

Development of a Streaming DAQ System for Beam-Size Monitoring at SuperKEKB

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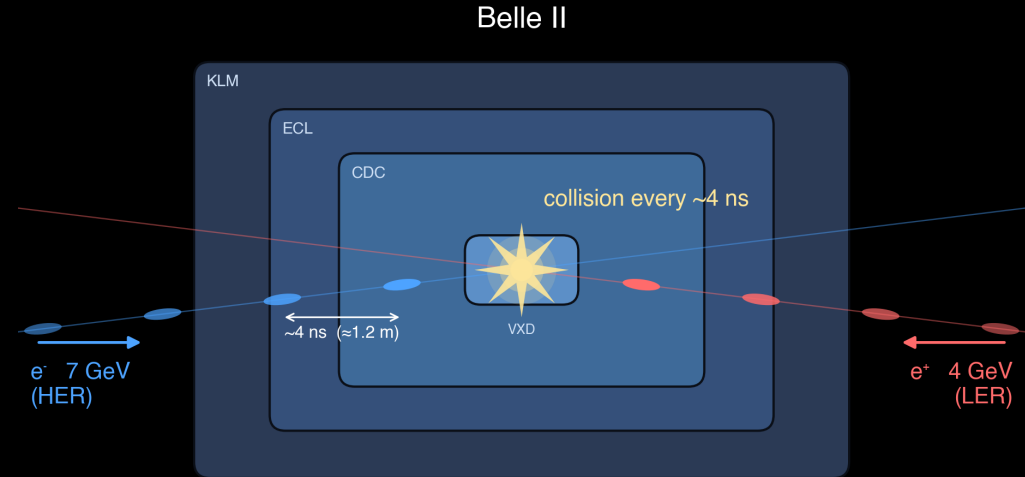
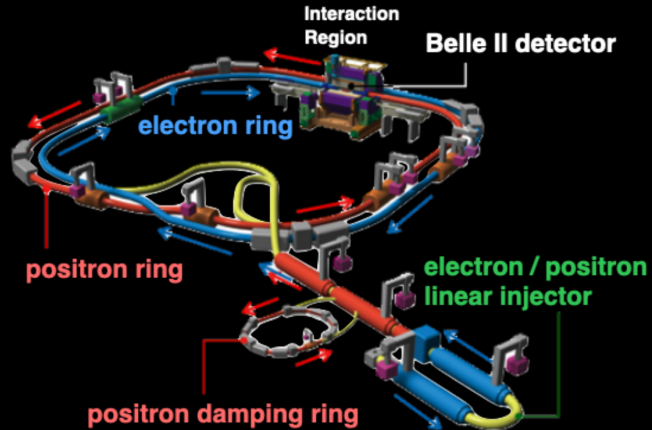
University of Hawai'i · KEK

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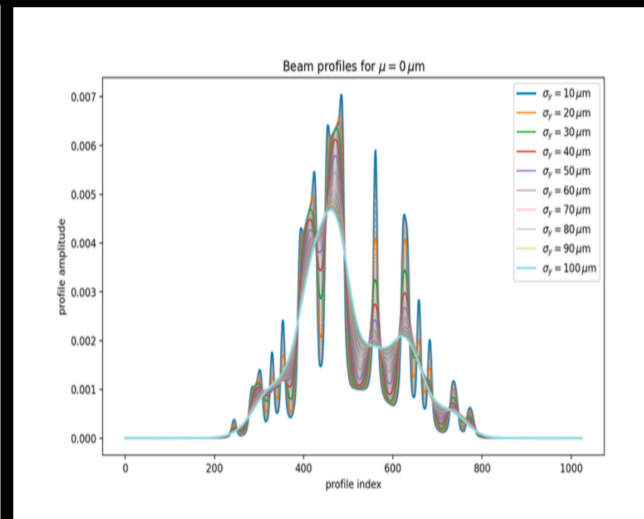
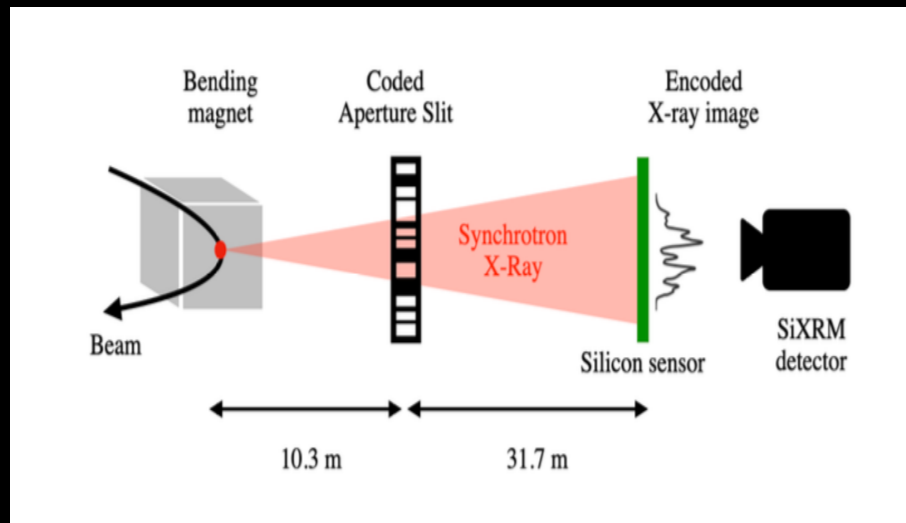


SuperKEKB/Belle II



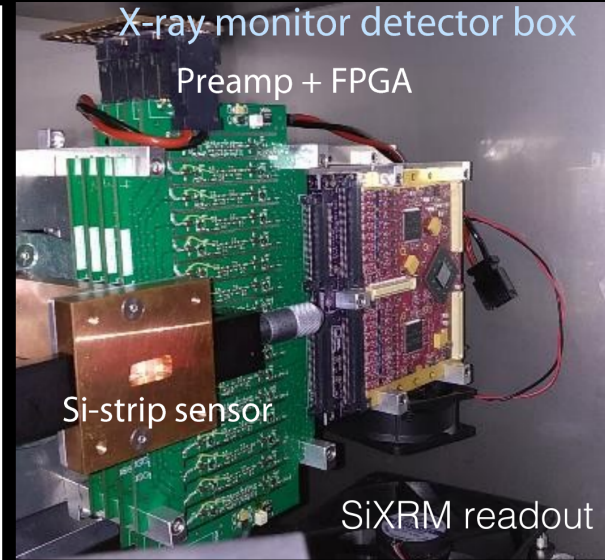
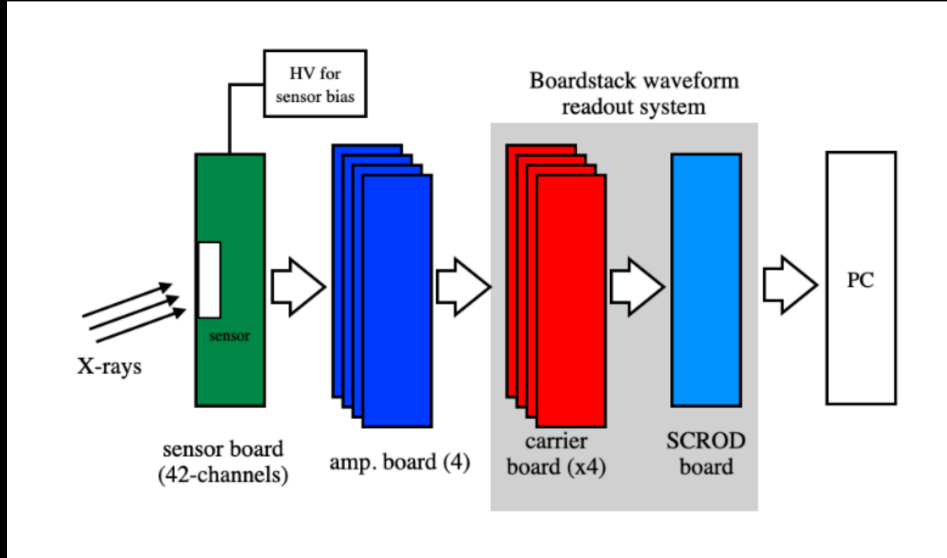
- e^+e^- collider at KEK (Japan): 7 GeV e^- (HER) $\times$ 4 GeV e^+ (LER), 3 km rings; Belle II studies flavor physics.
- "Nano-beam" scheme: vertical beam size at the collision point squeezed to well below $1\ \mu\text{m}$.
- World-record luminosity $5.3 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (2026) — the beam size must be monitored and kept small.

X-Ray Beam Size Monitor — Coded-Aperture Imaging



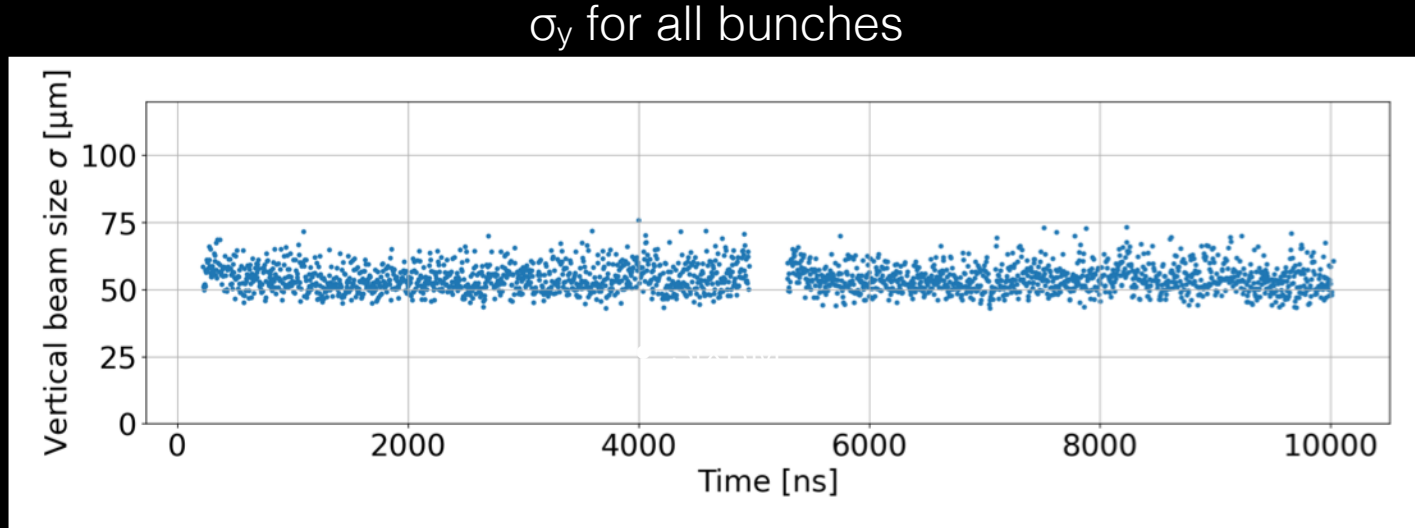
- Synchrotron X-rays from a bending magnet pass through a coded-aperture mask.
- The beam size is encoded in how much the pattern is smeared.
- σ_y (and position μ) from a fit to templates computed for each beam size.

SiXRM Detector



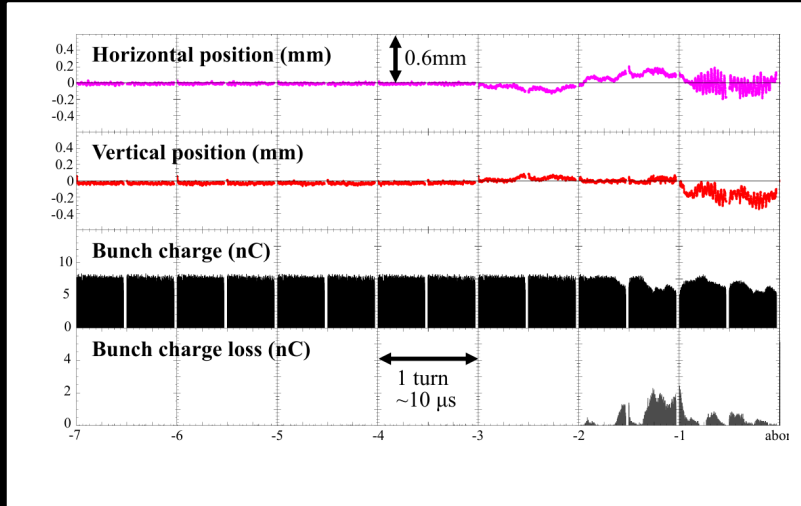
- Si strip sensor (SiXRM): bunch-resolved — 128 strips, 50 μm pitch, 42 wire-bonded
- Readout: Belle II TOP boardstack — IRSX waveform sampling at 2.7 GSa/s, 128 channels.
 - ▶ Triggered "sweep" mode: ~ 12 RF buckets per acquisition (~ 50 ms); analysis offline

First Bunch-by-Bunch Vertical Beam Size at SuperKEKB

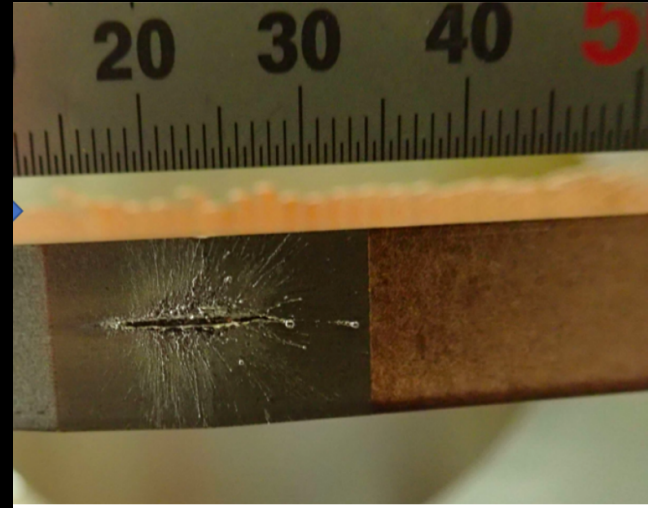


- 2429 HER measurements (Nov 2025 – Feb 2026).
- Precision better than $6.4 \mu\text{m}$ — arXiv:2607.08205 (NIM A, under review).
- **First bunch-by-bunch σ_y at SuperKEKB, consistent with the CMOS monitor.**

Sudden Beam Loss (SBL)



Bunch-by-bunch orbit and charge before an abort (LER)

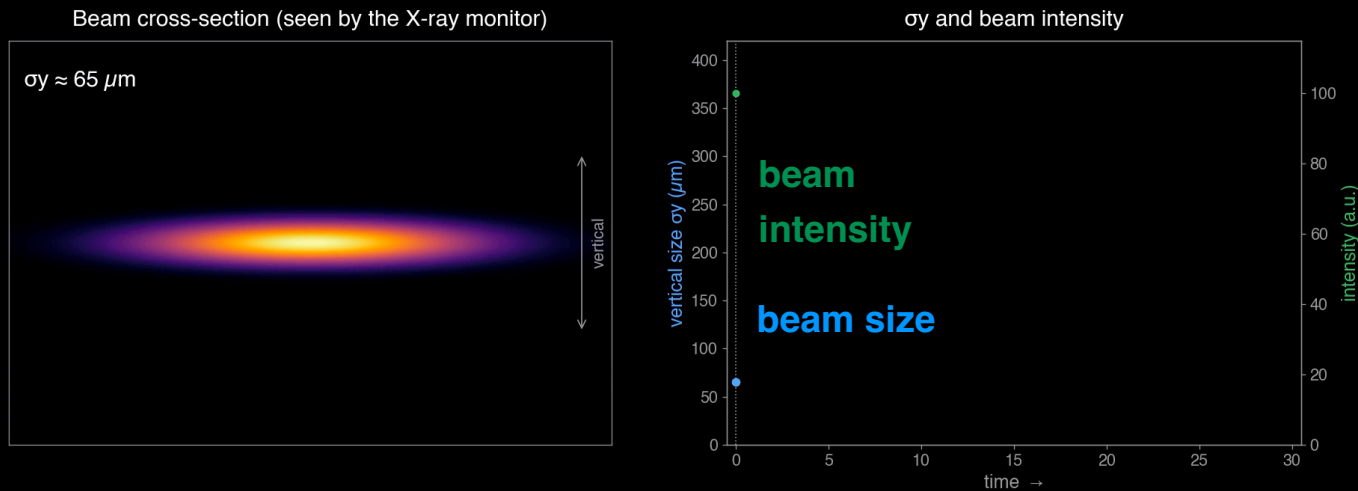


Collimator head damaged by an SBL

- Part of the beam is lost within a few turns (one turn $\approx 10 \mu\text{s}$), with no clear warning;
- The cause still unknown and it damages collimators and Belle II inner detectors (2% of the pixel detector permanently lost).
- Limits the beam current, and hence the luminosity.

Beam-Size Blow-Up at SBL

*illustration



- Turn-by-turn vertical beam size σ_y measured before an SBL in HER.
- σ_y started to grow ~ 24 turns (~ 0.24 ms) before the beam was lost.
- Bunch-by-bunch σ_y , in real time, could provide an early warning for the abort system.

Why a New Readout

Now: Belle II TOP boardstack

Triggered, ~12 buckets per 50 ms
Analysis offline



Next: ZCU216 RFSoc

Every bunch, every turn
 σ_y computed in the FPGA

What makes it hard

Offline → FPGA

an NN replaces the template fit:
simple, fast, fixed latency

650 Gb/s raw

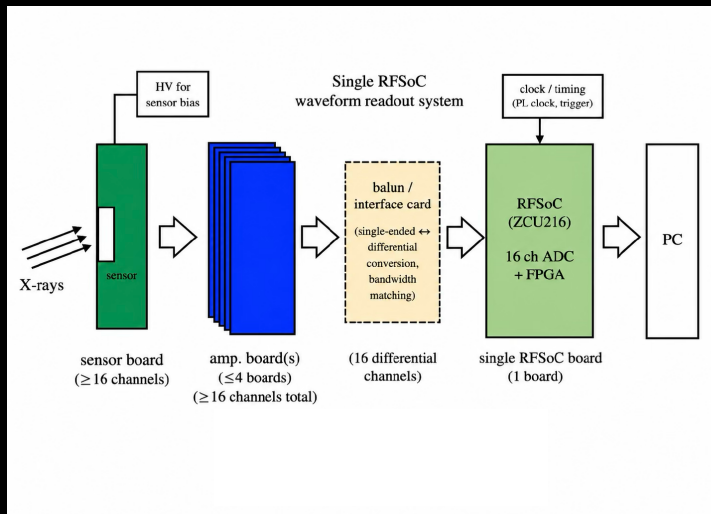
no full waveforms:
record only the beam size

$\geq 18 \mu\text{s}$ warning

needed before the loss;
firmware latency $\approx 1.2 \mu\text{s}$

Channels: start with 16, then scale up to 32 / 48

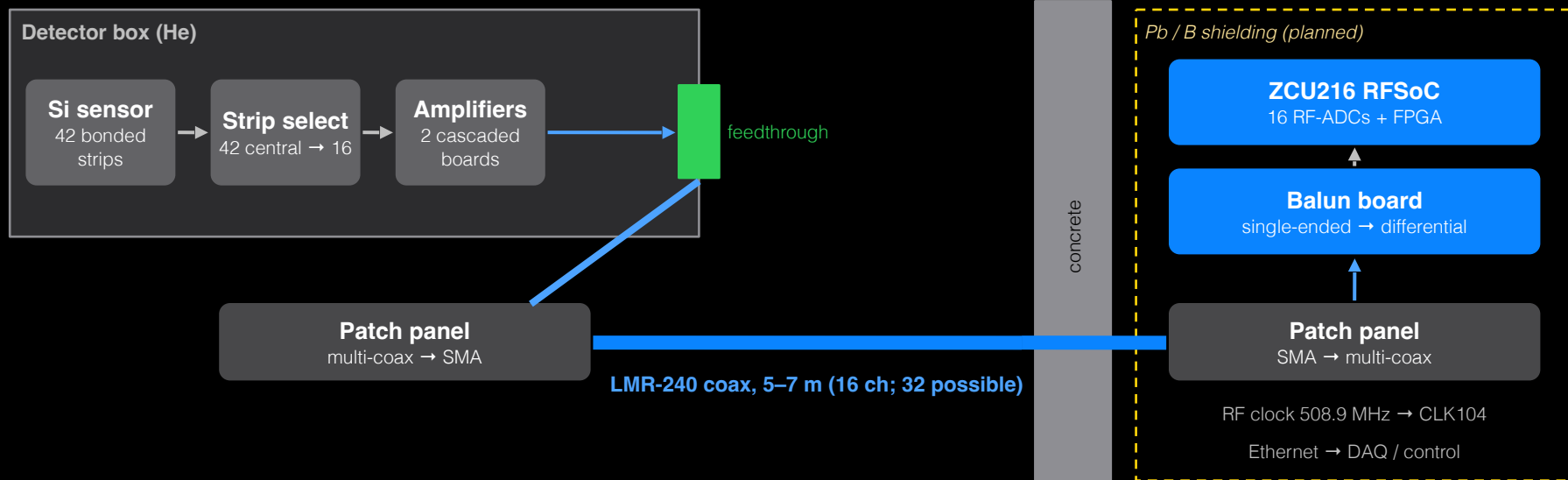
Readout Upgrade for Streaming DAQ



- AMD ZCU216 RFSoc: 16 RF-ADC channels, continuous digitization at 2.544 GSa/s.
 - Sampling locked to the 508.9 MHz RF ($f_s = 5 f_{RF}$) through the CLK104 PLL
 - Beam size computed in the FPGA, with a path to the abort system.
- **From triggered snapshots to a continuous, full-turn measurement.**

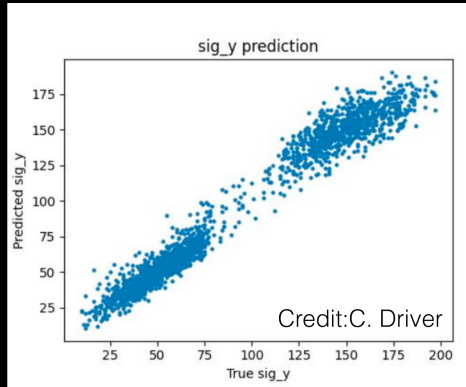
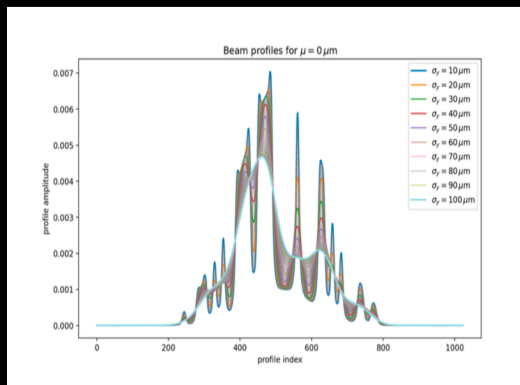
Readout Configuration for 2027

SuperKEKB tunnel, HER X-ray line (D04)



- Front end stays in the detector box; the RFSoc sits behind the concrete, away from the beam line.
- Short, low-loss coax: cable loss is small, so two amplifier stages restore the present signal level.
- Only the bonded, central strips are amplified; two interleaved 16-channel groups allow a later 32-channel upgrade.

Neural-Network Beam-Size Estimator in the FPGA



Toy MC profiles and σ_y prediction — Credit: C. Driver

Nominal σ_y (μm)	30	50	70	90	120	160	200
NN σ_y (μm)	33	55	73	104	139	185	202

Full firmware chain in simulation, pseudo data, 8-bunch images

- $16 \rightarrow 64 \rightarrow 64 \rightarrow 2$ (σ_y , μ), quantized.
- hls4ml $\rightarrow$ Verilog IP, fixed latency; rebuilt for 254 MHz (ReuseFactor 8)
- We train it on toy MC and test it against the 2025 beam data. We also ran the full firmware chain in simulation with pseudo data.
- Monotonic over 30–200 μm ; placeholder network still biased at large σ_y .

Status, Plan and Summary

● Oct 2026

ZCU216 bench test at KEK (pseudo data, loopback)

● Jan 12–15, 2027

Installation in HER; beam back ~Jan 25

● 2027 runs

Shadow mode: σ_y of every bunch, abort not connected

● Later

Threshold from SBL events
→ PXD HV / beam abort

Summary

First bunch-by-bunch σ_y at SuperKEKB with SiXRM; $< 6.4 \mu\text{m}$, consistent with CMOS

Streaming readout: ZCU216 RFSoc, every bunch on every turn

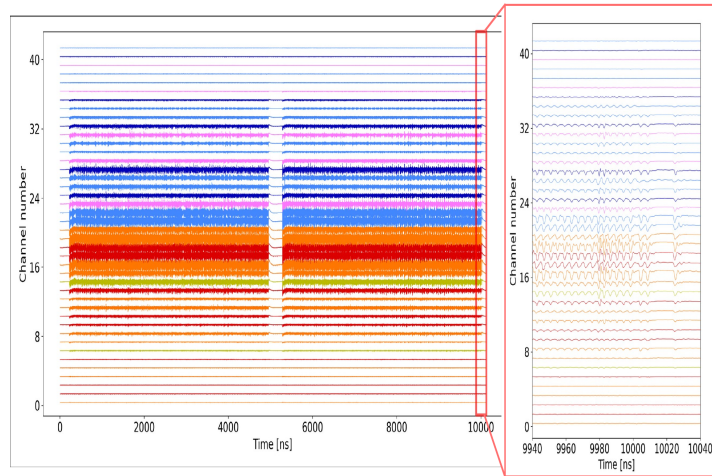
In-FPGA analysis: running baseline, 8-bunch images, NN σ_y , event capture

Scaling: 16 → 32 → 48 channels

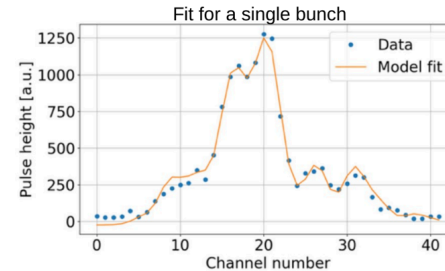
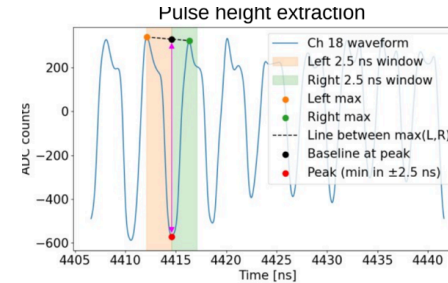
→ **Goal: a real-time precursor of sudden beam loss**

Backup

From Waveforms to Pulse Heights

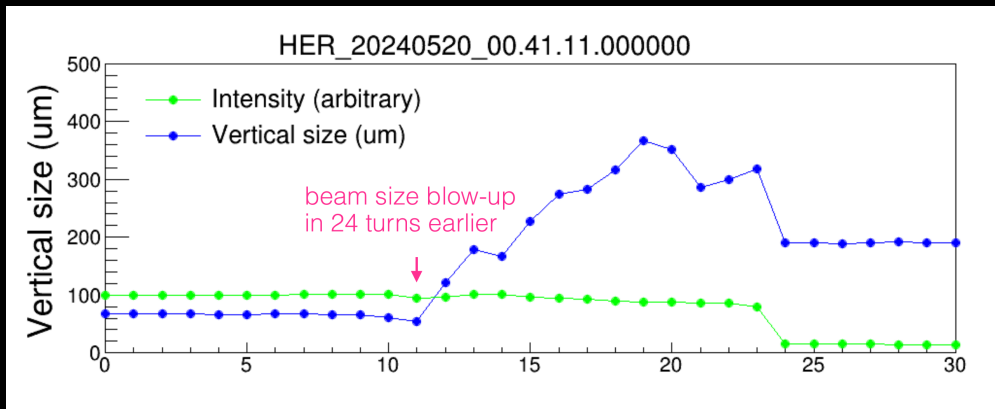


2026-02-02, HER (800 mA): Concatenated waveform obtained over multiple turns
1 Pulse = signal from 1 bunch



- HER, 800 mA: one pulse per bunch, waveforms concatenated over many turns.
- Per bunch: spline interpolation $\rightarrow$ timing alignment $\rightarrow$ peak $\rightarrow$ baseline subtraction $\rightarrow$ gain calibration.
- Template fit of the 42-channel profile $\rightarrow$ σ_y , μ for each bunch.

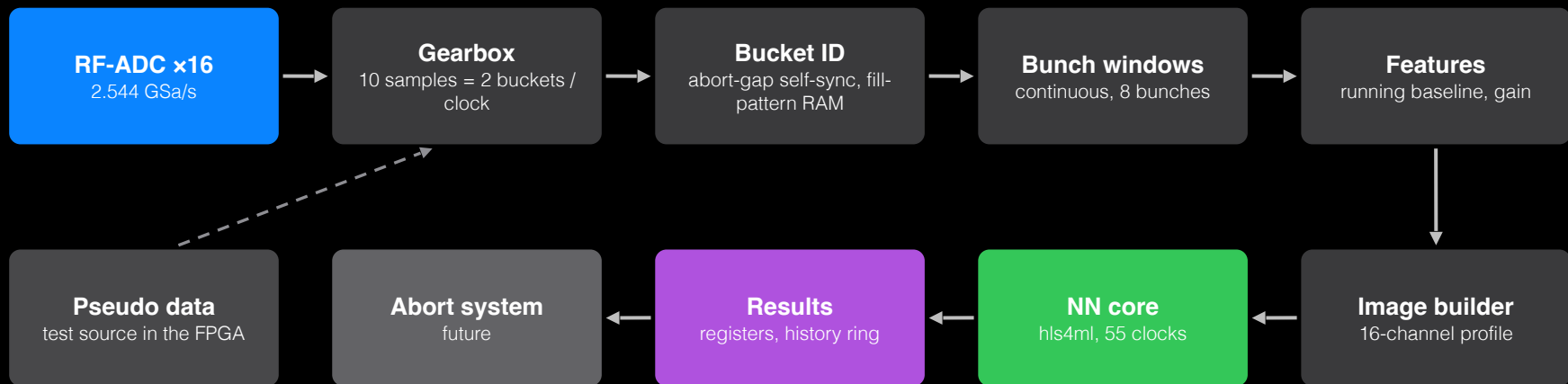
Beam-Size Blow-Up as an SBL Precursor



**Can we see the precursor
bunch by bunch,
in real time?**

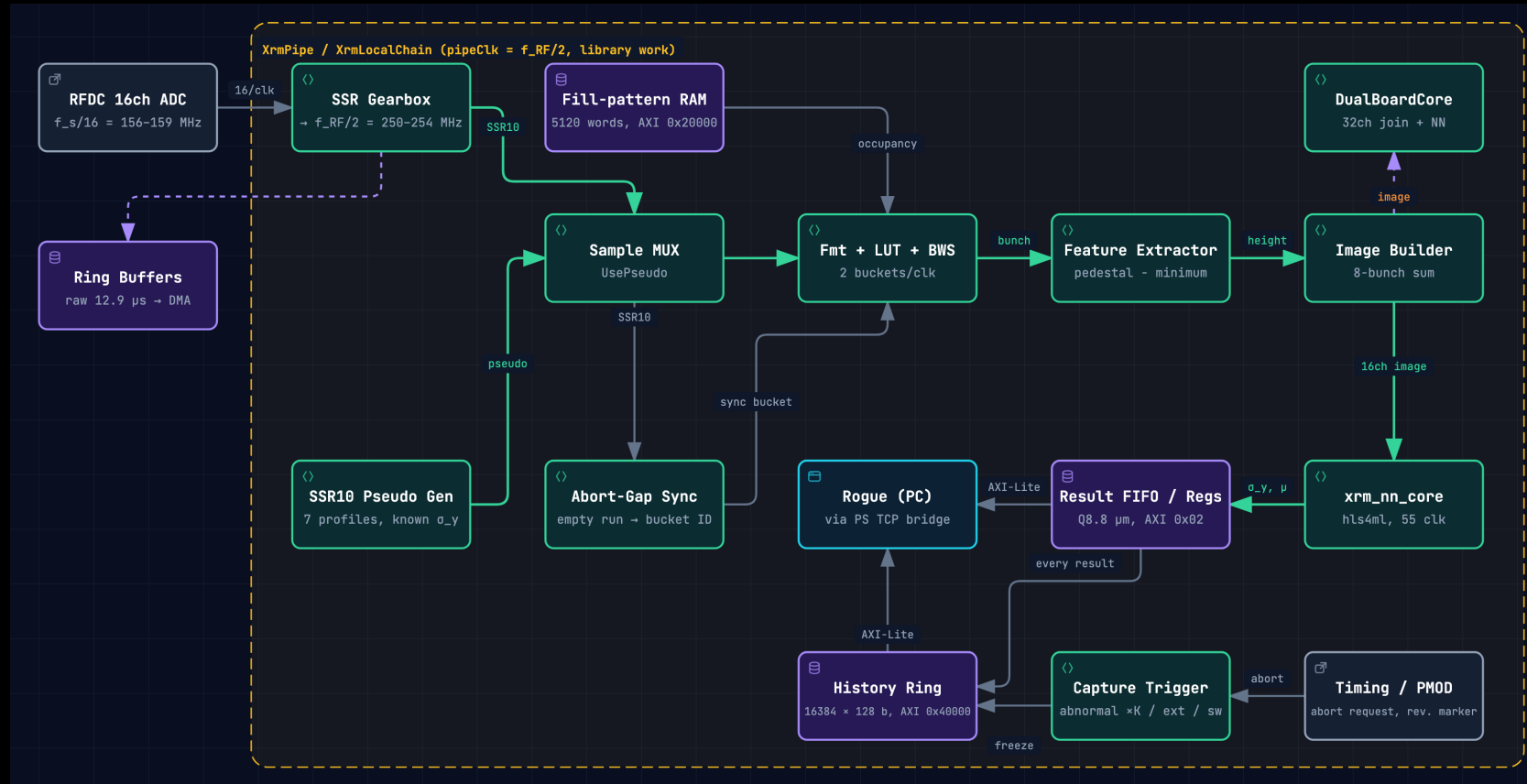
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Firmware — From Samples to a Beam Size



- Whole chain on one clock, $f_{\text{RF}}/2 \approx 254$ MHz; one image per 8 bunches → 256 σ_y per HER turn.
- Bucket phase recovered from the two abort gaps — no revolution-marker cabling needed.
- Verified in simulation (GHDL + Icarus) with pseudo data; first Vivado build in progress.

Firmware Block Diagram



Clocking and Sample Format

	Value
RF frequency	508.887 MHz, 5120 buckets per turn
Sampling	$f_s = 5 f_{RF} = 2544.4 \text{ MSa/s}$, via CLK104 (LMK04828)
RFDC side	16 channels, 16 samples per clock ($f_s/16$)
XRM chain	10 samples per clock = 2 buckets, $f_s/10 = f_{RF}/2$
Images	8 consecutive bunches summed per channel
NN core	one image per clock, 55-clock latency