Development and beam observations of an ultra-fast bunch-by-bunch X-ray beam size monitor at SuperKEKB

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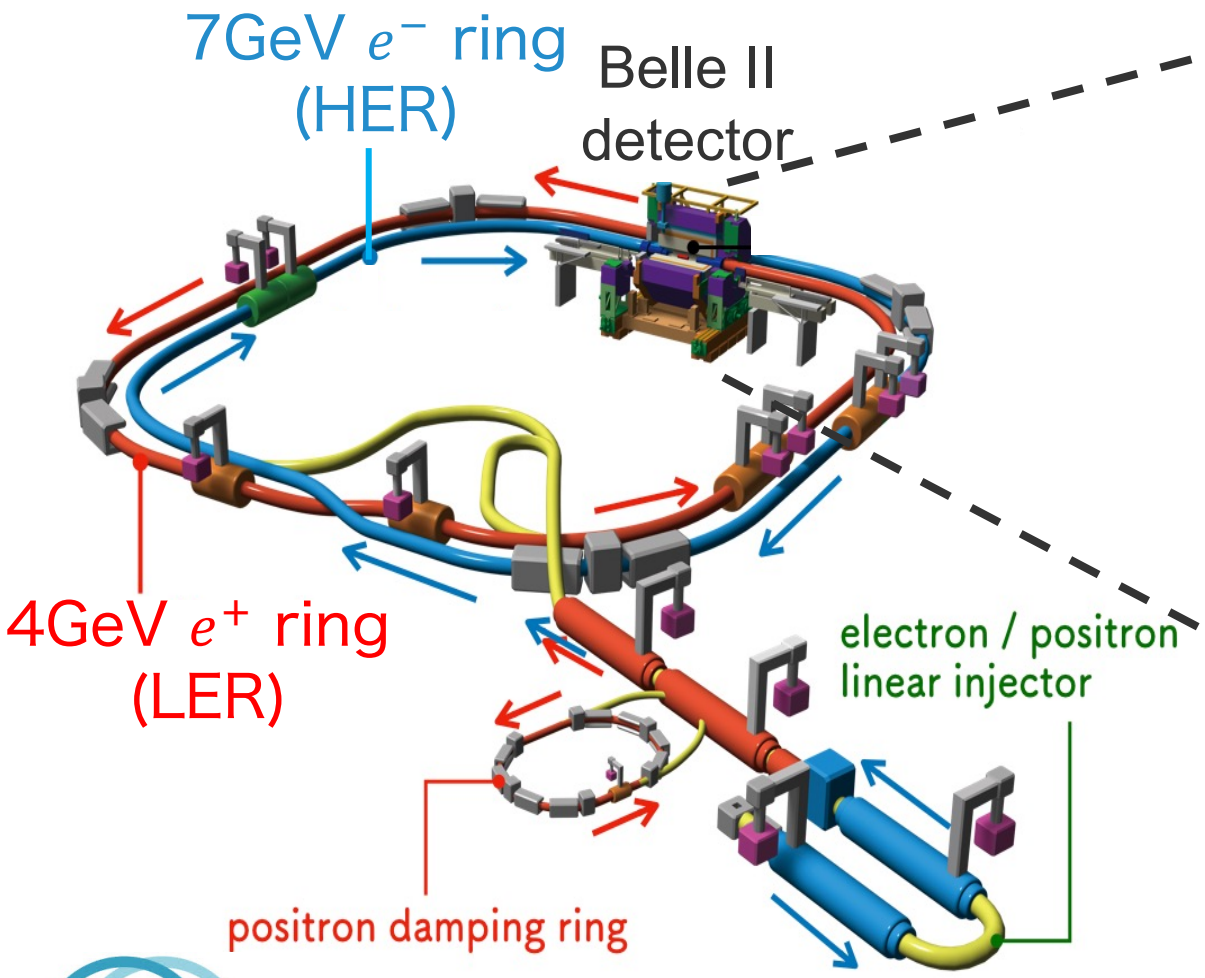
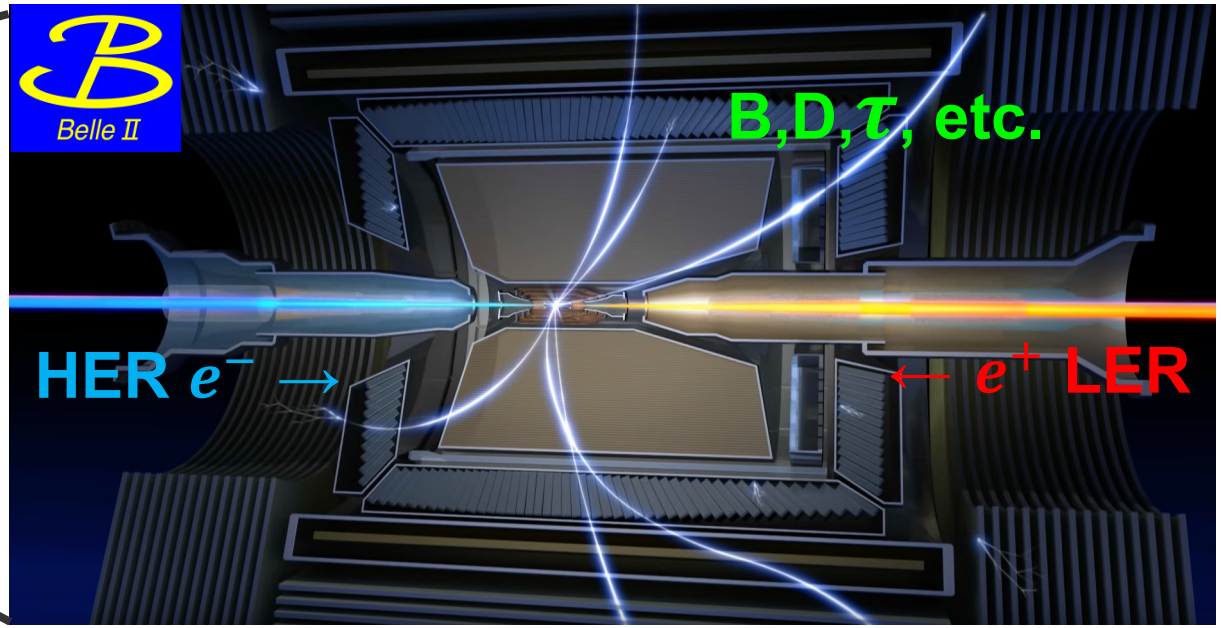
SuperKEKB

High-luminosity electron–positron collider
at KEK in Japan for the search for new physics



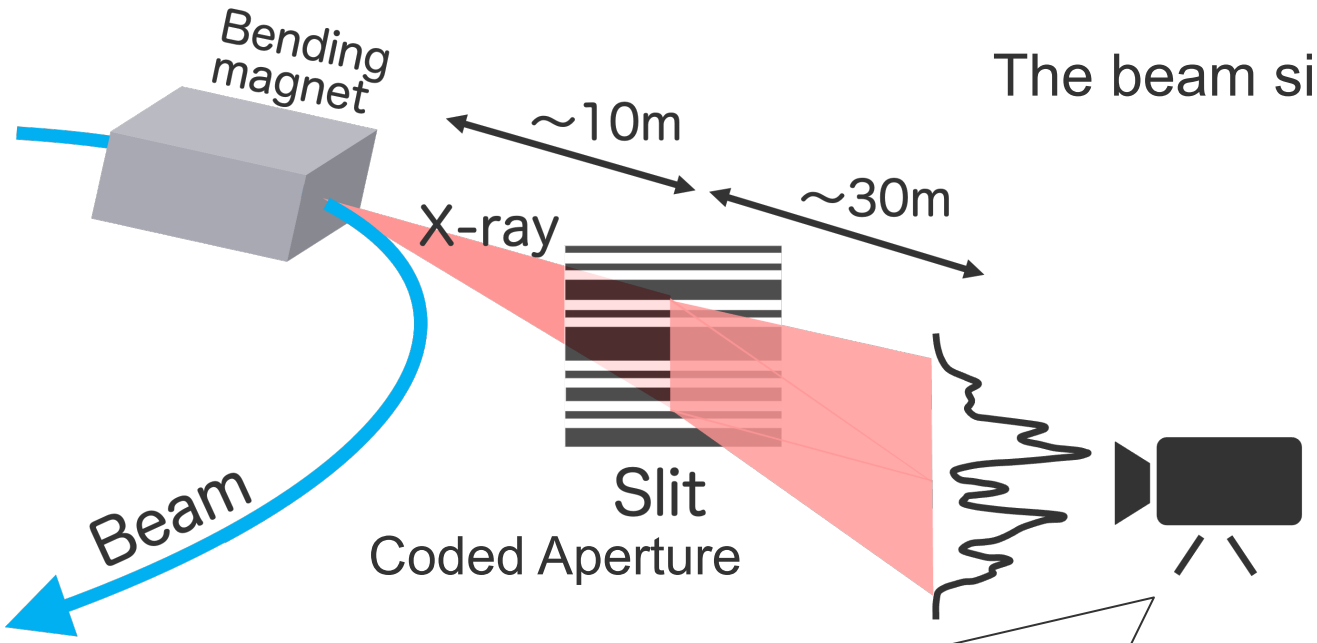


High-current, multi-bunch collisions with the nano-beam scheme

→ Measurement and understanding of the beam size are crucial

X-ray Beam Size Monitor

Synchrotron X-rays from a bending magnet are imaged through a multi-slit mask.
The beam size is obtained by fitting the shape of the X-ray image.



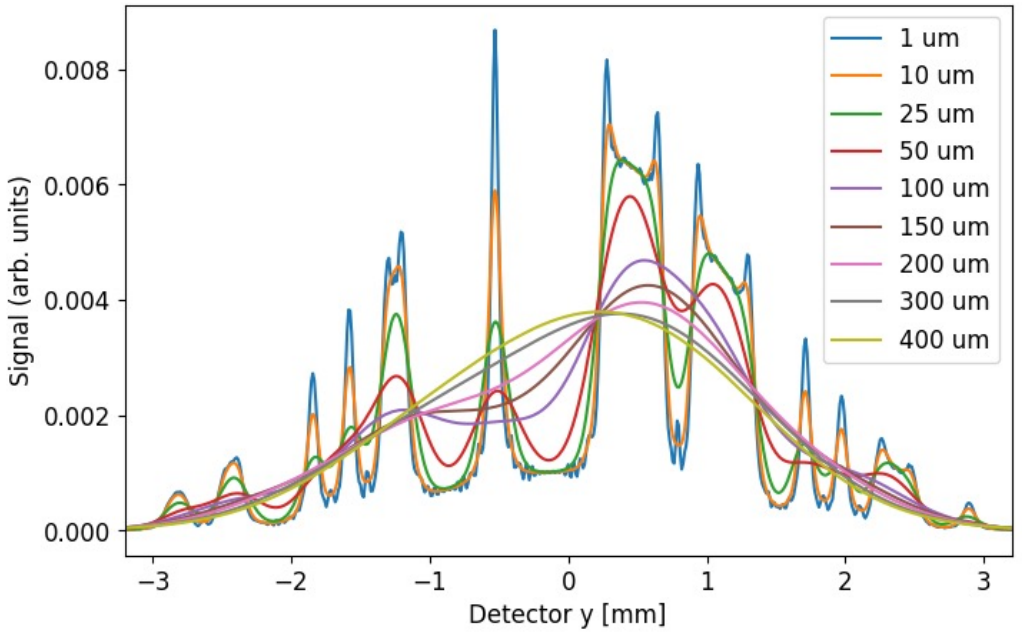
Conventional: scintillator + CMOS camera

This project:

silicon sensor for high-speed sampling

The beam size is extracted from the image sharpness ↓

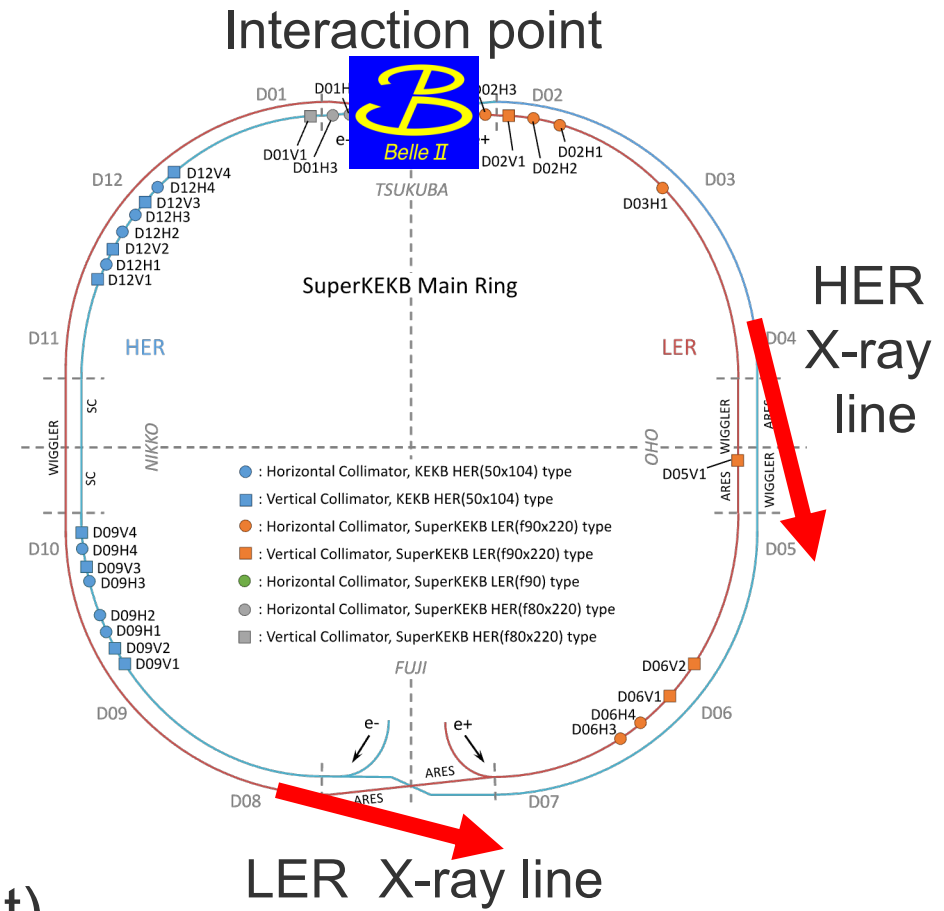
X-ray Images corresponding to different vertical beam sizes



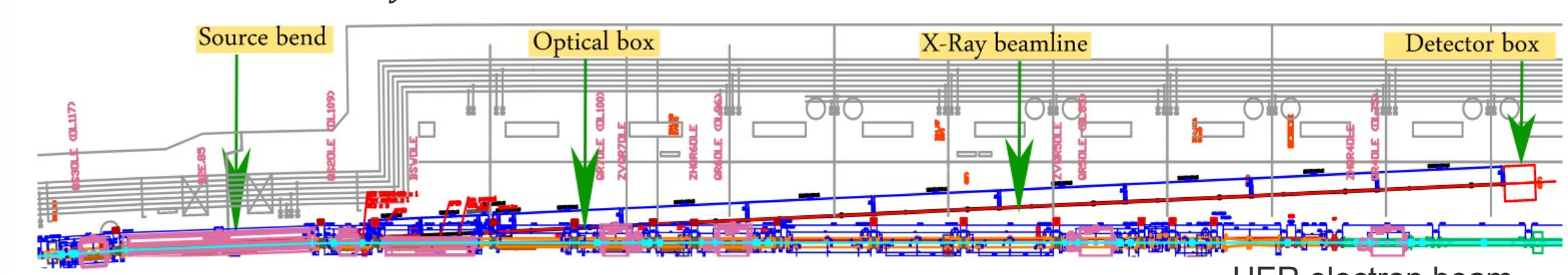
E. Mulyani *et al, NIM A* 919 (2019) 1–15

X-ray Beamline

- One X-ray extraction line is installed for each ring: HER (electron) and LER (positron).
- Synchrotron X-rays are extracted tangentially from the last bending magnet in the arc section.

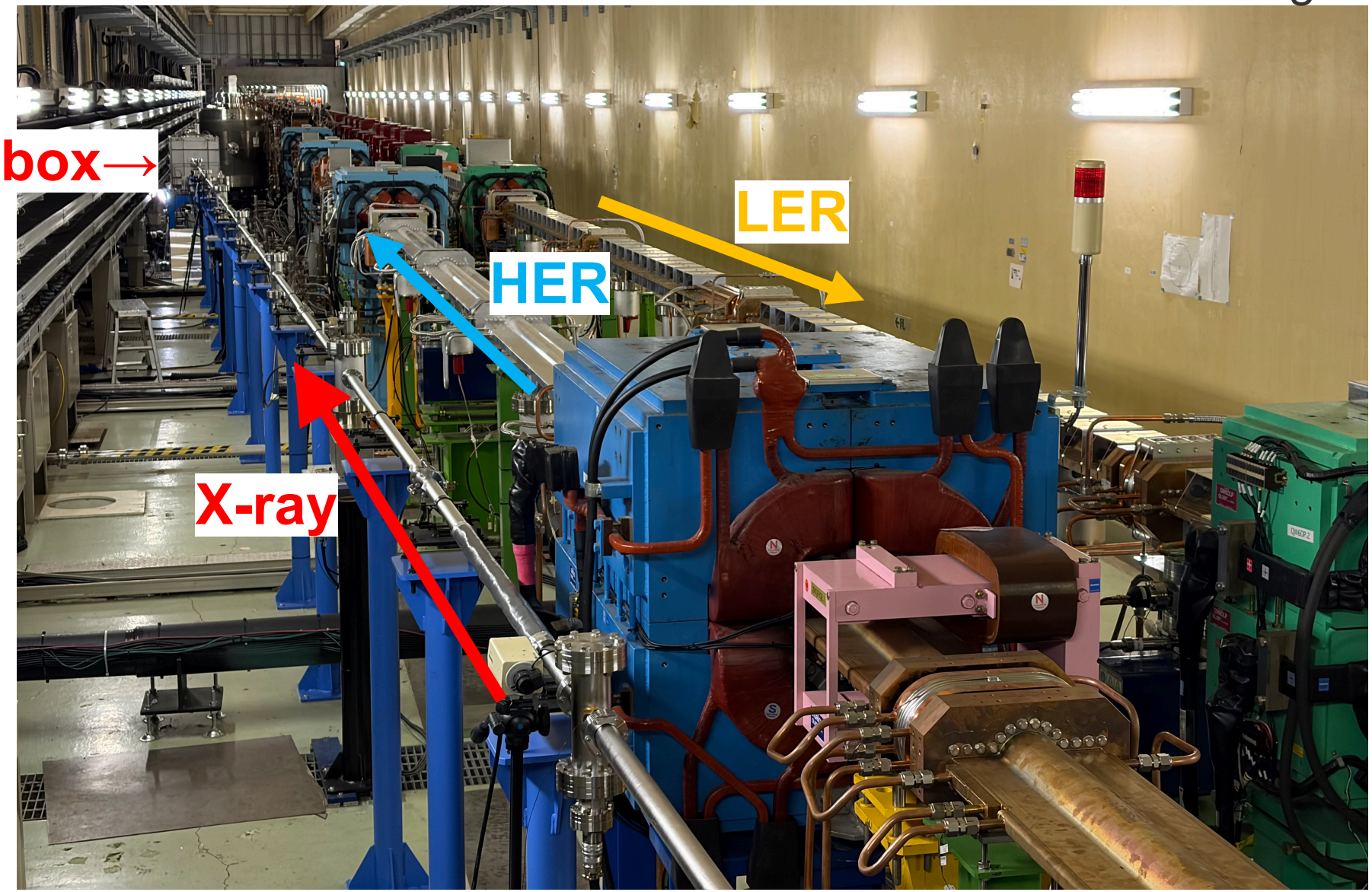


HER X-ray line (β_y = 28 m at the SR source point)



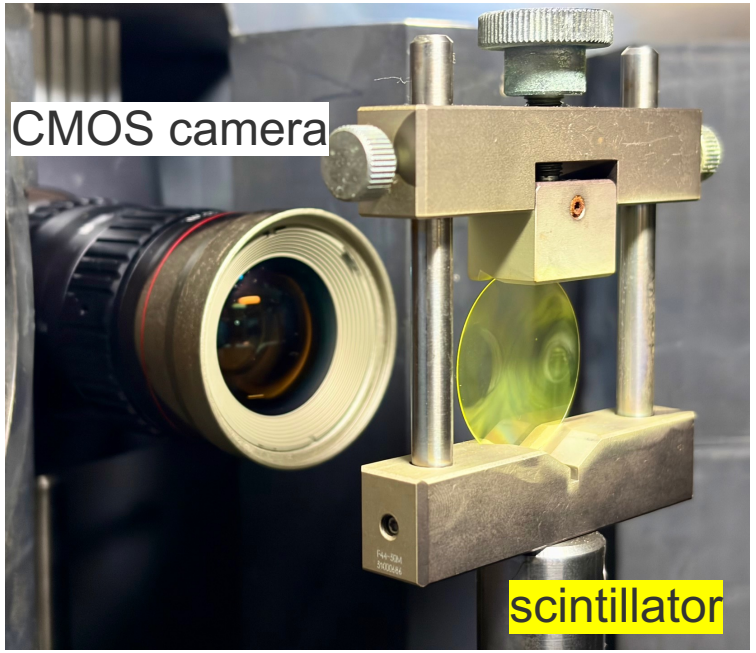
X-ray Beamline

Oho straight section



Motivation

Conventional system



- Conventional X-ray beam size monitor
  - X-rays → scintillator → CMOS camera
  - Exposure time: > tens of μs
  - Frame rate: < 100 Hz
- This is too slow to observe fast beam dynamics
  - Measures the beam size averaged over many bunches (bunch spacing ~4 ns)
  - Cannot resolve beam-size variation along the bunch train (electron cloud, fast-ion, sudden beam loss, etc.)

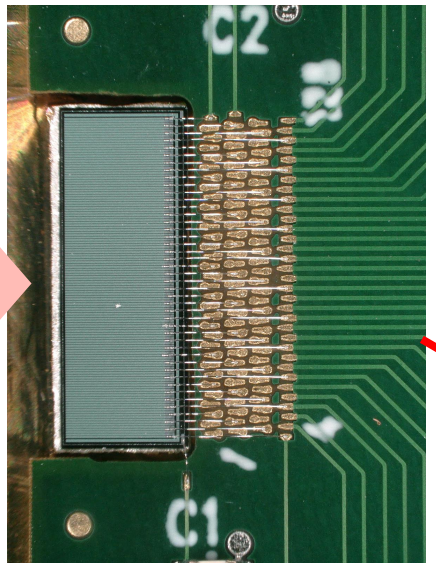
Our approach

Silicon strip sensor for fast bunch-by-bunch beam size measurements

Bunch-by-Bunch Beam Size Monitor (SiXRM)

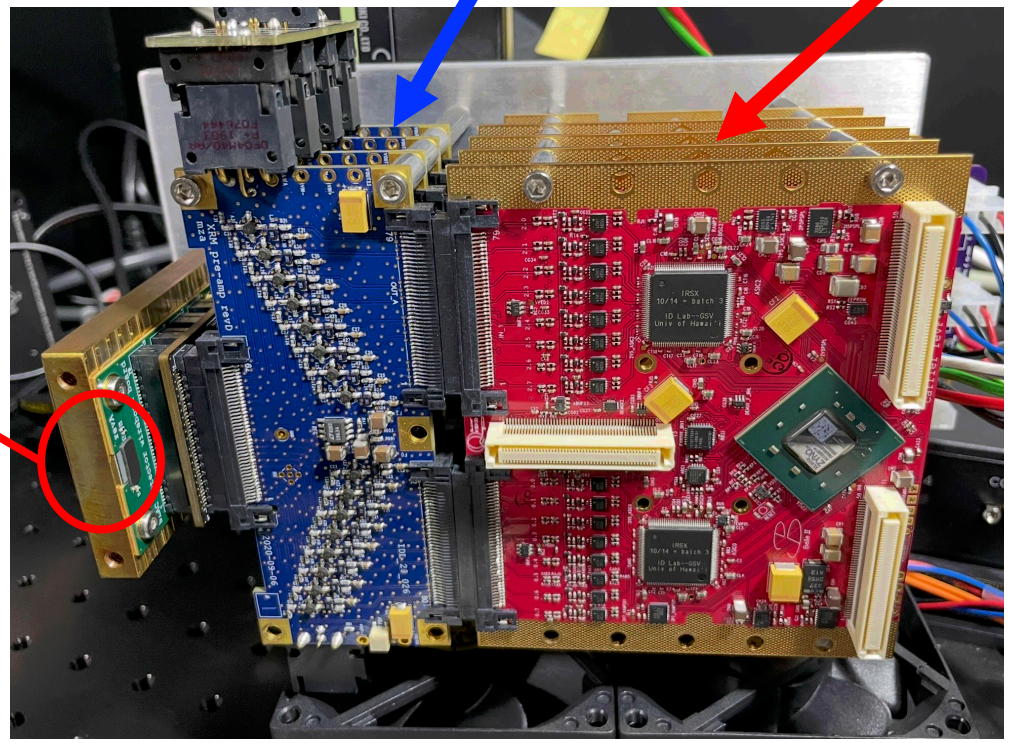
- 128-ch silicon strip sensor + preamplifier + DAQ (Hawaii × KEK collaboration)
- 2.7 GSa/s sampling enables bunch-by-bunch beam size measurement
- Vertical (Y) beam size only
- ~20 s to acquire one full turn

128ch Si strip sensor



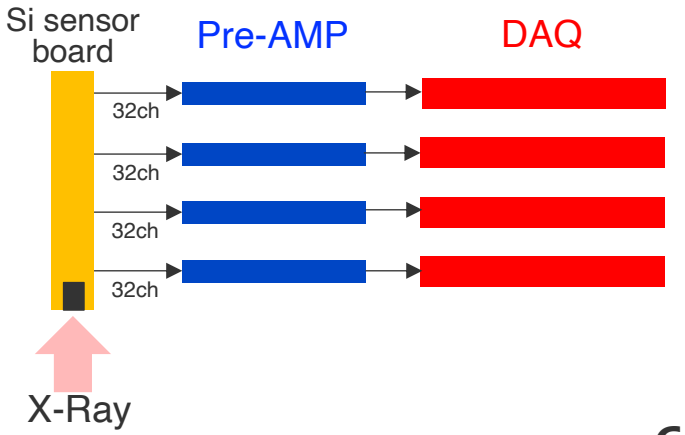
X-ray

42 channels currently used due to wire-bonding limitations

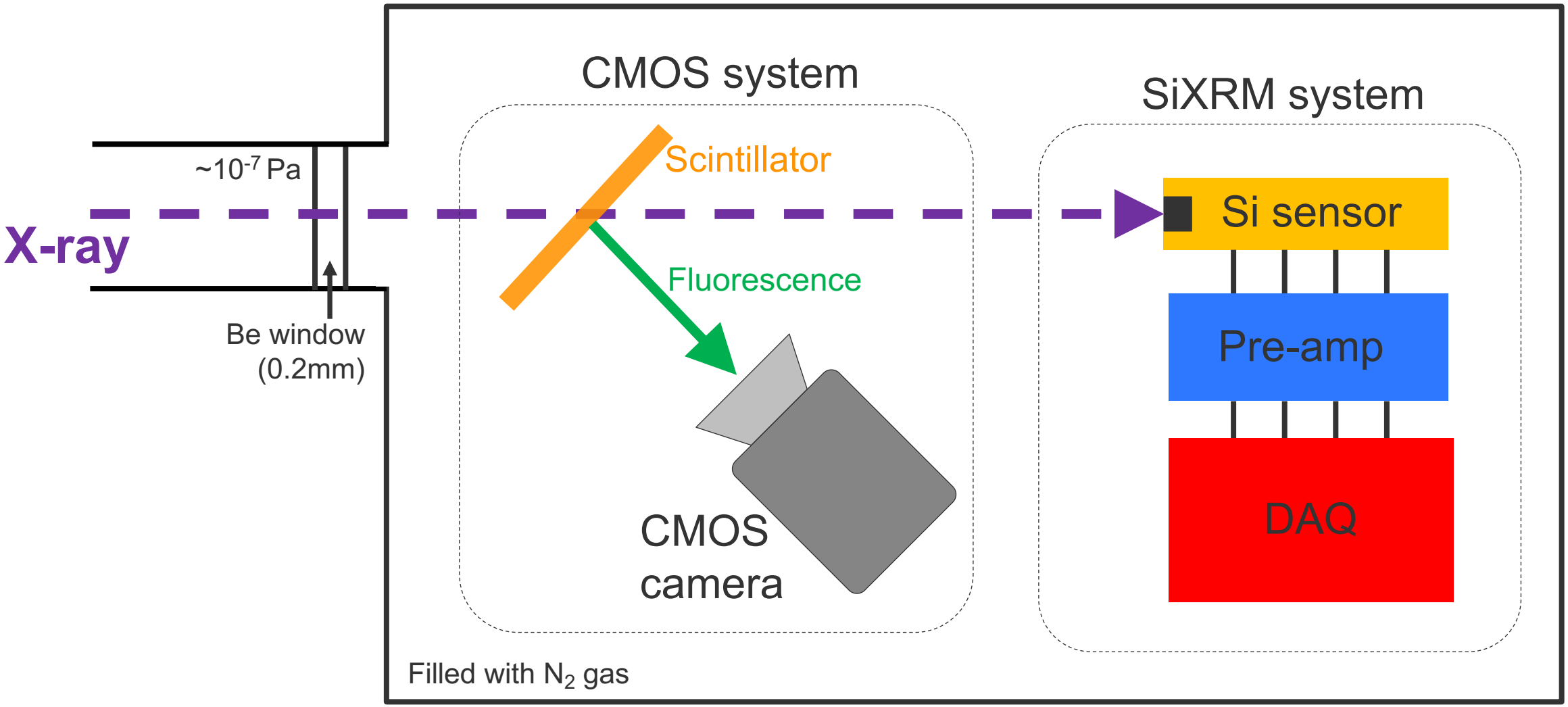


Belle II TOP SCROD+Carrier boardstacks

Top View



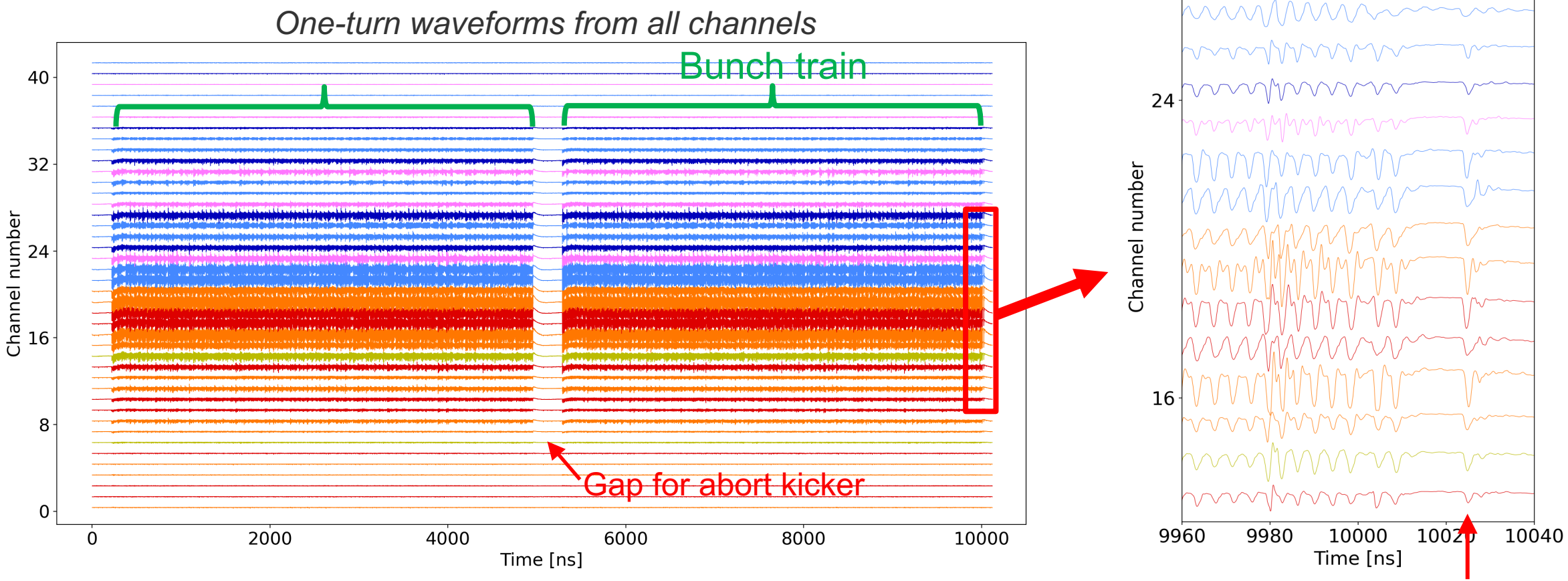
Detector Box



X-rays can be measured simultaneously with the CMOS camera and SiXRM.

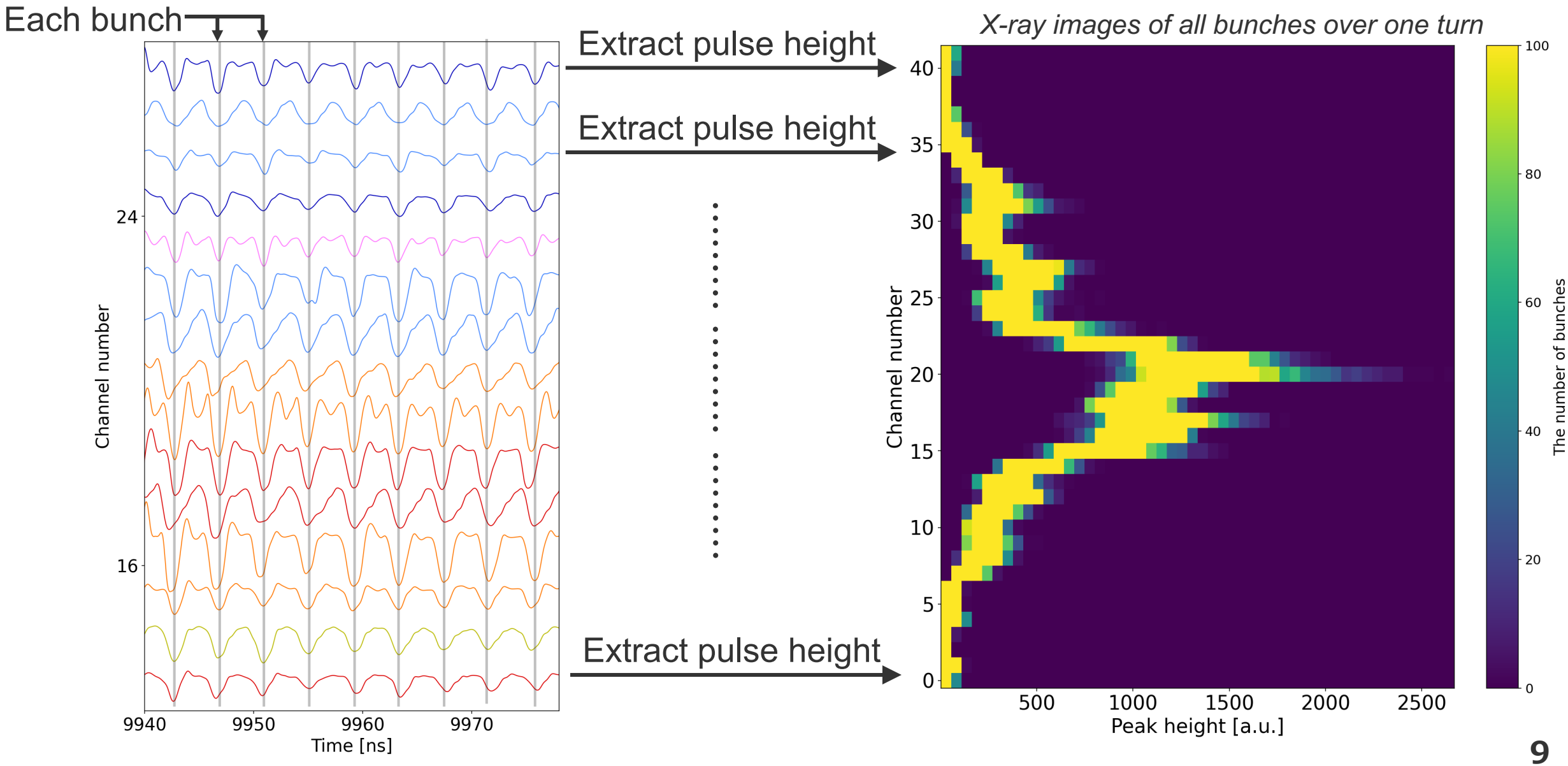
Beam Observation in the HER

2026/02/02 09:02 Beam current ~800mA



Record a 12-RF-bucket waveform window and repeat over all buckets
Concatenate the windows to reconstruct one full turn
Acquisition time: ~50 ms/window, ~20 s/turn

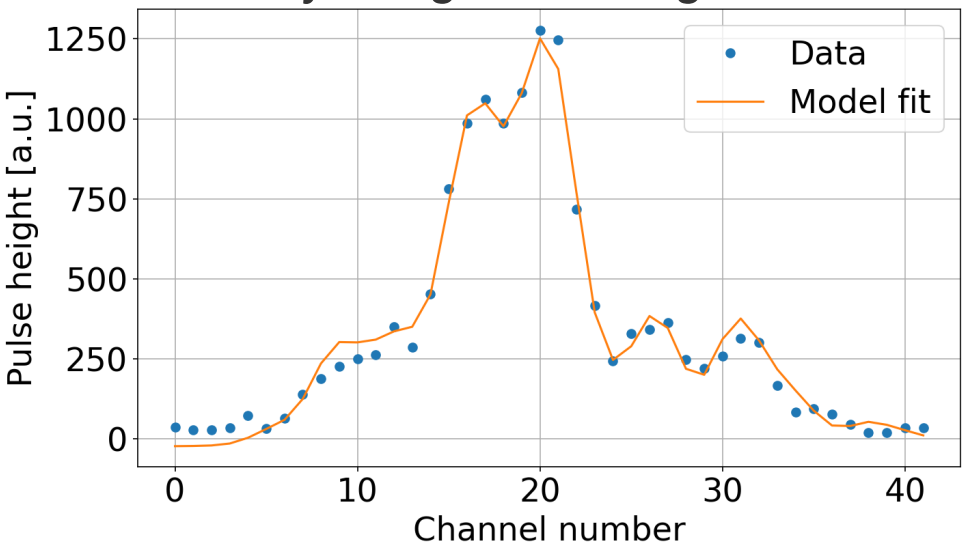
X-ray Image Reconstruction



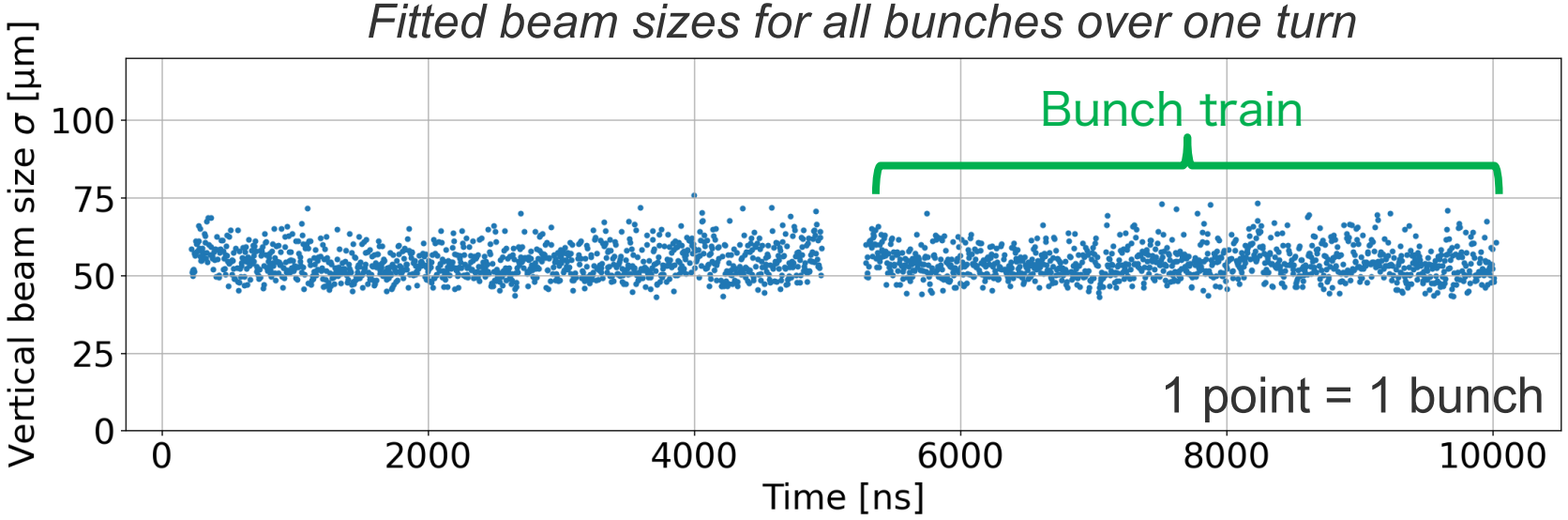
Beam Size Extraction

- Perform a fit for the reconstructed X-ray image of each bunch.
- Fit each image with simulated templates for various beam sizes and positions using the least-squares method.

X-ray image of a single bunch



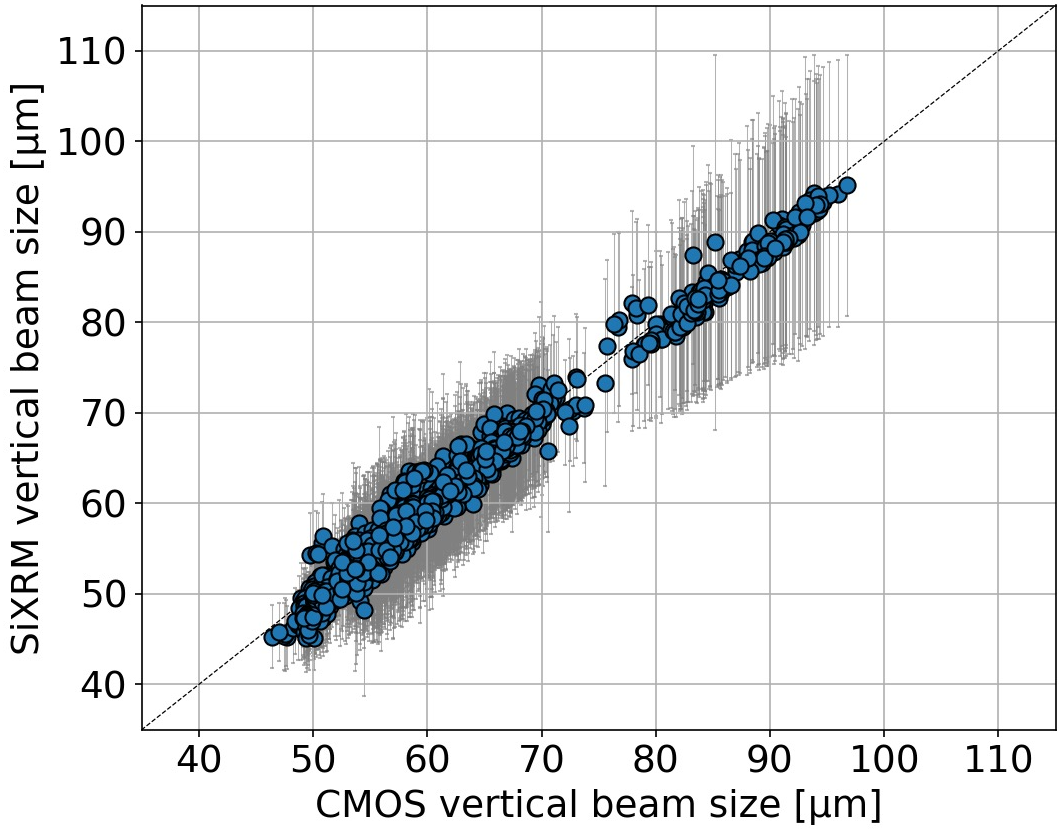
Fitted beam sizes for all bunches over one turn



First successful bunch-by-bunch beam size measurement at SuperKEKB using a silicon sensor

Comparison with the CMOS System

- Compare SiXRM with the conventional CMOS measurement (multi-bunch average)



2,429 measurements at HER (Nov. 2025 – Feb. 2026)

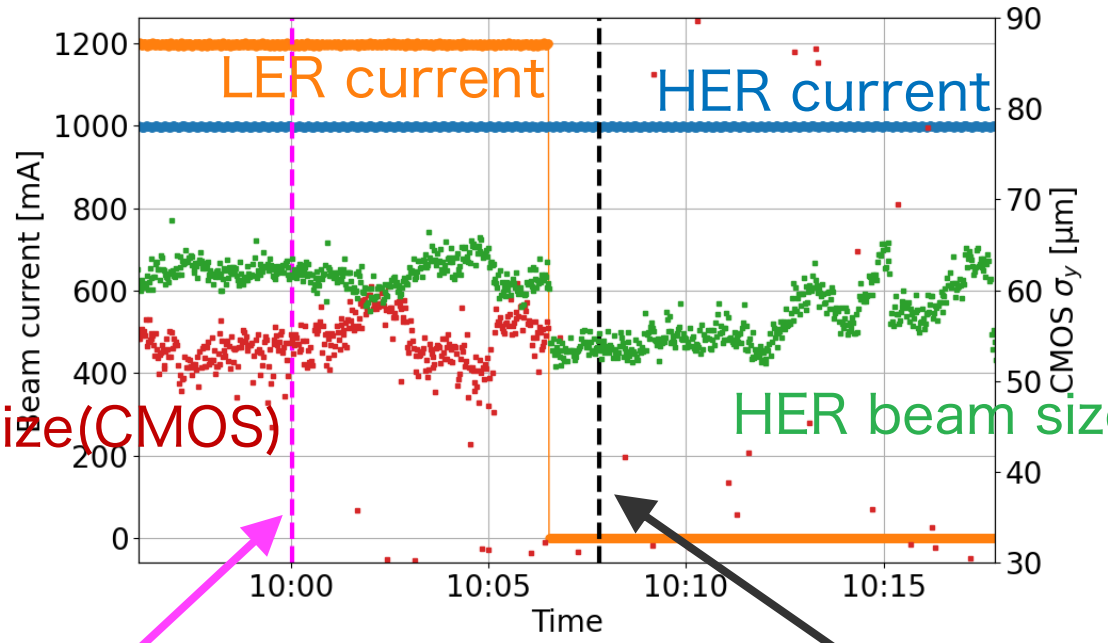
- One point = one measurement (one turn)
- SiXRM beam size (vertical axis)
  = mean over all bunches in one turn
- Error bars
  = bunch-to-bunch standard deviation

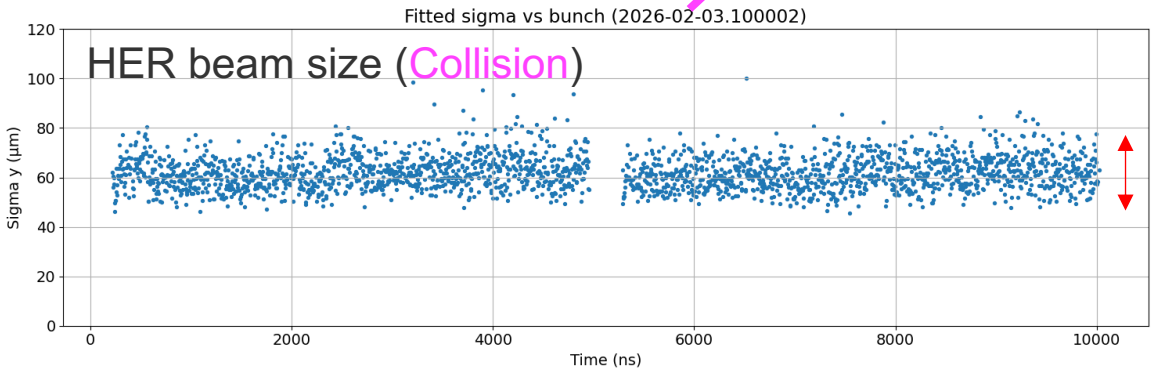
※ CMOS camera system resolution: ~1 μm (1σ std.)

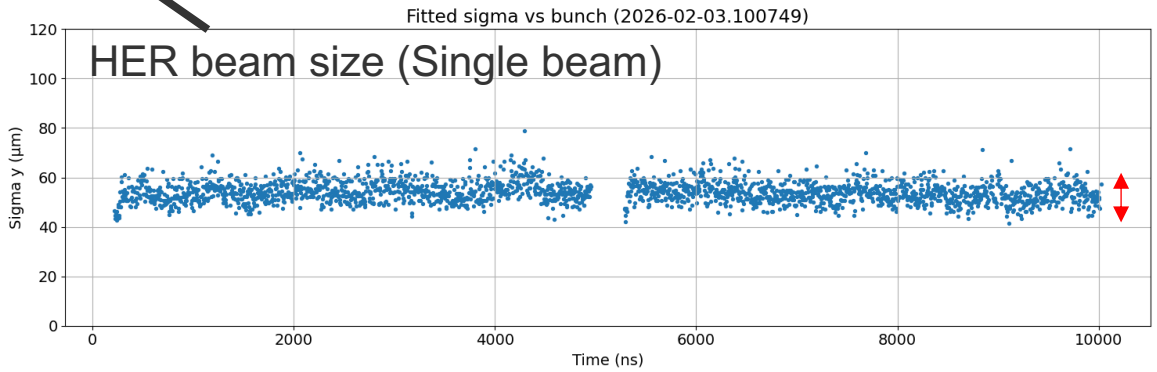
Good agreement with the CMOS system confirms the SiXRM performance

Observation Example – Collision vs. Single-Beam

Operation history
on Feb. 3, 2026



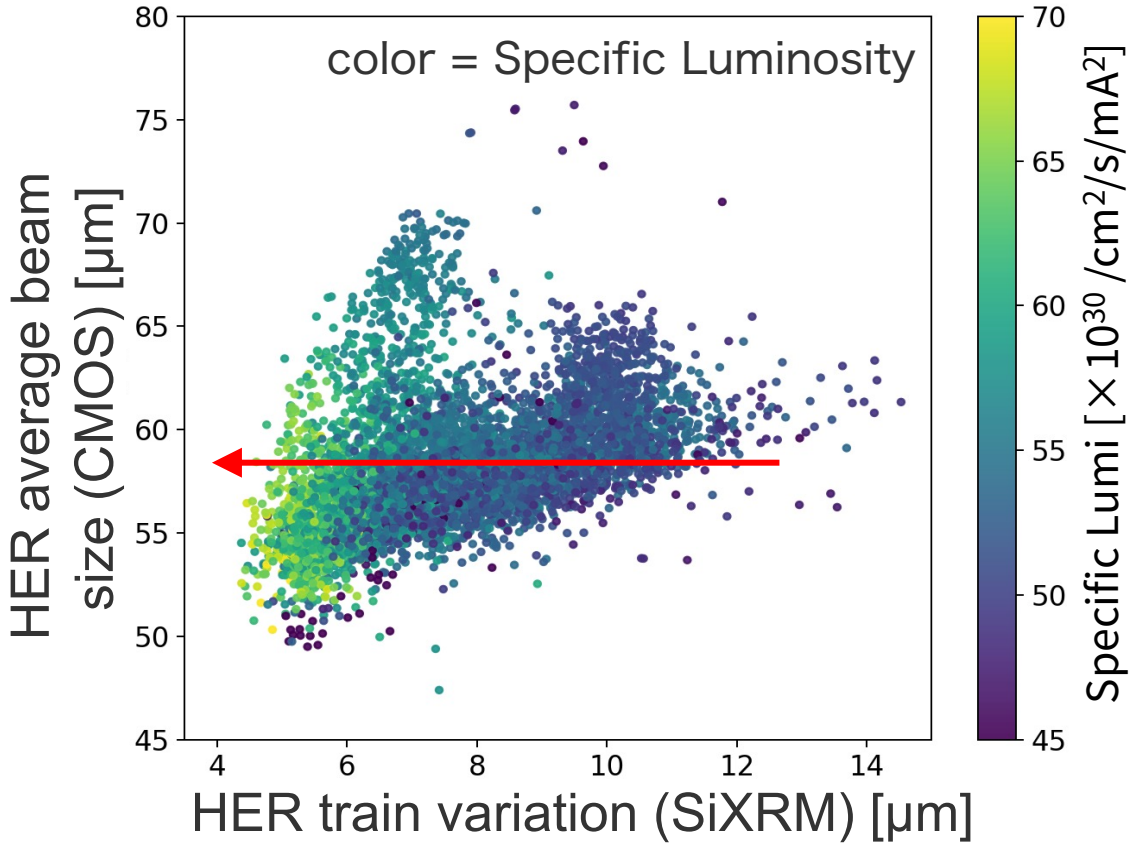




- Larger bunch-to-bunch beam-size variation during collision
- Variation quantified by the standard deviation σ over all bunches in one turn

Beam-Size Variation Along the Bunch Train

Train variation (SiXRM) vs. average HER beam size (CMOS)



Specific luminosity = luminosity normalized by the number of bunches and bunch currents

When the average beam size increases …

The bunch train not only grows overall, but also shows larger bunch-to-bunch beam-size variation.

New insight from SiXRM

Even at similar average beam size, smaller train variation corresponds to higher specific luminosity.

SiXRM Upgrade Plan

- Current limitations
  - Only 6 bunches per shot → cannot capture many bunches / multiple turns
  - 2.7 GSa/s sampling is not synchronized with the 509 MHz RF
  - ADC electronics near the sensor are exposed to X-ray radiation

- Upgrade
  - Replace the readout with AMD/Xilinx RFSoC
    RFSoC = High-speed multi-channel ADC + FPGA + CPU
  - Use 3 × ZCU216 boards
    16-ch, 14-bit, 2.5 GSa/s ADC per board
  - Keep only the preamplifier near the sensor
    Transmit signals by cable and place the RFSoC behind shielding
    → Protect electronics from radiation

RFSoC ZCU216 board

See **WEP016** for upgrade details.

Summary

- Developed and installed SiXRM in the electron ring, achieving the first successful X-ray bunch-by-bunch beam size measurement at SuperKEKB.
- Good agreement with the conventional CMOS system validates the measurement
- Bunch-to-bunch beam-size variation is correlated with collision conditions and luminosity.
- Analyses are ongoing to understand beam-beam effects and beam instabilities.
- A readout upgrade is in progress, aiming for full bunch-by-bunch and turn-by-turn measurements.

Thank you for your attention.