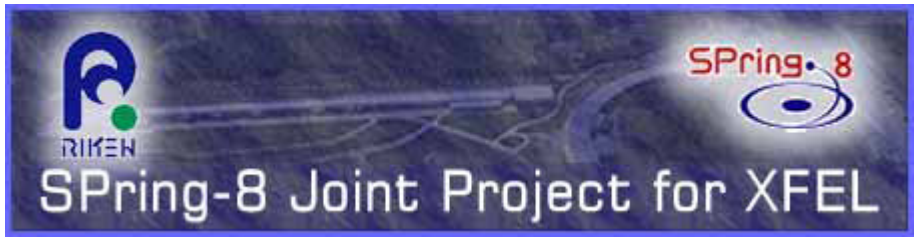


Beam Diagnostic System of XFEL/SPring-8

H. Maesaka*, S. Inoue, T. Ohshima, S. Matsubara,
A. Higashiya, M. Yabashi, T. Shintake and Y. Otake
RIKEN/SPring-8,

H. Ego, K. Yanagida and H. Tomizawa,
JASRI/SPring-8

DIPAC 2009

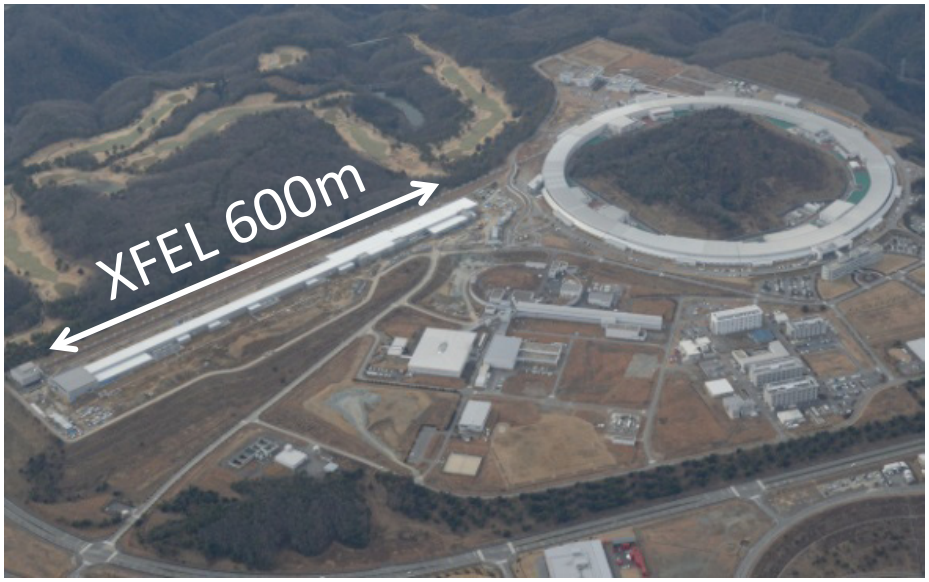
25th, May 2009

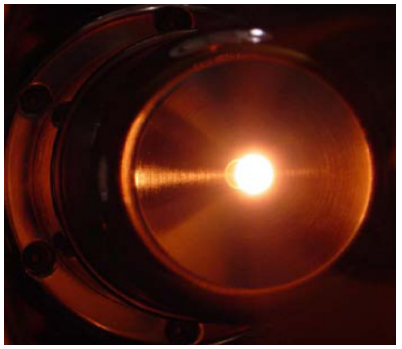
Outline

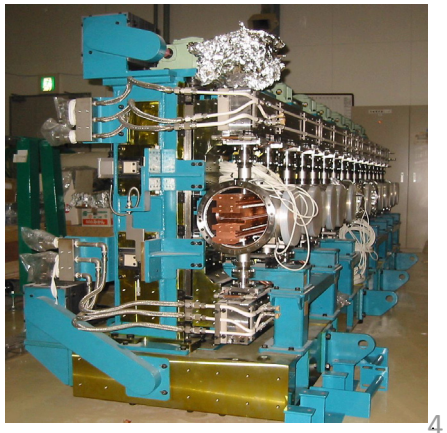
- Introduction
  - X-ray FEL Project at SPring-8
  - SCSS Test Accelerator
  - XFEL Machine Layout and Parameters
- Beam Diagnostic System
  - Requirements and Solutions
  - RF Cavity BPM
  - Transverse Beam Profile Monitor
  - Current Transformer
  - Temporal Bunch Structure Measurement
- Summary

Introduction

X-ray FEL Project at SPring-8



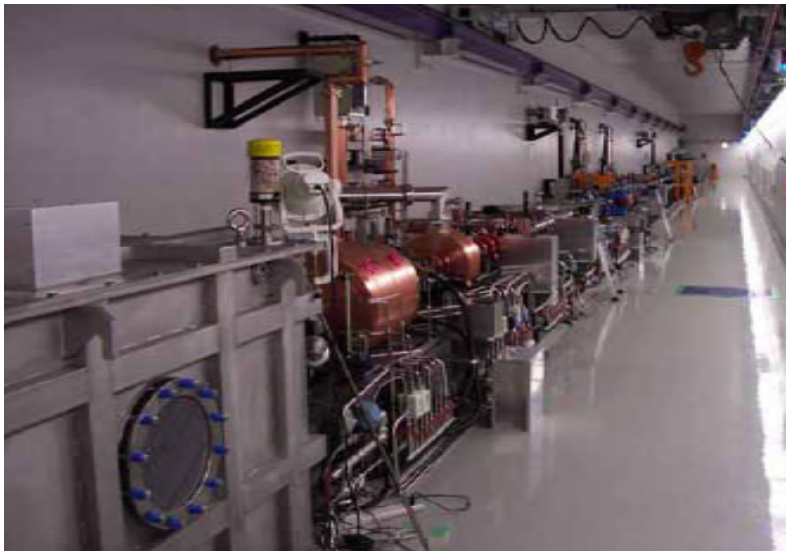


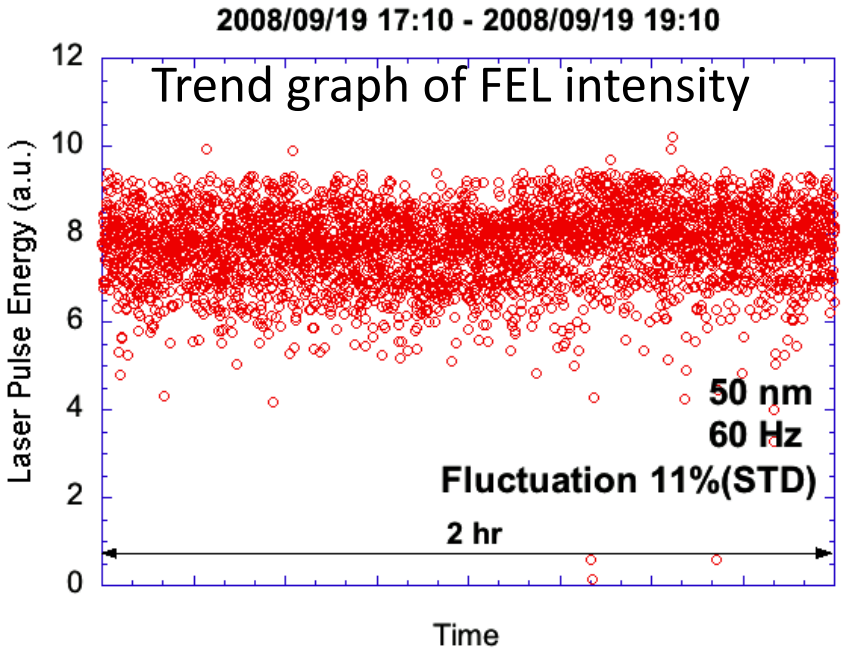


- X-ray wavelength: < 0.1 nm
- Self-amplified spontaneous emission (SASE) process
- Beam energy: 8 GeV
- Key technologies
  - Low-emittance thermionic electron gun: 0.6 π mm mrad
  - High-gradient C-band accelerator: 35 MV/m
  - Short-period in-vacuum undulator: λ_u = 18 mm, K < 2.2
- First FEL light will be delivered in 2011.

SCSS Test Accelerator

- Extreme ultraviolet (EUV) FEL facility
  - Wavelength: 50 – 60 nm for saturated output
  - Beam energy: 250 MeV
- Saturated EUV laser light has been stably generated since 2006.

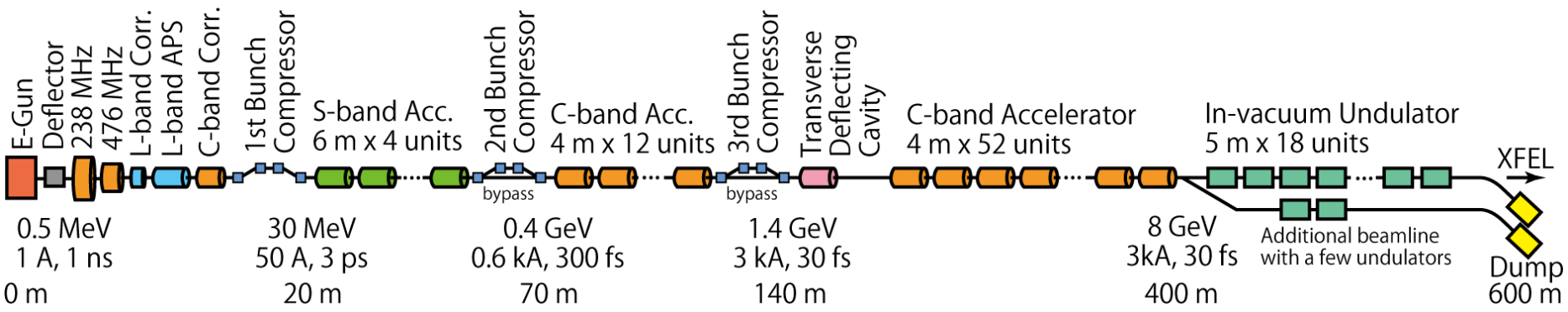




XFEL Building

- Construction was completed in March 2009.

XFEL Machine Layout



- 8GeV linear accelerator
  - 238 MHz, 476 MHz, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz)
- Bunch compression
  - Velocity bunching in the low energy region
  - Three bunch compressors
  - Bunch length: 1 ns → 30 fs (FWHM)
  - Peak current: 1 A → 3 kA
- Coherent X-rays are generated by in-vacuum undulators

XFEL Machine Parameters

Beam Energy	8 GeV
Bunch Charge	0.3 nC
Normalized Slice Emittance	0.7 π mm mrad
Repetition Rate	60 pps maximum
Peak Current	3 kA
Bunch Length	30 fs (FWHM)
Beam Radius	40 μm (RMS)
Undulator Period	18 mm
Undulator K-value	2.2 maximum
Undulator Gap	3 mm minimum
Number of Periods	275 x 18 = 4950

Requirements and Solutions for the Beam Diagnostic System

- High-resolution beam position monitor (BPM)
  - To maintain the overlap between an electron beam and X-rays in the undulator section with 4 μm precision
  - Position resolution < 0.5 μm

  → RF cavity BPM
- High-resolution transverse beam profile monitor
  - Beam radius: 40 μm (RMS)
  - For emittance and Twiss parameter measurement etc.
  - Spatial resolution < 10 μm

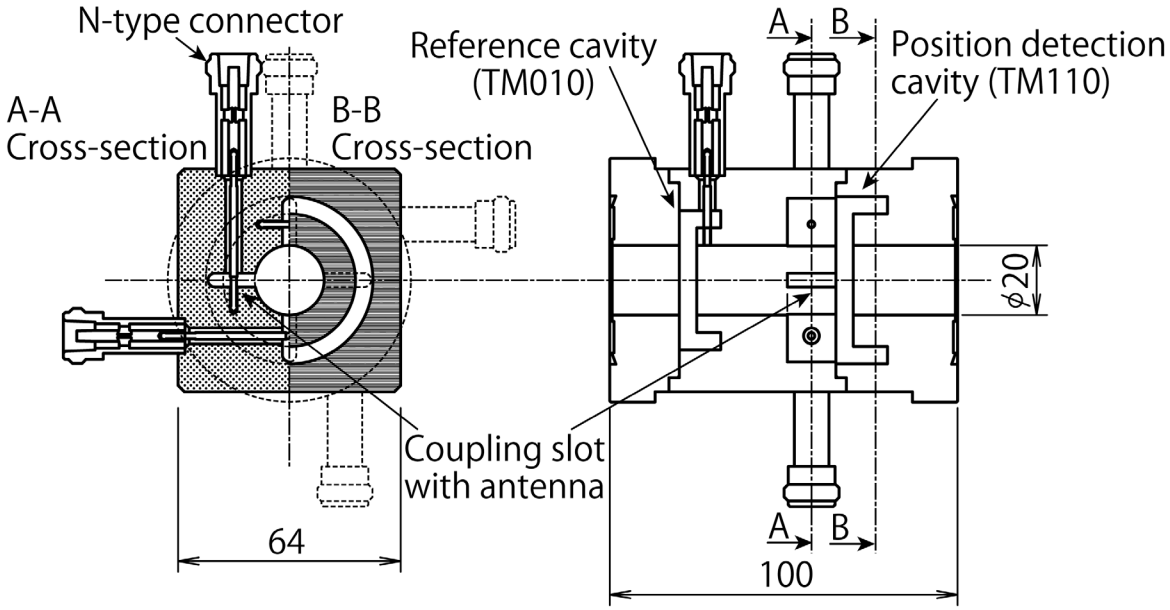
  → OTR monitor and fluorescent screen monitor with a custom imaging system
- Noise-free high-speed current transformer (CT)
  - Need to reduce noise coming from the power supply of a klystron.
  - Rise time < 1 ns

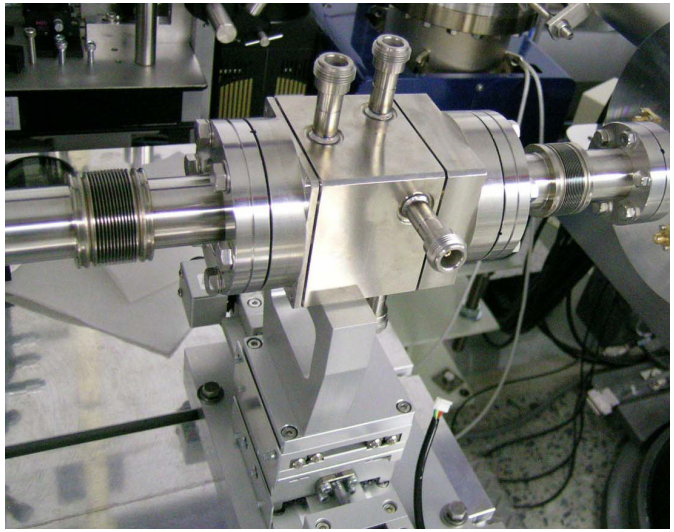
  → Differential CT
- Temporal bunch structure measurement system
  - Bunch Length: 30 fs (FWHM)
  - Temporal resolution < 10 fs

  → C-band transverse RF deflecting cavity

RF Cavity BPM

RF Cavity BPM

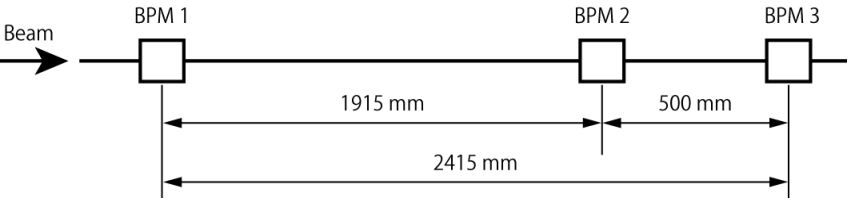


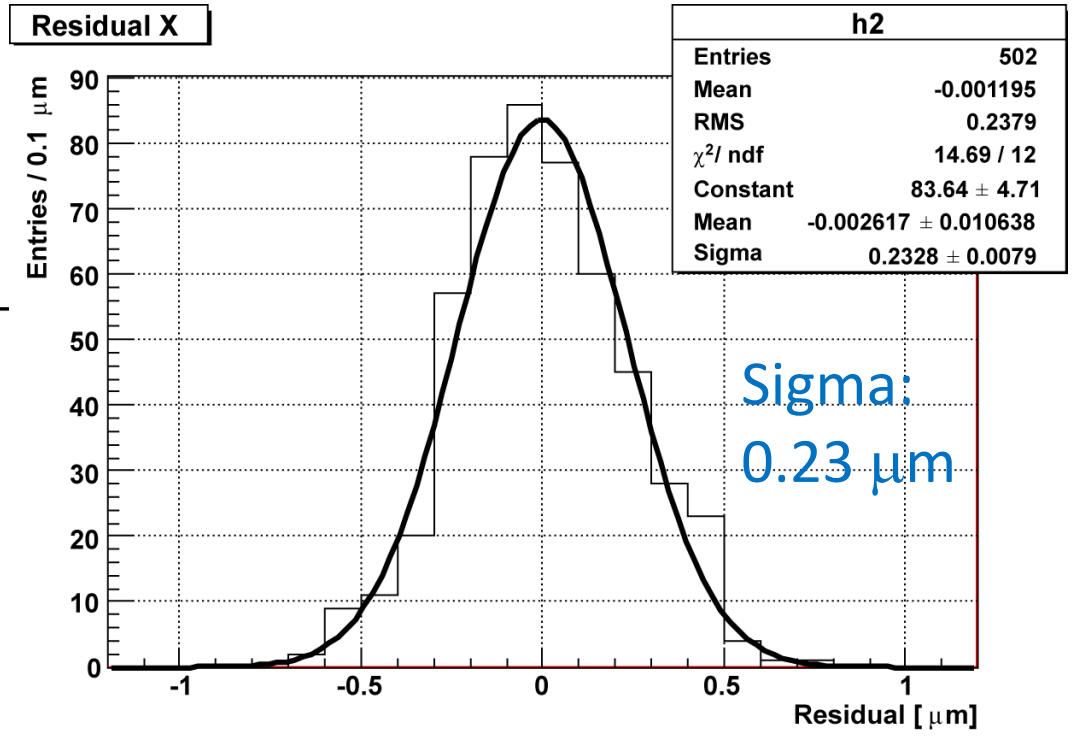


- Details will be reported by MOPD07 in the today's poster session.
- Resonant Frequency: 4760 MHz
- Required position resolution: < 0.5 μm

RF-BPM Resolution

- Position resolution: 0.2 μm
  - Measured with three adjacent BPMs.
  - Compare the 2nd BPM data with the interpolation from 1st and 3rd BPMs.





Beam Profile Monitor

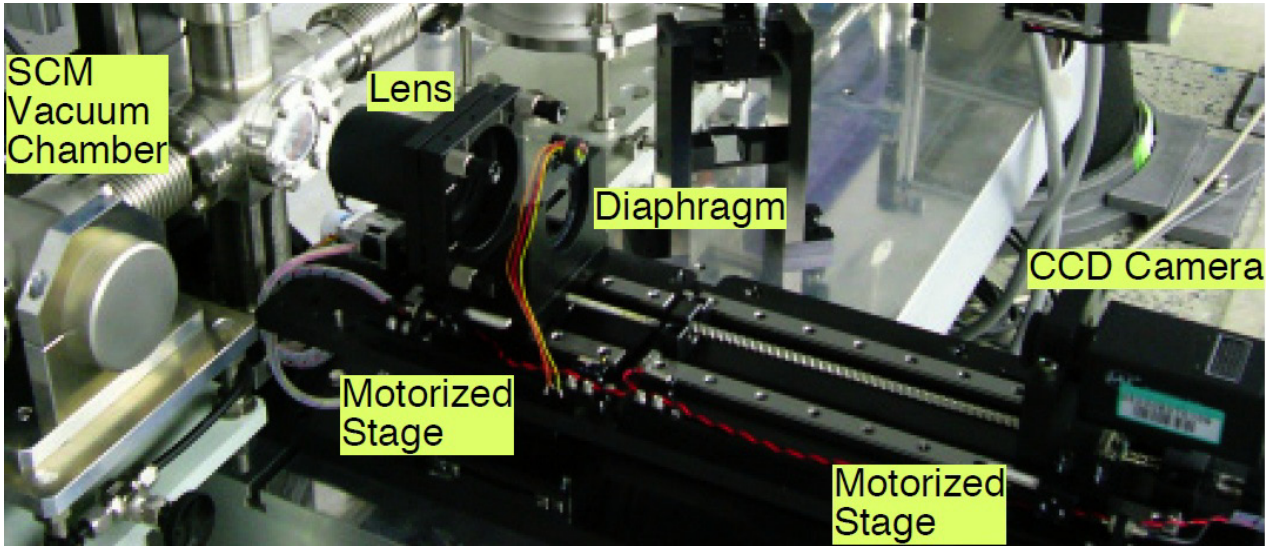
Precise Beam Profile Monitor

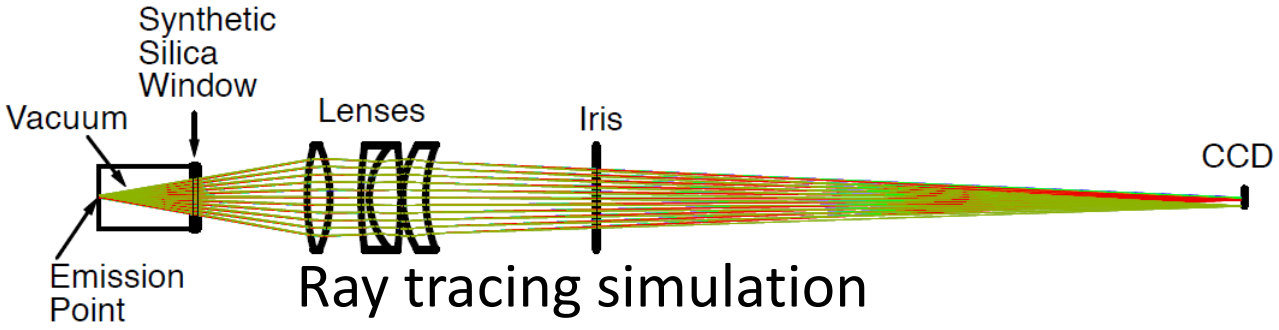
- Requirements
  - Spatial resolution: < 10 μm
    - Beam radius is 40 μm (RMS) in the undulator section.

  → Custom imaging system
- Screen type
  - Fluorescent screen for low energy part (< 100 MeV)
    - Ce: YAG etc.
  - Optical transition radiation (OTR) for high energy part
    - Stainless steel foil

K. Yanagida *et al.*, "Development of Screen Monitor with a Spatial Resolution of Ten Micrometers for XFEL/SPring-8", Proceedings of LINAC'08.

Imaging System



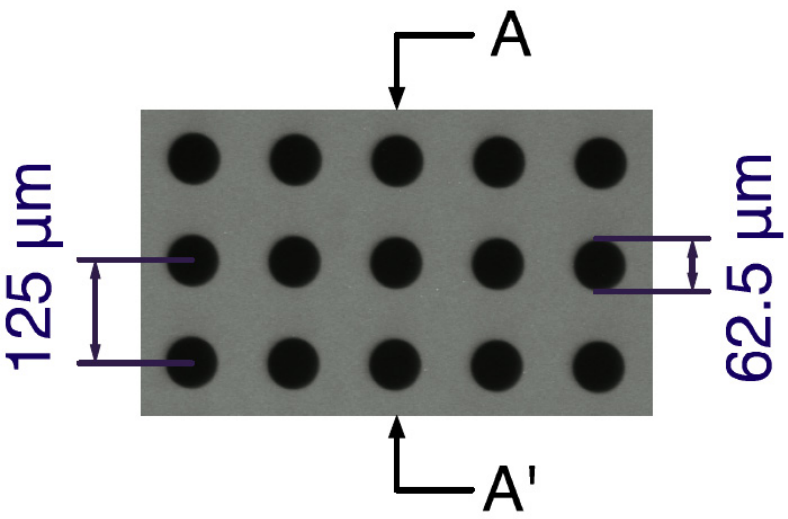


Ray tracing simulation

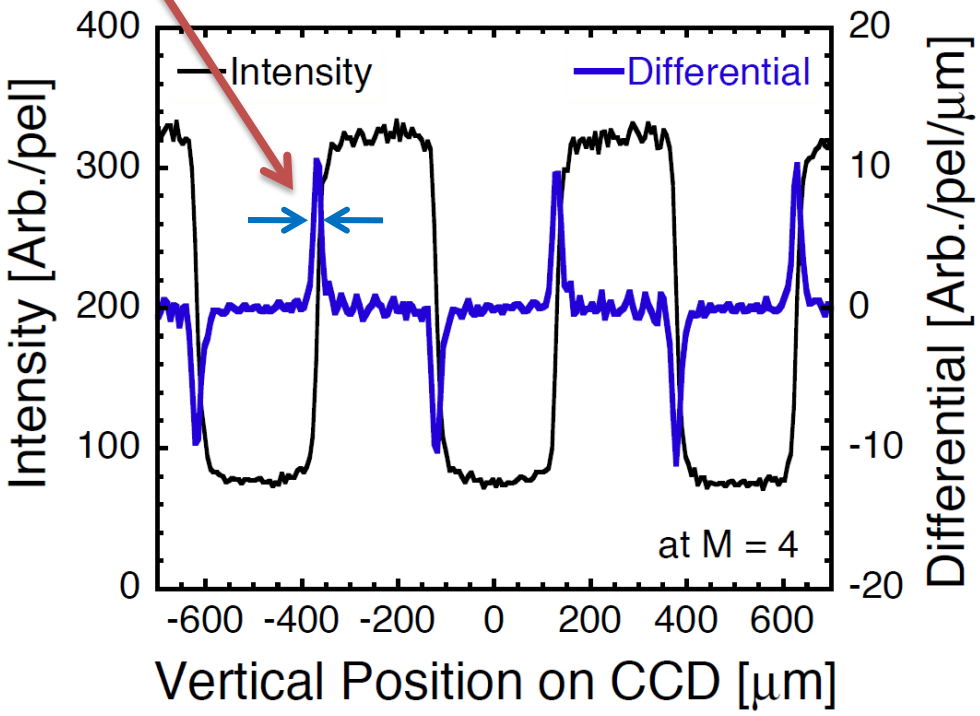
- Custom-made lens system
- Variable magnification: x1 – x4
  - Lens and CCD camera are mounted on a motorized stage
  - x1 optics: Beam finding
  - x4 optics: Precise measurement

Spatial Resolution

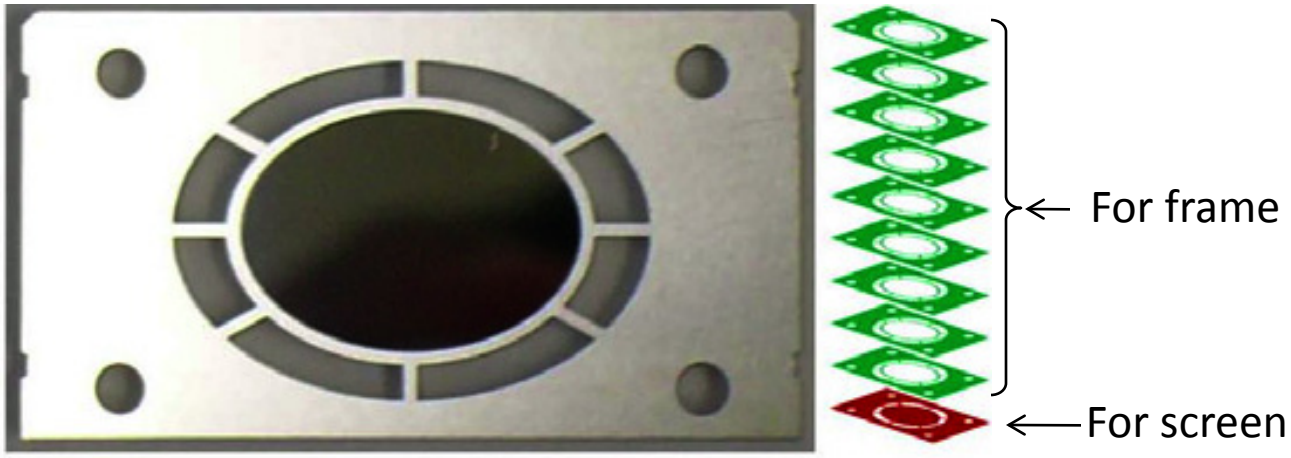
- Spatial resolution of the imaging system was measured by using a grid distortion pattern.
- Spatial resolution: 2.5 μm (HWHM)
  - x4 optics
  - Consistent with lens simulation



Grid distortion pattern

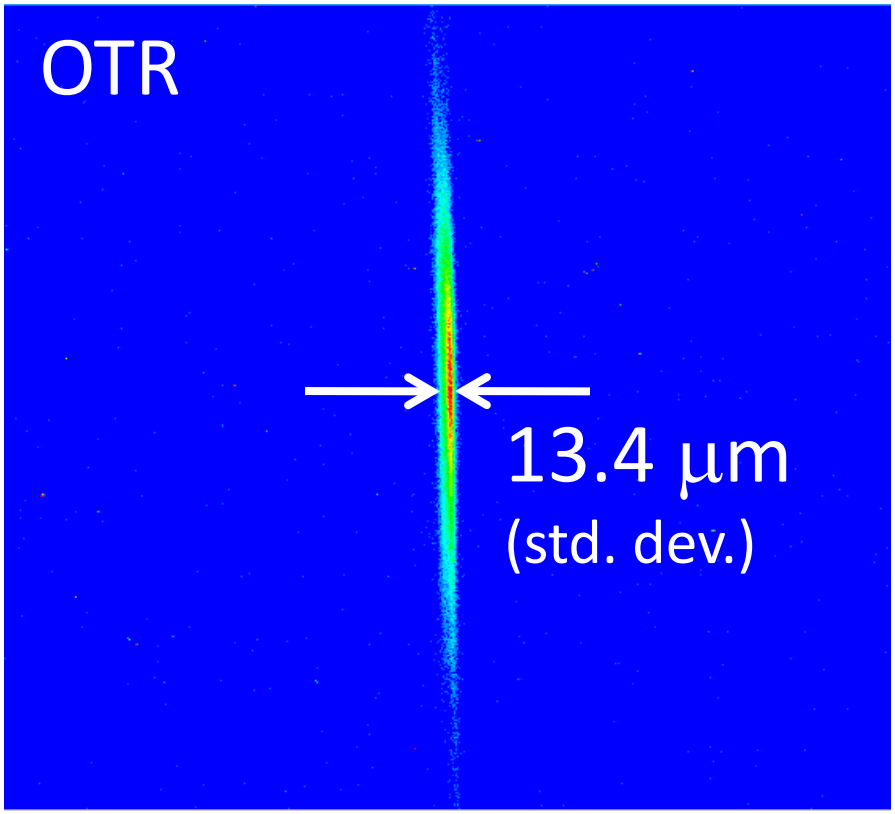


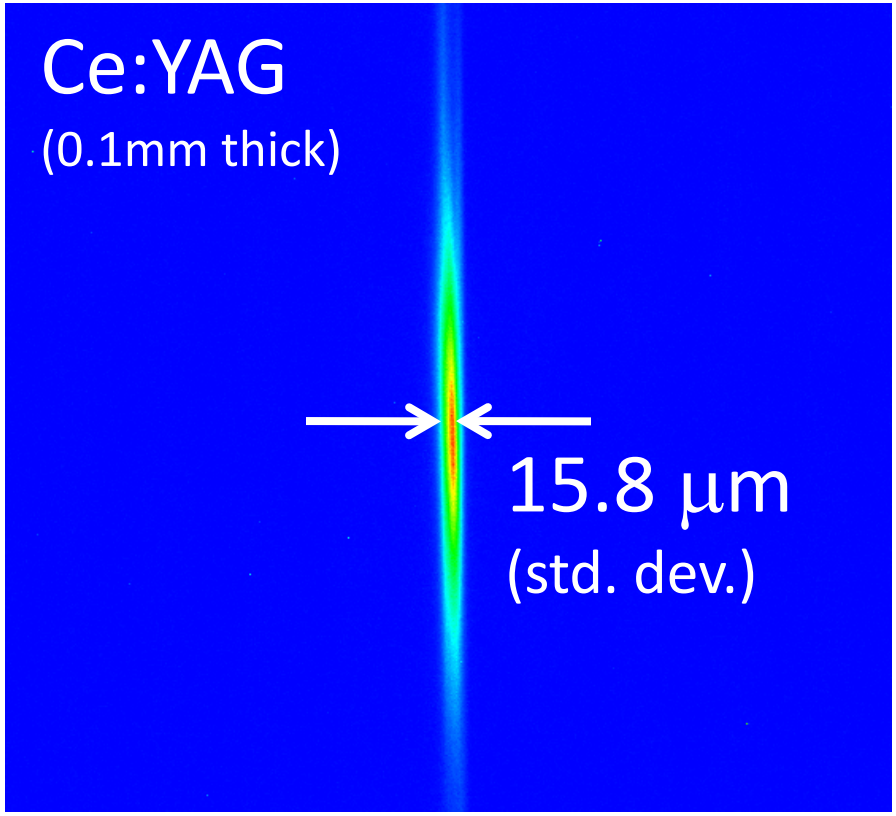
OTR Target



- Thin stainless steel foil
  - Thickness: 0.1 mm
  - To reduce radiation damage of other components.
- 1mm-thick frame to support the foil
  - Ten 0.1 mm thick foils are stacked and unified by a diffusion bonding technique.
- Surface roughness: several 10 nm
- Flatness: 3 μm

Beam Images

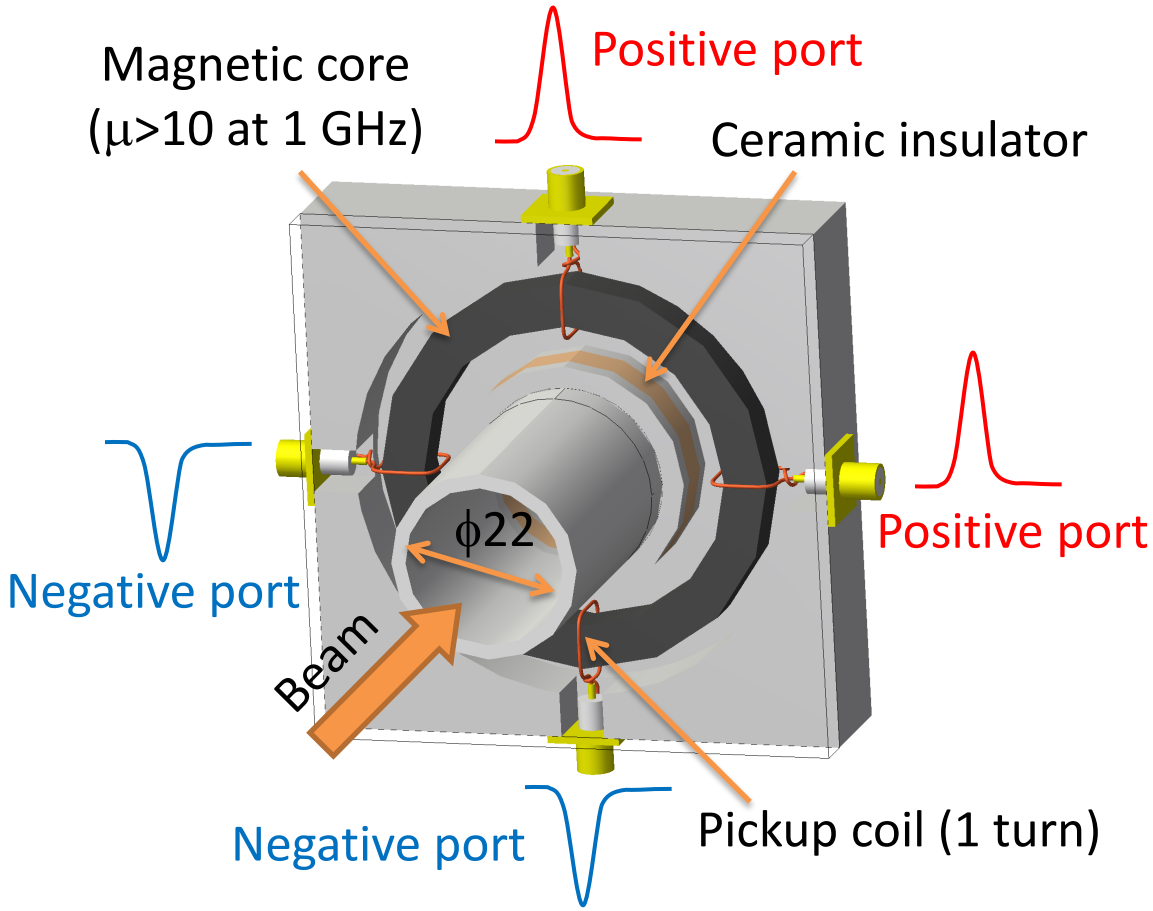


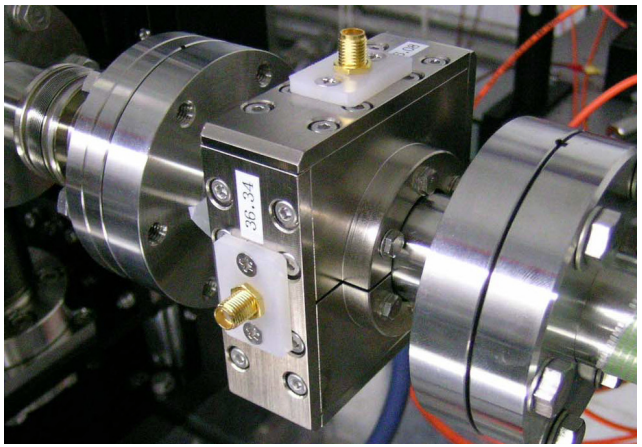


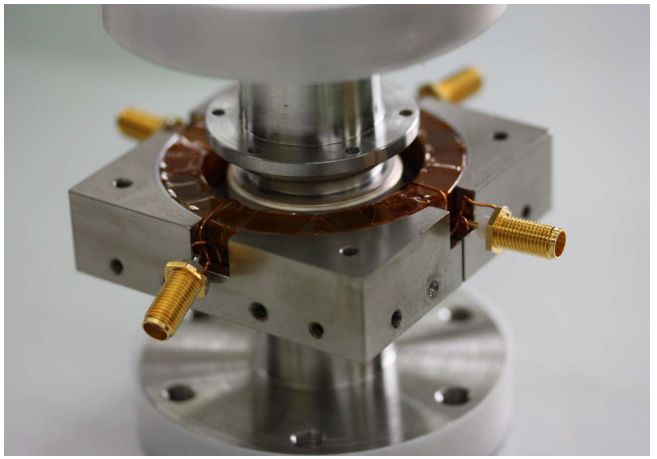
- Taken at the SCSS test accelerator
  - Beam energy: 250 MeV
  - Horizontally focused by Q-magnet.
- Image width is consistent with the natural divergence due to beam emittance
- Deterioration of Ce:YAG image is small (< 10 μm).

Current Transformer

Differential Current Transformer



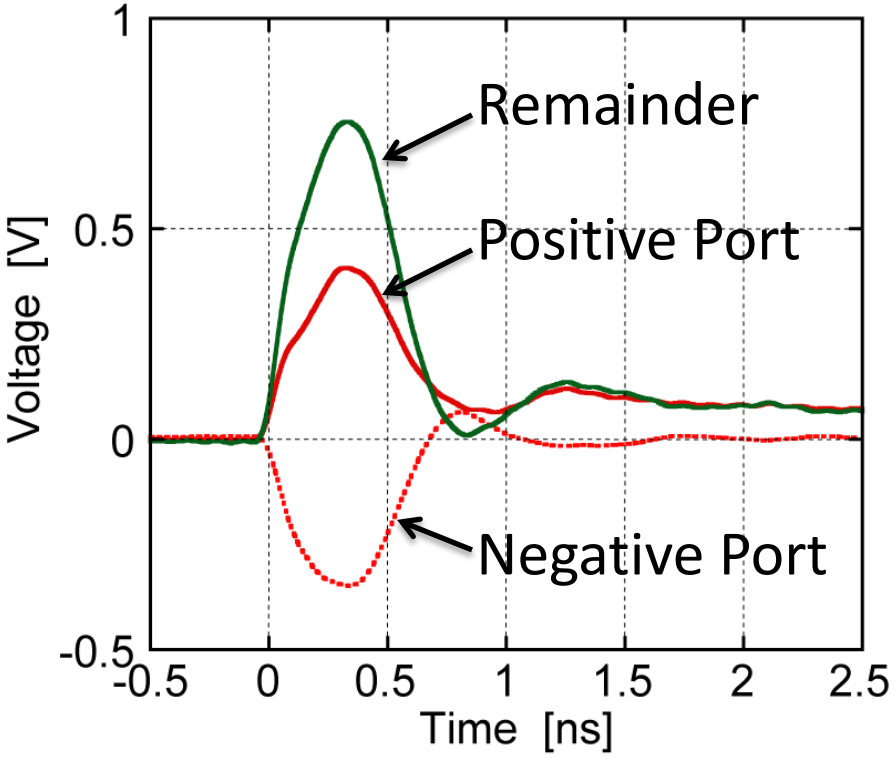




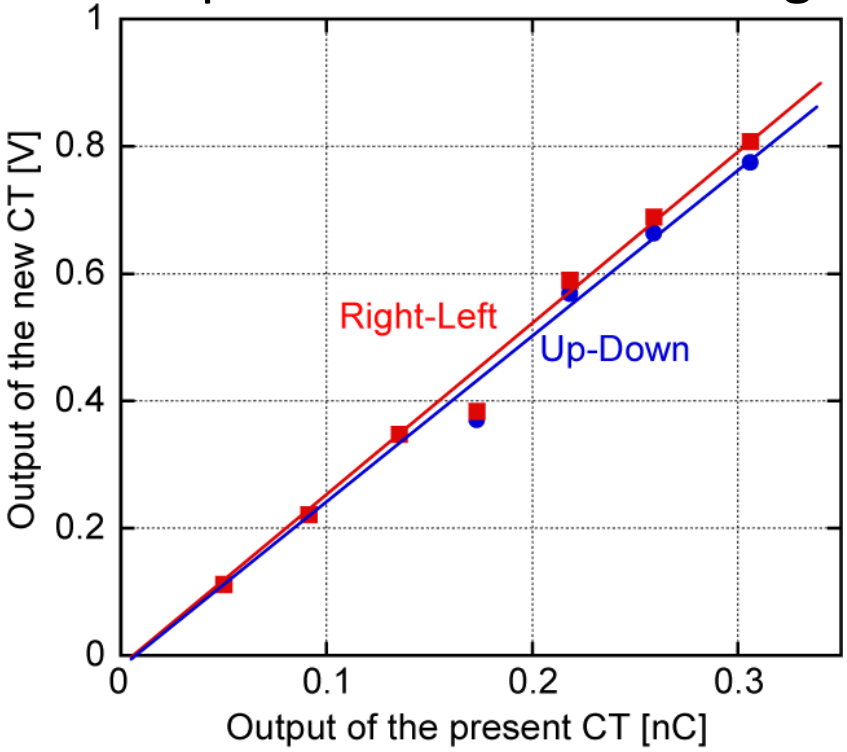
- 2 positive ports and 2 negative ports
- Common-mode noise can be subtracted

CT Results

Output Pulse

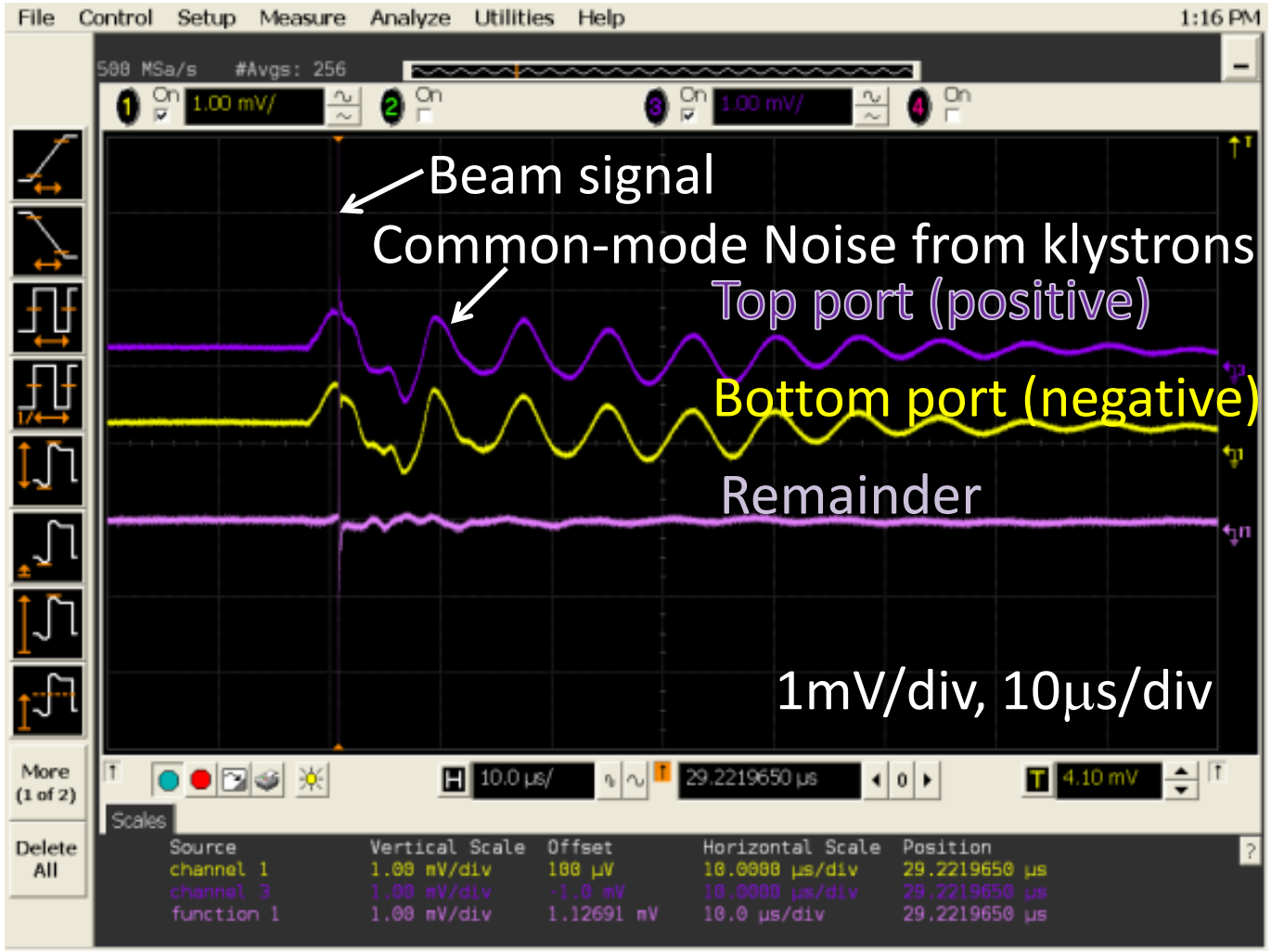


Comparison with an existing CT



- Rise time: 0.2 ns
- Pulse height is proportional to the beam charge

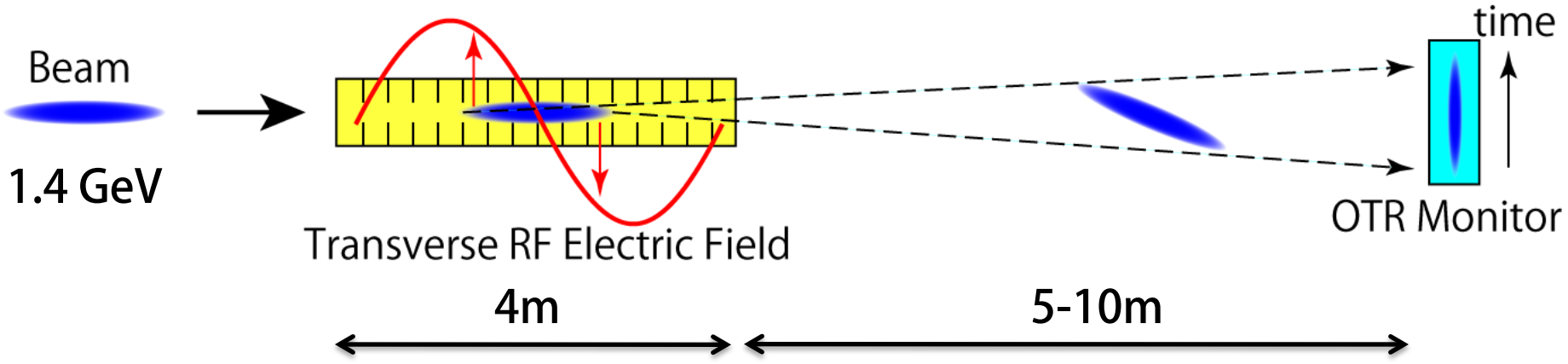
Common-mode Noise Reduction



- Common-mode noise was reduced to 1/10.

Transverse RF Deflector

Temporal Structure Measurement



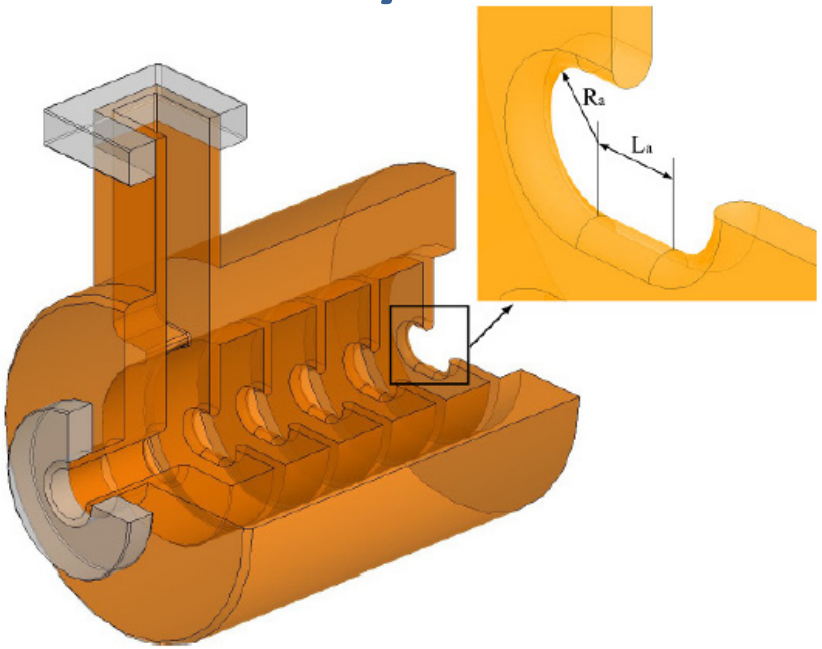
- Temporal beam structure is converted to spatial distribution by transverse RF voltage.
- Beam image is taken by an OTR monitor.
- Required temporal resolution: < 10 fs
  - 100 fs/mm on the screen (after 5–10m drift space)
  - Deflecting voltage: 40 MV at crest phase
- Installed downstream of 3rd Bunch compressor

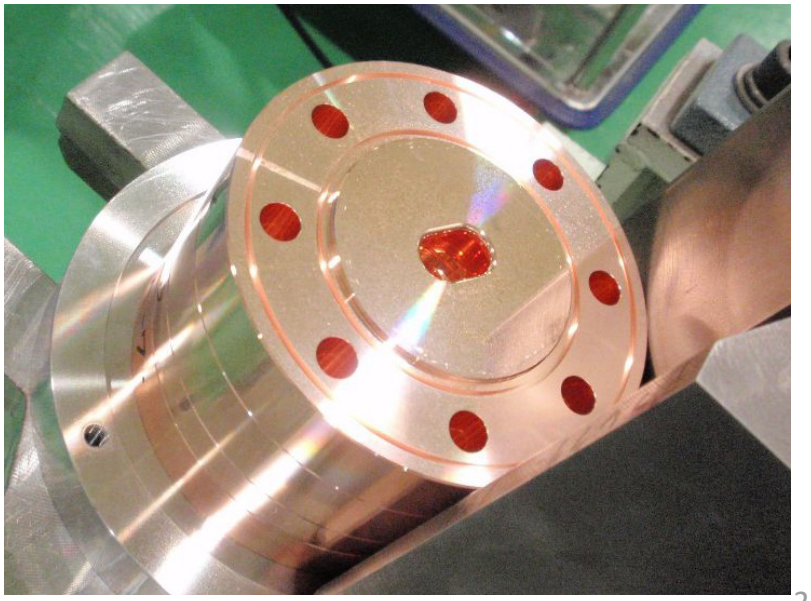
C-band RAIDEN Cavity

- Racetrack-shaped Iris-coupling DEflectioN structure
  - To separate x- and y-mode

H. Ego *et al.*, "Design of the Transverse C-band Deflecting Structure for Measurement of Bunch Length in X-FEL", Proceedings of EPAC'08.

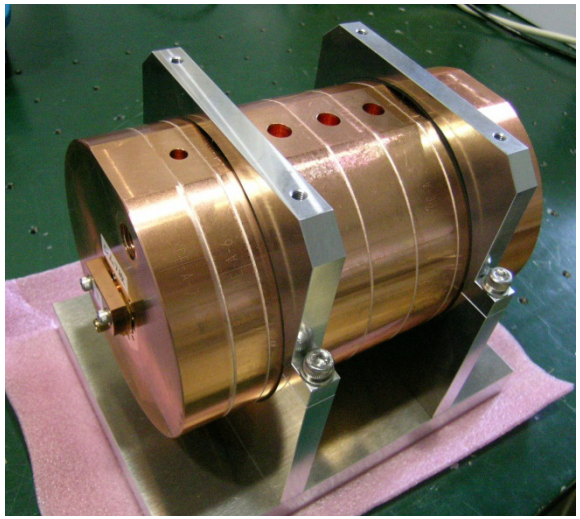
- Resonant Frequency: 5712 MHz
  - To obtain higher kick voltage
  - To fully utilize the C-band accelerator resource
- Backward traveling wave of HEM11-5π/6 mode
- Deflecting voltage: 40 MV
  - When 1.7m x 2 cavities are driven by 50 MW klystron.

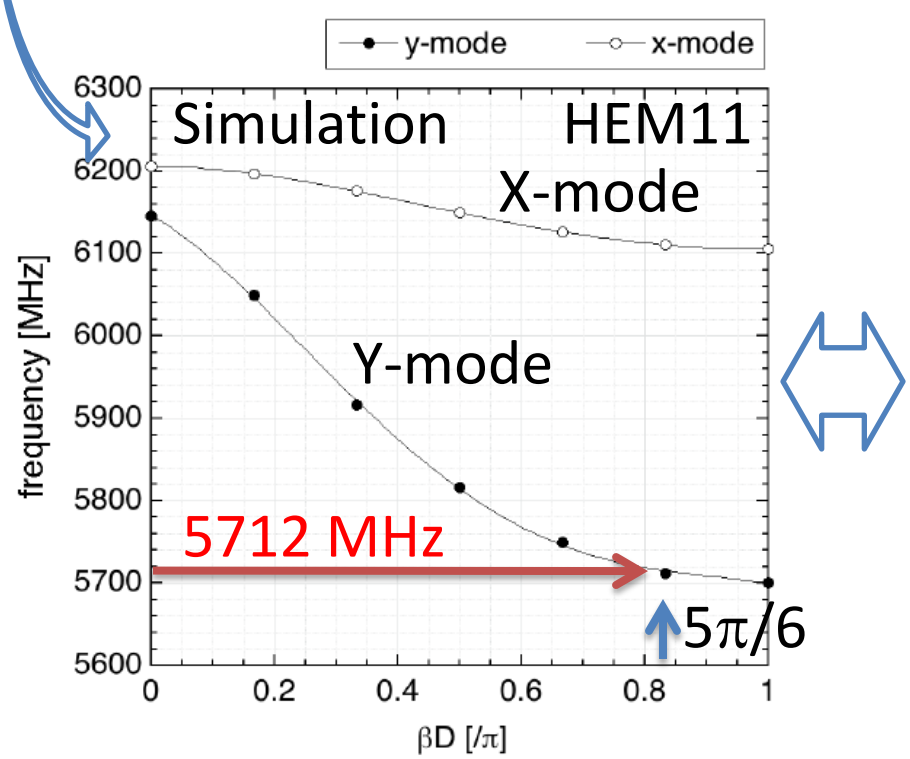


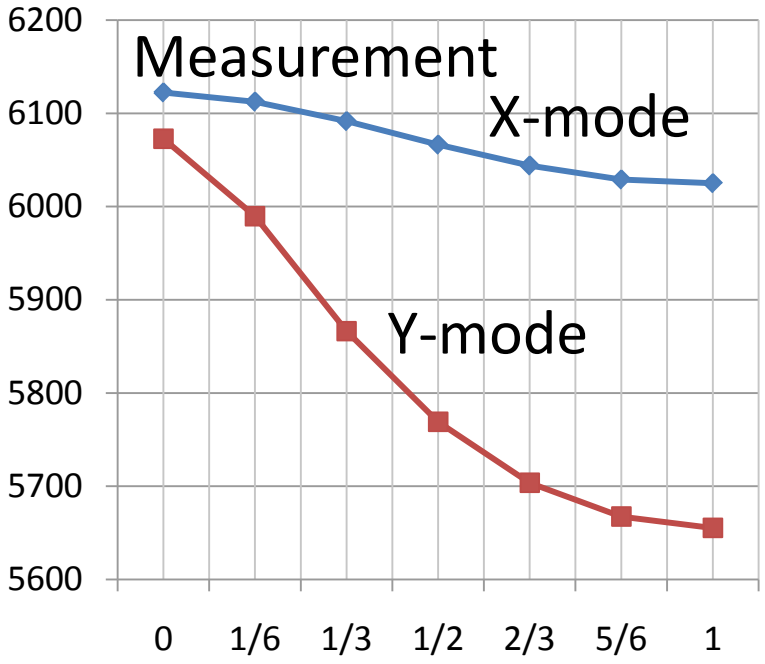


Low-level RF Measurements

- Measured with a 7-cell model.
- Pass band
  - Y-mode is clearly separated from x-mode.
- Shunt impedance
  - Bead perturbation measurement
  - Simulation: 13.9 MΩ/m
  - Measurement: 13.7 MΩ/m





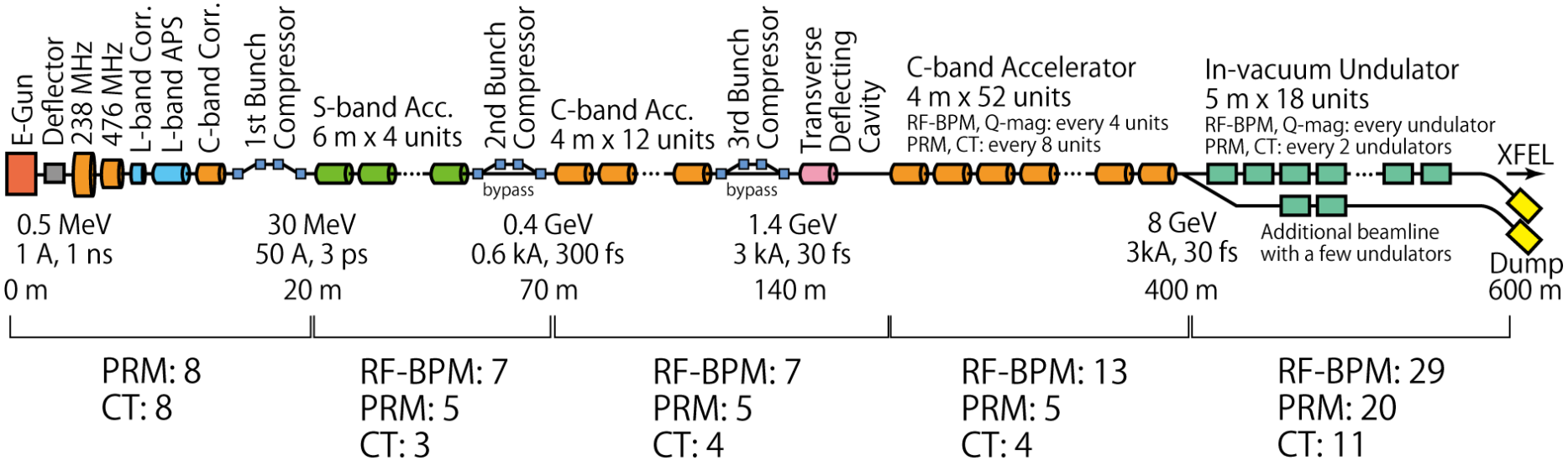


Summary

- RF cavity BPM
  - Position resolution: 0.2 μm
- Beam Profile Monitor
  - Spatial resolution of the imaging system: 2.5 μm
  - Variable magnification: x1 – x4
  - Thin OTR target and Ce:YAG fluorescent screen
- Current transformer
  - Differential output
  - Rise time: 0.2 ns
- Transverse RF deflector
  - For Temporal Bunch Structure Measurement
  - C-band RAIDEN cavity (racetrack-shape iris)
  - Will be installed downstream of the third bunch compressor.
- Beam monitors are ready for XFEL
  - Design work has been almost completed.
  - Performance was confirmed to be sufficient by beam tests.

Supplements

Quantity of Beam Monitors



- RF cavity BPM (RF-BPM): 56
- Beam profile monitor (PRM): 43
- Current transformer (CT): 30
- Transverse RF deflector: 1

Detection Principle of RF-BPM

- TM110 dipole resonant mode of a pillbox cavity

$$E_z = E_0 \, J_1\left(\frac{\chi_{11} r}{a}\right) \cos\phi \, e^{j\omega t}$$

  - E-field is linear around the axis

- Output voltage

$$V = V_1 q x + j V_2 q x' + j V_3 q + V_n$$

Noise

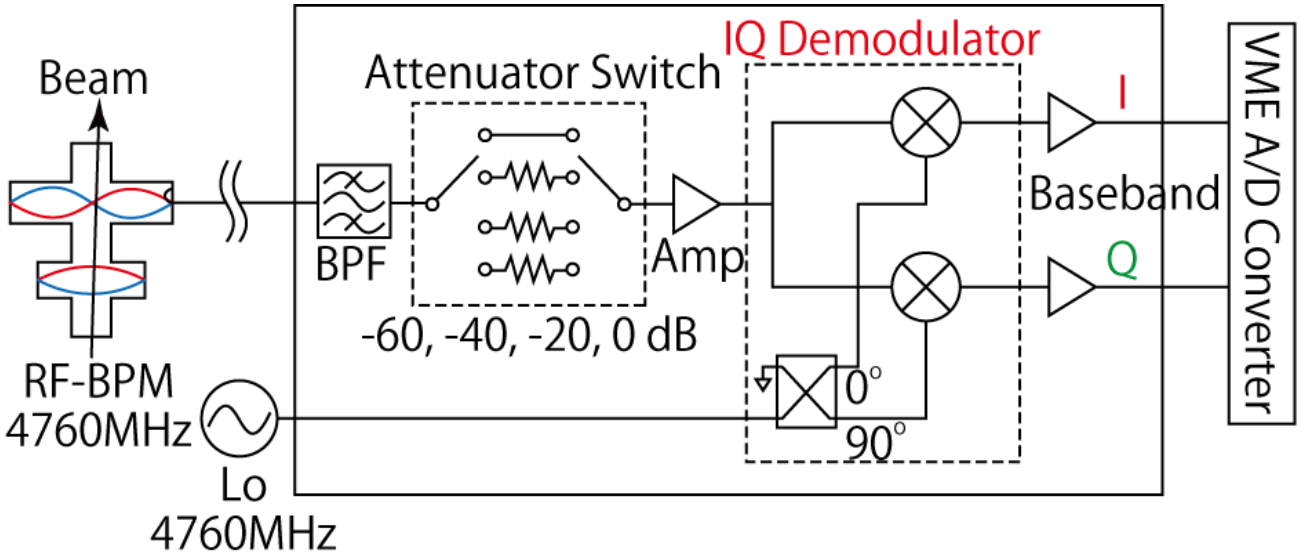
Position signal
In-phase

Slope signal
Quadrature-phase

Leakage of TM010 mode
Quadrature-phase

- Need to discriminate in-phase component from quadrature.

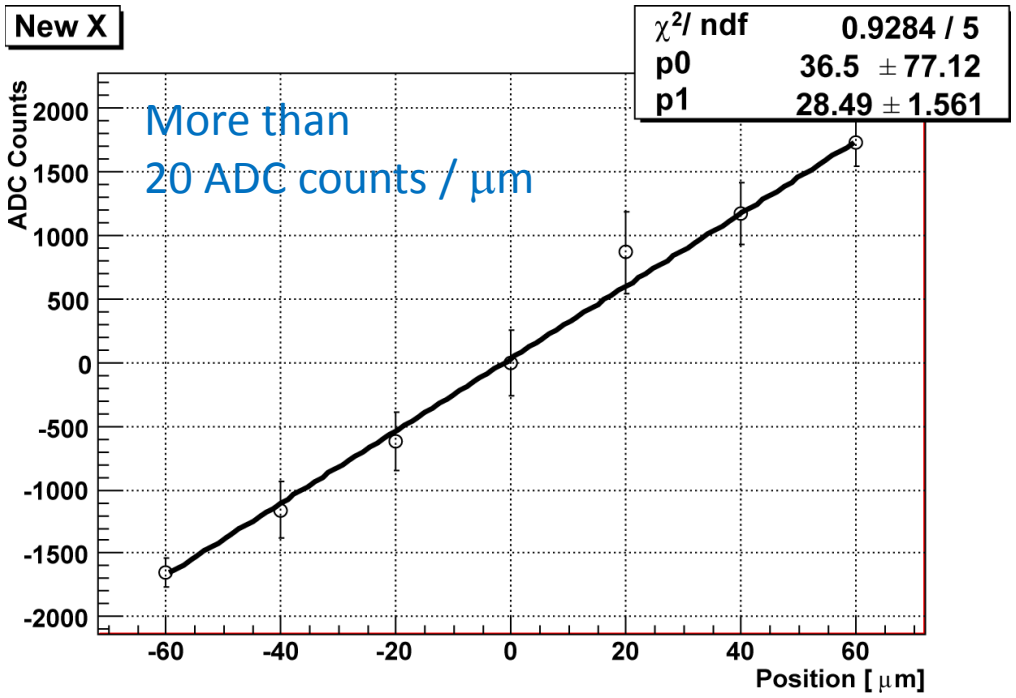
BPM Electronics



- IQ demodulator
- Attenuator switch extends the dynamic range to 100 dB
  - From sub-μm to a few mm
- Baseband signals are recorded by a 12-bit VME waveform digitizer.

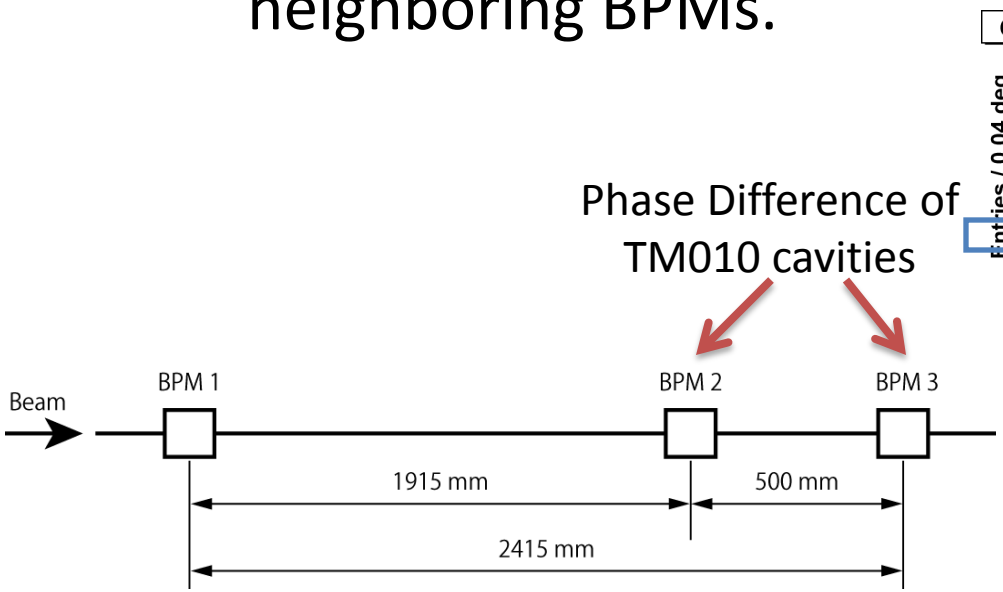
Position Sensitivity

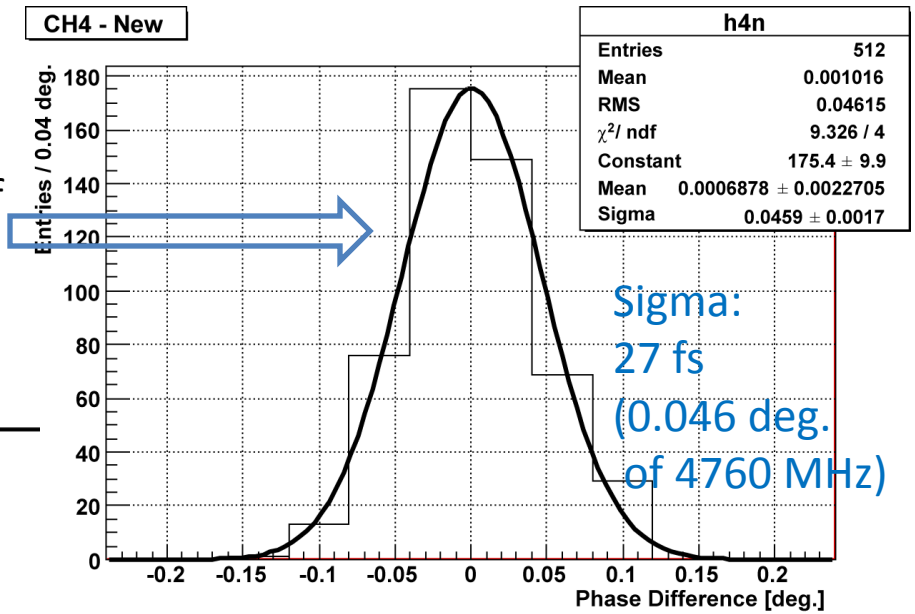
- Measurement
  - Motorized stage of the BPM was moved
  - Beam was fixed
- Position sensitivity: 0.1 μm
  - More than 20 ADC counts / μm
  - ADC noise < 2 counts (RMS)



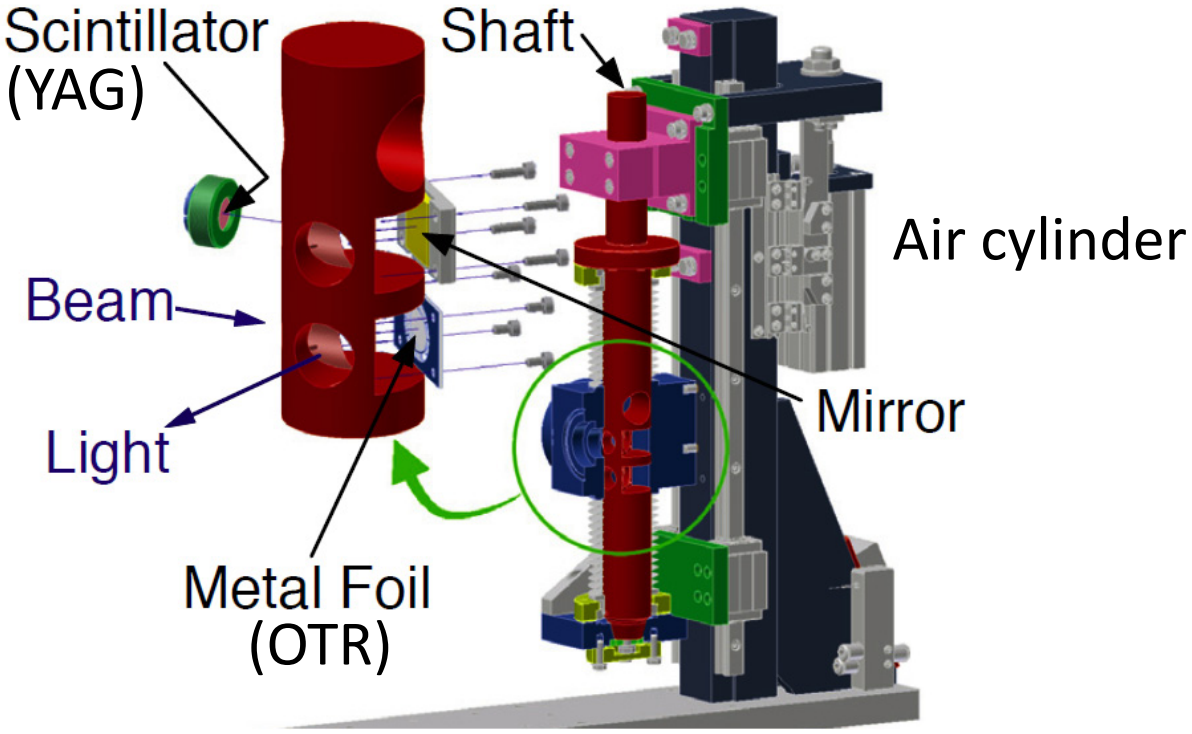
Beam Arrival Timing Resolution

- Beam arrival timing can be measured by the phase of the reference cavity (TM010).
  - Useful to monitor the timing drift of the machine
  - Required temporal resolution: < 50 fs
- Arrival timing resolution: 25 fs
  - Measured by the reference cavities of two neighboring BPMs.



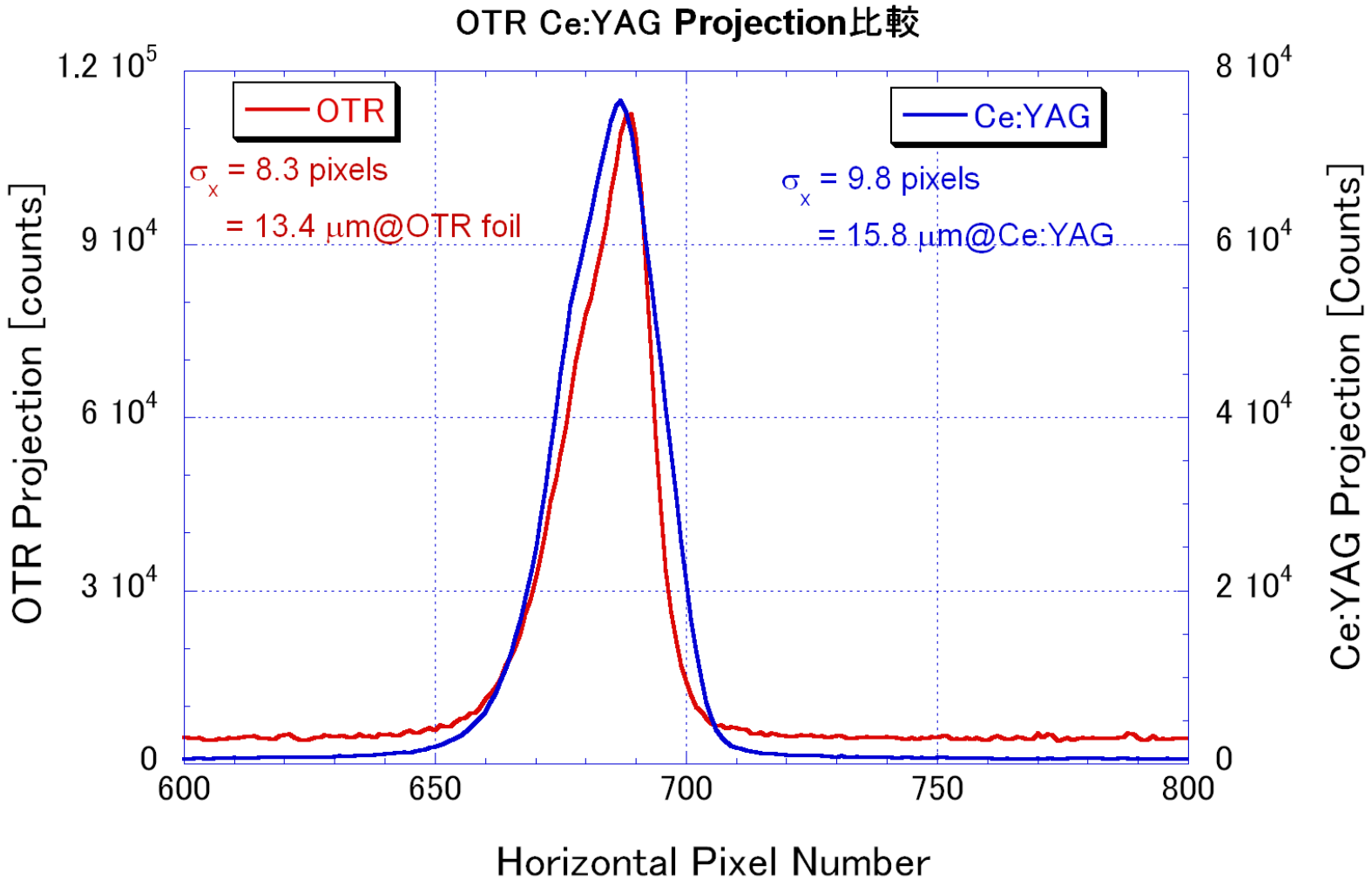


Screen Actuator



- 3-state pneumatic actuator
  - 2 screens and a beam hole
  - For the beam energy of 30 – 300 MeV
    - Because of the poor OTR yield

Projection of Beam Image



Parameters of RAIDEN Cavity

Total Deflecting Voltage	V_y	40	MV
RF deflecting phase	φ_a	0	degree
Fractional bunch length for X-ray oscillation	σ_z	200	fs
Beam energy at the deflector	p_z c	1.45	GeV
Resonant frequency	f_a	5712	MHz
Type of structure		CZ	
Resonant mode		HEM11	
Phase shift per cell	βD	$5\pi/6$	rad
Group velocity	v_g /c	-2.16	%
Filling time	T_f	0.27	μs
Unloaded Q	Q_a	11500	
Transverse shunt impedance	z_y	13.9	MΩ/m

Machining of the Cell

- Race-track iris
  - Made by a precise milling machine
  - Electrochemically polished
  - Surface roughness: 1 μm pk-pk
- Other part
  - Machined by a precise lathe with a diamond bit
  - Roughness < 1 μm pk-pk