TUOC04

# Development of Beam Position Monitor for the SPring-8 Upgrade

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# Outline

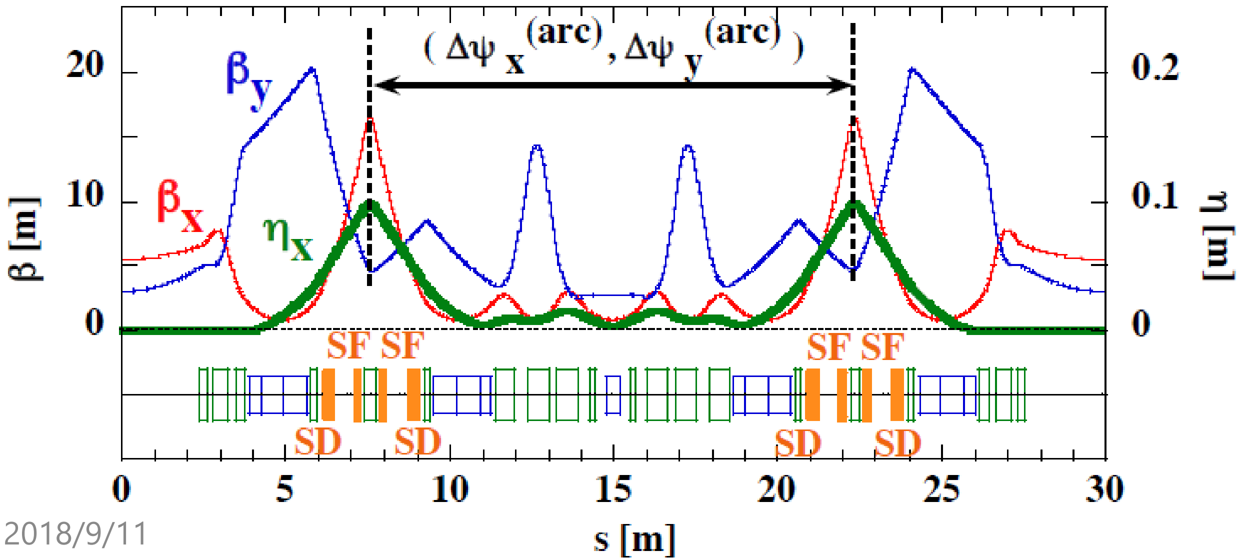
- Introduction
  - SPring-8 upgrade
  - Overview of the BPM system
- Design of the BPM System
  - BPM electrode, block, cables, readout electronics
- Beam Test
  - Evaluation of signal waveform and intensity, position resolution, electric center, long-term stability, Temperature rise, etc.
  - Evaluation of radiation resistive cables
- Half cell mockup
  - Check mechanical interference, Evaluate alignment precision, Measure vibration, etc.
- Summary

# SPring-8 Upgrade and BPM System

- SPring-8 Upgrade Project
  - Beam Energy: 6 GeV
  - Lattice: 5-bend achromat (5BA)
  - Natural Emittance: ~140 pm rad (without radiation damping of IDs)
- Optical axis stability is quite important to fully utilize brilliant X-rays.
  - Source size ~ 28 x 6 μm² rms, Divergence ~ 5 x 17 μrad rms @ 10 keV

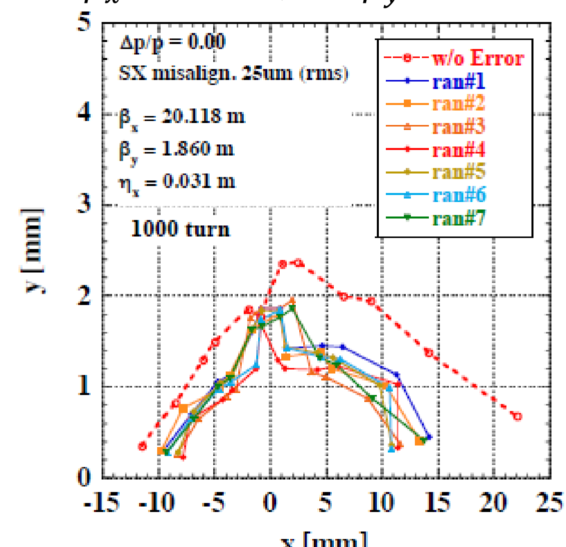
  → Beam orbit stability: ~ 1 μm, ~ 1 μrad → BPM stability (COD mode): ~ 1 μm
- Single-pass resolution and electric center accuracy are also crucial for beam commissioning.
  - To achieve first beam storage, an electron beam must be guided within 100 μm rms with respect to the magnetic center of each quadrupole.

Linear Optics




Dynamic Aperture

$\beta_x = 20.1$ m, $\beta_y = 1.86$ m

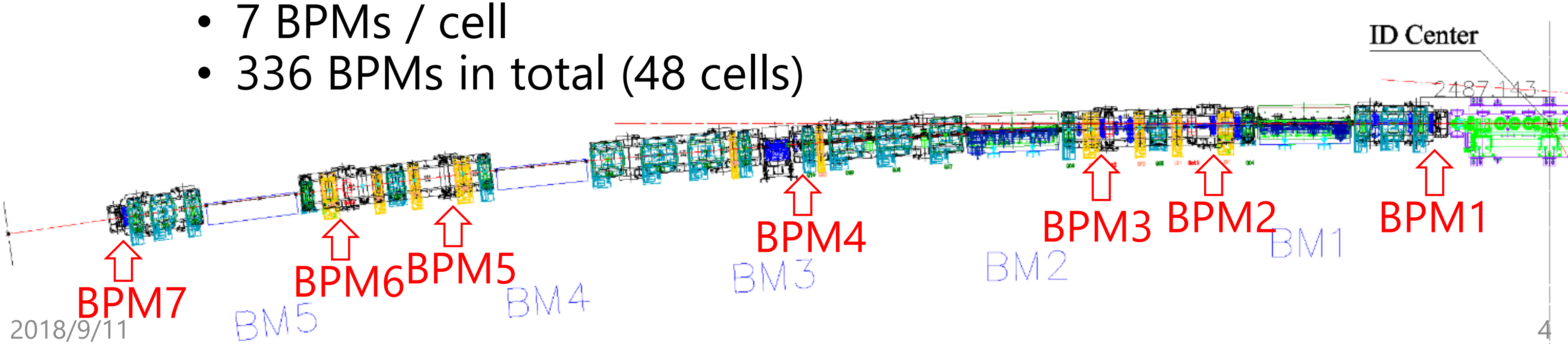


# Overview of the BPM System

- **Requirements for the BPM System**
  - Position resolution
    - COD mode: 0.1 µm rms (100 mA, 1 kHz bandwidth)
    - SP mode: 100 µm rms (100 pC single-bunch)
  - Long-term stability
    - COD mode: 5 µm peak-to-peak for 1 month
  - Electric center accuracy
    - COD mode: 10 µm std. after beam-based alignment
    - SP mode: 100 µm std. (2σ max.)

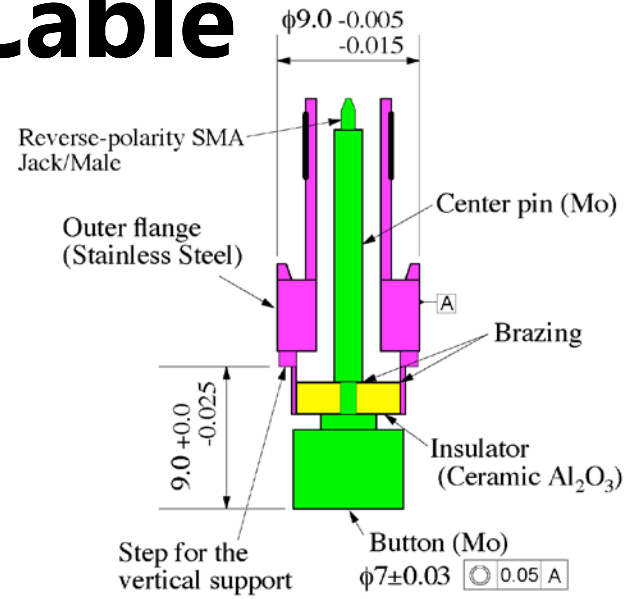
- **BPM type:** Button electrode

- **BPM arrangement**
  - 7 BPMs / cell
  - 336 BPMs in total (48 cells)



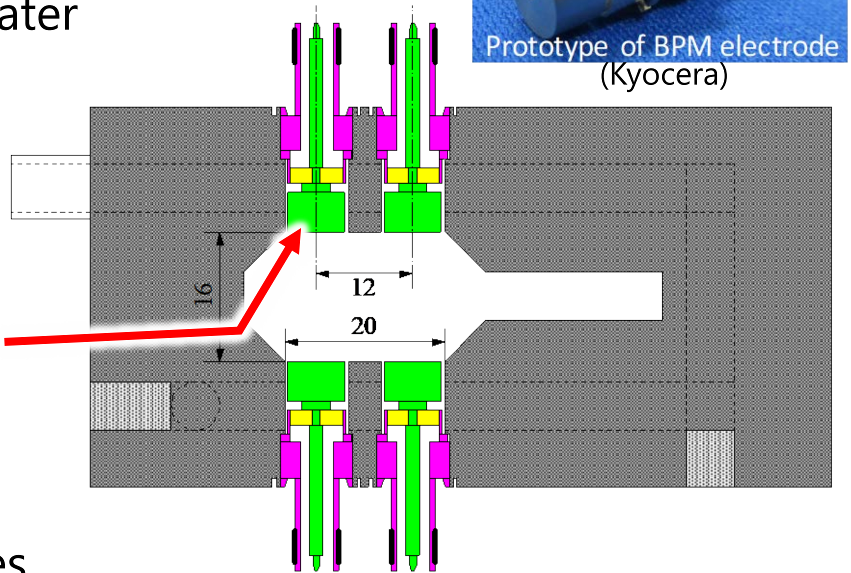
# BPM Electrode, Block, Cable

- BPM Electrode and Block
  - Electrode material: Molybdenum
    - Non-magnetic
    - High conductivity → Small heat dissipation
    - Similar thermal expansion to insulator ceramics
  - Electrode dimensions: Φ 7 mm x 5 mm
  - Hole diameter: 8 mm (gap 0.5 mm)
  - Electrode span: 12 mm (H) x 16 mm (V)
    - Obtain sufficient signal intensity
    - Suppress Trapped mode heating
  - Block material: Stainless steel 316L
    - Conductivity is lower than molybdenum → larger trapped-mode heating on the block side
  - Temperature rise is reduced by cooling water
    - Suppress temperature deformation
- Prototype test results
  - Machining accuracy
    - All 10 μm order tolerances were satisfied.
  - Electron-beam welding of electrodes
    - Surface position error due to the shrinkage of welded part was less than 50 μm
    - Electric center error was calculated to be less than 80 μm
- Radiation resistant signal cables
  - Candidates: $SiO_2$ or PEEK semi-rigid cables





Prototype of BPM electrode (Kyocera)

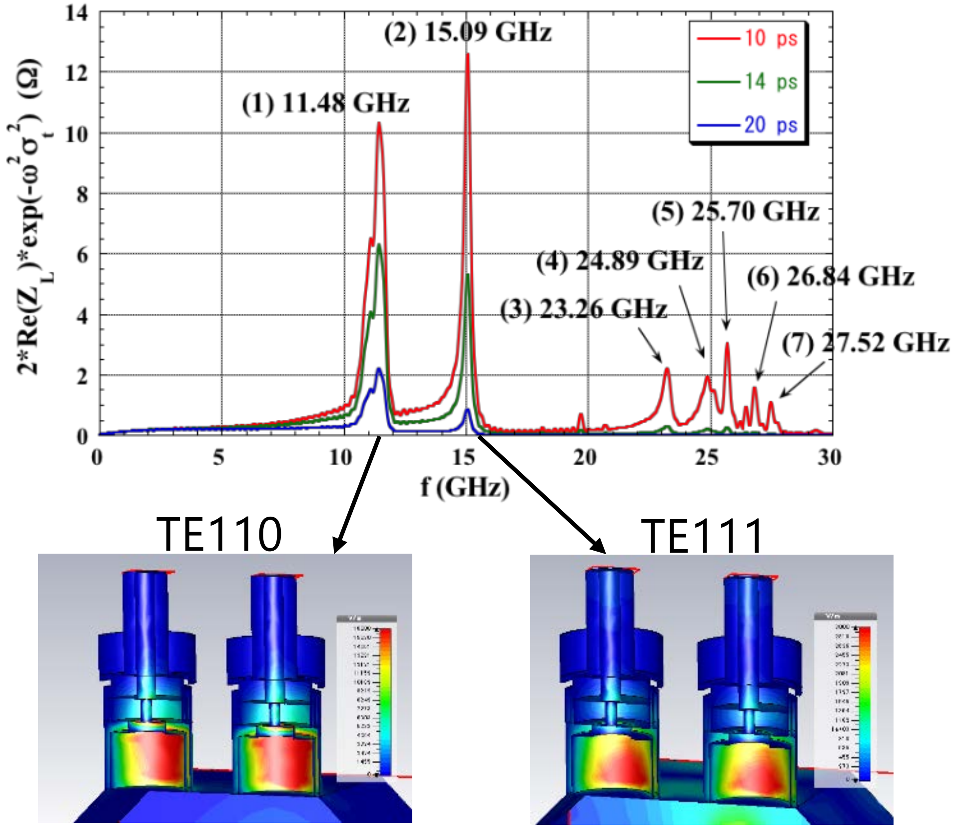


Cross-section is the same as vacuum chamber

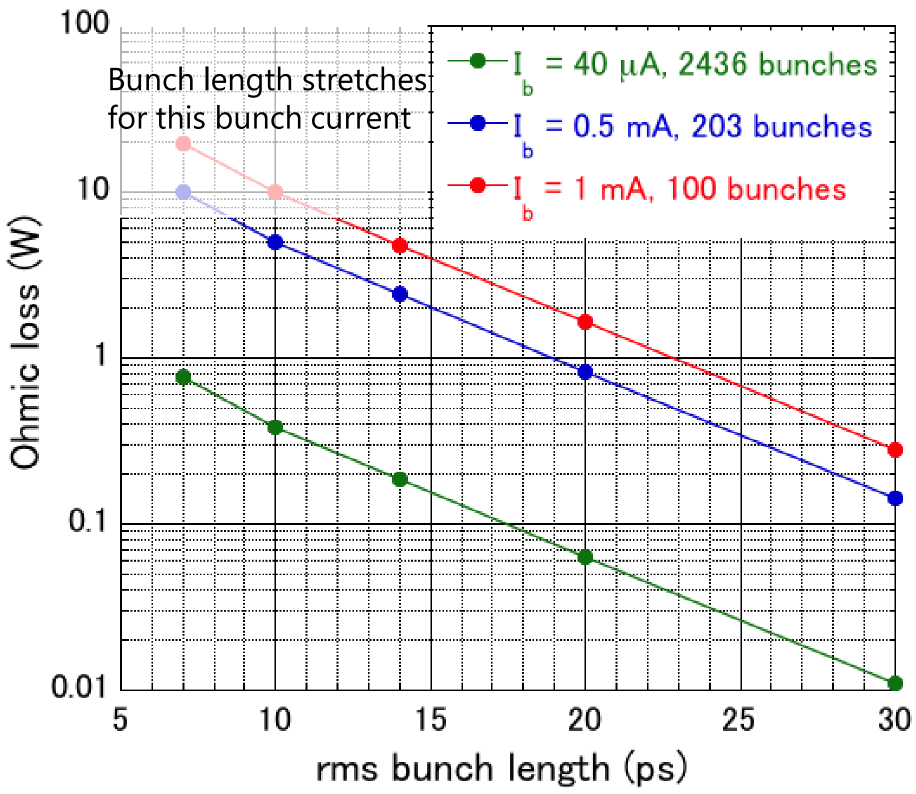
# Trapped-mode Heating

- Trapped modes are analyzed by 3D electro-magnetic simulation.
- Trapped-mode heating depends on the bunch length
  - Bunch length also depends on the bunch current
  - >10 ps rms for 0.5 mA/bunch and > 14 ps rms for 1 mA/bunch
- Heat dissipation in the BPM block is 5 W maximum (100 mA total current)

Trapped mode spectrum (for each bunch length)

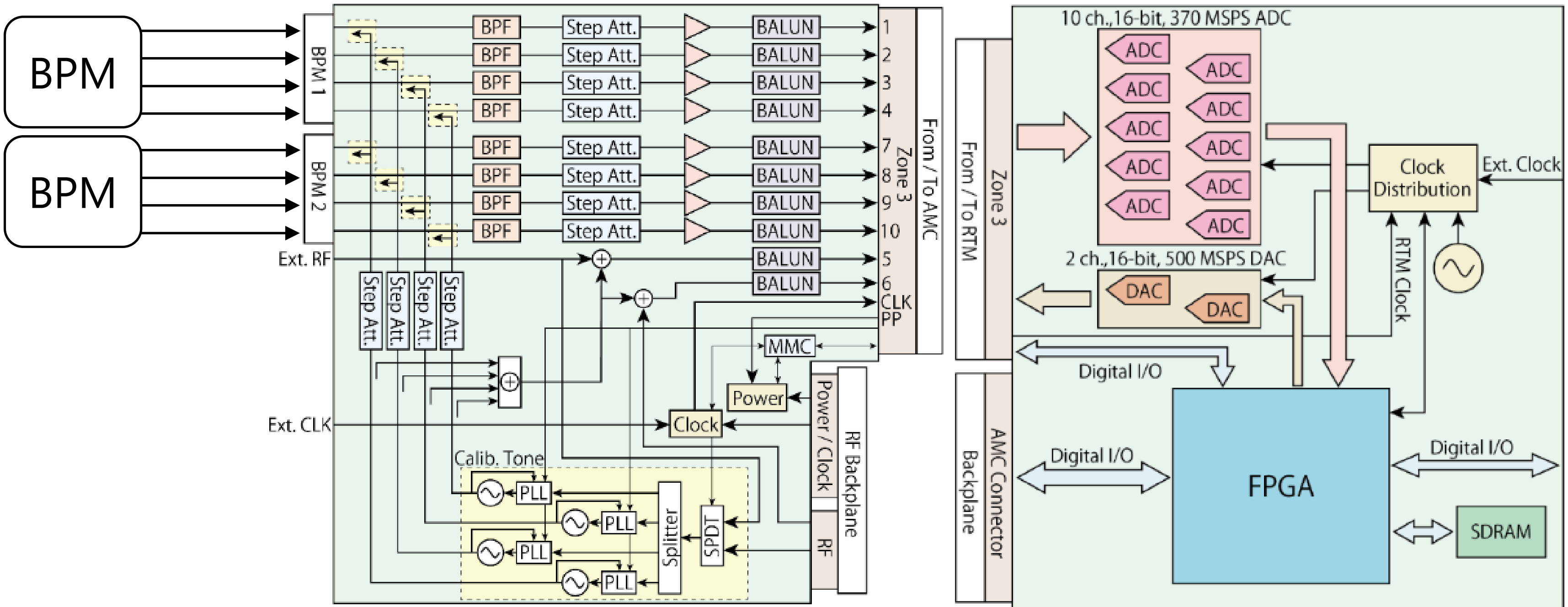



Heat dissipation v.s. Bunch length



# BPM Readout Electronics

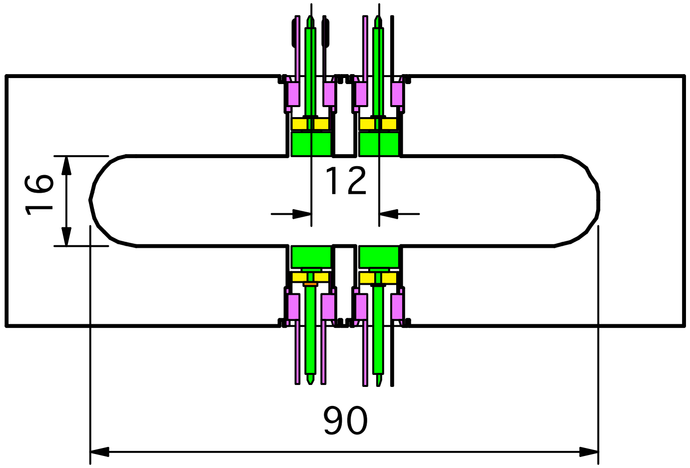
**RF Frontend (RTM)** (Rear Transition Module) | **High-speed Digitizer (AMC)** (Advanced Mezzanine Card)




- Developing electronics using MicroTCA.4 High-speed digitizer
  - Digitizer was developed for LLRF system upgrade
    - 10 ch., 370 MSPS, 16-bit ADCs
  - Signals synchronized to the 508.76 MHz acceleration RF are extracted by band-pass filters
  - Level adjust by step att. and amp.
  - Under-sampling scheme
- Evaluating Libera Brilliance+ in parallel

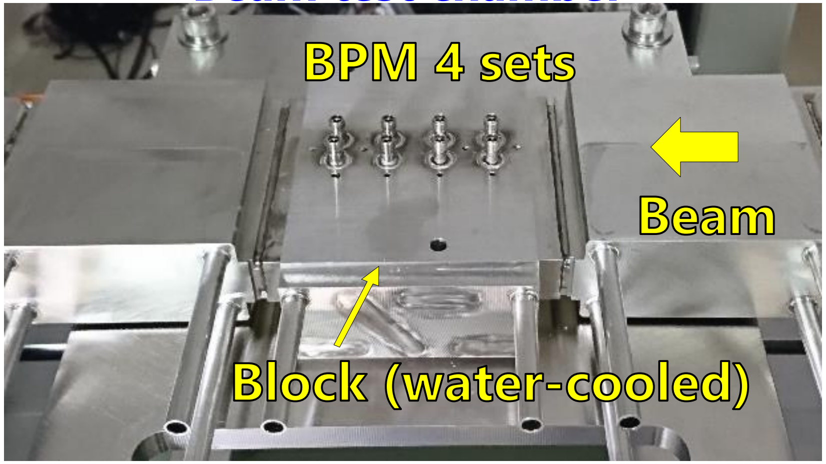
# Beam Test in the current SPring-8

Cross-section




Vertical aperture and span of the electrodes are same as the BPM for SPring-8 upgrade

Beam test chamber



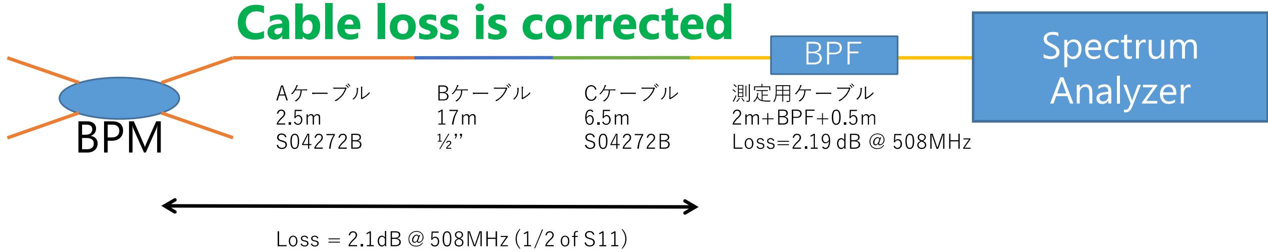

- Evaluation contents
  - Signal waveform and intensity, Position resolution, Long-term stability, Electric center accuracy, Temperature rise
- Setup
  - 16 electrodes (4 BPM sets)
    - Span of the electrodes are the same as the design value
  - Radiation-resistant cables
  - Readout electronics is Libera Brilliance+

# Signal Intensity and Waveform

## Signal intensity from 100 mA stored current at 508.58 MHz

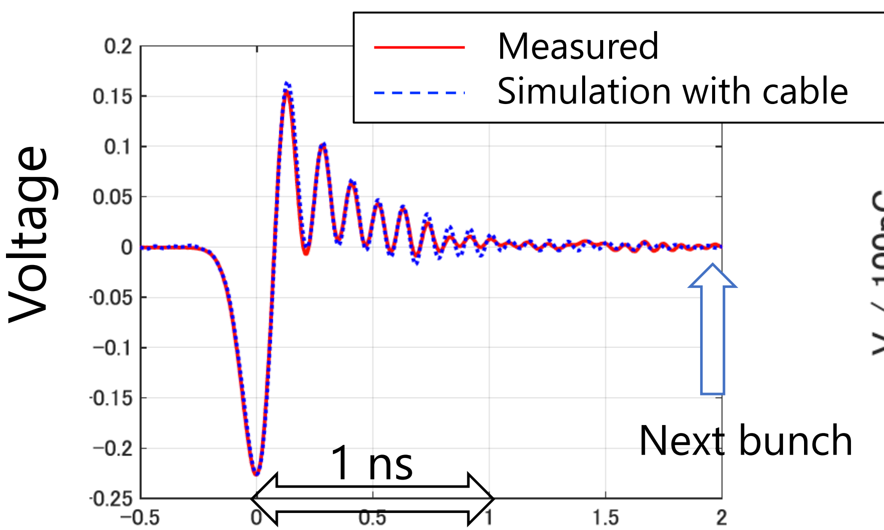
| BPM | 4 ch. average |
|---|---|
| BPM-1 | **–12.58 dBm** |
| BPM-2 | **–12.66 dBm** |
| BPM-3 | **–12.35 dBm** |
| BPM-4 | **–13.31 dBm** |
| Sim. | –12.5 dBm |

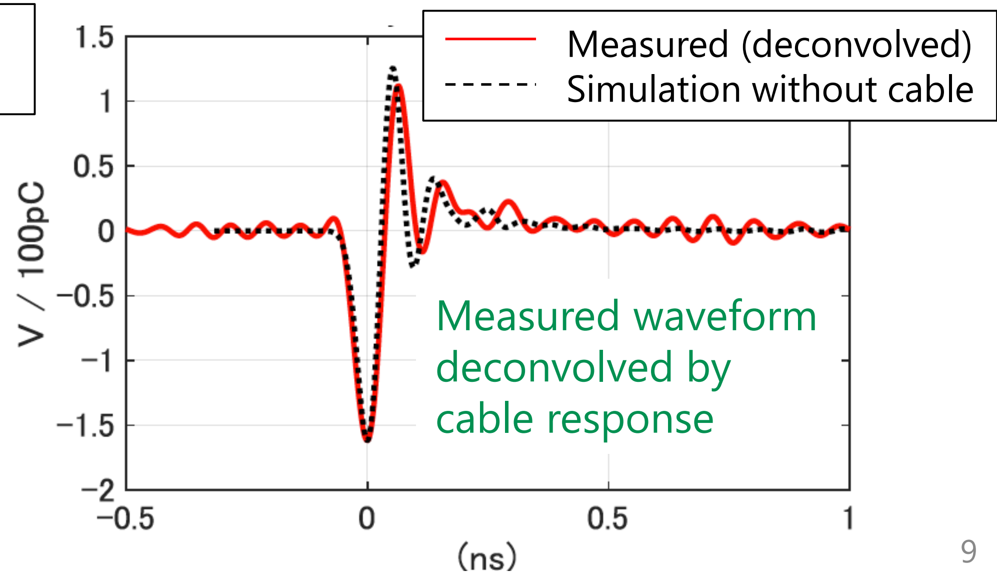
**Cable loss is corrected**




**Appropriate signal intensity and waveform obtained, consistent with RF simulation**

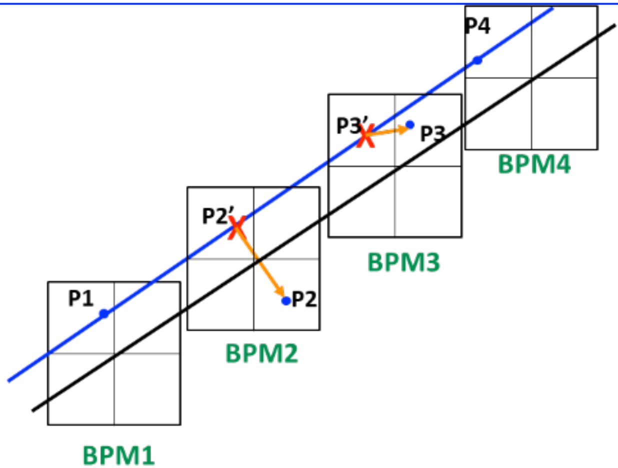
## Signal waveform (Single-bunch)



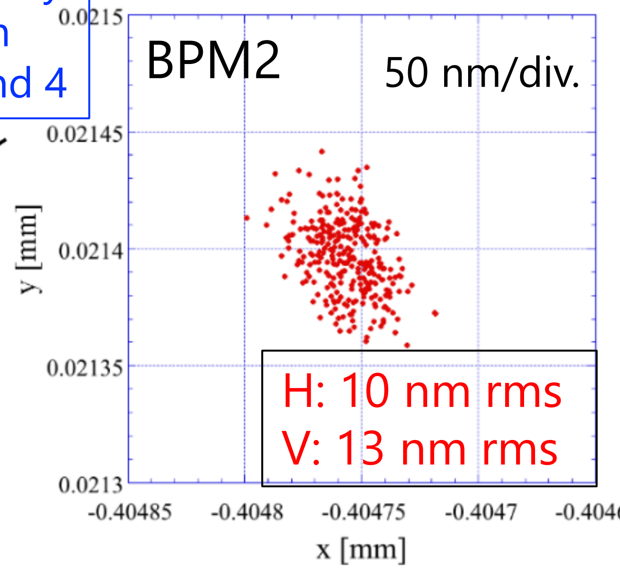



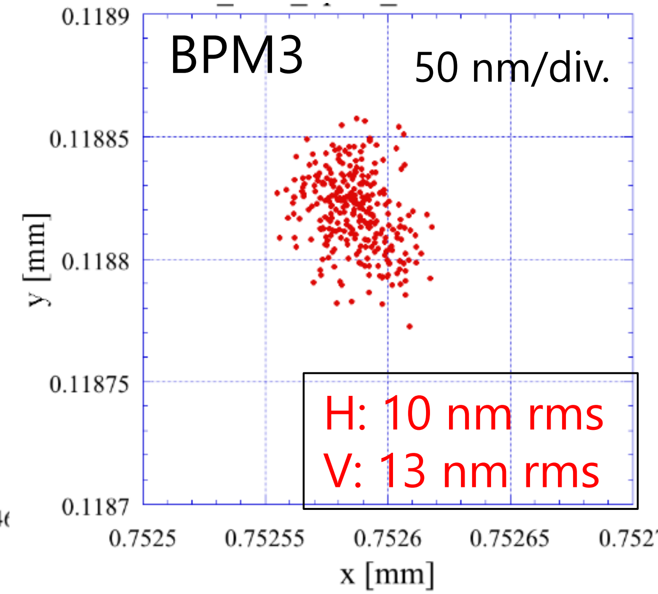
# Position Resolution (Libera Brilliance+)

Position resolution was obtained by the deviation of BPM 2 or 3 from the reference made by BPM 1 and 4




## COD Resolution (Slow Acquisition [SA] 10 Hz)

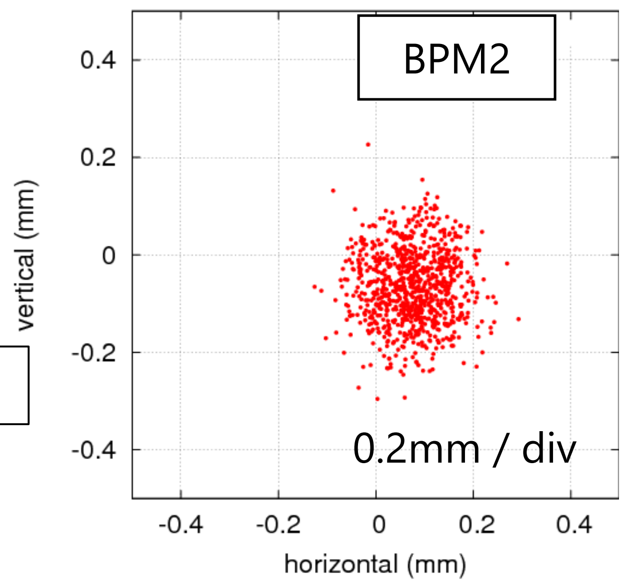


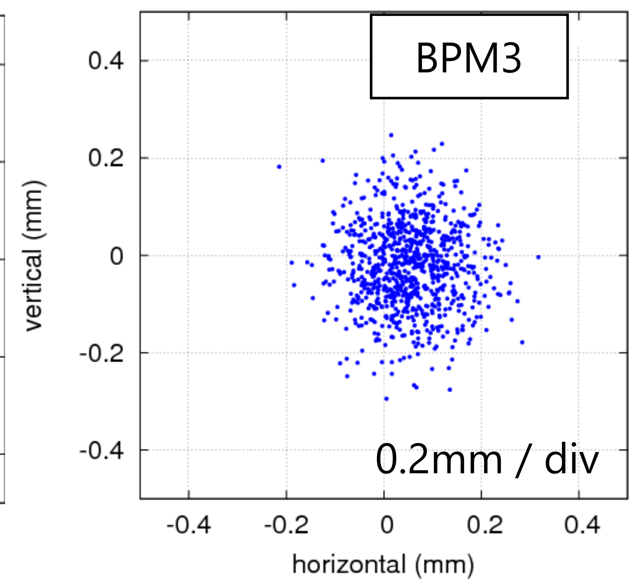




## Single Pass Resolution (turn-by-turn, 100 pC single-bunch)

| | H (μm) | V (μm) |
|---|---|---|
| BPM2 | 65.5 | 75.3 |
| BPM3 | 78.8 | 87.8 |

< 100 μm rms



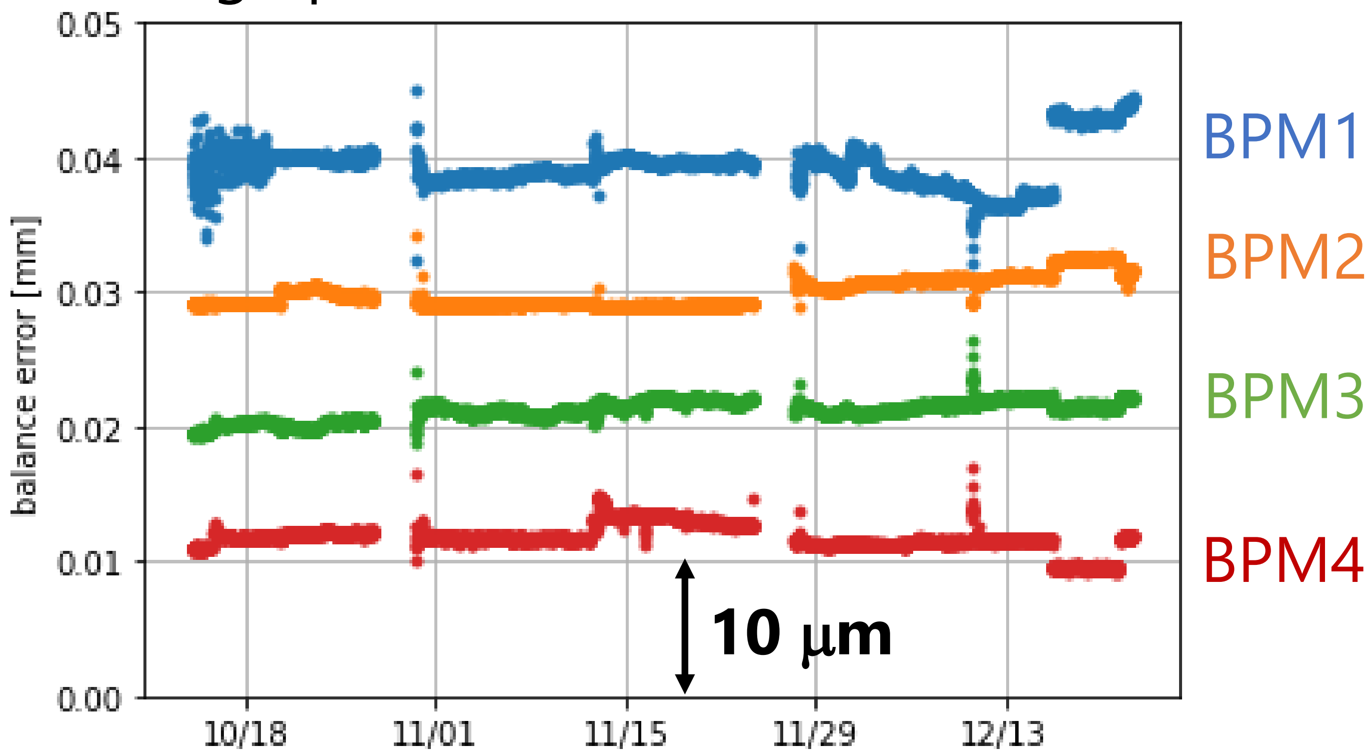



# Long-term Stability (Libera Brilliance+)

Stability was evaluated from balance error

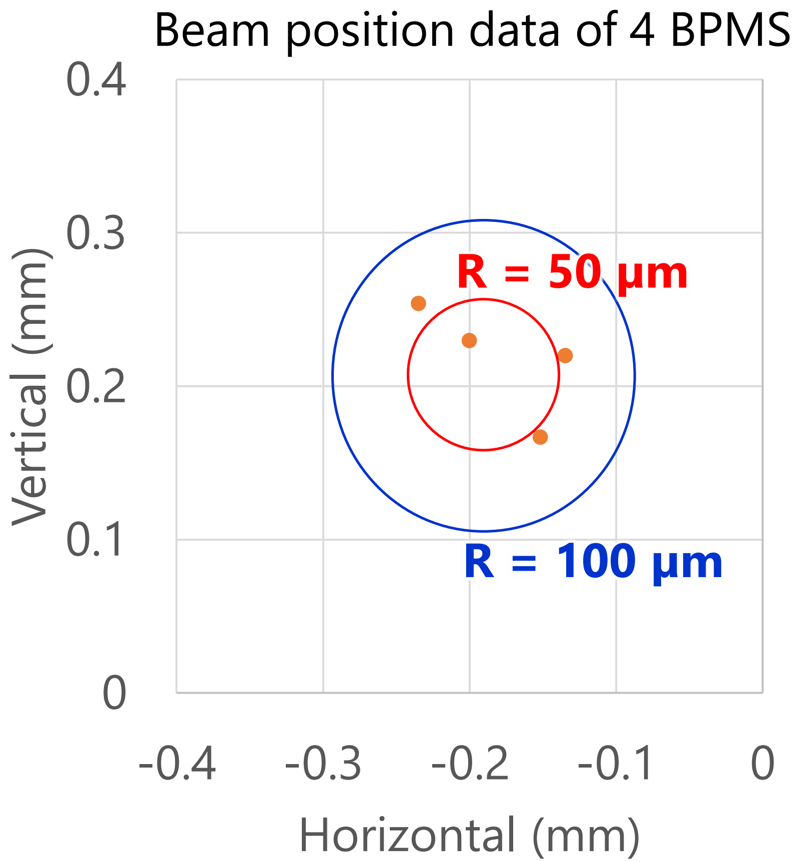
Beam position can be calculated from three electrodes out of four. (four combinations)
Balance error is defined as the maximum difference among the four position values.

Trend graph of the balance error for 2.5 months




**Stability with in one operation period (~4 weeks): 5 μm**

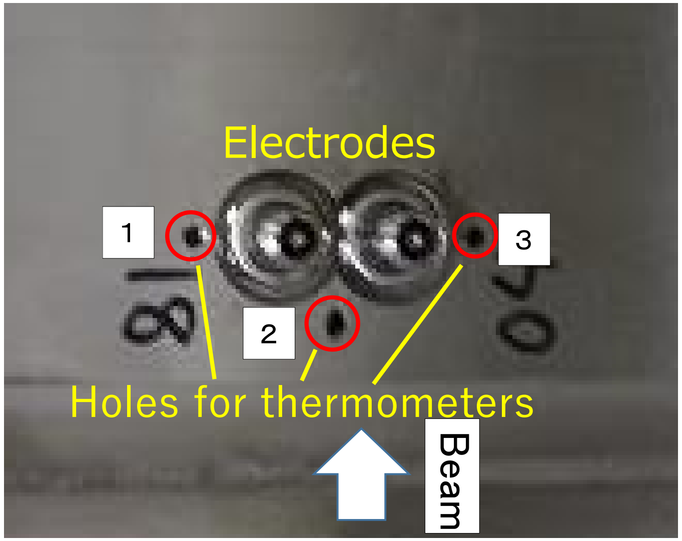
# Electric Center

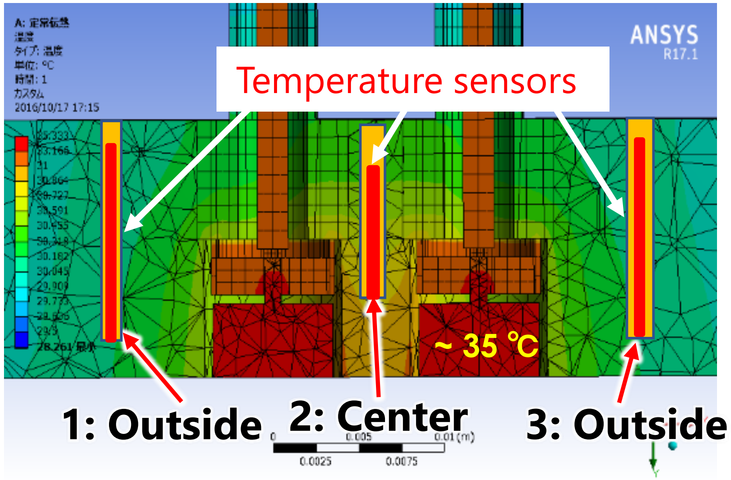



- **Measured beam positions of 4 BPMs were within a circle of 100 μm radius.**
- **Electric center error is expected to be within 100 μm std.**

# Temperature rise of BPM Block

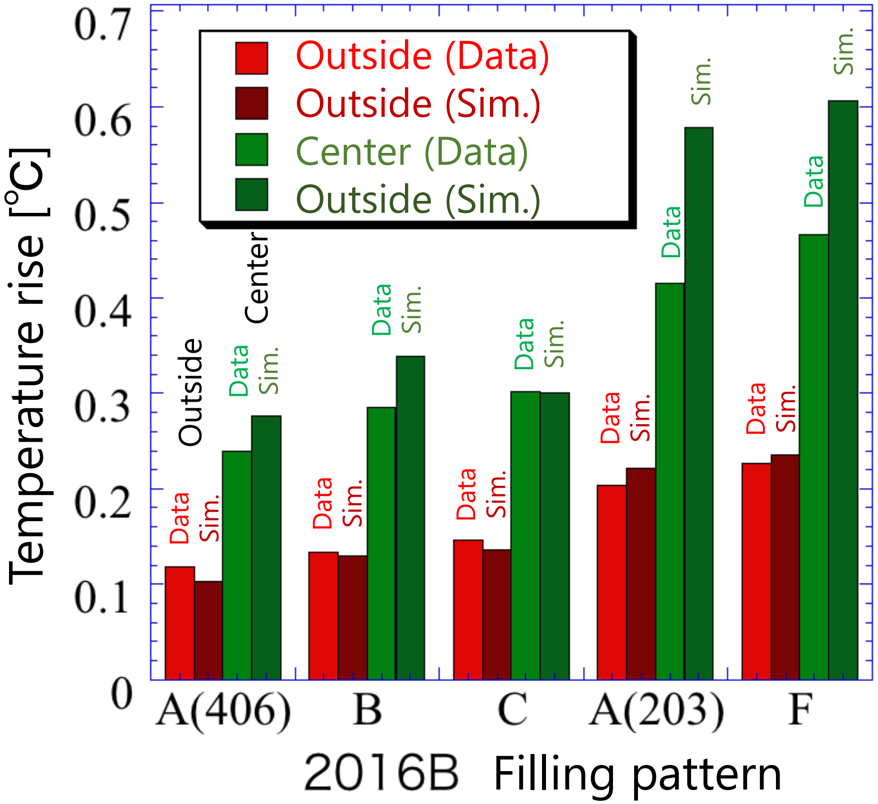
## Thermometer around the electrodes




Platinum resistance temperature detectors

**Temperature rise after beam storage**
**(29.9 ℃ in case of no beam)**




A (406): 406 bunches
A (203): 203 bunches
B: 4 bunch train x 84
C: 11 bunch train x 29
F: 1/14 fill + 1.6 mA x 12

Heat dissipation was also consistent with the temperature rise of the cooling water.

Temperature simulation was confirmed to be consistent with the measurement.

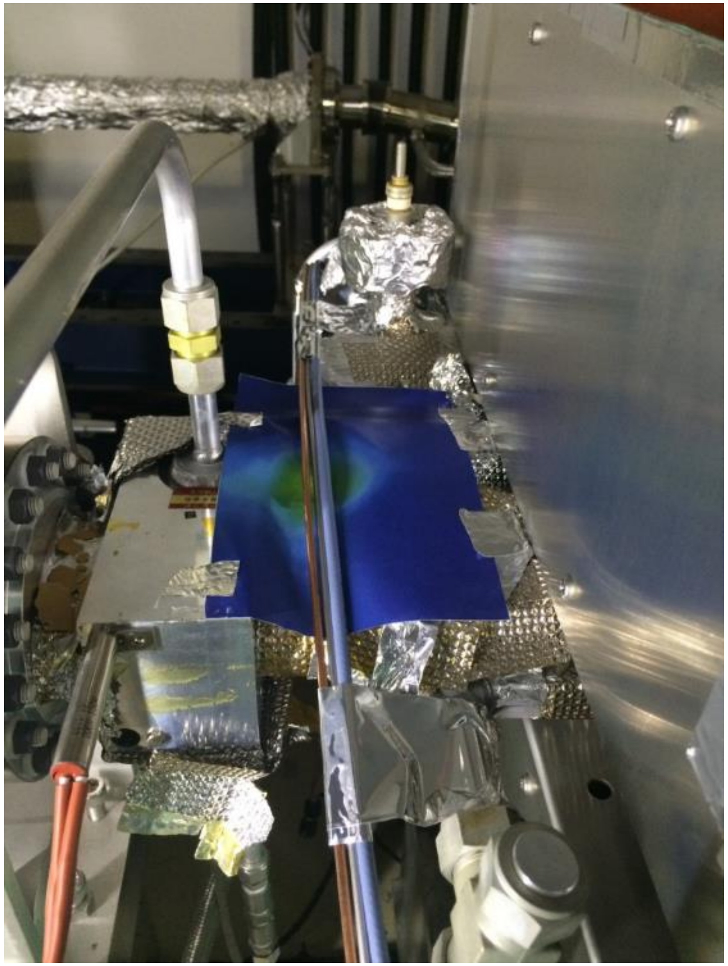
# Irradiation Test of Signal Cables

- Sample cables
  - $SiO_2$ semi-rigid cable
    - Radiation resistant
  - PEEK semi-rigid cable
    - Radiation resistant
  - S04272B flexible cable
    - Used in current SPring-8

- Test place: above an X-ray absorber
  - High dose from scattered X-rays
  - Dose rate: 4.9 kGy/Ah

- Total dose corresponds to more than 10 years of machine operation.

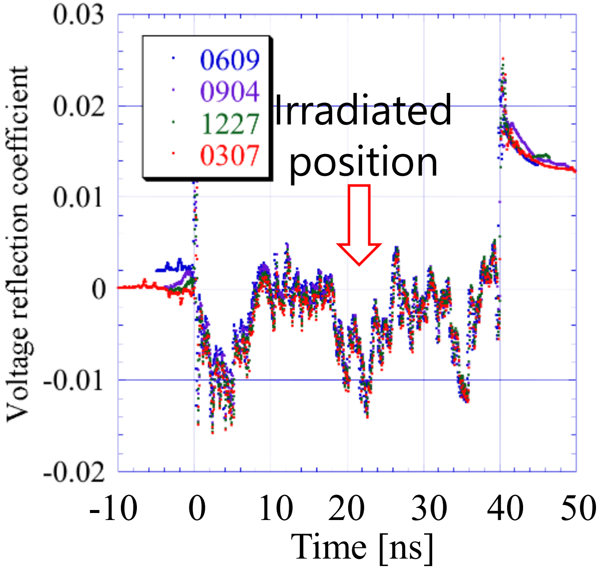
- Characteristic impedance was measured by Time-Domain Reflectometry (TDR)



Three cables on the X-ray absorber (PEEK, $SiO_2$, S04272B)

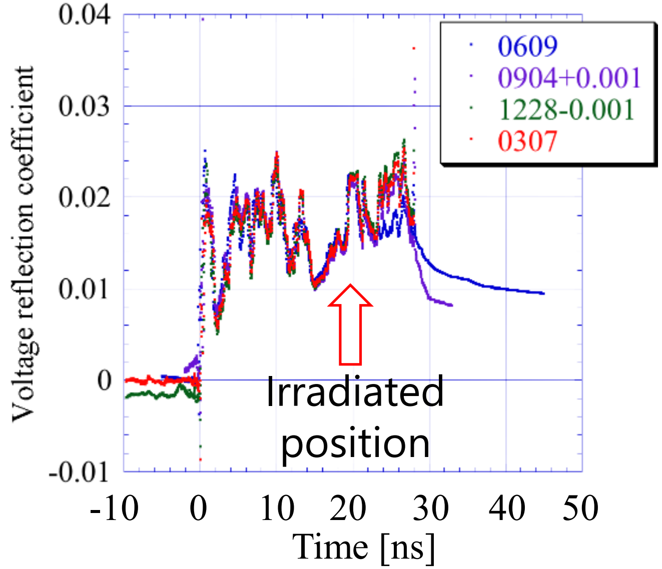
# TDR Data

$SiO_2$ semi-rigid cable
(Radiation resistant)



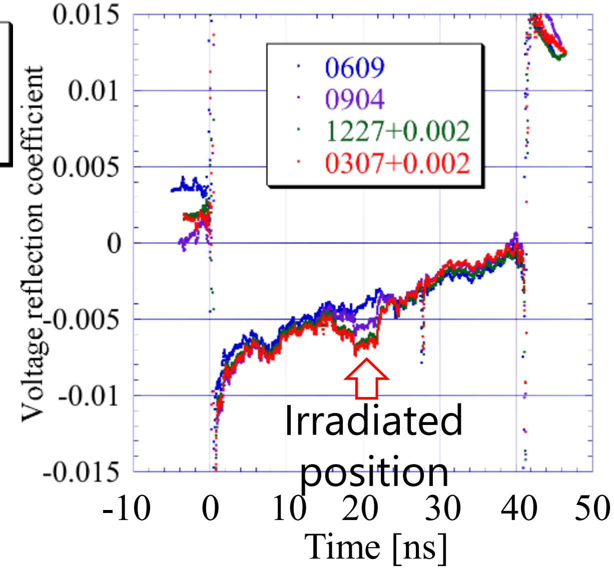

No difference

PEEK semi-rigid cable
(Radiation resistant)




No difference

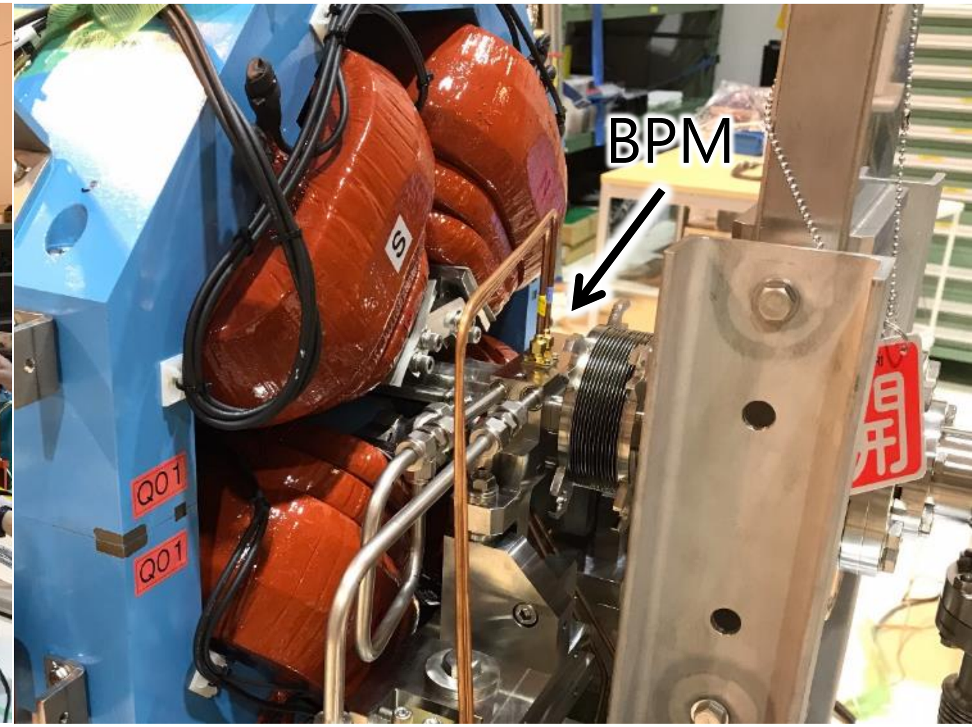
S04272 flexible cable
(current SPring-8 BPM)




Difference at the irradiated position

- TDR waveform was measured every certain period and all data are ploted.
- No significant damage can be found in $SiO_2$ and PEEK semi-rigid cables.
- Radiation damage can be seen in the TDR waveform of S04272.
- $SiO_2$ and PEEK are sufficiently resistant to radiation for more than 10 years.

# Half Cell Mockup




- Dummy BPM block is attached to long vacuum chamber.
- Installed into the half cell mockup.
- All the BPMs were aligned with 0.1 mm precision.
    - Electric center is corrected according to the survey result.
    - Electric center alignment error can be reduced
        - Tolerance 0.1 mm std. (2σ cut)
- Mechanical interference, vibration, etc. are evaluated.

# Summary

- Precise and stable BPM is necessary for SPring-8 upgrade.
  - COD BPM stability: 5 μm peak-to-peak for 1 month
  - Electric center accuracy: 100 μm std. (2σ max.)
  - Single-pass resolution: 100 μm rms (100 pC)
- Design and prototyping of BPM
  - Molybdenum BPM electrode + Stainless-steel BPM Block
  - Machining precision was confirmed to be within the tolerance.
  - Development of MicroTCA.4-based electronics and evaluation of Libera Brilliance+
- Beam test
  - Signal waveform and intensity, position resolution, electric center, long-term stability satisfied the requirements.
  - Temperature of the BPM block agreed well with simulation.
  - Radiation resistance of signal cables was enough for more than 10 year operation.
- Evaluation with the half cell mockup is in progress.
- Development of the BPM system for the SPring-8 upgrade will be completed soon.