# Status of the PAL-XFEL Construction

## 0.1-nm Hard X-ray XFEL

- Project Period: 2011 ~ 2015
- Total Budget: 400 M$
- 10-GeV Electron Linac (Normal Conducting S-band, 60 Hz)
- Total Length: 1.1 km


Heung-Sik Kang,
on behalf of PAL-XFEL Team
Pohang Accelerator Laboratory, Pohang, South Korea

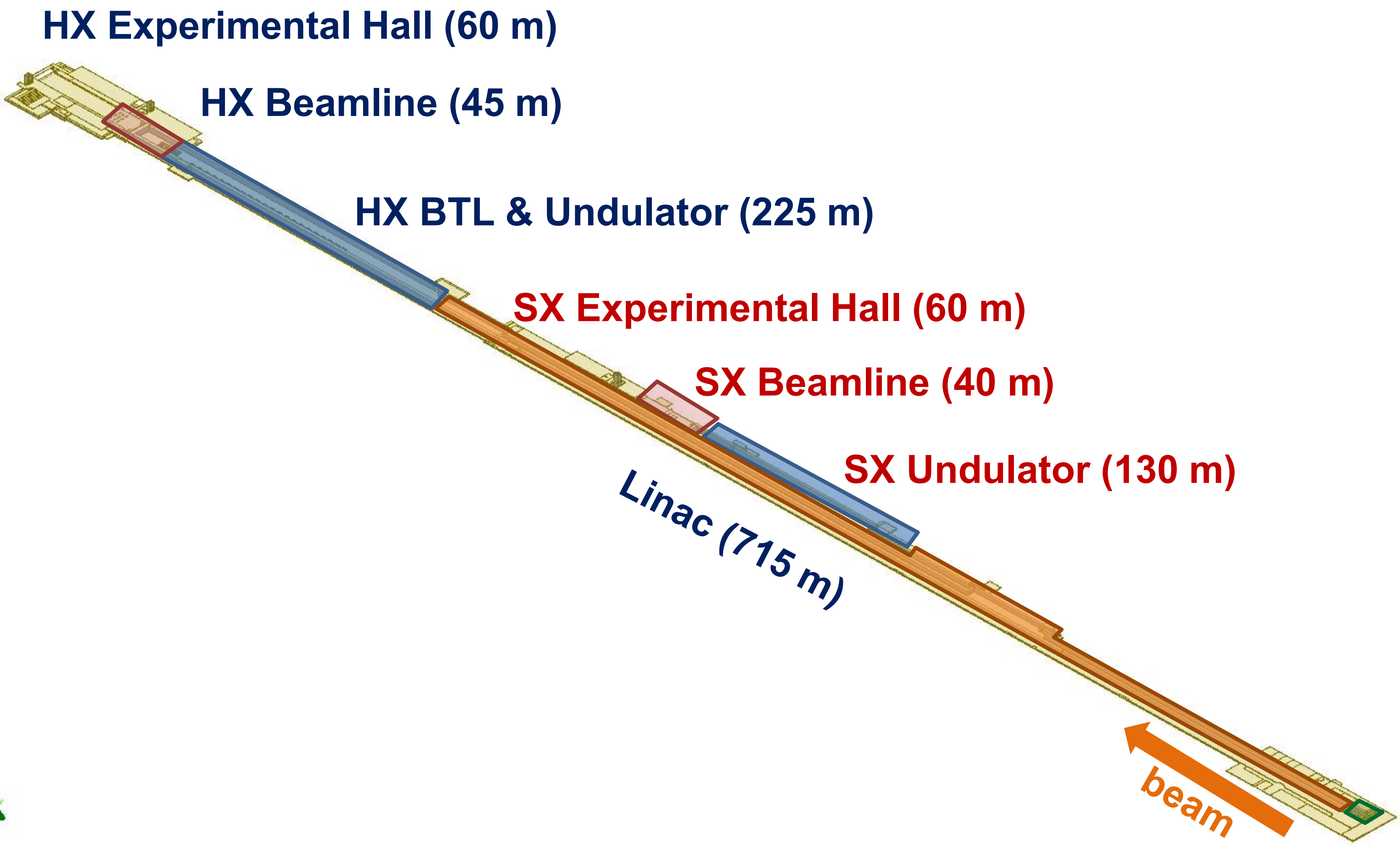
# Outline

- Introduction
- Status of Installation
- Sub-System Preparation
- Commissioning Schedule

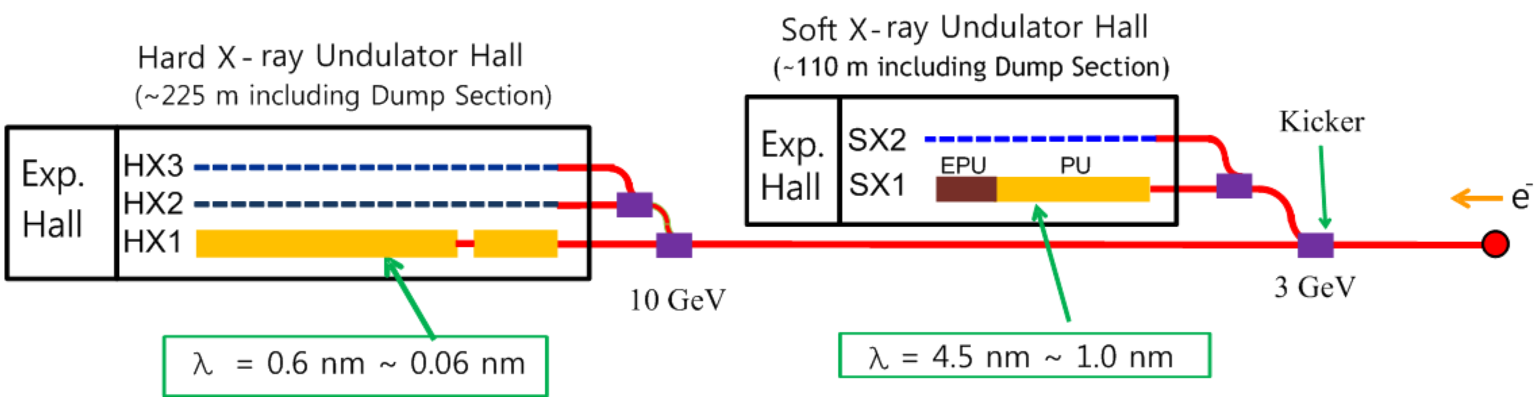
# Hard X-ray FEL Facilities

| | LCLS-1 | SACLA | EU-FEL | PAL-XFEL | SwissFEL |
|---|---|---|---|---|---|
| Electron Energy, GeV | 14 | 8 | 17.5 | 10 | 5.8 |
| Photon energy, keV | 12.4 | 15 | 25 | 12.4 | 12 |
| Accelerator Type | **NCRF (S-band)** | **NCRF (C-band)** | **SCRF (L-band)** | **NCRF (S-band)** | **NCRF (C-band)** |
| Repetition rate | 120 | 50 | 500,000 | 60 | 100 |
| Undulator | out-of-vacuum, fixed gap | In-vacuum, variable gap | out-of-vacuum, variable gap | out-of-vacuum, variable gap | In-vacuum, variable gap |
| First lasing | 2009 | 2011 | **2016** | **2016** | **2017** |
| Operation mode | SASE, Self-seeding | SASE, Self-seeding | SASE, Self-seeding | SASE, Self-seeding | SASE, Self-seeding |

# Building Layout



# Undulator Lines

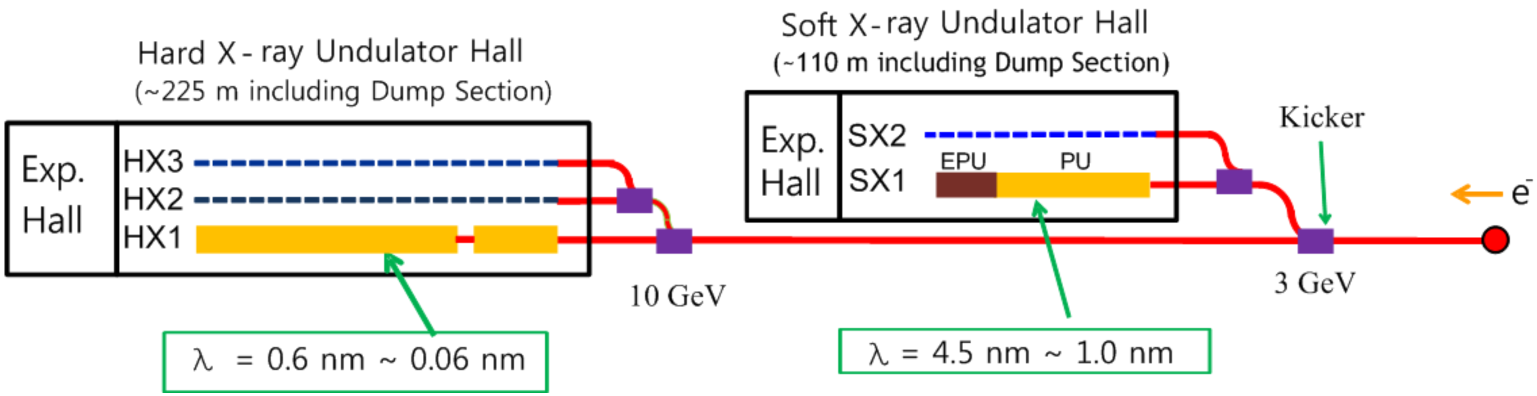


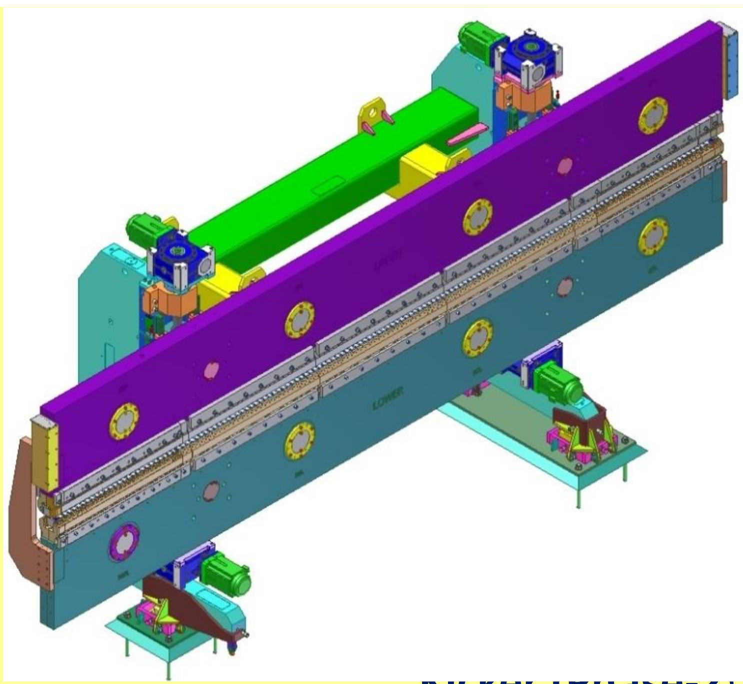

## Main parameters

| | |
|---|---|
| $e^-$ Energy | 10 GeV |
| $e^-$ Bunch charge | 20-200 pC |
| Slice emittance | 0.4 mm mrad |
| Repetition rate | 60 Hz |
| Pulse duration | 5 fs – 100 fs |
| SX line switching | DC (Phase-1) |
| | Kicker (Phase-2) |

| Undulator Line | HX1 | SX1 |
|---|---|---|
| Wavelength [nm] | 0.06 ~ 0.6 | 1 ~ 4.5 |
| Beam Energy [GeV] | 4 ~ 10 | 3.15 |
| Wavelength Tuning [nm] | 0.6 ~ 0.1 (energy)<br>0.1 ~ 0.06 (Gap) | 4.5 ~ 3 (Beam energy)<br>3 ~ 1 (Undulator gap) |
| Undulator Type | Planar variable gap, out-vacuum | Planar + APPLE II<br>variable gap, out-vacuum |
| Undulator Period / Gap [mm] | 26 / 8.3 | 35 / 8.3 |
| Operation Mode | SASE (2016)<br>Self-Seeding (2017) | SASE |

# Undulator Lines



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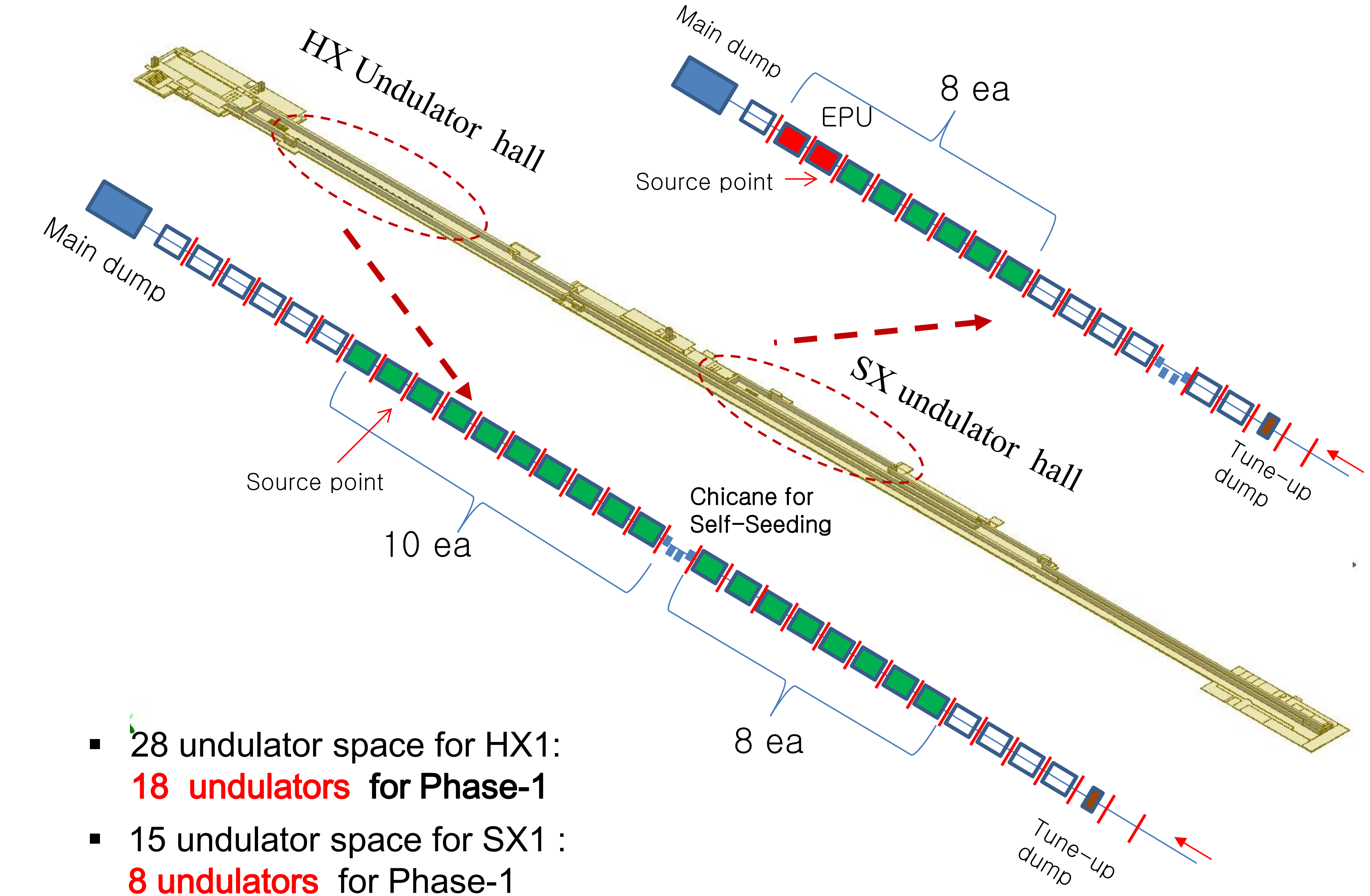
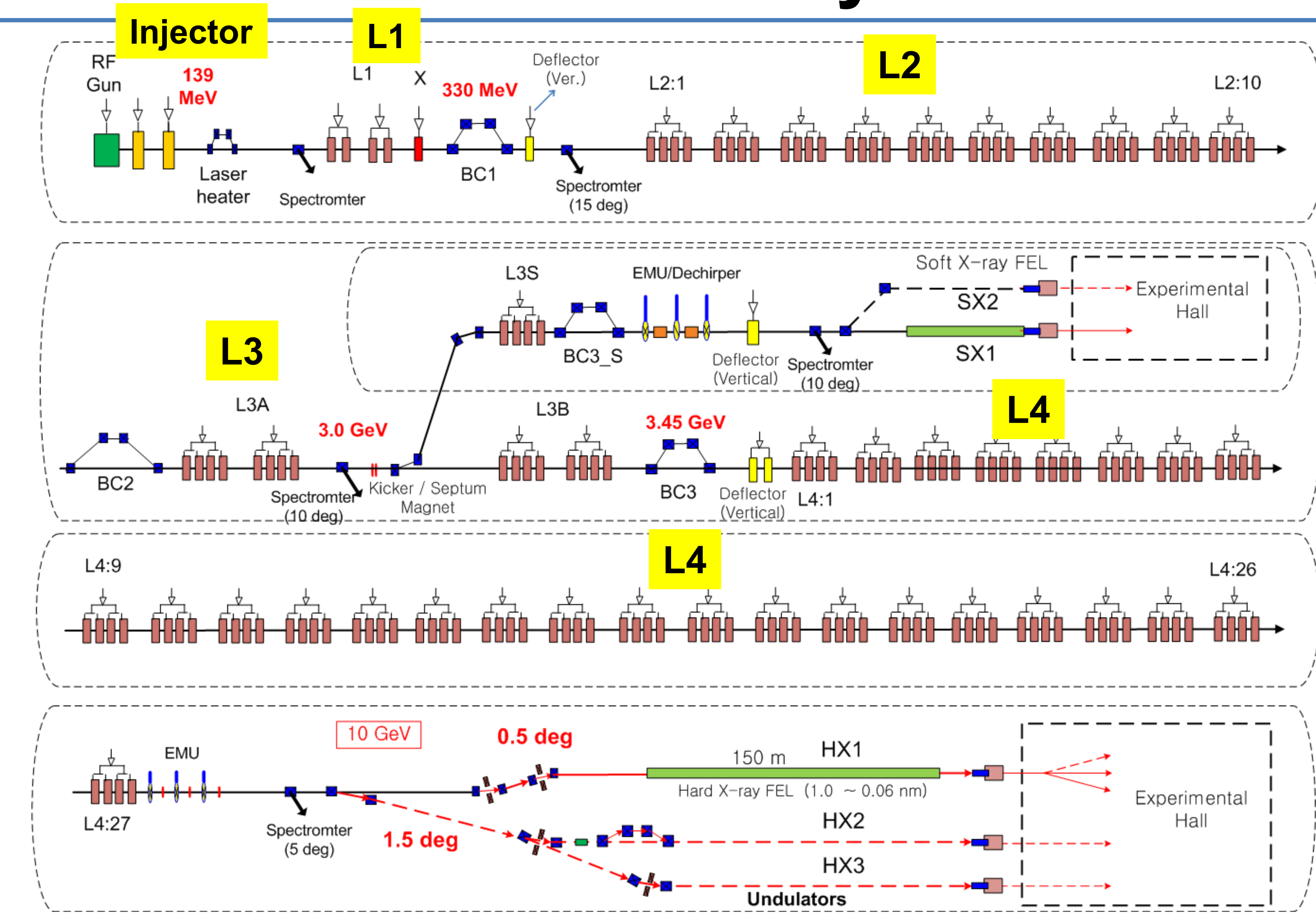
# Undulator Layout

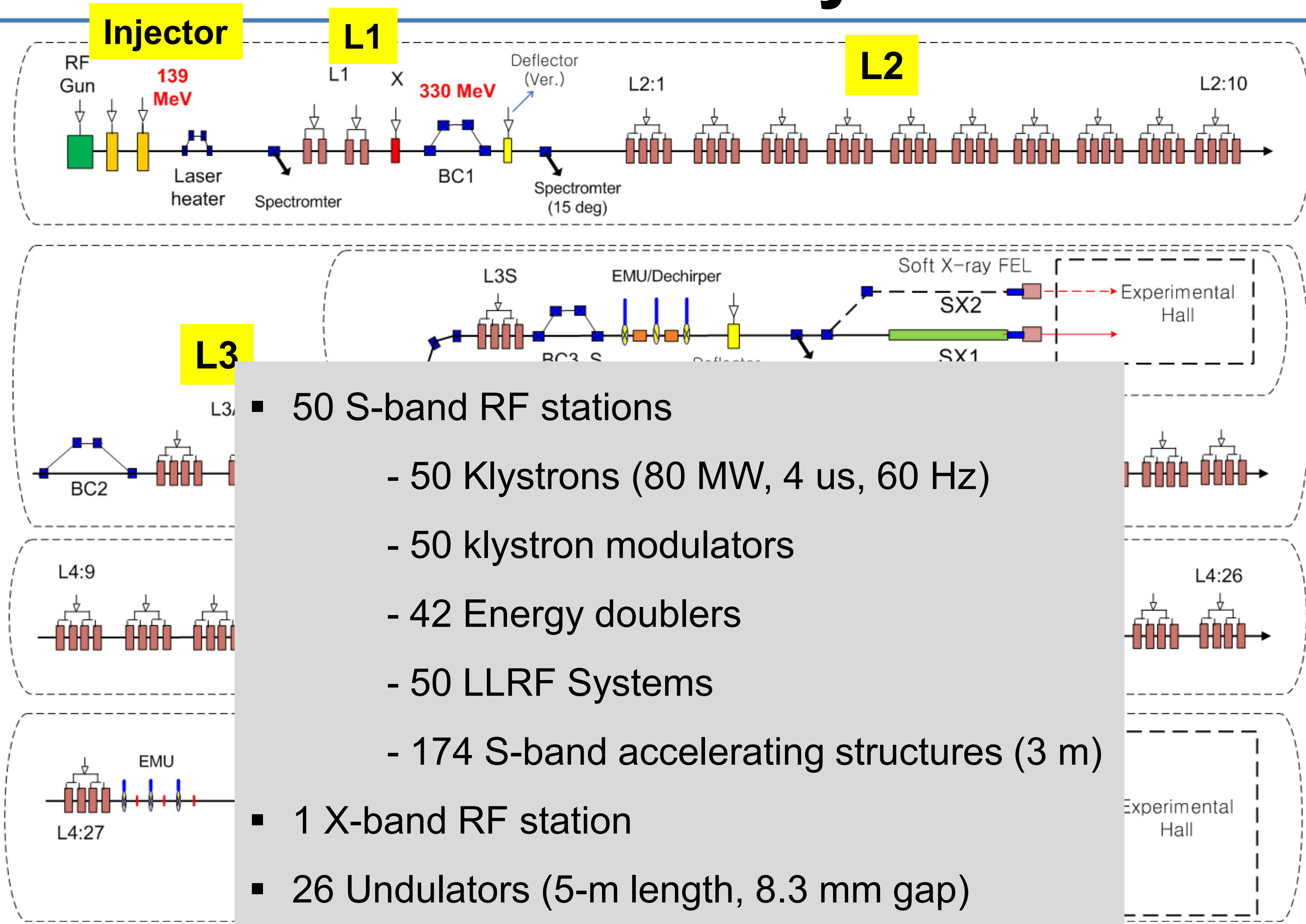



- 28 undulator space for HX1: **18 undulators for Phase-1**
- 15 undulator space for SX1 : **8 undulators** for Phase-1

# PAL-XFEL Layout



# PAL-XFEL Layout




- 50 S-band RF stations
  - 50 Klystrons (80 MW, 4 us, 60 Hz)
  - 50 klystron modulators
  - 42 Energy doublers
  - 50 LLRF Systems
  - 174 S-band accelerating structures (3 m)
- 1 X-band RF station
- 26 Undulators (5-m length, 8.3 mm gap)

# Features of PAL-XFEL (1)

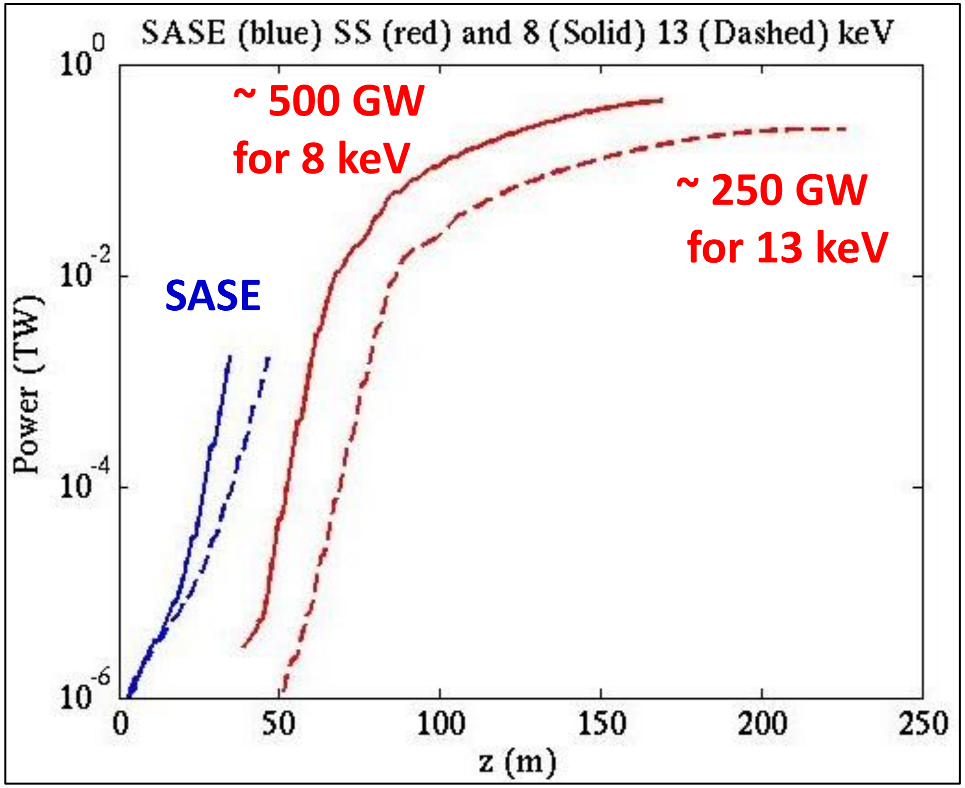
- Multiple beamline operation
  - **Simultaneous operation of Soft & Hard X-ray Beamline**
  - 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second
- A very long Undulator Hall (225 m)
  - **enough to install 28 undulators (5 m x 28 = 140 m)**
  - **Suitable for Self-seeding and undulator tapering for TW FEL**
  - Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm
- Ultra stable pulse RF system
  - **Klystron beam voltage stability : < 30 ppm**
- New concepts and Ideas
  - Dechirper for energy chirp control
  - Two diamond crystal holder for self-seeding monochromator

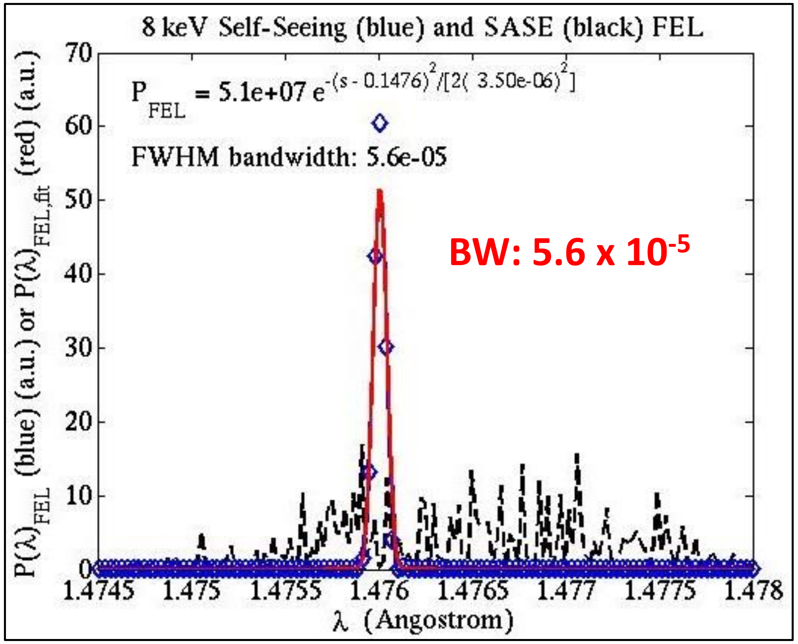
# Features of PAL-XFEL (2)

- Multiple beamline operation
  - **Simultaneous operation of Soft & Hard X-ray Beamline**
  - 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second
- A very long Undulator Hall (225 m)
  - **enough to install 28 undulators (5 m x 28 = 140 m)**
  - **Suitable for Self-seeding and undulator tapering for TW FEL**
  - Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm
- Ultra stable pulse RF system
  - **Klystron beam voltage stability : < 30 ppm**
- New concepts and Ideas
  - Dechirper for energy chirp control
  - Two diamond crystal holder for self-seeding monochromator

# Self-Seeding Simulation for PAL-XFEL

Self–seeding + undulator tapering



# Features of PAL-XFEL (3)

- Flexibility for multiple beamline operation
  - **Simultaneous operation of Soft & Hard X-ray Beamline**
  - 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second
- A very long Undulator Hall (225 m)
  - **enough to install 28 undulators (5 m x 28 = 140 m)**
  - **Suitable for Self-seeding and undulator tapering for TW FEL**
  - Able to achieve Photon flux of over $1 \times 10^{12}$ photons/pulse at 0.1 nm
- Ultra stable pulse RF system
  - **Klystron beam voltage stability : < 30 ppm**
- New concepts and Ideas
  - Dechirper for energy chirp control
  - Two diamond crystal holder for self-seeding monochromator

# Ultra Stable Pulse RF System

- **Electron Beam Stability Requirements**
  - **Beam energy jitter : < 0.02 %**
  - **Beam arrival time : < 20 fs**
  - **Emittance growth : < 10%**
  - **Beam current change: < 10%**
- **Stability Requirements determined by Start-to-End simulation**

| | L1 | X | L2 | L3, L4 |
|---|---|---|---|---|
| RF Phase [degrees] | 0.05 | 0.1 | 0.05 | 0.5 |
| RF Amplitude [%] | 0.02 | 0.04 | 0.02 | 0.1 |

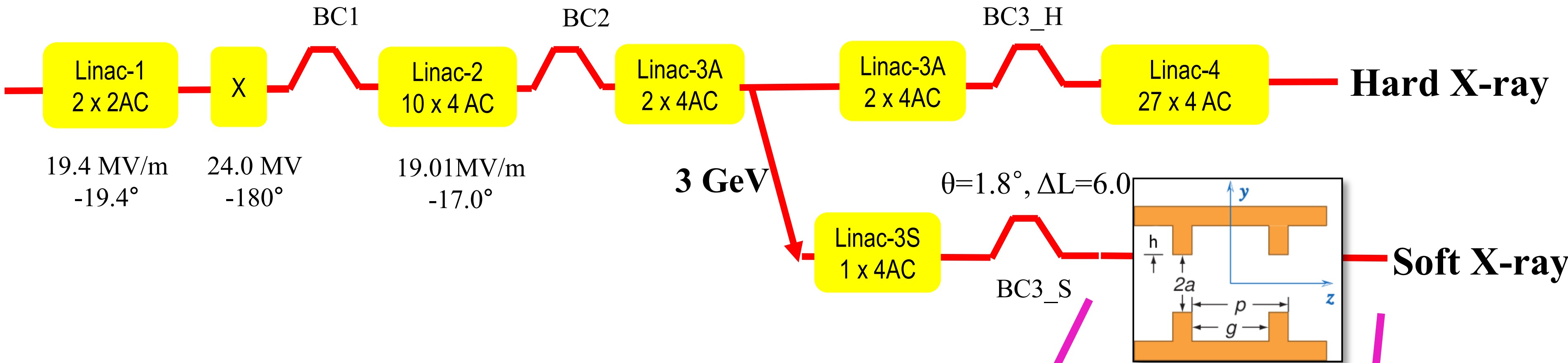
- **Stability Requirements for RF System**

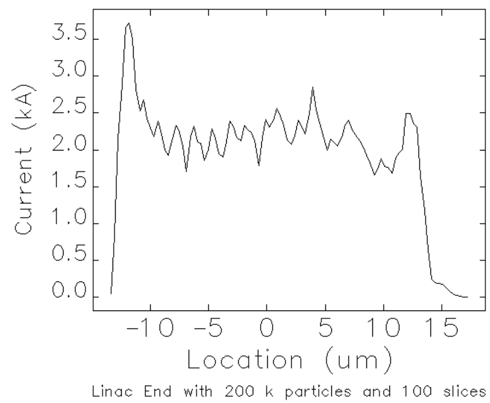
  - **S-band RF phase : 0.03 degree**
  - **S-band RF amplitude : 0.02%**
  - **X-band RF phase: 0.06 degree**

# Features of PAL-XFEL (4)

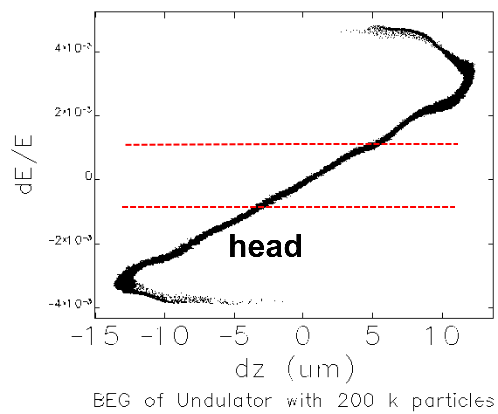
- Flexibility for multiple beamline operation
  - **Simultaneous operation of Soft & Hard X-ray Beamline**
  - 120 Hz operation in a non-sled mode & Two bunch operation (20 ns separation) → 240 pulses per second
- A very long Undulator Hall (225 m)
  - **enough to install 28 undulators (5 m x 28 = 140 m)**
  - **Suitable for Self-seeding and undulator tapering for TW FEL**
  - Able to achieve Photon flux of over 1 x $10^{12}$ photons/pulse at 0.1 nm
- Ultra stable pulse RF system
  - **Klystron beam voltage stability : < 30 ppm**
- New concepts and Ideas
  - Dechirper for energy chirp control
  - Two diamond crystal holder for self-seeding monochromator

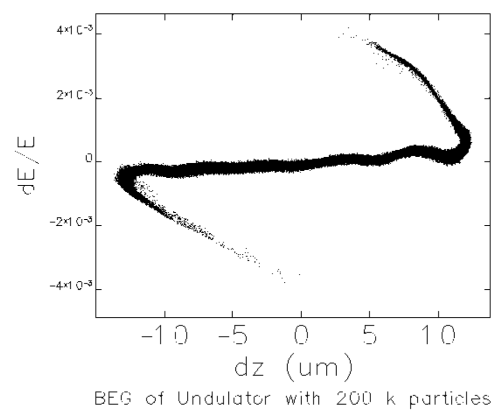
# Start-to-End Simulation for Soft X-ray FEL Line




- Correlated energy spread after final compression is larger than FEL parameter (1 x$10^{-3}$ )

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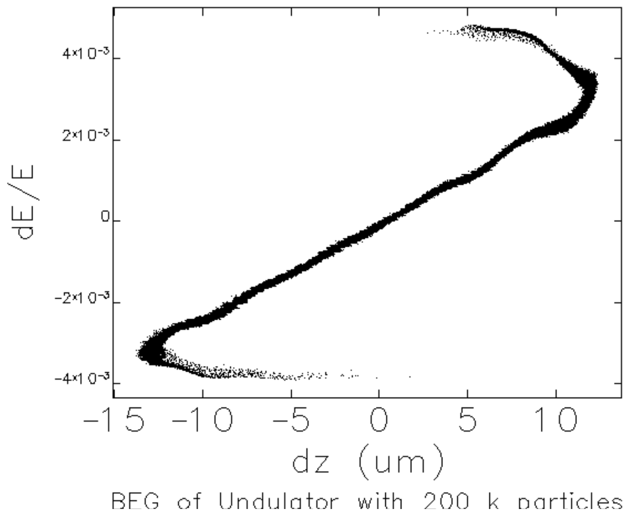
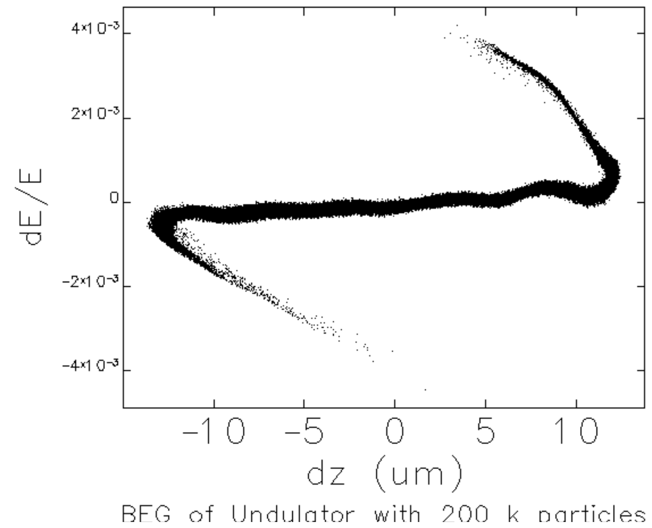
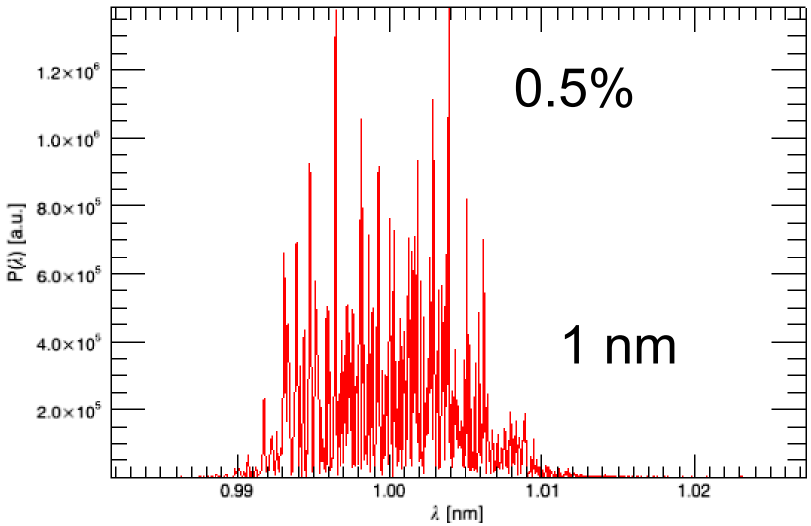
# SASE Bandwidth vs. Energy Chirp

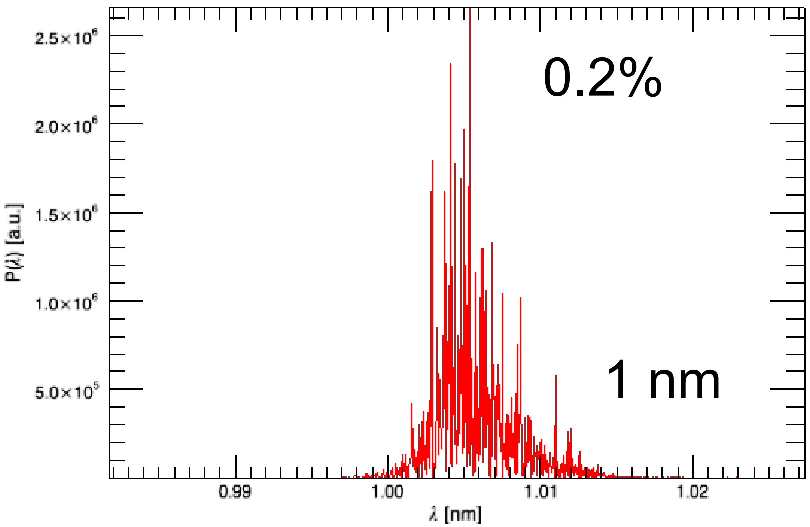
**PAL-XFEL Soft X-ray FEL Line**




**Dechirper**





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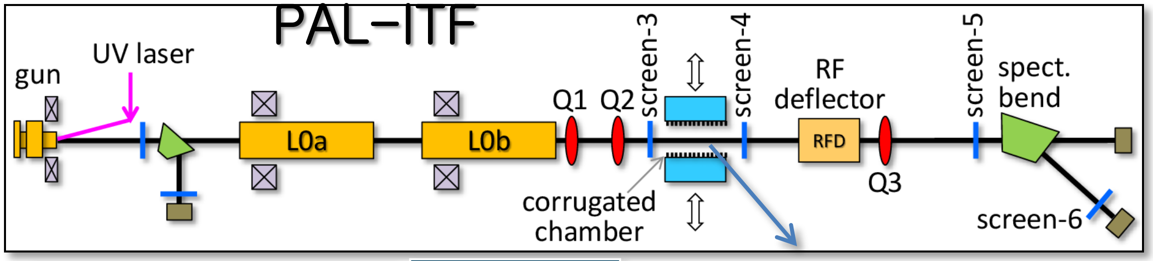
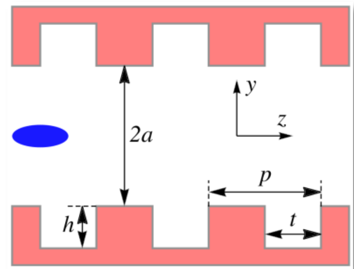
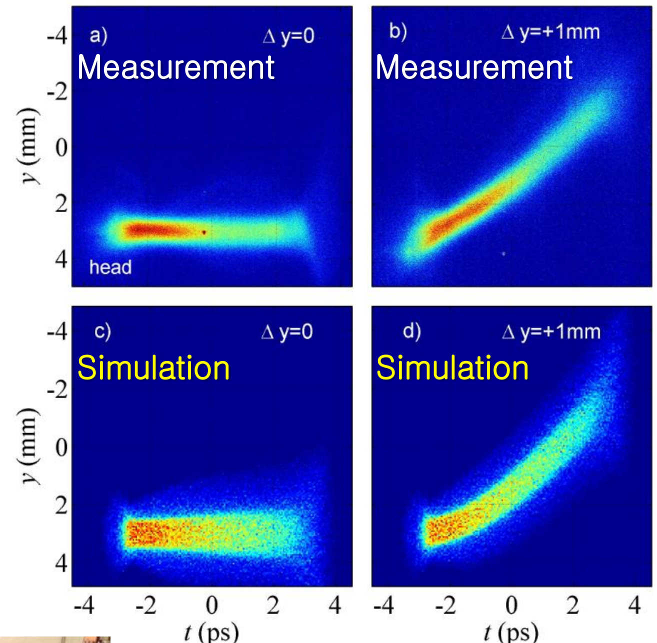
# Wakefield Dechirper Chamber – Simulation & Measurement



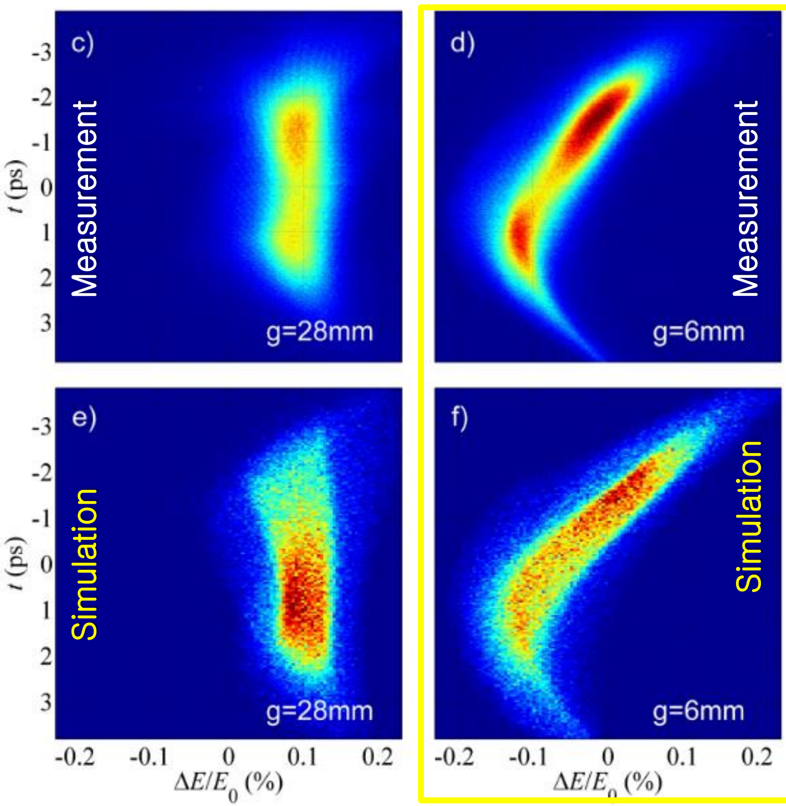



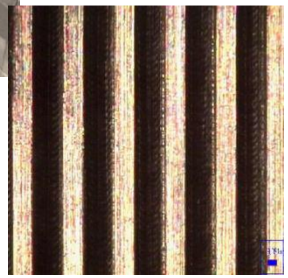

corrugated chamber

Time-resolved T-wake meas. & sims.



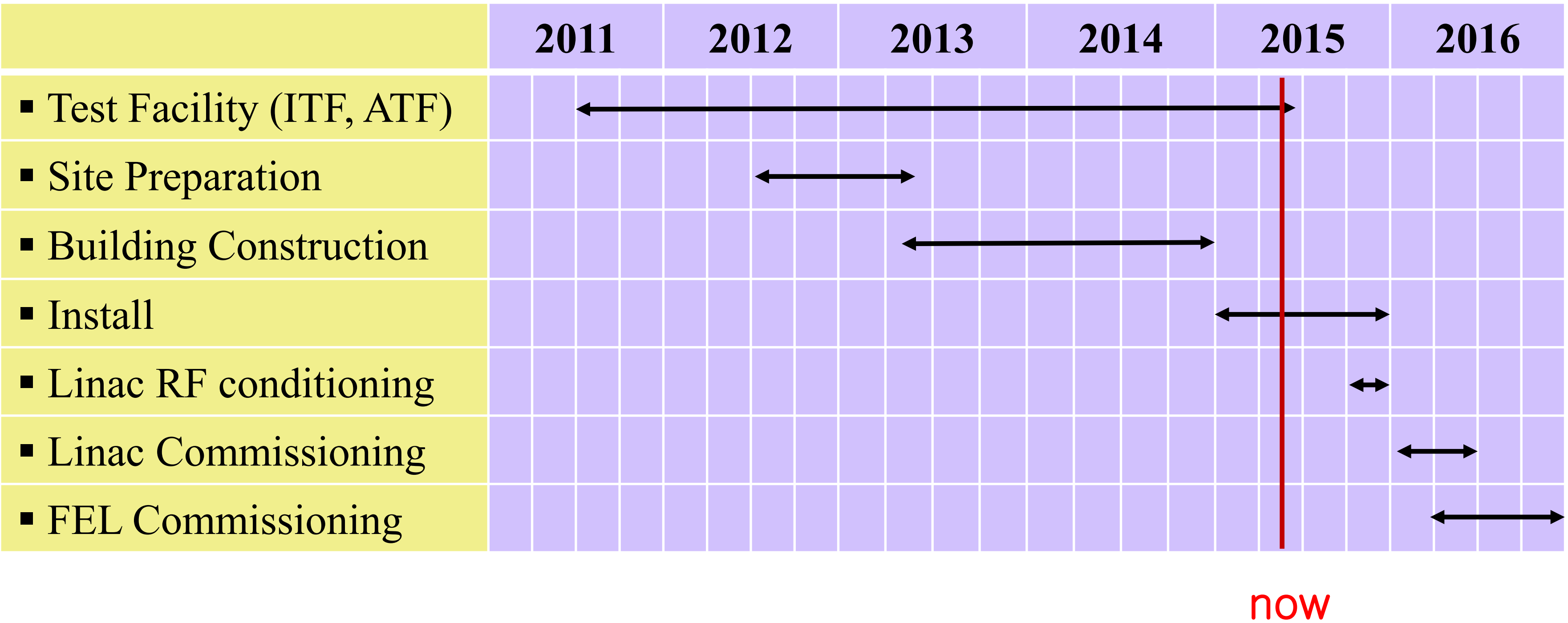

Time-resolved chirp meas. & sims.



# STATUS OF INSTALLATION

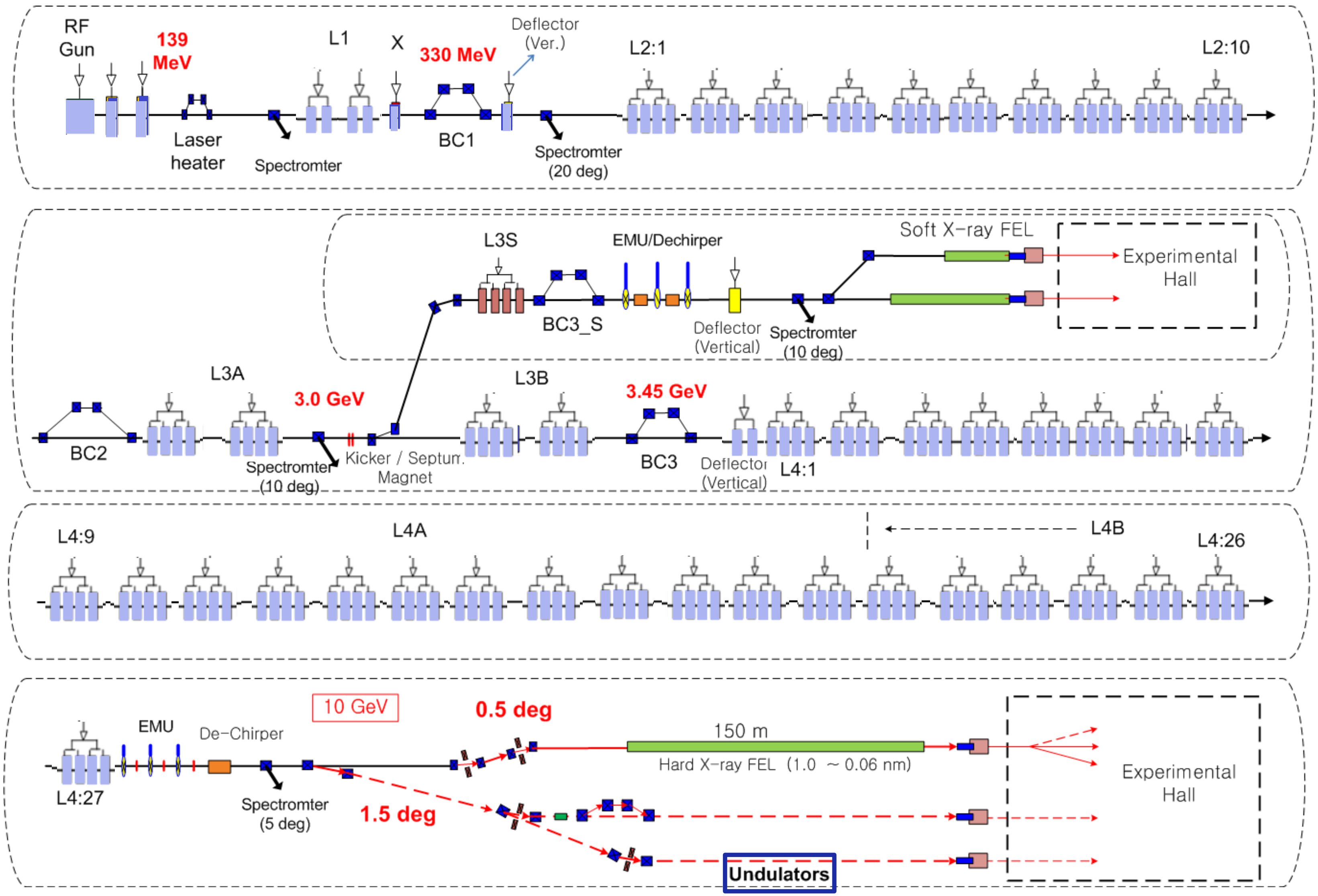
# Project Schedule



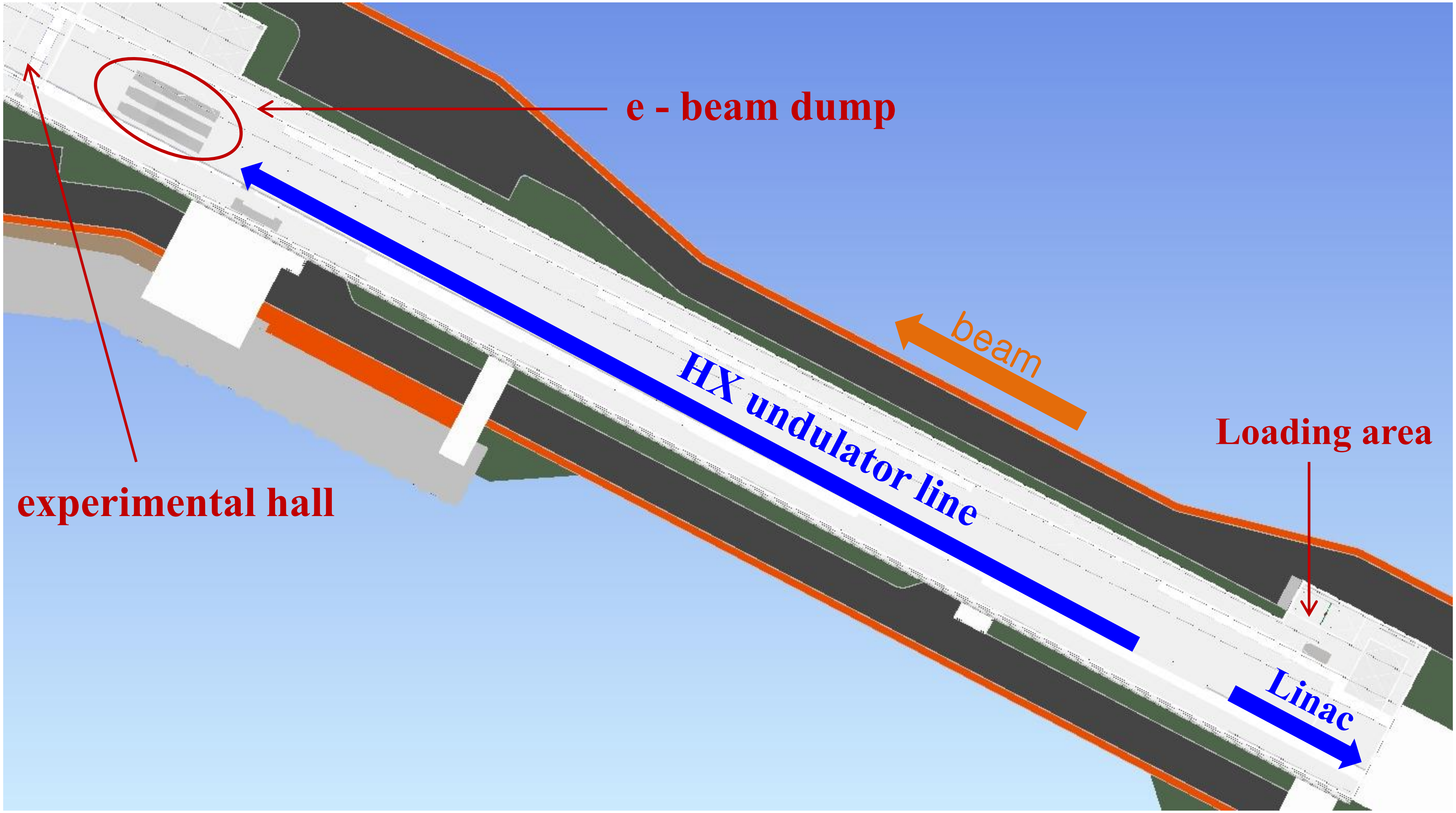

Undulator Install June 2015 - Dec. 2015

# Monthly Installation Plan of the Linac

| 2014 | | 2015 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | Dec. | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |

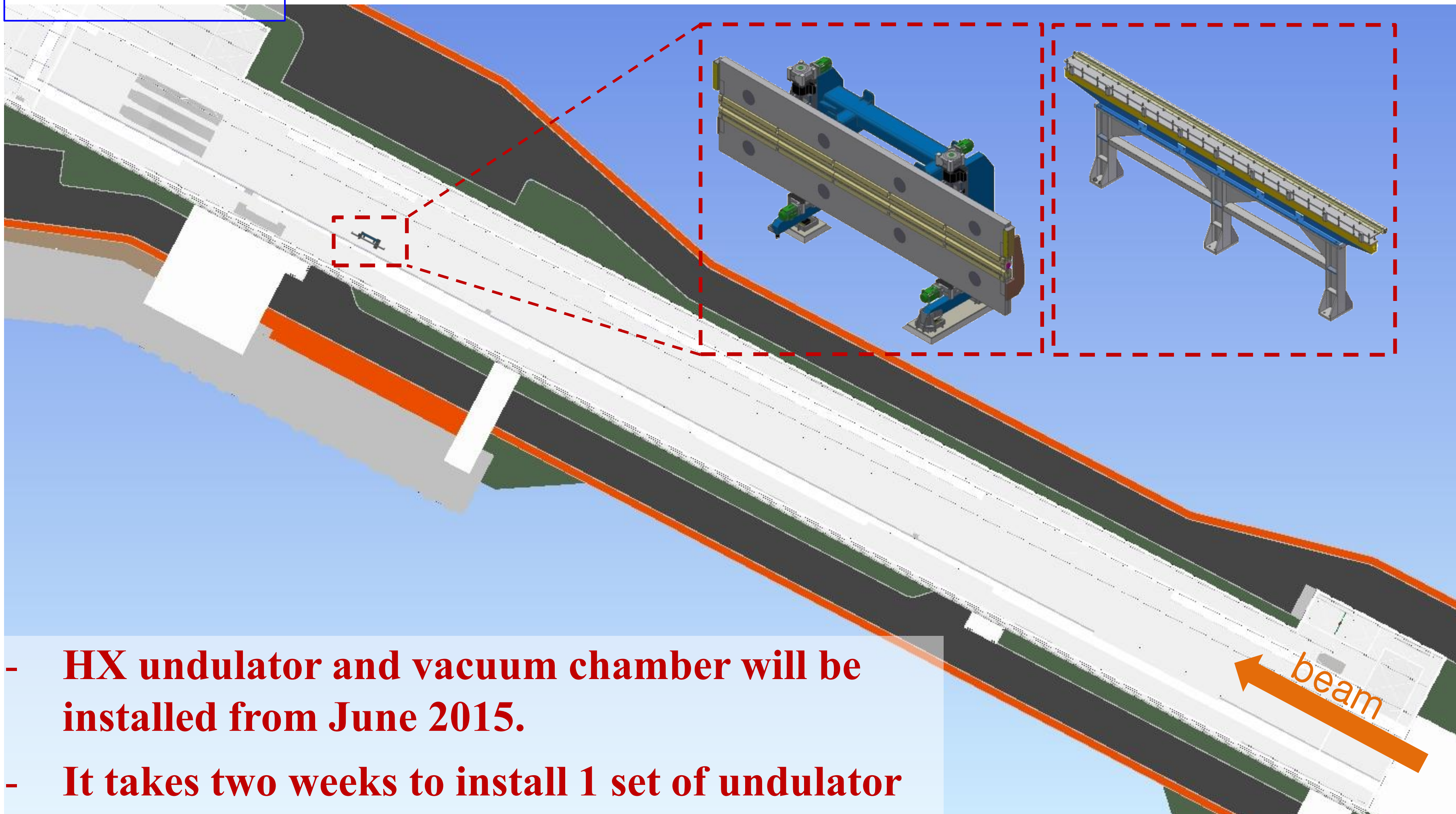


# Undulator Installation Plan



# Undulator Installation Plan: Undulator & Vacuum chamber

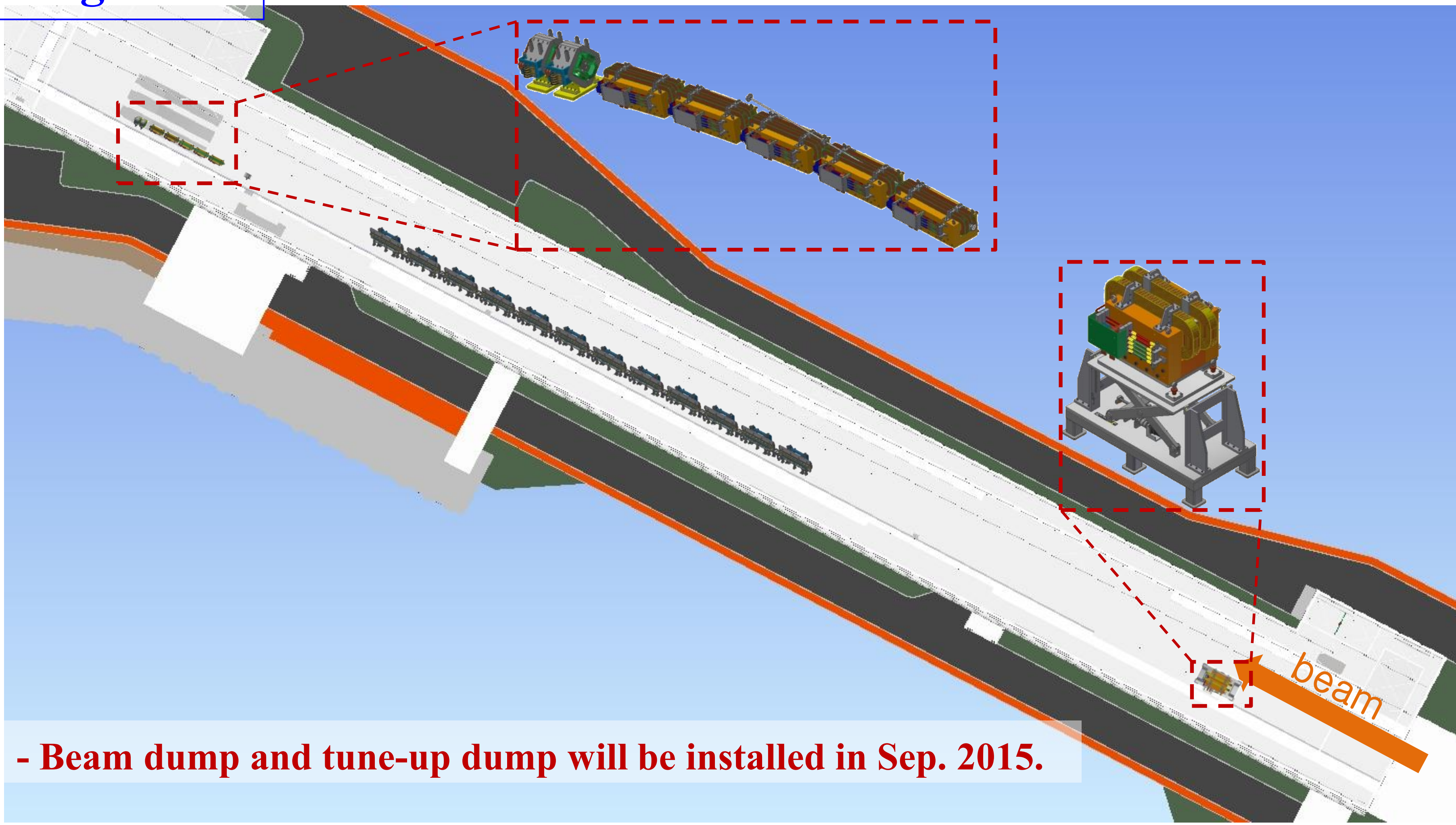
**June 2015**




- HX undulator and vacuum chamber will be installed from June 2015.
- It takes two weeks to install 1 set of undulator and chamber

# Undulator Installation Plan : Beam dump & Tune-up dump

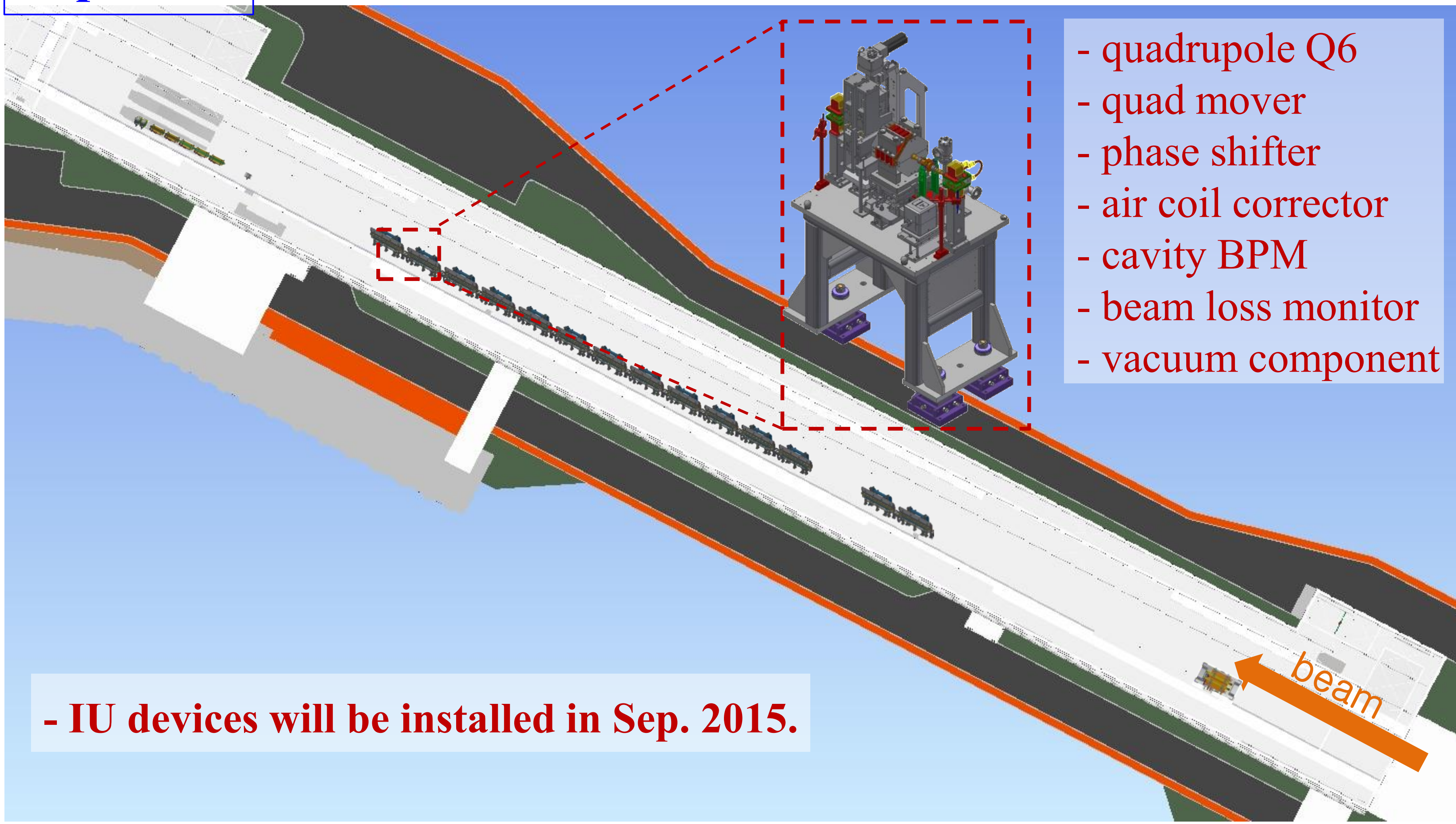
**Aug. 2015**




**- Beam dump and tune-up dump will be installed in Sep. 2015.**

# Undulator Installation Plan: Undulator Intersection Components

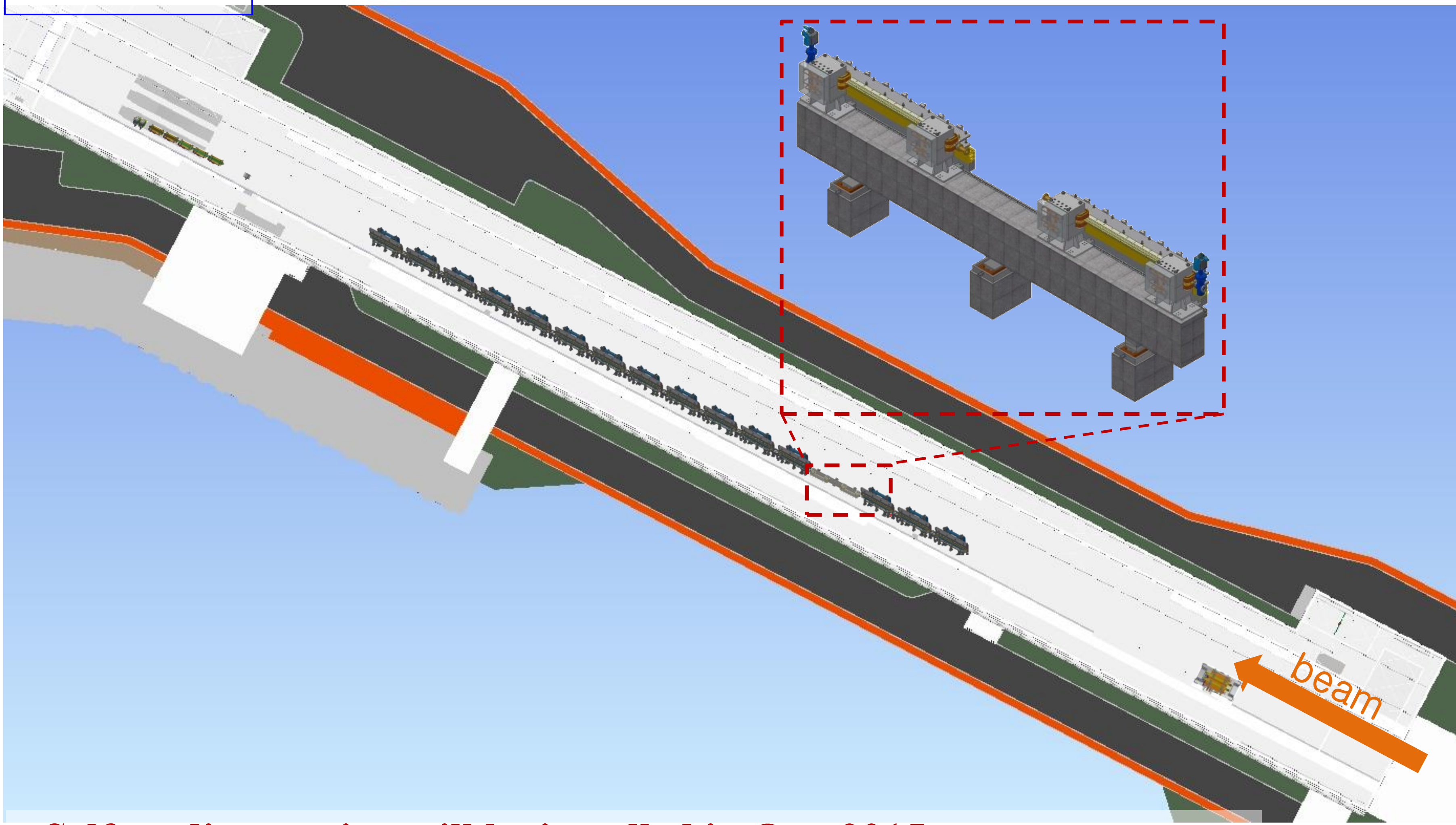
Sep. 2015




**- IU devices will be installed in Sep. 2015.**

# Undulator Installation Plan: Self-seeding section

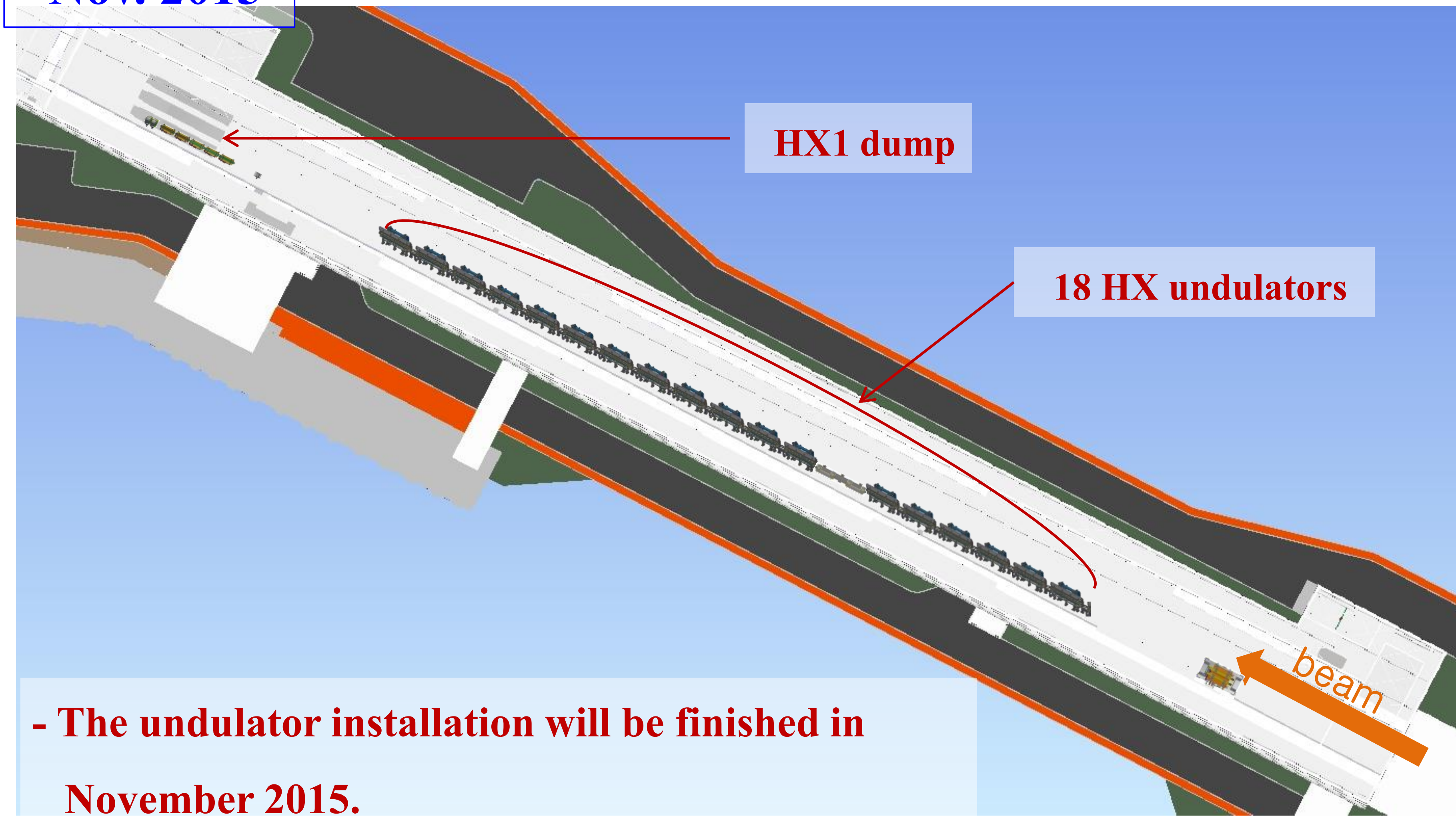
**Oct. 2015**




**- Self seeding section will be installed in Oct. 2015.**
**(except monochromator)**

# Undulator Installation Plan

**Nov. 2015**




**- The undulator installation will be finished in November 2015.**

# Aerial View of PAL (July 2012)

# Aerial View of PAL (July 2013)

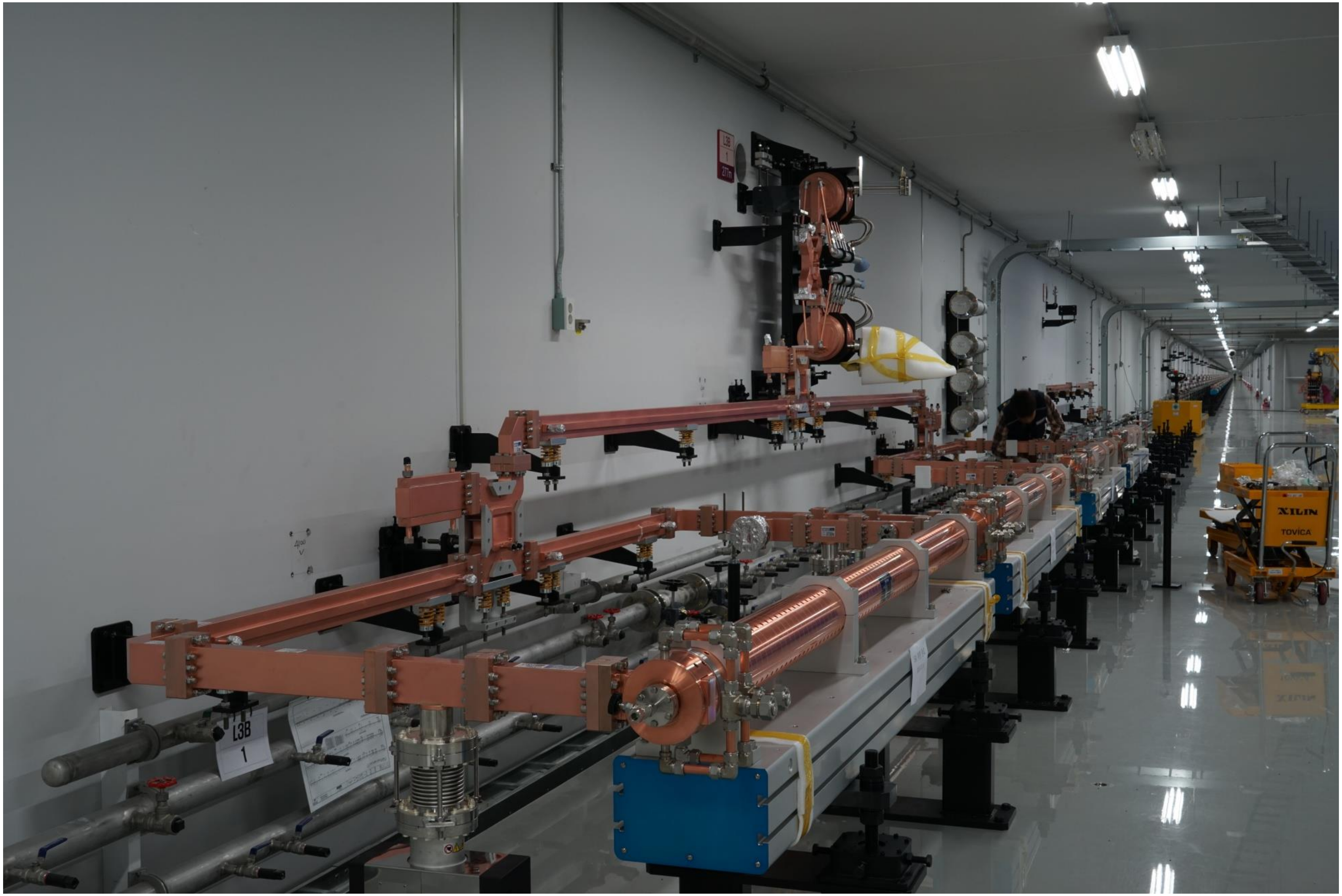
# Aerial View of PAL (July 2014)

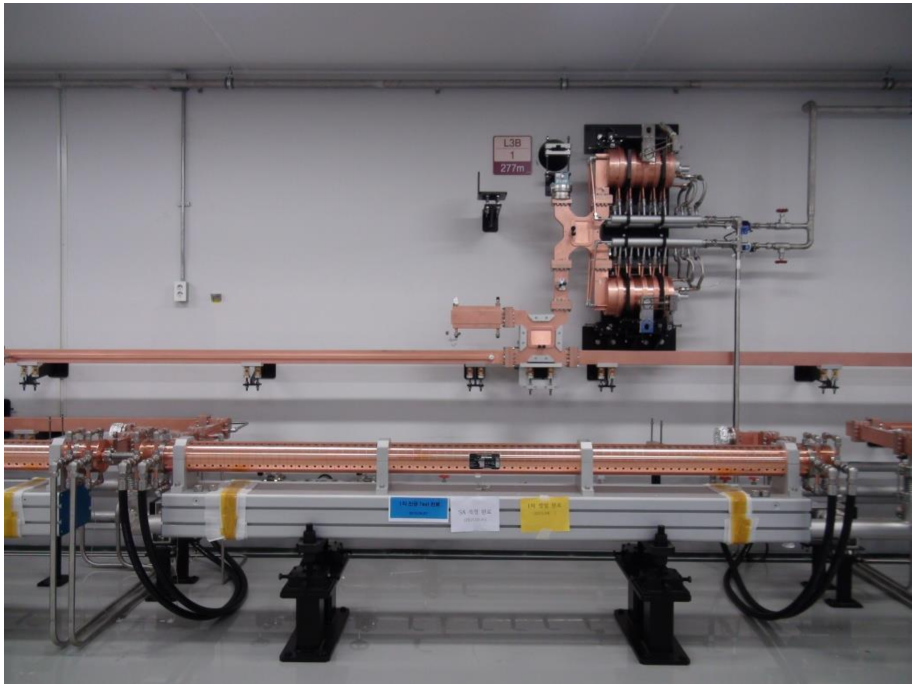
# Aerial View of PAL (January 2015)

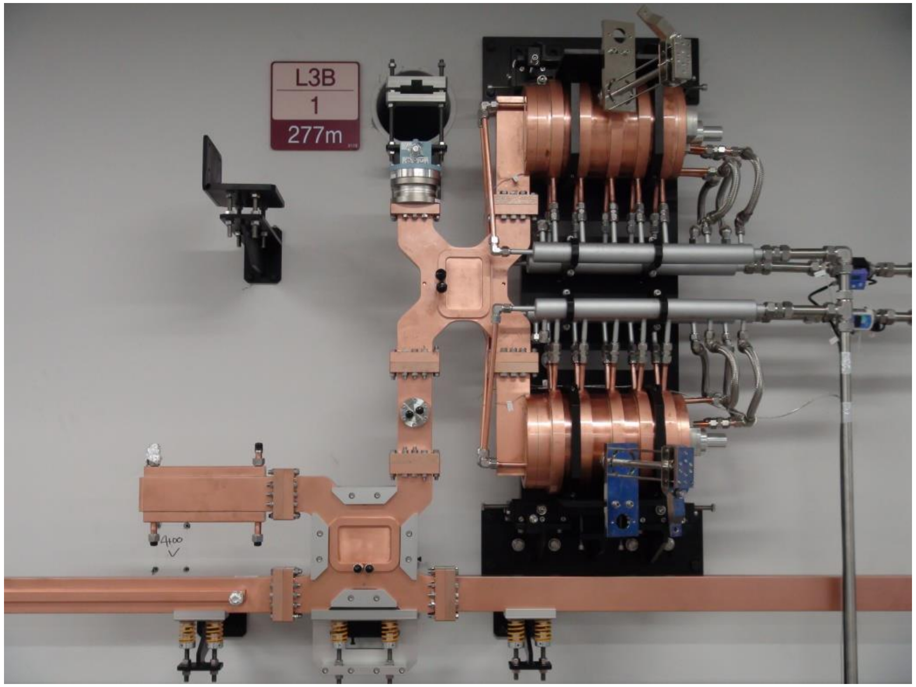
# First Installation of S-band accelerating structures (21 January 2015)

# Linac Tunnel

# Linac Tunnel






L3B
1
277m

# Modulators at Klystron Gallery

# Modulators at Klystron Gallery

# Hard X-ray Undulator hall

# Hard X-ray Experimental Hall

SUB-SYSTEM Preparation

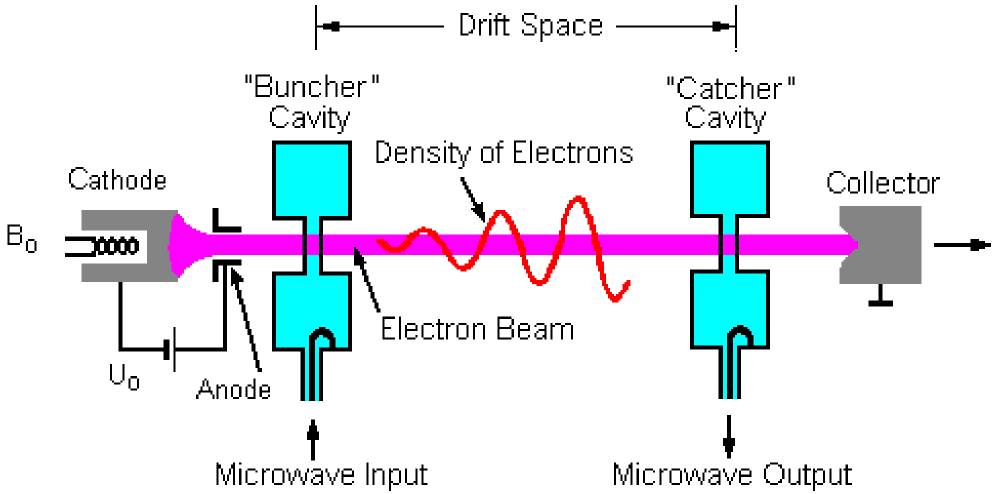
# 1. LINAC RF

# Number of Major RF Components

| Classification | Section | K&M | A/S | Energy Doubler | Energy (GeV) |
|---|---|---|---|---|---|
| Injector linac | | 3 | 2 | 0 | 0.139 |
| Hard X-ray main linac | L1 | 2 | 4 | 0 | 0.33 |
| | L2 | 10 | 40 | 10 | 2.52 |
| | L3A | 2 | 8 | 2 | 3.0 |
| | L3B | 2 | 8 | 2 | 3.45 |
| | L4 | 27 | 108 | 27 | 10 |
| Soft X-ray linac | | 1 | 4 | 1 | 3~3.5 |
| Deflector (S-band) | L1, L3 | 3 | 4 | 0 | |
| Linearizer (X-band) | L1 | 1 | 1 | 0 | |
| Total No. | | **51** | **180** | **42** | |

# Linac RF Stability

Since the intra-**pulse feedback is not feasible in the RF** of the normal conducting Linac, RF stability is solely **determined by klystron Voltage stability**

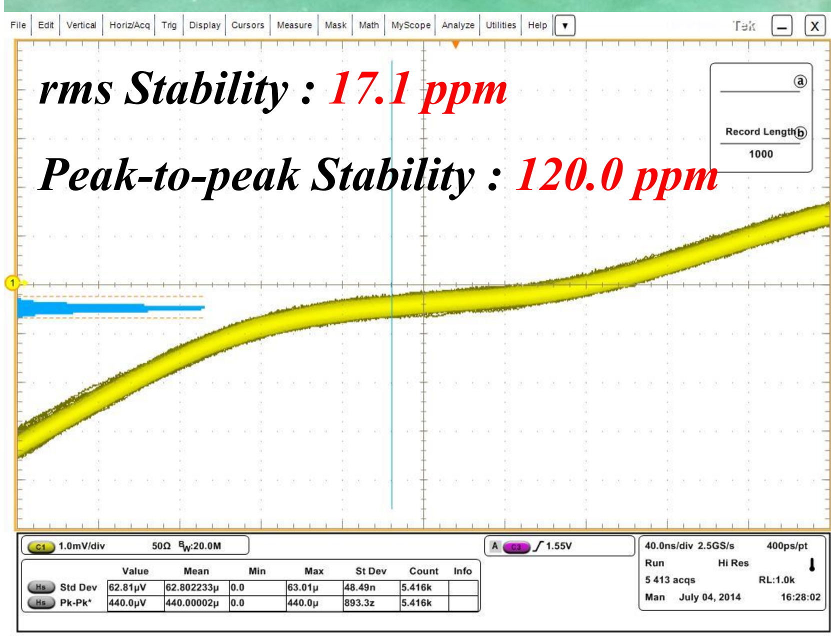



$$\frac{\Delta V}{V} = -\frac{m c^2}{e} \frac{\lambda_0}{L} \frac{(\gamma^2 - 1)^{3/2}}{V_0} \frac{\Delta\theta}{360}$$

| | S-band | X-band |
|---|---|---|
| Frequency [GHz] | 2.856 | 11.424 |
| **RF phase stability Goal [degrees]** | **0.03** | **0.06** |
| Klystron beam voltage stability [ppm] | **55** | **31** |

# Ultra-Stable Modulator

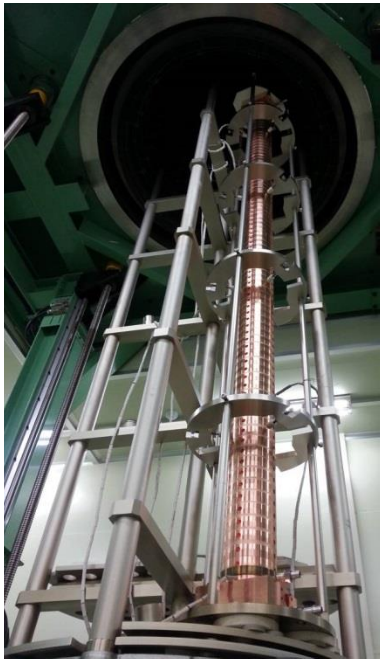
| | Unit | Value |
|---|---|---|
| RF output power | MW | 80 |
| Max. peak power | MW | 200 |
| Beam voltage | kV | 400 |
| Beam current | A | 500 |
| Beam pulse width | μs | 8 |
| Repetition rate max. | Hz | 60 |
| Pulse transformer turn ratio | | 17 |
| Perveance | μp | 2 |

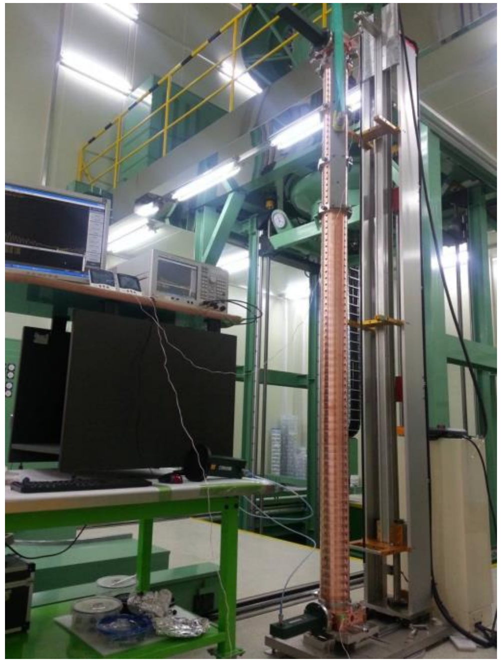



Collaborated with two Korean companies

- POSCO-ICT
- Dawon-Sys

# S-band Accelerating Structure



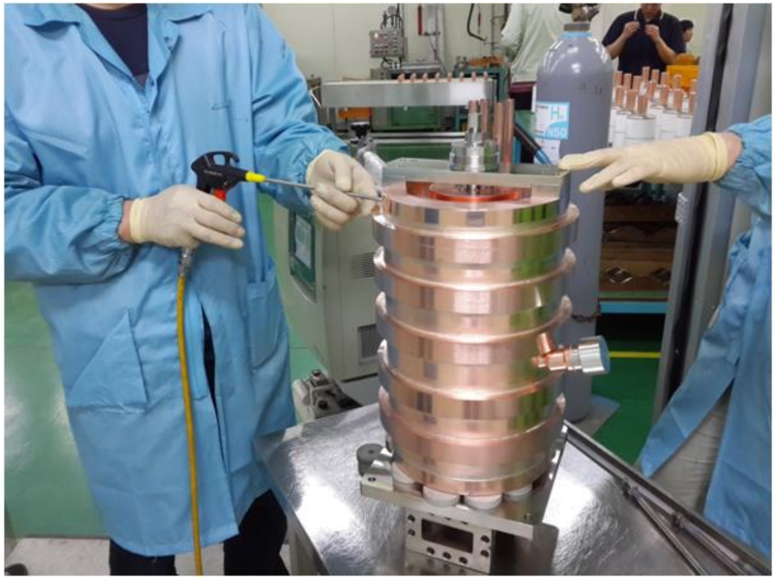


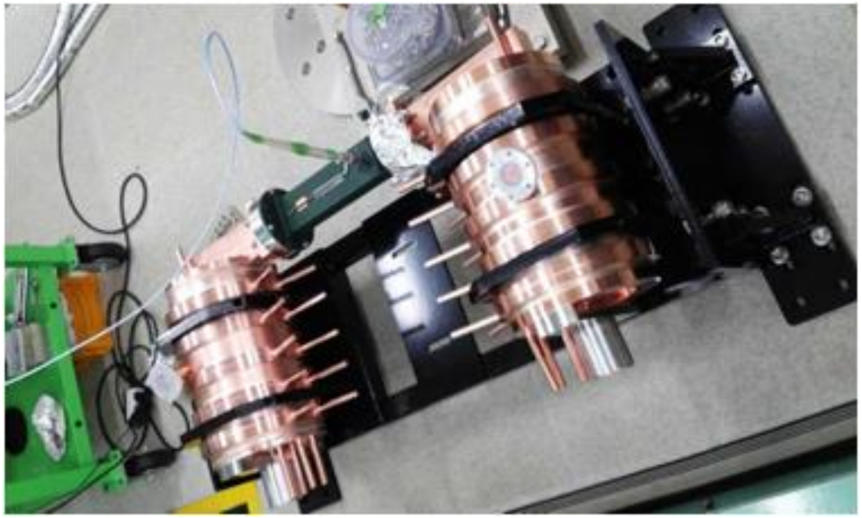
- Accelerating gradient of 27 MV/m
- Qausi-symmetric coupler with racetrack shape

- Collaborated with a Korean company
  ： Vitzro-Tech, Korea

- 120 modules made by MHI, Japan

# S-band Energy Doubler





- Two-hole coupling to withstand 380 MW peak RF power

* Collaborated with a Korean company
: Vitzro-Tech, Korea

# LLRF controller

LLRF


- 10 Channels for pulse measurement
- 2 Channels for pulse generation
- IQ modulation & demodulation
- Arbitrary pulse-shaping function
- Klystron beam V & I measurement
- IPC based computation system
- Beam synchronous acquisition

Solid-State Amplifier

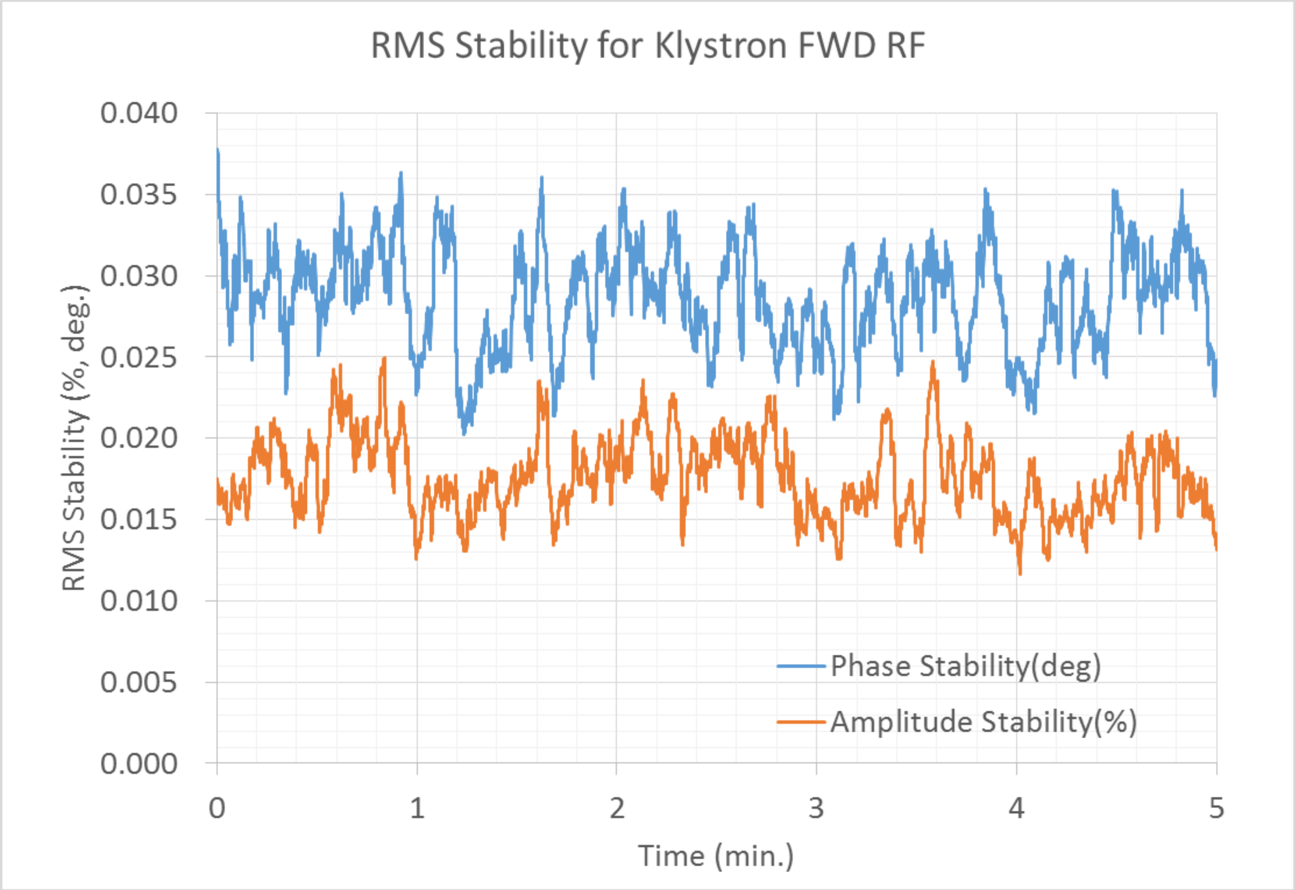

- Pulsed output power
- Power control : 600~900W

* Collaborated with a Korean company : MOBIIS, Korea

# RF Stability Performance

- Using a Modulator, E37320 Klystron, SLED & LLRF for PAL-XFEL
- RMS Stability : Amplitude~0.02%, Phase~0.03° (for Klystron FWD)

※ averaged for 500ns within pulse



SUB-SYSTEM Preparation

# 2. UNDULATOR

# High Precision Undulator

## PAL-XFEL Undulator Error Budget for 0.1 nm

| Parameter | σ | $P_i/P_0$ | tolerance |
|---|---|---|---|
| Launch Angle, μrad | 1.73 | 98 % | 0.35 |
| Cell Phase, degree | 55.6 | 99.6 % | 5.0 |
| Phase Shift, degree | 55.6 | 99.6 % | 5.0 |
| Break Length, mm | 11.8 | 99.9 % | 0.5 |
| ΔK/K (gap control, 1 μm) | 0.00053 | 95 % | 0.00017 |
| Quad position, μm | 3.63 | 95% | 1.2 |
| Seg. Ver. Pos. , μm | 0.0183 $mm^2$ | 98% | 61 |
| Jaw Pitch, μrad | 60.8 | 99.5% | 6.1 |

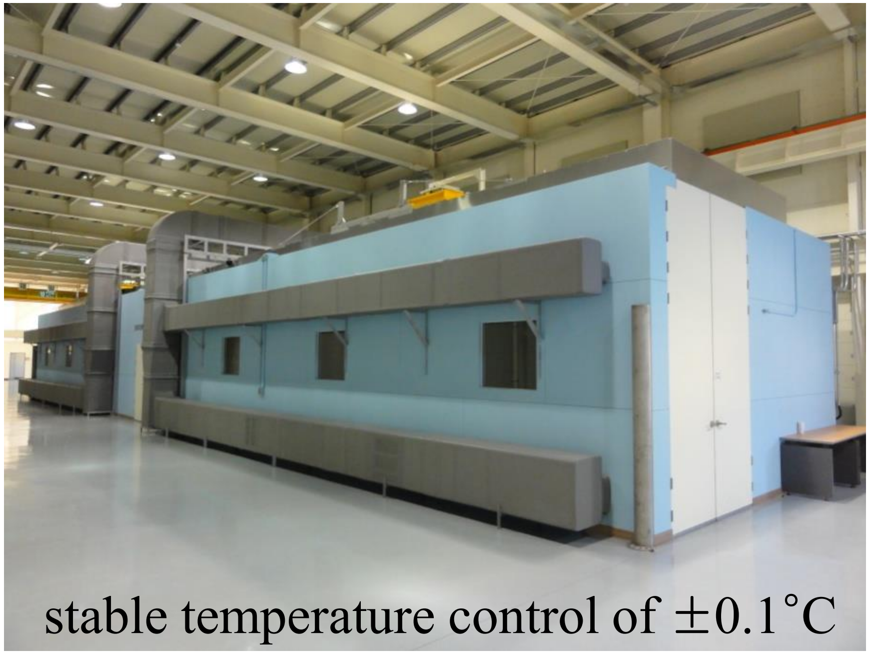
**Undulator Stability Requirement**

- **Field accuracy: < 2 x 10-4**
- **Gap setting accuracy: < 1 um**

# Prototype Undulator

- EU-XFEL undulator design is benchmarked. A MOU to use the EU-XFEL design is agreed in June 2011 between PAL and EU-XFEL.
- PAL modified the design including the new magnetic design, EPICS IOC, and updated tolerances reflecting new parameters.
- A fully assembled HXU prototype was delivered in Dec 2012 and measured at the undulator measurement lab.

Undulator Measurement Room

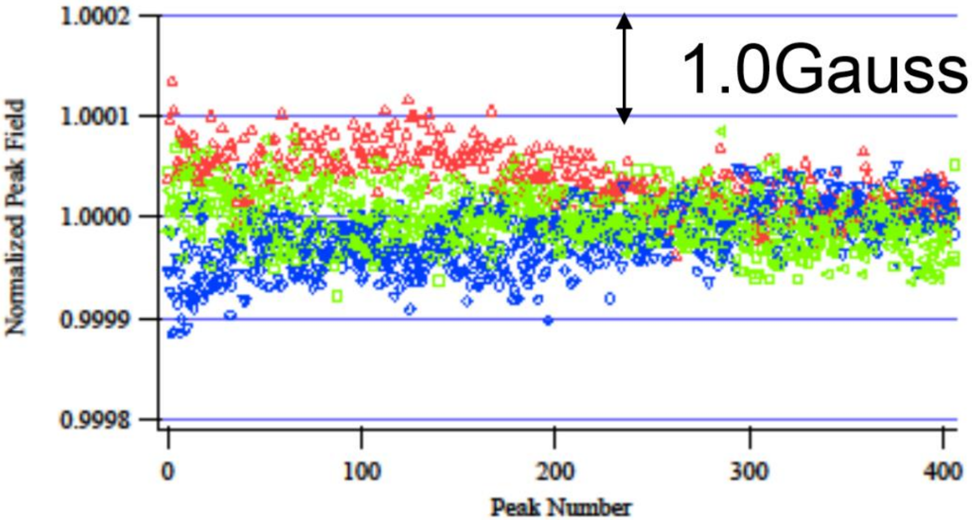


stable temperature control of ±0.1°C

Prototype Undulator under field measurement

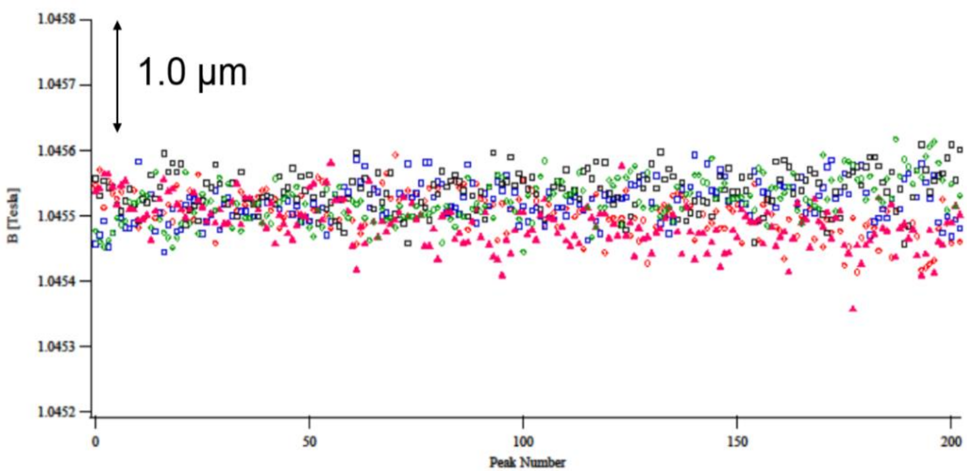
# Field & Gap Reproducibility Errors

- Field Errors



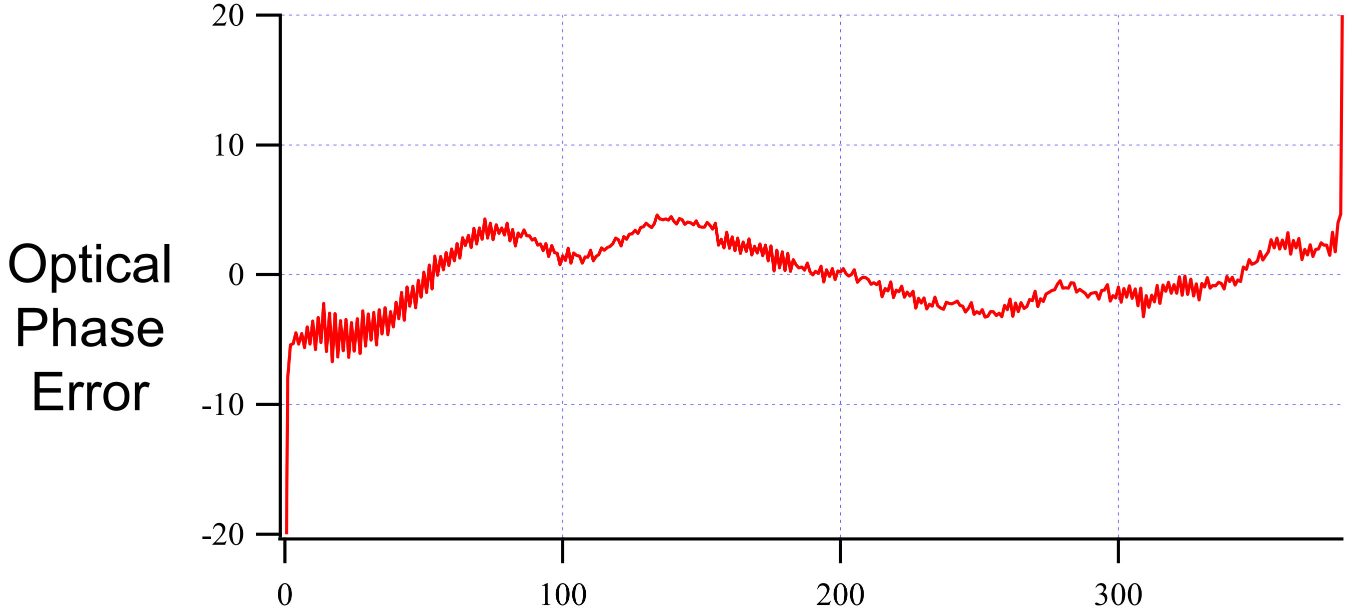

- The peak fields from 5 measurements are overlapped.
- B errors are about ±1.0 G.
- Orbit error from the measurements is less than 1 um.

- Gap Reproducibility Errors




- The peak fields from 5 measurements are overlapped. Between each measurement, gap is opened to 100 mm and closed to measurement gap.
- 1.5 Gauss difference translates to 1.0 µm gap error.

# Measured Optical Phase Analyzed Using B2E




- Initial optical phase errors were very large because of girder deformations about 50 μm.
- The optical phase errors is corrected to about 3.0 degree (rms) at the tuning gap.
- In production phase, we expect 1 day for vertical orbit correction, 1 day for correction of dominant quad components, 3 days for the phase/horizontal orbit tuning.

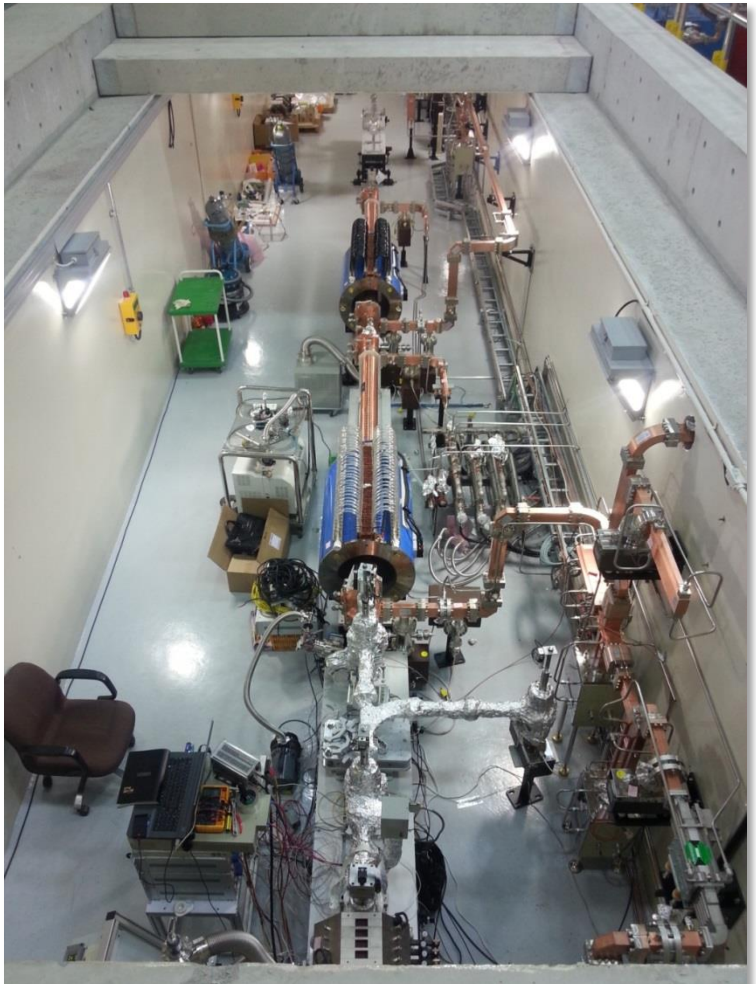
# First Undulator under field measurement

| Symbol | Unit | Nominal value |
|---|---|---|
| E | GeV | 10.000 |
| g | mm | 8.30 |
| $\lambda_u$ | mm | 26.0 |
| $L_{und}$ | m | 5.0 |
| $\lambda_r$ | nm | 0.1 |
| $B_{eff}$ | Tesla | 0.8124 |
| K | | 1.9727 |
| Optical phase error | degree | less than 5.0 |

SUB-SYSTEM Preparation

# 3. INJECTOR & INJECTOR TEST FACILITY

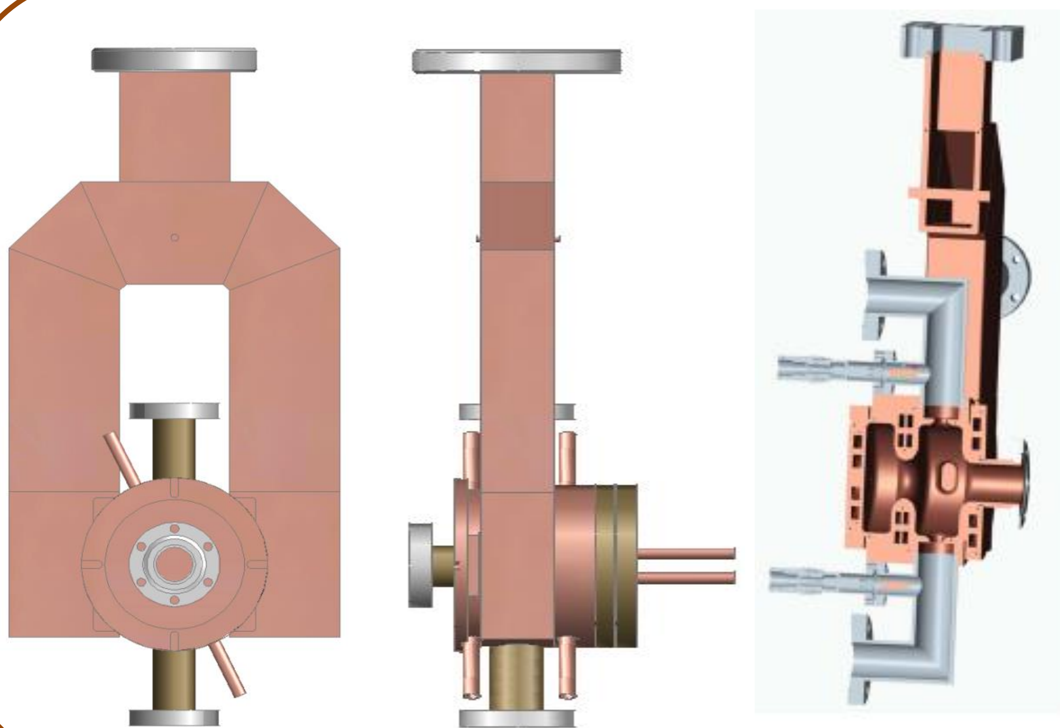
# Injector Test Facility for PAL-XFEL



**ITF Tunnel**

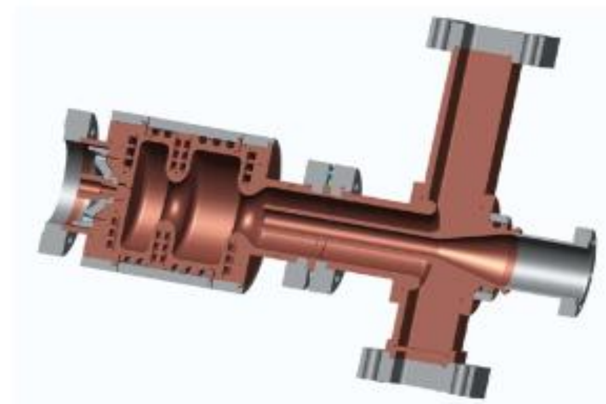

ITF Modulator / Klystron

# Two candidate designs for the PAL-XFEL gun



**PAL-XFEL baseline gun :** dual-coupler gun with additional two-holes to reduce quadrupole field

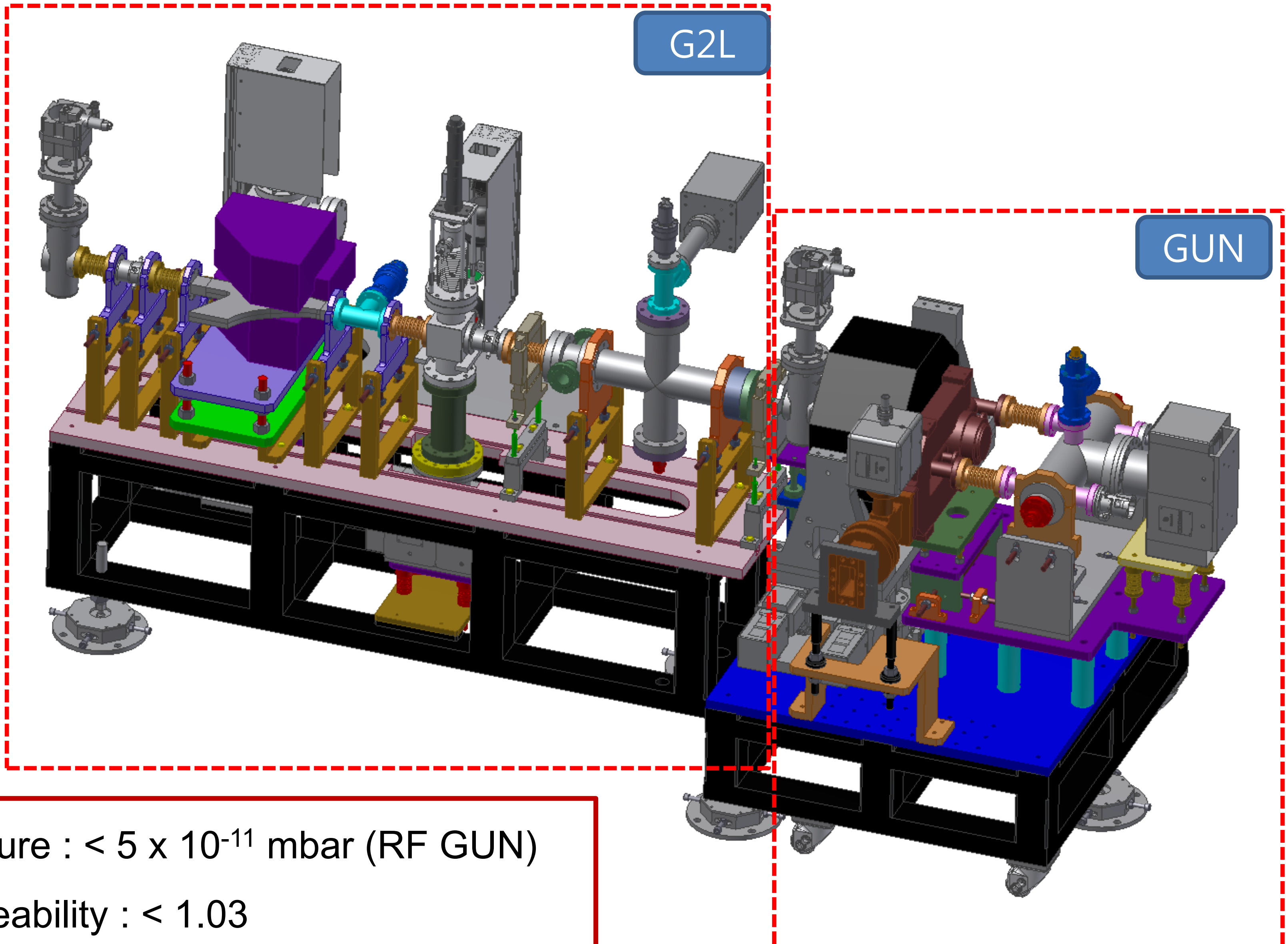
**PRST AB 14, 104203 (2011)**
Emittance growth due to multipole transverse magnetic modes in an rf gun



**Alternative gun design :**

**fully-symmetric coaxial coupler and cathode plug.**

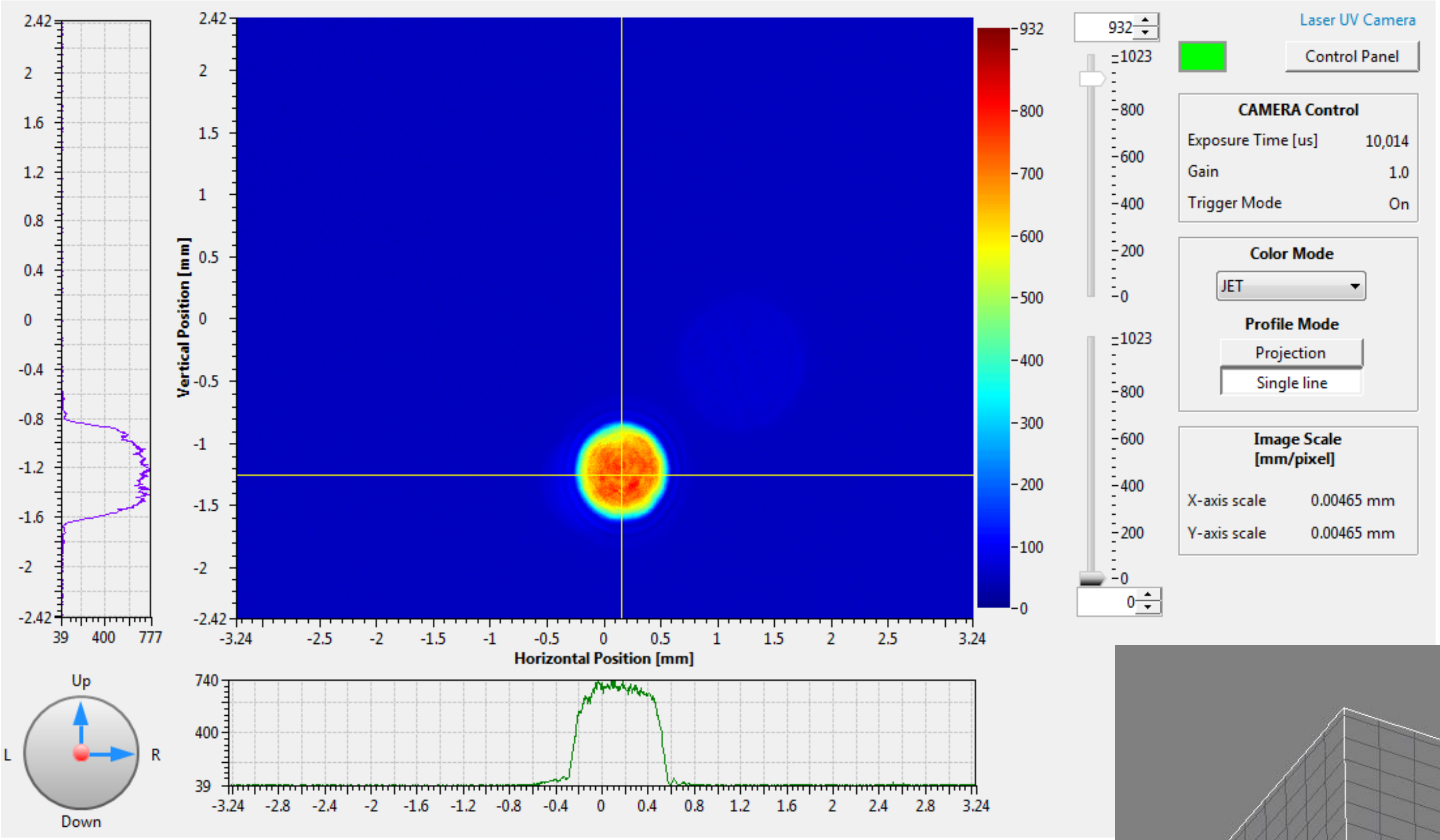
# Gun Part of Injector

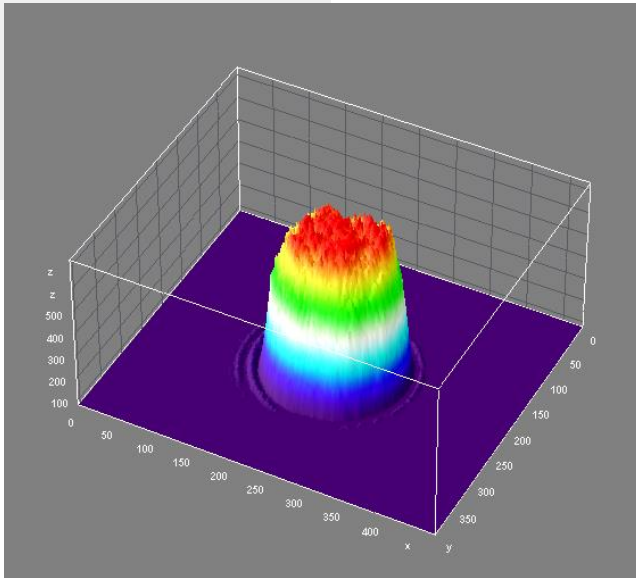



Pressure : < 5 x $10^{-11}$ mbar (RF GUN)

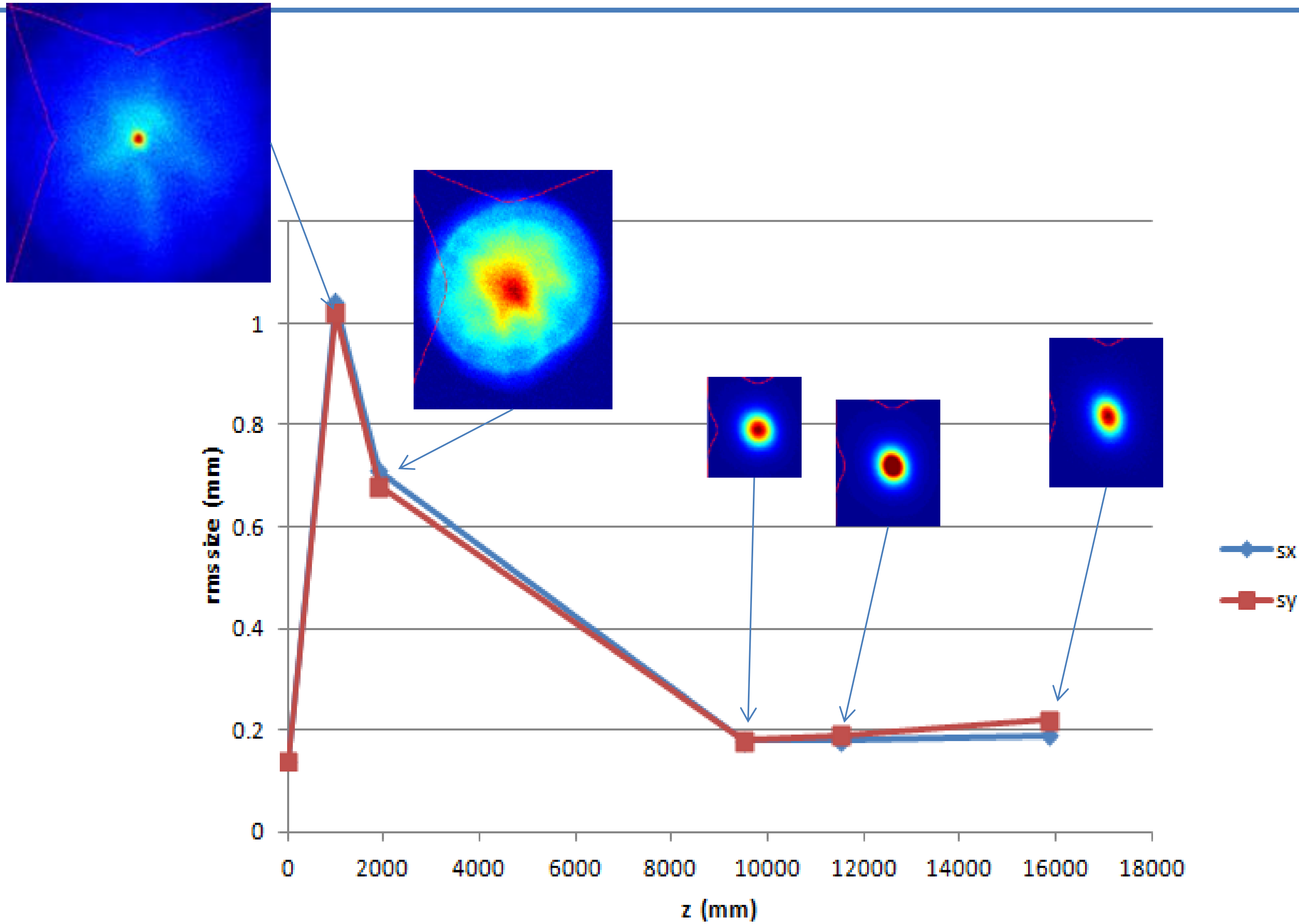
Permeability : < 1.03

# Laser Beam Profile



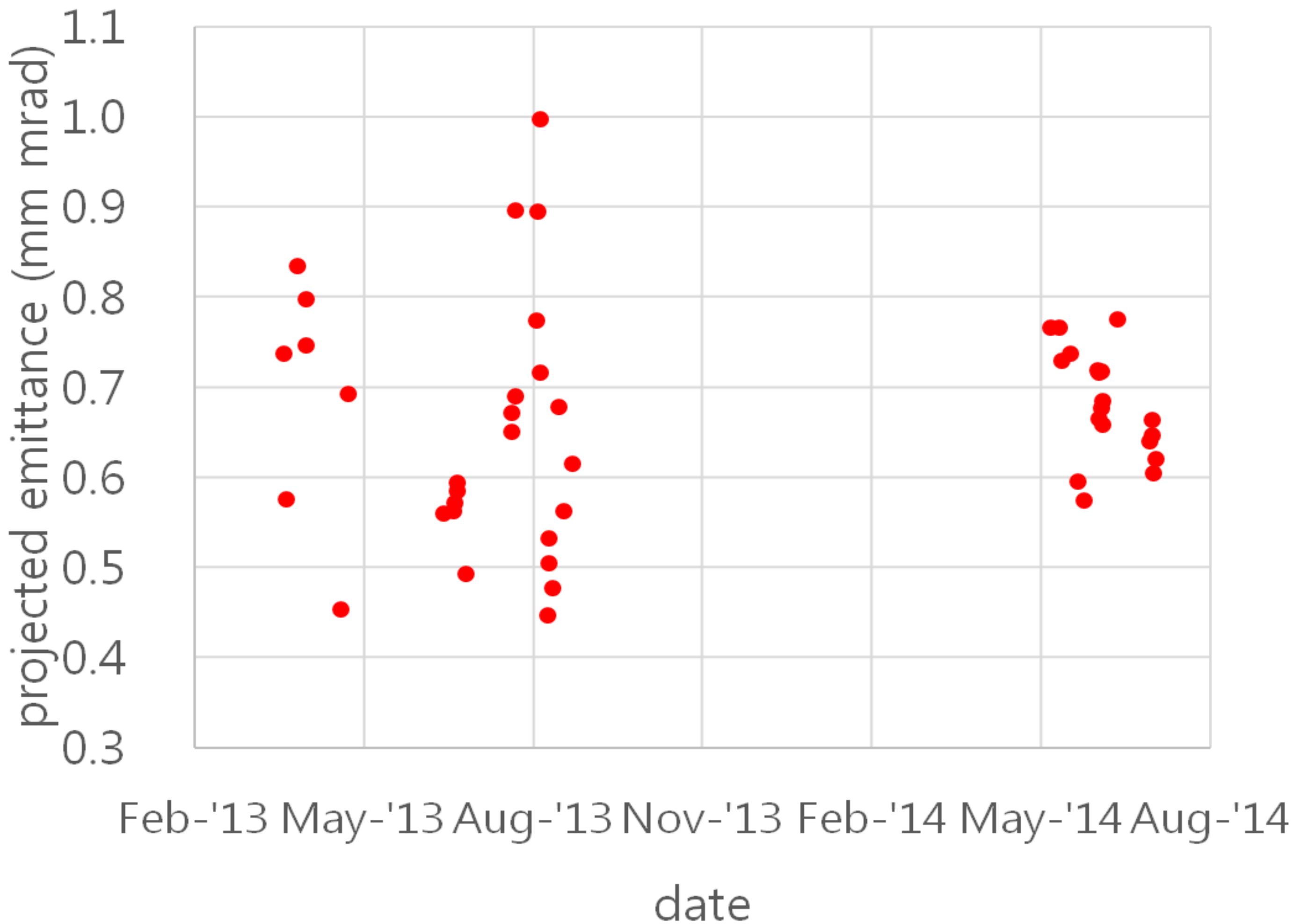



# Longitudinal Evolution of Transverse Profiles



# Emittance Measurement Result

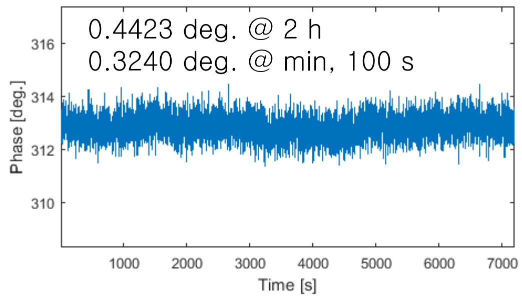
## - History of Projected Emittances (95%) at 200 pC

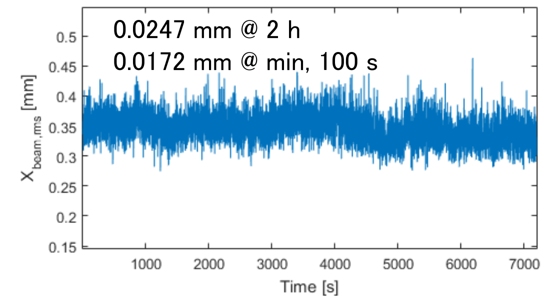


# Effect of synchronization between RF and Laser

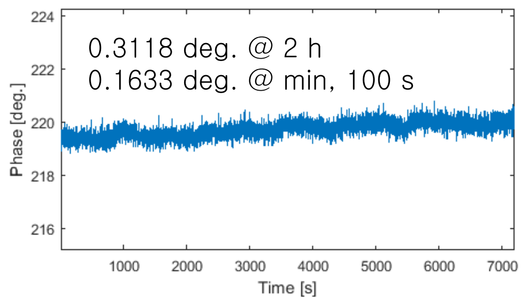
## Beam Arrival Time

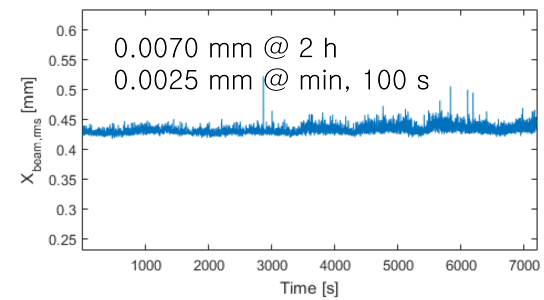
## Horizontal E-beam size



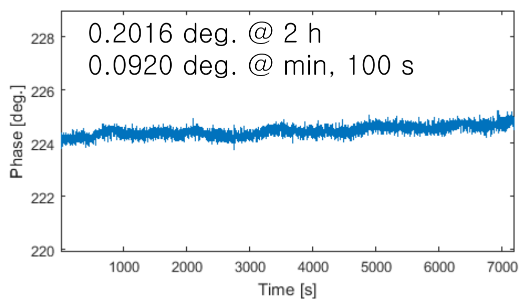



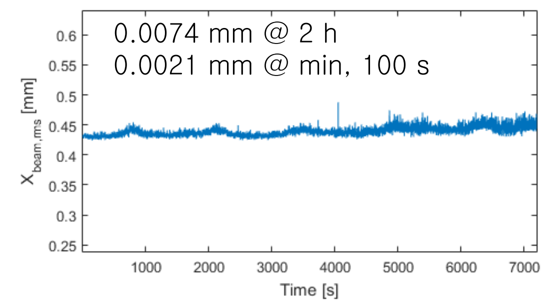

**Purifying of Laser Oscillator RF signal (79.33 MHz) by adding Low pass filter**




**Control of Laser oscillator sync. gain**

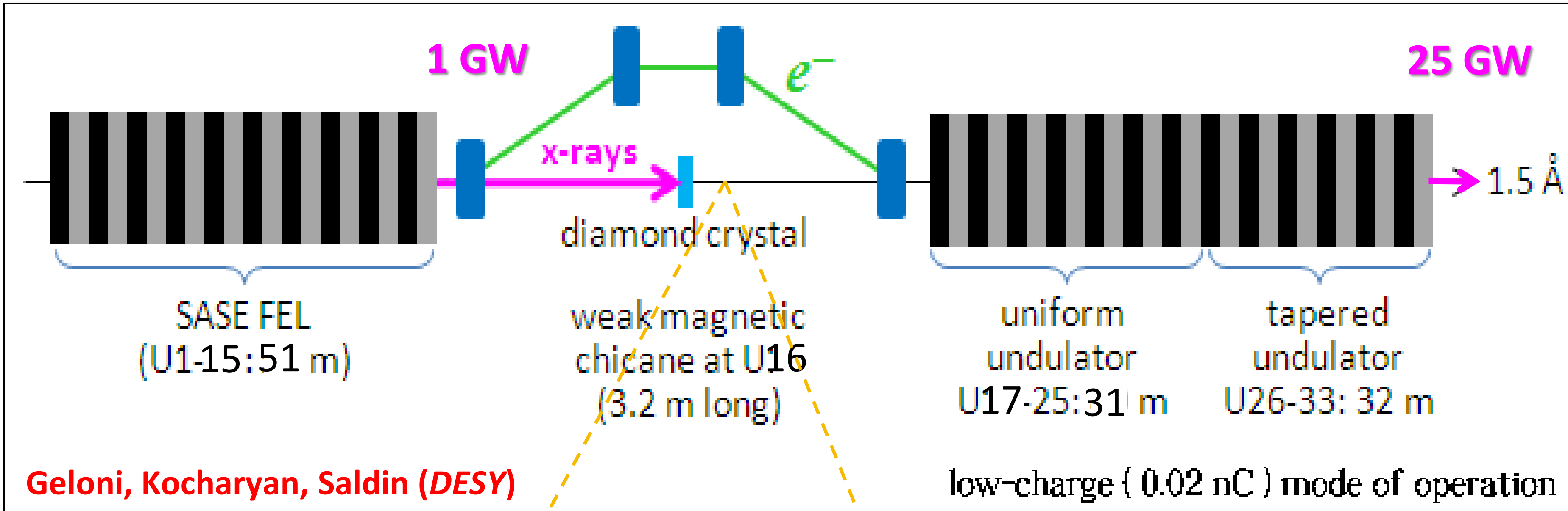


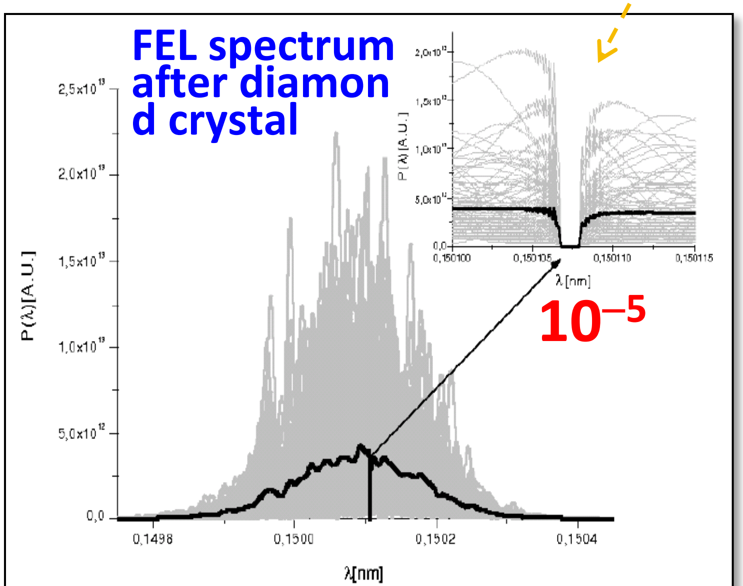



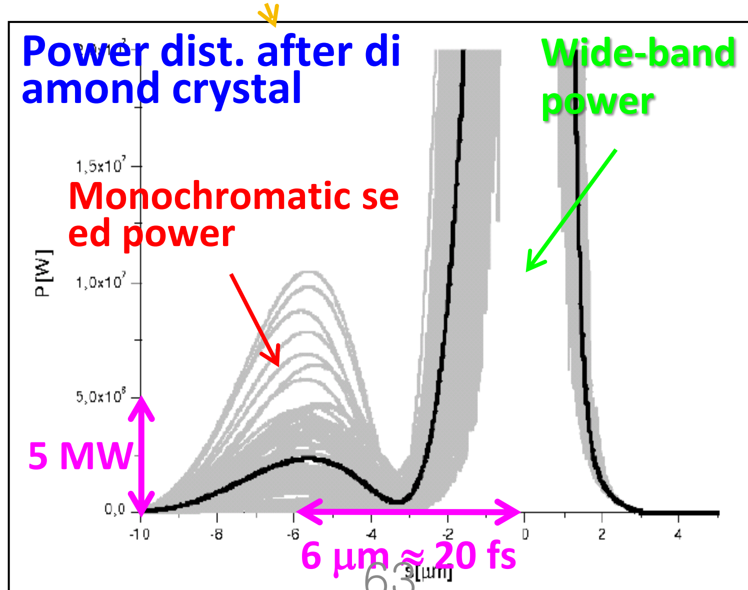
SUB-SYSTEM Preparation

# 4. SELF-SEEDING MOCHROMATOR

# Hard x-ray self-seeding @ *LCLS*




Self-seeding of 1-µm $e^-$ pulse at 1.5 Å yields **$10^{-4}$ BW** with low charge mode

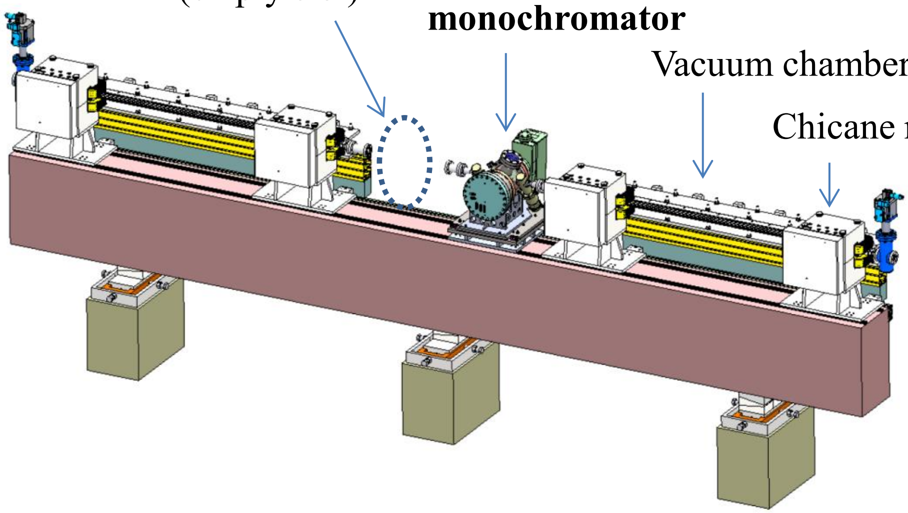
*courtesy of P. Emma*

# PAL-XFEL self-seeding collaboration project

- PAL-XFEL self-seeding team made a contract with ANL to develop a novel self-seeding monochromator for PAL-XFEL.
- Our self-seeding monochromator is based on the LCLS design.
- Two diamond crystals with (400) and (220) orientations will be installed into single chamber.
- The monochromator is designed to cover the photon energy from 5 keV to 10 keV.
- PAL and ANL focus on development of all diamond based crystal holder. The new holder might be resistive to thermal instability.
- The monochromator will be ready for installation in PAL-XFEL in Oct. 2016.

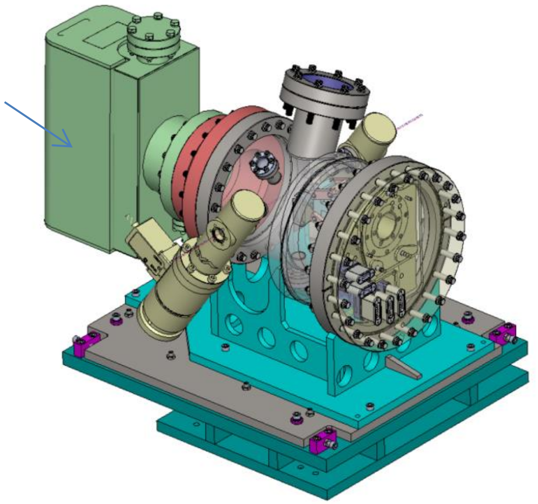
# Self-Seeding Monochromator

## PAL-XFEL hard x-ray self-seeding setup

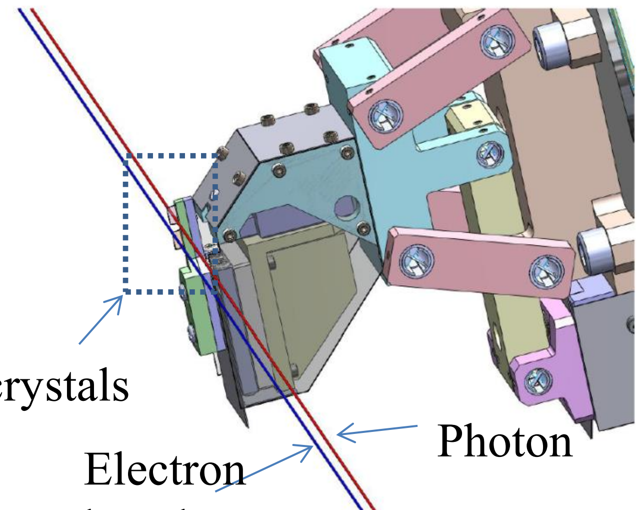



Designed by Bongi Oh (Chicane setup, PAL) and Dr. Deming Shu (Monochromator, ANL)

## Monochromator chamber

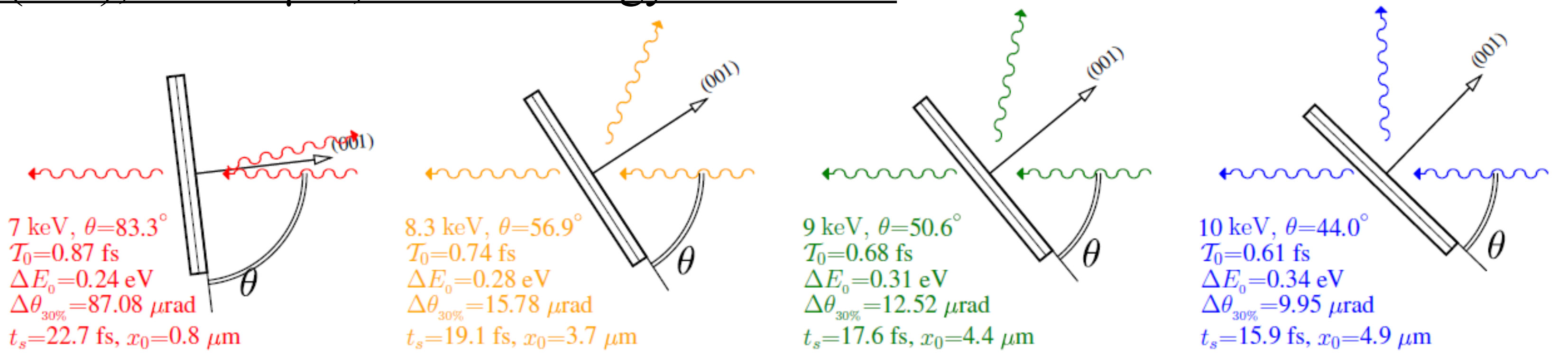



## Mounting assemblies inside the chamber



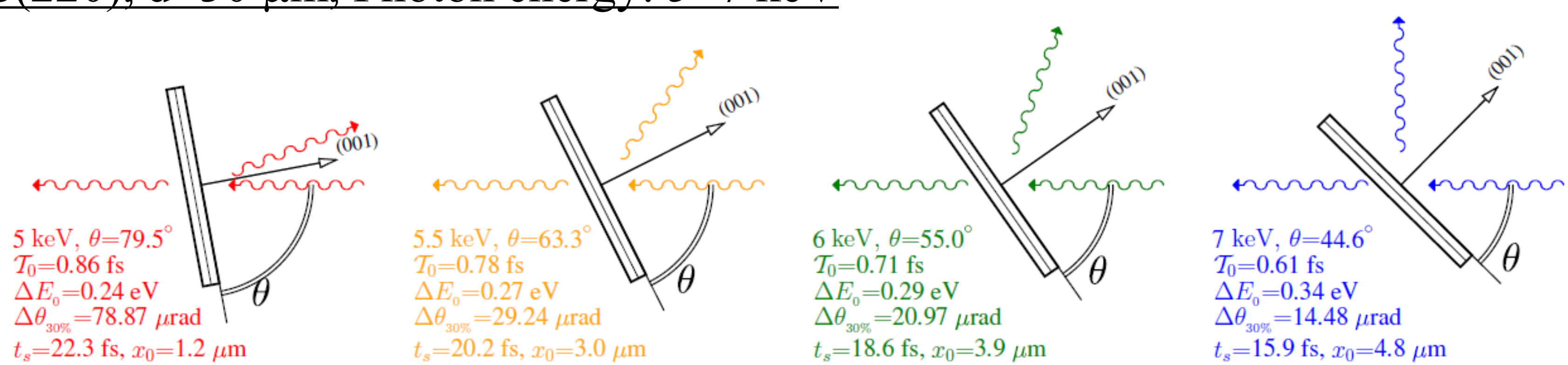
# Diamond crystals; diffraction angle dependence

## C(400), d=100 μm, Photon energy: 7~10 keV




$T_0$; characteristic time, $\Delta E_0$; energy bandwidth
$\Delta\theta_{30\%}$; admissible strain, $t_s$= time delay, $x_0$= spatial offset

## C(220), d=30 μm, Photon energy: 5~7 keV

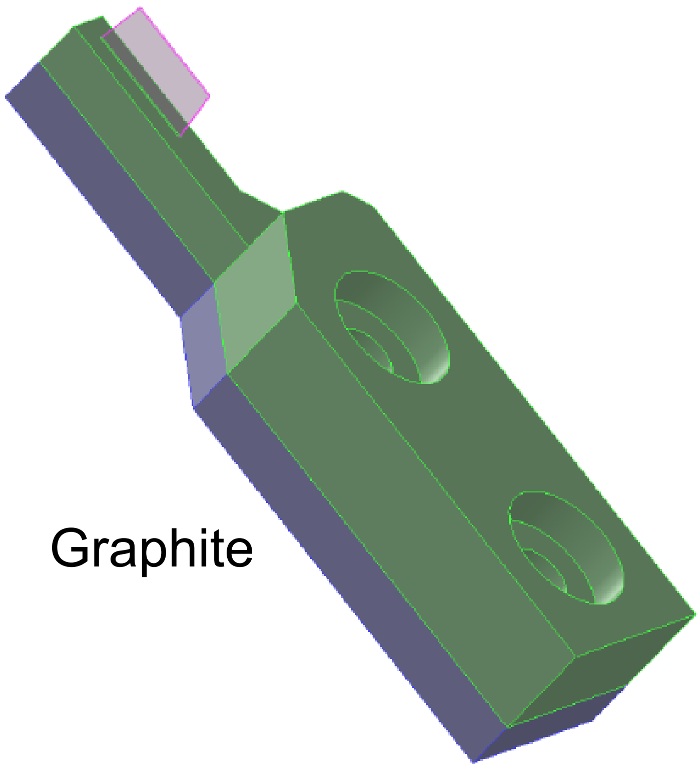



*PR STAB 15.* (2012) 050706, *PR STAB* 15 (2012) 100702.

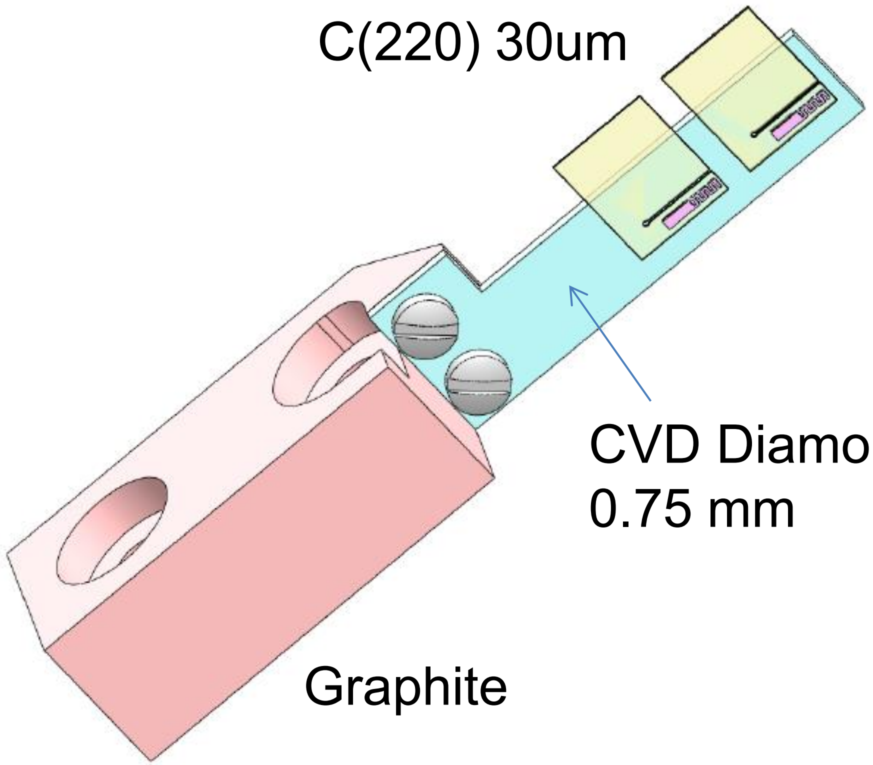
Courtesy of Yuri Shvyd'ko

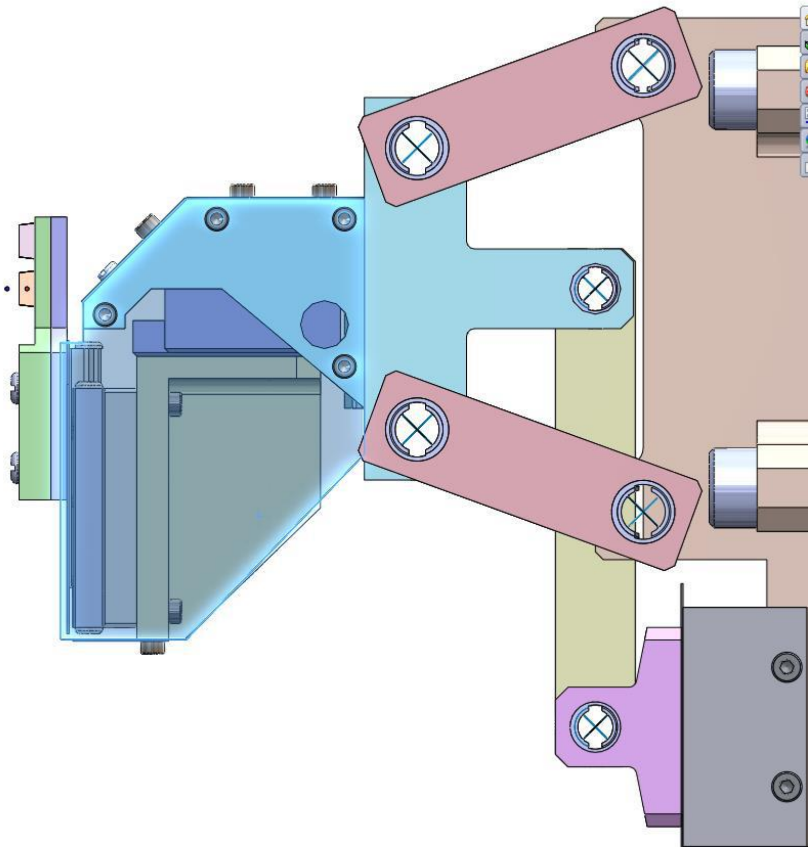
# Diamond Crystal Holder

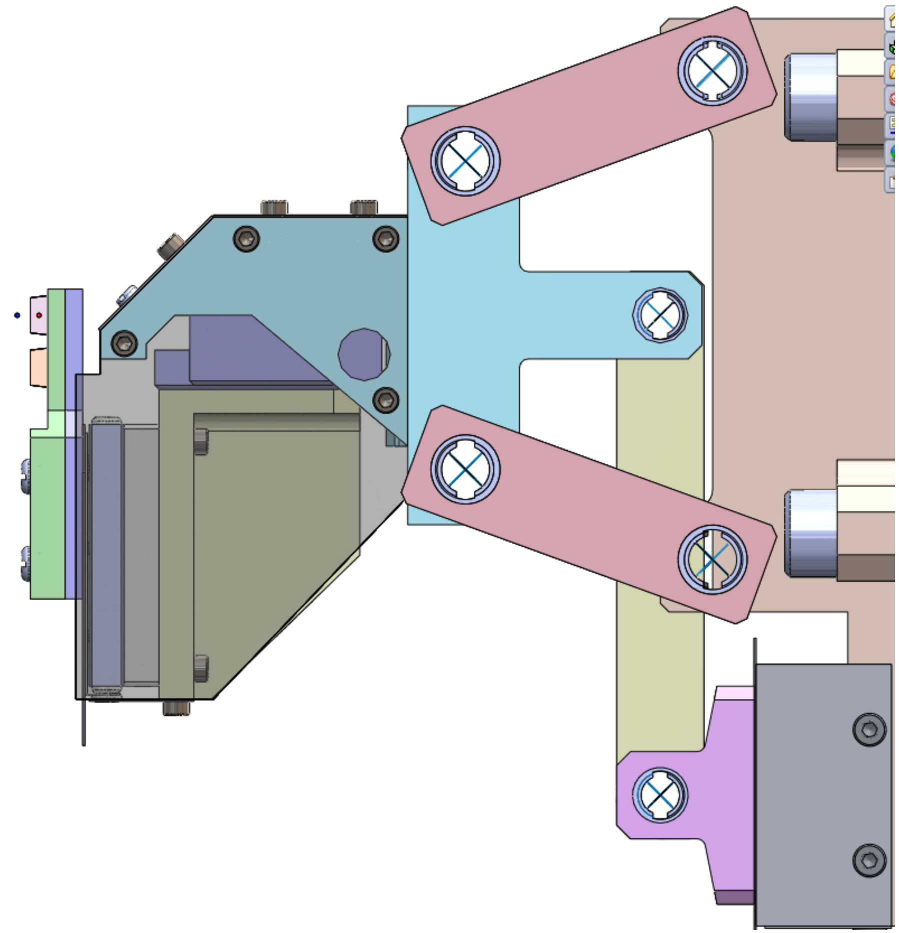
Diamond Crystal holder design for LCLS




Diamond Crystal holder design for PAL-XFEL







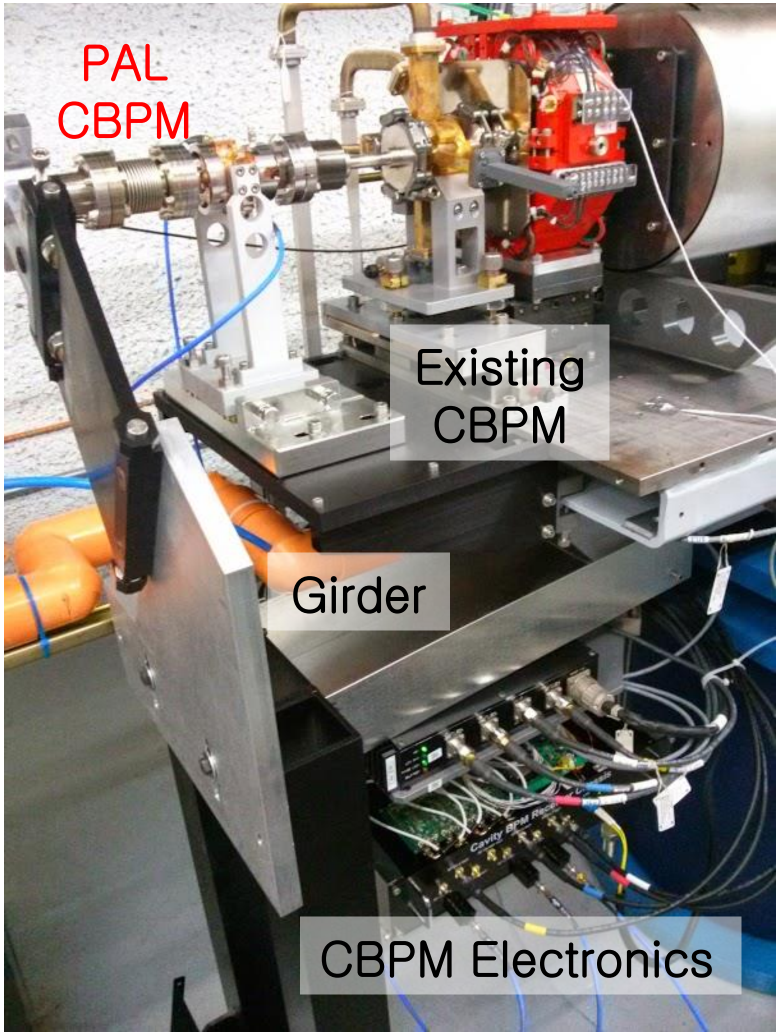
SUB-SYSTEM Preparation

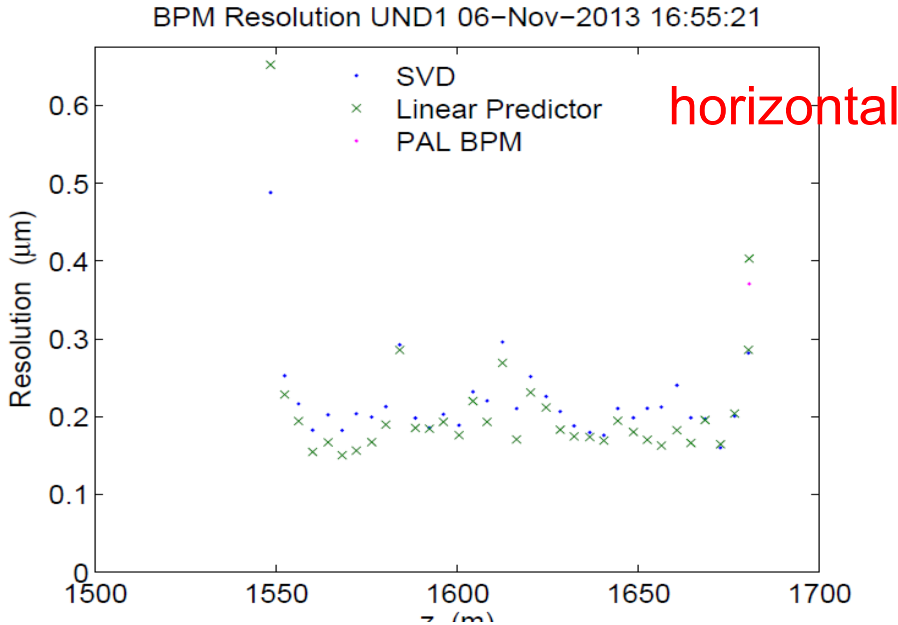
# 5. CONTROL SYSTEM

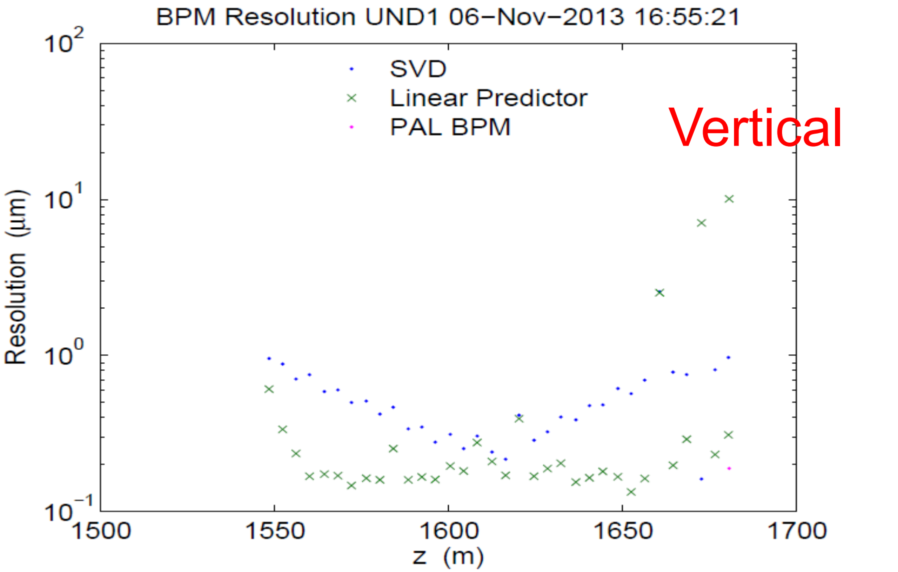
# Diagnostics and Control


- Event timing system delivered from SLAC was successfully tested at ITF in April 2014
- Stripline BPM control system
  - mTCA BPM control system successfully commissioned in June 2014 : 3 - 4 μm at 200pC, 12 μm at 10pC
  - 140 Stripline BPM control system (mTCA based ) contracted with SLAC in October 2014
    - 144 RTMs & 17 EVR fan-out module : SLAC
    - mTCA Crate, CPU, power module, AMC module : PAL
  - 155 stripline BPM pick-up was contracted with a Korean company
- Cavity BPM
  - 100 cavity BPMs contracted with a company in November 2014
  - Cavity BPM electronics is being tested at SLAC to be contracted in early 2015.
- Main control system (operator interface, control servers, and DB) is contracted with COSY-Lab.

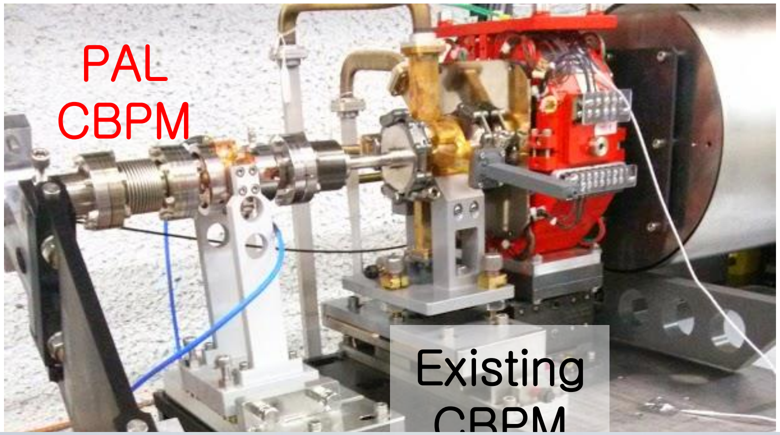
# CBPM: LCLS Beam Test (Nov. 2013)

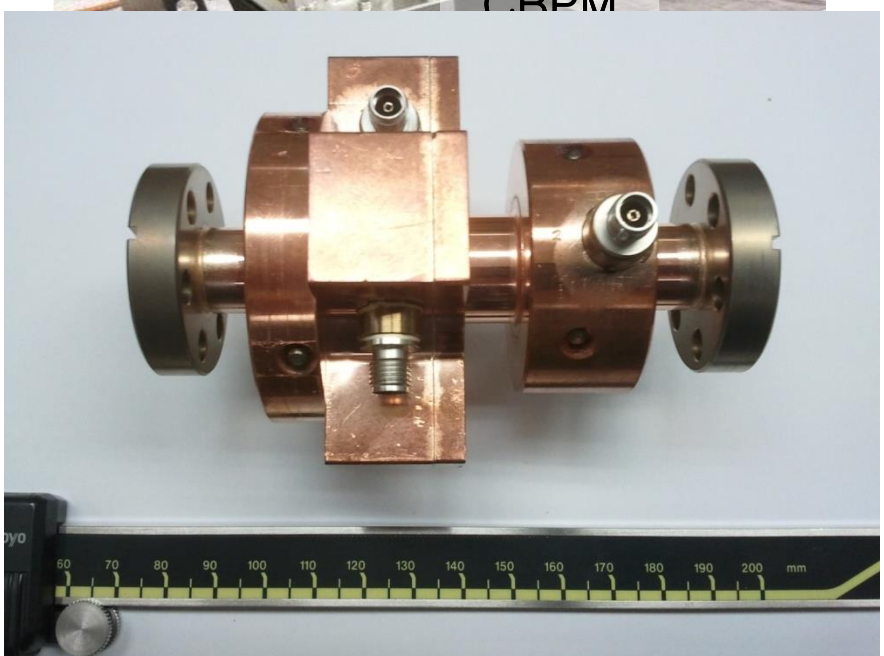


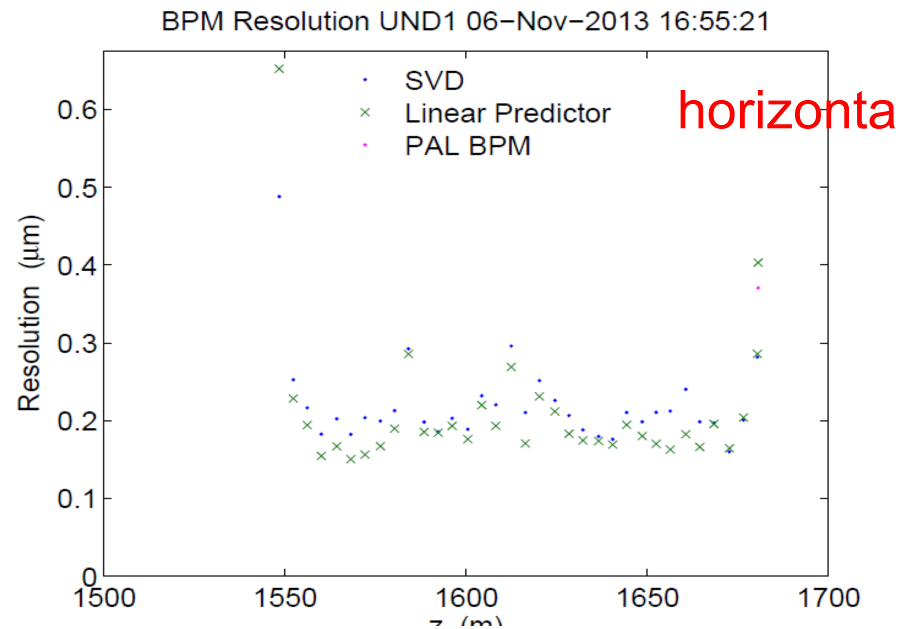



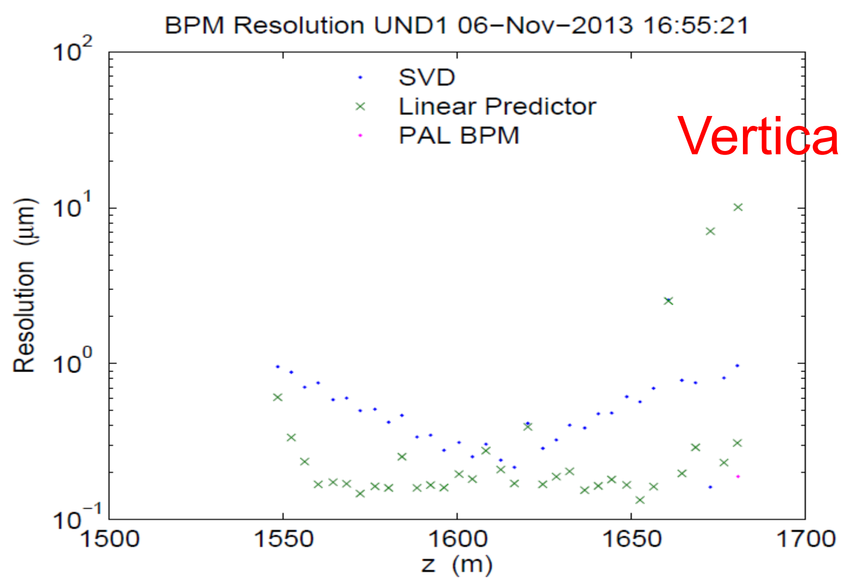



# CBPM: LCLS Beam Test (Nov. 2013)

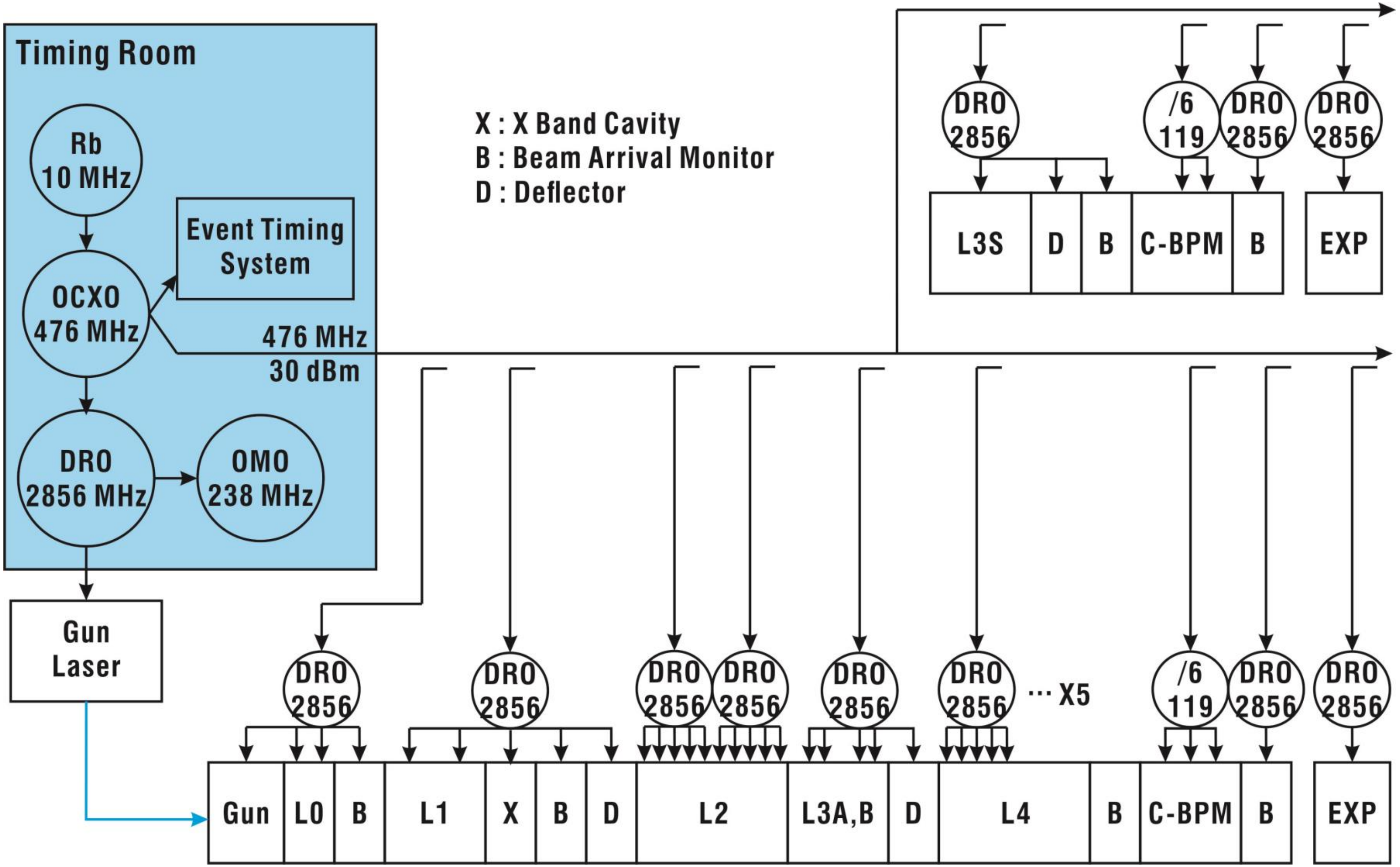


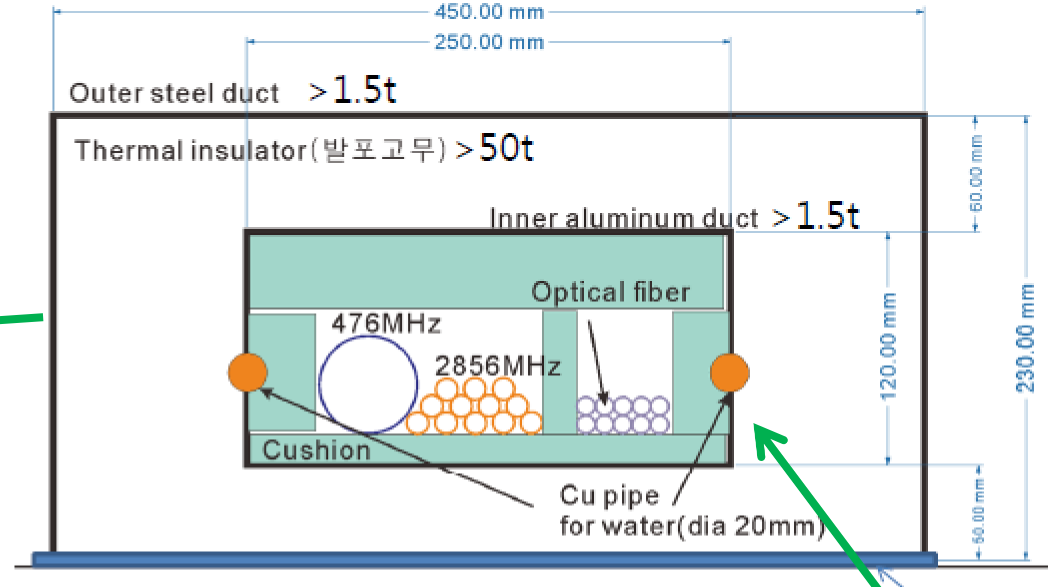


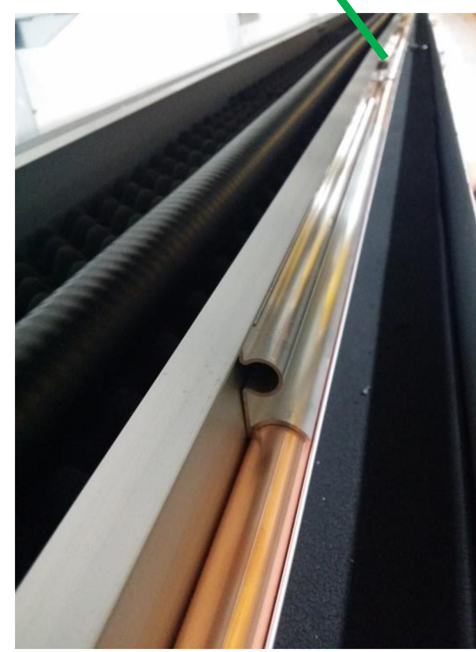



# RF timing distribution system



# Temperature stabilized duct



# Install and FEL Commissioning

- Linac RF conditioning / Injector commissioning 2015. 10 ~ 2015. 12
- 1st FEL commissioning for 0.3 nm HX @10 Hz 2016. 01 ~ 2016. 06
- 2nd FEL commissioning for 0.1 nm HX @10 Hz 2016. 09 ~ 2016. 12

| | 2015 | | | | | | | | | | | | 2016 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | O | N | D | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | O | N | D |
| **ITF operation** | → | → | → | → | → | → | → | | | | | | | | | | | | | | | | | |
| **Injector install** | | | | | | | | → | → | | | | | | | | | | | | | | | |
| **Linac install** | → | → | → | → | → | → | → | → | → | | | | | | | | | | | | | | | |
| **Undulator Install** | | | | | | → | → | → | → | → | → | → | | | | | | | | | | | | |
| **Control system test** | | | | | | | | | → | → | → | → | → | | | | | | | | | | | |
| **Linac RF conditioning** | | | | | | | | | | → | → | → | | | | | | | | | | | | |
| **Injector commissioning** | | | | | | | | | | → | → | → | | | | | | | | | | | | |
| **Linac commissioning** | | | | | | | | | | | | | → | → | → | → | | | | | | | | |
| **0.3 nm FEL commission** | | | | | | | | | | | | | | | → | → | → | → | | | | | | |
| **0.1 nm FEL commission** | | | | | | | | | | | | | | | | | | | | | → | → | → | → |

❖ **HX undulator hall should be accessible during the Linac RF conditioning**

# We hope
# A successful FEL commissioning in 2016!!

**Thank you for your attention**