특론: 가속기 실험실습 I

(NUCE719P-01/PHYS715P-01, 정모세)

eLABs 시설을 이용한 빔운전 및 RF/빔진단 기초 1

성창규

XFEL 가속기제어팀

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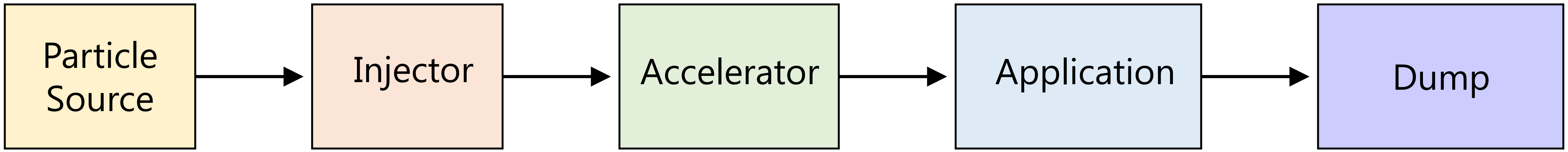
- 가속기의 구성
- PAL eLABs 소개
- 가속장치 데모 및 eLABs 를 이용한 실습

생김새가 다른 인간도 구성하는 기본 뼈대는 동일한 것처럼
모양과 크기가 다른 가속기도 공통되는 기본 뼈대로 구성 되어있다

▪ 가속기의 구성 (가속기의 뼈대)



- Accelerating cavity
- Magnets
- Diagnostics

✓ Vacuum

✓ Radiation

✓ Control

✓ etc..

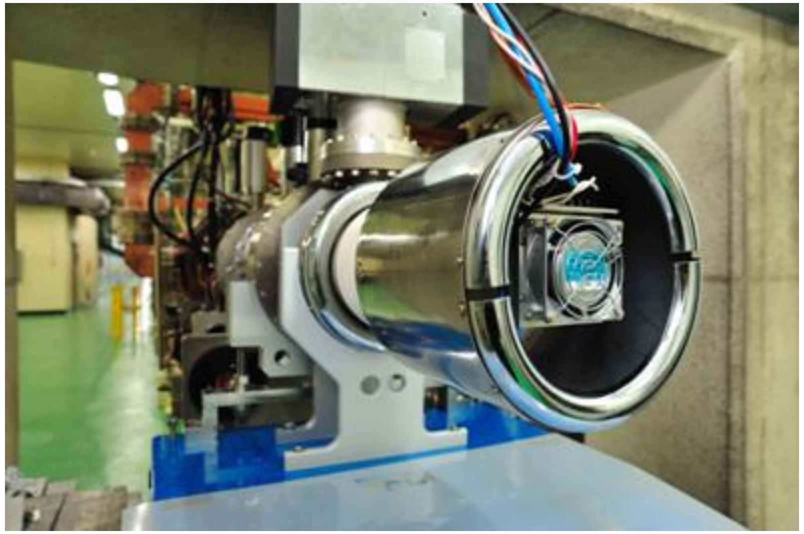
• Particle Source

❖ PLS-II

➢ Thermionic cathode → Thermal emission

✓ High charge

Parameter	Value
Beam voltage	80 kV
Bias voltage (VDC)	0 – 1000 V
Peak beam current	> 2 A
Pulse width (FWHM)	2 ns
Repetition rate	10 Hz

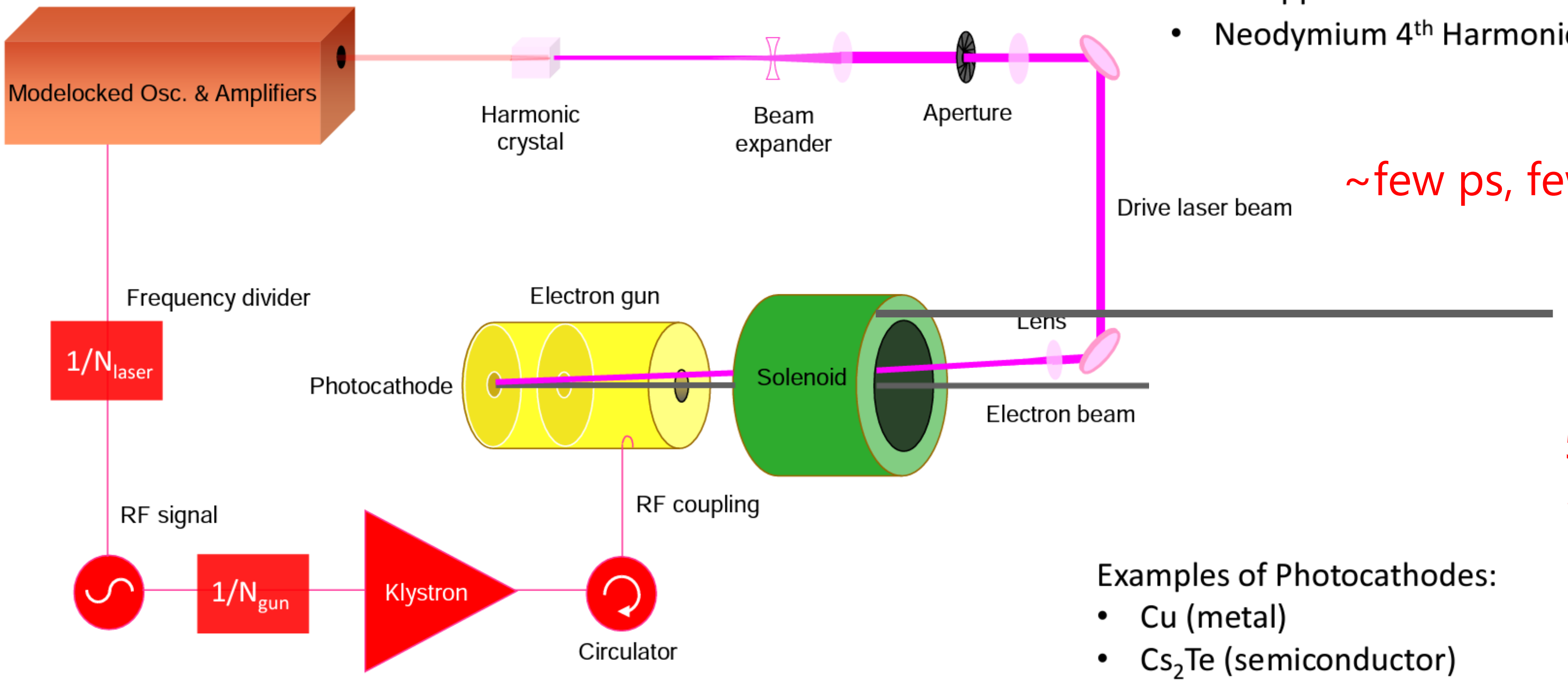


• Particle Source

❖ PAL-XFEL

➢ Photocathode RF gun → Photoemission (광전효과)

✓ Short pulse beam generation



Examples of Drive Lasers

- Ti:Sapphire 3rd Harmonic ~260 nm
- Neodymium 4th Harmonic ~266 nm

~few ps, few uJ

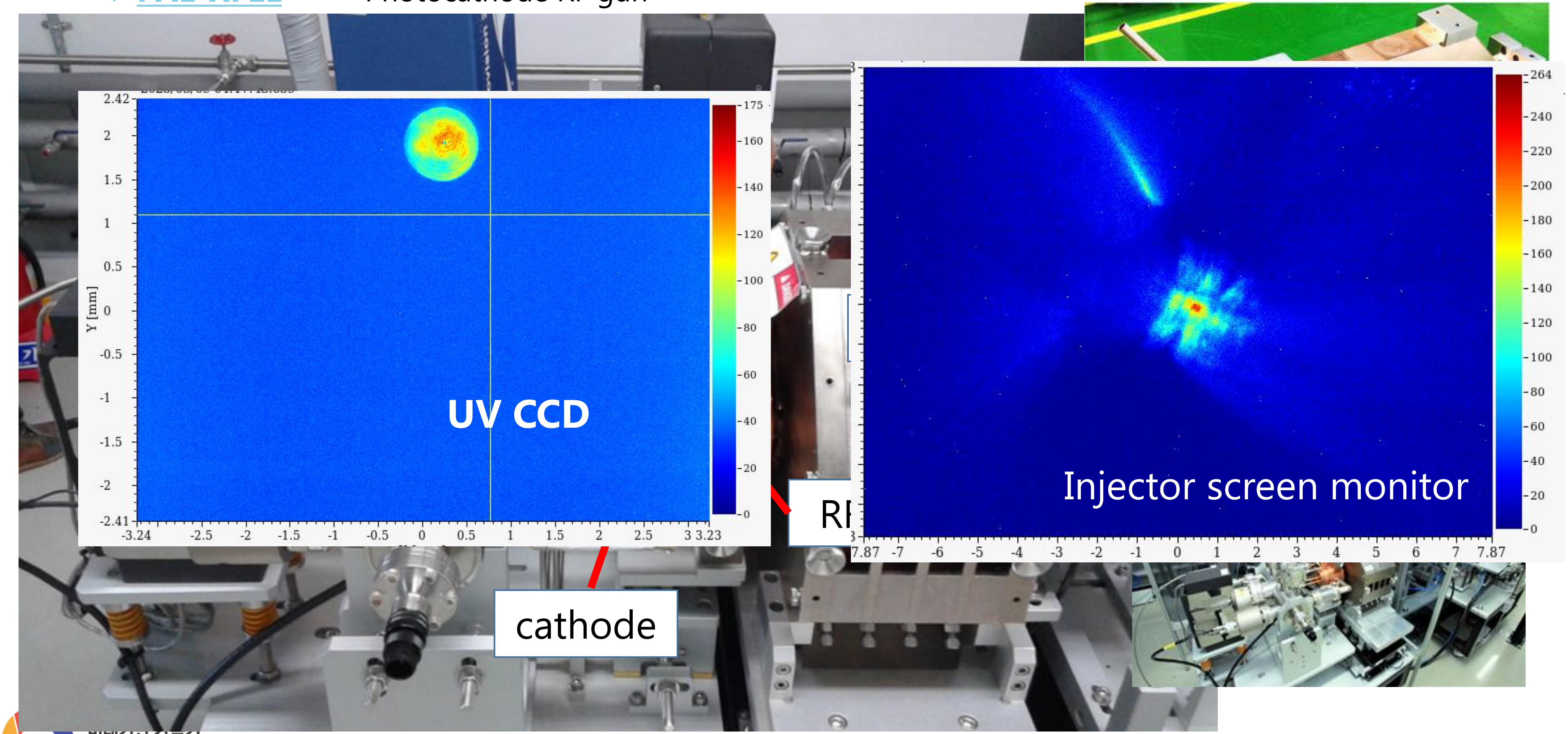
5~6 MeV
~ 250 pC e-beam

Examples of Photocathodes:

- Cu (metal)
- Cs_2Te (semiconductor)

- **Particle Source**

❖ PAL-XFEL   Photocathode RF gun

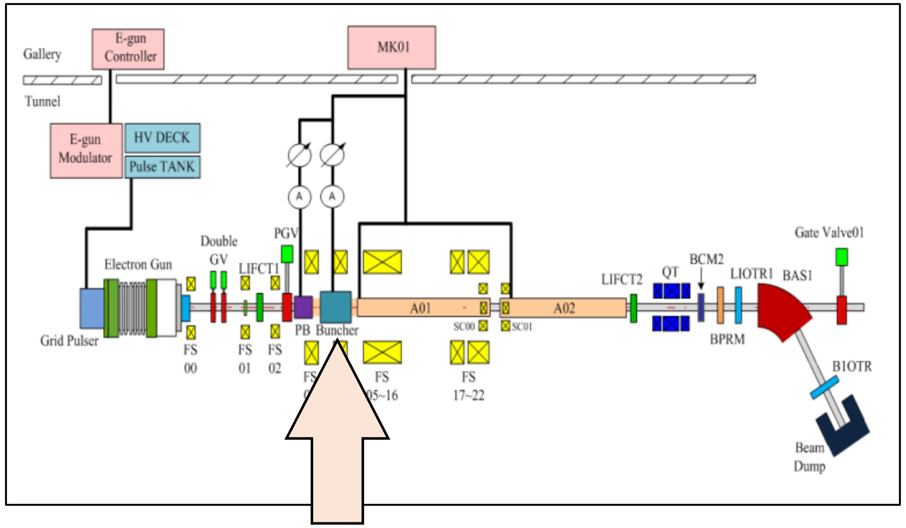


Injector

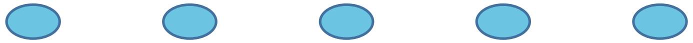
➢ *<u>"가속구간 입사를 위한 빔 최적화"</u>*

❖ **<u>PLS-II</u>** → Bunching

➢ Buncher (2856 MHz / 350 ps)



2 ns



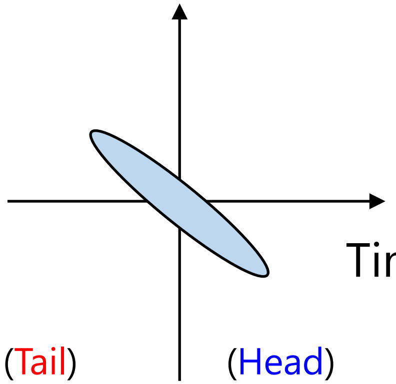
… → 5 bunch (every 0.1 s)

❖ <u>PAL-XFEL</u>

- Emittance optimization (space-charge compensation)
- Energy chirp control → ***Beam current (Pulse length)***

➢ RF accelerating field phase (2.856 GHz)

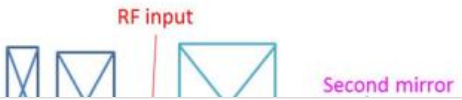
➢ X-band linearizer cavity (11.424 GHz)



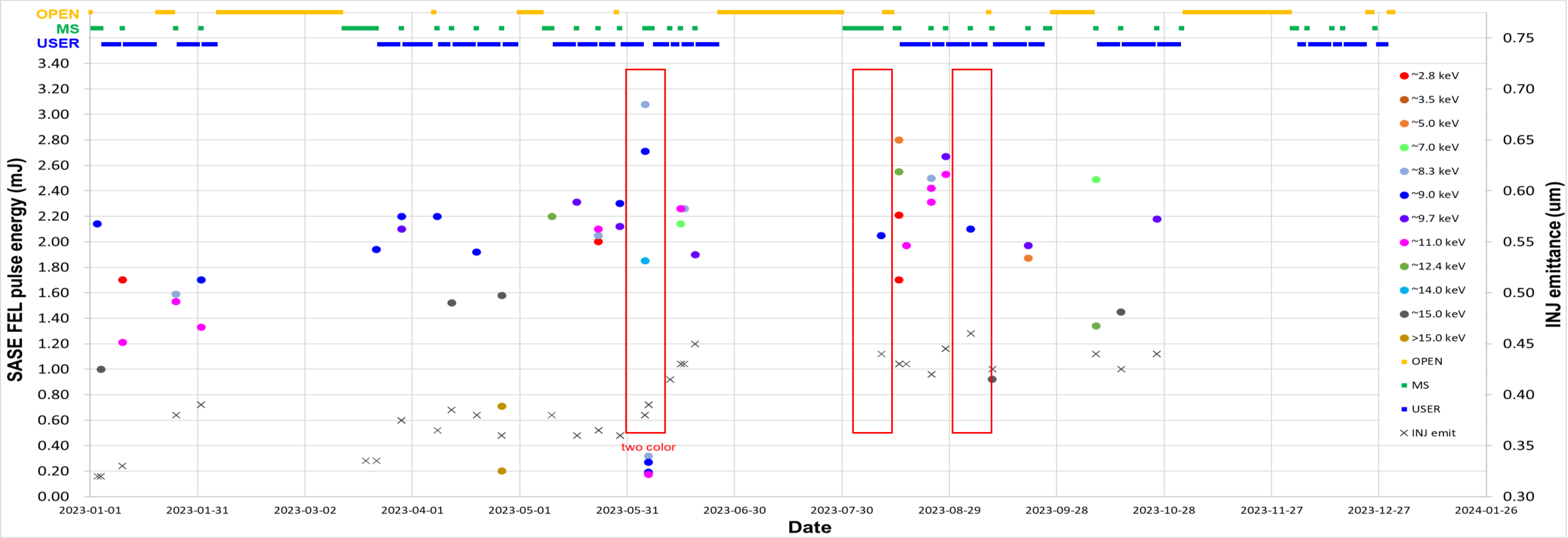
PS → INJ → ACC → App → DUMP

• Injector

❖ PAL-XFEL → Emittance optimization



➢ Electron beam generation with photocathode



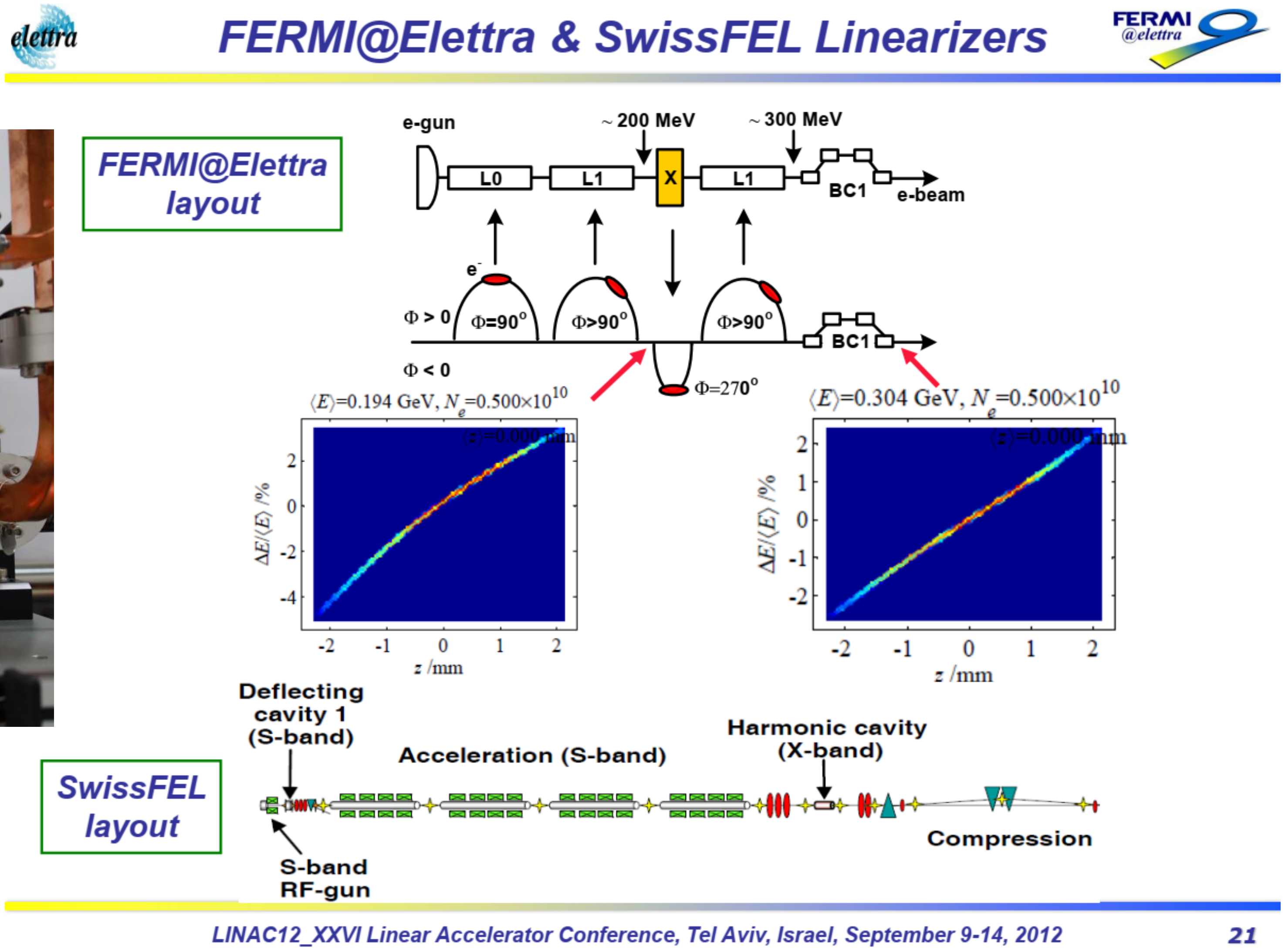
➢ **Injector emittance determines the beam performance at end station**

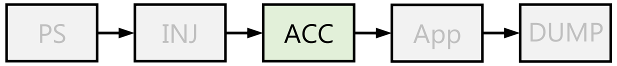
※ 2023년 제공 SASE HXFEL 에너지 영역별 pulse energy & injector emittance

미래기반 가속기 전문인력양성 사업단

- **Injector**

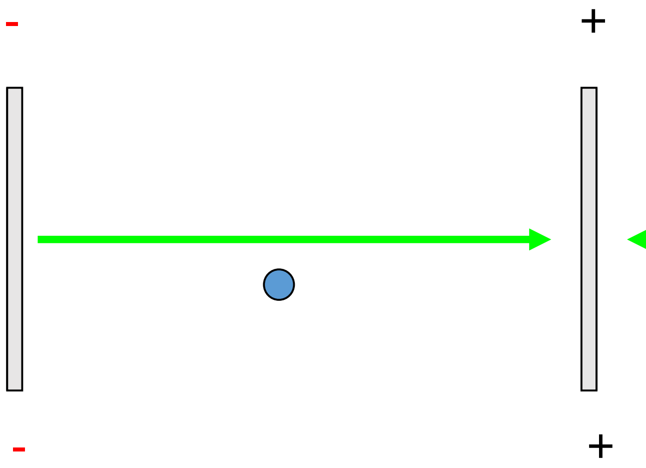
  ❖ PAL-XFEL → Energy chirp control

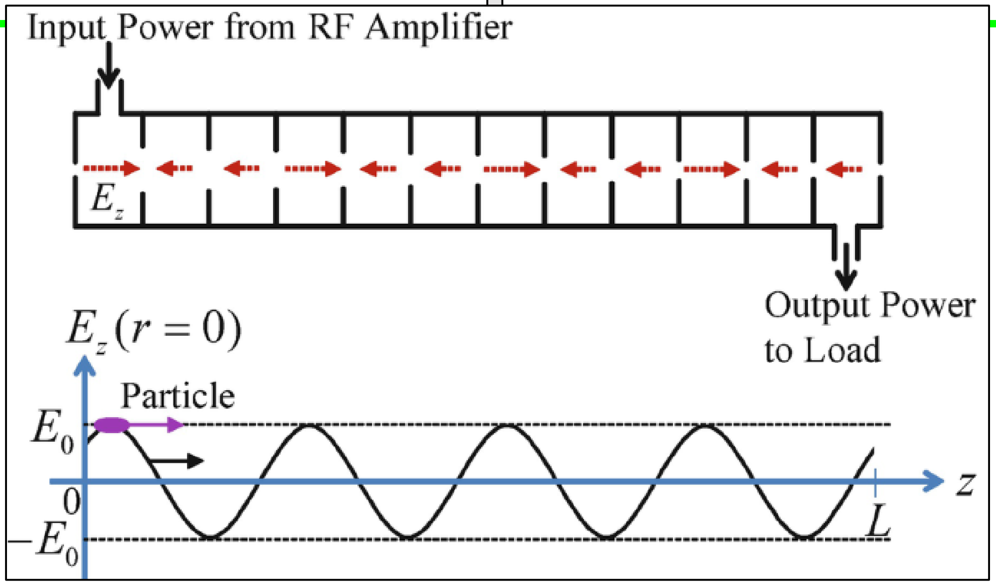




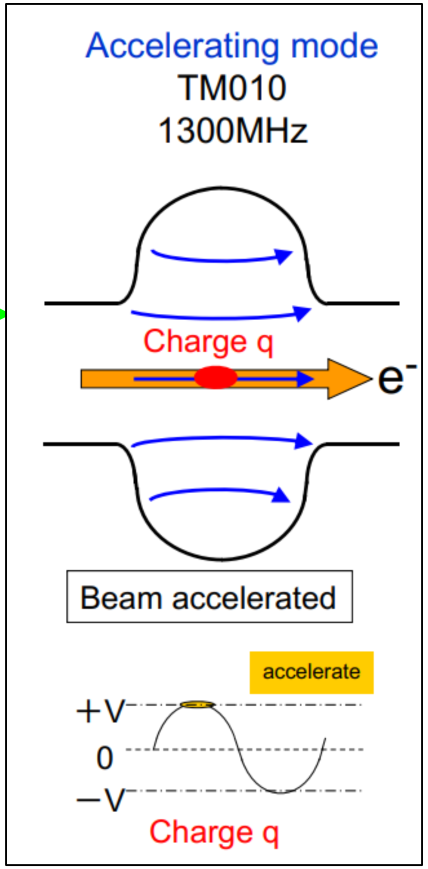
• Accelerator

❖Time-varying (RF, AC) electric field for accelerating particle





Traveling wave acceleration



Standing wave acceleration

- ✓ Traveling wave (filling in space)
- ✓ Standing wave (filling in time)

❖ Plasma acceleration (Laser-driven, Beam-driven)

*Animation from *"Introduction to RF for Accelerators" by G. Burt*

• Accelerator

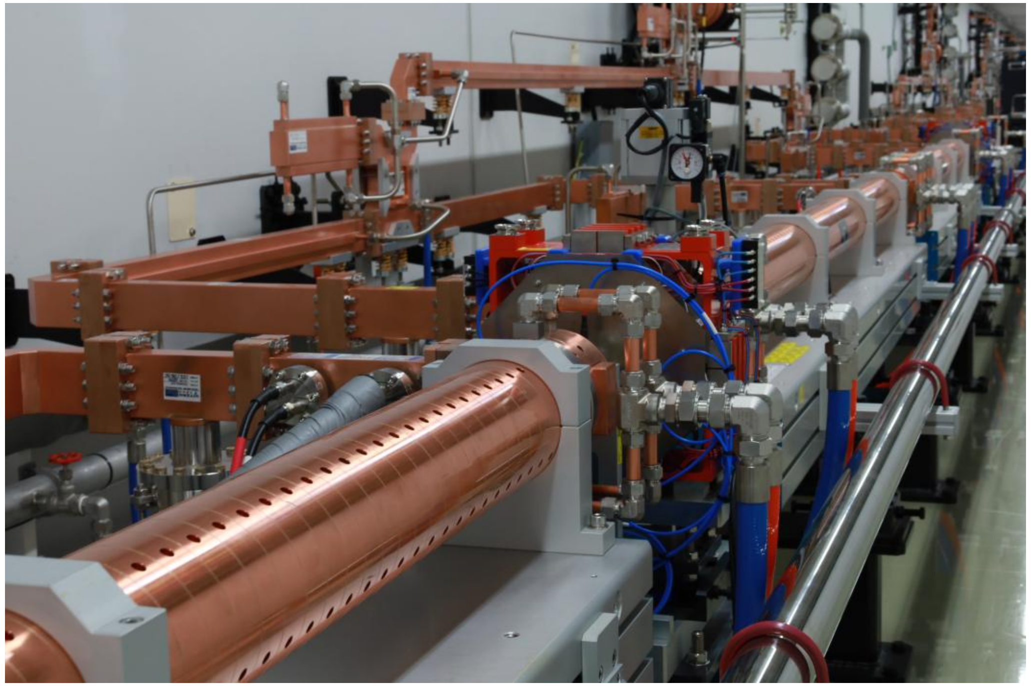
❖ Accelerating cavity @ PAL-XFEL

✓ Normal conducting (Tube) → Traveling wave

✓ 전체 길이 약 700 m

✓ 330 MeV → 11 GeV (Maximum @ HX) / 3 GeV (@SX)

= Accelerating voltage (*Energy gain): 10670 MV (HX 기준)*



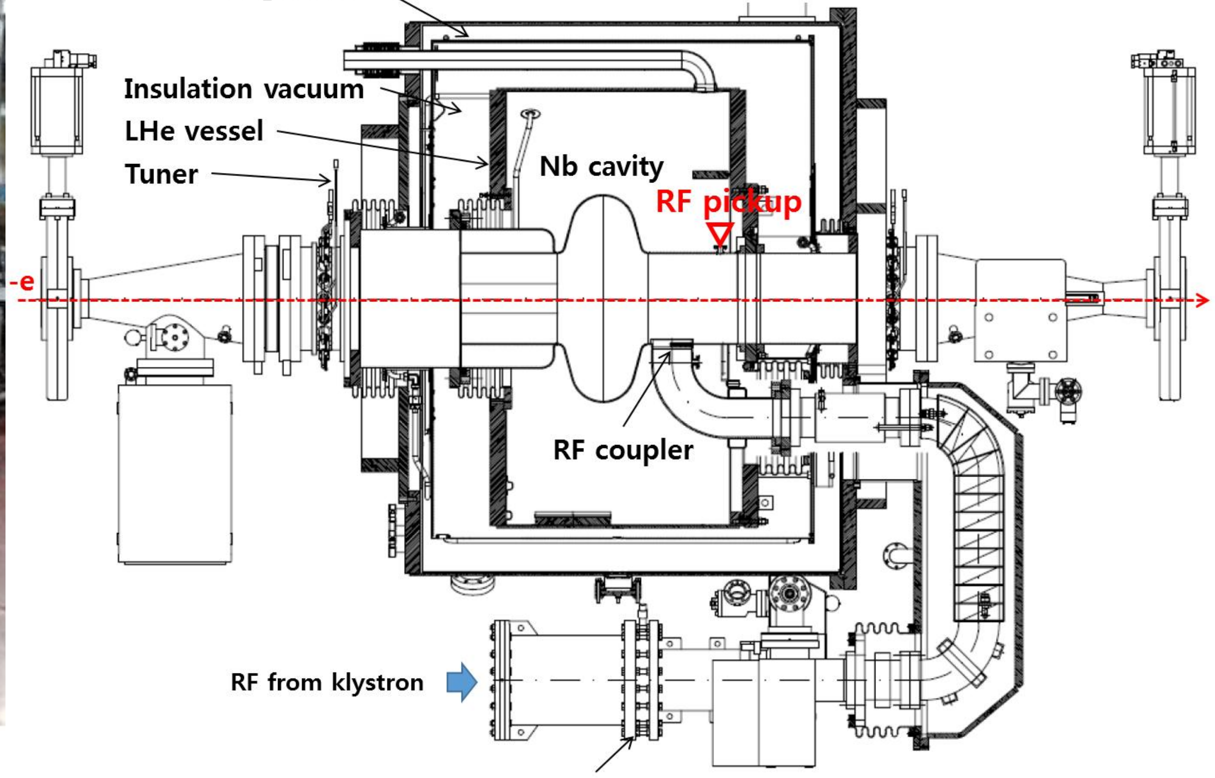
• Accelerator

❖ Accelerating cavity @ **PLS-II**

✓ Superconducting → Standing wave

❖ PLS-II 저장링 (3)

✓ Energy loss: ~ 1 MeV per turn (3 GeV e- beam)

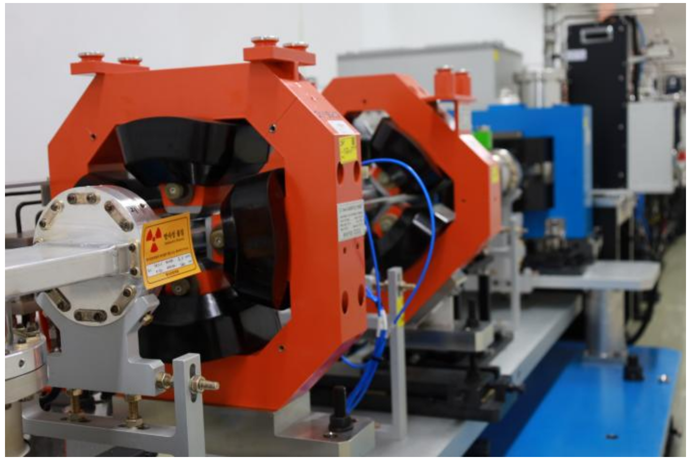


Accelerator

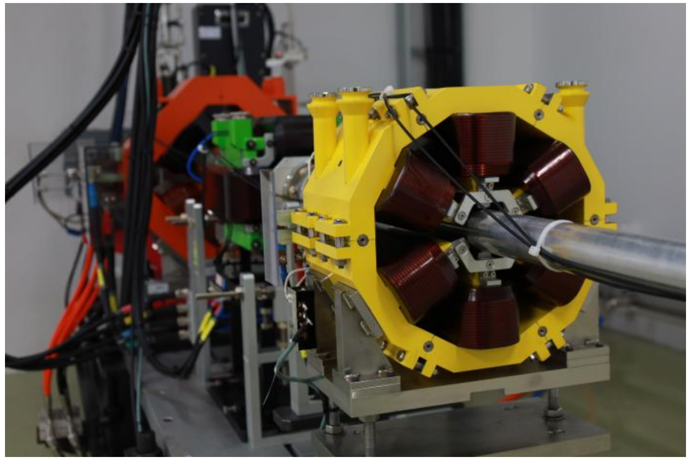
- ❖ Magnet
  - ✓ Multipole magnet
  - ✓ Electromagnet magnet

▪ Dipole magnet

▪ Quadrupole magnet

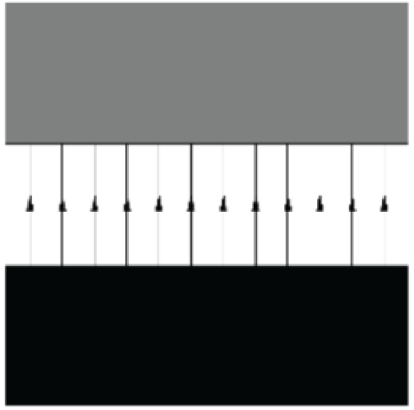


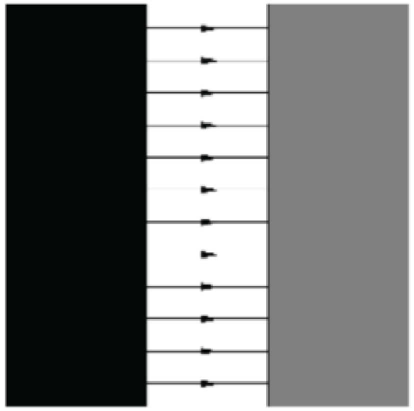
▪ Sextupole magnet

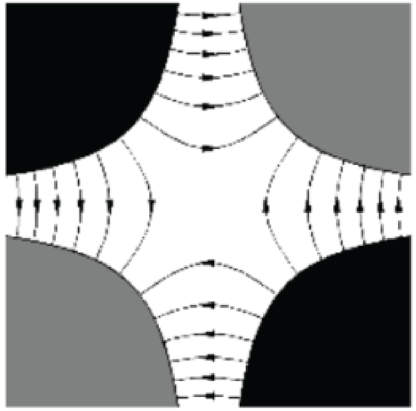


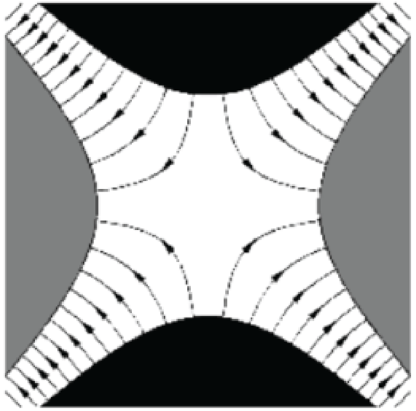
Bending

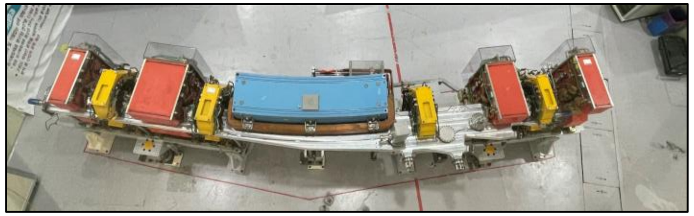
Focusing
(defocusing)











PS → INJ → ACC → App → DUMP

• Accelerator

❖ Instruments and Diagnostics

- Beam instruments : 빔을 잘 만들었는지 확인하고 잘 전송하기 위해 빔의 상태를 확인하는데 사용하는 도구

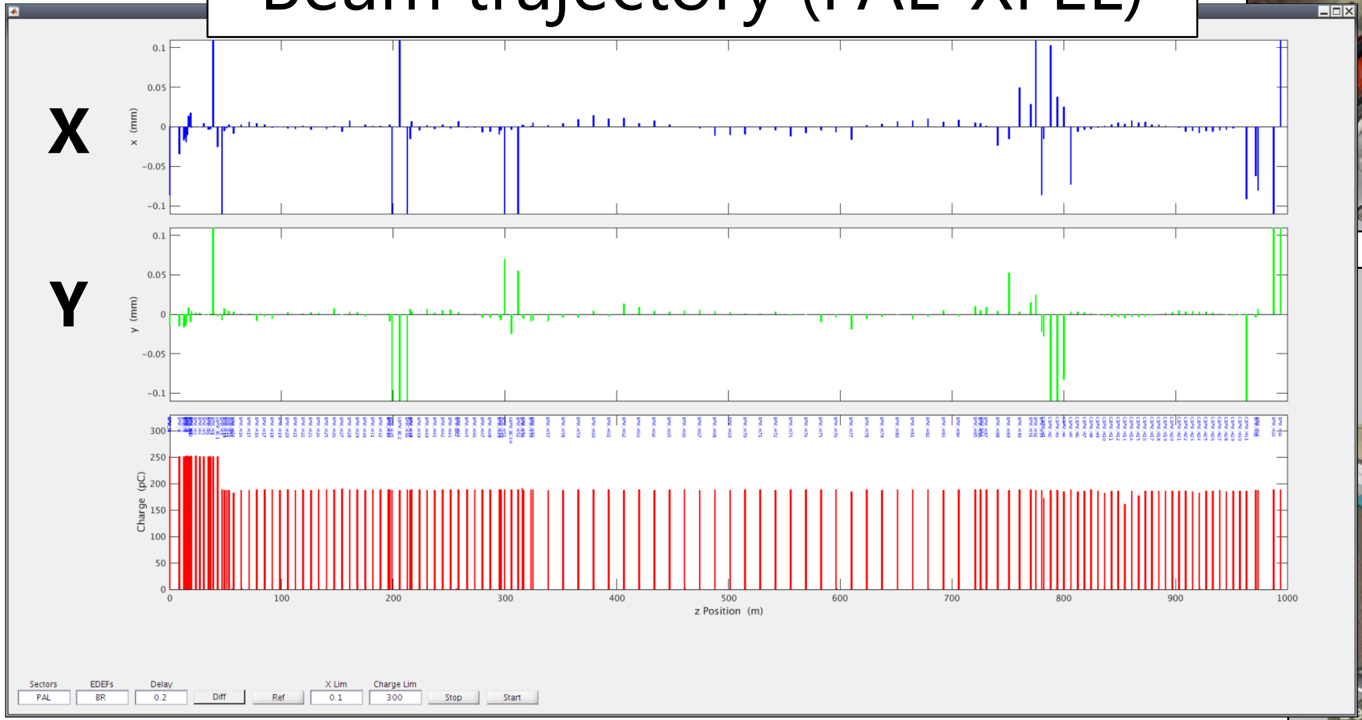
- Beam diagnostics ('진단'): 도구를 이용해서 빔의 상태를 분석하는 과정

빔 파라미터	진단 장치 또는 진단 기법
에너지	Phase probe Spectrometer magnet
전하량 / 전류	Integrated current transformer (ICT) Faraday cup
빔 길이 **(bunch length)**	Deflecting cavity (TCAV) ***Wakefield (Dechirper)*** Cherenkov diffraction radiation detector
형상 **(Transverse profile)**	Screen monitor
에미턴스 **(Emittance)**	Wire scanner Slit scanner Quadrupole magnet scan Pepper-pot
위치	Stripline beam position monitor (BPM) Cavity BPM
손실	Photomultiplier tube (PMT) Ion chamber

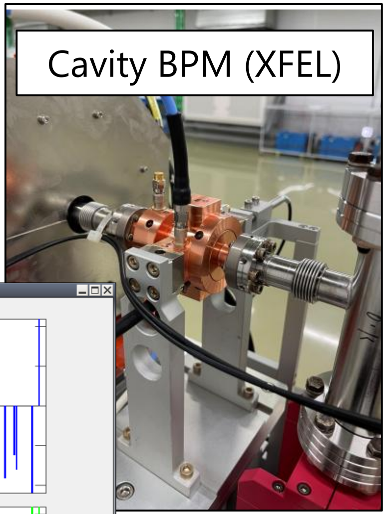
• Accelerator (Instruments)

- Beam position monitor (BPM)

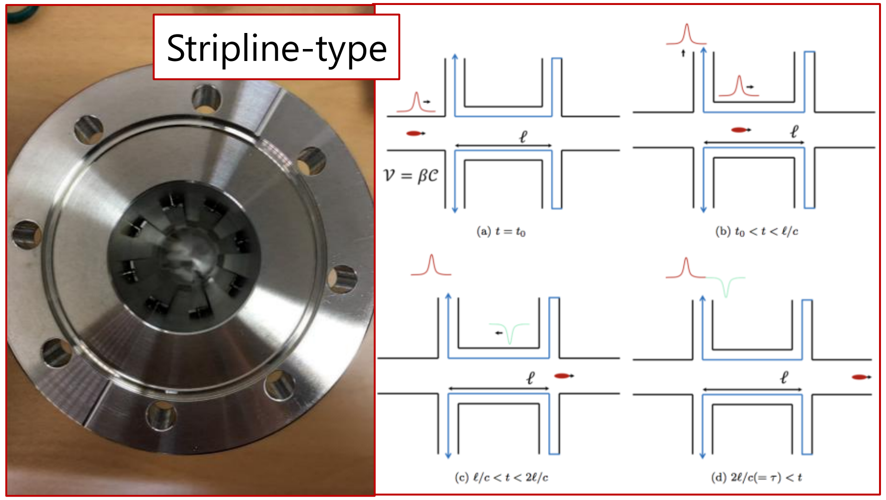
Beam trajectory (PAL-XFEL)

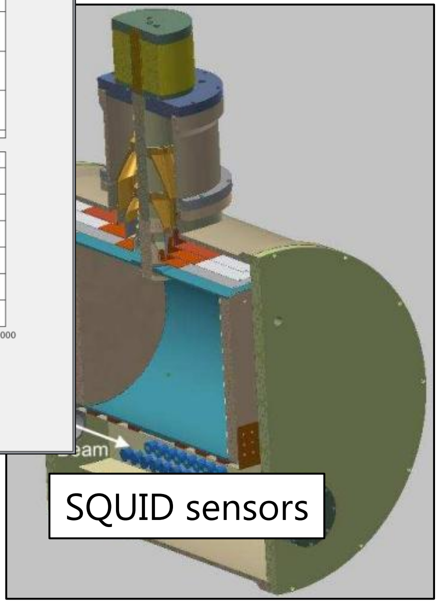


Cavity BPM (XFEL)

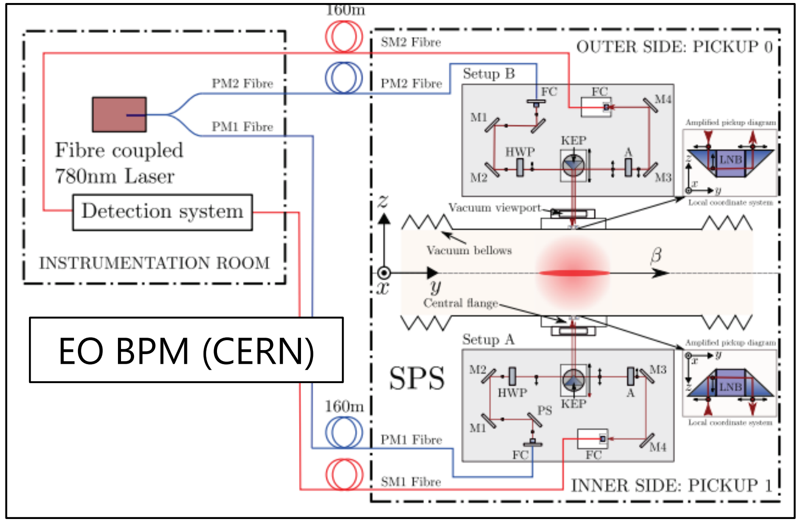


Stripline-type





SQUID sensors

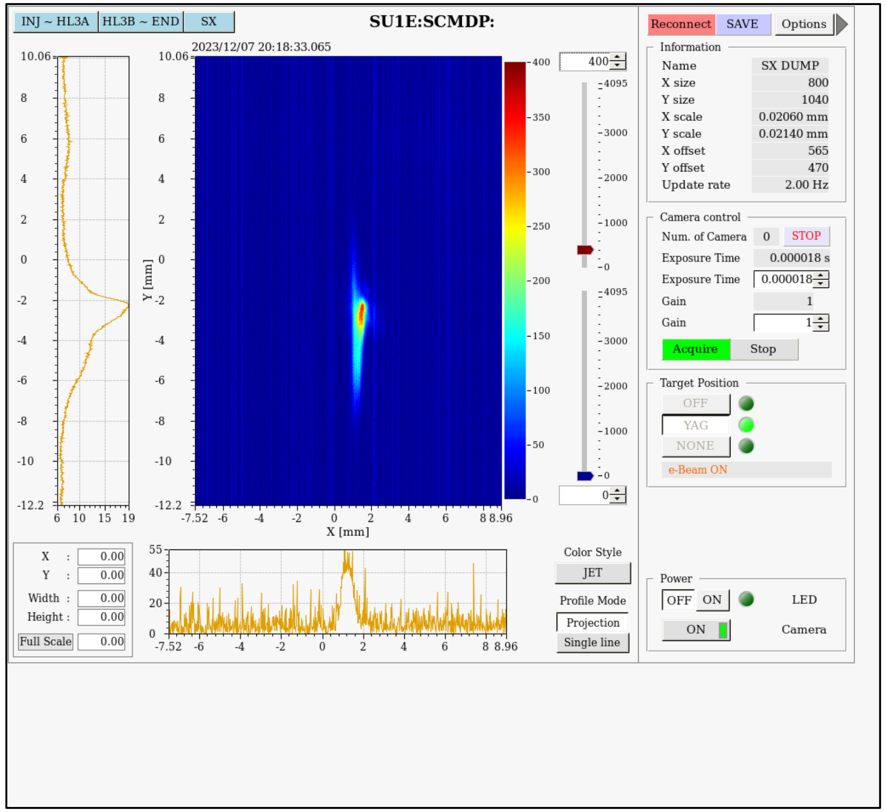


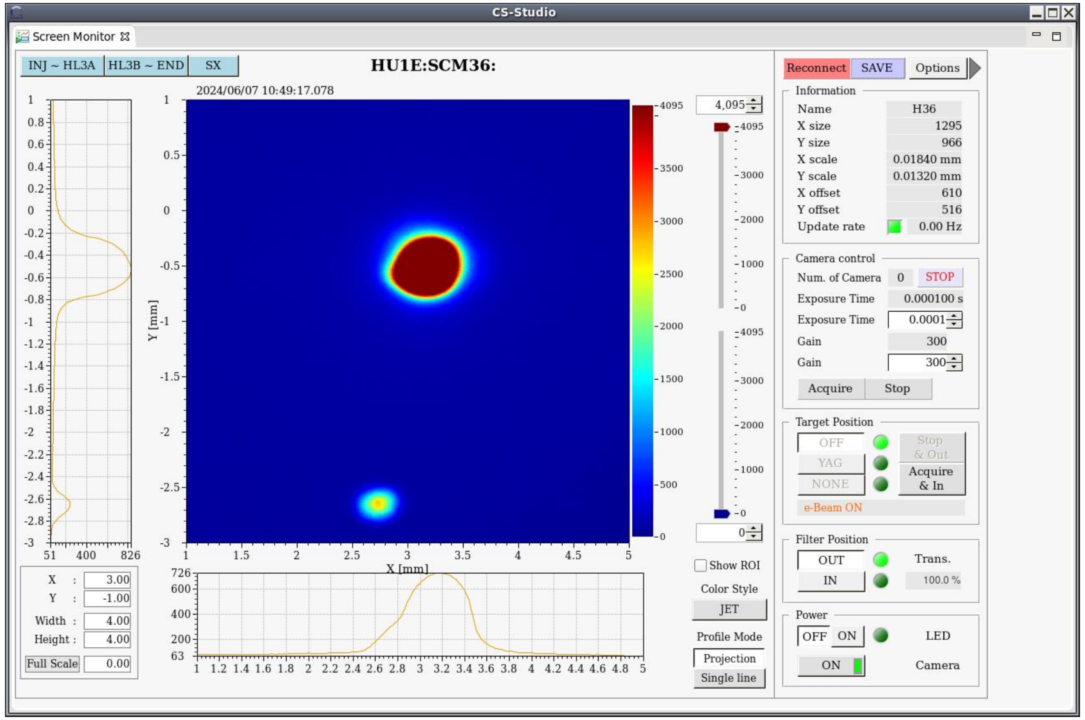
EO BPM (CERN)

PS → INJ → ACC → App → DUMP

• Accelerator (Instruments)

- Screen monitor (PAL-XFEL)



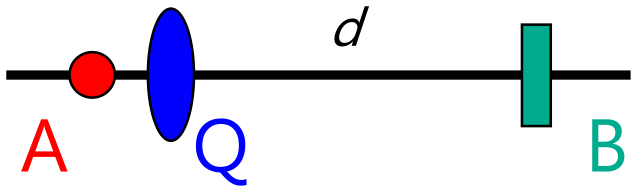


Electron beam (PAL-XFEL SX)

Photon (2.47 keV)

• Accelerator (Diagnostics)

- Quadrupole magnet scan: **Emittance** measurement
  - ➢ **Beam emittance** at the location **A** by measuring beam size at **B** for different **Q** settings
  - ➢ Well-demonstrated method under uncoupled linear beam dynamics
    - ✓ Linear transformation of beam matrix under linear system



$$\Sigma_B = M\Sigma_A M^T$$

✓ $\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} < x^2 > & < xx' > \\ < xx' > & < x'^2 > \end{bmatrix}$

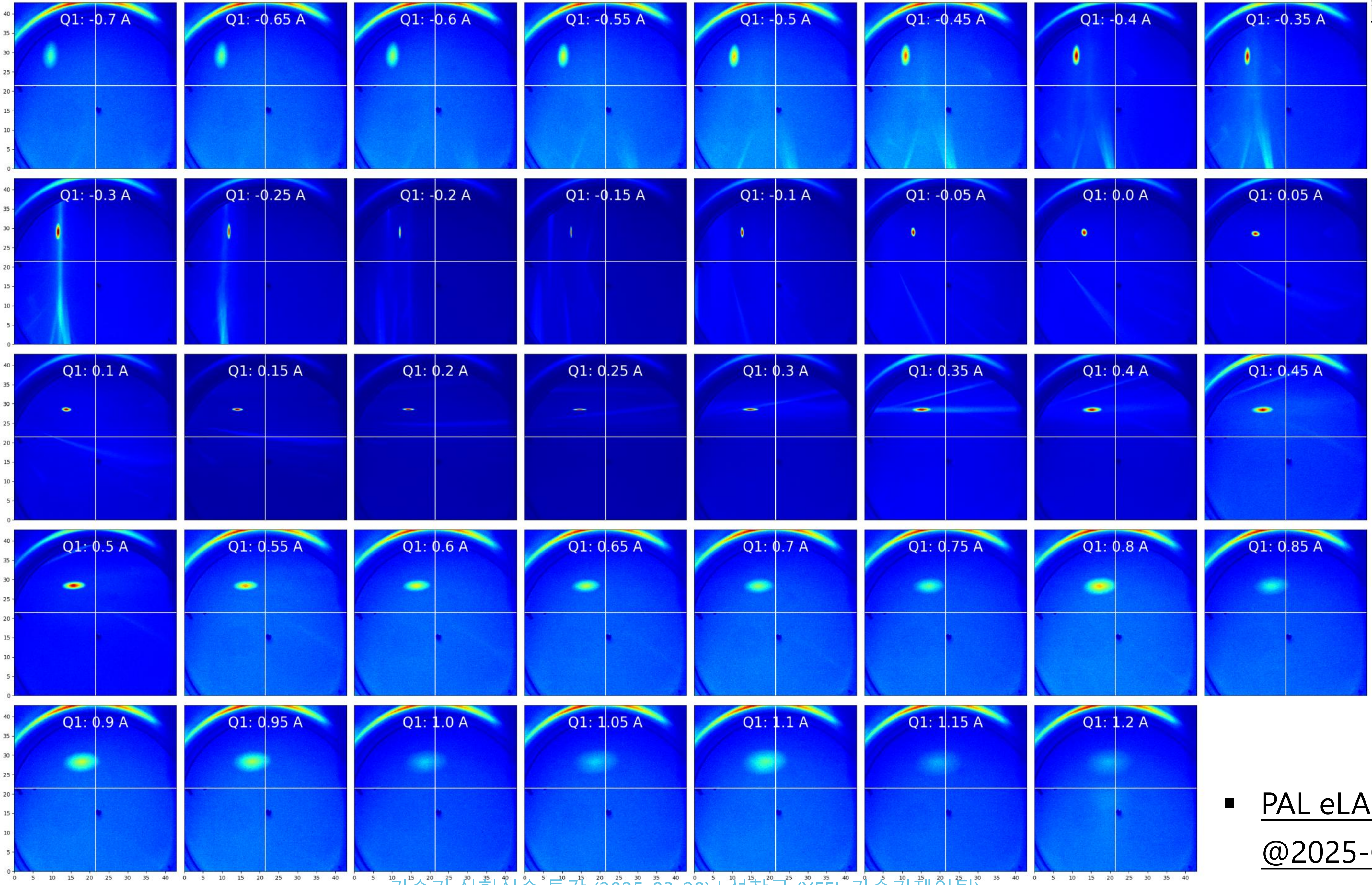
✓ $\mathrm{M} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ k\ell & 1 \end{bmatrix}$

$$\sigma_{11}^{meas} = \left(\sigma_{11}^{quad} d^2 \ell^2\right) k^2 + \left(2d\ell\sigma_{11}^{quad} + 2d^2\ell\sigma_{12}^{quad}\right) k + \left(\sigma_{11}^{quad} + 2d\sigma_{12}^{quad} + d^2\sigma_{22}^{quad}\right)$$

- Projected emittance $\epsilon_{x,rms} = \sqrt{\det(X)} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$

- Normalized emittance $\epsilon_{x,norm} = \beta\gamma\epsilon_{x,rms}$

App DUMP

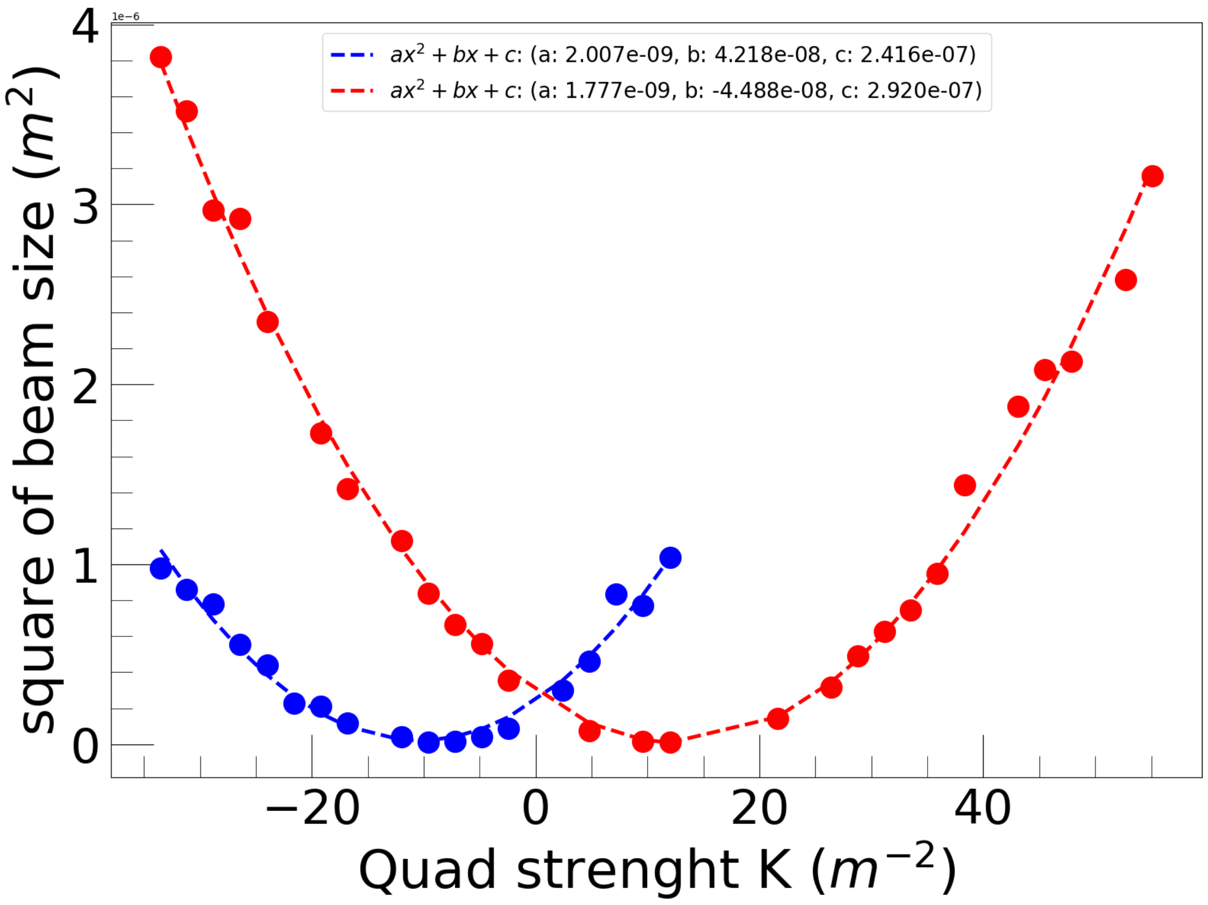


- PAL eLABs @2025-02-21

• Accelerator (Diagnostics)

❖ Emittance measurement by quadrupole magnet scan for MeV-UED electron beam at eLABs

Parameters	Value
Beam energy*	3.08 MeV / 3.50 MeV
Norm. X emit. ($\gamma\beta\epsilon_x$)	0.0806 / 0.0916 (μm)
Norm. Y emit. ($\gamma\beta\epsilon_y$)	0.0542 / 0.0616 (μm)



*Beam energy determined by (diffraction pattern / bending magnet)

PS → INJ → ACC → App → DUMP

• Application

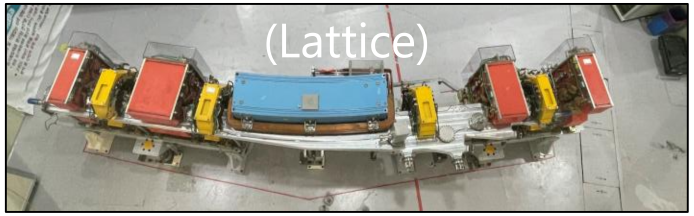
❖ Beamline

- ✓ Storage ring (PLS-II)
- ✓ Undulator (PAL-XFEL)

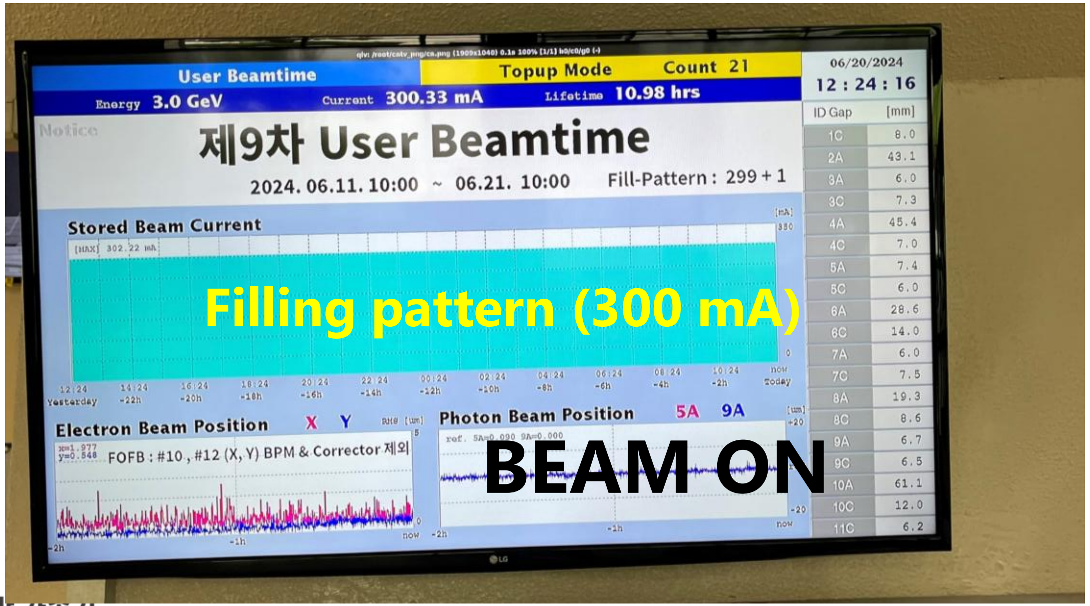
➢ *가속기 활용 연구를 위한 가속 장치의 역할*

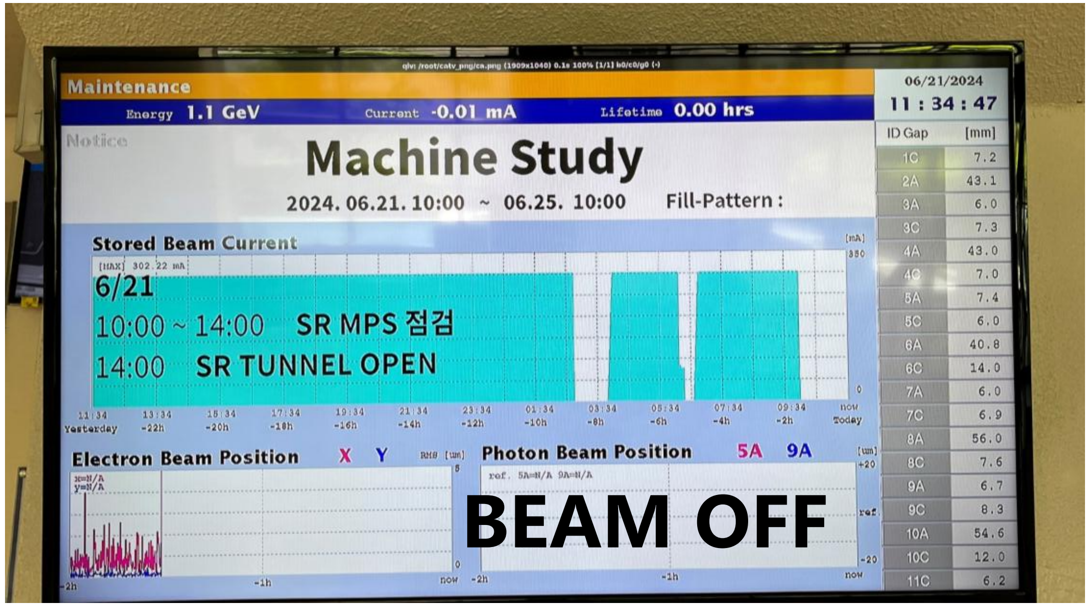
• Application

❖ Storage ring @ **PLS-II**
(저장링)



✓ 300 개의 전자 빔 번치를 동시에 저장 (300 mA)
→ Bunch-to-bunch spacing 2 ns
✓ 전자 빔 번치가 scattering 등에 의해 시간이 지날수록 전류 감소
→ beam lifetime
✓ *전류가 일정하게 유지될 수 있도록* 전자 빔 추가 투입
→ Top-up mode (filling pattern)





• Application

❖ Undulators @ PAL-XFEL

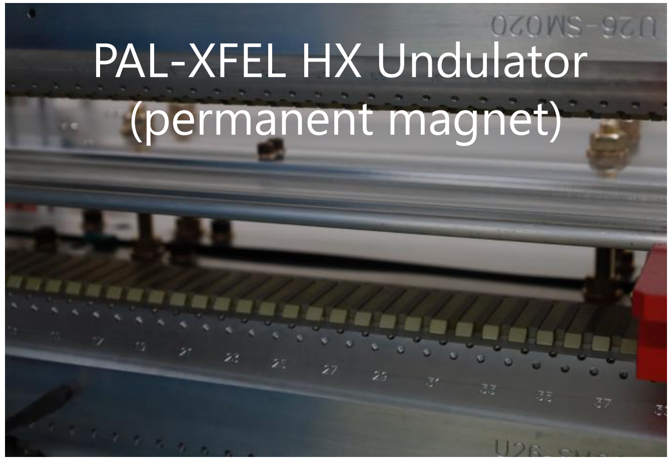
✓ Undulator

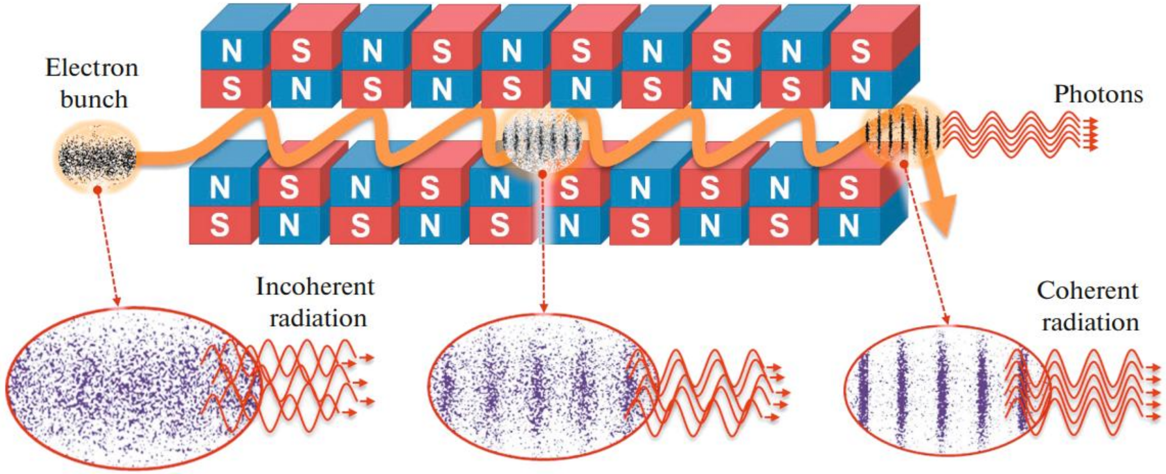
✓ Beam-based alignment (BBA)

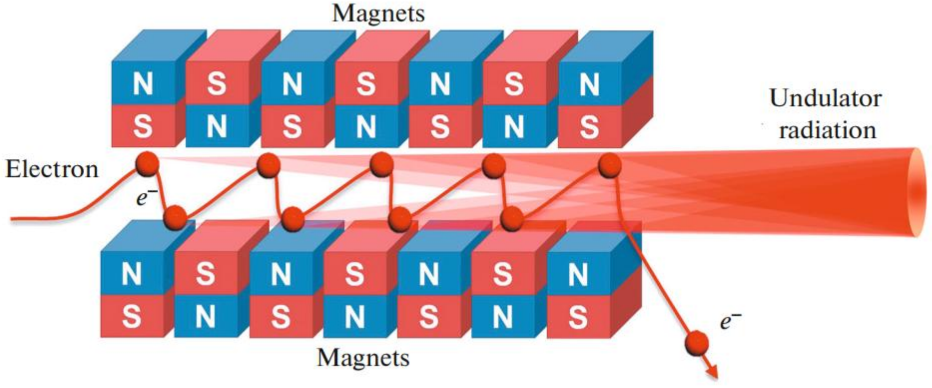
✓ Undulator tapering

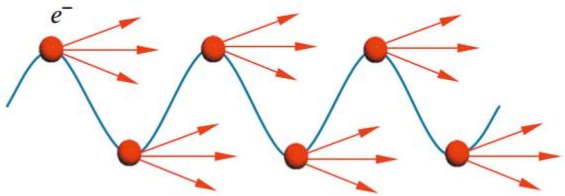
❖Undulator

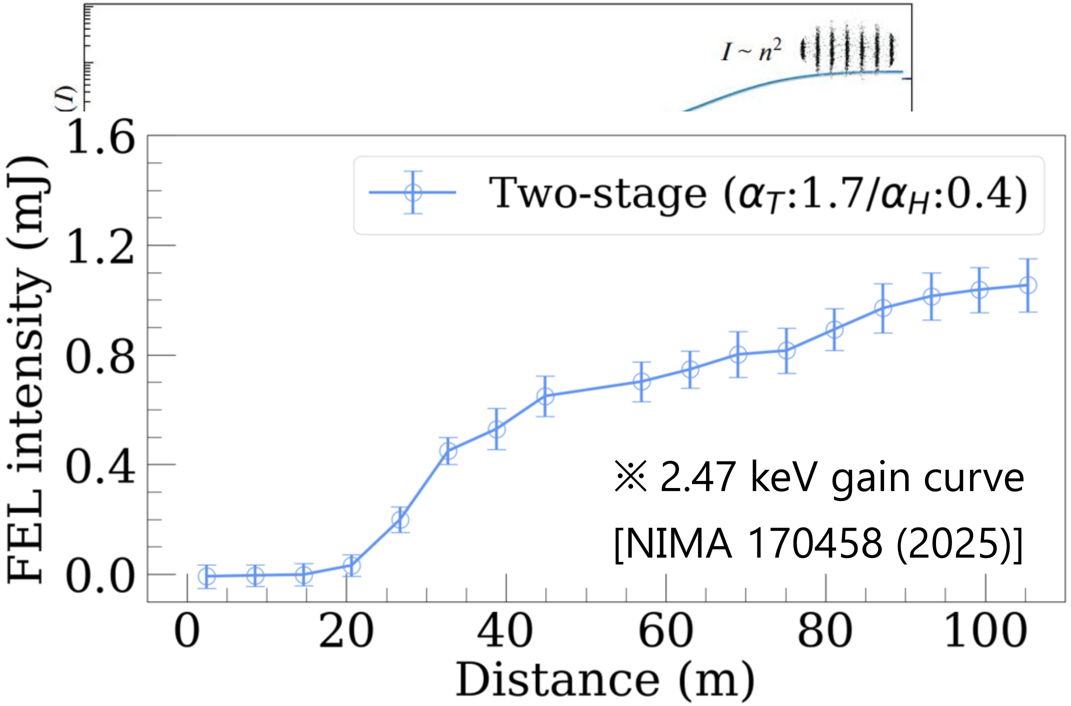

HXU26-U106
PAL-XFEL


PAL-XFEL HX Undulator
(permanent magnet)

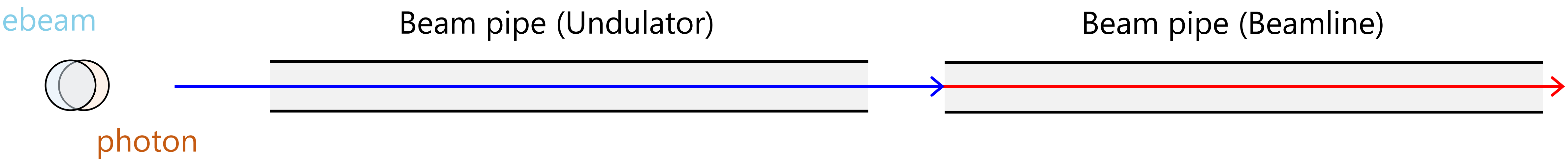

Electron bunch
Photons
Incoherent radiation
Coherent radiation


Magnets
Undulator radiation
Electron
e^-
Magnets

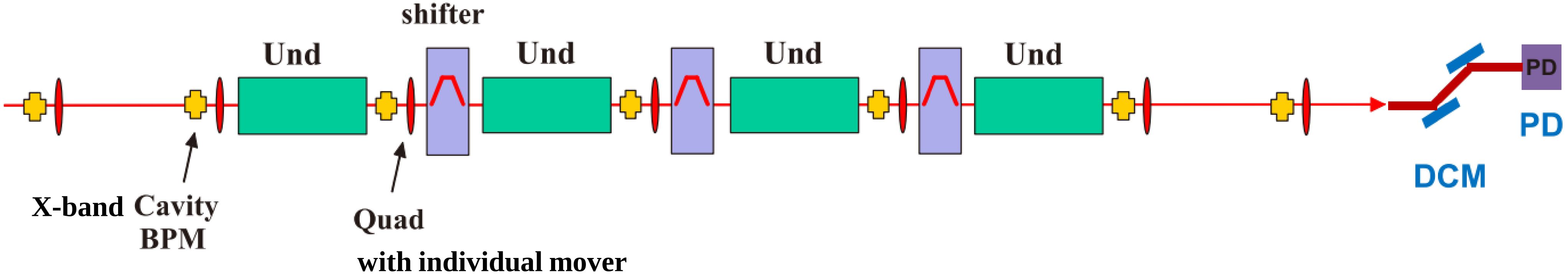

e^-

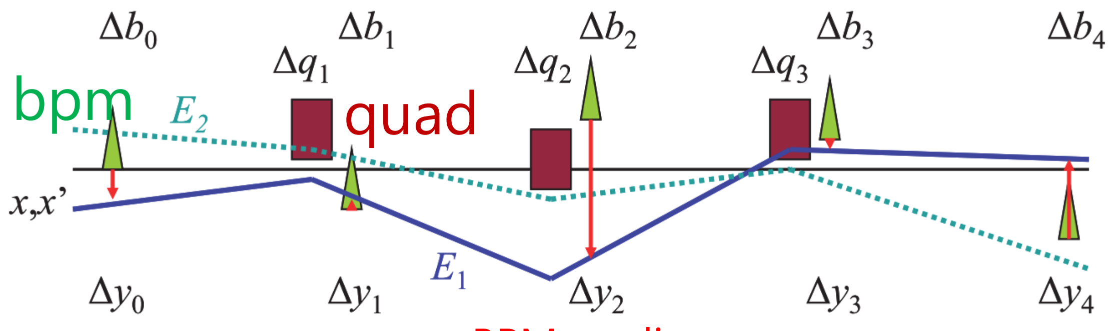

$I \sim n^2$
FEL intensity (mJ)
Two-stage (α_T:1.7/α_H:0.4)
※ 2.47 keV gain curve
[NIMA 170458 (2025)]
Distance (m)

Undulator beam-based alignment (BBA)



P. Emma, R. Carr, and H.-D. Nuhn, NIMA **429**, 407 (1999)
H.-S. Kang, H. Loos, PRAB **22** 060703 (2019)

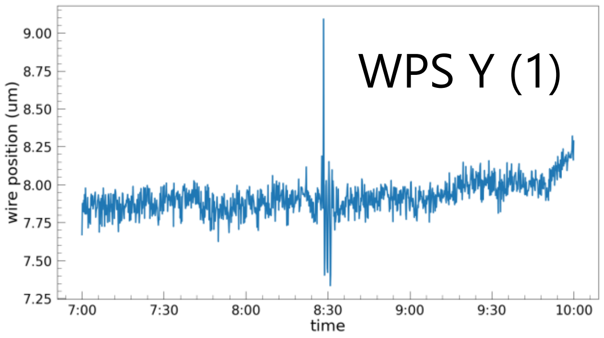


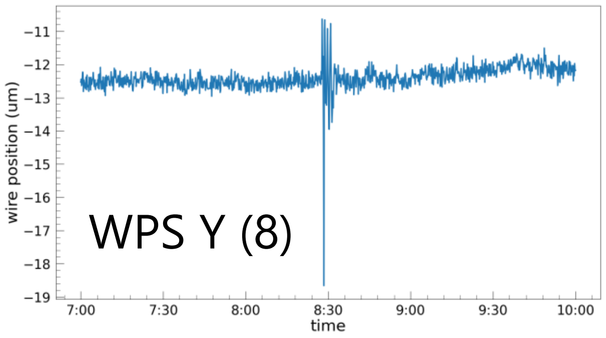


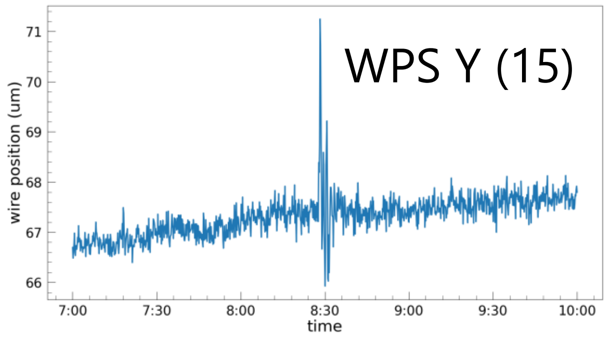
[Ref] I. Nam, KPS'24 (2024)

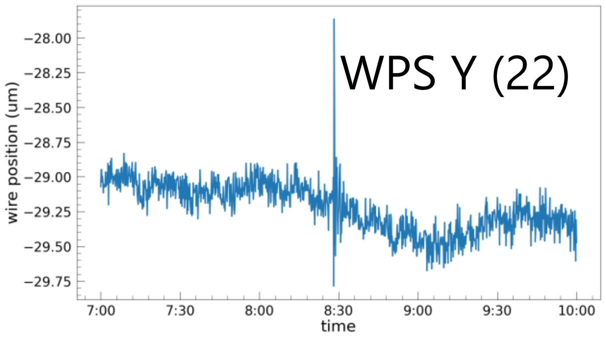
Undulator alignment

- ✓ 지반 거동 모니터링 시스템 (Wire position sensor, WPS)
- ✓ 지반 움직임에 따른 전자빔과의 정렬 오차 발생

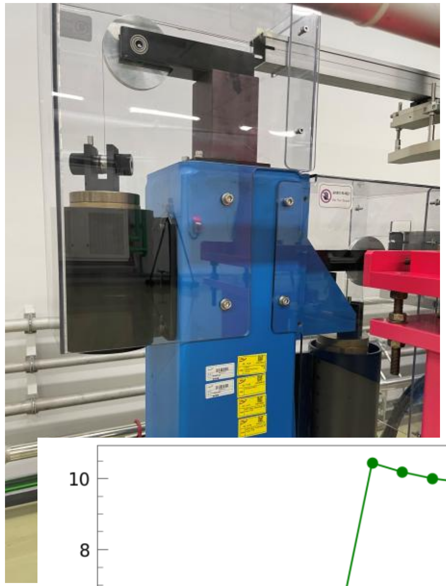


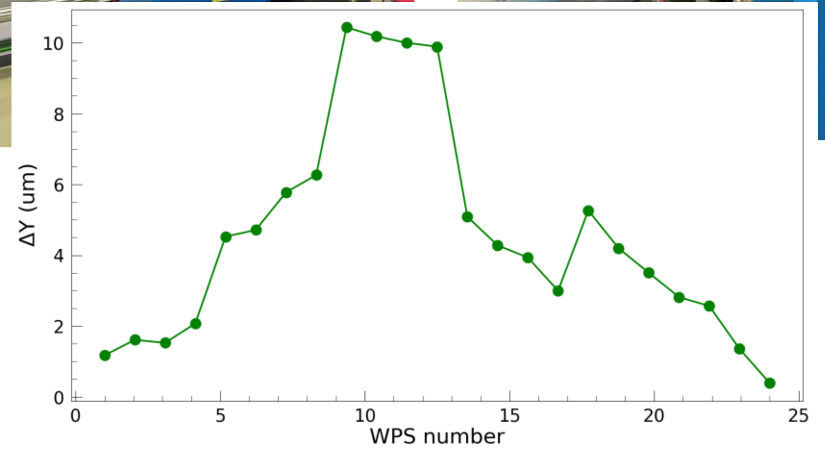




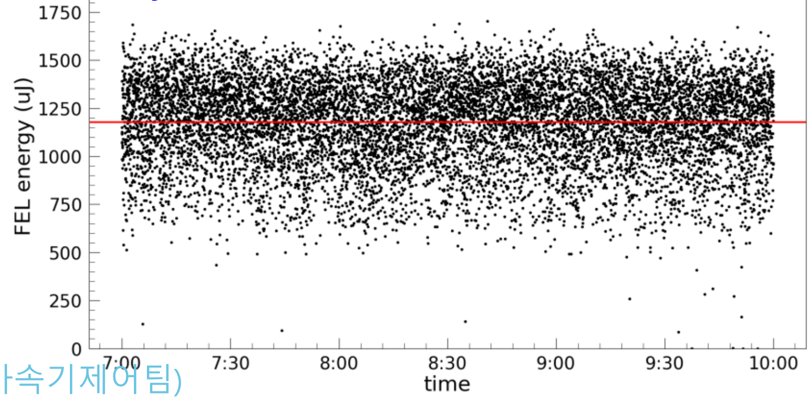


➢ *지진에 의한 지면 흔들림 감지 (6/12)*





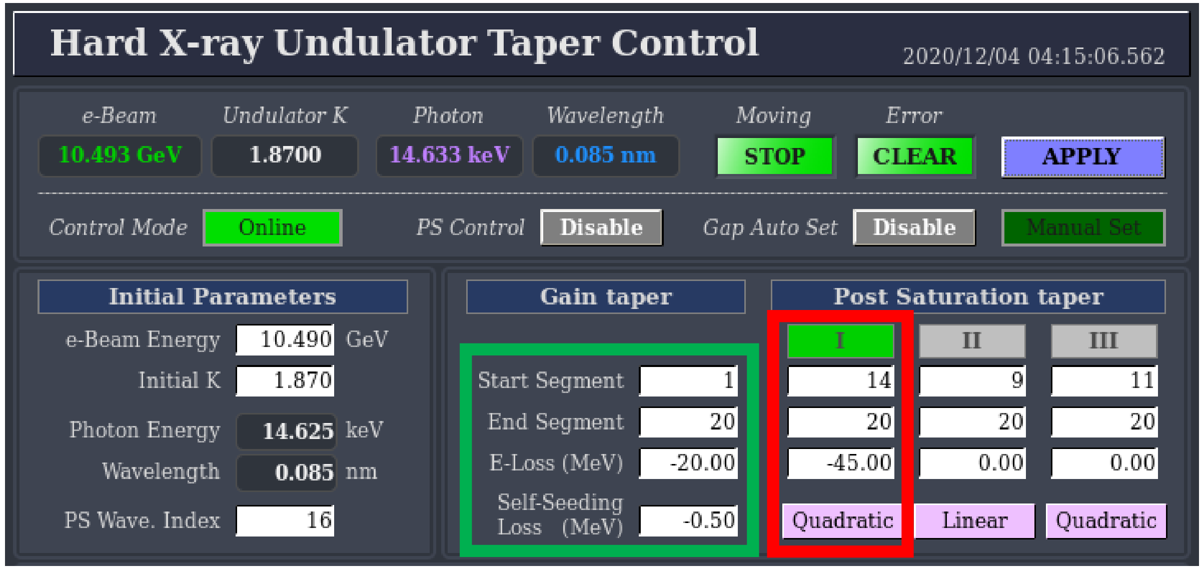
FEL intensity (2024-06-12 9.7 keV Self-seeding)

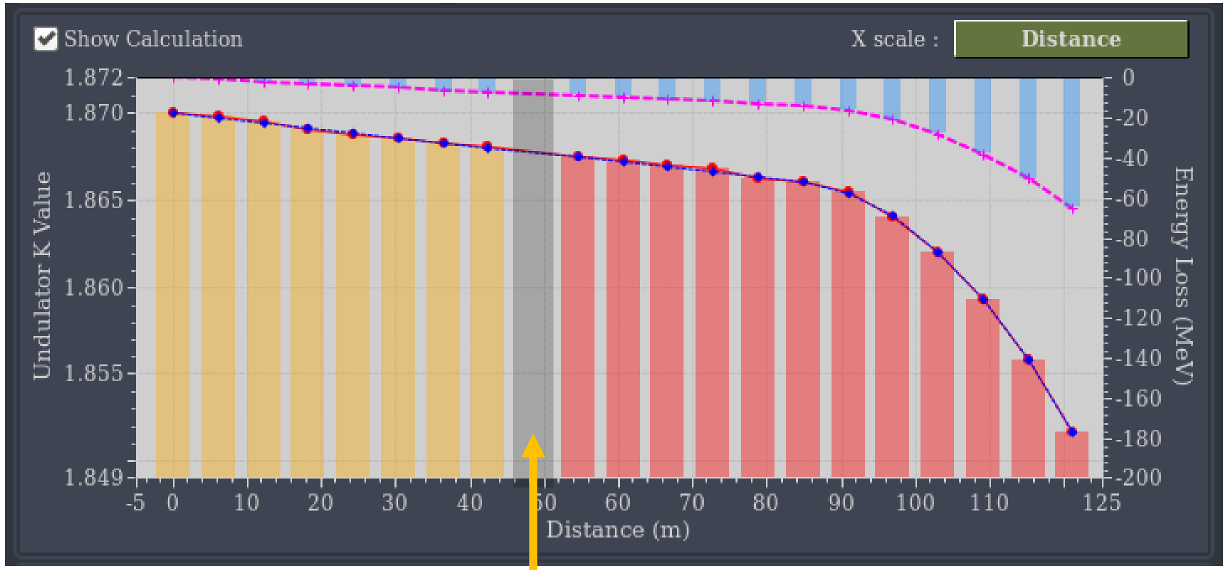


Undulator tapering

PS → INJ → ACC → App → DUMP

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$





energy loss due to the resistive wakefield effect → linear

energy loss due to the FEL lasing → quadratic

self-seeding section

Electron beam energy at the i-th undulator

$$\begin{cases} E_i = E_{init} + \dfrac{\Delta E_{linear}}{N_{tot}} \cdot i \quad (i < n_{quad,start}) \\ E_i = E_{init} + \dfrac{\Delta E_{linear}}{N_{tot}} \cdot i + \dfrac{\Delta E_{quadratic}}{(N_{tot} - n_{quad,start})^2} \cdot (i - n_{quad,start})^2 \quad (i \geq n_{quad,start}) \end{cases}$$

⇒

Undulator resonance condition

Losing energy as radiating X-ray

$$K = \sqrt{2 \cdot \left(\frac{2\gamma^2 \lambda_r}{\lambda_u} - 1\right)}$$

Lower K according to decreased e-beam energy

미래기반 가속기 전문인력양성 사업단

[Ref] I. Nam, KPS'24 (2024)

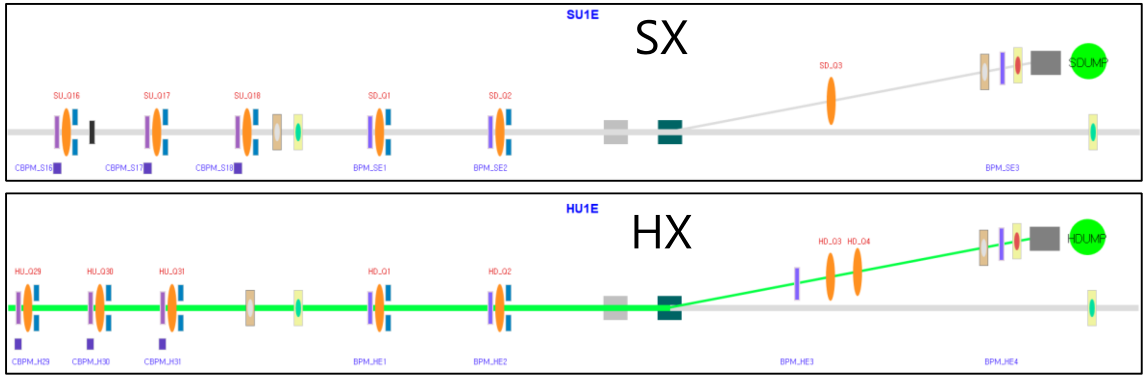
Undulator tapering

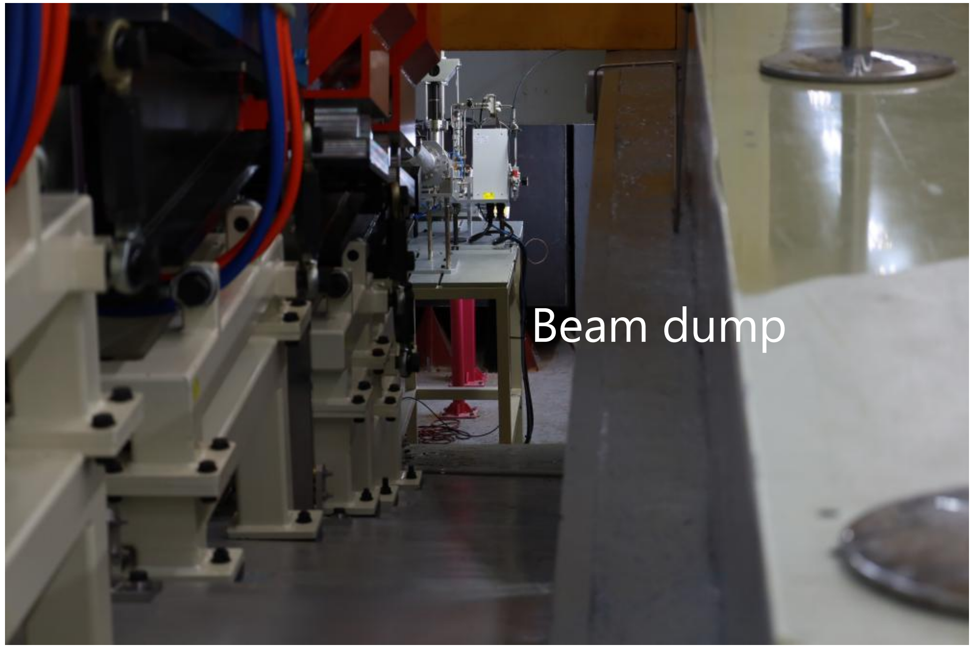
[Ref] I. Nam, KPS'24 (2024)

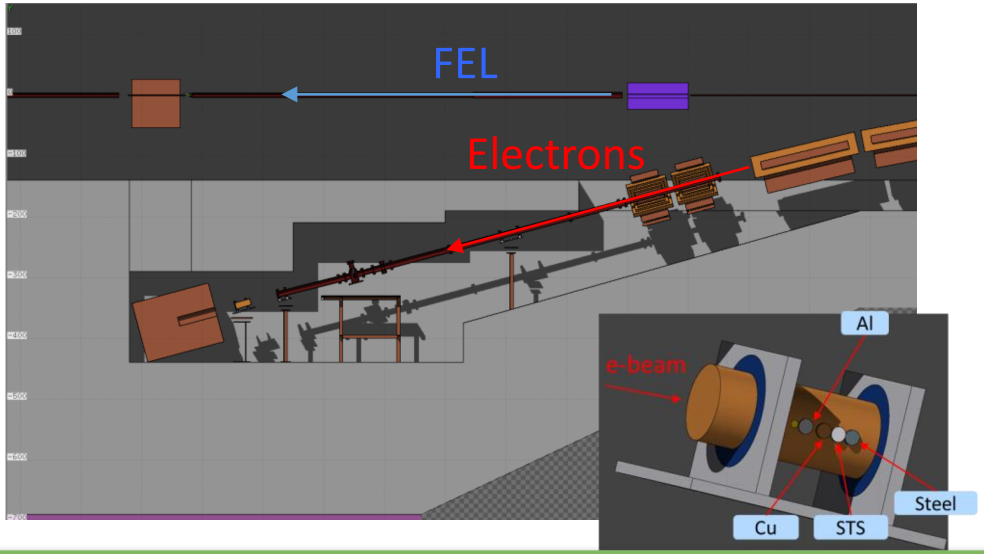
PS → INJ → ACC → App → DUMP

• Dump

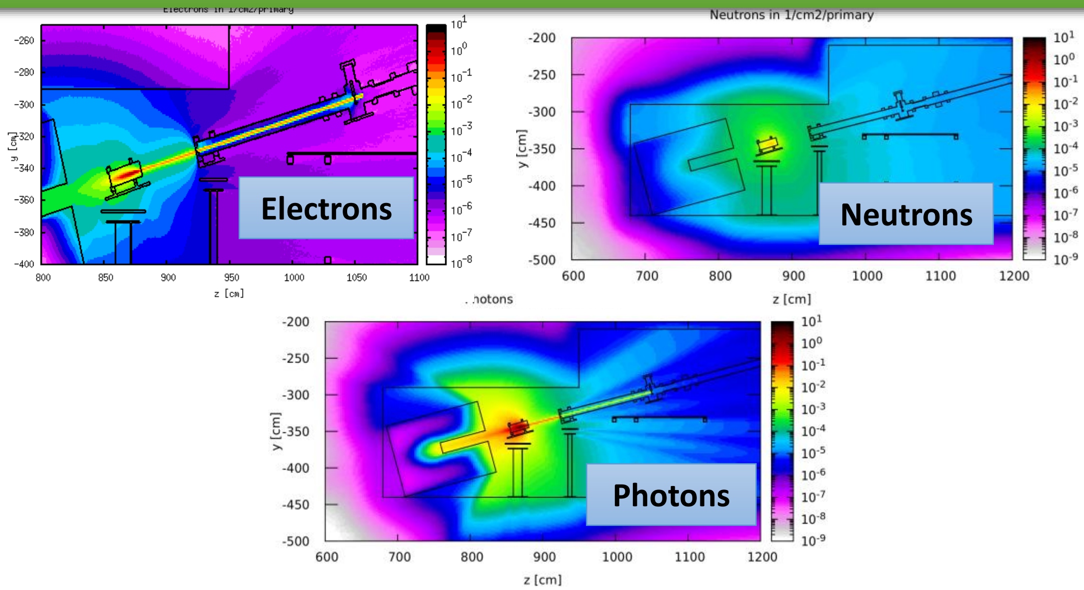
❖ PAL-XFEL







Stray Radiation Fields in XFEL Main Beam Dump Bunker by 9.6 GeV electrons using FLUKA code [1]



❖ 최대 10 GeV 전자 빔을 순식간에

✓ 빔라인에 영향을 최소화하기 위해

[1] Nam-Suk Jung, National Workshop on Radiation Safety in Particle Accelerator, 15 Nov. 2022, Seoul, Korea

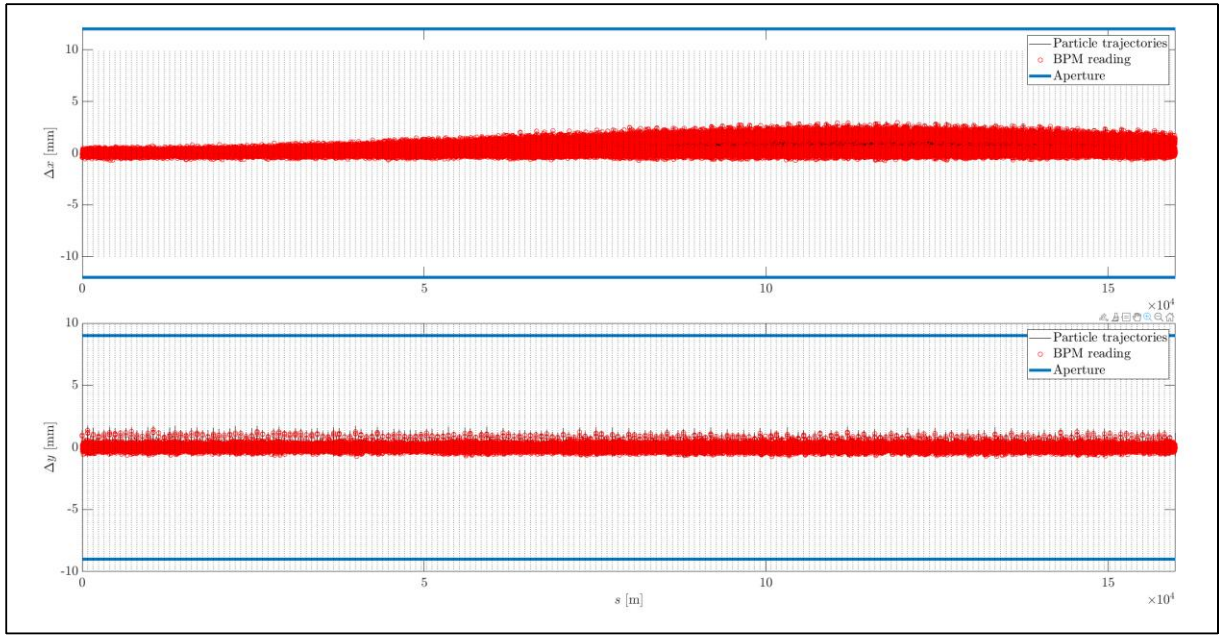
- **Dump**

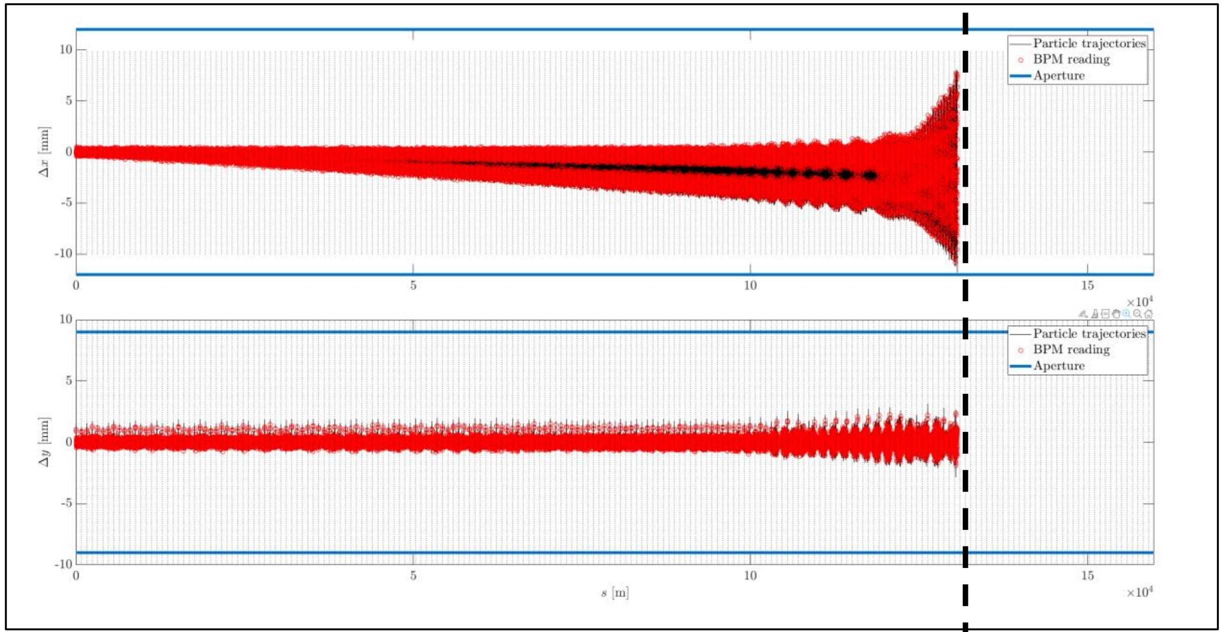
❖ **PLS-II**

➢ Dump X

➢ Turn off SRF

200 turn





RF ON

RF OFF

✓ 가로축: 전자빔 저장링 회전 수

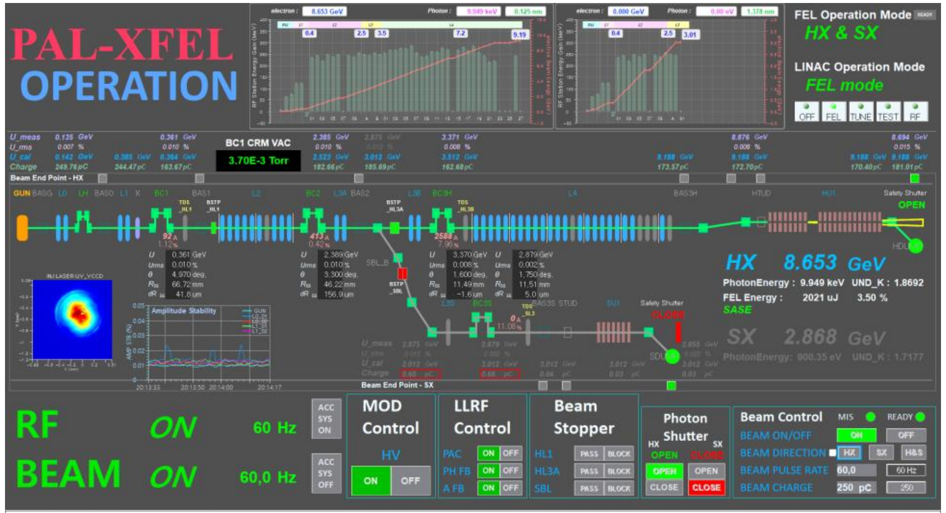
✓ 세로축: 전자빔 위치 (위/아래: X/Y)

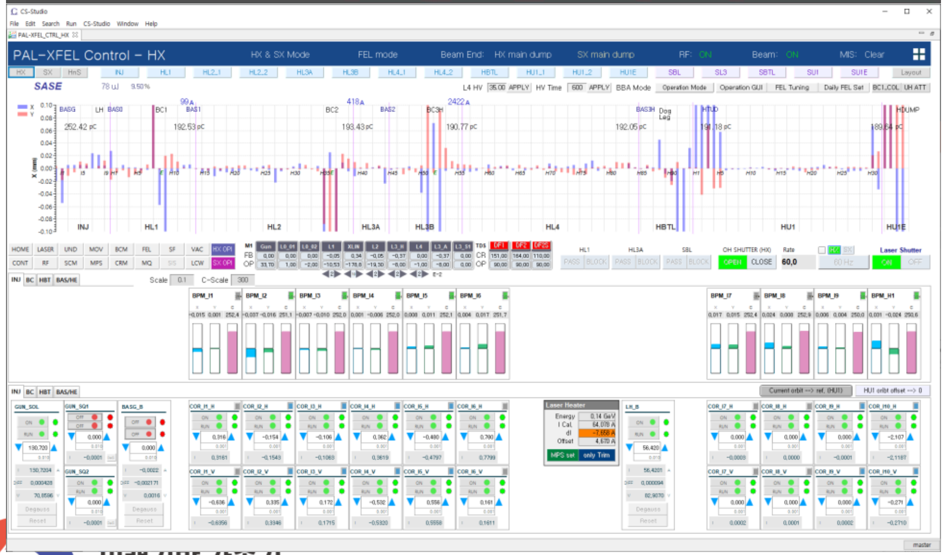
*Simulation by 김준하 (4GSR 빔물리진단제어팀)

**Lattice for 4GSR storage ring was used

• Control (PAL-XFEL)

❖ EPICS (Experimental Physics and Industrial Control System)





Category	Devices	# of Devices	Monitoring PV	Monitoring Parameters
RF	Modulator	51	1275	Klystron, HV, Interlock
	LLRF	51	357	SSA Status, Stability
Magnet	MPS	645	9675	Magnet Current, Interlock
Laser	Laser	2	20	Cleanroom Temp/RH, Power
Diagnostics	SBPM / CBPM	196	588	Beam Position, Electronics status
	CRM	4	8	Intensity
Motion	Phase shifter	28	56	Gap value, Motion status
	Quad Mover	29	58	Positon, Motion status
	Collimator	16	64	Positon, Motion status
	Beam Stopper	3	3	Position
Vacuum	Gauge	129	129	Vacuum Level
	Valve	83	83	Open/Close status
Utility	LCW	2	18	Temperature
	Chiller	1	5	Temperature
Interlock	MIS	-	92	Device Status with Hard wiring
	PSI	28	41	RMS, Tunnel Door
Etc.	Soft Interlock	-	122	Status calculation device, Beamloss
Beamline	Attenuator	1	11	Position
	Mirror	2	2	Position
	GMD	2	2	Intensity
	Total	~1.5k	~13k	

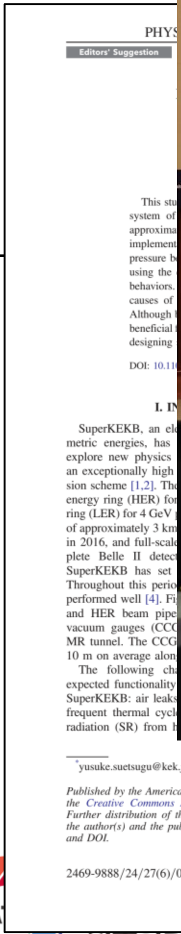
PAL-XFEL Operation Monitoring Parameter

[Ref] 허하수, 장재명, 김도하, 권영호, 온성민, 박종현, KPS' 24 (2024)

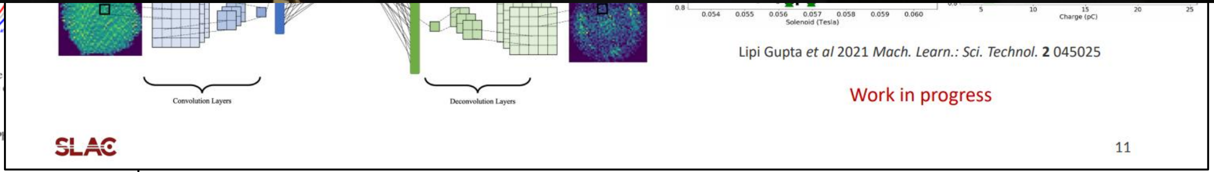
• Control + AI (Machine learning)

❖ Anomaly detection

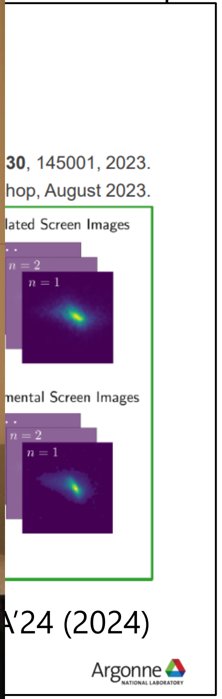
✓ 이상



❖ Optimization



❖ Diagnostics

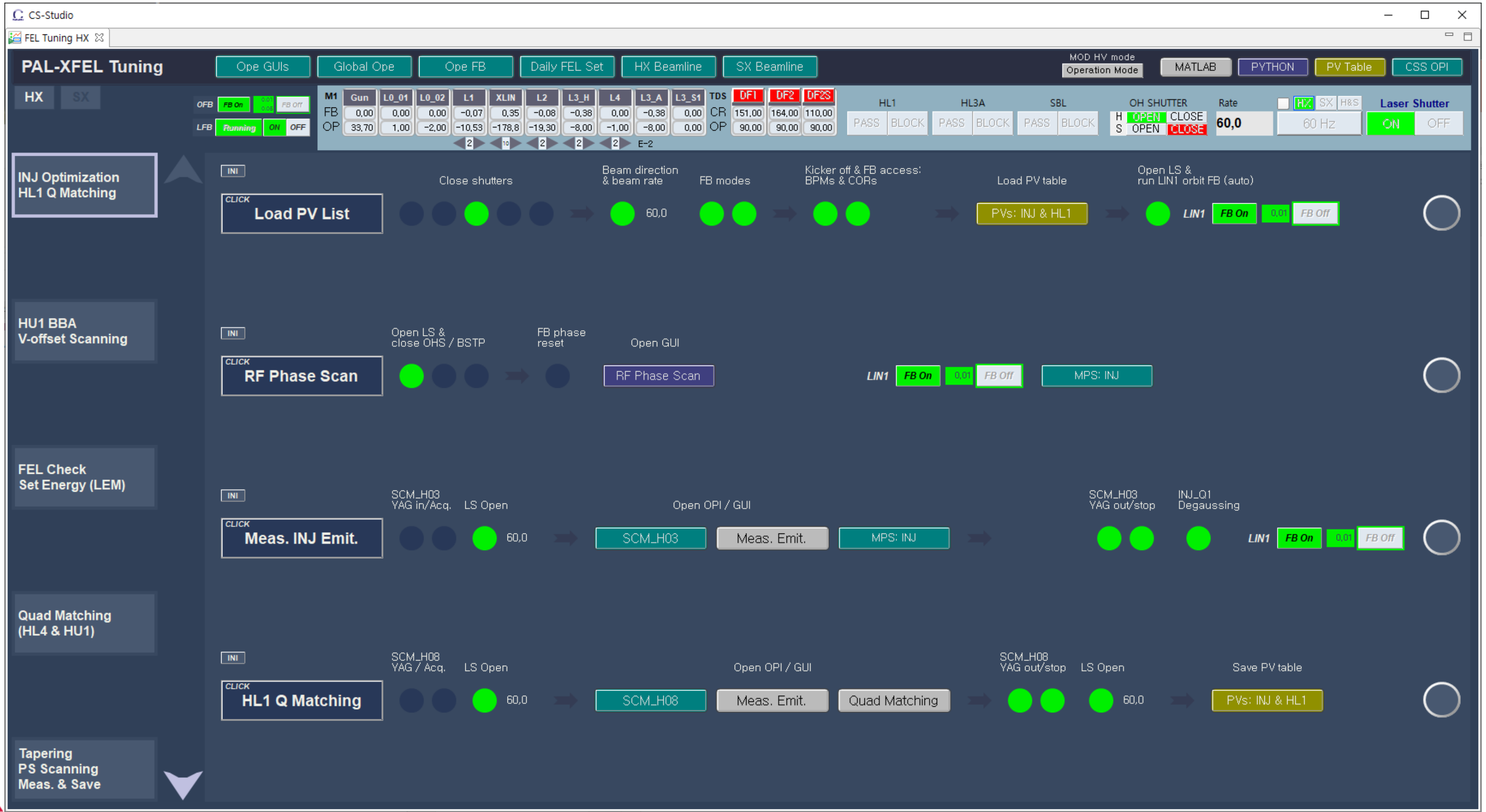


- # Operation (PAL-XFEL)

❖ Beam tuning **→ *Machine learning → 빔 최적화 효율화***

✓ 빔타임 직전 하루동안 빔 최적화 → 최소 10~12시간 소요 (*한 개의 빔 최적화 시, 예: 9.5 keV*)

✓ 2 개 이상 에너지 요구하는 경우 새벽 3시~ 이후 종료 (*예: 5.0 keV, 10.0 keV & SX*)



FEL Tuning - HX

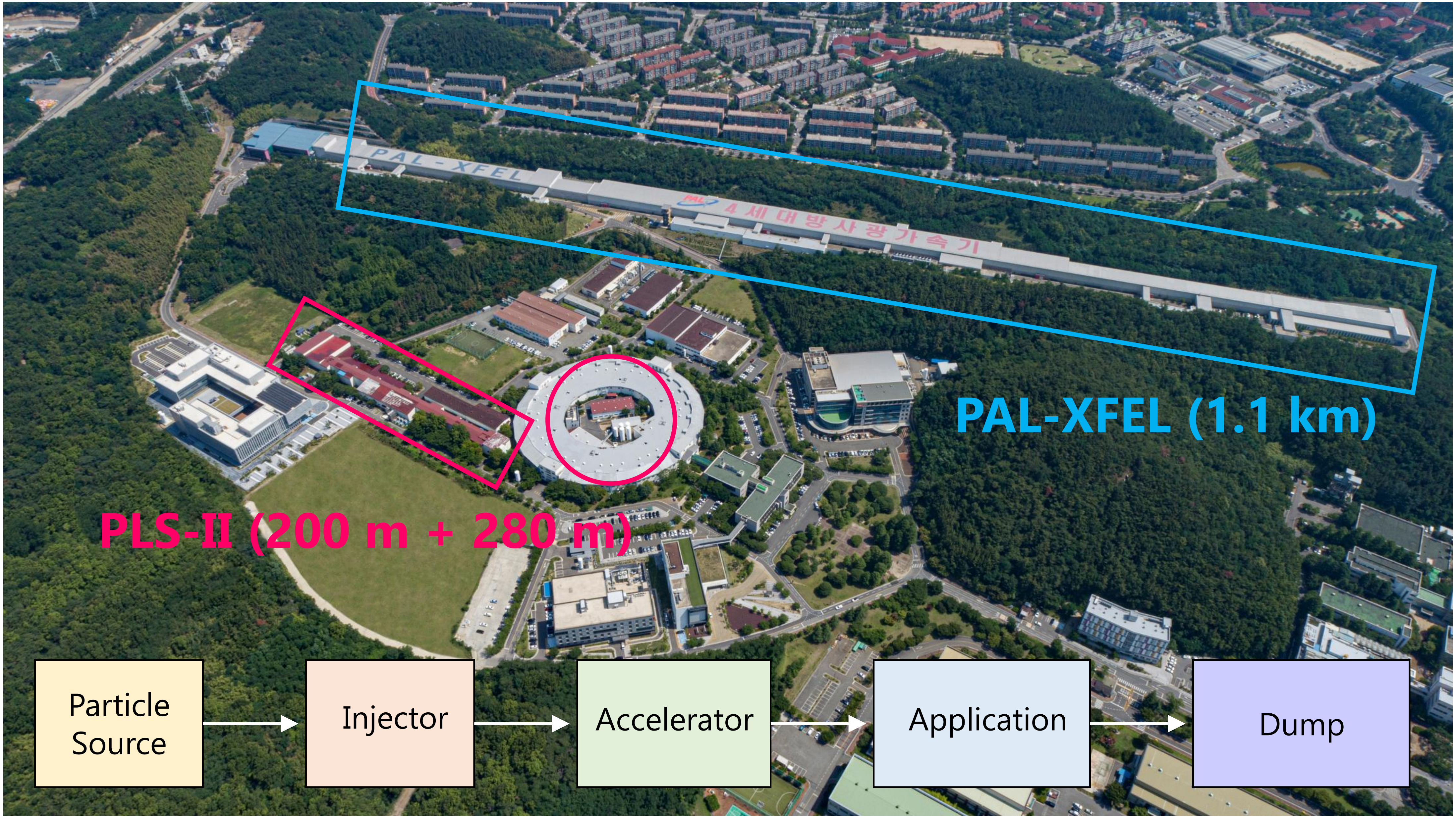
문서 토론

(PAL-XFEL HX Tuning에서 넘어옴)

목차 숨기기

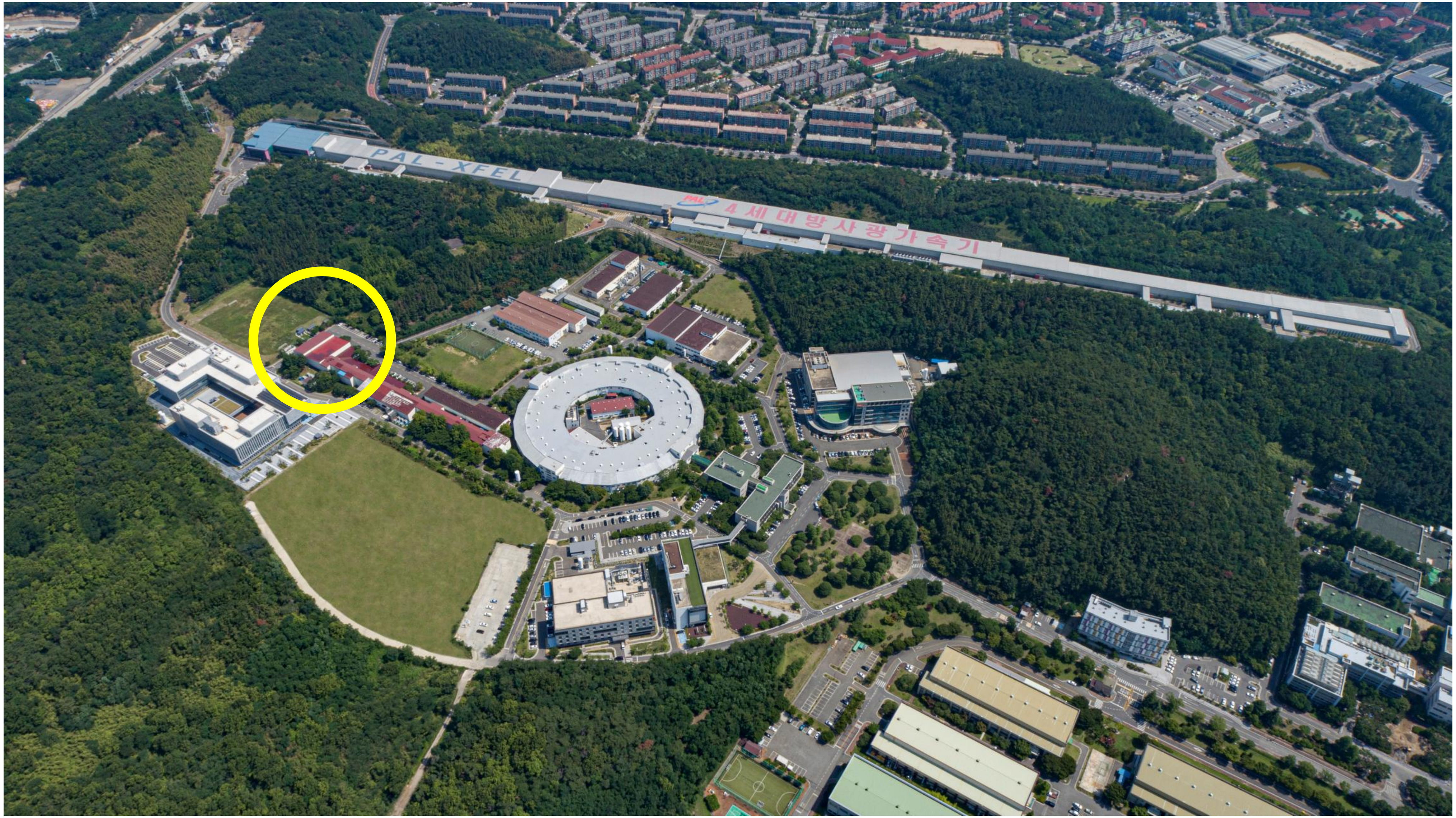
1 Introduction
2 FEL Tuning Procedure
3 Electron Beam Optimization (Accelerator)
3.1 Injector (INJ) Optimization
3.1.1 Emittance Measurement
3.2 HL1 Optimization
3.2.1 OPI - HL1 Q Matching
3.2.2 HL1 Emittance Measurement
3.2.3 HL1 Q Matching
3.3 HL4 Optimization
3.3.1 Set Linac Energy
3.3.1.1 HL4 Emittance Measurement
3.3.1.2 HL4 Q Matching
3.4 HU1 Optimization
3.4.1 HU1 Q Matching
4 Photon Optimization (Undulator)
4.1 Undulator BBA
4.1.1 Instruction
4.1.1.1 HU1 BBA
4.1.1.2 Energy Change
4.2 Undulator V-Offset Scanning
4.2.1 Instruction
4.3 Undulator Tapering
4.4 Phase Shifter (PS) Scanning
4.5 Self-Seeding (SS)
4.5.1 Instruction
5 FEL Measurement
5.1 E-loss Scanning
5.2 Spectral Bandwidth
5.3 Pulse Duration

Summary

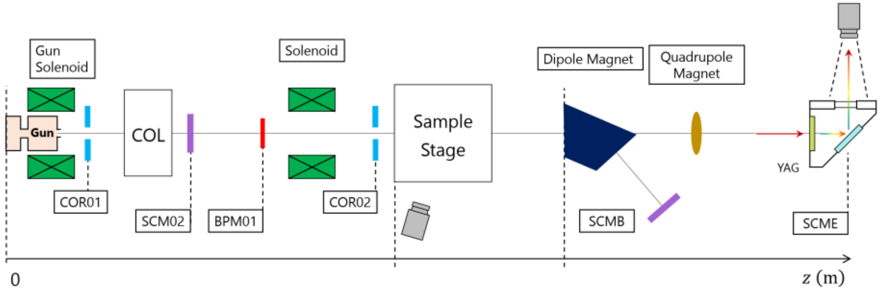

PAL-XFEL
4세대방사광가속기
PAL-XFEL (1.1 km)
PLS-II (200 m + 280 m)
Particle Source
Injector
Accelerator
Application
Dump

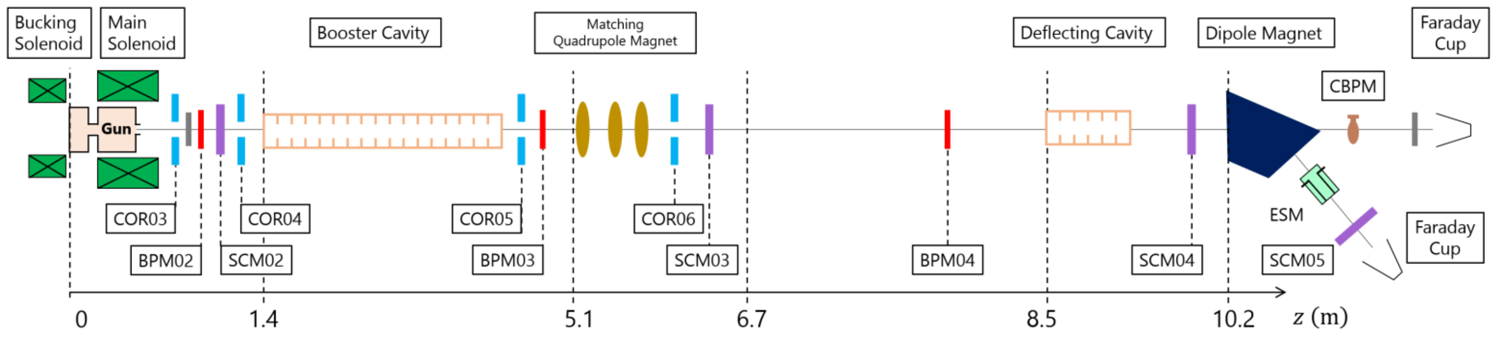
- 가속기의 구성
- PAL eLABs 소개
- 가속장치 데모 및 eLABs 를 이용한 실습

Electron Linear Accelerator for Basic Science



▪ Introduction to PAL eLABs

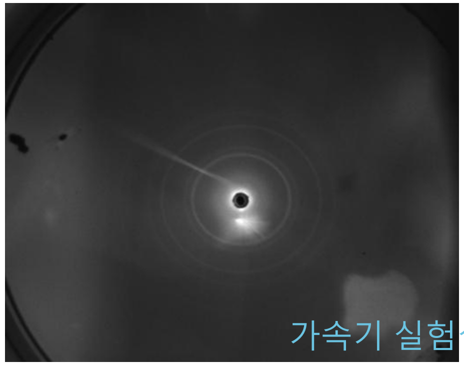




➢ MeV-UED* experiment

- ✓ Beam energy: 3-5 MeV
- ✓ Beam charge < 1 pC

- Experimental demonstrations
  - ✓ Al, MoO3, Bismuth samples



*Ultrafast electron diffraction

➢ Advanced accelerator researches

- ✓ Beam energy < 70 MeV
- ✓ Beam charge < 300 pC

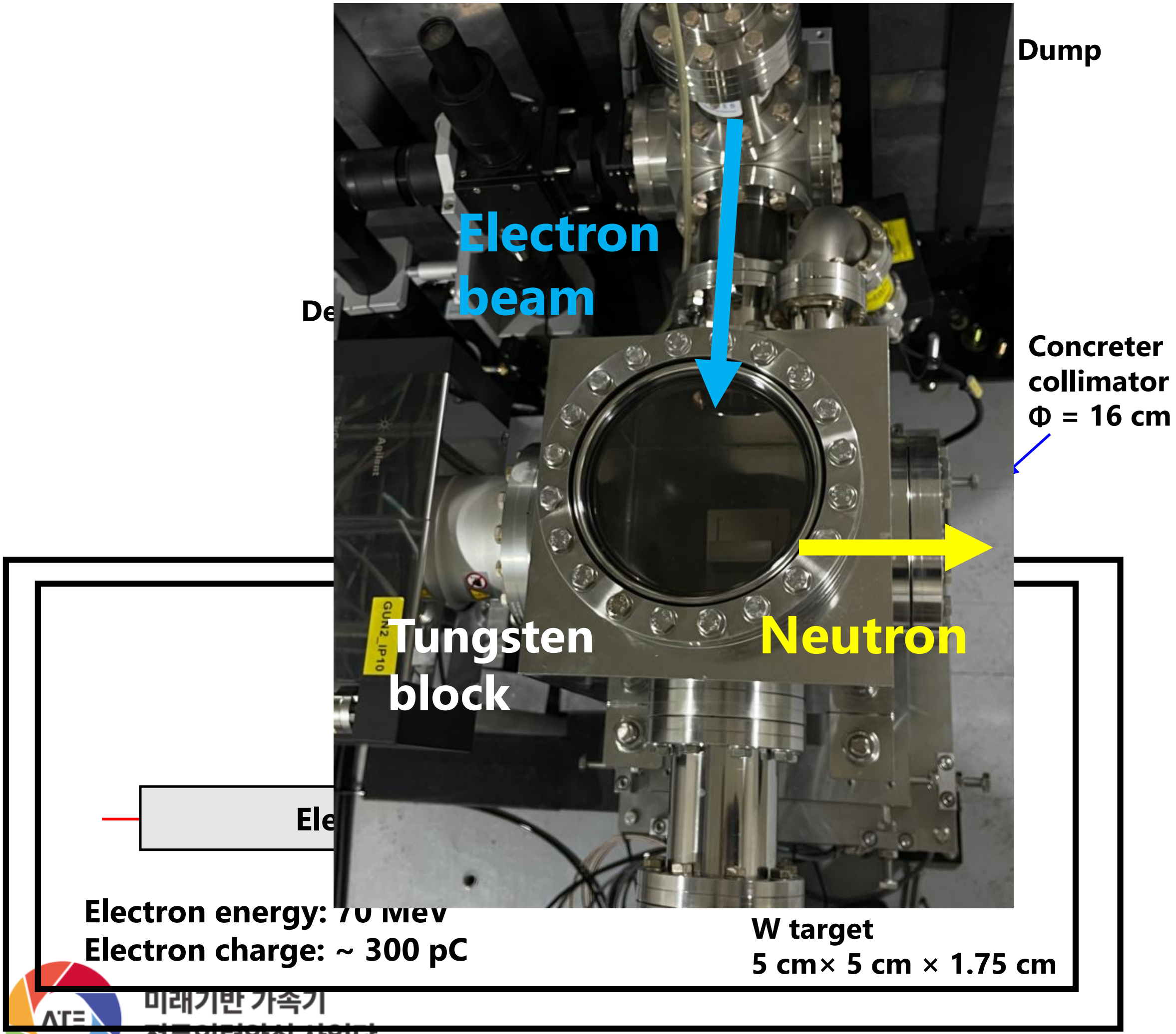
- Research plans
  - ✓ Demonstration of various beam diagnostic systems
  - ✓ Photoneutron production and detection
  - ✓ Cherenkov radiation monitor

▪ Photoneutron Production and Detection (Mahdi Bakhitari) @2023-05

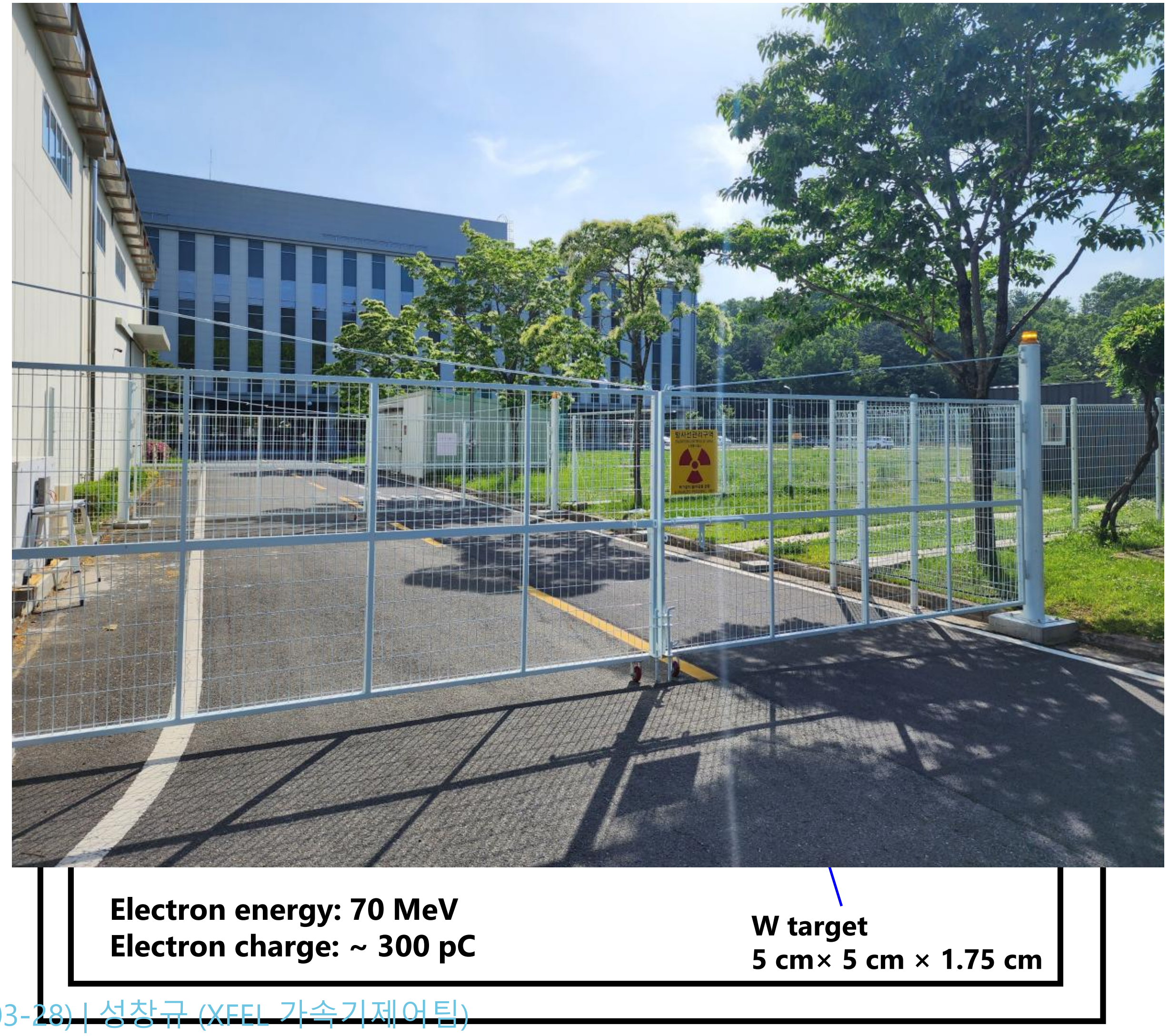
✓ eLABs linac operation (70 MeV)

- Measurement using neutron time of flight (TOF) method

1- Fast neutron measurement setup



2- Thermal neutron measurement setup



▪ 가속장치 데모 및 eLABs 를 이용한 실습

- ➢ Microwave measurement for pillbox cavity
  - ✓ Resonant frequency, quality factor (*VNA), impedance (using **TDR)
- ➢ Beam position monitoring using conducting wire
- ➢ Electron beam operation of eLABs

*VNA: Vector network analyzer

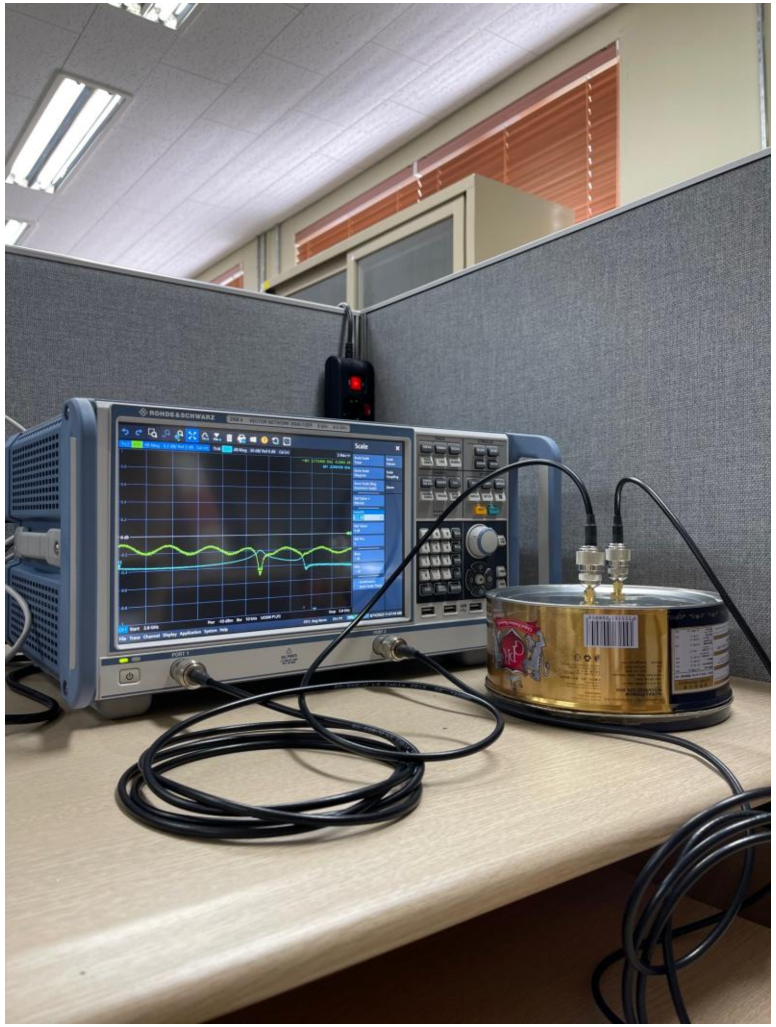
**TDR: time domain reflectometry

▪ Microwave measurement for pillbox cavity

- ➢ Pillbox cavity: Normal conducting standing wave cavity

- ➢ Microwave measurement:
  - ✓ Resonant frequency
  - ✓ Quality factor
  - ✓ Frequency tuning
  - ✓ Impedance

❖ Vector network analyzer (VNA) & time domain reflectometry (TDR)



▪ Figure of merit (성능지수) for cavity

❖ 가속관이 제 역할을 할 수 있는지 평가하는 지수

➢ Resonant frequency (공진 주파수): Cavity 구조와 연관

→ Cavity = RLC 회로 → Cavity 구조는 Inductance (L) & Capacitance (C) 와 연관

✓ Frequency tuning (Mechanical, cooling temperature)

➢ Quality factor (Q): 가속 전압을 얼마나 정확한 주파수로 전송하고 얼마나 오래 유지하는지

✓ 가속 전압의 시간에 대한 손실률 (Time domain)

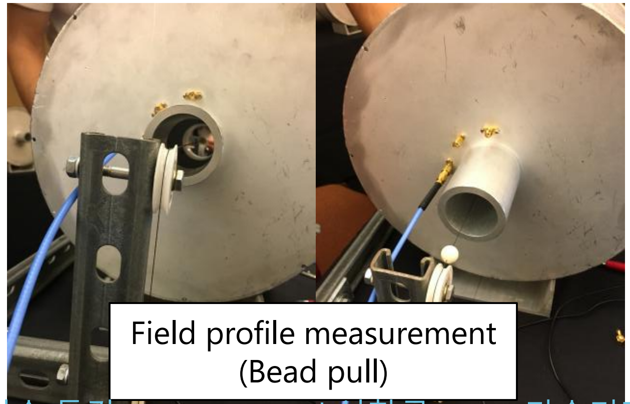
$$Q = \frac{\text{Energy stored in cavity}}{\text{Time average power loss}} = \frac{2\pi f_0 U}{P_{\text{loss}}}$$

✓ 공진 주파수와 3 dB bandwidth 간의 비율 (Frequency domain)

$$Q = \frac{f_0}{\Delta f}$$

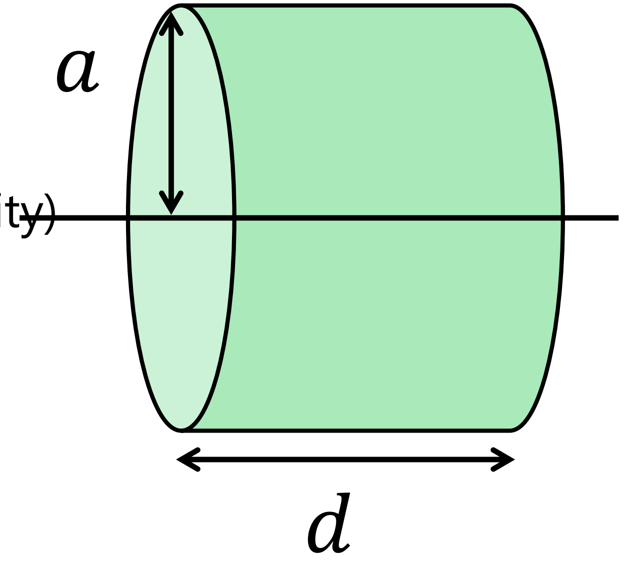
→ $Q = 10^6$: 100 MHz 공진 주파수에 100 Hz bandwidth

➢ Field profile (bead-pull method)



Field profile measurement
(Bead pull)

▪ Resonance frequency of pillbox cavity



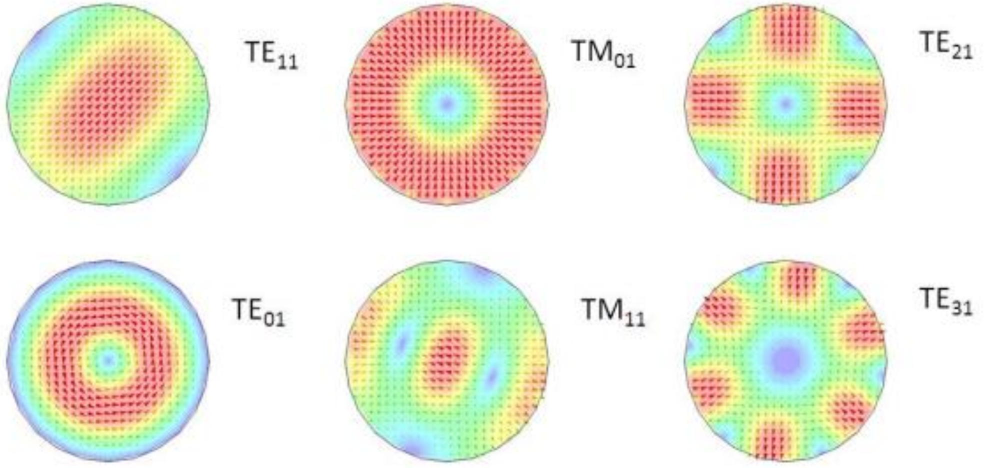
1. Maxwell's equations with boundary conditions for cavity (cylindrical conducting cavity)
2. Time-varying electromagnetic field (wave) in the cavity
3. Frequency of EM wave depends on the **mode** (due to periodicity)
   - ❖ Transverse electric (TE) mode = *No longitudinal electric field*
   - ❖ Transverse magnetic (TM) mode = *No longitudinal magnetic field*
   - ❖ *Transverse electromagnetic (TEM) mode: Coaxial structure*
4. Resonance frequency for pillbox cavity (TE_{nml}, TM_{nml} modes)

$$f_{nml}^{TE} = \frac{c}{2\pi}\sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}$$

$$f_{nml}^{TM} = \frac{c}{2\pi}\sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}$$

*p'_{nm}, p_{nm}: roots of the $J'_n(k_c a), J_n(k_c a)$, respectively

Electric field lines from CERN accelerator school



▪ Geometry of pillbox cavity (실습)

$$f^{TE}_{nml} = \frac{c}{2\pi}\sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}$$

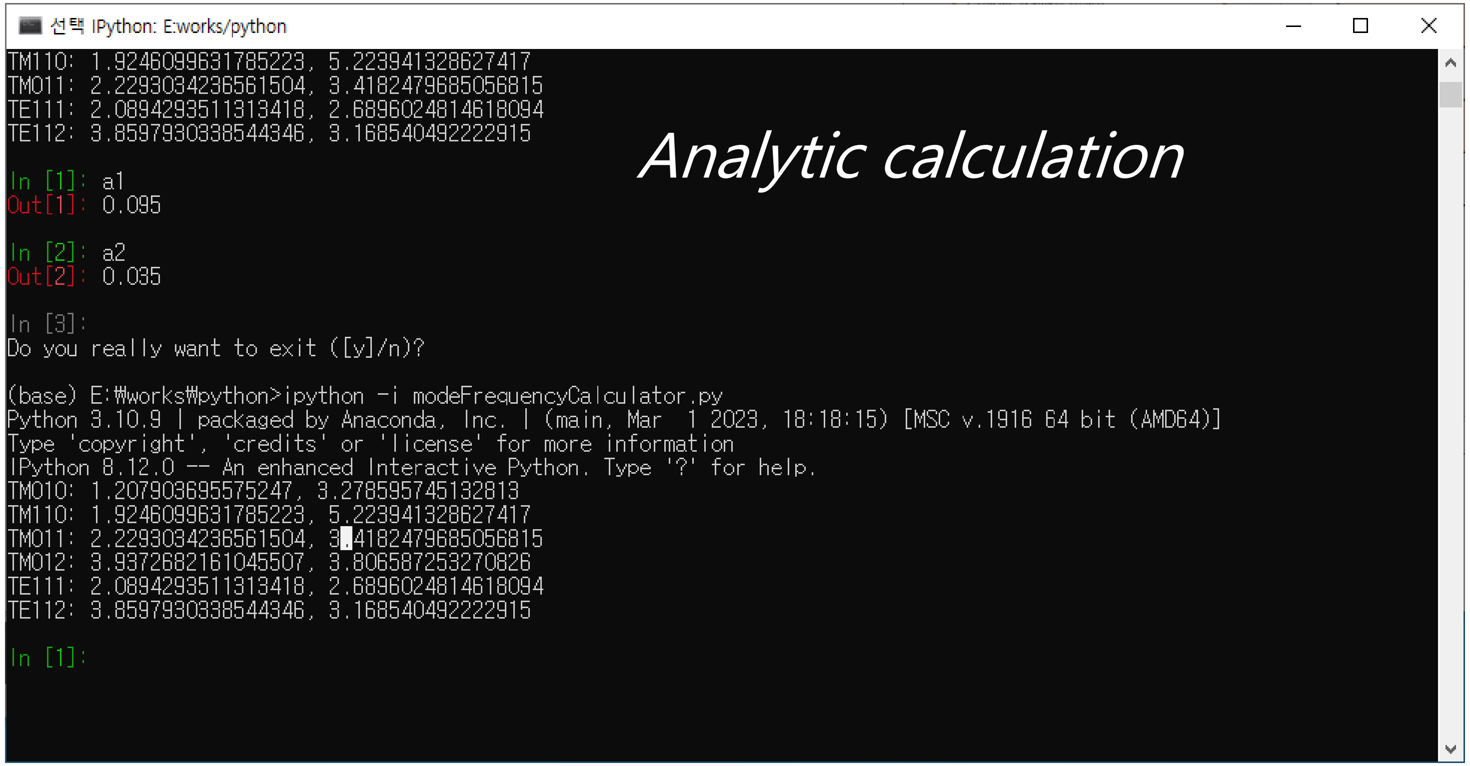
$$f^{TM}_{nml} = \frac{c}{2\pi}\sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}$$

	Cavity 1	Cavity 2
반지름 (mm)	95	35
길이 (mm)	80	155
주파수 (GHz)	1.207 (TM010) 1.922 (TM110) 2.080 (TM011) 2.412 (TE111) 2.575 (TE112)	2.686 (TE111) 3.161 (TE112) 3.275 (TM010) 3.415 (TM011) 3.731 (TM012)

Fundamental mode → 1.207 (TM010) / 2.686 (TE111)

	p'_{nm}			p_{nm}		
n	p'_{n1}	p'_{n2}	p'_{n3}	p_{n1}	p_{n2}	p_{n3}
0	3.832	7.016	10.174	2.405	5.520	8.654
1	1.841	5.331	8.536	3.832	7.016	10.174
2	3.054	6.706	9.970	5.135	8.417	11.620

▪ Resonance frequency estimation



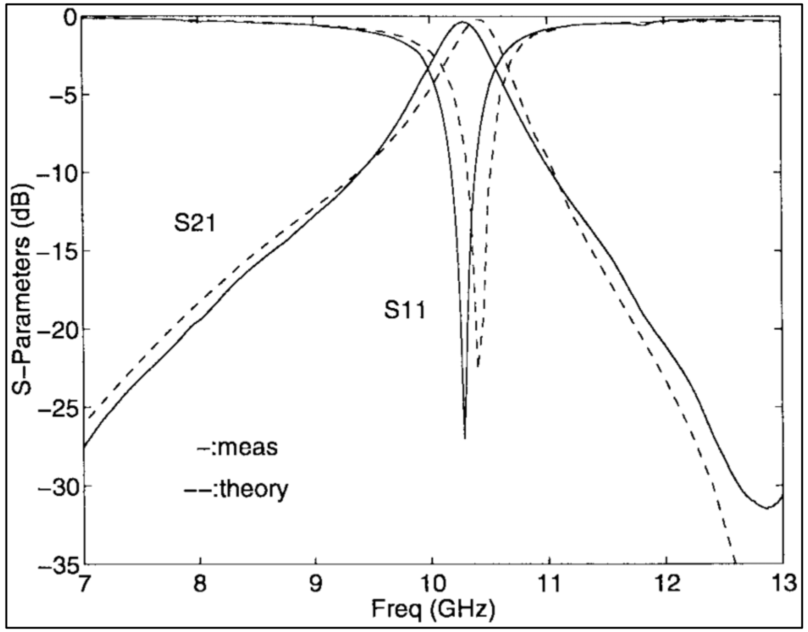
Mode	Frequency	Mode	Frequency
1	1.2073e+00 GHz	1	2.6863e+00 GHz
2	1.9223e+00 GHz	2	2.6864e+00 GHz
3	1.9223e+00 GHz	3	3.1608e+00 GHz
4	2.0802e+00 GHz	4	3.1610e+00 GHz
5	2.0802e+00 GHz	5	3.2755e+00 GHz
6	2.2205e+00 GHz	6	3.4150e+00 GHz
7	2.4127e+00 GHz	7	3.7311e+00 GHz
8	2.4231e+00 GHz	8	3.7998e+00 GHz
9	2.5746e+00 GHz	9	3.8129e+00 GHz
10	2.5998e+00 GHz	10	3.8130e+00 GHz

CST simulation (Eigenmode solver)

▪ Quality factor evaluation

- S parameter (Scattering parameter)
  - ✓ 입력 신호 대비 출력 신호의 비율
  - ✓ S_{ab}: a = 출력 신호 포트 / b = 입력 신호 포트

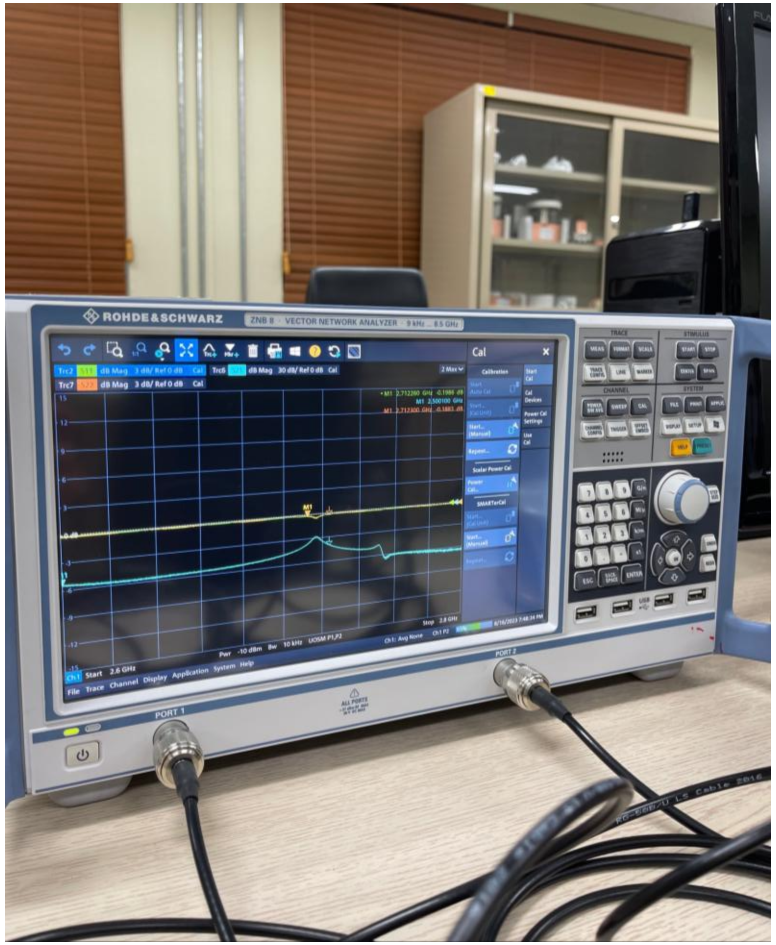
    ex) S11 반사특성, S21 투과특성



▪ Instructions for using VNA

➢ VNA measures the response of device to the signal in frequency domain

1. 주파수 범위 설정 (ex: 1 GHz ~ 3 GHz)
   ➢ 계산한 공진 주파수 범위에 맞게
2. Calibration (케이블 손실 등 보정)
3. DUT (Device Under Test) 연결 후 측정
   → S11, S21, S22
4. Marker 를 이용해서 S11이 최소가 되는 주파수 탐색
5. 공진 주파수 중심으로 Bandwidth 계산해서 Quality factor 측정
6. 주파수 범위를 좁혀가며 반복

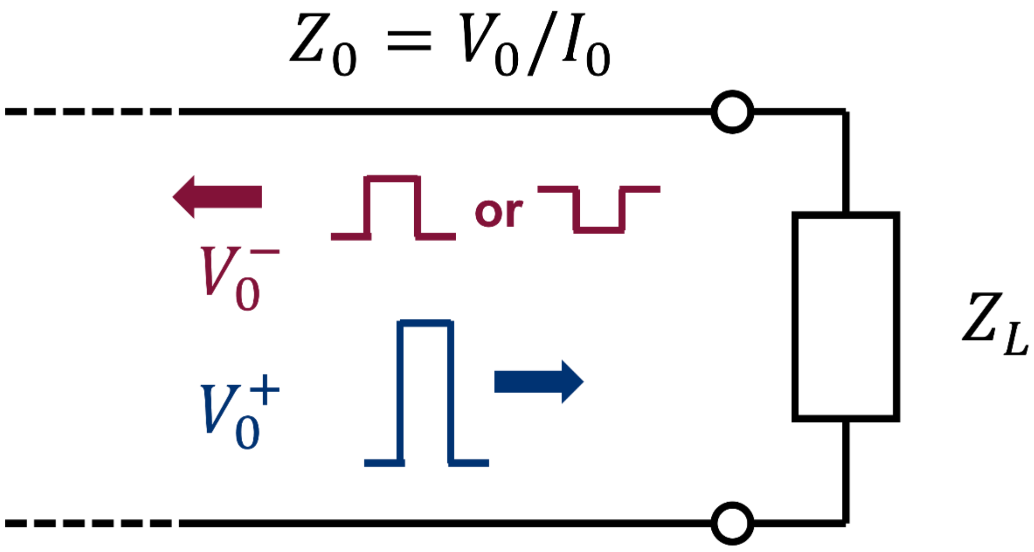


▪ Time domain reflectometry (TDR)

➢ TDR measures the response of device to the signal in time domain

✓ Discontinuous impedance reflects the incident (voltage) wave flowing through the transmission line

✓ Amplitudes of incident and reflected wave
→ Impedance of device under test



$$Z_L = \frac{V_0^+ + V_0^-}{V_0^+ - V_0^-} Z_0$$

✓ Z_L: Impedance of stripline

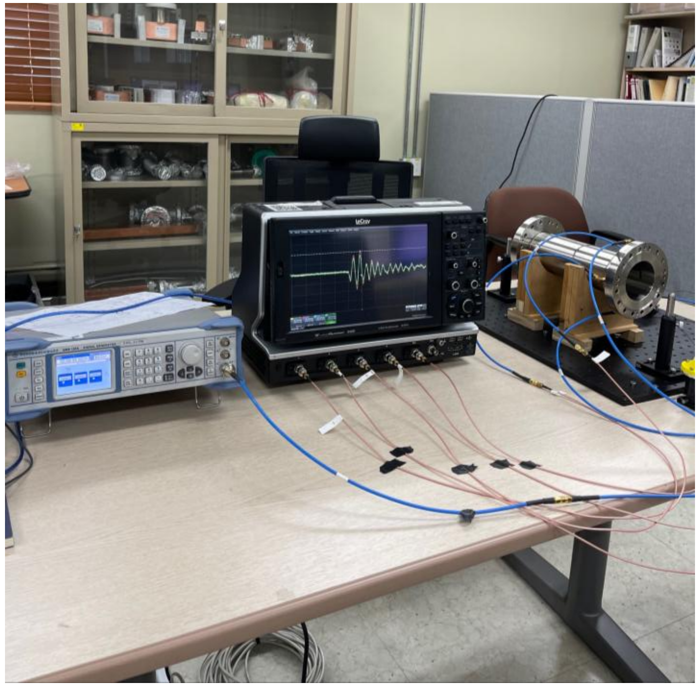
✓ Z_0: Impedance of transmission line (50 Ω)

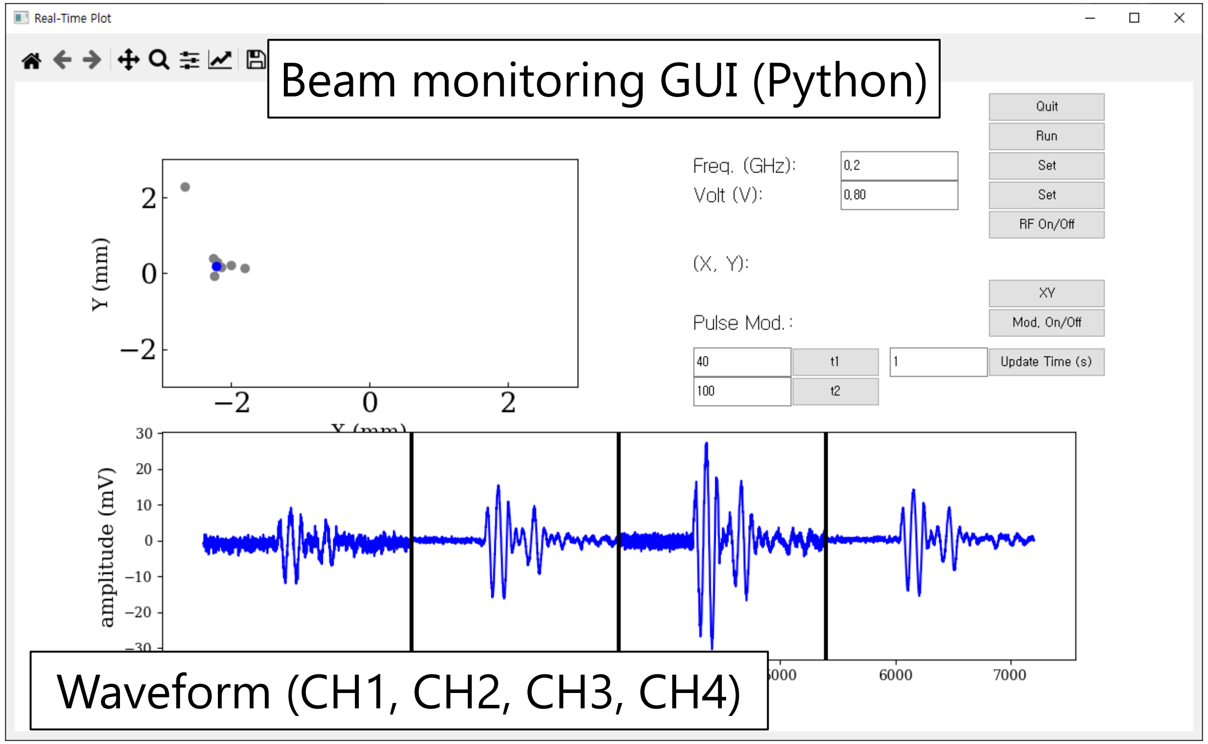
✓ V_0^+: Incident voltage wave amplitude

✓ V_0^-: Reflected voltage wave amplitude

▪ Beam position monitoring with conducting wire

- ✓ Move the conducting wire in the BPM
- ✓ Change signal amplitude (beam charge)
- ✓ Move the BPM with fixed wire (alignment)





CH1: +X
CH2: +Y
CH3: -X
CH4: -Y

▪ Principle of beam position monitoring (Pickup)

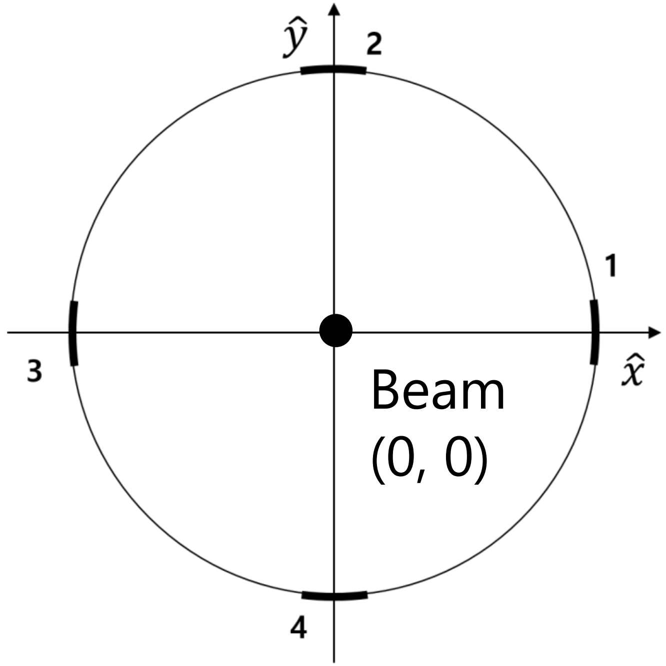
➢ Pickup BPM: Button-type BPM, Stripline-type BPM

✓ 4 채널에서 빔이 만드는 전기 신호를 측정

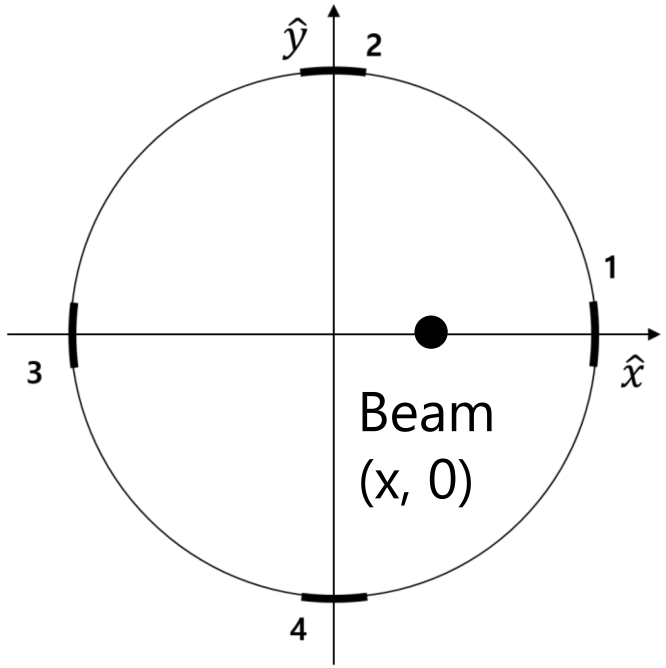
✓ 측정 신호 크기의 비교를 통해 빔의 위치 확인

→ 측정 신호 크기가 같다 = 빔이 중심에 있다

→ 측정 신호 크기가 다르다 = 빔이 중심으로부터 이동했다

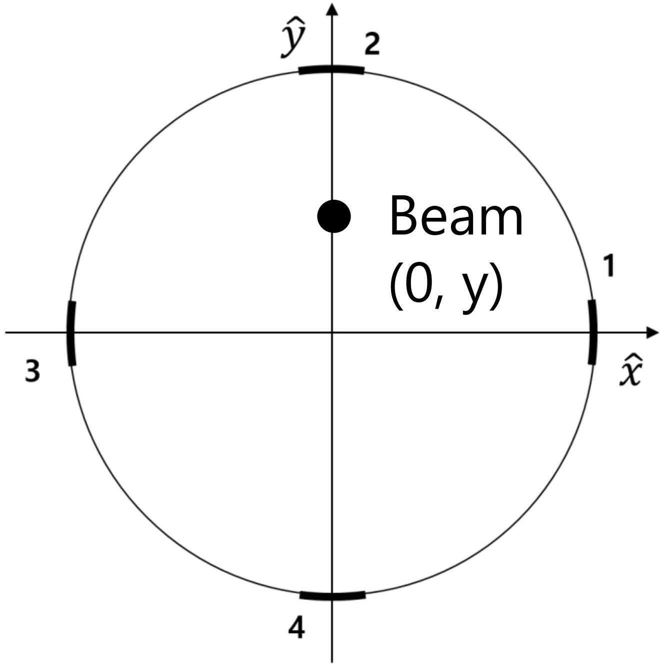


$V_1 = V_2 = V_3 = V_4$



$V_2 = V_4 \quad V_1 > V_3$

$(V_1 - V_3) \sim A\Delta x$



$V_1 = V_3 \quad V_2 > V_4$

$(V_2 - V_4) \sim B\Delta y$

- **Start-to-end operation of eLABs**

Q&A