FEL 2012, Nara, Japan

세계수준의 연구센터
World Class Institute

Status of the KAERI Table-top THz Free-Electron Laser Development

2012. 8. 29

Y. U. Jeong[1], S. H. Park[1], K. Lee[1], K.-H. Jang[1], J. Mun[1,2], K. N. Kim[1,3], H. N. Kim[1], S. Park[1,4], S. Bae[1], Y.-H. Cha[1], B. H. Cha[1], S. Miginsky[1,5], B. Gudkov[1,5], and N. Vinokurov[1,5]

[1]Korea Atomic Energy Research Institute, [2]Chungnam National University, [3]Kongju National University, [4]Kyungpook National University, [5]Budker Institute of Nuclear Physics

한국원자력연구원
Korea Atomic Energy Research Institute

2RC THz Pump X-ray Probe

WCI Outline 센터의 개요

Quantum-Beam based Radiation Research Center

Goal

- Development of **Cutting-edge** Quantum-beam-based Radiation Sources
- Investigation of **Innovative** Application Technologies in Nuclear and Bio Science
- Cultivating & Training of **Young Scientists** via Int'l Research Co-operation Network

Structure

Director: Nicolay Vinokurov
(Budker Inst. of Nuclear Physics, Russia)
Accelerator physics

Deputy Director: Young Uk Jeong
(Korea Atomic Energy Research Institute)
Free electron laser

Members
- 4 foreign researchers
- 4 KAERI researchers
- 5 researchers from Korean universities
- 10 ~ 15 post-doctors/students
- 3 Administrative supporting members

International Advisory Committee
- 5 international outstanding scholars

Global Network
- 15 Domestic Institutions
- 27 Foreign institutions (10 nations)

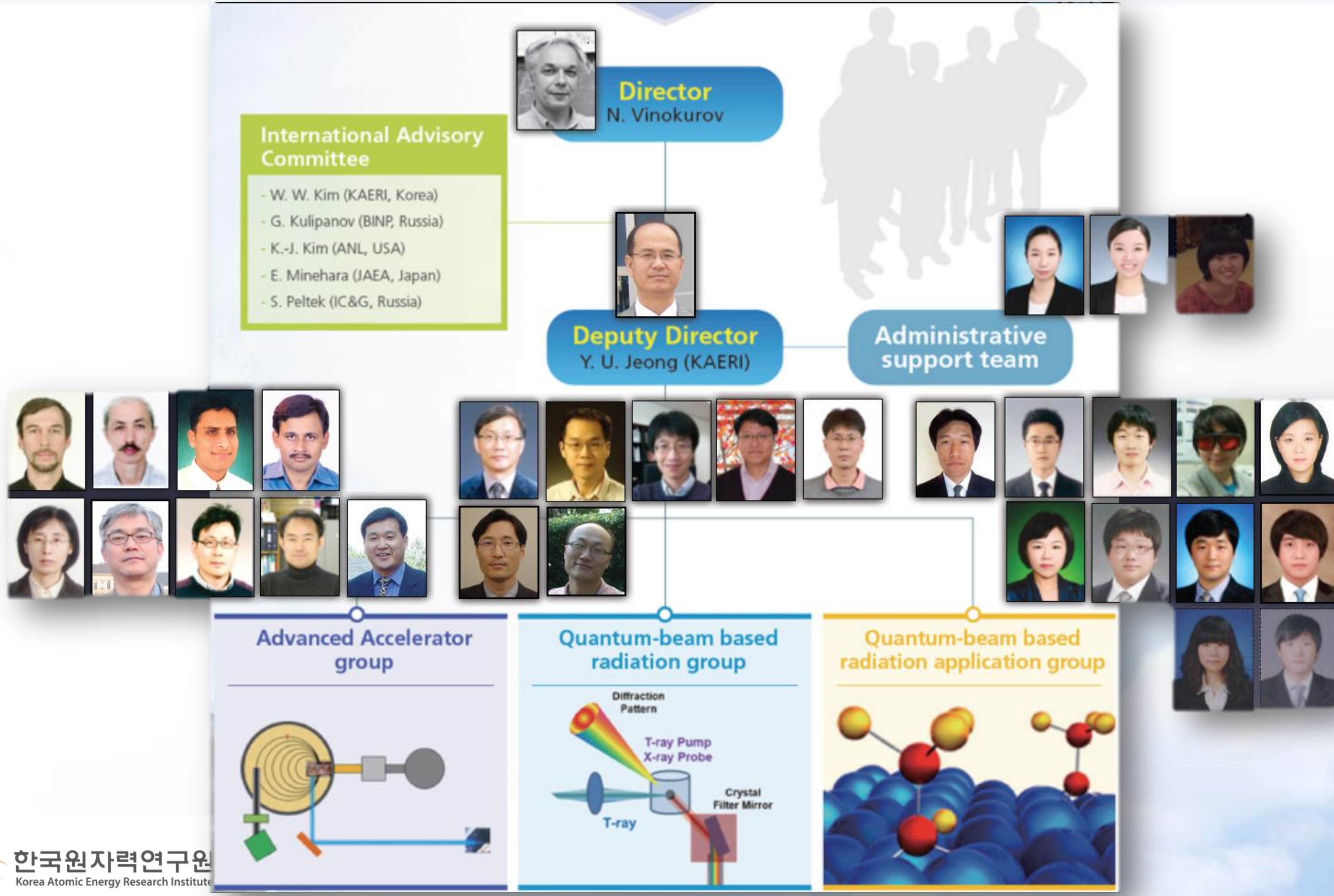
Fund

in 100M KRW

	1st year	2nd	3rd	4th	5th	Total
WCI	25	25	25	25	25	125
KAERI	13	16	16	16	16	77
Total	38	41	41	41	41	202

X-ray
Ultraviolet
Infrared
Terahertz

WCI Members 센터의 구성



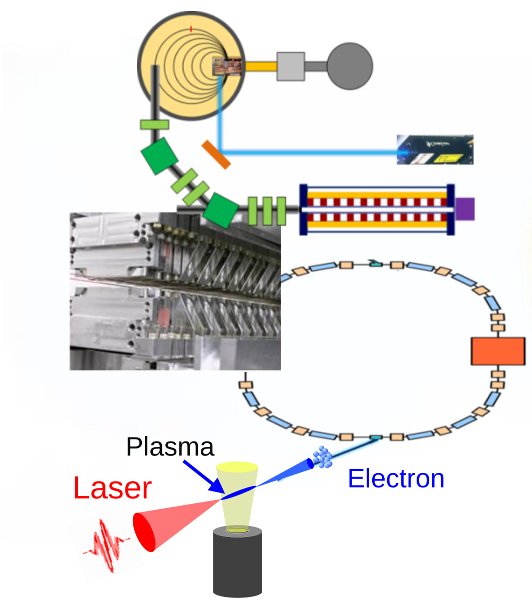
WCI Research Areas 주요 연구분야

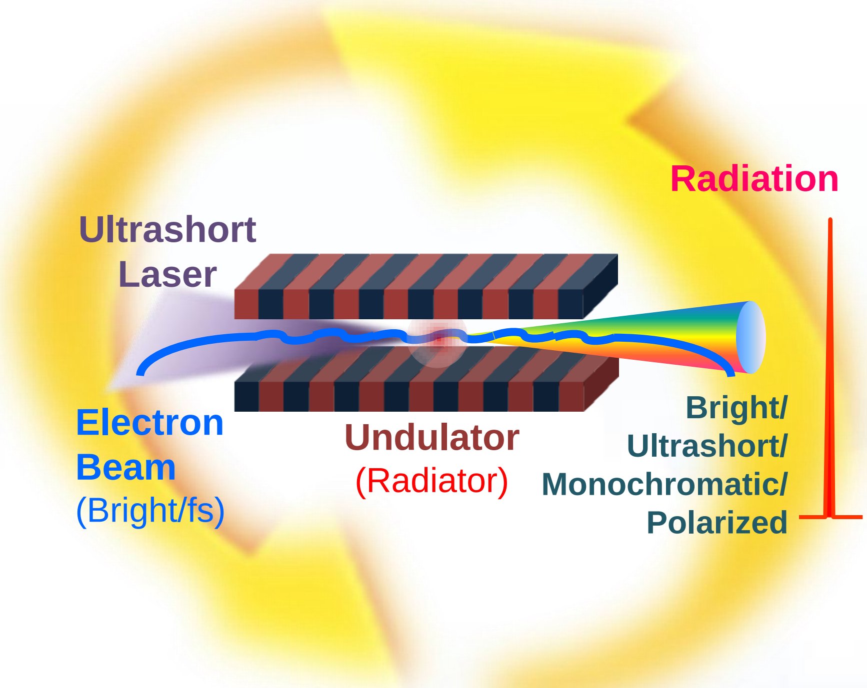
Core Technologies

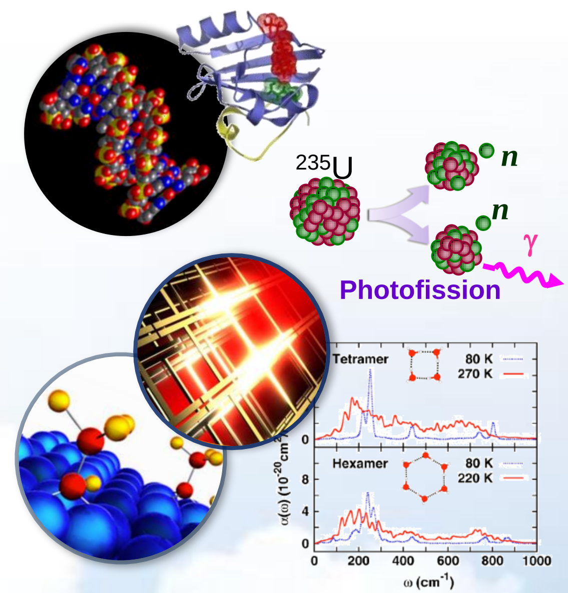
Accelerators

Radiations

Applications





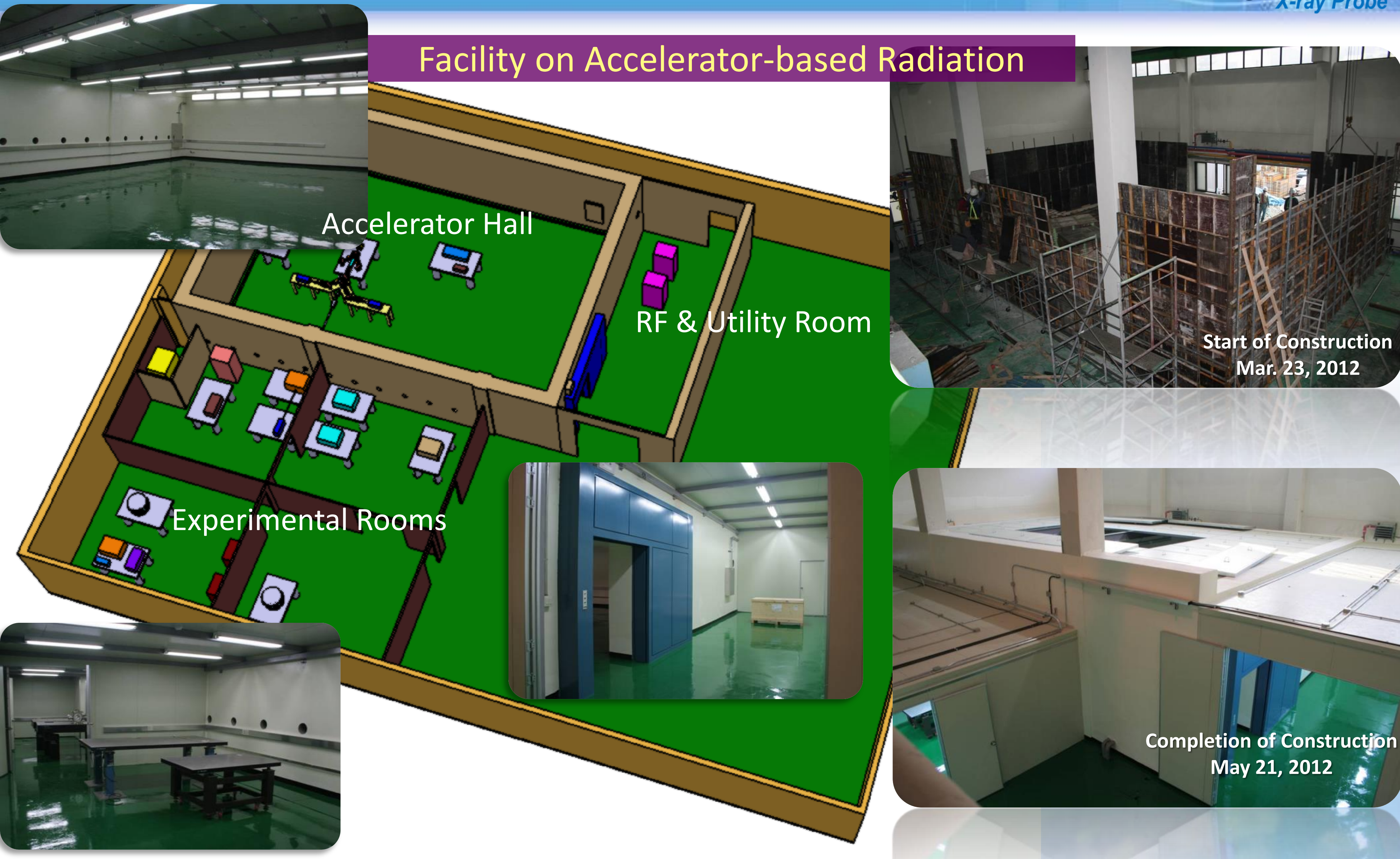


- RF Photogun-based Accelerator
- Laser Accelerator Injection to Storage Ring
- Variable-period Undulator

- Generation of Ultra-short T-ray & X-ray from a Photocathode-based Accelerator and a 30 Terawatt Laser

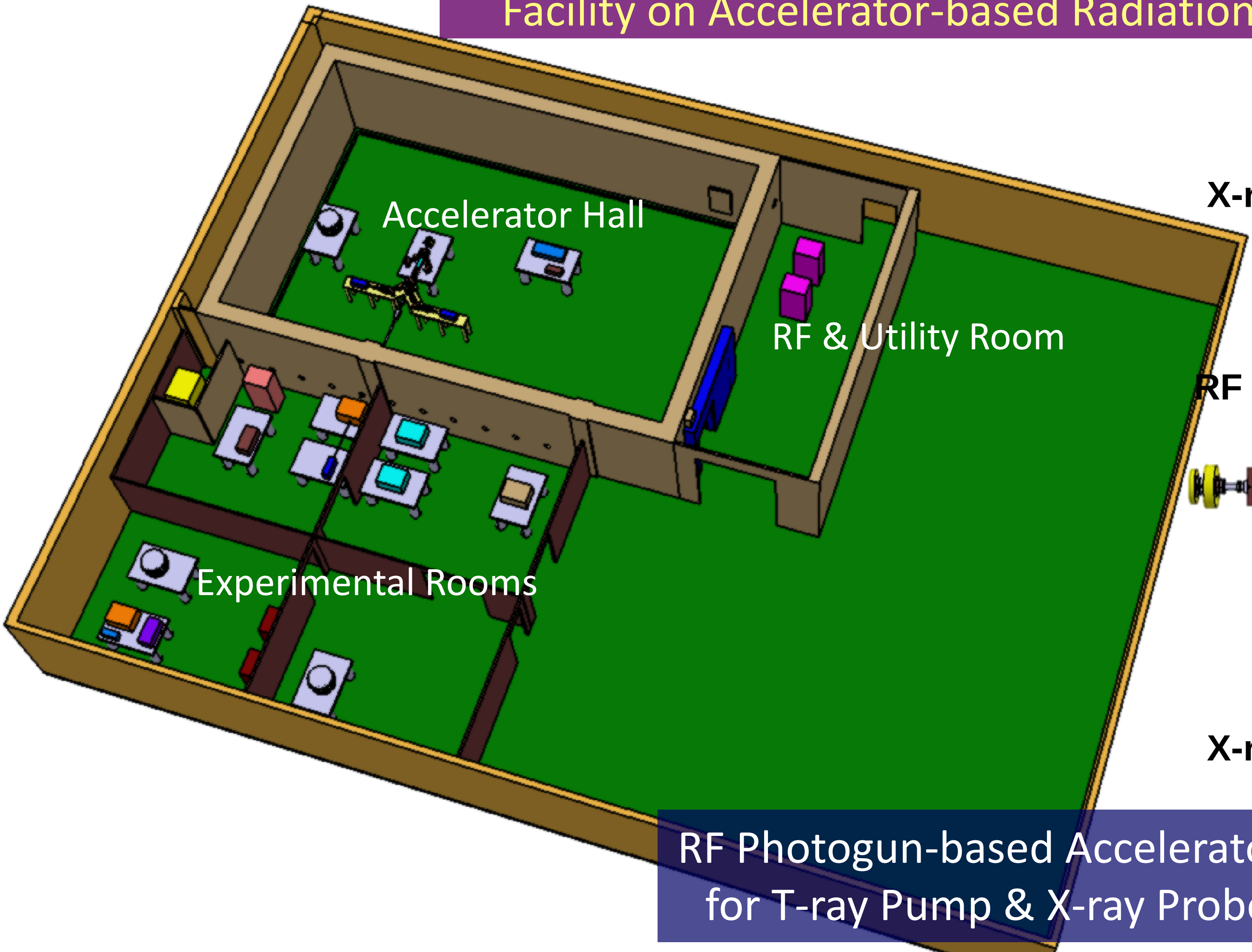
- Monitoring of Radioactive Gas
- Study on THz Meta Materials
- Development of new Bio Technologies

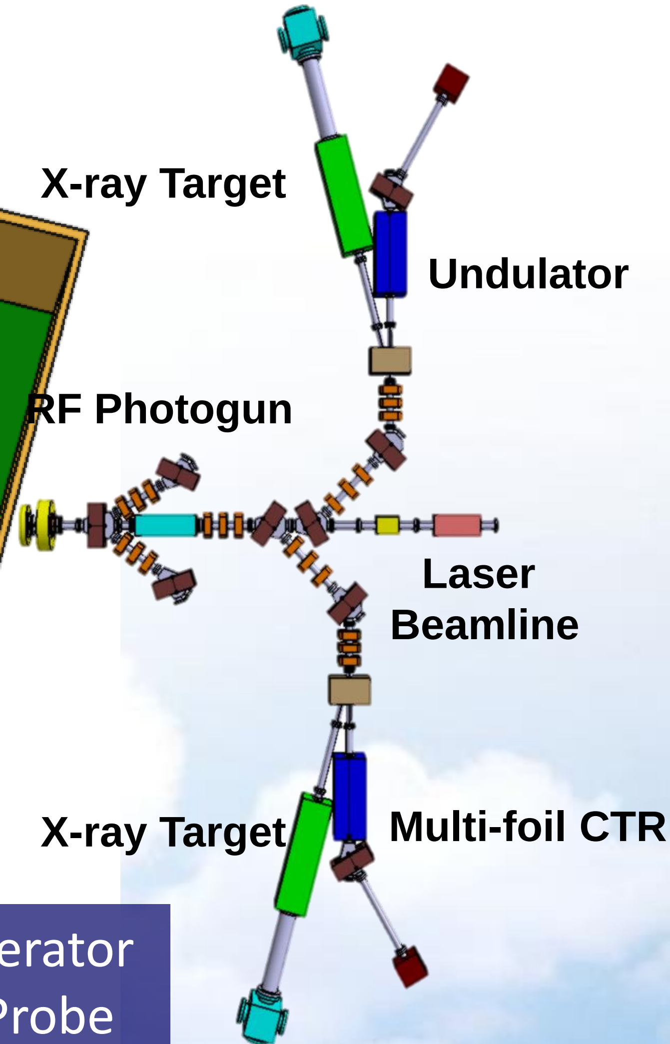
Construction of New Facilities



Construction of New Facilities

Facility on Accelerator-based Radiation





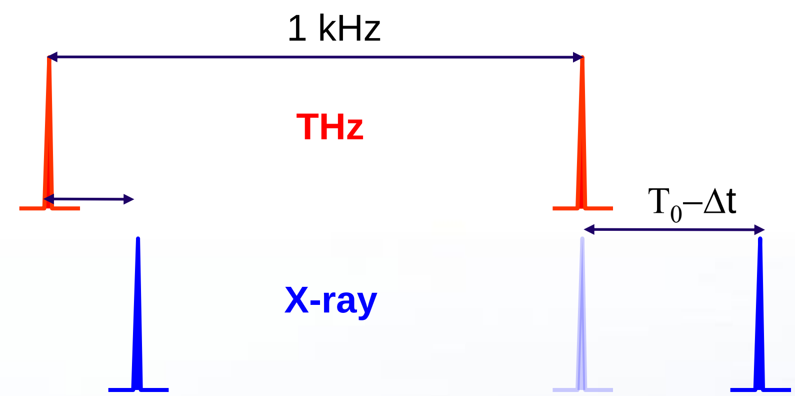
RF Photogun-based Accelerator for T-ray Pump & X-ray Probe

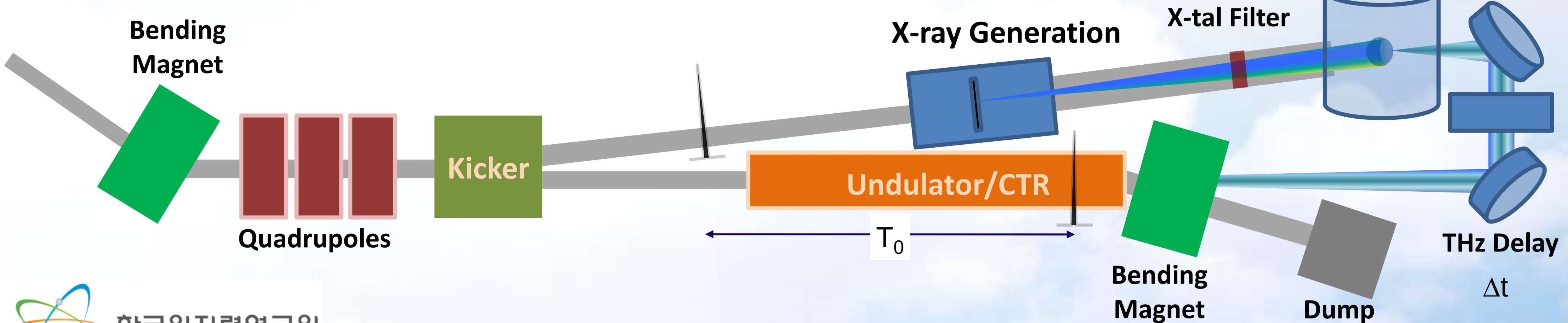
T-ray Pump & X-ray Probe

- Photocathode laser : 0.5-1 mJ, 267 nm, 0.1-10 ps
- **High-repetition RF photogun-based accelerator** :
  6-10 MeV, sub-ps, double bunch, 1 kHz
- Double-bunch beam acceleration : T_0 ~ 10 ns
- Fast kicker to split the bunches for T-ray & X-ray generation
- **T-ray generation**
  - Coherent undulator radiation for narrow-band T-ray
  - Multi-foil coherent transition radiation for wide-band T-ray

THOB03 : N. Vinokurov, et al., The Generator of High-power Short THz Pulses

- **X-ray generation** : high-Z thin target + crystal filter





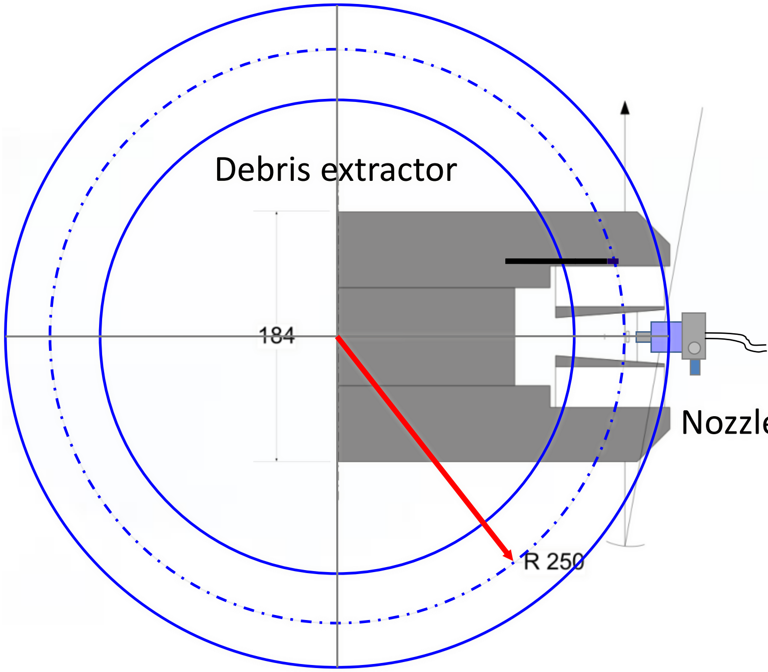
KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

THPD60 : K. Lee, et al., Design Status of Compact T-ray Pump and X-ray Probe System

Construction of New Facilities

Facility on Laser-based Radiation

Demonstration of a Laser Accelerator Injection to Storage Ring

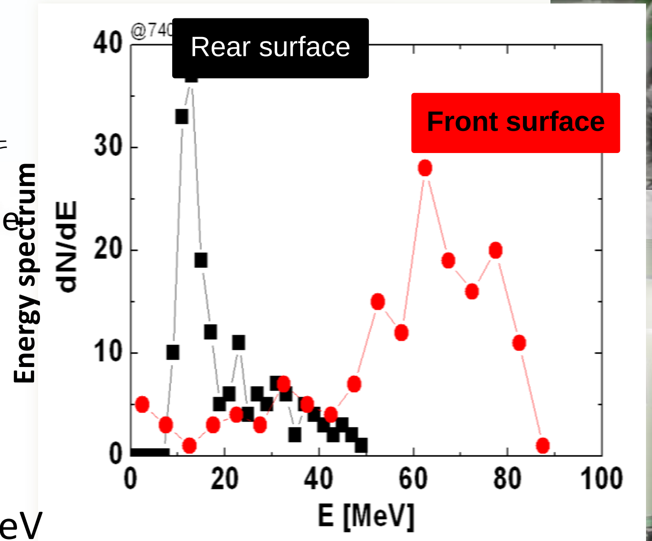


Target inside a Bending magnet

- E-beam energy: < 50 MeV
- Another serious issue to be overcome
  - Control of beam quality such as **energy spread & divergence**

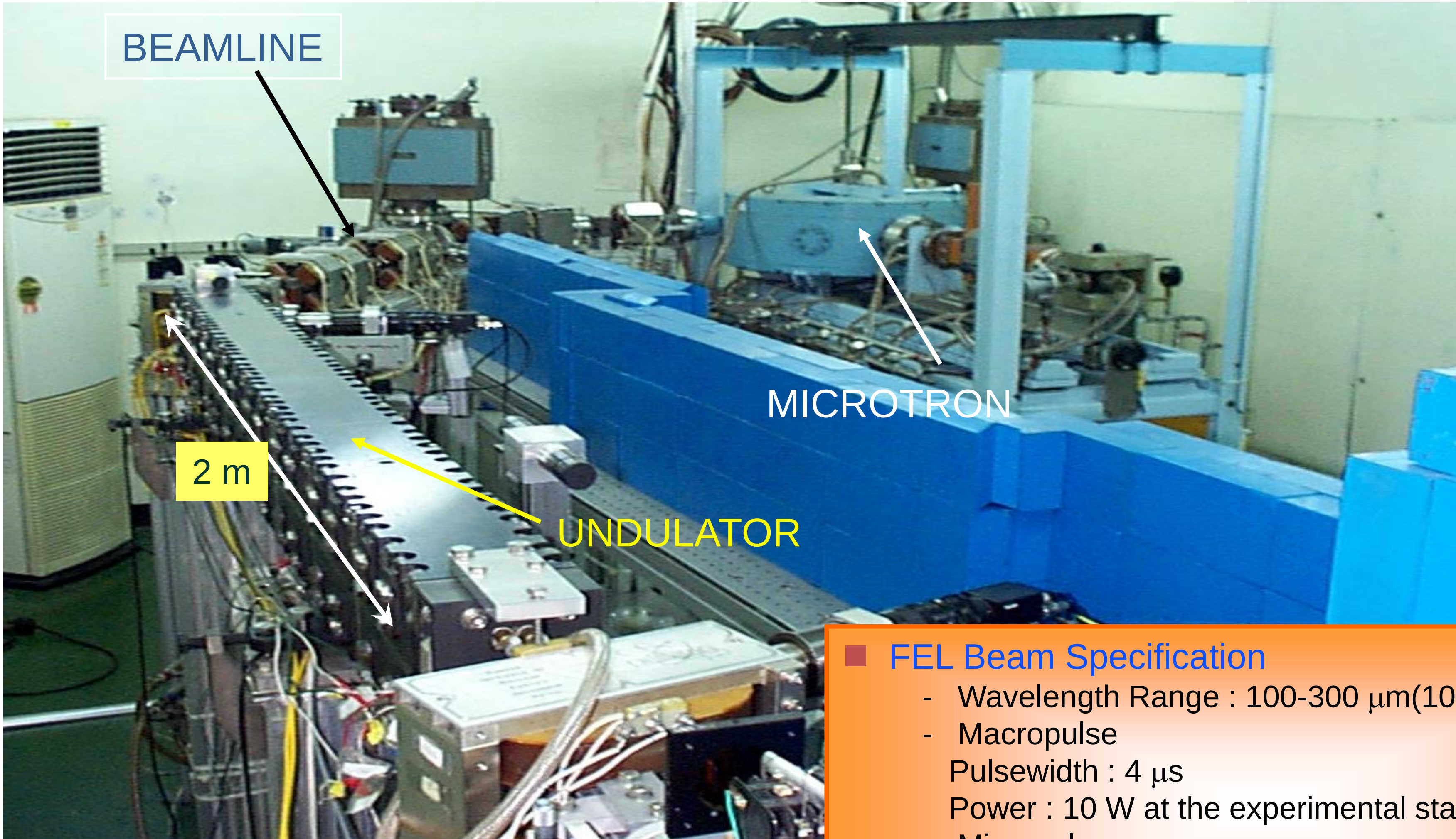
Laser Proton Acceleration for Cancer Therapy

- New Accelation Model



Laser-based Radiation & Particle Generation

KAERI Compact THz FEL

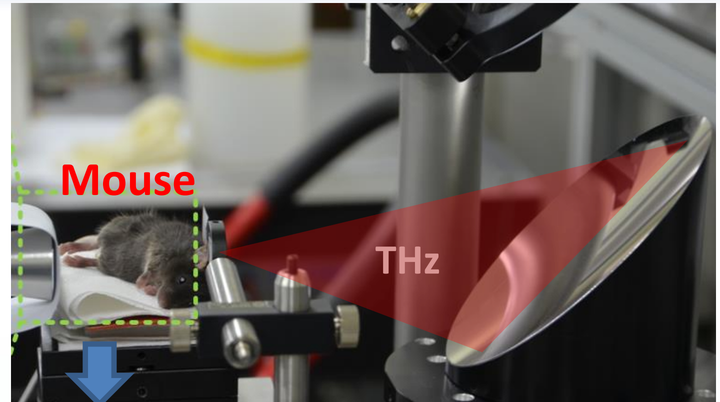


- FEL Beam Specification
  - Wavelength Range : 100-300 μm(100-1200 μm)
  - Macropulse
    Pulsewidth : 4 μs
    Power : 10 W at the experimental stage
  - Micropulse
    Pulsewidth : 10-20 ps
    Power : 100 W at the experimental stage
  - Pulse Energy Fluctuation : <10% rms

한국원자력연구원
KAERI
Korea Atomic Energy Research Institute

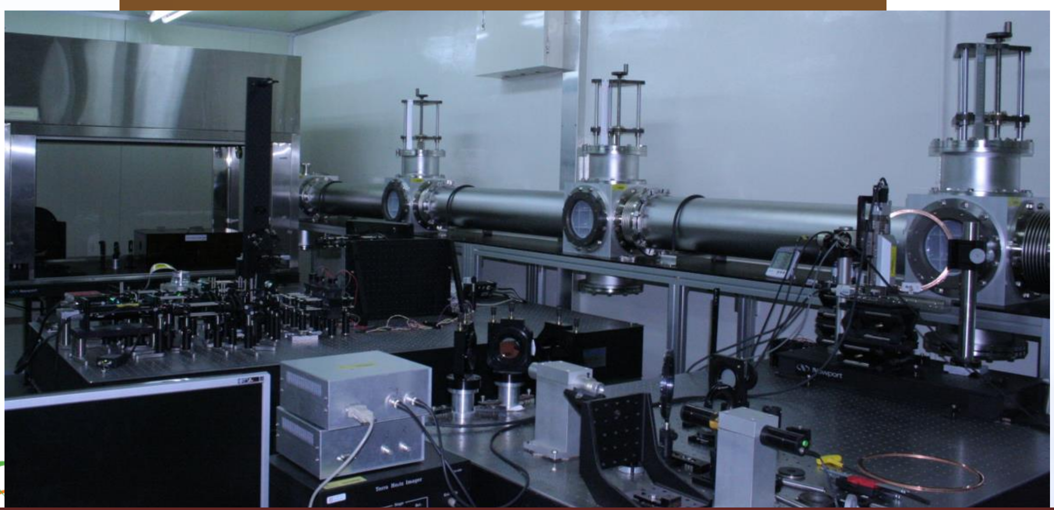
Application Experiments with THz FEL

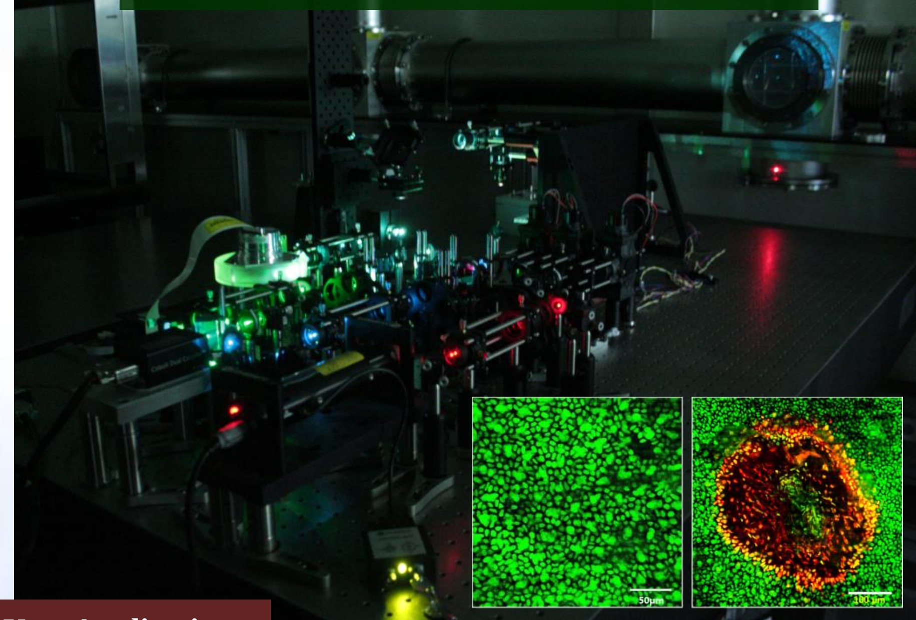
- In vivo THz-Bio interaction study with a laser-scanning confocal microscope (P. Kim, KAIST)
- Nonlinear THz meta material study (B. Min, KAIST)
- THz study on strongly correlated electron systems (J. Lee, GIST)



In Vivo THz-Bio Interaction Study with a Laser Scanning Confocal Microscope (Prof. P. Kim, KAIST)

Upgrading a THz Transport Line for 4 User Experimental Stages





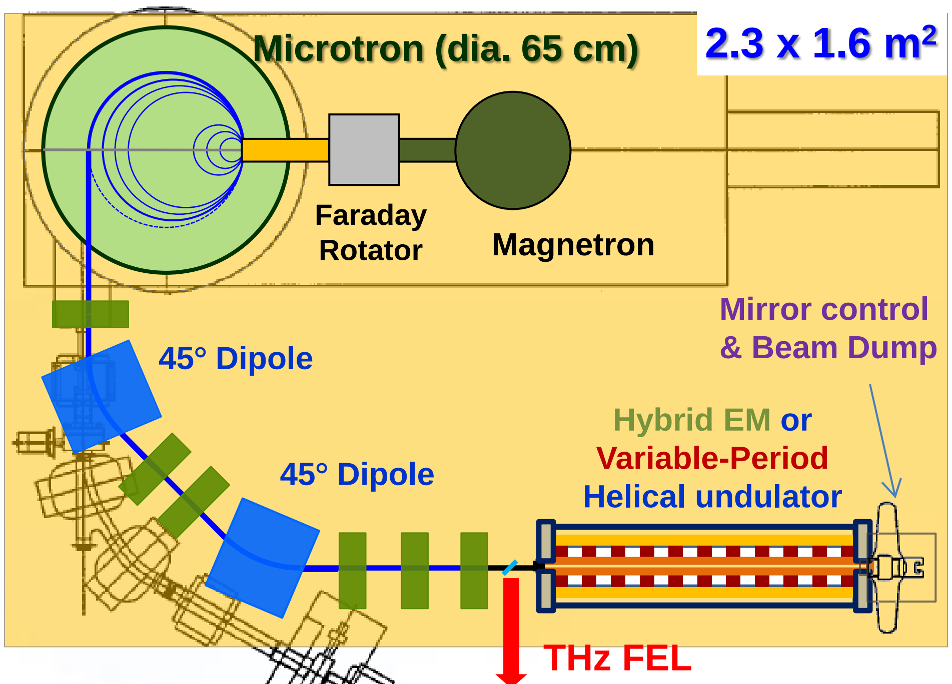
WEPD63 : S. Bae, et al., Development of a THz-FEL Beam Delivery System for User Applications

A Table-top THz FEL

WCI THz Pump 2RC X-ray Probe

Scale: 20 : 1

5.0 x 2.7 m²



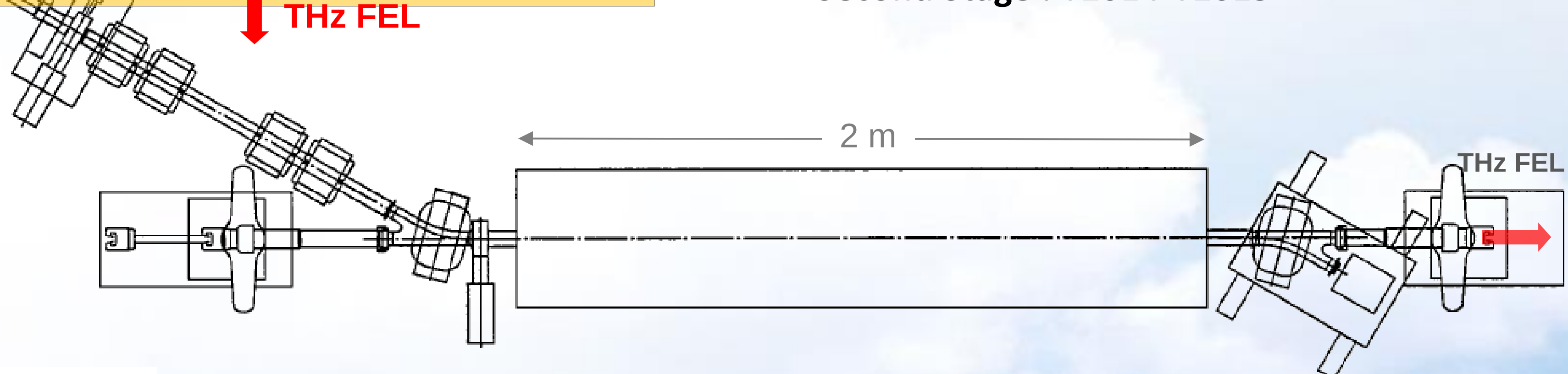
← Table-top size

Development of a Table-top THz FEL

First Stage : Y2011-Y2013

Development of a THz Inspection System

Second Stage : Y2014-Y2015



Existing KAERI THz FEL System : **5.0 x 2.7 m²**

Design on Much More Compact Source , See

WEPD61 : K.-H. Jang, et al., Dispersion Relation and Radiation Properties of the Defected 1-D Metalic Photonic Crystal

Contents 목차

Ⅰ. Microtron

Ⅱ. Beam Optics

Ⅲ. Undulators

Ⅳ. Waveguide Resonator

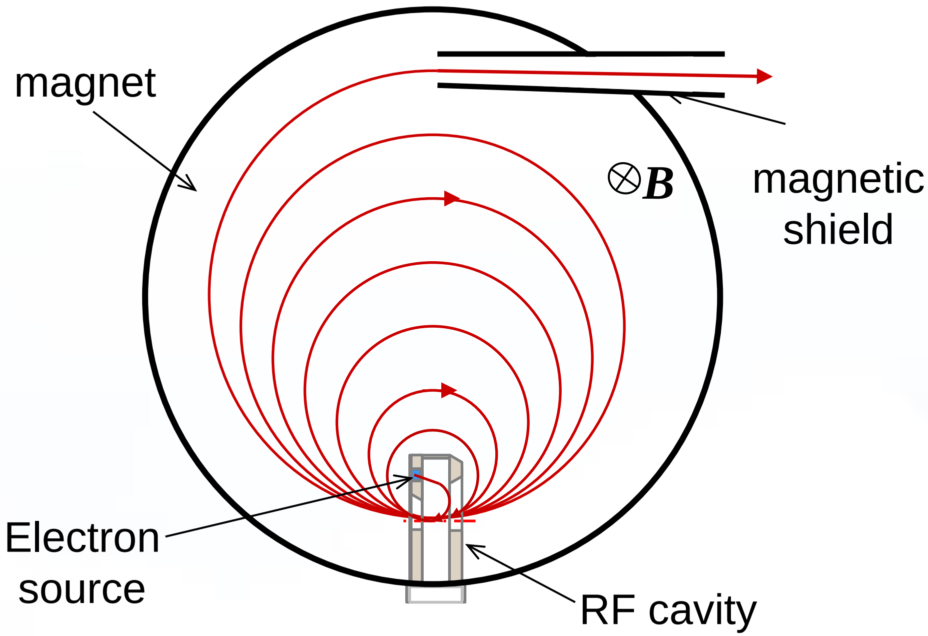
Ⅴ. Conclusions

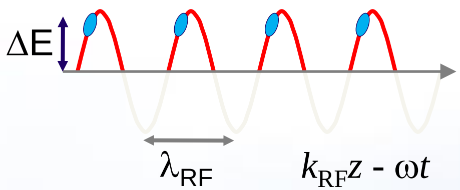
I. Microtron 마이크로트론 가속기

Microtron : Basic Theory

(MKS)

1944 Veksler





Eq. of motion $\frac{d}{dt}\left(\gamma\vec{\beta}m_0 c\right) = -e\left(\vec{E} + c\vec{\beta}\times\vec{B}\right)$

Circular motion $\frac{\gamma m_0 v^2}{r} = evB \qquad \omega = \frac{v}{r} = \frac{eB}{\gamma m_0}$

Orbit period $T = \frac{2\pi}{\omega} = \frac{2\pi m_0}{eB}\gamma = \frac{2\pi E_e}{ec^2 B}$

Period at nth orbit & time difference btwn. orbits

$$T_n = \frac{2\pi m_0}{eB}\gamma_n \Rightarrow \Delta T = T_{n+1} - T_n = \frac{2\pi m_0}{eB}\Delta\gamma_g$$

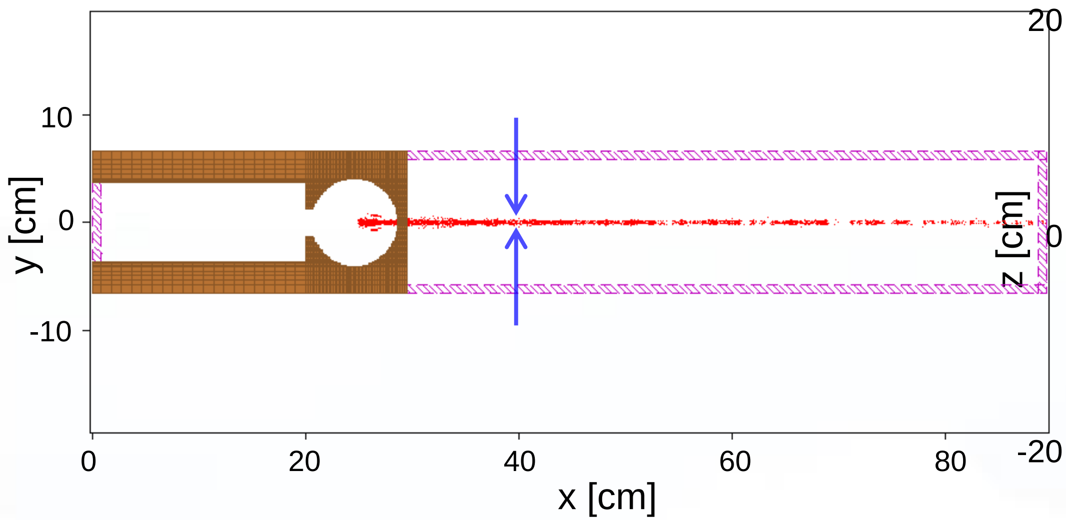
Energy at nth orbit $\gamma_n = \gamma_1 + (n-1)\Delta\gamma_g$

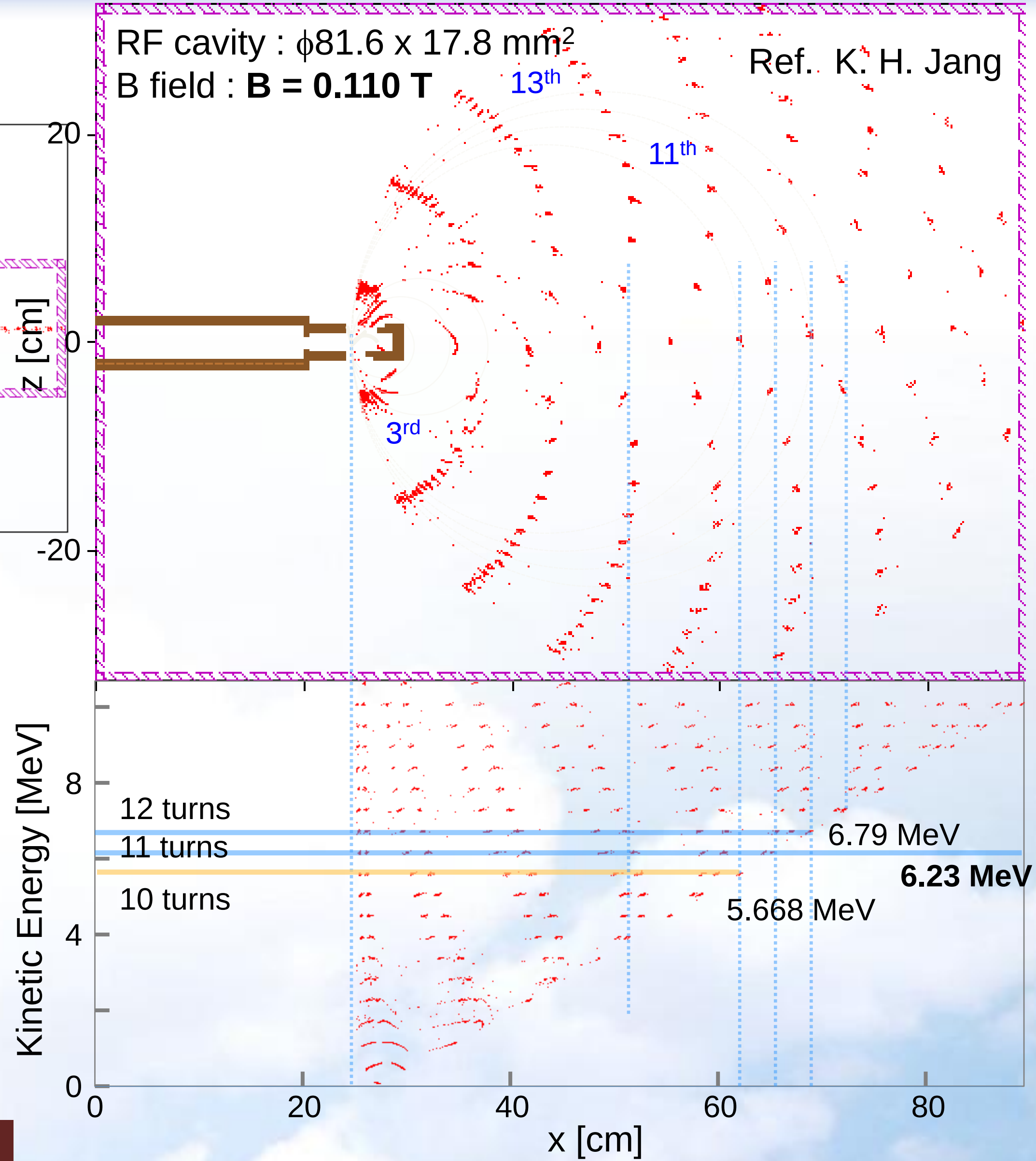
1st orbit, n = 1, $\gamma_1 = 1 + \gamma_{inj} + \Delta\gamma_g$ (with gun)

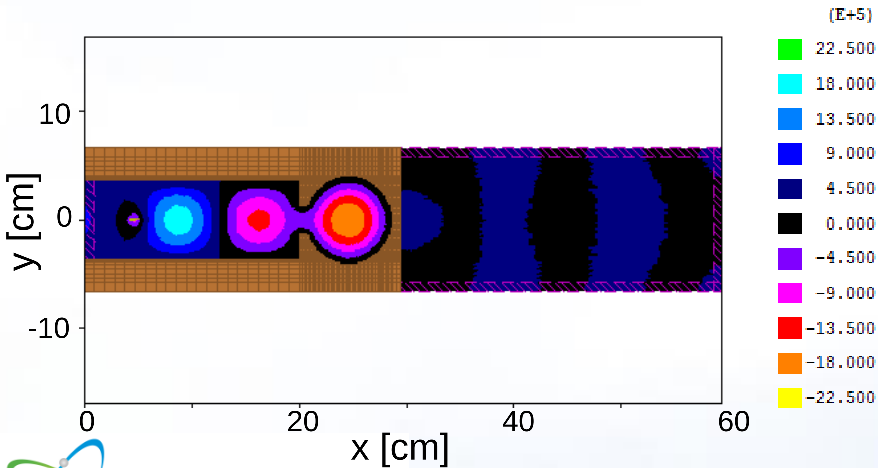
$\gamma_1 = 1 + k\Delta\gamma_g$ (without gun)

At 2.8 GHz, l′ = 2 and l = 1, B = 0.09 ~ 0.12 T & phase stable region ~ 90° to 122.5°

Simulation of Microtron : Magic3D

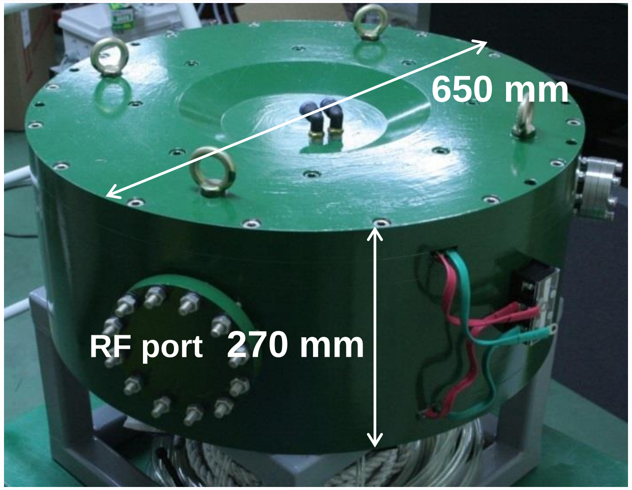


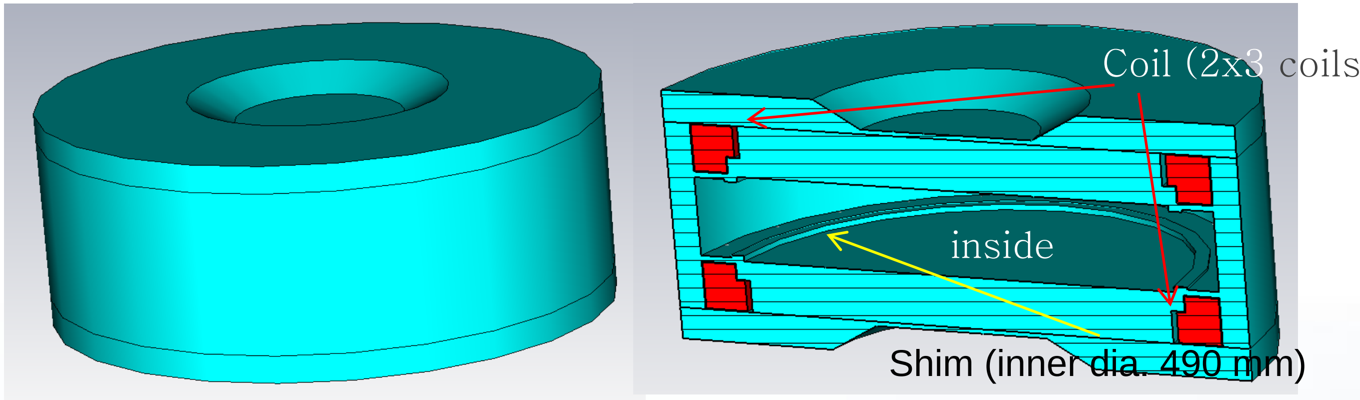


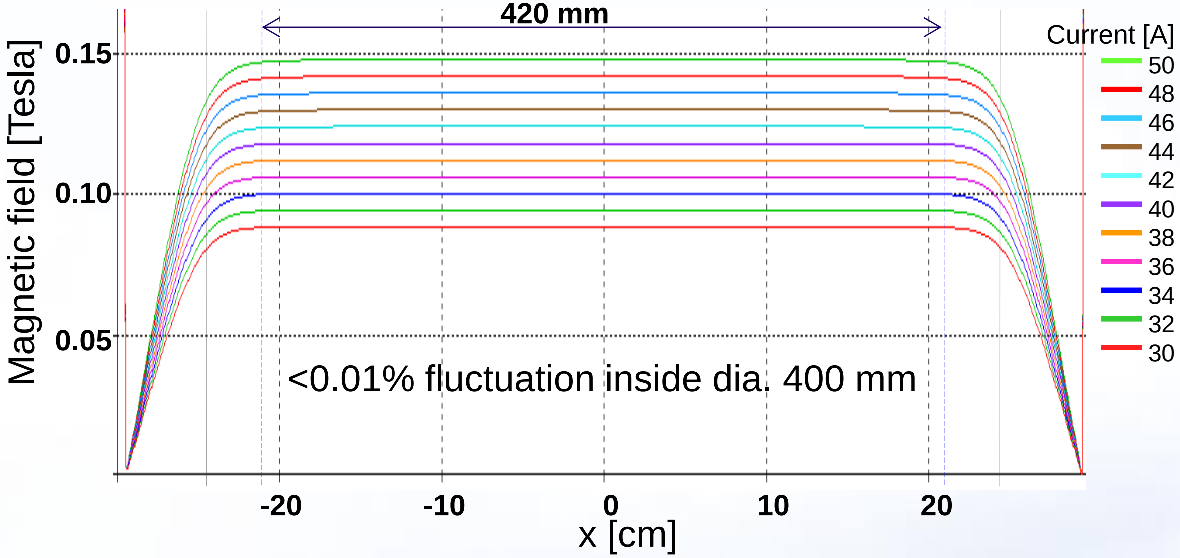


한국원자력연구원

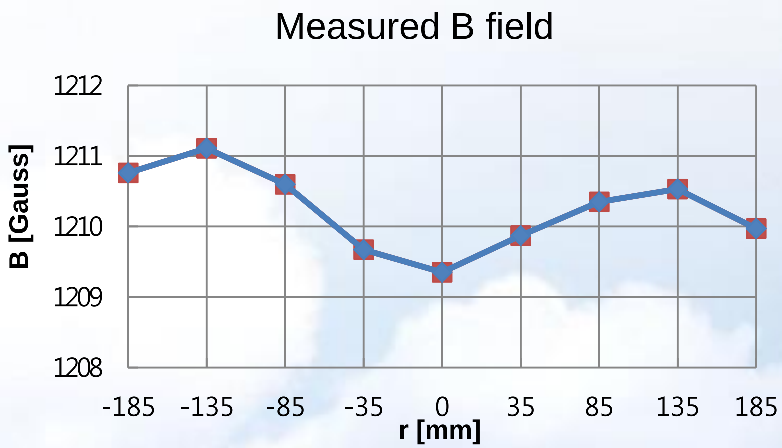
Microtron Main Magnet







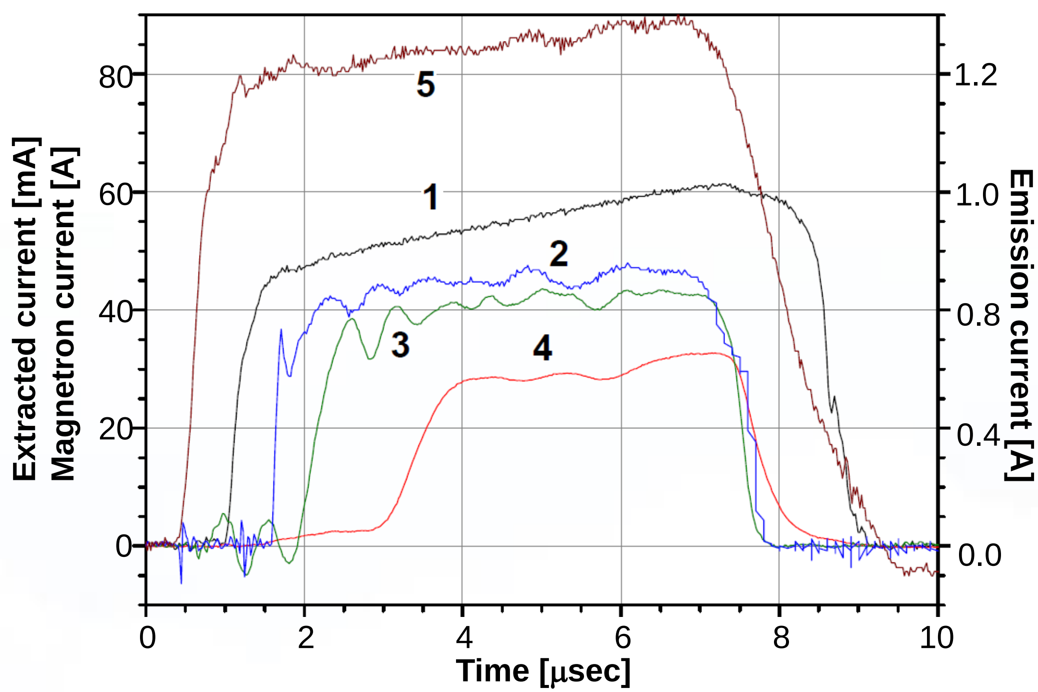
Field distribution of Microtron magnet



0.15% fluctuation at 0.121 Tesla
(measurement error included)
→ 0.174% energy deviation at 6.9 MeV

RF Magnetron Modulator

Measured pulse shapes of THz FEL



1 – Emission current [A]

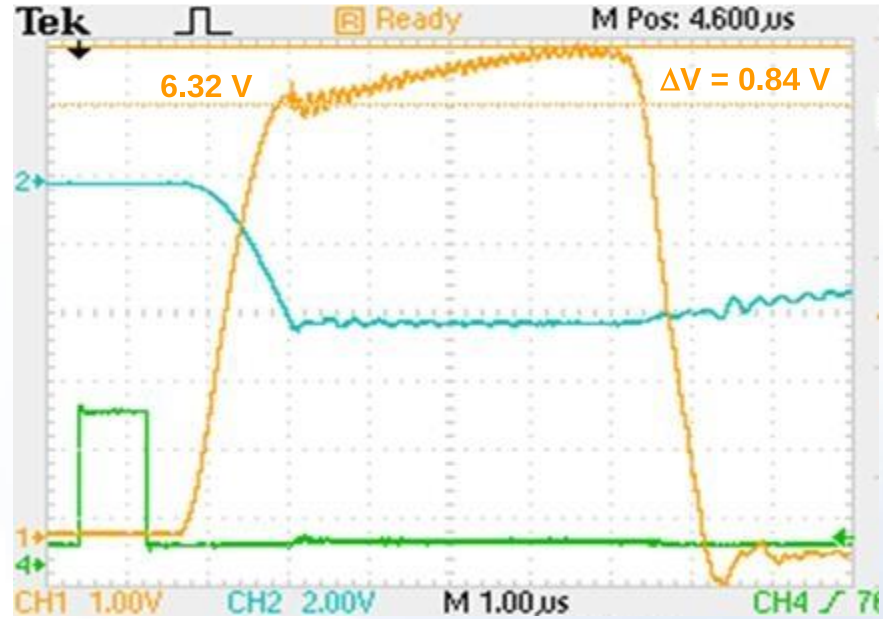
2 – Accelerated current [mA] at the 12th orbit

3 – Beam current [mA] at the entrance of the undulator

4 – FEL lasing power signal (macropulse) (in rel. units)

5 – Magnetron pulse current [A]

(Tested with E2V M5028/MG6030)



Peak power : 7 MW

Current range : 0 – 120 A

Voltage range : 0 – 60 kV

Rep. rate : 1 – 200 Hz

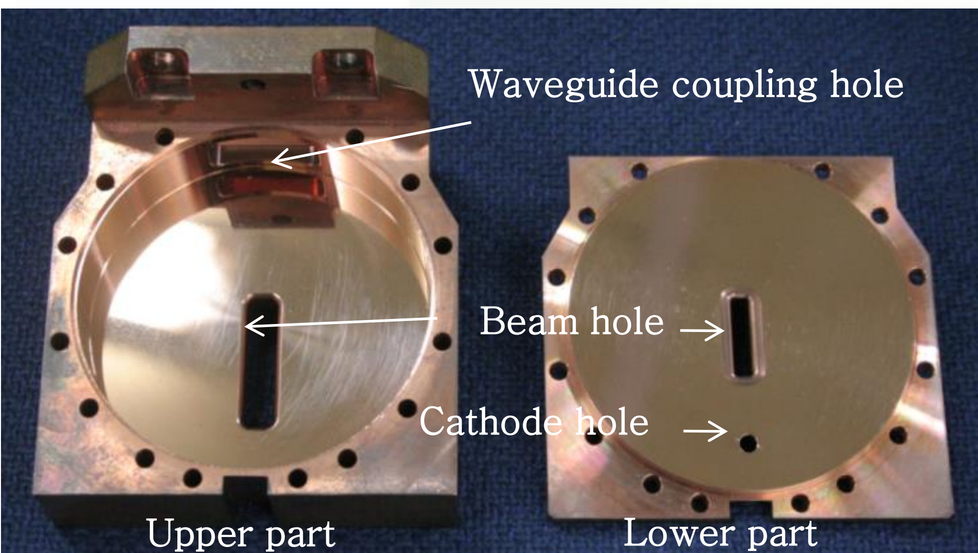
Pulse length : 7 μsec

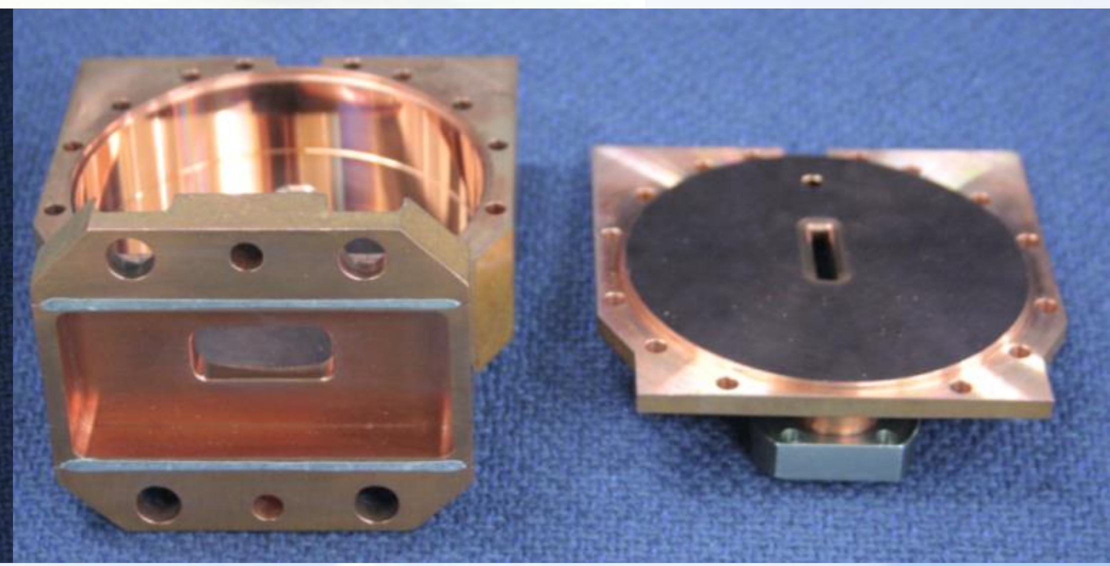
Dimension : 64×53×109 cm^3

Weight : 250 kg

한국원자력연구원 KAERI Korea Atomic Energy Research Institute

RF Cavity & WG Module

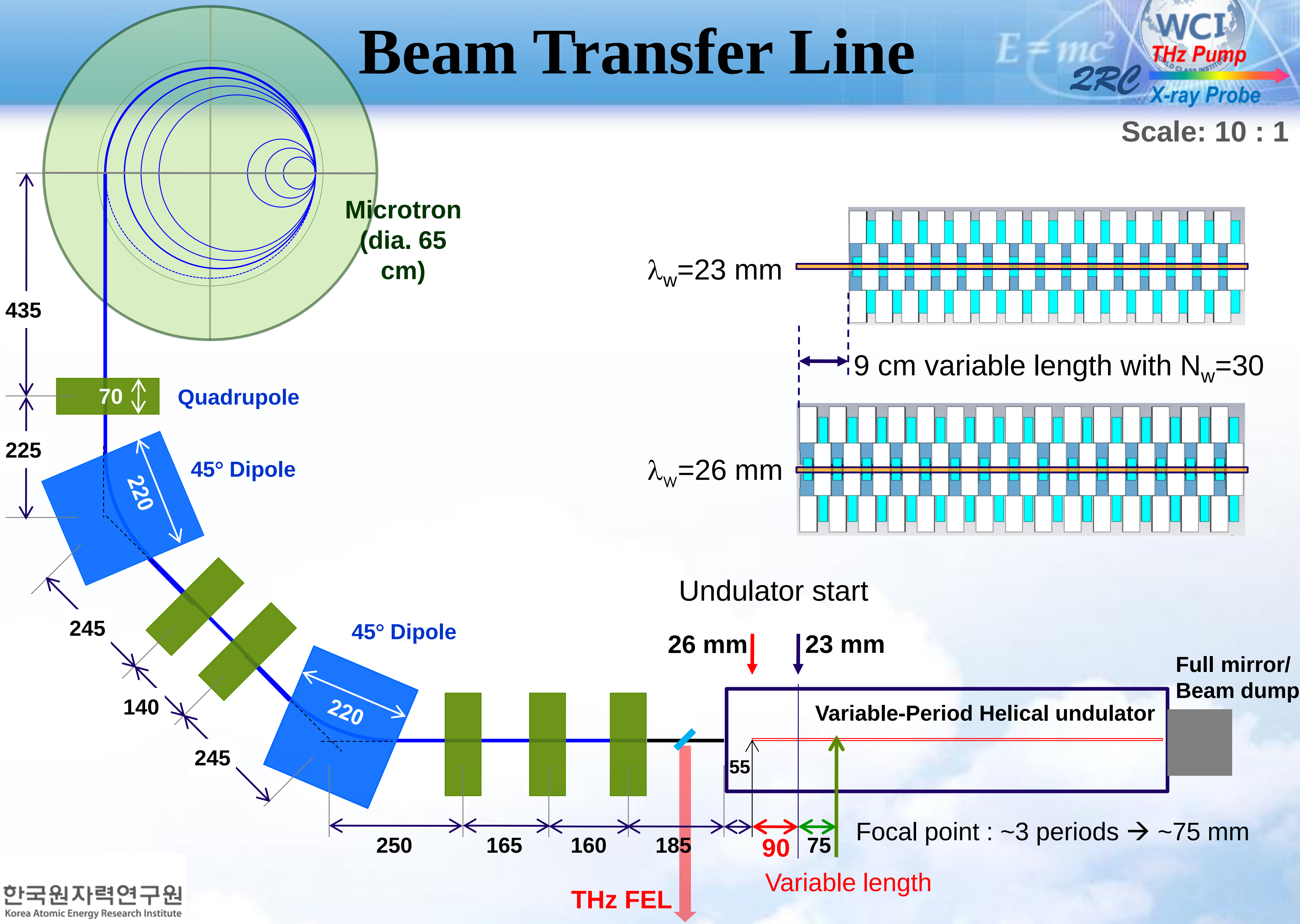




II. Beam Optics 전자빔 광학계

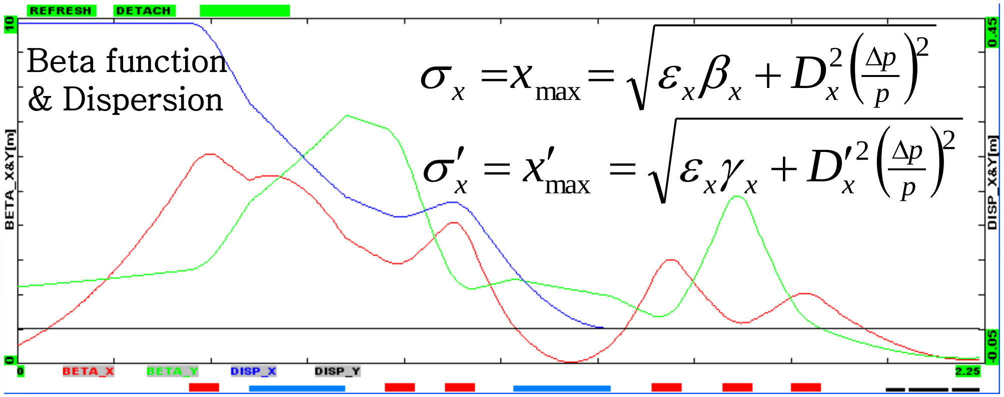
Beam Transfer Line

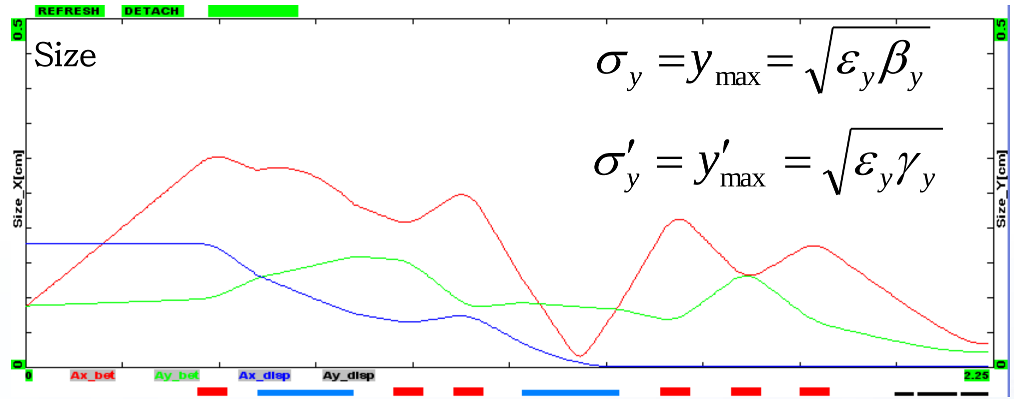
Scale: 10 : 1



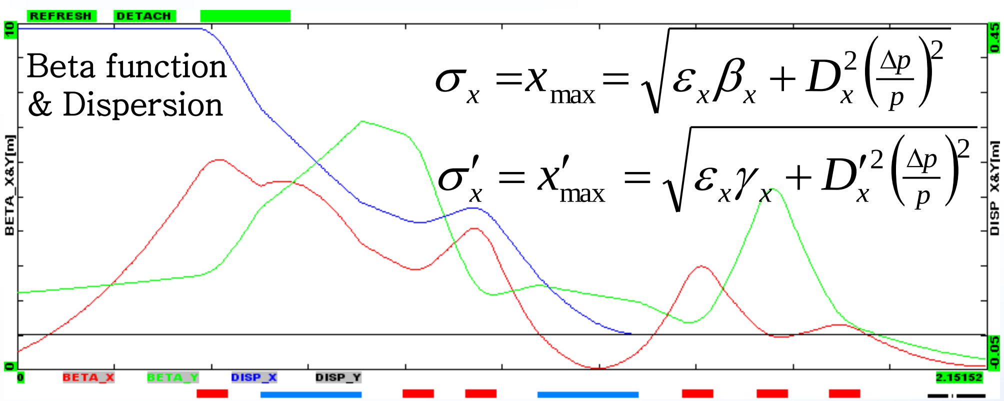
Beam Optics of Transfer Line

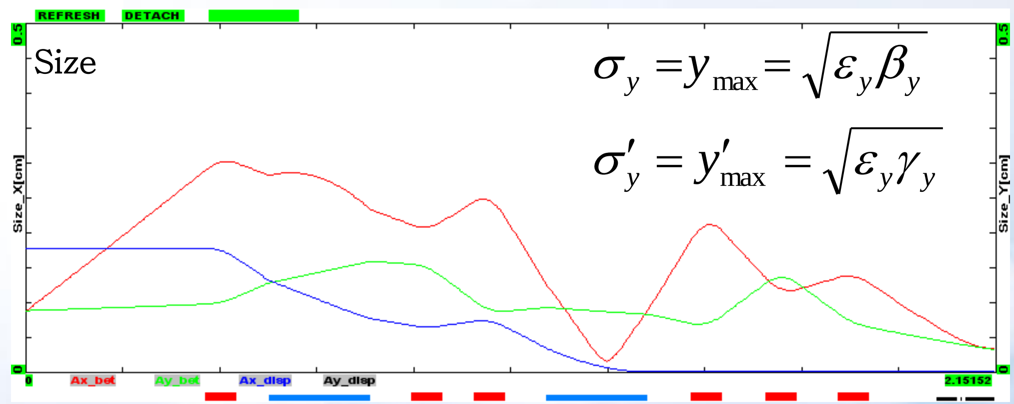
λ_w 23 mm





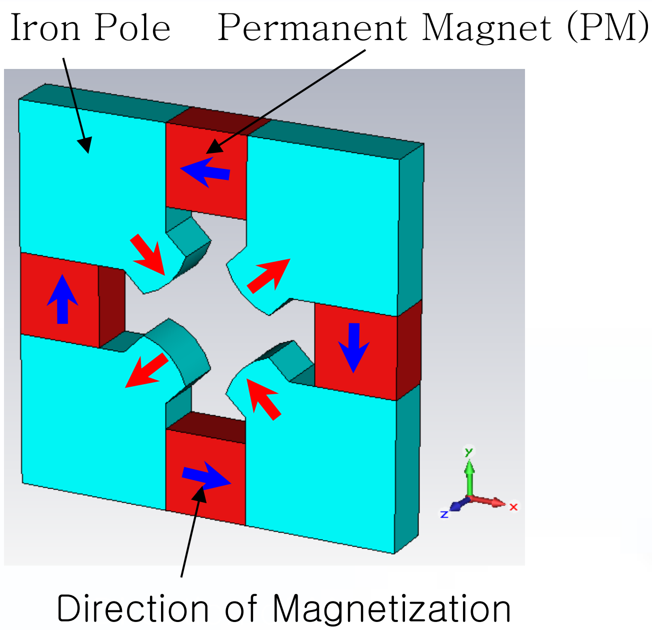
λ_w 26 mm

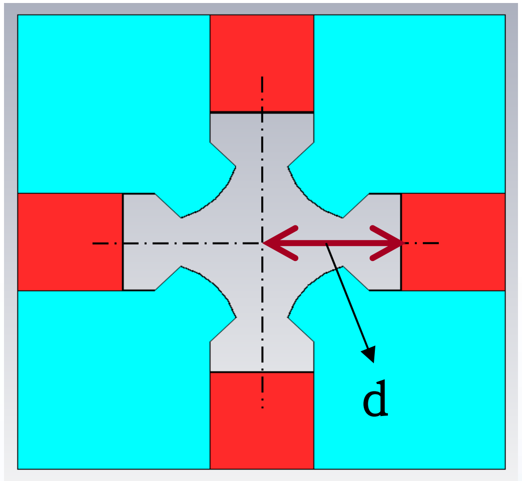


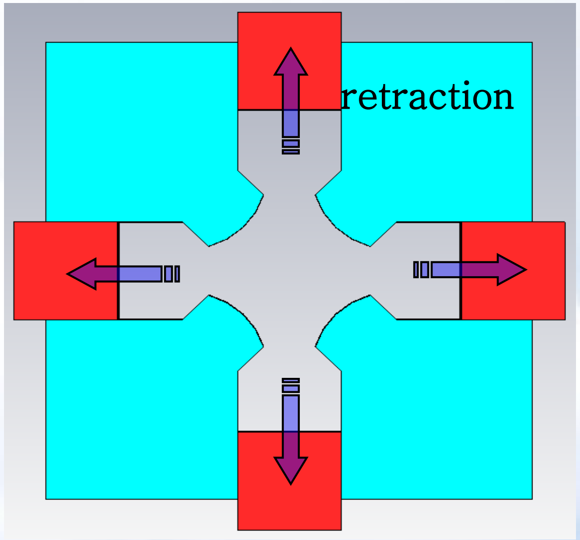


KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

Compact PM Quadrupole





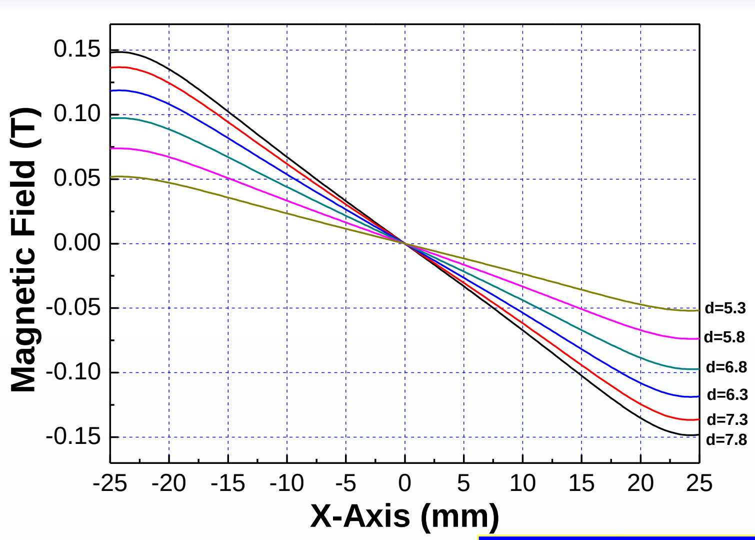


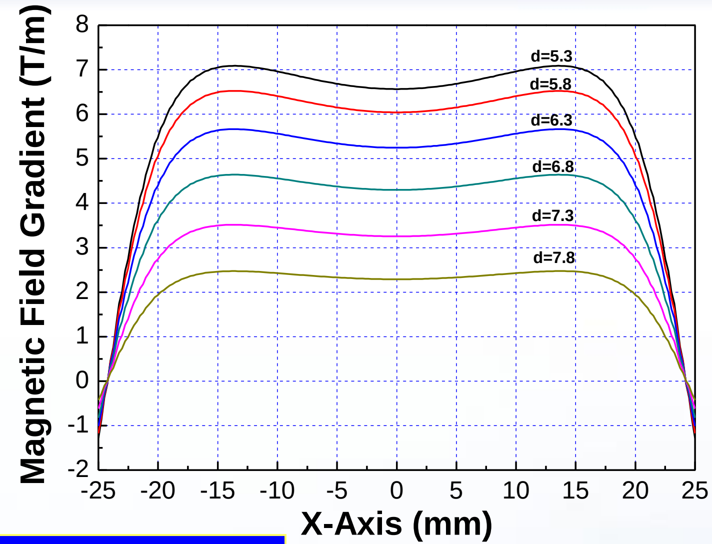
*Dimension : 156 x 156 x 20 mm

Design parameters

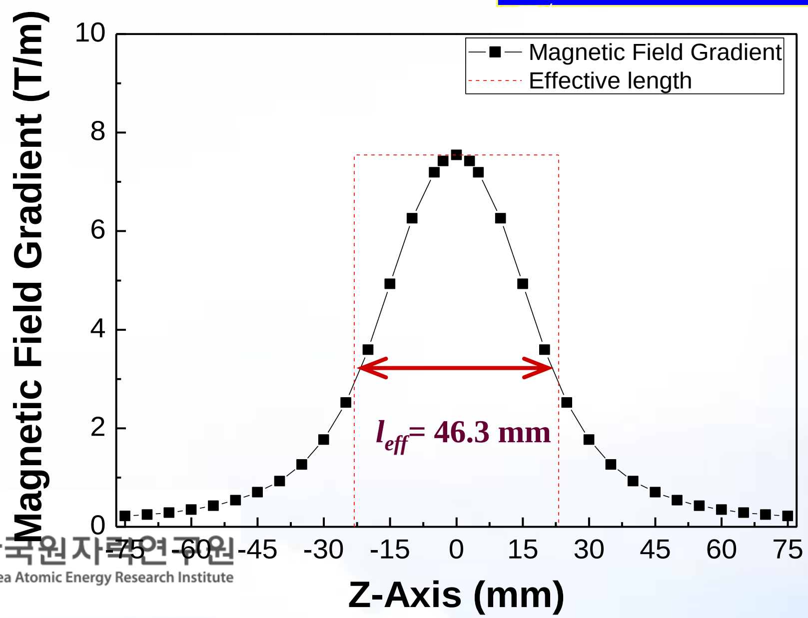
Permanent Magnets (Br)	NdFeB (1.2 T)
Iron Poles	Soft Iron
Effective centerline dia.	30mm
Retraction length of PM (d)	5.3 ~ 7.8 mm

Compact PM Quadrupole





Magnetic Field Gradient on axis = 2 ~ 7



$$f = \frac{1}{K \cdot l_{eff}}$$: focal length of QM

l_{eff} : effective magnetic length

$$K[m^{-2}] = \frac{q}{p} G \approx 0.2998 \frac{G[T/m]}{p[GeV/c]}$$

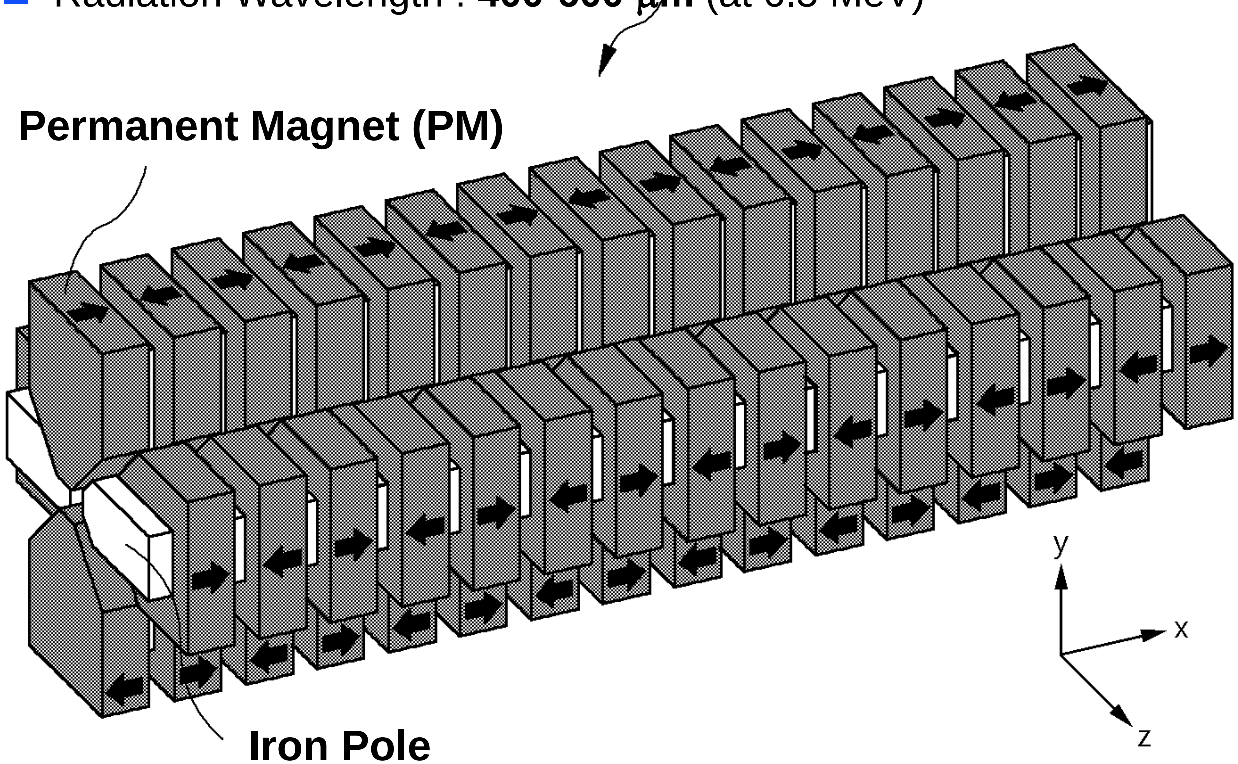
: quadrupole focusing strength

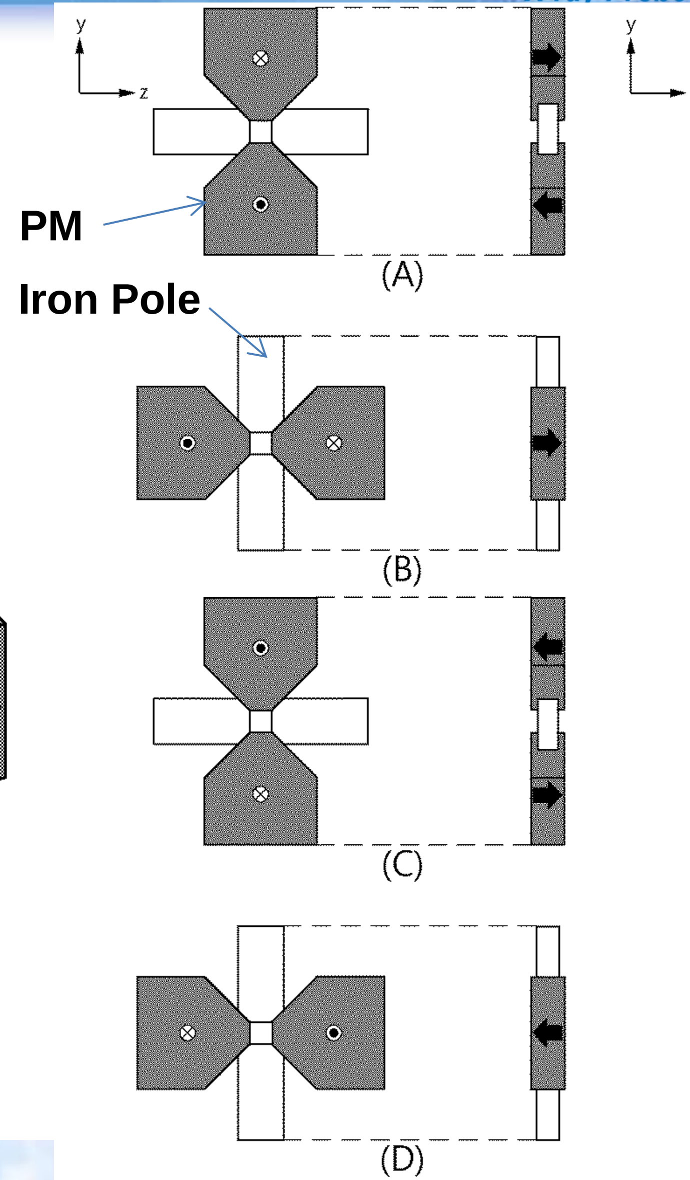
* Effective magnetic length : 46.3 mm
* Focal length of QM : 5~17 cm

III. Undulator 교번자장기

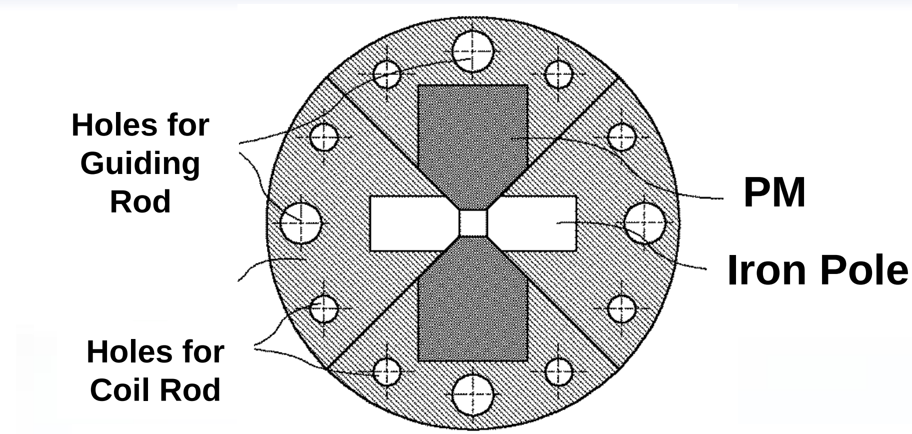
Variable-Period PM Helical Undulator

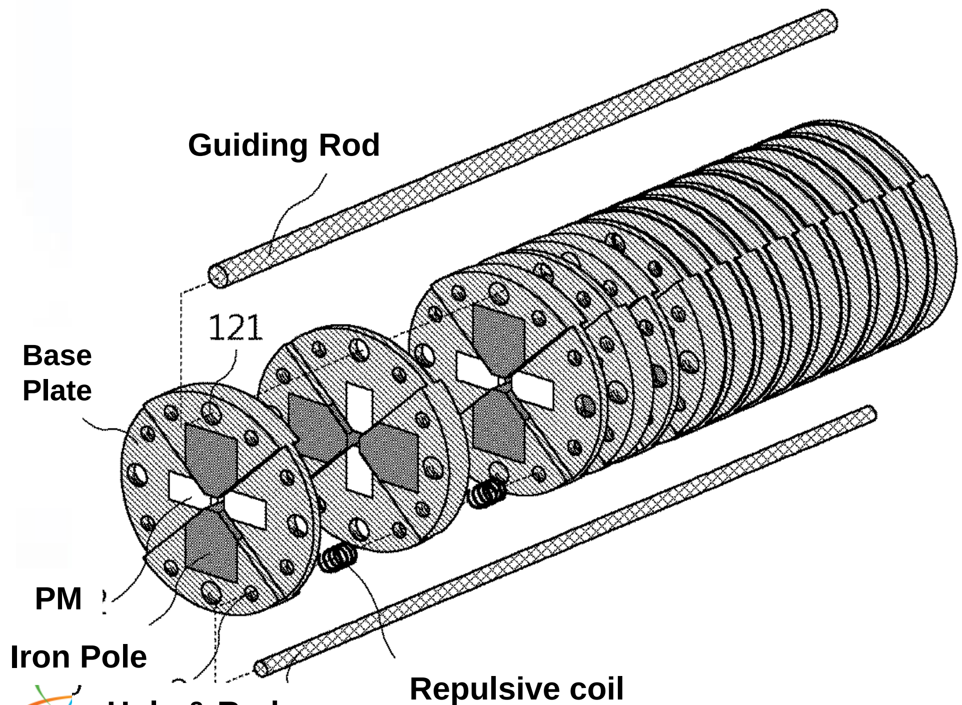
- Quadrupole-type Permanent-Magnet Helical Undulator
- **Variable Period : λ_w = 23~26 mm** with N_w = 30
- Total Length : 70~80 cm; Gap Diameter : 5 mm
- **Magnetic Field Strength on Axis : 1 T** (K-value : **2.1-2.4**)
- Cross-sectional Size of Undulator : 140 mm x 160 mm
- Radiation Wavelength : **400-600 μm** (at 6.5 MeV)

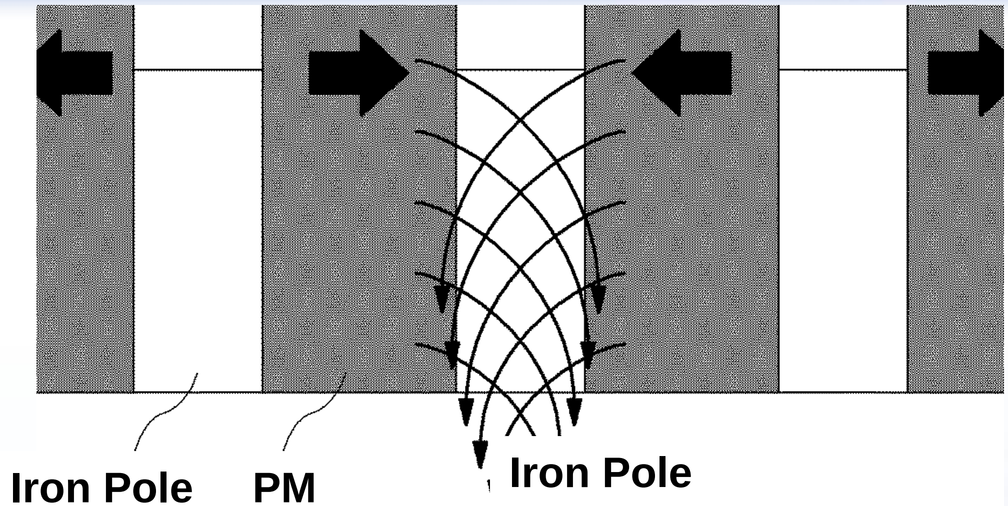


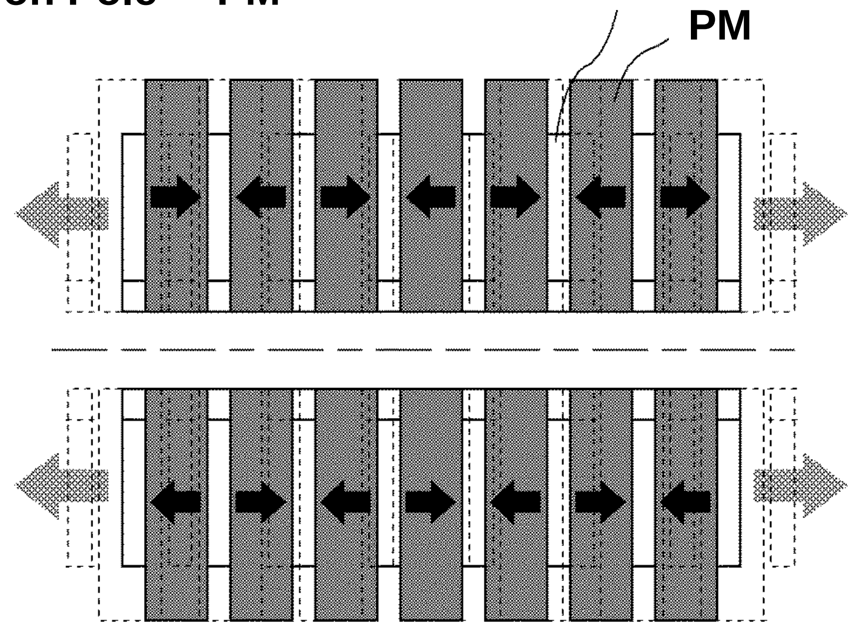


Variable-Period PM Helical Undulator





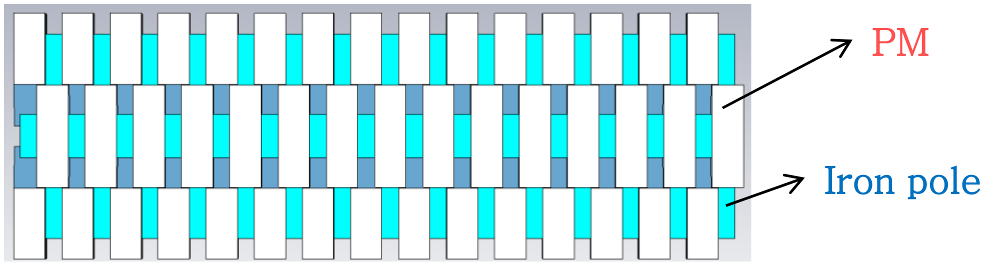




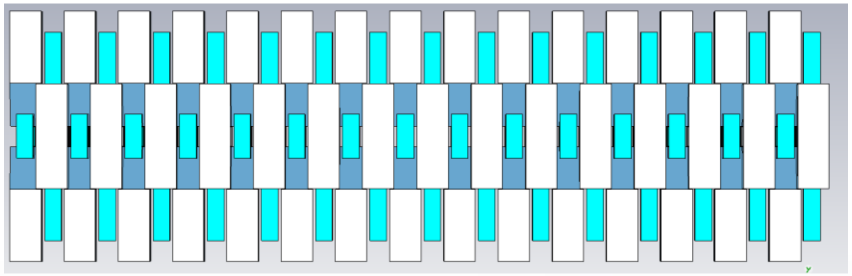
THPD26 : J. Mun, et al., Design and Fabrication of a Variable-period Helical Undulator for a Table-top Free-electron Laser

Variable-Period PM Helical Undulator

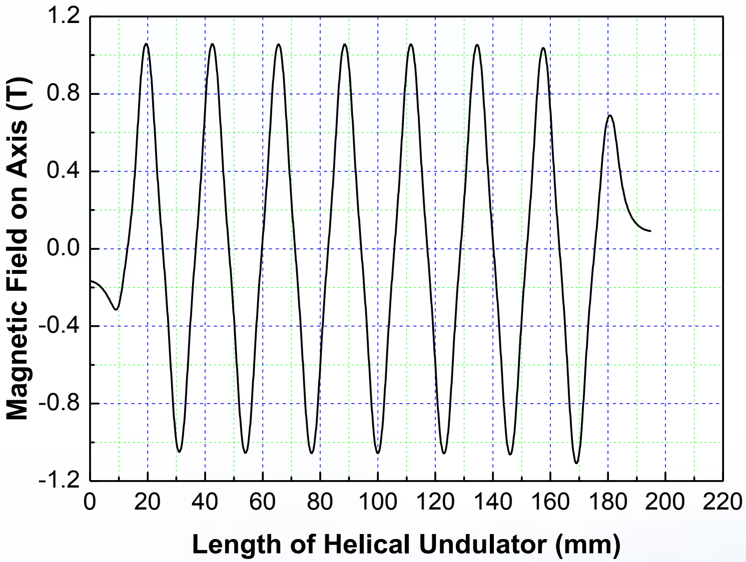
Period, lw = 23 mm



Period, lw = 26 mm

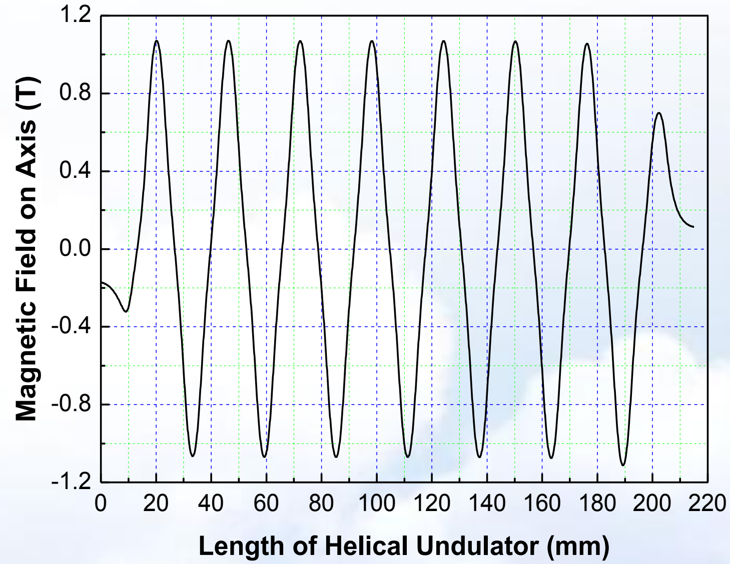


Period, lw = 23 mm



Peak magnetic field on axis = 1.06 T

Period, lw = 26 mm



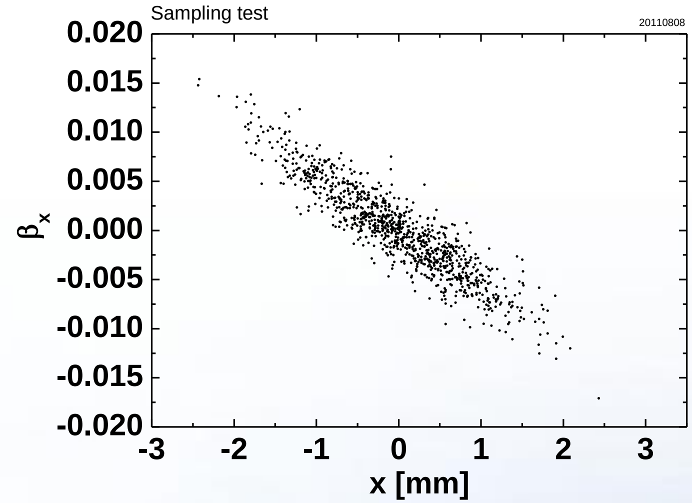
Peak magnetic field on axis = 1.07 T

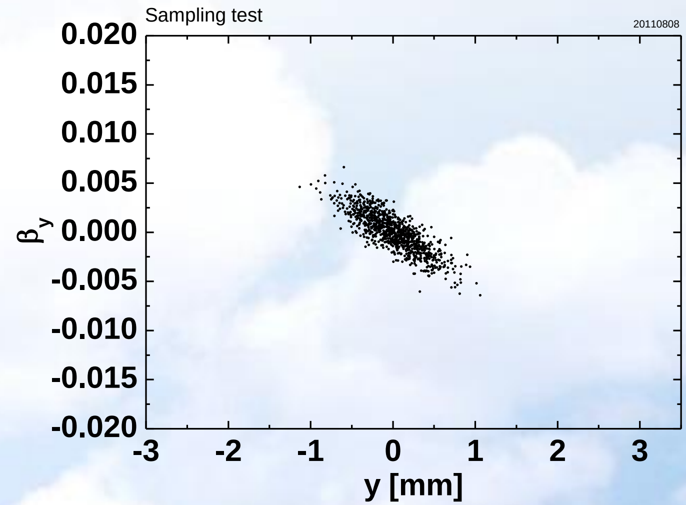
Electron beam dynamics – Simulation

Simulation parameters

	Parameters	Values
e-beam	E	6.5 MeV (γ=13.7)
	ΔE	0.4%
	ε_x	1.5 mm mrad
	ε_y	0.35 mm mrad
	σ_x	0.8093 mm
	$\sigma_{x'}$	-4.517 mrad
	σ_y	0.3172 mm
	$\sigma_{y'}$	-1.603 mrad
	σ_z	3 mm
Undulator	B_w	10,320 Gauss
	N_w	25
	$N_{adiabatic}$	Input 2, output 2
	R_{wg}	2 mm

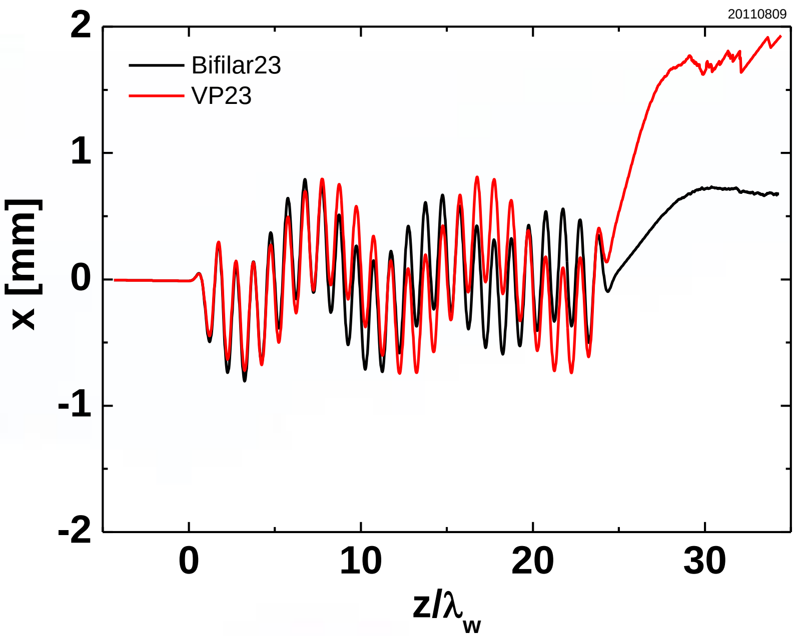
Initial phase-space dist'n



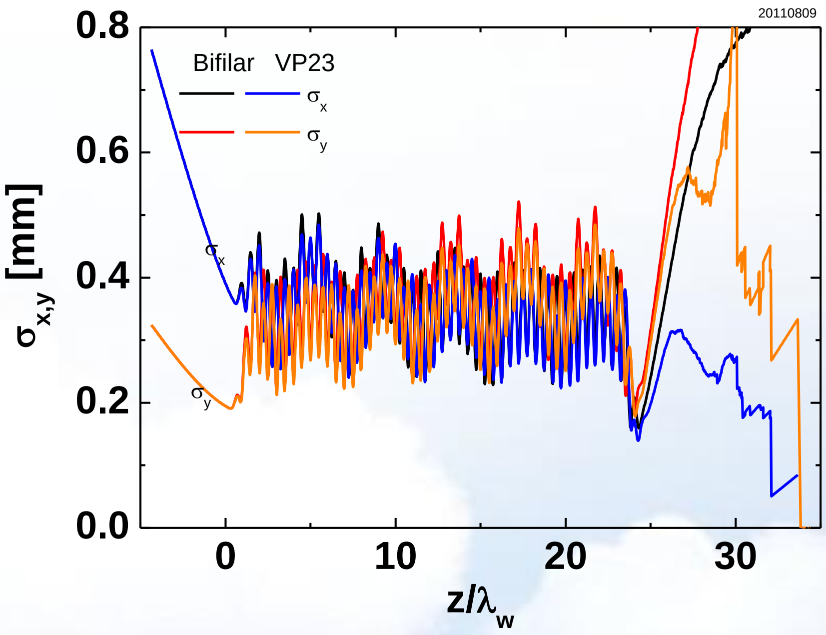


Electron beam dynamics – Simulation

- **Average position in x**

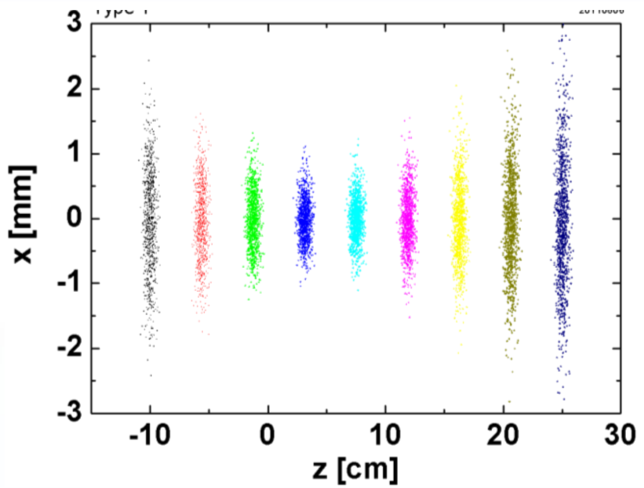


- **Transverse beam size**

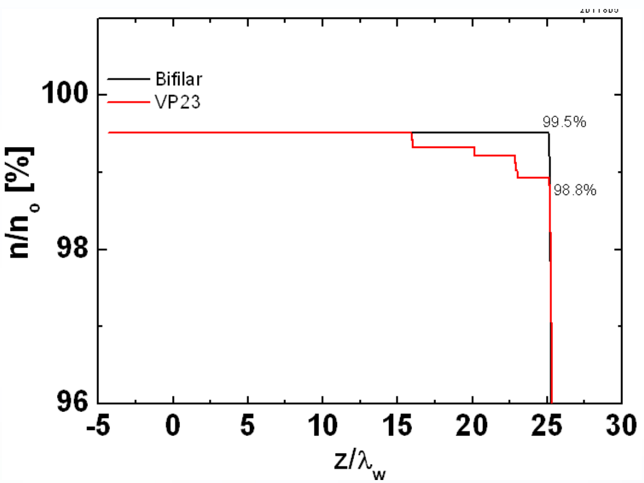


KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

Electron beam dynamics – Simulation



Evolution of Electron Beam through Undulator



Beam Transportation Ratio through Undulator

- Parameters of Electron Beam at the Entrance of the Undulator

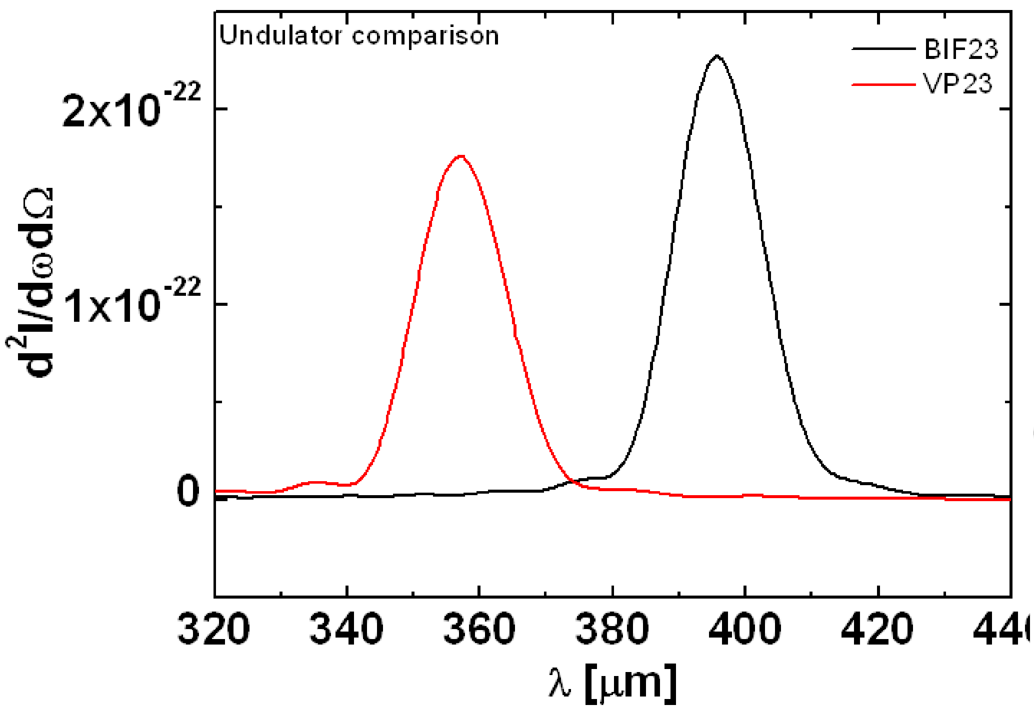
E_o	σ_E	σ_z	ε_x	ε_y	σ_x	$\sigma_{x'}$	σ_y	$\sigma_{y'}$
6.5 MeV	0.4%	1 cm	1.5 mm mrad	0.35 mm mrad	0.8093 mm	4.517 mrad	0.3172 mm	1.603 mrad

- Parameters of the V-P Helical Undulator

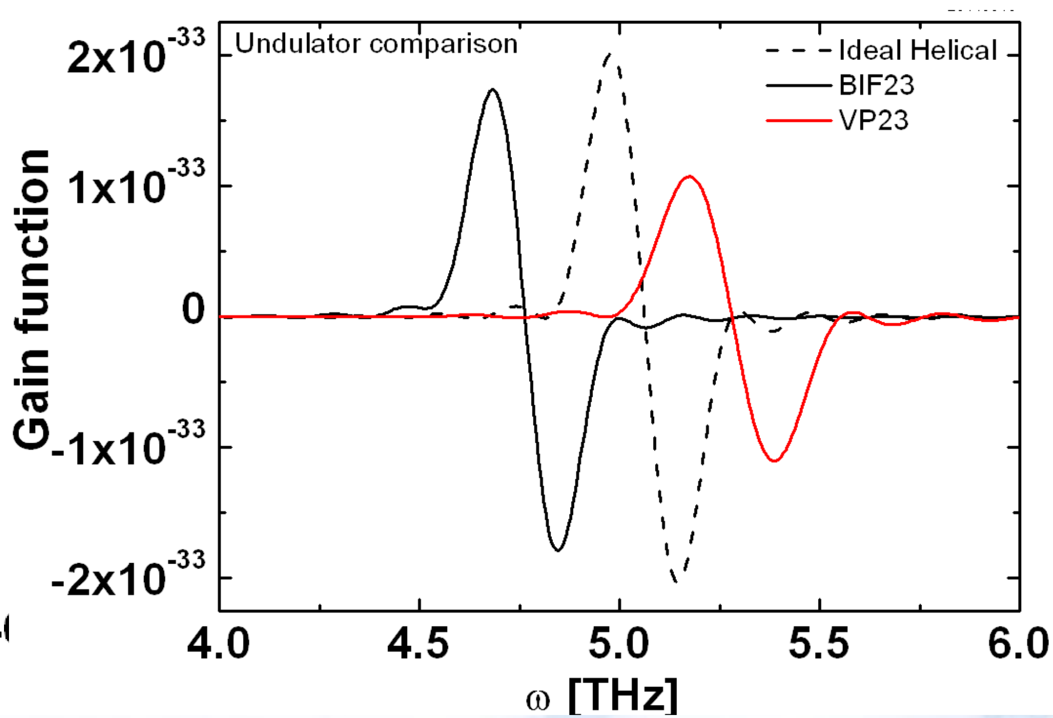
B	λ_w	N_w	Entrance adiabatic #	Exit adiabatic #	R_{wg}
10.320 Gauss	2.3 cm	1 cm	2	0	2 mm

SE & Gain Function – Simulation

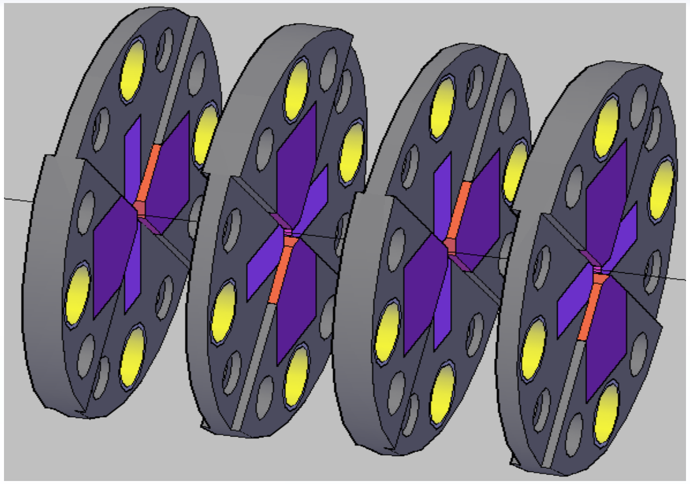
Spontaneous Emission Spectrum



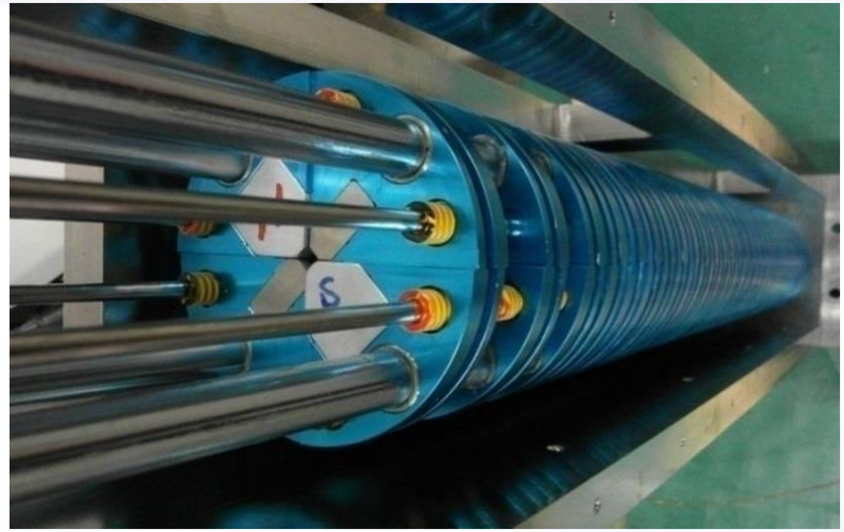
FEL Gain Function



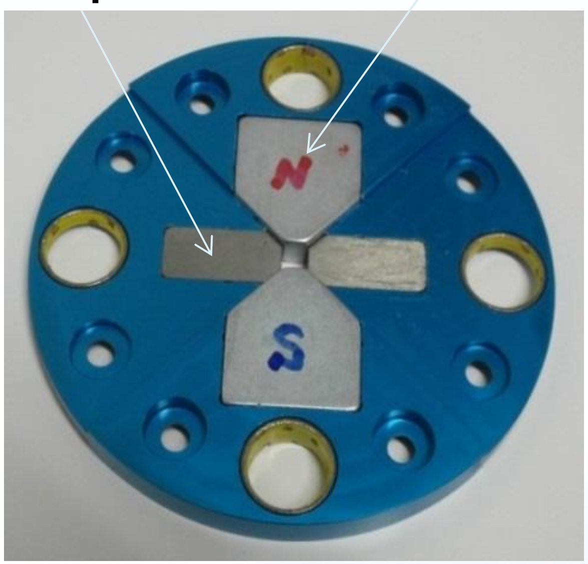
Variable-Period PM Helical Undulator

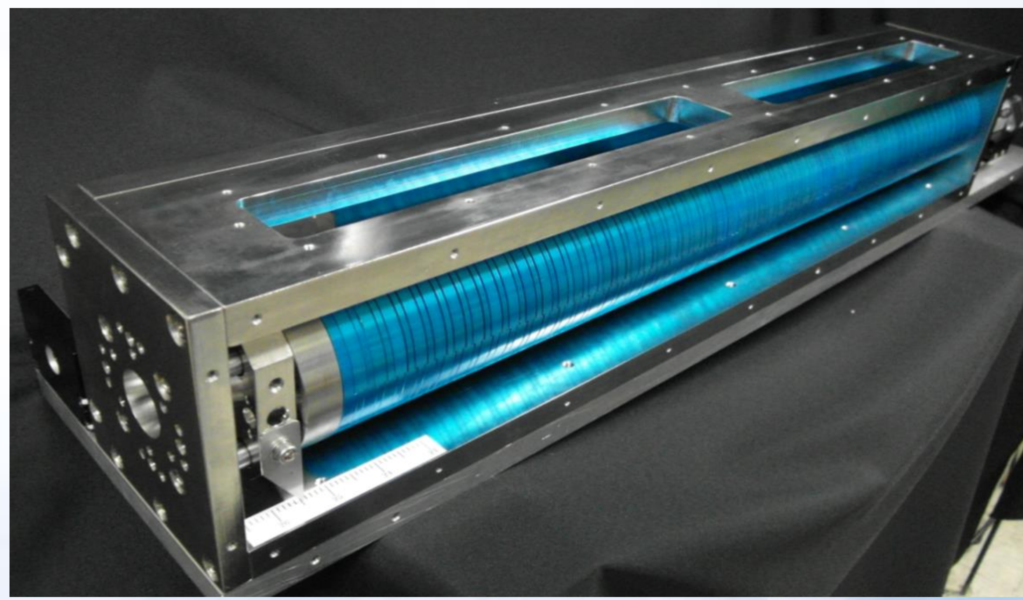


1-period



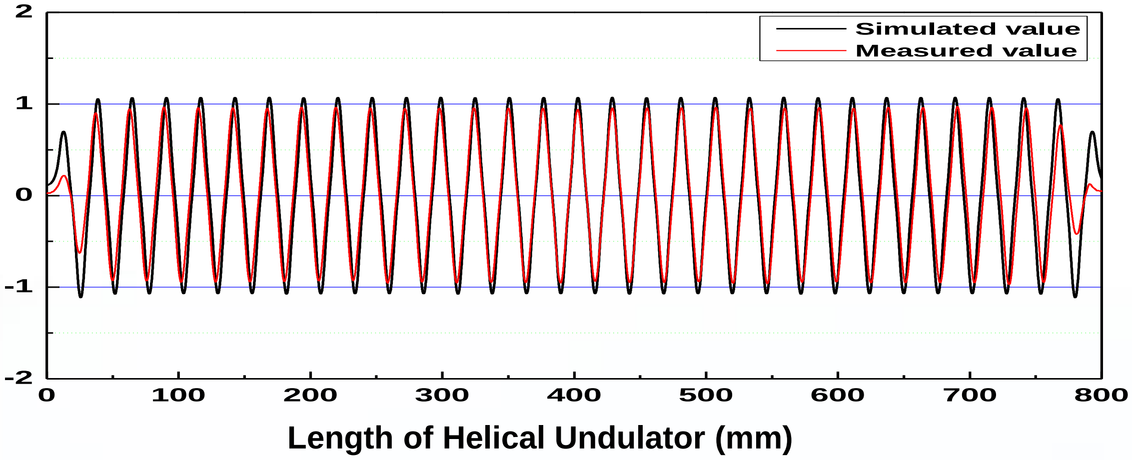
Iron pole PM



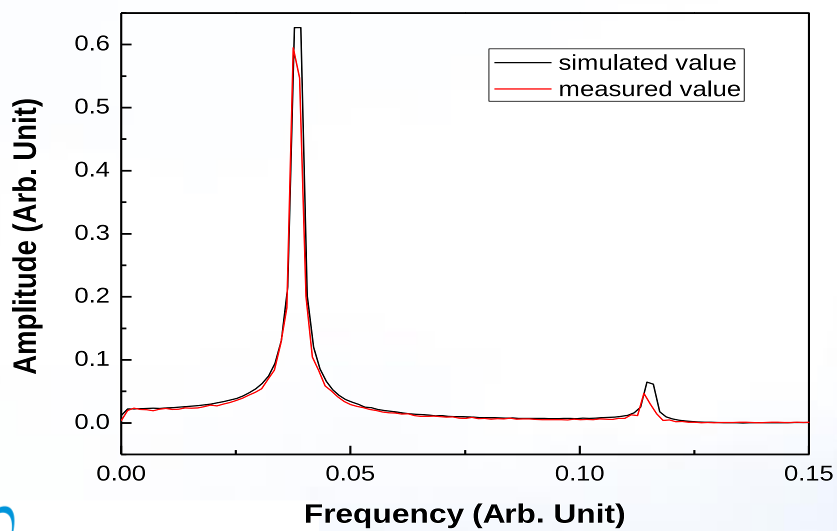


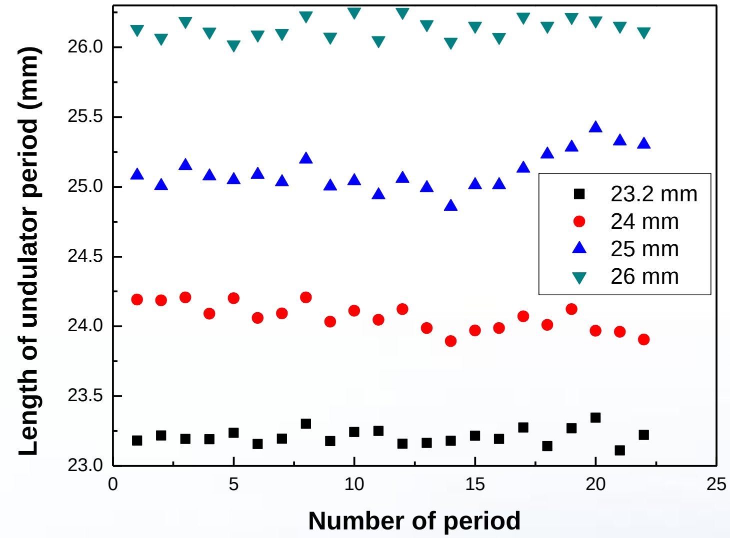
THPD26 : J. Mun, et al., Design and Fabrication of a Variable-period Helical Undulator for a Table-top Free-electron Laser

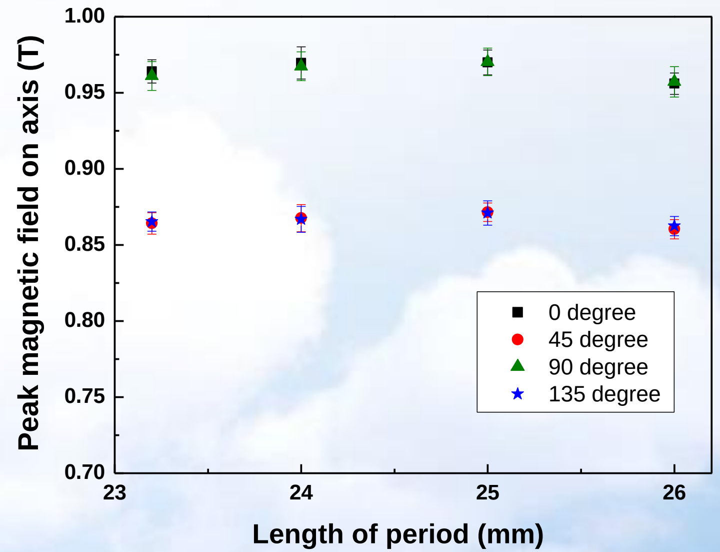
Variable-Period PM Helical Undulator



FFT





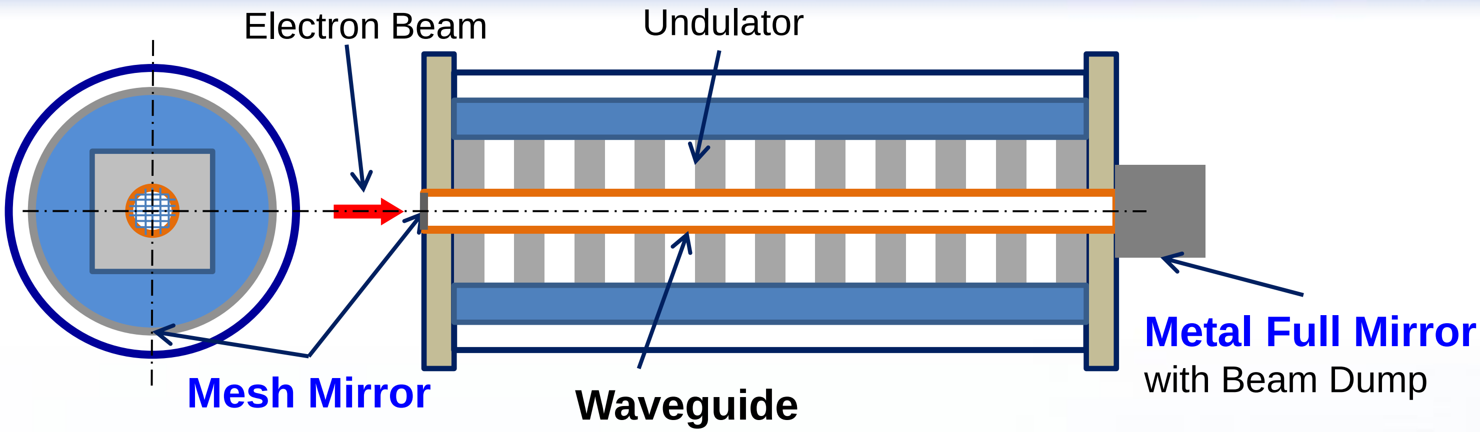


IV. Waveguide Resonator 도파관 공진기

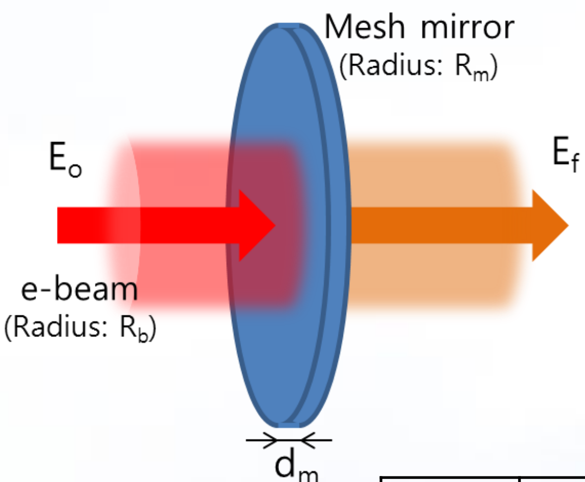
FEL Resonator

Ref. K. Lee

Outcoupling Mirror



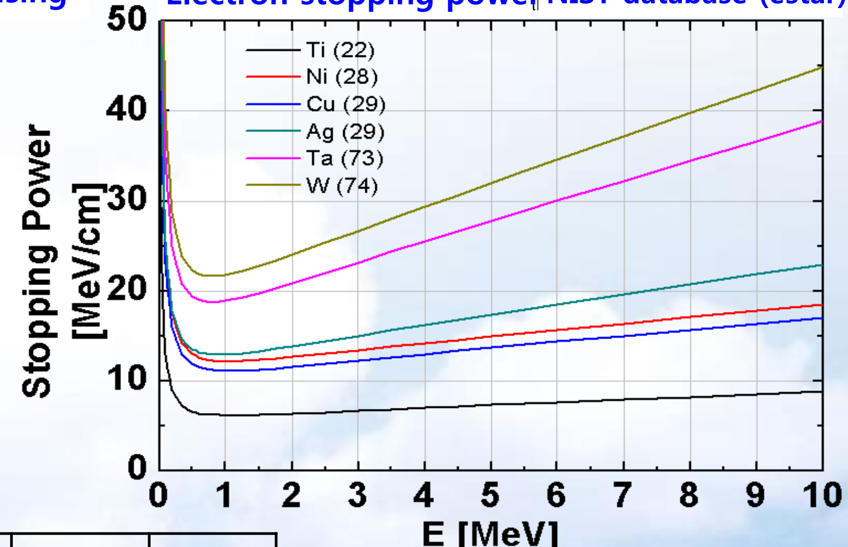
Heat Rising due to e-beam



Saturation of temperature rising

Material	T^H_{sat} [°C]
Al (13)	181.08
Ti (22)	949.13
Ni (28)	616.75
Cu (29)	402.35
Ta (73)	1950.48
W (74)	1400.91

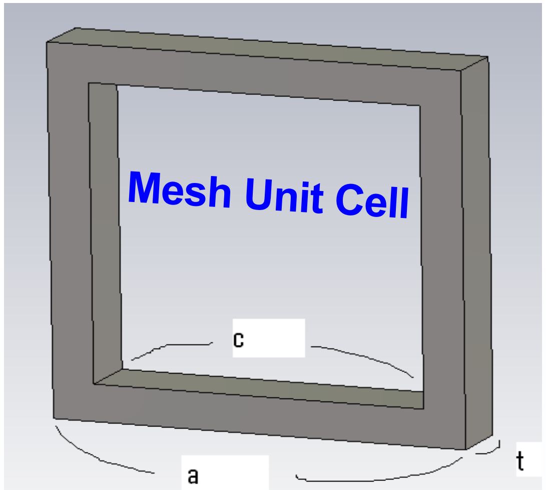
Electron stopping power NIST database (estar)



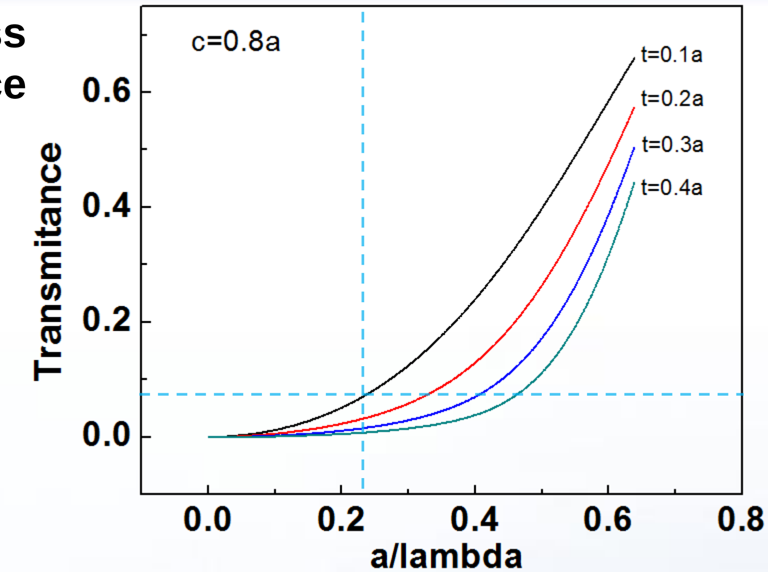
I_o [mA]	τ_p [μs]	E_o [MeV]	d_m [μm]	R_m [cm]	f [Hz]	R_b [cm]
60	5.5	6.5	10	0.2	200	0.05

FEL Resonator (Outcoupling Mesh Mirror)

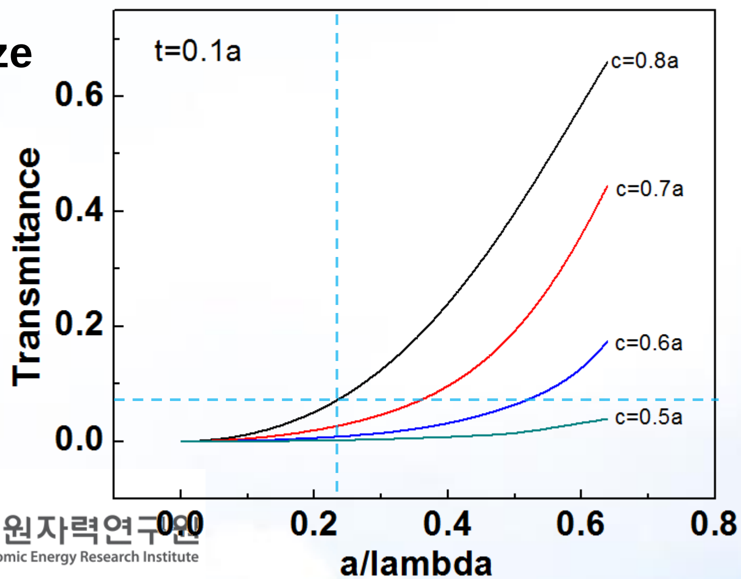
Transmittance



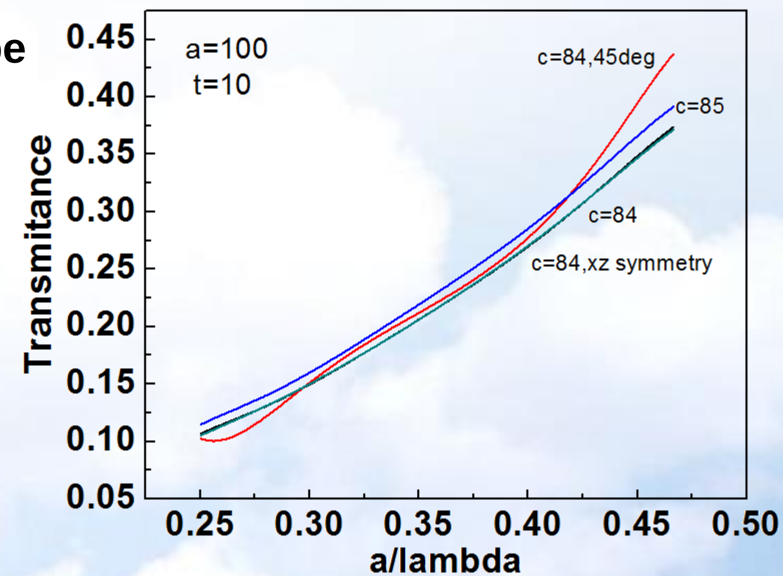
Thickness dependence



Cell size



Shape



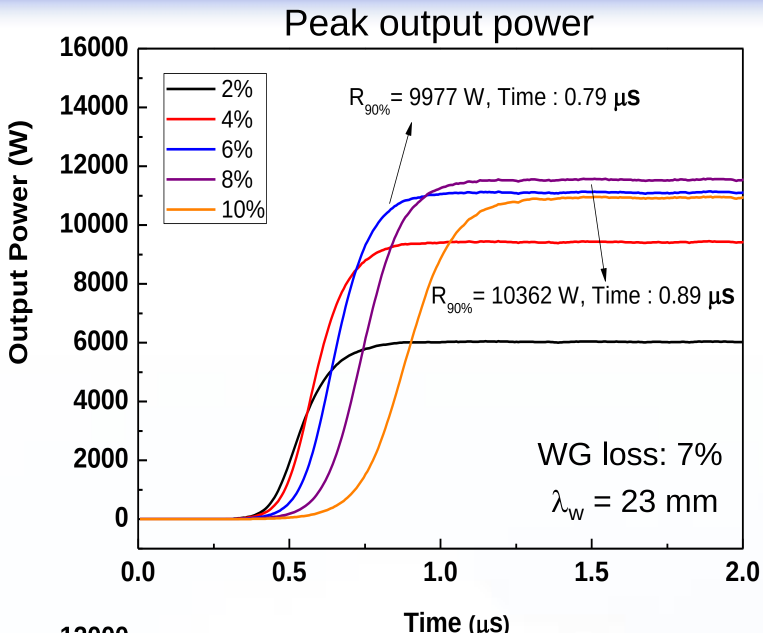
THz FEL Simulation (Peak Output Power vs. WG Losses)

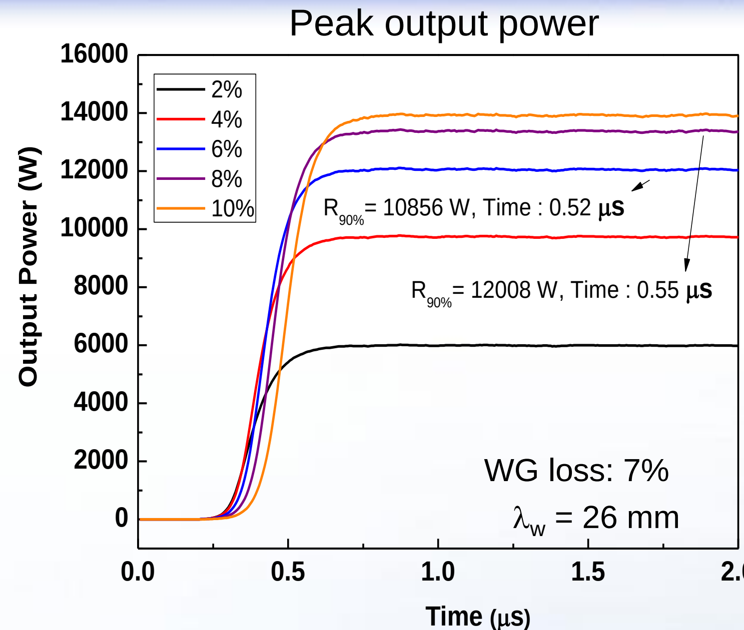
Ref. J. Suhwoo

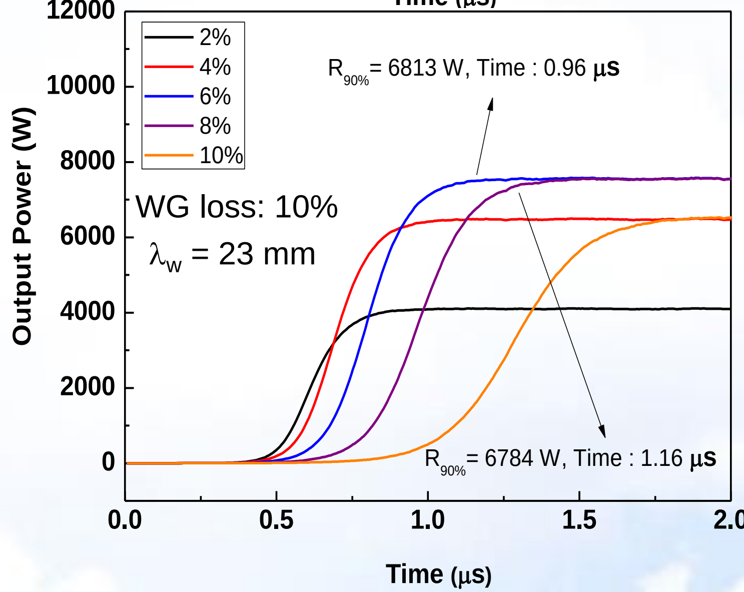
Input parameters

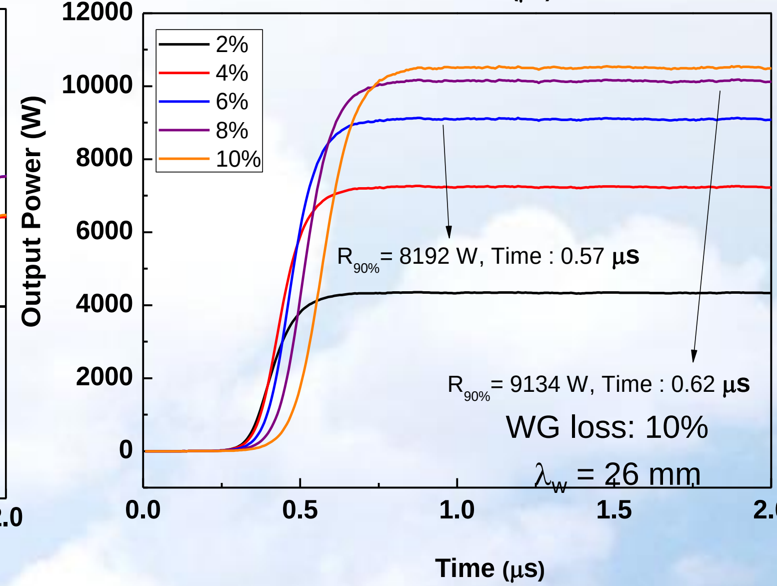
Electron beam	Energy	6.5 MeV
	Current	0.5 A
	Beam Radius	0.5 mm
	Pulse Width	10 ps
	Outcoupling ratio (%)	2, 4, 6, 8, 10
Wave-guide	Mode Type	TE_{11}
	Radius	2 mm
	Loss	7%, 10%
Helical undulator	B Field Strength	10 kG
	Period length λ_w	23, 26 mm
	# of period (N_w)	**26**

Emittance : 5 mm mrad
Energy spread : 0.4%

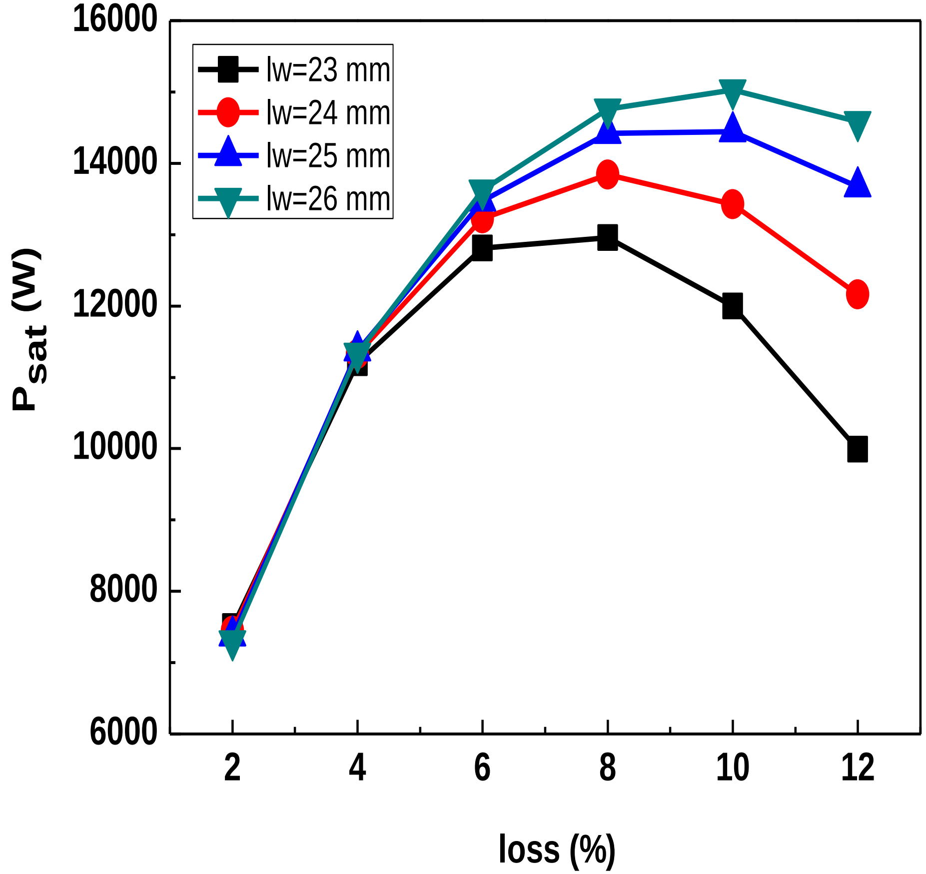


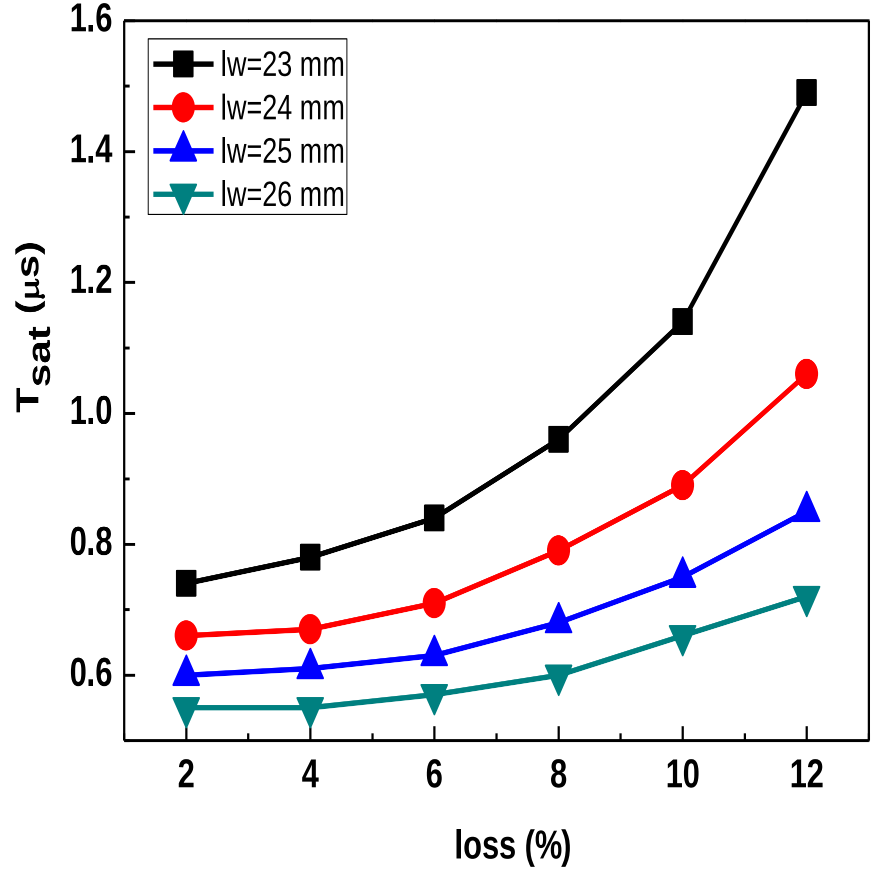






THz FEL Simulation (Peak Output Power vs. WG Losses)





Parameters for KAERI Table-top THz FEL

Electron Beam		
Energy (Peak current)		6.5 MeV (0.5 A)
Emittance		< 5 mm mrad
Energy spread		~ 0.4%
Undulator (Helical)		
Type		Variable period/permanent M
Period (Number of periods)		23 - 26 mm (30)
Peak magnetic induction (K-value)		10 kG (2.15 – 2.43)
Waveguide mode (Radius)		TE_{11}, HE_{11} (2 mm)
THz beam		
Wavelength (frequency)		400–600 μm (0.5–0.75 THz)
Average power		~ 1 W
Micropulse	Pulse duration	10 – 20 ps
	Power	15– 30 kW
	Repetition rate	2.8 GHz
Macropulse	Pulse duration	4 μs
	Repetition rate	200 Hz

Summary

- New design can reduce the size of THz FEL system to 2.3x1.6 m^2.
- New microtron can operate at higher B-field to reduce the size.
- Cooling capacity of RF cavity should be increased by 10%.
- Simulation result at B=1.1 kG is well agreed with the analytical calculation and the simulation is underway for B = 1.144 kG.
- Designed beam lattice can adjust the beta functions to match the initial requirement for variable-period helical undulator only varying ONE focusing quadrupole.
- Outcoupling mesh mirror may be fit for a compact THz FEL.
- The set-up for preliminary THz inspection test is underway.

Opening ceremony, Sep. 23 2011

www.QRC.or.kr

We are looking for
Ambitious, Talent, Diligent, and Humanistic
young friends, if any.

BS in Busan, Oct. 20-21 2011

60th Birthday of Nikolay