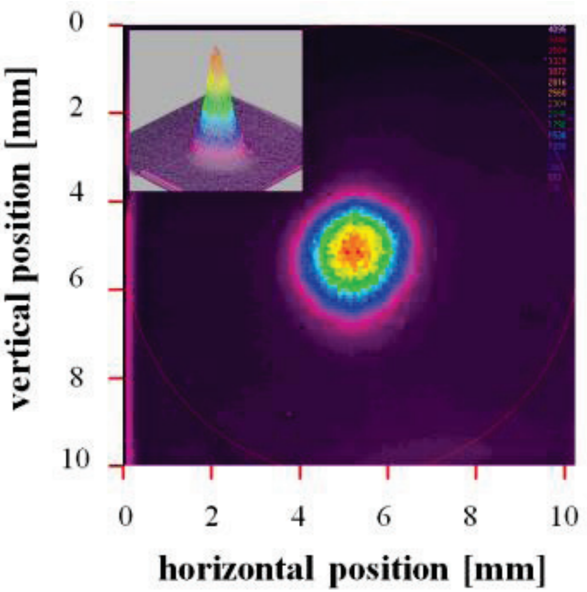
Gun solenoid & bucking coil



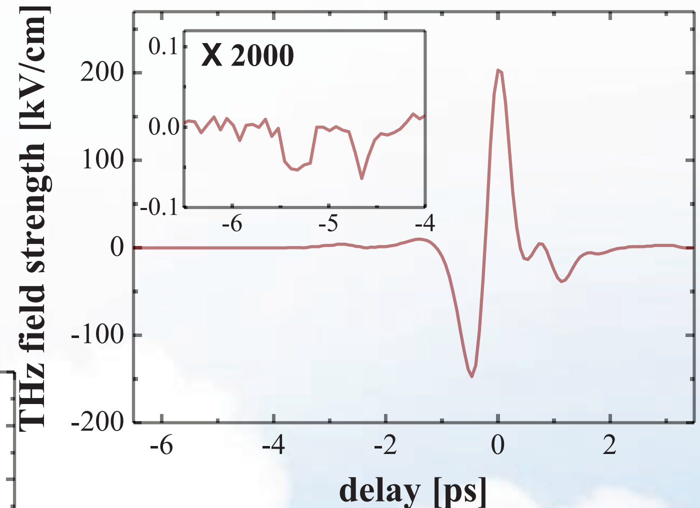
π mode & coaxial coulpler

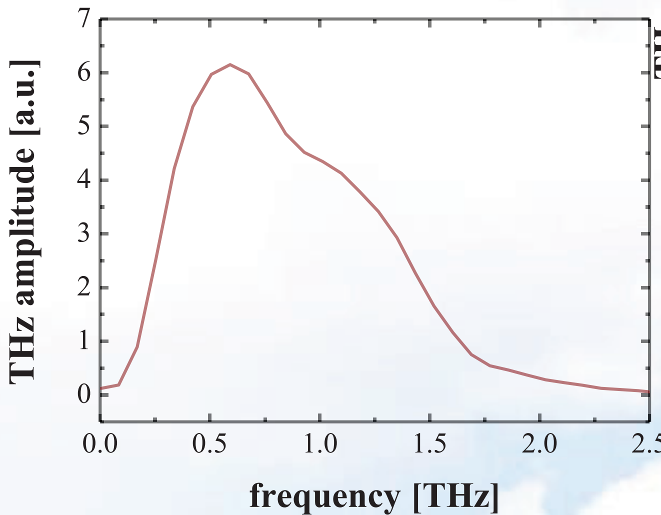
Pumping Source of the UED Beamline

High-power single-cycle terahertz pulse generation via efficient phase-matching through wave front tilting in prism-cut LiNbO3

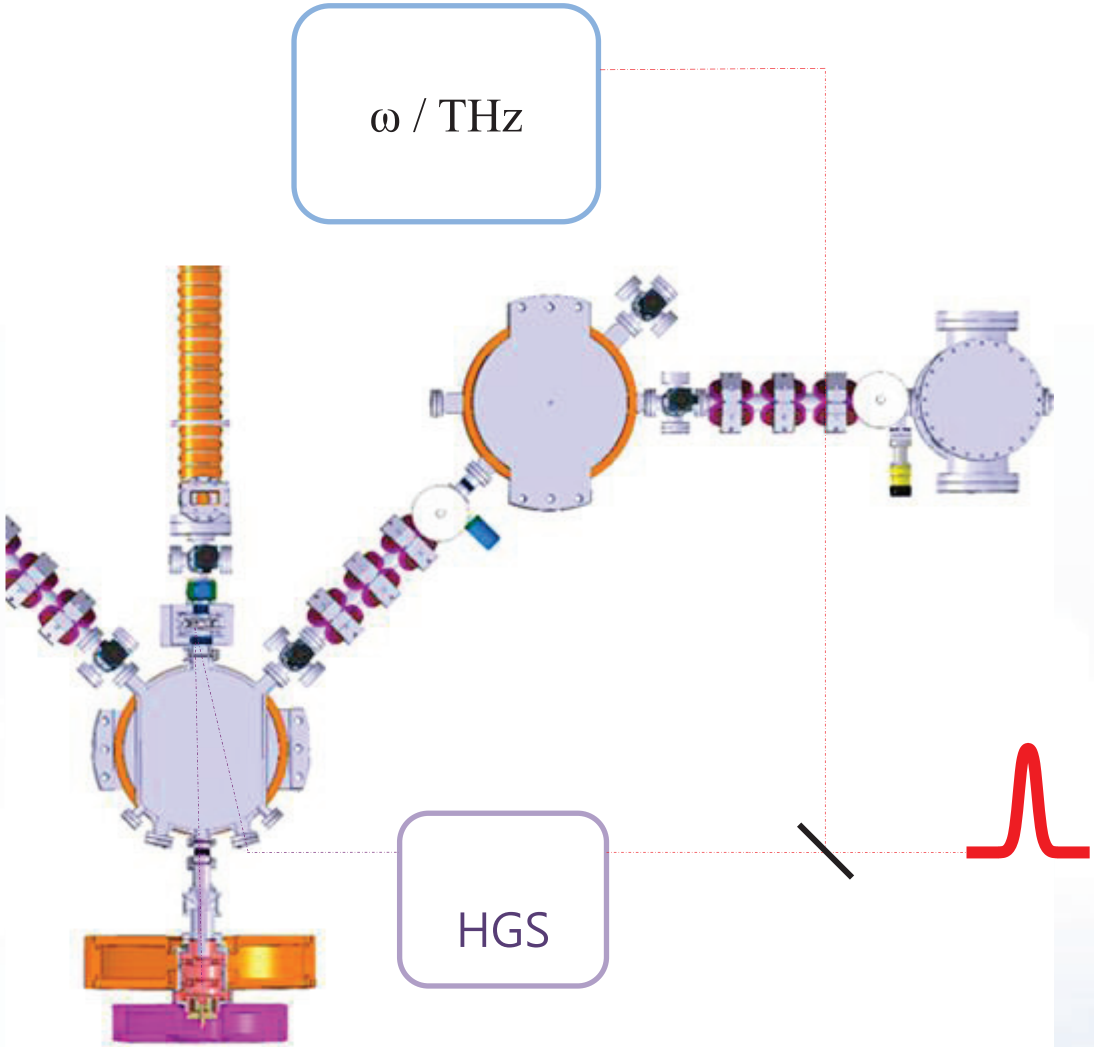


Extremely high signal-to-noise ratio (>1:15000)
THz field amplitude: > 400 kV/cm
THz output power: **3.5 mW** (~1.4×10^{-3})

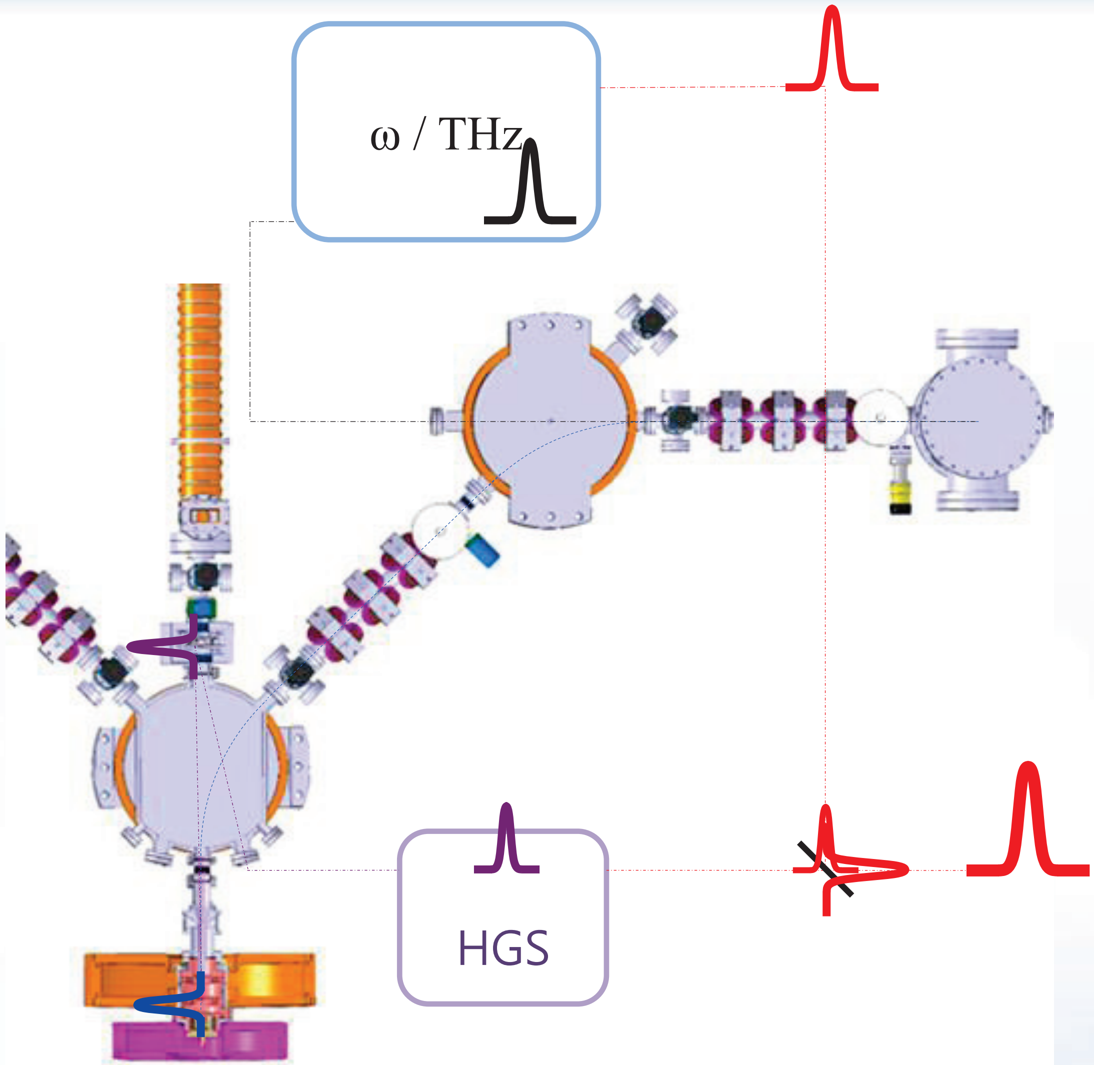


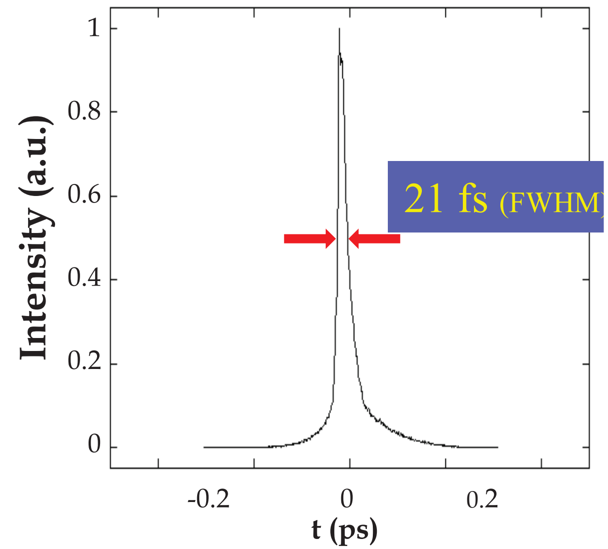


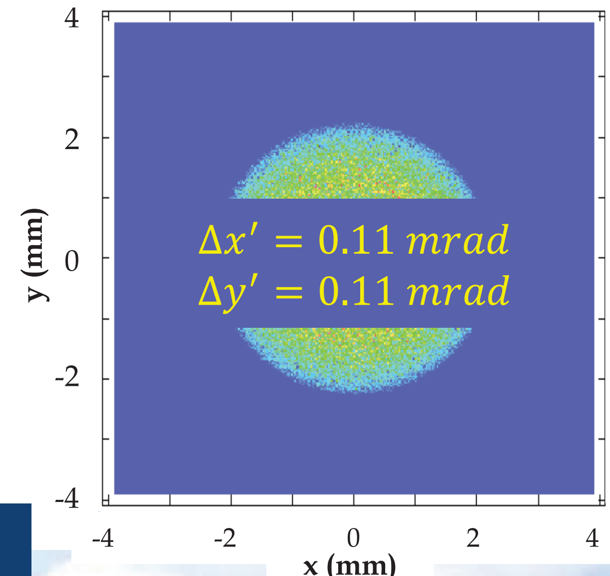
Scheme of the UED Beamline



Scheme of the UED Beamline







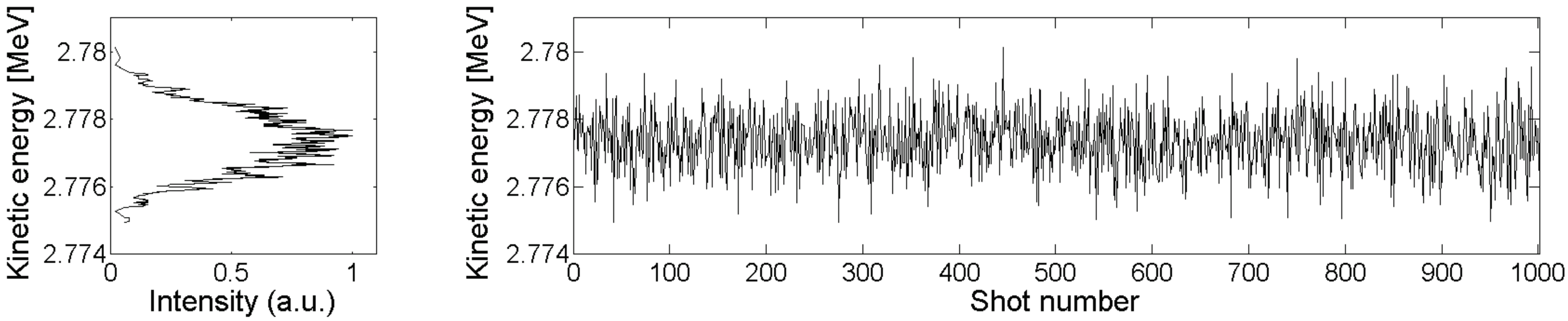
THP009 In-Hyung Baek, *et al.*,
"Spatiotemporal Optimization of UV-Pump Pulses for the Ultrafast Electron Diffraction"

Electron Beam Parameters for UED

Beam Parameters	Desired	Simulation	Units
Number of Electrons	> 10^6	6.25×10^6	electrons
Beam Kinetic Energy	~ 3	2.8	MeV
Energy Spread (rms)	< 0.1	0.17	%
Norm. Transverse Emittance	< 0.2	0.3	mm mrad
Bunch Duration (FWHM)	< 100	21	fs
Angular Spread (rms)	< 0.025	0.11	mrad

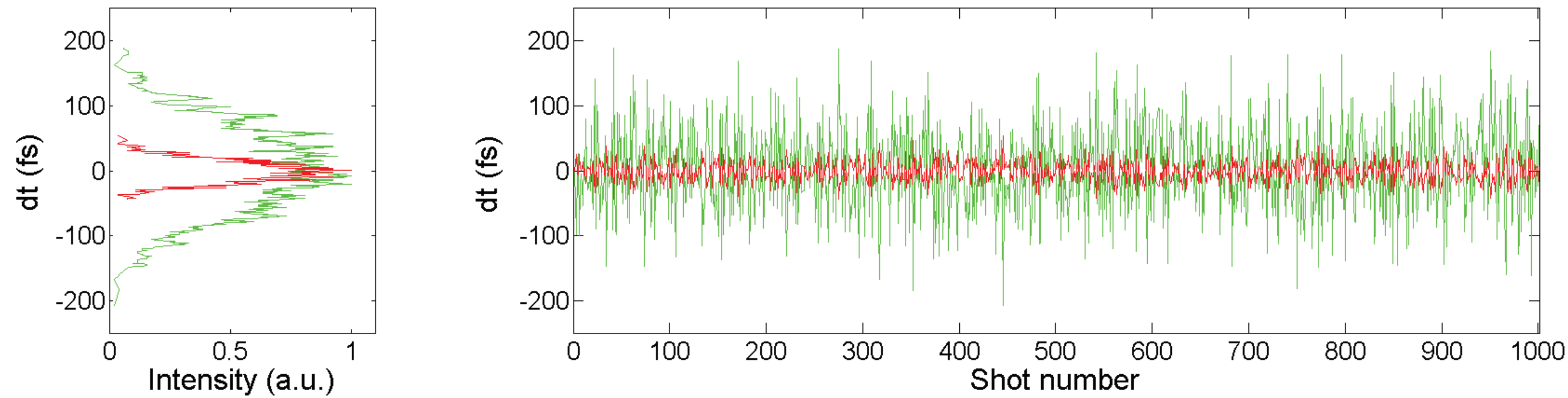
Low Timing Jitter

Energy Fluctuation, ΔE_{jitter} = 0.1 % (rms)



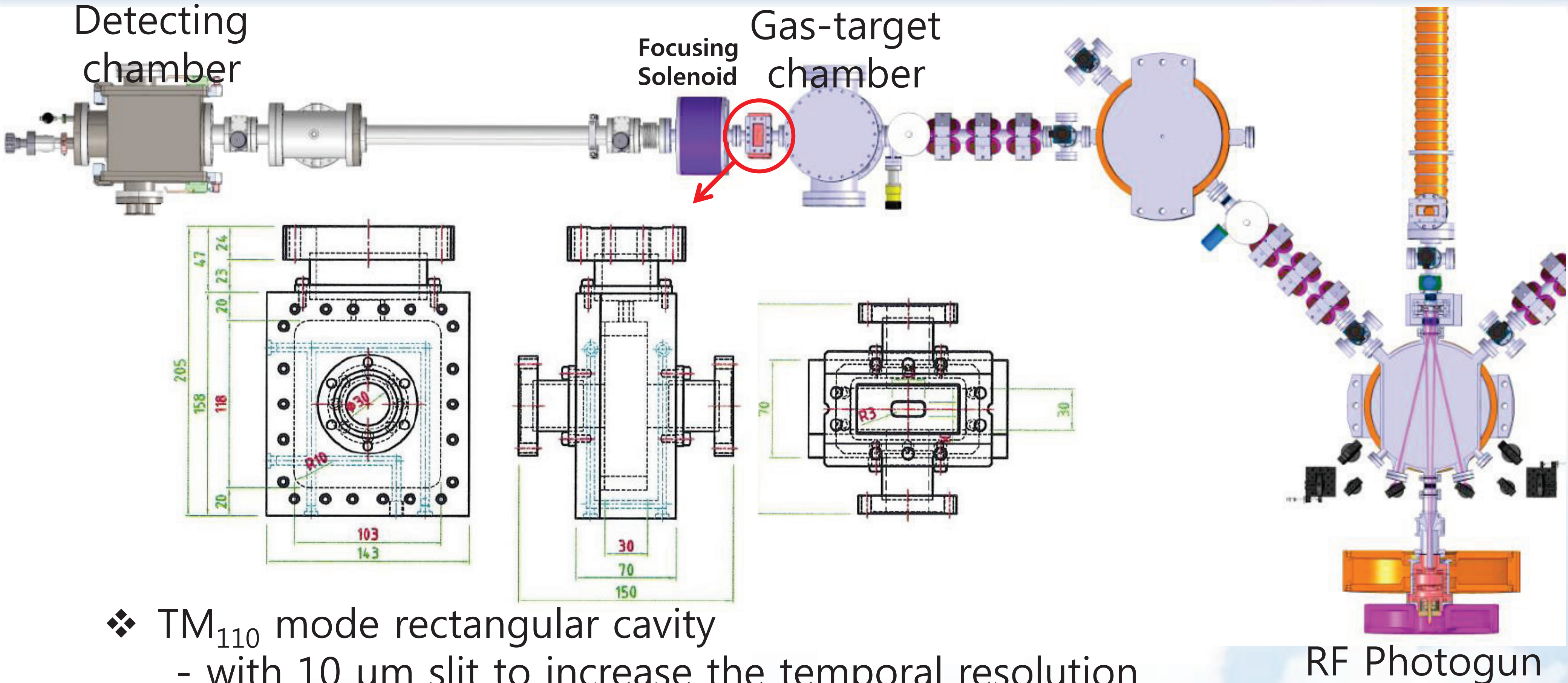
Δt_{jitter} (rms)

3 m with isochronous bend = 14 fs **3 m straight line = 55 fs**



THP010 **Hyun Woo Kim, *et al.*,**
"Analysis of Beam Stability in the KAERI Ultrashort Pulse Accelerator"

Deflecting Cavity

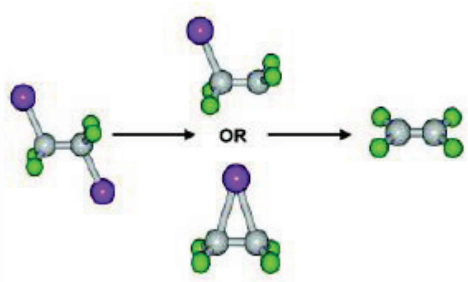


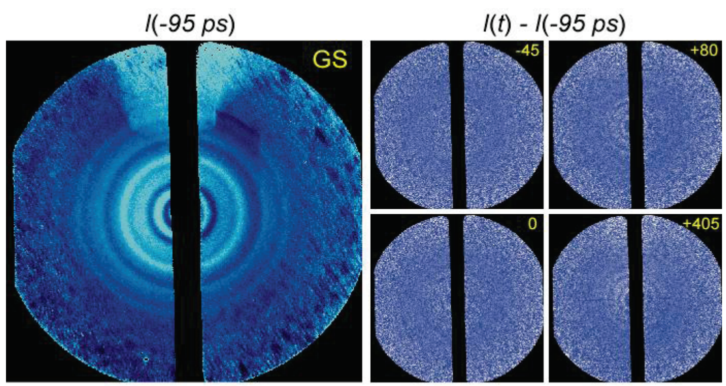
- ❖ TM_{110} mode rectangular cavity
  - with 10 μm slit to increase the temporal resolution
  - Resonance frequency : 2.856 GHz
  - Deflecting voltage : ~ 50 kV
  - Expecting time resolution : < 100 fs

Examples : Chemical Reaction Study

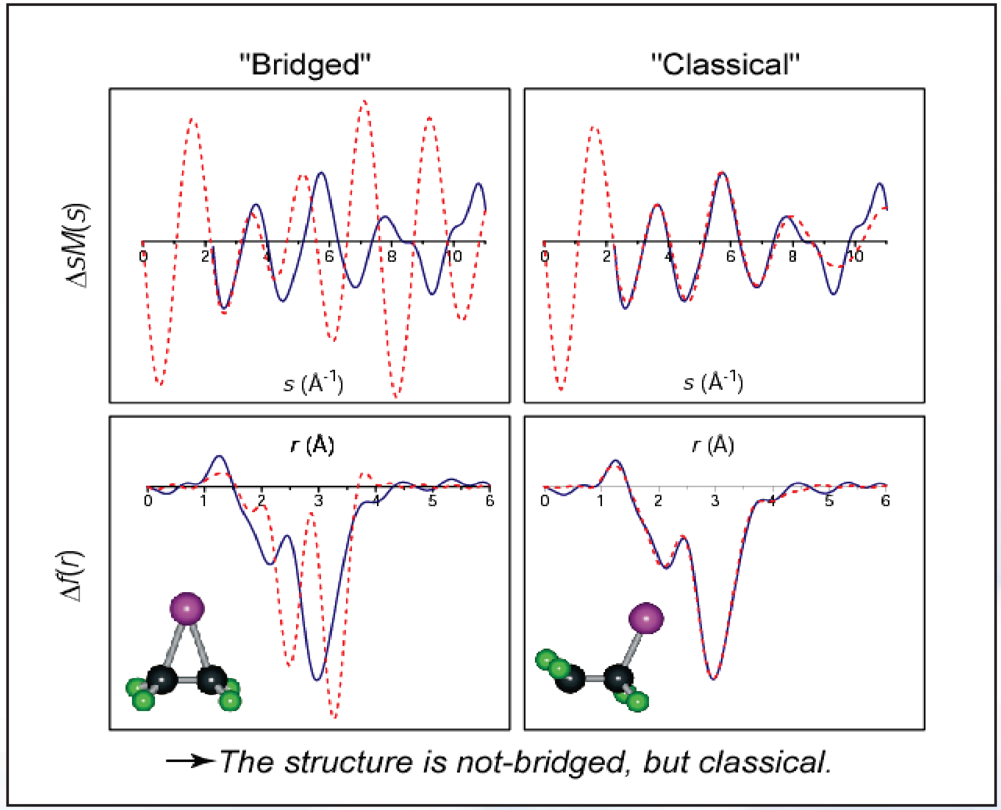
Direct Imaging of Transient Molecular Structures with Ultrafast Diffraction

Prof. Hyotcherl Ihee
(KAIST)
Femto Chemistry





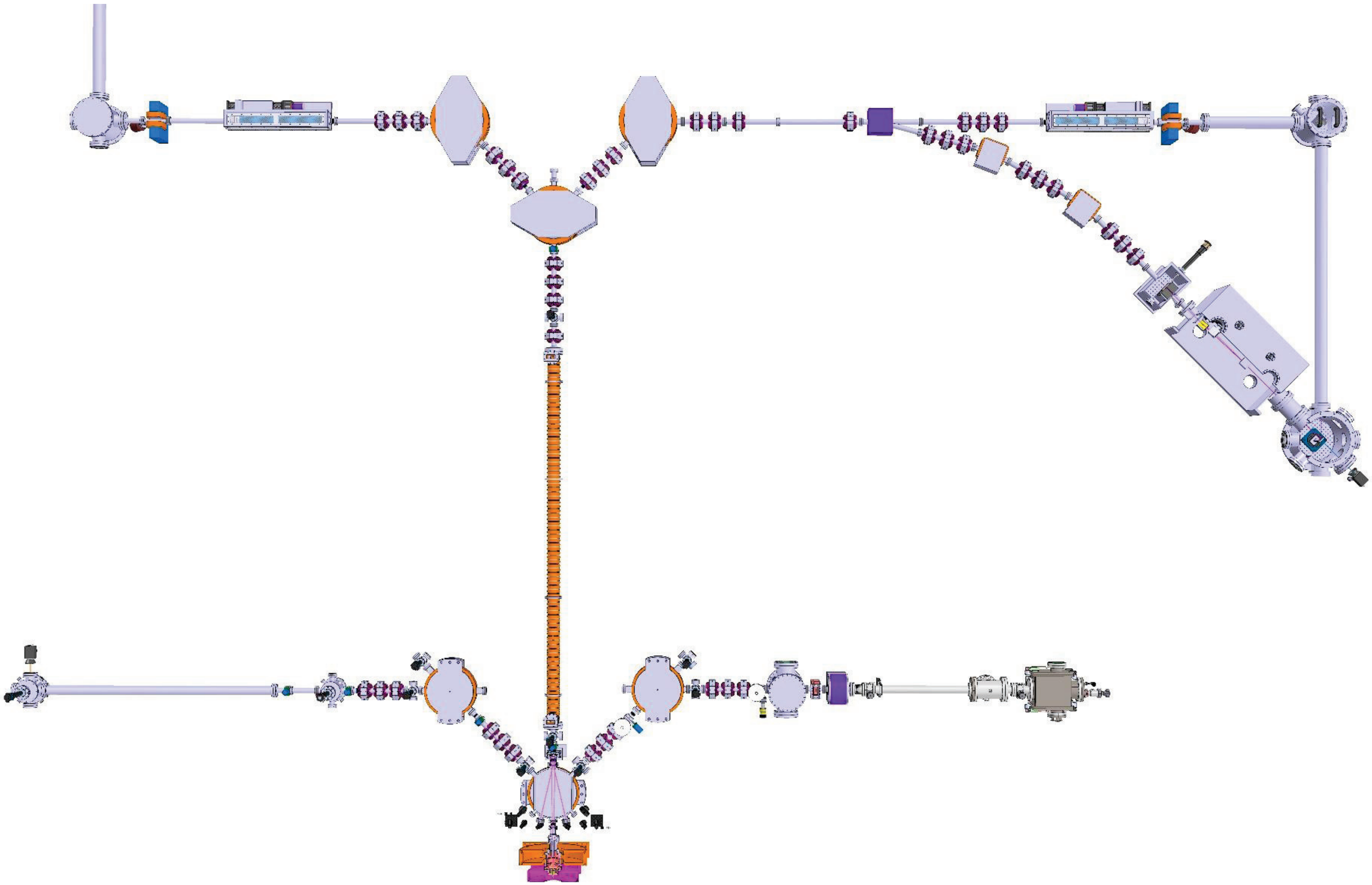
Difference images show faint rings resulting from structural changes



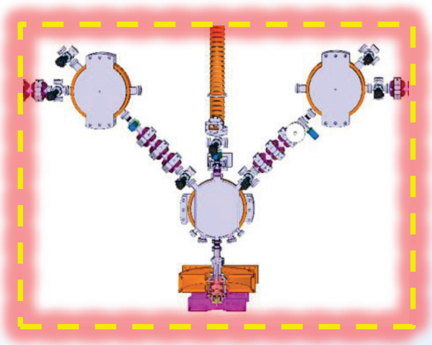
Ihee et. al., Science (2001)

Courtesy : Prof. H. Ihee (KAIST/IBS)

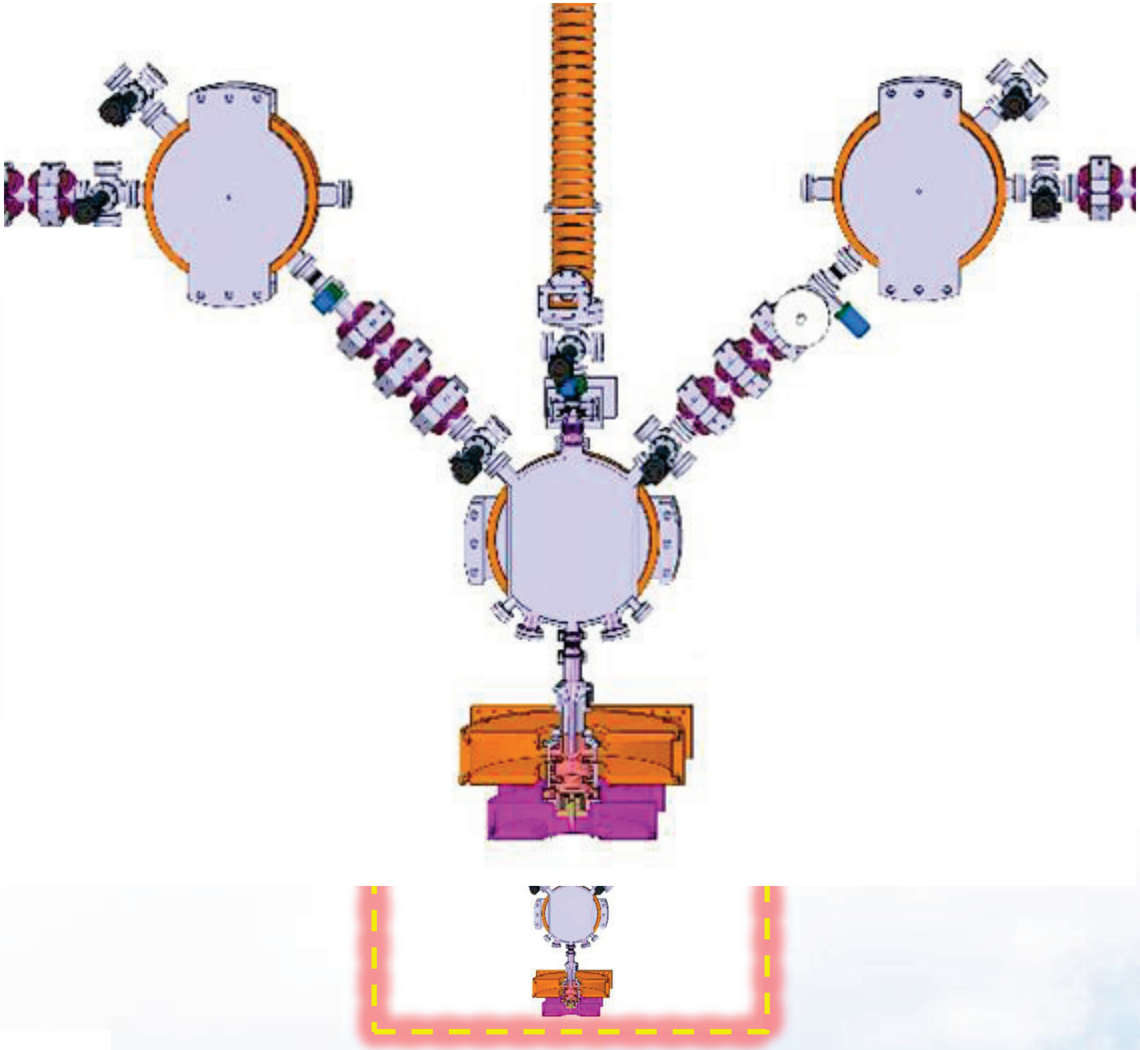
Scheme of the THz/X-ray Beamline



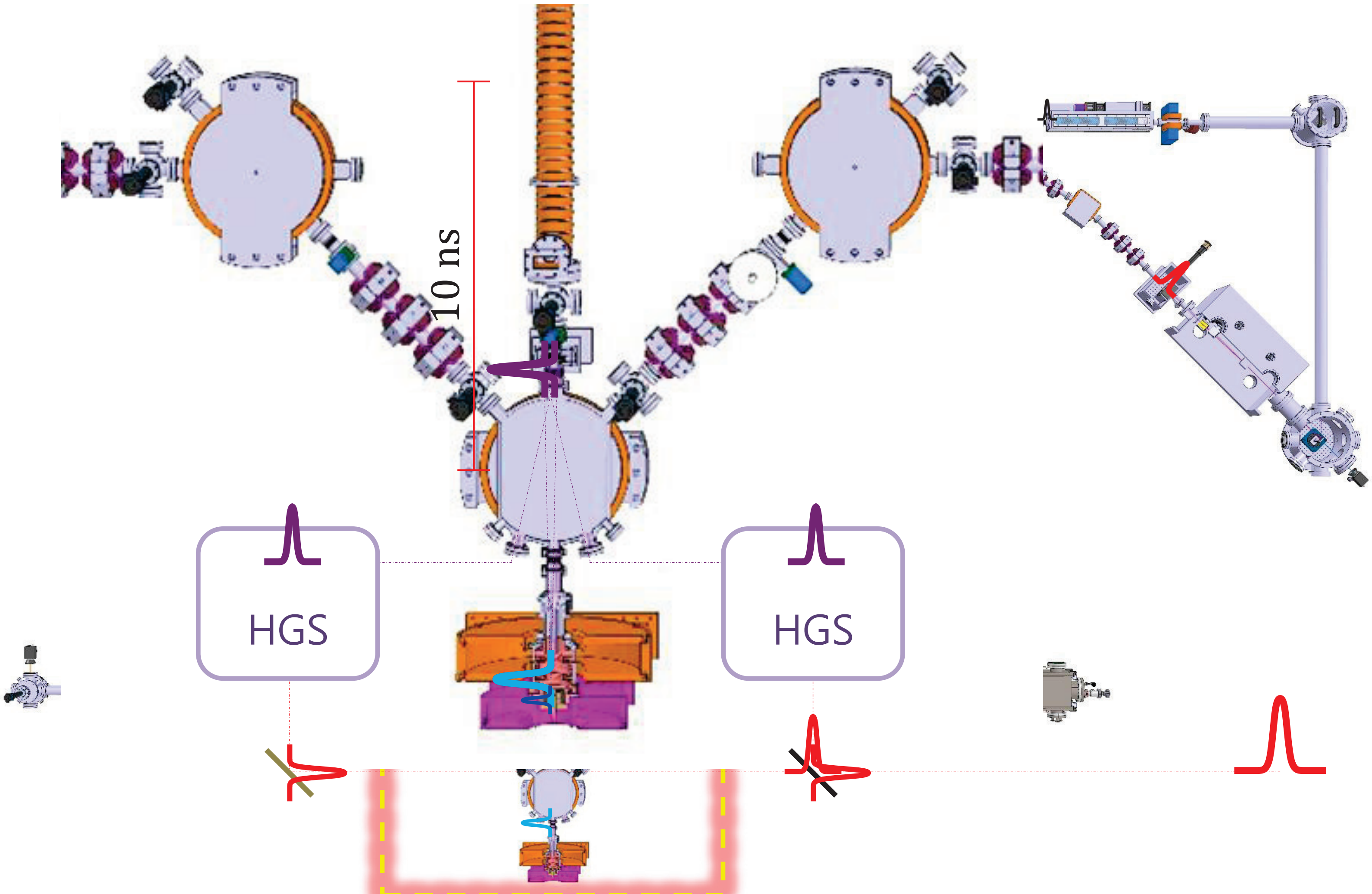
Scheme of the THz/X-ray Beamline



Scheme of the THz/X-ray Beamline



Scheme of the THz/X-ray Beamline



Applications & Collaborators

Bio Science

Prof. Gun-Sik Park
(Seoul Nat'l Univ.)
THz-Bio Interaction

Prof. Pilhan Kim
(KAIST)
In-vivo THz-Bio Imaging

Accelerator

Dr. Jaehoon Kim
(KERI)
Laser Acceleration

Dr. Jang-Hee Han
(Pohang Acc. Lab.)
RF Photogun

THz Optics

Prof. Bunki Min
(KAIST)
THz Meta Materials

Prof. Rotermund Fabian
(Ajou Univ.)
Intense THz Generation & Nonlinear THz Optics

Prof. Jaewook Ahn
(KAIST)
Sub-wavelength THz Optics

Prof. Hyunyong Choi
(Yonsei Univ.)
Ultrafast THz Dynamics

Pump & Probe

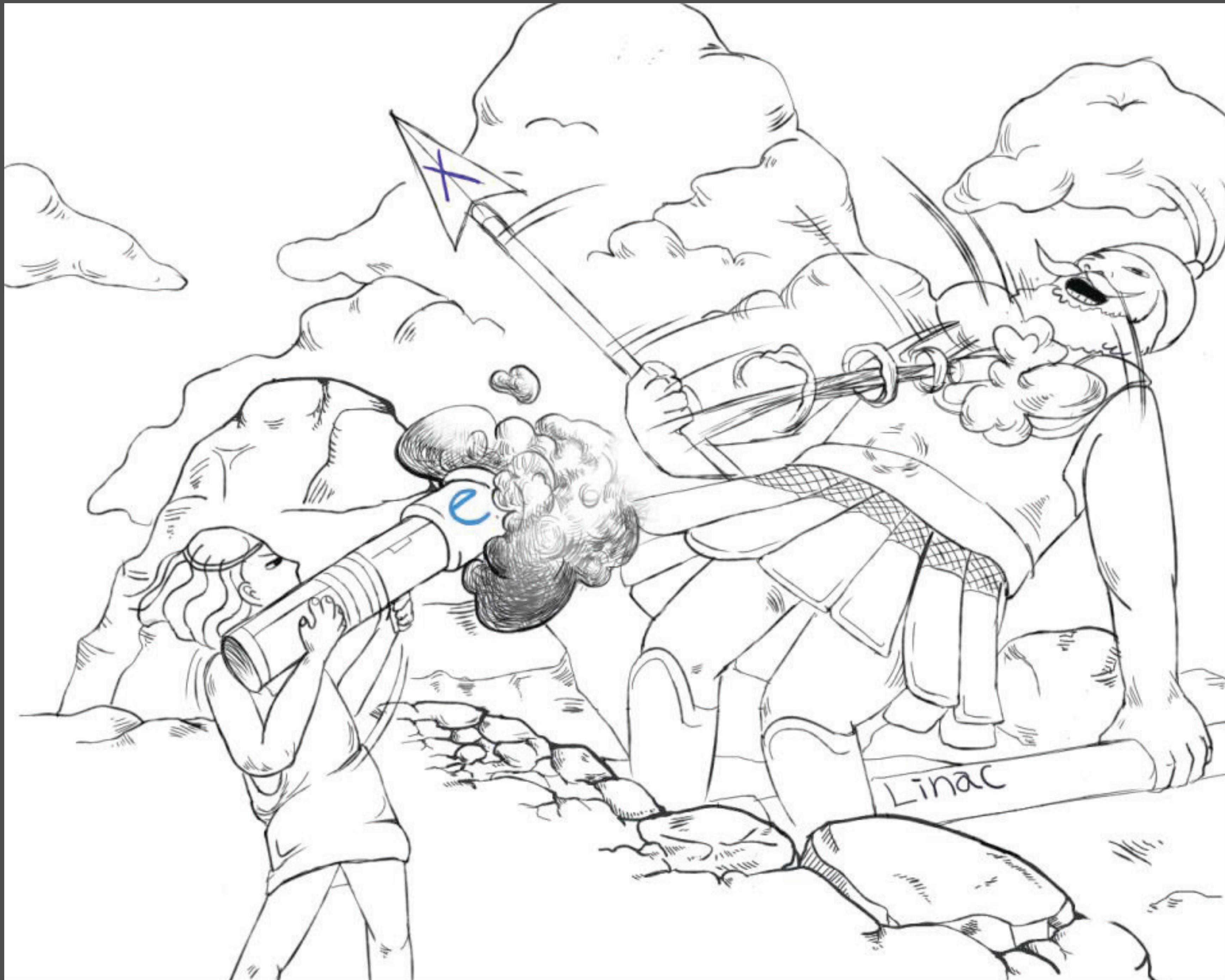
Prof. Hyotcherl Ihee
(KAIST)
Femto Chemistry

Prof. Kyungwan Kim
(Chugbuk Nat'l Univ.)
THz Pump & Probe

Dr. Jaehun Park
(Pohang Acc. Lab.)
Pump-probe Chemistry

Prof. Jungwon Kim
(KAIST)
Laser-based Timing & Synchronization

!
e
Linac


X
e
Linac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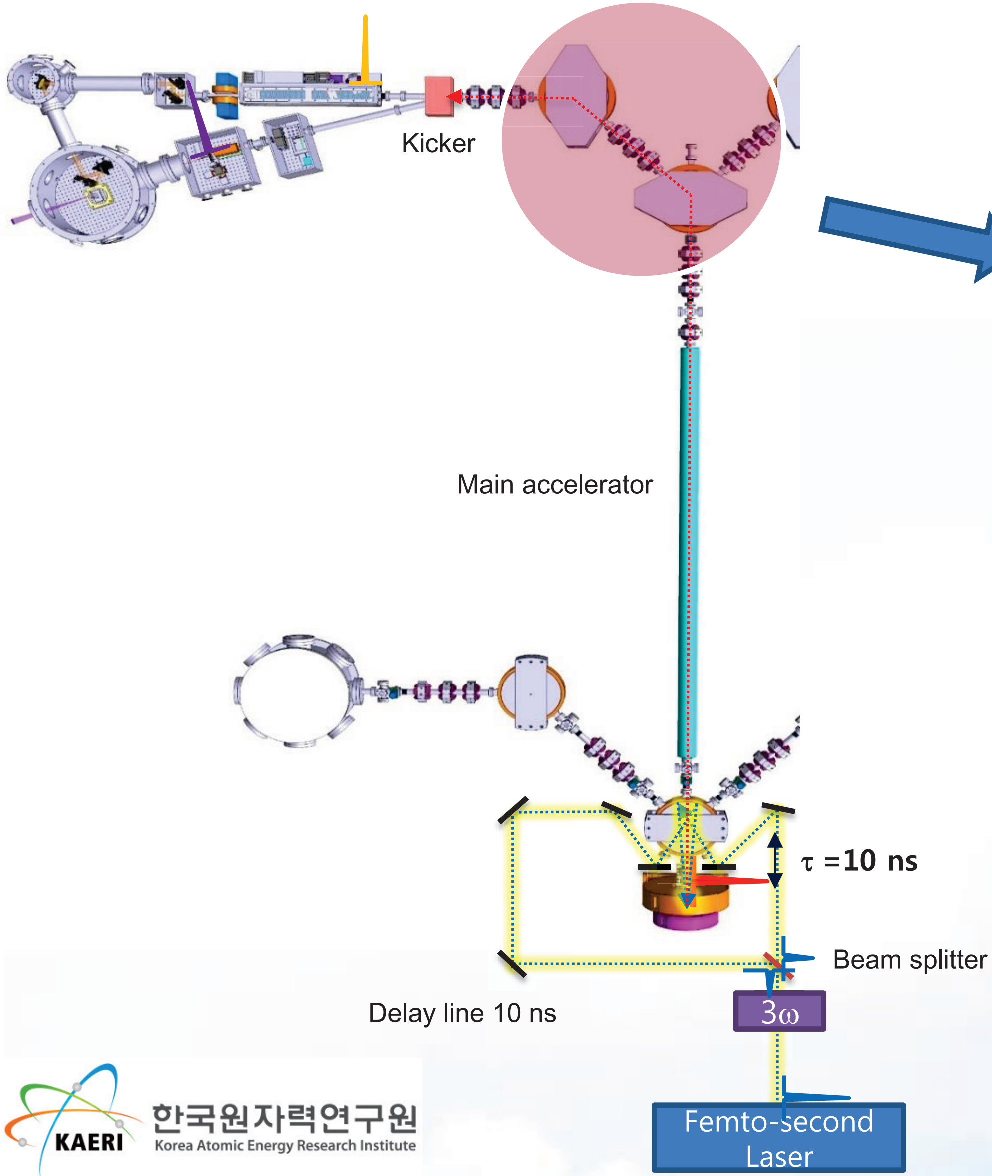
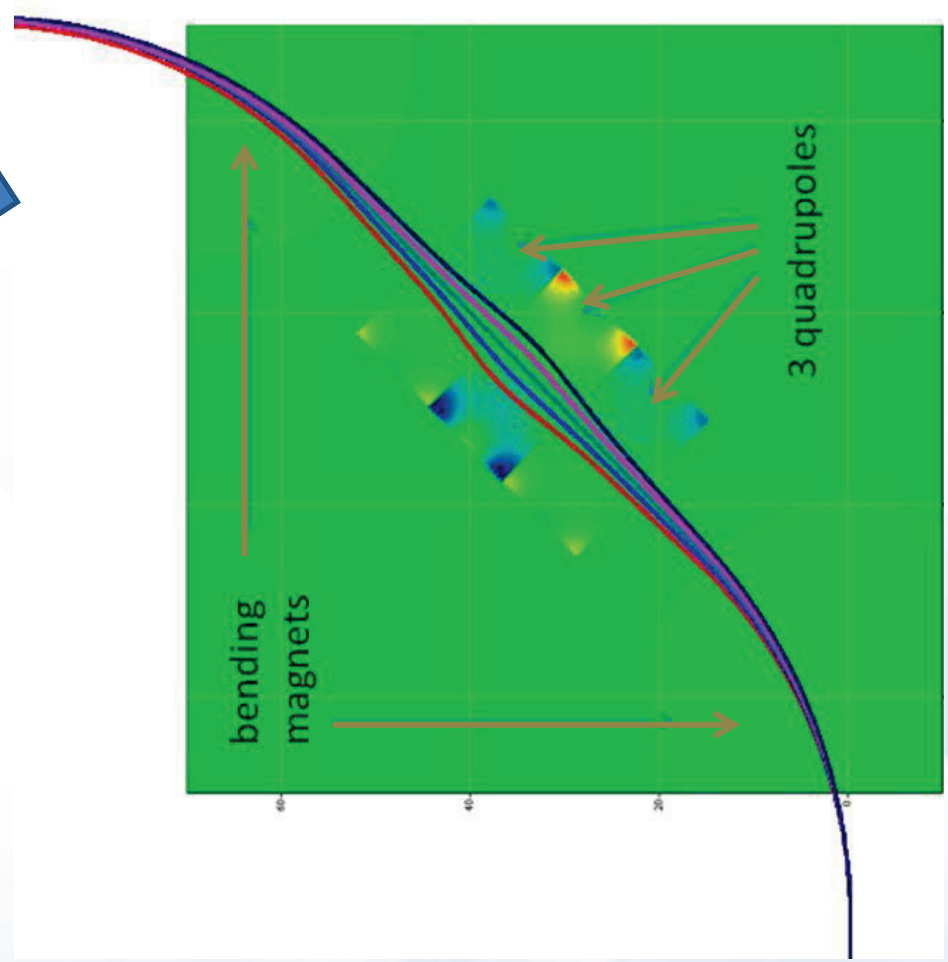
Thank You !!

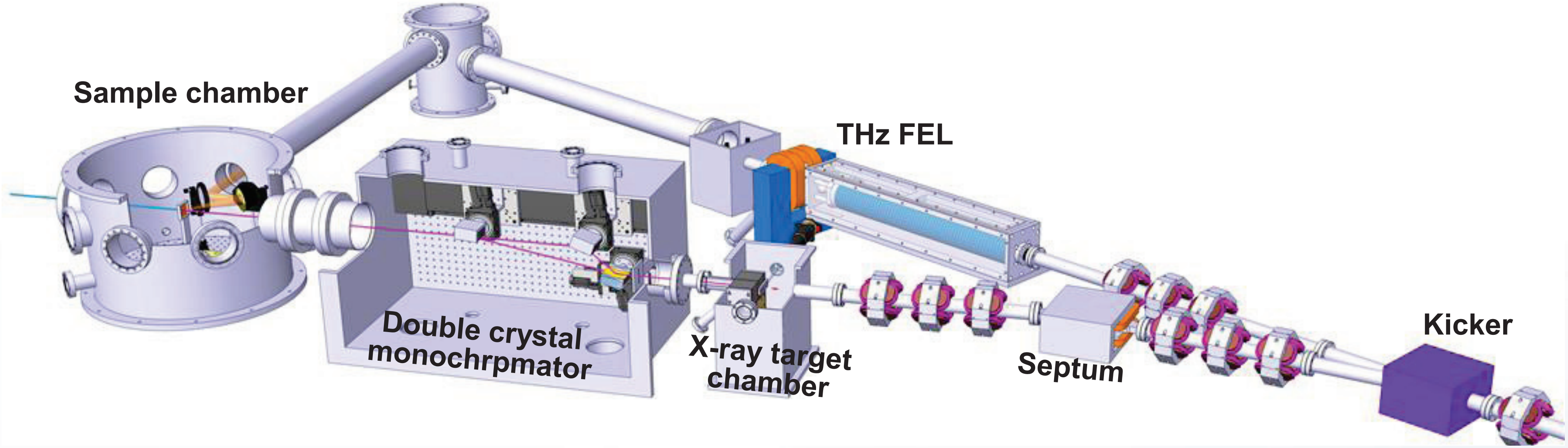
IV. X-ray & T-ray Beamlines

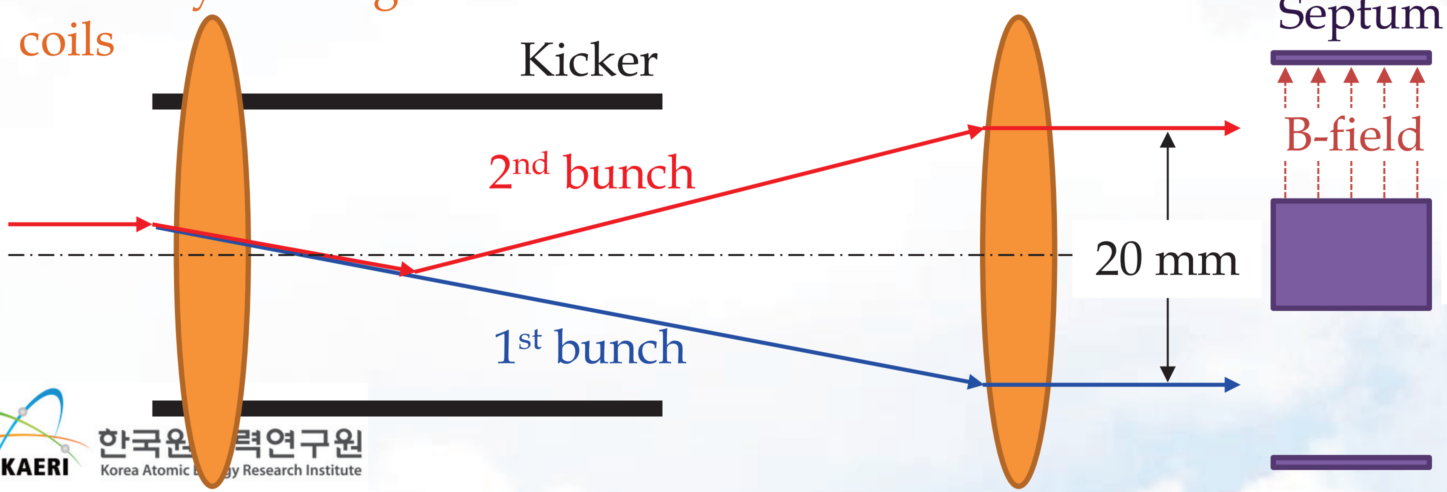
Compression Magnets

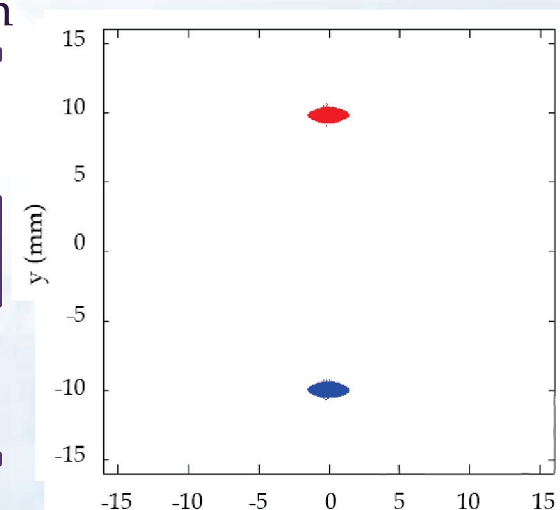




T-ray-pump/X-ray-probe Beamline







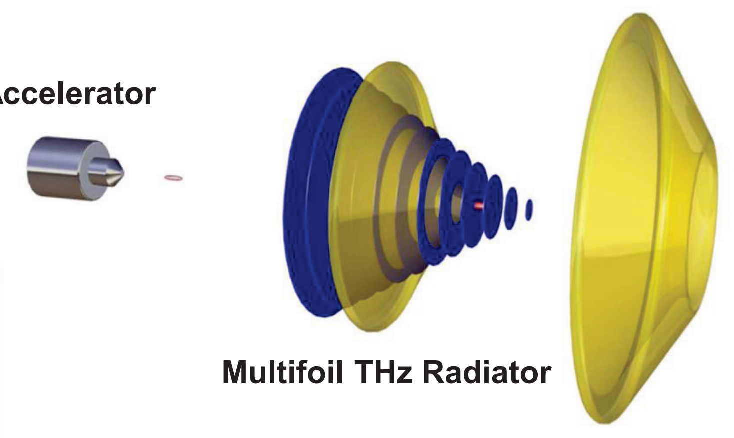
Simulation Result : THz/X-ray Beamline

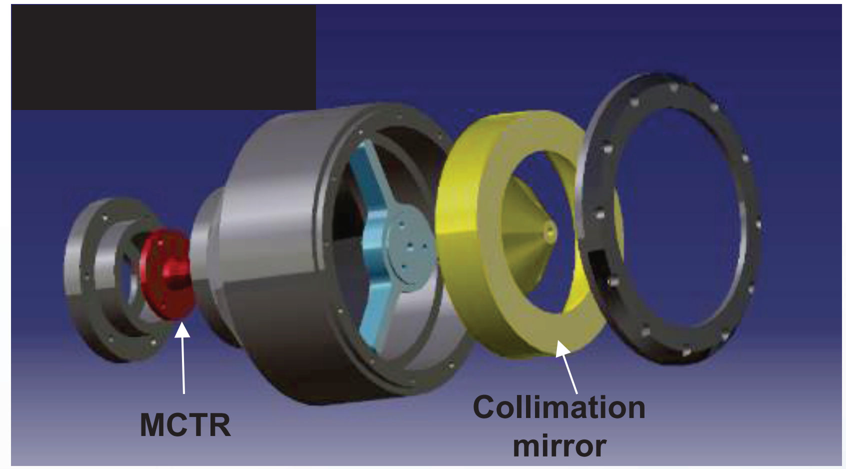
Electron Beam Parameters	THz	X-ray	Units
Beam Kinetic Energy	24.3	24.3	MeV
Energy Spread (rms)	1.13	1.13	%
Norm. Transverse Emittance (x/y)	1.6	1.7 / 2.7	mm mrad
Longitudinal Emittance (95%)	14	129	keV mm
Bunch Duration (FWHM)	40	150	fs
Beam Size - x/y (rms)	0.22/0.19	0.14/0.14	mm
Time of Flight	35.9	44.6	ns
Peak Current	3	0.6	kA

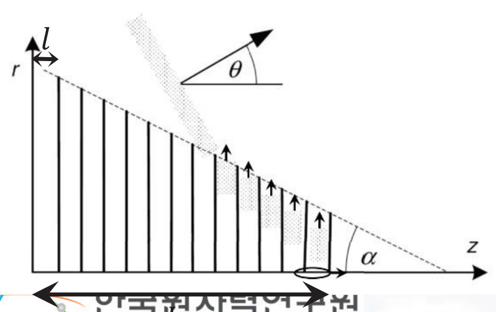
Multifoil High-power Terahertz Radiator

Ultrashort High-power THz Beam

$$\frac{W}{W_{CTR}} \approx \frac{L}{l}\frac{\sqrt{\pi}}{2\ln(r_{max}/a)}$$







Cone half angle without reflection

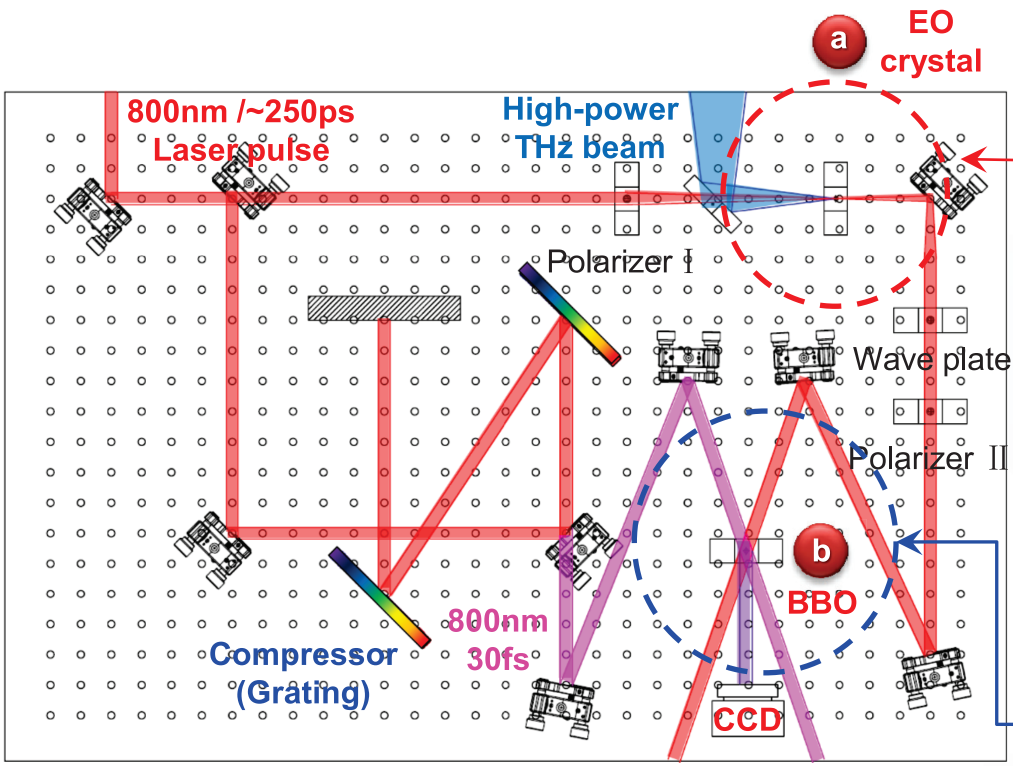
$$a_0 = \arctan\frac{n \pm \sqrt{n^2 - 1 + 1/n^2}}{n^2 - 1}$$

Refraction angle

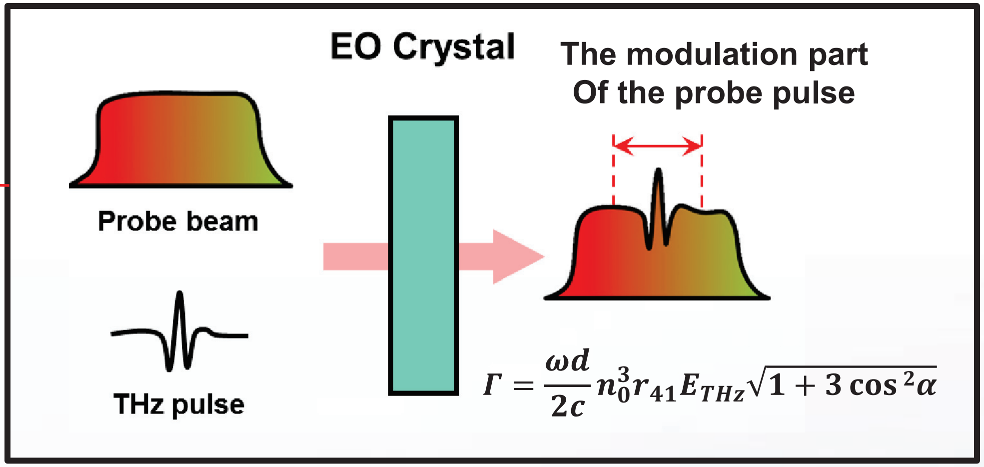
$$\theta = arccos(\cos\alpha - n\sin\alpha) - \alpha$$

MCTR THz wave Parameters	Value	Unit
Spectral Width	0.5~3	THz
Pulse Duration (FWHM)	<1	ps
Pulse Energy	> 100	μJ
Peak Power	> 100	MW
Peak Electric Field	> 1	MV/cm
Polarization	Radial	

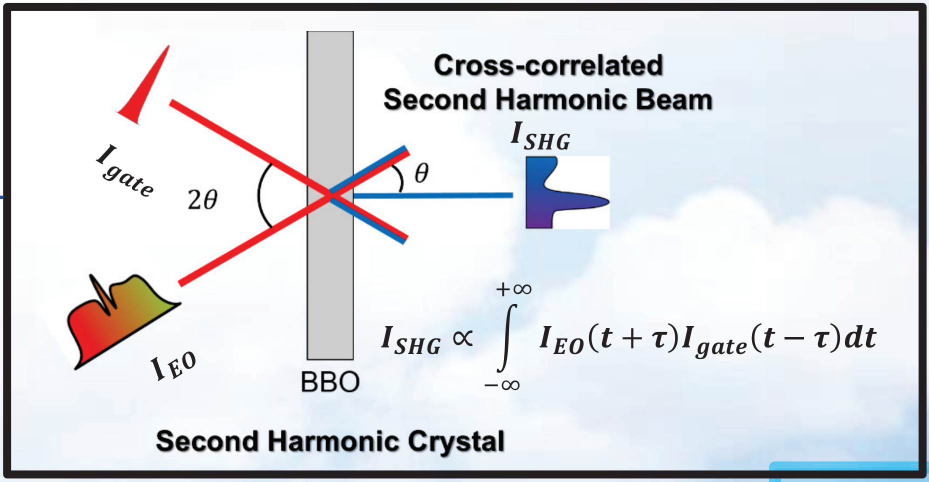
Multifoil High-power Terahertz Detection



a. Electro-optic effect

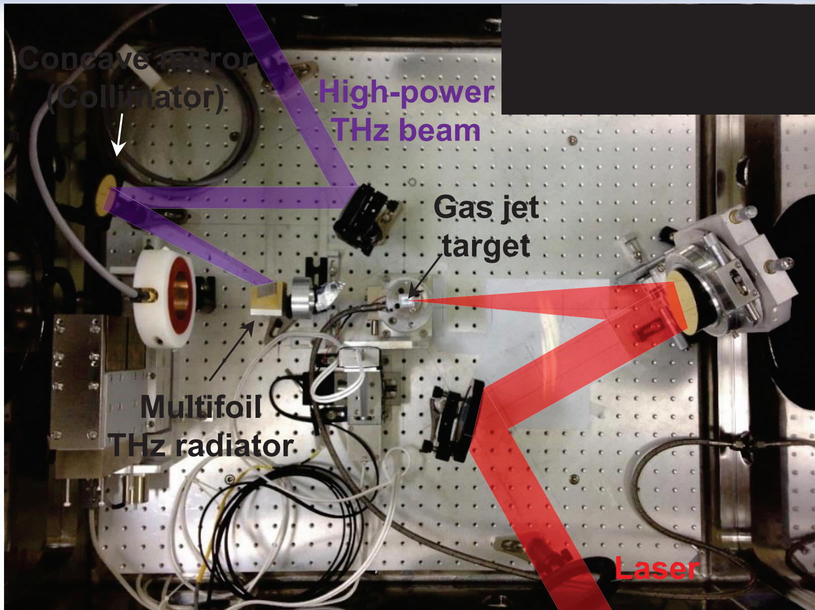


b. Single-shot cross correlation



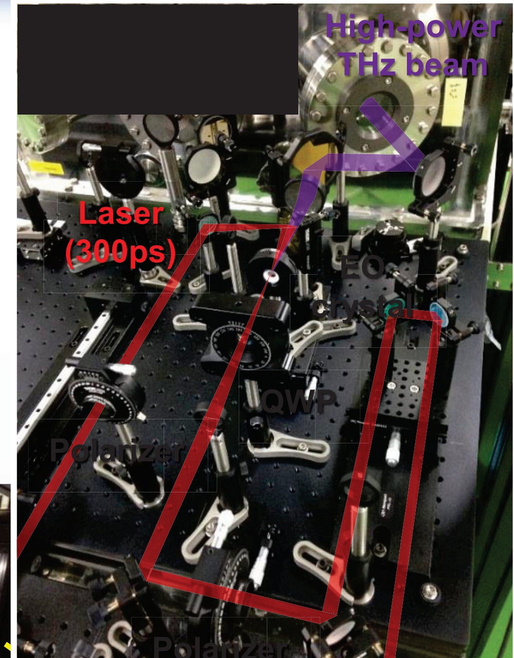
MOP029 Jeongsang Jo,
"Single-shot Detection of High-Power Ultrashort Terahertz Pulses generated by a Multi-foil Radiator with Laser-accelerated Electron Pulses"

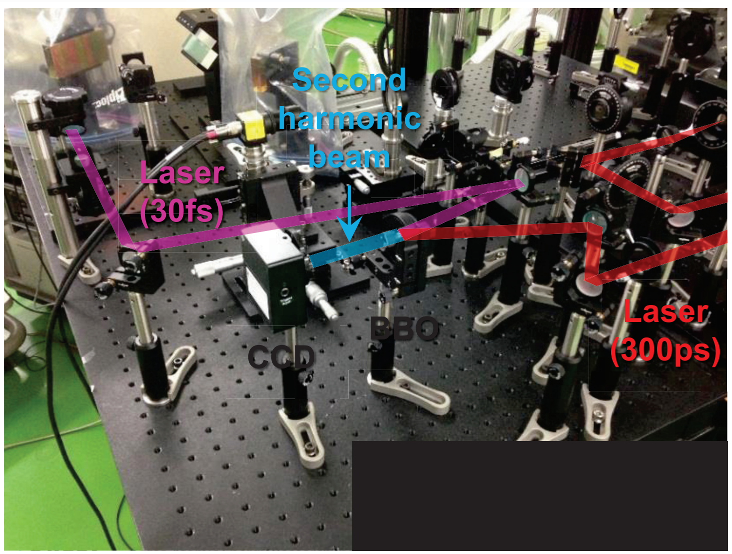
Multifoil High-power Terahertz Experiment with Laser-plasma Electron Beams

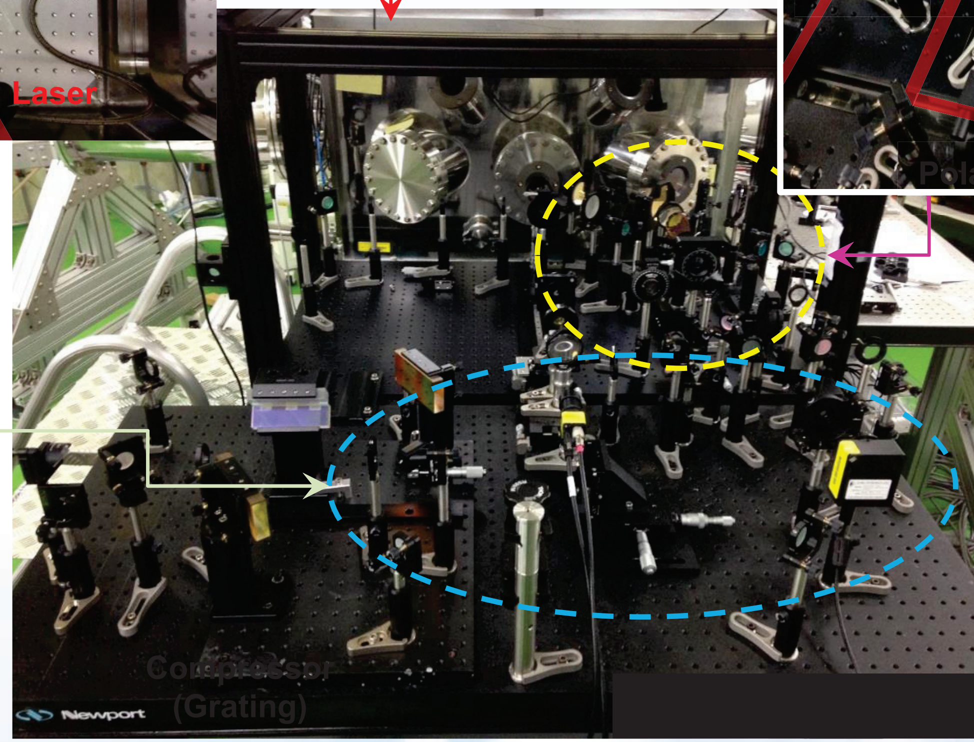


Electron Bunch
- E > 20 MeV
- τ < 1 ps

Inside chamber

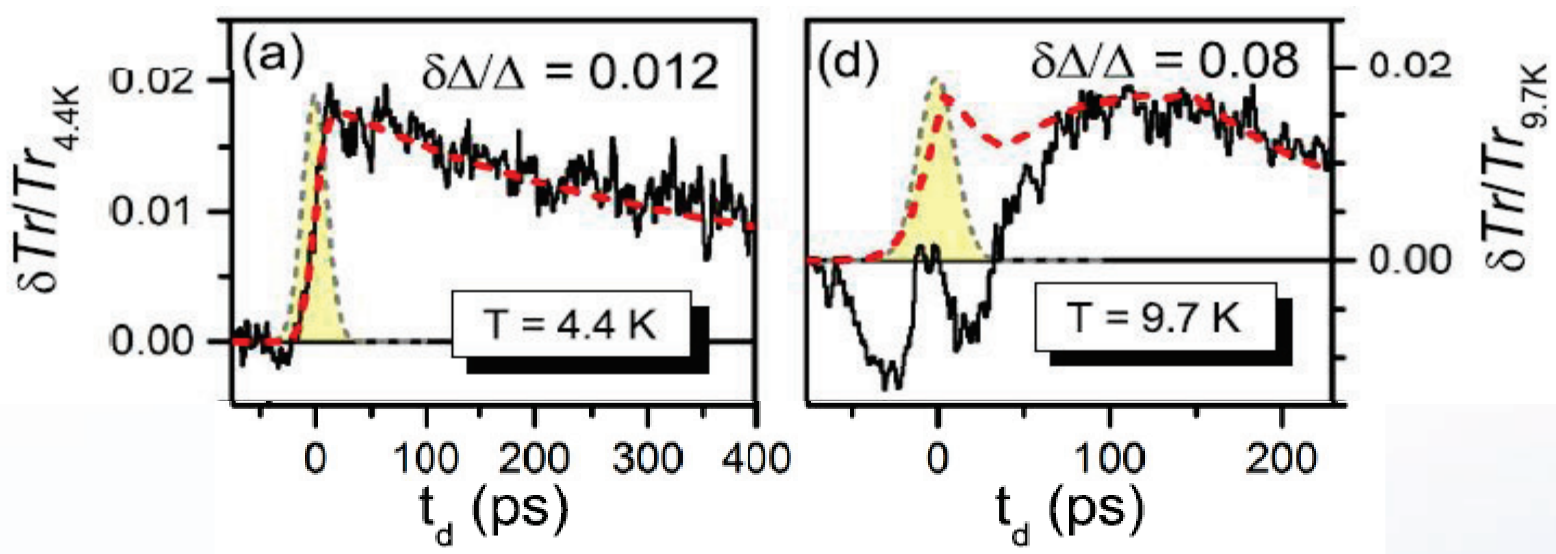






SC Enhancement by THz Irradiation

NbN thin film, T_c~16 K



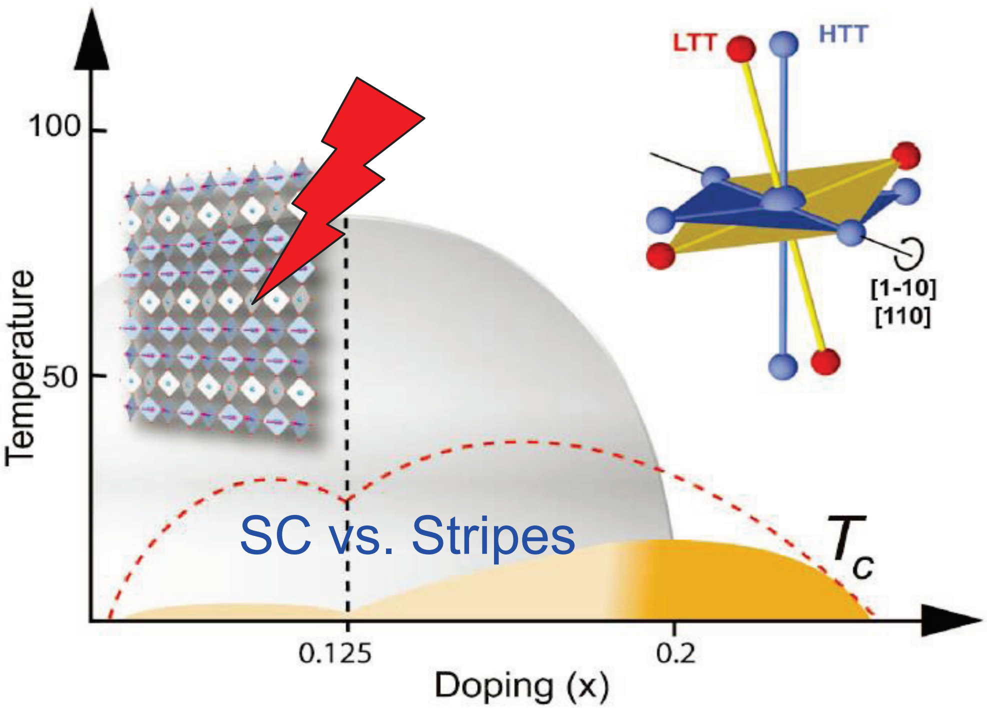
$\hbar\omega_{pump} < 2\Delta(T)$ $\hbar\omega_{pump} \approx 2\Delta(T)$

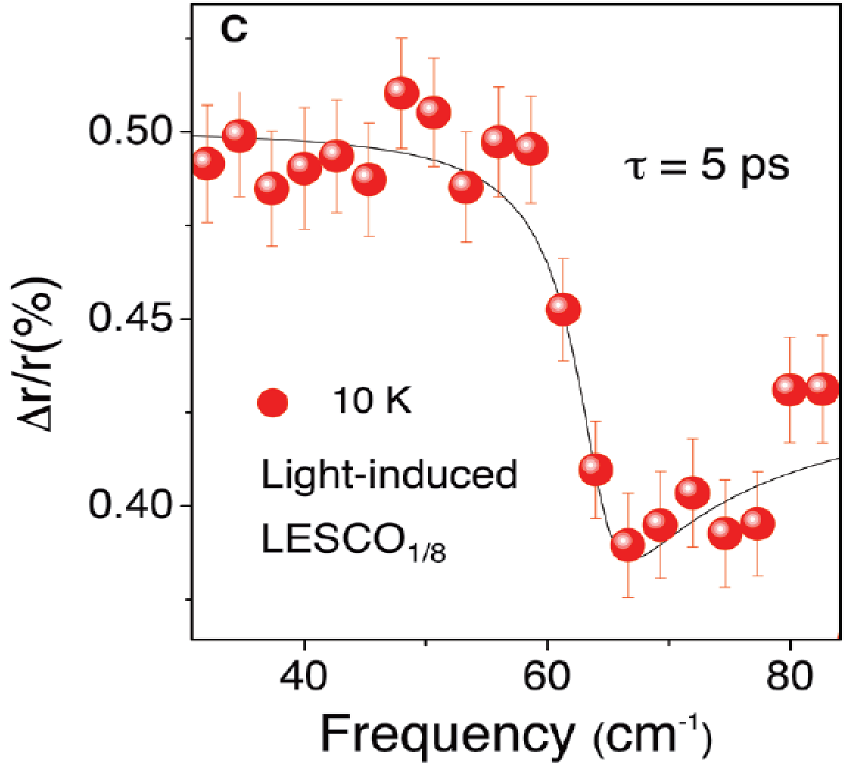
Pumping thermal quasiparticles transiently enhances the superconductivity.
$\rightarrow$ Needs spectroscopic verification

M. Beck *et al.*, Phys. Rev. Lett. **110**, 267003 (2013)

SC & Ultrafast Lattice Dynamics

Schematic phase diagram of
$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$

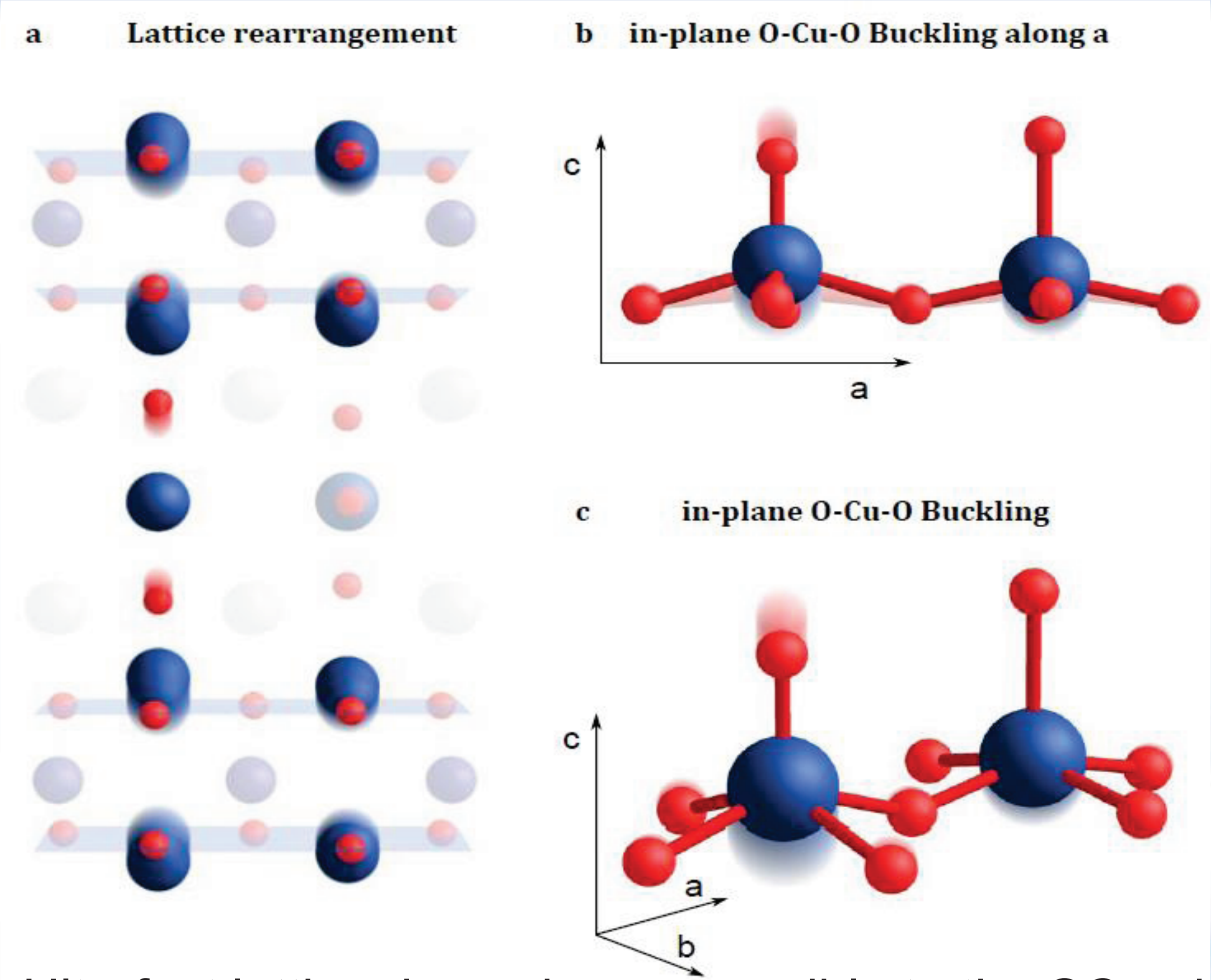




Pumping phonon transiently enhances the superconductivity in cuprates.

D. Fausti *et al.*, Science **331**, 189 (2011), W. Hu et al., Nat. Mat. **13**, 705 (2014)

SC & Ultrafast Lattice Dynamics



Ultrafast lattice dynamics responsible to the SC enhancement has been investigated in YBCO.

R. Mankowsky *et al.*, arXiv:1405.2266