WEBO03

Development of MicroTCA.4-Based BPM Electronics for SPring-8 Upgrade

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Outline

- Introduction
  - SPring-8 upgrade project
  - Overview of the BPM system
- Design of the BPM electronics
  - Requirements for the BPM electronics
  - Signal processing and beam position calculation logic
- Beam test results
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  - Long-term stability
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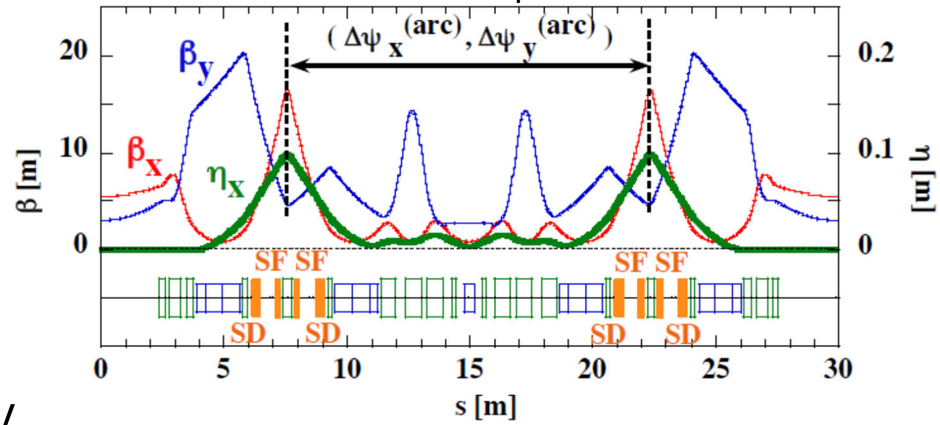
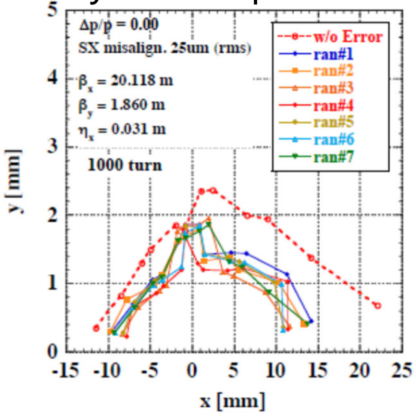
SPring-8 Upgrade Project

- SPring-8 Upgrade Project (SPring-8-II)
  - Beam Energy: 6 GeV
  - Lattice: 5-bend achromat (5BA)
  - Natural Emittance: ~100 pm rad (with radiation damping of IDs)
- Optical axis stability is quite important to fully utilize brilliant X-rays.
  - Source size: ~ 28 x 6 μm^2 rms
  - Divergence: ~ 5 x 17 μrad^2 rms @ 10 keV
  - → Beam orbit stability: ~1 μm, ~1 μrad
  - → BPM stability (COD mode): ~1 μm
- Single-pass (SP) resolution is also important for beam commissioning.
  - To achieve the first beam storage, the transverse beam position must be steered within 100 μm rms with respect to the magnetic center of each quadrupole.
    - Due to narrow dynamic aperture.

Linear Optics

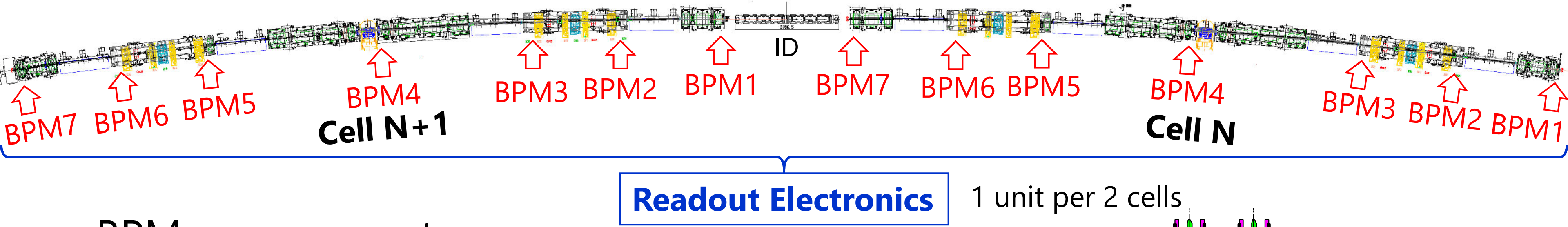


Dynamic Aperture

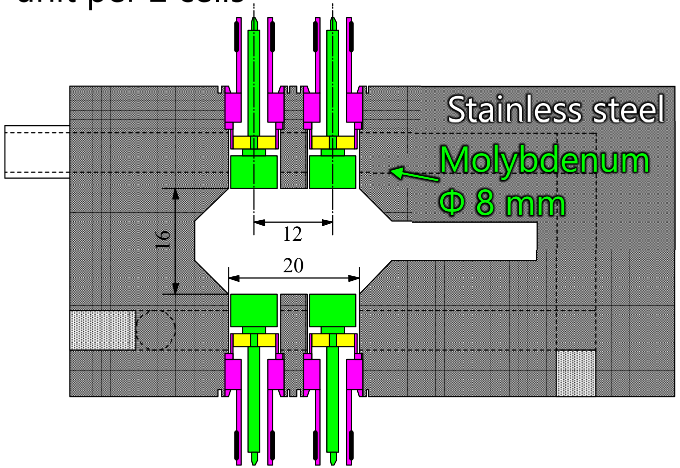


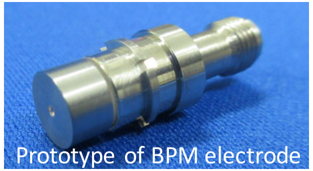
$\beta_x = 20.1$ m,
$\beta_y = 1.86$ m

Overview of the BPM System

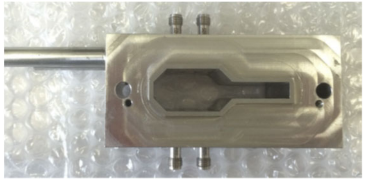


- BPM arrangement
  - 7 BPMs / cell
  - 336 BPMs in total (48 cells)
  - 24 readout units (1 unit per 2 cells)
- Requirements for the BPM System
  - Position resolution
    - COD mode: < 1 µm rms (100 mA, 1 kHz bandwidth)
    - SP mode: < 100 µm rms (0.1 nC single-bunch)
  - Long-term stability
    - COD mode: 5 µm peak-to-peak for 1 month





Prototype of BPM electrode (Kyocera)



Prototype of a BPM head

Requirements for the BPM Electronics

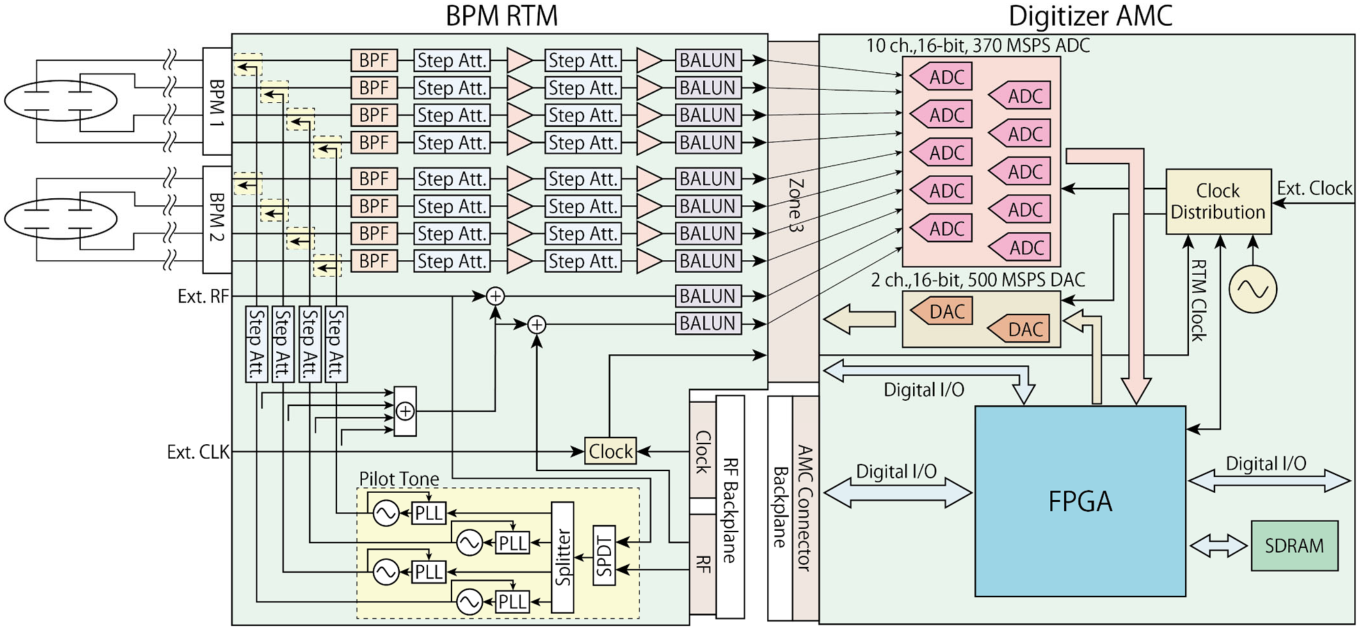
- The signal from each BPM electrode should be detected stably and precisely.
  - The BPM signal is synchronized to the acceleration RF (508.76 MHz)
- Required amplitude stability: 0.1% (0.01 dB) peak-to-peak
  $(\simeq 2 \cdot 5\ [\mu\mathrm{m}]\ /\ 7\ [\mathrm{mm}])$
  - BPM conversion coefficient ($k_{x,y}$): ~7 mm
  - Required position stability: 5 µm

$$X = k_x \cdot \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4}$$

$$Y = k_y \cdot \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

- Required Signal-to-Noise ratio: > 35 (31 dB)
  $(\simeq 0.5 \cdot 7\ [\mathrm{mm}]\ /\ 100\ [\mu\mathrm{m}])$
  - Required SP resolution: 100 µm rms (0.1 nC single-bunch)
- An in-situ gain correction mechanism should be equipped for better stability.
  - Pilot tone etc.
- High-speed COD BPM data is needed for an abnormal orbit interlock to prevent any damages of accelerator and beamline components.
  - Response time < 1 ms → 10 kHz update rate.
  - This data can also be used by a fast orbit feedback.
- The beam position should also be calculated from three electrodes in case of the trouble of an electrode.
  - The data from three electrodes (four combinations) are also useful to evaluate the stability by comparing the four values.

Overview of the BPM Electronics



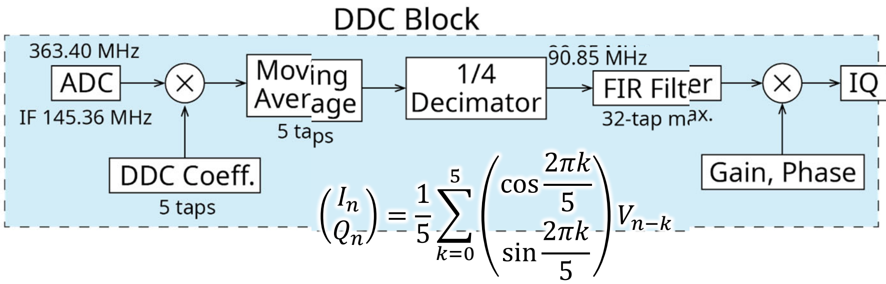
- MicroTCA.4 high-speed digitizer AMC (advanced mezzanine card)
  - 10 ch., 370 MSPS, 16-bit ADCs, Under-sampling scheme
  - It was developed for the upgrade of the low-level RF system.
- A BPM RF frontend RTM (rear transition module) was newly developed.
  - 508.76 MHz signals are extracted by SAW band-pass filters (~10 MHz BW).
  - The signal level is adjusted by step attenuators and amplifiers.
    - Attenuation: 0 – 63 dB, Gain > 40 dB
  - Pilot tone generators for gain calibrations

- Signal level
  - 100 mA uniform filling: –6 dBm
  - 0.1 nC single bunch: –53 dBm
- ADC full scale: +10 dBm

→ SP (single bunch): –20 dB FS (gain > 40 dB)

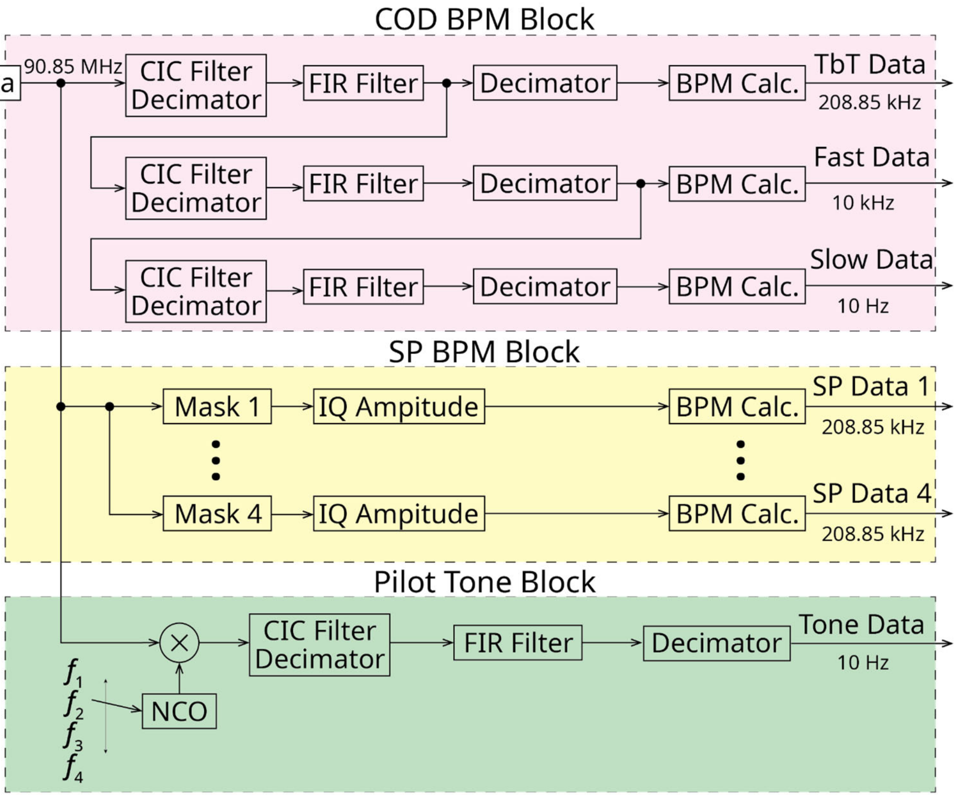
→ COD (100 mA): – 6 dB FS (att: ~40 dB)

Signal Processing



$$\begin{pmatrix} I_n \\ Q_n \end{pmatrix} = \frac{1}{5}\sum_{k=0}^{5}\begin{pmatrix} \cos\frac{2\pi k}{5} \\ \sin\frac{2\pi k}{5} \end{pmatrix} V_{n-k}$$

- The 508.76 MHz signal is digitized by an ADC with a 363.40 MHz clock (5/7 of the RF frequency).
- The in-phase and quadrature (IQ) data is obtained by a 5-tap digital down converter (DDC).
- The COD BPM block generates turn-by-turn (TbT, 208.85 kHz), fast (10 kHz), and slow (10 Hz) data.
- The SP BPM block can select 4 bunches with 4 masks and calculates the beam positions of the 4 bunches.
- The pilot tone block extracts the pilot tone signal with an NCO (numerically controlled oscillator).
  - The NCO frequency is changed every 1 second and outputs each tone signal one after another.



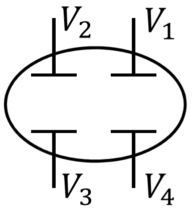
IF: Intermediate Frequency
FIR filter: Finite Impulse Response filter
CIC filter: Cascaded Integrator-Comb filter

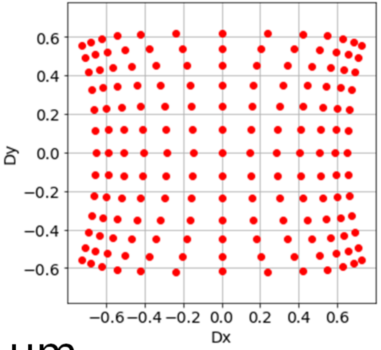
Beam Position Calculation

- We use 7th order polynomial to obtain the beam position.

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \sum_{n=0}^{7} \sum_{m=0}^{7-n} \begin{pmatrix} a_{nm} \\ b_{nm} \end{pmatrix} D_x^n D_y^m$$

$$D_x = \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4}, \quad D_y = \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}$$

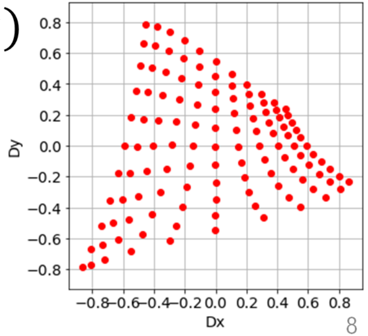




  - a_{nm}, b_{nm}: Conversion coefficients
  - The error on the position calculation is suppressed to less than 1 μm for the measurement range of $|x|, |y| < 6\ \mathrm{mm}$.
- The BPM logic also calculates the beam position from 3 electrodes (4 combinations).

$$\begin{pmatrix} X_1 & X_2 & X_3 & X_4 \\ Y_1 & Y_2 & Y_3 & Y_4 \end{pmatrix} = \sum_{n=0}^{7} \sum_{m=0}^{7-n} \begin{pmatrix} c_{nm} \\ d_{nm} \end{pmatrix} \begin{pmatrix} D_2^n D_4^m & D_2^n D_3^m & D_1^n D_3^m & D_1^n D_4^m \end{pmatrix}$$

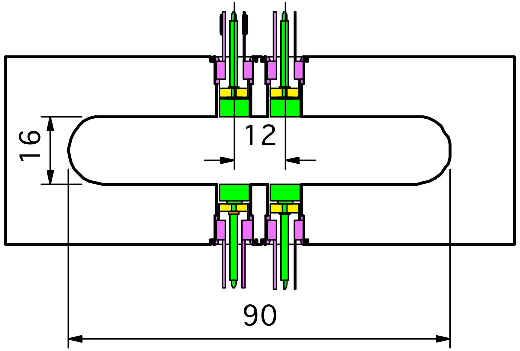
$$D_1 = \frac{V_1 - V_2}{V_1 + V_2}, \quad D_2 = \frac{V_3 - V_4}{V_3 + V_4}, \quad D_3 = \frac{V_1 - V_4}{V_1 + V_4}, \quad D_4 = \frac{V_3 - V_2}{V_2 + V_3}$$



  - c_{nm}, d_{nm}: Conversion coefficients

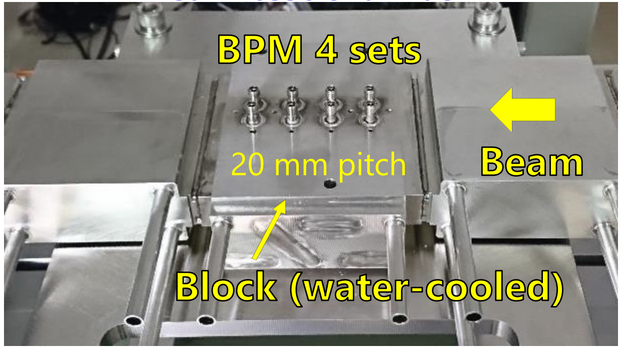
Beam Test in the Current SPring-8 Ring

BPM Cross-section



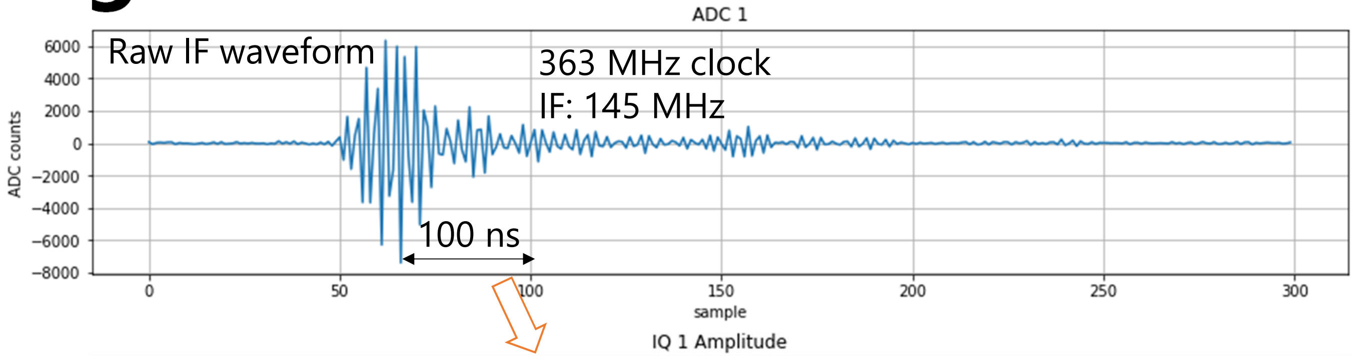
Vertical aperture and span of the electrodes are same as the BPM for SPring-8 upgrade

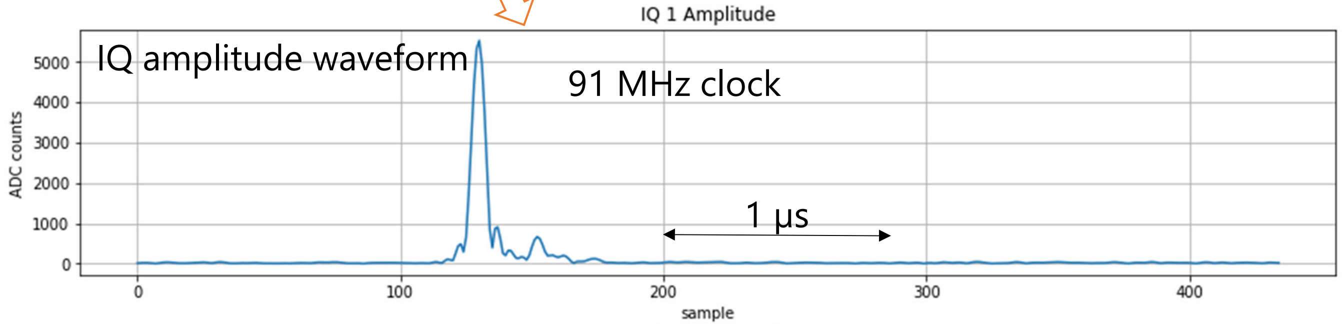
Beam test chamber

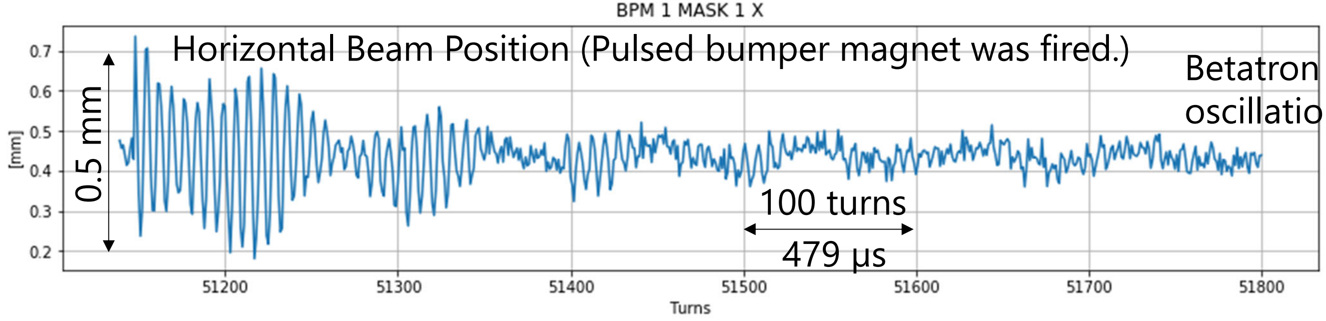


- Setup
  - 16 electrodes (4 BPM sets)
  - Span of the electrodes are the same as the design value.
  - 2 BPMs were read out by the new electronics.
  - The electronics are enclosed in a 19-inch rack with a constant temperature and humidity controller. (0.04°C and 10%RH peak-to-peak)
- We evaluated the position resolution and long-term stability.

Single Bunch Waveforms

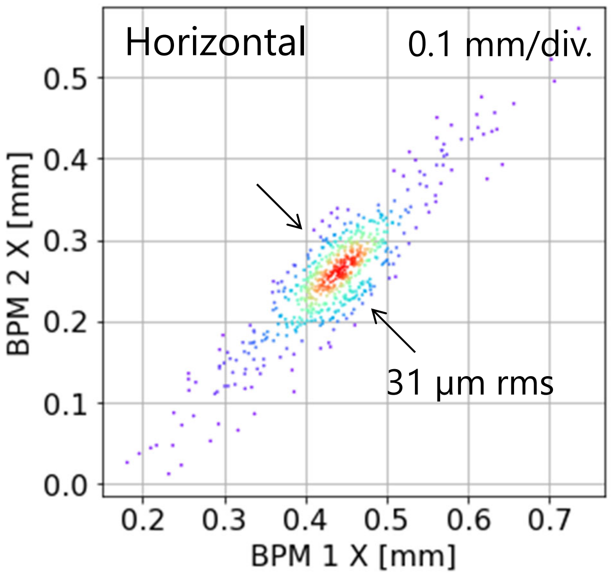


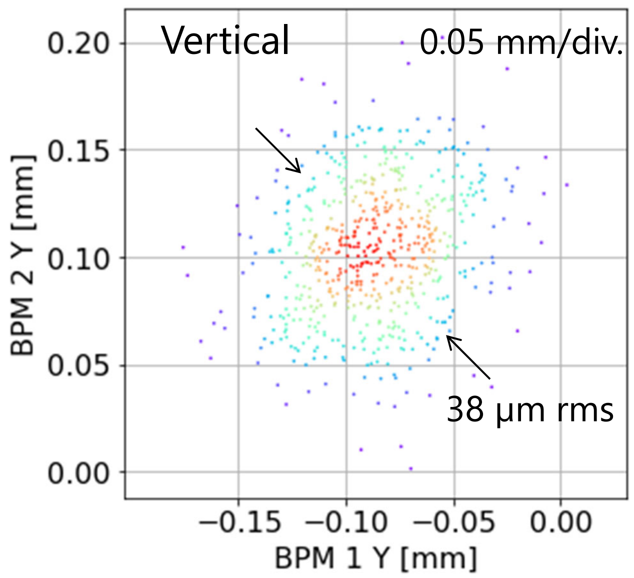




Betatron and synchrotron oscillations were observed.

Single-pass (SP) BPM Resolution

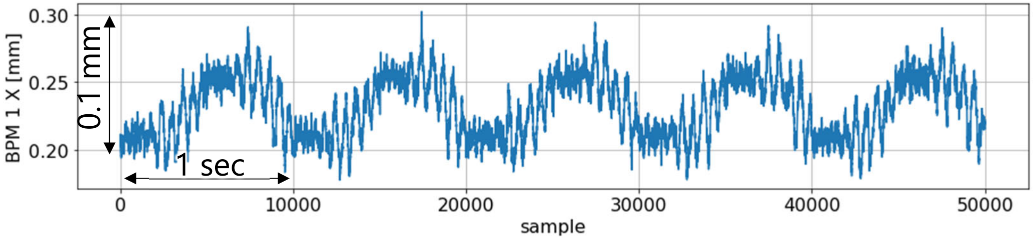




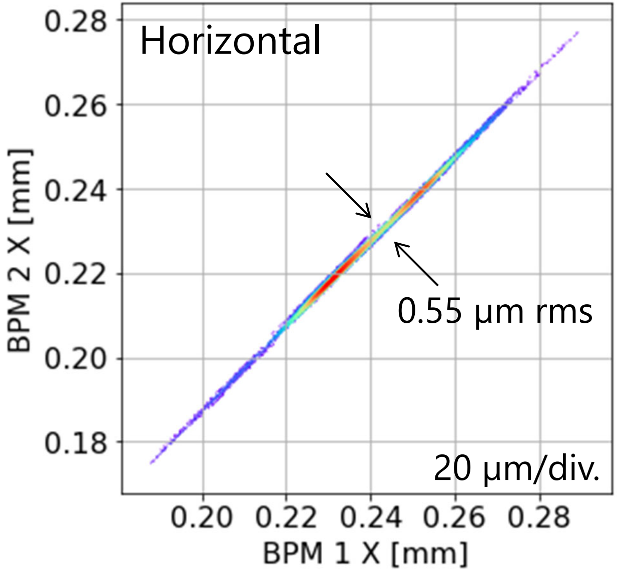
Requirement: < 100 μm

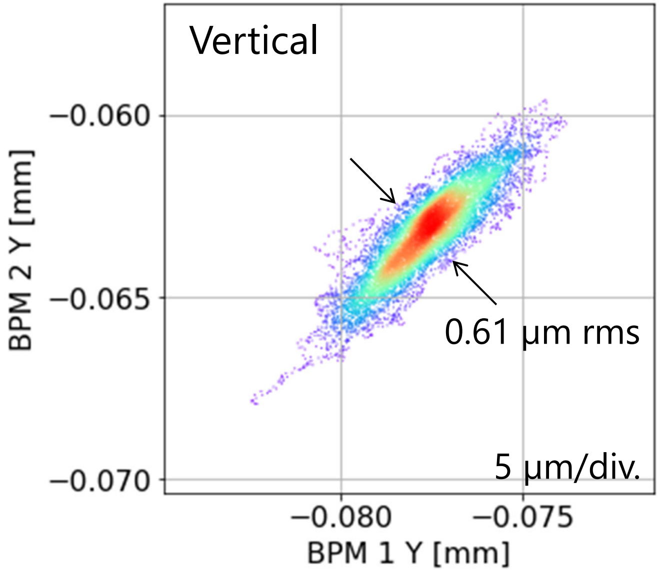
- Bunch charge: 0.13 nC
- Pulsed bumper magnet was fired.
- BPM Resolution: 22 μm (H), 27 μm (V)
  - The resolution is $1/\sqrt{2}$ of the rms of the difference, assuming the two BPMs have the same resolution.
- We took data with different beam charges and confirmed that the resolution is inversely proportional to the charge.

COD BPM Resolution (Fast Data)



- We intentionally shook the beam orbit with a fast magnet (1 Hz).
- Stored beam current: 30 mA
- ADC input: –6 dB FS

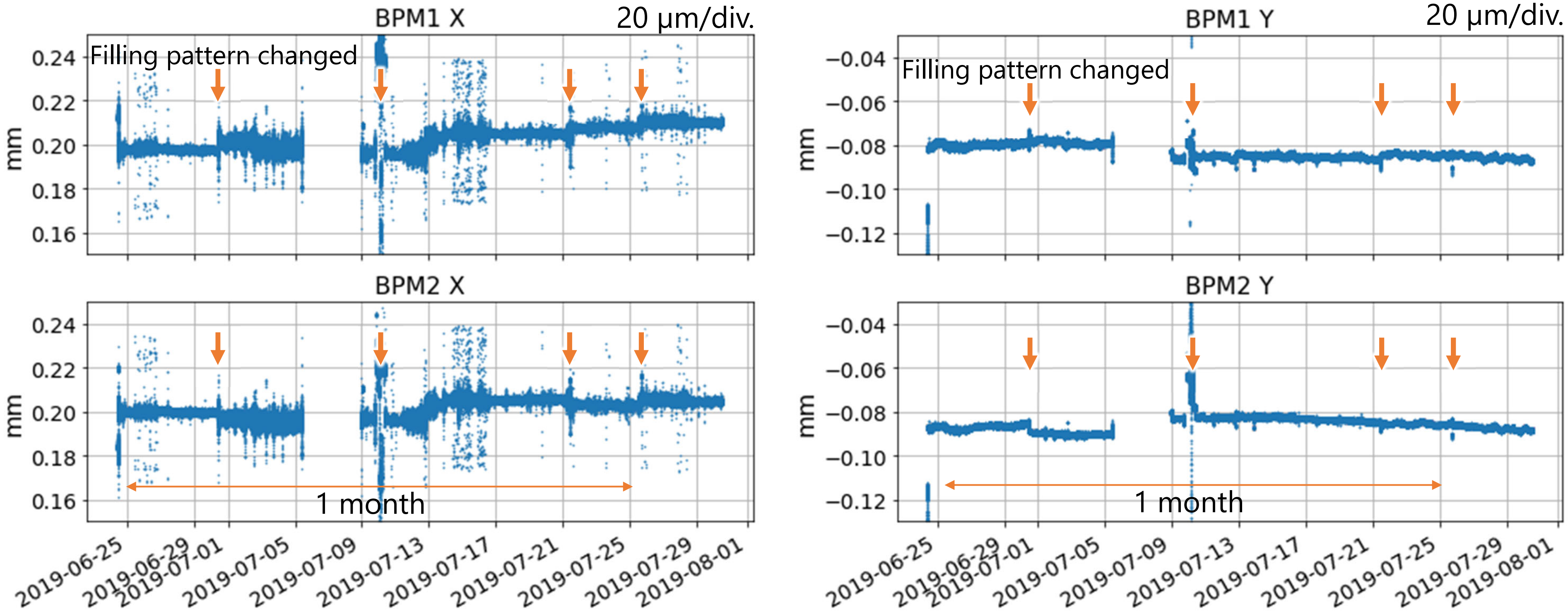




- COD BPM resolution: 0.39 μm (H), 0.43 μm (V) (2 kHz BW).

Requirement: < 1 μm

Long-term Stability

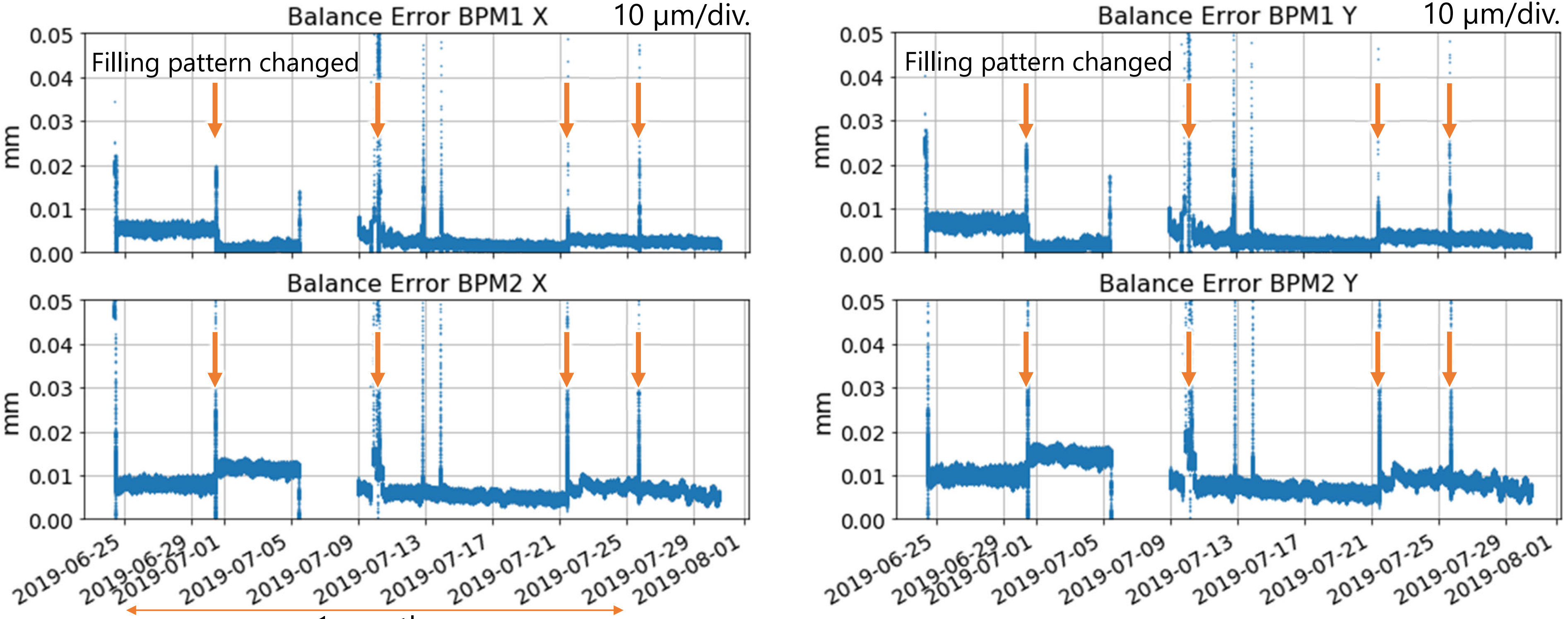


- The beam orbit was stabilized by the present BPM system.
- The new BPM shows stable position data with 10 μm stability for 1 month.

Balance Error

Stability can also be evaluated from balance error.

- Beam position can be calculated from three electrodes out of 4. (4 combinations)
- Balance error is defined as the maximum difference among the 4 position values.



1 month

Stability for 1 month: < 10 µm

Summary and Outlook

- We have developed a stable and precise BPM system for SPring-8-II.
  - Required position stability: 5 μm peak-to-peak for 1 month (100 mA)
  - Required position resolution: 100 μm rms (0.1 nC single-bunch)
- We designed a MicroTCA.4-based BPM readout system.
  - The same digitizer AMC as the LLRF upgrade. (10 ch., 16-bit, 370 MSPS)
  - A new BPM RTM (RF frontend) was developed.
  - The COD BPM logic provides the date streams of turn-by-turn (209 kHz), fast (10 kHz) and slow (10 Hz).
  - The SP BPM logic calculates the beam positions of 4 bunches.
  - A pilot tone function was also implemented.
- We performed a beam test at the present SPring-8 ring.
  - Position resolution: ~30 μm rms (0.13 nC single bunch)
  - Long-term stability: < 10 μm peak-to-peak for 1 month.
- Next tasks:
  - We will implement a gain correction process by using pilot tone data.
  - Some more electronics will be installed to the present SPring-8 BPM system to evaluate the stability and reliability.