Beam Profile Monitors for Electron Beams in PAL-XFEL

June 12, 2023

Changbum Kim
On behalf of PAL-XFEL
Pohang Accelerator Laboratory

POHANG ACCELERATOR LABORATORY

Contents

- PAL-XFEL
- Transverse Profile Monitors
    - Screen Monitor
    - Wire Scanner
- Lattice Matching

PAL-XFEL

Apr. 2011: PAL-XFEL project started

Apr. 2016: Commissioning started

Jun. 2017: User-service started
- 120 days for user (95% of availability)

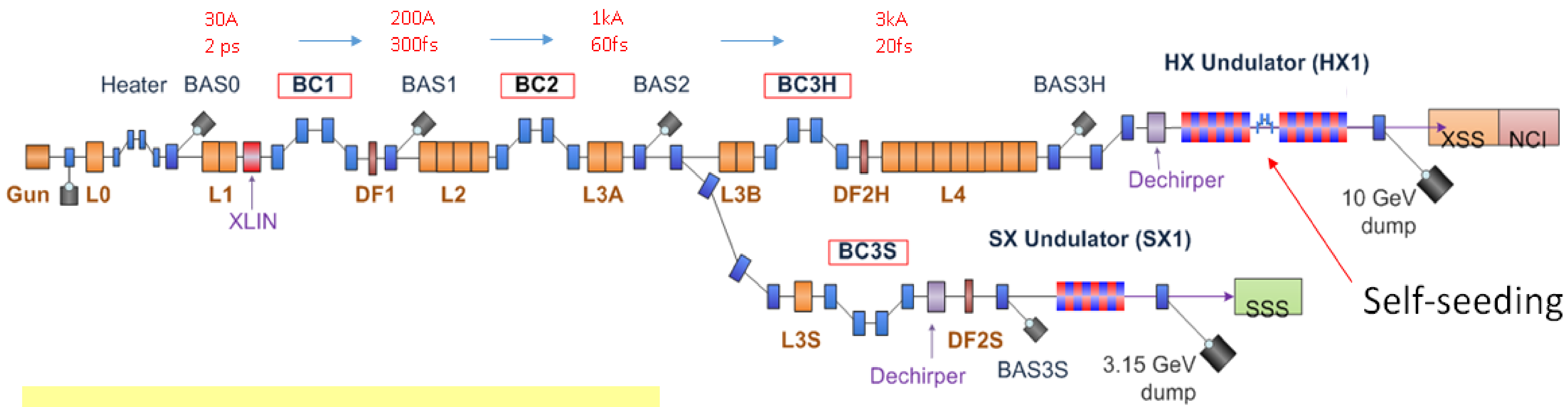
Achieved in 2018
- 140 days for user (95% of availability)

Achieved in 2019
- 160 days for user (96.8% of availability)

Achieved in 2020
- 170 days for user (96.9% of availability)

Achieved in 2021
- 180 days for user (96.9% of availability)

Layout & Parameters of PAL-XFEL



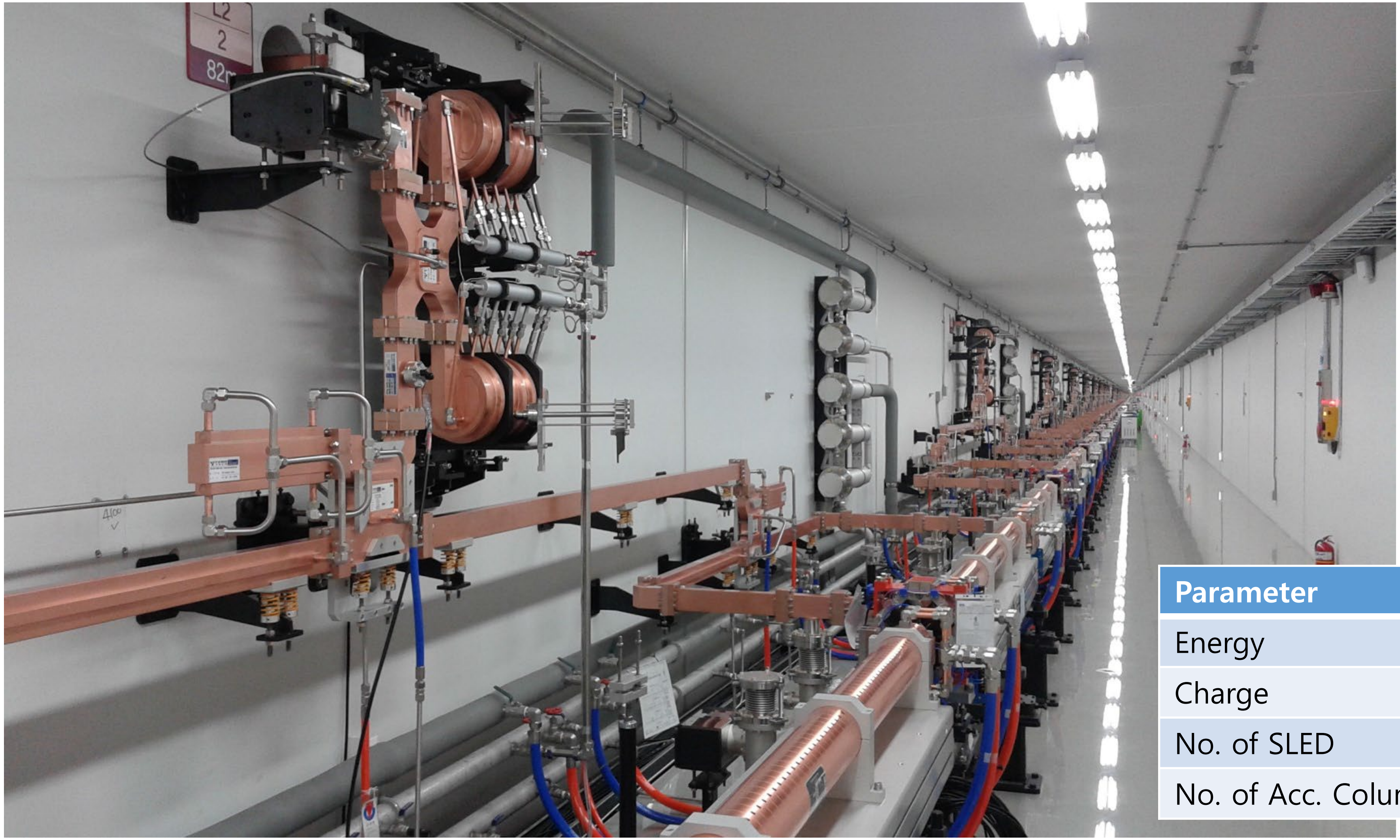
Main parameters

e^- Energy	11 GeV
e^- Bunch charge	20-200 pC
Slice emittance	< 0.4 mm mrad
Repetition rate	60 Hz
Bunch length	5 fs – 50 fs
Peak current	3 kA
SX line switching	Kicker Magnet

Undulator Line	HX	SX
Photon energy [keV]	2.0 ~ 15.0	0.25 ~ 1.25
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	Energy	Gap
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

POHANG ACCELERATOR LABORATORY

Linear Accelerator Tunnel

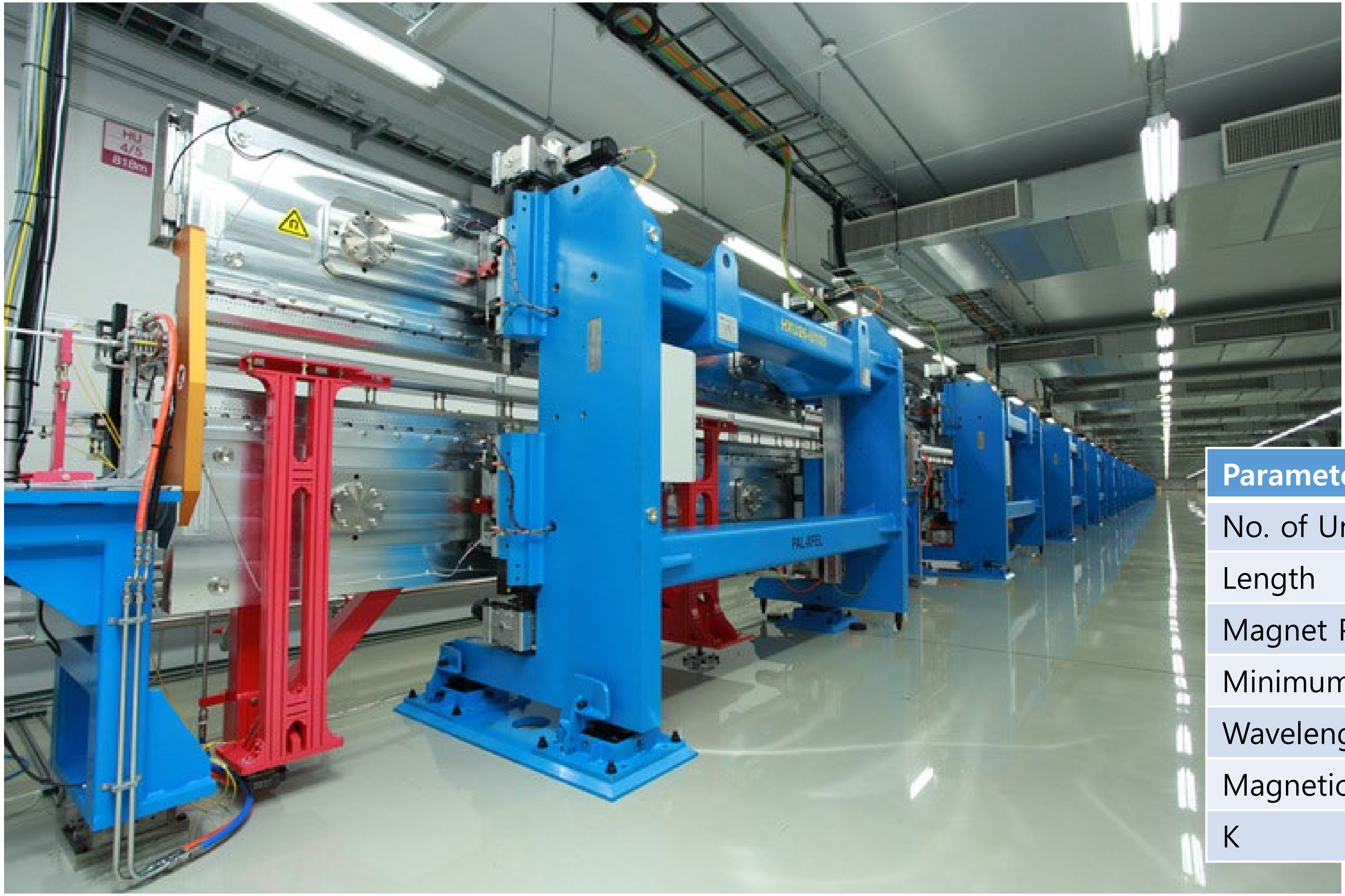


Parameter	Unit	Value
Energy	GeV	11
Charge	pC	200
No. of SLED		42
No. of Acc. Column		173

Klystron & Modulator Gallery

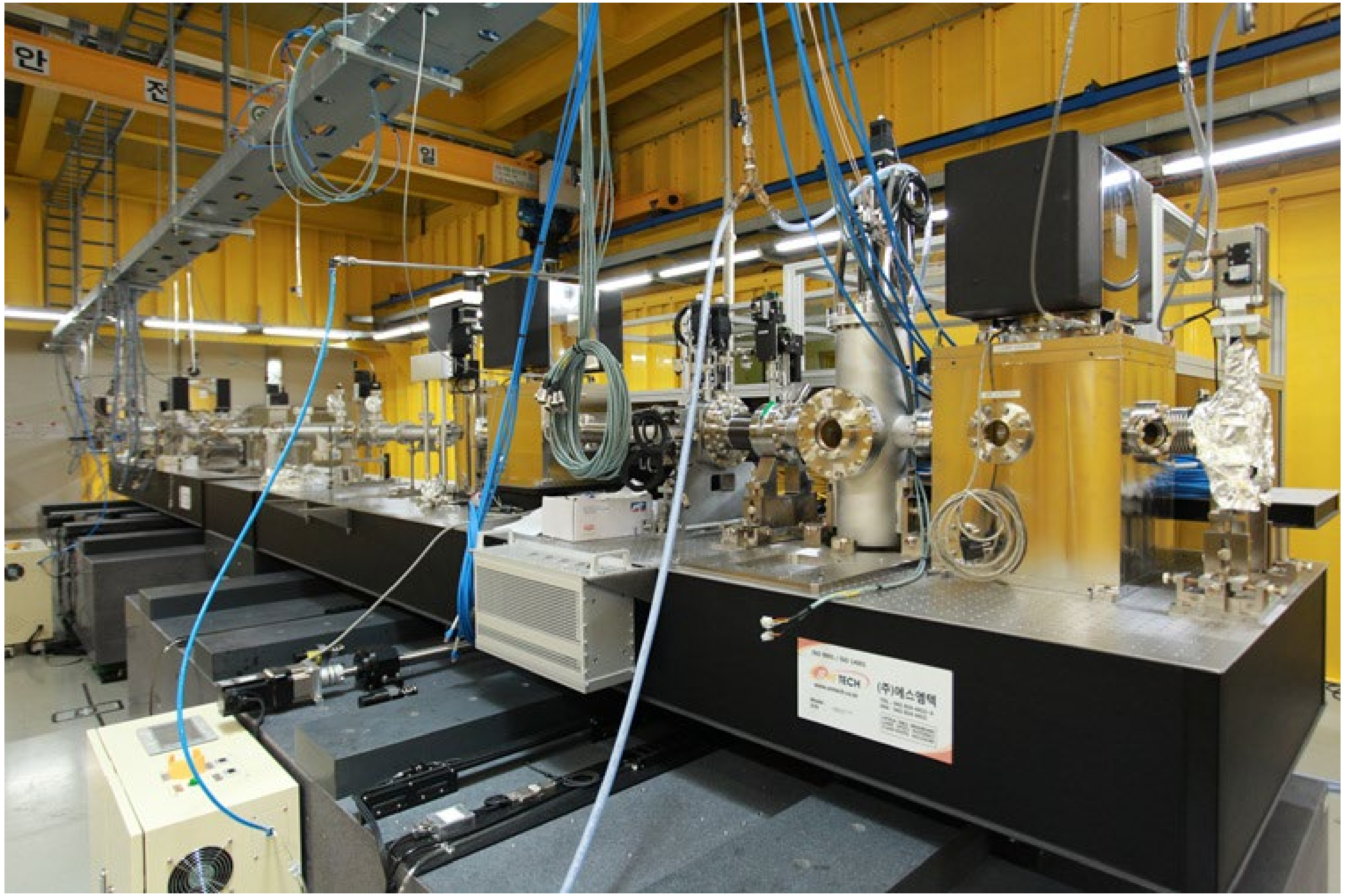
Parameter	Unit	Value
RF frequency	MHz	2856
No. of Klystron & Modulator		51
Max. repetition rate	Hz	60
RF pulse width	μs	4

Undulators



Parameter	Unit	Value
No. of Undulator		21
Length	m	5
Magnet Period	mm	26.0
Minimum Gap	mm	8.3
Wavelength	nm	0.1
Magnetic field	Tesla	0.8124
K		1.9727

Beamline



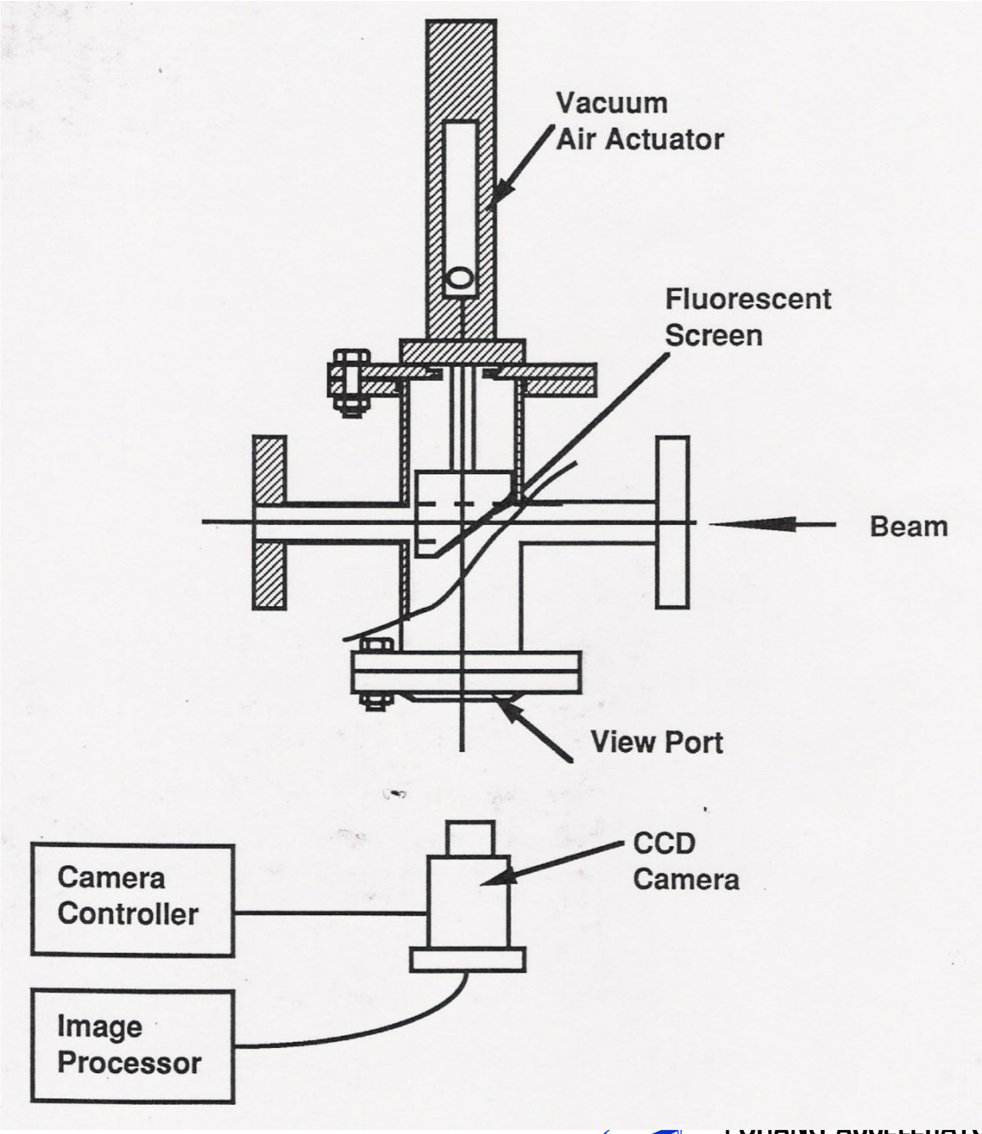
Experimental Station: Hard X-ray Pump & Probe, Coherent X-ray Imaging, Soft X-ray Pump & Probe

Diagnostics for PAL-XFEL

Parameter	Instruments	Number	Resolution
Beam Position & Beam Energy	Stripline BPM	160	< 5 um
	Cavity BPM	49	< 1 um
Beam Size	Screen Monitor	54	< 10 um
	Wire Scanner	9	< 10 um
Bunch Length	Coherent Radiation Monitor	4	-
	Transverse Deflecting Cavity	3	< 10 fs
Beam Charge	Turbo ICT	10	< 1 pC
Beam Arrival Time	Beam Arrival Time Monitor	10	< 30 fs
Beam Loss	Beam Loss Monitor	26	-

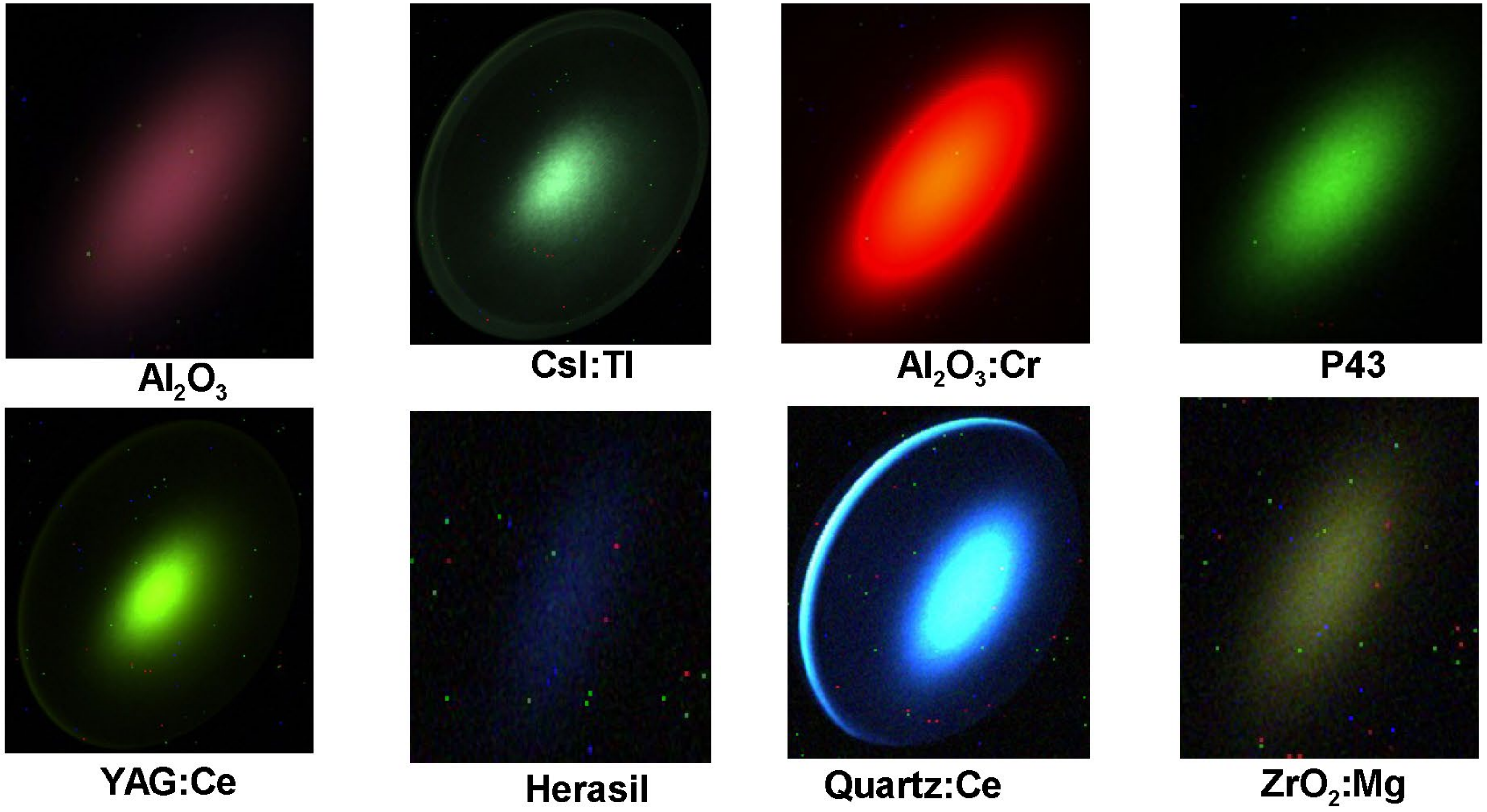
Screen Monitor

- Generally destructive to the beam (energy absorbed, scattering of particles as they pass through screen)
- Camera shutter should be synchronised to beam arrival for best results
- Full 2D transverse profile in one shot
- Actuator required to remove screen from beam path



Various Targets

- Example: Color CCD camera



  - very different light yield i.e. photons per ion‘s energy loss
  - different wavelength of emitted light

Phosphor Screens

- High conversion efficiency (300-400 photons from one 10 keV electron on a 5 μm thick layer)
- Relatively long fluorescence decay time (up to many ms)
- Opaque, thus typically used as thin layer of small grains (down to 1 μm) deposited on a substrate
- Resolution is about twice phosphor layer thickness
- Layers are mechanically fragile and can be damaged by high intensity beam

Proxitronic data sheet

Type	Composition	Light Emission				Decay Time	
		Range		Maximum	Color	Decay of Light Intensity	
		from	to	typically at		from 90 % to 10 % in	from 10 % to 1 % in
P 43	Gd_2O_2S:Tb	360 nm	680 nm	545 nm	green	1 ms	1,6 ms
P 46	$Y_3Al_5O_{12}$:Ce	490 nm	620 nm	530 nm	yellow green	300 ns	90 μs
P 47	Y_2SiO_5:Ce,Tb	370 nm	480 nm	400 nm	blue white	100 ns	2,9 μs
P 20	(Zn,Cd)S:Ag	470 nm	670 nm	550 nm	yellow green	4 ms	55 ms
P 11	ZnS:Ag	400 nm	550 nm	450 nm	blue	3 ms	37 ms

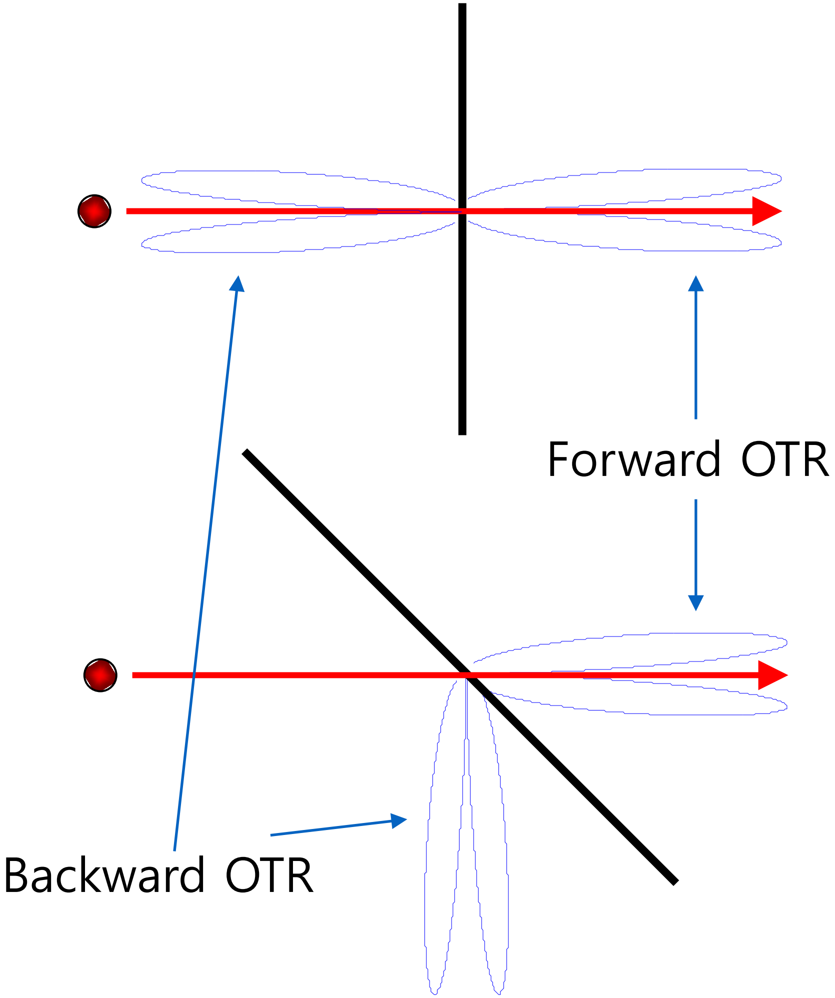
Scintillator Screens

- Optical transparency at wavelengths of their own specific emission energy
- Resolution is comparable to screen thickness
- Short fluorescence decay times (< 1 μs)
- Some have high mechanical strength, so thin (> 50 μm), freestanding screens are feasible
- Desirable:
  - High density, more energy absorbed for same thickness
  - High conversion efficiency, more photons per energy absorbed

	YAG:Ce	**LuAG:Ce**	**YAP:Ce**	**BGO**
Density [g/cm^3]	4.57	6.73	5.37	7.13
Hardness [Mho]	8.5	8.5	8.6	5
Chemical formula	$Y_3Al_5O_{12}$	$Lu_3Al_5O_{12}$	$YAlO_3$	$Bi_4(GeO_4)_3$
Wavelength of max. emission [nm]	550	535	370	480
Decay constant [ns]	70	70	25	300
Photon yield at 300 K [10^3 Ph/MeV]	35	20	25	8-10

Optical Transition Radiation (OTR) Target

- Transition Radiation is created when relativistic charged particle cross a dielectric boundary
- Typically, metal targets are used, as metals have large negative dielectric constant at optical frequencies
- A part of the emitted photons (OTR) is in the visible and can be used to image the particle distribution
- Forward OTR is emitted in a cone around the particle trajectory
- Backward OTR is emitted in a cone around the 'reflected' particle trajectory



Properties of OTR

- Intensity scales with:

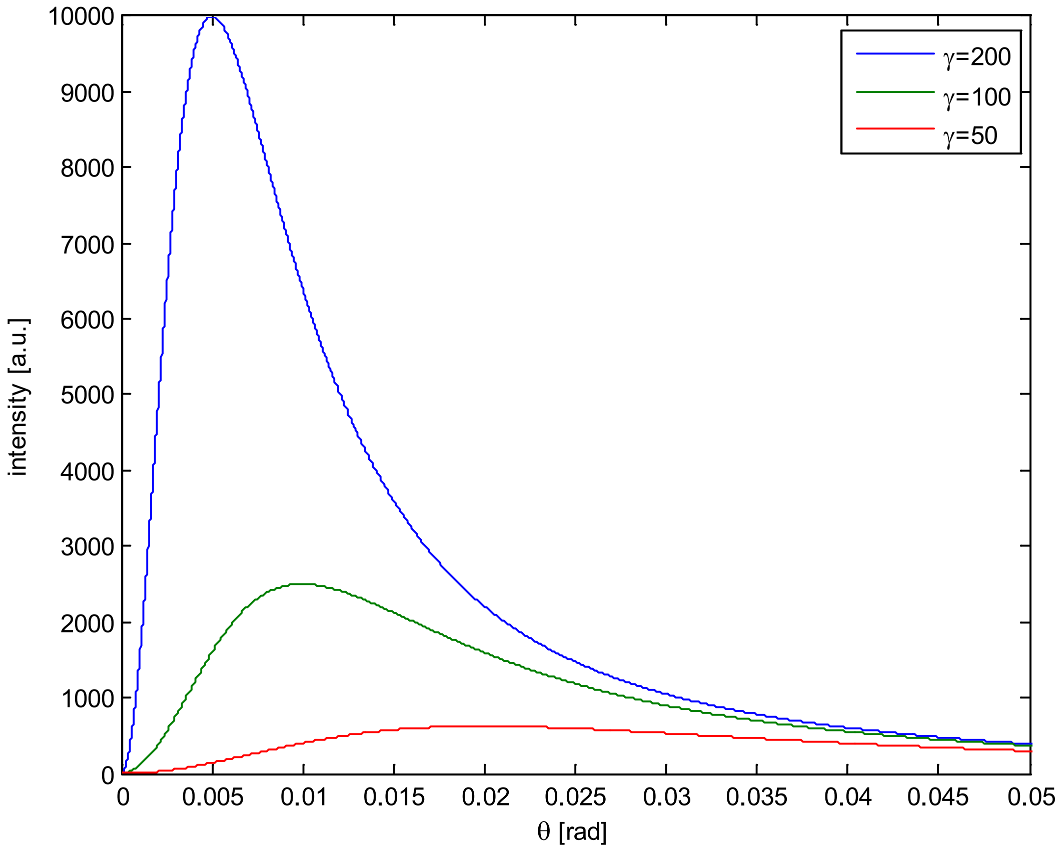
$$I \propto \frac{\theta^2}{(\theta^2 + \gamma^{-2})^2}$$

- Maximum at 1/γ

- Number of (visible) photons per particle:

$$N = \frac{1}{137\pi}(2\ln\gamma - 1)\cdot\ln\left(\frac{\lambda_{red}}{\lambda_{blue}}\right)$$

- Practically: 1-3% of particle number

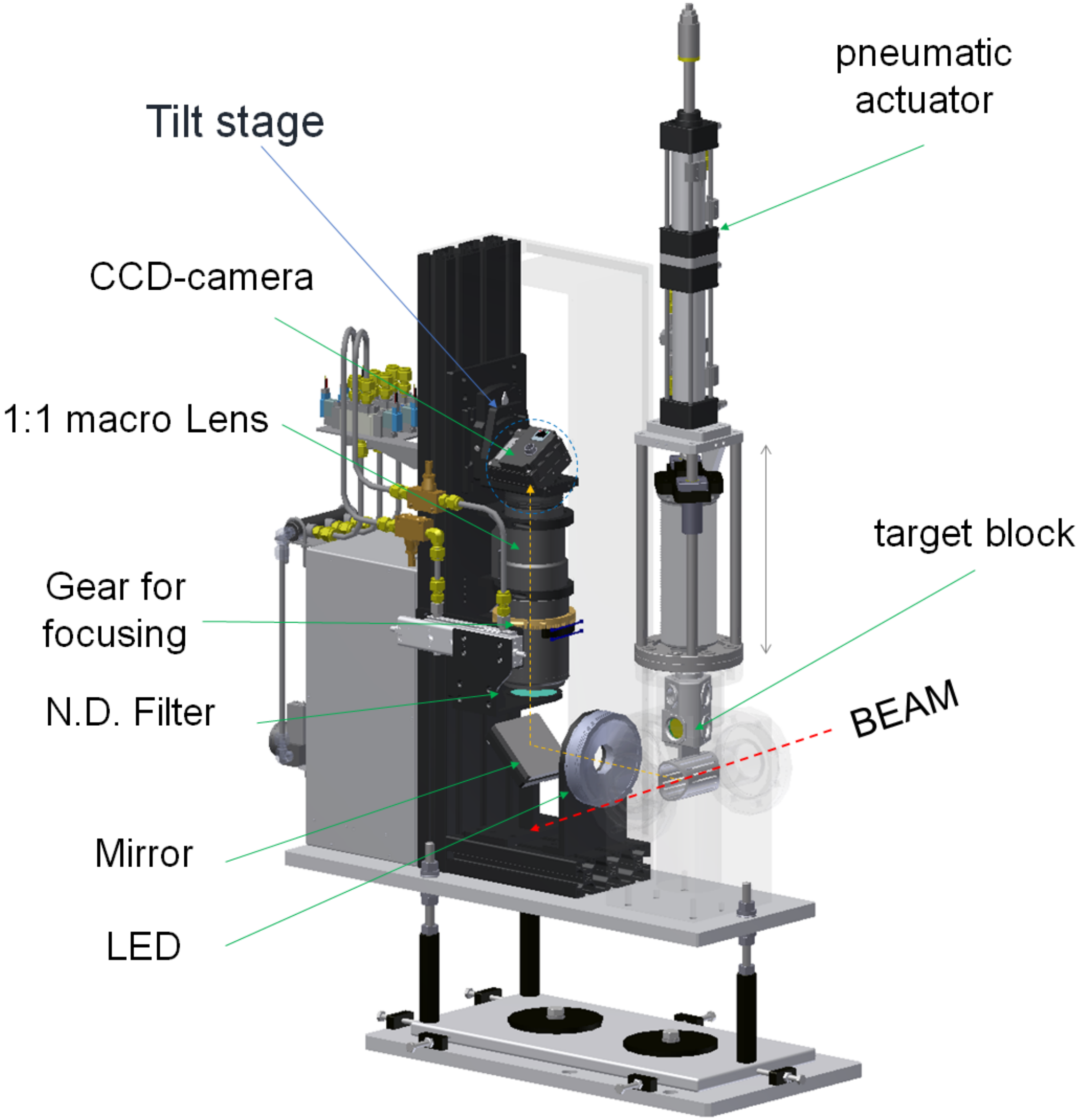


POHANG ACCELERATOR LABORATORY

Advantages & Disadvantages of OTR

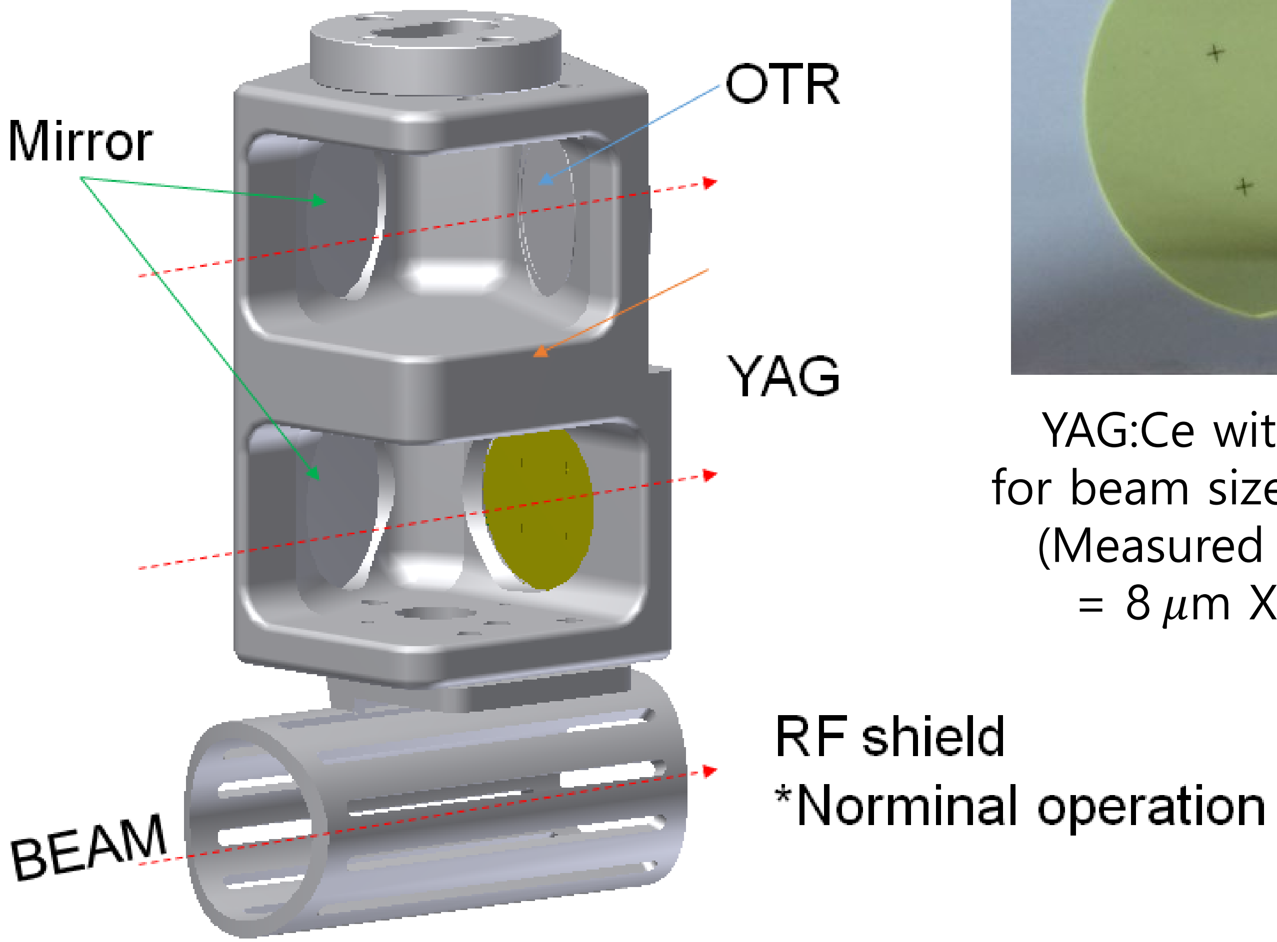
- Advantages
  - Like a phosphor screen, but without resolution limits (resolution possible down to optical wavelength)
  - No saturation, linear intensity to destruction threshold ($>10^{12}$ e^-/mm^2)
- Disadvantages
  - Few photons per electron, which are emitted into a large angle at low particle energies
  - Practically only feasible for strongly relativistic particles ($\gamma>100$)

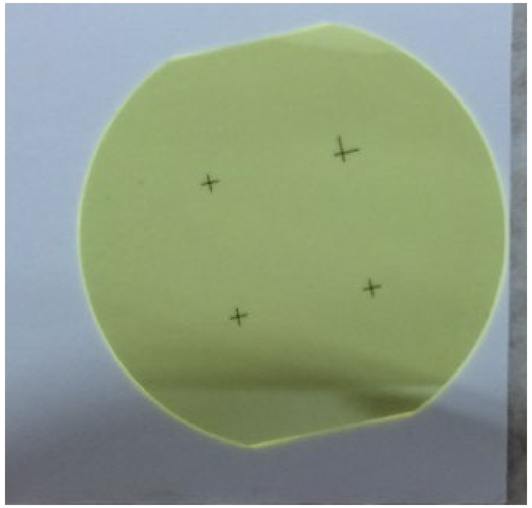
Screen Monitor for PAL-XFEL



- 3-position pneumatic actuator
- RF shield for reducing the wake field
- Scintillator (YAG:Ce)
- OTR Target (Al-foil)
- LED backlight lamp
- Neutral density filter
- DSLR lens
- DC motor for remote focusing
- GigE camera
- Tilt stage for Scheimflug's geometry

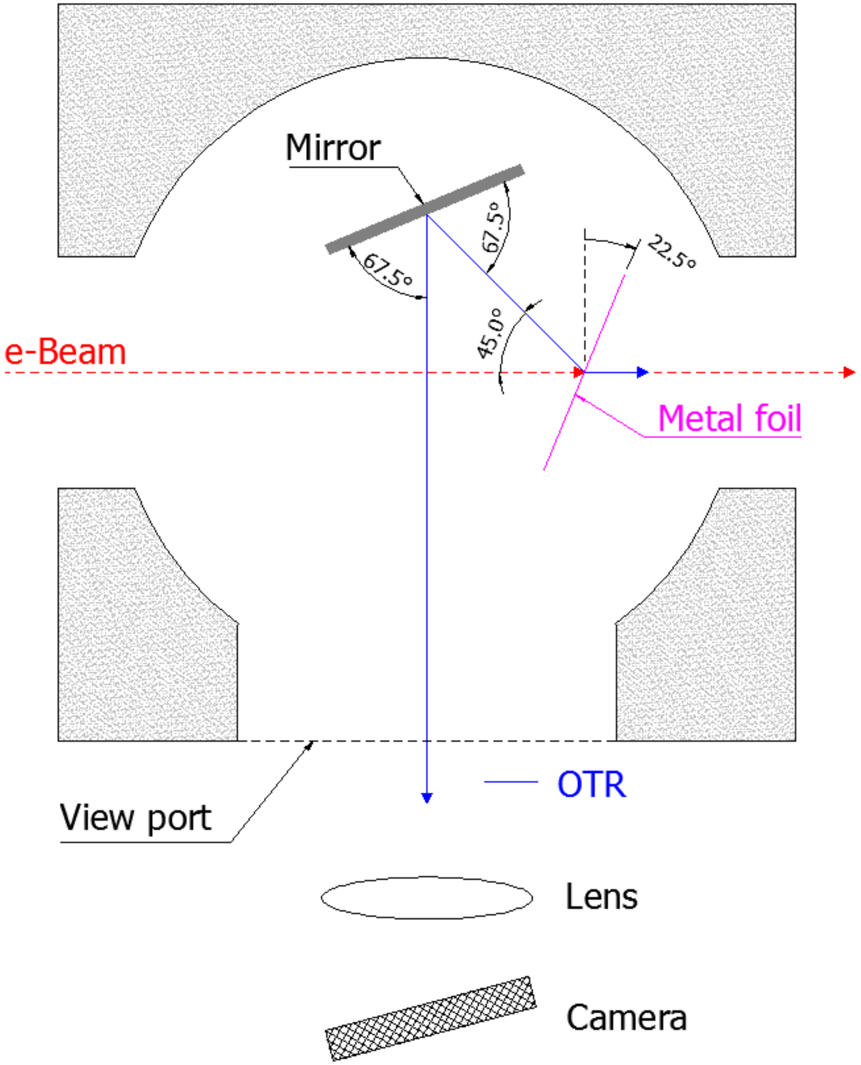
Target Holder



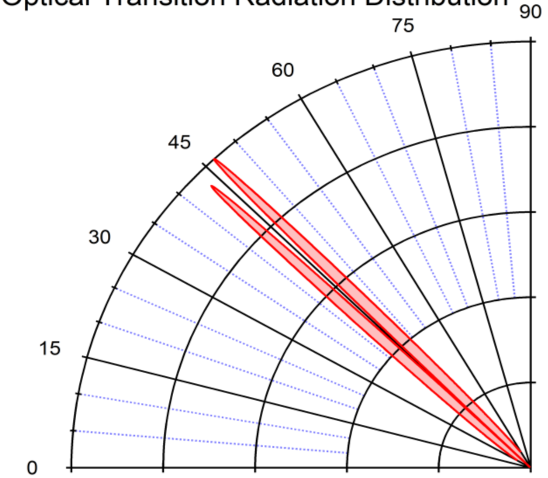


YAG:Ce with markers
for beam size callibration
(Measured resolution
= 8 μm X 6.5 μm)

OTR Target



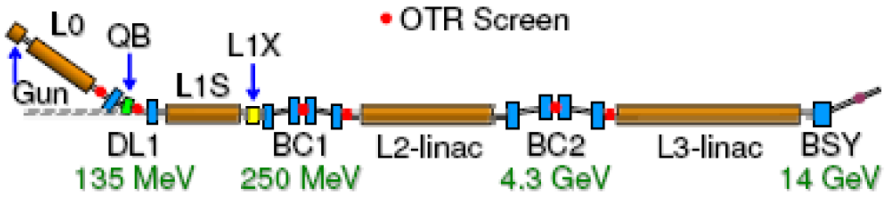
- OTR imaging with Al foil
  - thickness : 1 µm
- Target rotation: 22.5 °



Unexpected COTR @ LCLS

R. Akre et al., Phys. Rev. ST Accel. Beams **11** (2008) 030703 H. Loos et al., Proc. FEL 2008, Gyeongju, Korea, p.485.

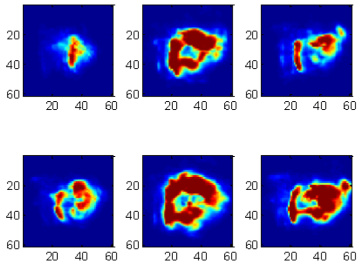
- Linac Coherent Light Source (LCLS) @ SLAC



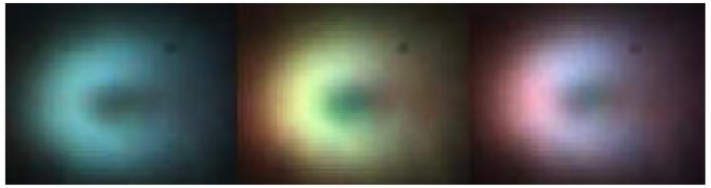
  - uncompressed beam, OTR behind BC1
  - $\sigma_t = 2.4$ ps (rms)
  - scan of quad QB $\rightarrow$ intensity varies by factor 4 ($\sigma_{x,y}$ increased by 25 %)

comparison with incoherent level $\rightarrow$ only fraction of $3 \cdot 10^{-5}$

- OTR monitor observation with BC1, BC2 switched on
  - OTR 12



  - OTR 22



measured spot is no beam image!

  - strong shot-to-shot fluctuations
  - doughnut structure
  - change of spectral contents

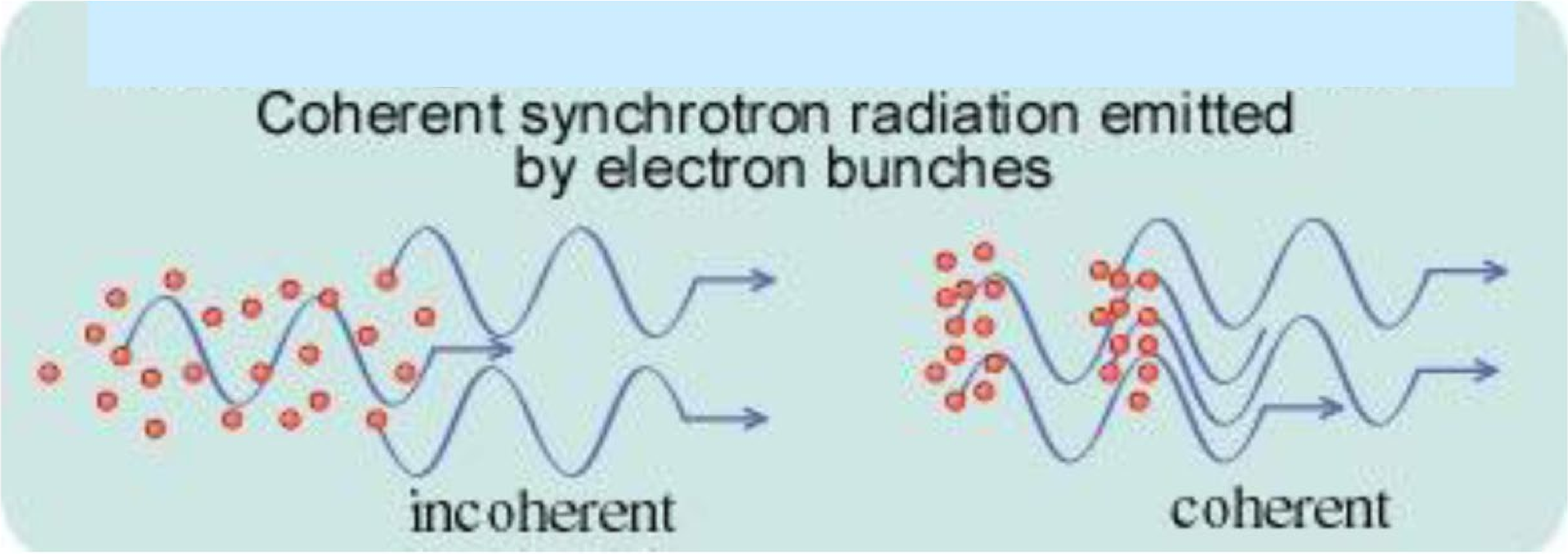
courtesy:

S. Wesch (DESY)

- interpretation of coherent formation in terms of "Microbunching Instability"

E.L. Saldin et al., NIM **A483** (2002) 516 Z. Huang and K. Kim, Phys. Rev. ST Accel. Beams **5** (2002) 074401

Radiation Power of Incoherent and Coherent Radiation



$$\text{Radiation power} \propto \left(\sum_{j=1}^{N} E_j \, e^{i\phi_j} \right)^2 = \sum_{j=1}^{N} E_j^2 + \sum_{\substack{j=1 \\ j \neq k}}^{N} \sum_{k=1}^{N} E_j E_k^* \, e^{i(\phi_j - \phi_k)}$$

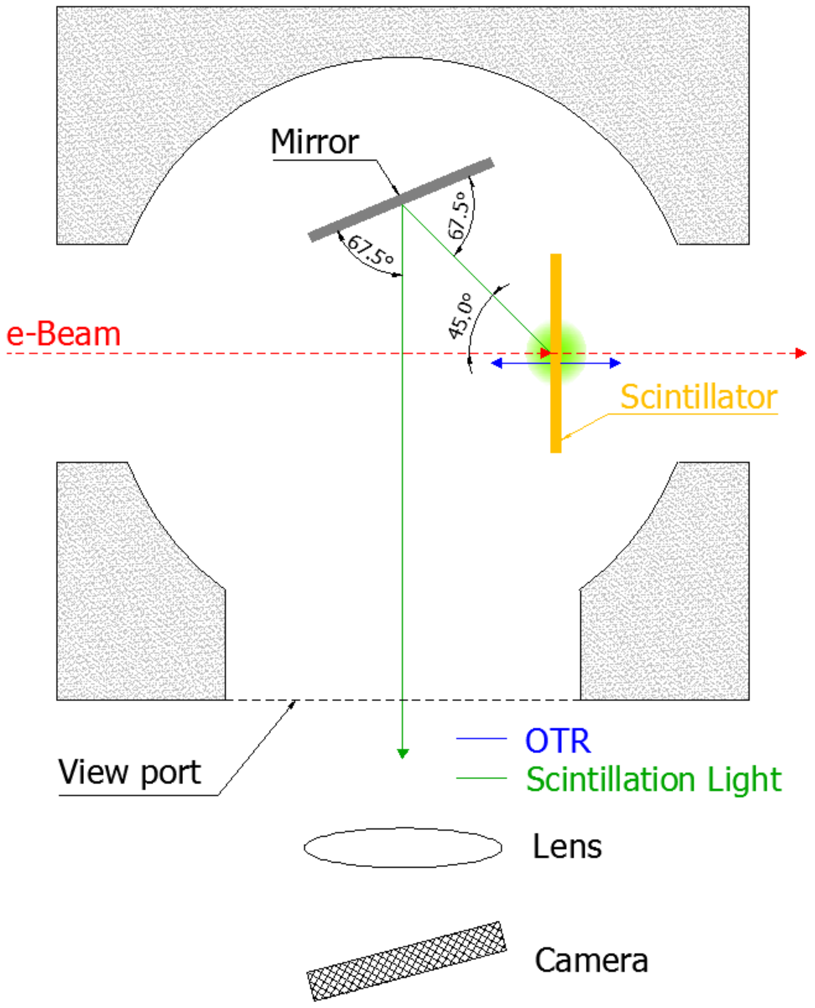
If $\phi_j \approx \phi_k \; \forall \; j$ then the 2nd term >> 1st term as there are N^2 of them and results in coherent emission.

Scintillator Target

- YAG:Ce scintillator
  - Thickness : 100 or 30 μm
- Observation geometry of 45° with respect to the beam axis

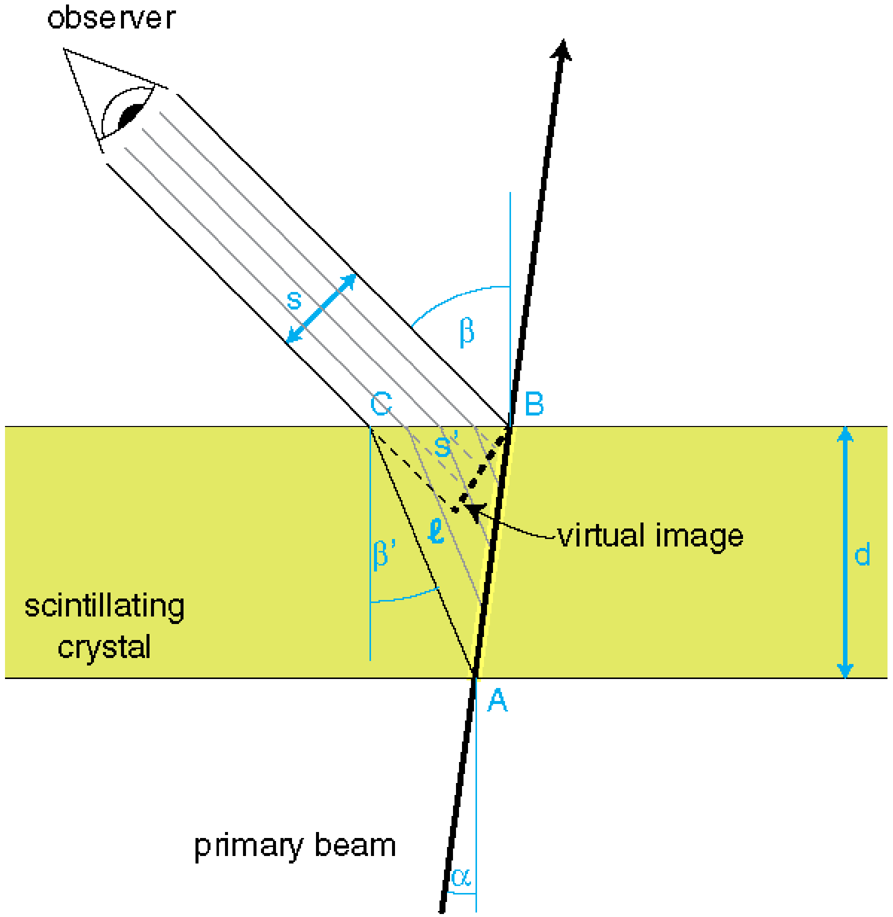
⇒ Minimized holder size

⇒ Big error from target thickness



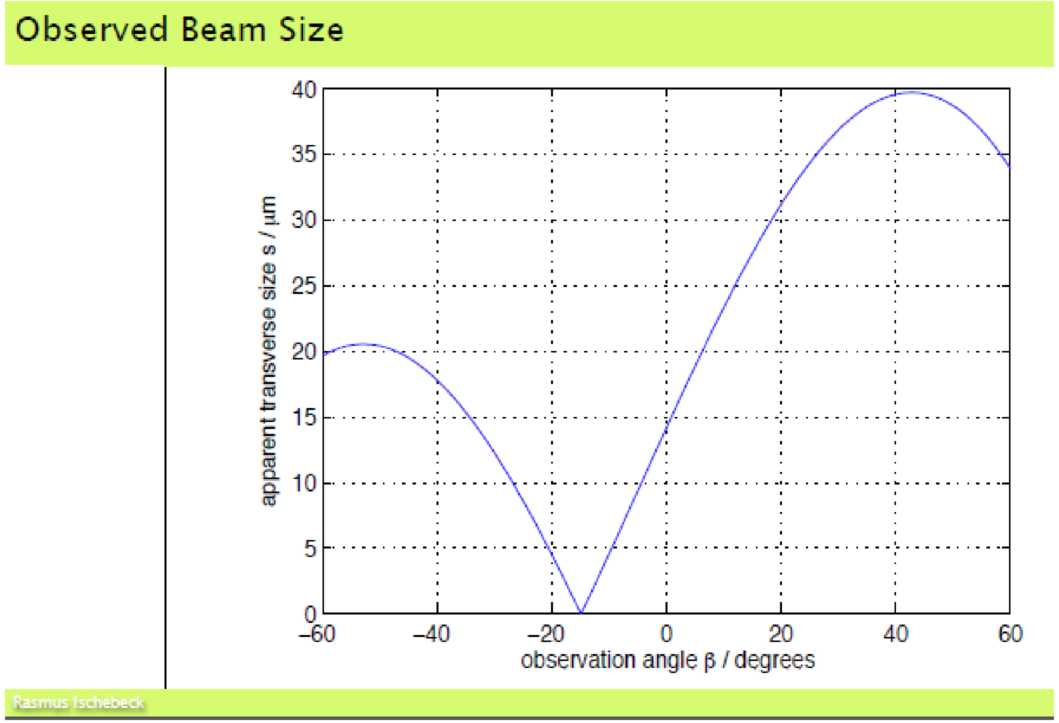
POHANG ACCELERATOR LABORATORY

Beam Size with Observation Angle



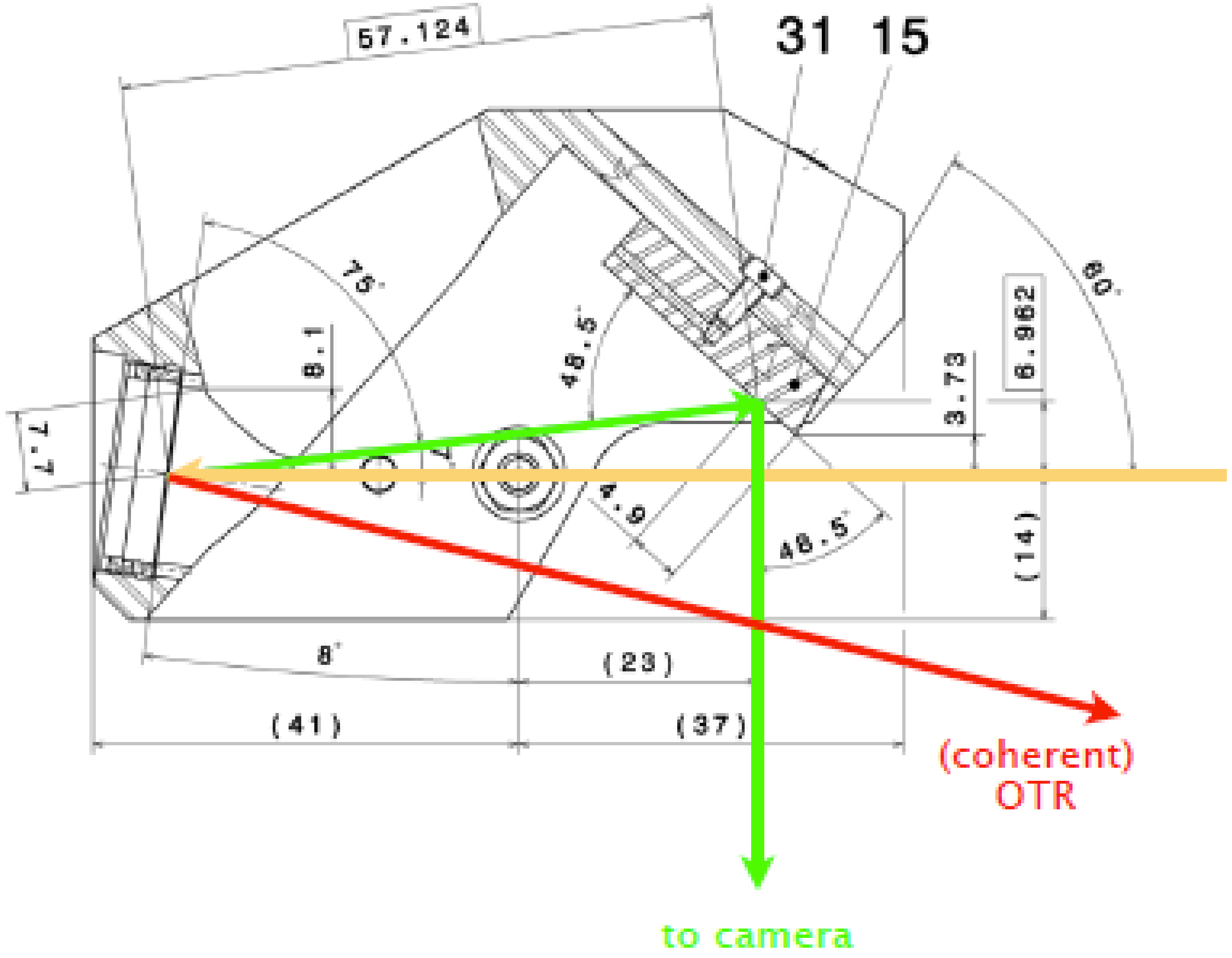
Observation of light from a scintillating crystal with an arbitrary observation angle β

$$s = d\cos\beta \cdot \sqrt{\frac{1}{1-\frac{\sin^2\beta}{n^2}} + \frac{1}{\cos^2\alpha} - 2\frac{\cos\left[\arcsin\left(\frac{\sin\beta}{n}\right)+\alpha\right]}{\sqrt{1-\frac{\sin^2\beta}{n^2}}\cos\alpha}}.$$



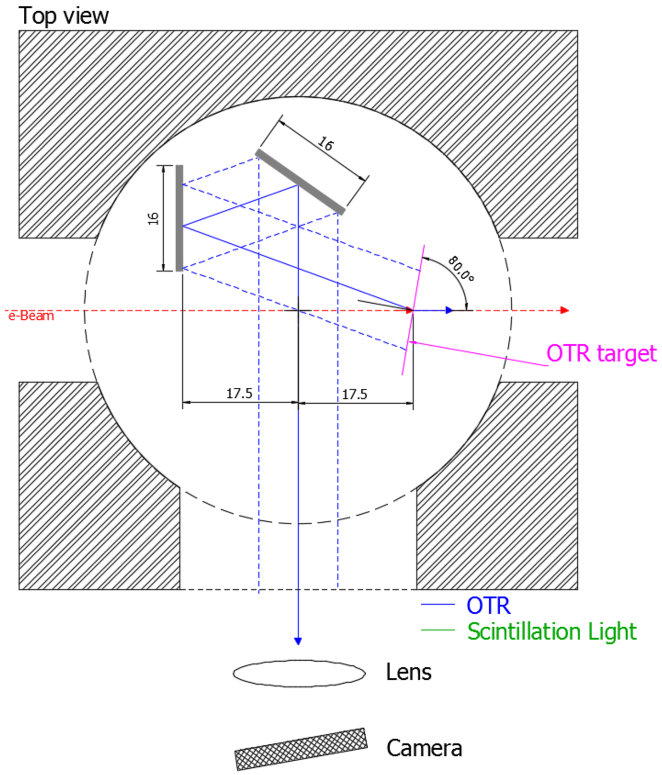
R. Ichebeck *at al.*, Phys. Rev. ST Accel. Beams **18**, 082802 (2015)

SwissFEL Screen Monitor

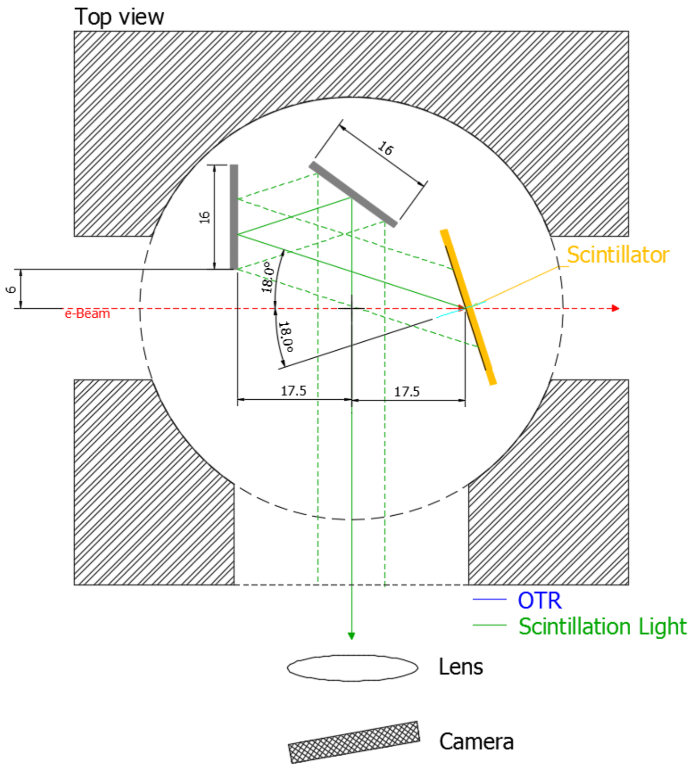


R. Ichebeck *at al.*, Phys. Rev. ST Accel. Beams **18**, 082802 (2015)

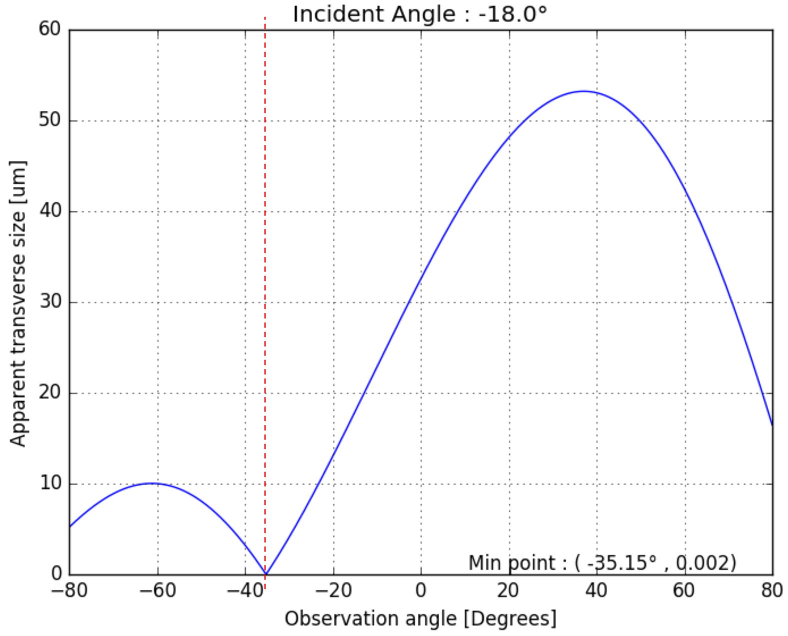
Geometry of New Target Holder



OTR Target

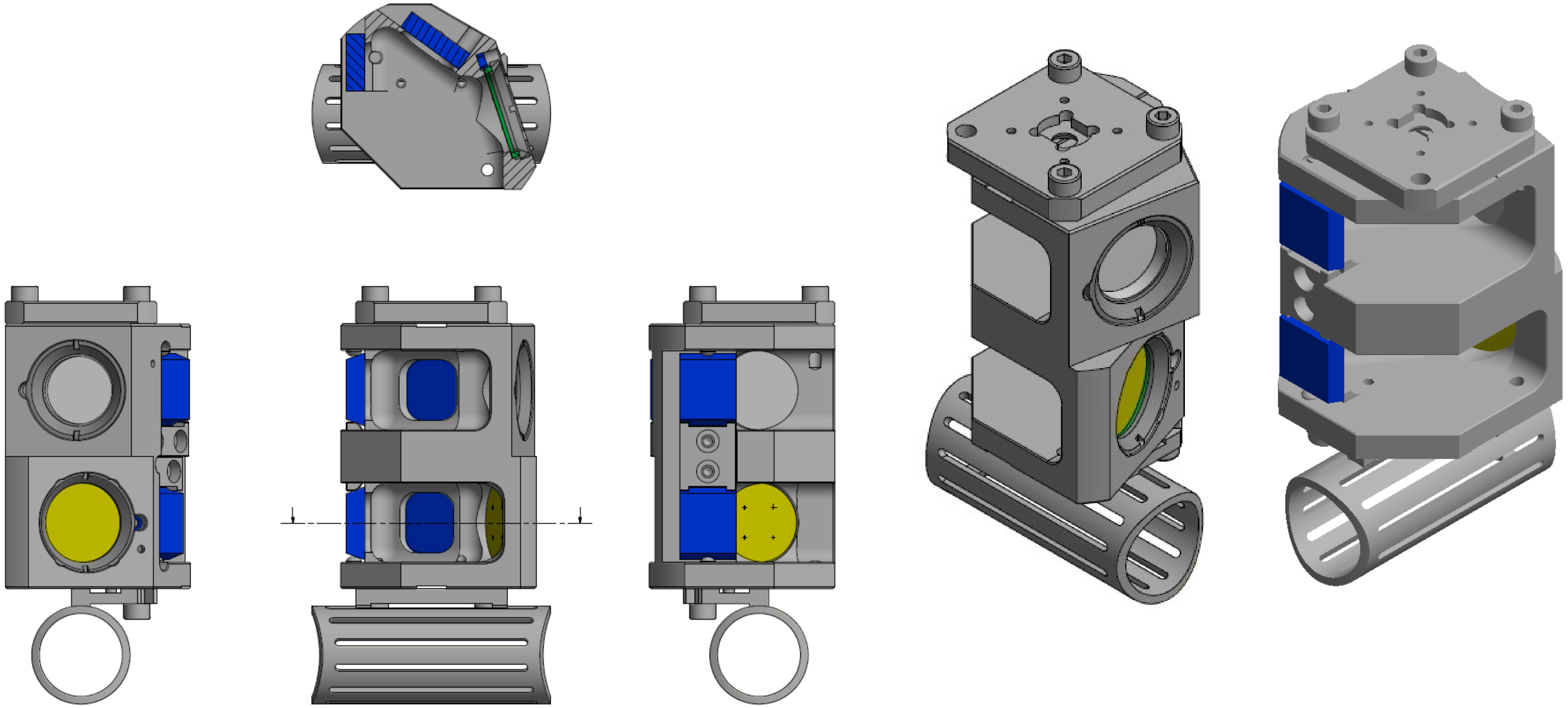


YAG Target

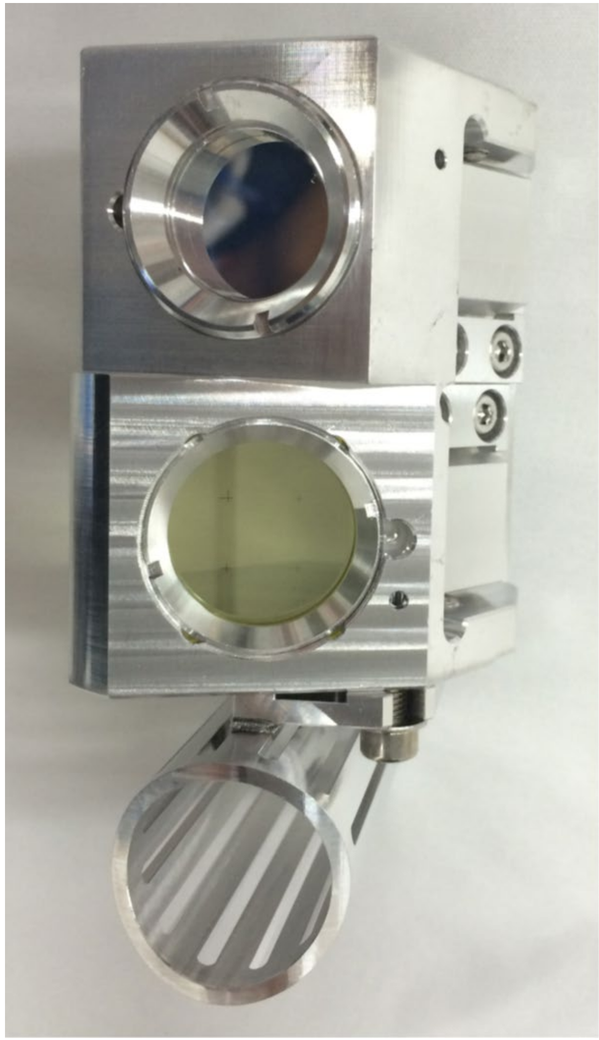


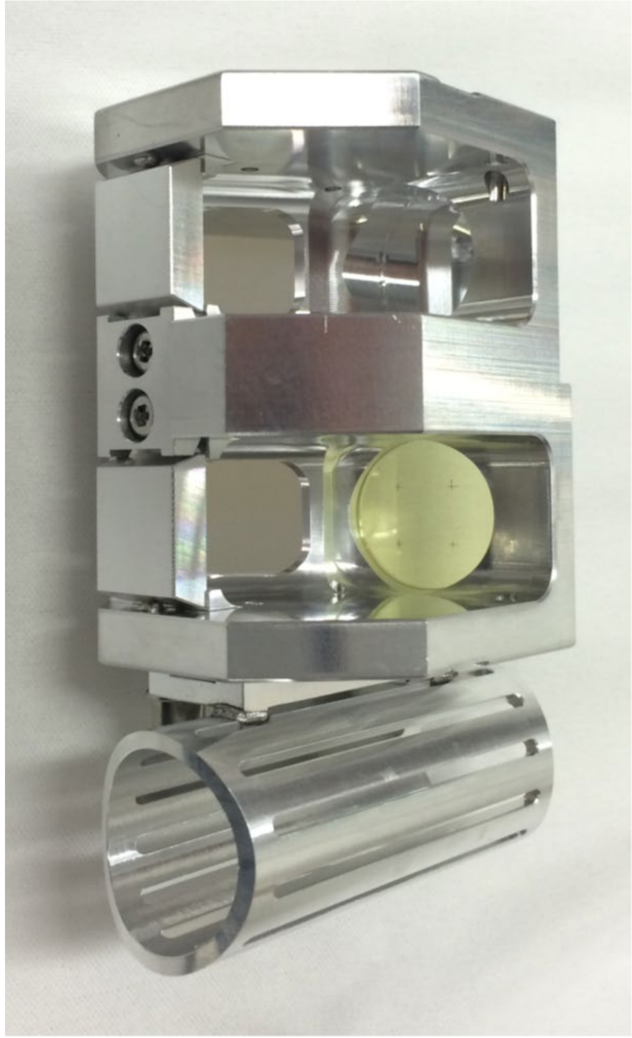
Incident Angle (α) : -18°
Observation Angle (β) : -36°

3D Design of New Target Holder

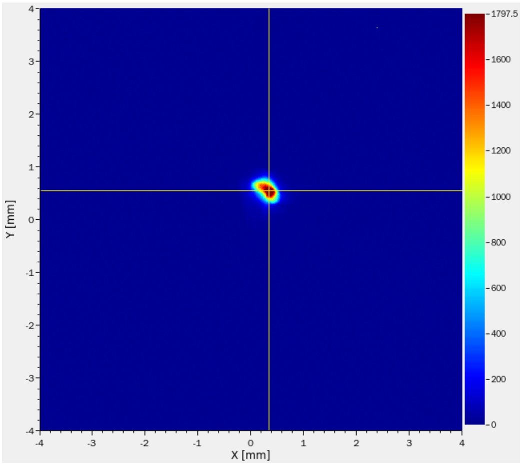
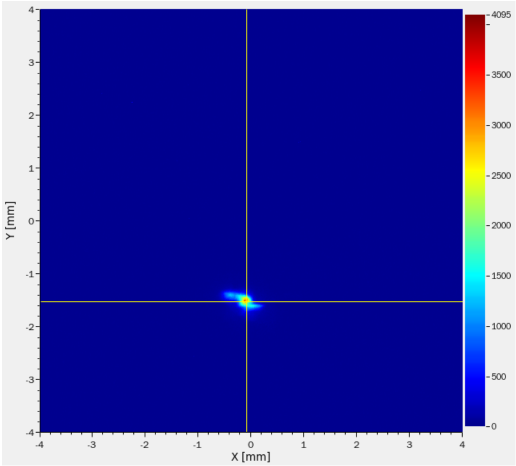
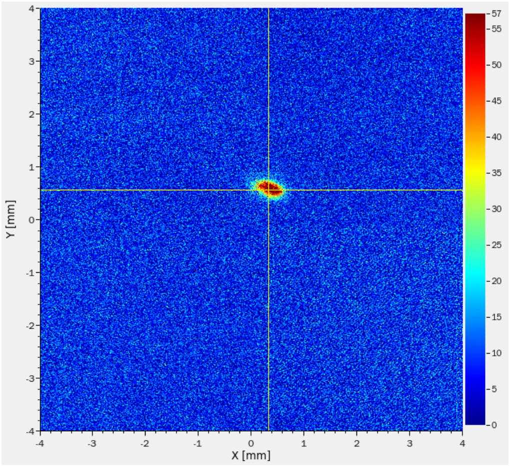
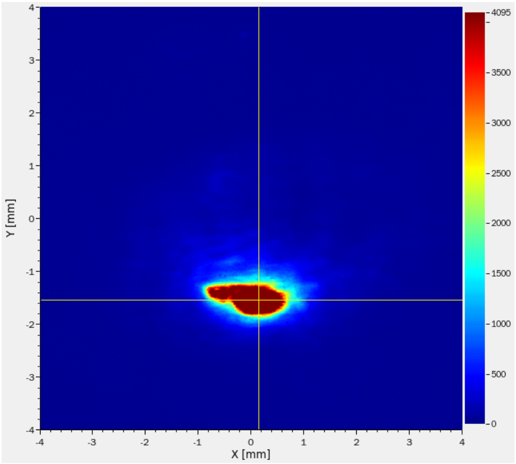


Pictures of New Target Holder

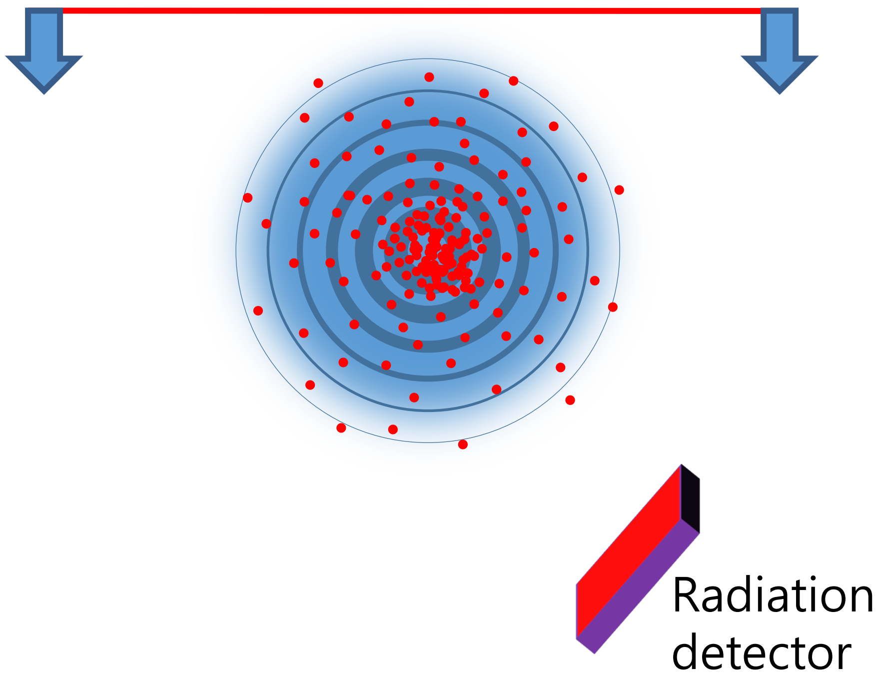


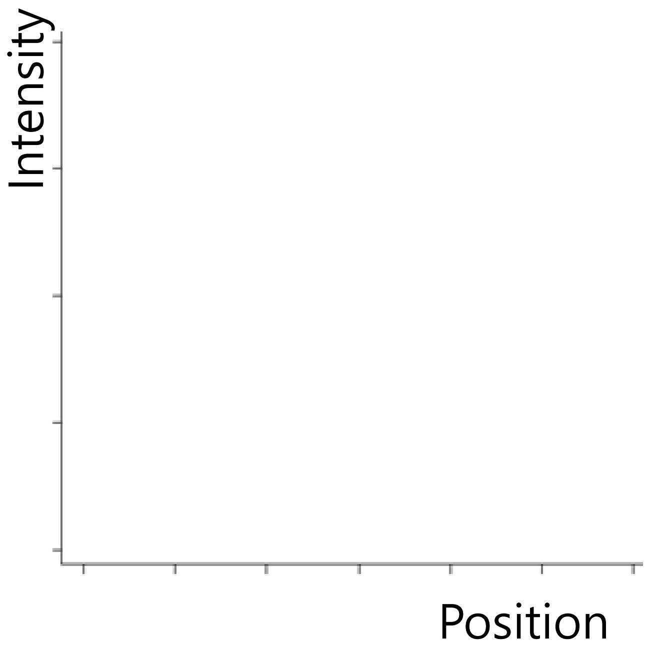


Measurement Results of Screen Monitor

	BC Off	BC On
YAG:Ce		
OTR		

Working Principle of Wire Scanner



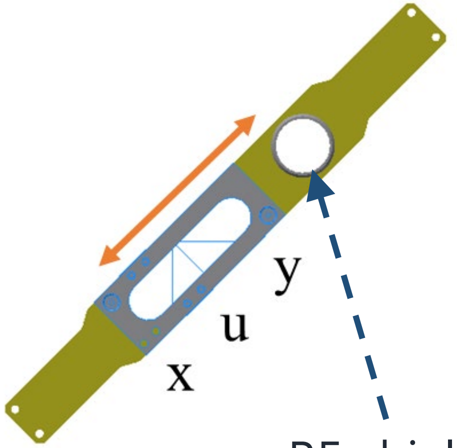


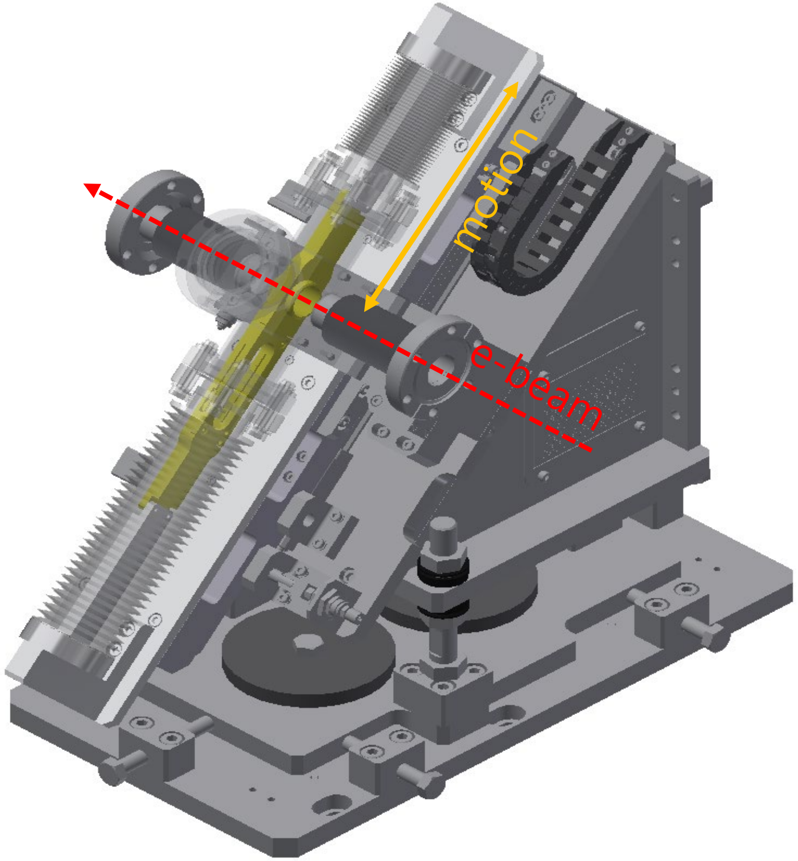
- 1D Profile is measured either as intensity of radiation (Bremsstrahlung) or as secondary emitted electron current over position of wire
- Resolution down to wire diameter (5-6 μm)
- Instead of movement, many wires can be used in a ‘harp’

Wire Scanner of PAL-XFEL

Screen monitor and wire scanner

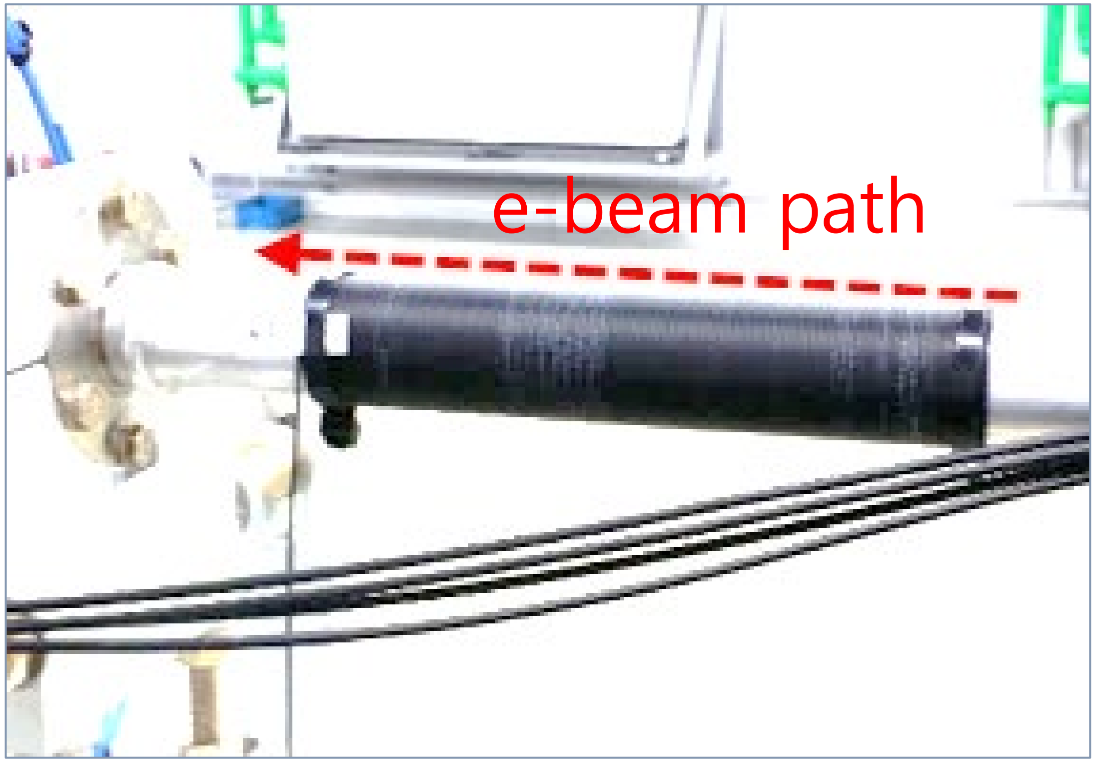
Wire material
- Tungsten (18 μm)
- Carbon (34 μm)



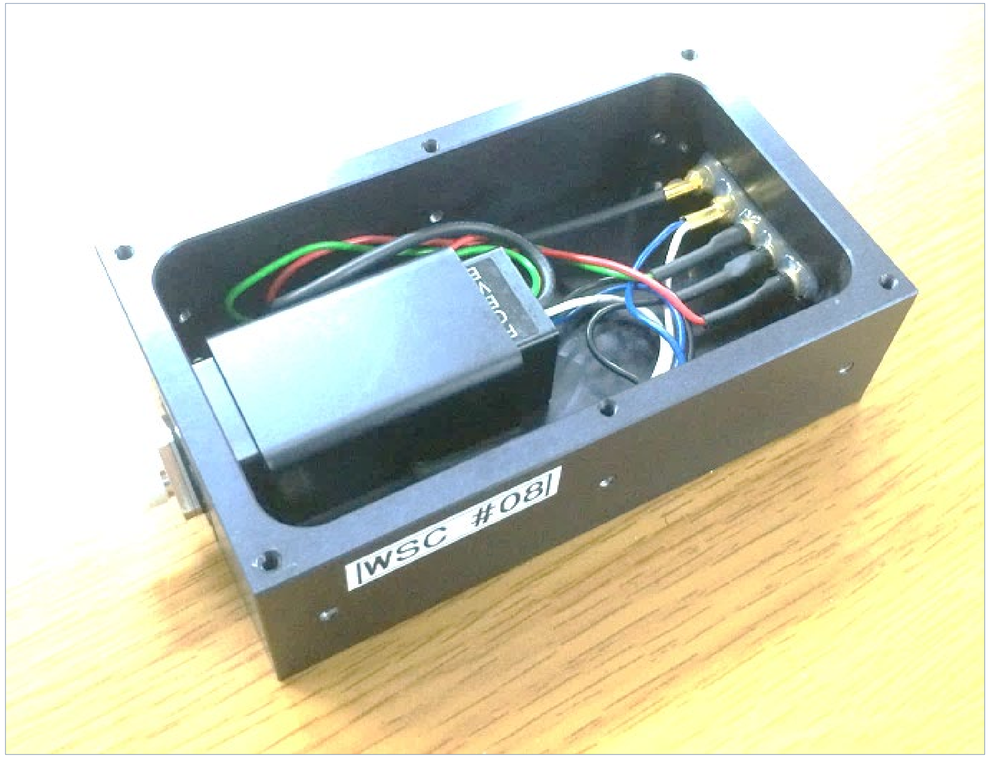


- Three wires and a RF shield tube to minimize wakefield effect
- The stage mounted on 45° motion stage with linear motor
- Ironless linear motor to minimize the magnetic field at the beam position

Beam Loss Monitor for Linac



BCF-20 Scintillating fiber (ø = 250 μm)
- 492 nm peak emission wavelength
- 2.7 ns decay time



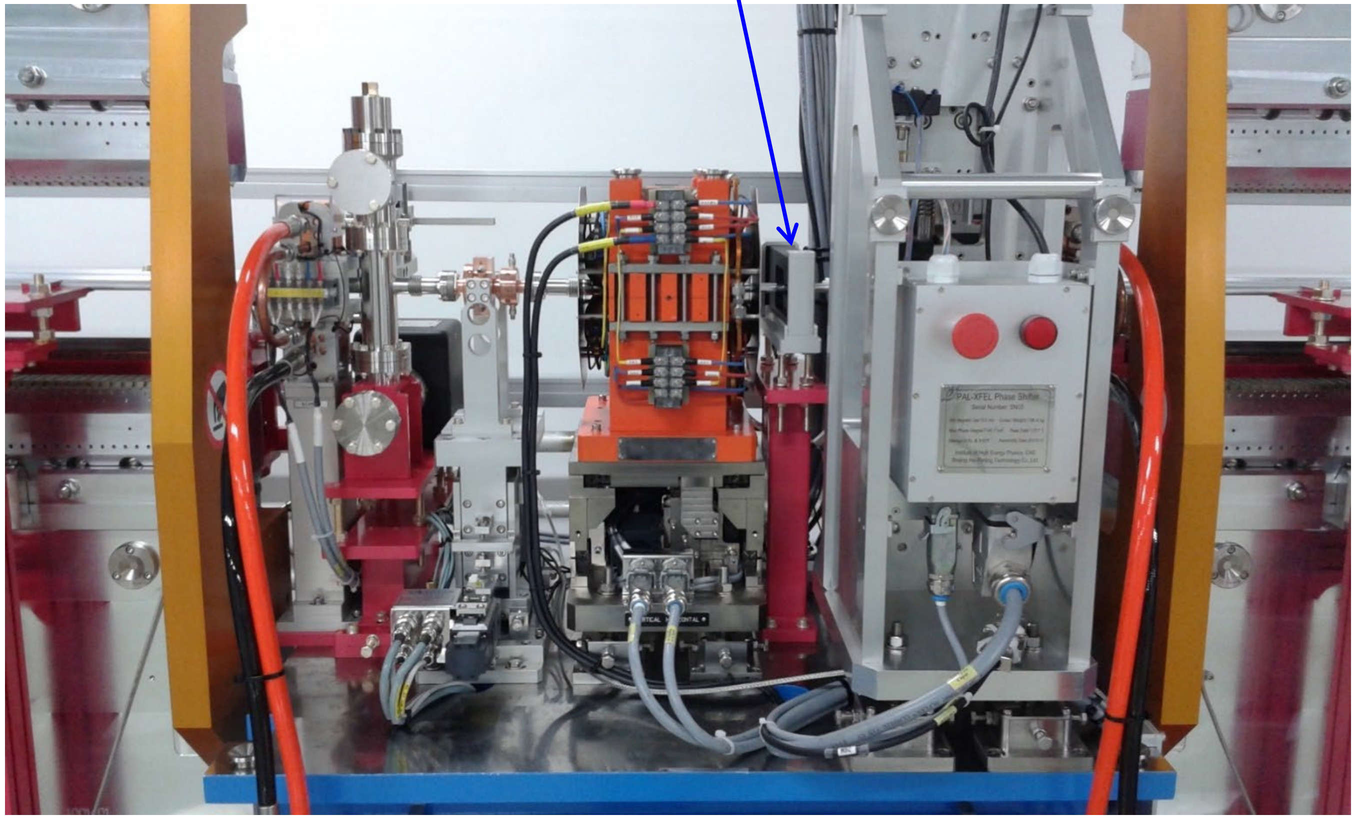
Hamamatsu H10722-110
- 230 ~ 700 nm spectral response

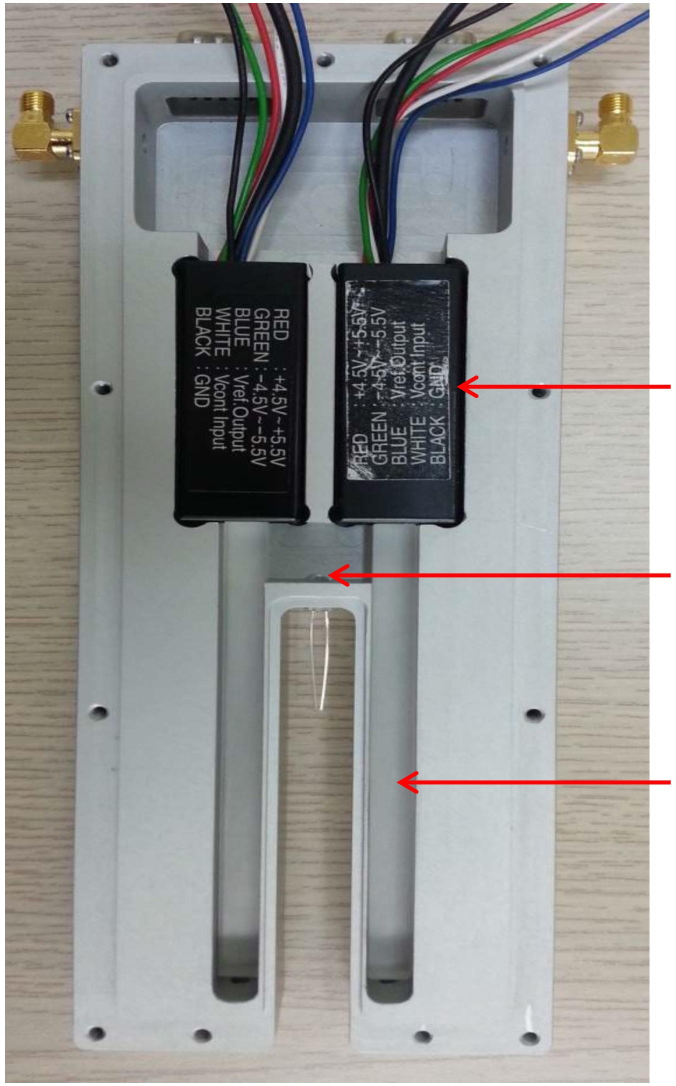
- Optical fiber is wound on the vacuum chamber for Cherenkov radiation
- Optical fiber is shielded from external light and connected directly to the PMT head

POHANG ACCELERATOR LABORATORY

Beam Loss Monitor for Undulator

Beam loss monitor



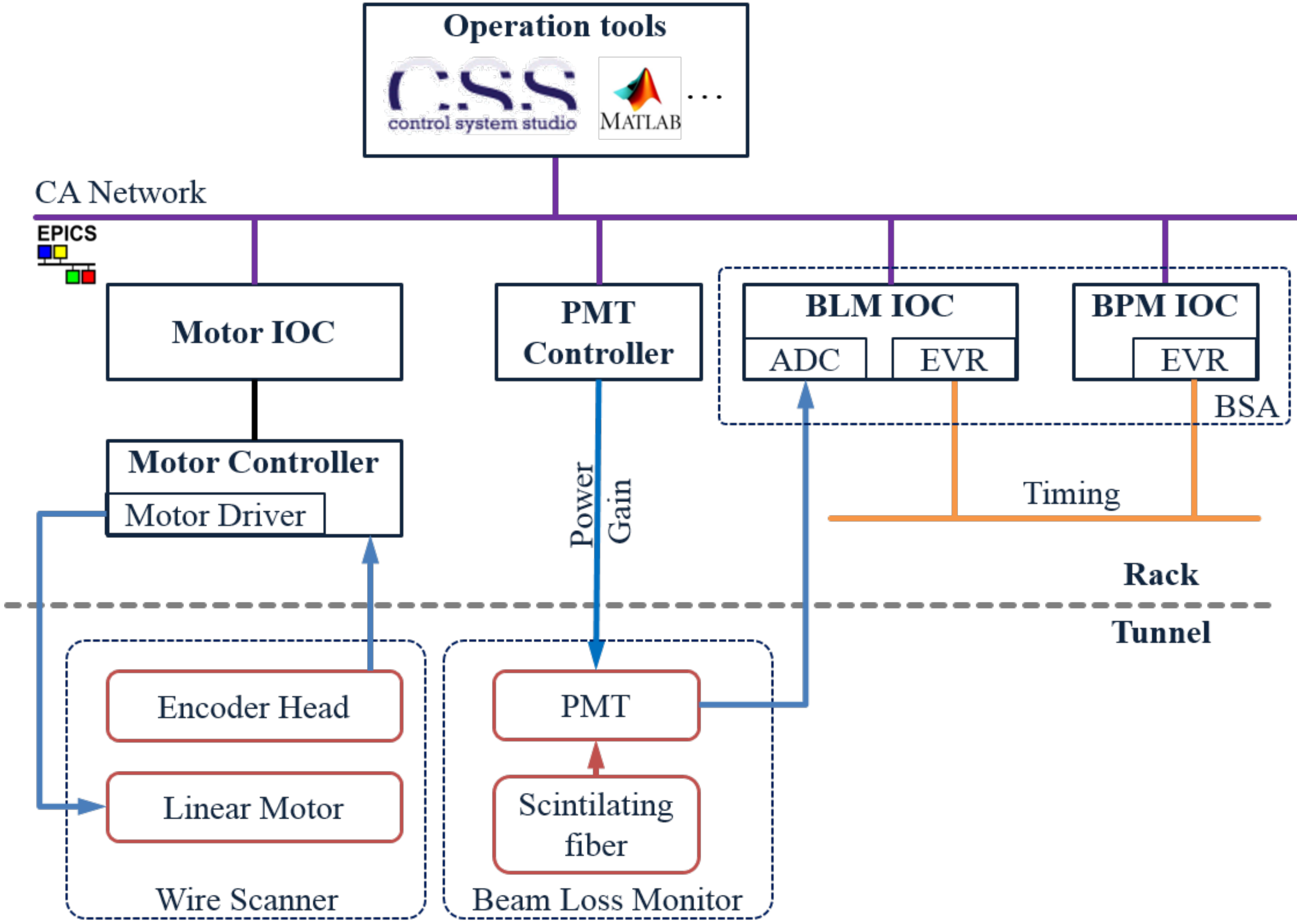


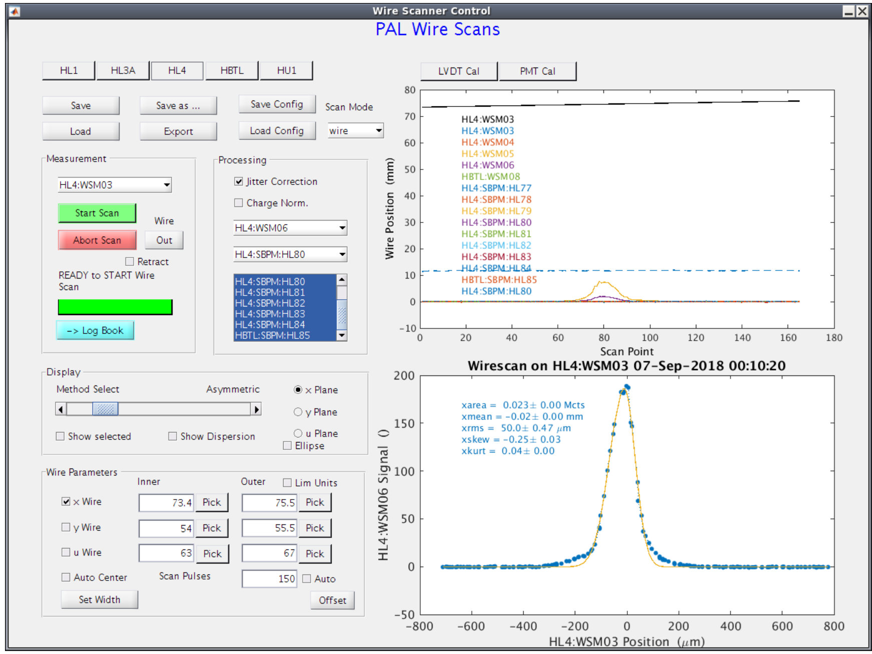
PMT module

LED (for heartbeat)

PMMA rod (for radiator)

Control Layout & Measurement GUI

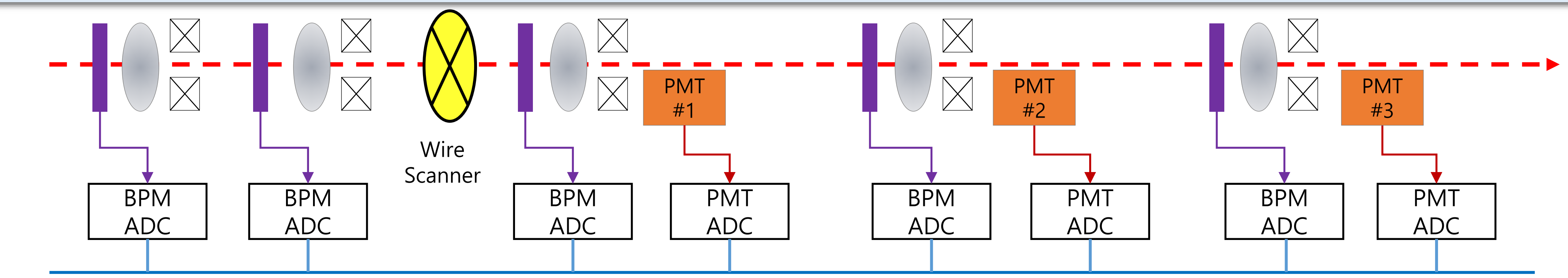


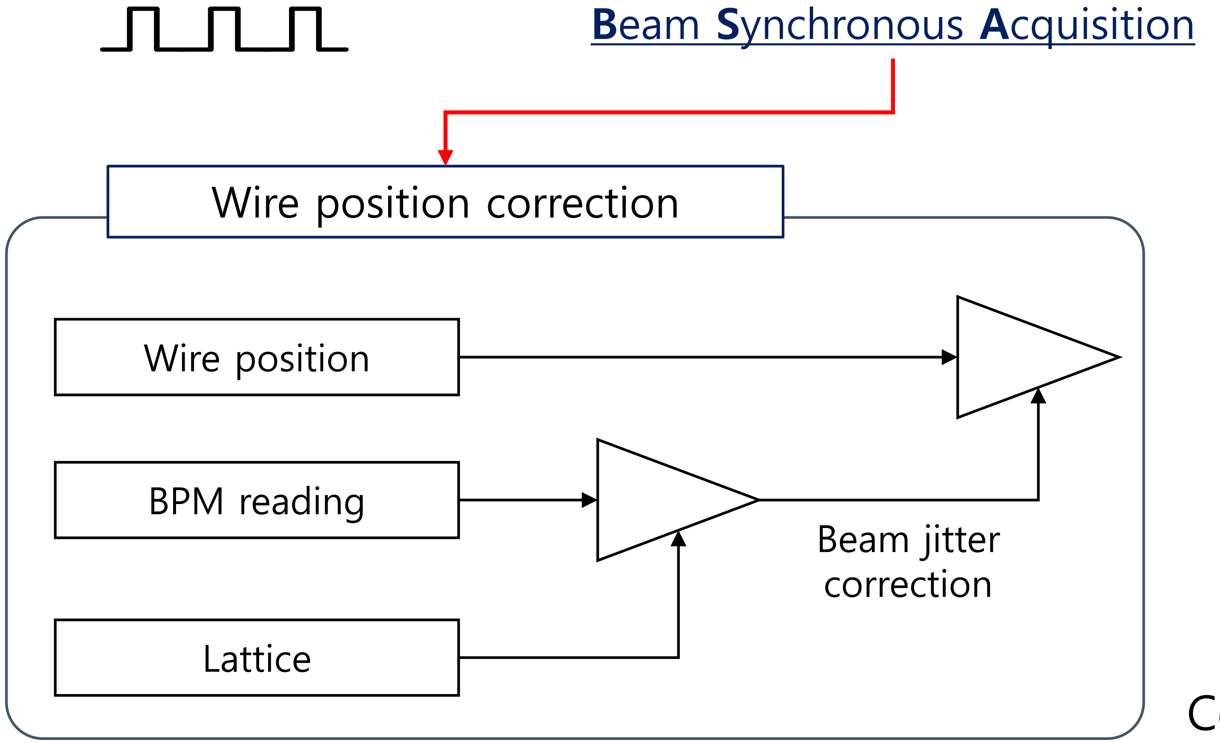


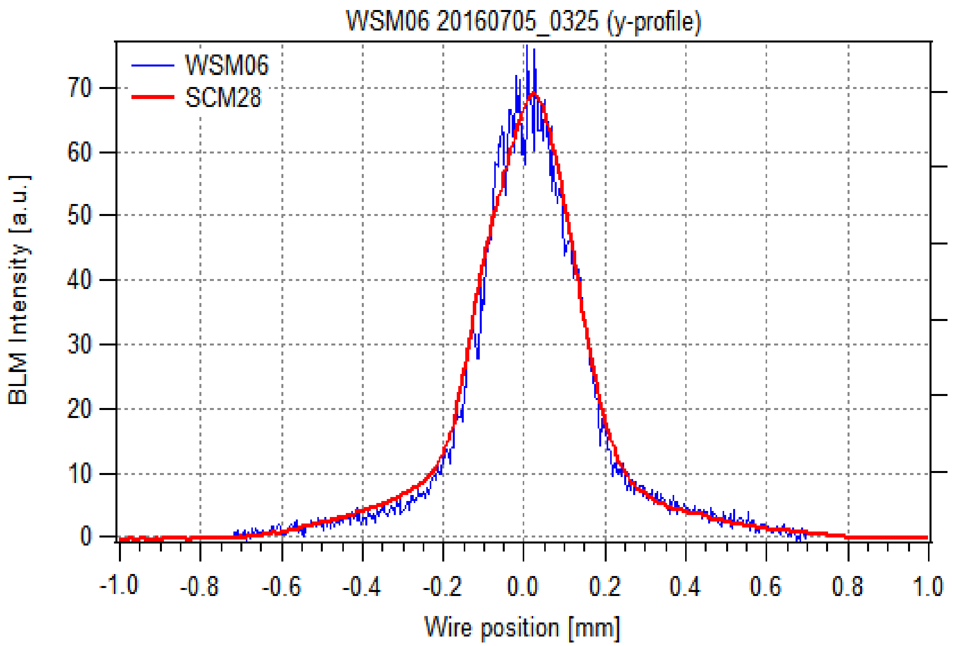
Wire Scanner GUI

POHANG ACCELERATOR LABORATORY

Correction of Beam Position Jitter







Comparison between Wire Scanner & Screen Monitor

POHANG ACCELERATOR LABORATORY

Limitations of Wire Scanners

Smallest measurable beam size limited by wire diameter

(smallest usually few μm)

High beam density (small size and high intensity) can destroy wire

(due to heat load)

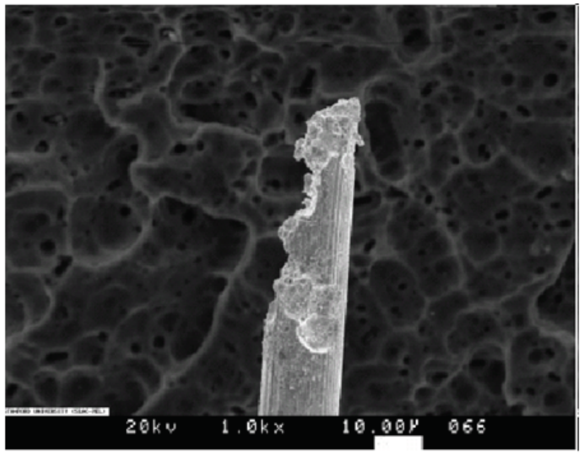


FIGURE 3. Failed 15 μm diameter tungsten wire showing the rough surface resulting from many discharges.

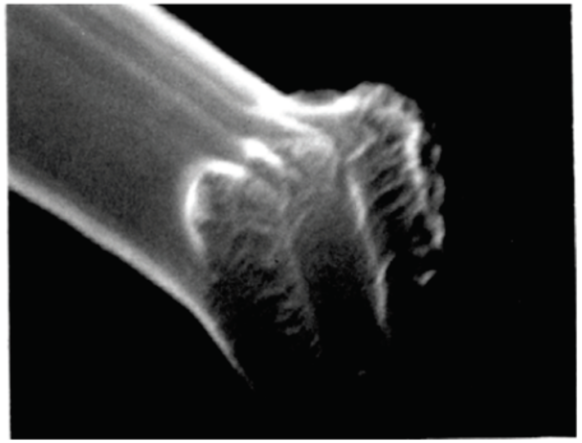
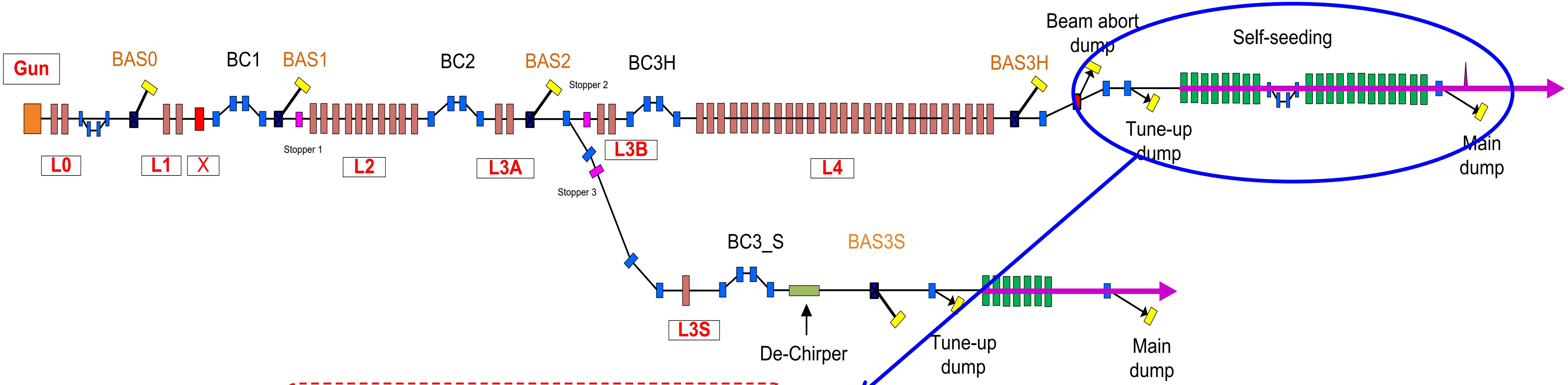
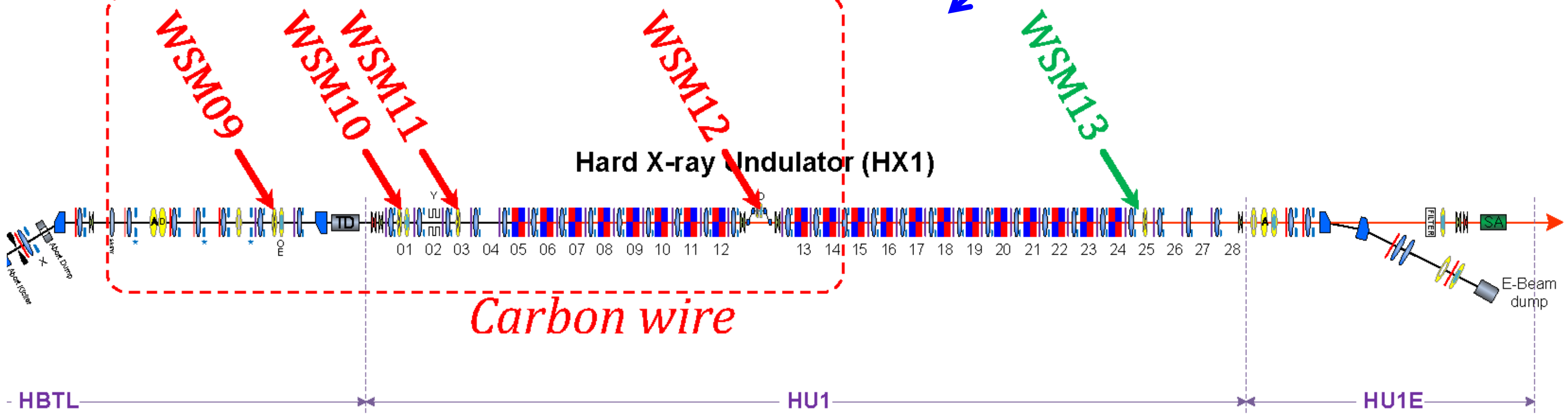


Figure 2: Broken 4μm carbon wire at SLC. It is possible to observe how successive pulses have eroded the wire.

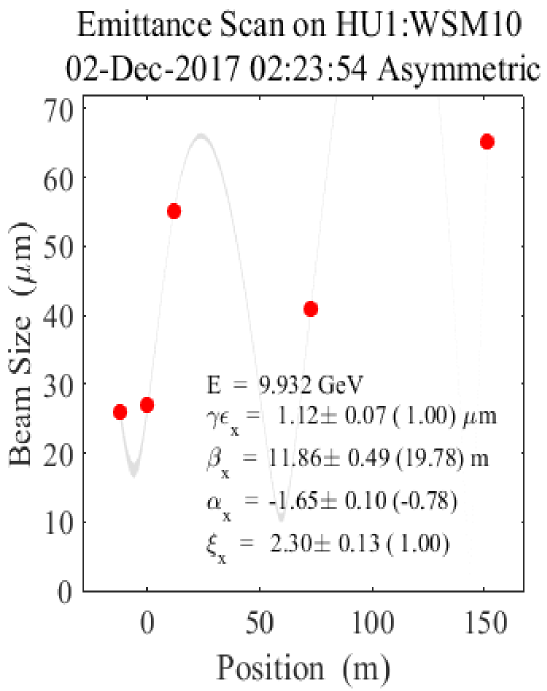
PAL POHANG ACCELERATOR LABORATORY

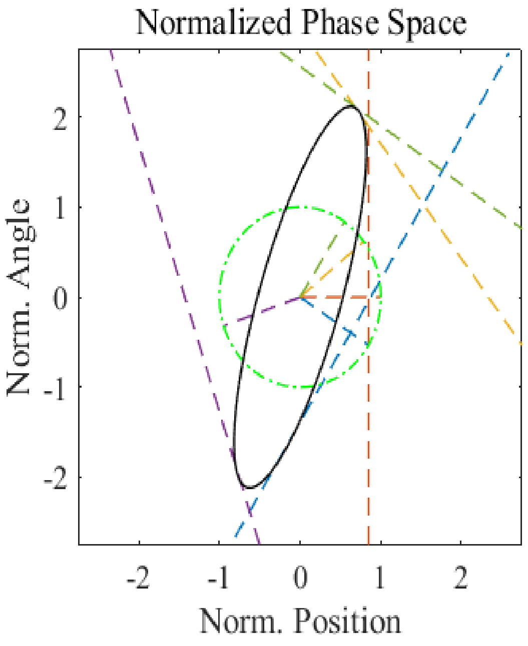
Lattice Matching with Wire Scanners

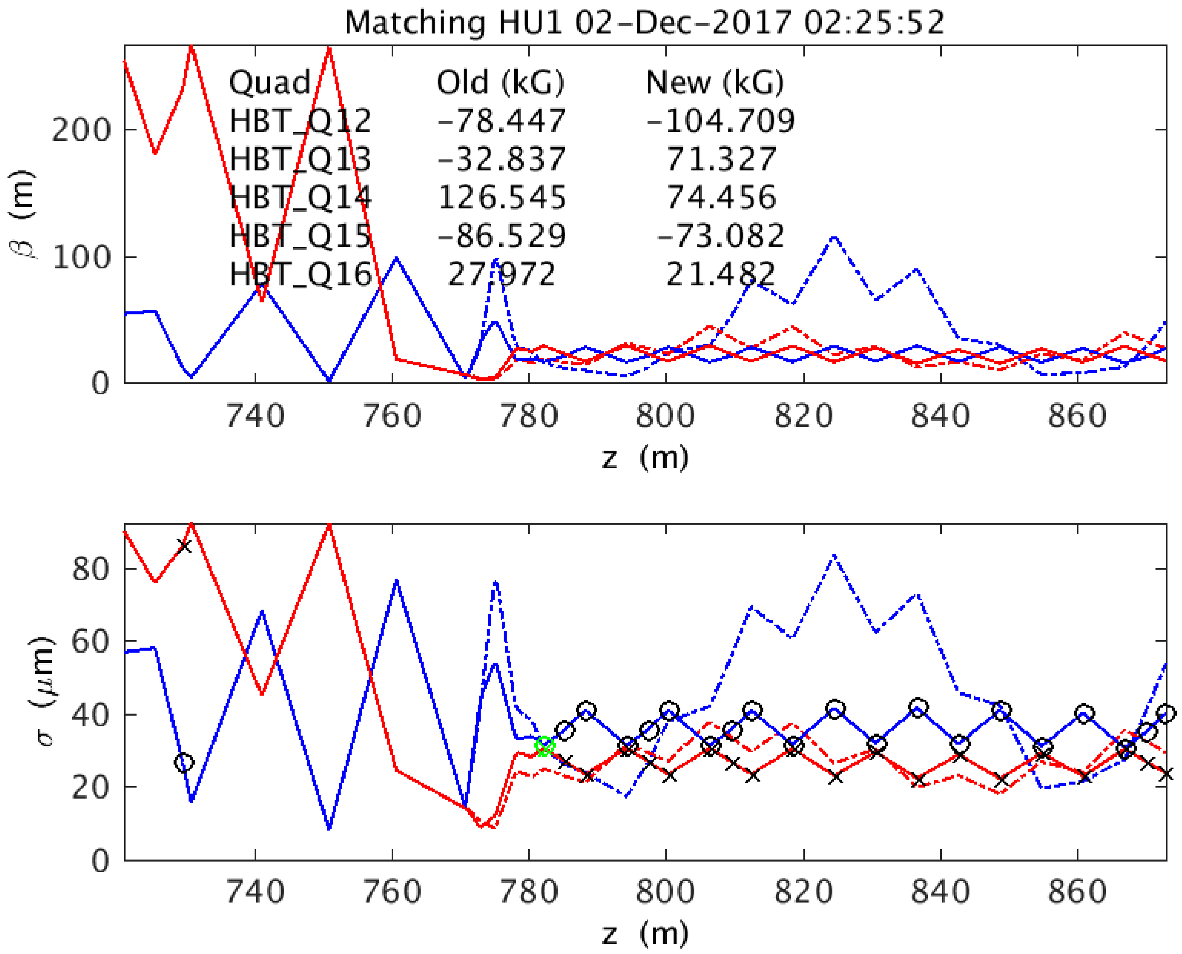




Before Lattice Matching in Undulator

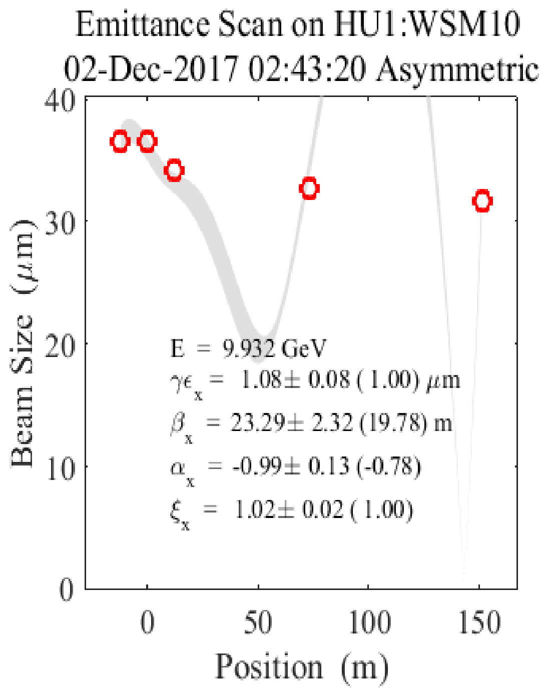


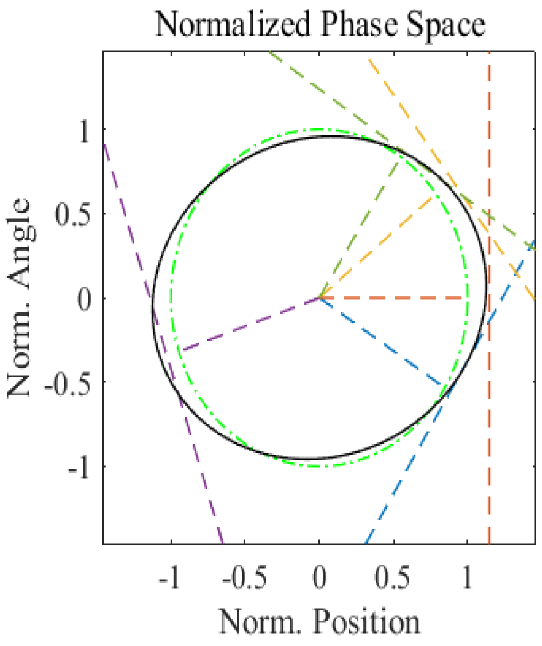


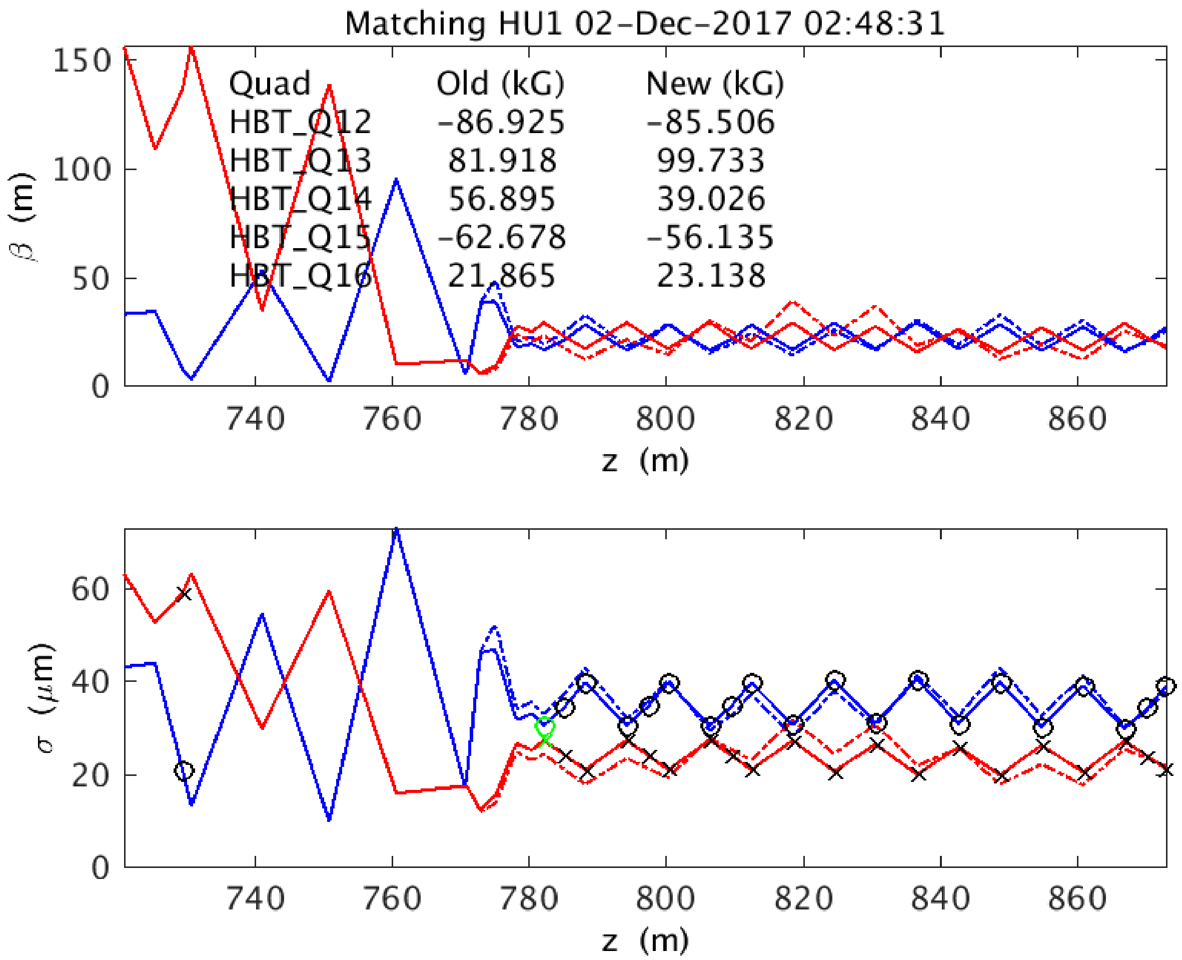


POHANG ACCELERATOR LABORATORY

After Lattice Matching in Undulator







Thanks to:

All Members in PAL-XFEL and Domestic/International Collaborations

POHANG ACCELERATOR LABORATORY