Diagnostic Systems for the PAL-XFEL Commissioning

2016. 9. 12

Changbum Kim on behalf of instrument & control group

Pohang Accelerator Laboratory

Contents

- Introduction of the PAL-XFEL
- Commissioning Results
- Diagnostic System of the PAL-XFEL

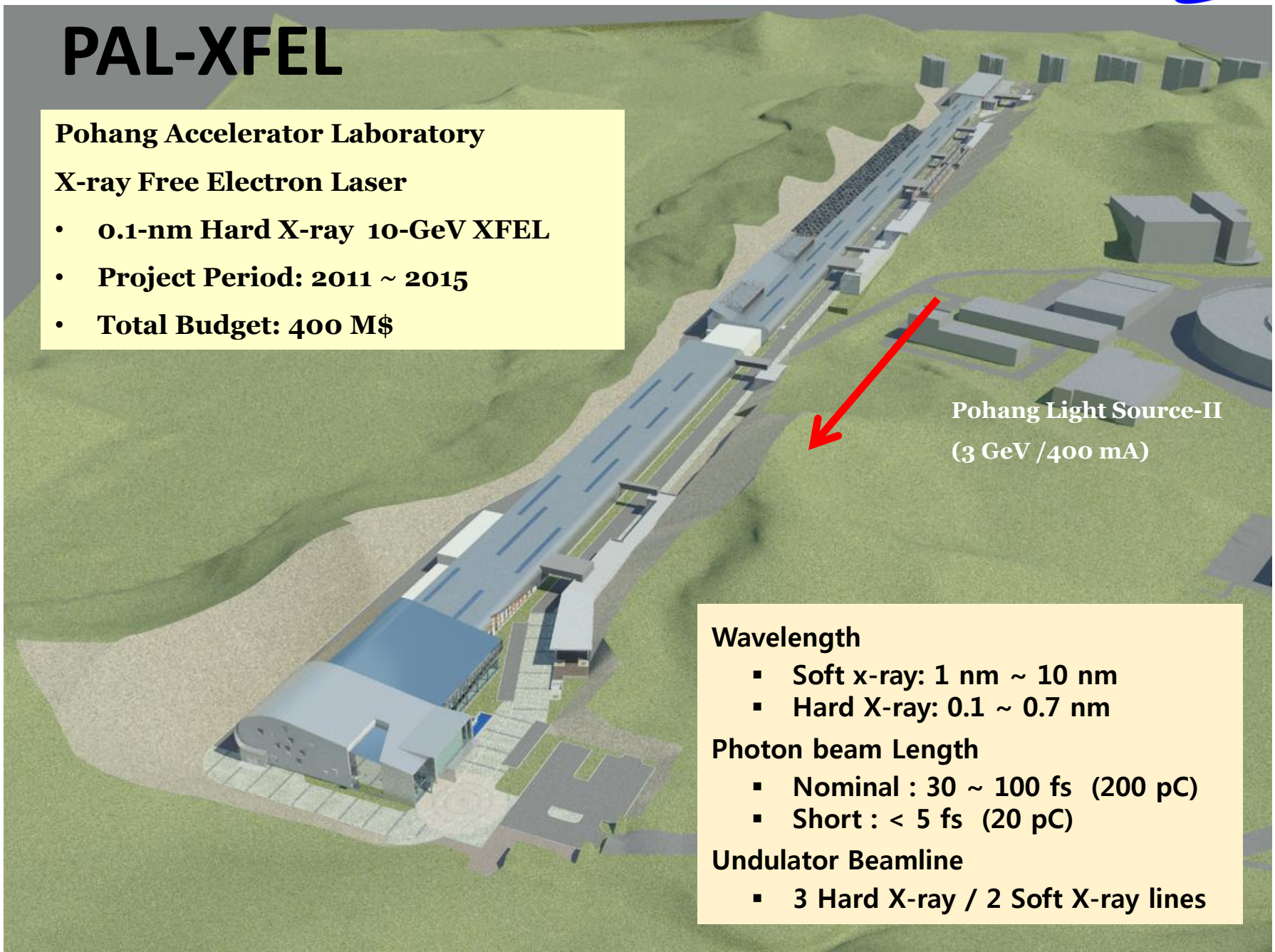
PAL-XFEL

PAL-XFEL

Pohang Accelerator Laboratory

X-ray Free Electron Laser

- **0.1-nm Hard X-ray 10-GeV XFEL**
- **Project Period: 2011 ~ 2015**
- **Total Budget: 400 M$**



Pohang Light Source-II

(3 GeV /400 mA)

Wavelength

- **Soft x-ray: 1 nm ~ 10 nm**
- **Hard X-ray: 0.1 ~ 0.7 nm**

Photon beam Length

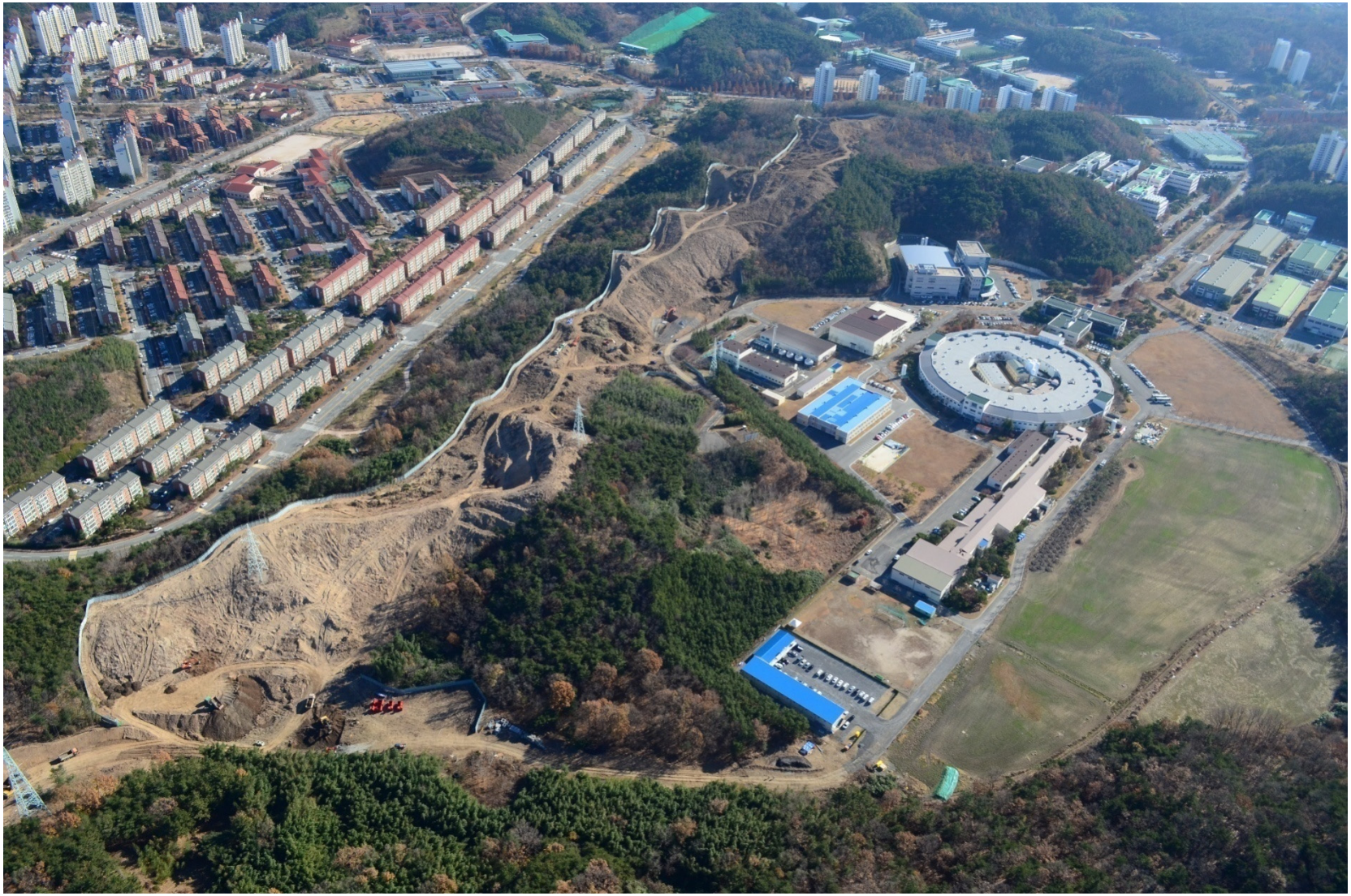
- **Nominal : 30 ~ 100 fs (200 pC)**
- **Short : < 5 fs (20 pC)**

Undulator Beamline

- **3 Hard X-ray / 2 Soft X-ray lines**

Aerial View of PAL (July 2012)

Aerial View of PAL (Nov. 26, 2012)



Aerial View of PAL (Mar. 21, 2013)

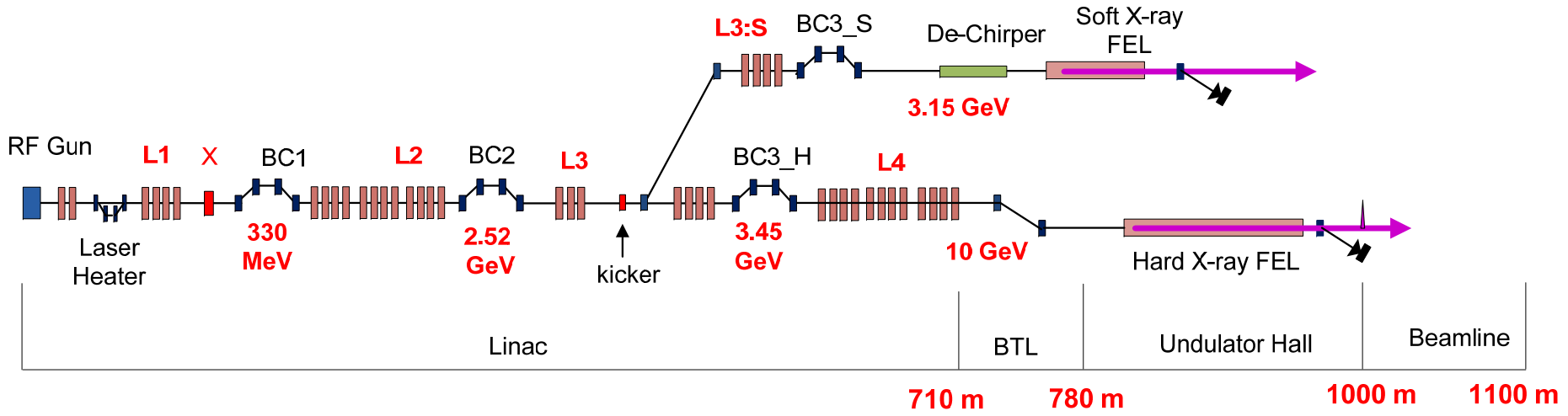
Aerial View of PAL (July 20, 2013)

Aerial View of PAL (Jan. 23, 2014)

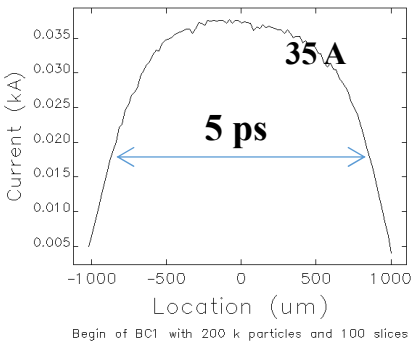
Aerial View of PAL (Jan. 4, 2015)

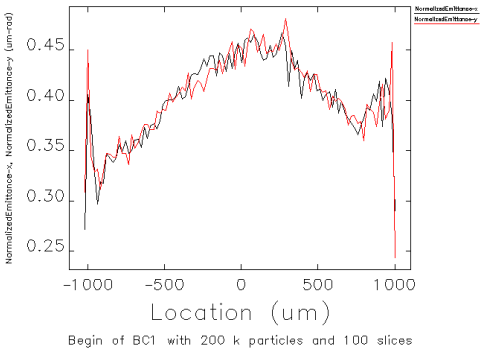
Linac Hall		780
	1. Assembly	10
	2. Linac	720
	3. BTL	50
Undulator Hall		225
XFEL Beamline		105
	1. Front-end	25
	2. Optics Hutch	20
	3. Experimental Hall	60
Total Length [m]		1110

PAL-XFEL Layout

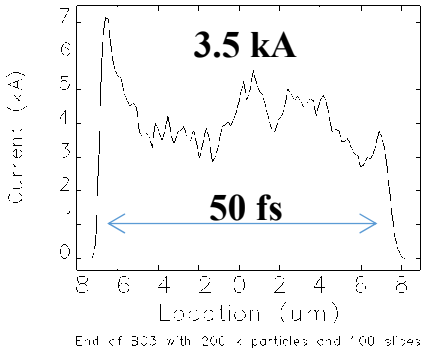


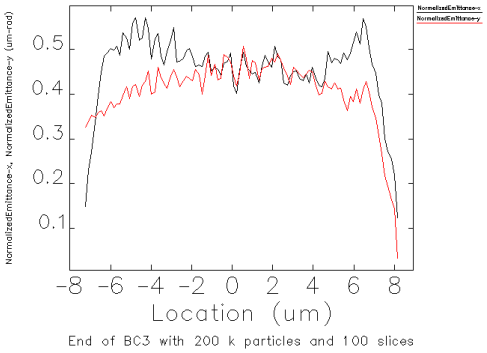
After Gun



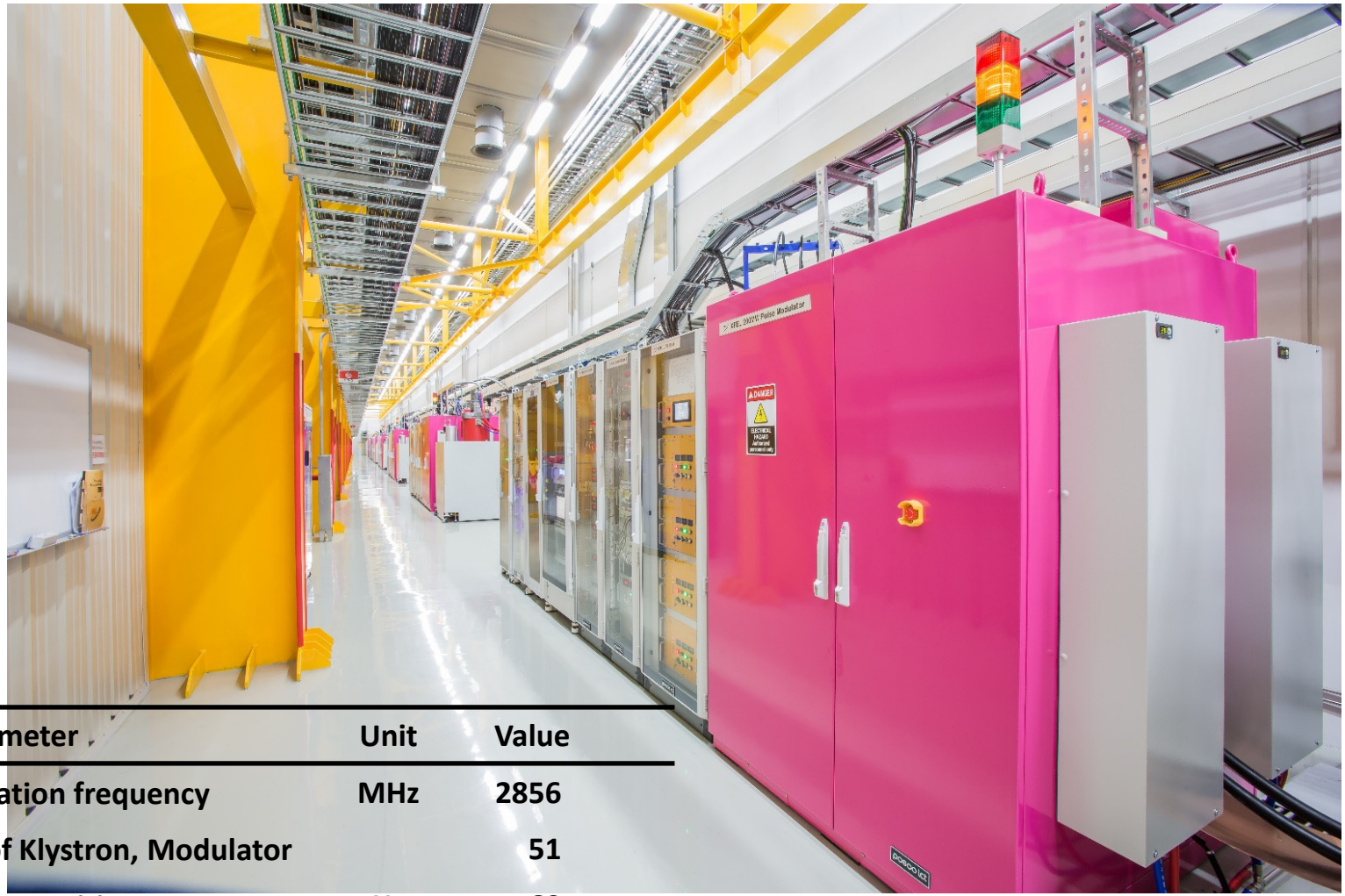


Before Undulator



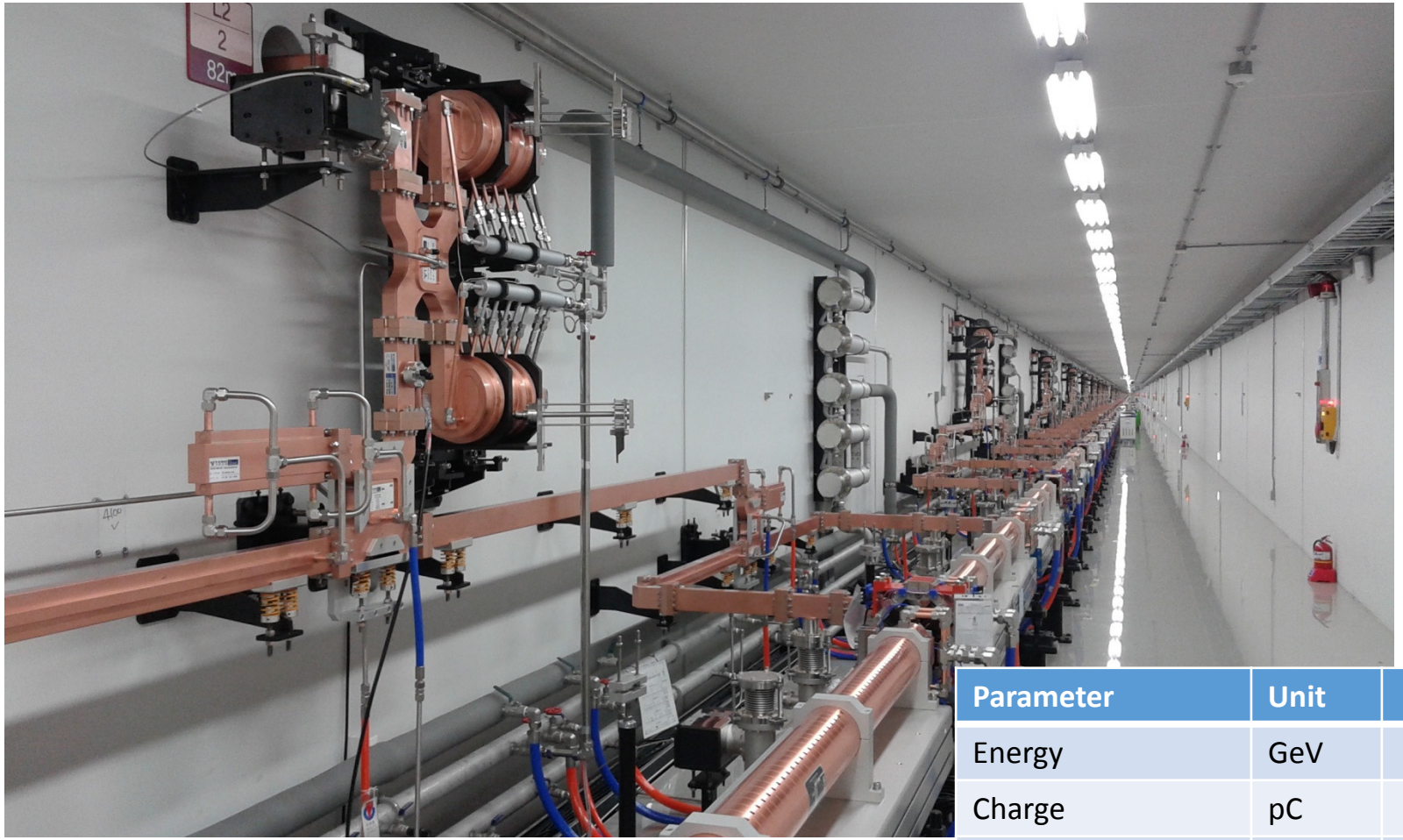


PAL-XFEL K&M Gallery



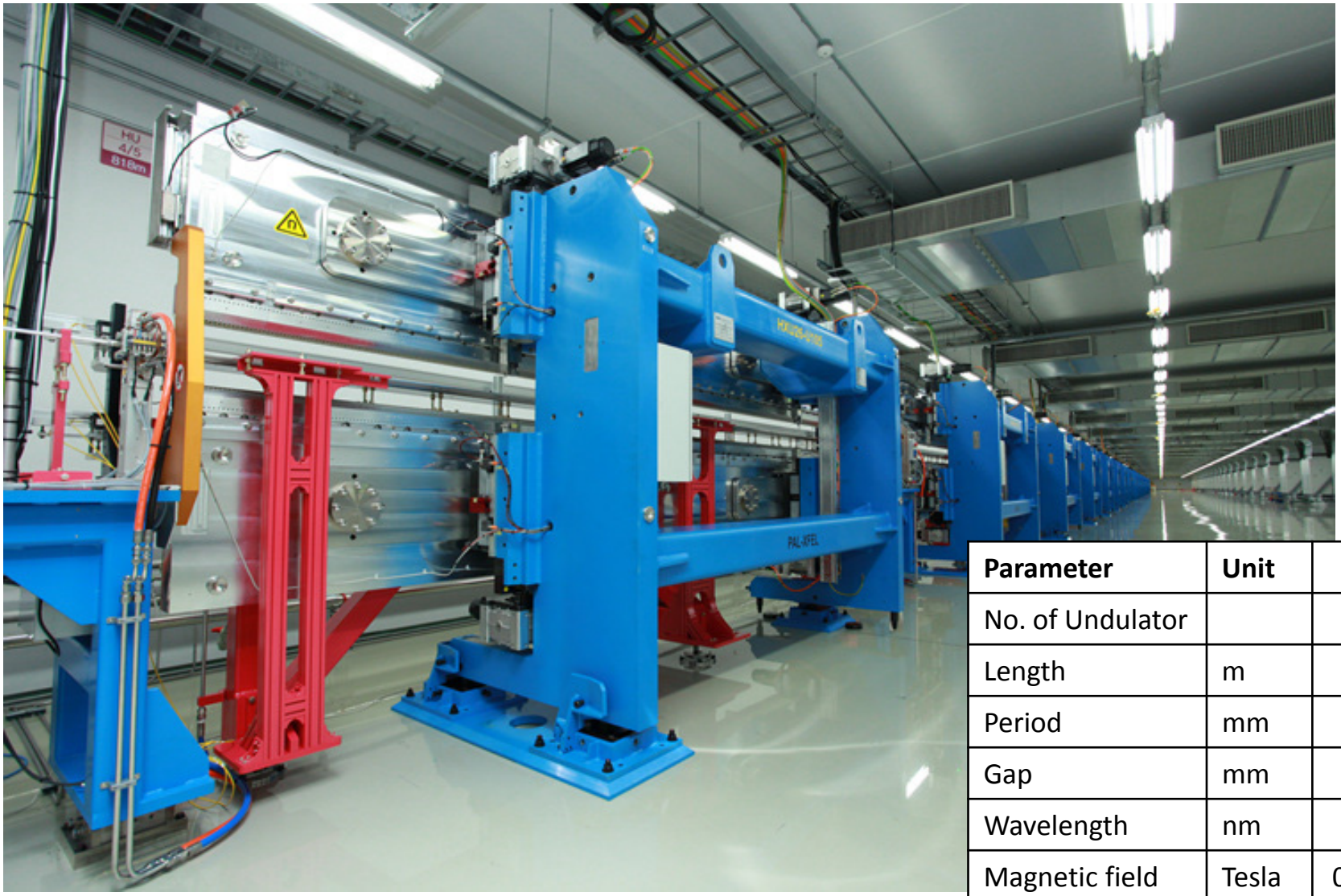
Parameter	Unit	Value
Operation frequency	MHz	2856
No. of Klystron, Modulator		51
Max. repetition rate	Hz	60
Operation pulse length	μs	4

PAL-XFEL Linac



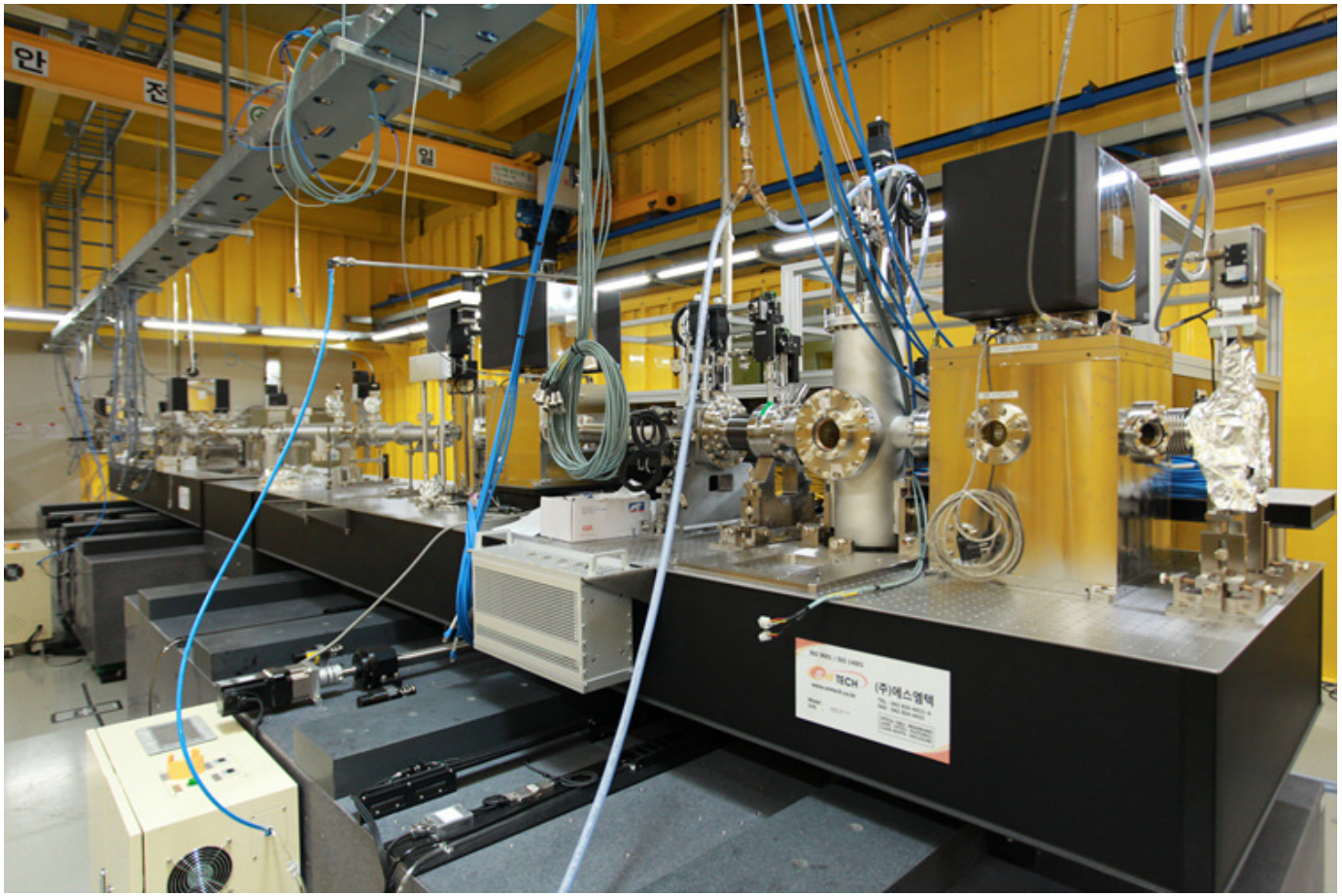
Parameter	Unit	Value
Energy	GeV	10
Charge	pC	200
No. of SLED		42
No. of Acc. Column		173

PAL-XFEL Undulator



Parameter	Unit	Value
No. of Undulator		20
Length	m	5
Period	mm	26.0
Gap	mm	8.3
Wavelength	nm	0.1
Magnetic field	Tesla	0.8124
K		1.9727

PAL-XFEL Beamline



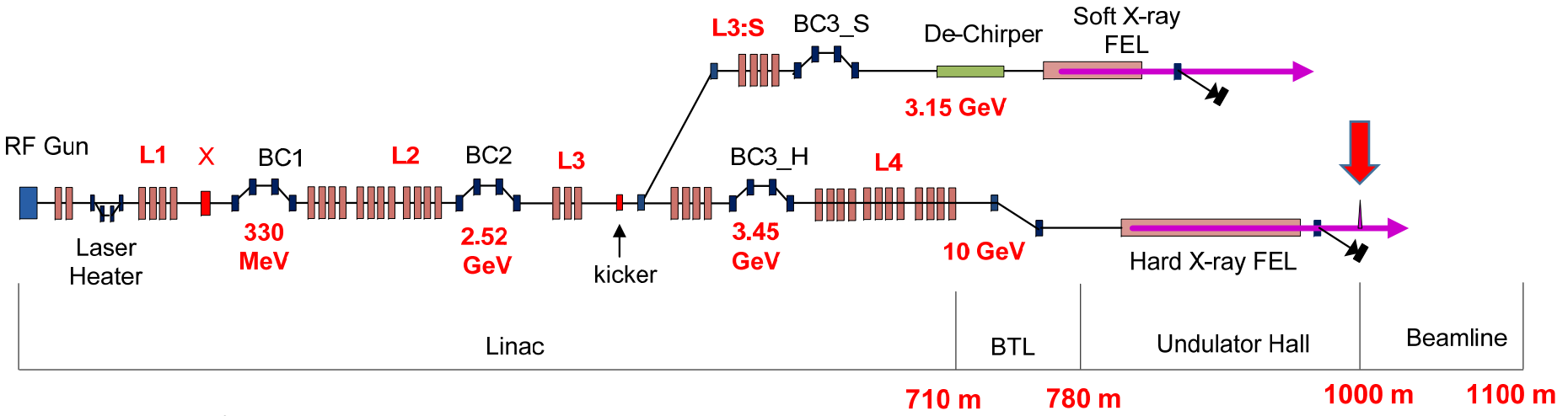
3 Experimental Station:
Coherent X-ray Imaging, Hard X-ray Pump & Probe, Soft X-ray Pump & Probe

PAL-XFEL Commissioning

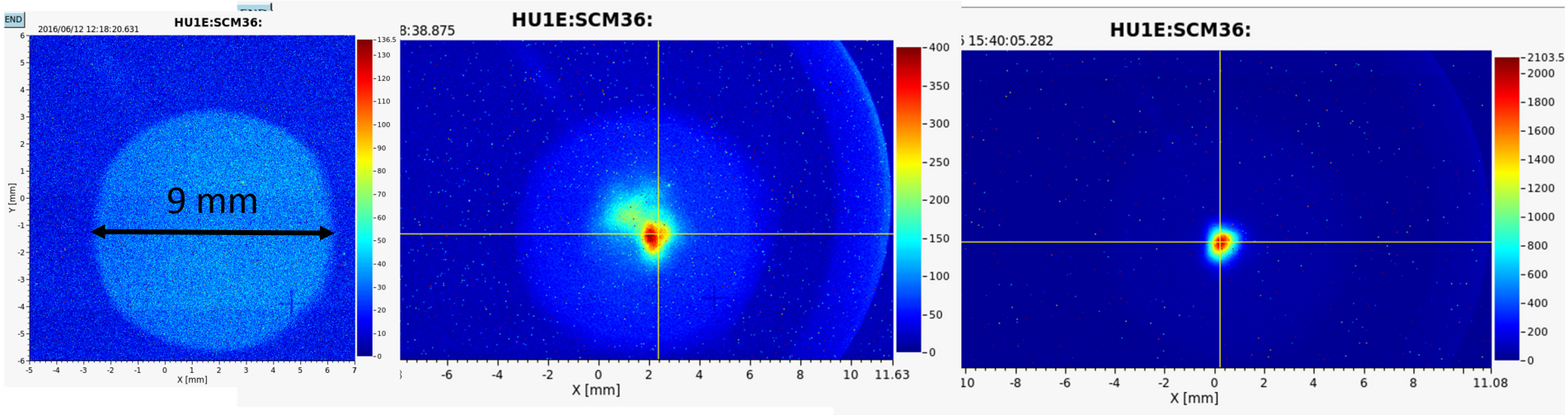
Commissioning Status

- Nov. 2015 RF conditioning started
- Apr. 14, 2016 Beam commissioning started
- Apr. 25, 2016 10 GeV acceleration achieved
- June 12, 2016 Undulator radiation observed
- June 14, 2016 First SASE FEL lasing at 0.5 nm
- July 2016 Summer maintenance
- Aug. 6, 2016 Beam commissioning restarted

First FEL Lasing at 0.5 nm

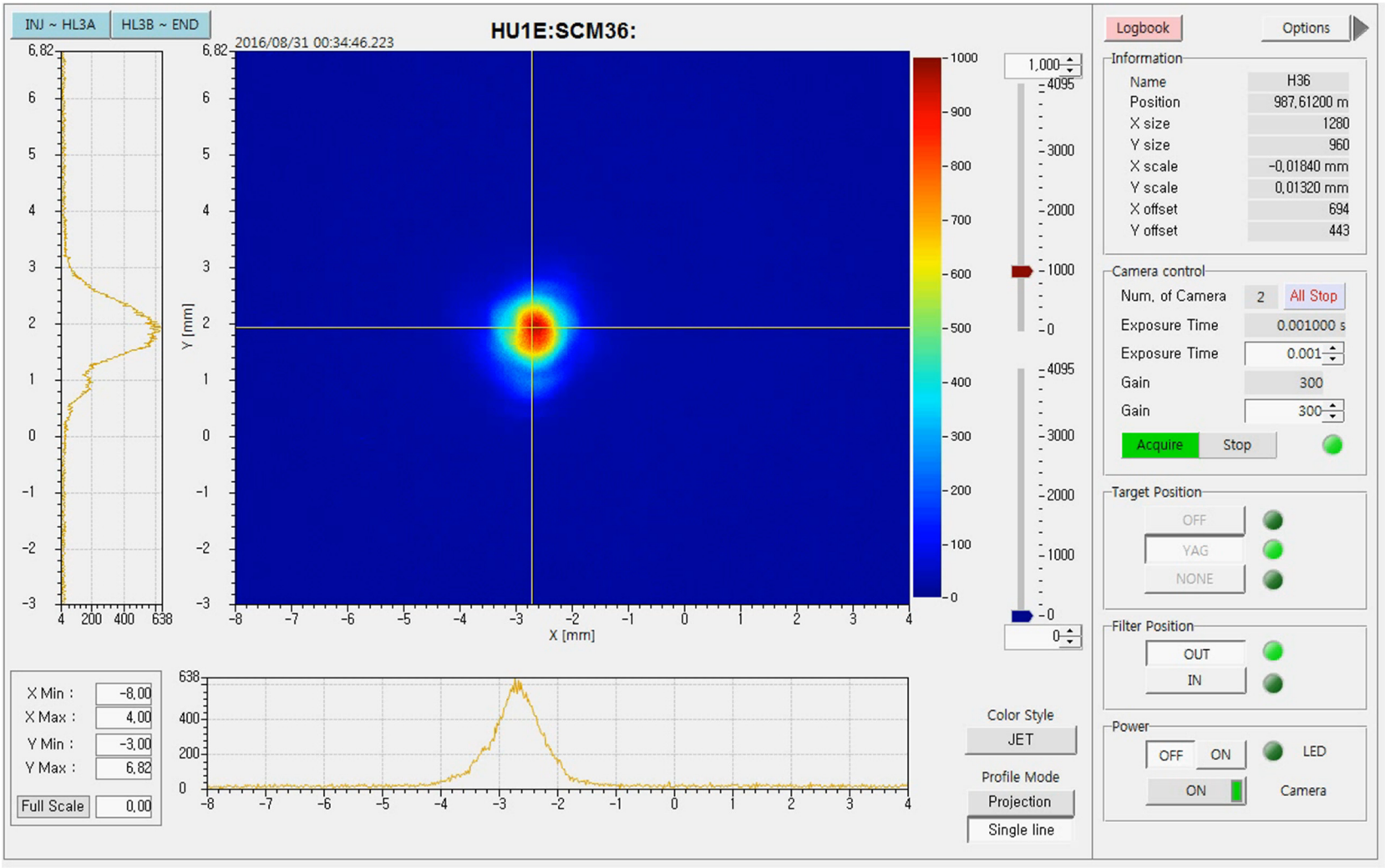


Spontaneous radiation



June 12, 2016 June 14, 2016 June 16, 2016

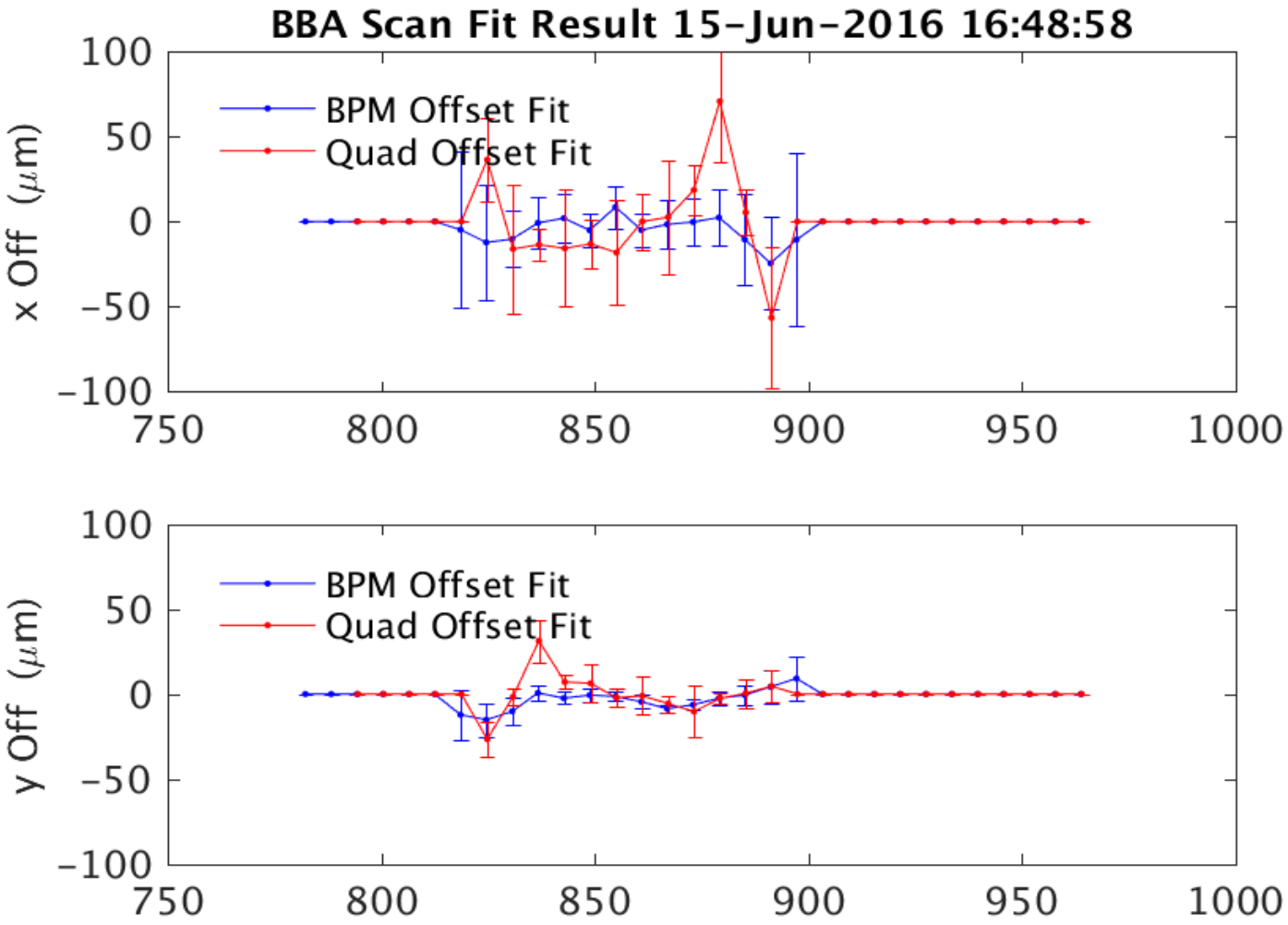
SASE FEL


INJ ~ HL3A
HL3B ~ END
HU1E:SCM36:
2016/08/31 00:34:46.223
Y [mm]
X [mm]
X Min : -8,00
X Max : 4,00
Y Min : -3,00
Y Max : 6,82
Full Scale 0,00
Color Style
JET
Profile Mode
Projection
Single line
Logbook
Options
Information
Name H36
Position 987,61200 m
X size 1280
Y size 960
X scale -0,01840 mm
Y scale 0,01320 mm
X offset 694
Y offset 443
Camera control
Num. of Camera 2
All Stop
Exposure Time 0.001000 s
Exposure Time 0.001
Gain 300
Gain 300
Acquire
Stop
Target Position
OFF
YAG
NONE
Filter Position
OUT
IN
Power
OFF
ON
LED
ON
Camera

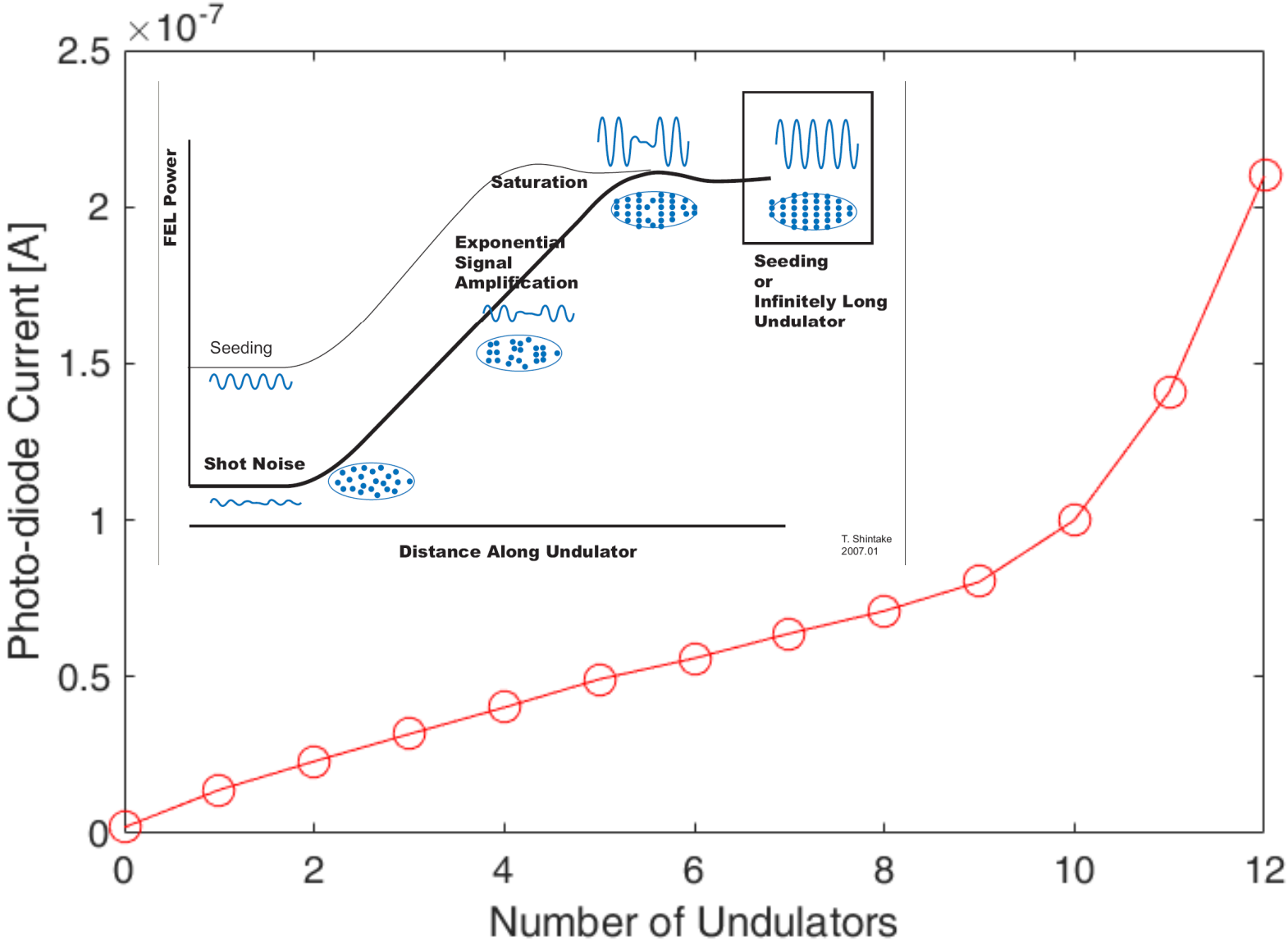
Beam Based Alignment (BBA)

- All undulator gap open
- BBA without Corrector magnets for 4 energies
  - Quadrupole offsets are applied to quadrupole movers.
  - BPM offsets are applied.
  - The electron beam goes a straight line.
- All undulator gap close
- BBA with Corrector magnets for 4 energies
  - The electron beam goes the straight line again.
  - The electron beam can be overlapped with the undulator radiation.

BBA for Undulator

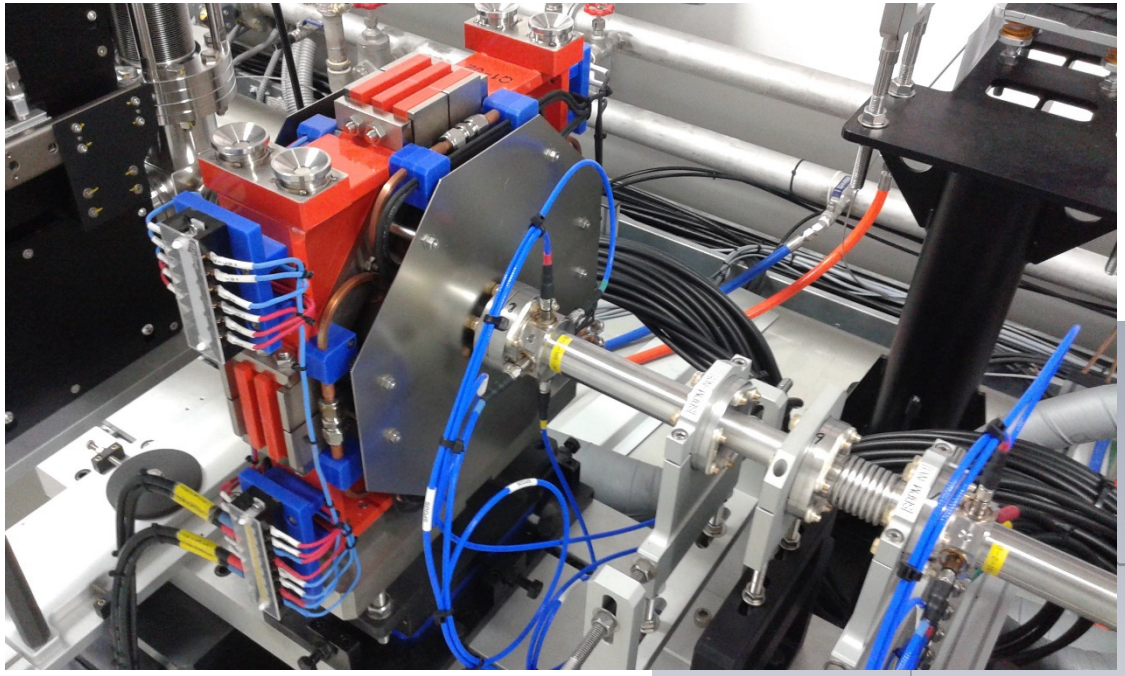


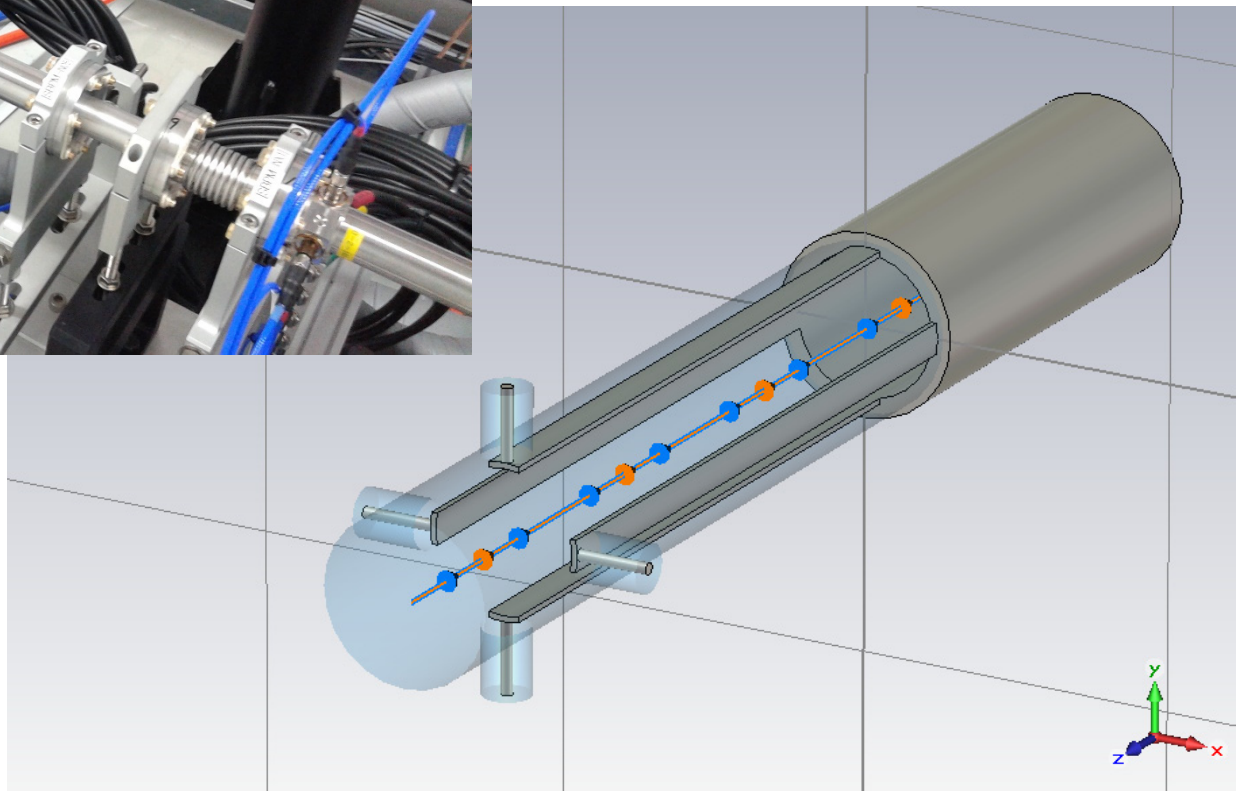
FEL Intensity vs. Undulator



Beam Position Monitor

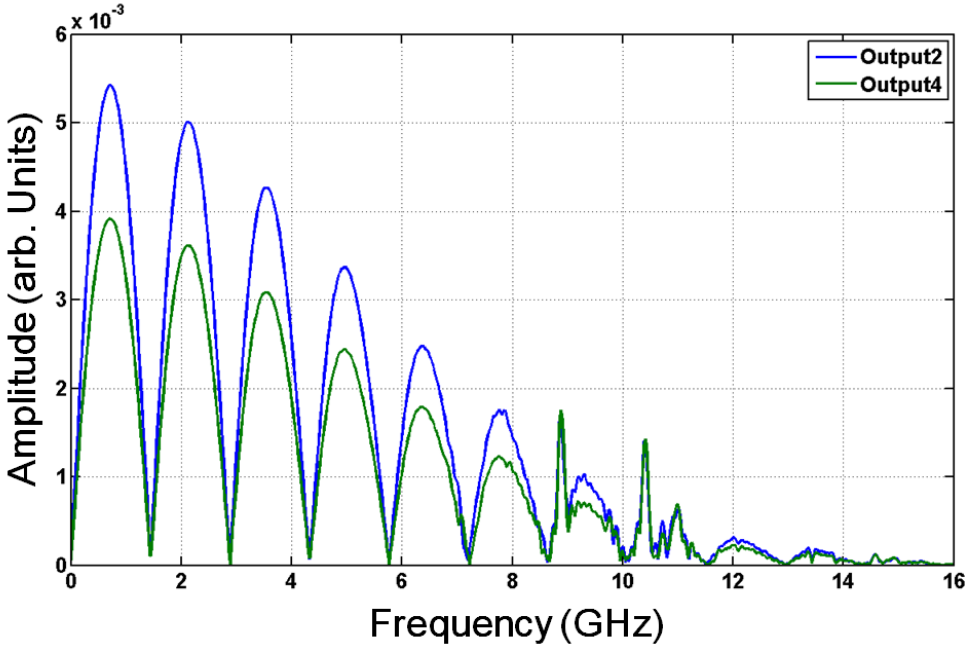
Stripline BPM Design

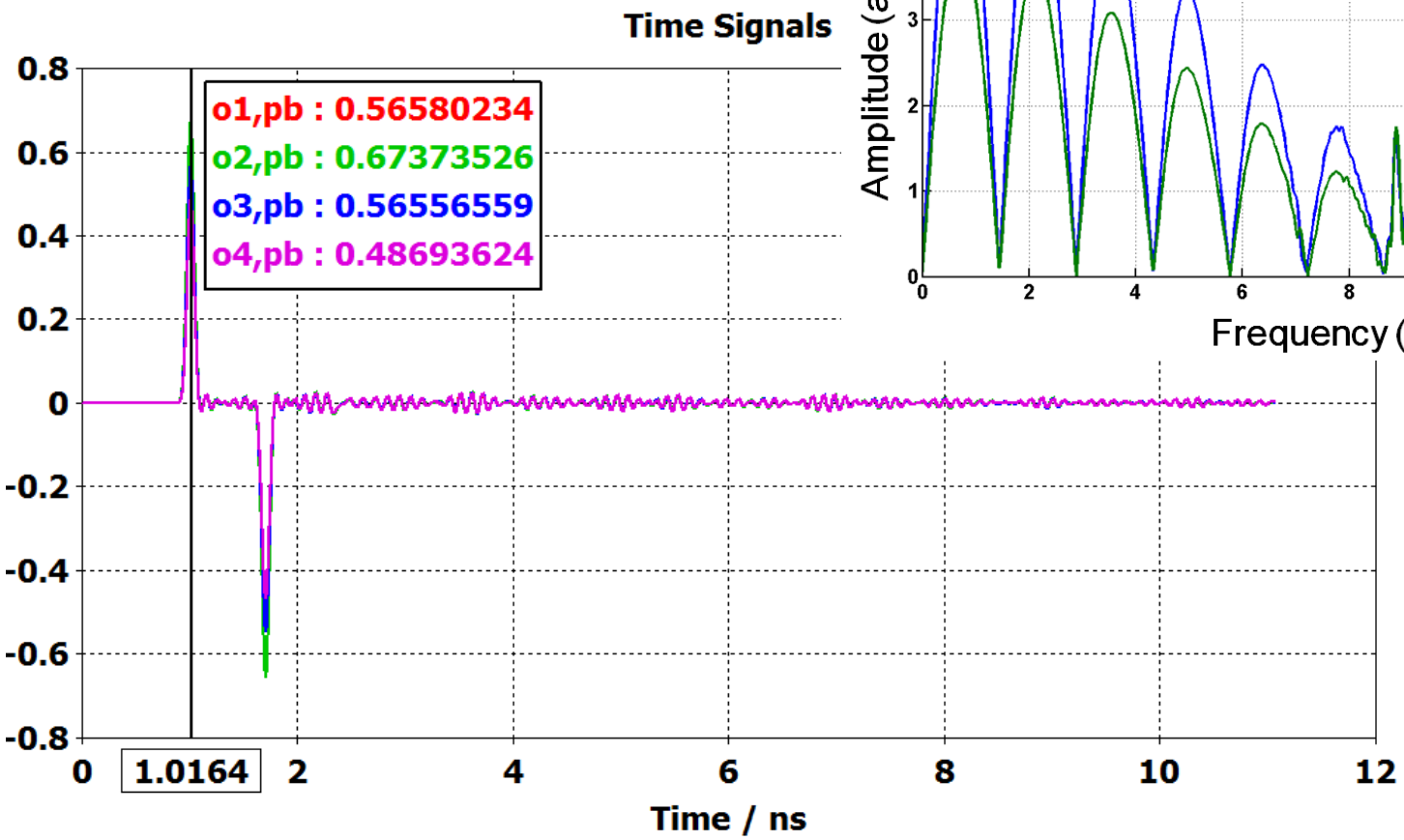




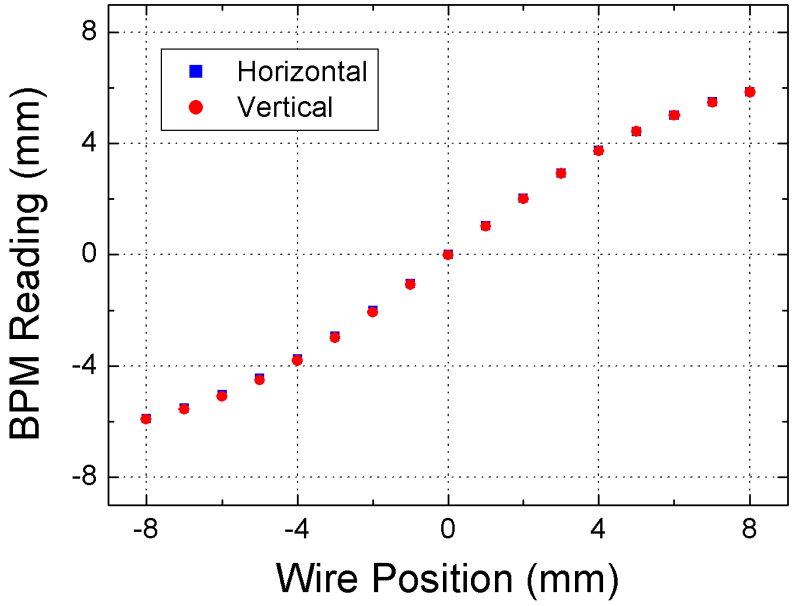
CST Simulation

Simulation Results

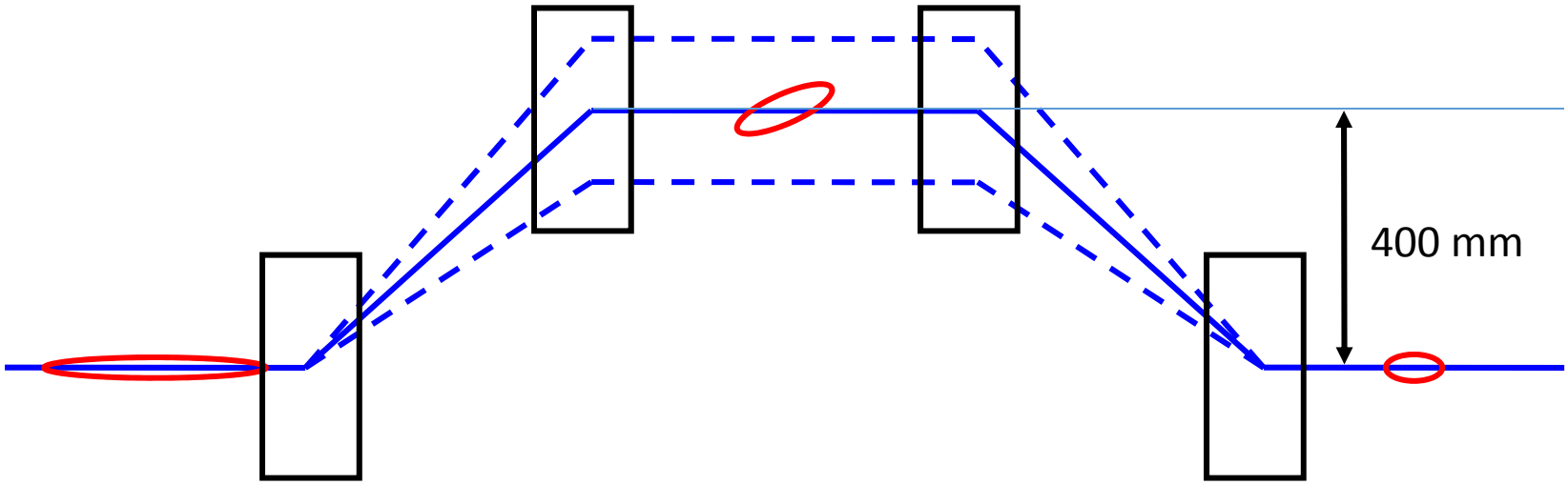




Wire Test Stand

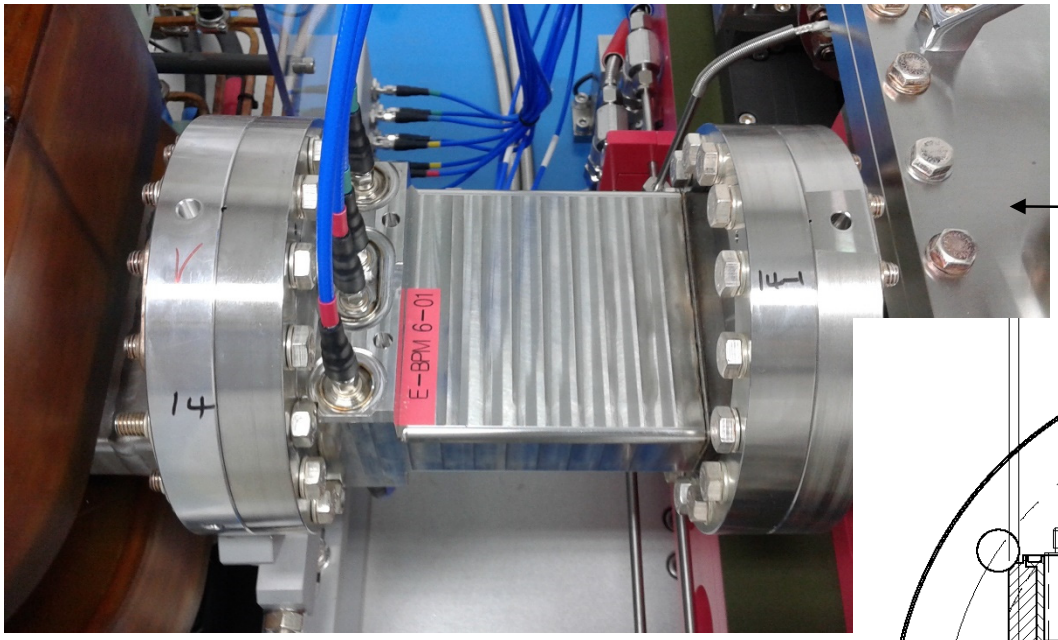


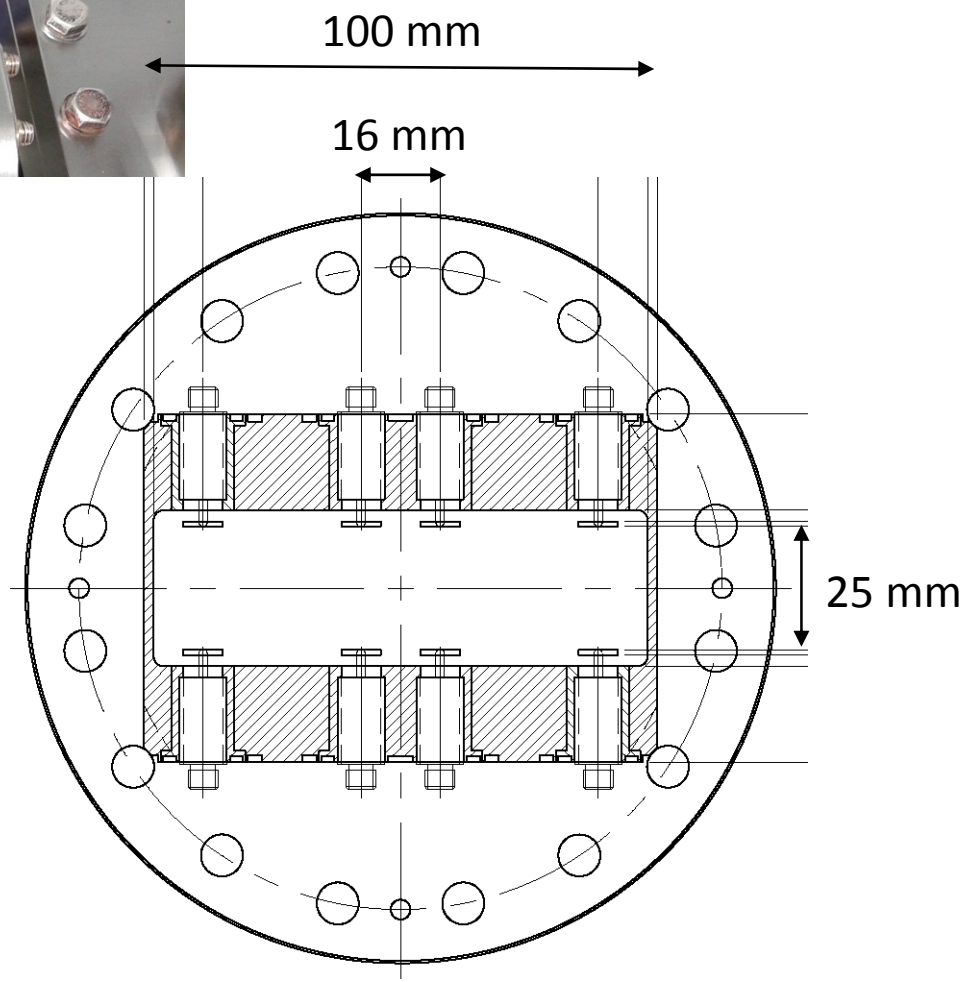
Bunch Compressor



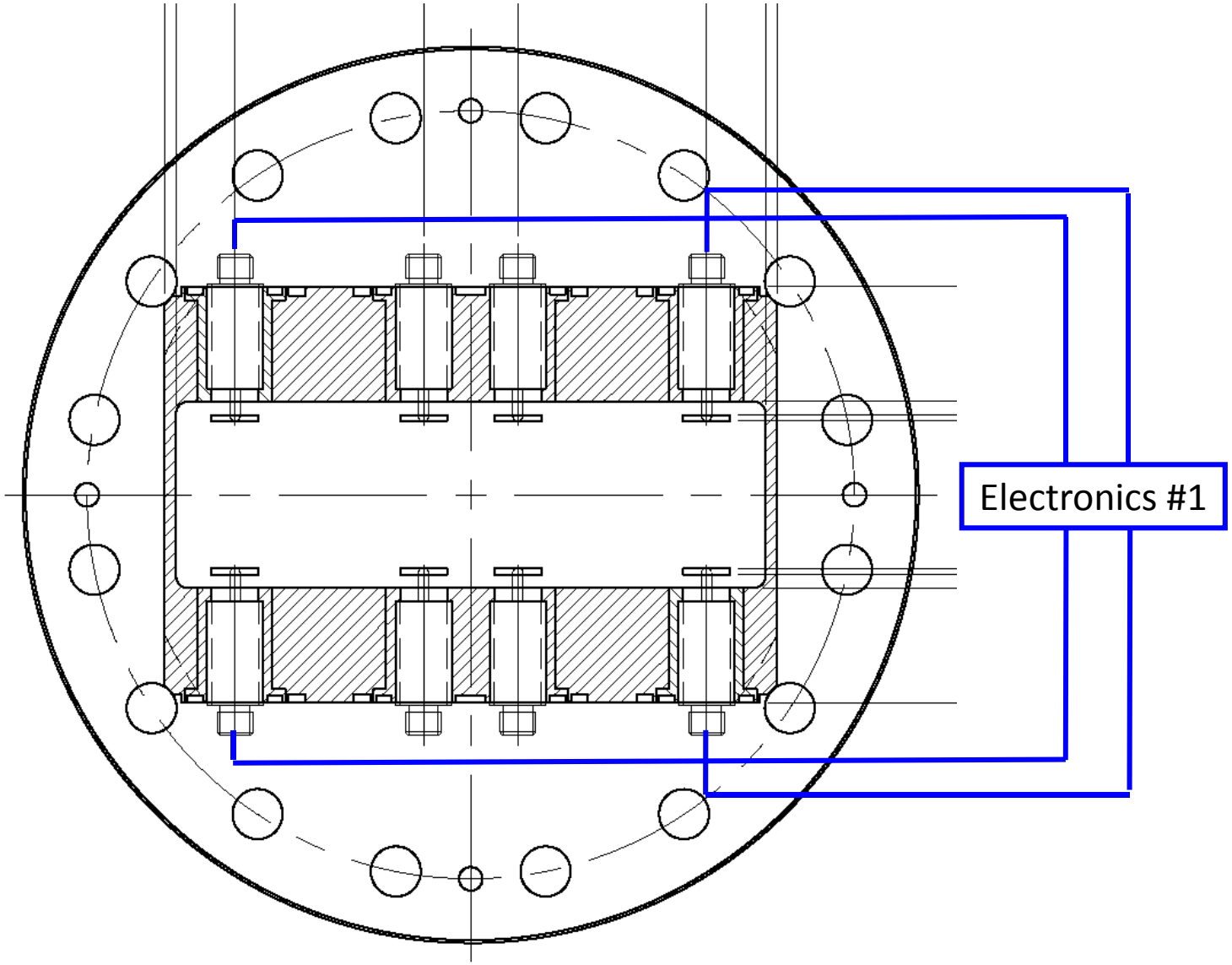
- Requirement
  - Wide dynamic range
  - High resolution
  - Energy measurement & energy feedback

Bunch Compressor BPM

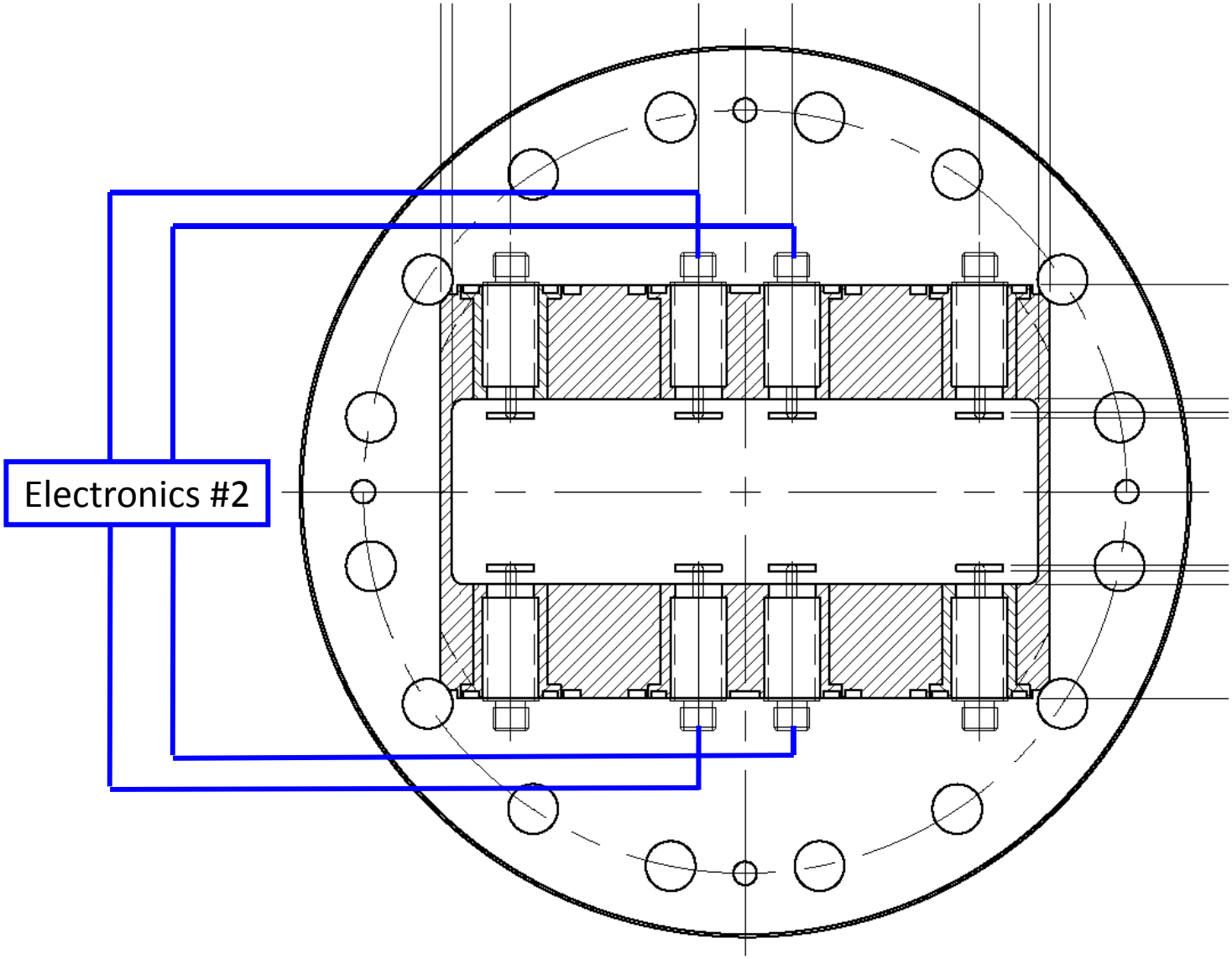




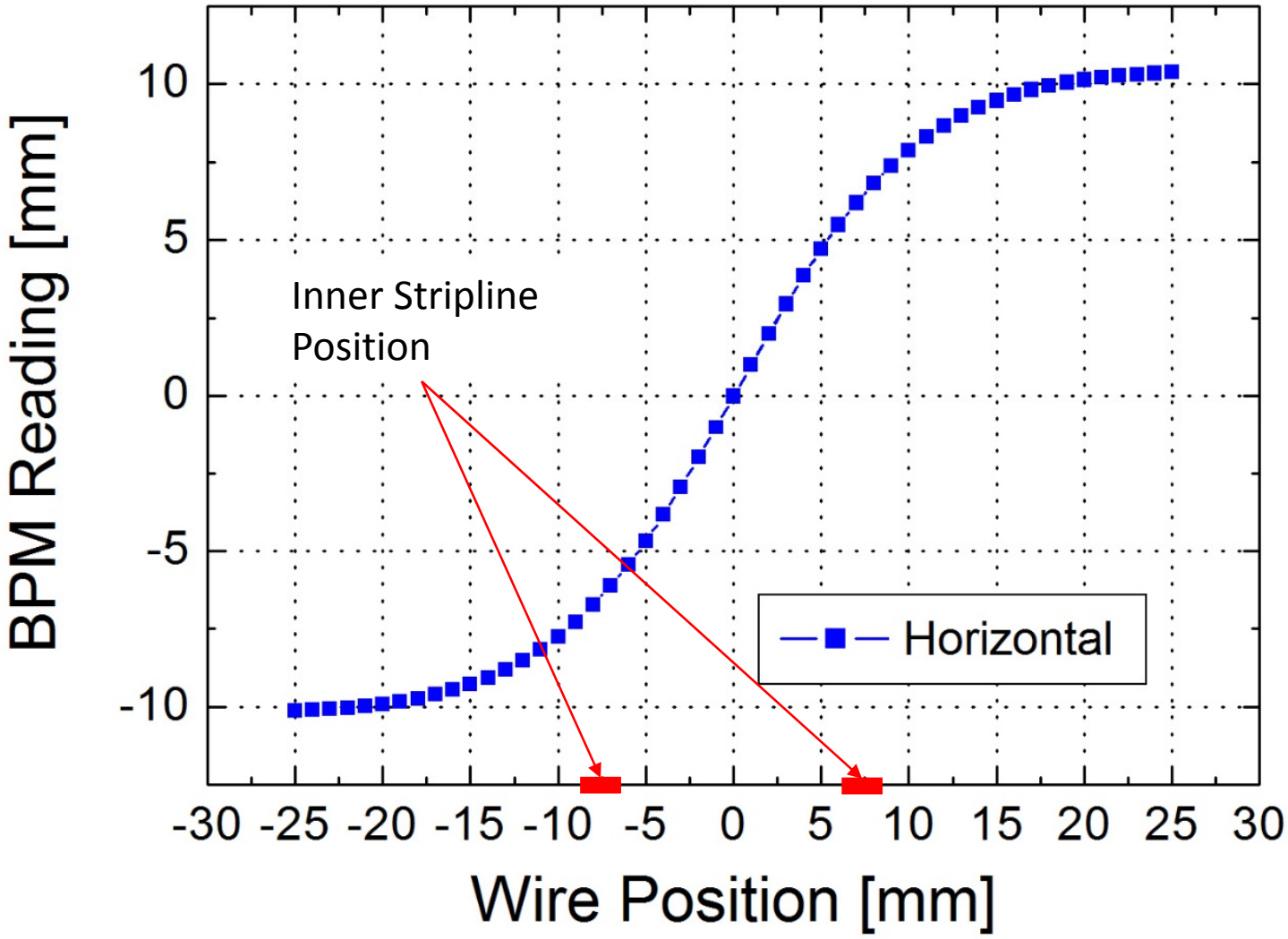
BC BPM (Outer Stripline)



BC BPM (Inner Stripline)

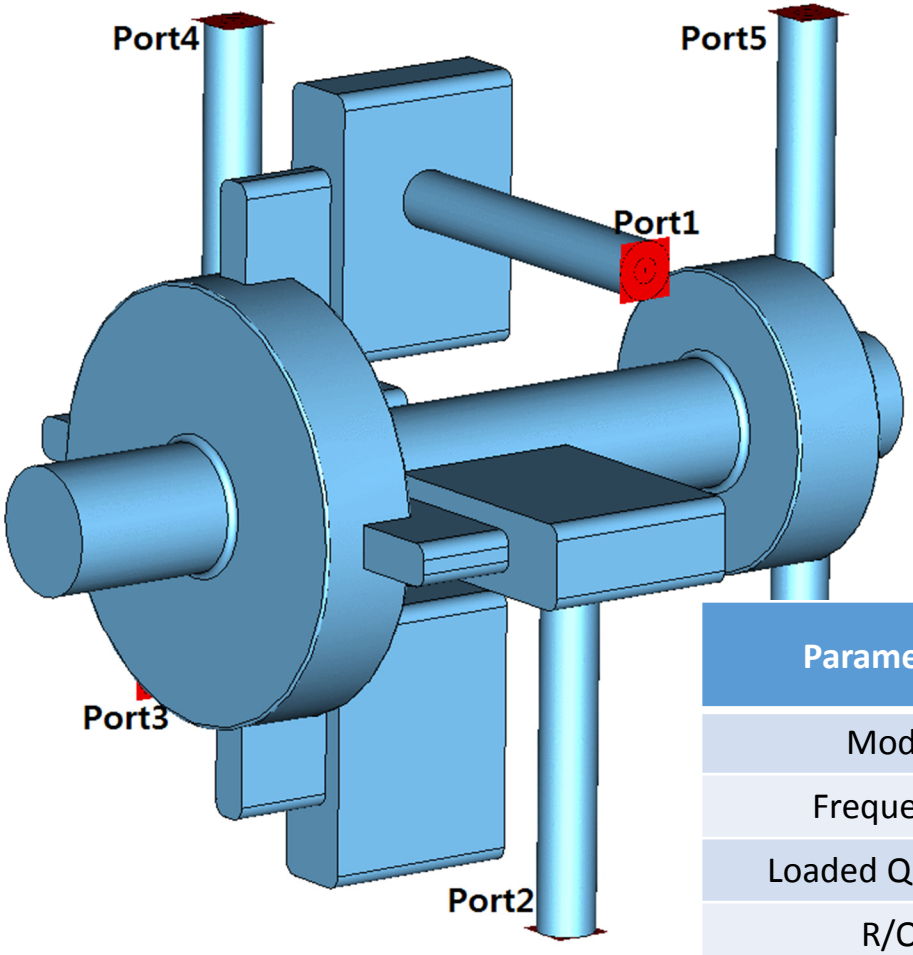


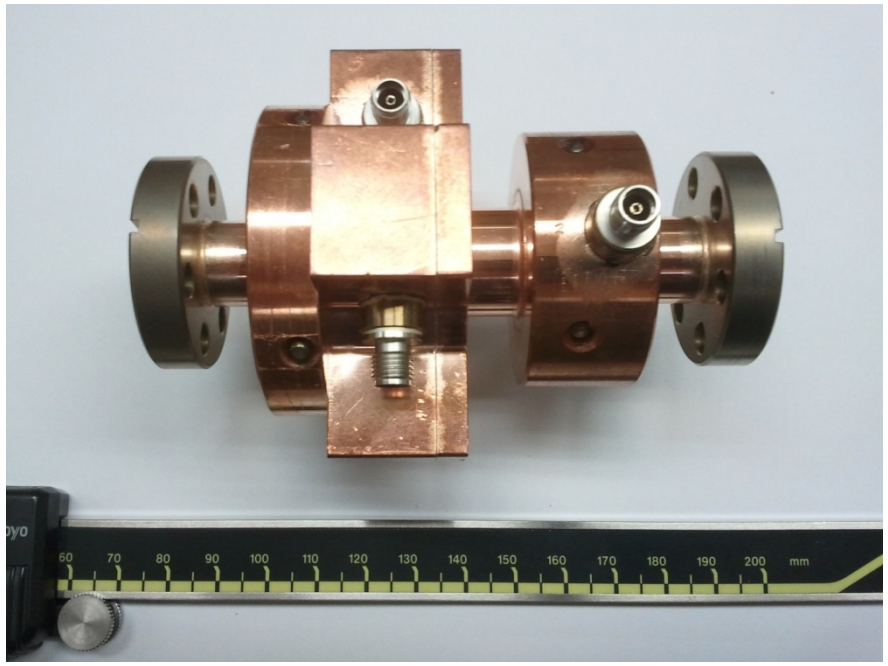
Wire Test Result (Inner Stripline)



Cavity Beam Position Monitor (Collaboration with SLAC)

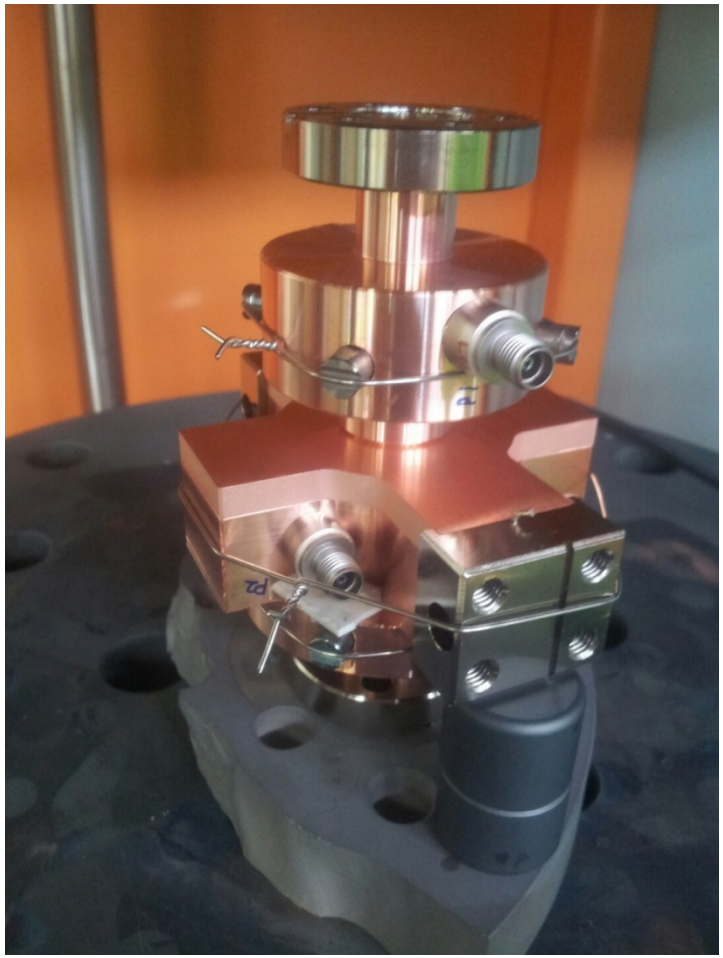
X-Band Cavity BPM



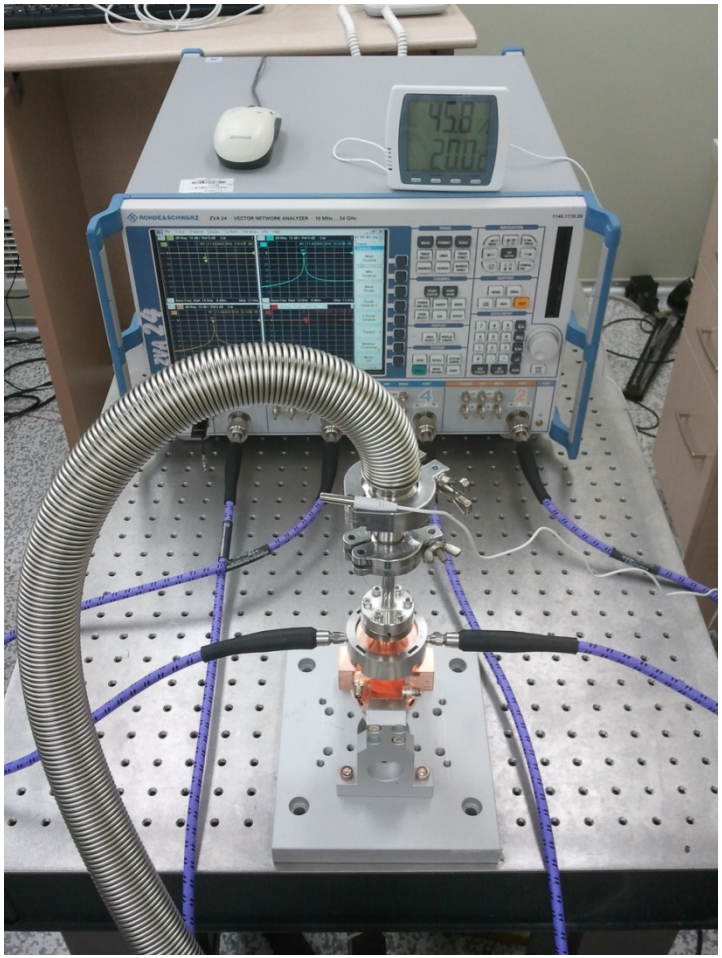


Parameters	XY Cavity (Dipole Cavity)	Reference Cavity (Monopole Cavity)
Mode	TM110	TM010
Frequency	11.424 GHz	11.424 GHz
Loaded Q Factor	2000 – 3000	2000 – 3000
R/Q	> 2 Ohms/mm	> 12 Ohms
Induced Voltage	> 5 mV/pC·mm	> 20 mV/pC
X/Y Cross Talk Level	< -20 dB	-

Brazing & Tuning

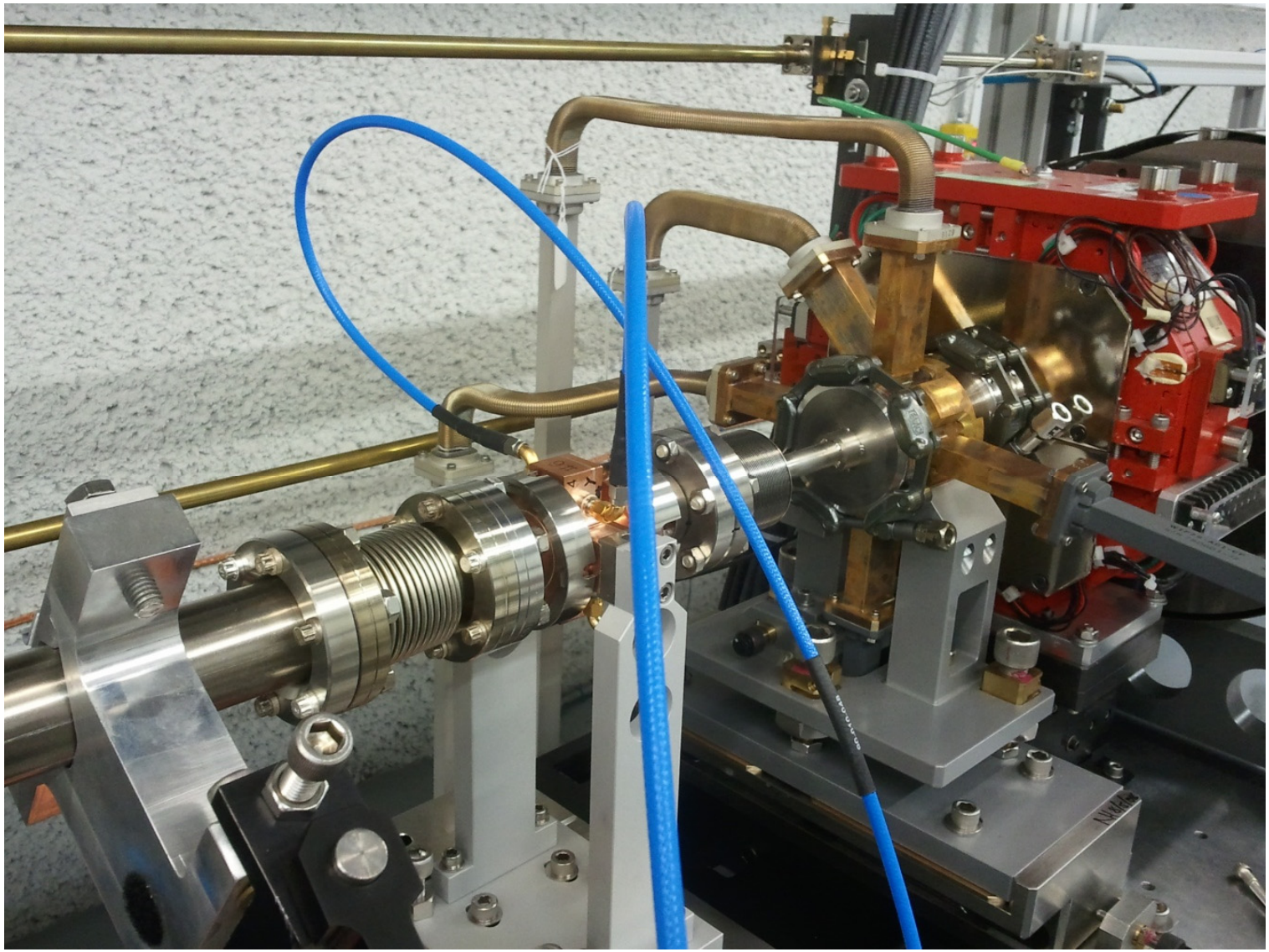


Brazing



Cavity BPM Tuning

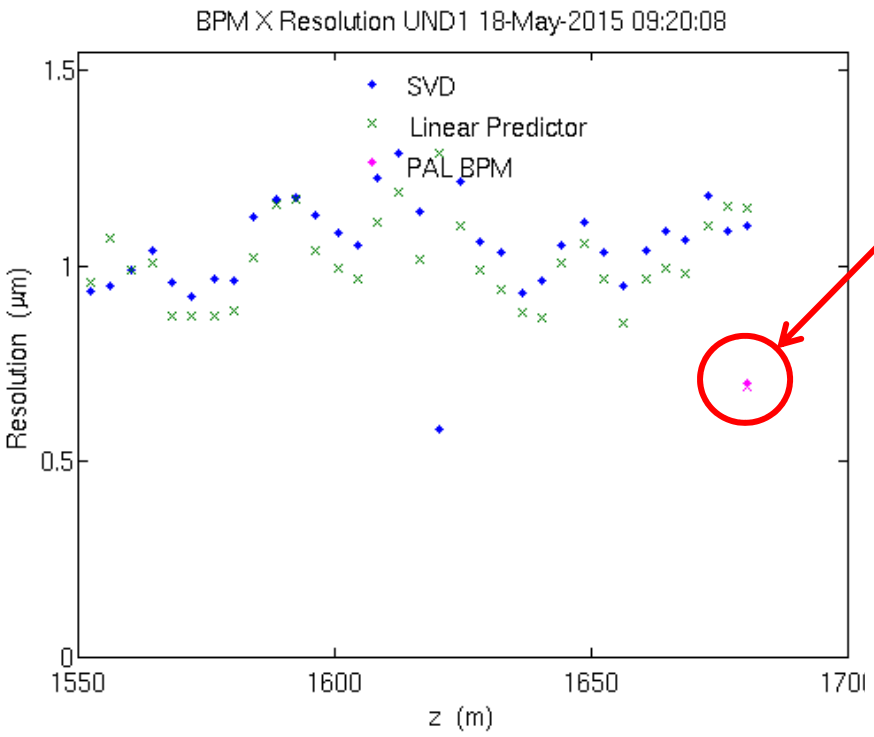
Cavity BPM for LCLS Beam Test

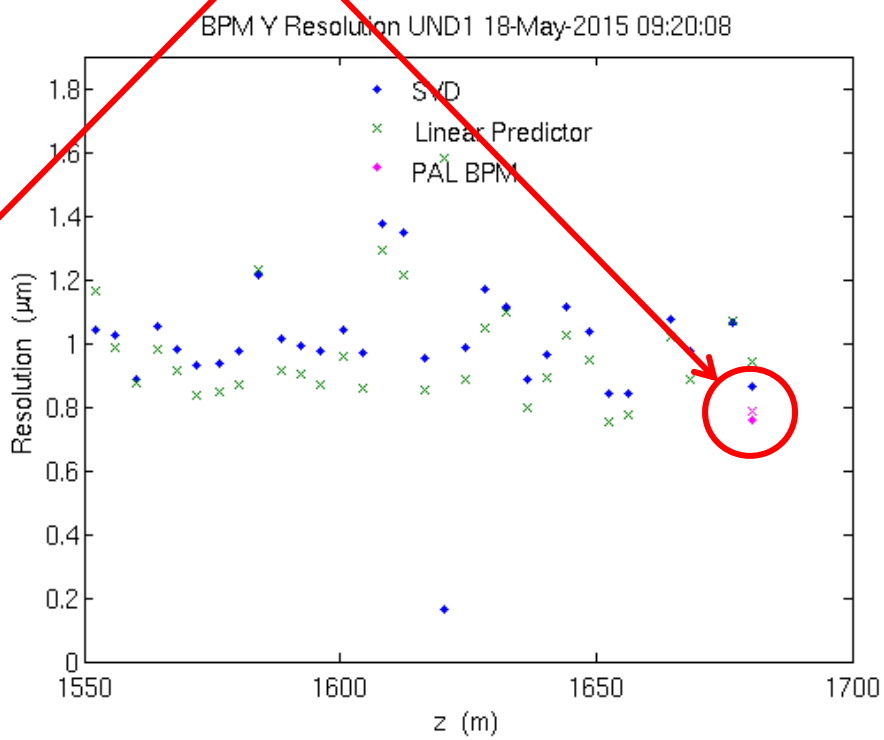


LCLS Resolution Test Result

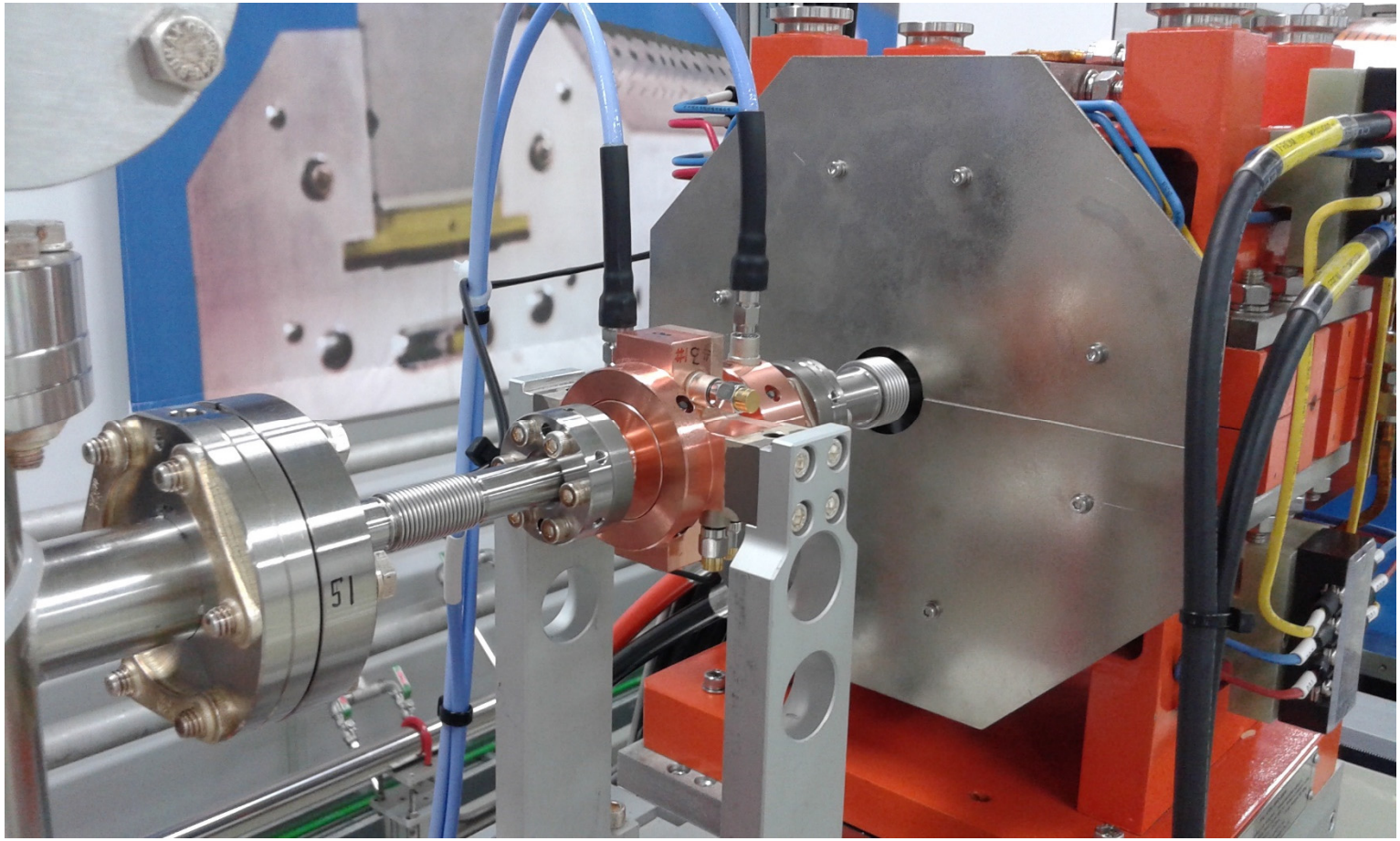
- Measured Resolution: 700 nm (x), 800 nm (y) @ 25 pC

New Cavity BPM

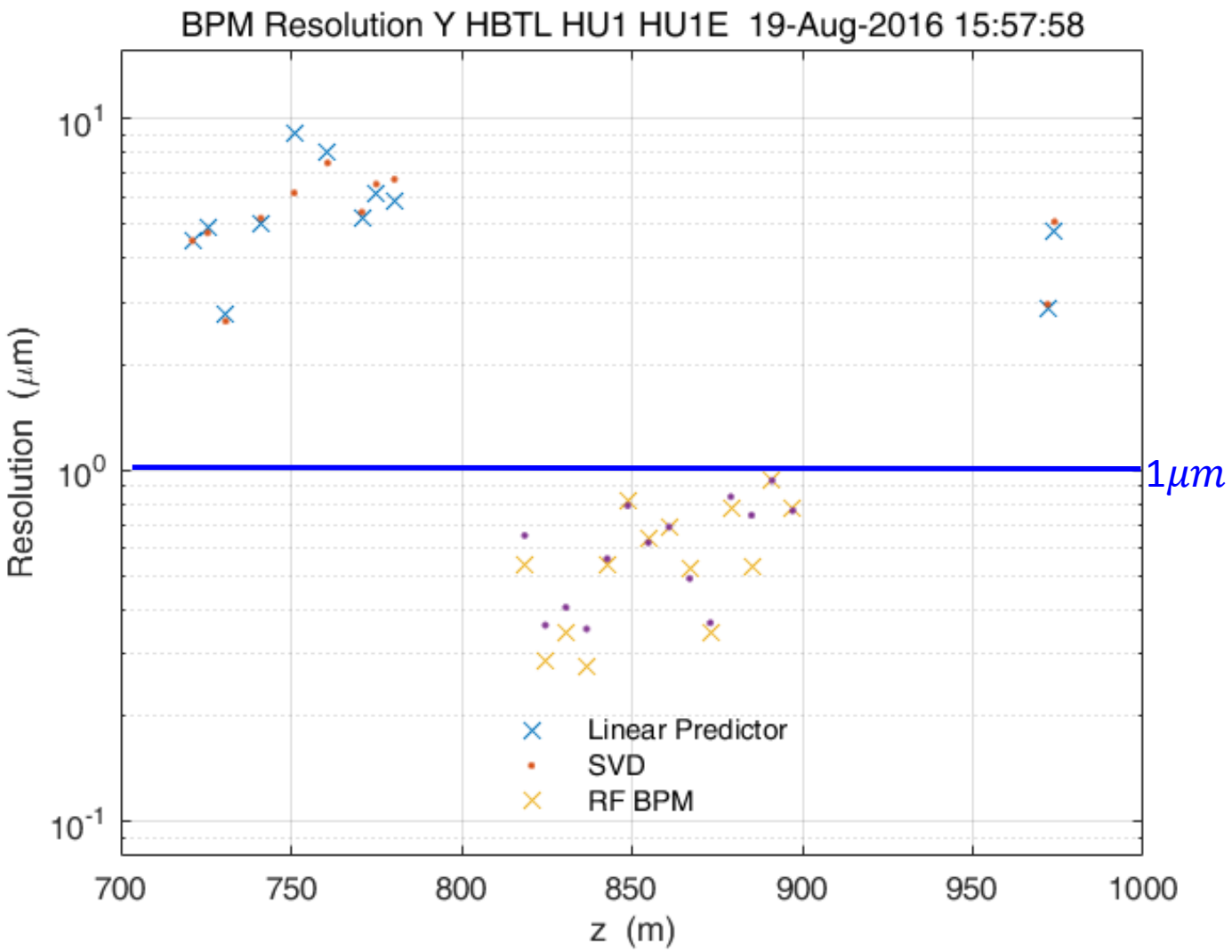




PAL-XFEL Cavity BPM

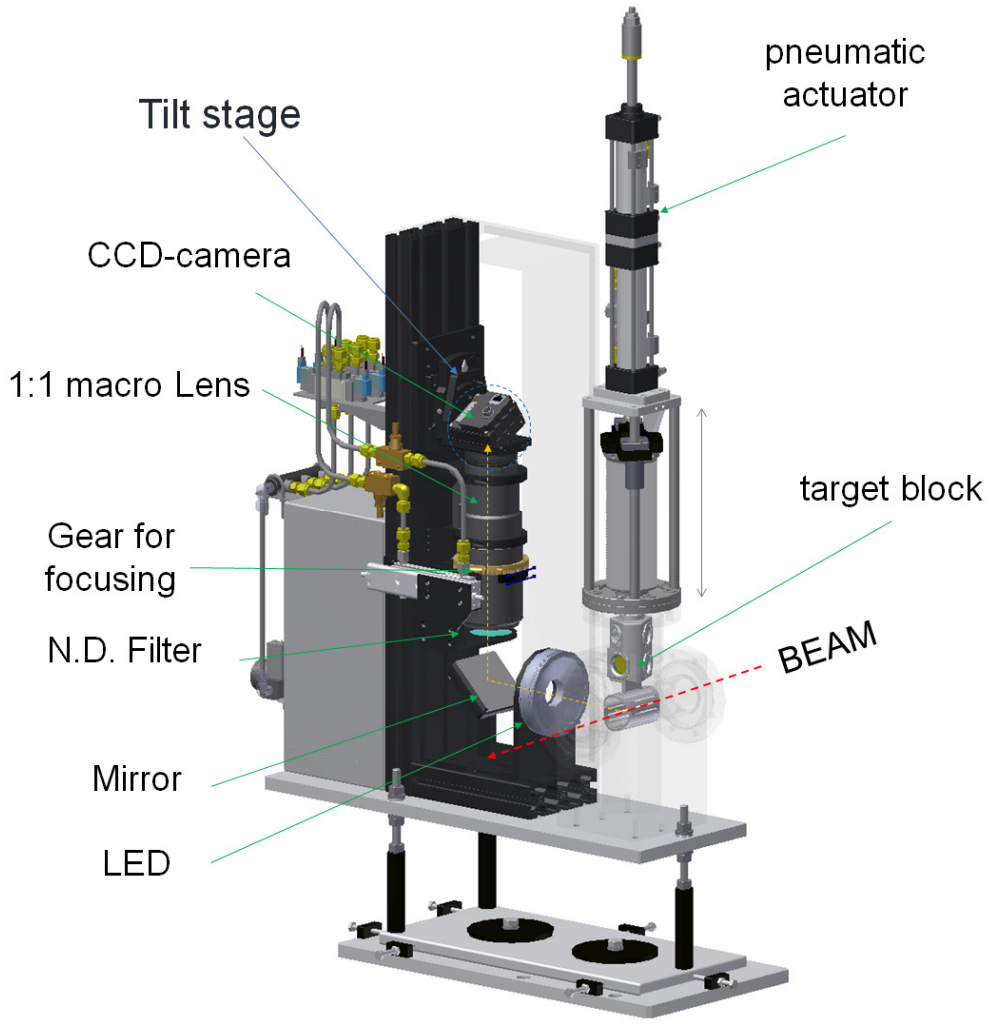


Cavity BPM Resolution



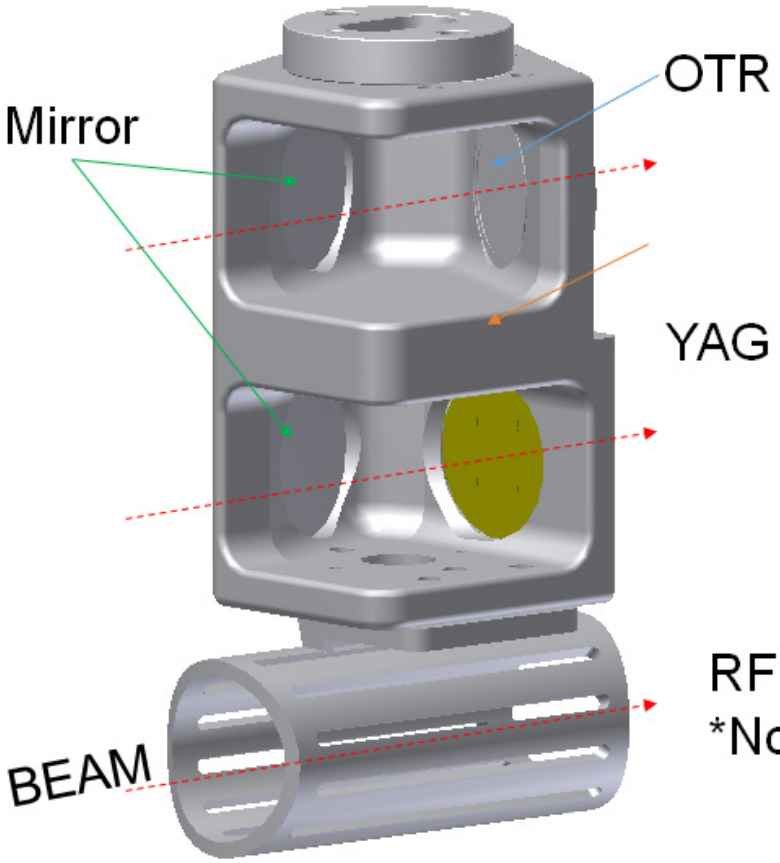
Transverse Profile

Screen Monitor

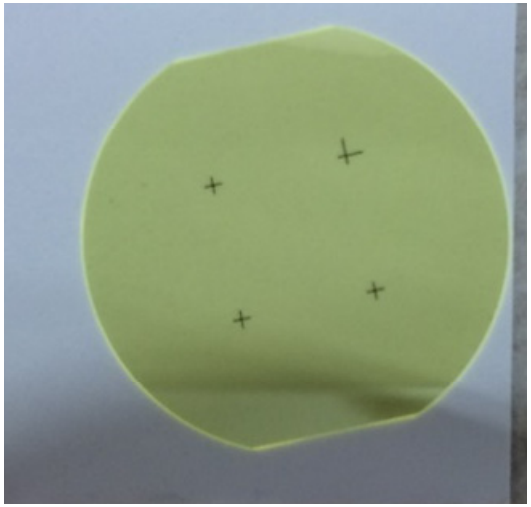


- 3-position pneumatic actuator
- RF shield for reducing the wake field
- Scintillator (YAG:Ce)
- OTR Target (Al-foil)
- LED backlight lamp
- Neutral density filter
- DSLR lens (Magnification : x1)
- DC motor for remote focusing
- Tilt stage for Scheimflug's geometry
- GigE camera

Target Holder

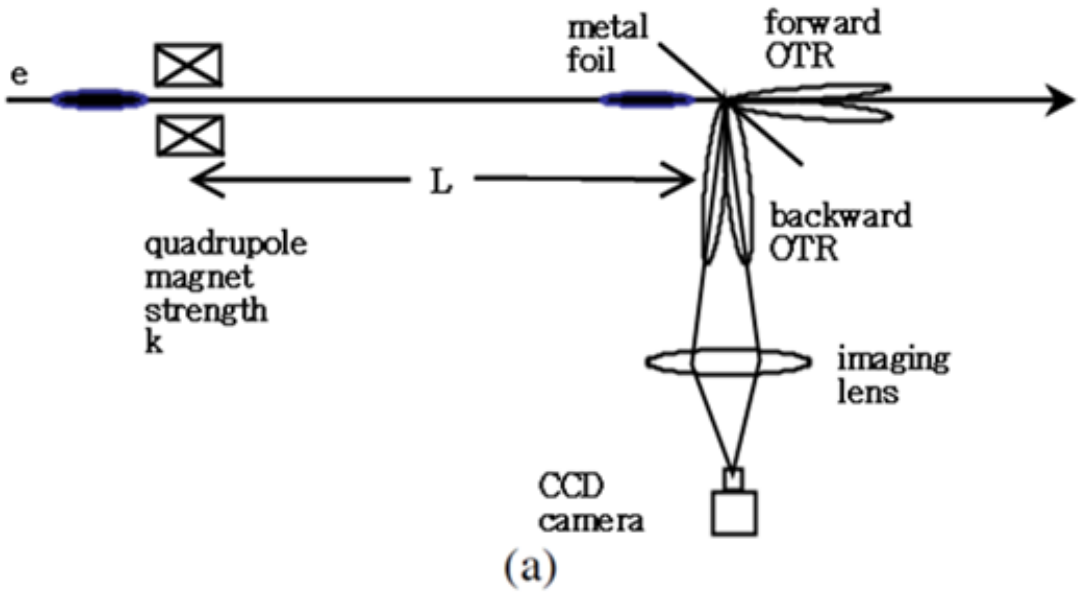


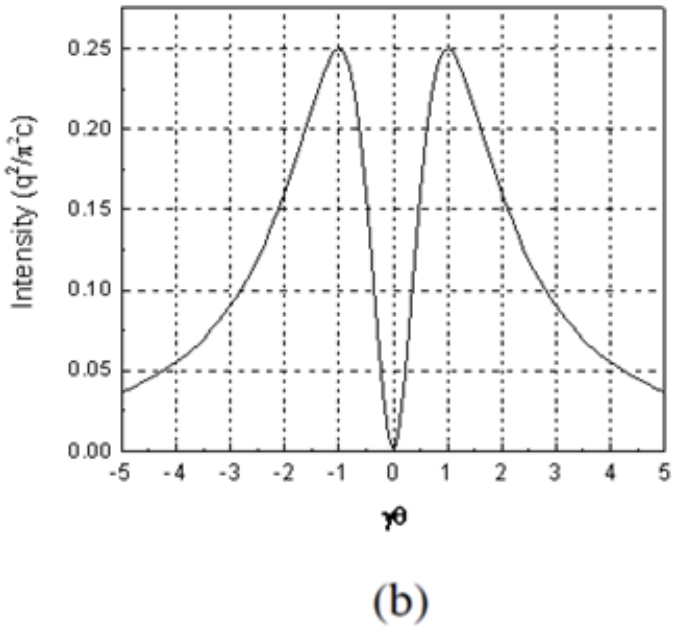
RF shield
*Norminal operation



YAG:Ce with patterning
for size calibration
(Measured resolution
= 8μm X 6.5 μm)

Optical Transition Radiation



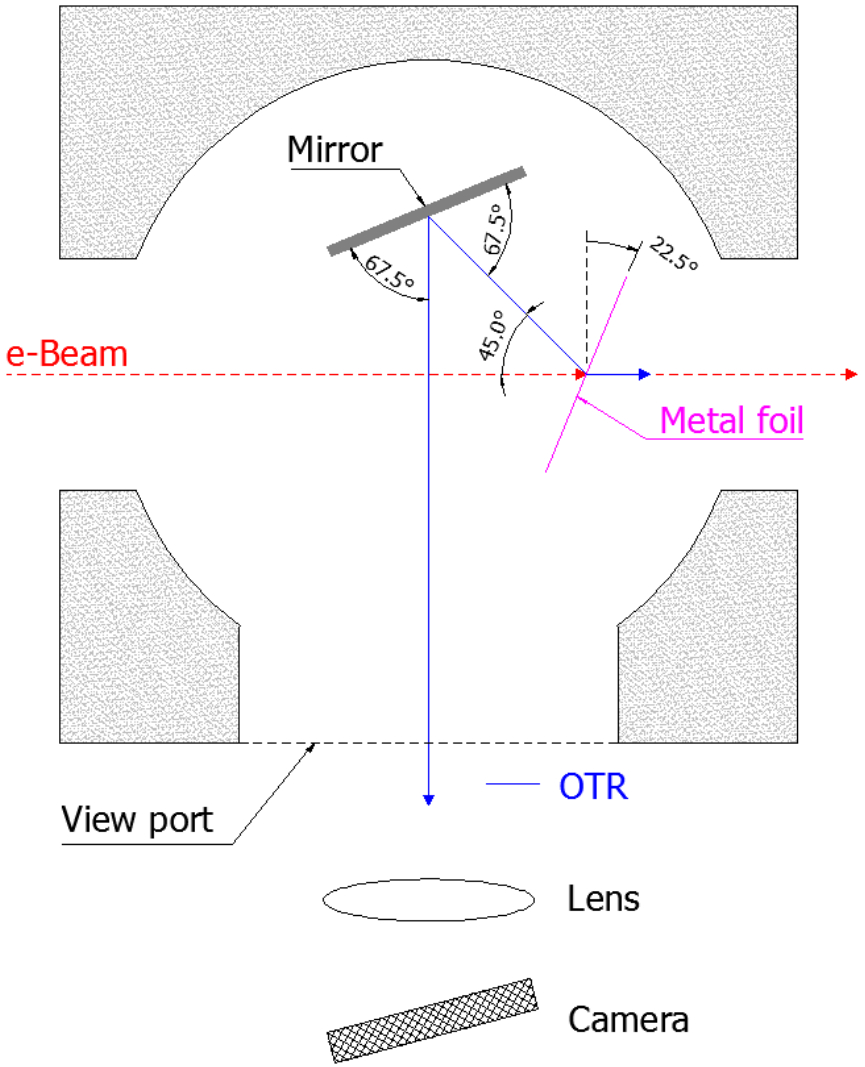


OTR measurement setup and angular profile

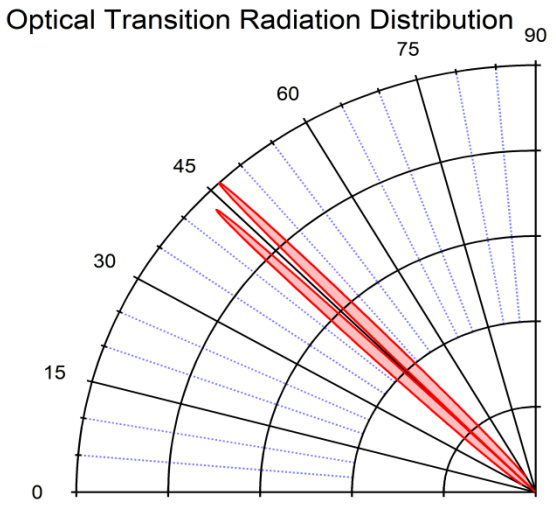
$$\text{Radiation power} \propto \left(\sum_{j=1}^{N} E_j e^{i\phi_j} \right)^2 = \sum_{j=1}^{N} E_j^2 + \sum_{\substack{j=1 \\ j \neq k}}^{N} \sum_{k=1}^{N} E_j E_k^* e^{i(\phi_j - \phi_k)}$$

Coherent OTR can make a saturated beam image.

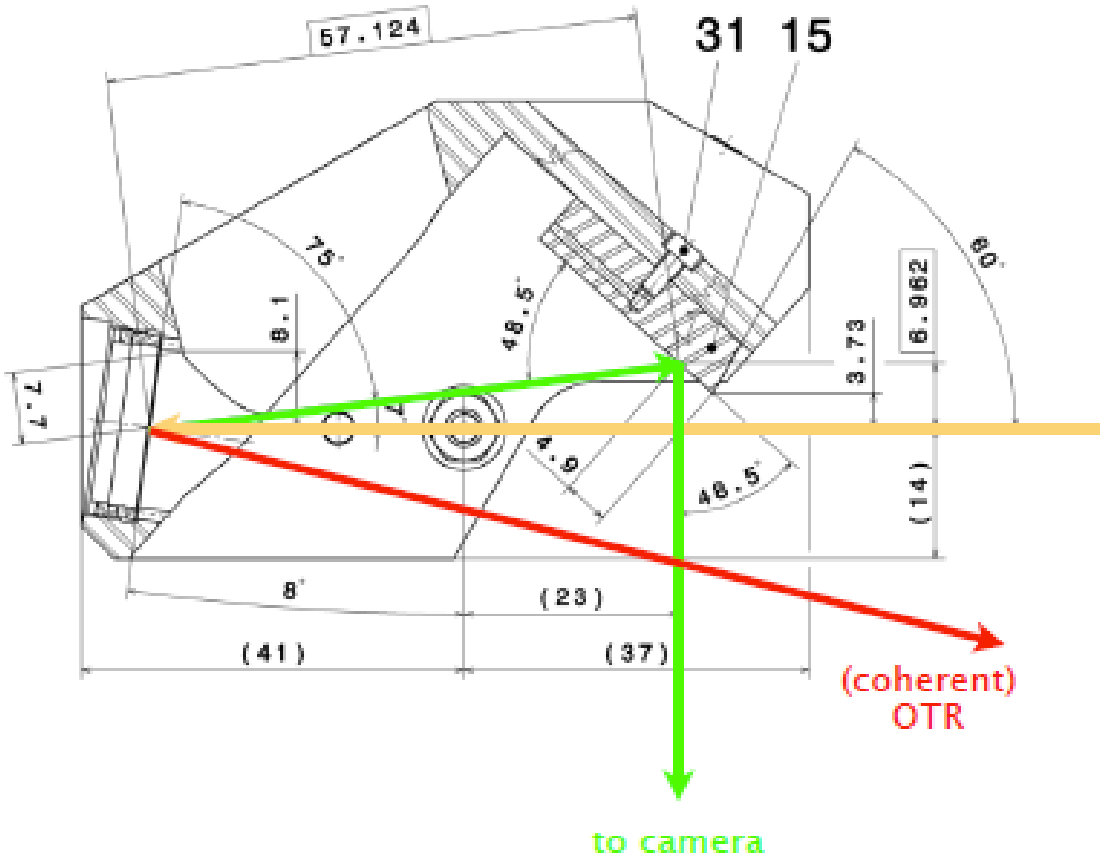
OTR Target



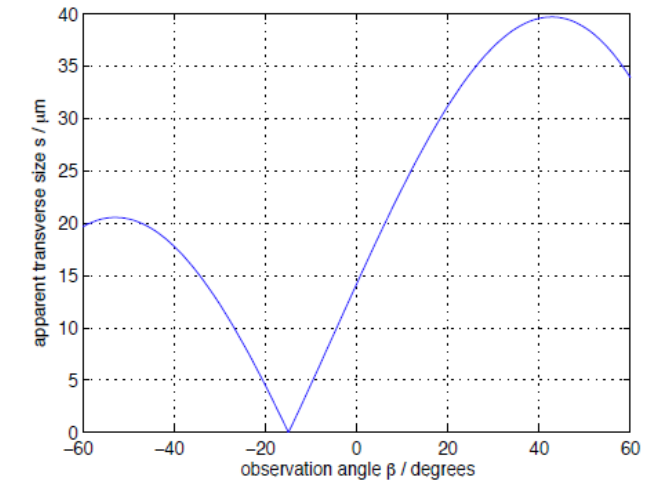
- OTR imaging with Al foil
  - thickness : 1 μm
- Target rotation: 22.5 °



SwissFEL Screen Monitor



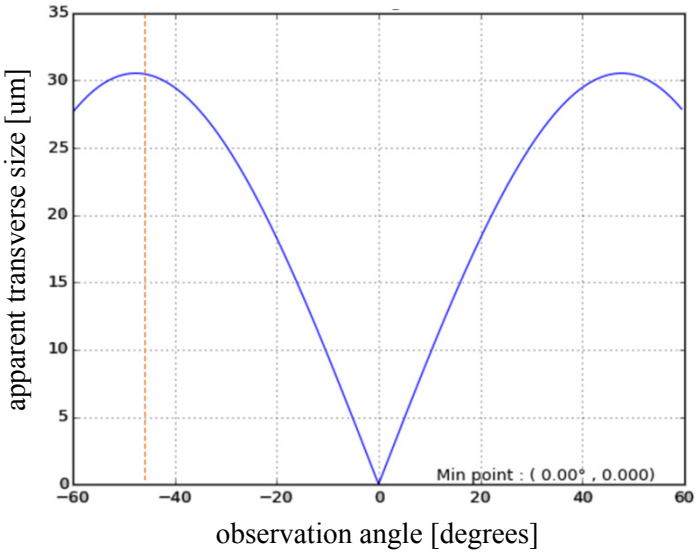
Observed Beam Size

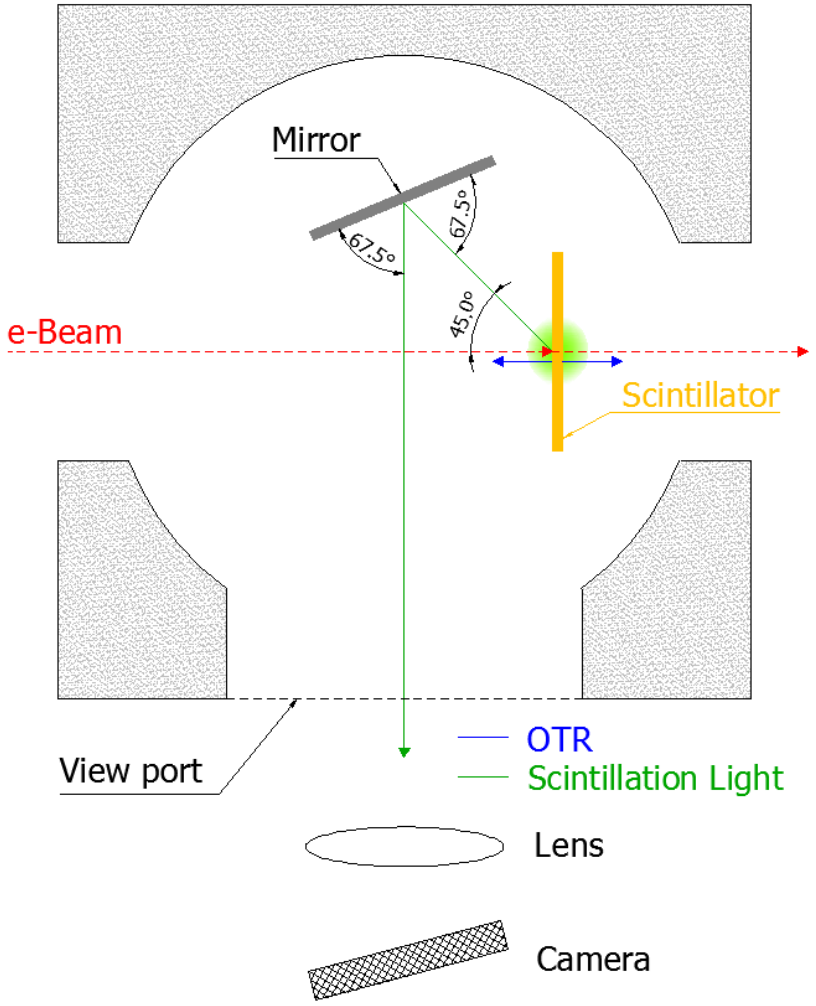


R. Ichebeck *at al.*, Phys. Rev. ST Accel. Beams **18**, 082802 (2015)

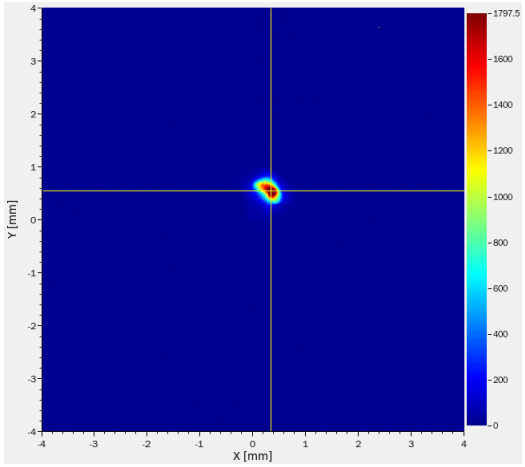
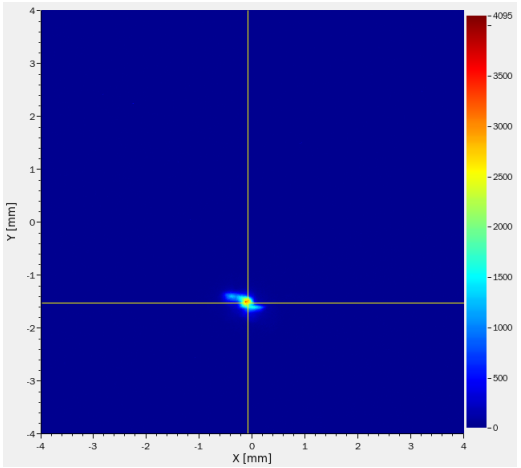
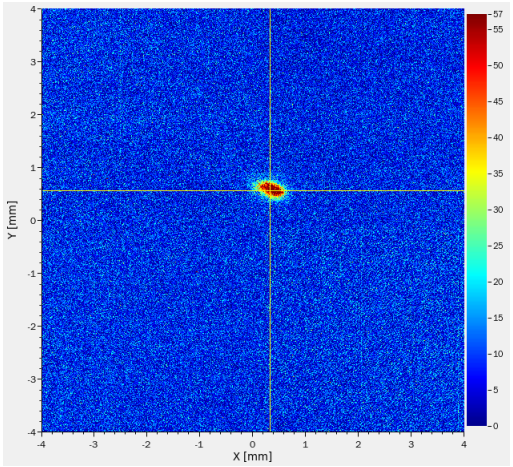
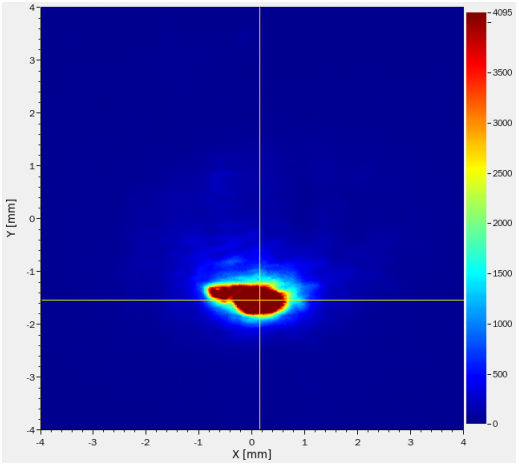
Scintillator Target

- YAG:Ce scintillator
  - Thickness : 100 or 30 um
- Observation geometry of 45° with respect to the beam axis
  ⇒ Minimized holder size

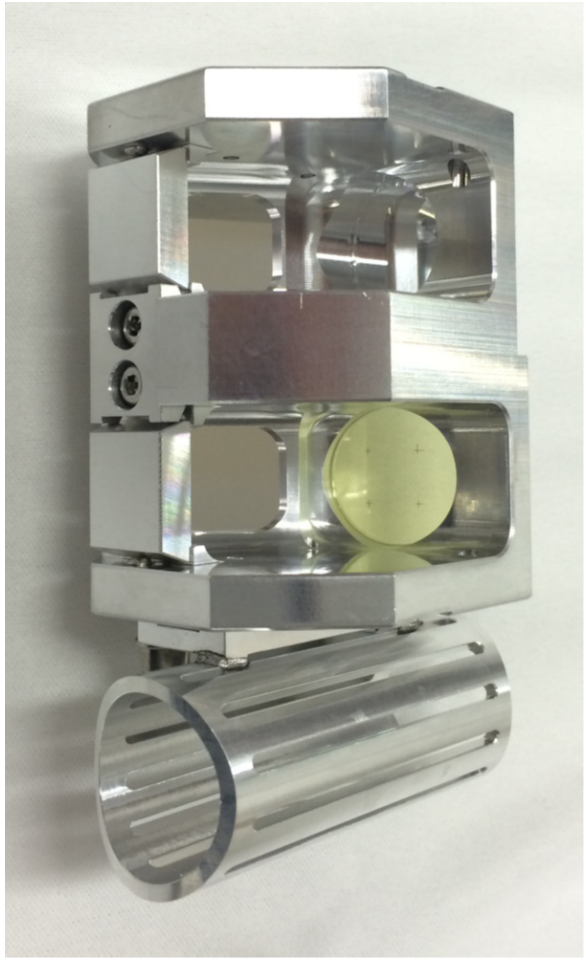


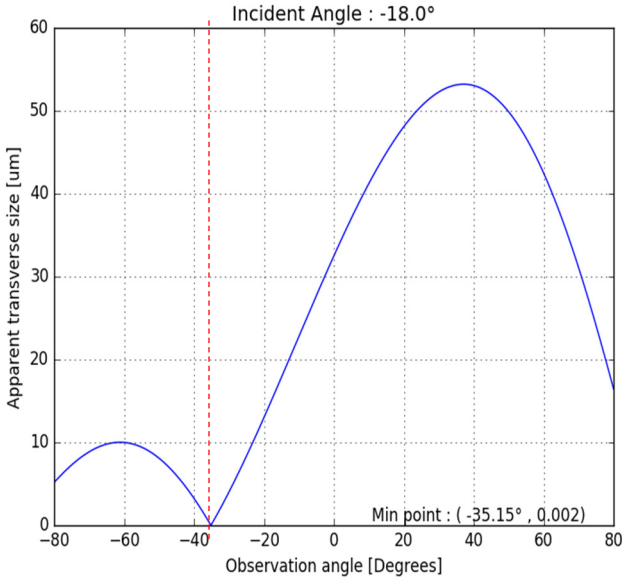


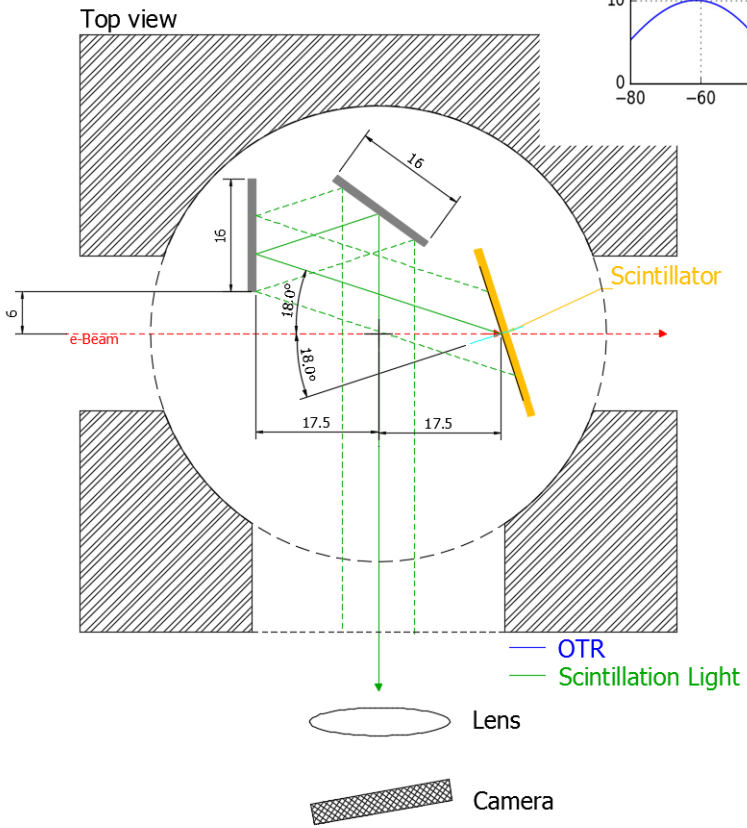
COTR Measurement Results

	BC Off	BC On
YAG:Ce		
OTR		

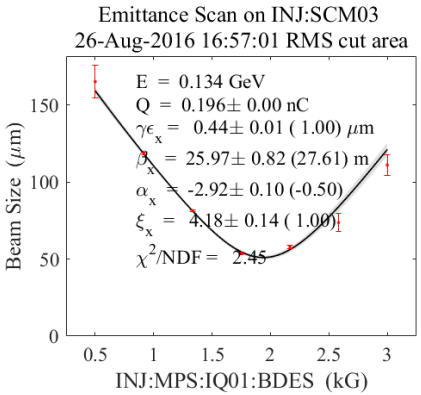
New Target Holder

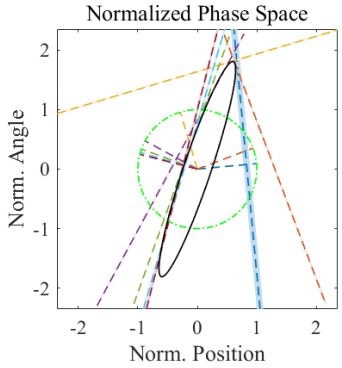


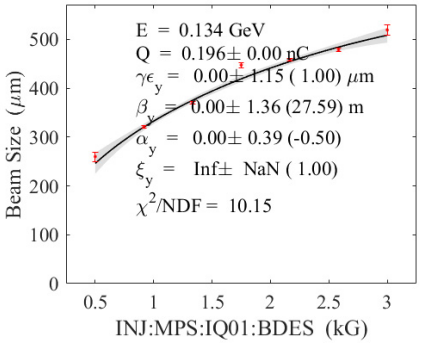


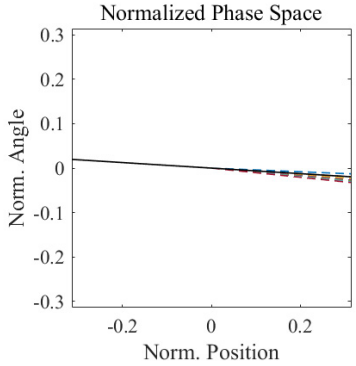


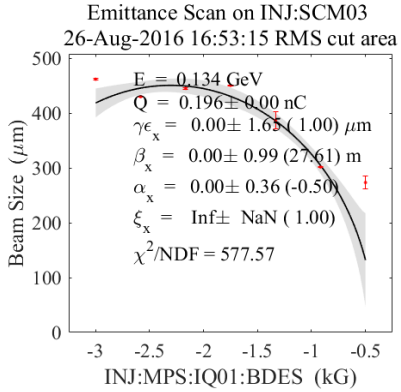
Emittance Measurement

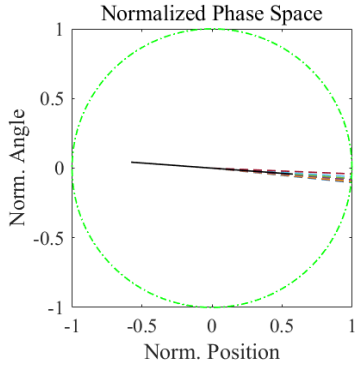


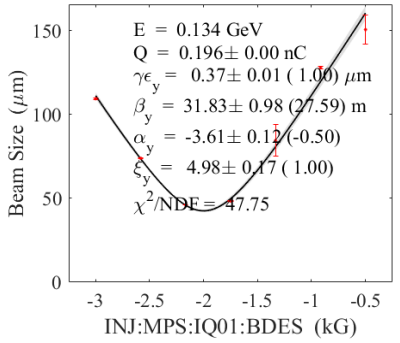


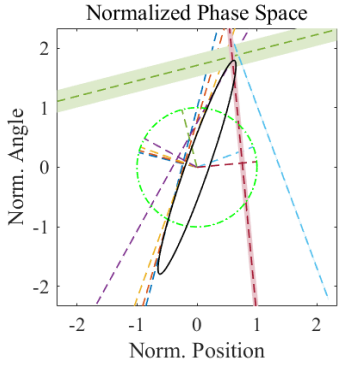












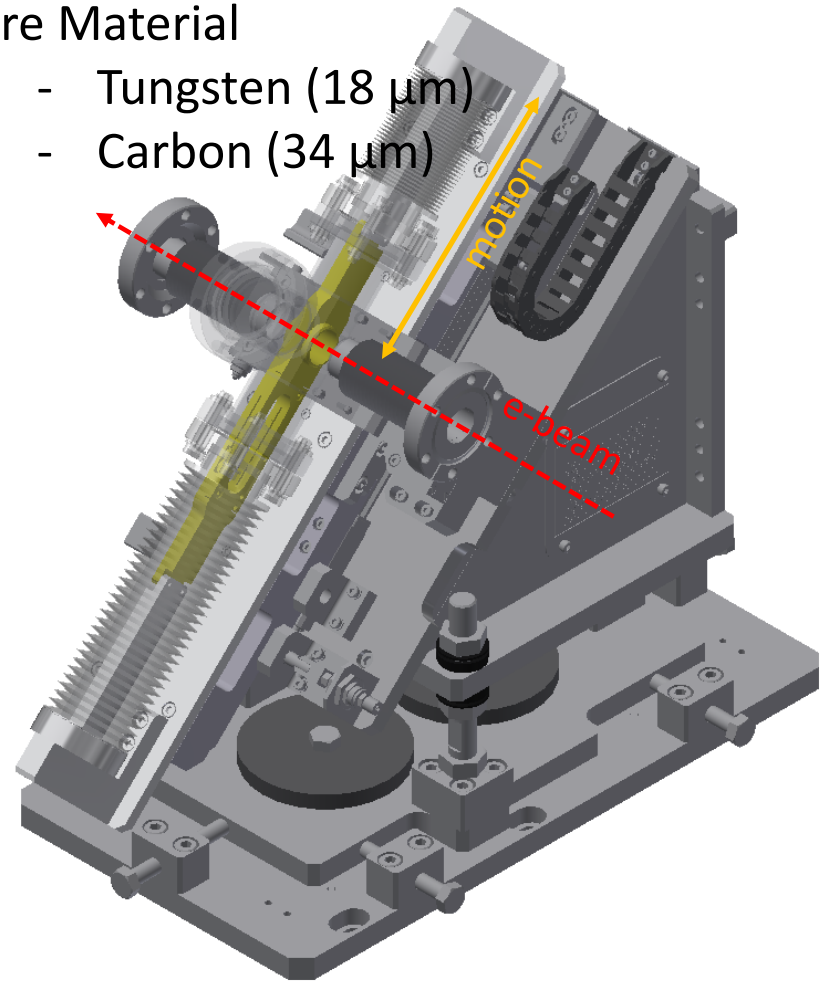
Horizontal: 0.44 mm-mrad

Vertical: 0.37 mm-mrad

Wire Scanner

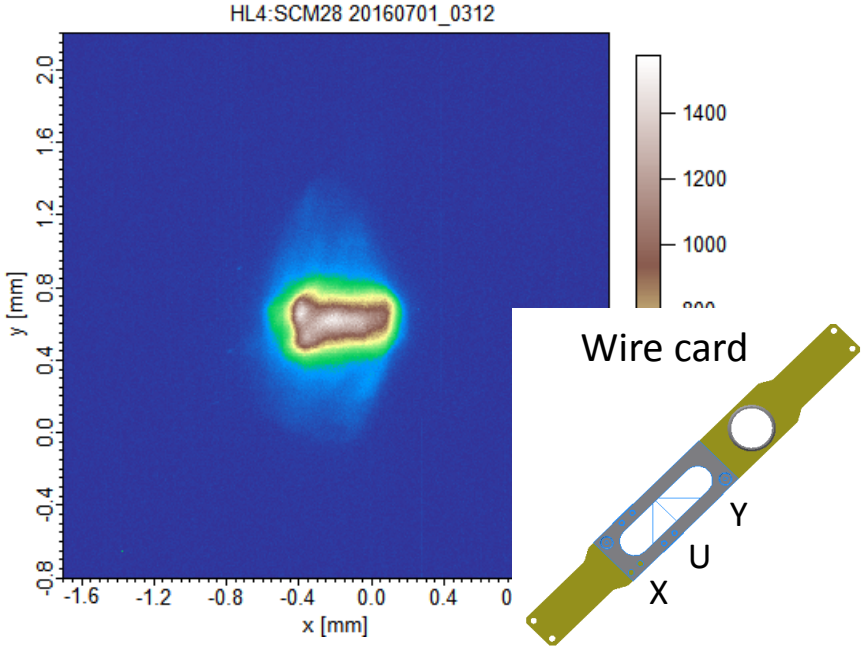
Wire Material

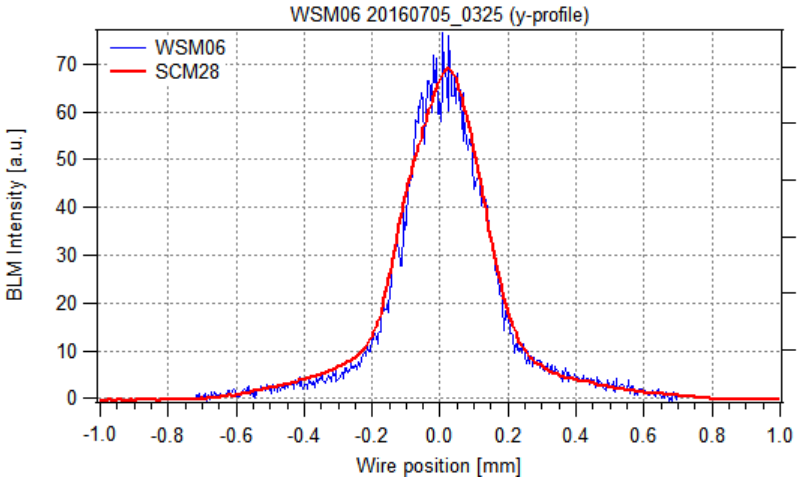
- Tungsten (18 μm)
- Carbon (34 μm)

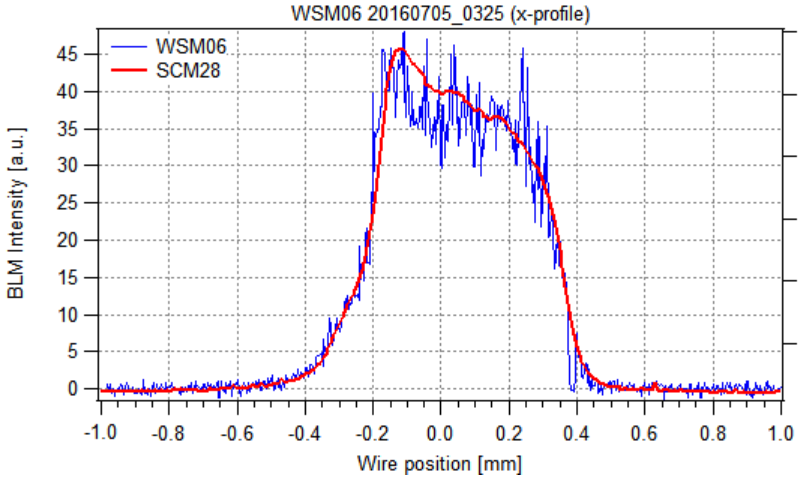


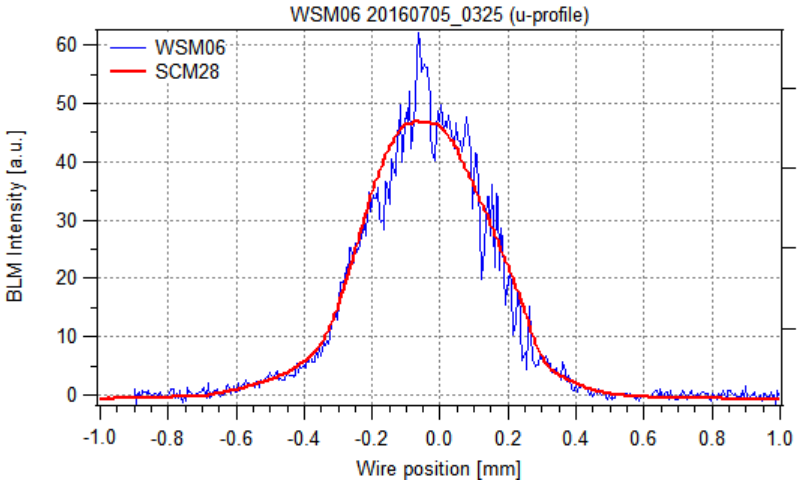
Screen Monitor
and Wire Scanner

Screen & Wire scanner profile :





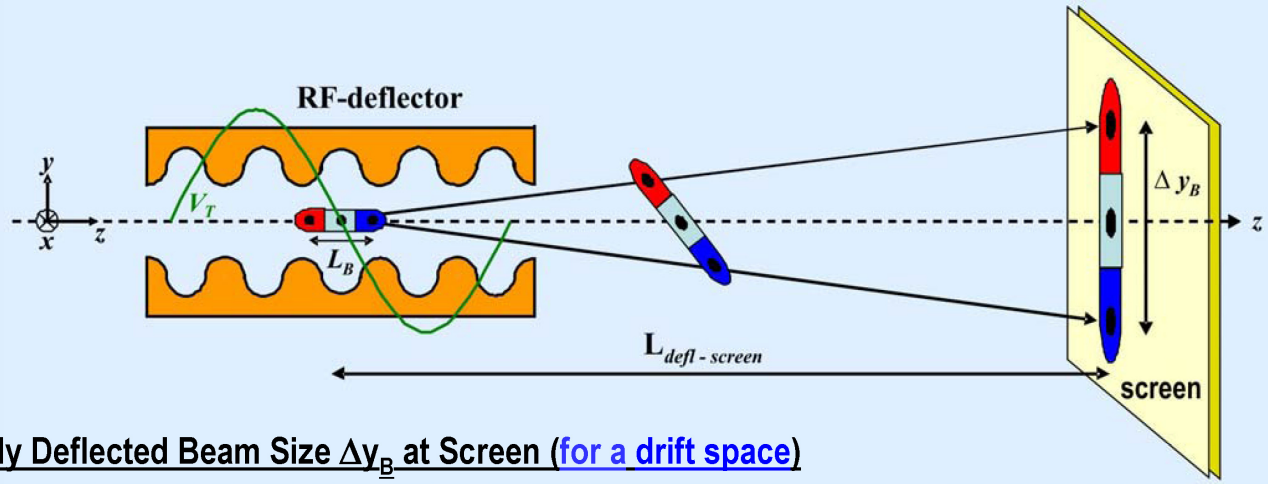




*wire position with motor position PV, **manual scale fit

Longitudinal Profile

Principle of Bunch Length Measurement with RF Deflector



Transversely Deflected Beam Size Δy_B at Screen (for a drift space)

$$\Delta y_B = \frac{\omega_{RF} V_T}{2c\,E/e} \cos(\varphi_{RF})\; L_B\; \Delta L_{def-screen}$$

Assuming…:

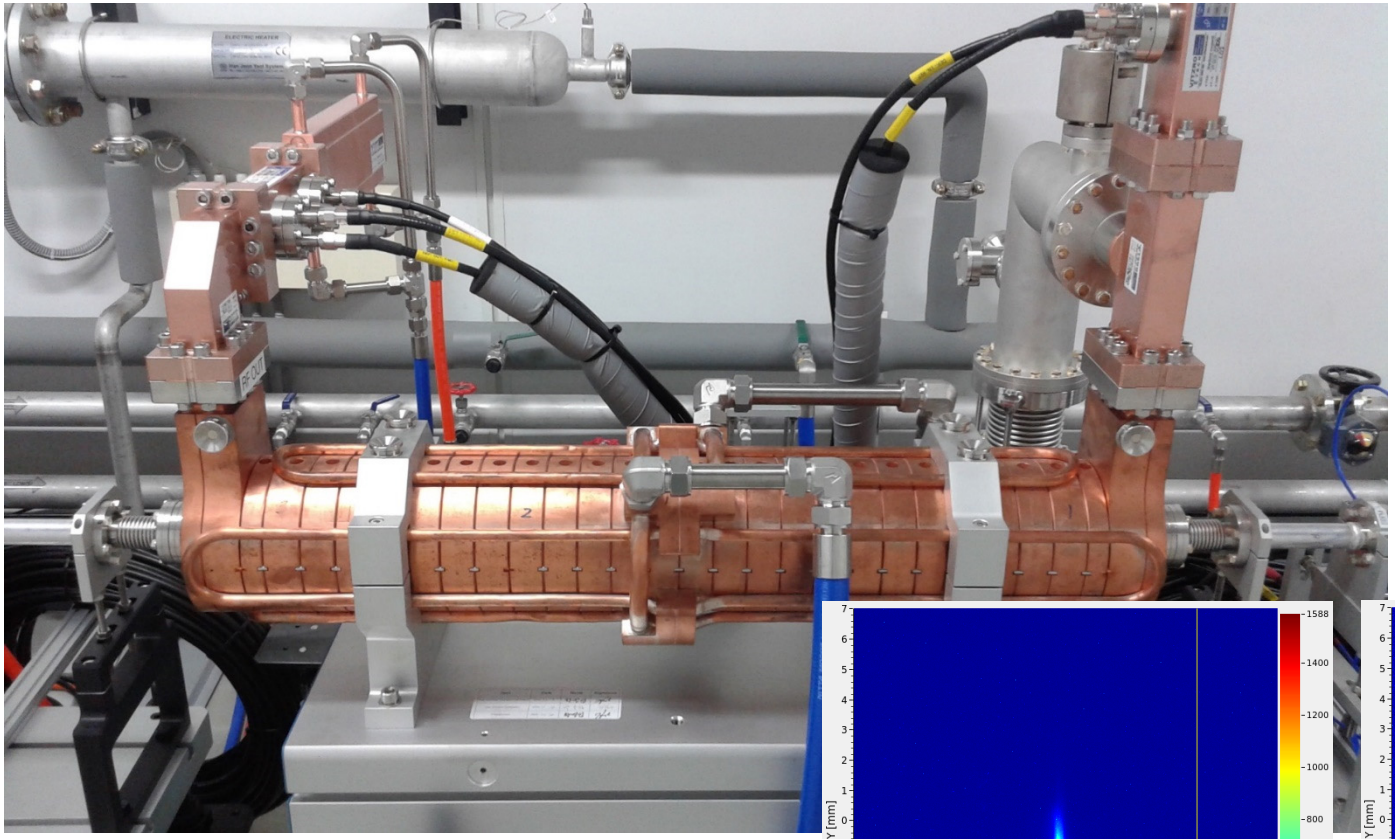
- φ_{RF} = 0° at the center of the bunch results in shearing of particle density distribution without changing mean particle position
- longitudinal stability (bunch arrival time vs. RF phase) must be high in case of averaging of measurements
- pencil-like beam (zero-emittance)
- no beam offset in the RF deflector

Example:

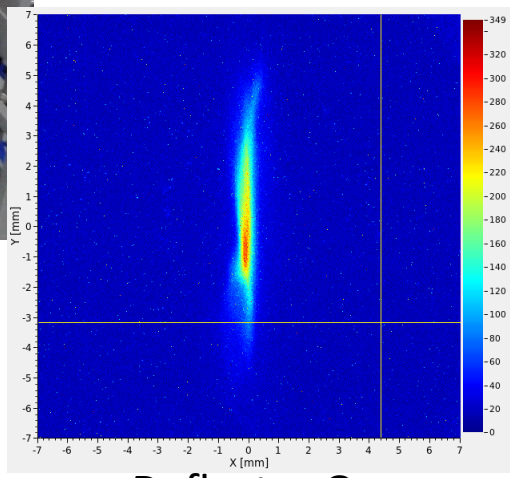
Parameters for 250 MeV PSI FEL Injector Test Facility

ω_{RF}	=	$2\pi \cdot 3$	GHz
V_T	=	2.5	MV
c	=	$3 \cdot 10^8$	ms^{-1}
E	=	250	MeV
L_B (FWHM)	=	600	fs
	=	200	μm
$\Delta L_{def-screen}$	=	12.25	m
Δy_B	=	770	μm

Transverse Deflecting Cavity

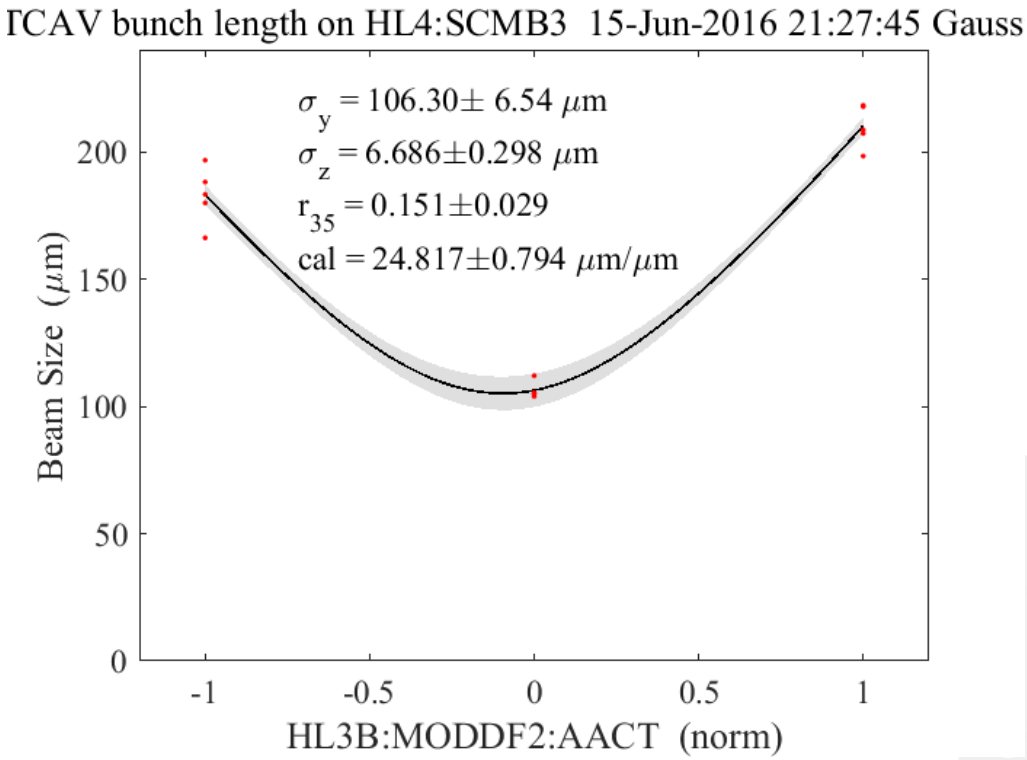


Deflector Off

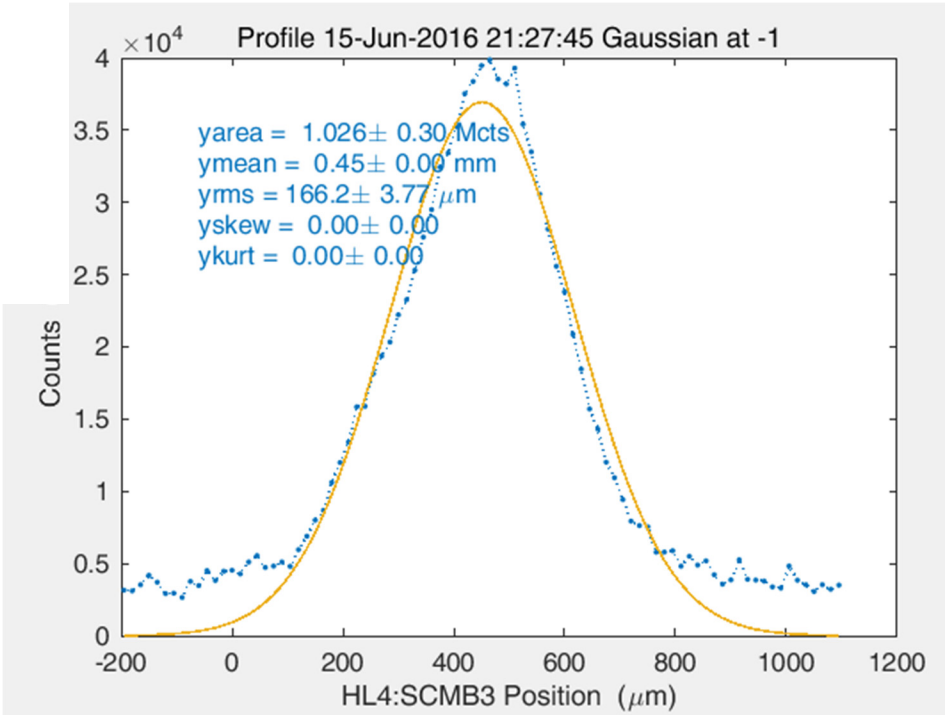


Deflector On

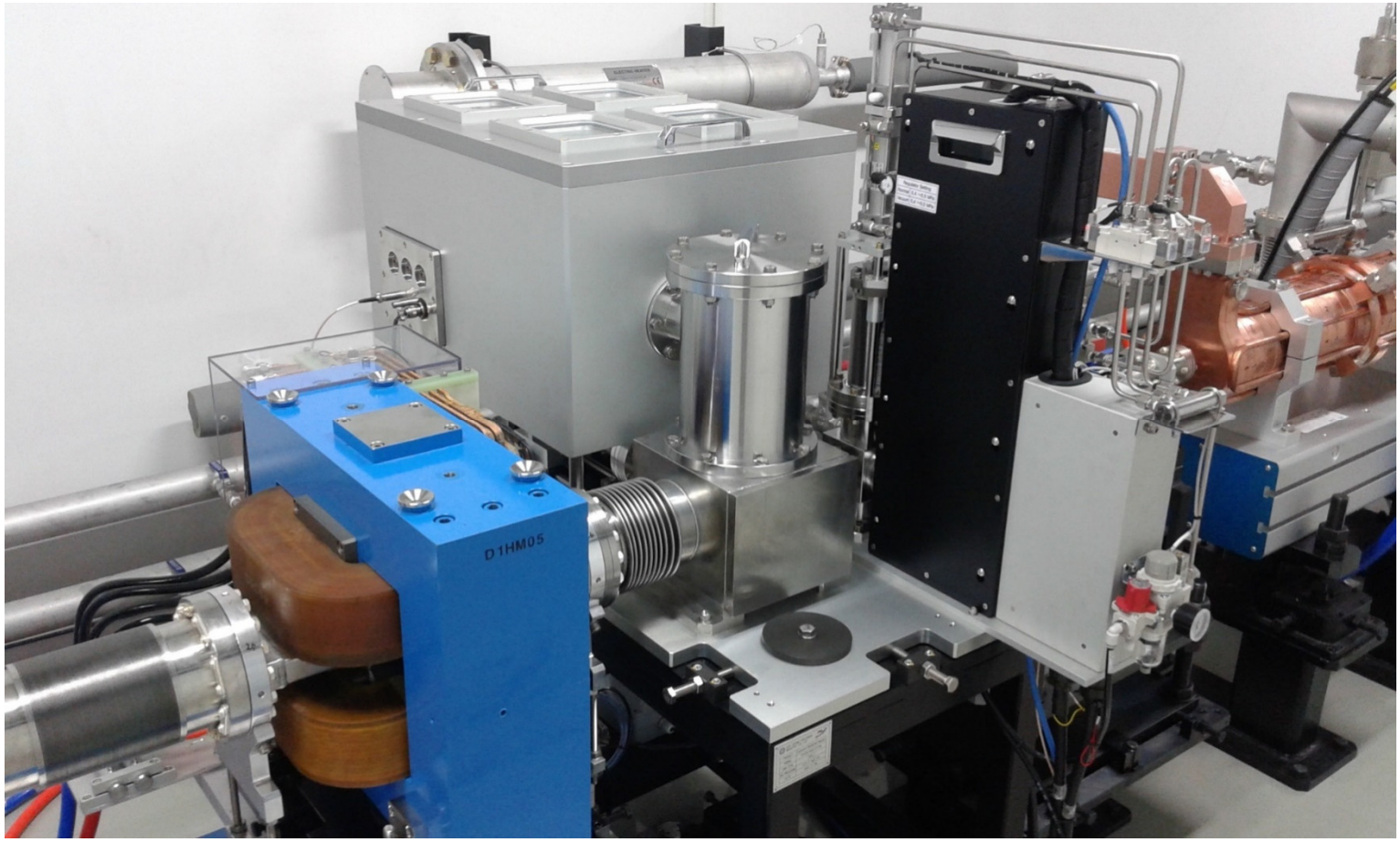
Bunch Length Measurement



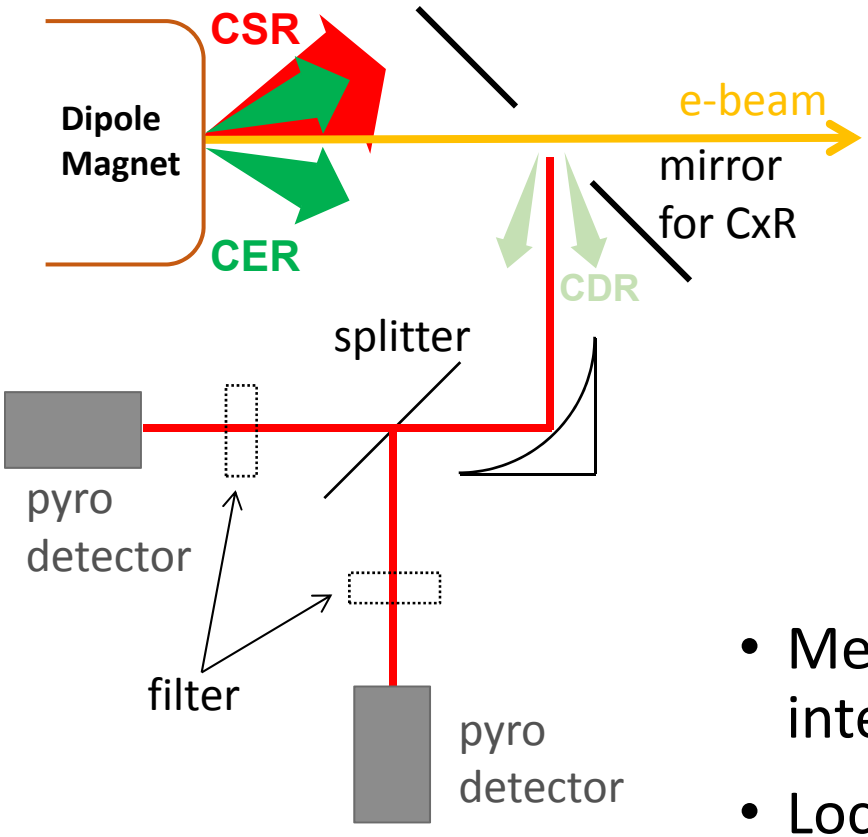
Bunch length
6.7 μm = 22 fs
(170 pC → 3.07 kA)

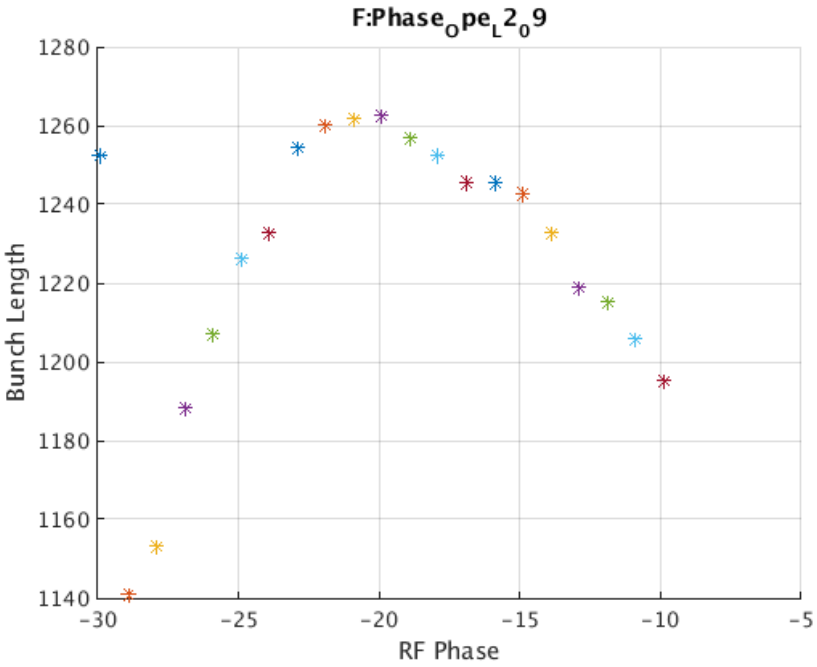


Coherent Radiation Monitor



Coherent Radiation Monitor





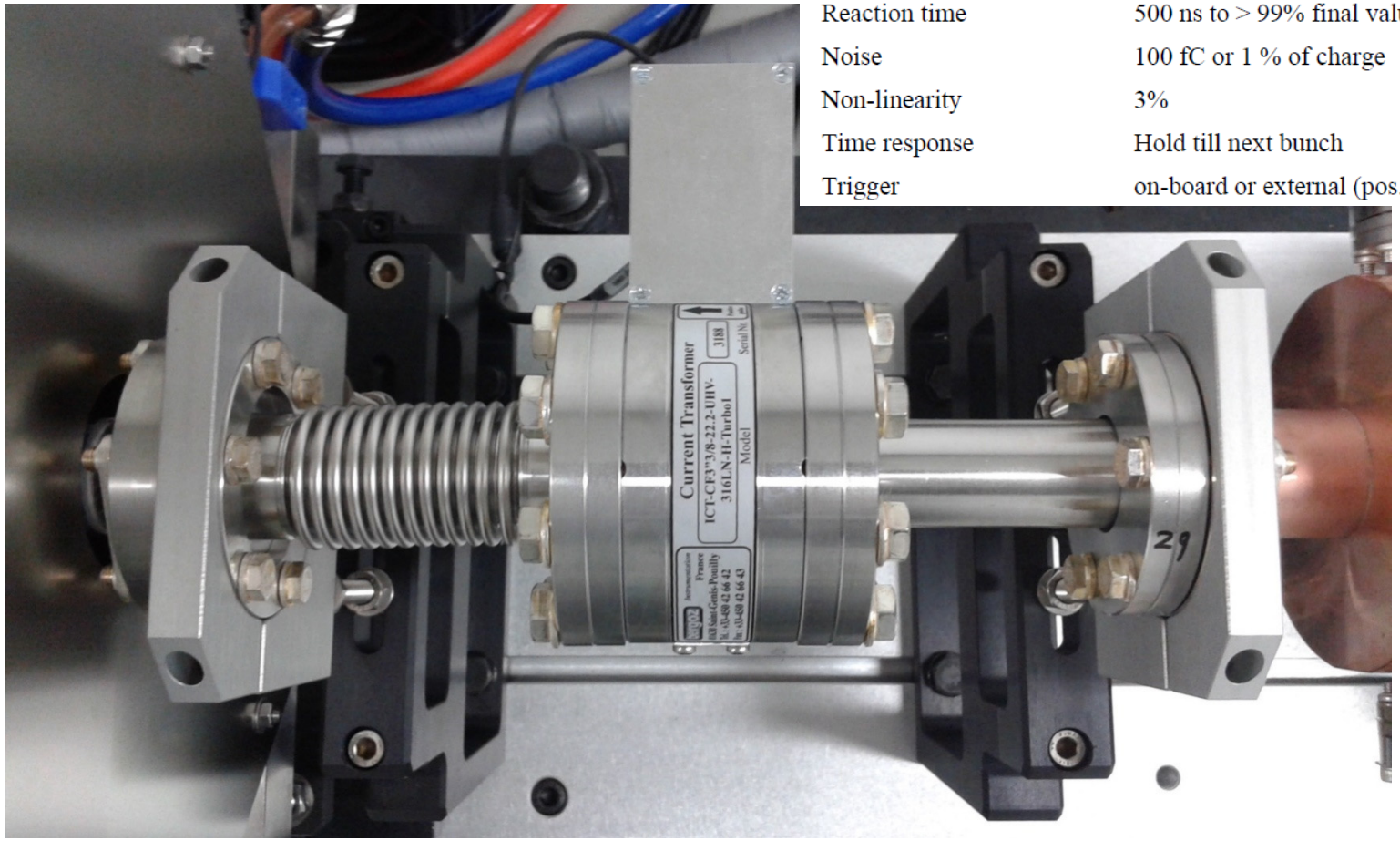
- Measure coherent radiation intensity with pyro-detectors
- Located after bunch compressors
- Calibration with the transverse deflecting cavity
- Bunch length monitor & feedback

Beam Charge Monitor

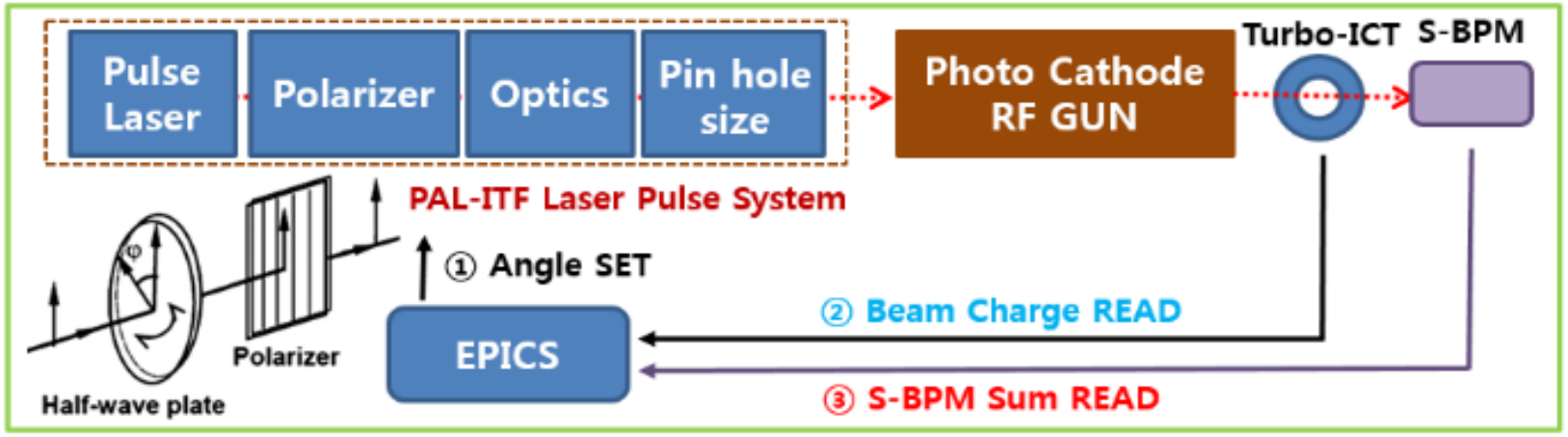
Turbo-ICT

Charge measurement:

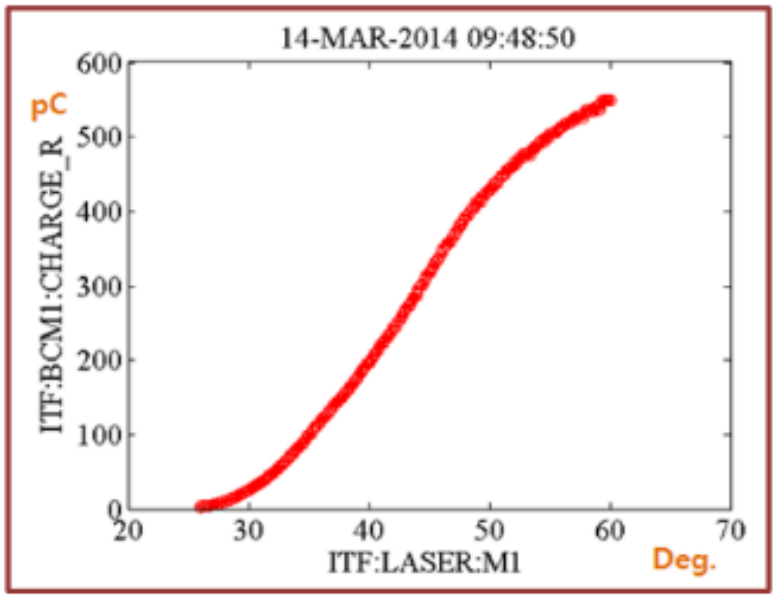
BCM-RF mode	S&H
Input charge	200 pC max (more without front-end amplifier)
Measurement single range	100 fC – 200 pC
Bunch repetition rate	Single bunch – 2 MHz
Output voltage	0 / 5V, log of the beam charge
Reaction time	500 ns to > 99% final value
Noise	100 fC or 1 % of charge
Non-linearity	3%
Time response	Hold till next bunch
Trigger	on-board or external (pos. edge, > 2.4V, > 30 ns width)



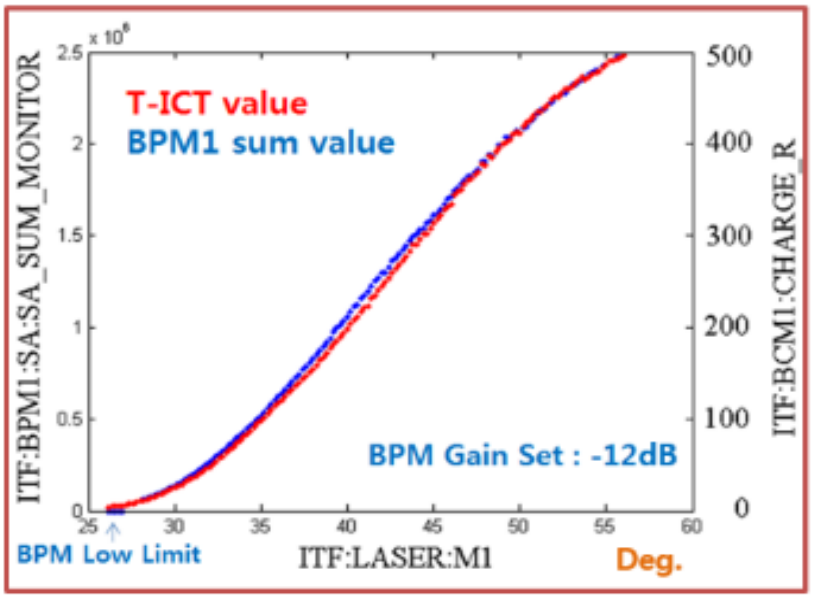
Beam Charge Monitor



Half-wave plate Angle vs. Charge

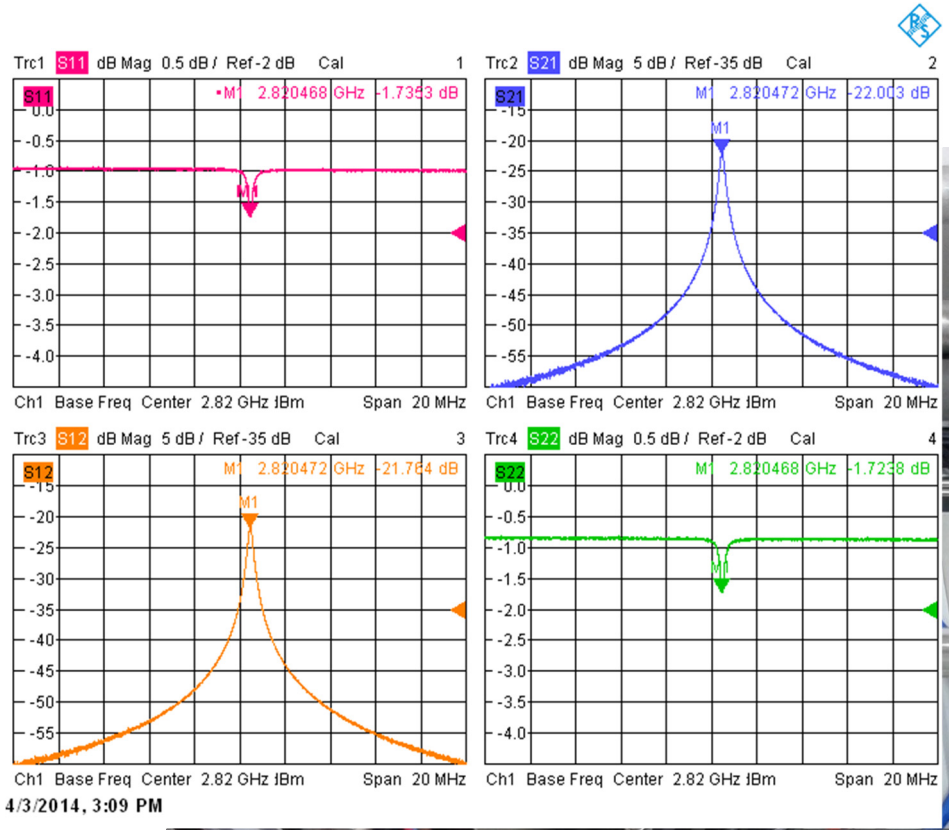


T-ICT value vs. S-BPM sum



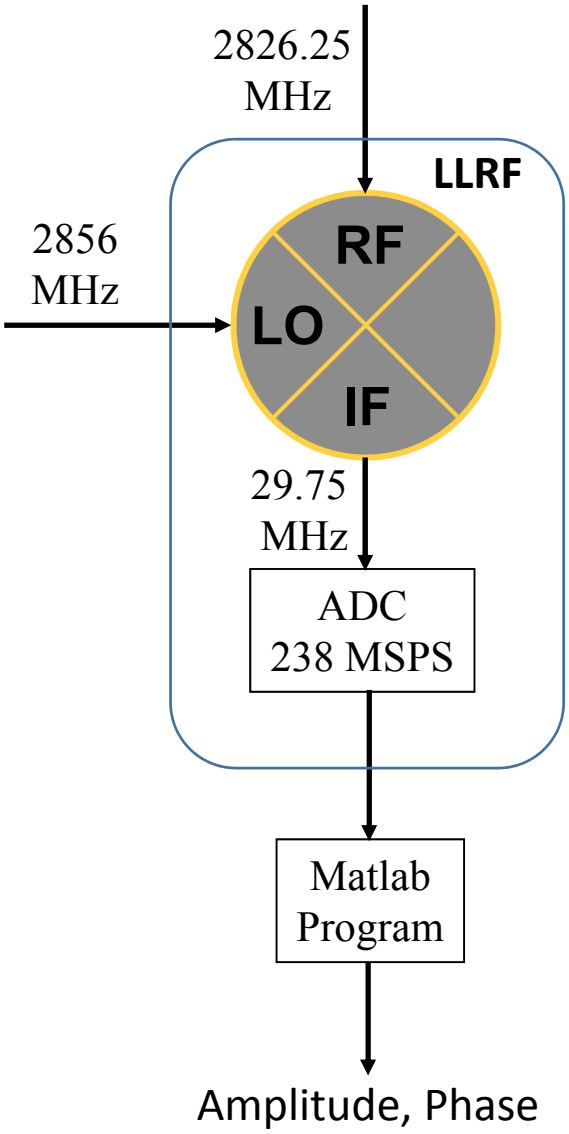
Beam Arrival Monitor

Beam Arrival Monitor Pickup

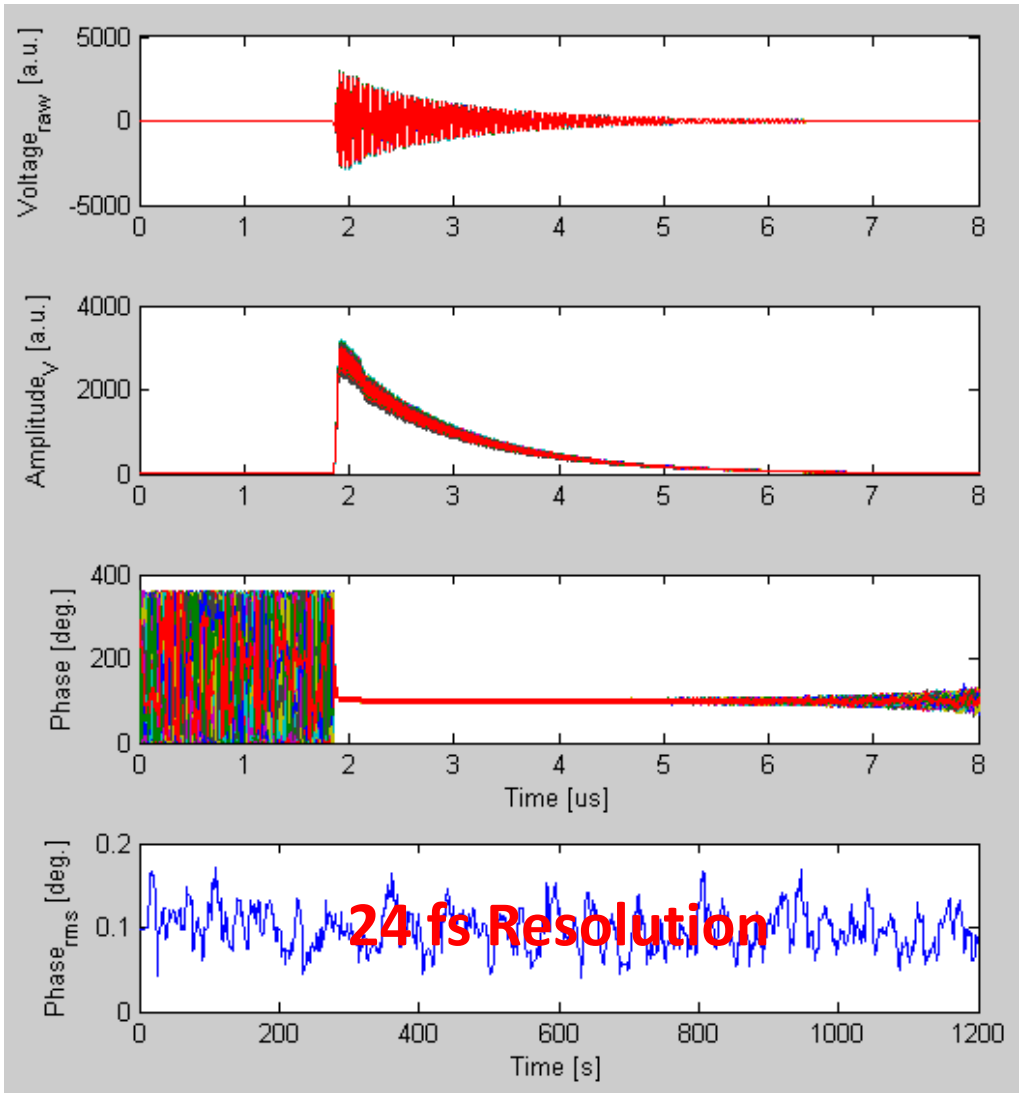


Parameter	Value	Unit
Operating Frequency	2,823	MHz
Coupling Coefficient	0.1	
Quality Factor	10,000	

Beam Arrival Monitor Signal



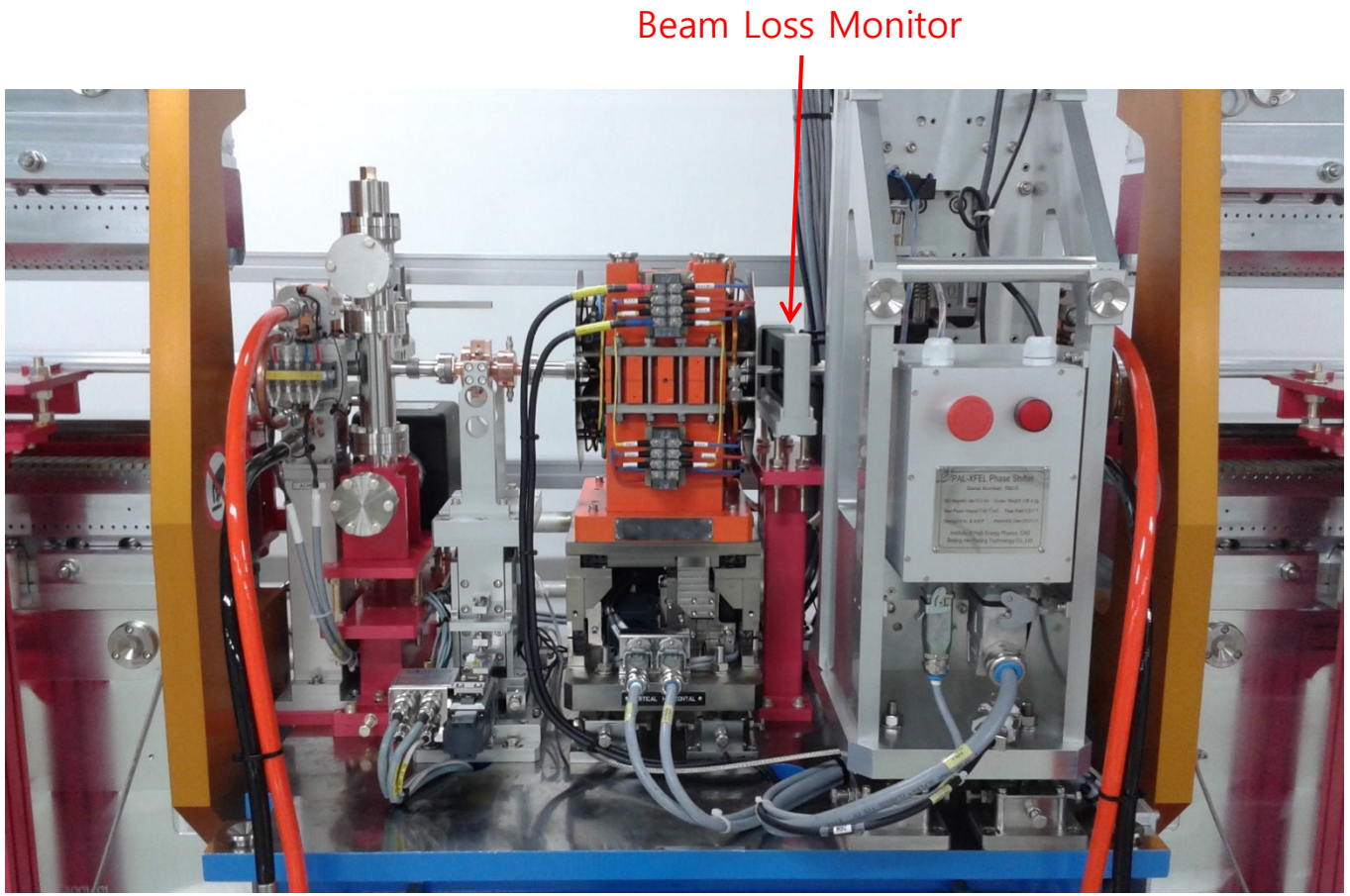
Using LLRF @ ITF (10Hz, 200 pC, total 20 min)



Beam Loss Monitor

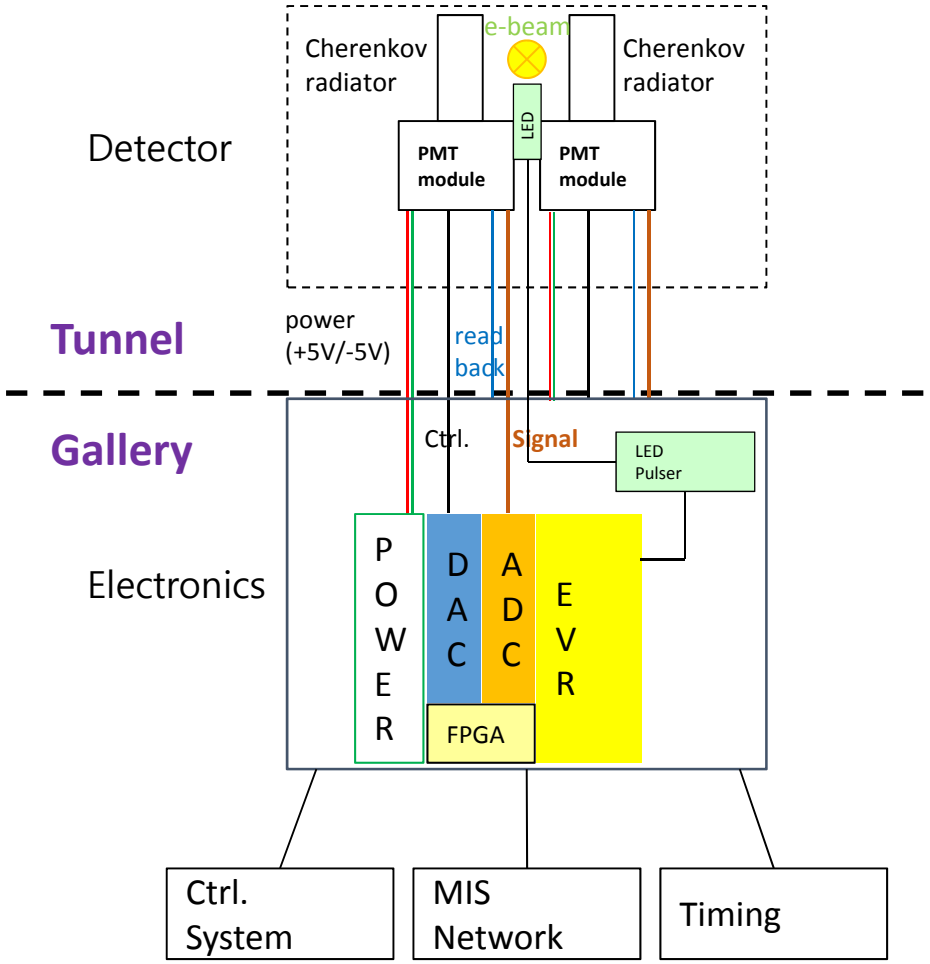
Beam Loss Monitor

- 1 beam loss monitor per 1 undulator
- To protect undulator magnets
- Cherenkov radiator (acrylic or fused-silica rods) with PMT

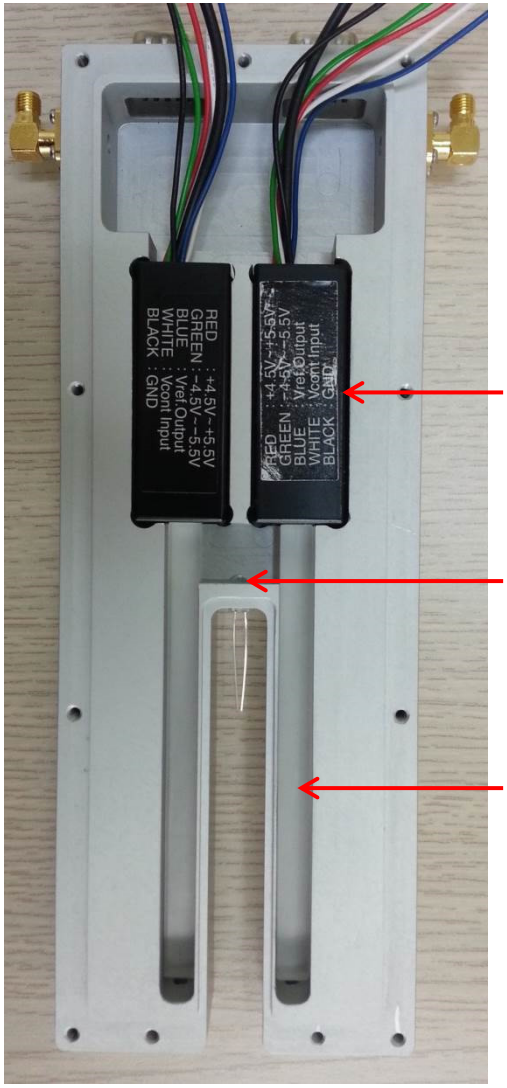


Beam Loss Monitor

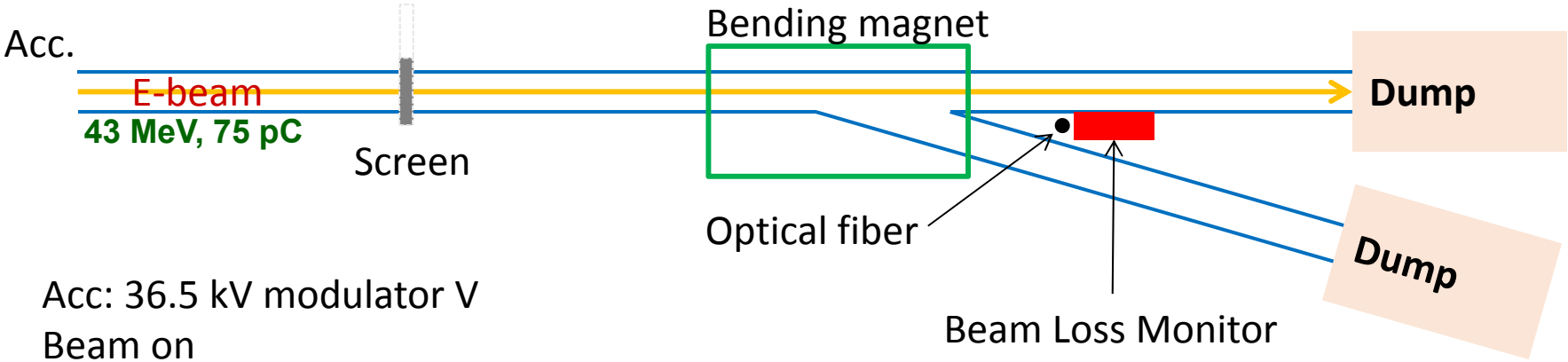
Conceptual Design



Proto-type Detector

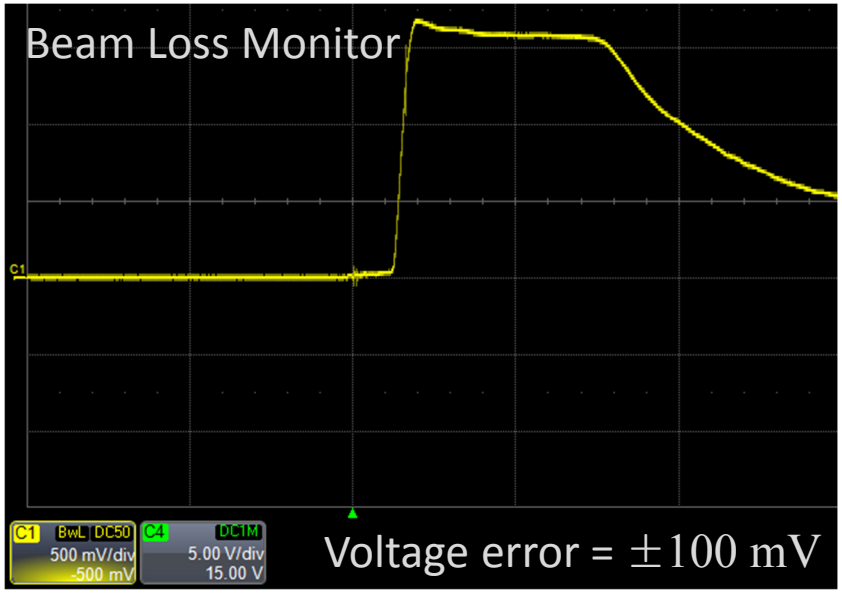


BLM Head vs. Optical Fiber

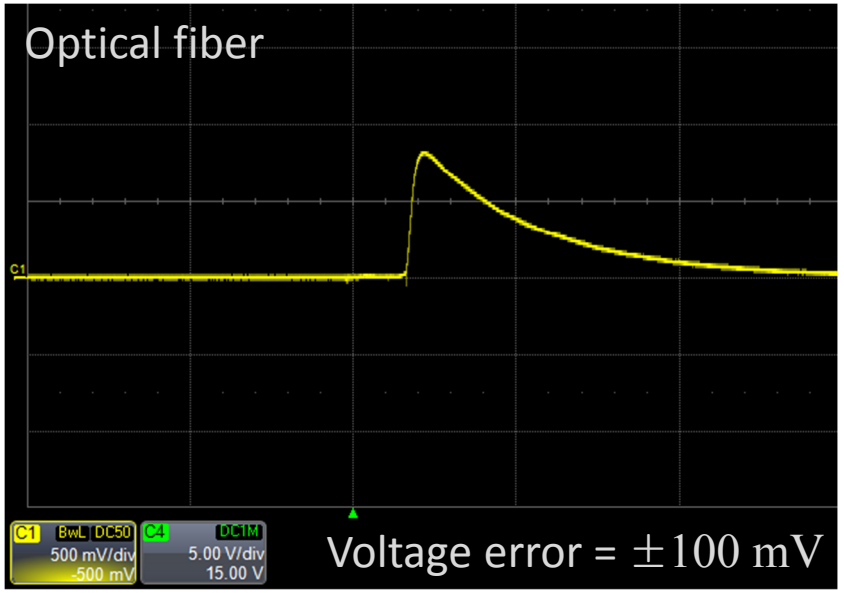


Acc: 36.5 kV modulator V
Beam on
Screen on
Bending off

PMT ctrl. V = 0.6 V



PMT ctrl. V = 0.6 V



Diagnostic Systems for PAL-XFEL

Parameter	Instruments	Number	Resolution
Beam Position & Beam Energy	Stripline BPM	160	< 7 um
	Cavity BPM	49	< 1 um
Beam Charge	Turbo ICT	10	< 1 pC
Beam Size	Screen Monitor	54	< 10 um
	Wire Scanner	9	< 10 um
Bunch Length	Transverse Deflecting Cavity	3	< 20 fs
	Coherent Radiation Monitor	4	-
Beam Arrival Time	Beam Arrival Time Monitor	10	< 30 fs
Beam Loss	Beam Loss Monitor	26	-

Summary

- The PAL-XFEL construction was started 2011 and finished at the end of 2015.
- The commissioning was started in April 2016 and the first SASE FEL was observed at the end of June.
- For the successful commissioning, various kinds of diagnostic instruments were installed in the PAL-XFEL to measure beam parameters.

Thank you
for your attention