SFR 2016, BINP, Novosibirsk

세계수준의 연구센터
World Class Institute

Ultrafast Pump-probe Facility based on an RF Photogun

6 July 2016

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WCI Center for Quantum-Beam-based Radiation Research

Korea Atomic Energy Research Institute

KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

2RC THz Pump X-ray Probe

WCI Structure 센터의 구성

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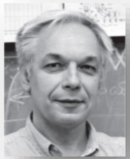
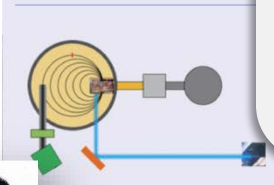


Deputy Director
Y. U. Jeong (KAERI)

ADMINISTRATION

Advanced Accelerator group



- 조직 구성
  - 센터장 (본부장위임전결)
  - 부센터장 (부장위임전결)
  - 행정지원팀 (2명)
  - 3개 연구 조직
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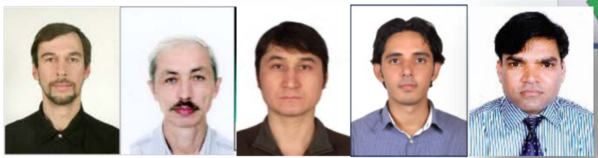
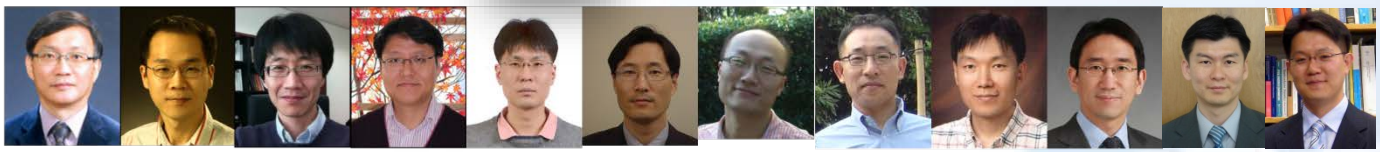
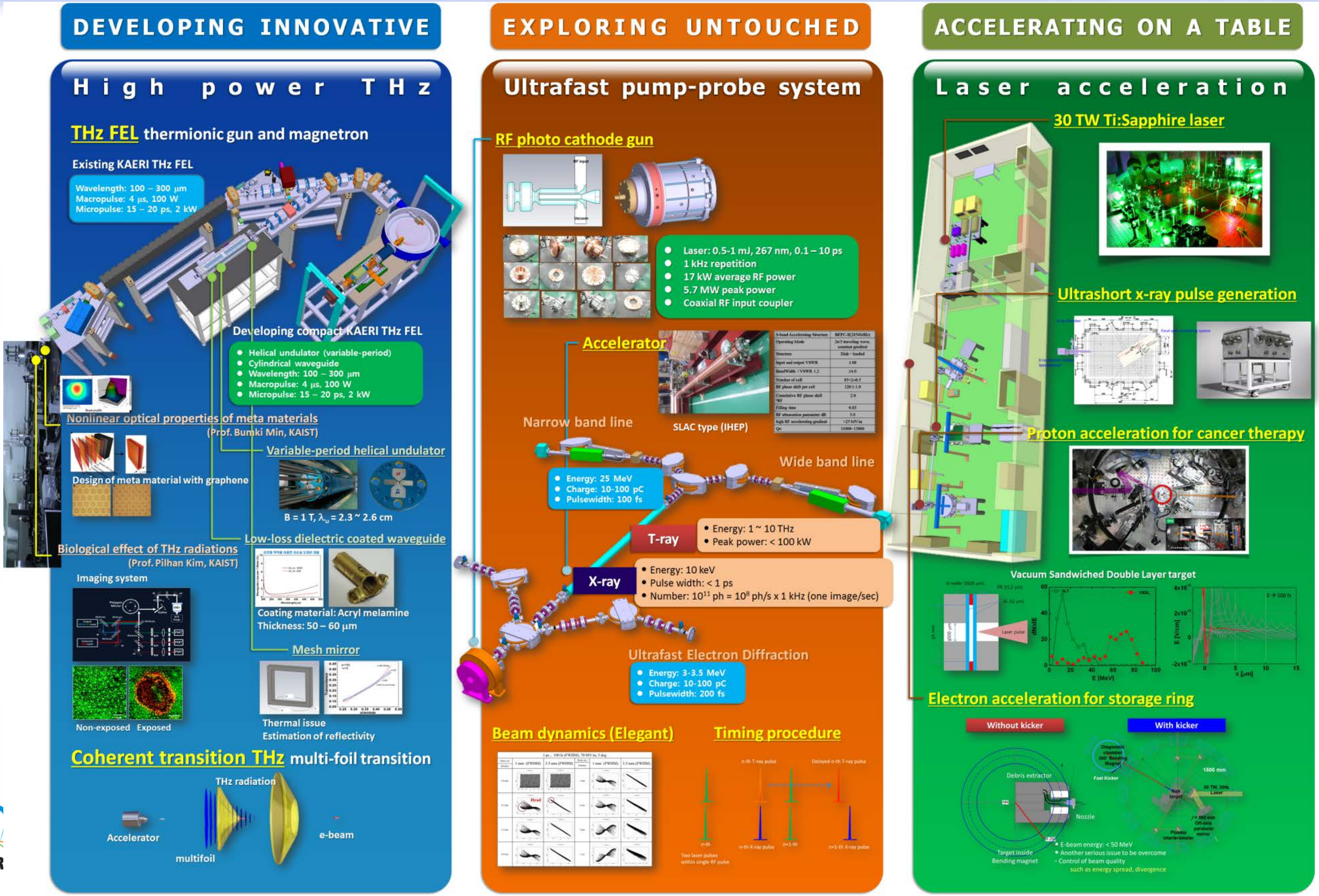


DOMESTIC COLLABORATORS



- 인적 구성
  - 해외연구원: 6명
  - 국내타기관 연구원: 12명
  - KAERI 연구원: 4명
  - KAERI 연구보조원: 15명
  - 전담행정요원: 1명

Research Contents of the WCI Center



Resolving Power

분해능

Louis de Broglie (1892~1987)
1929 Novel Prize Laureate

$$\Delta l \approx \lambda$$

Matter Wave, Wavelength $\lambda = \frac{h}{p}$

h : Plank constant
p : Momentum

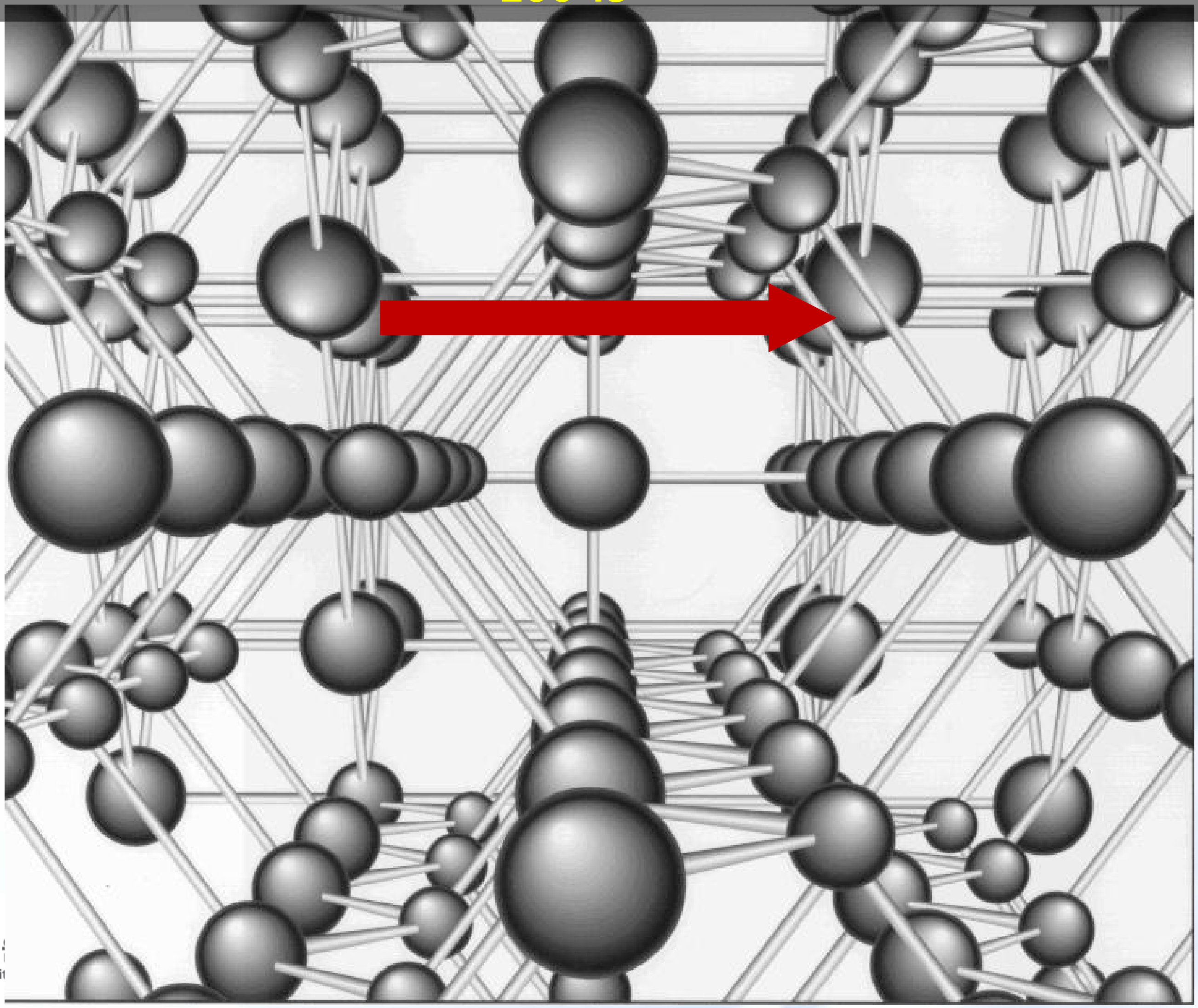
Electron Kinetic Energy [MeV]	0.01	0.1	1	10	100
λ	0.124 nm	12.4 pm	1.24 pm	0.124 pm	12.4 fm

Size of Molecules : 0.1 ~ 100 nm

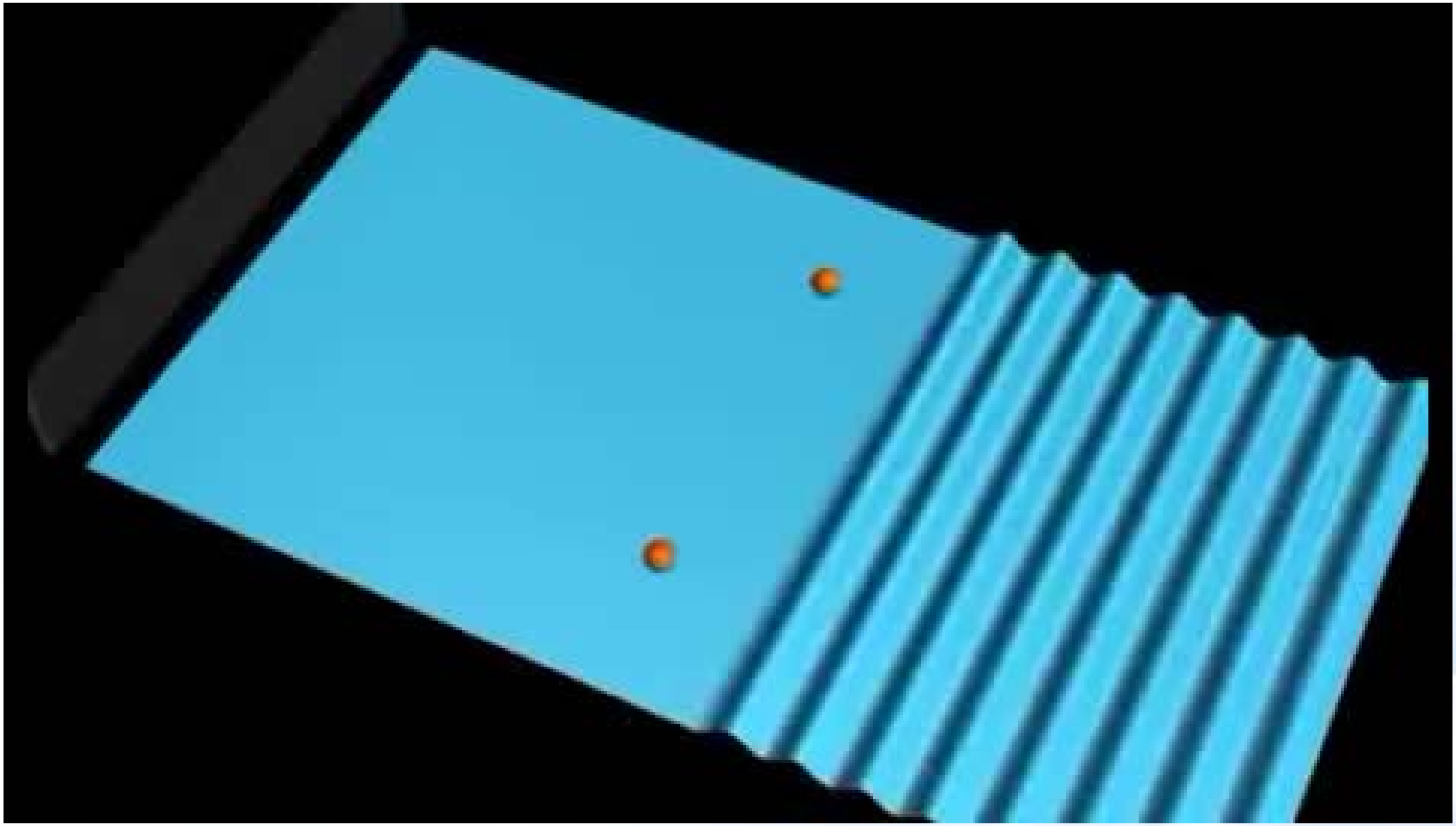
한국원자력연구원 KAERI Korea Atomic Energy Research Institute

Temporal Resolution 시간 분해능

The time taken for a sound wave to propagate the inter-atomic distance
~100 fs



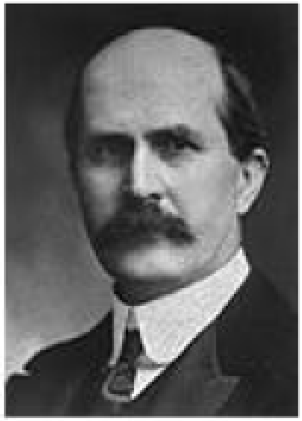
Interference by Diffraction 회절/간섭



$$\Delta l \approx \lambda L/d$$

X-ray Diffraction 엑스선 회절

The Nobel Prize in Physics 1915



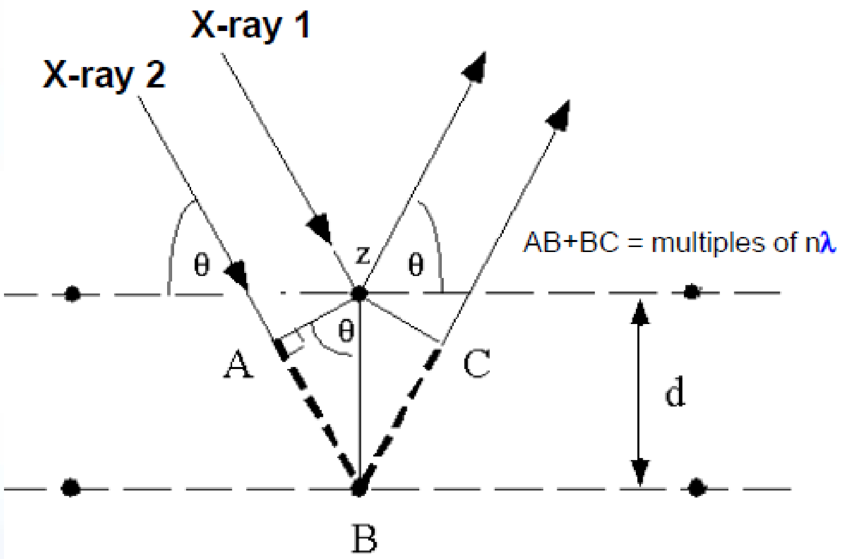
Sir William Henry Bragg

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

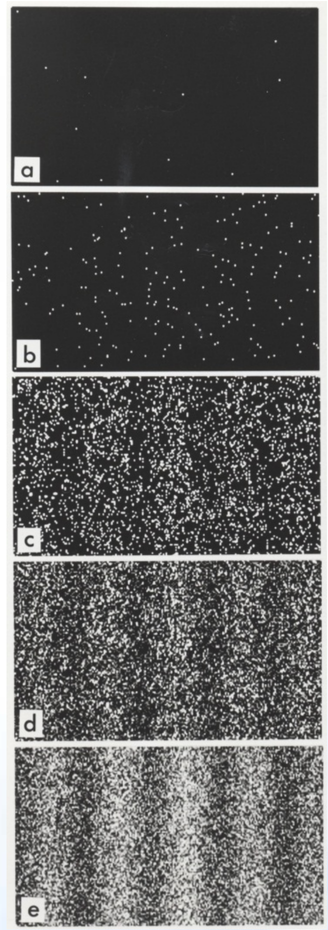
$$n\lambda = 2d\sin\theta$$



Electron Diffraction 전자 회절

- **Matter wave, de Broglie equation**

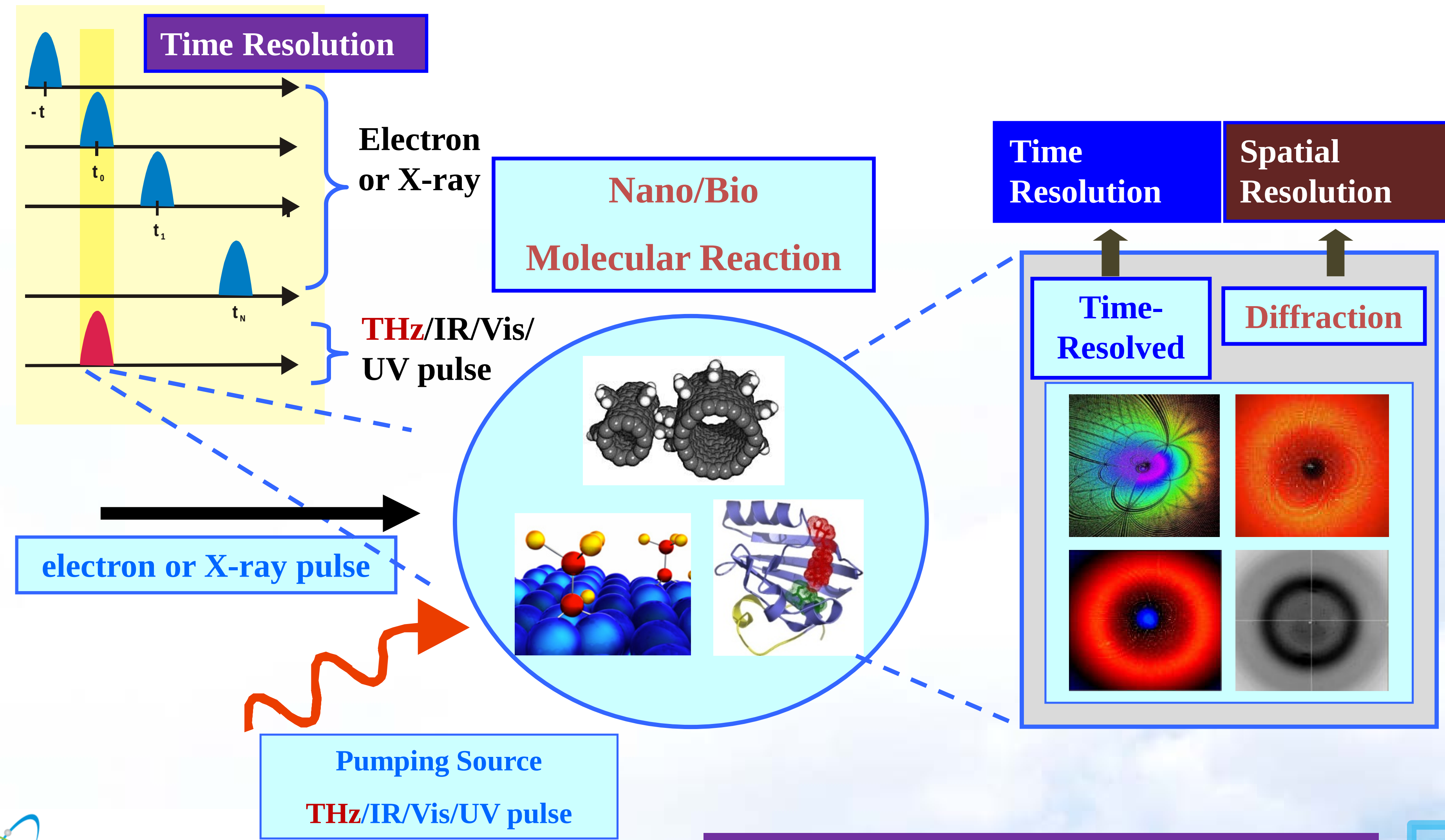
$$\lambda = \frac{h}{p} = \frac{h}{mv} \sim 0.4\,pm$$ **for 2.5 MeV electron beam**



Electron diffraction by double slit

from Wikipedia

Time-resolved Diffraction

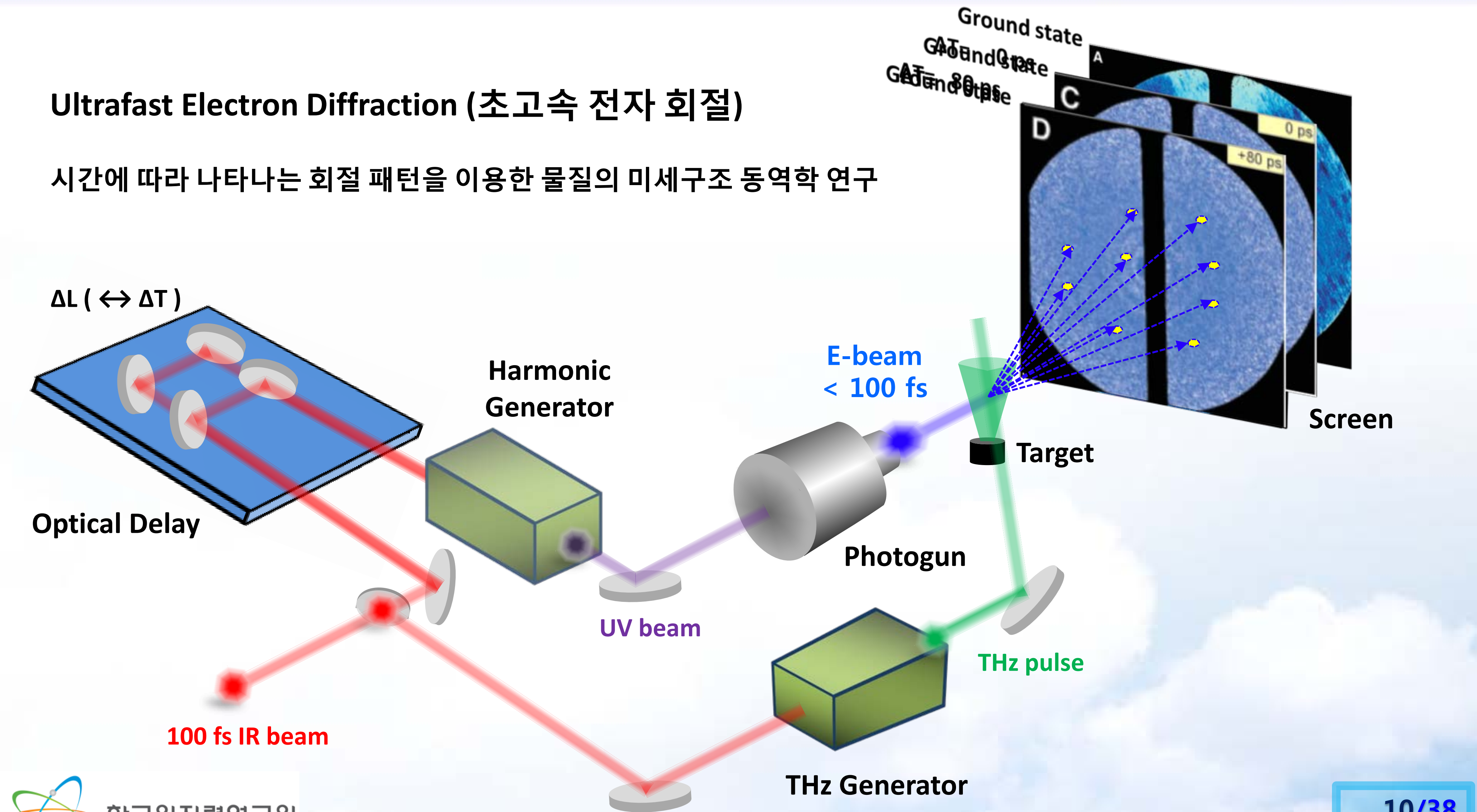


Courtesy : Prof. H. Ihee (KAIST/IBS)

Ultrafast Electron Diffraction (UED)

Ultrafast Electron Diffraction (초고속 전자 회절)

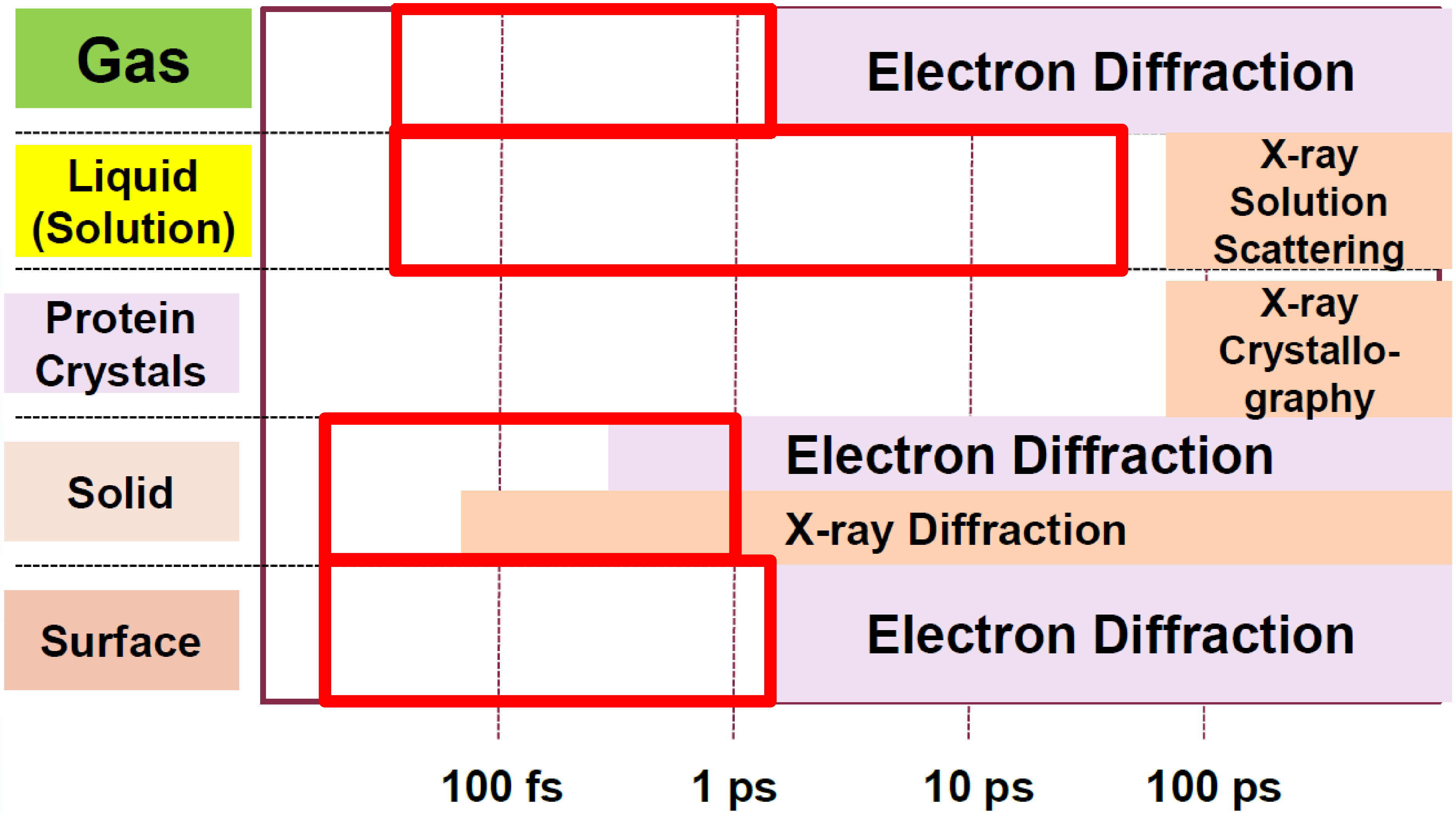
시간에 따라 나타나는 회절 패턴을 이용한 물질의 미세구조 동역학 연구



X-FEL v.s. UED 엑스선과 전자 비교

	X-FEL	UED
Source	X-ray	Electron
Wavelength	10-0.1 nm	0.1-0.001 nm
Interaction with	Electrons	Nuclei & Electrons
Scattering Power	Low	High
Penetration Depth	High	Low
Minimum Photon/Particle Numbers for Single-shot Measurement	10^{12} photons	10^{6} electrons
Facility Size	Huge (~ km)	Compact (~ m)
Coherence Length	A few mm	A few nm

Time Resolution achieved by Time Resolved Diffraction



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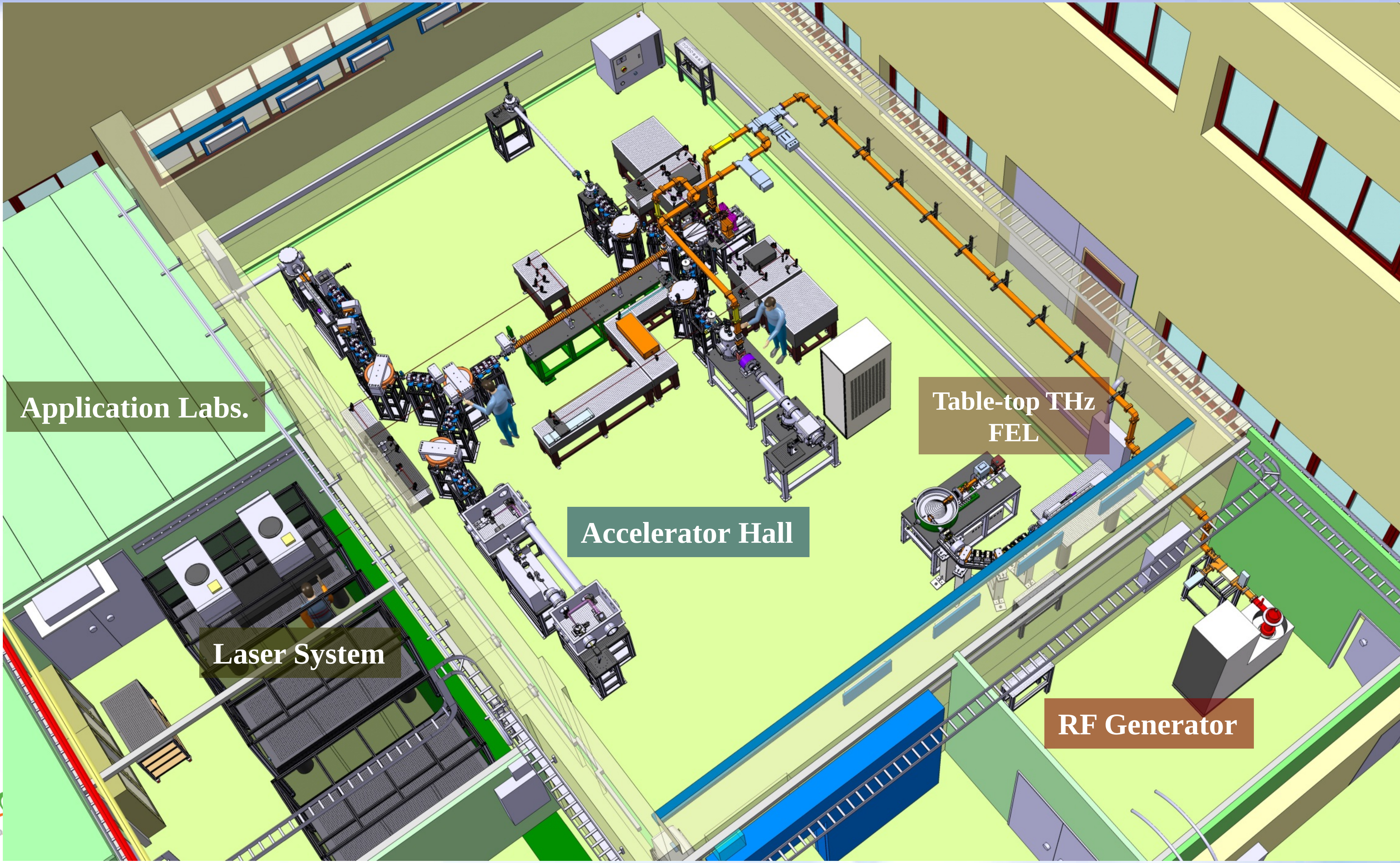
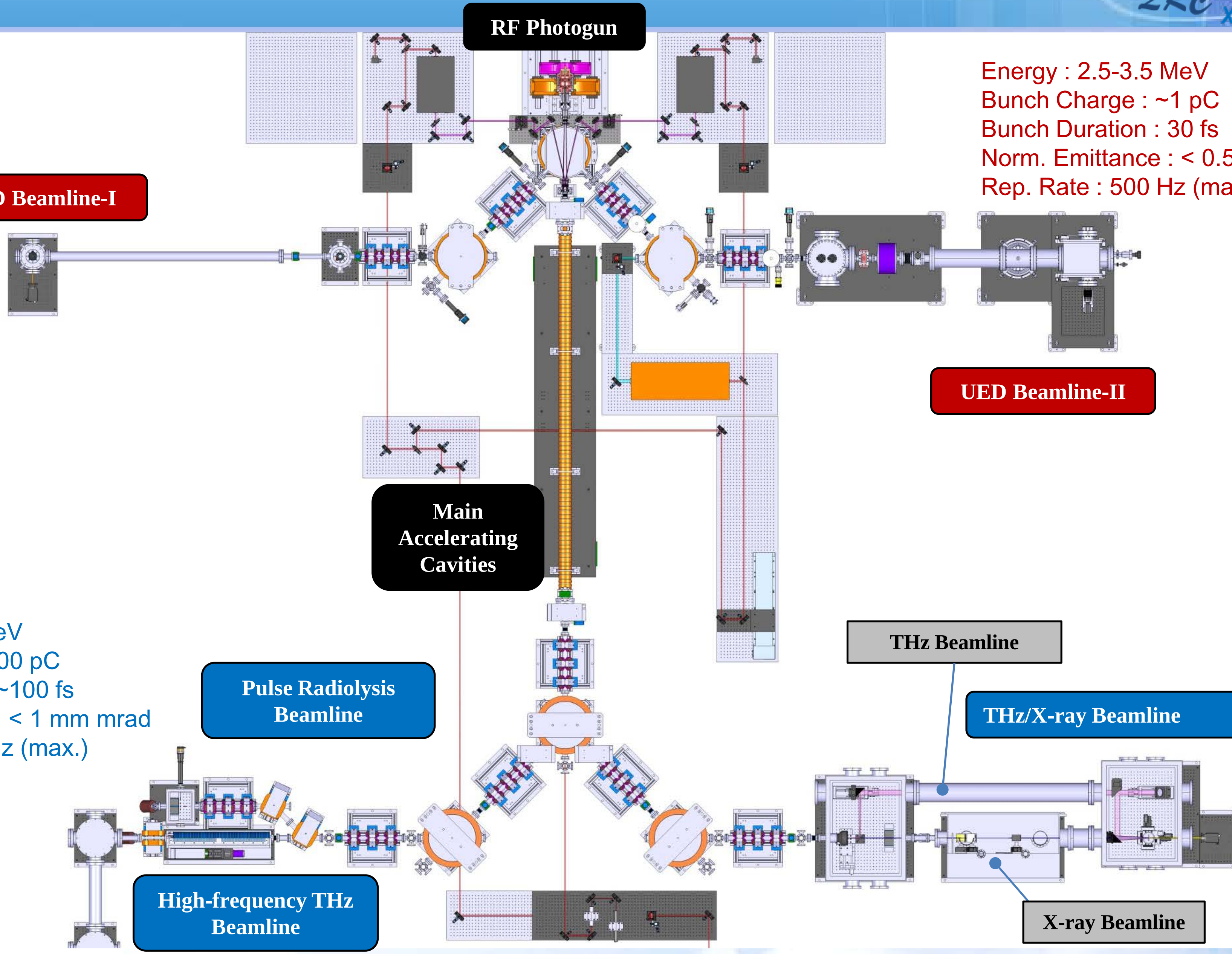
Courtesy : Prof. H. Ihee (KAIST/IBS)

Accelerator Facility Overview



Accelerator Facility Overview

Energy : 2.5-3.5 MeV
Bunch Charge : ~1 pC
Bunch Duration : 30 fs
Norm. Emittance : < 0.5 mm mrad
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.)

KAERI

Accelerator Facility Overview

시설 개관 E = mc²

2RC WCI THz Pump X-ray Probe

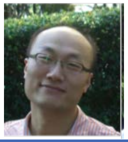
Beam Simulation

Hyunwoo Kim

Laser

In Hyung Baek

RF Photogun



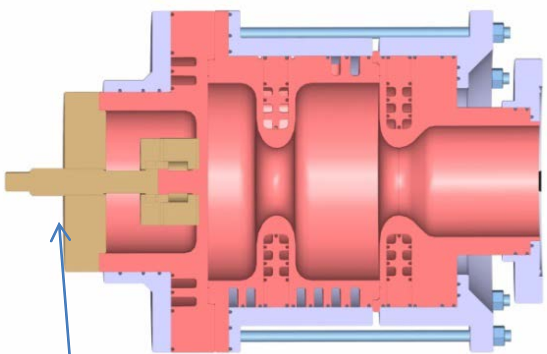
Kyuha Jang,
Jang-Hui Han

Synchronization

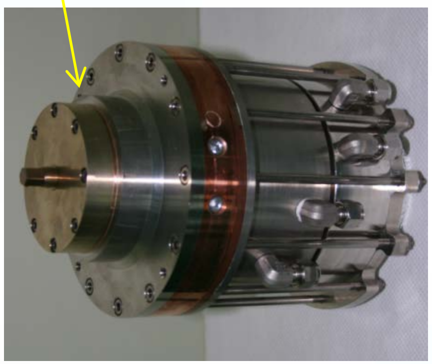
Jungwon Kim

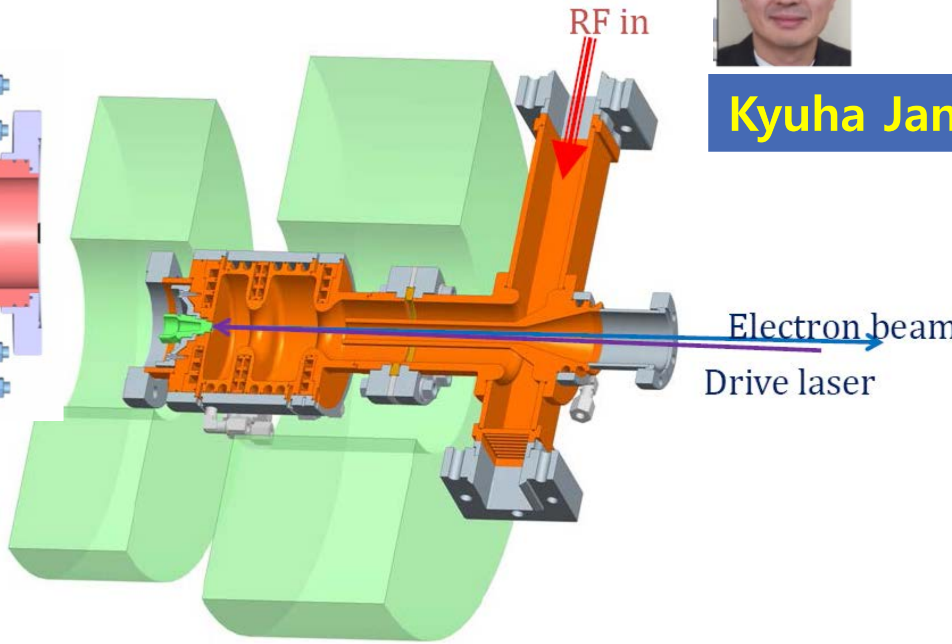
Current Beamline

Coaxial-type RF Photogun

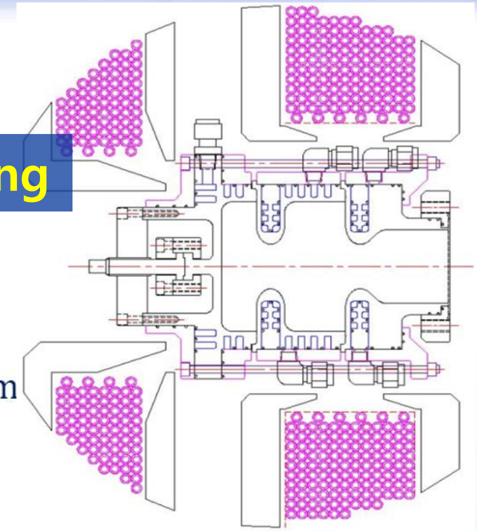


Frequency Tuning Mechanics



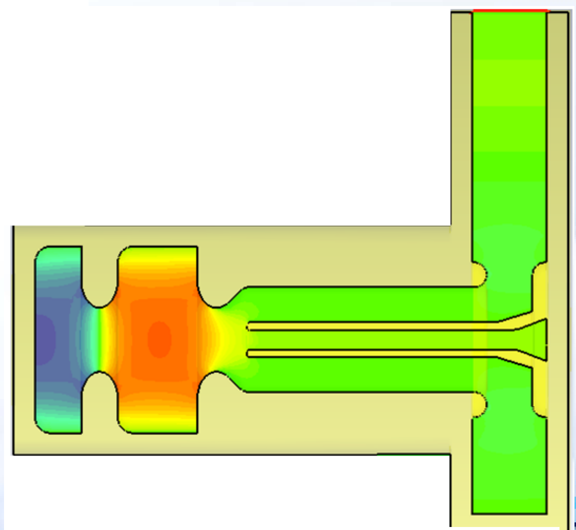


Kyuha Jang

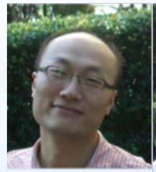


Gun solenoid & bucking coil

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



π mode & coaxial coulpler



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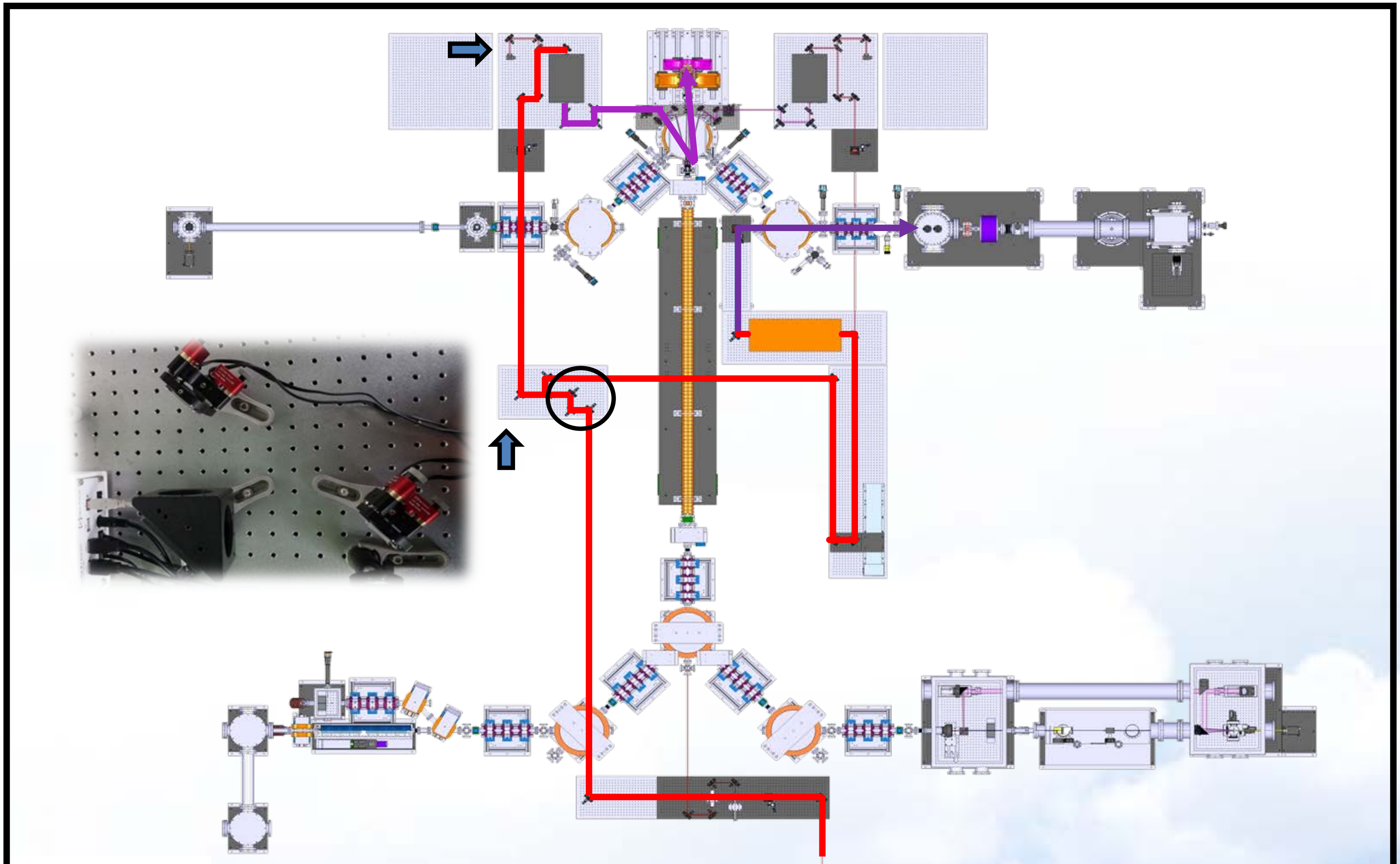
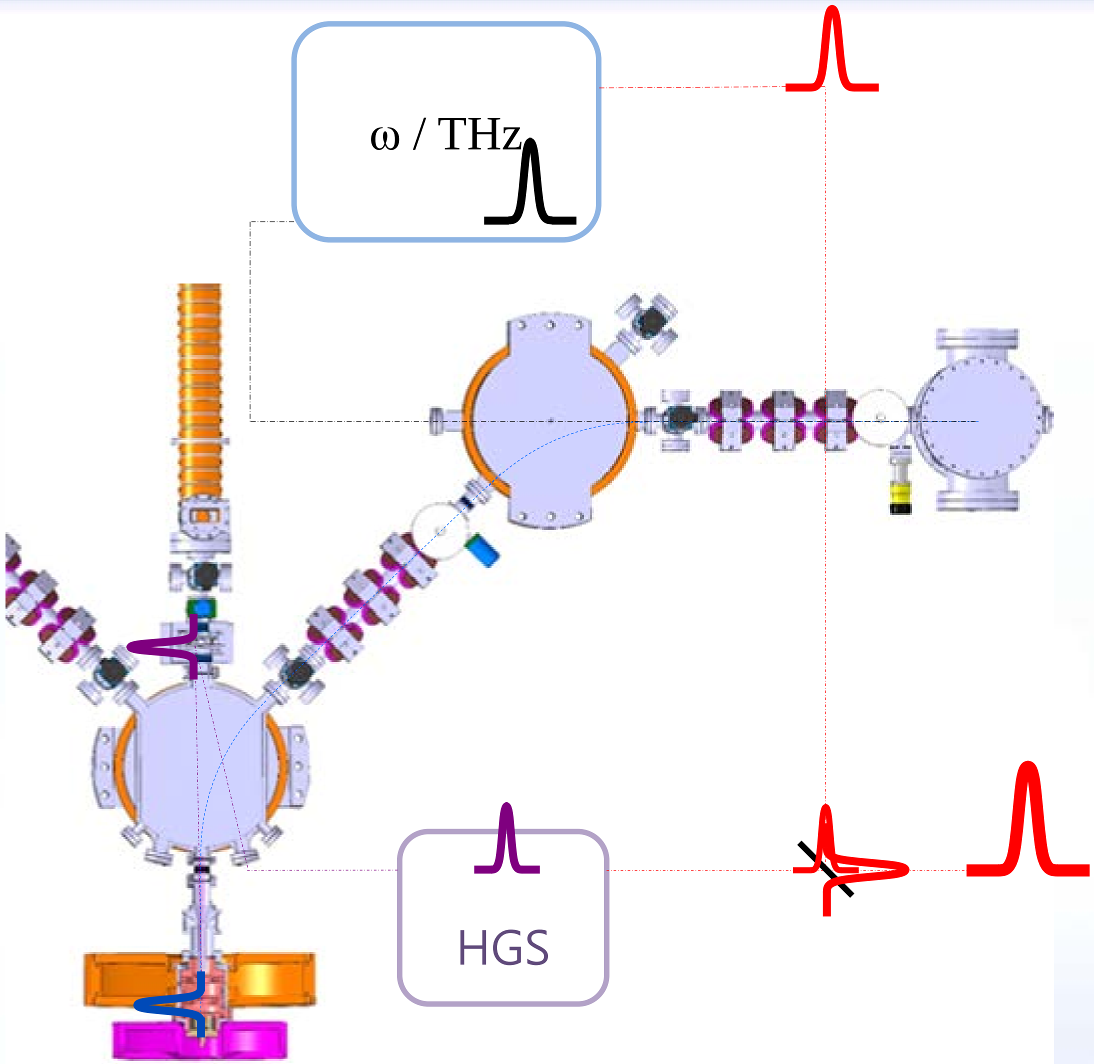
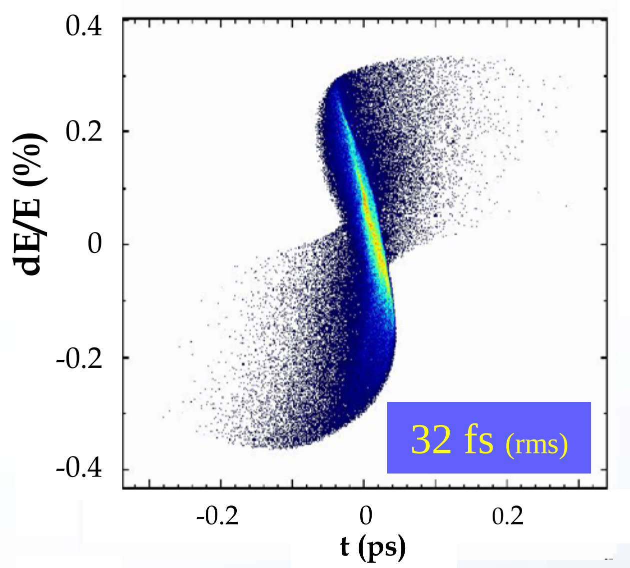
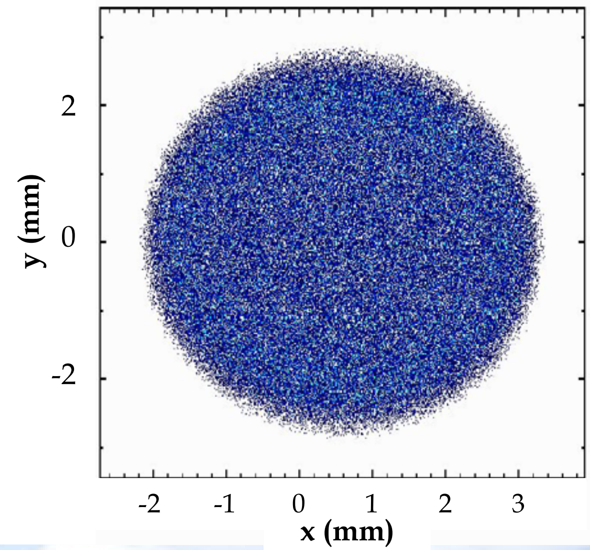
Laser Beam Pathways for UED



Scheme of the UED Beamline



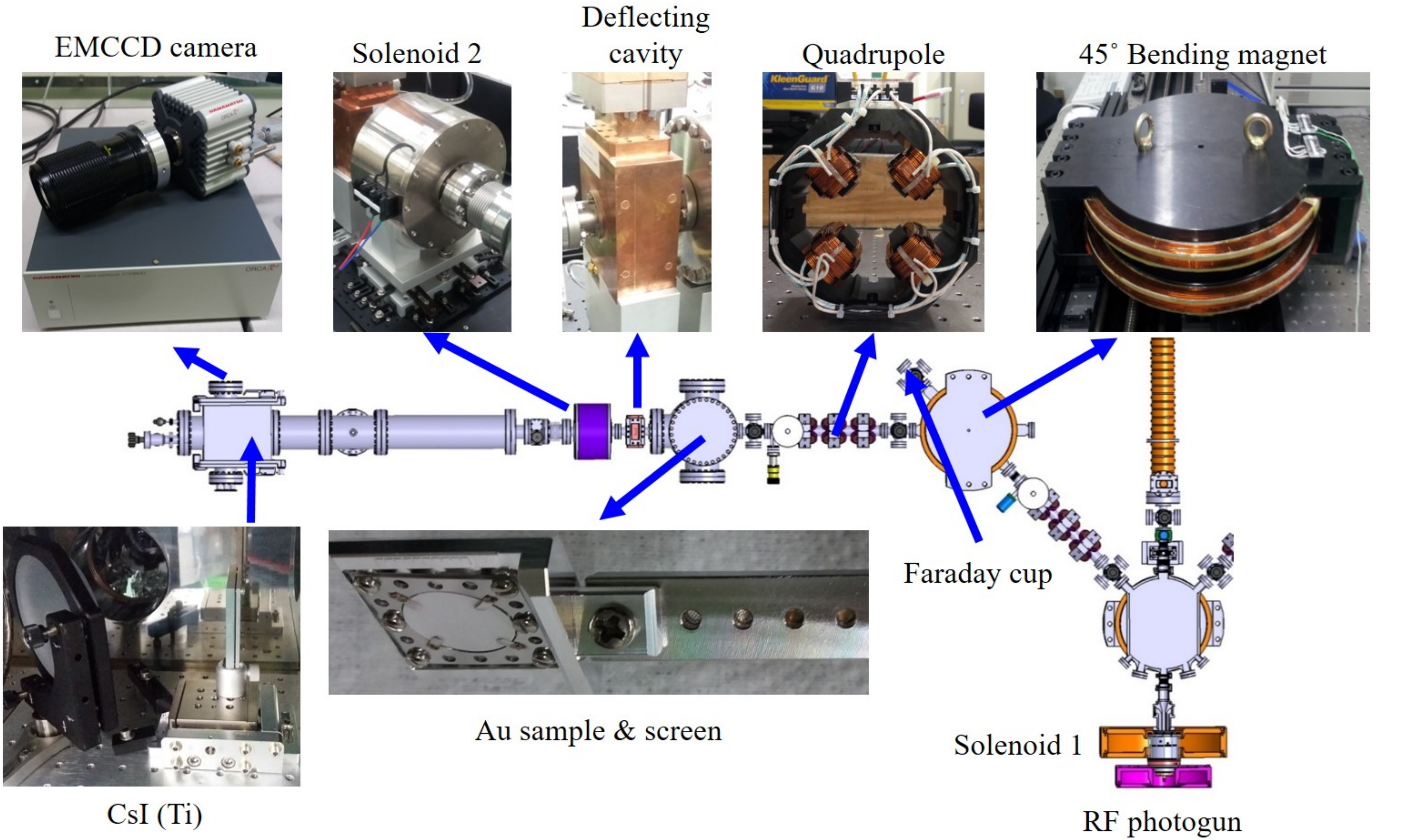




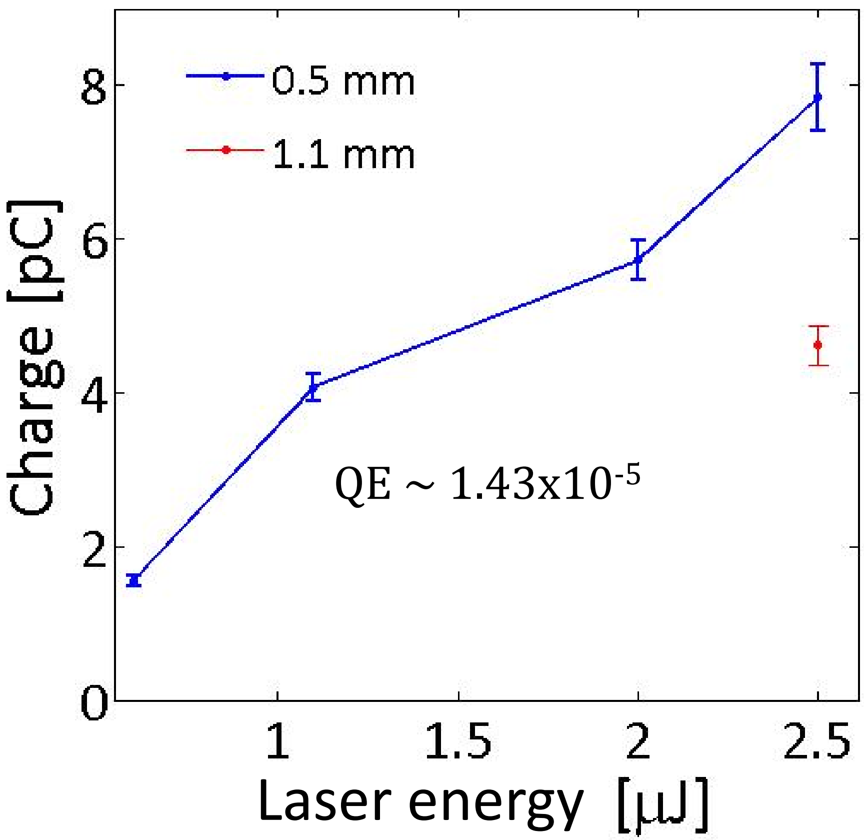
Electron Beam Parameters for UED

Beam parameters	Desired	Simulation	unit
Number of electrons	$> 10^6$	6.25×10^6	electrons
Beam kinetic energy	~ 3	3	MeV
Energy spread (rms)	< 0.1	0.17	%
Normalized emittance	< 0.3	0.29	mm mrad
Coherence length	> 2	1.8	nm
Bunch length (rms)	< 100	32	fs
Timing jitter	< 30	12	fs

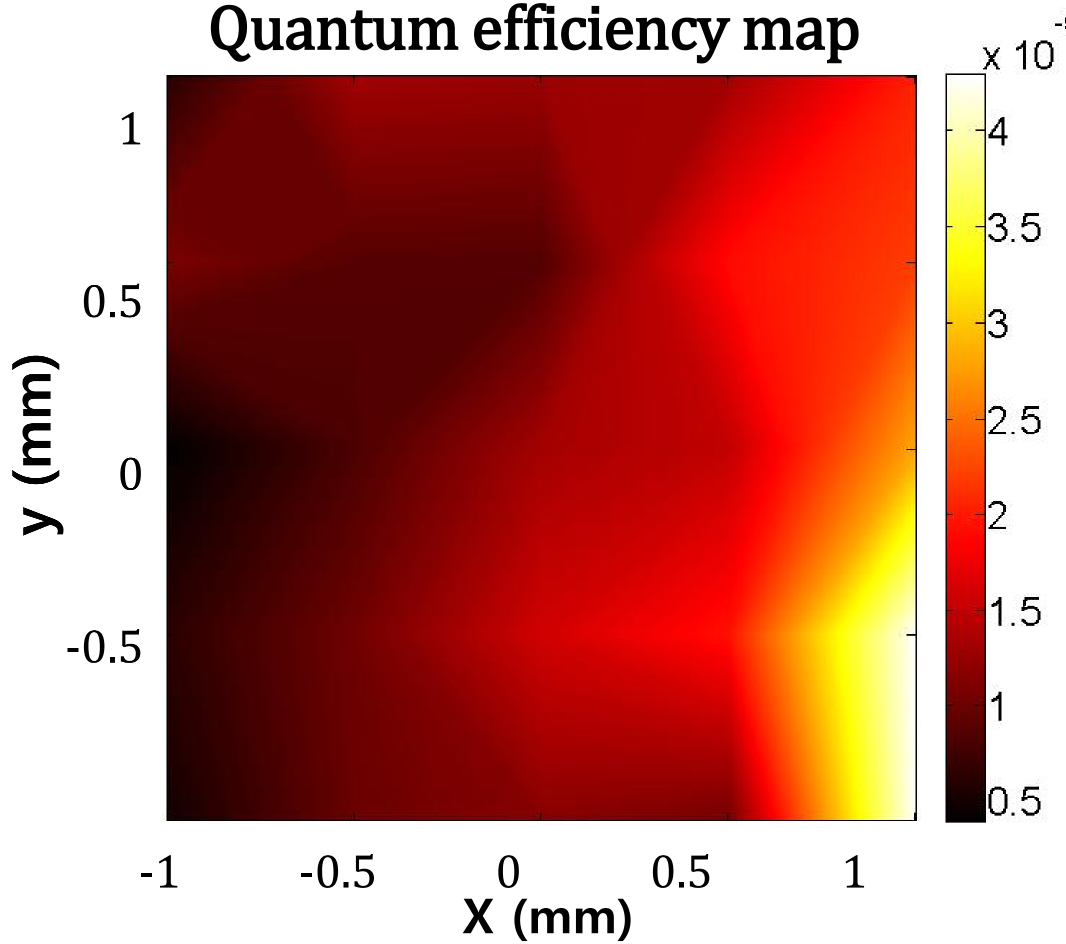
Experimental Setup for UED



Quantum Efficiency of Cu Cathode



Quantum efficiency map

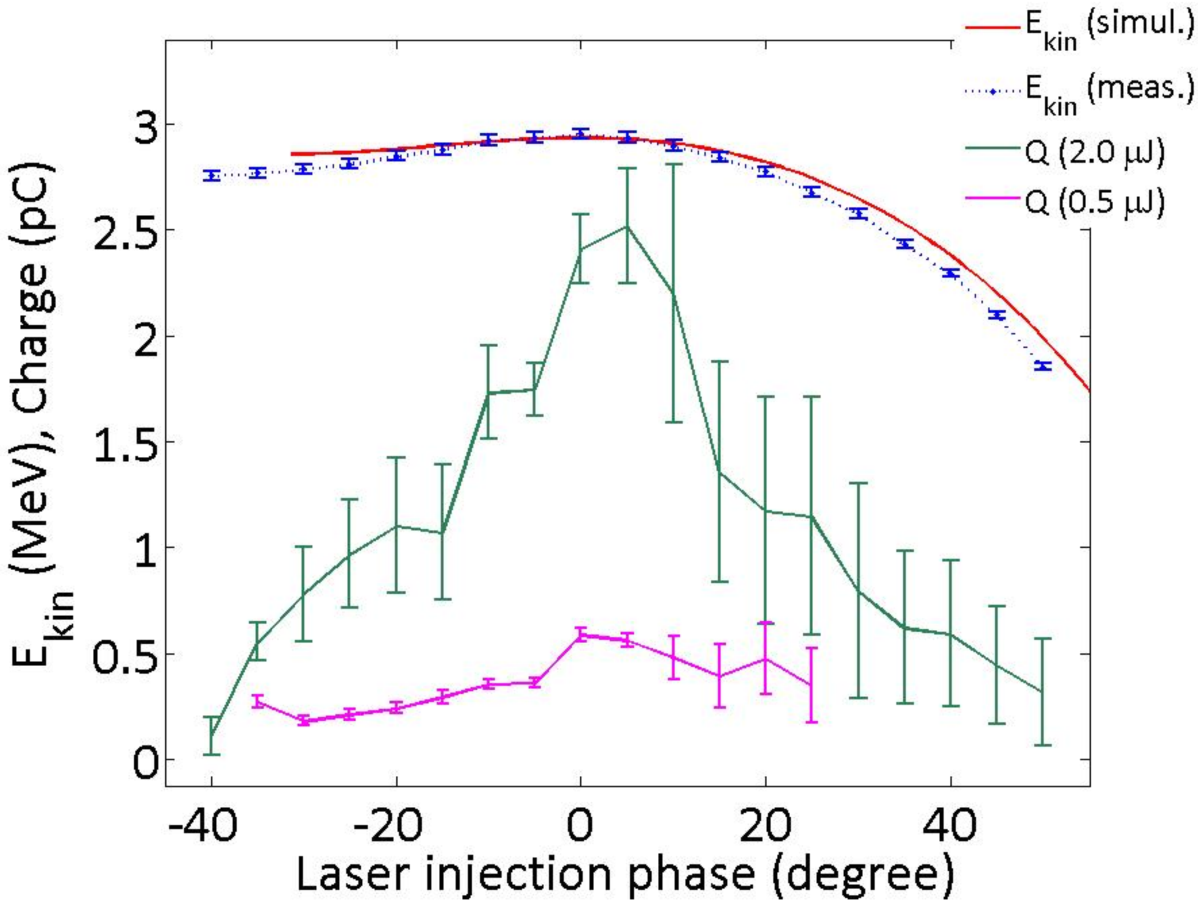


Charge & Beameam Energy

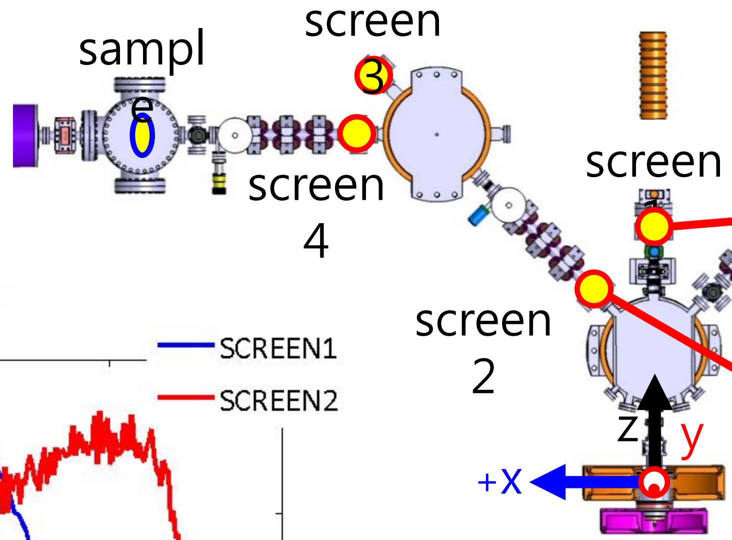
Laser (FWHM)	
Wavelength	267 nm
Spot size	~ 0.5 mm
Pulse length	~ 130 fs

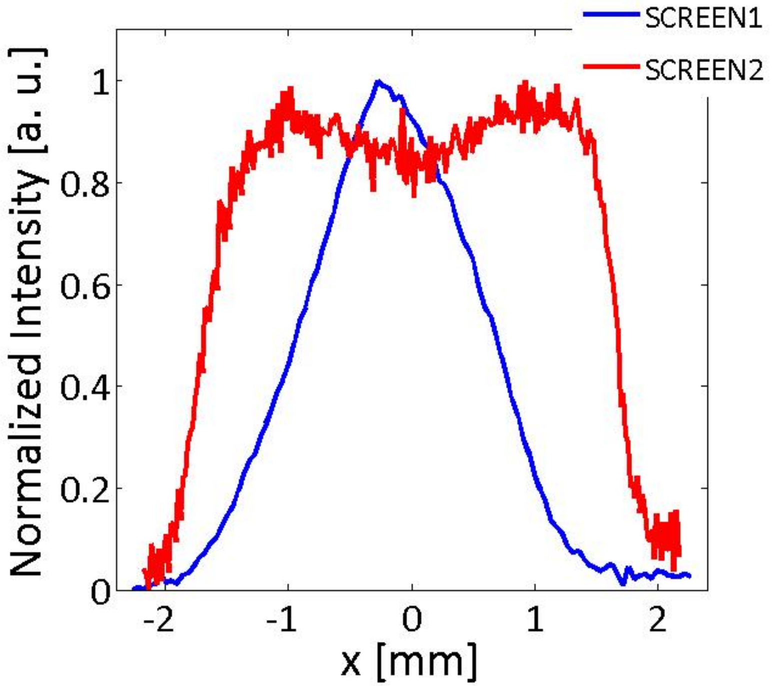
RF (Klystron)	
HV	1030 V
RF Power	5 MW
Pulse width	2.5 μs

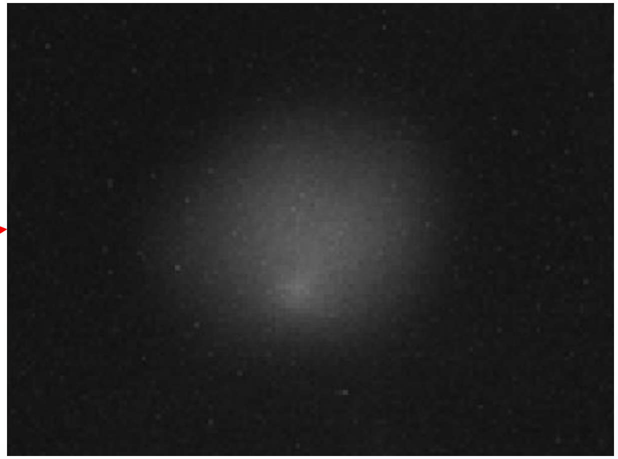
Magnet	
Solenoid	110 A

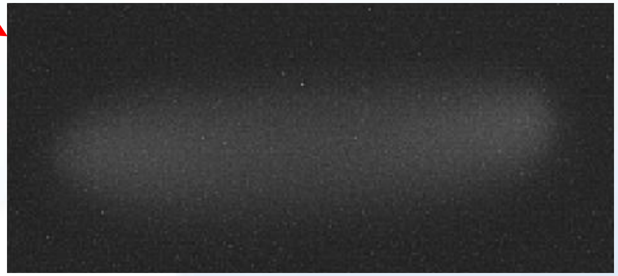


Energy Spread of Electron Beam









$$\sigma_{S2} = \sqrt{\sigma_{S1} + (\eta\delta)^2}$$

$\sigma_{S2} = 1.018\ mm$

$\sigma_{S1} = 0.691\ mm$

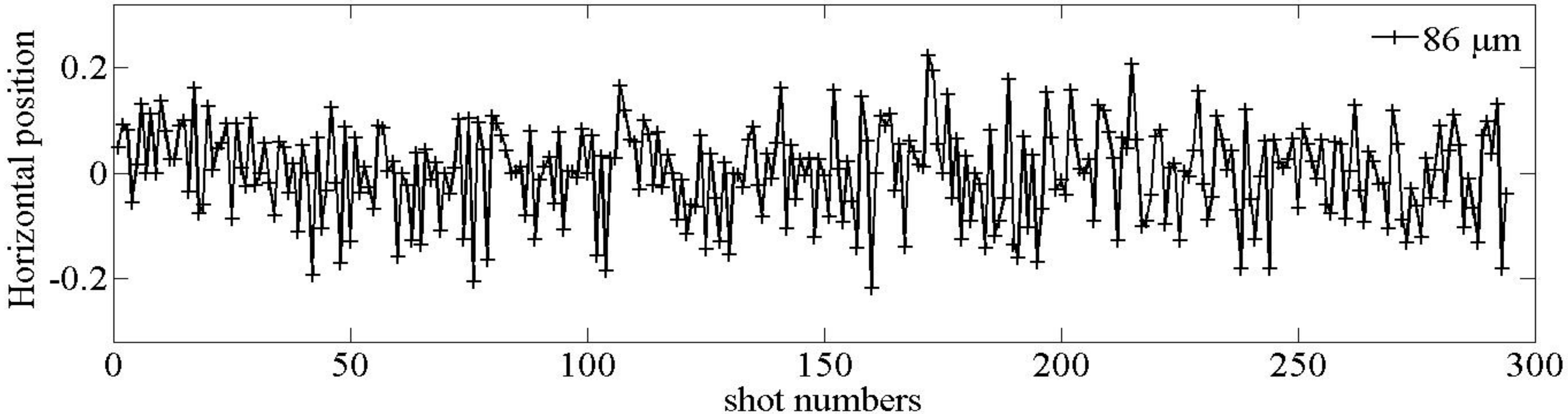
$\eta \sim 0.23\ m$

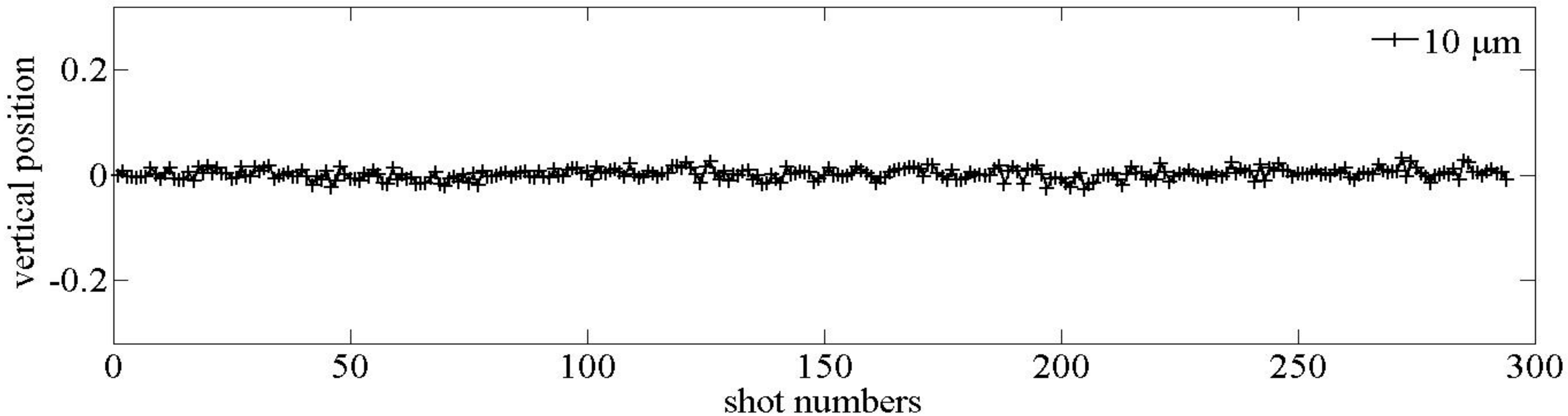
$\boldsymbol{\delta \sim 0.28\%}$

simulation : 0.17%

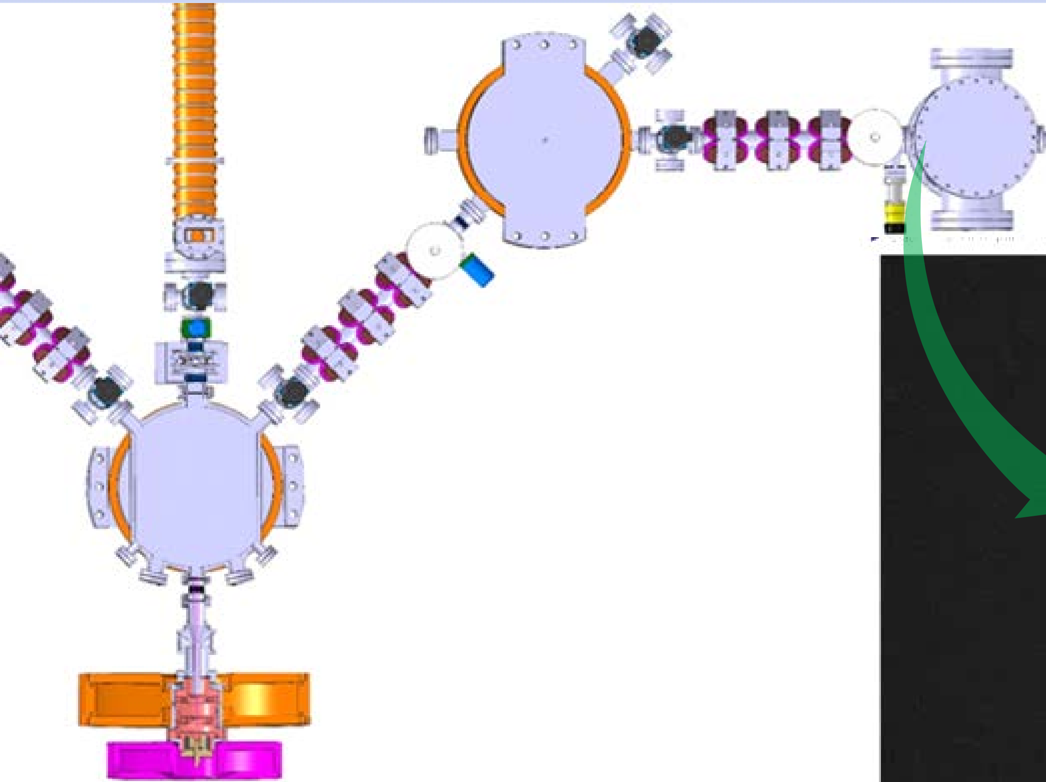
Pulse-to-pulse Energy fluctuation of e-beam

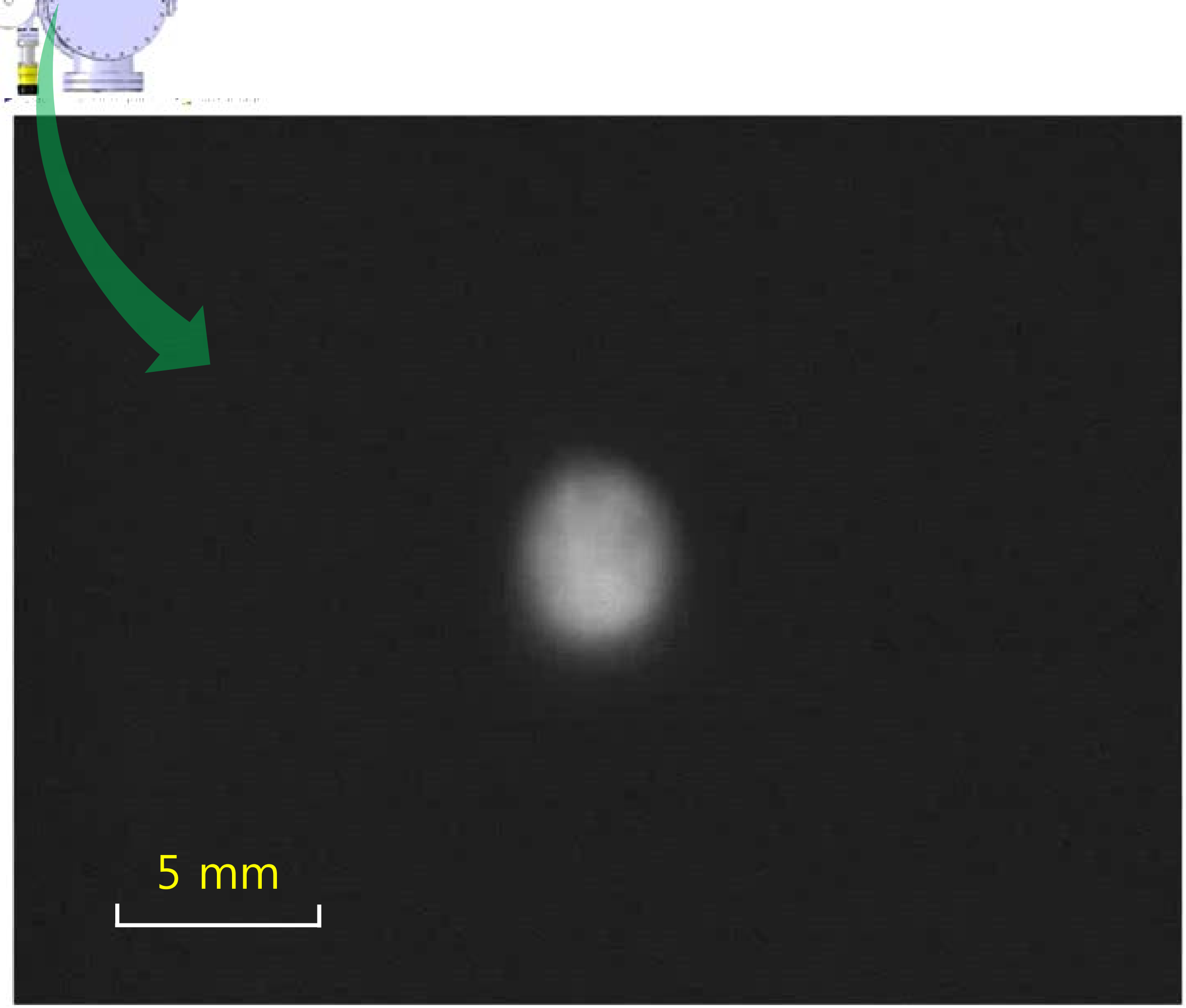
$\Delta E = 0.06\%$





Electron Beam at the Sample





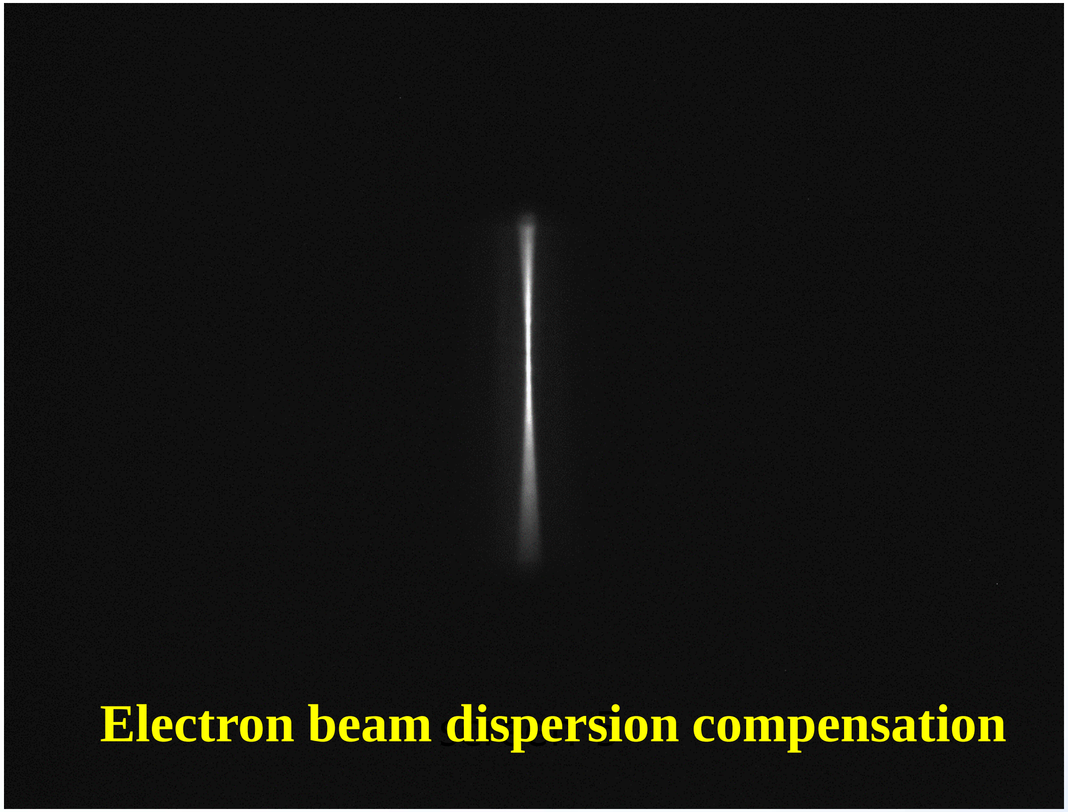
UED Beam Emittance Measurement

Q = 1.7 pC

p = 3.42 MeV/c

ε_x= 0.30 mm mrad,

ε_y= 0.33 mm mrad

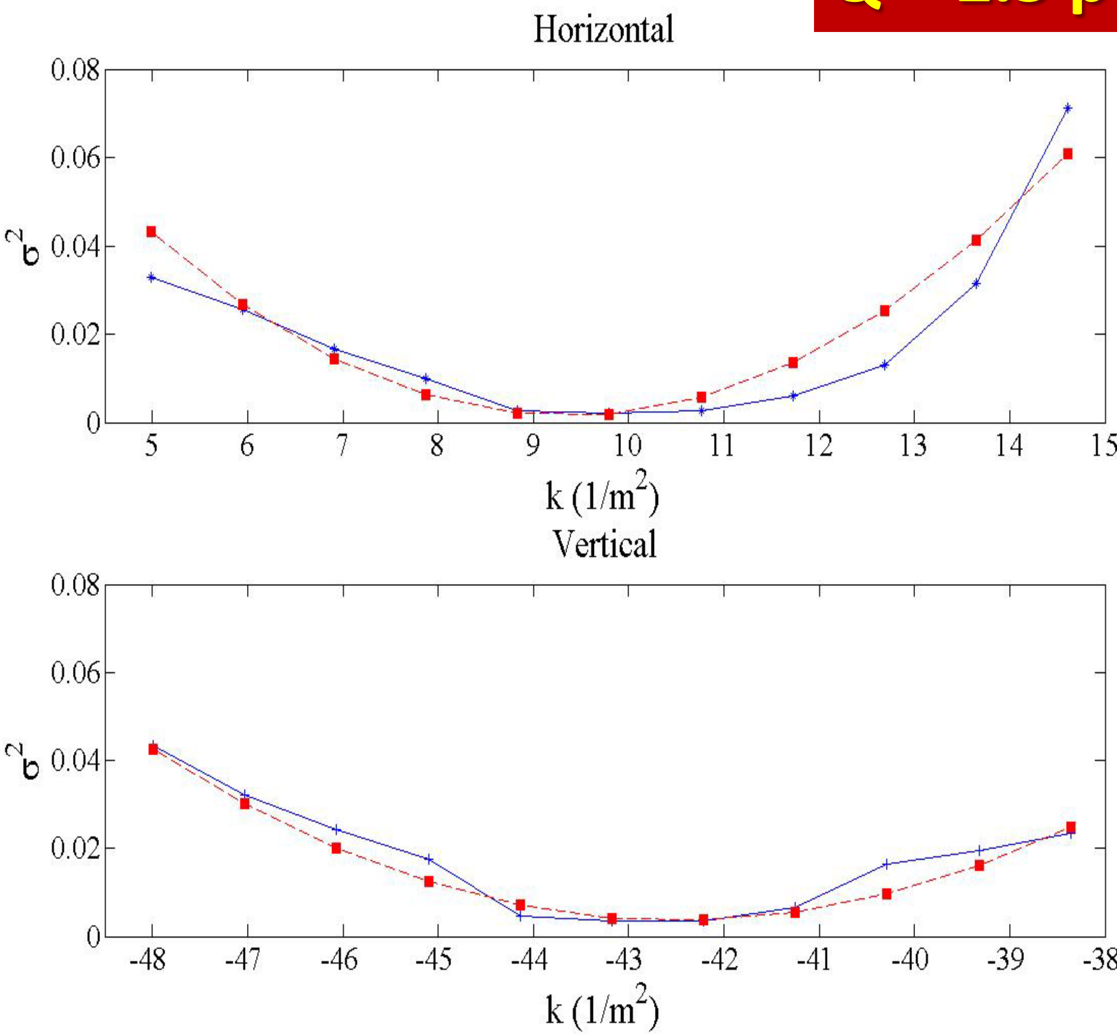


Parameters	Value
RF power set value	1030 V
RF power to the gun	~ 5 MW
Laser transverse size	~ 0.5 mm (H/V) (in diameter)
Laser pulse power	~ 0.7 μJ
Laser pulse length	~ 130 fs
Solenoid current	110 A

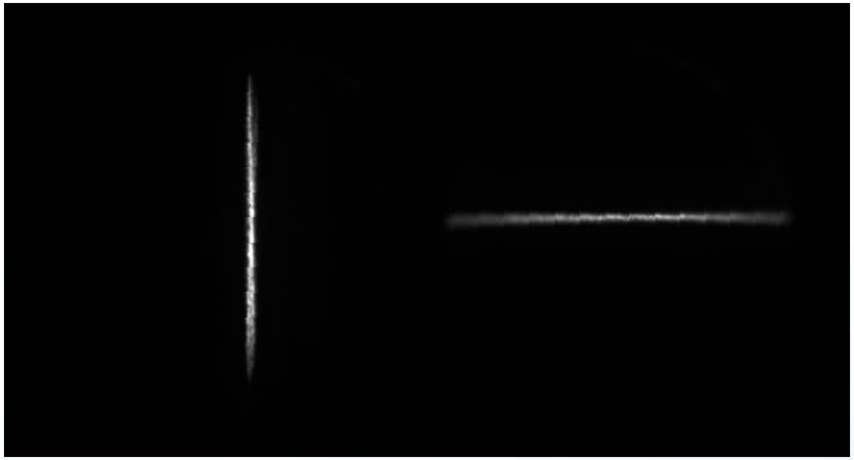
	Current	Gradient	K-value
QM1	-0.92	-0.4497	-40.9127
QM2	2.415	1.2729	115.8187
QM3	-0.92	-0.4497	-40.9127
QM4	1.1	0.5488	49.9315

UED Beam Emittance Measurement

Q = 2.5 pC



screen @ sample position



Parameters	Value
α_x	-12.65
α_y	-41.69
β_x	15.68 m
β_y	9.52 m
ε_{nx}	**0.38 μm**
ε_{ny}	**0.4 μm**

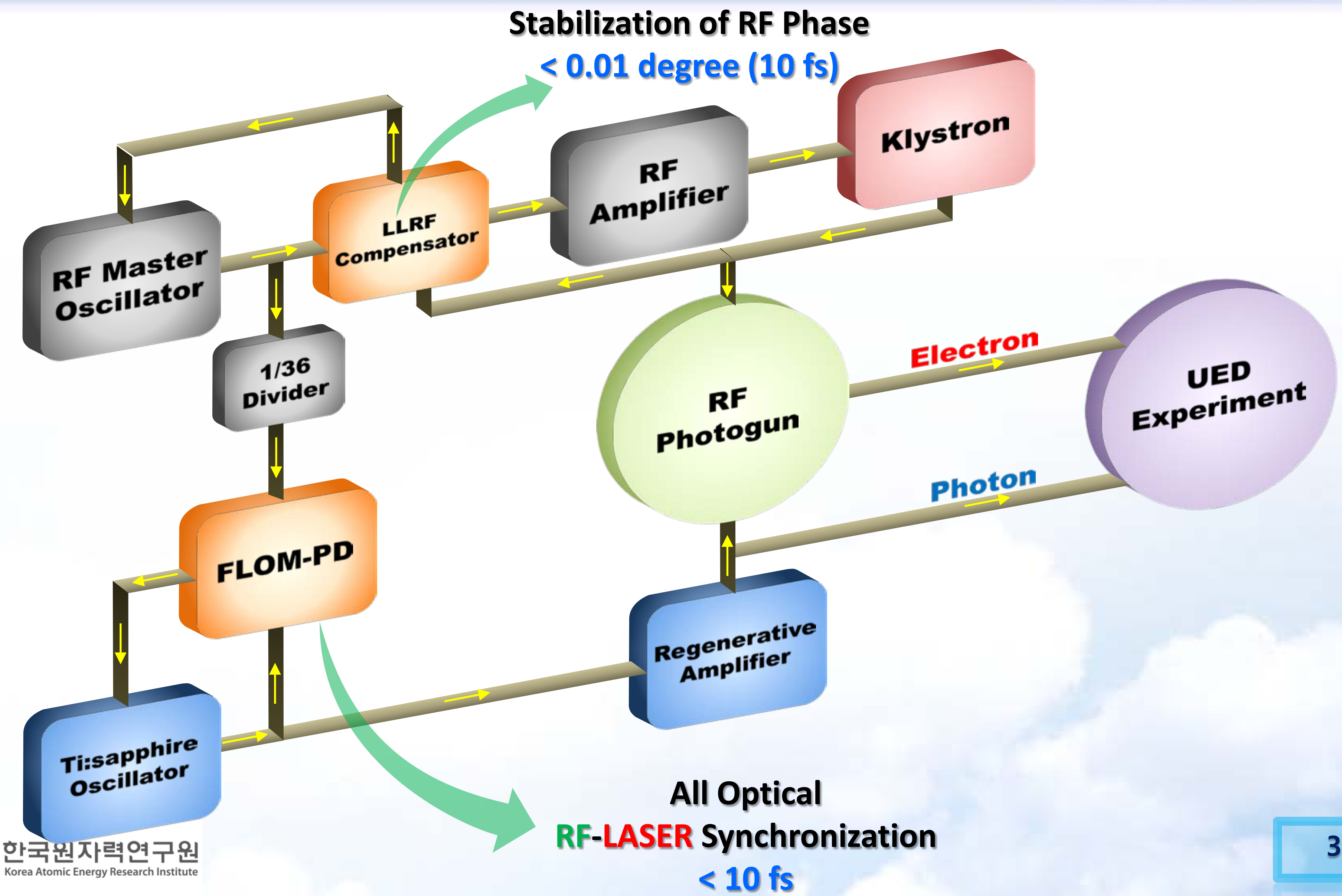
Sources of Timing Fluctuation

1. Timing Fluctuation between Laser Pulses and RF Phase
   - Laser Oscillator v.s RF Master Oscillator : 10 fs
   - Laser Oscillator v.s Regenerative Amplifier
   - RF Master Oscillator v.s Klystron : 10 fs
   - RF Travelling from Klystron to Photogun
   - Laser Travelling from Regen. Amplifier to Photogun

2. RF Amplitude Fluctuation : $< 10^{-4}$

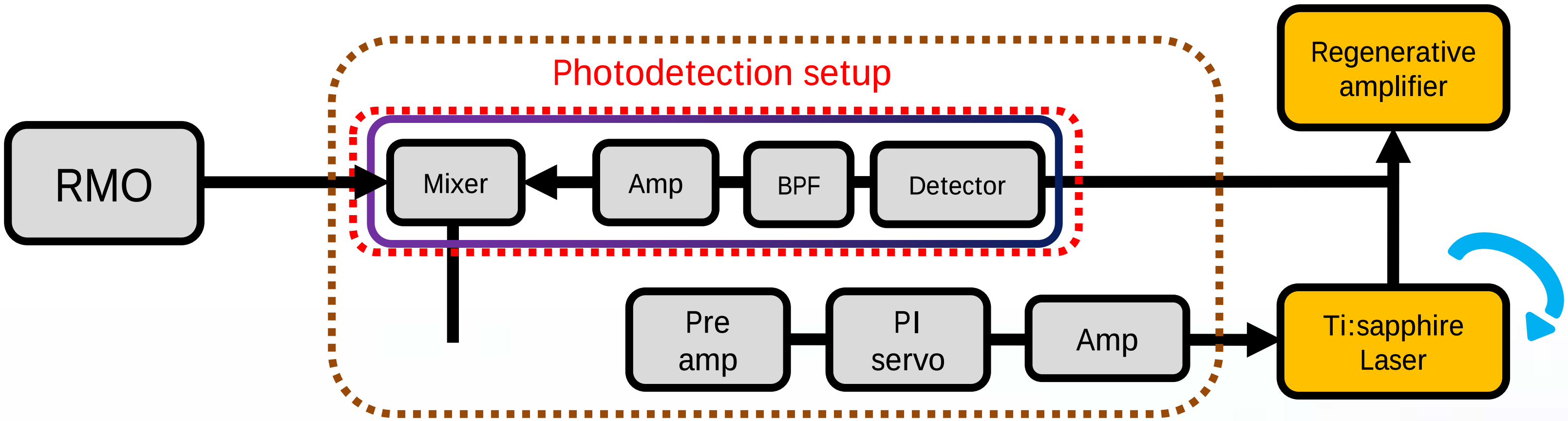
3. Timing Fluctuation by Photogun Temperature
   - Injection Phase Fluctuation
   - Electron Energy Fluctuation

Timing Synchronization 시간동기화

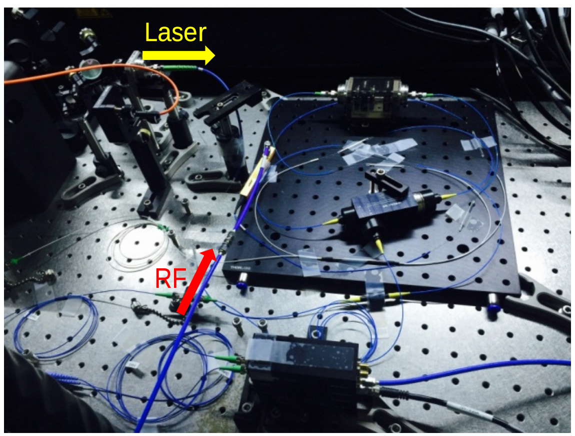


FLOM-PD activation

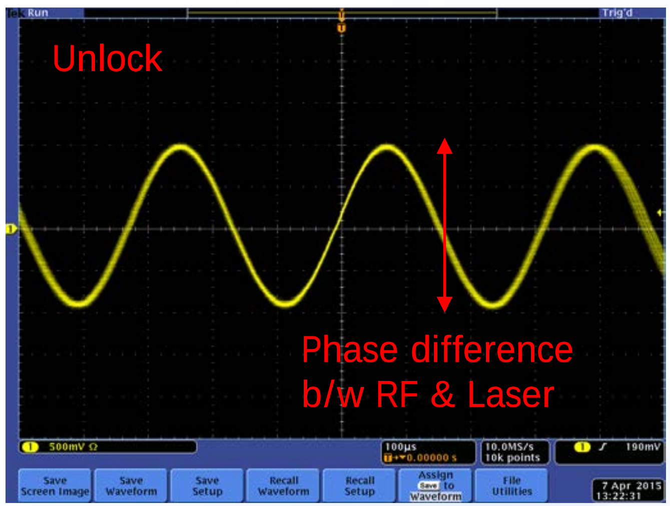
Prof. Jungwon Kim
(KAIST)

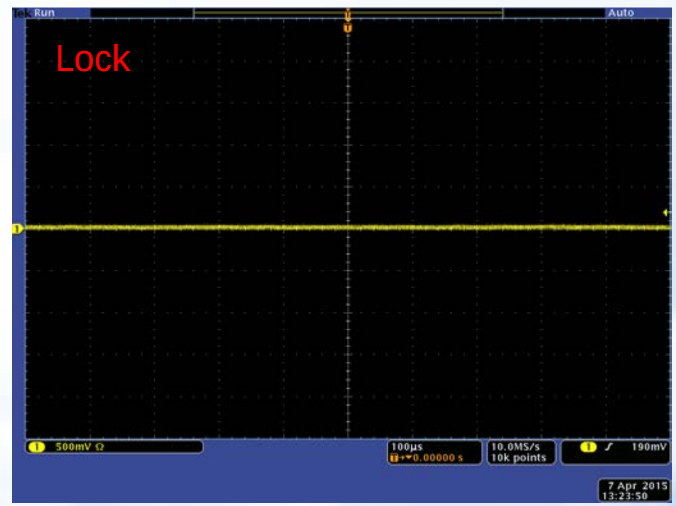


FLOM-PD (Frequency Loof Optical Modulation – Phase Detector)



Photograph of FLOM-PD





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RF Phase Fluctuation by Temperature

RF Photogun Temperature Fluctuation by Cooling Water causes Pulse-to-pulse RF Phase Fluctuation

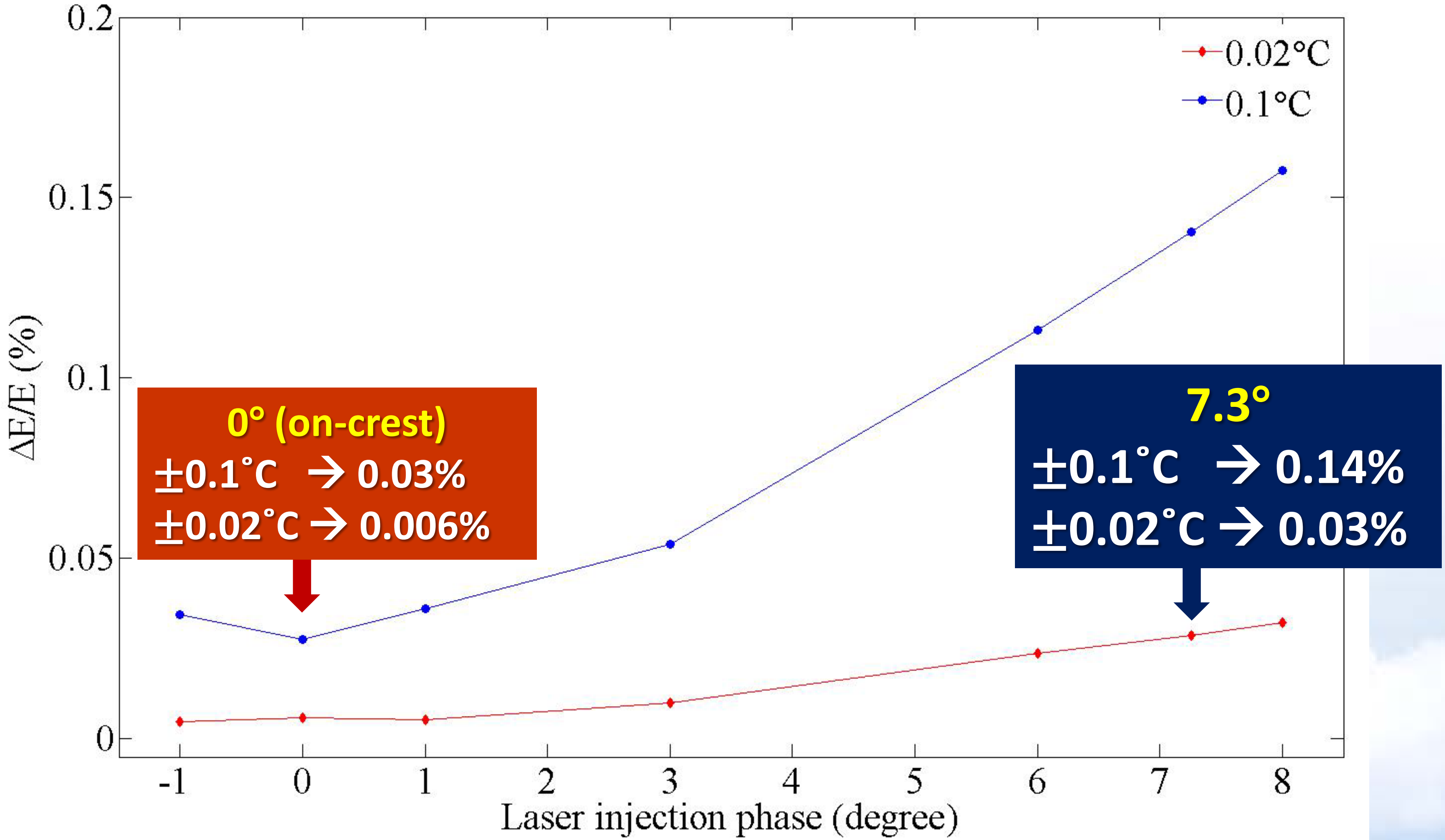
Now

$\Delta T = 0.1^{O}C \rightarrow \Delta \phi = 1.09$ degree

Soon

$\Delta T = 0.02^{O}C \rightarrow \Delta \phi = 0.22$ degree

Energy Fluctuation by Phase Fluctuation



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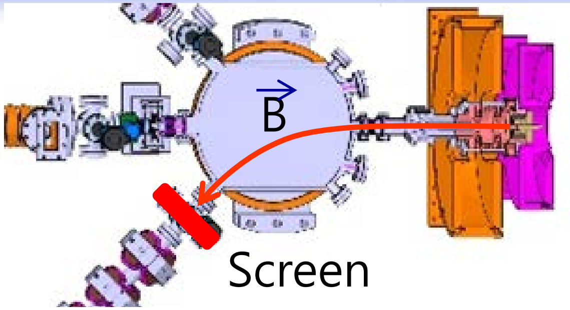
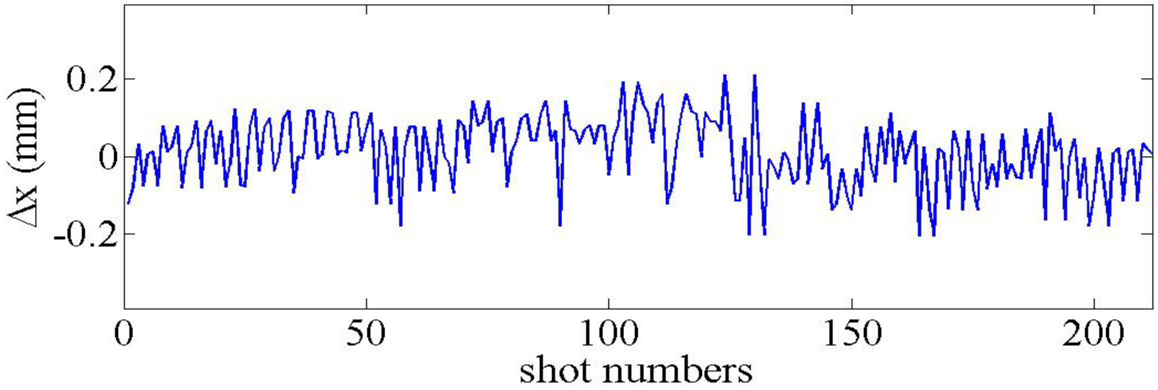
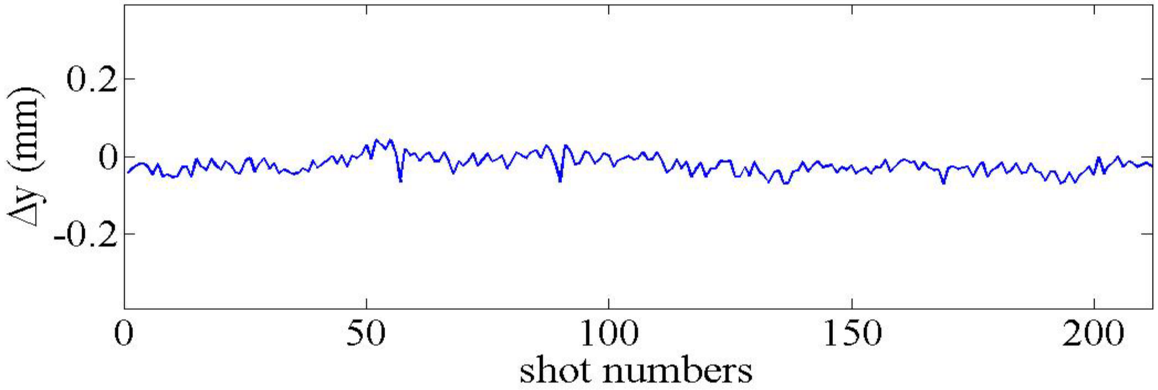
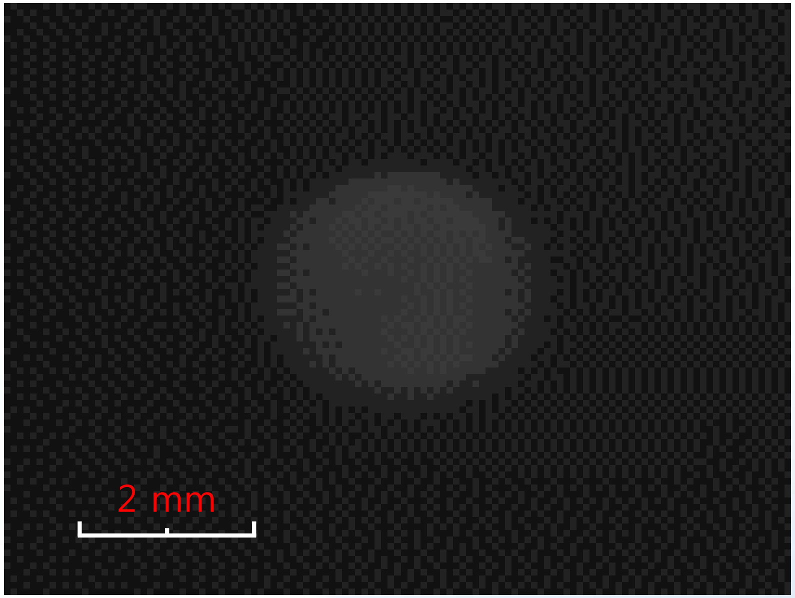
Energy Fluctuation Measurement







Laser Injection Phase : 0° (on-crest)

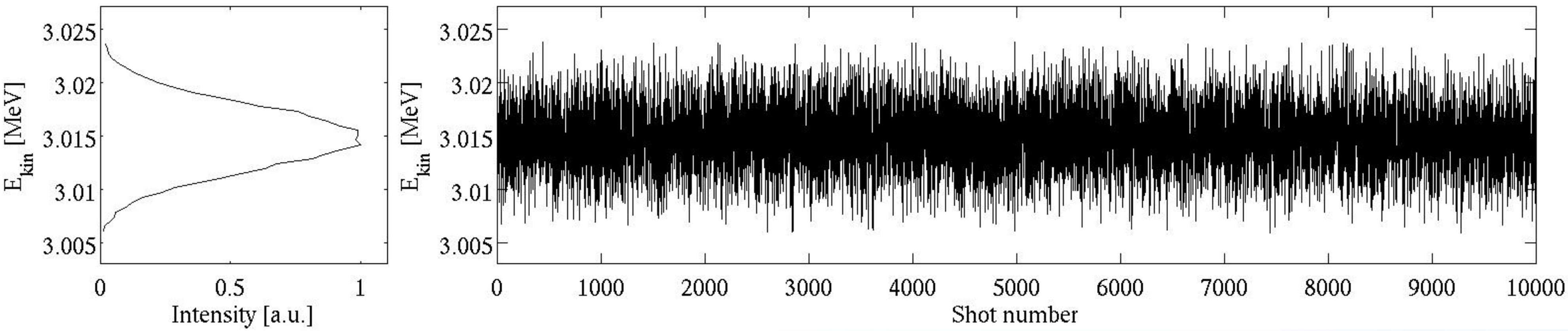


Δx = 0.09 mm → ΔE = 0.063%

Δy = 0.02 mm

Low Timing Jitter for Energy Fluctuation

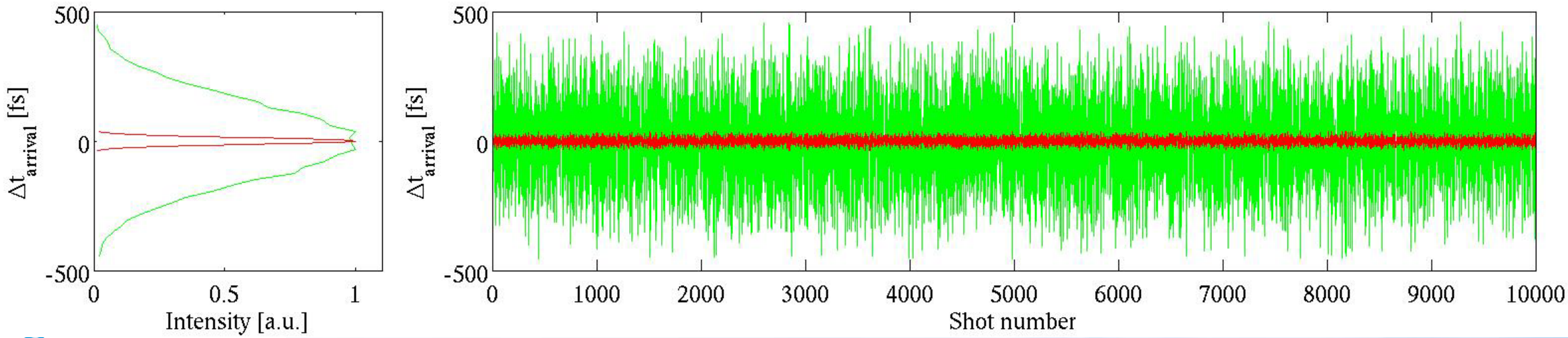
Energy Fluctuation, ΔE_{jitter} = 0.1% (rms)



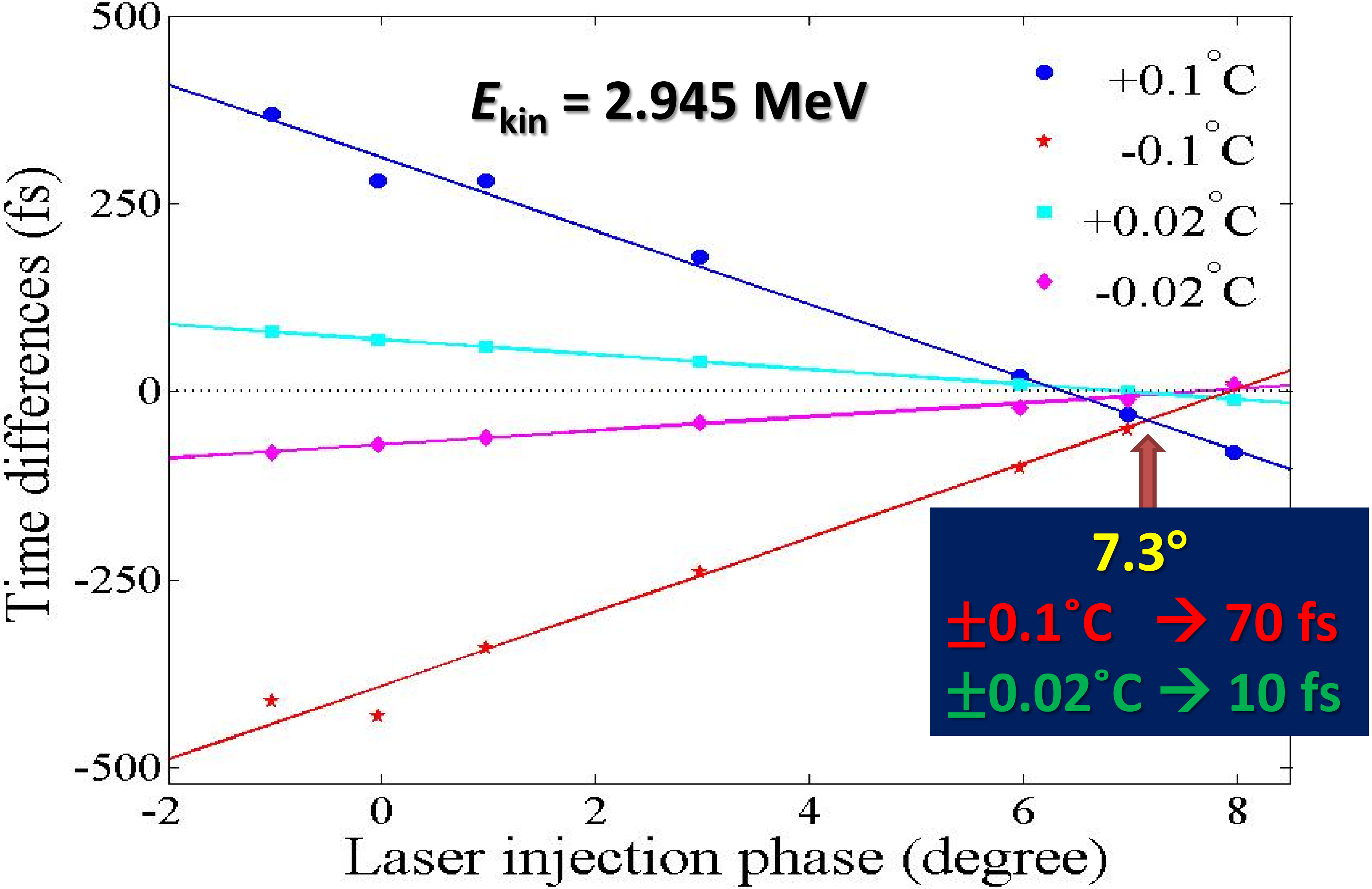
Δt_{jitter} (rms)

3 m with isochronous bend = 12 fs

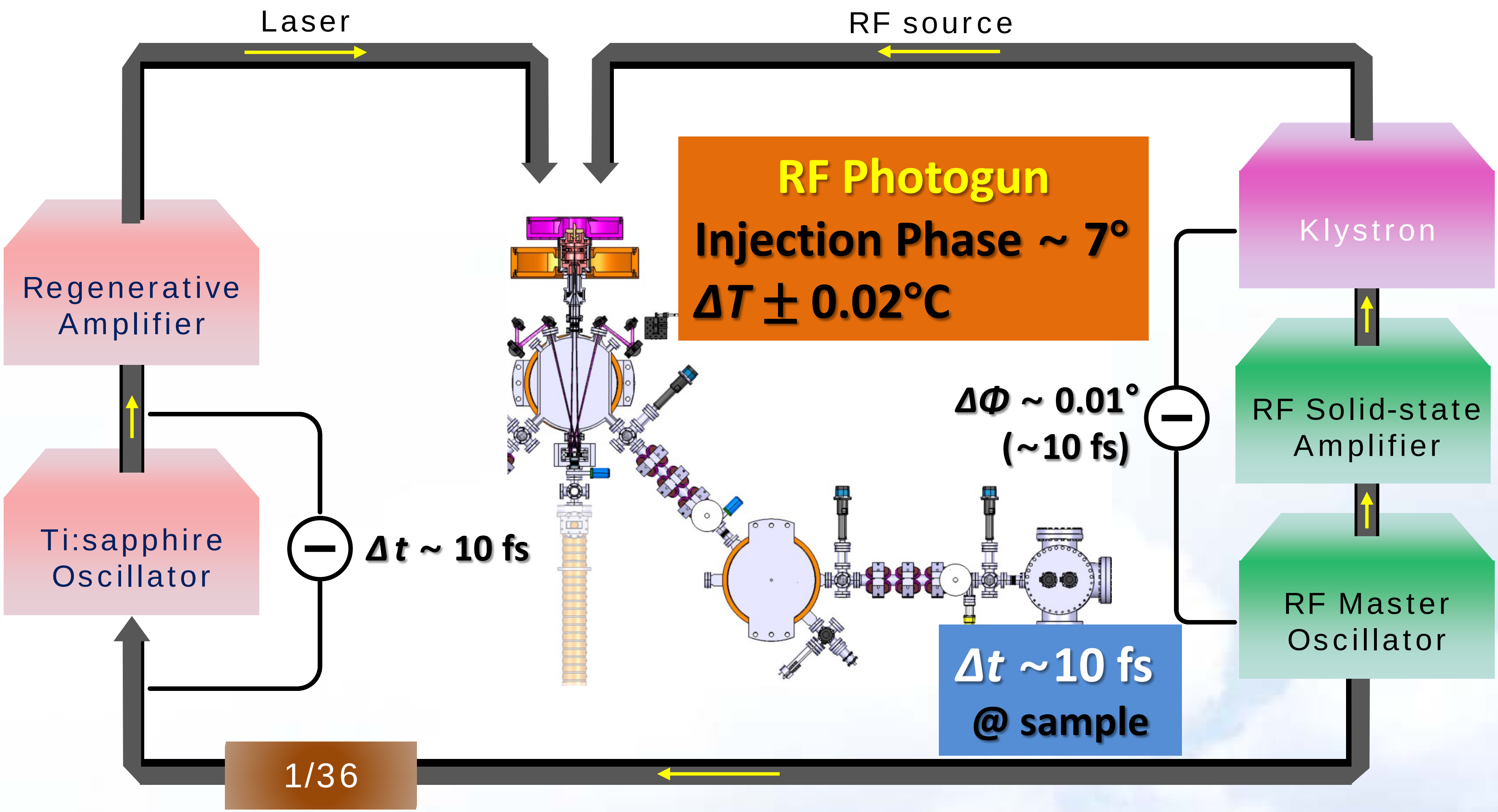
3 m straight line = 152 fs



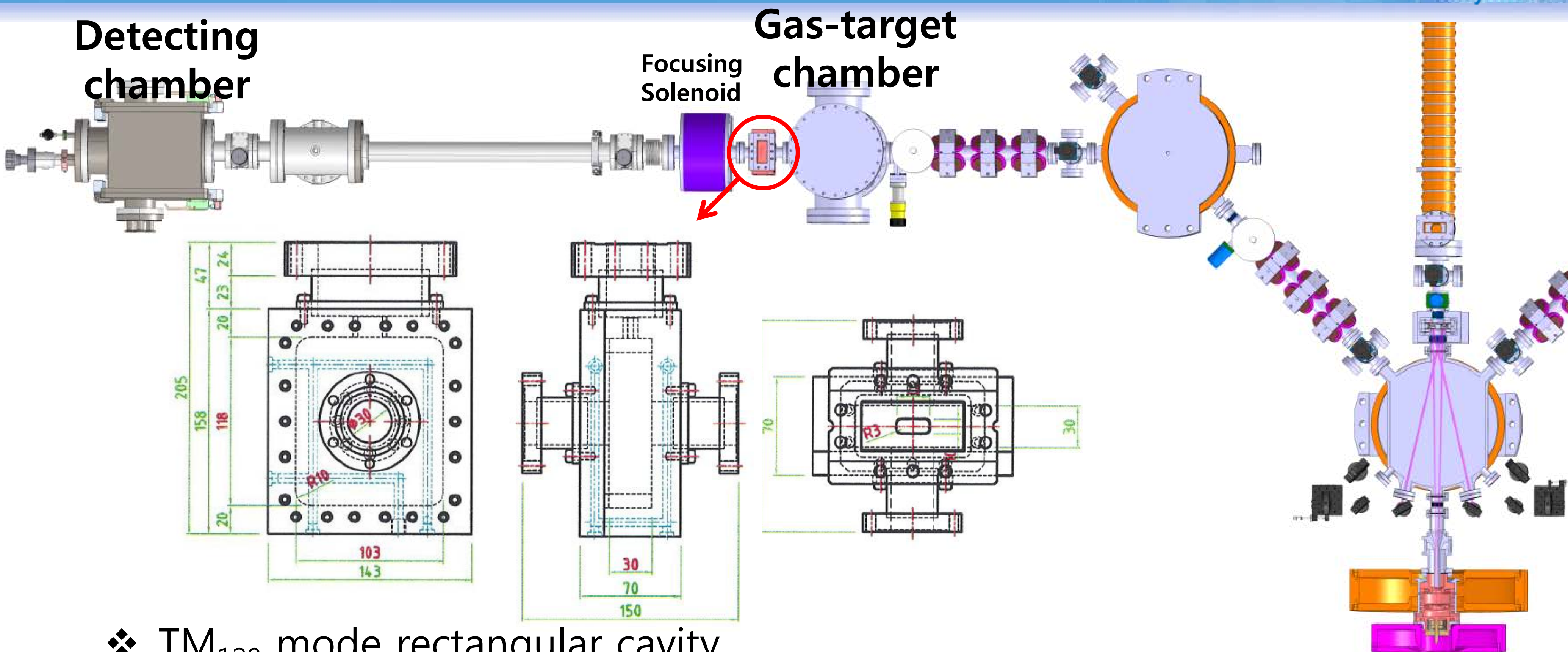
Timing Jitter by Phase Fluctuation



Timing Synchronization 시간동기화



Deflecting Cavity



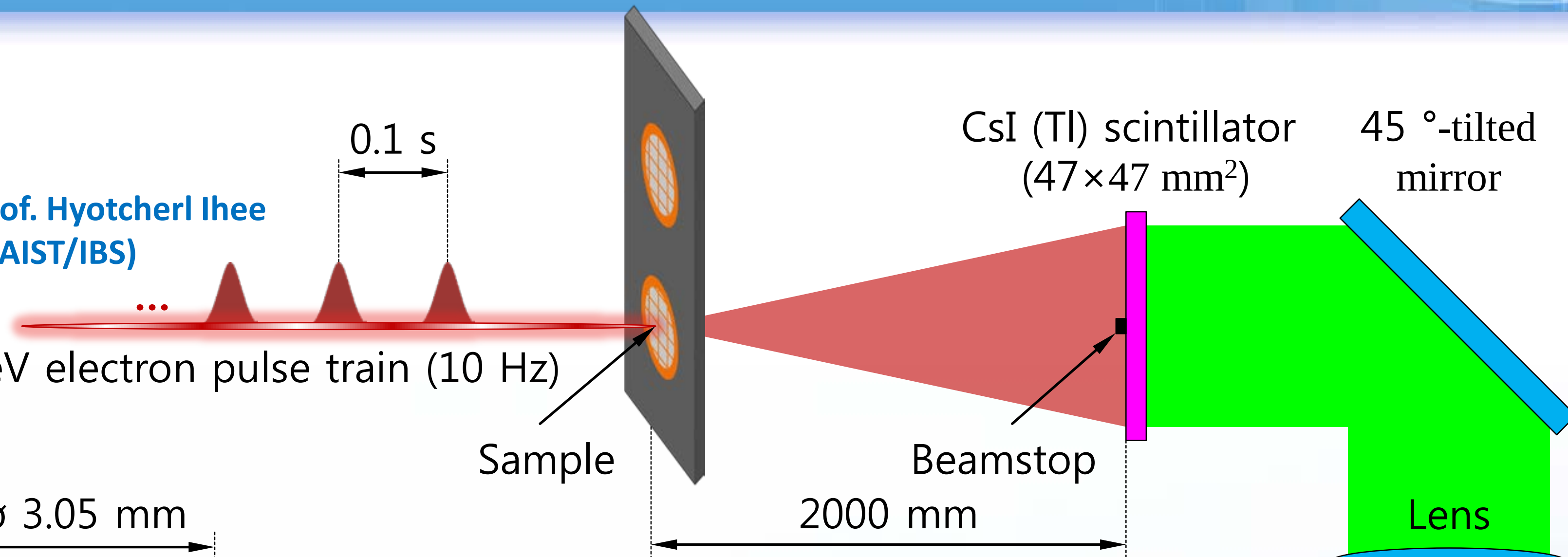
❖ TM_{120} mode rectangular cavity

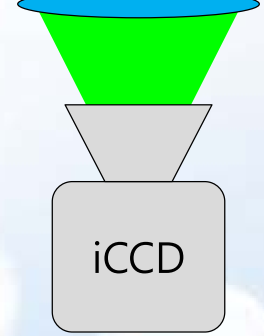
- with 10 μm slit to increase the temporal resolution
- Resonance frequency : 2.856 GHz
- Deflecting voltage : > 50 kV
- Expecting time resolution : < 100 fs

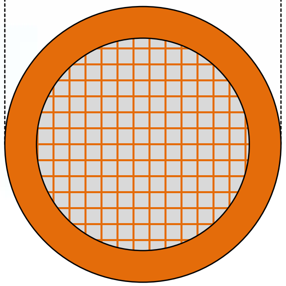
Sunjeong Park

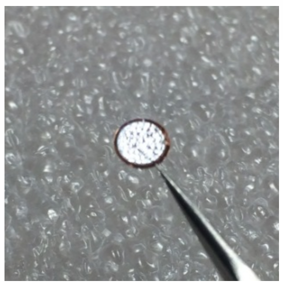
Electron Diffraction of Al Polycrystal Film

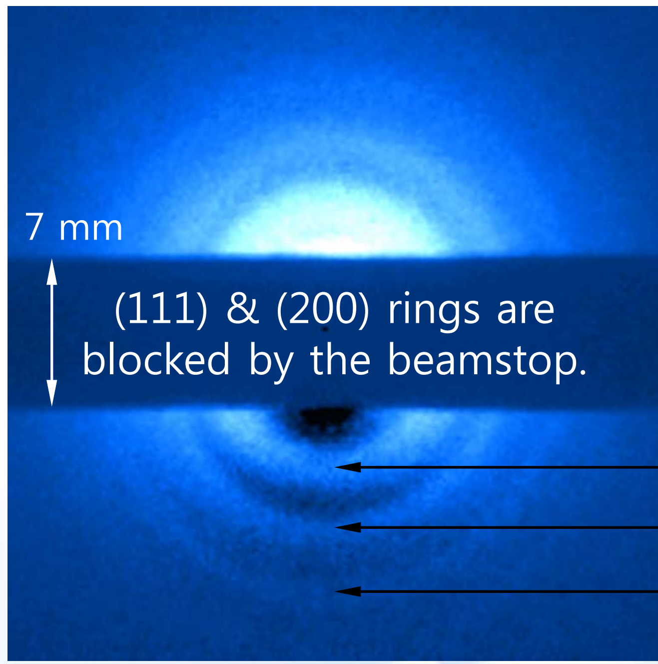
Prof. Hyotcherl Ihee
(KAIST/IBS)











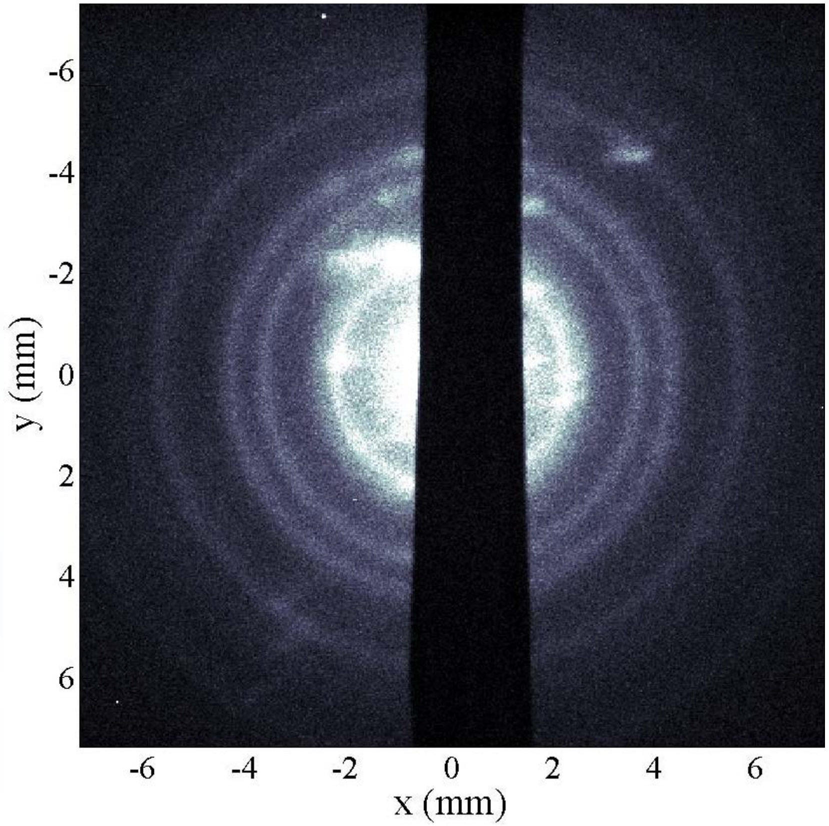
TEM mesh grid

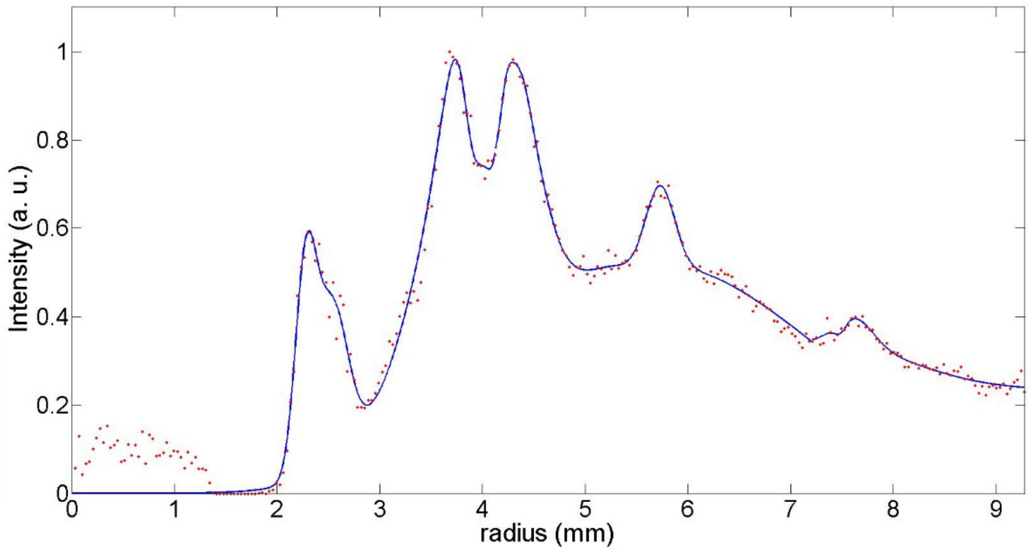
- Formvar/Carbon supports
- Hole diameter of 300 μm

Aluminum thin film

- Polycrystalline (a = 4.049 Å)
- Film thickness of 200 nm

UED : TEM grid + C (30 nm) + Au sample (50 nm)





- Integrate between -15° ~ 15°
  blue line : Sum of Gaussian fit
  red dot : experimental data

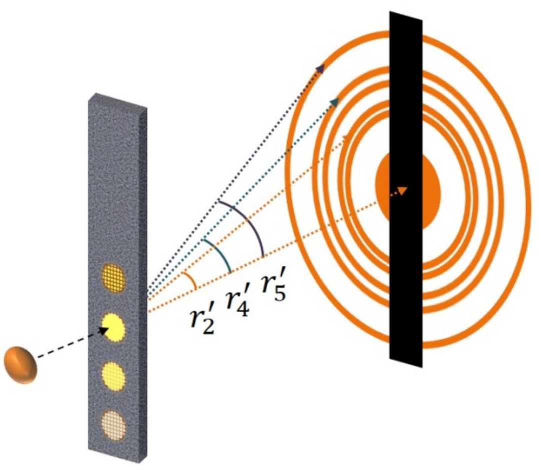
- Beam parameters
  Q = 2.53 pC, E_k = 2.96 MeV, ε_n = 0.4 μm
  D_{beam}@sample ~ 3 mm

- Andor EMCCD
  Gain : 280, Exposure time : 10 μs (min)
  Binning : 2, Integrated 20 shots

한국원자력연구원
KAERI Korea Atomic Energy Research Institute

UED Simulation : ASTRA

Beam parameters	Experiment	Simulation
Charge	2.53 ± 0.08 pC	2.5 pC
Kinetic Energy	2.96 MeV	2.96 MeV
Norm. emittance	0.4 mm-mrad	0.4 mm-mrad
Beam	-	0.09 mrad



$$\lambda_e = \frac{hc}{p}$$

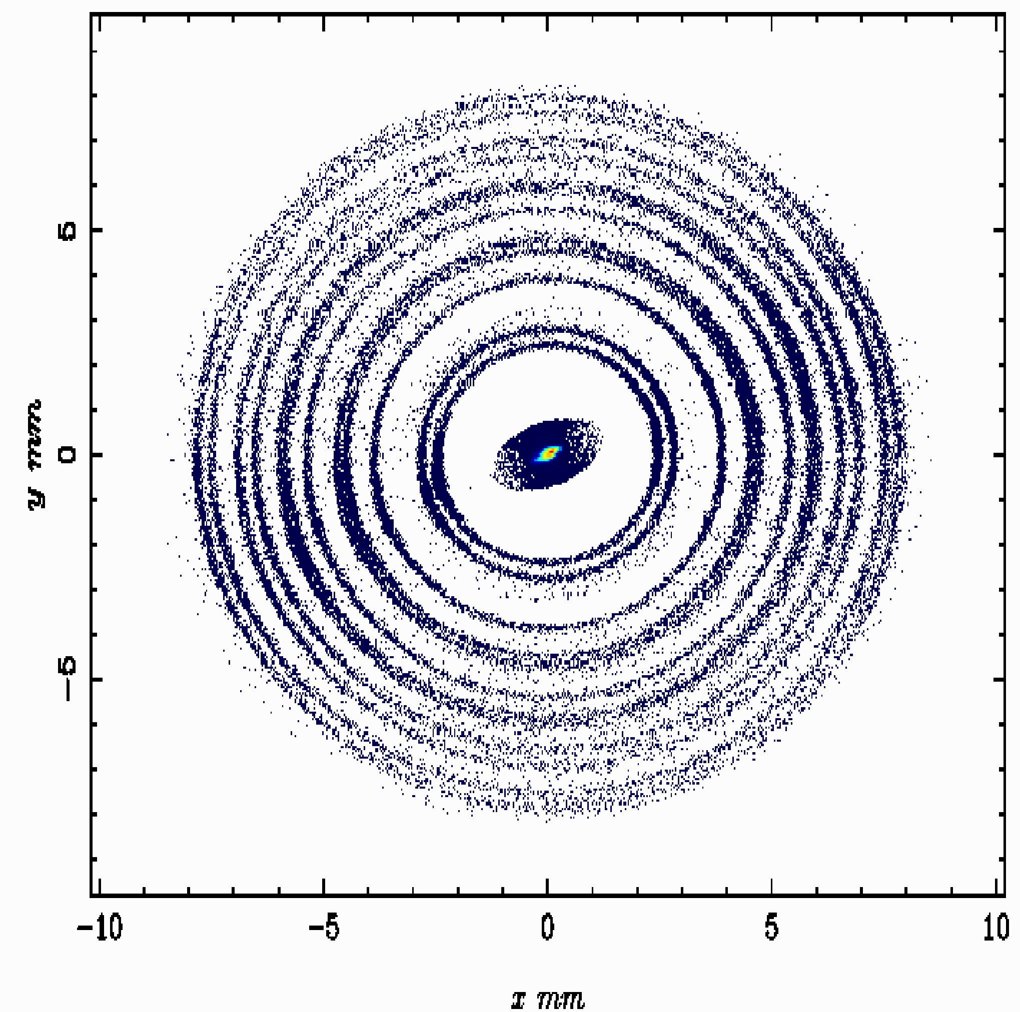
h = plank constant
c = speed of light
p = momentum of electron beam

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

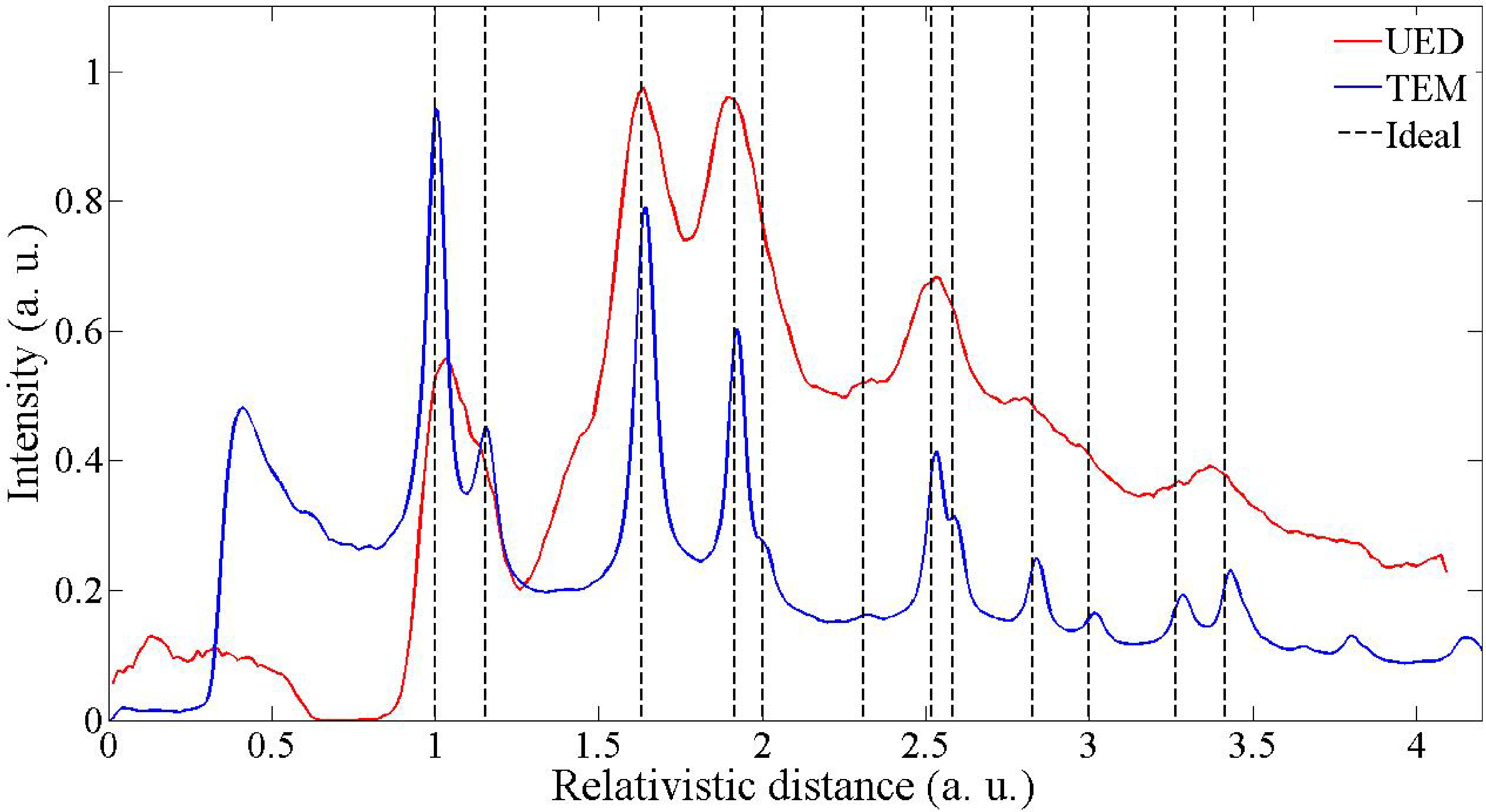
h, k, l = Miller index
a = cell parameters (4.0786 Å)

$$r = L \tan\left[2\sin^{-1}\left(\frac{\lambda_e}{2d_{hkl}}\right)\right] \approx \frac{L\lambda_e}{d_{hkl}}$$

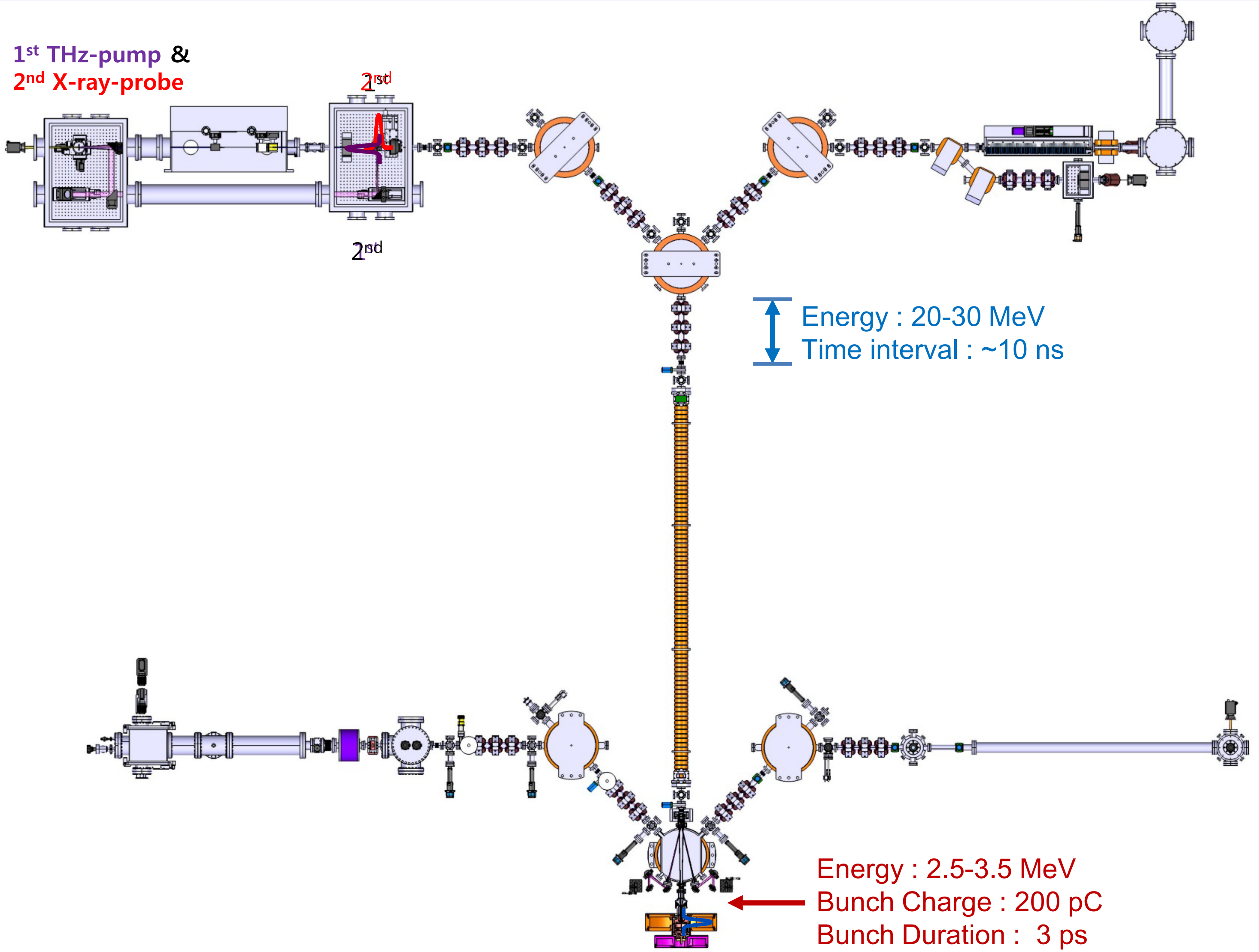
r = pattern radius
L = camera distance



Diffraction Patterns of Au Polycrystal



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

Thank You !!