Hard X-ray FEL Lasing Through BBA and Radiation Spectrum Analysis

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On behalf of PAL-XFEL commissioning team

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- Introduction to PAL-XFEL
- e-BBA
- Radiation spectrum analysis
- PAL-XFEL commissioning status
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PAL-XFEL

0.1 nm hard X-ray FEL using a 10 GeV normal conducting linac

Apr. 2011: PAL-XFEL project started
Jun. 2012: Ground-breaking
Dec. 2014: Building completed
Jan. 2016: Installation completed
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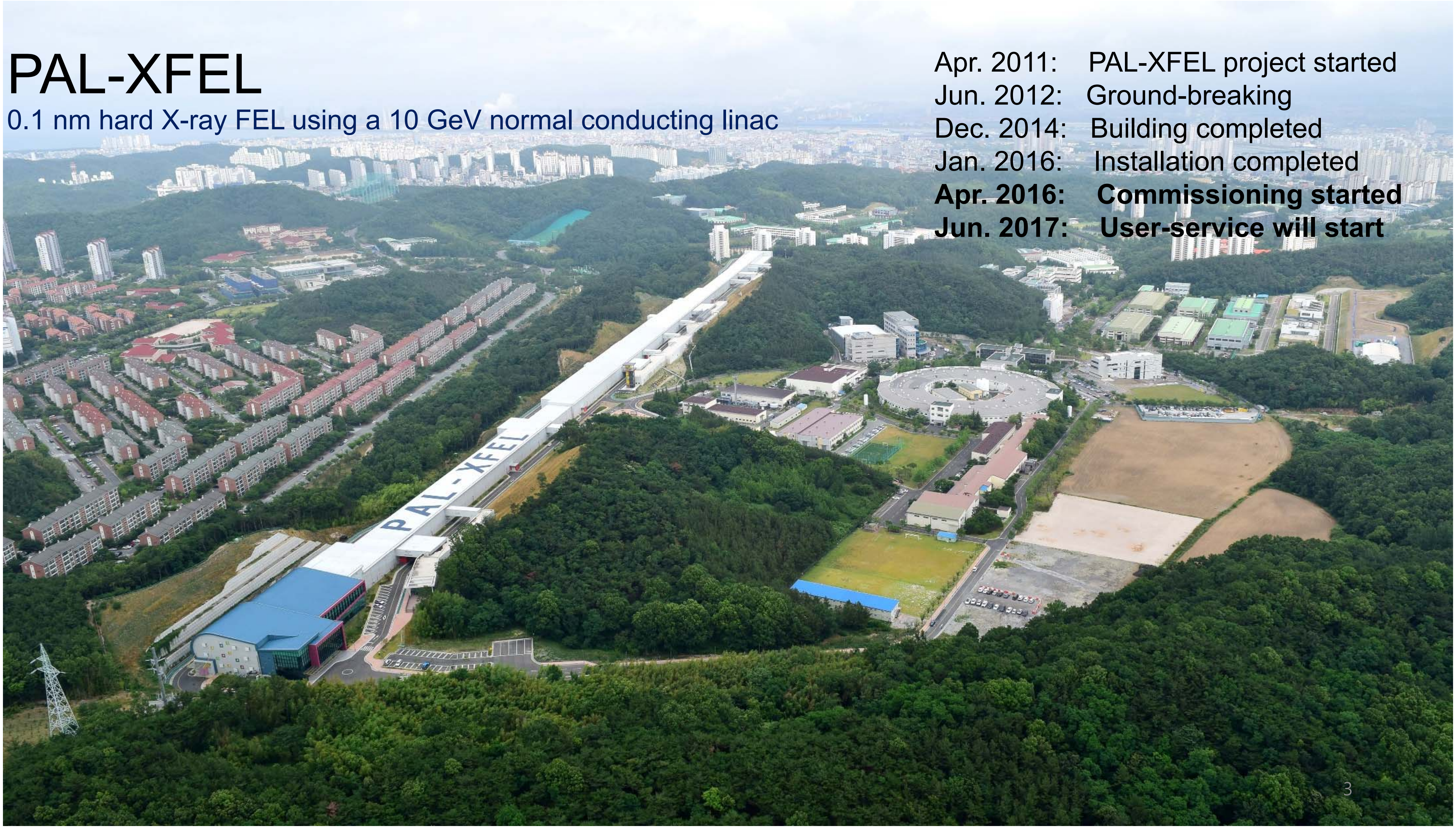
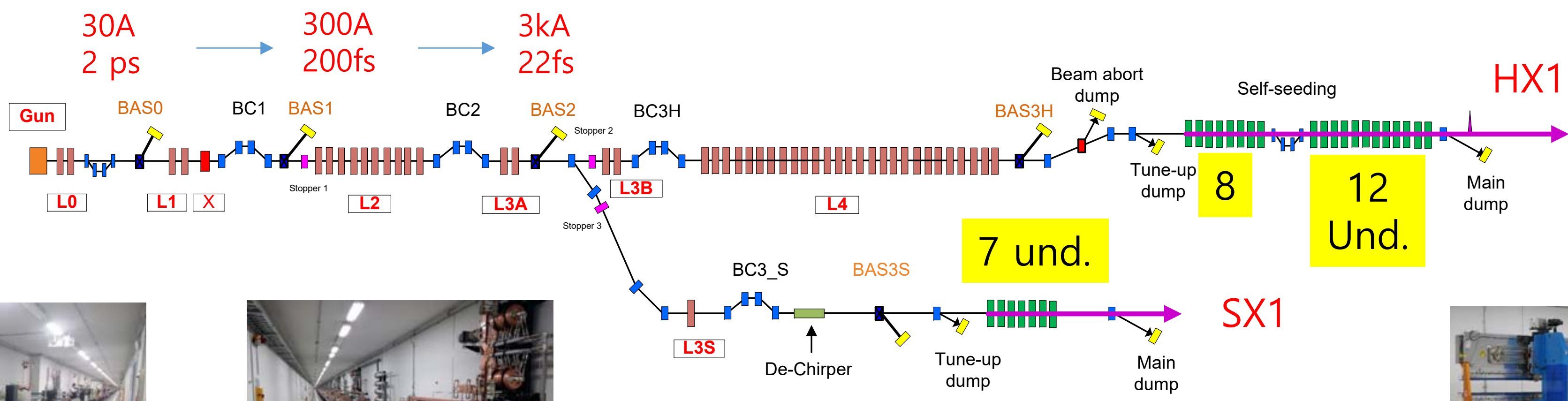
Jun. 2017: User-service will start



PAL-XFEL Parameters

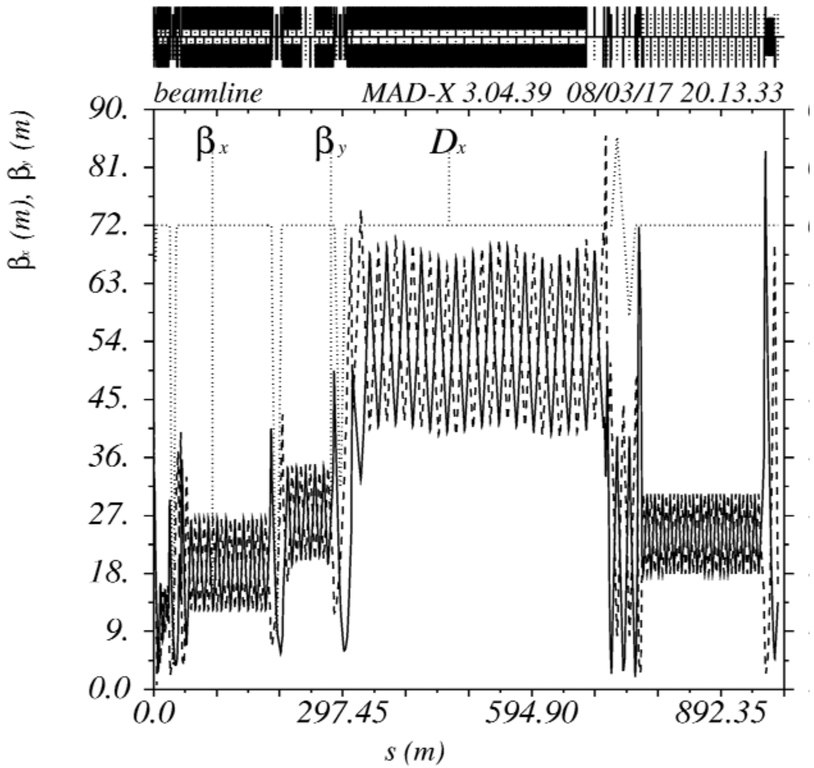


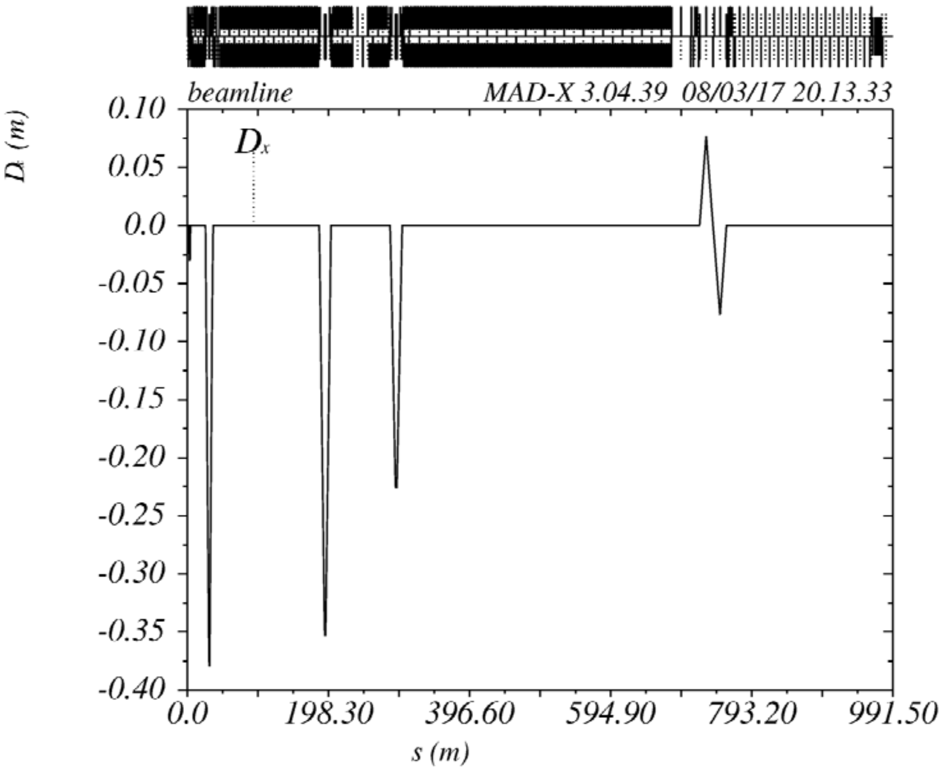
Main parameters

e^- Energy	10 GeV
e^- Bunch charge	20-200 pC
Slice emittance	0.5 mm mrad
Repetition rate	60 Hz
Pulse duration	10 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

Undulator Line	HX1	SX1
Wavelength [nm]	0.1 ~ 0.6	1 ~ 4.5
Beam Energy [GeV]	4 ~ 10	3.15
Wavelength Tuning [nm]	0.6 ~ 0.1 (energy or gap)	4.5 ~ 3 (energy) 3 ~ 1 (gap)
Undulator Type	Planar, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 8.3

Lattice Function



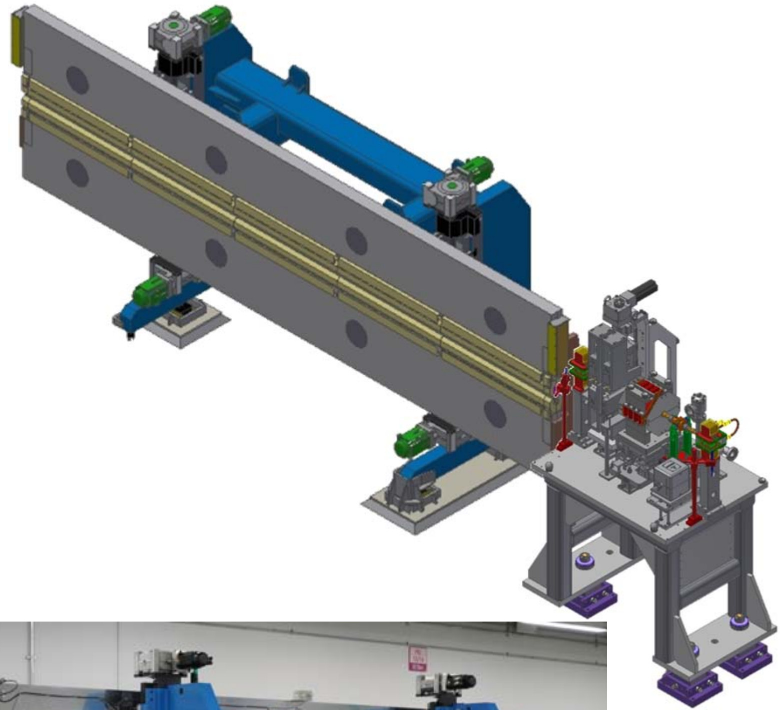


Klystron Gallery

Linac Tunnel

Undulator Hall

Undulator Design



- We adopted the European XFEL undulator design, which features a 5-m-long, planar, permanent magnet and an out-vacuum variable-gap undulator
- and modified its magnet design according to the PAL-XFEL undulator parameters

Symbol	Unit	Nominal value
E	GeV	10.000
g	mm	8.30
λ_u	mm	26.0
L_{und}	m	5.0
λ_r	nm	0.1
B_{eff}	Tesla	0.8124
K		1.9727
Optical phase error	degree	less than 5.0

Why we need e-BBA & K-tuning?

- **SASE FEL** is an interactive process between e-beam and photon beam through 100-m long undulators.
- **Dispersion-free orbits** straight to within a few micrometres over the gain length is required to maximize the **spatial overlap between the electron and photon beams**.

  - **e-beam based BBA** (LCLS, fixed gap undulator)

  - **photon beam based BBA** (SACLA, variable-gap in-vacuum undulator)
- **PAL-XFEL: variable gap out-vacuum undulator**
  - **e-BBA**
  - **Radiation spectrum analysis (K-tuning)**
- **Radiation spectrum analysis**

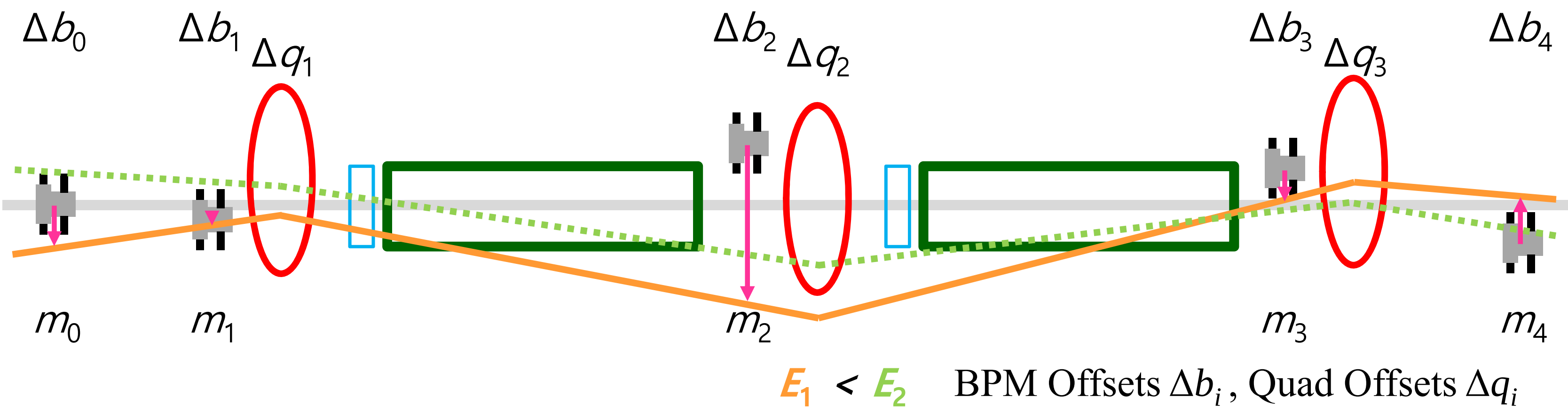
  -> accurate gap distances for *K* in each undulator segment

  -> undulator field centre offsets,

, which is particularly critical for variable-gap undulators.

Electron beam-based BBA (1)

- BBA measurement algorithm
  - Henrik Loos, LCLS FAC, June 8, 2009)
  - P. Emma *et al.* Beam-based alignment for the LCLS FEL undulator. *NIM* A **429**, 407-413 (1999).

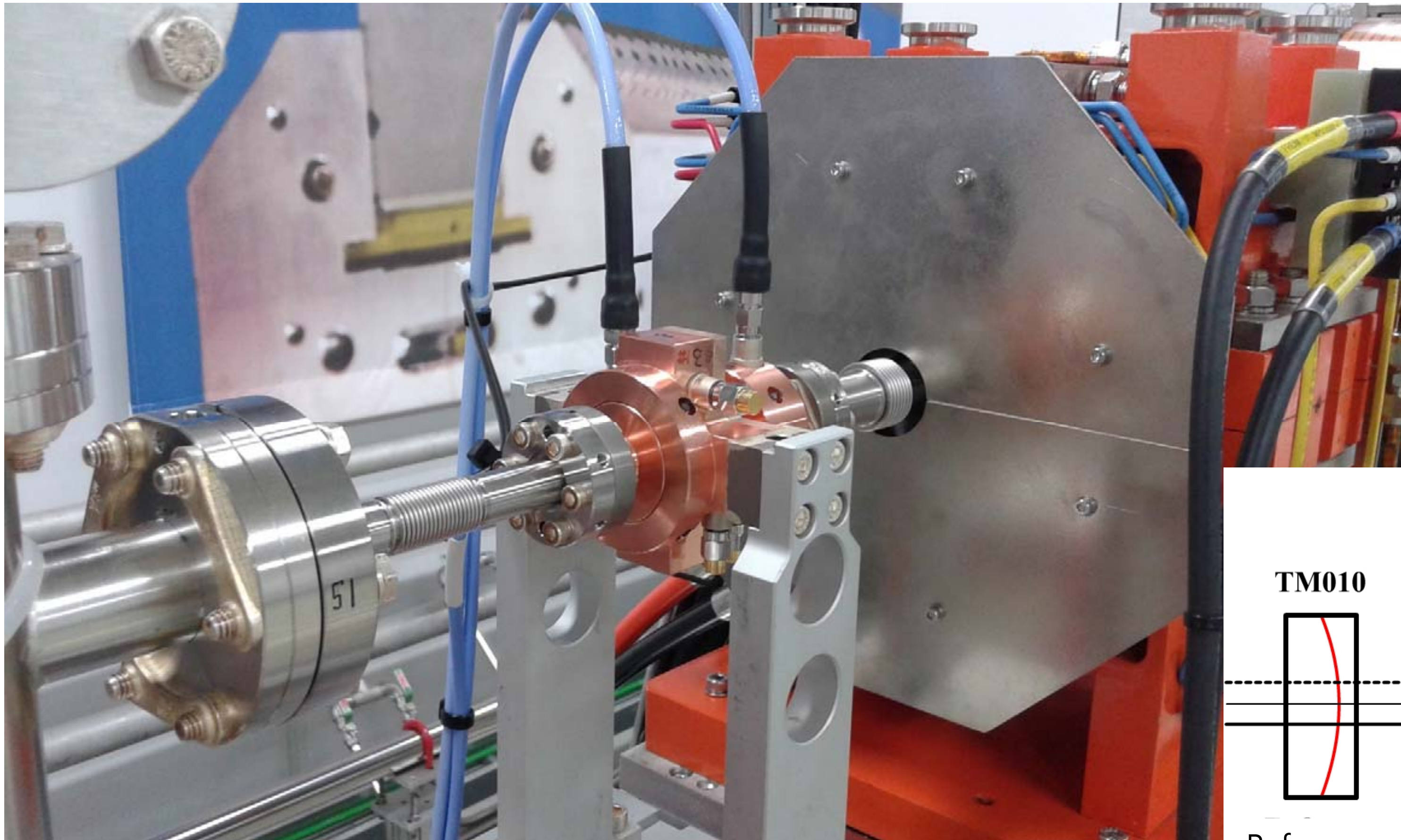


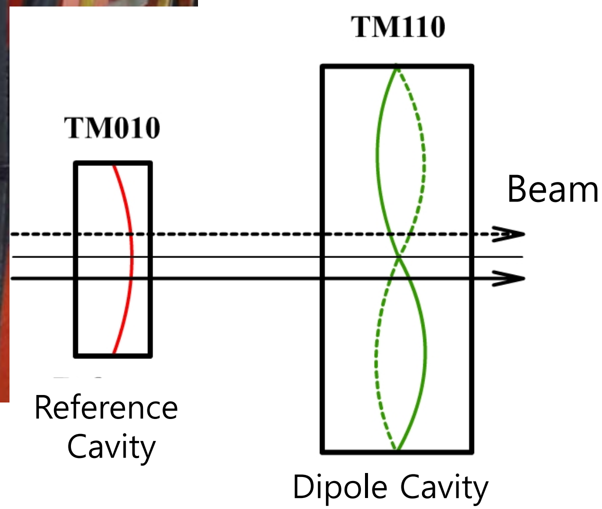
- Model beam position (m_j) at BPMs as function of

initial launch at 1st BPM (x_i), quad offsets (Δq_i), BPM offsets (Δb_i)

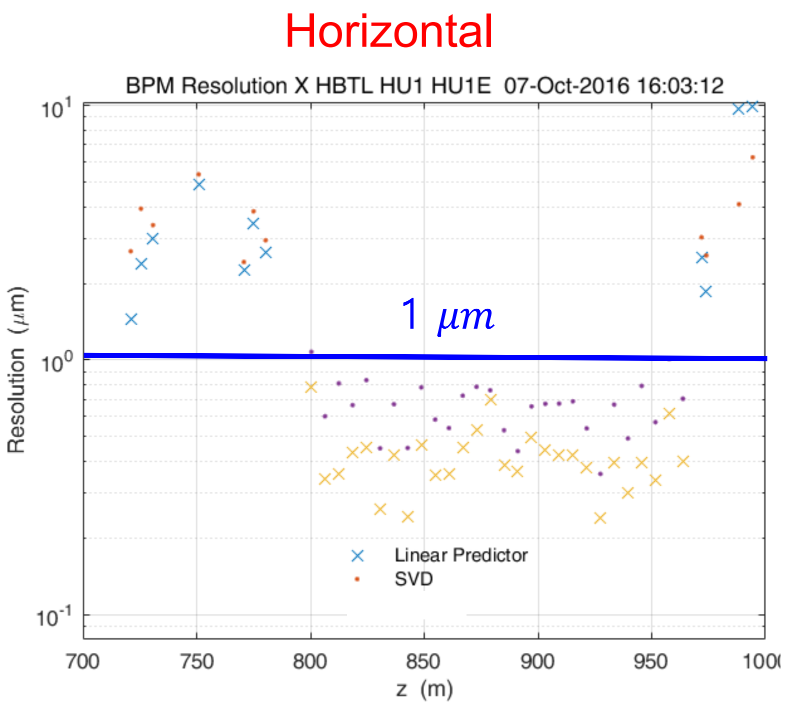
- $m = [R_x\ R_q\ R_b][x'\ \Delta q'\ \Delta b']'$

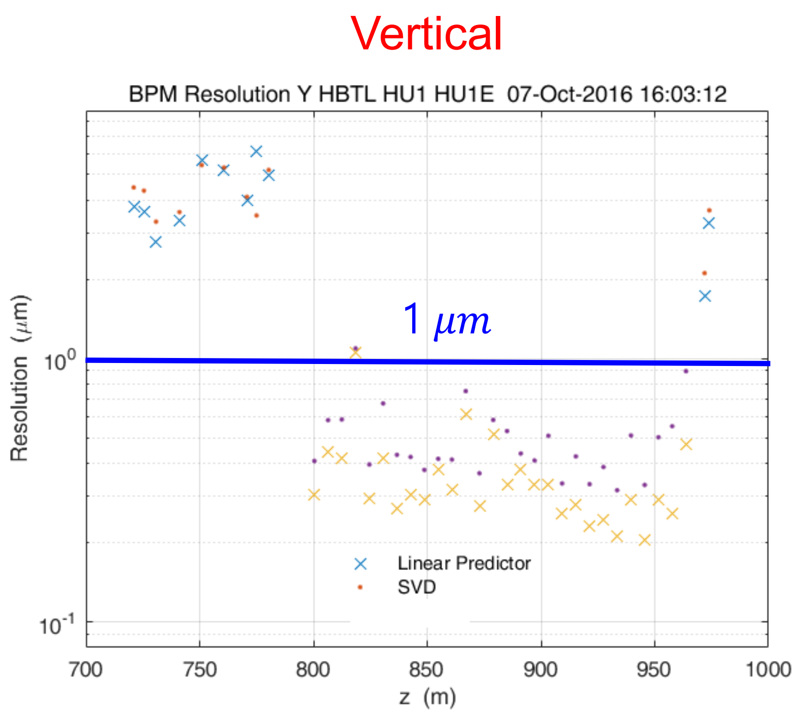
PAL-XFEL Cavity BPM: X-band BPM





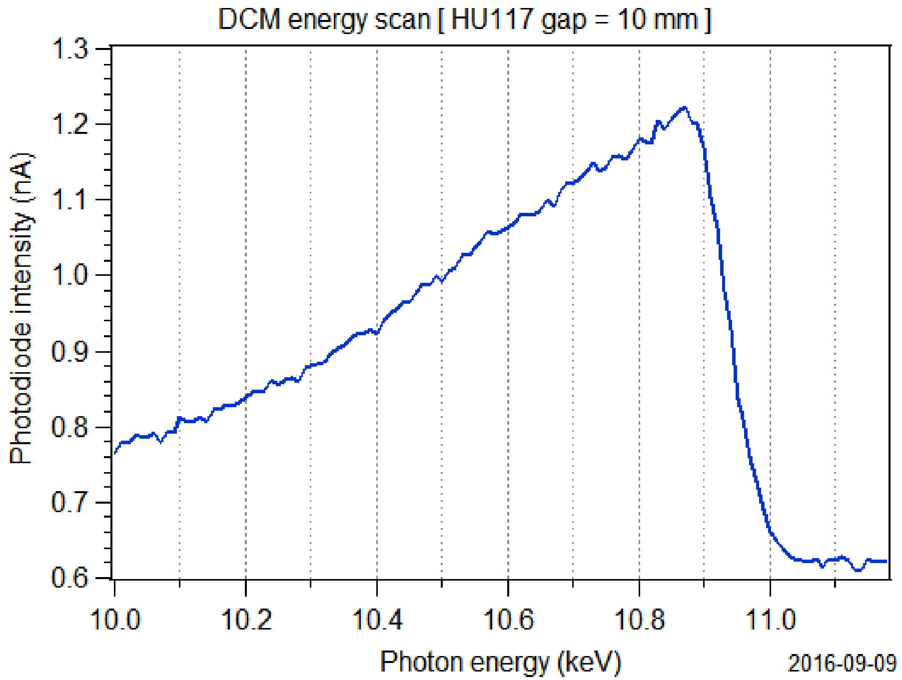
HX Cavity BPM Resolution

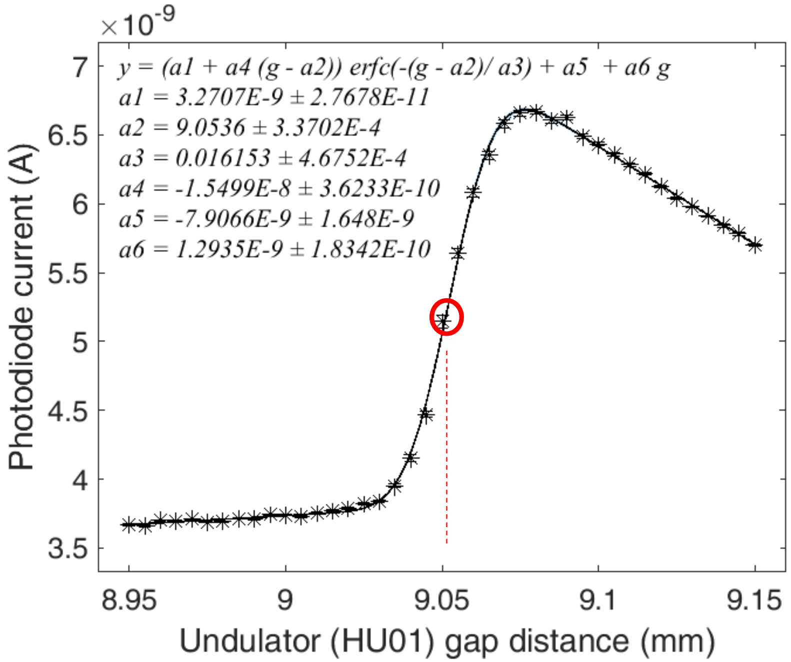


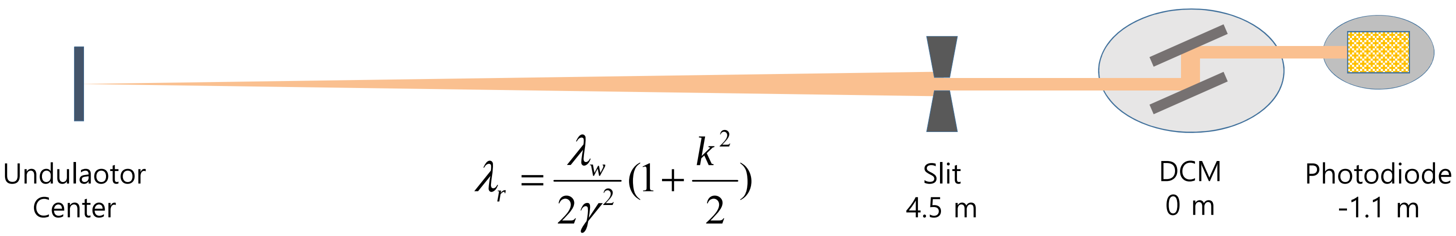


Radiation Spectrum Analysis: K-tuning

T. Tanaka *et al. Phys. Rev. ST Accel. Beam* **15**, 110701 (2012).







$$\lambda_r = \frac{\lambda_w}{2\gamma^2}(1+\frac{k^2}{2})$$

PAL-XFEL Commissioning

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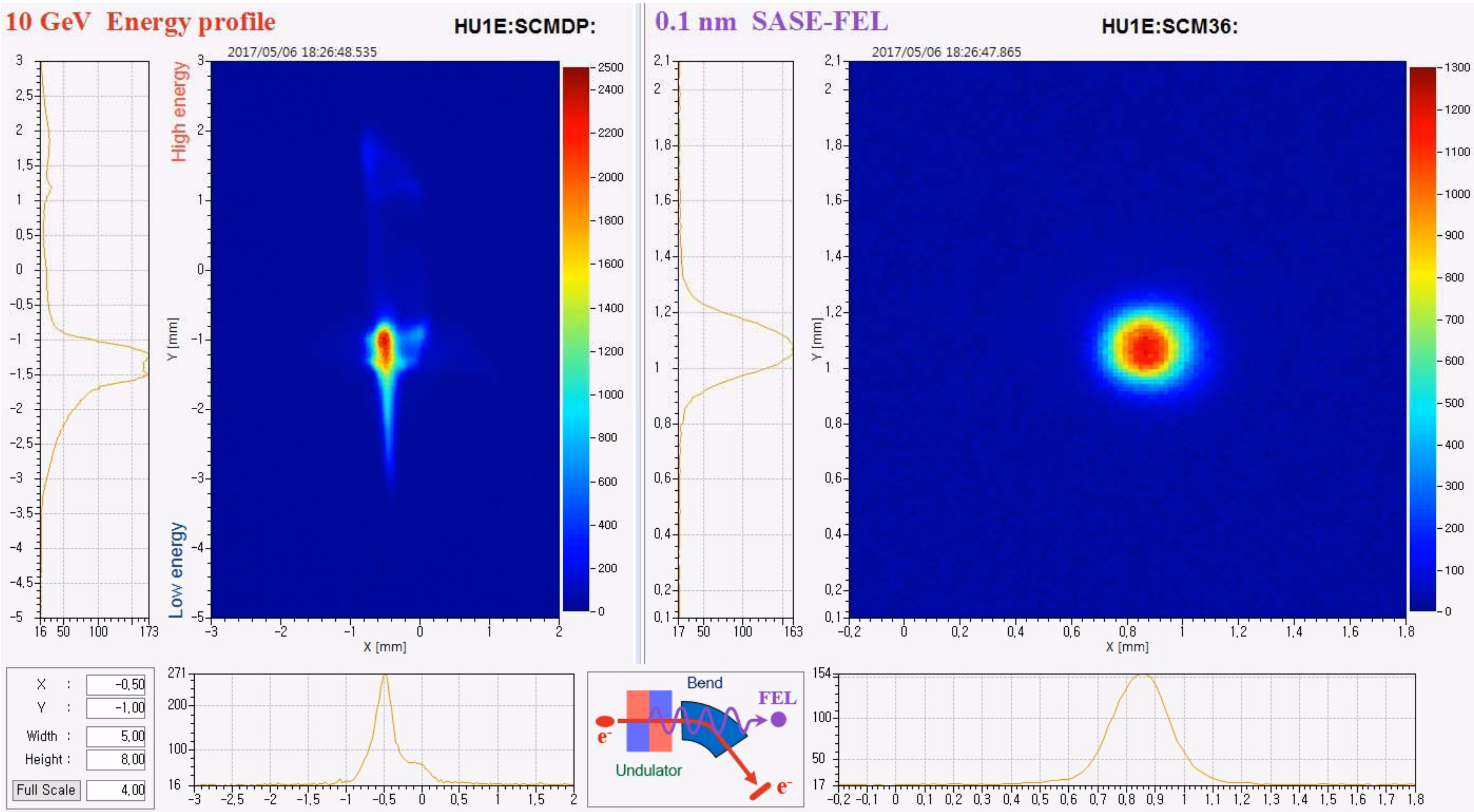
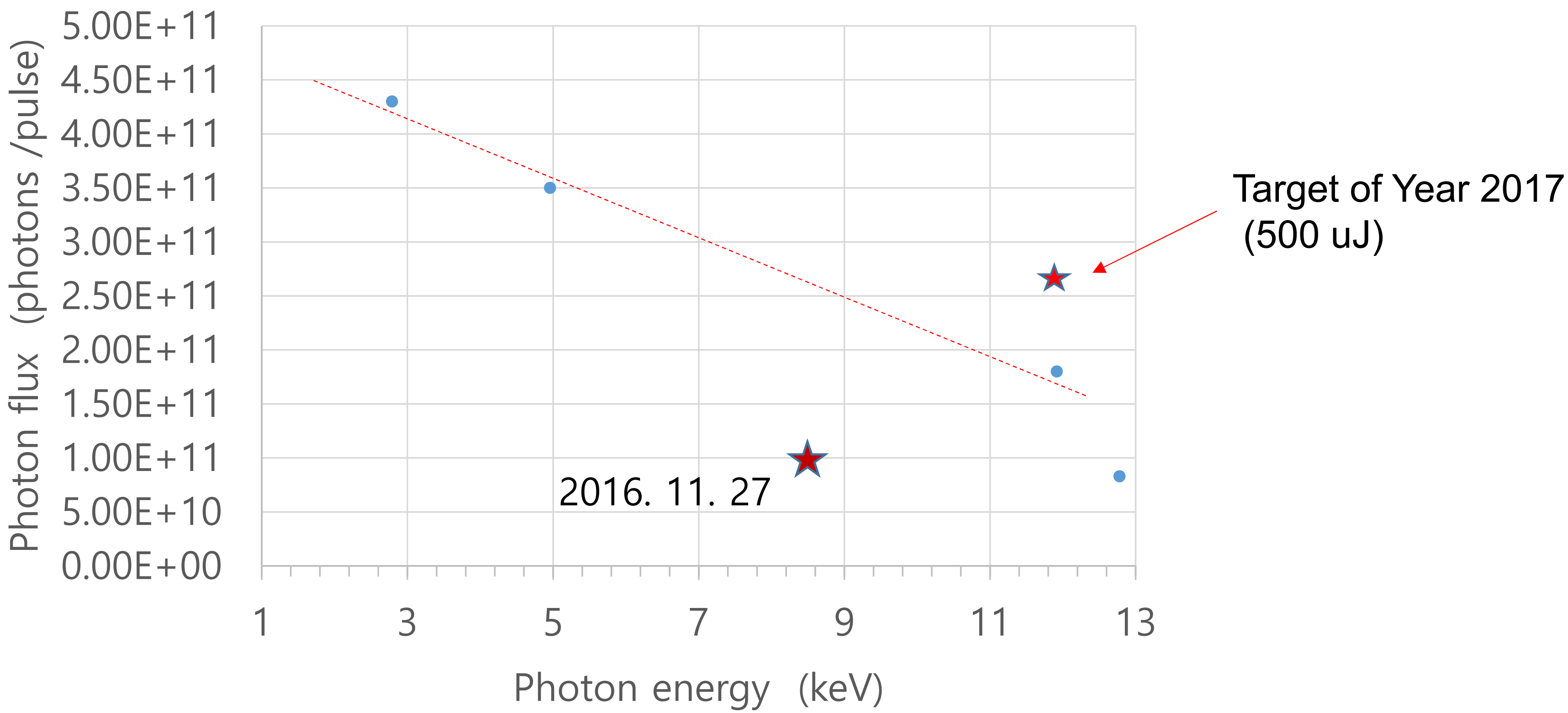
- **14 Jun. 2016 First SASE lasing at 0.5 nm**
- **28 Oct. 2016 Lasing at 0.15 nm**
- **27 Nov. 2016 Saturation of 0.15 nm**
- **16 Mar. 2017 Saturation of 0.1 nm**

Stability of 0.104 nm FEL



Photon flux of Hard X-ray FEL (As of May 7, 2017)

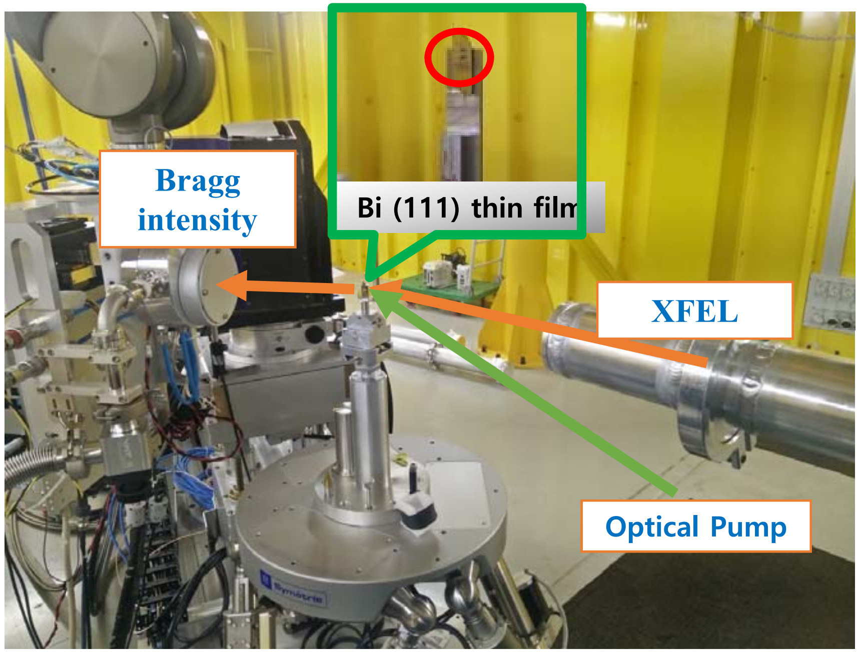


Date				Apr. 5	Apr. 07
wavelength, nm	0.097	0.104	0.25	0.444	0.444
photon energy, keV	12.78	11.92	4.96	2.79	2.79
FEL pulse energy, mJ	0.17	0.34	0.28	0.177	0.192
Number of photon per FEL pulse	8.3E+10	1.8E+11	3.5E+11	4.0E+11	4.3E+11


PAL-XFEL Beamline
▪ Photon energy: 2.8~12.9 keV
▪ Beam lines: 3 hard 2 soft X-ray beamlines (~80 m)
Hard X-ray Endstation I
Soft X-ray
Soft X-ray Endstation I
Hard X-ray Endstation II
Hard X-ray

Demo Experiment: **Optical Laser Pump – XFEL Probe X-ray Diffraction**

Bismuth (111) thin film



Bi(111) thin film (50 nm) on GaSb(111)/Si(111)
X-ray: 6 keV
X-ray size: ~ 60 x 60 um^2
Laser: 800 nm, 100 fs
Detector: MPCCD 0.5M

Summary

- The **e-BBA** of the undulator lines enabled us to obtain **dispersion-free orbits** straight to within a few micrometres to maximize the spatial overlap between the electron and photon beams.
- The **radiation spectrum analysis** facilitated identification of the **undulator field centre offsets** and **accurate gap distances** for K in each undulator segment, which is particularly critical for variable-gap undulators.
- Using this procedure, we successfully achieved saturation of both 0.1 nm and 1.5 nm FEL beams in a very reliable and robust manner and delivered the FEL beams to each beamline for commissioning.

Acknowledgement

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Thank you for your attention