# Current Status of PAL-XFEL

October 24, 2016
@ 5-way Meeting

In Soo Ko
on behalf of PAL-XFEL Team

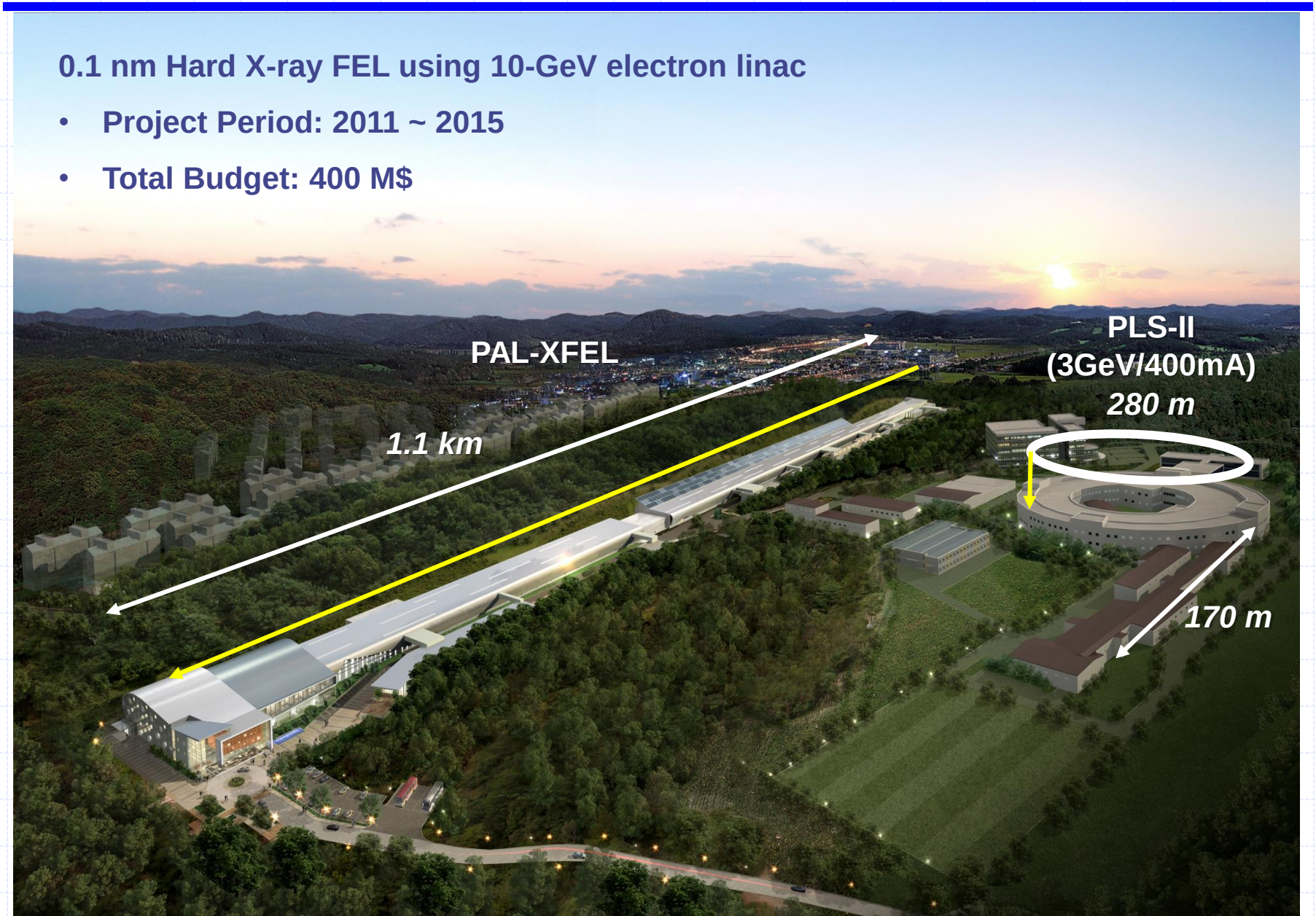
# Outline

- Project Overview
- Site and Construction
- Linac
- Undulators
- Beamlines
- Commissioning Results

# Overview of PAL-XFEL

**0.1 nm Hard X-ray FEL using 10-GeV electron linac**

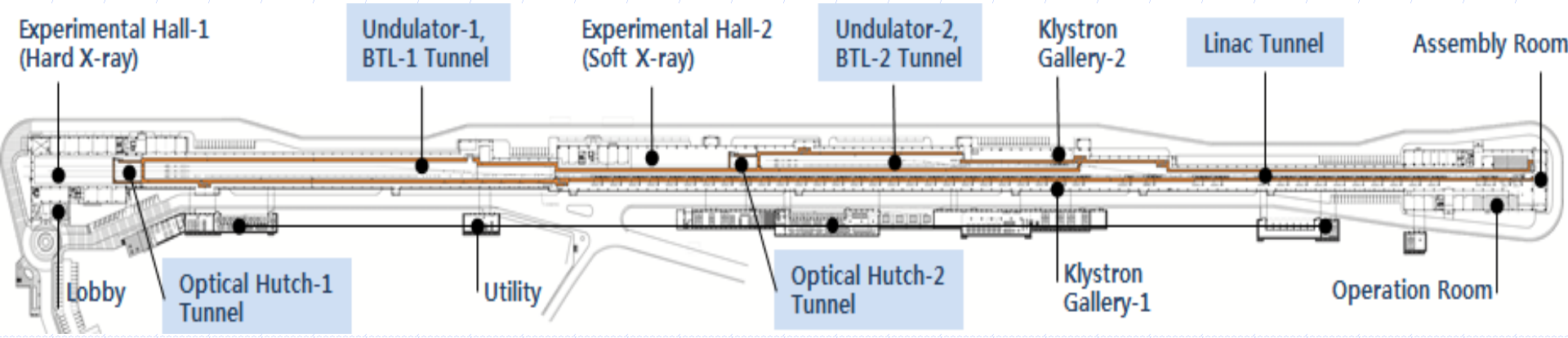
- **Project Period: 2011 ~ 2015**
- **Total Budget: 400 M$**

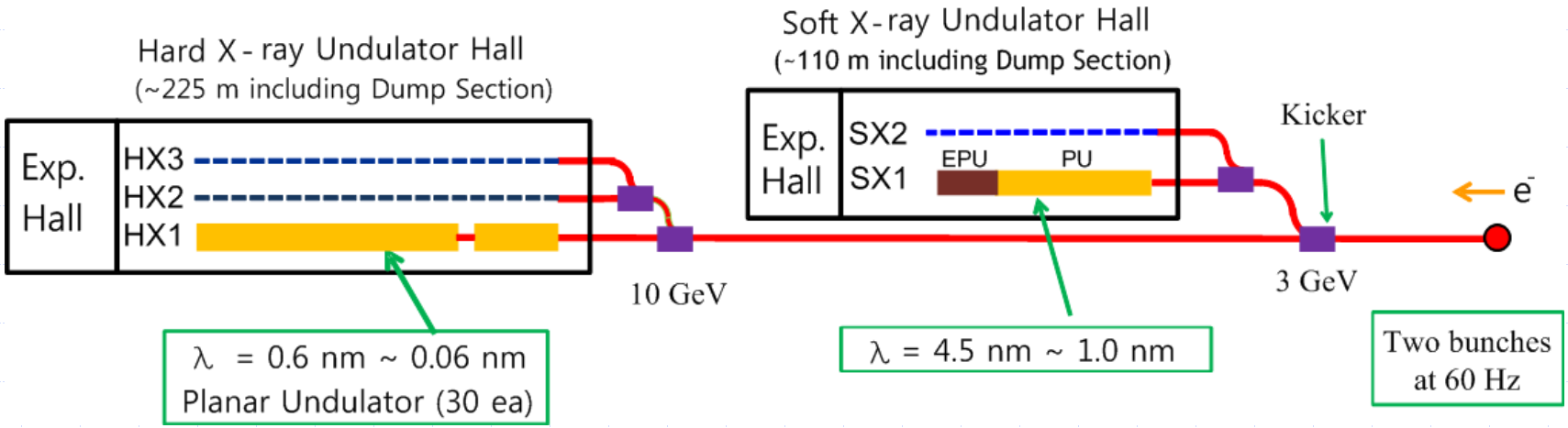


# Supports from Local Governments

- Supports from Local Governments
  - 13 BWon (~13 MUSD) from Kyungbuk Province
  - 13 BWon from Pohang City
- Science Hall
  - 5-story building
  - Auditorium (capacity: 300)
  - Cafeteria
  - Exhibition floors and offices
- Guest House
  - 7-story building
  - Capacity: 180 (220 maximum)
- Buildings ready in Summer 2016

# General Layout



# Site and Buildings: Summary

- Site: Soil removed and replaced: ~1.2 million $m^3$
- Building
  - Length of machine building: 1.11 km
  - Building floor (total): 36,764 $m^2$
  - Utility building: 6 (located south side with road separation)
  - Total concrete used: ~100,000 $m^3$
  - Electricity: 25 MVA max (added to existing 25 MVA)
  - Cooling tower: 500 RT x 3
  - Total cable used: ~ 500 km
- Machine Building: PEB steel structure
  - Wind load: 63 m/s (in US rule)
  - Seismic intensity: 0.19
  - Undulator hall temperature: $25 \pm 0.1$ $^oC$
- Building permission issued on Feb. 17, 2015

# July 27, 2016

# Machine

- Linac
  - RF photocathode gun
  - S-band (2,856 MHz) copper structure (180 in total)
  - 80-MW klystron (50) and X-band klystron (1)
  - Injector Test Facility (ITF) closed on September 30, 2015
  - Tunnel components of ITF moved to main linac
- Undulator
  - Out-vacuum
  - Variable gap
  - Deformations and errors during transportation and installation measured and confirmed OK
- Beamline components in optical hutch
  - Clean rooms for detectors and lasers ready
  - Sample preparation labs (wet and dry) ready

# Klystron Gallery (Feb. 23, 2015)

# Klystron/Modulator and Cooling

# Linac Tunnel (Jan. 21, 2015)

# Injector Section

# Linac Tunnel

# SX Branch Line

# Main Control Room

# HX Undulator Hall (July 17, 2015)

# Undulator being installed

# HX undulators installed

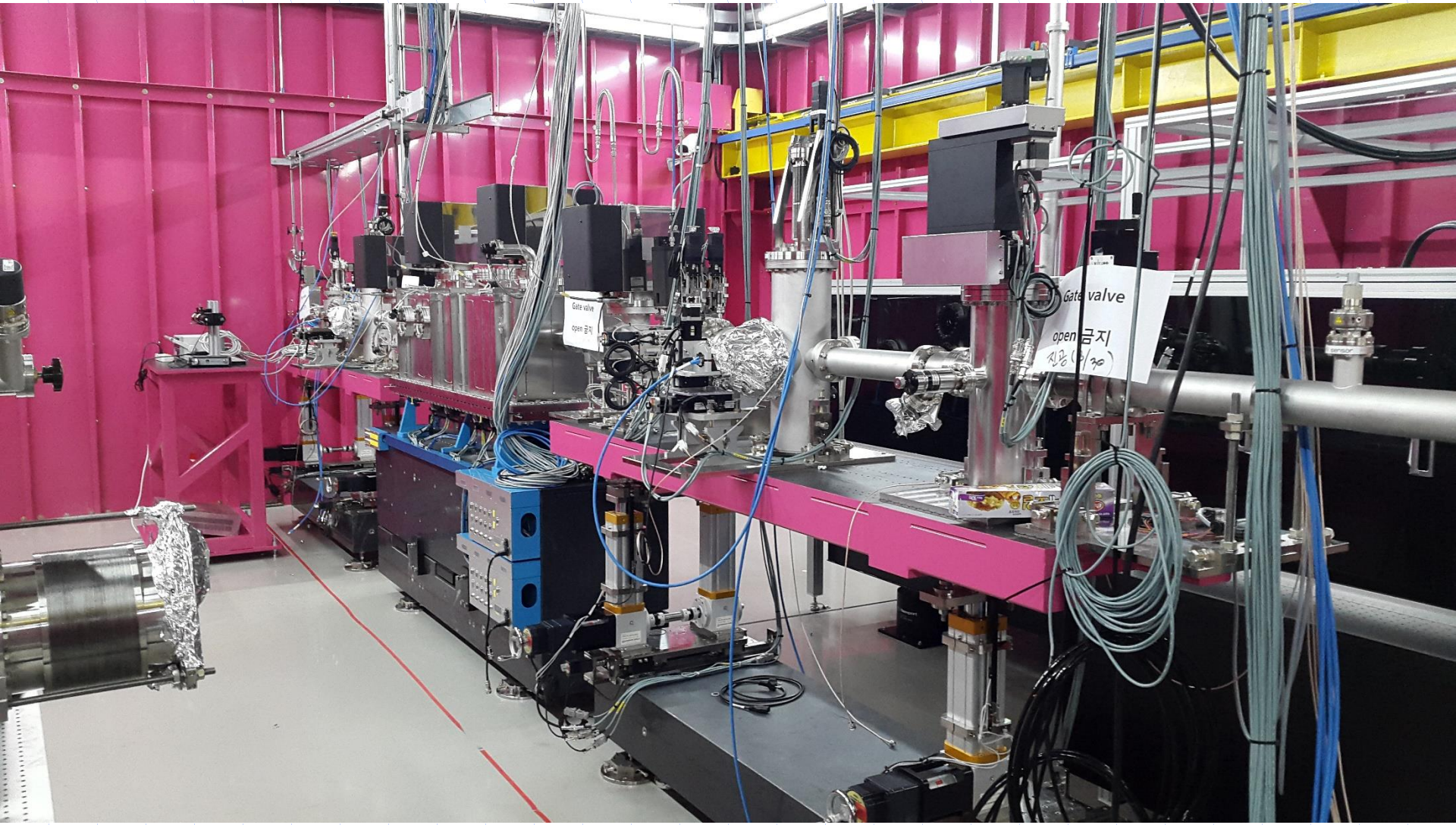
# HX Optical Hutch

# Hard X-ray Experiment Hutches

# HX XPP Hutch

***Robotic arm for detector***

# HX CXI Hutch

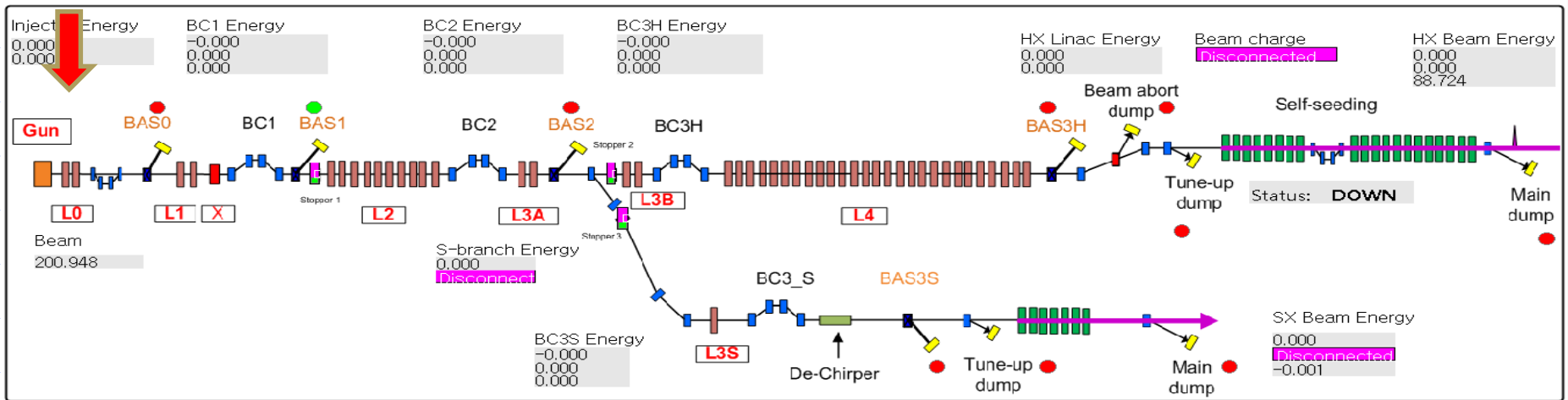


# HX Beamline Control Room


PAL-XFEL

# First-stage Commissioning (April~June, 2016)

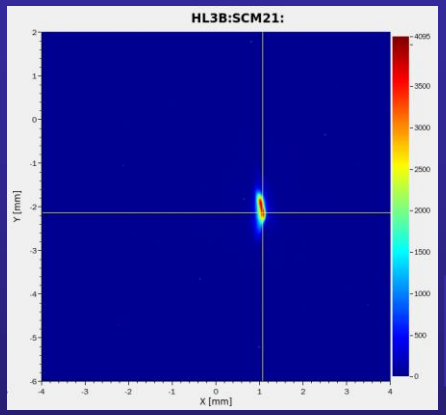
| Date | Location (m) | Electron Energy (GeV) | Remarks |
|---|---|---|---|
| April 12, 2016 | | | Permission issued by Nuclear Safety Committee |
| April 14 | 0 | 0.152 | E-Gun and BAS0 |
| April 18 | 57 | 0.355 | BAS1 |
| April 19 | 195 | 0.355 | Before BC2 (No acceleration by L2) |
| April 20 | 252 | 2.545 | BAS2 |
| April 21 | 715 | 3.150 | BAS3 (No acceleration after BAS2) |
| April 25 17:30 | 715 | 10.0 | BAS3 |
| May 19 | 794 | 10.0 | Tuneup dump |
| June 2 | 990 | 10.0 | Passing HX undulator line, beam at dump |
| June 14 06:00 | 995 | 4.0 | First Lasing observed at SCM36 |
| June 21 03:00 | 1,030 | 4.0 | Photon beam at DCM in Optical Hutch |



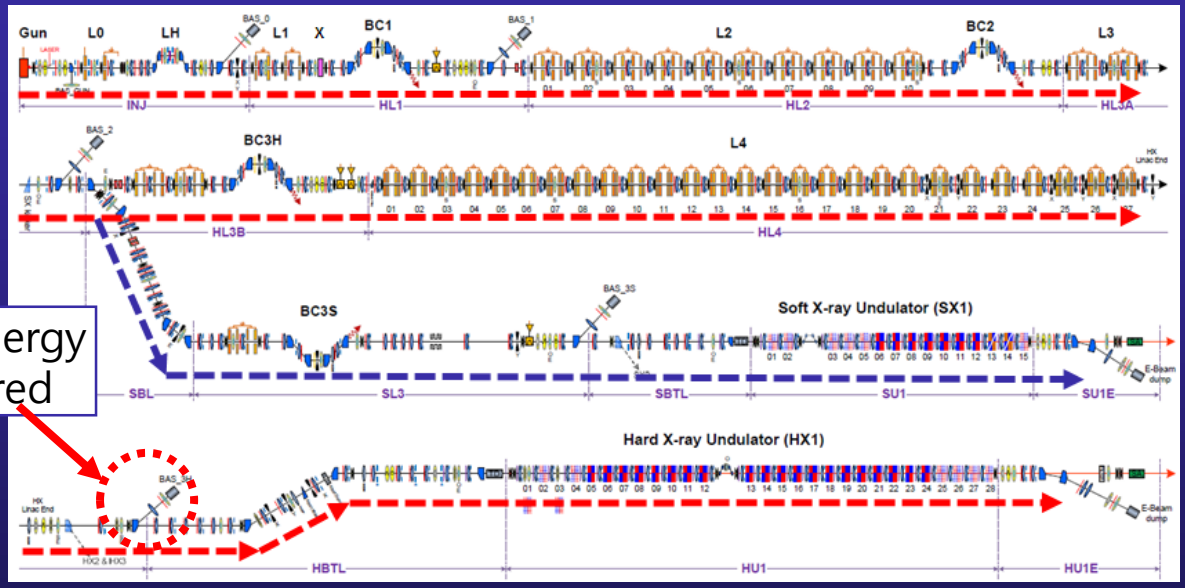
# 10 GeV Achieved

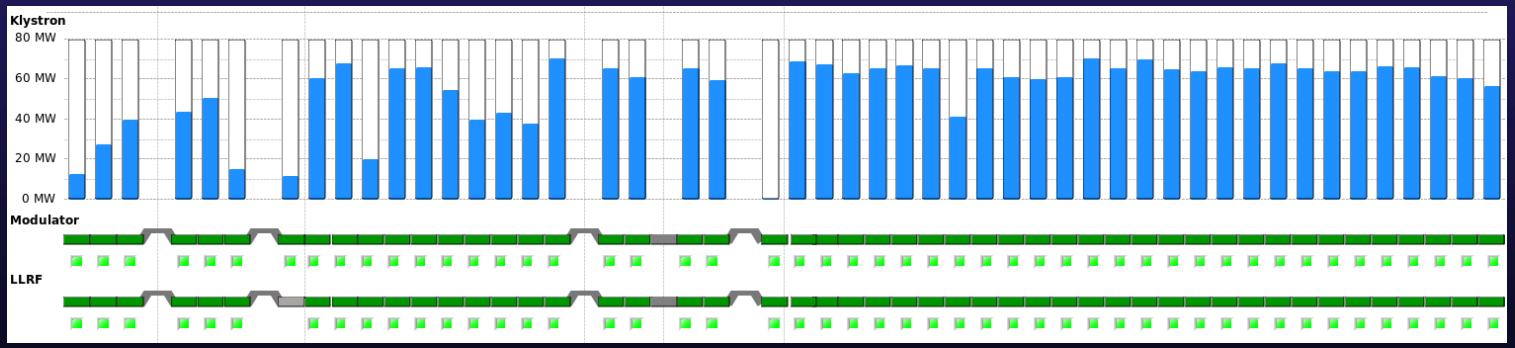
PAL-XFEL
Beam Commissioning

## On 25th April (12th day of beam commissioning)

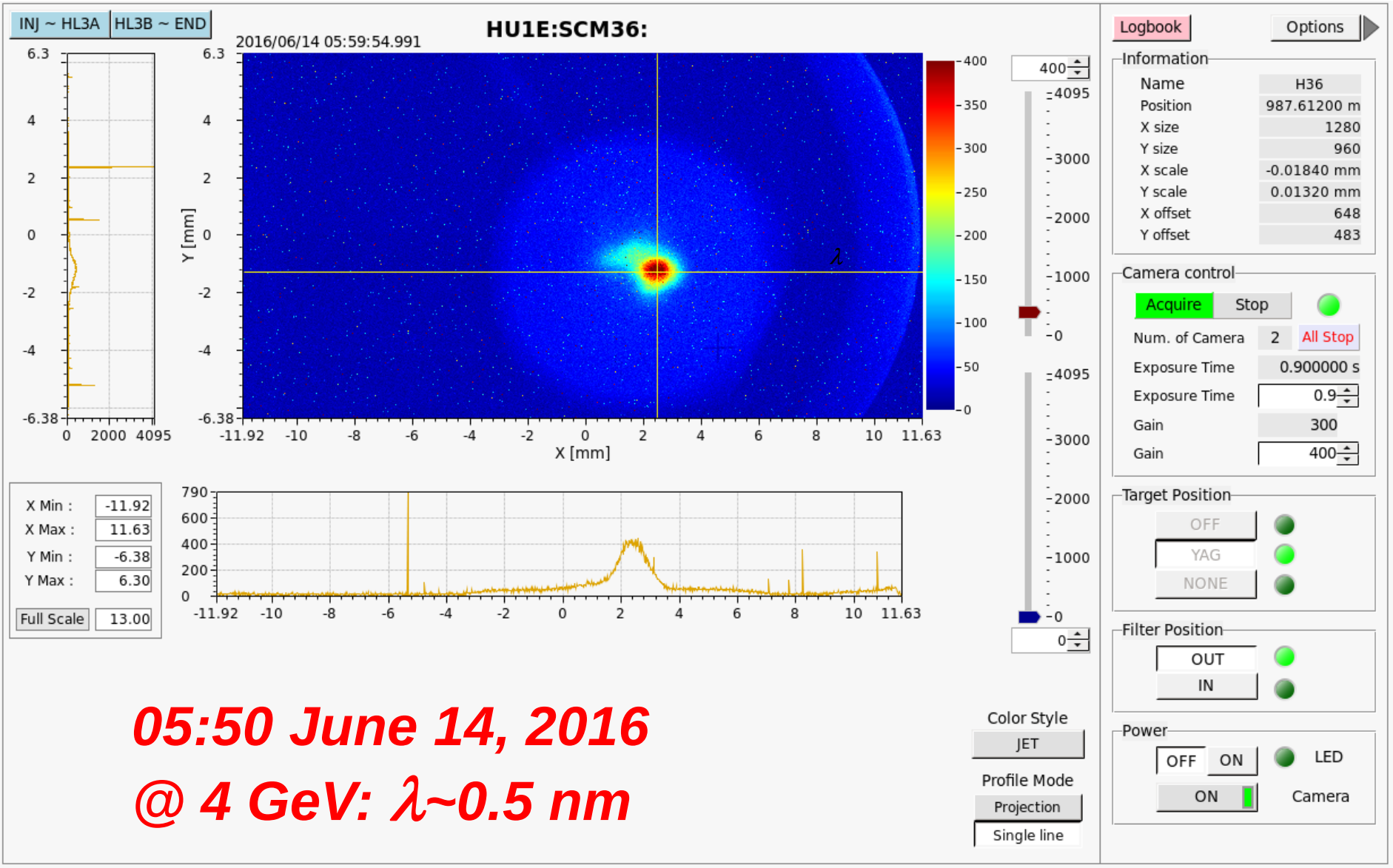



beam energy measured



# First Lasing succeed !!!

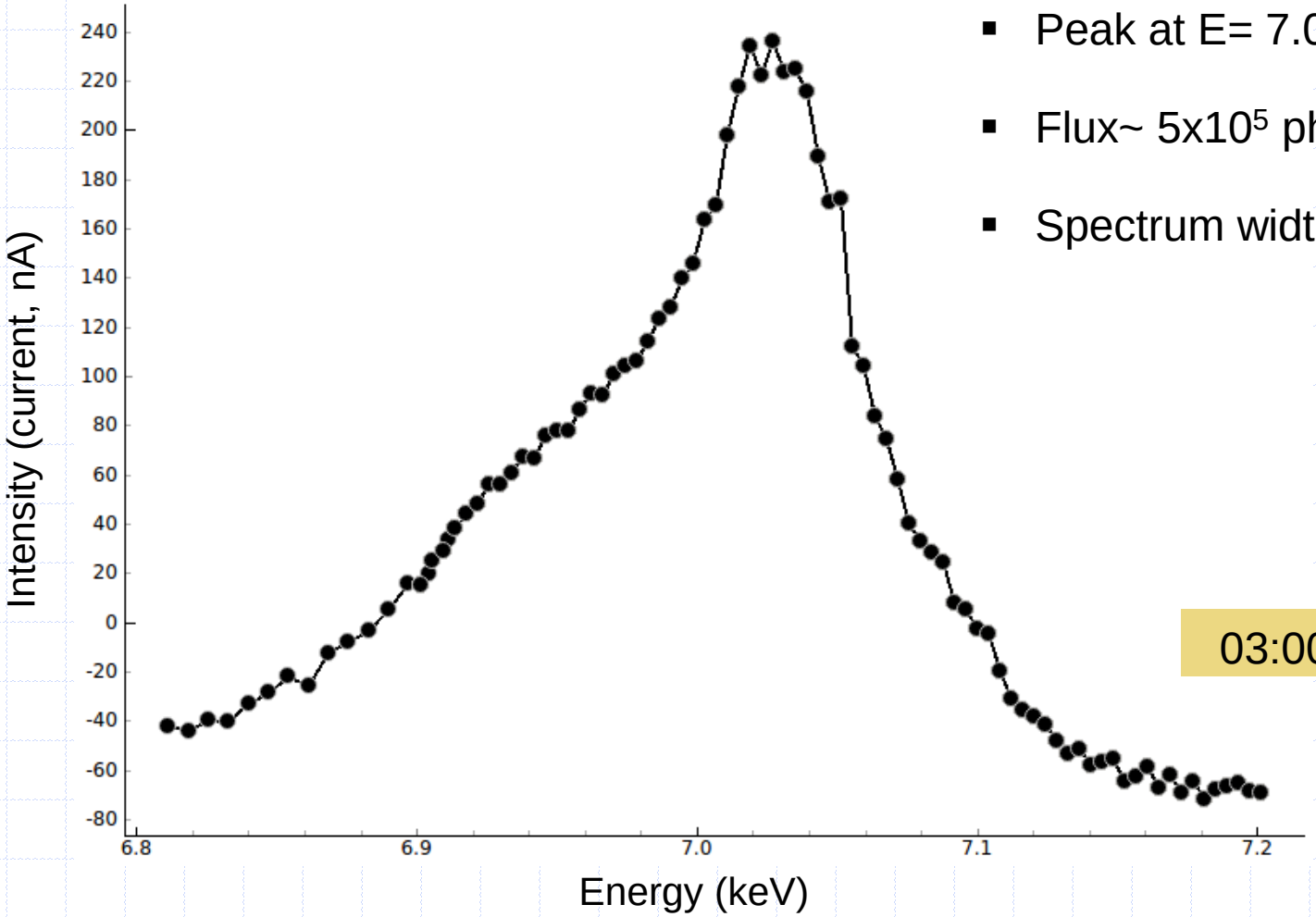



***05:50 June 14, 2016***

***@ 4 GeV: λ~0.5 nm***

# Spectrum by DCM

## 3rd Harmonic Spectrum with 100 pulses




- Peak at E= 7.02720 keV
- Flux~ $5 \times 10^5$ photons/pulse
- Spectrum width (FWHM)~ 60eV

03:00 June 21 2016

# Maintenance in July/August 2016

- Many parts replaced and reinforced
- Control S/W upgraded and added
- HLS installed
- Survey work
- Beam operation resumed on Aug. 16. (E=10.35 GeV same day)
- FEL (0.5nm) back on Aug. 26.

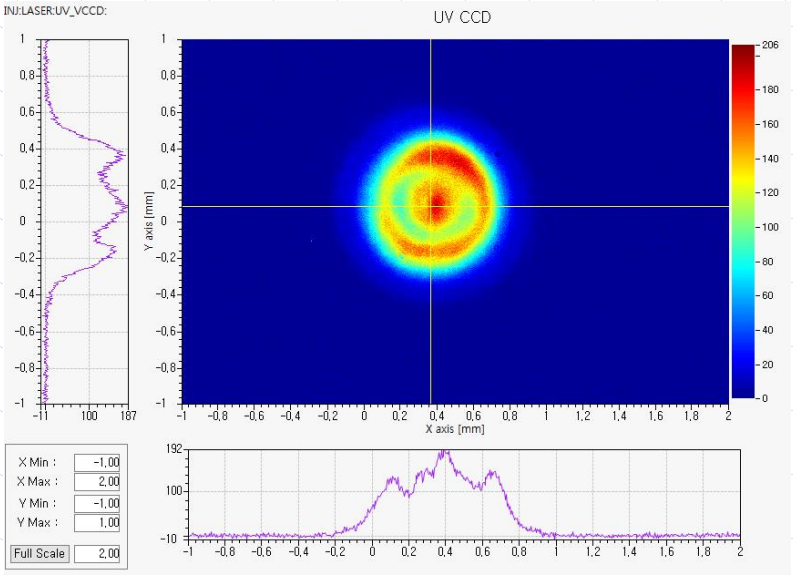
# Commissioning Phase 2

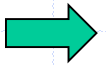
- After summer maintenance, the commissioning resumed on August 16, 2016.

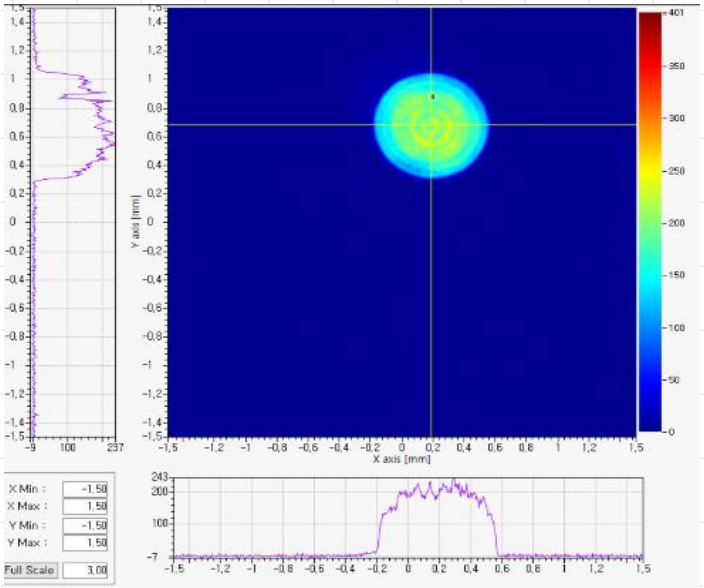
| | |
|---|---|
| Aug. 30: | 0.5 nm (3rd) lasing recovered |
| Sept. 9: | Beamline commissioning (0.5 nm) |
| Sept. 12: | Earthquake |
| ~ Sept. 29: | Machine mostly downed for Dedication Ceremony |
| Oct. 3: | Commissioning resumed |
| Oct. 8: | 0.35 nm SASE Lasing |
| Oct. 16: | 0.2 nm SASE Lasing |

# Emittance (Projected) Improved

## UV laser beam profile for Photocathode Gun

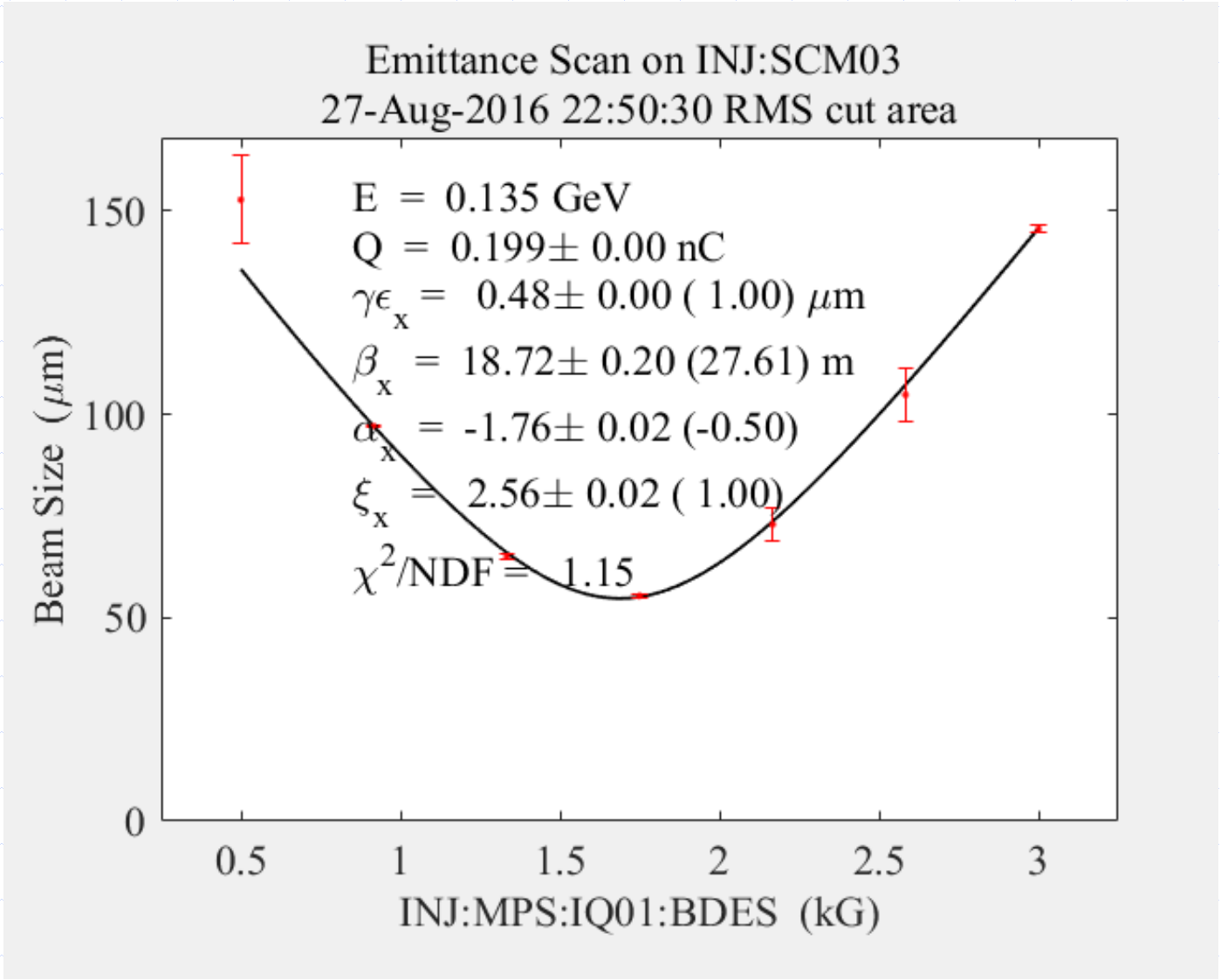


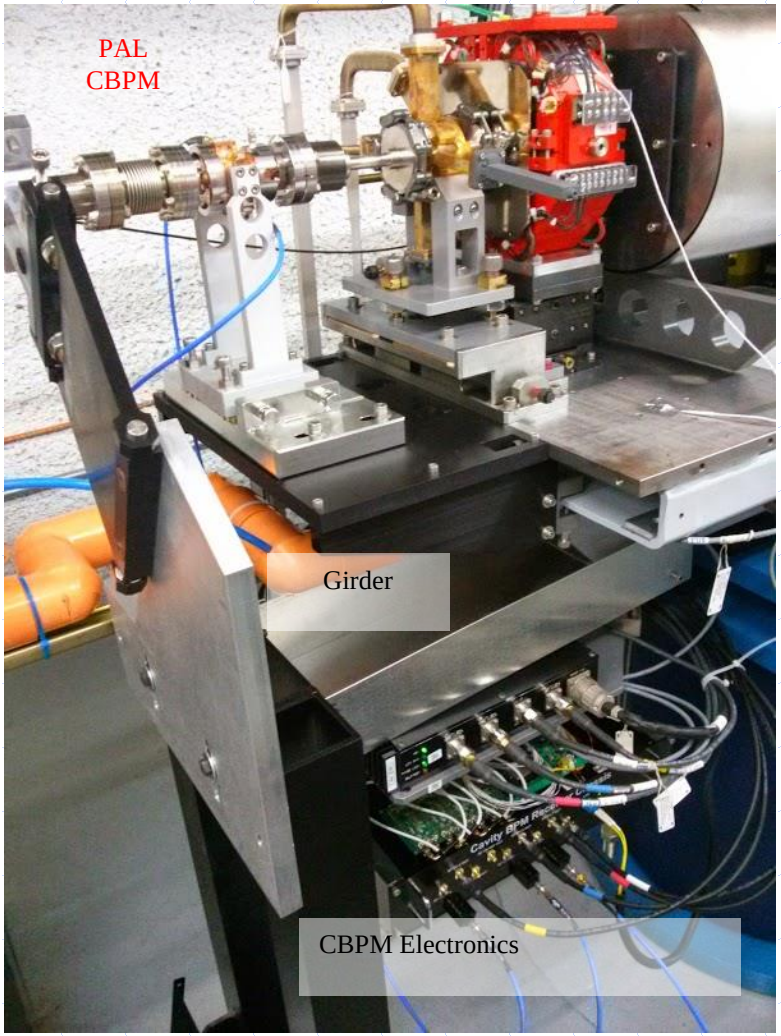


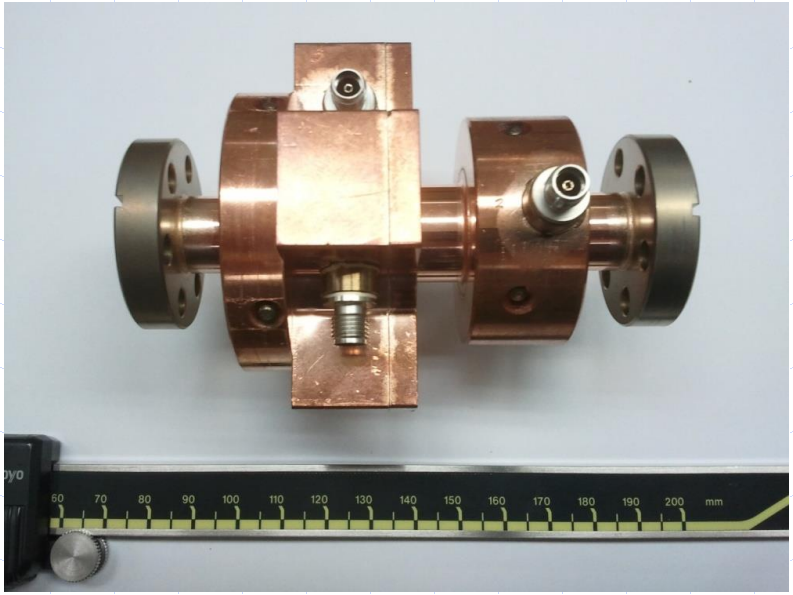

Horizontal emittance: 0.88 mm-mrad at 200 pC
Vertical emittance: 0.58 mm-mrad

Horizontal: 0.48 mm-mrad at 200 pC
Vertical: 0.42 mm-mrad

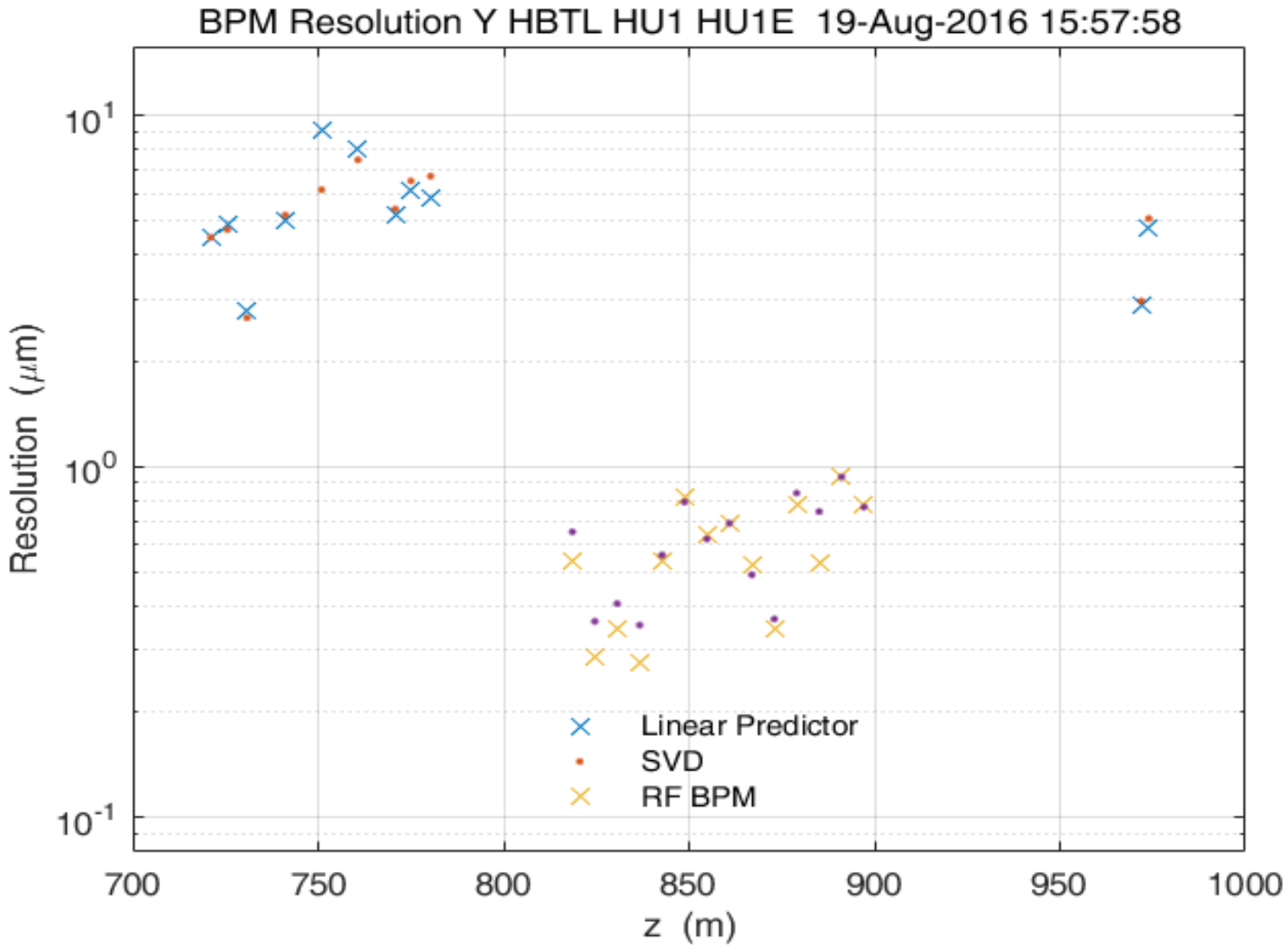

Emittance Scan on INJ:SCM03
27-Aug-2016 22:50:30 RMS cut area
E = 0.135 GeV
Q = 0.199± 0.00 nC
$\gamma\epsilon_x$ = 0.48± 0.00 ( 1.00) $\mu$m
$\beta_x$ = 18.72± 0.20 (27.61) m
$\alpha_x$ = -1.76± 0.02 (-0.50)
$\xi_x$ = 2.56± 0.02 ( 1.00)
$\chi^2$/NDF = 1.15
Beam Size ($\mu$m)
150
100
50
0
0.5
1
1.5
2
2.5
3
INJ:MPS:IQ01:BDES (kG)

# Cavity BPM


PAL
CBPM
Girder
CBPM Electronics


60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 mm

# BPM Resolution

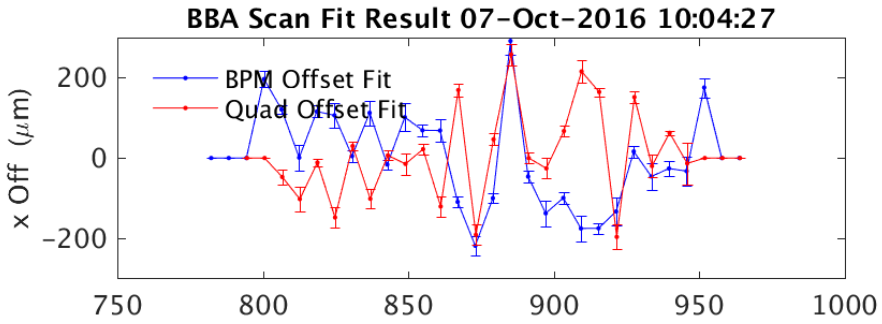


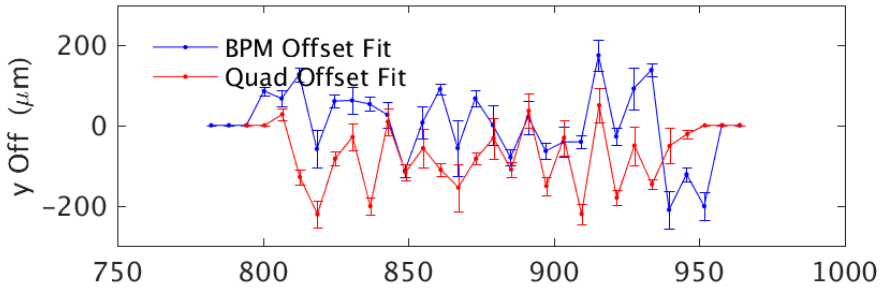
# BBA for Undulators

- To establish a straight orbit along the undulators
- All correctors of undulator line are turned OFF
- BPM offsets and quad offsets are calculated to get dispersion-free straight orbit

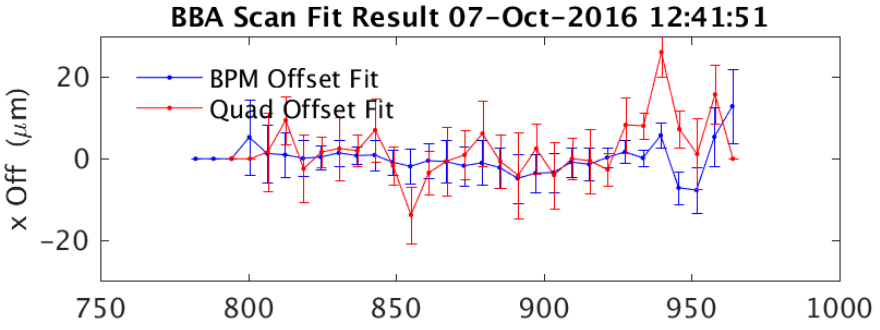
- Beam energy: 4, 5.2, 6.7, 10 GeV
- Undulator gap: 9 mm
- Number of undulators: 20

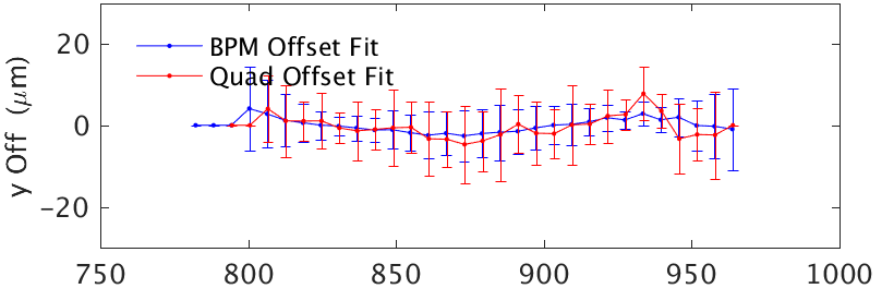
1-st



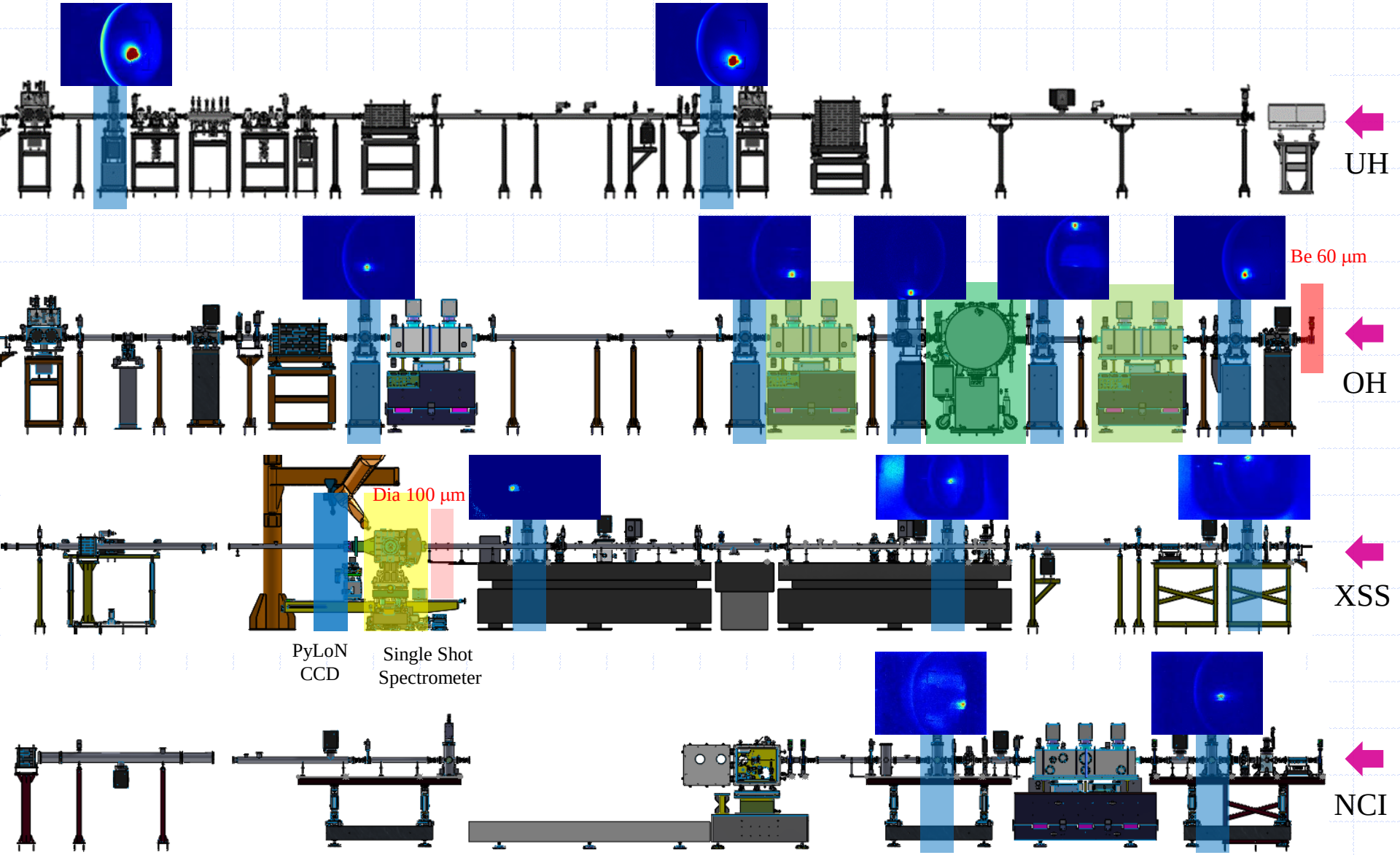




8-th

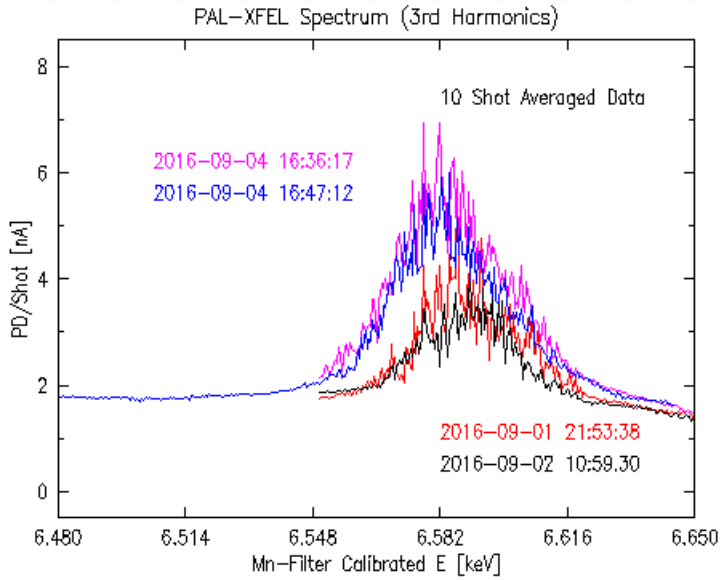


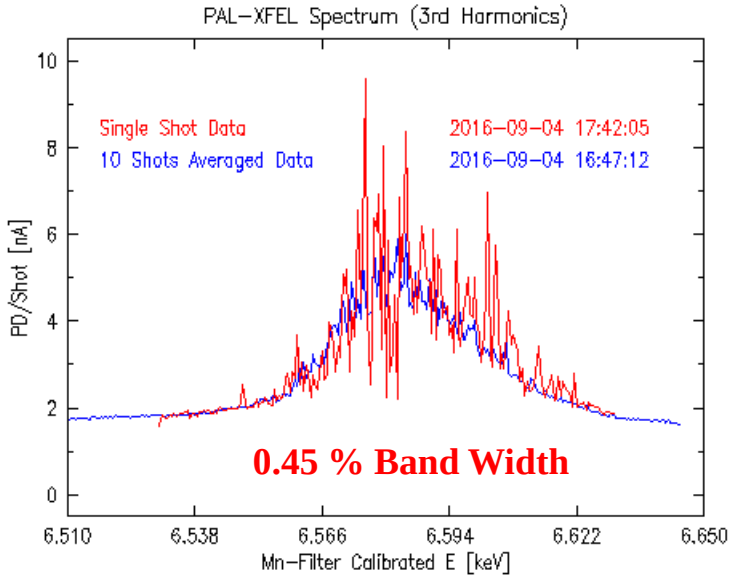



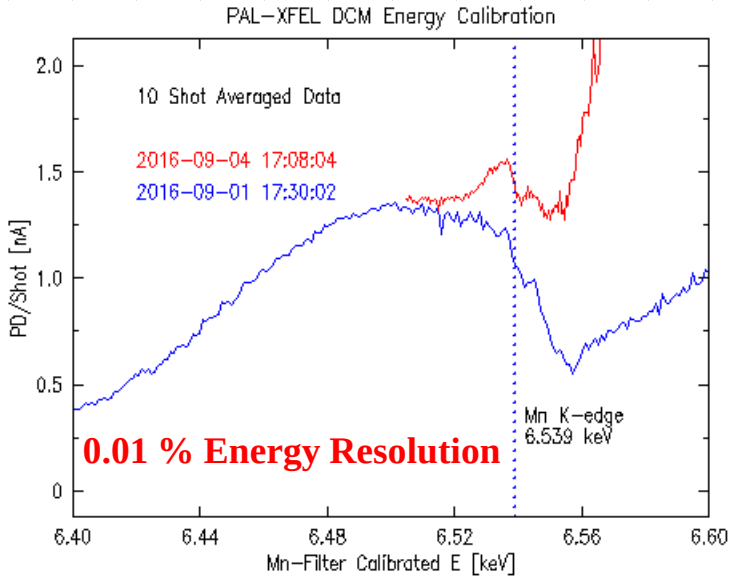
# PAL-HXFEL Beamline Layout & Beam Profile

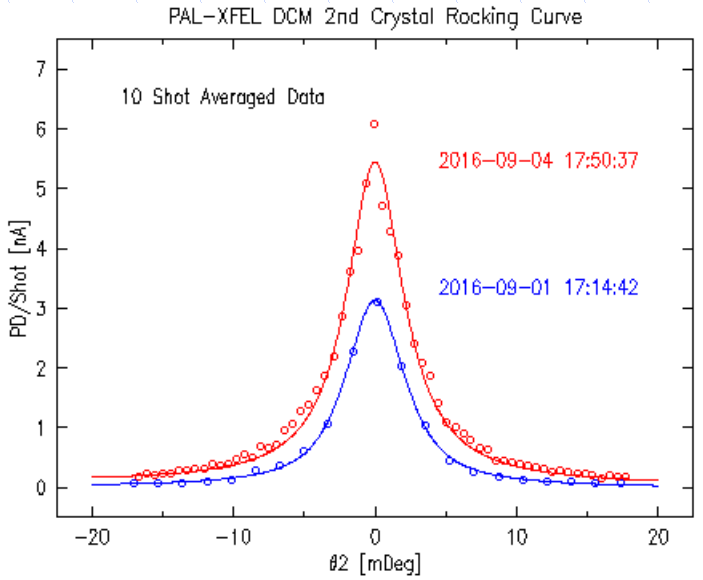


# DCM Alignment & Calibration: XFEL Spectrum



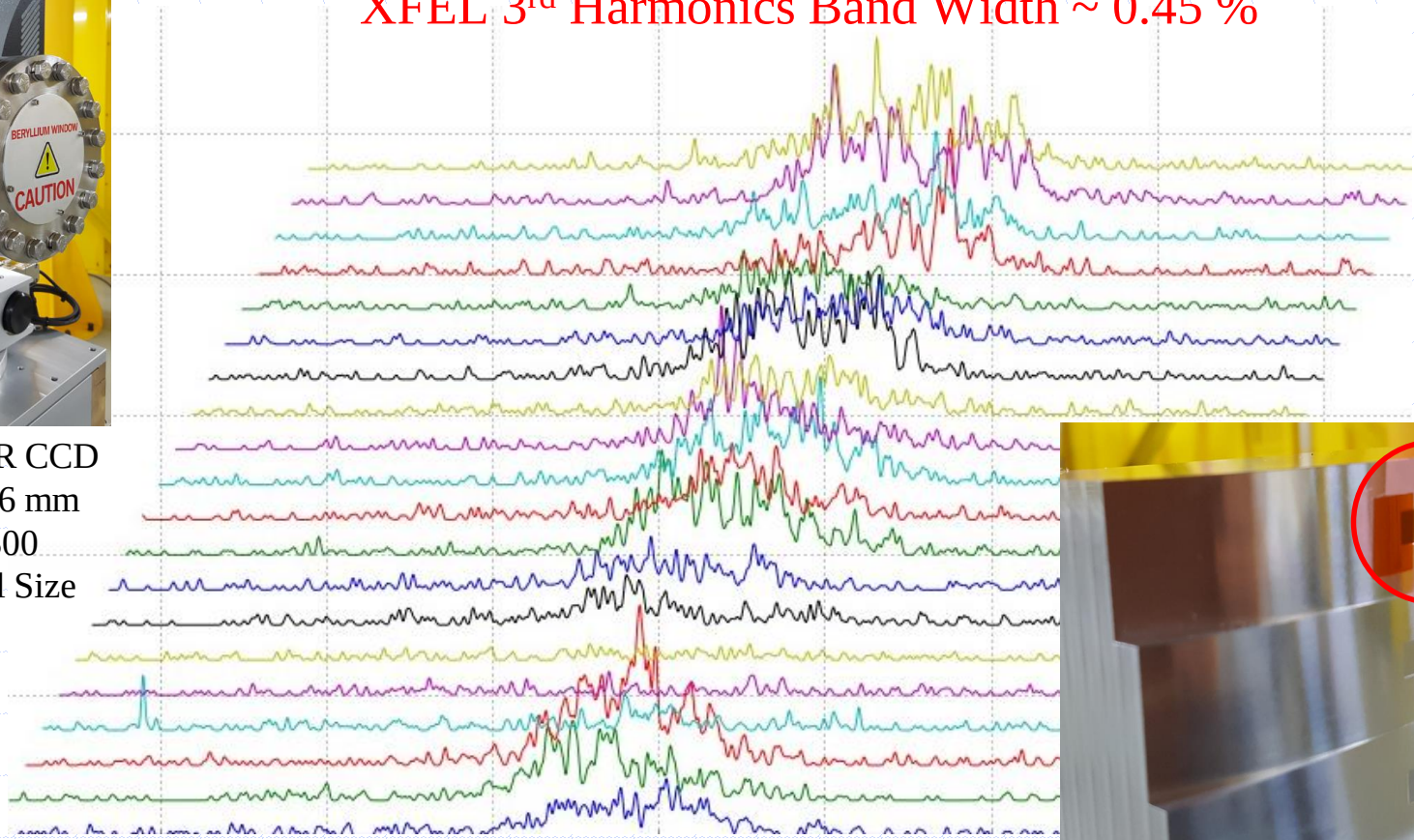



# Single Shot Spectrum Measurement (PyLoN)


PyLoN:1300R CCD
26.8 mm x 26 mm
1340 x 1300
20 μm Pixel Size

2016-09-04 13:31:14

XFEL 3rd Harmonics Band Width ~ 0.45 %



E

6.6 keV

30 eV

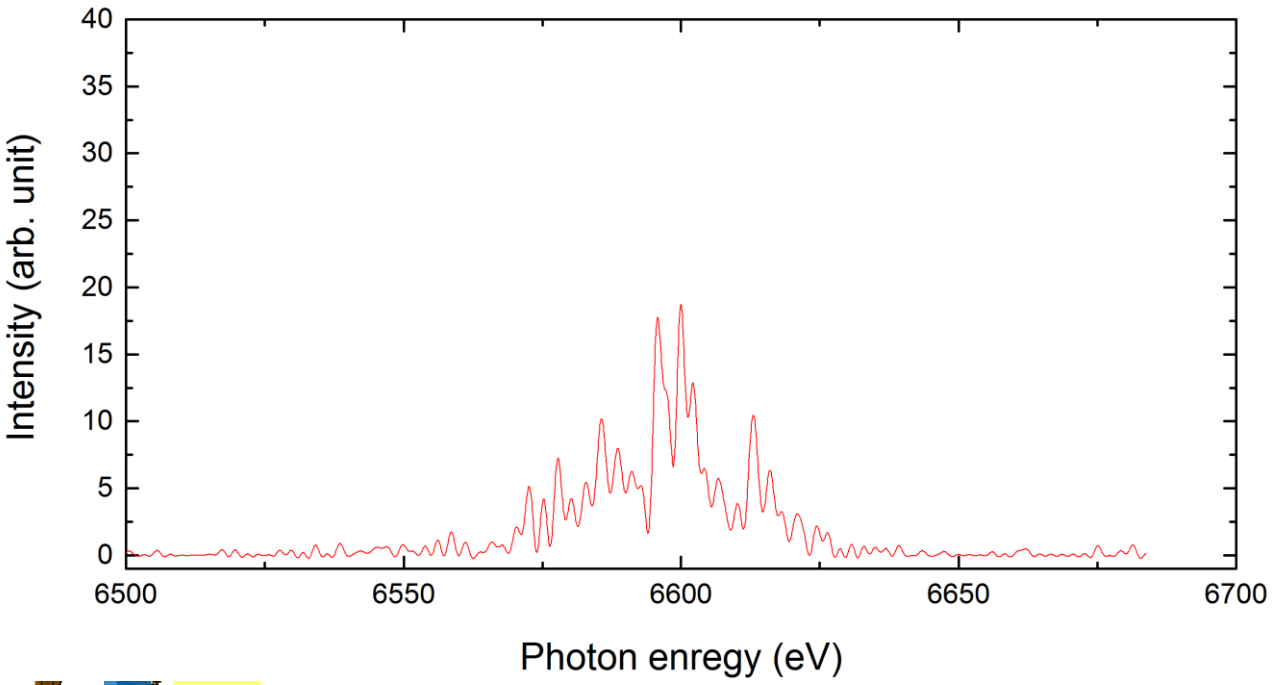


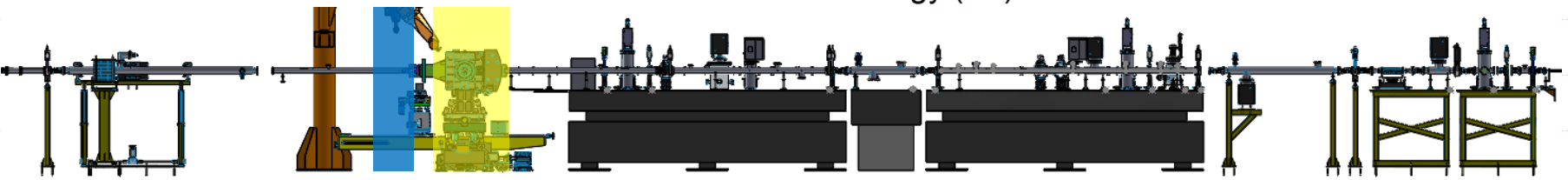
Bend (R=100 mm) Si(111) Sliver
15 mm x 5 mm x 0.01 mm

# Single Shot Spectrum Measurement (PyLoN)

2016-09-04 13:31:14

2016-09-04 13:35:13



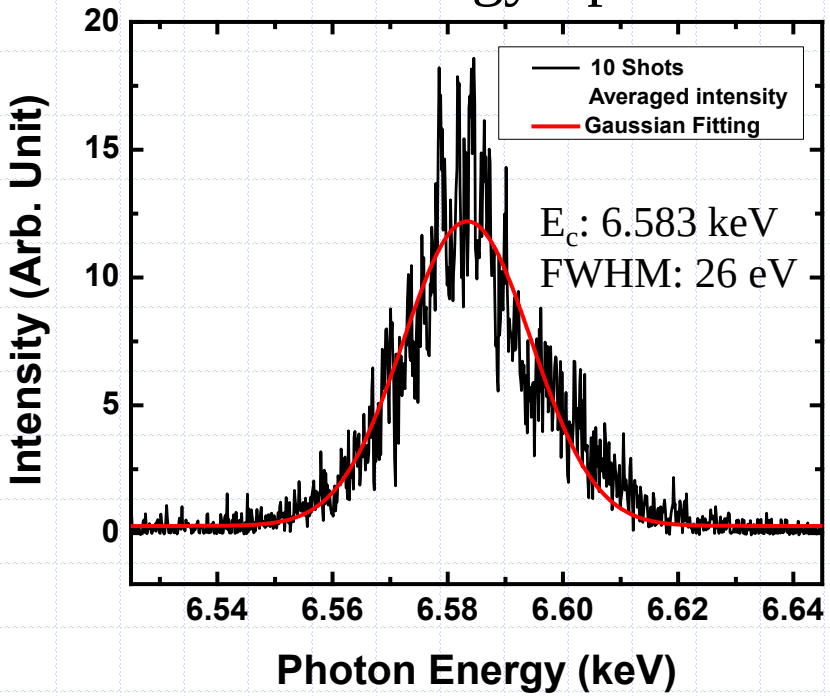
PyLoN CCD

Single Shot Spectrometer

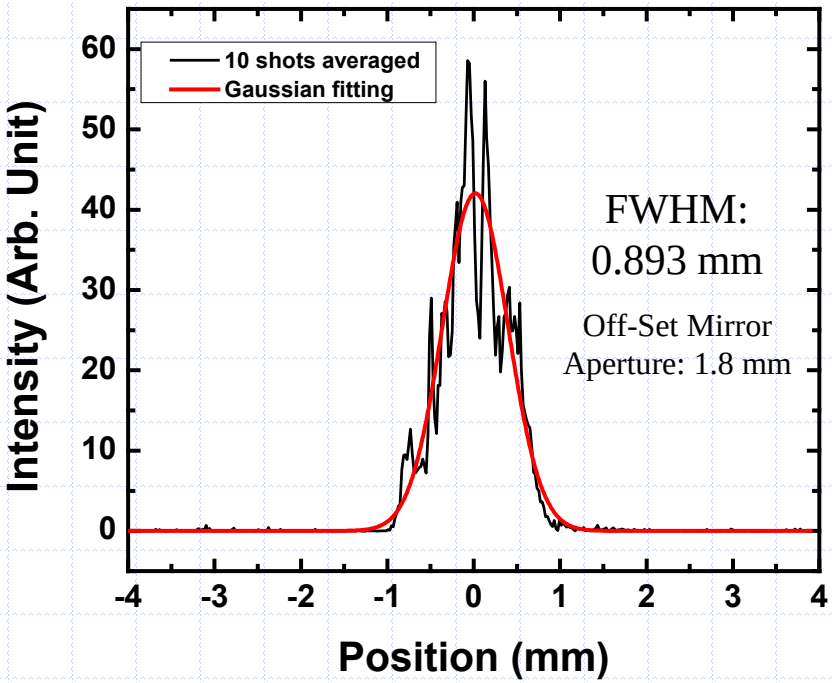
XSS

# Single Shot Spectrum Measurement (PyLoN)

## XFEL Energy Spectrum

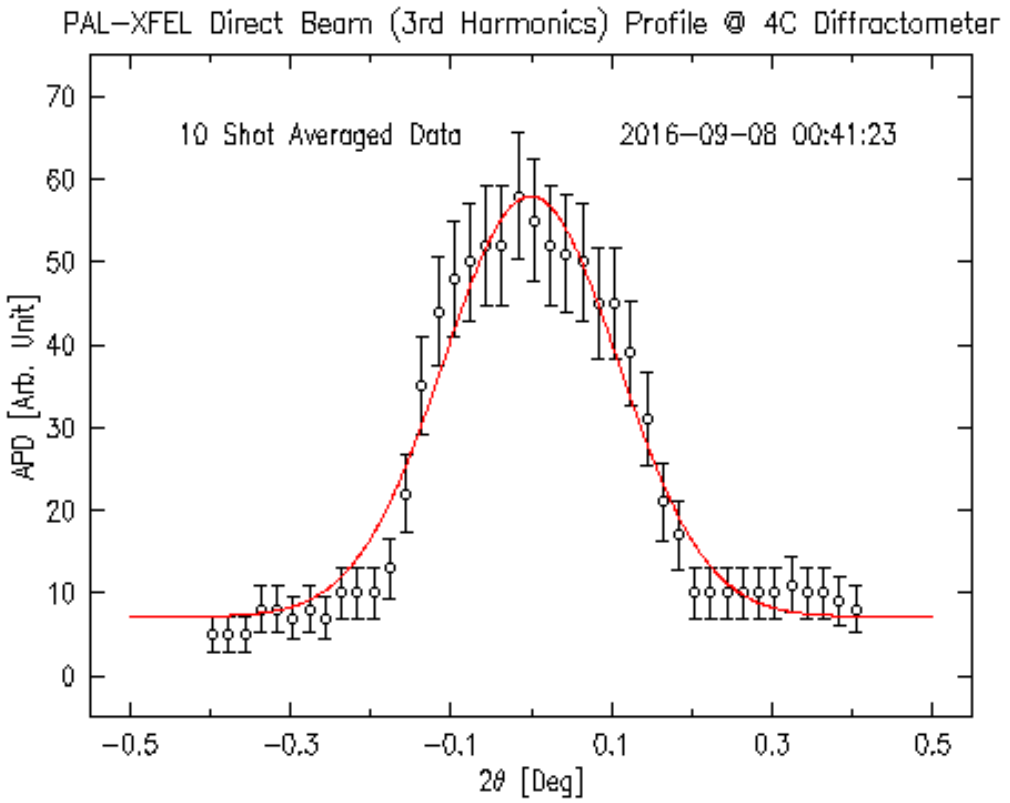



## Vertical Beam Size




| Experimental condition | |
|---|---|
| Photon energy | 6.583 keV |
| Bragg angle [deg] | 17.5 (Si 111) |
| Radius of coverture [mm] | 100 |
| Crystal to detector [mm] | 1489.7 |
| Full bandwidth [eV] | 186.18 (1340 pix) |
| Resolution [eV/pix] | 0.1389 |
| Beam size [mm] | ~ 2 |

# PAL-HXFEL Monochromatic Direct Beam Profile



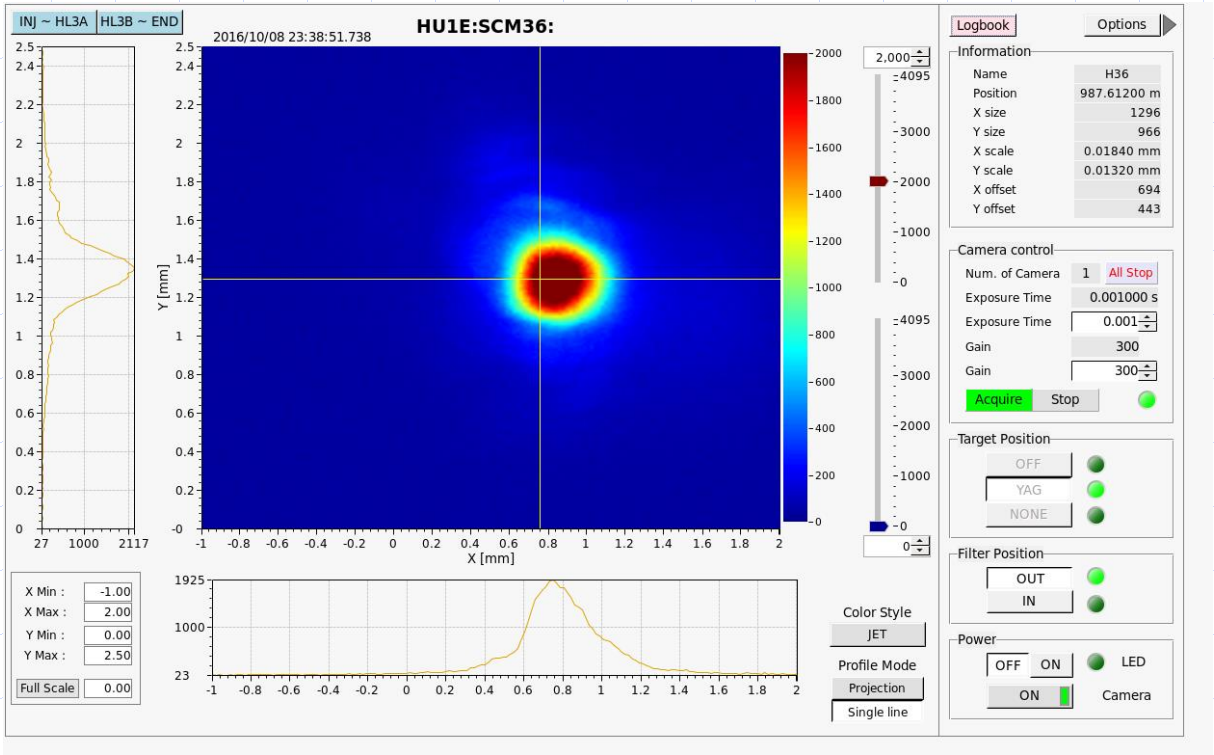

Band Width of Monochromatic XFEL Beam ~ 1.33 x $10^{-4}$

Si(111) DCM

# 0.35 nm FEL

- Beam energy: 5.2 GeV
- Undulator gap: 9 mm
- Undulator K: 1.87
- Number of undulators: 20
- Undulator BBA is applied
- K-tuning & Phase-matching data are not applied

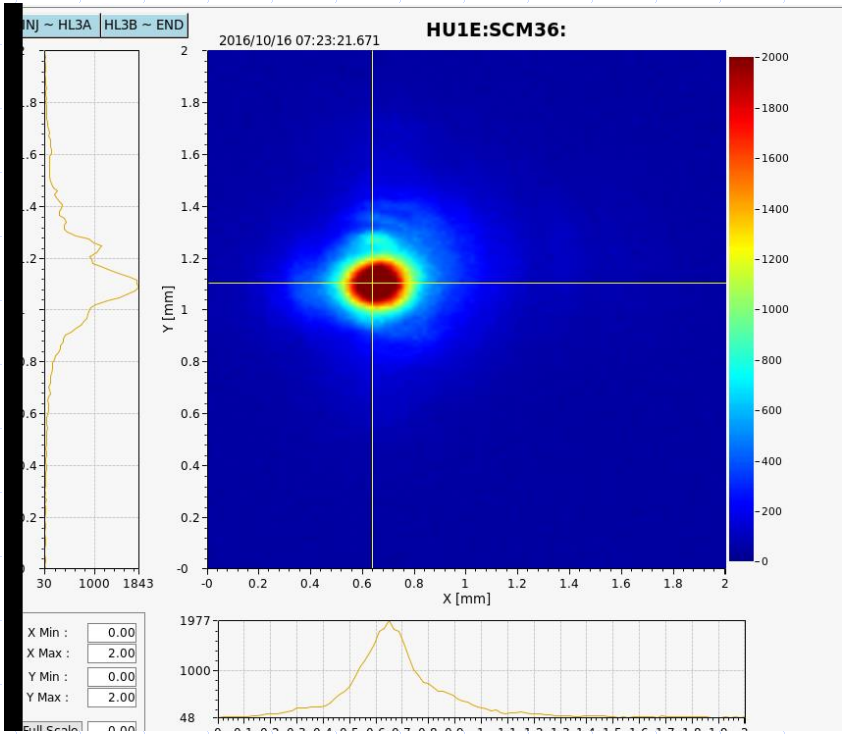
14:13 October 8, 2016

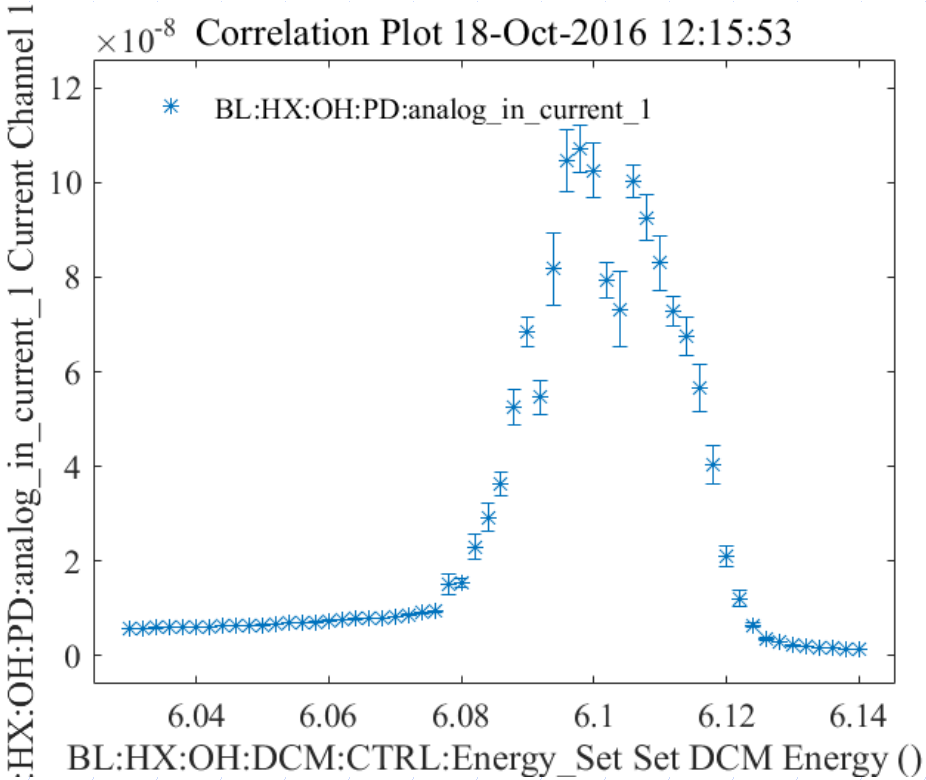


# 0.2 nm FEL

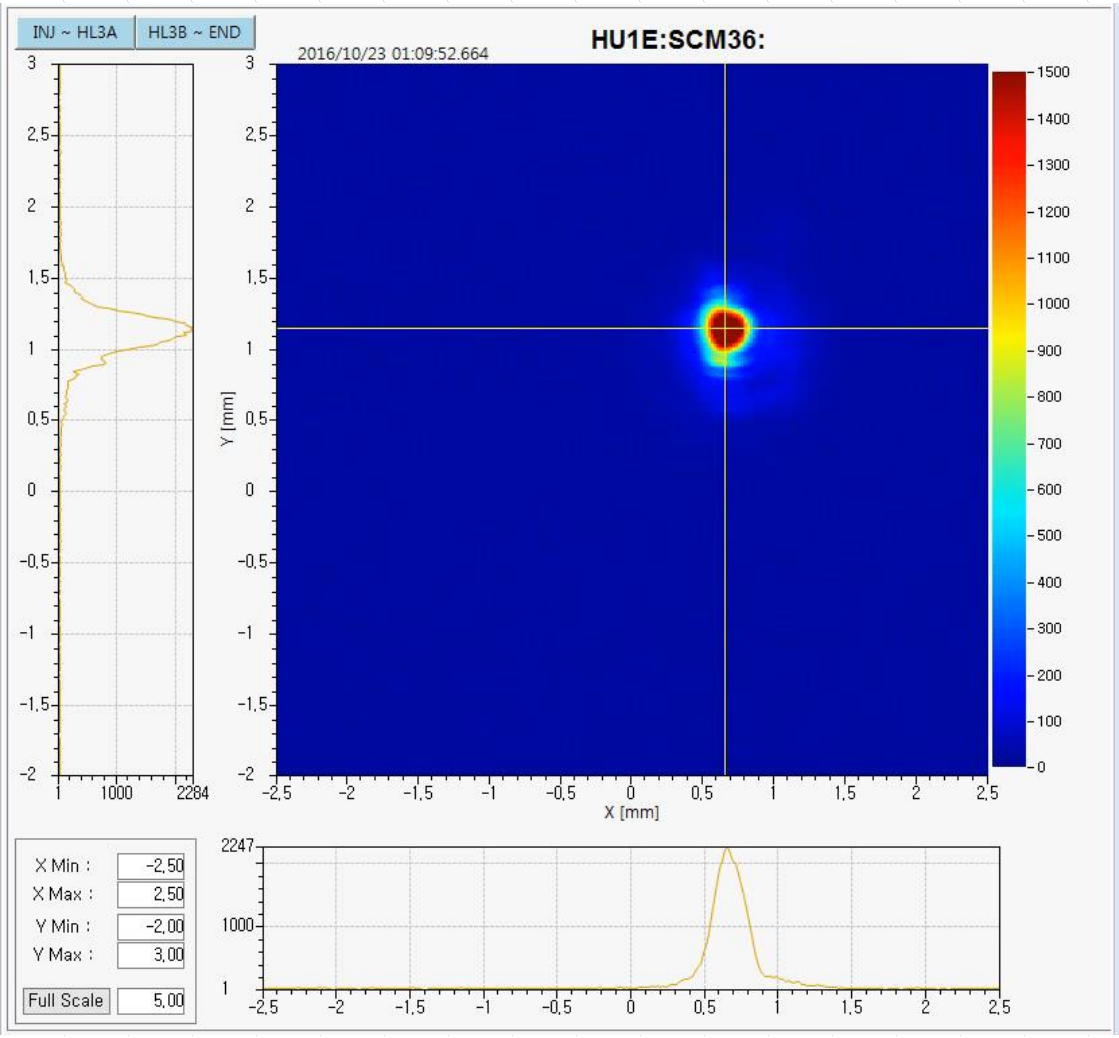
- Beam energy: 6.7 GeV
- Undulator gap: 9 mm
- Undulator K: 1.87
- Number of undulators: 20
- K-tuning & Phase-matching data are applied

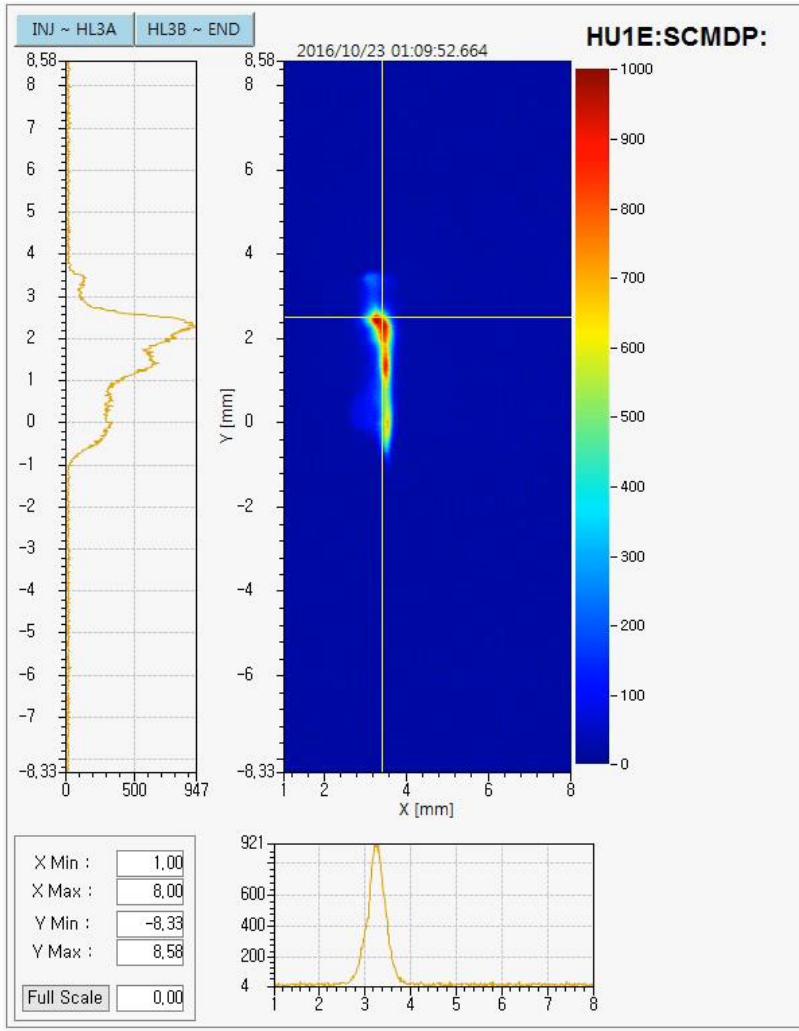
01:22 October 16, 2016



# 0.2 nm lasing on Oct. 23



# Summary (electron path)

- Operation license issued on April 12, 2016
- 10-GeV electron achieved on April 25, 2016
- Electron beam passed undulators on June 3, 2016
- Coherent X-ray Lasing on June 14, 2016
  - 4 GeV, 200 pC, $\lambda$~0.5nm
- Further works
  - Commissioning at higher energies (6 GeV ~ 10 GeV)
  - Commissioning for SX beamline
  - Various Feedback (phase vs. energy, orbit, etc)
- Rebuild Injector Test Facility with new gun

# Summary (photon path)

- Third Harmonic spectrum of Coherent X-ray measured by DCM (June 21 and September 4, 2016)
- Photon beam arrived at XPP and CXI Hutches (September 7, 2016)
- Single shot spectrum measured by PyLoN (September 4) and MPCCD (September 7)
- Earthquake (magnitude 5.8 on Sept. 12) triggered PSI interrupt
- 0.2 nm SASE FEL obtained on Oct. 16, 2016

- 5-way meeting (October 24~26, 2016) at PAL
- Achieving SASE FEL toward 0.1 nm
- Pilot Experiments in December
- Open to Users in early 2017

# Dedication on Sept. 29, 2016