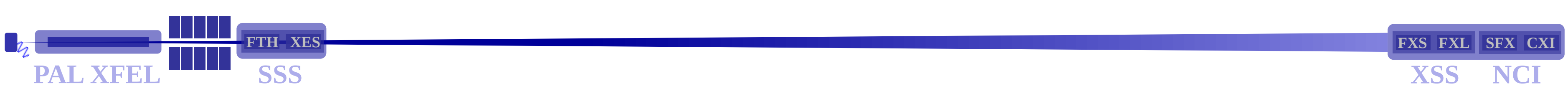
Undulator BBA & FEL Commissioning for PAL-XFEL

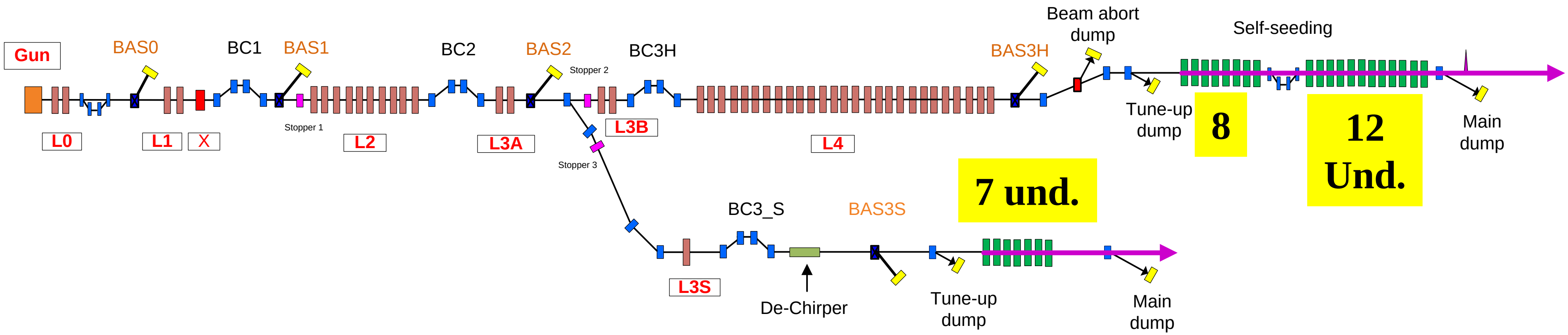
Heung-Sik Kang

on behalf of PAL-XFEL team

Pohang Accelerator Laboratory



PAL-XFEL Layout

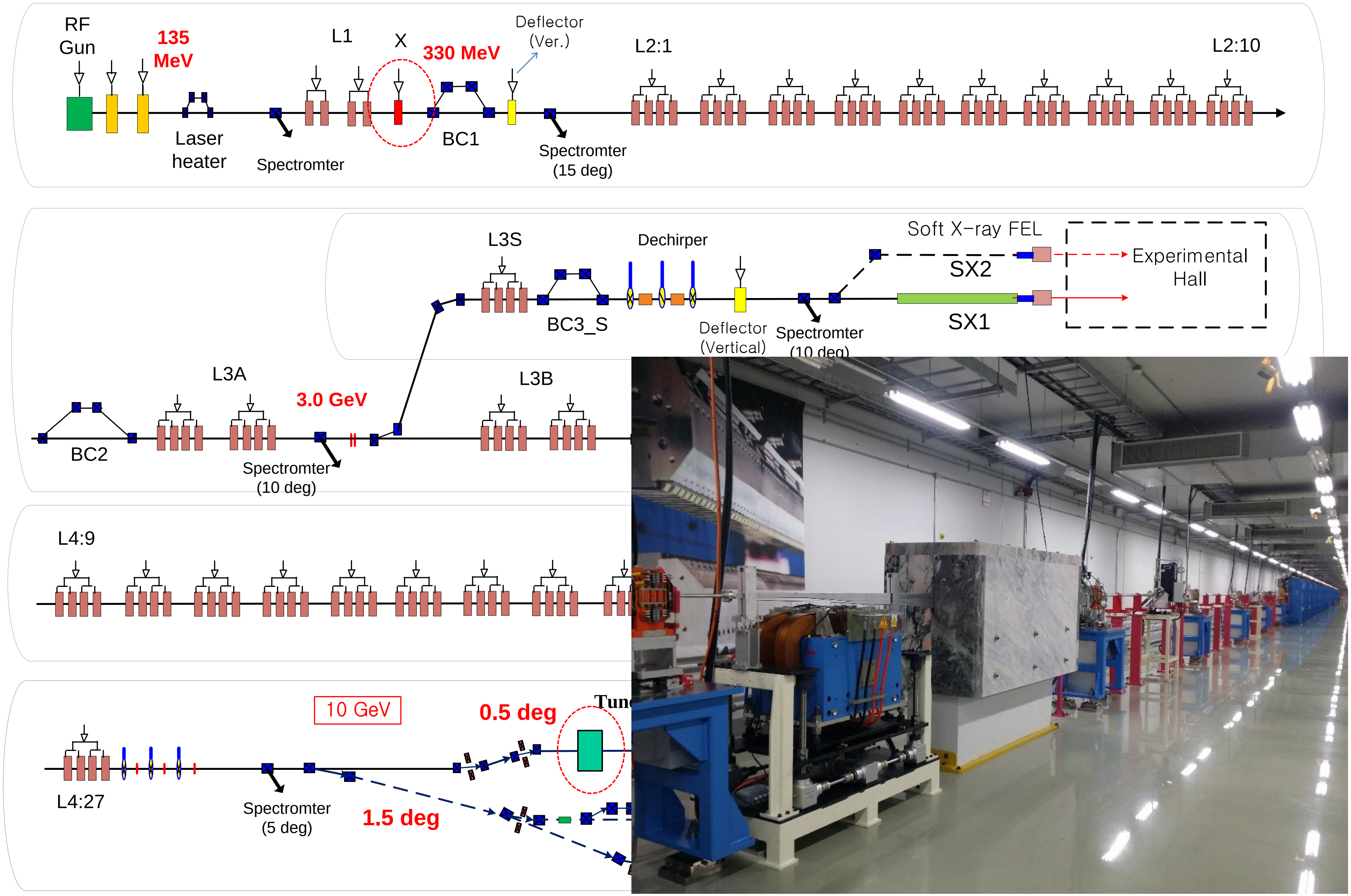


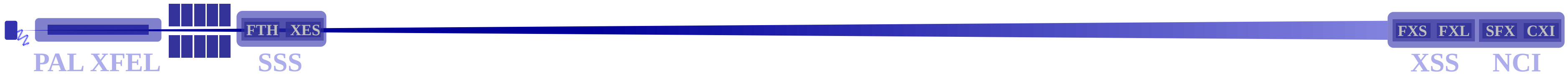
Main parameters

e^- Energy	10 GeV
e^- Bunch charge	20-200 pC
Slice emittance	0.5 mm mrad
Repetition rate	60 Hz
Pulse duration	5 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

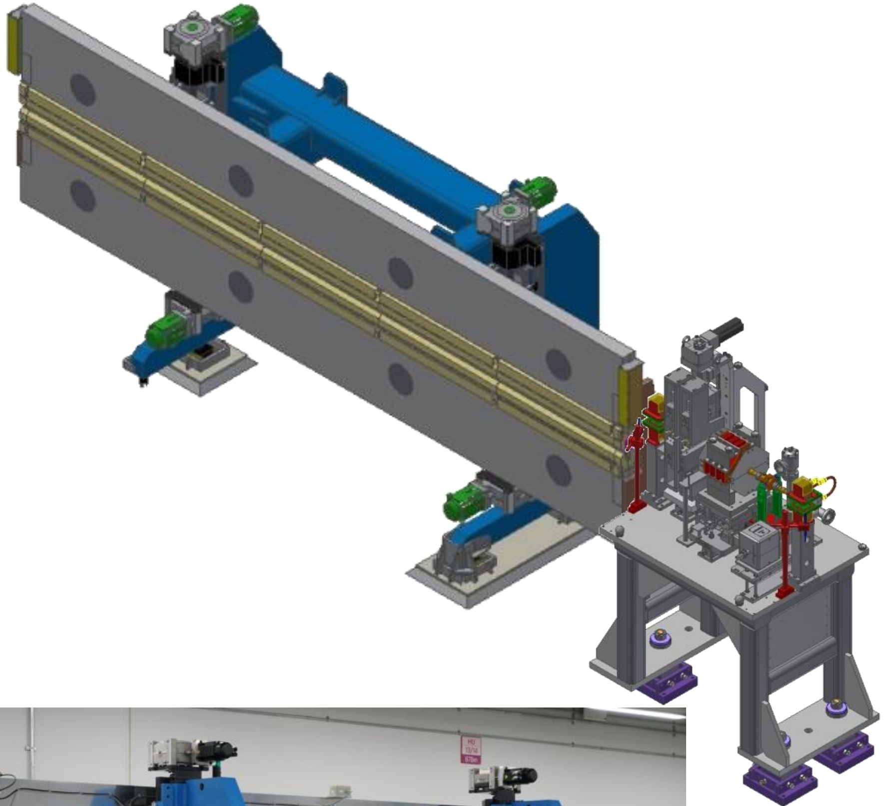
Undulator Line	HX1	SX1
Wavelength [nm]	0.1 ~ 0.6	1 ~ 4.5
Beam Energy [GeV]	4 ~ 10	3.15
Wavelength Tuning [nm]	0.6 ~ 0.1 (energy or gap)	4.5 ~ 3 (energy) 3 ~ 1 (gap)
Undulator Type	Planar, out-vac.	Planar, out-vac
Undulator Period / Gap [mm]	26 / 8.3	35 / 8.3

PAL-XFEL Layout (Detail)





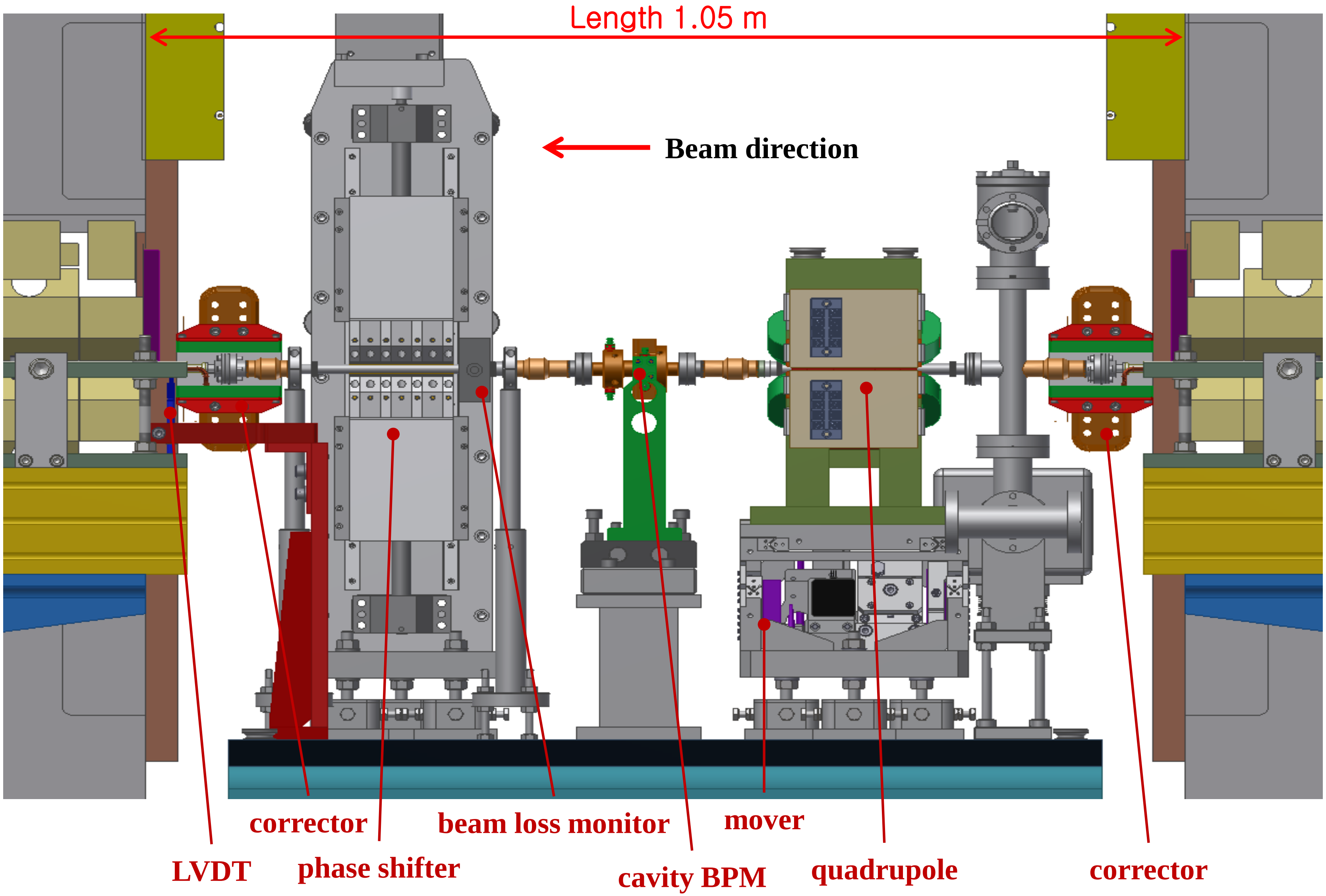
Undulator

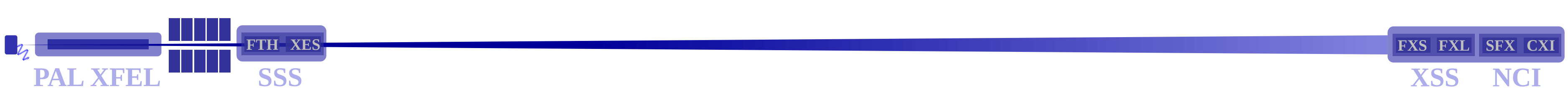


- **EU-XFEL undulator design is benchmarked.**
- **PAL modified the design including the new magnetic design, EPICS IOC, and updated tolerances reflecting new parameters.**

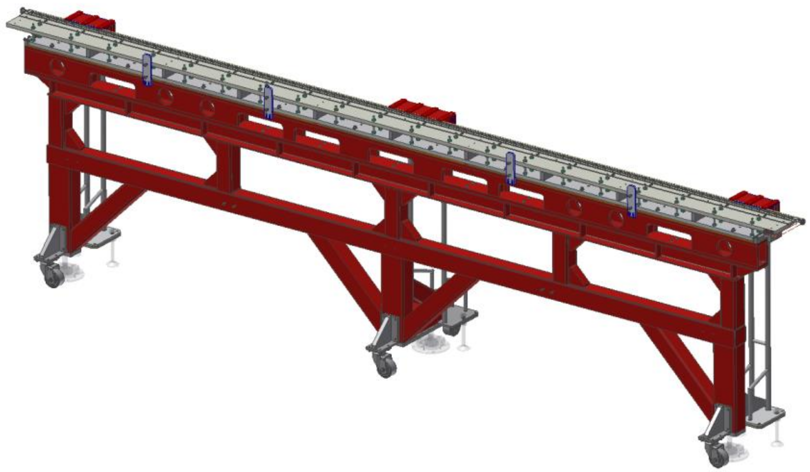
Symbol	Unit	Nominal value
E	GeV	10.000
g	mm	8.30
λ_u	mm	26.0
L_{und}	m	5.0
λ_r	nm	0.1
B_{eff}	Tesla	0.8124
K		1.9727
Optical phase error	degree	less than 5.0

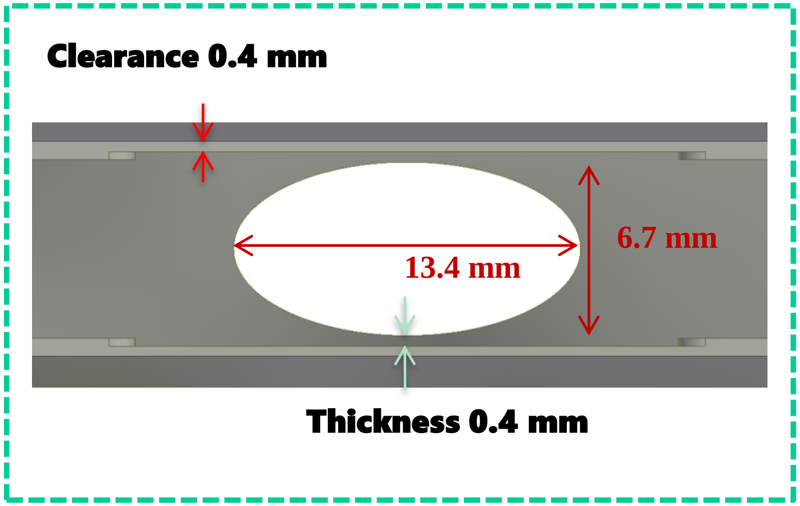
Undulator Intersection

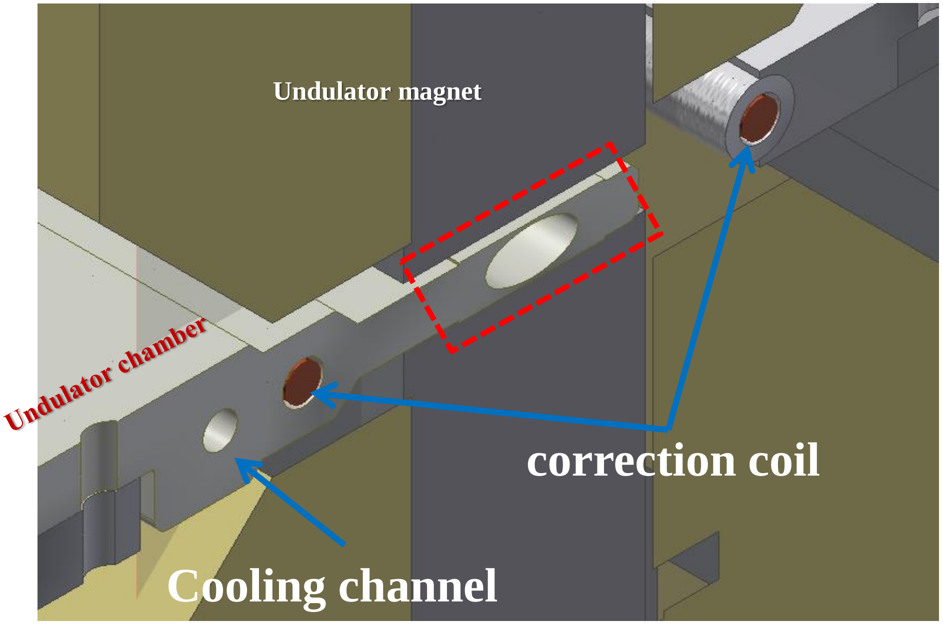




Undulator Vacuum Chamber



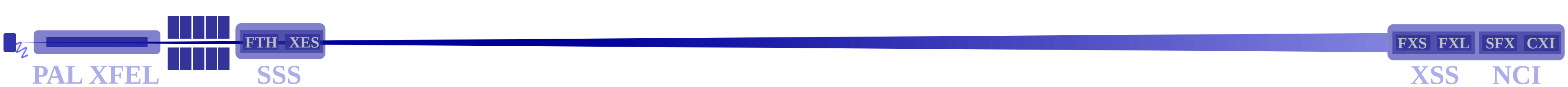




- Surface roughness : < 150 nm
  - Chemical polishing
- Oxide layer thickness : < 7 nm
  - Chemical Cleaning

Commissioning Status

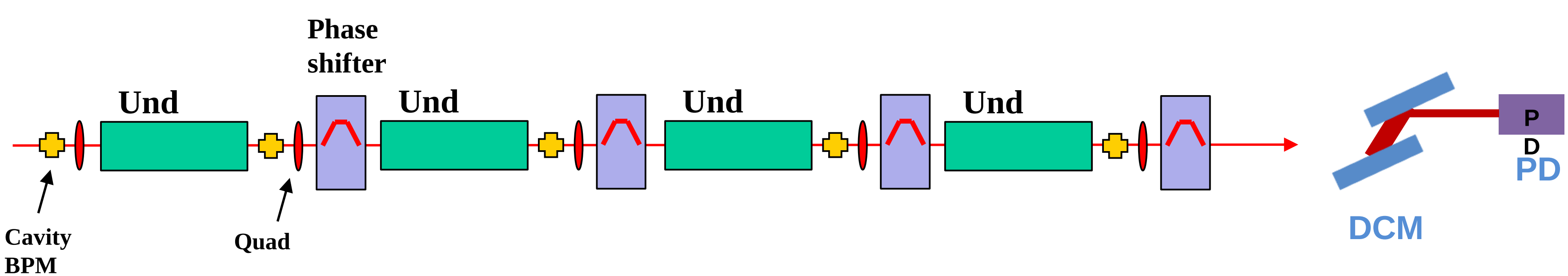
◆ Nov 2015	RF conditioning Started
◆ 14 April 2016	Beam commissioning Started
◆ 25 April	10 GeV acceleration Achieved
◆ 03 June	Dipole edge radiation Observed
◆ 12 June	Undulator radiation Observed
◆ 14 June	First SASE lasing at 0.5 nm
◆ July	Summer maintenance for 1 month
◆ 30 August	SASE lasing at 0.5 nm (재현)
◆ 09 September	Beamline commissioning with 0.5 nm FEL is Completed
◆ 08 October	Lasing at 0.35 nm
◆ 16 October	Lasing at 0.2 nm
◆ ?	Lasing at 0.15 nm

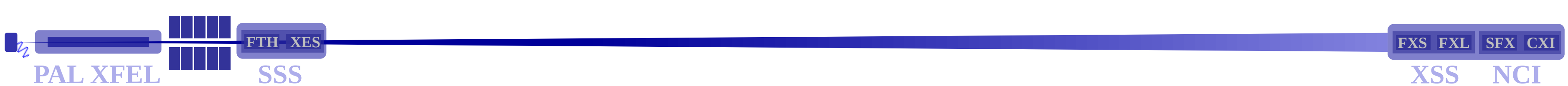


Beam Based Alignment for Undulators

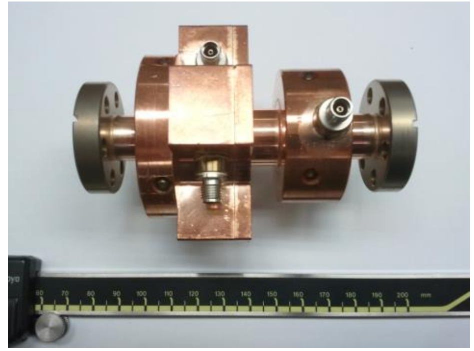
- To establish a straight orbit along the undulators
- All correctors of undulator line are turned OFF and Undulator gap are fully open (200 mm)
- BPM offsets and quad offsets are calculated to get dispersion-free straight orbit
- All cavity BPMs and quads have its own mover which can move up to +/-1 mm with precision of 1 um for horizontal and vertical directions.
- Cavity BPM's resolution is essential for BBA performance

- Beam positions are measured at four different beam energy: 4, 5.2, 6.7, 10 GeV
- At least 7 or 8 steps is required. It takes about 2 to 3 hours

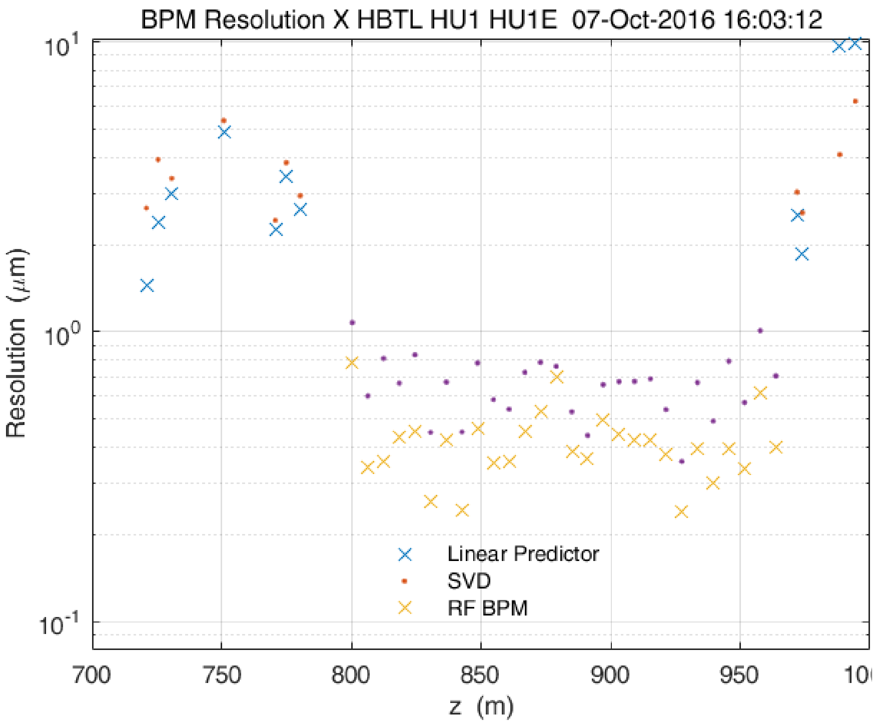




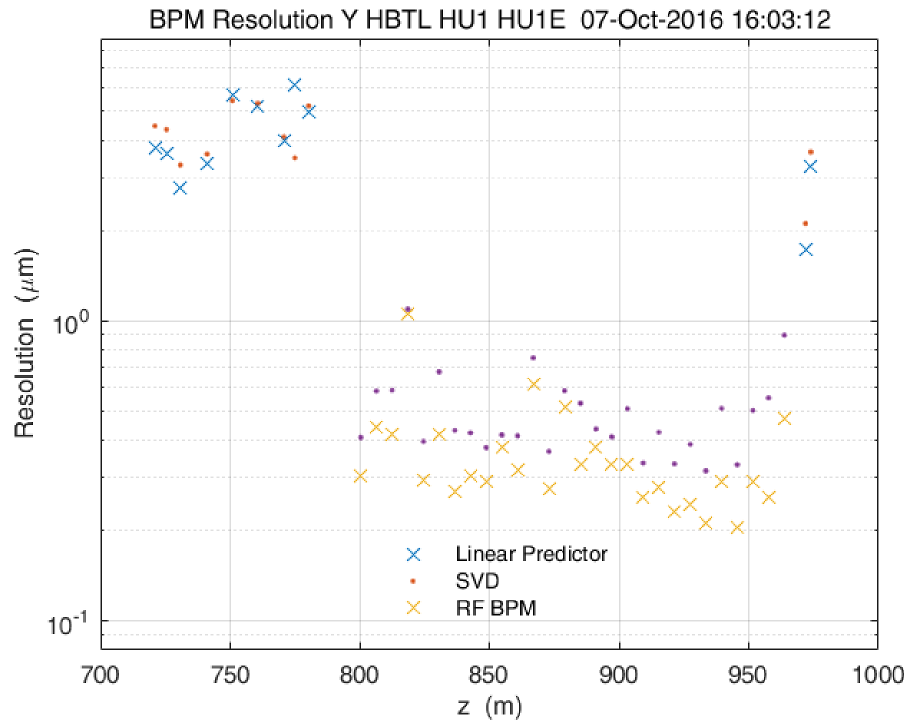
Cavity BPM resolution



horizontal



vertical



Beam Based Alignment for Undulators

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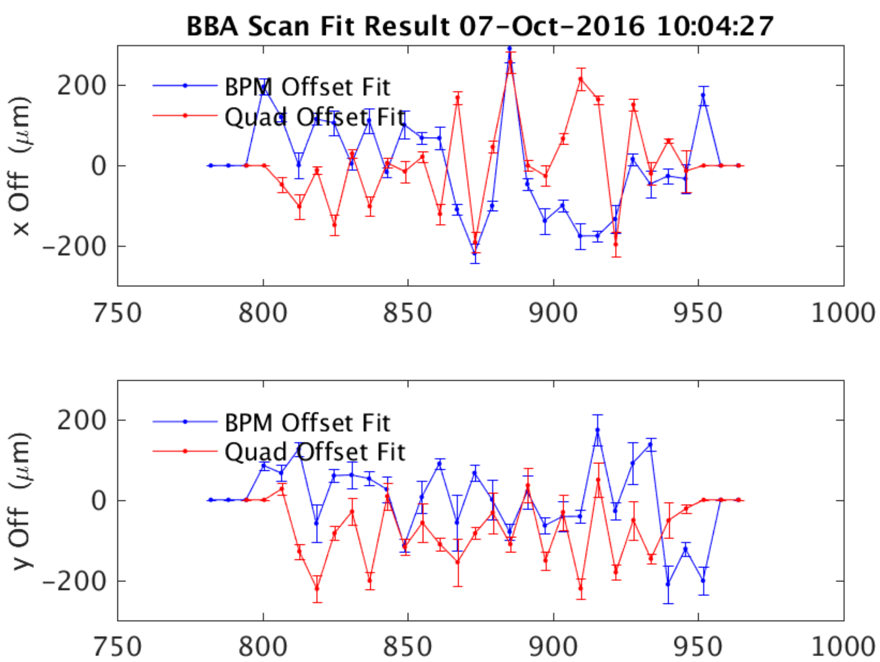
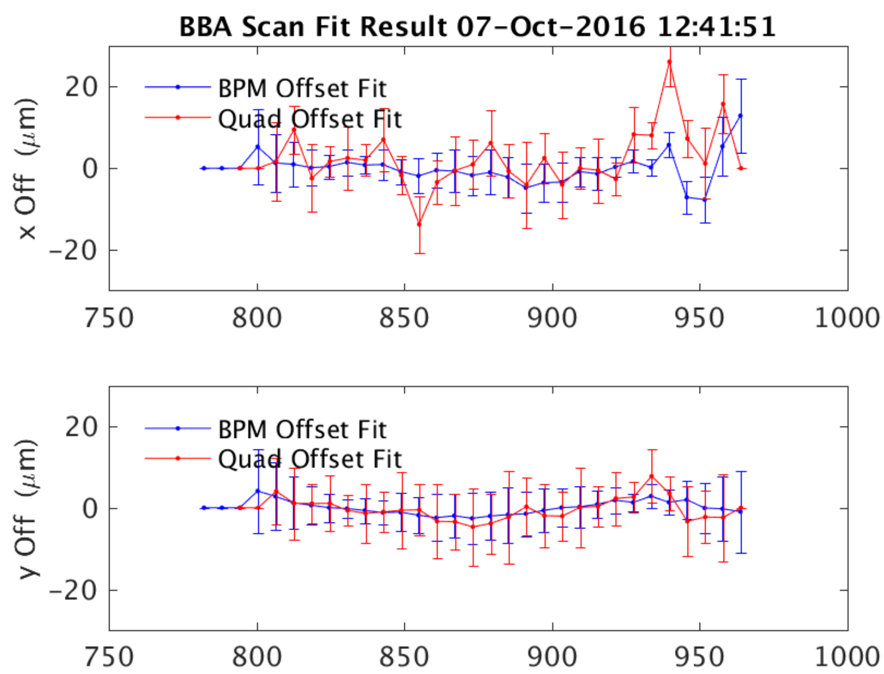
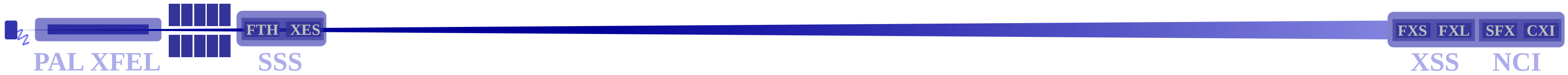
1-st step

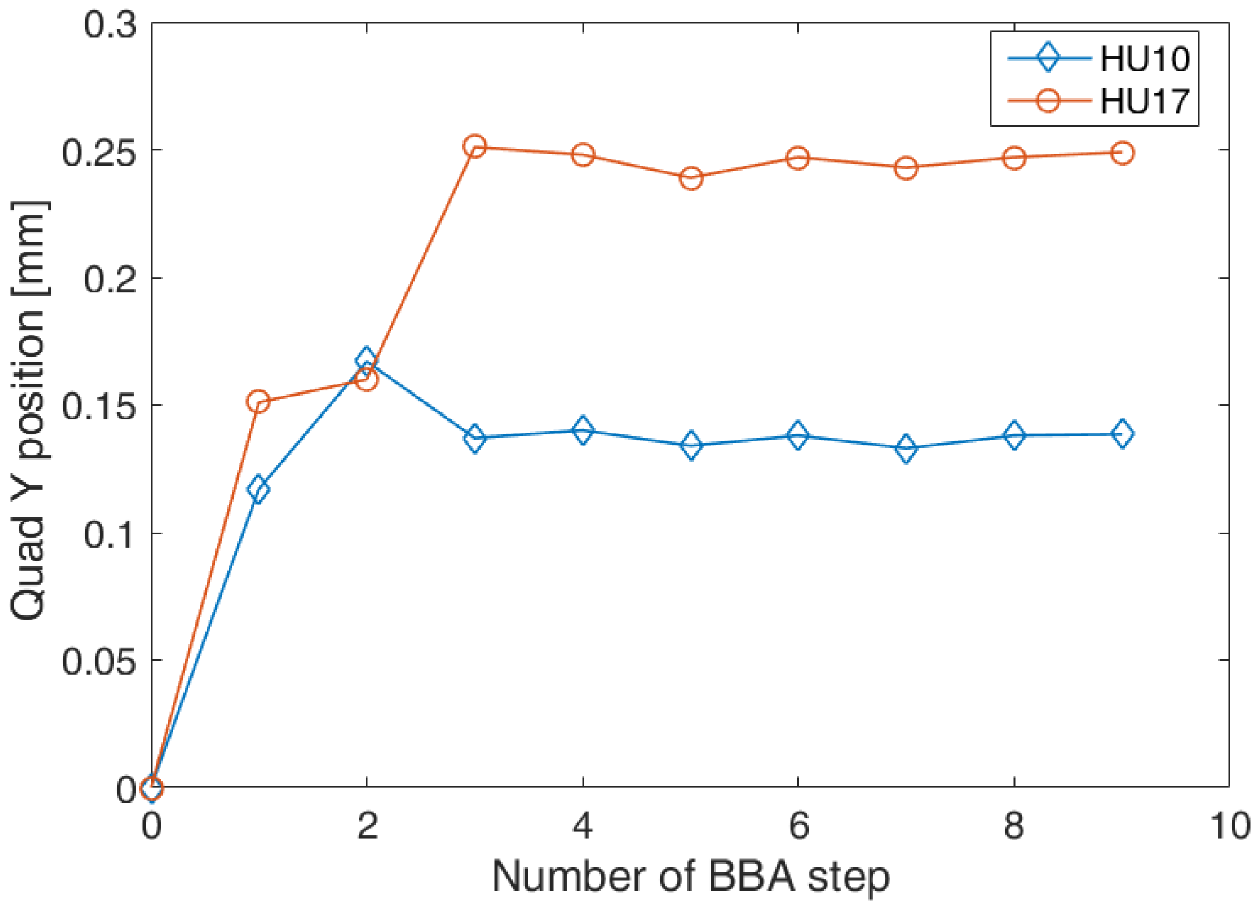


8-th step





Quad Position vs. Number of BBA step



BBA Scan Orbit

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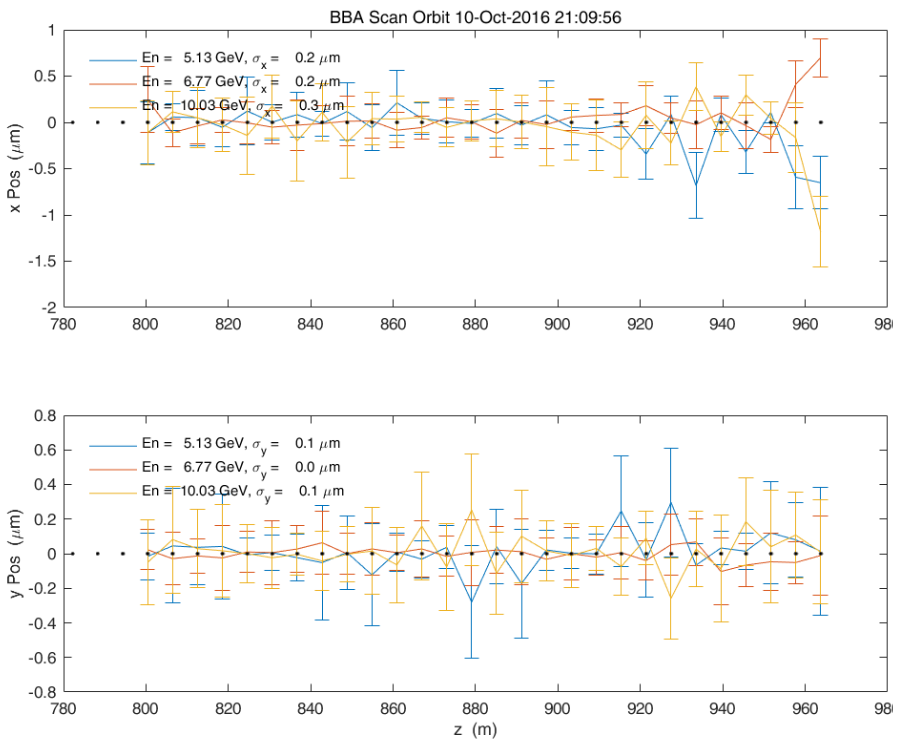
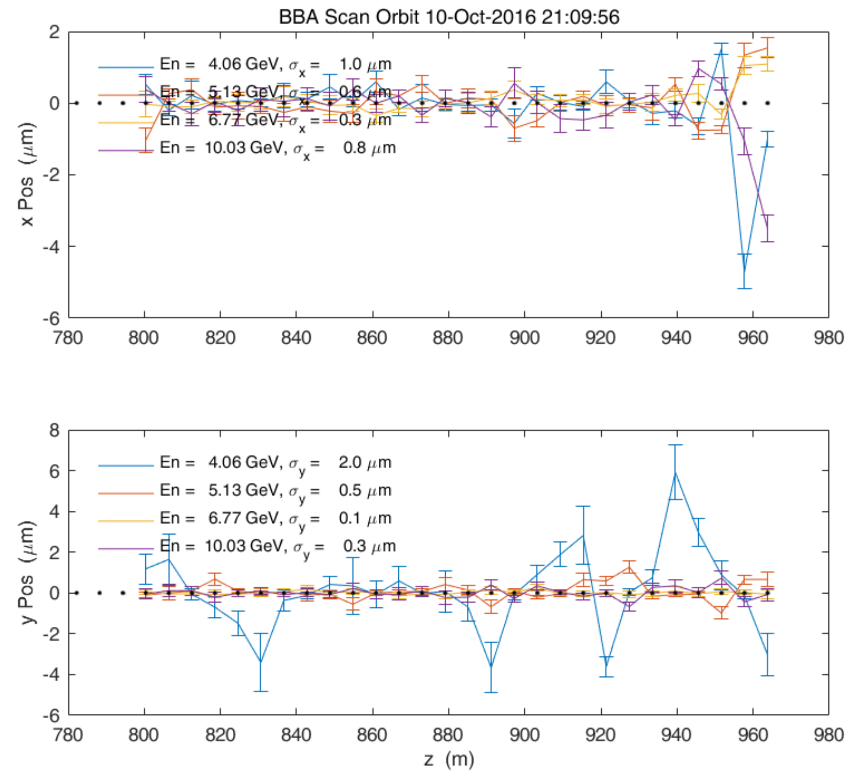
3 Energy: 5.2, 6.7, 10 GeV

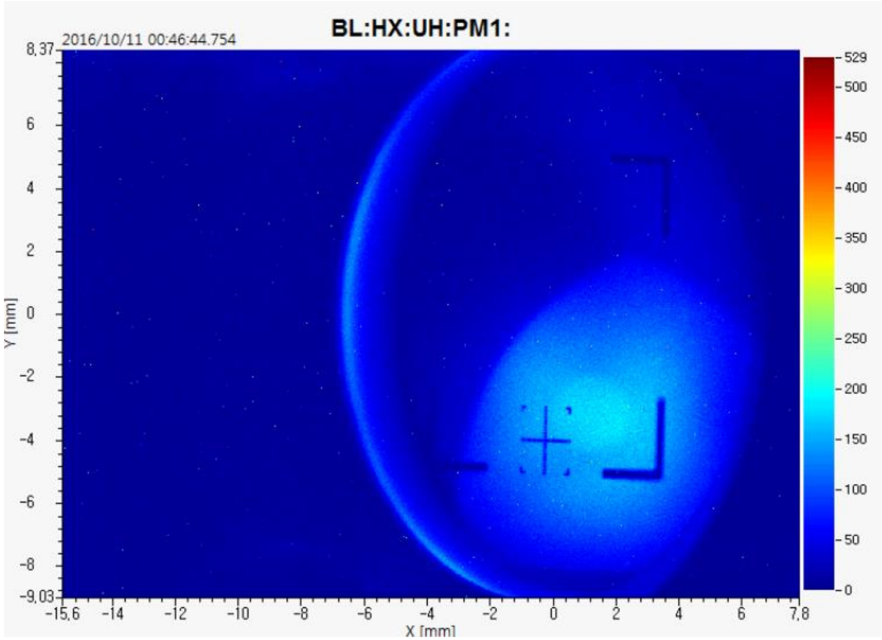
4 Energy: 4, 5.2, 6.7, 10 GeV



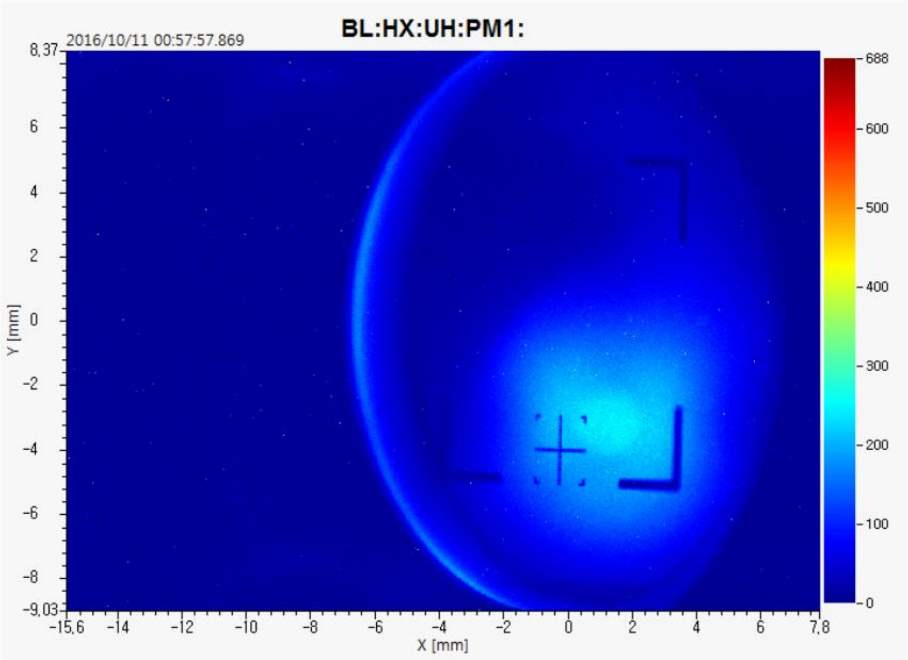


Undulator Radiation

HU122

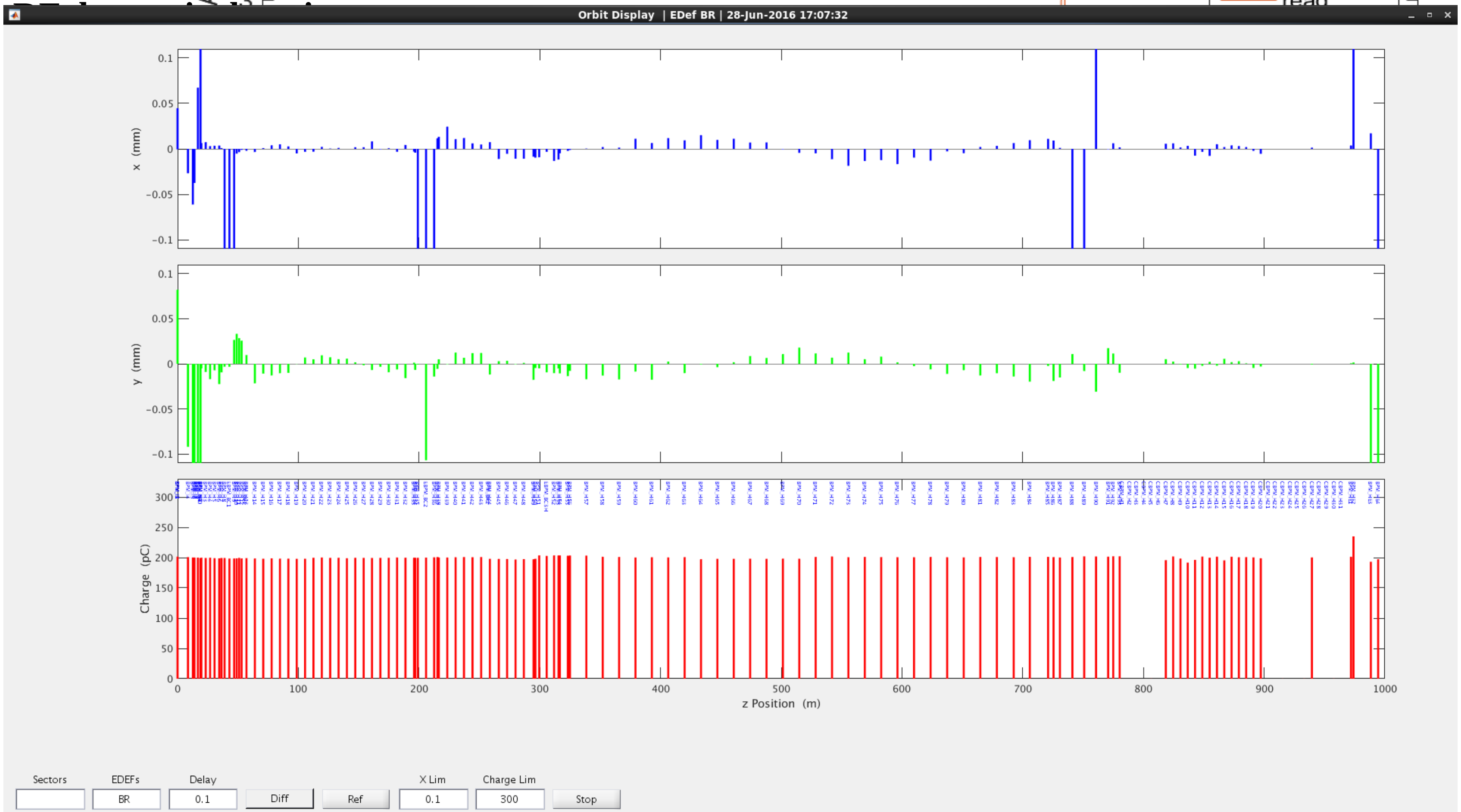


HU124

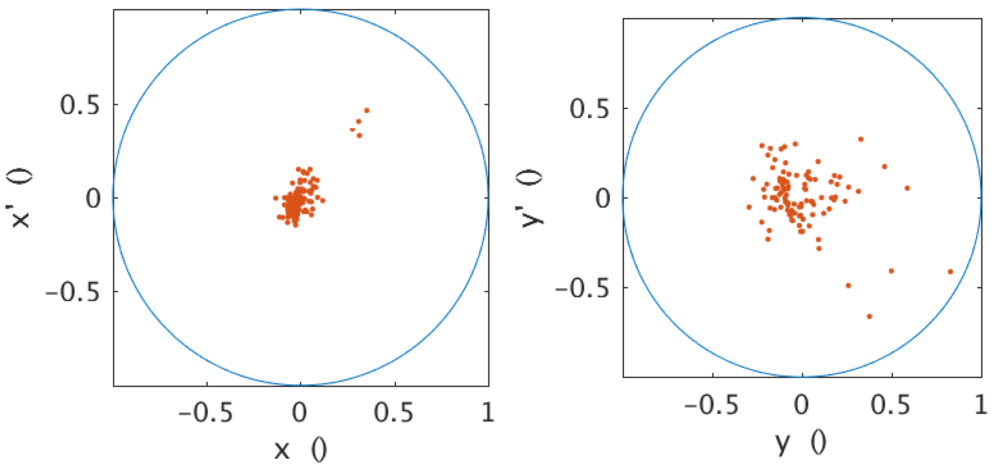


Global Orbit Feedback

- Global orbit feedback runs from Injector end to Main dump
- It uses the design lattice function and the calculated beam energy by LEM (Linac Energy Management)
- LEM calculates the beam energy for each quadrupole using the

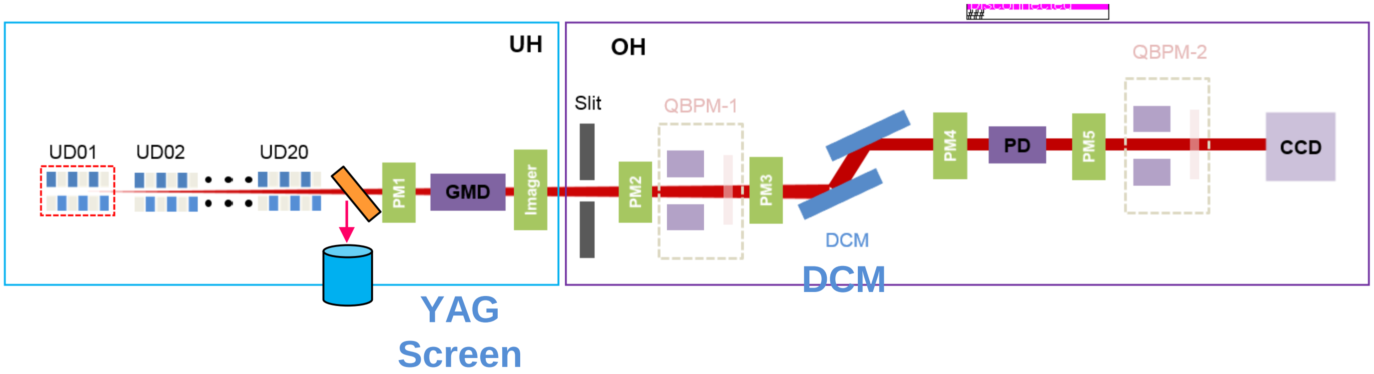


Electron Beam Stability

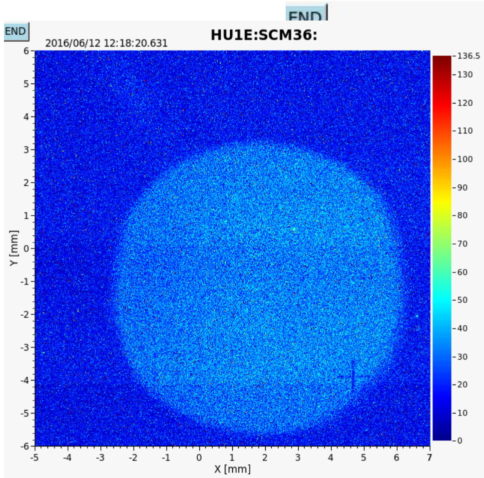


- ✓ Circle represents a phase space of 1 um emittance electron beam
- ✓ Electron beam jitters in position and angle are much smaller than the phase space

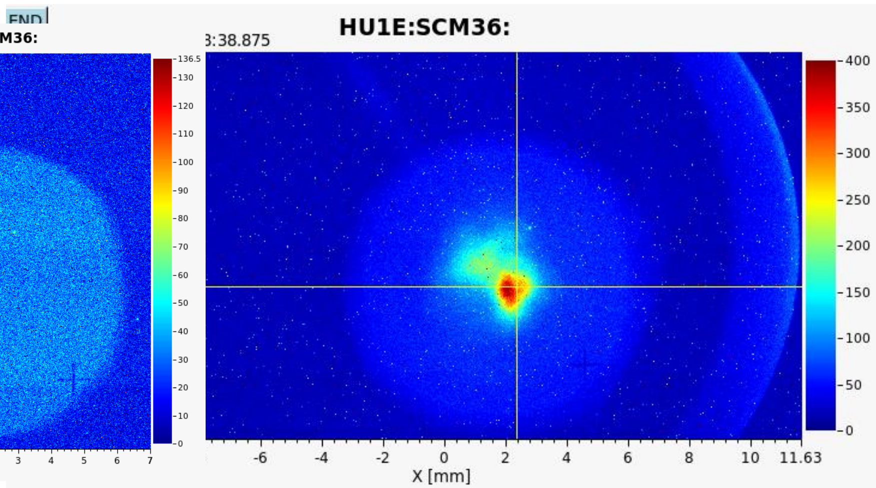
First Lasing at 0.5 nm on 14 June



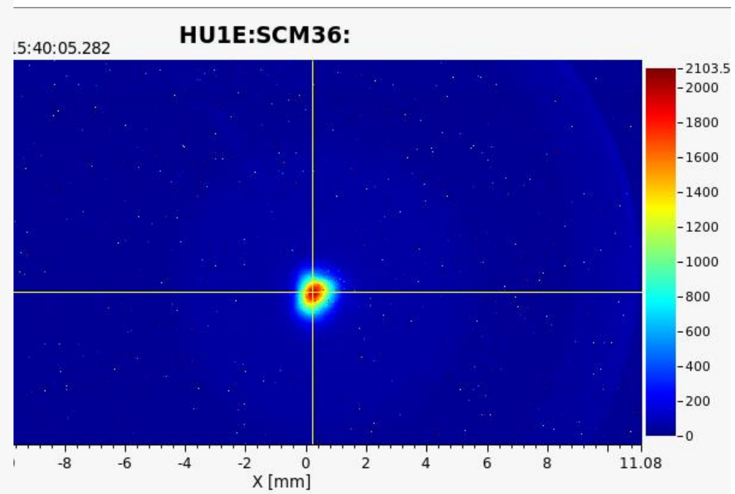
Spontaneous radiation



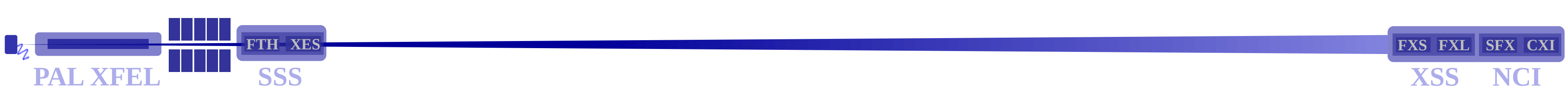
12 June 2016



05:01, 14 June 2016



16 June 2016



0.35 nm FEL (08 Oct. 2016, 2:13 pm)

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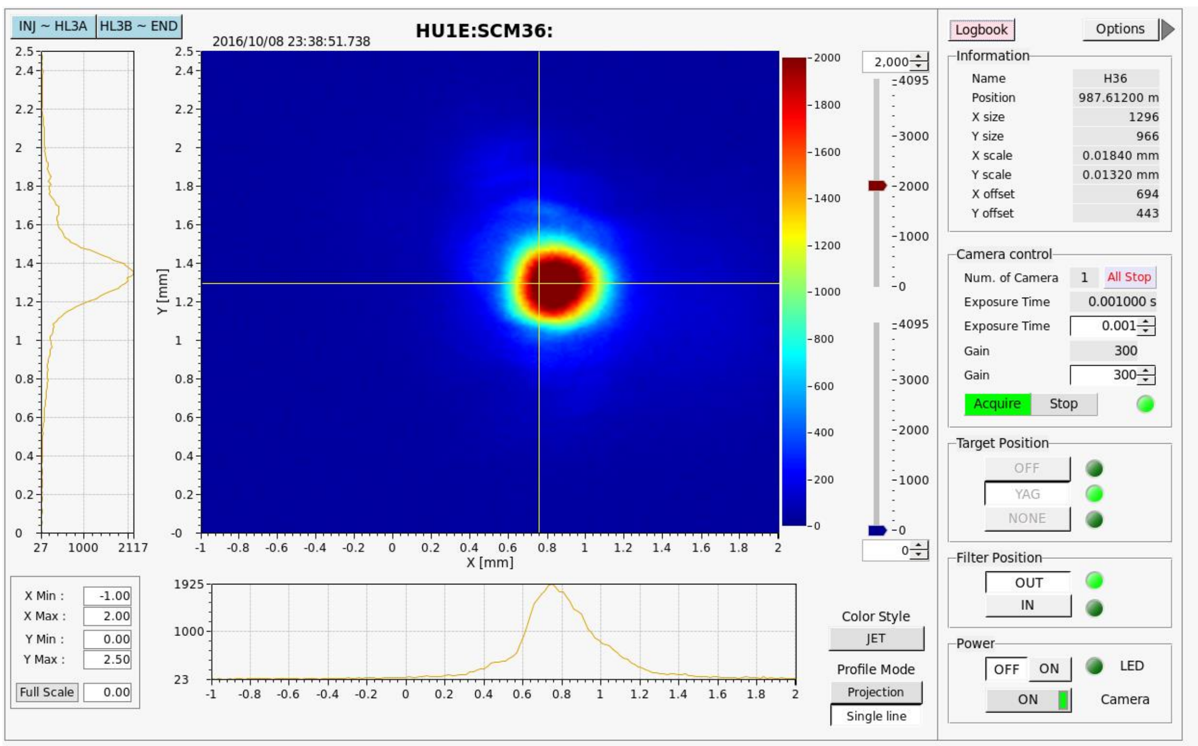
- Beam energy: 5.2 GeV
- Undulator gap: 9 mm
- Undulator K: 1.87
- Number of undulators: 20
- Undulator BBA is applied

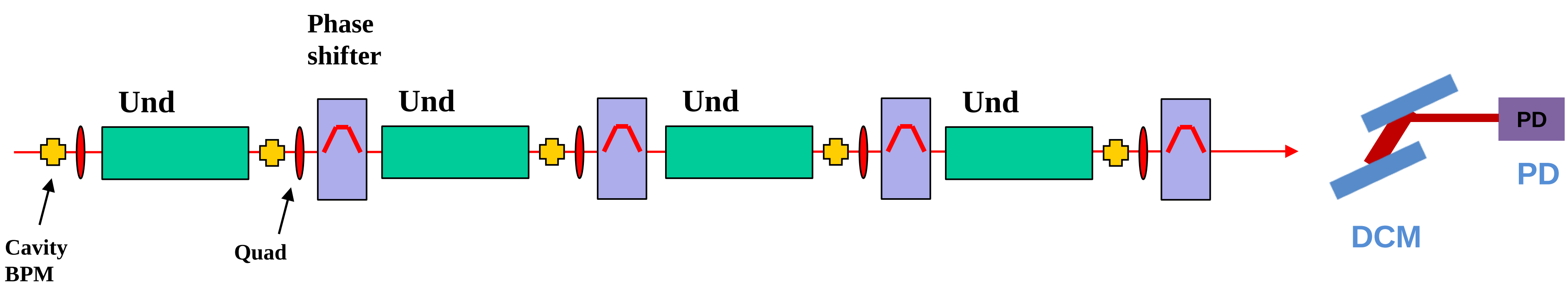


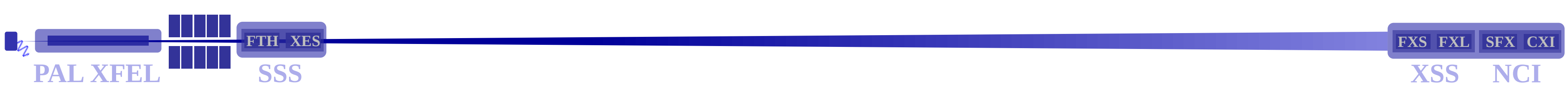
Undulator Optimization

✓ **Lasing of 0.15 nm FEL is not so easy to achieve as 0.5 nm FEL.**
✓ **Requirements for lasing are very stringent.**
✓ **Procedures for Undulator optimization are established**

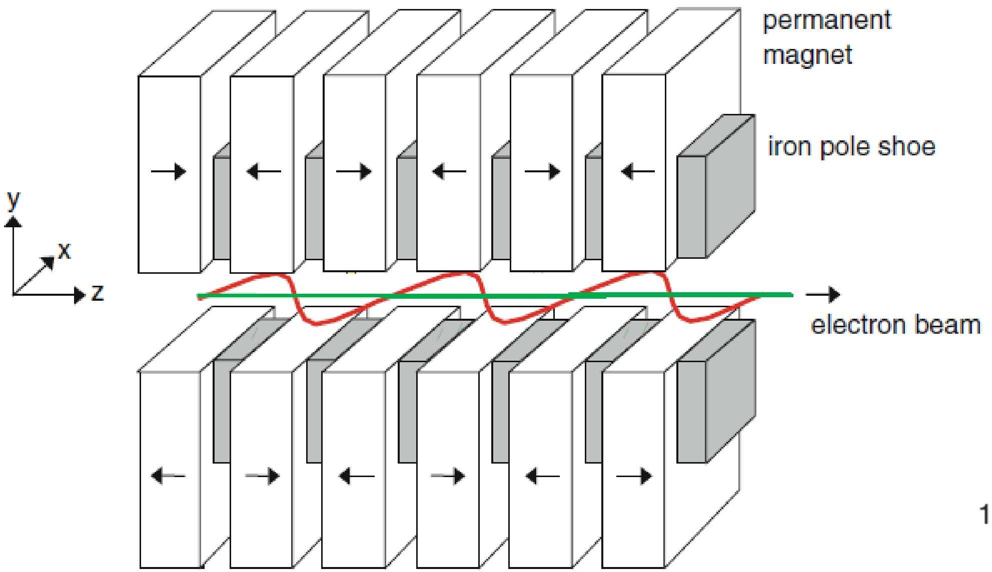
- **K-value tuning**
- **Undulator Field Center**
- **Phase matching**
- **Undulator Tapering (TBD)**

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

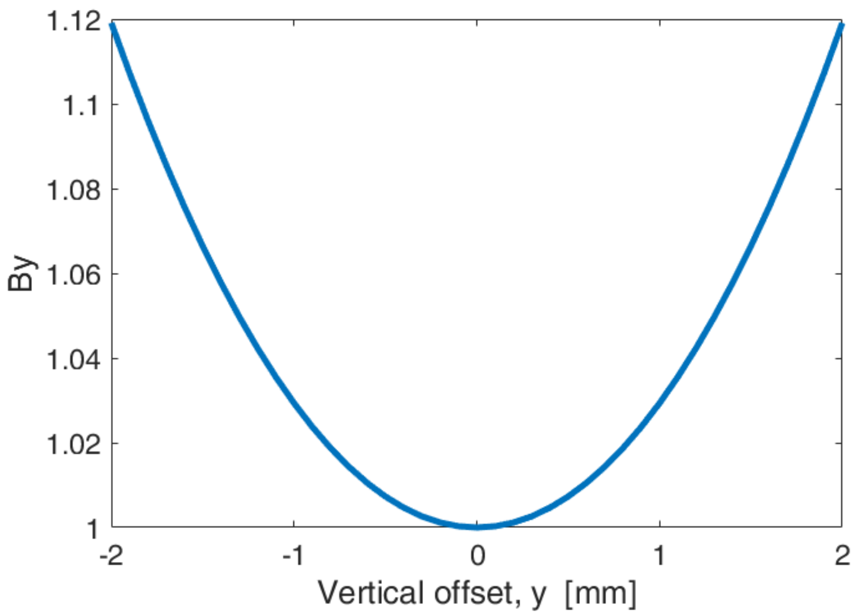




Undulator Field



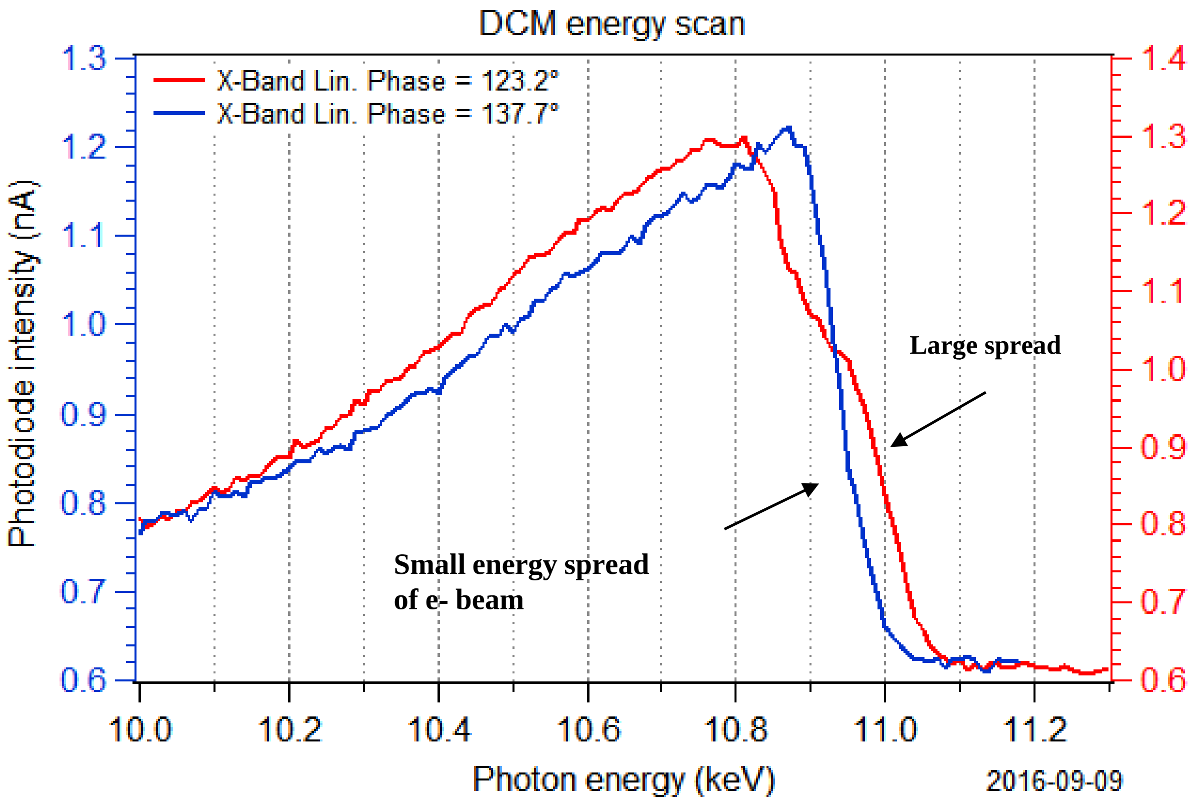
$$B_x = 0\,,$$
$$B_y = -B_0 \cosh(k_u y)\sin(k_u z)\,,$$
$$B_z = -B_0 \sinh(k_u y)\cos(k_u z)\,.$$

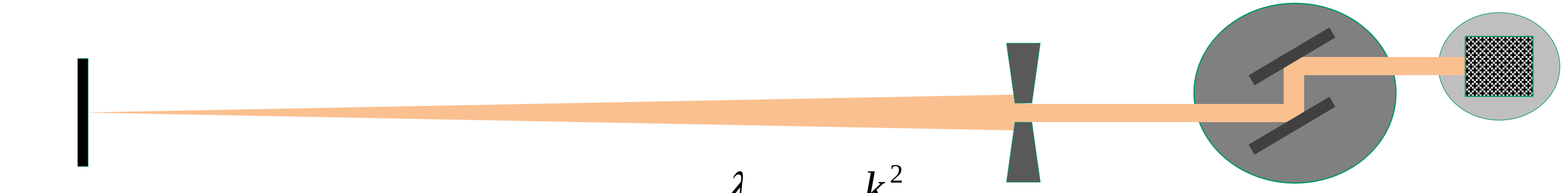


$$\lambda_r = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{k^2}{2}\right)$$

$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})$$

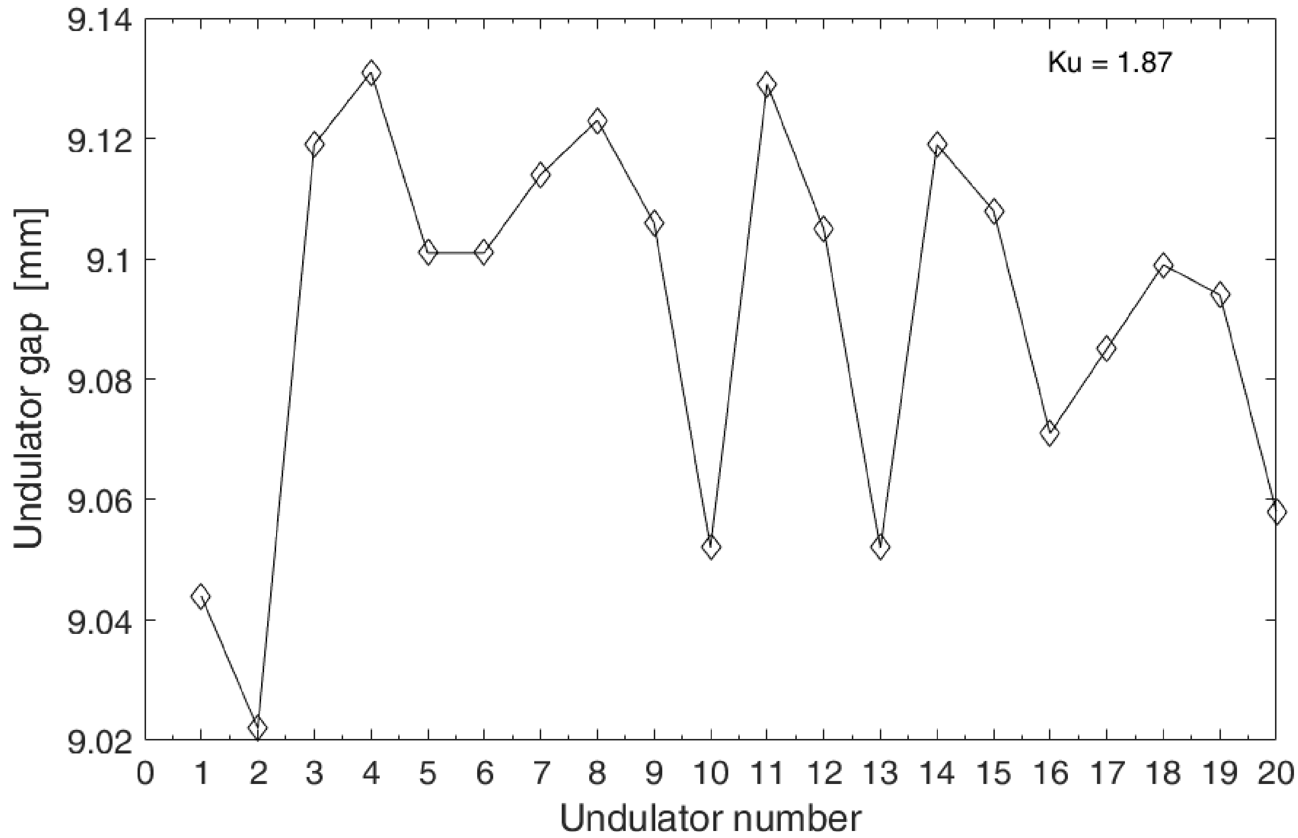
Undulator K-tuning





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

K-tuning Gap



Ku = 1.87
Undulator gap [mm]
9.14
9.12
9.1
9.08
9.06
9.04
9.02
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Undulator number

Undulator Field Center

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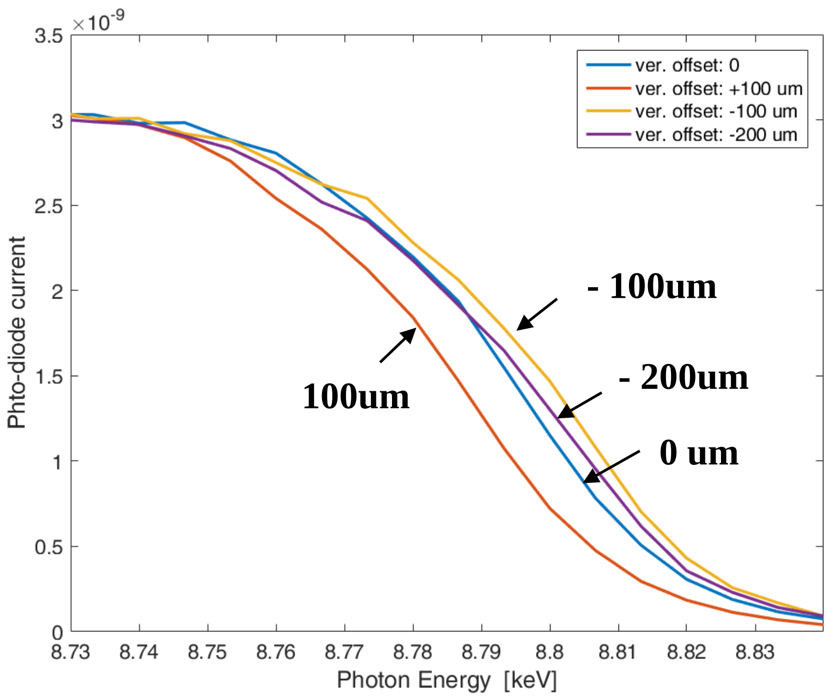
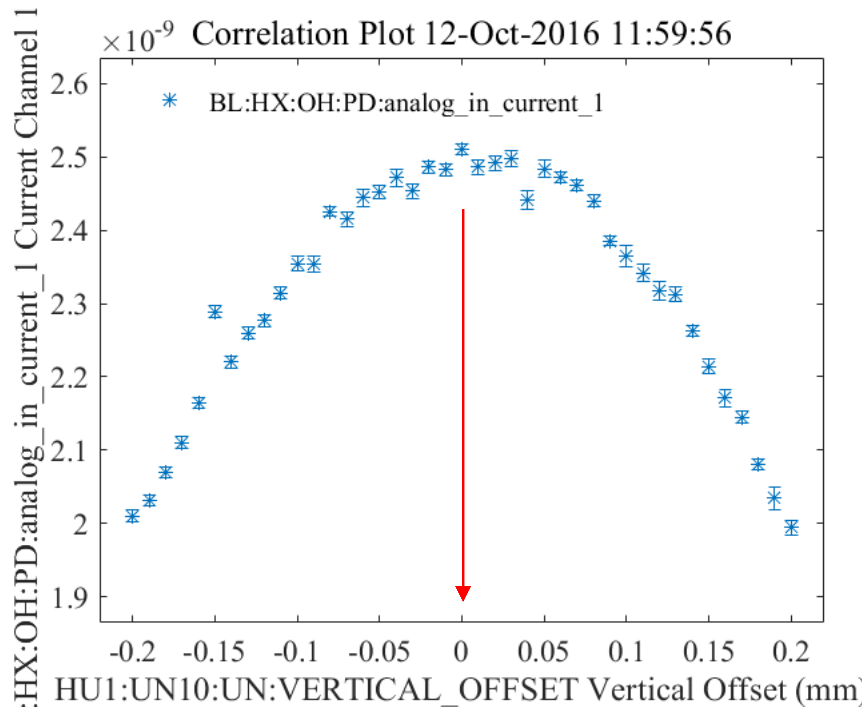
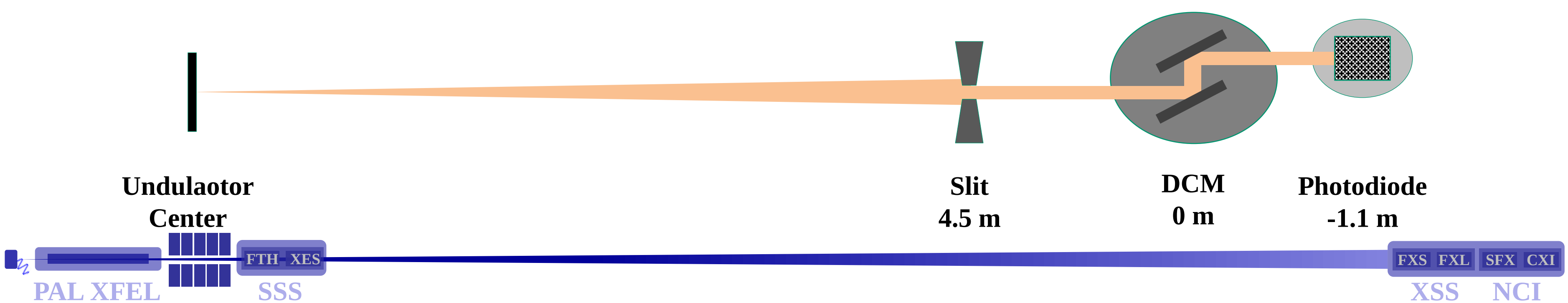
Undulator Radiation Spectrum for Different Vertical offset

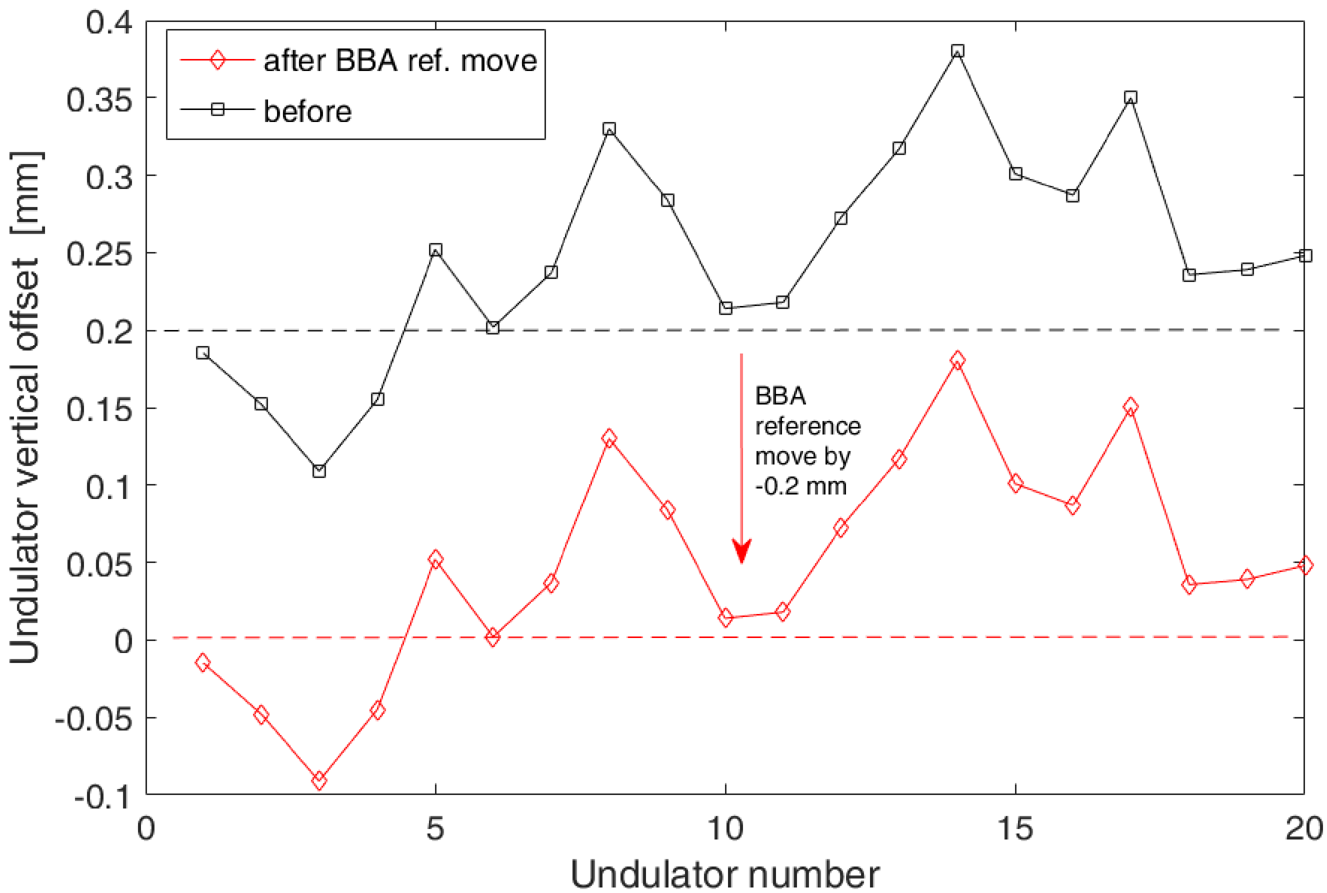


Undulator Field Center Position

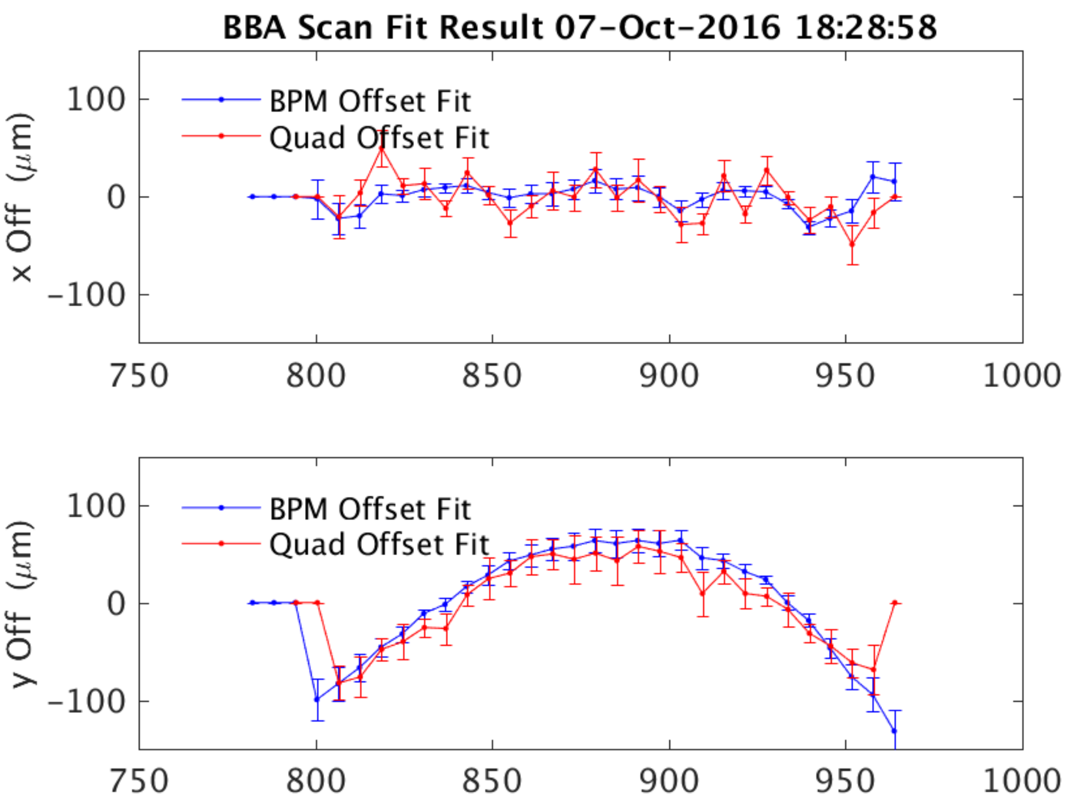




Undulator Vertical Offset



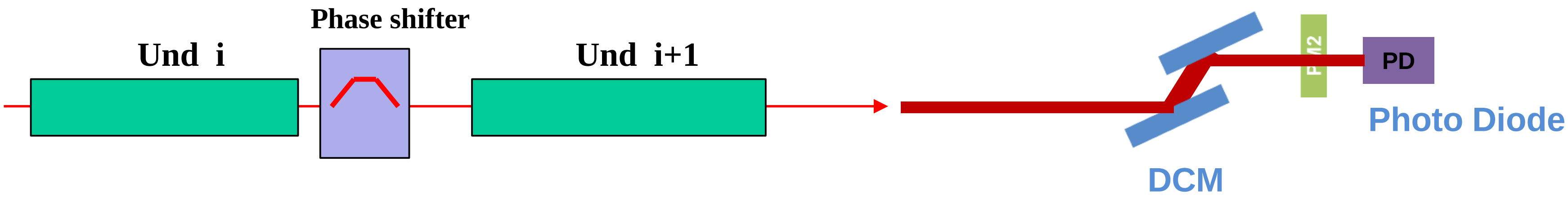
BBA with Undulator gap closed



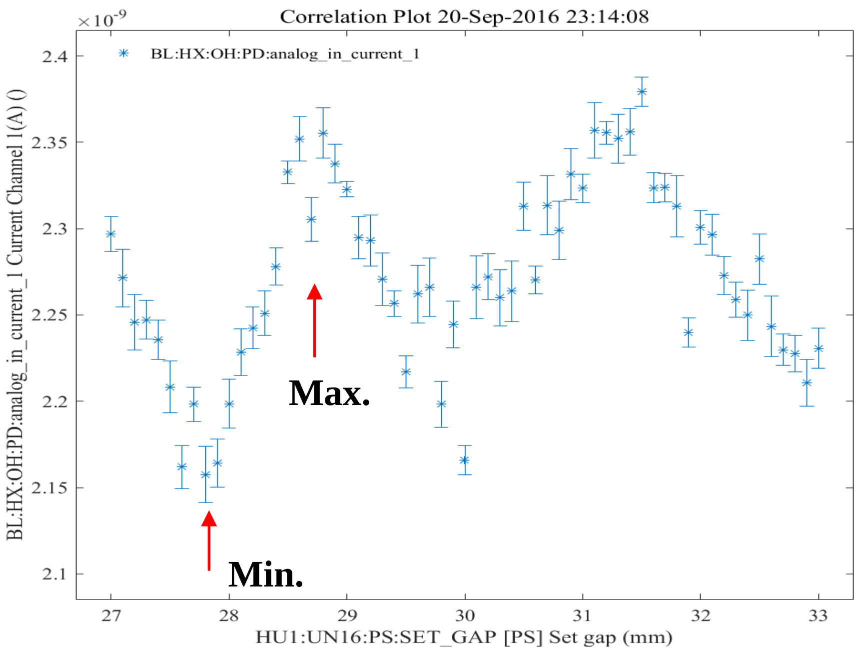
- ✓ BBA was done with undulator gap closed to 9 mm
- ✓ In vertical plane, **a bow pattern** of BPM offsets and quad offsets is clearly shown
- ✓ It is because the undulator natural focusing strength increases as the vertical offset of undulator increases.
- ✓ It is not corrected in the BBA
- ✓ Decide to use OPEN GAP

$$\frac{d^2 y_{\beta n}}{dz^2} \approx -\left(\frac{K_0^2 k_u^2}{2\gamma_0^2}\right) y_{\beta n} \equiv -k_{n0}^2 y_{\beta n},$$

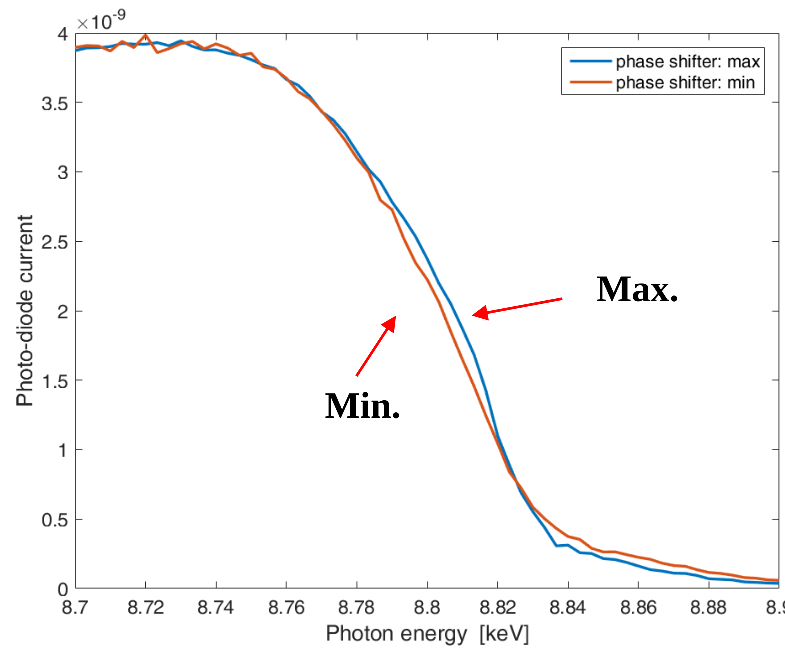
Phase Matching by Phase-shifter



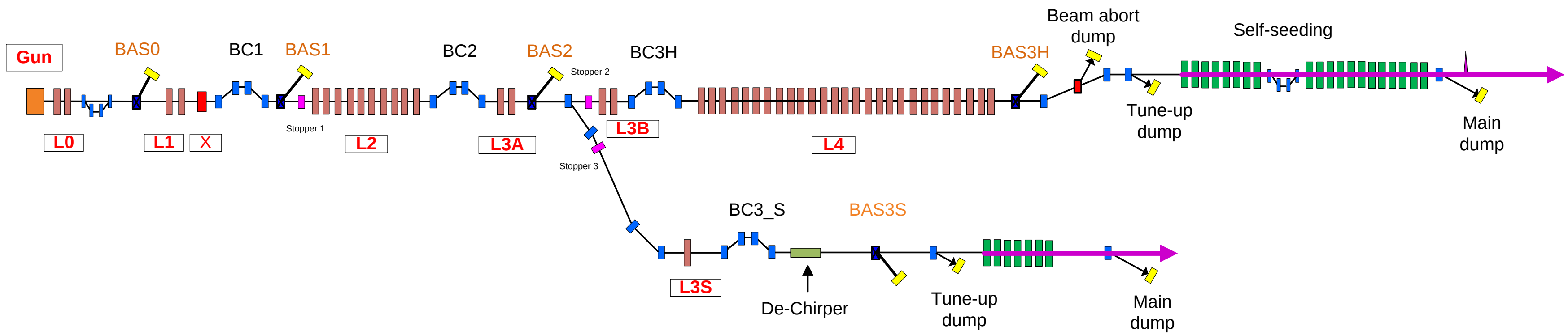
Phase scan of Phase-shifter



Radiation Spectrum from two undulators

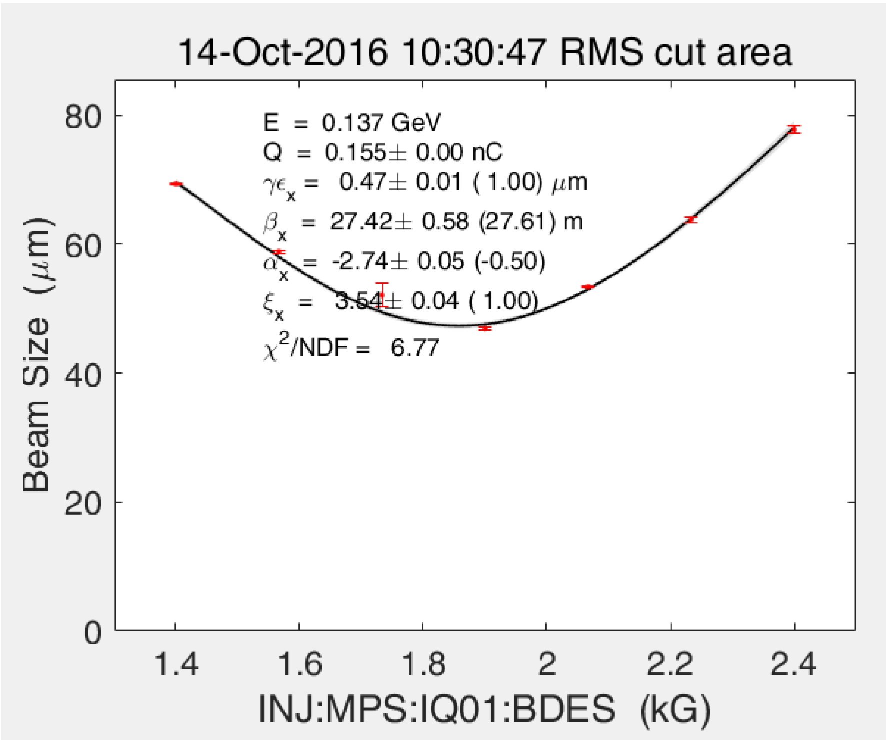


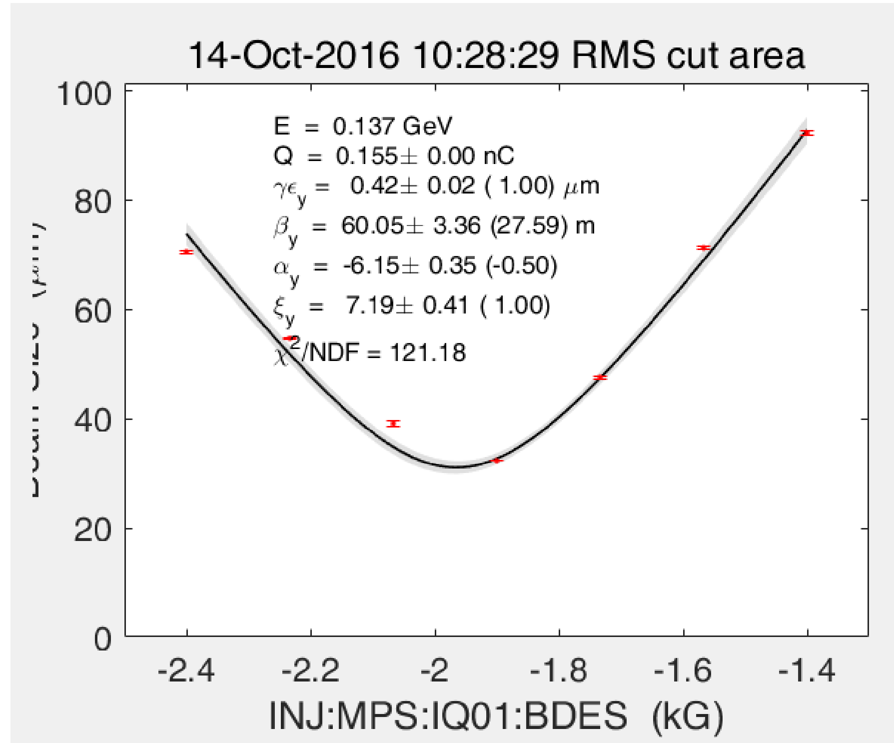
Electron Beam Manipulation



- R56
  - BC1: 66.7 mm
  - BC2: 45 mm
  - BC3: 0 mm
- Bunch length
  - Injector: 877.5 um
  - BC1: 92 um (CR = 9.5)
  - BC2: 3.8 um (CR = 24.0)
- Beam charge
  - Injector: 150 pC
  - BC1: 120 pC
  - BC2: 120 pC or 80 pC (by using a collimator at BC2)
  - Undulator: 80 pC
- Emittance (Projected)
  - Injector: 0.48 / 0.42 mm-mrad
  - Linac End: 1.23 / 2.69 mm-mrad
- RF phase
  - Gun : -37.5
  - L1: -19.5
  - X-linearizer: -180
  - L2: -17.0
  - L3, L4: 0.0

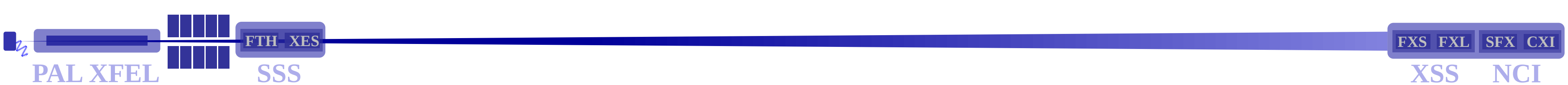
Injector Emittance (Projected)





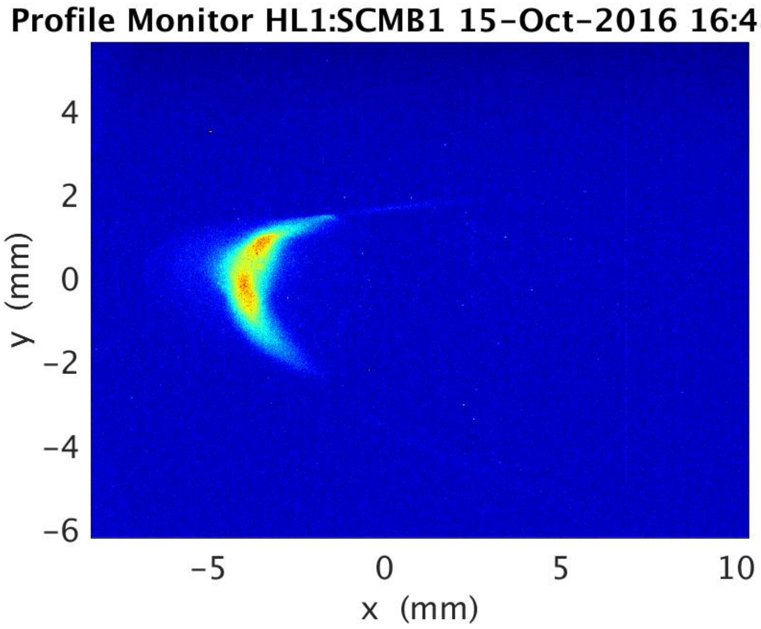
Horizontal: 0.47 mm-mrad at 150 pC

Vertical: 0.42 mm-mrad at 150 pC

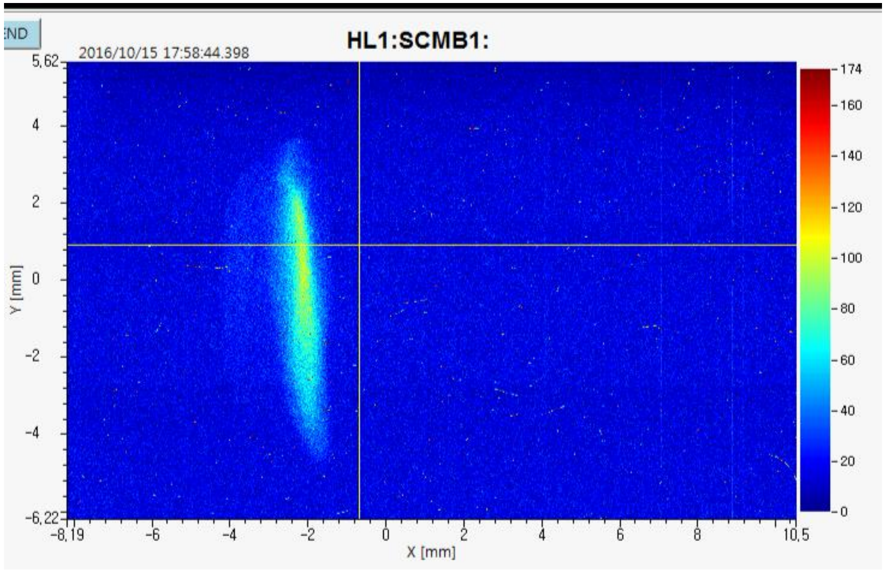


X-linearizer

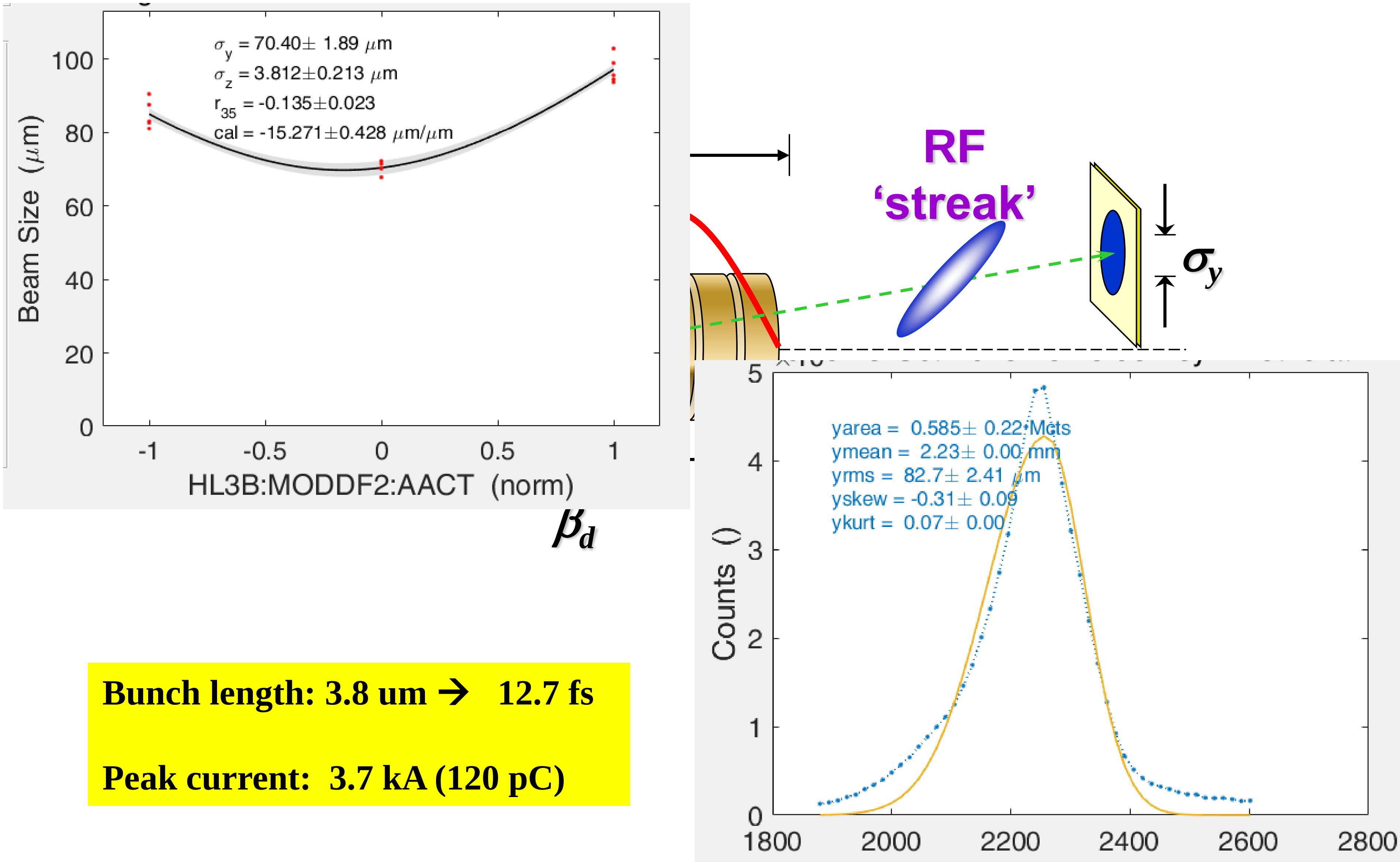
OFF



ON

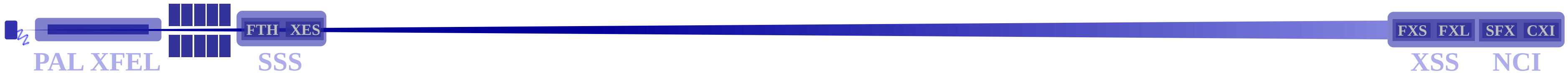


Bunch Length Measurement



Bunch length: 3.8 um → 12.7 fs

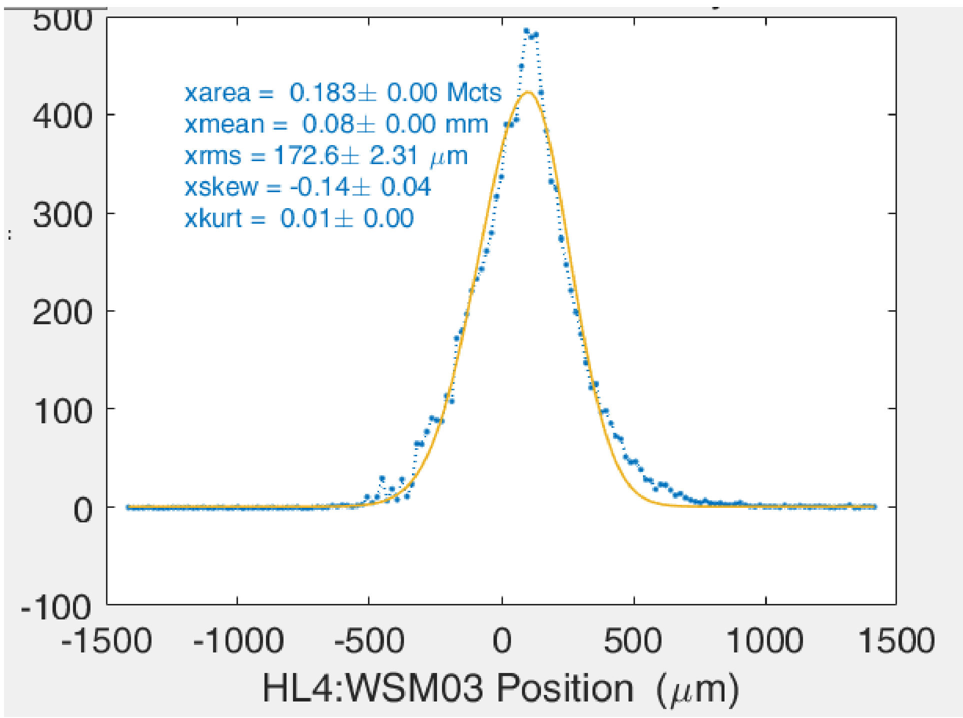
Peak current: 3.7 kA (120 pC)



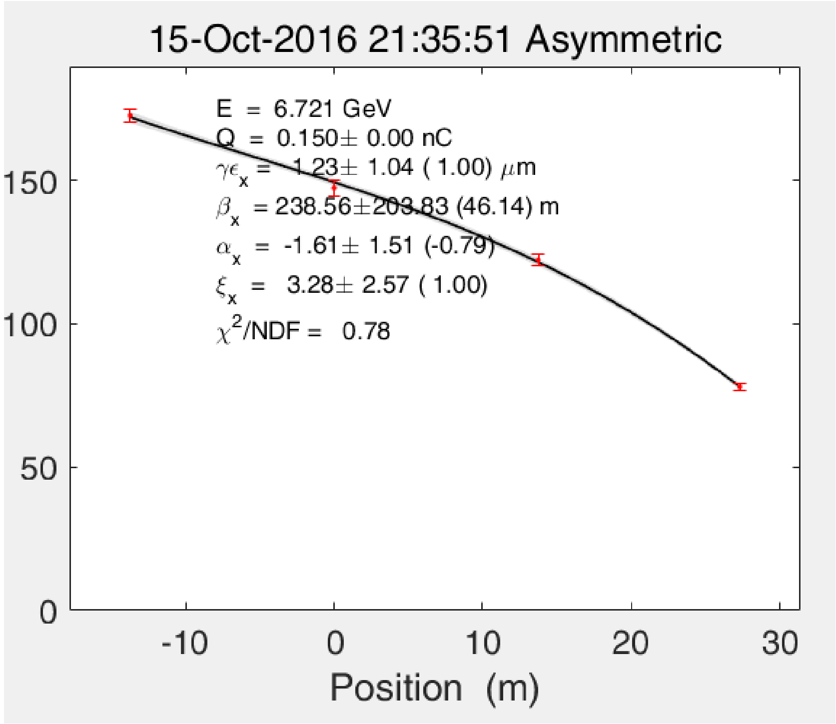
Projected Emittance at Linac End

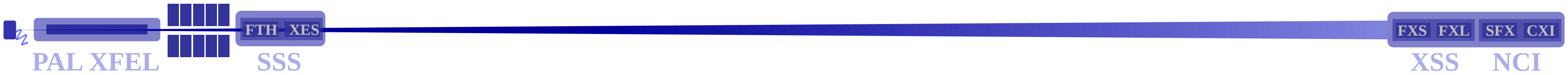
- Emittance measured with four wire scanners @120 pC
  - Hor. emittance: 1.23 mm-mrad
  - Ver. emittance: 2.69 mm-mrad

Beam size measurement with wire scanner



Hor. emittance





0.2 nm FEL (16 Oct. 2016, 1:22 am)

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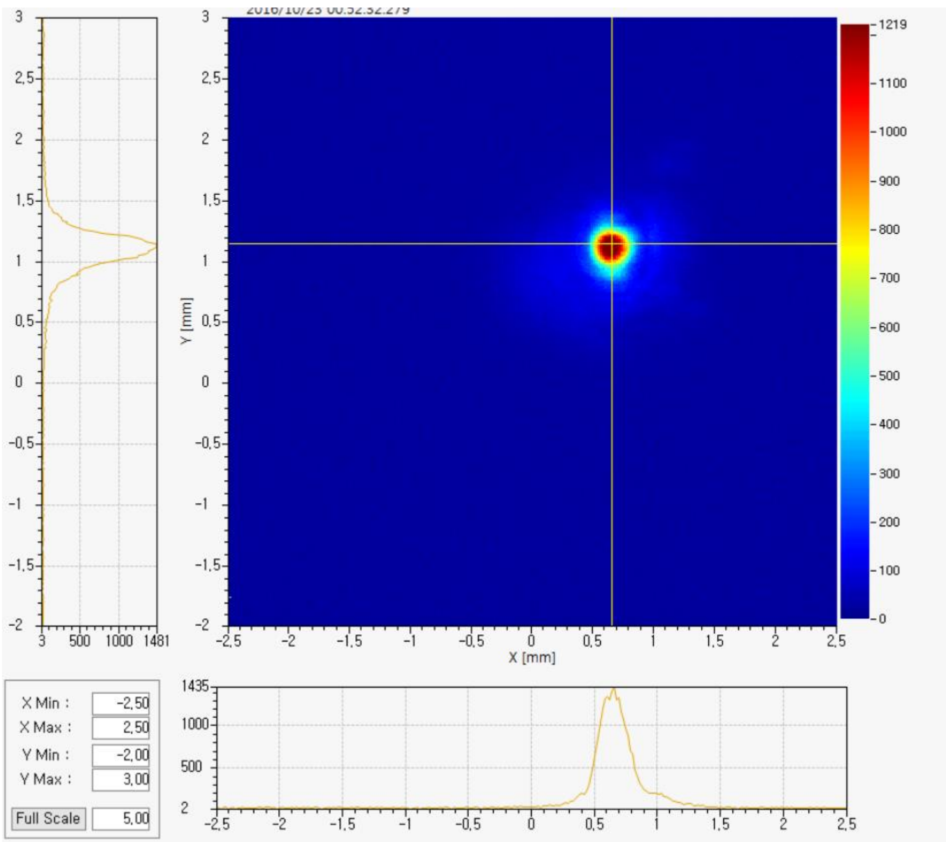
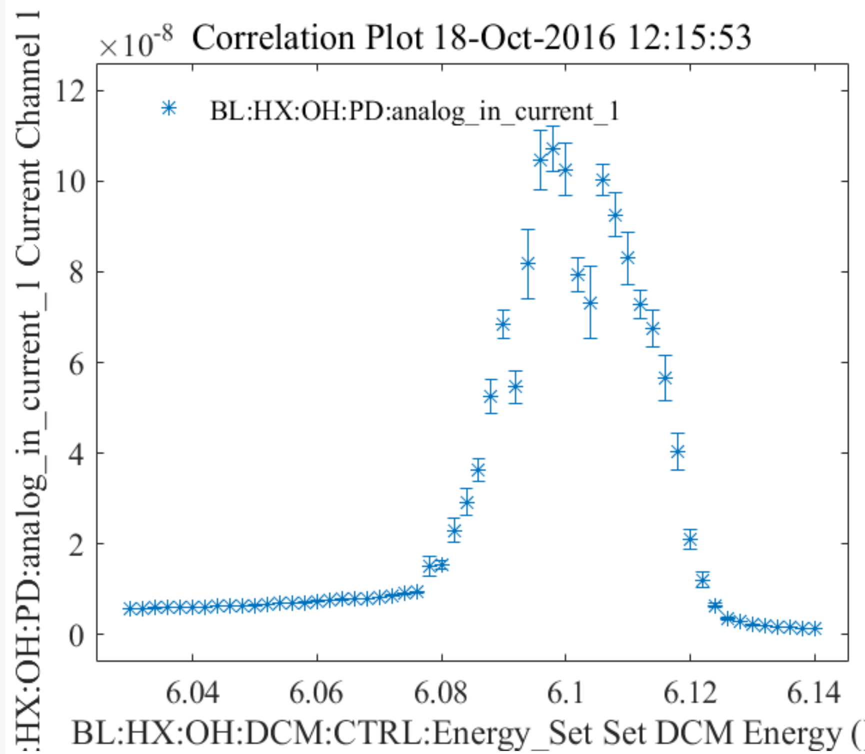
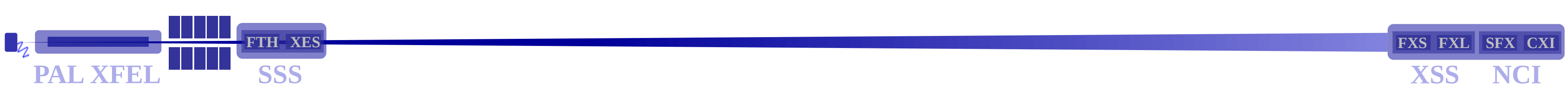
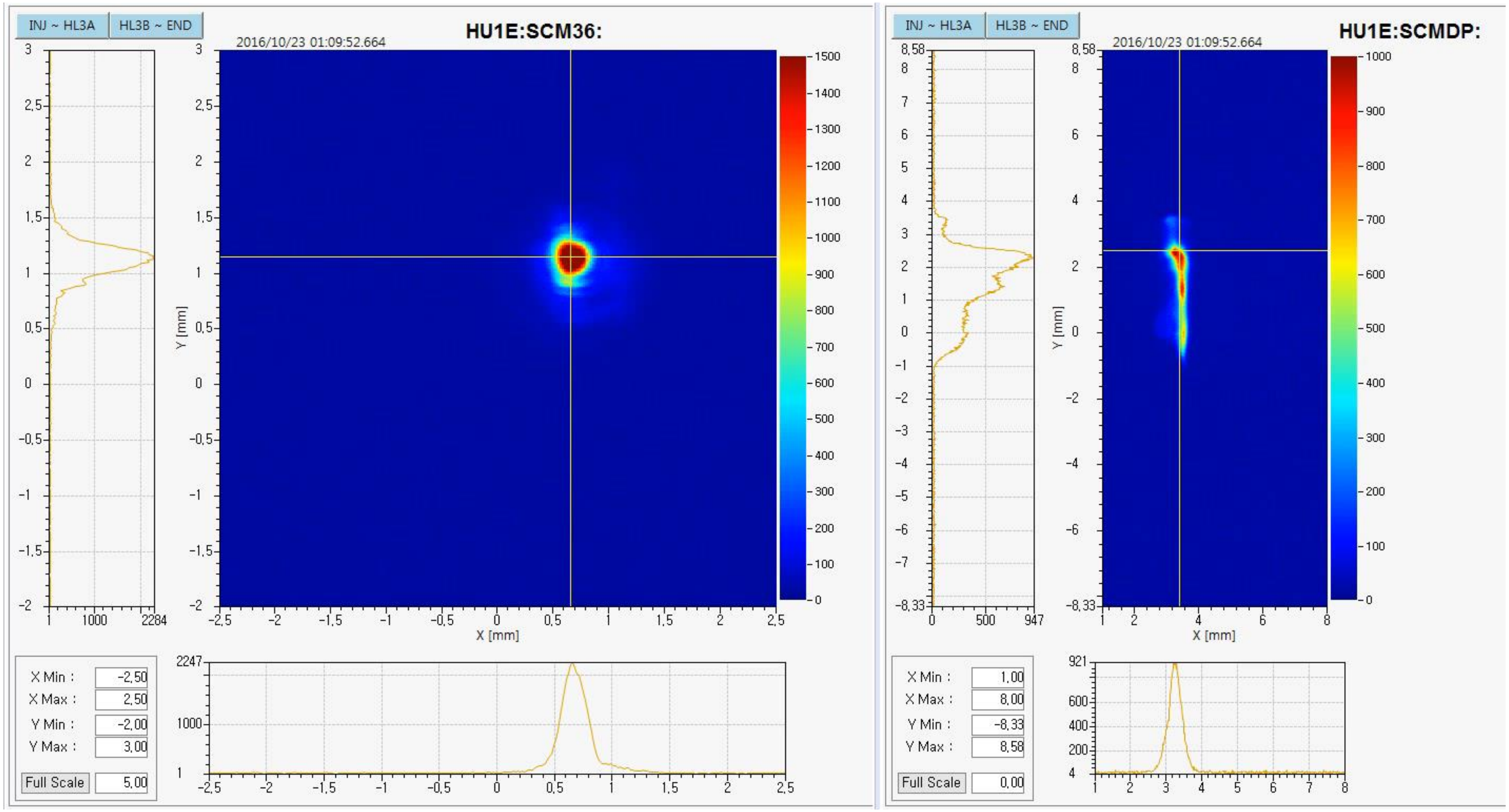
- Beam energy: 6.7 GeV
- Undulator gap: 9 mm
- Undulator K: 1.87
- Number of undulators: 20
- K-tuning & Phase-matching data are applied

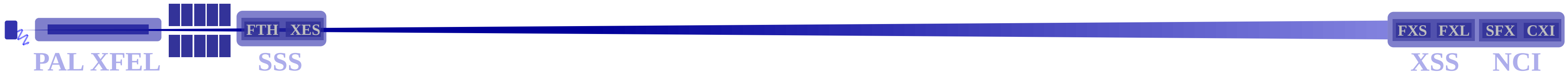




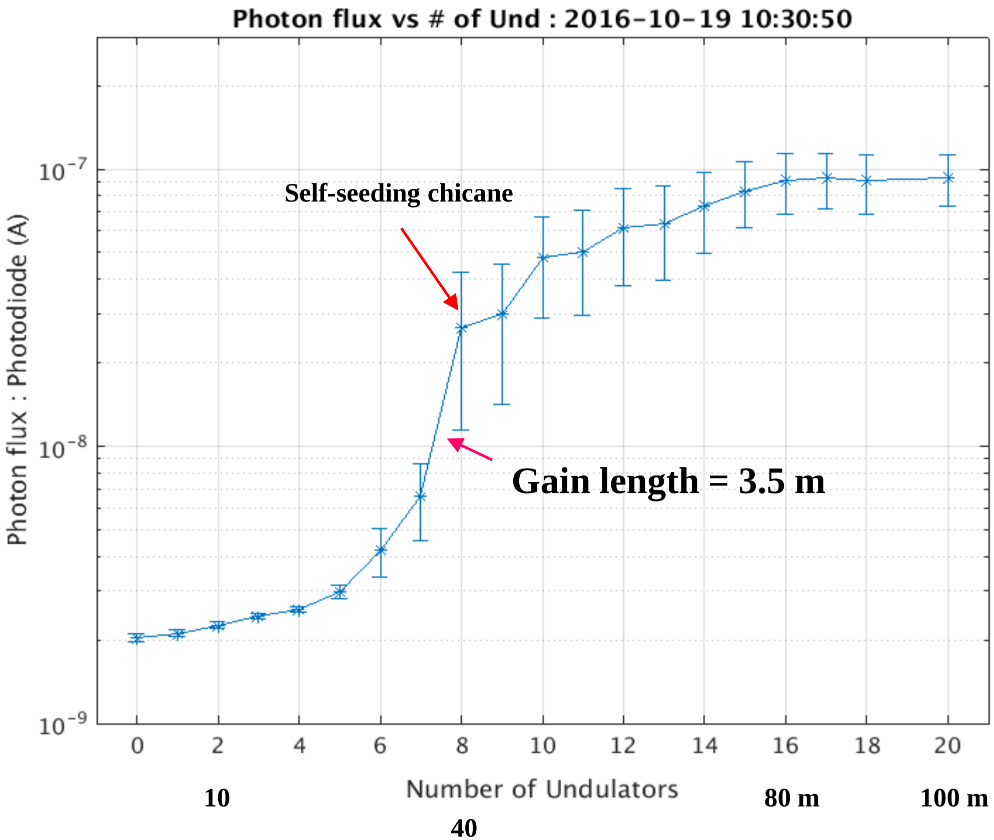


Movie of 0.2 nm FEL

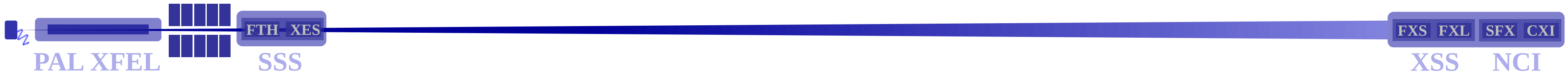


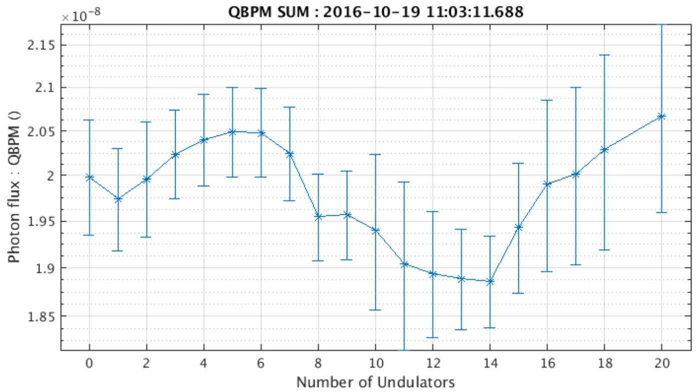


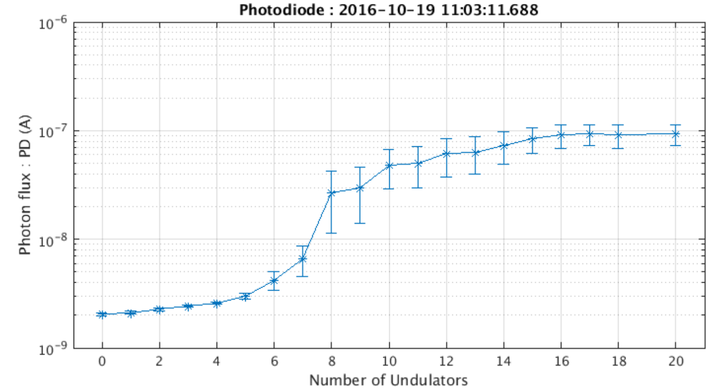
Saturation of 0.2 nm FEL

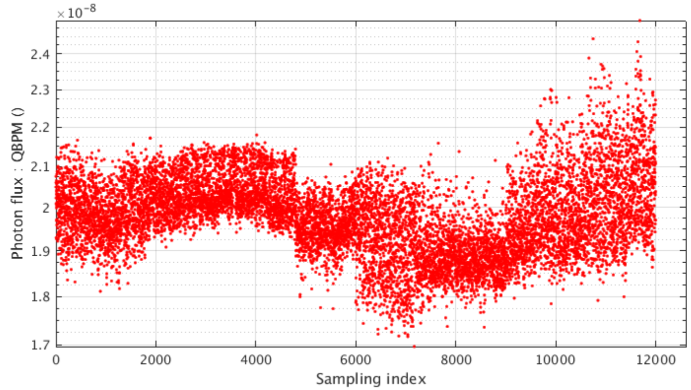


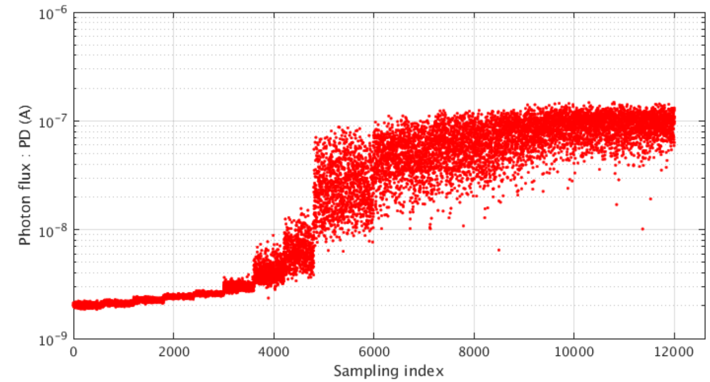
- ✓ **Preliminary measurement** with a photo-diode & DCM
- ✓ Same **K** for all undulators
- ✓ No substantial increase after Self-Seeding Chicane
- ✓ FEL is saturated?

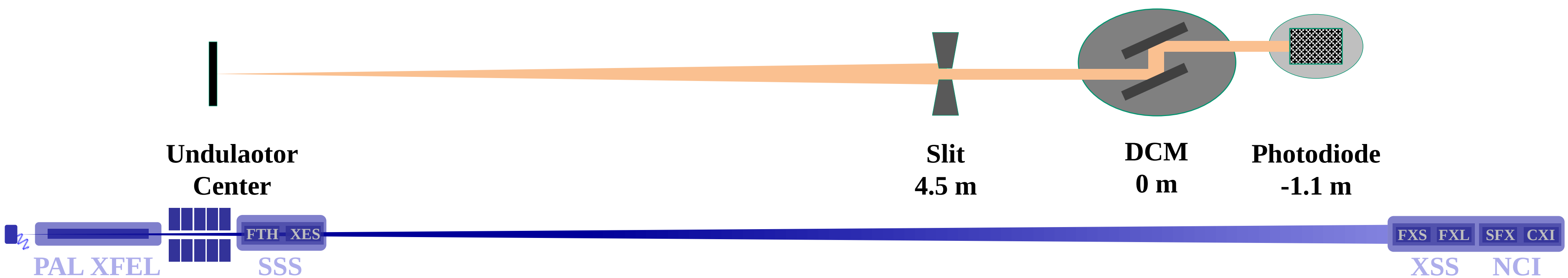



QBPM SUM : 2016-10-19 11:03:11.688
×10^-8
Photon flux : QBPM ()
Number of Undulators


Photodiode : 2016-10-19 11:03:11.688
Photon flux : PD (A)
Number of Undulators


×10^-8
Photon flux : QBPM ()
Sampling index

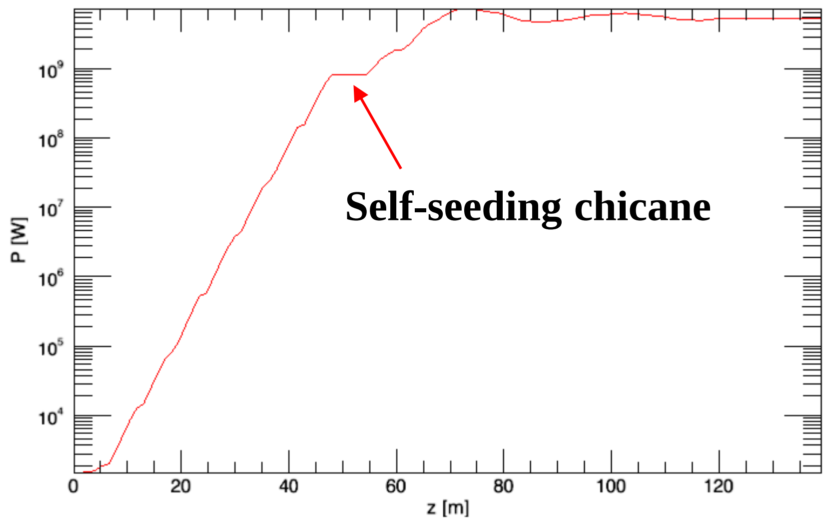

Photon flux : PD (A)
Sampling index

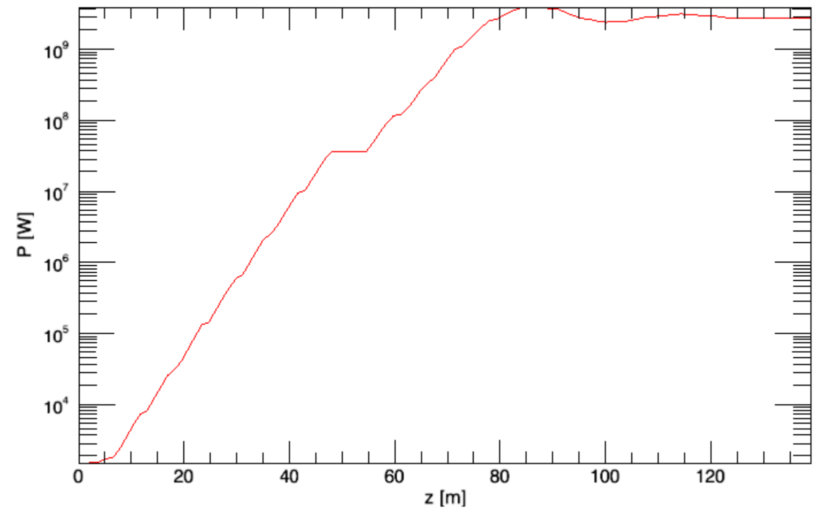

Undulaotor
Center
Slit
4.5 m
DCM
0 m
Photodiode
-1.1 m
FTH
XES
PAL XFEL
SSS
FXS
FXL
SFX
CXI
XSS
NCI

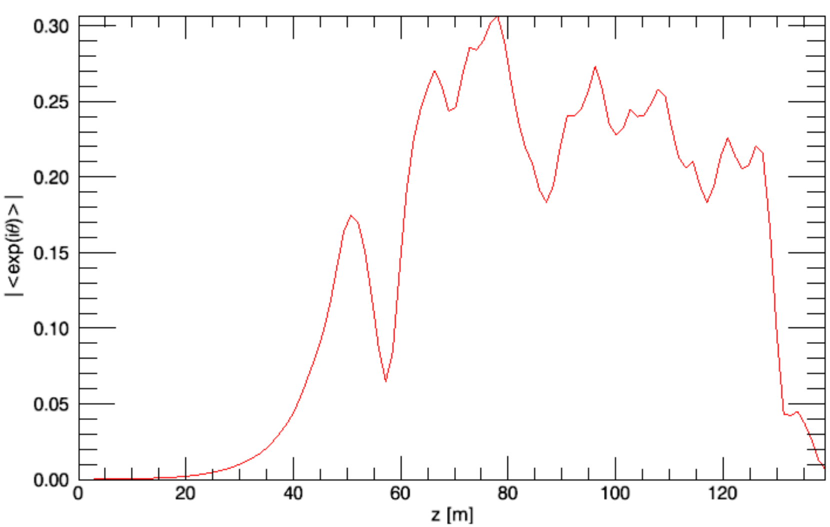
Genesis Simulation for 0.2 nm

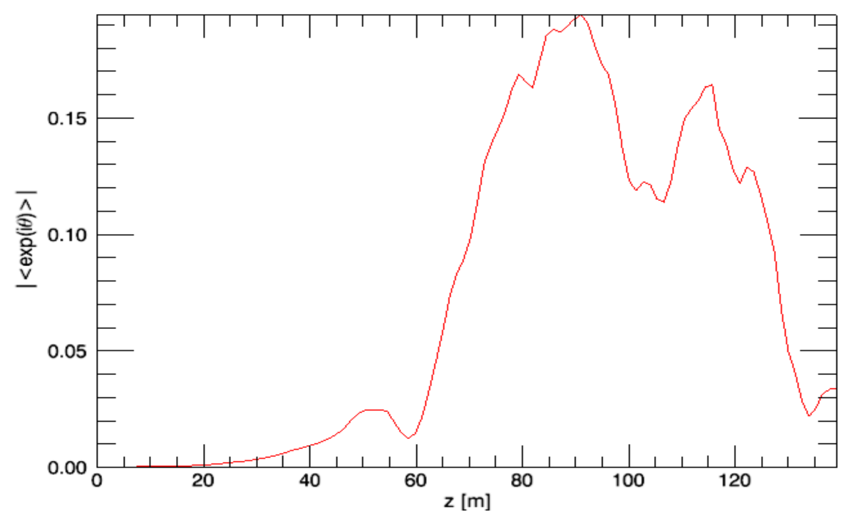
- **Emittance (slice): 0.6 um**
- **Peak current : 3 kA**

- **Emittance (slice): 0.9 um**
- **Peak current : 3 kA**



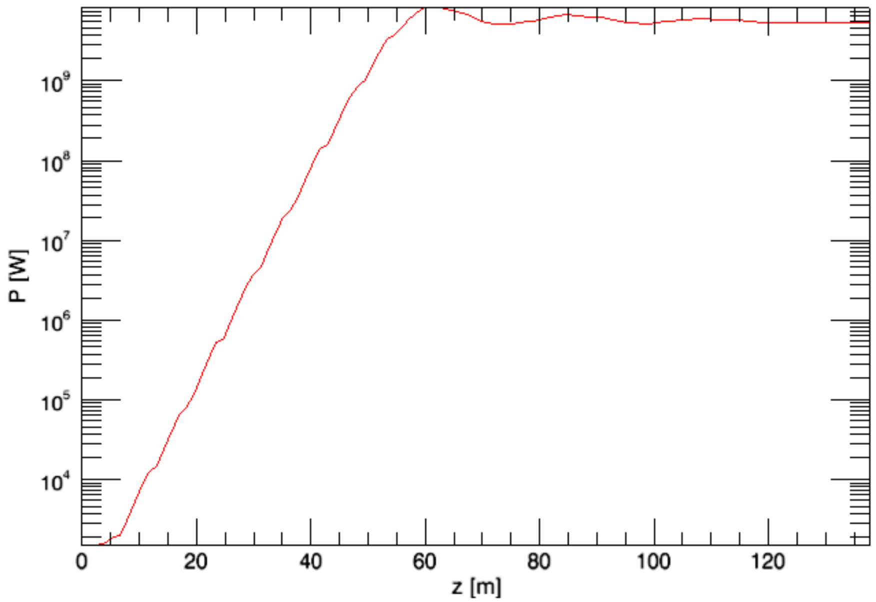


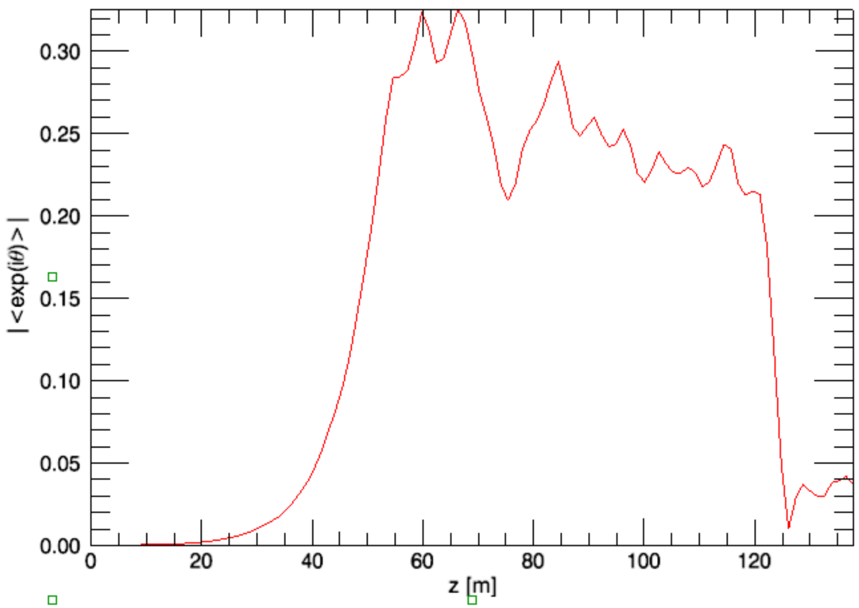




Genesis Simulation for 0.2 nm w/o self-seeding

- **Emittance (slice): 0.6 um**
- **Peak current : 3 kA**





Genesis for 0.15 nm & 0.35 nm

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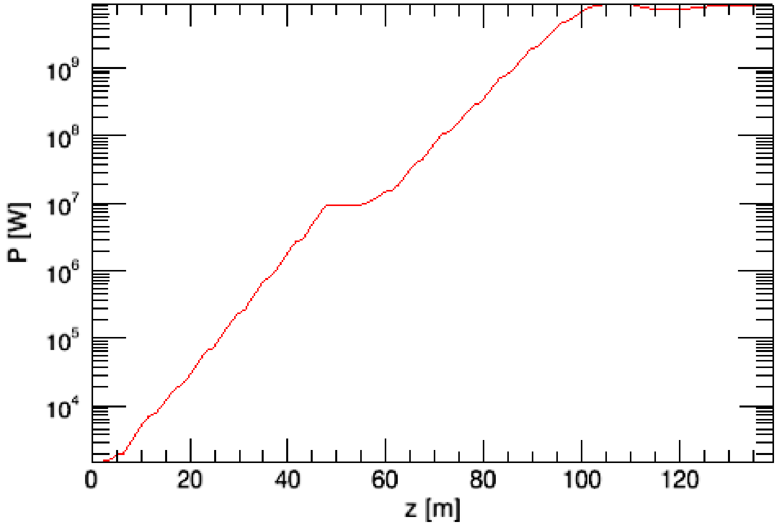
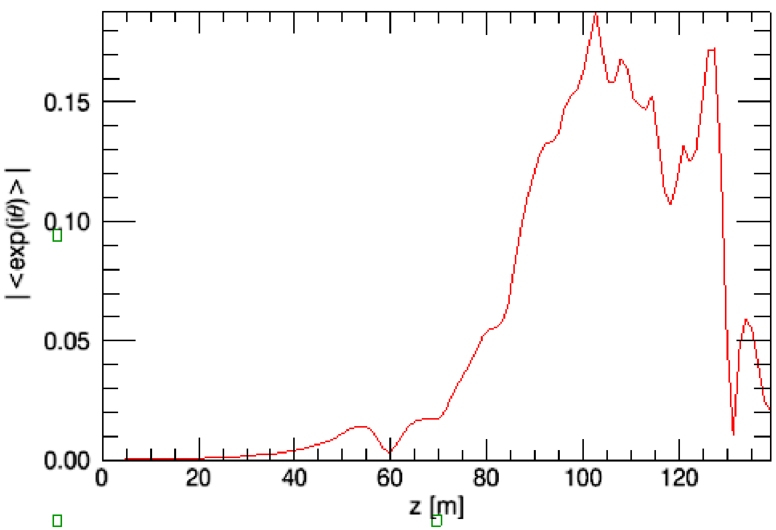
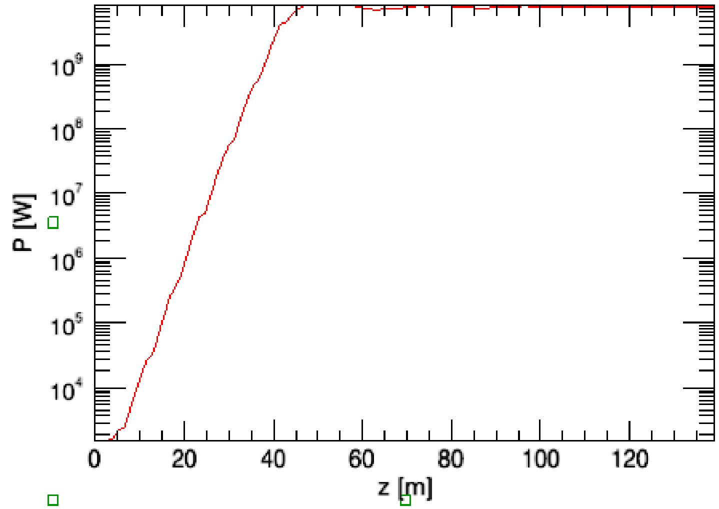
- Emittance (slice): 0.6 um
- Peak current : 3 kA

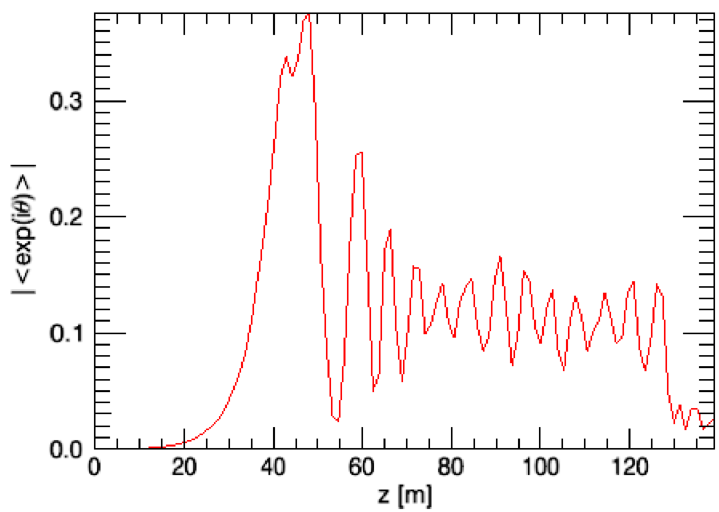
- **0.15 nm**





- **0.35 nm**



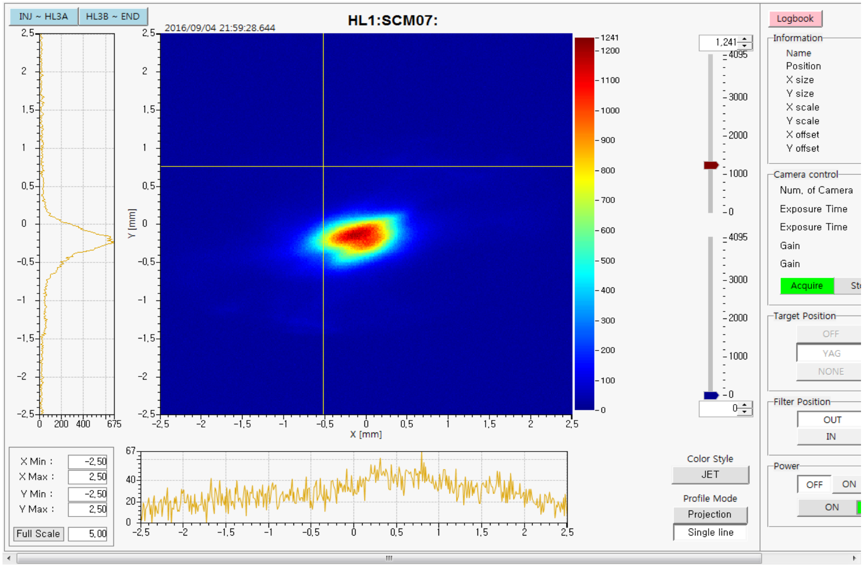


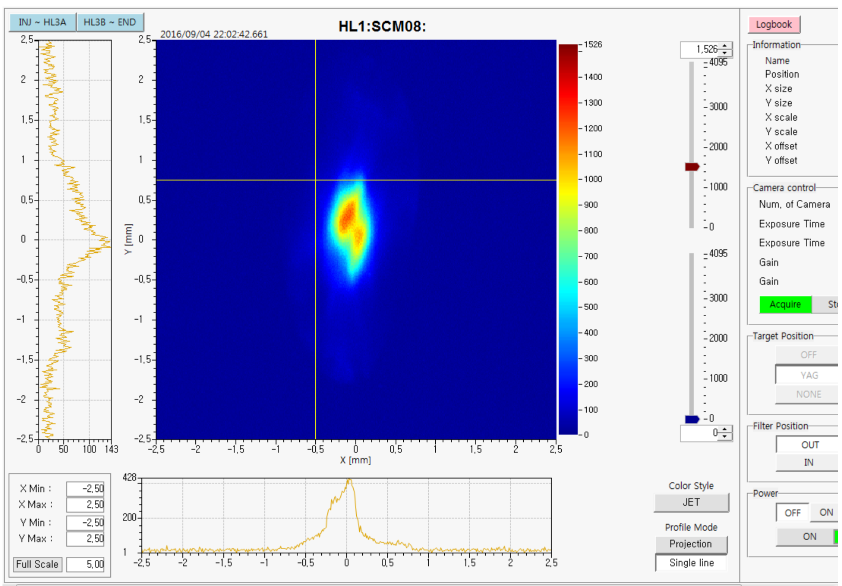
FEL Intensity Limiting Factors

✓ Factors to be considered as FEL Intensity Limitation

1) Vertical emittance growth
   - dispersion at L1 & L2 → Redo the Linac BBA is necessary
   - twin beam from laser → Replacement of bad optics components
2) Emittance growth due to strong CSR
   - Currently overcome by BC2 collimator
   - Need to decrease Compression Ratio at BC2 by decreasing the laser pulse length
   - Or, to use three Bunch compressors
3) poor betatron matching to undulators
   - Undulator matching program is being prepared.
   - Four Wire scanners along the undulators were tested to find detector saturation → Detector to be improved for e-beam profile measurement
4) Correlated energy spread is too big (10-3). Chirp needs to be compensated.
5) Halo particles generated at the gun and laser
   - Decrease to gun phase to -30 or below
   - Improve the uniformity of laser profile

Vertical emittance growth





- ✓ Due to dispersion and **twin beam**
- ✓ Twin beam is generated at the gun.
  - Strongly depend on the cathode position of laser beam
  - It is thought due to degradation of optics from Laser system to Gun
  - To be improved soon

Summary

- 0.2 nm FEL lasing is achieved.
- Procedures for Undulator BBA, K-value tuning, undulator field centre, and phase matching are established.
- The saturation of 0.2 nm FEL is also achieved.

- An X-band deflector is absolutely necessary!!


Thank you for your attention