Beam operation at the PAL-XFEL Injector Test Facility

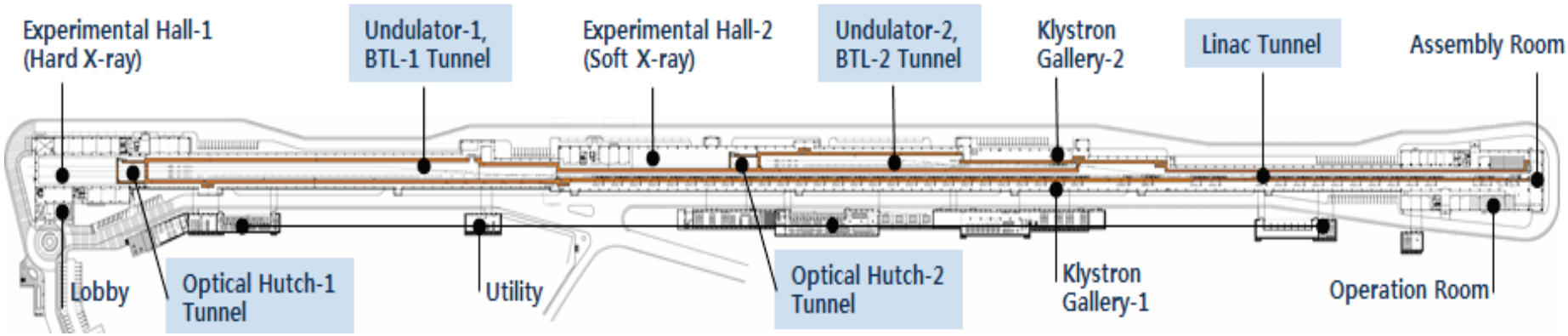
J.-H. Han, J. Hong, J. H. Lee, M. S. Chae, S.Y. Baek, H. J. Choi, T. Ha, J. Hu, W. H. Hwang, S. H. Jung, C. B. Kim, C. H. Kim, I.Y. Kim, J. M. Kim, S. H. Kim, H. S. Lee, S.-J. Lee, Y.Y. Lee, C.-K. Min, G.Y. Mun, D. H. Na, S.-J. Park, S.-S. Park, Y. J. Park, Y. K. Son, H. R. Yang, H.-S. Kang, I. S. Ko,

Pohang Accelerator Laboratory

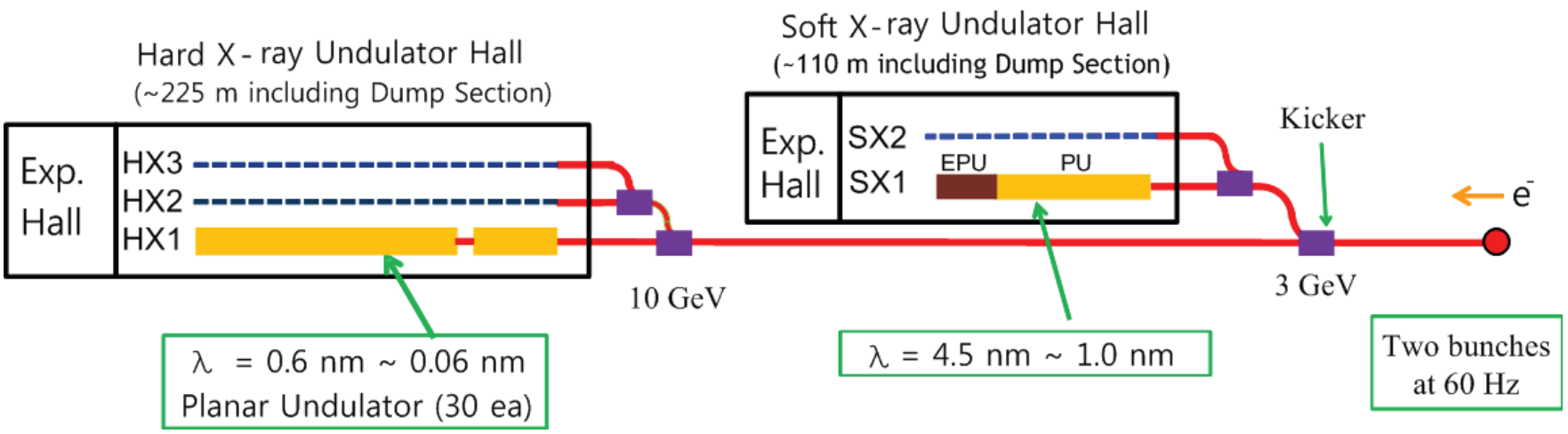
Contents

- PAL-XFEL Project
- Injector Test Facility
- Electron Beam Property Measurement
- Beam Test of Accelerator Components

PAL-XFEL Overview

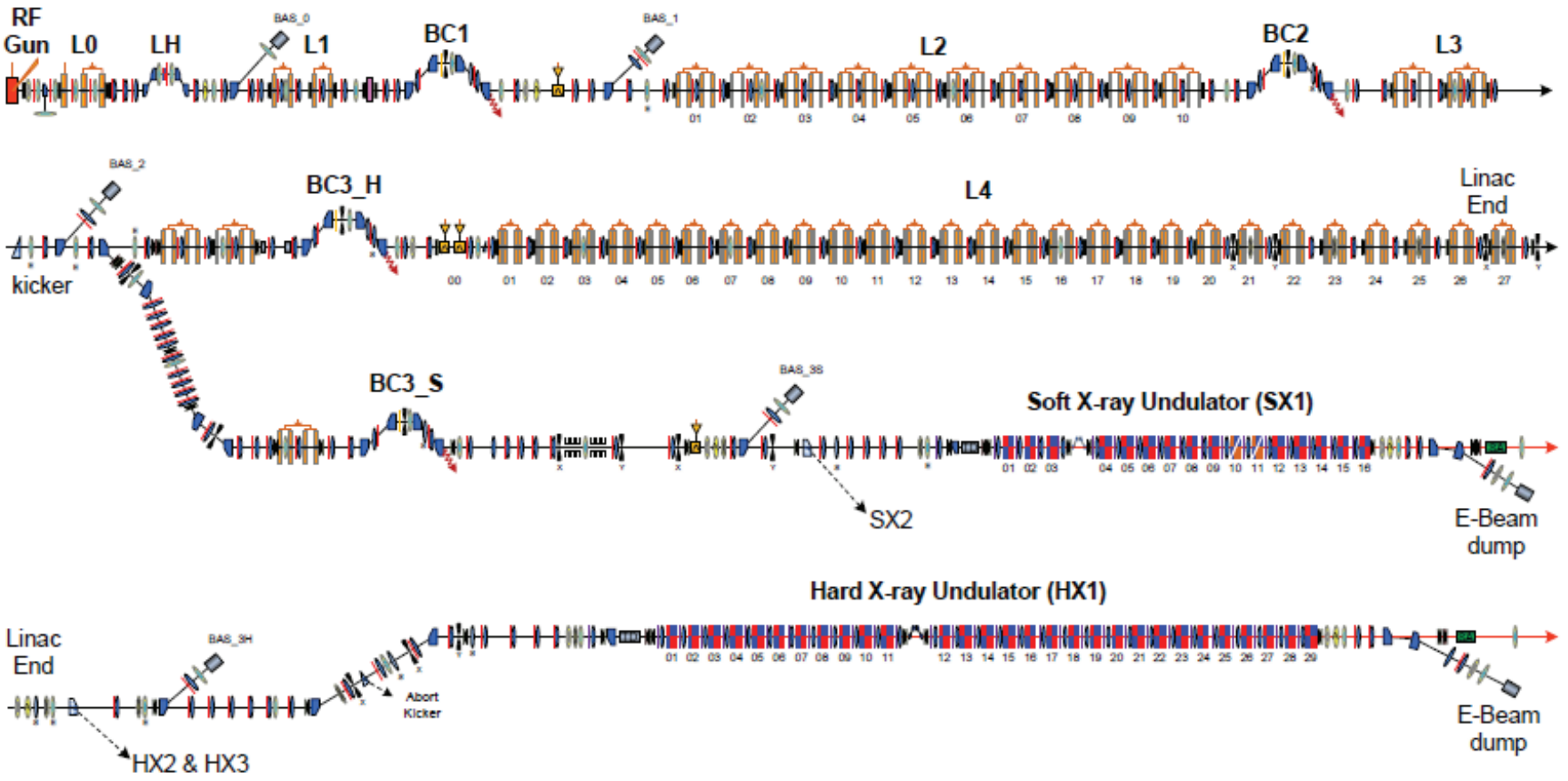


PAL-XFEL Parameters



Undulator Line	HX1	SX1
Wavelength	0.06 ~ 0.6 nm	1 ~ 4.5 nm
Electron Beam Energy	4 ~ 10 GeV	3.15 GeV
Wavelength Tuning	0.1 ~ 0.06 nm (Undulator Gap) 0.6 ~ 0.1 nm (Beam Energy)	3 ~ 1 nm (Undulator gap) 4.5 ~ 3 nm (Beam Energy)
Undulator Type	Planar	Planar + APPLE II
Undulator Period	26 mm	37 mm
Undulator Gap	8.3 mm	10 mm
Repetition Rate	60 Hz	

PAL-XFEL Layout



RF Gun	Dipole Magnet	Stripline BPM H116, S39	BCM H7, S3	fs streak camera	Kicker Magnet	
Laser	Quadrupole	Cavity BPM H31, S18	Screen H40, S10	Dechirper H0, S2	Safety Permanent Magnet	
X band Cavity	Plannar Undulator	Energy BPM H3, S1	Wire Scanner H8, S2	Deflector	Tune-up Dump	
Accelerating Column	EPU	CSR monitor H3, S1	Beam Arrival Monitor H4, S2	Collimator H10, S7	Gate valve H63, S14	
					Fast shutter H4, S3	

PAL-XFEL Commissioning

- The building is under construction, to be ready by December 2014
- Component installation from late autumn 2014 for a year
  - All accelerator components to be installed
- Beam commissioning from winter 2015
  - 10 Hz repetition rate
- First FEL expected in late spring 2016
  - 0.3 nm at hard X-ray beamline with 6 GeV

Test Facilities/Lab for PAL-XFEL (2012~)

- ITF (Injector Test Facility): Injector components and diagnostics commissioning
- ATF (Accelerator Test Facility): High power RF components R&D and test
- IDL (Insertion Device test Lab): Field measurement, control test
- PTF (Photon Test Facility): Photon Beamline components test, pump-probe test

PAL-XFEL Injector Test Facility (ITF)

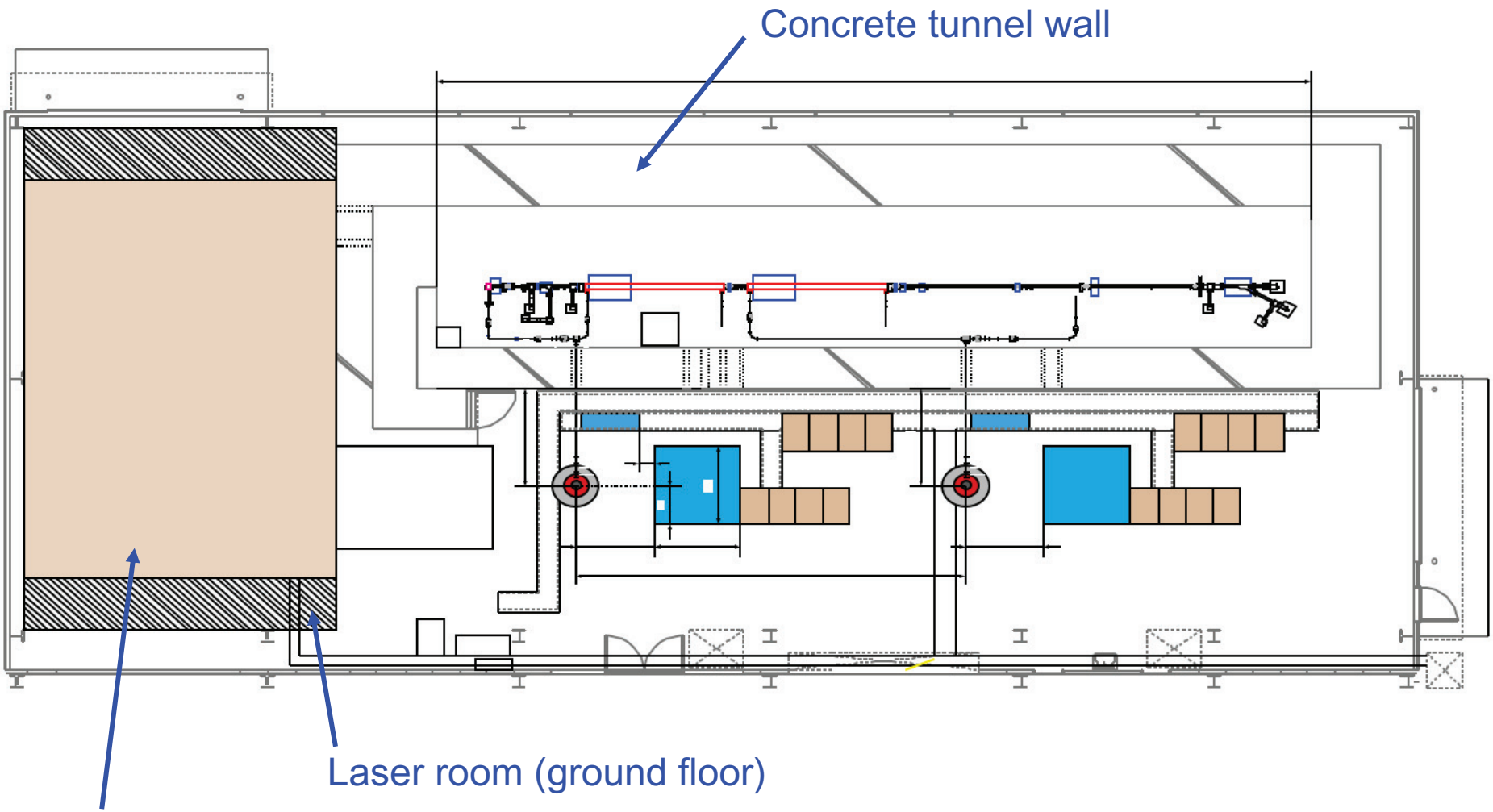
- Goal: Development and test of injector components
  Diagnostics test using electron beams

- S-band photocathode gun for beam generation
- Ti:sapphire laser system
- Two S-band 3 m traveling-wave structures. Max beam energy ~ 140 MeV

- Test of high power RF system (klystron, modulator, RF window, SiC load) and low level RF, solid state amplifier
- Test of various accelerator components
- Operation normally at 10 Hz, tested up to 60 Hz

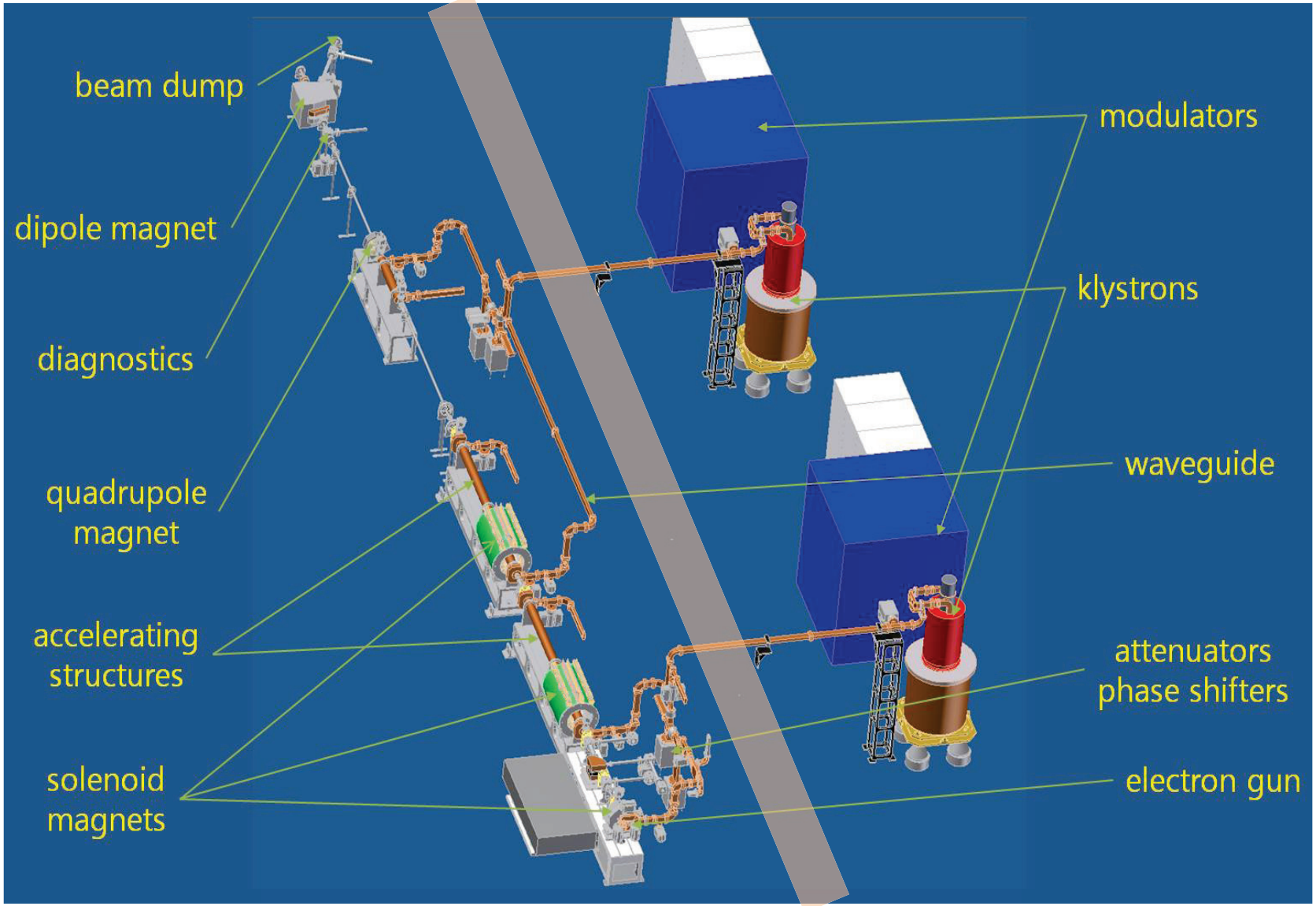
- Building construction started in 2011
- First electron beam in December 2012
- Operational until summer 2015

ITF Building

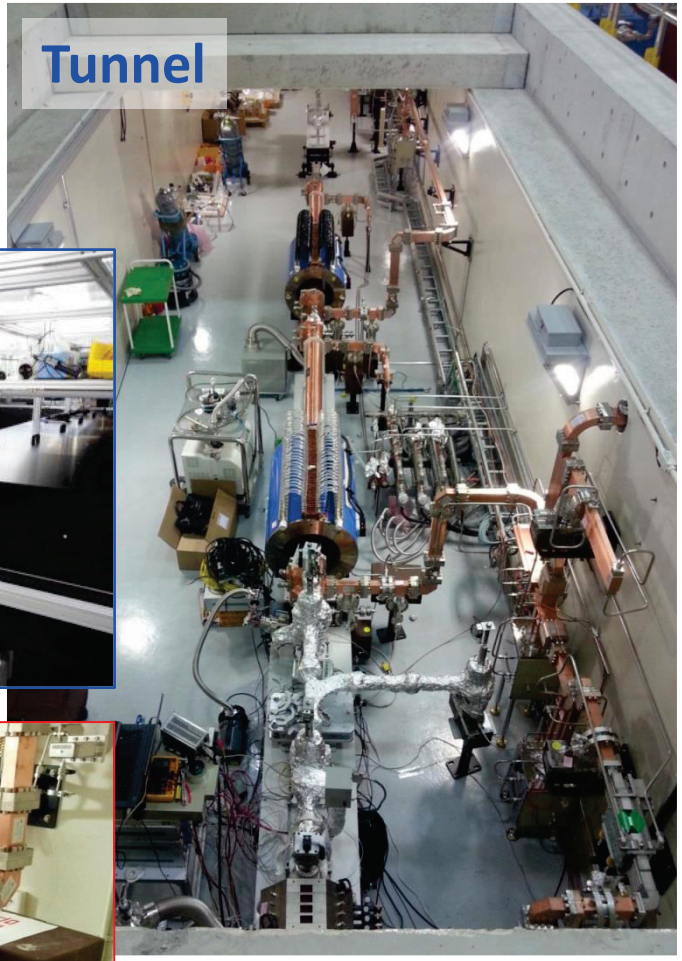


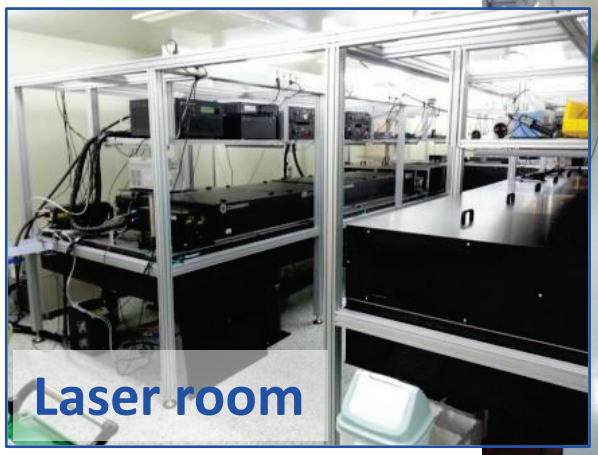
S. J. Park et al, IPAC2013, p. 2220

ITF Layout


beam dump
dipole magnet
diagnostics
quadrupole magnet
accelerating structures
solenoid magnets
modulators
klystrons
waveguide
attenuators
phase shifters
electron gun

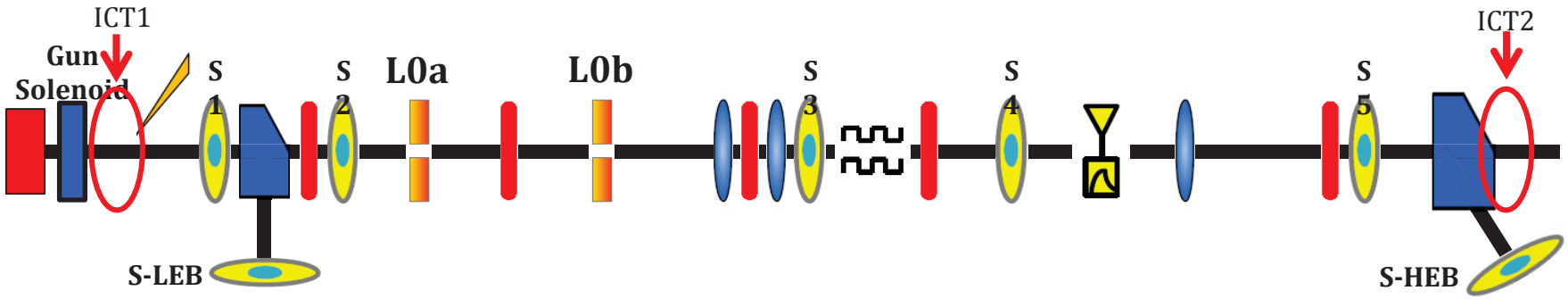
Installation

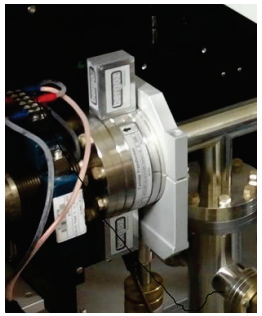


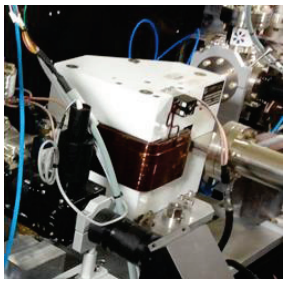


RF Amplitude & Phase Control of Gun

ITF Beam Diagnostic Components

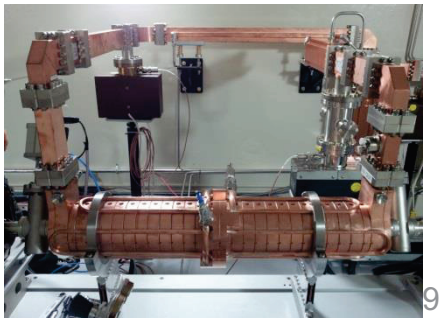


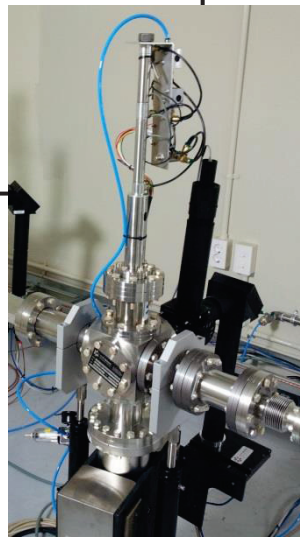


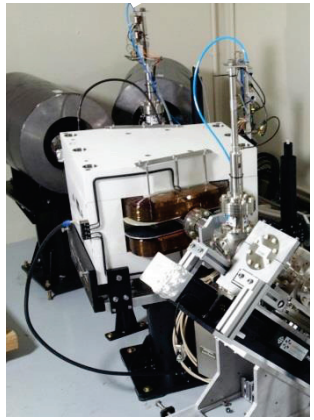


RF Gun | Accelerating Column | Deflector | Dipole Magnet | Dechirper

Screen | Stripline BPM | Laser | Quadrupole

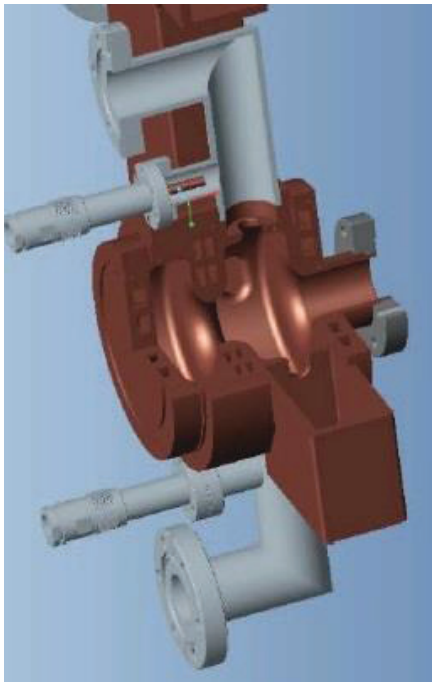


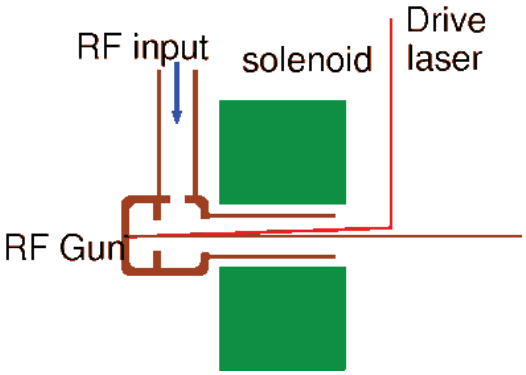




Gun1

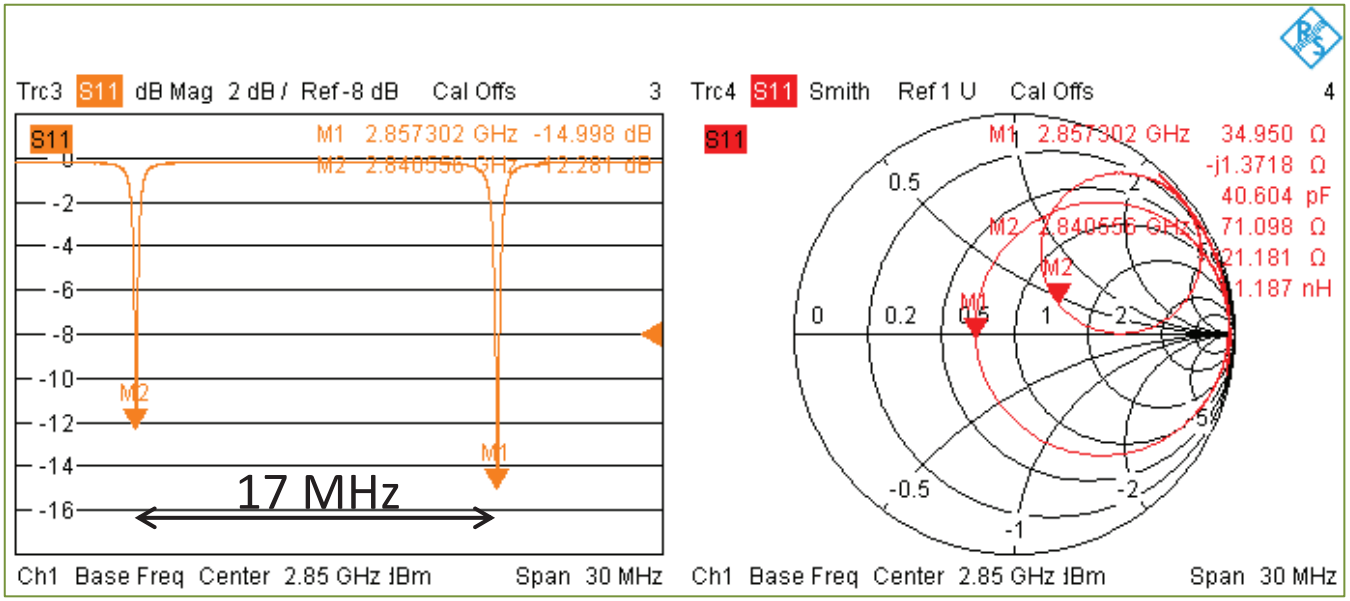
- Developed at PAL (with POSTECH) since 2005
- Design based on BNL S-band gun
- 1.61 cell & side coupling with 2 RF coupling and 2 pumping holes
- Drive laser normal incident to cathode
- Solenoid immediate downstream of the gun
- Designed for 120 Hz operation at 120 MV/m
- Beam commissioning ongoing at ITF
- RF operation is stable up to 30 Hz & 120 MV/m. 60 Hz test was done shortly in summer 2014





J . H. Hong et al, FEL2013, p. 279

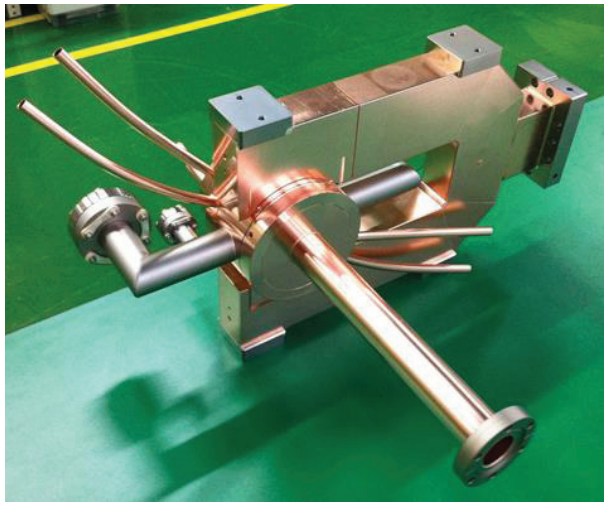
Cold Test and Installation of Gun1

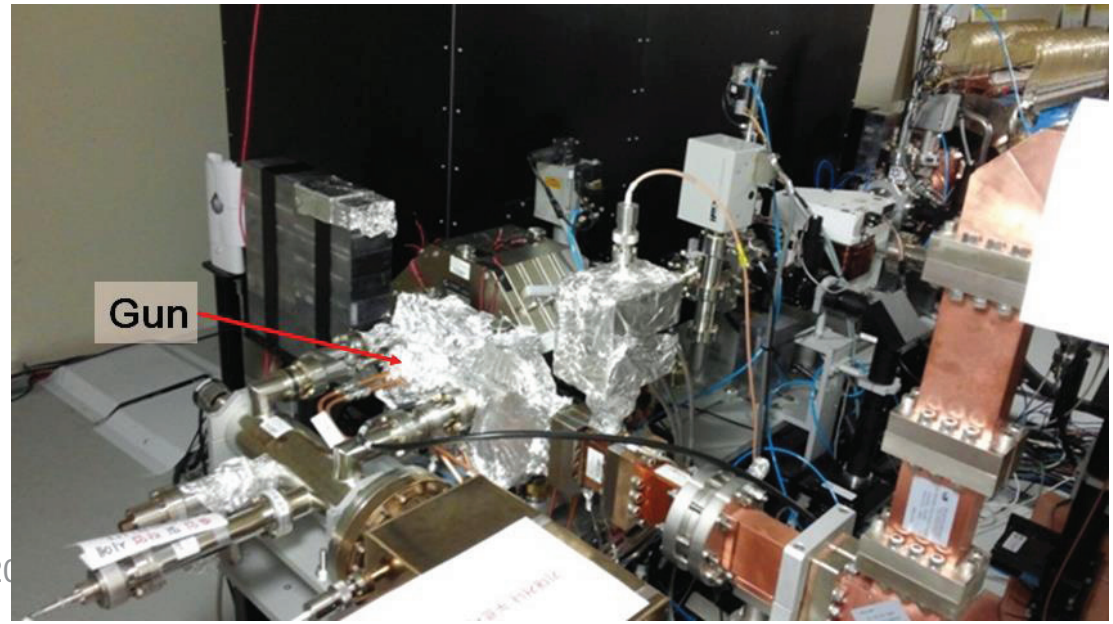


Cold test result

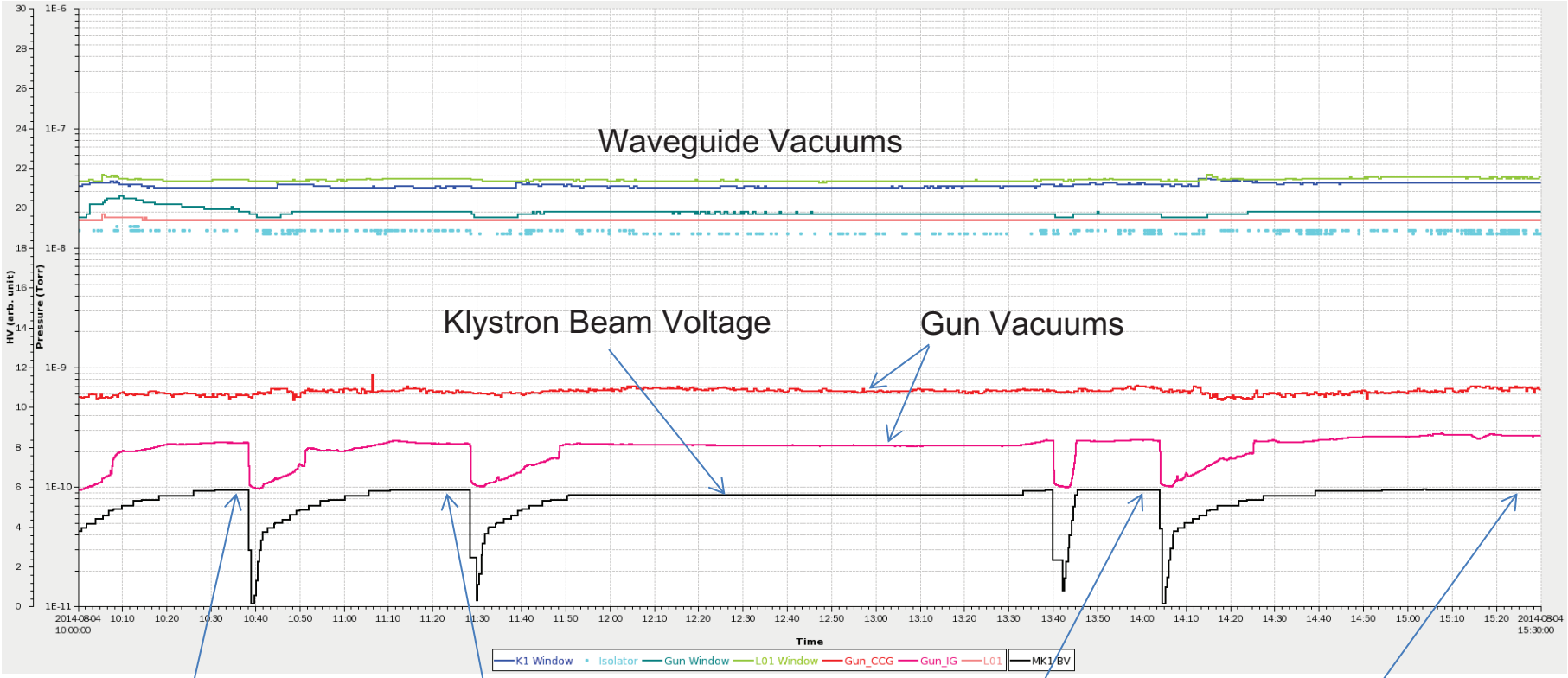
Gun installed in ITF

Gun after brazing





60 Hz Gun Operation



41.5 kV, 40 Hz (rf 1.5 us)

41.5 kV, 60 Hz (rf 1.5 us)

41.5 kV, 40 Hz (rf 1.75 us)

41.5 kV, 60 Hz (rf 1.75 us)

Laser System

Ti:sapphire Laser Parameters

Parameter	Value
Oscillator rep. rate	79.333 MHz
Amplifier rep. rate	120 Hz
Center wavelength	770 nm
Pulse duration	~150 ps
Pulse energy	20 mJ
Energy jitter (RMS)	~0.24 %

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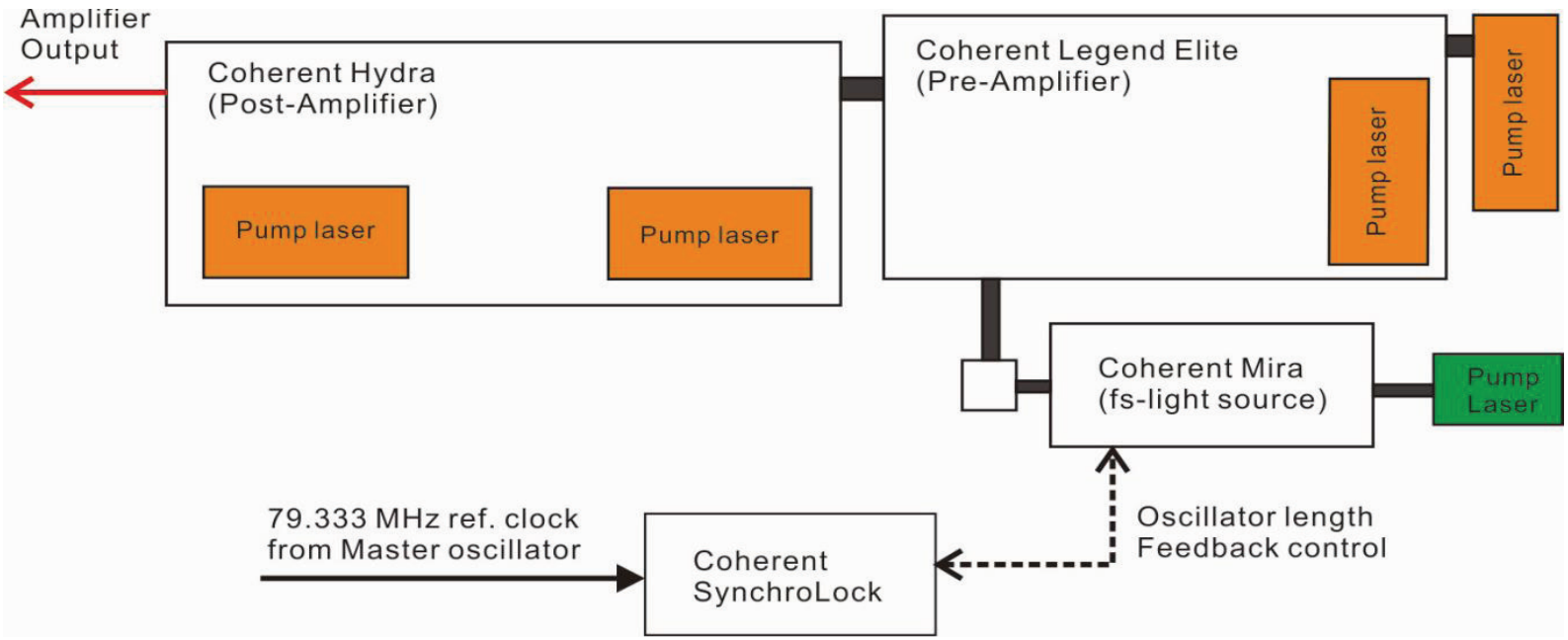
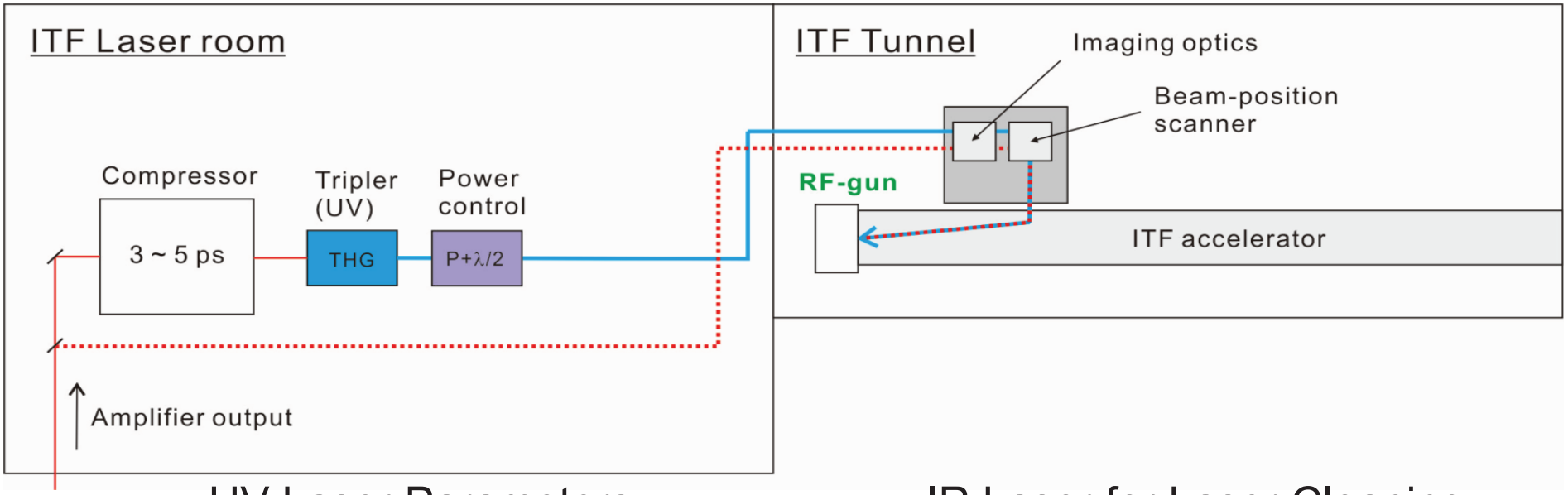
Photocathode Drive Laser Genearion

- Repetition rate of seed laser (Coherent Mira) set to 79.333 MHz, synchronized to the master oscillator.
- Regenerative amplifier (Coherent Legend Elite) used to generate pre-amplified output with about 150 ps and 120 Hz repetition rate.
- Post-power amplifier boosts output power up to 2.5 W (rms noise; 0.24 %)



UV & IR Laser Transportation



UV Laser Parameters

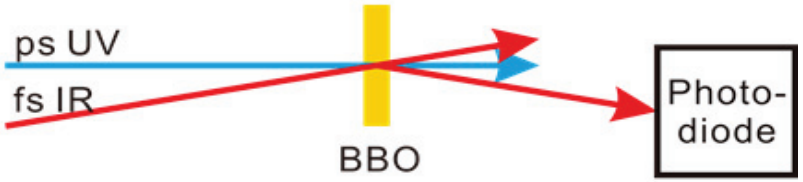
Parameter	Value
Center wavelength	257 nm
Pulse energy (variable)	Up to 1 mJ
Pulse duration (variable)	3~5 ps
Energy jitter (RMS)	~1 %
Beam size at cathode (variable)	<1 mm

IR Laser for Laser Cleaning

Parameter	Value
Center wavelength	770 nm
Pulse energy (variable)	< 400 uJ
Pulse duration	~ 150 ps
Energy jitter (RMS)	<1 %
Beam size at gun (variable)	< 1 mm

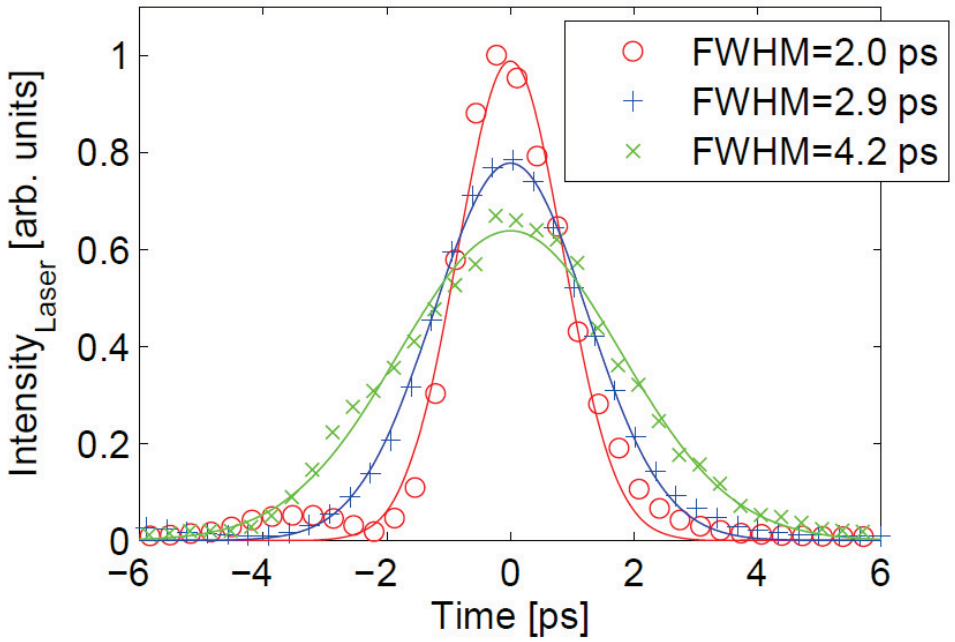
Drive Laser Pulse Length Measurement

Different frequency generation (DFG)



Pulse duration by DFG cross-correlation measurement

A drive laser pulse to the cathode is not affected by this measurement



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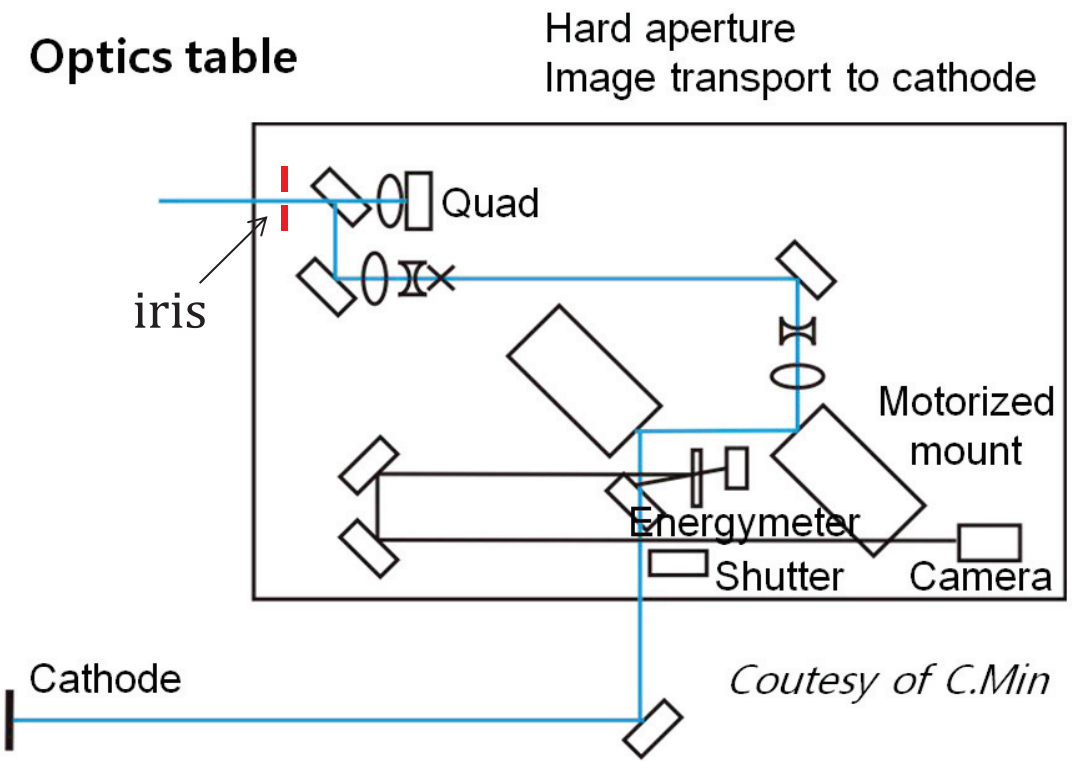
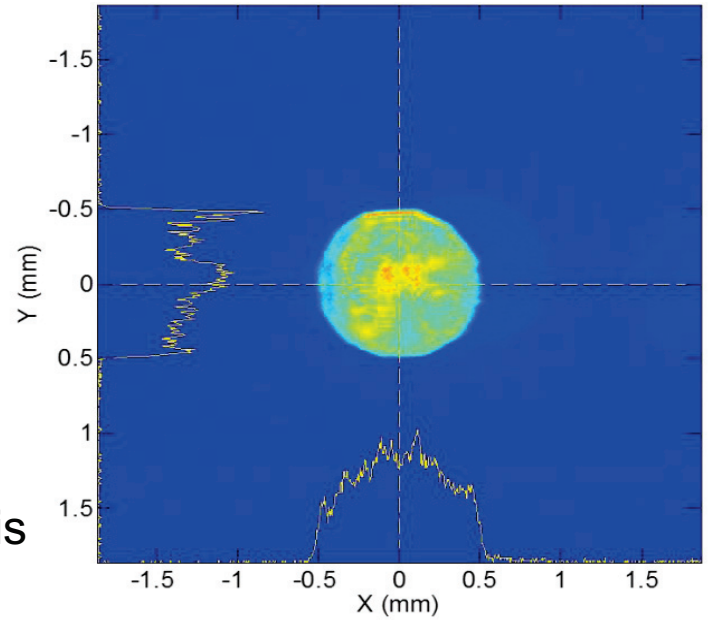
Drive Laser Shape Monitoring





Beam profile in virtual cathode camera, ϕ1 mm iris

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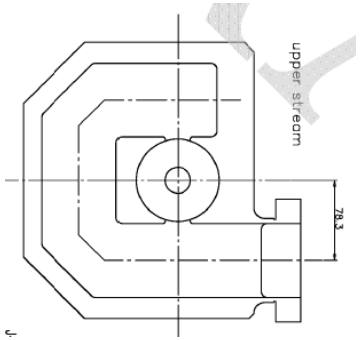
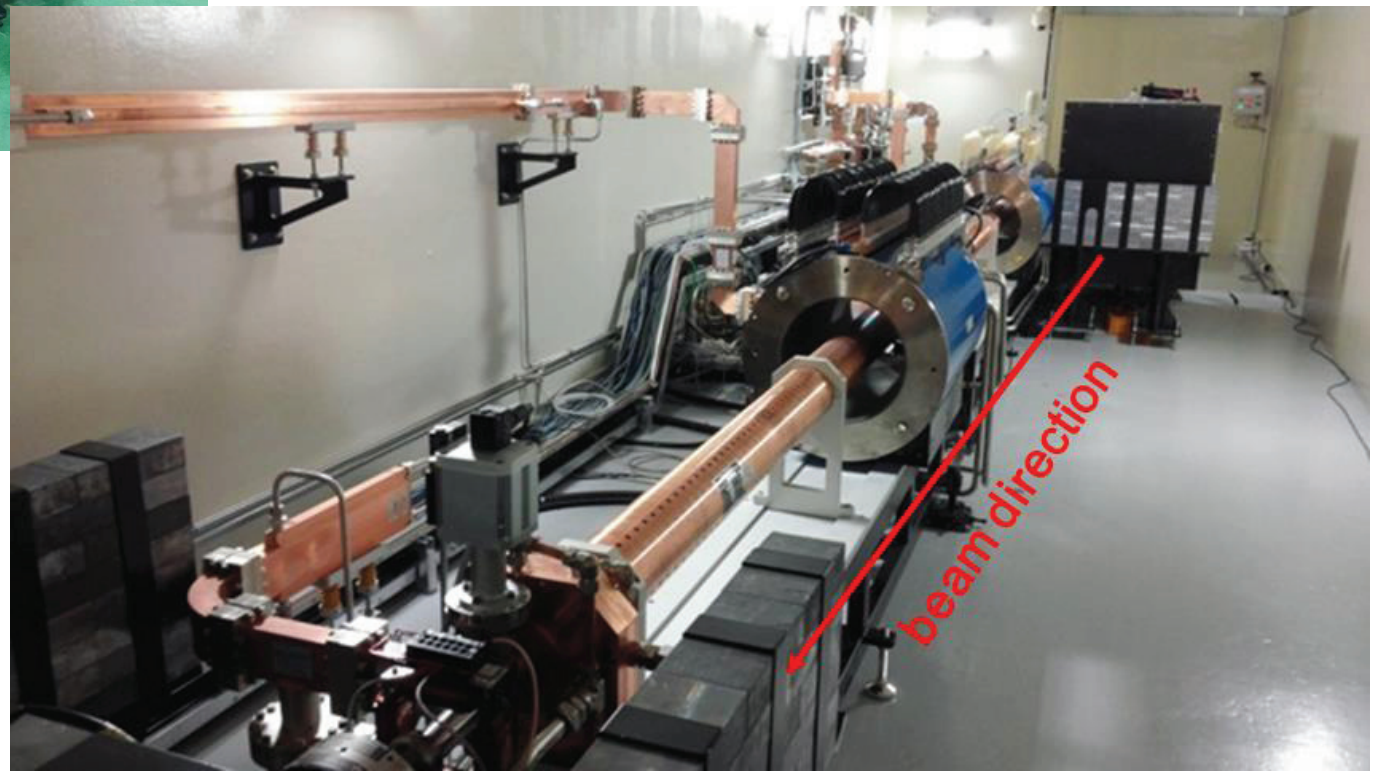
Accelerating Structures

Delivered from Mitsubishi Heavy Industries

Installed in ITF tunnel

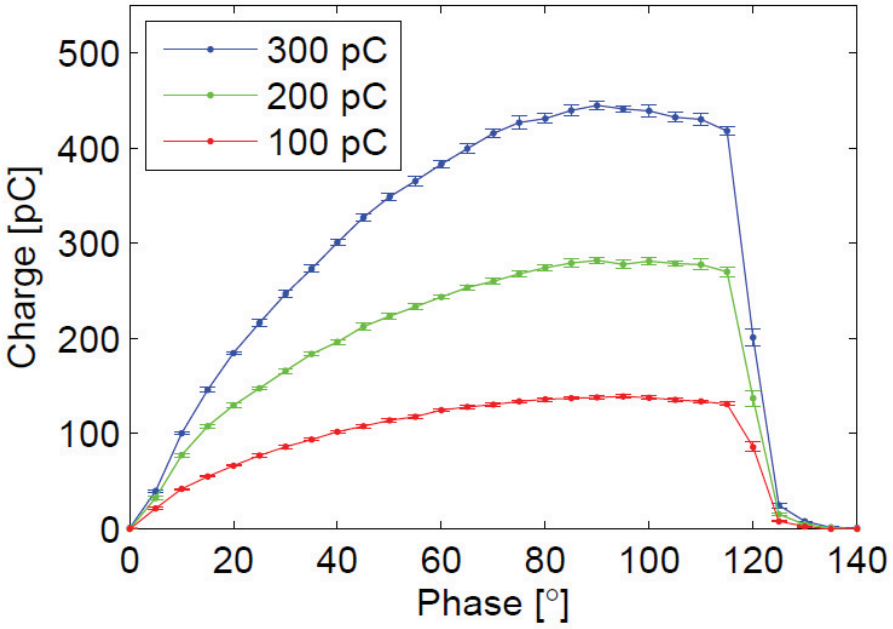


RF coupler

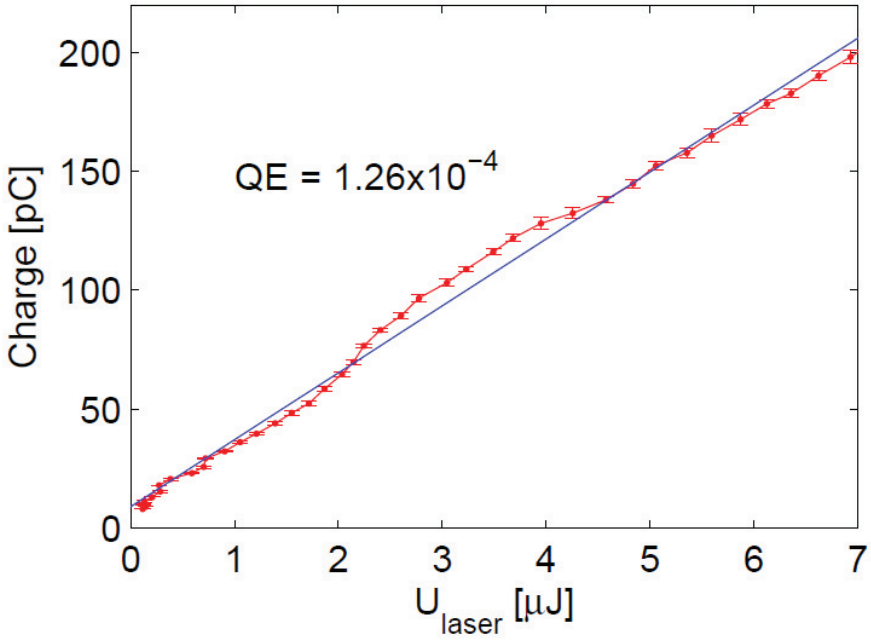


Bunch Generation at Cathode

Beam Charge VS Phase



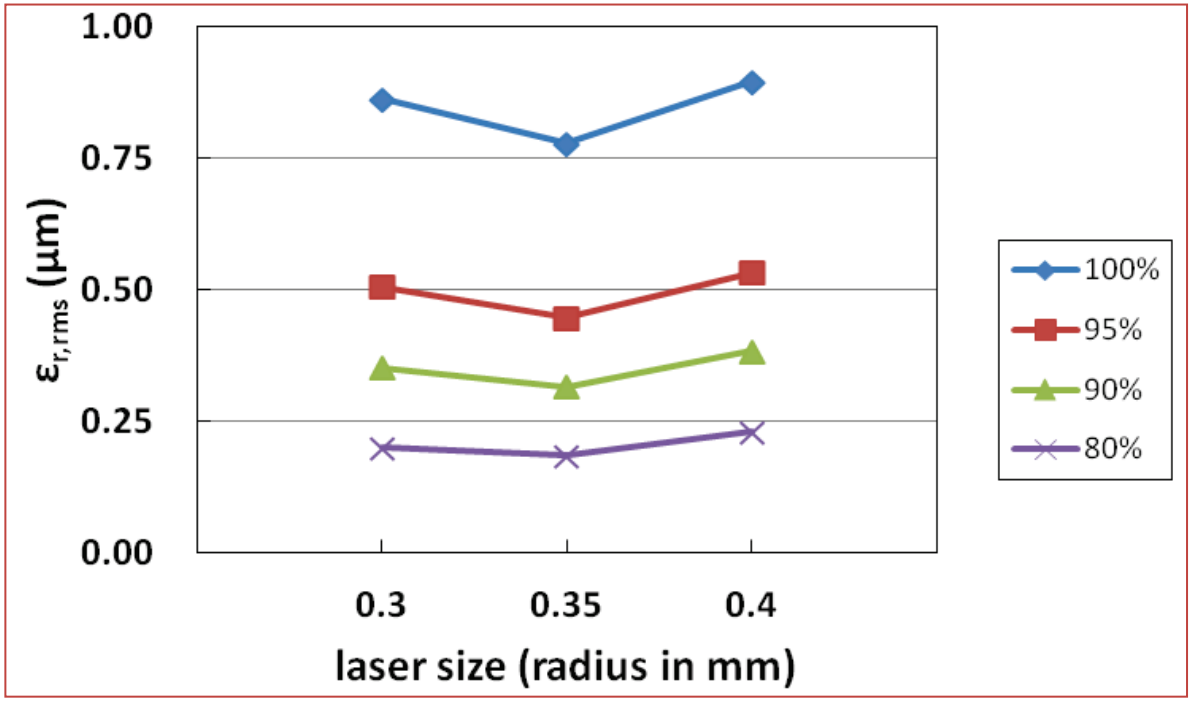
Quantum Efficiency



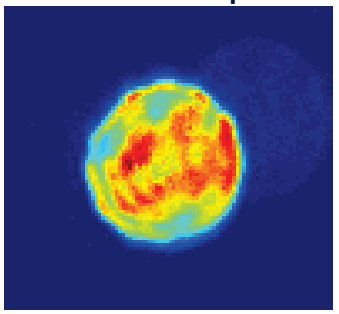
J. Hong et al, FEL2014, THP011

Best Results from ITF – July 2013

Parameter	Value
Beam energy	135 MeV
Charge	200 pC
Gun phase	35 degs
Acc's phase	on-crest (both)

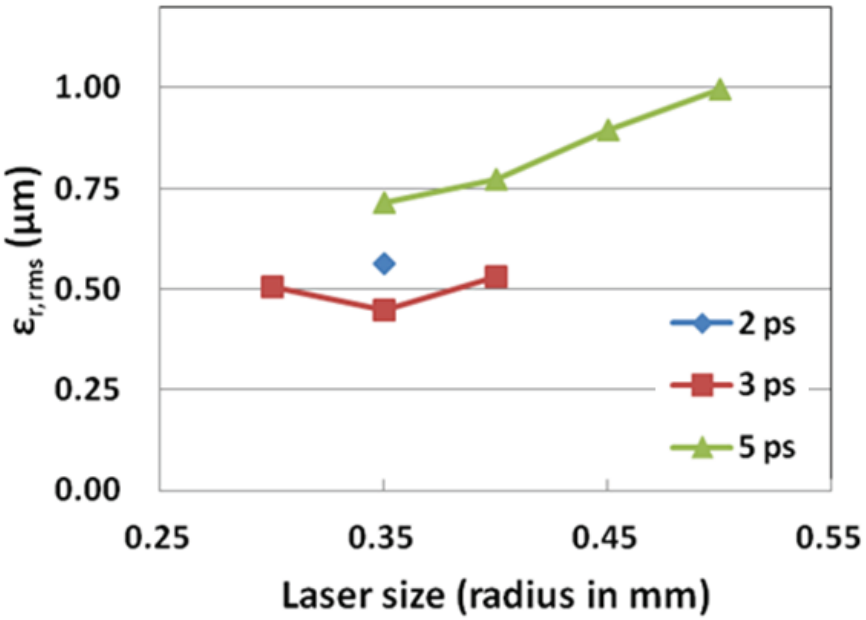


Laser beam profile

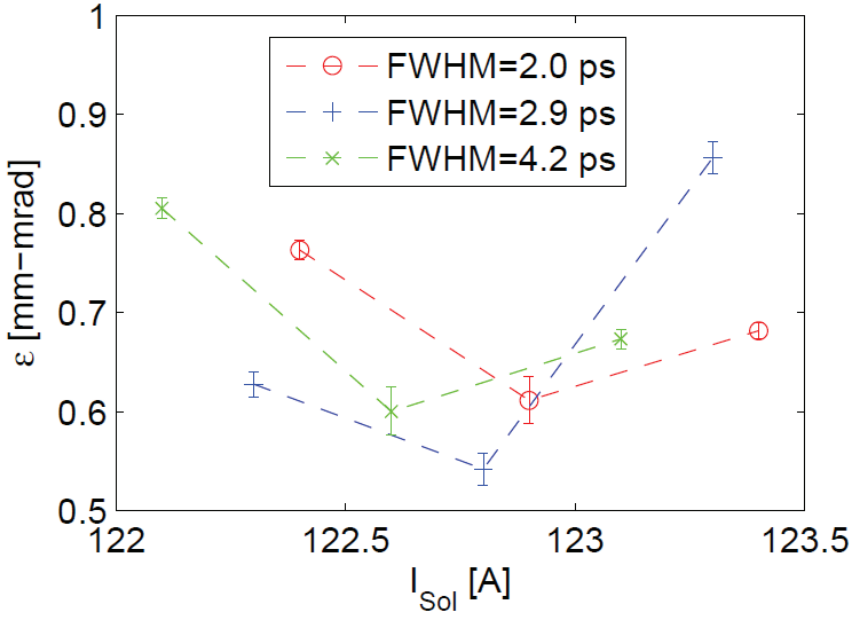


Emittance with Various Laser Size & Length at 200 pC

Measured in summer 2013

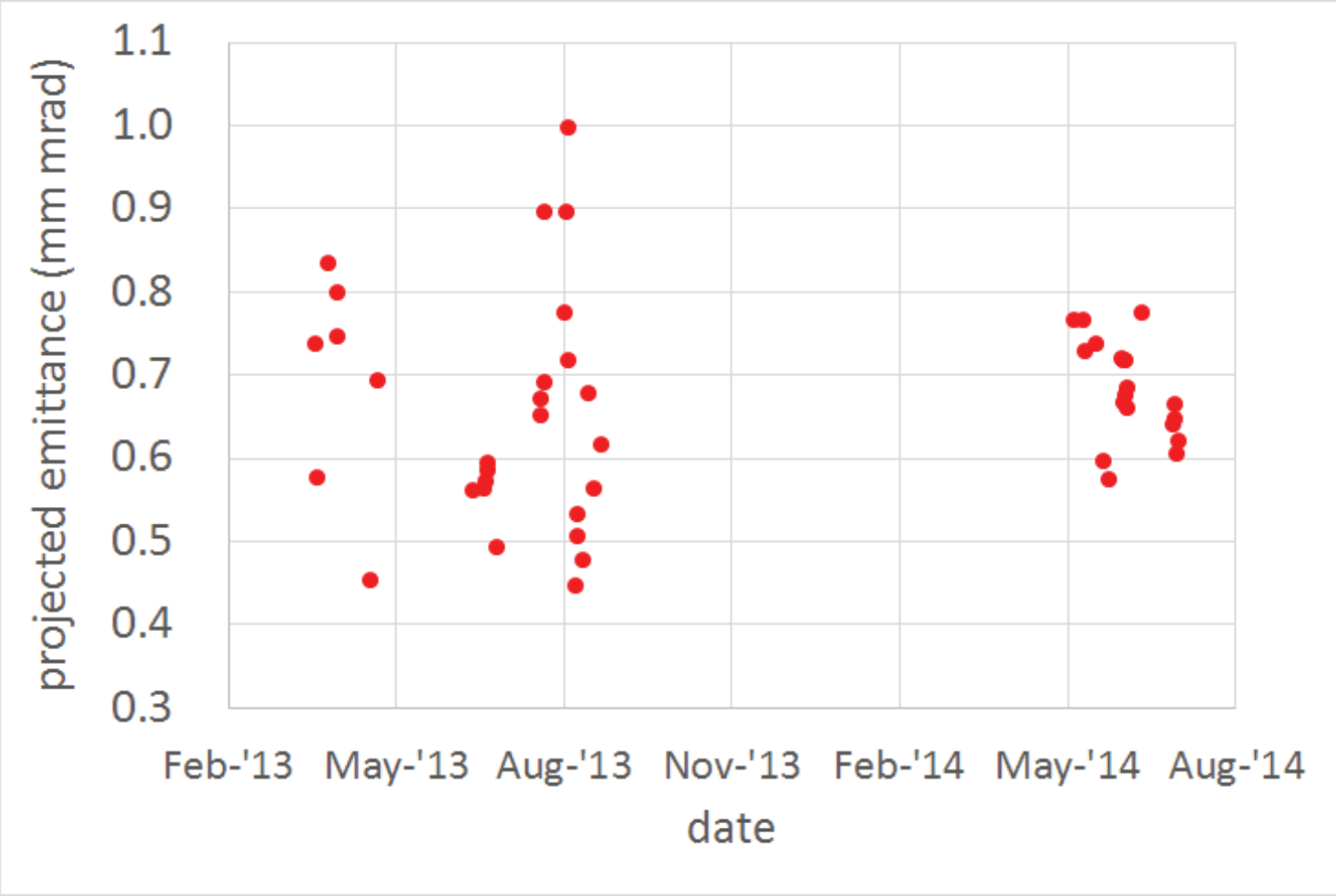


Measured in summer 2014

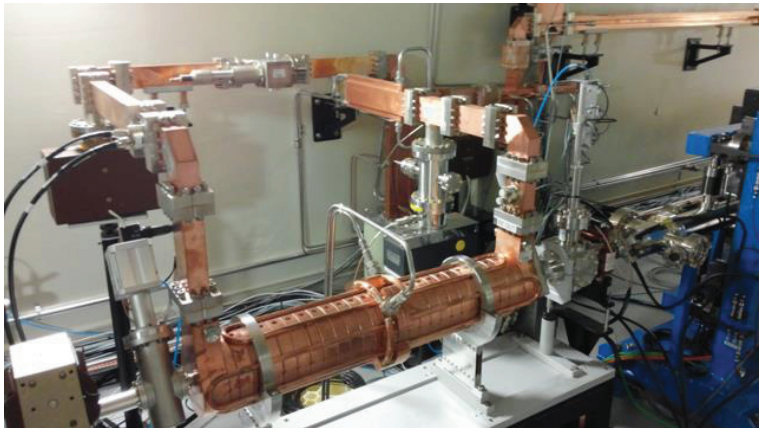


Minimum emittance with 3 ps laser pulse length
Both measurements show discrepancy to simulation
Emittance with longer laser pulse is lower according to simulation

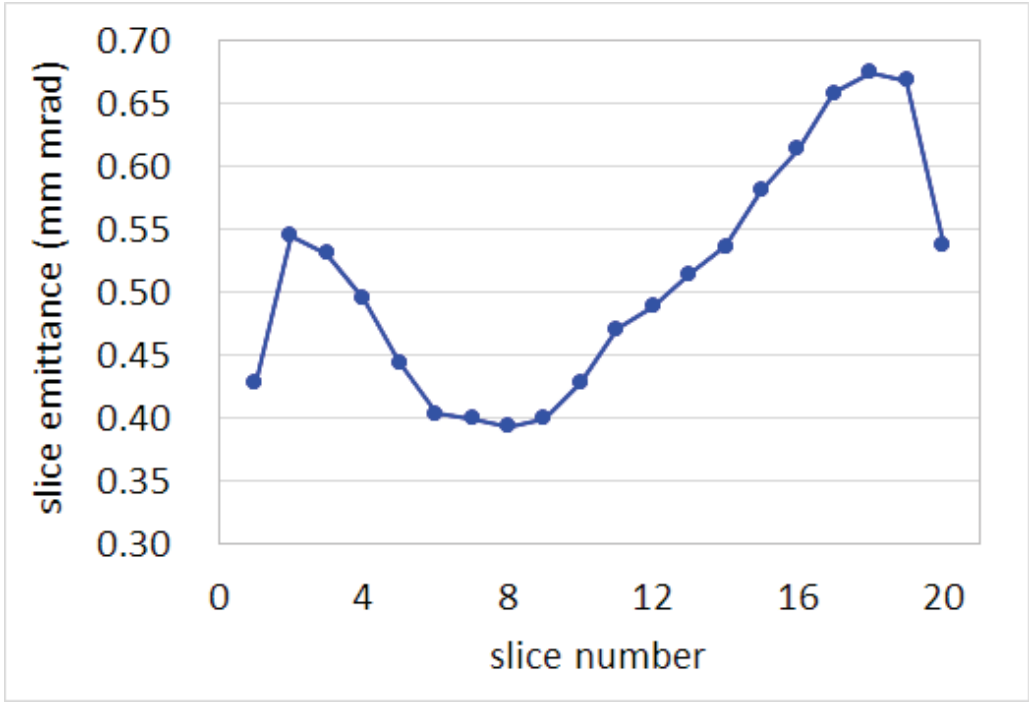
Emittance (95%) at 200 pC



Slice Emittance Measurement



RF deflector for vertical streaking
Horizontal emittance of bunch slices measured



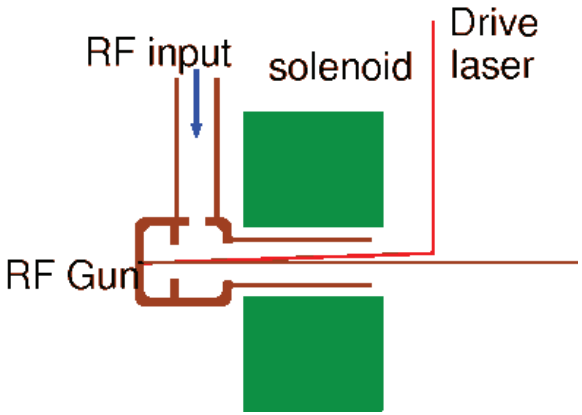
Measurement condition not optimized
Projected & slice emittance measurement planned in September 2014

J. H. Lee et al, FEL2014, THP013

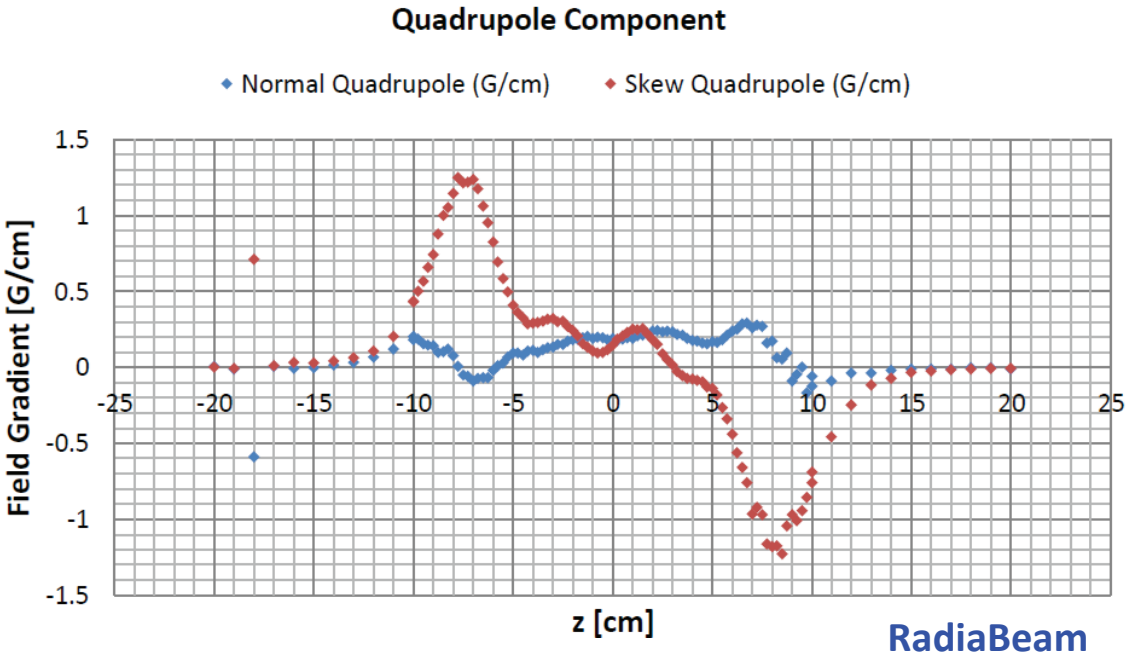
Possible Sources of Large Emittance Value – I

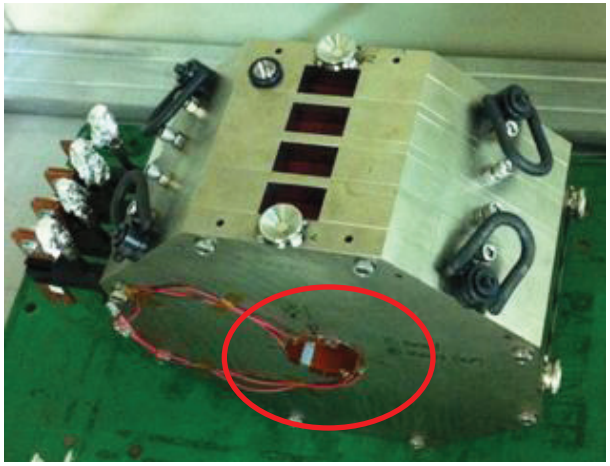
Higher order mode and field alignment of gun solenoid

Gun solenoid



Higher order mode of solenoid field

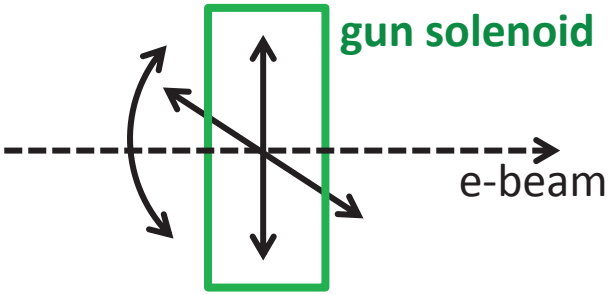


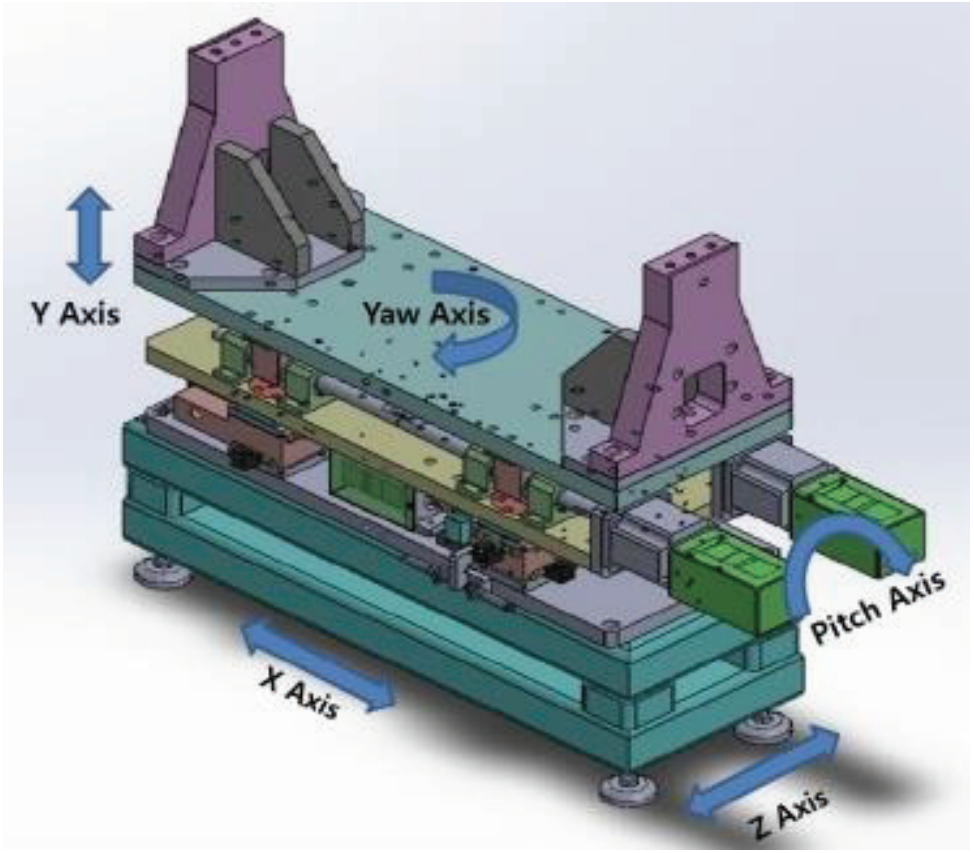


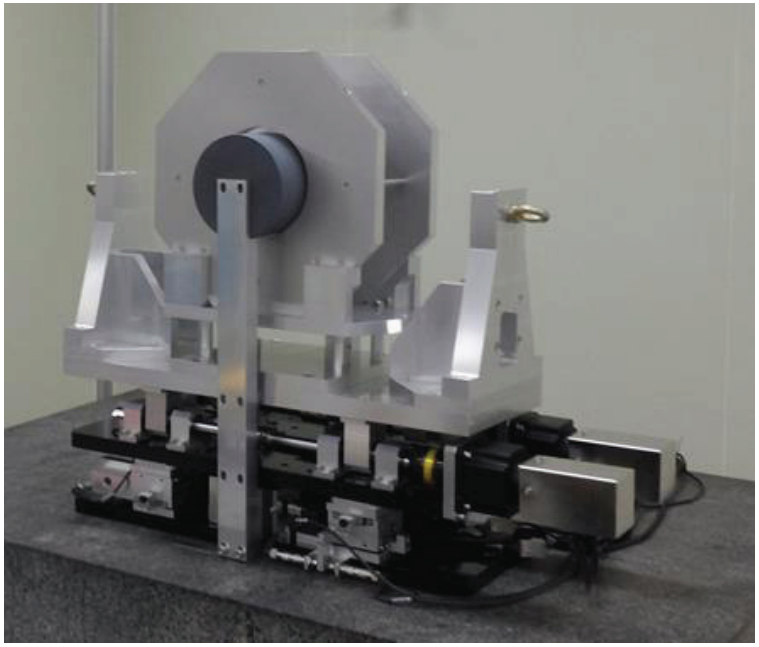
→ Corrector coils to be repaired in September 2014, for higher order mode compensation

Misalignment of Solenoid Field → BBA

Gun solenoid micro-mover is manufactured for beam-based alignment, to be installed at ITF in winter 2014

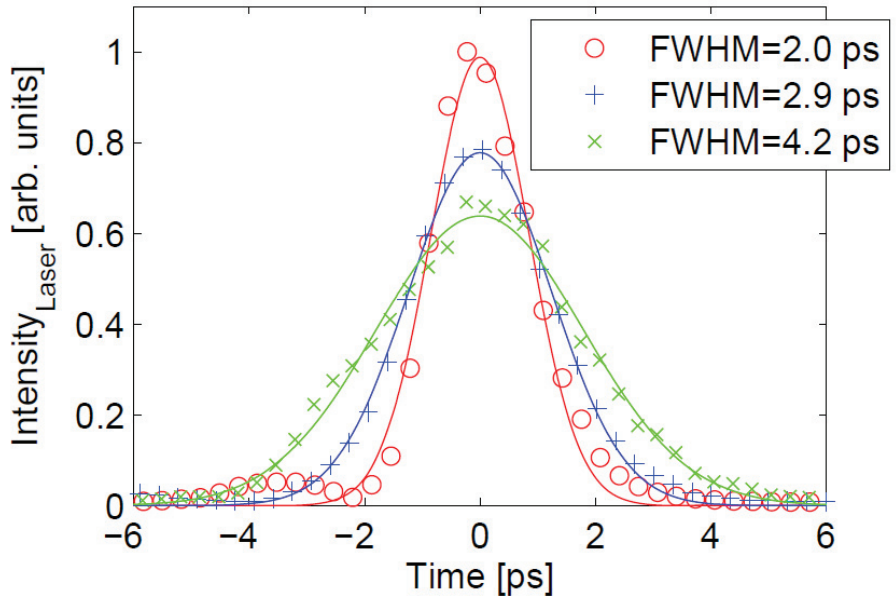


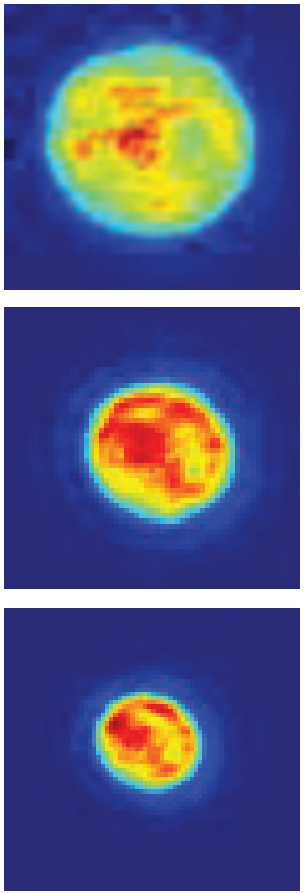




Possible Sources of Large Emittance Value – II

Non-ideal longitudinal & transverse profile of drive laser pulse

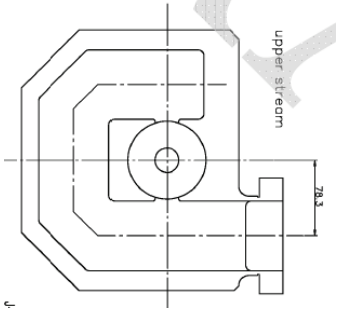


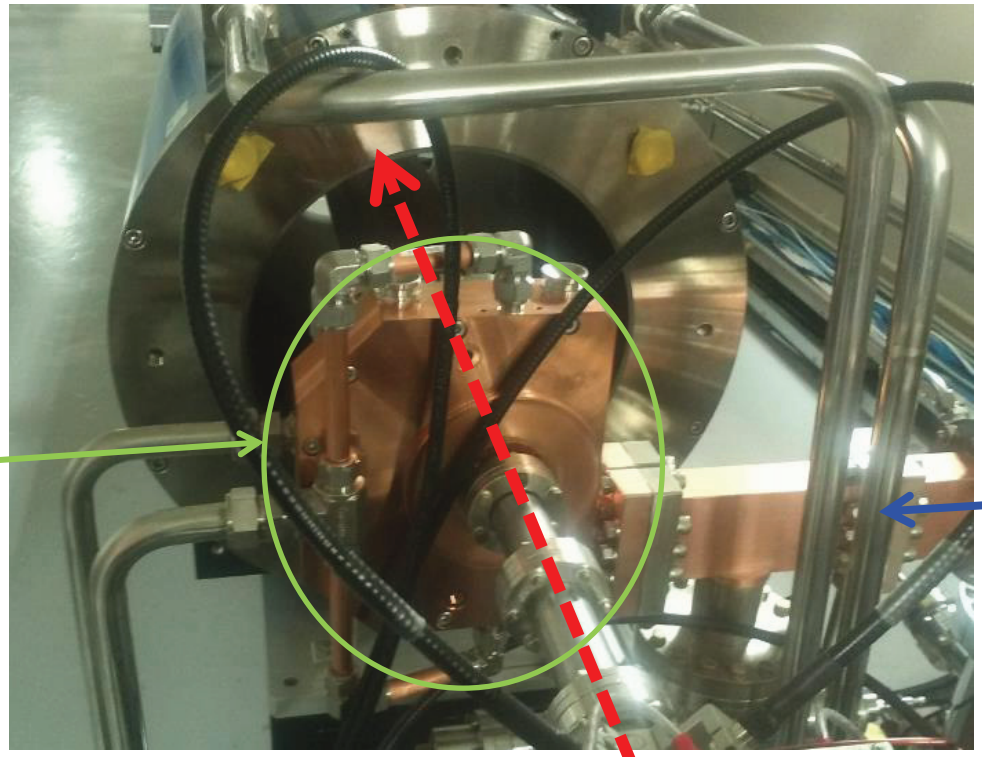


Possible Sources of Large Emittance Value – III

- Alignment of beam to RF and solenoid fields
  - -> New alignment done recently
- Non-symmetric RF coupler field of accelerating structures (?)
  - -> Study underway

MHI J-type coupler with circular coupler cell





Other Tests Done

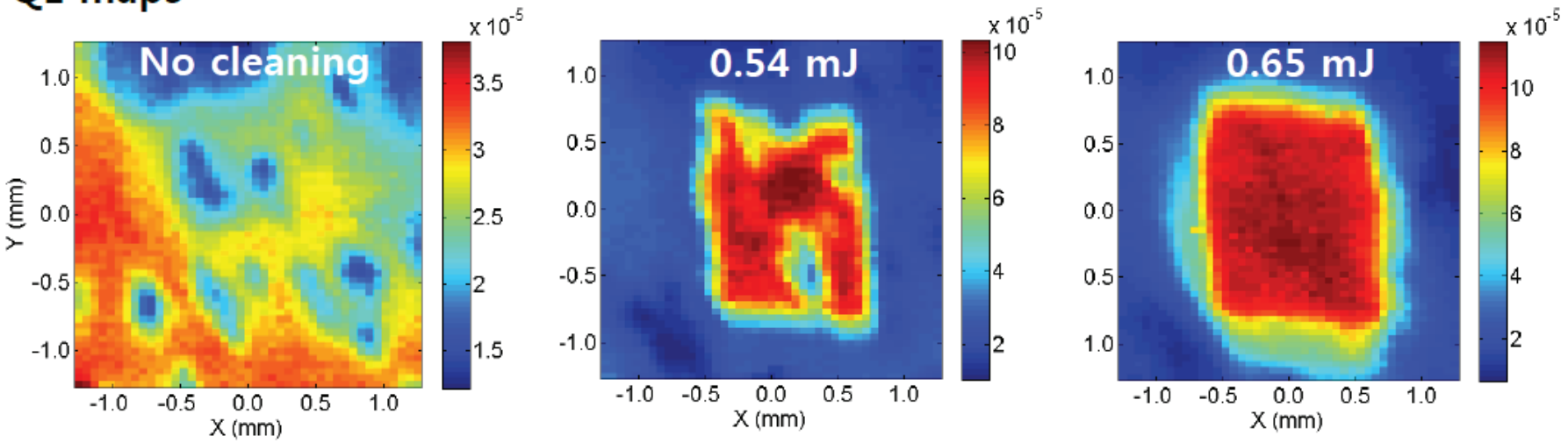
- Laser cleaning of cathode

- Beam test of accelerator components
  - Stripline BPM
  - Beam arrival time monitor (cavity type)
  - Dechirper
  - …

Laser Cleaning

150 ps long IR (760 nm) laser used for cleaning

QE maps

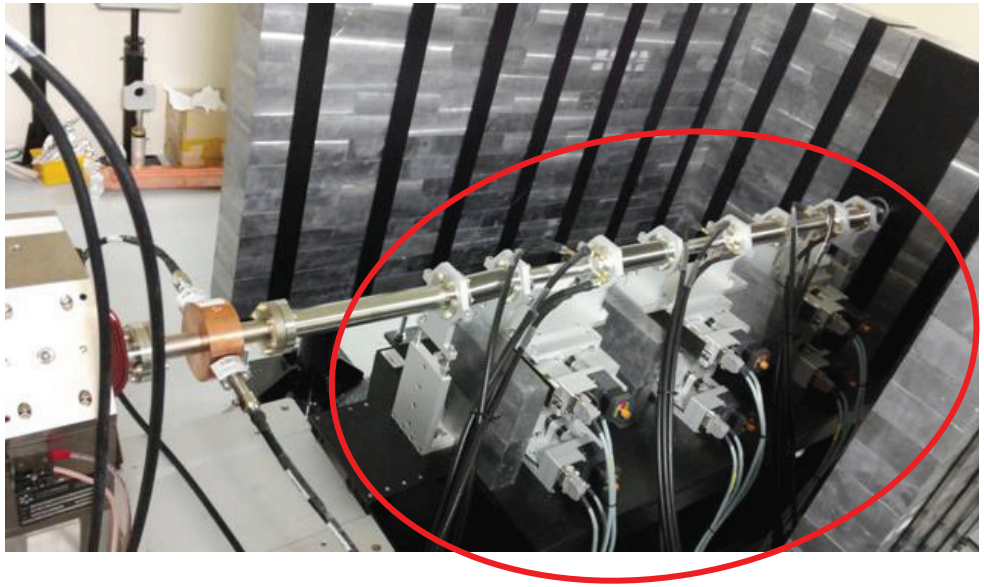


Photocathode is the central area of the copper gun cavity back plane

QE recovered from 4.0×10^{-5} to 1.3×10^{-4} and stayed for a few months

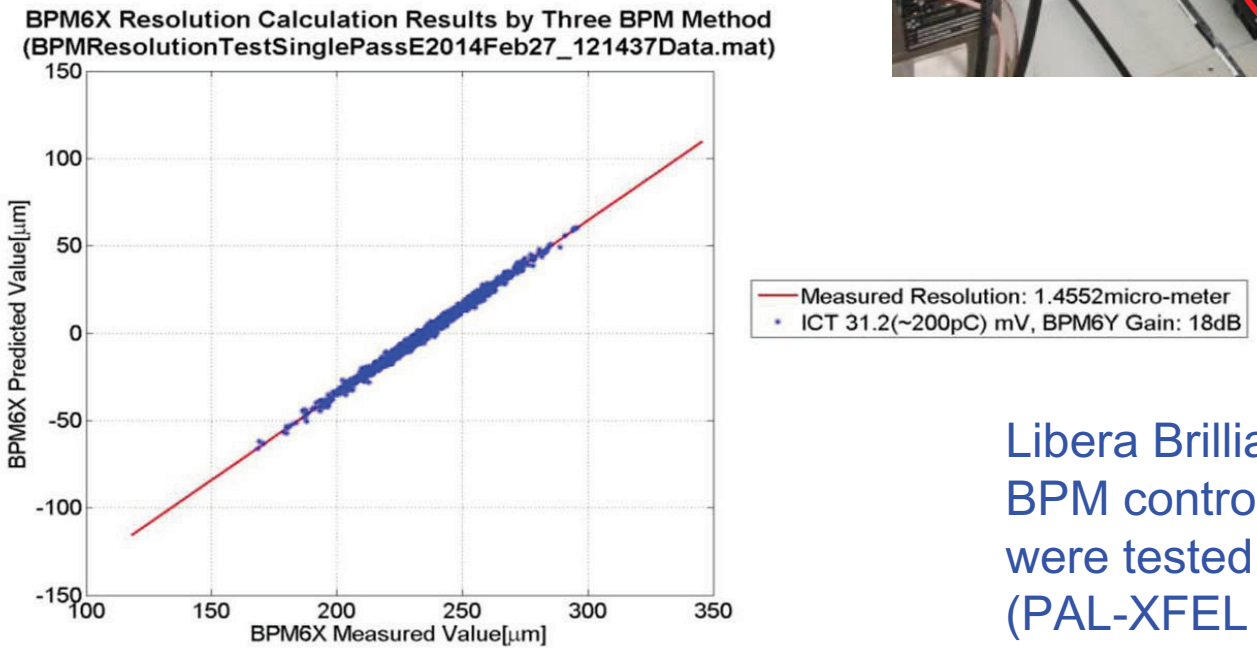
C. K. Min, 6th Hard X-ray Collaboration Meeting, DESY, 2014

Beam Test of Stripline BPM



Calibrated Libera Single Pass E

- KX = KY = 6.666 mm
- Attenuator setting = 18 dB
- Measured resolution = **1.4552 um**

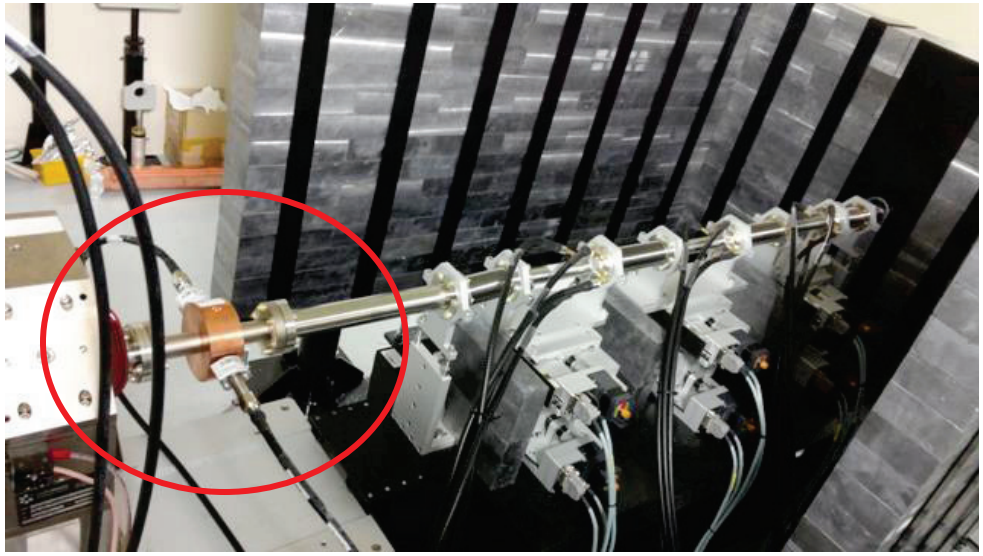


Libera Brilliance Single Pass and BPM controller produced by SLAC were tested at ITF ~ 3 μm with 200 pC (PAL-XFEL linac requirement < 5 μm)

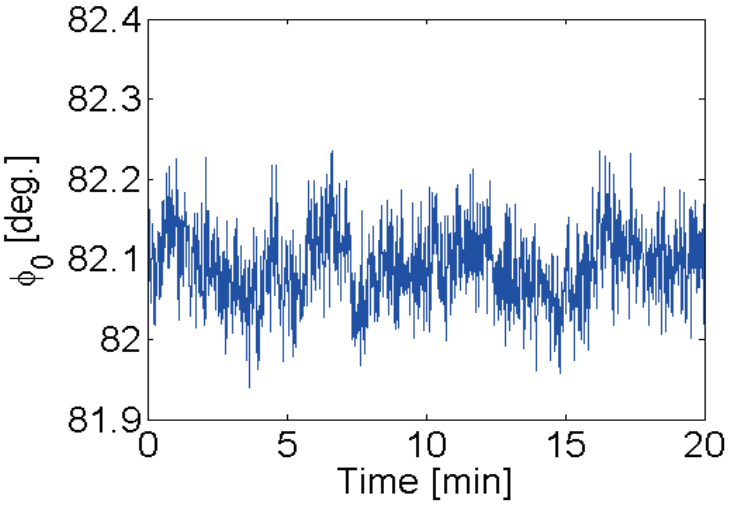
Beam Arrival Time Monitor

2.856 GHz signal analyzed with the LLRF module

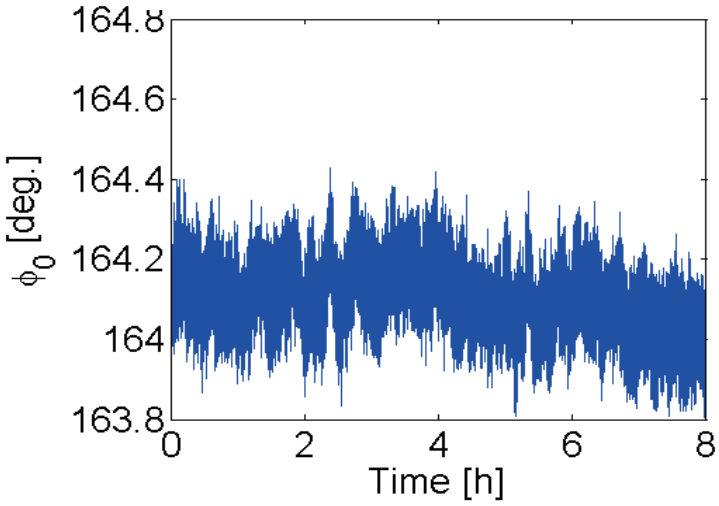
Time resolution ~ 10 fs



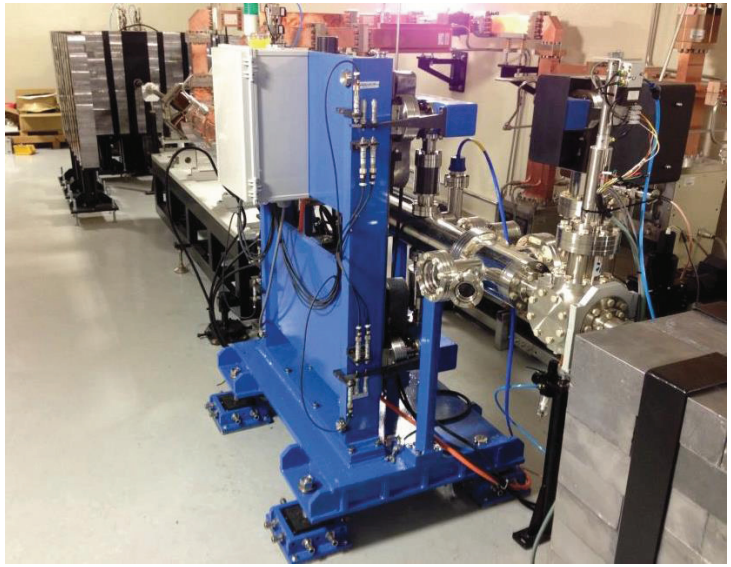
46 fs rms jitter for 20 min

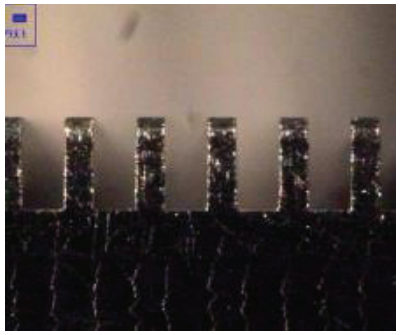


76 fs rms jitter for 8 hours



Corrugated-Wall Dechirper





Corrugated structure

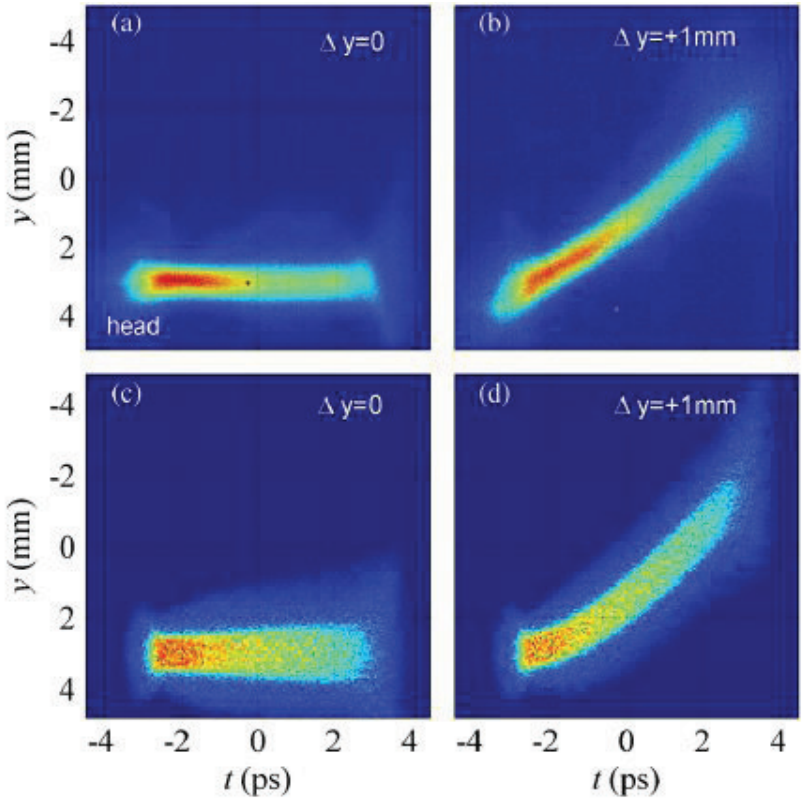


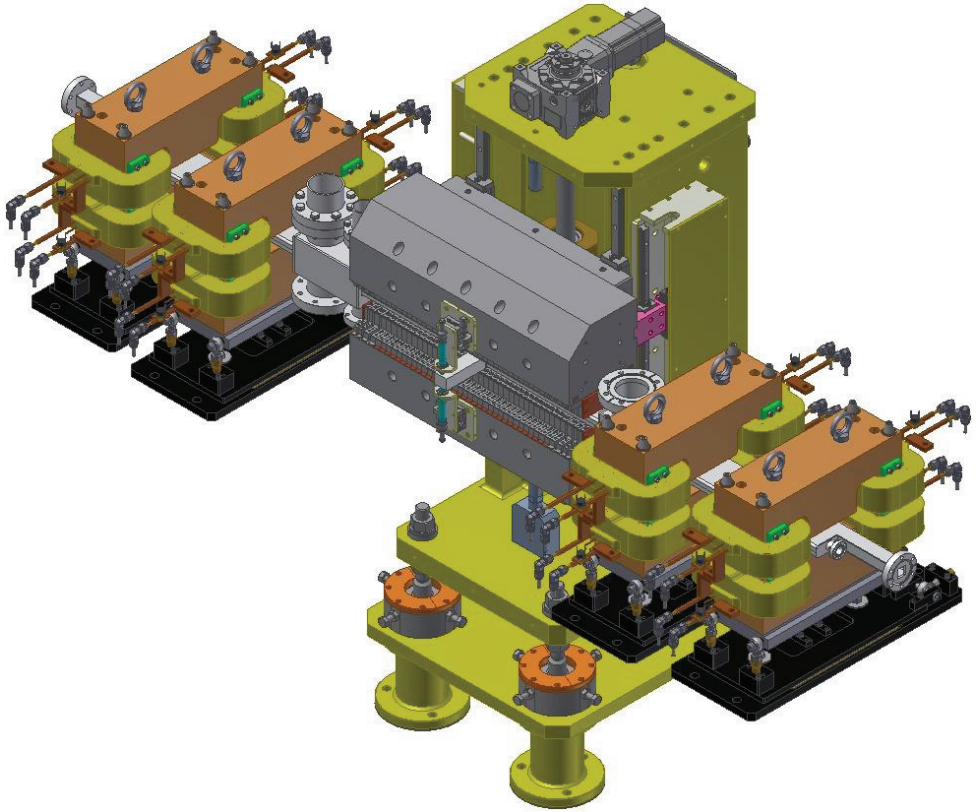
FIG. 7 (color online). Screen 6 images (*top-row*: measured, *bottom-row*: simulated, $Q = 150$ pC), with $g = 6$ mm, rf deflector switched off and L0a phase adjusted 10 degrees off crest, showing no dipole kick when gap is centered on the beam (*left*), but a strong tail kick with gap off axis by 1 mm (*right*). The bunch head is at left in each image.

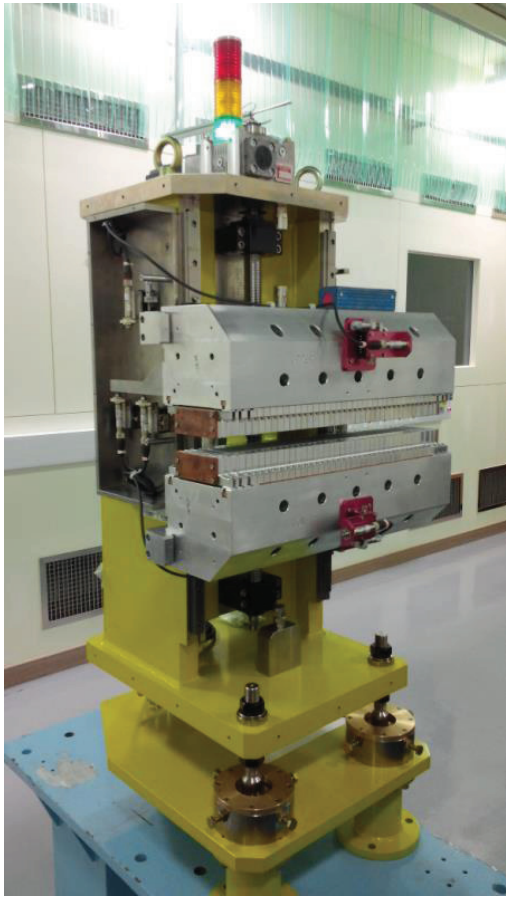
P. Emma et al., PRL 112, 034801 (2014)

Plans

- Vacuum line upgrade with low mu materials in winter 2014
- Laser shaping improvement for spatial & temporal
- Gun solenoid higher order mode cancelation in September 2014
- Finer beam-based alignment including gun solenoid micro-mover in winter 2014
- Test of new gun with coaxial coupler in winter 2014
- Laser heater test in winter 2014

Laser Heater

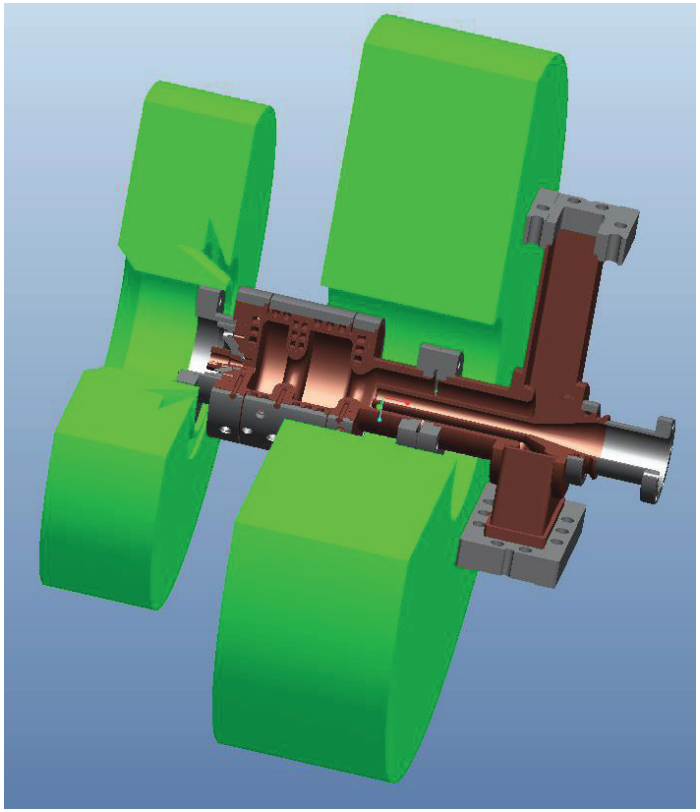




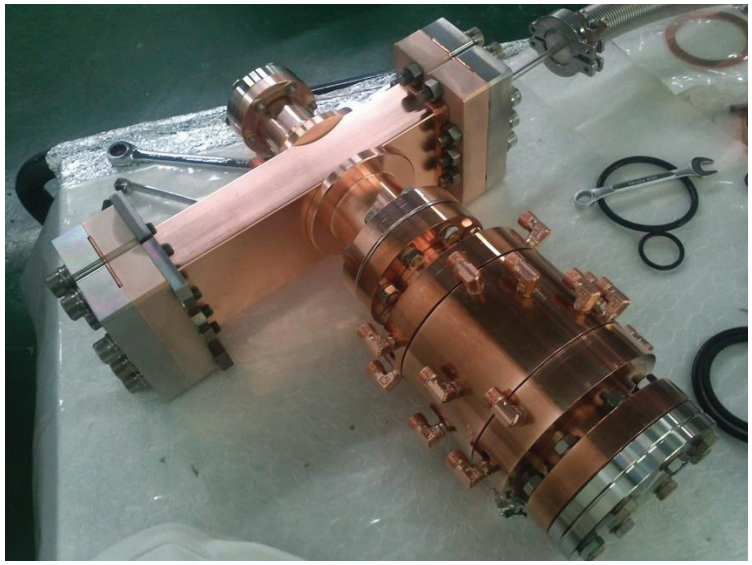
Undulator field measured at IDL

- Components are ready for installation
- Full beam test to be done at ITF for efficient injector commissioning at PAL-XFEL

Gun2



- 1.5 cell S-band gun with coaxial coupler
- Lower emittance and better thermal behavior expected



To be installed in the ITF tunnel in winter 2014

Summary

- PAL-FEL ITF is running for injector commissioning prior to main linac commissioning in a year
- Beam property measurement ongoing, the present beam quality satisfies the required parameter for initial beam commissioning of PAL-XFEL
- R&D and test of diagnostics, high power RF, laser ongoing
- New gun and laser heater to be tested
- ITF to be operational till summer 2015

Thanks