Beam Instrumentation Challenges for High-Energy and Low-Emittance Beam at SuperKEKB

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on behalf of the SuperKEKB beam monitor group

12th INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE

SASKATOON, CANADA

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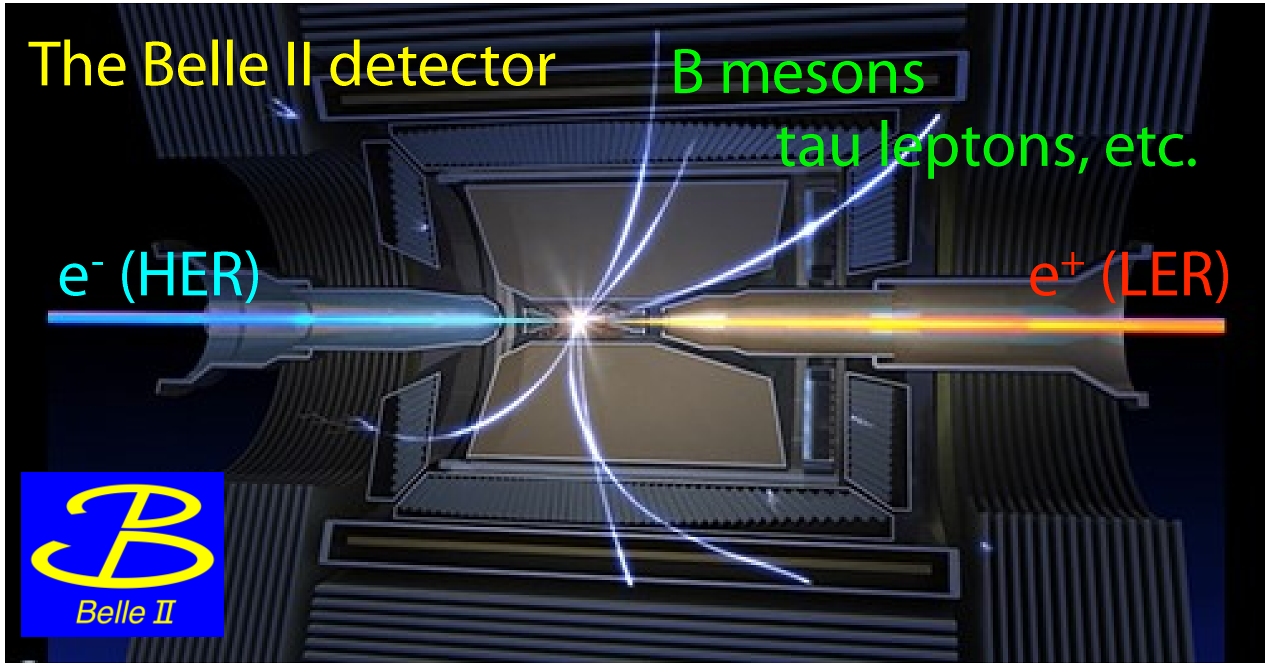
IBIC2023

Canadian Light Source | Centre canadien de rayonnement synchrotron

The Belle II experiment

The Belle II experiment is motivated to perform precise measurements for electroweak physics and search for beyond standard model.



Number of physics events

$$N = \sigma\,[\mathrm{cm}^2] \int L\,[\mathrm{cm}^{-2}\mathrm{s}^{-1}]\,dt\,[s]$$

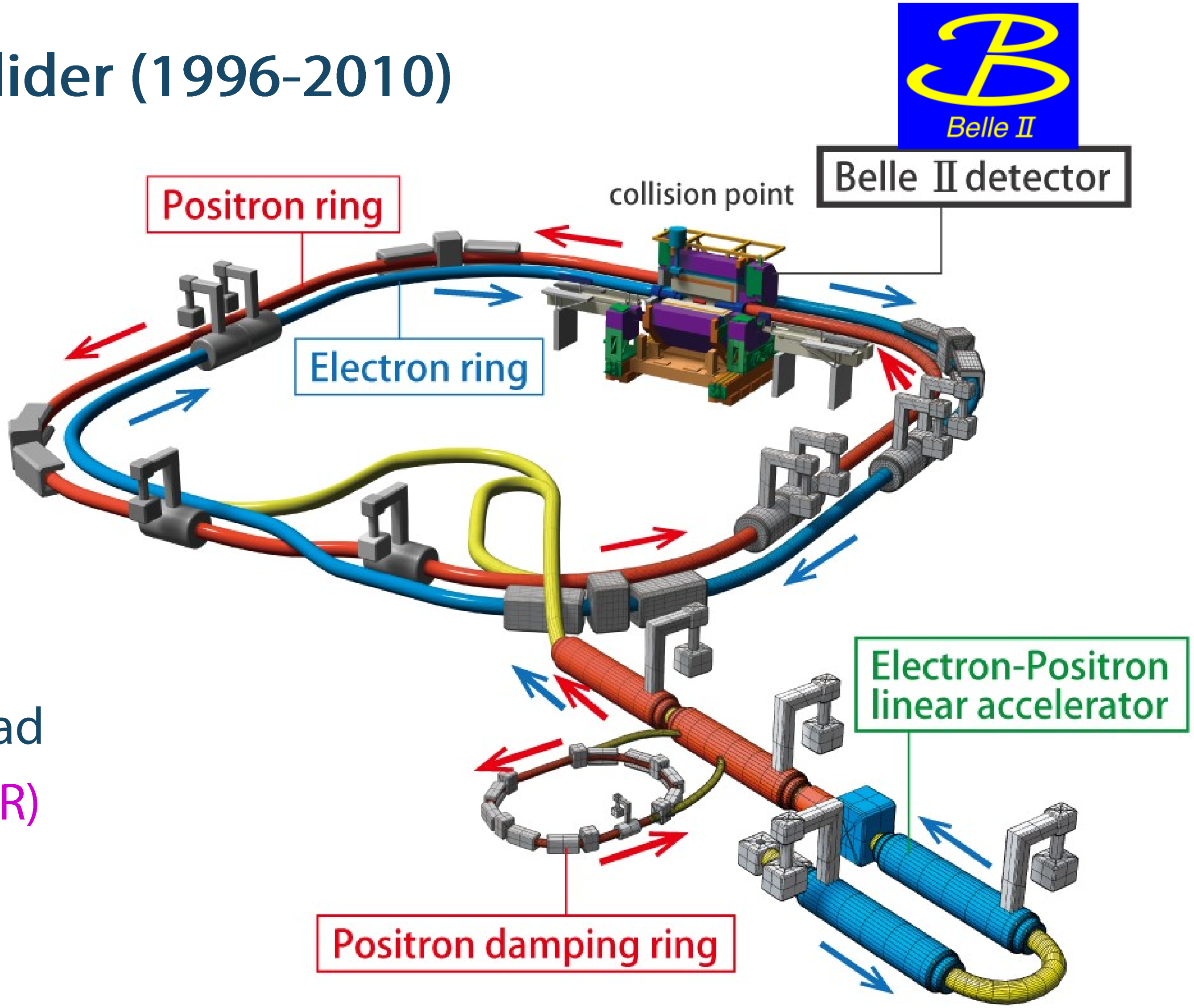
$$L \propto \frac{I_{\mathrm{HER}} I_{\mathrm{LER}}}{\sigma_x \sigma_y}$$

- High beam current
- Extremely small beam size "nano-beam collision scheme"

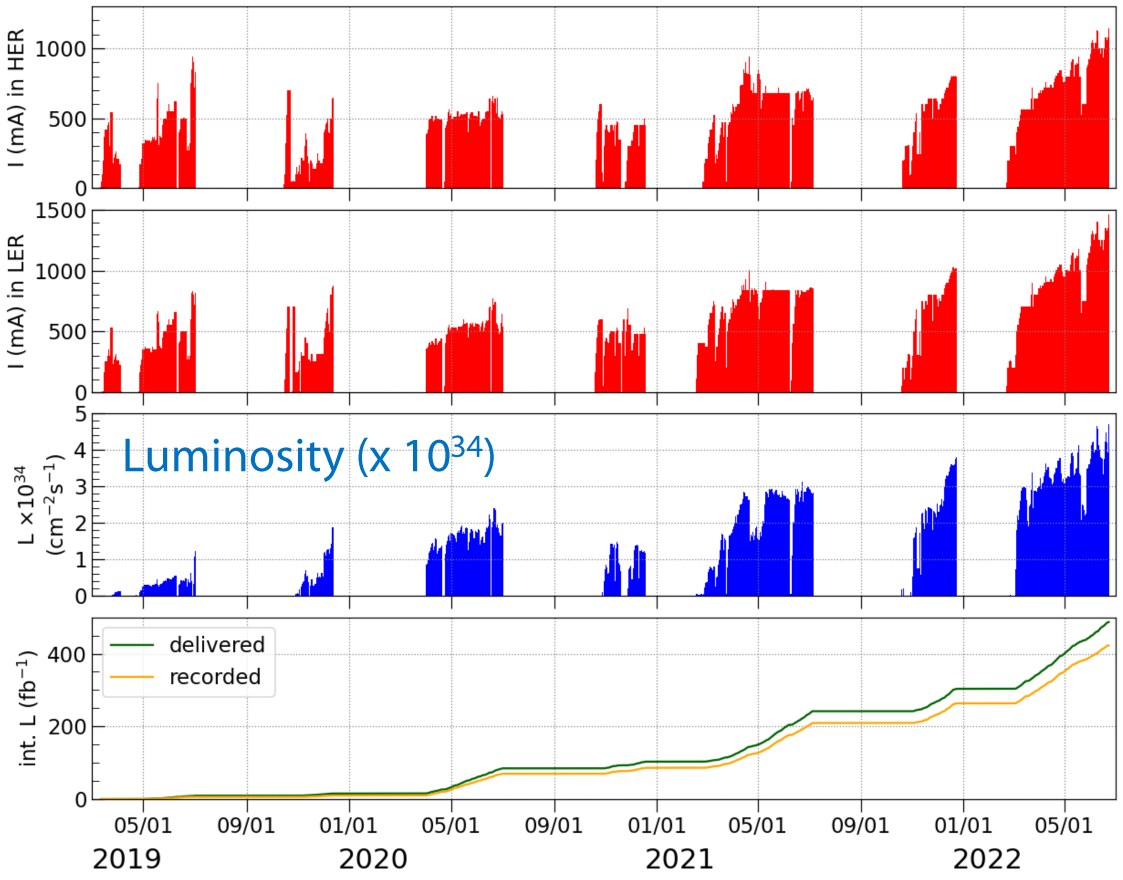
The SuperKEKB e+e- collider (KEK, 2016-)

The SuperKEKB e+e- collider

- **Major upgrade to the KEKB e^+e^- collider (1996-2010)**
- **Main rings**
  - 7 GeV e^- storage ring (HER)
  - 4 GeV e^+ storage ring (LER)
- **Injector complex**
  - Electron/positron linac
  - 1.1 GeV positron damping ring (DR)
- **Design parameters**
  - Horizontal crossing angle: 41.5+41.5 mrad
  - Beam Currents: 3.6 A (LER) and 2.6 A (HER)
  - $\beta_y^* \sim 0.3$ mm
  - $\sigma_x^* \sim 10\ \mu m$, $\sigma_y^* \sim 50$ nm, $\sigma_z \sim 6$ mm

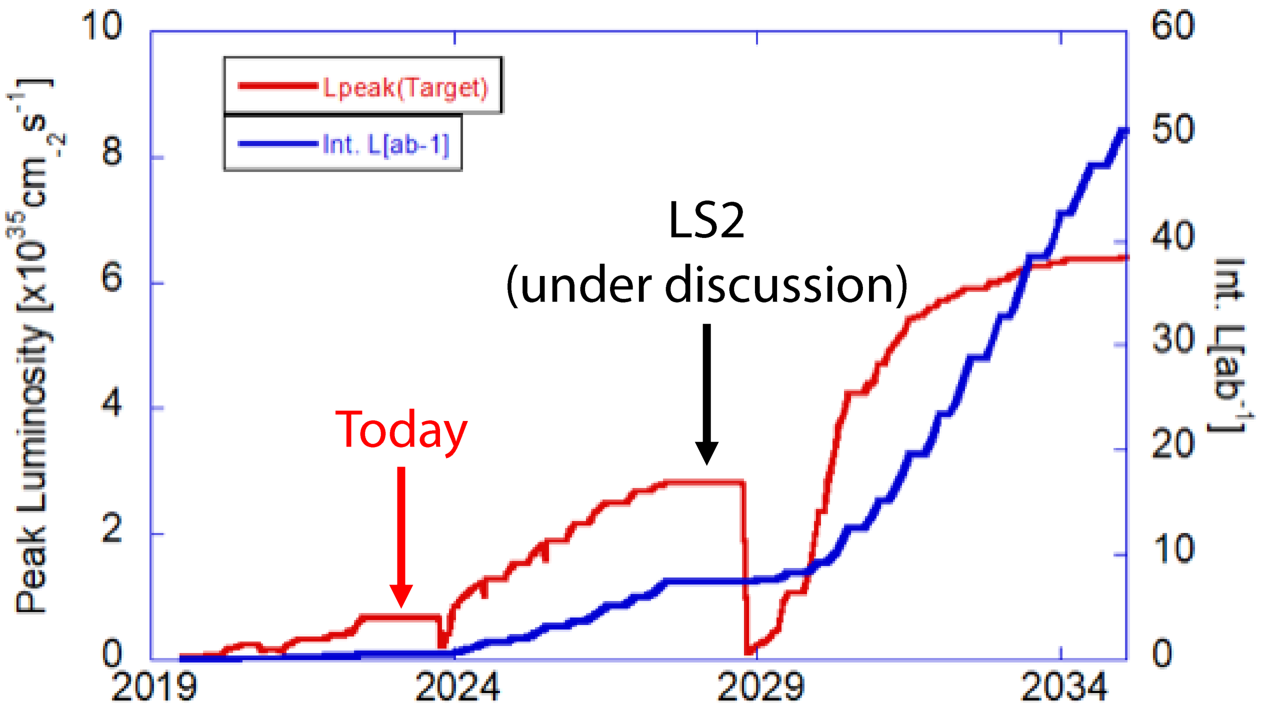


Luminosity achievement and future prospect



The world's highest luminosity in June 2022:
$L = 4.65 \times 10^{34}\ cm^{-2}s^{-1}$ ($I_{e+} = 1.46$ A, $I_{e-} = 1.14$ A)

- Long shutdown 1 "LS1" (July 2022 – December 2023) Upgrade/maintenance of SuperKEKB and Belle II
- Aiming at $2.4 \times 10^{35}\ cm^{-2}s^{-1}$ by summer 2026
- $6 \times 10^{35}\ cm^{-2}s^{-1}$ in early 2030s



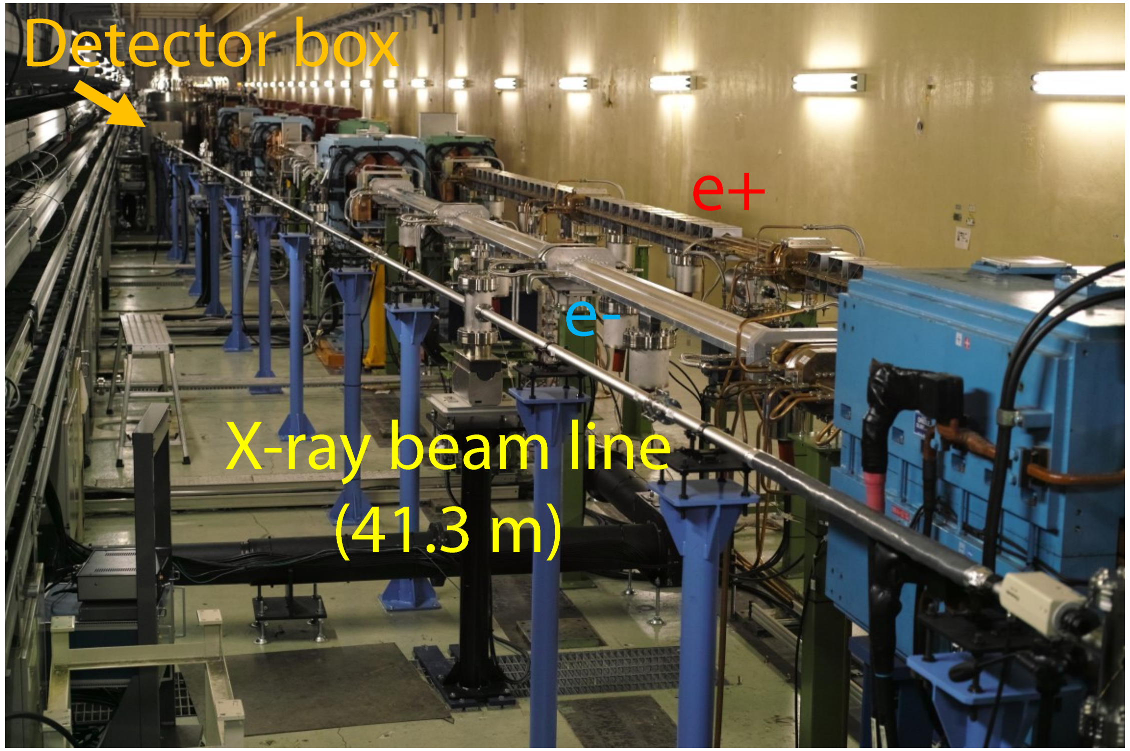
Beam instrumentations at SuperKEKB

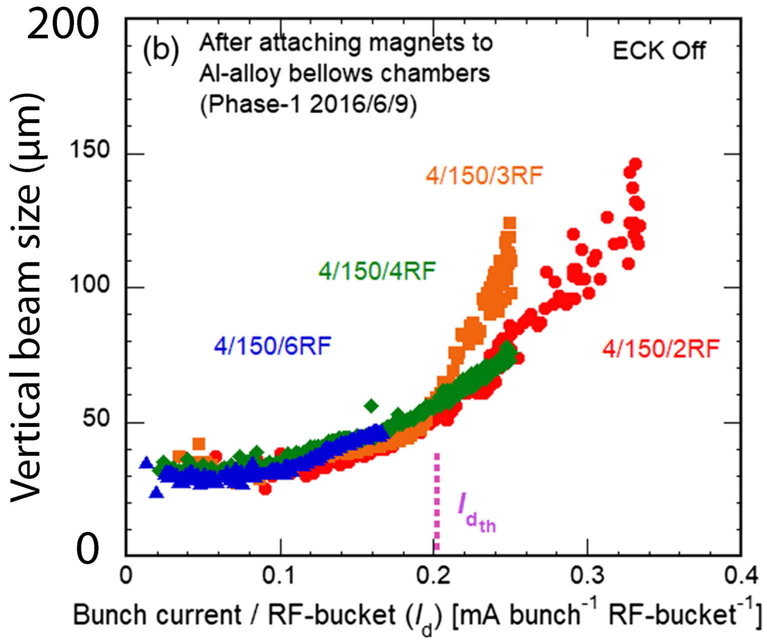
		HER	LER	DR
Beam profile monitors	X-ray beam size monitor	1	1	0
	Visible light beam profile monitor	1	1	1
	Coronagraph beam halo monitor (IPAC2022-TUOXGD1)	1	1	0
Beam position monitors	Narrowband beam position monitors	466	444	83
	Gated turn-by-turn beam position monitor	70	70	0
Feedback systems	Beam-orbit feedback at the interaction point	1	0	0
	Transverse bunch feedback system	2	2	1
	Longitudinal bunch feedback system (IBIC2019-MOPP028)	0	1	0
	Bunch current monitor	1	1	1
	Bunch oscillation monitor (IBIC2023-TUP002)	1	1	0
	Betatron tune monitor	2	2	1
Beam current monitor Beam loss monitor	DCCT/CT	1/1	1/1	1
	Displacement sensors	110	108	0
	Beam loss monitor (IPAC2023-MOPL072)	207		34

Vertical beam size monitors at SuperKEKB

Requirements for vertical beam size monitor

- Minimum vertical beam size (collision): 8 μm
- Maximum vertical beam size (beam tuning/study): 200 μm
- Exposure: shorter than 1 ms



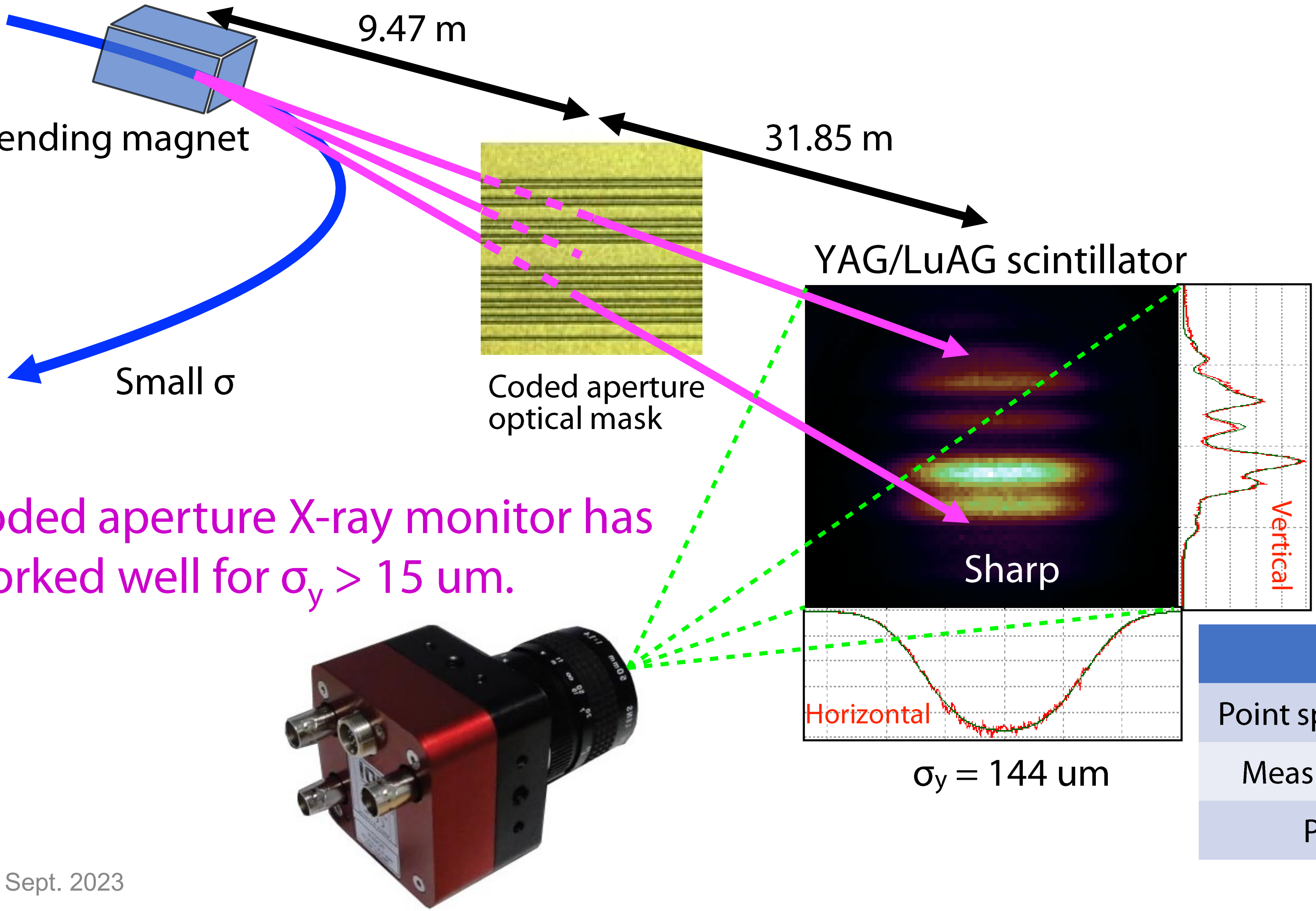


(Y. Suetsugu et. al., PRAB 22, 023201)

X-ray beam size monitor with coded aperture was newly developed for SuperKEKB.

(E. Mulyani et. al., NIM-A 919, 1)

X-ray beam size monitor with coded aperture

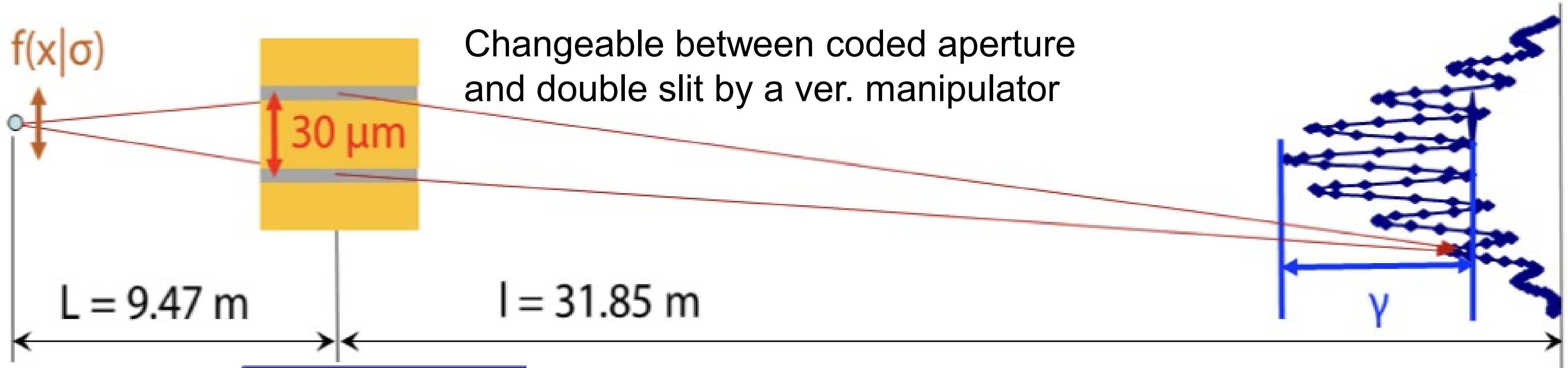


Coded aperture X-ray monitor has worked well for σ_y > 15 um.

	Value (μm)
Point spread function	6.6
Measurable range	15-200
Precision	< 1

X-ray beam size monitor with interferometry

- The SuperKEKB designed beam size at the X-ray line σ_y is 8 μm, smaller than measurable range.
- We renovated the present coded aperture-based system to novel interferometry system.

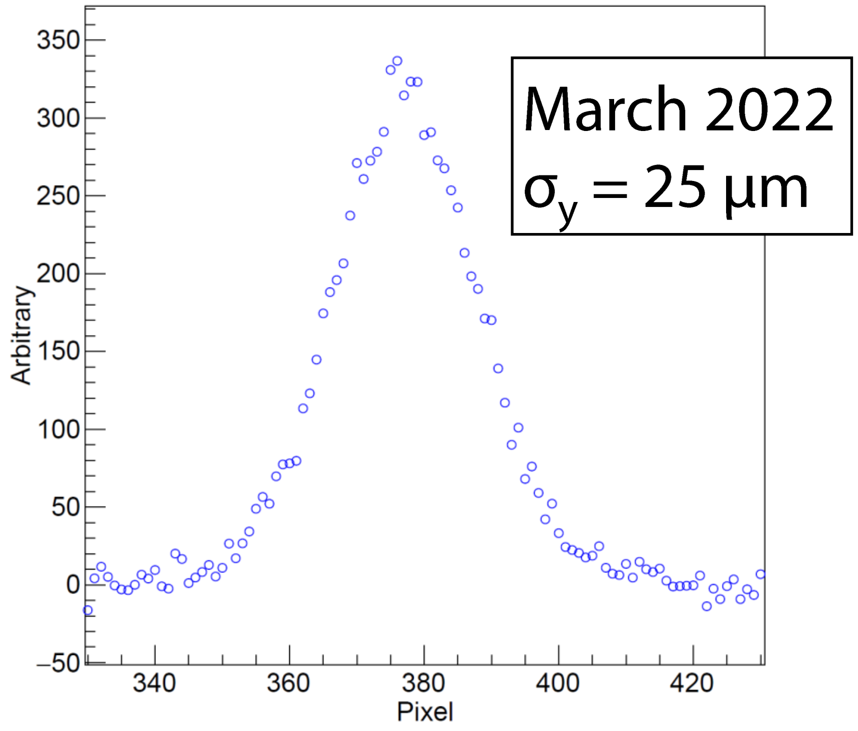


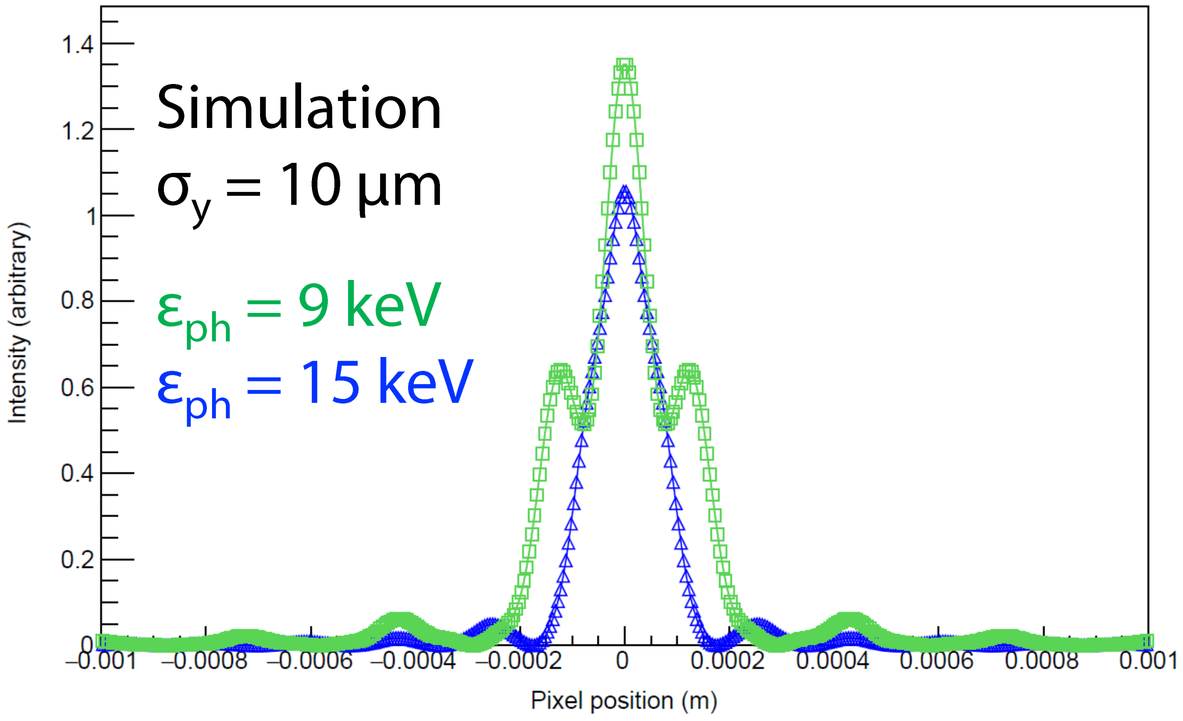
$$\sigma = \frac{\lambda L}{\pi D}\sqrt{\frac{1}{2}\ln\left(\frac{1}{\gamma}\right)}$$

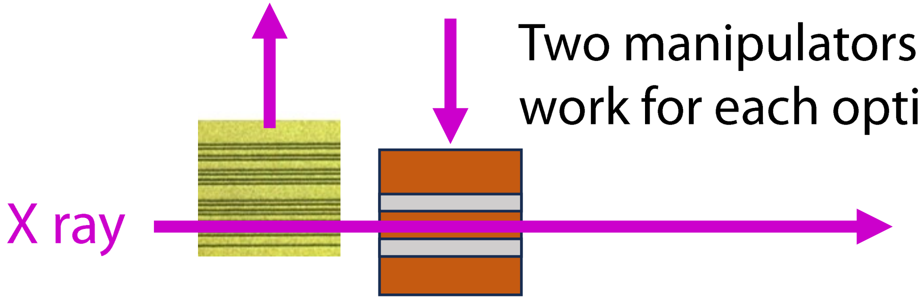
- σ_y is proportional to λ~0.1 nm (X ray) (visible light~600 nm).
- X-ray interferometer is able to measure $\sigma_y < 10$ μm.
- SuperKEKB become a benchmark for future colliders.

	SuperKEKB	FCC-ee/CEPC
Beam size σ_y	< 10 μm	< 10 μm
Slit distance D	30 μm	300 μm
Source to slit L	~10 m	~100 m

X-ray interferometer test data and simulation





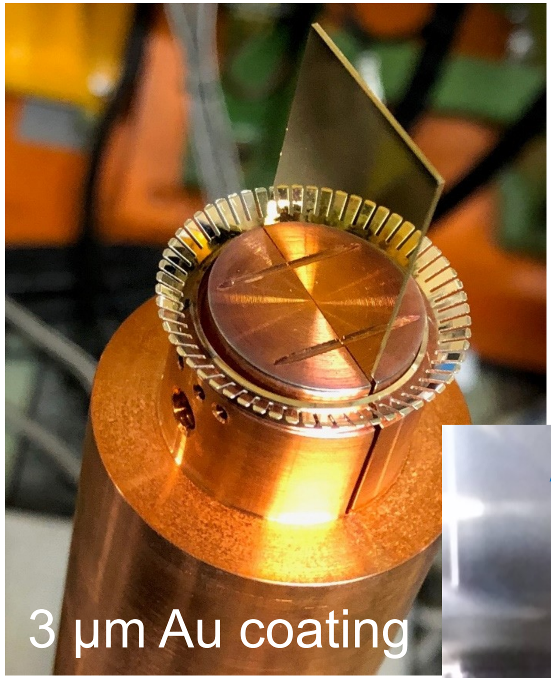


Two manipulators independently work for each optical mask.

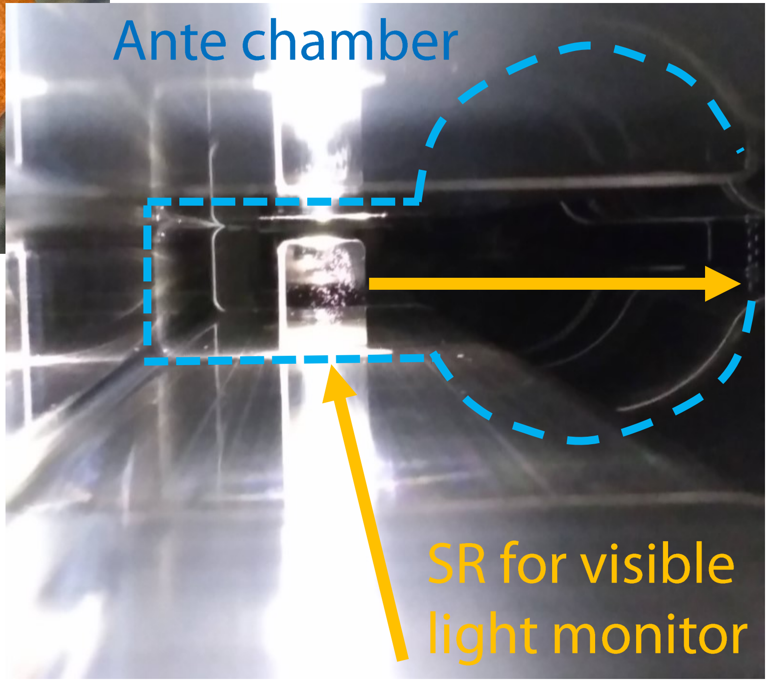
- No clear interference fringe was observed, understandable by $\sigma_y =$ 25 μm observed with the coded aperture before hand.
- 2nd round test with a test optics σ_y~10 μm
- X-ray filter R&D ongoing (Cu, noble gas, etc.)

Synchrotron radiation extraction mirror

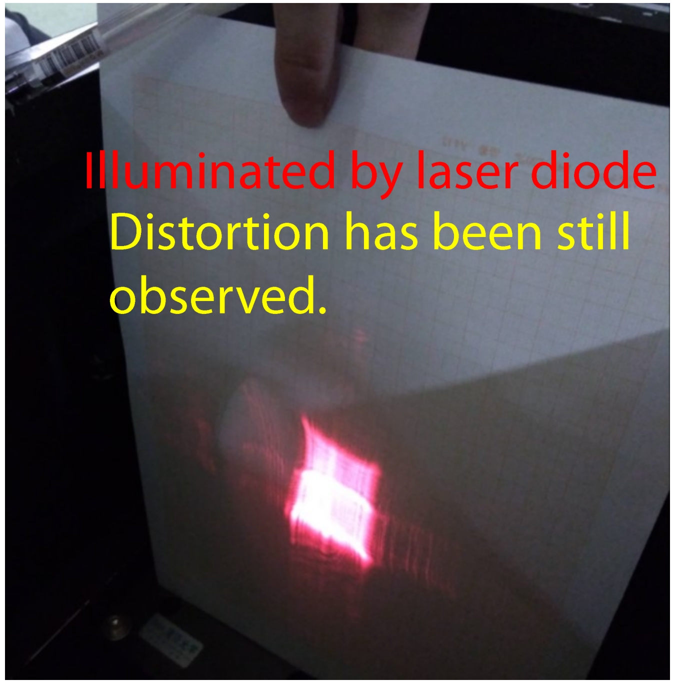
- The synchrotron radiation (SR) extraction mirror suffers from heat distortion due to incident SR, leading to systematic changes in magnification with beam current.
- **Quasi-single-crystalline chemical-vapor deposition (CVD) diamond mirrors**, very high heat conductance and a low thermal expansion coefficient, were developed and installed at SuperKEKB.



(IBIC2019, TUPP017)



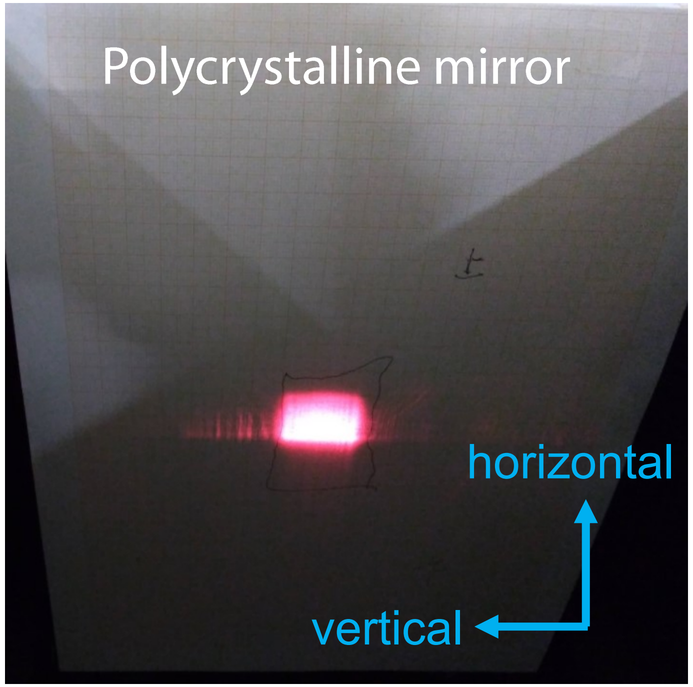
~10 m downstream

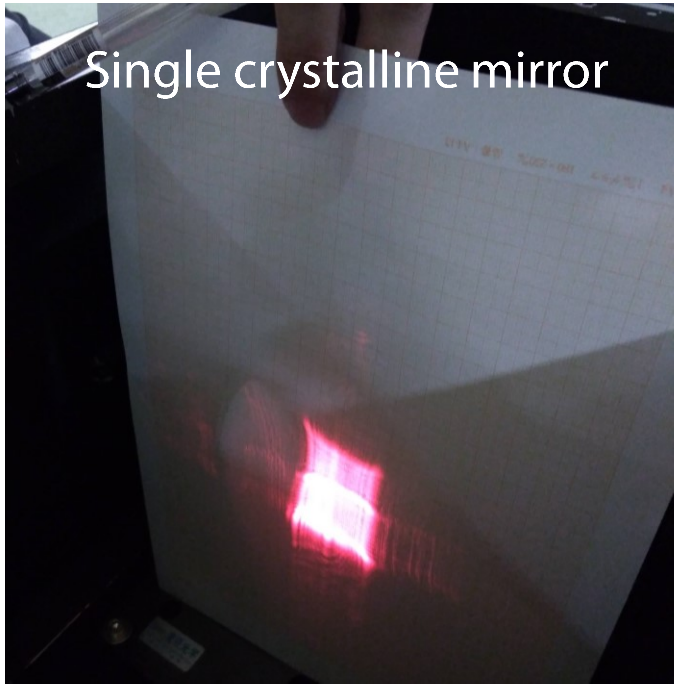


Polycrystalline diamond SR-extraction mirror

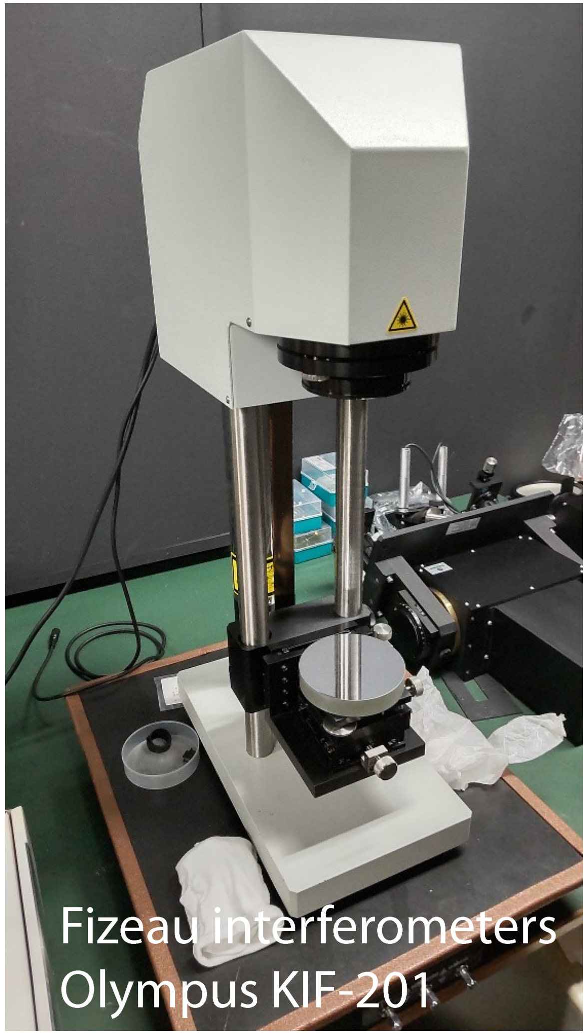
	Polycrystalline	Quasi single crystalline
Area size (mm^2)	**20 x 32 (one substrate)**	10 x 10 (6 pieces fused together)
Thickness (mm)	**1.2**	0.5
Conductance (W/mK)	**1800**	2000

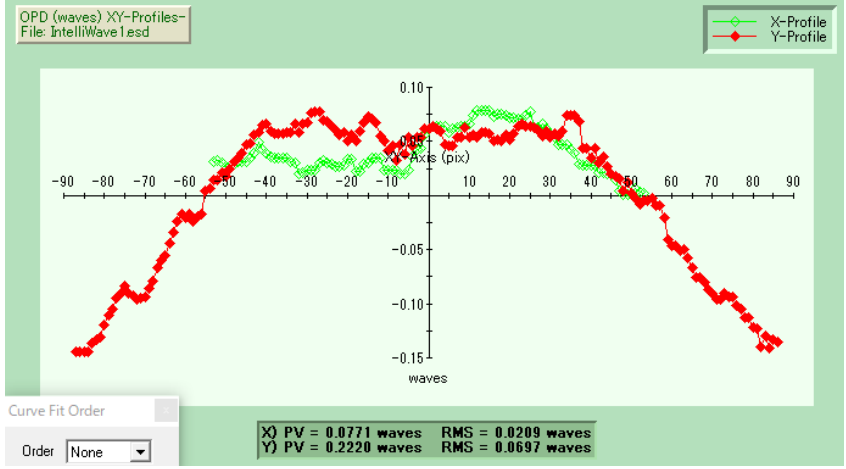
- A single substrate mirror should improve surface flatness.
- A thicker substrate gives a better optical polishing result.
- Platinum has 20 % higher reflective coefficient at < 500 nm than gold.

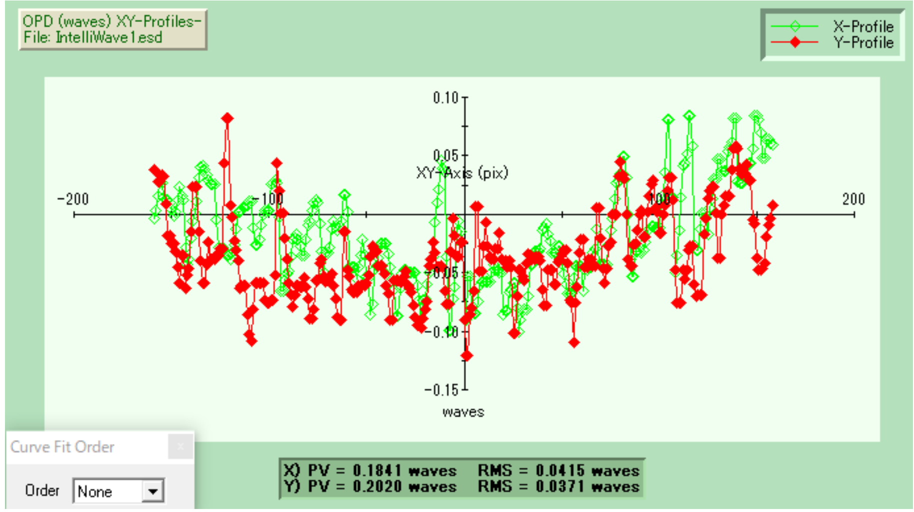


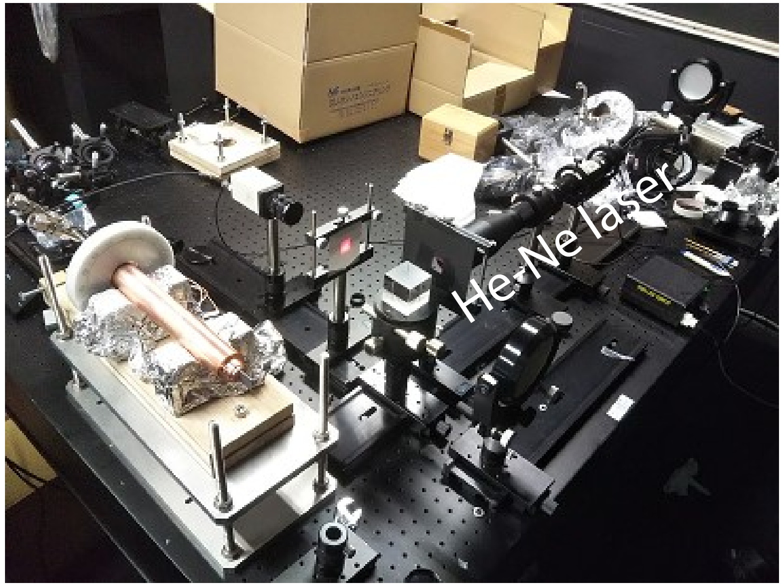


Surface flatness testing before installation





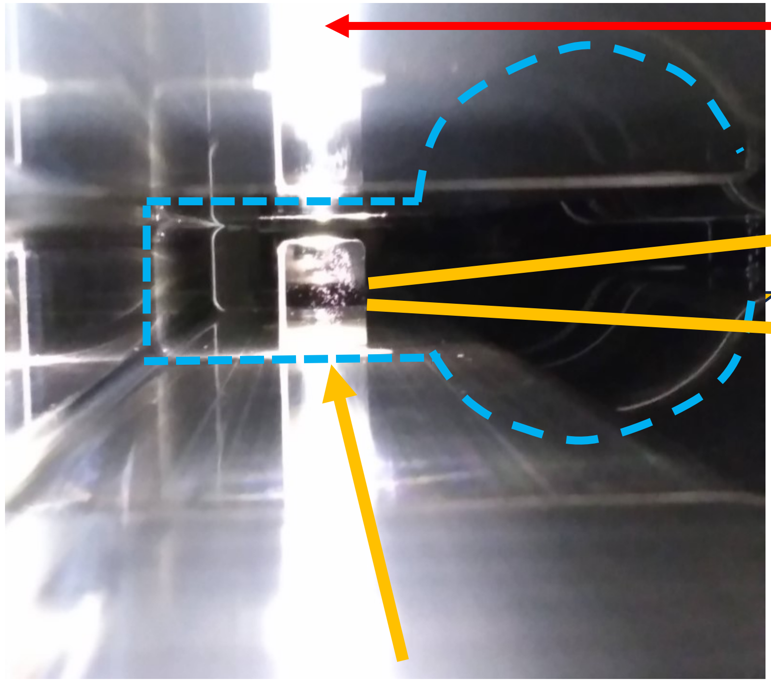


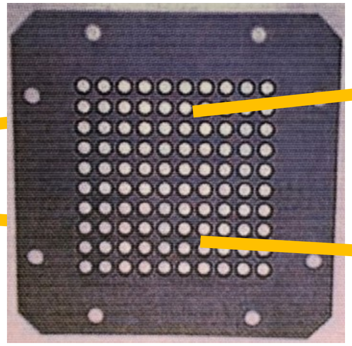


- The flatness of ~ $\lambda/4$ on the almost entire mirror surface
- Better than $\lambda/5$ excluding the outer edge area after gripped by the mirror holder

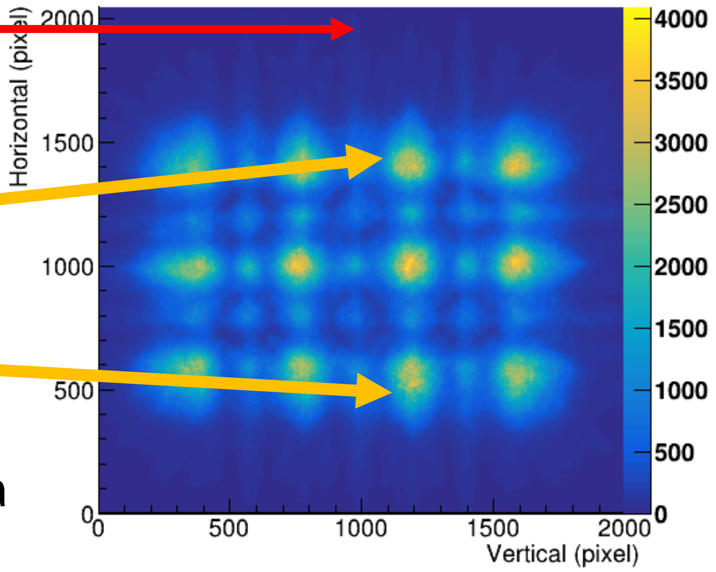
(IPAC2022, MOPOPT031)

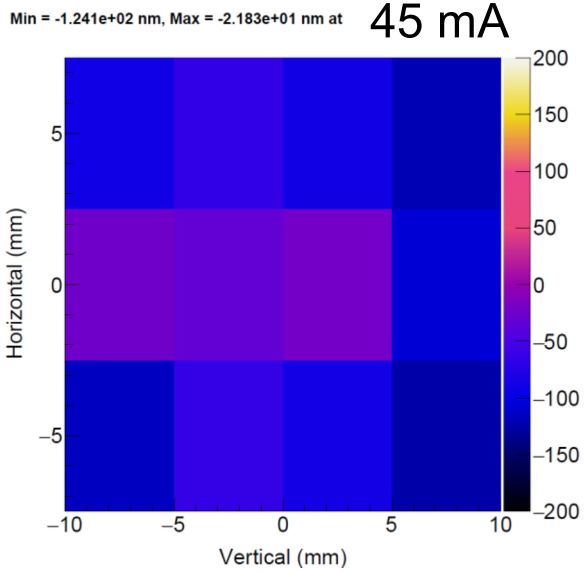
Hartmann test for thermal deformation

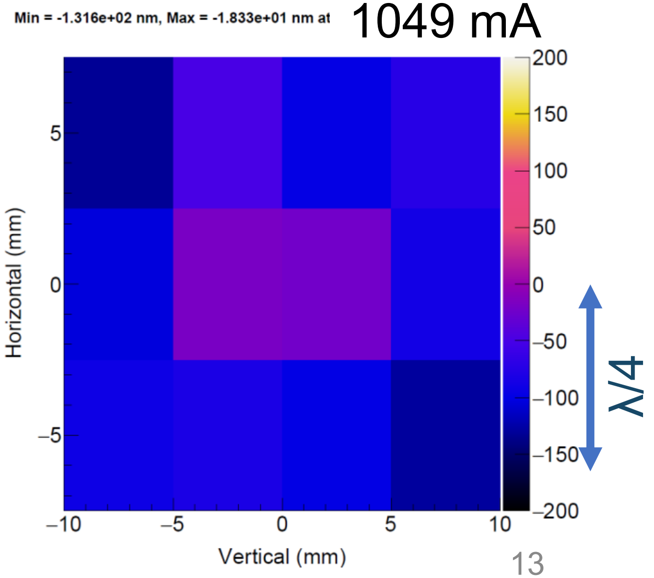




Hartmann test using a square array screen

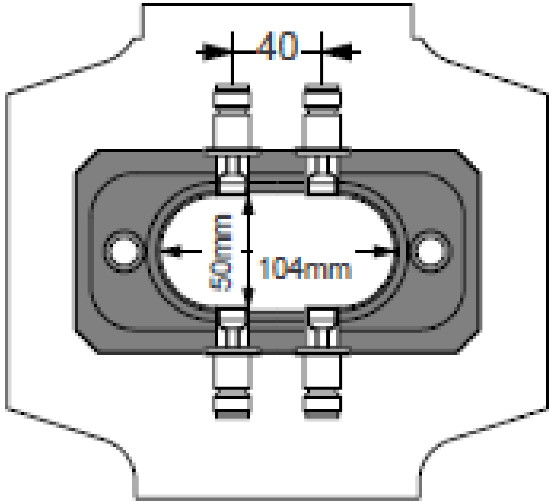


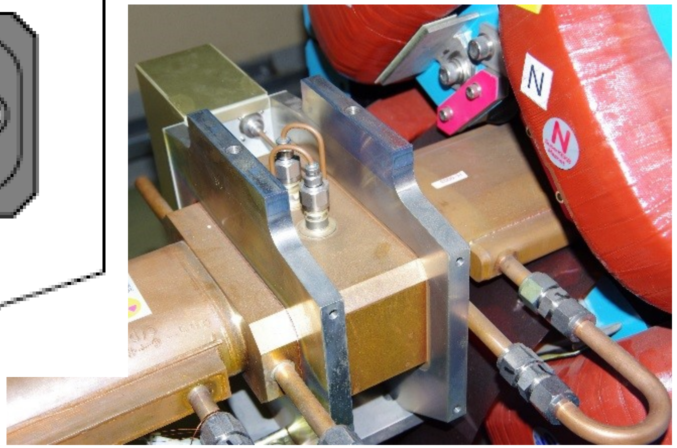


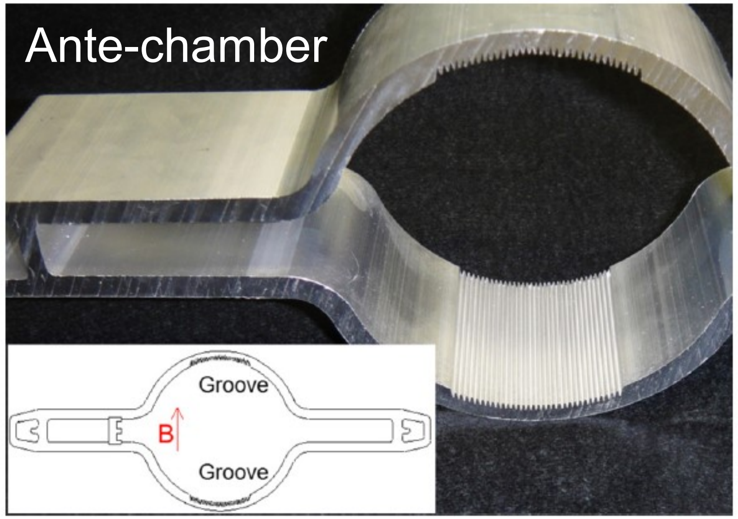


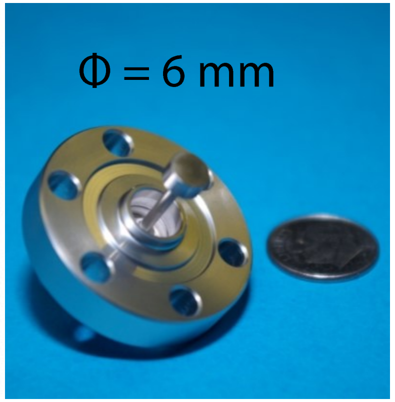
- The Peak to-Valley is < $\lambda/4$ below 1 A.
- No significant thermal deformation was found 1 year after installation
- Novel SR extraction mirror enabled beam halo measurements. (IPAC2022-TUOXGD1)

Beam position monitors



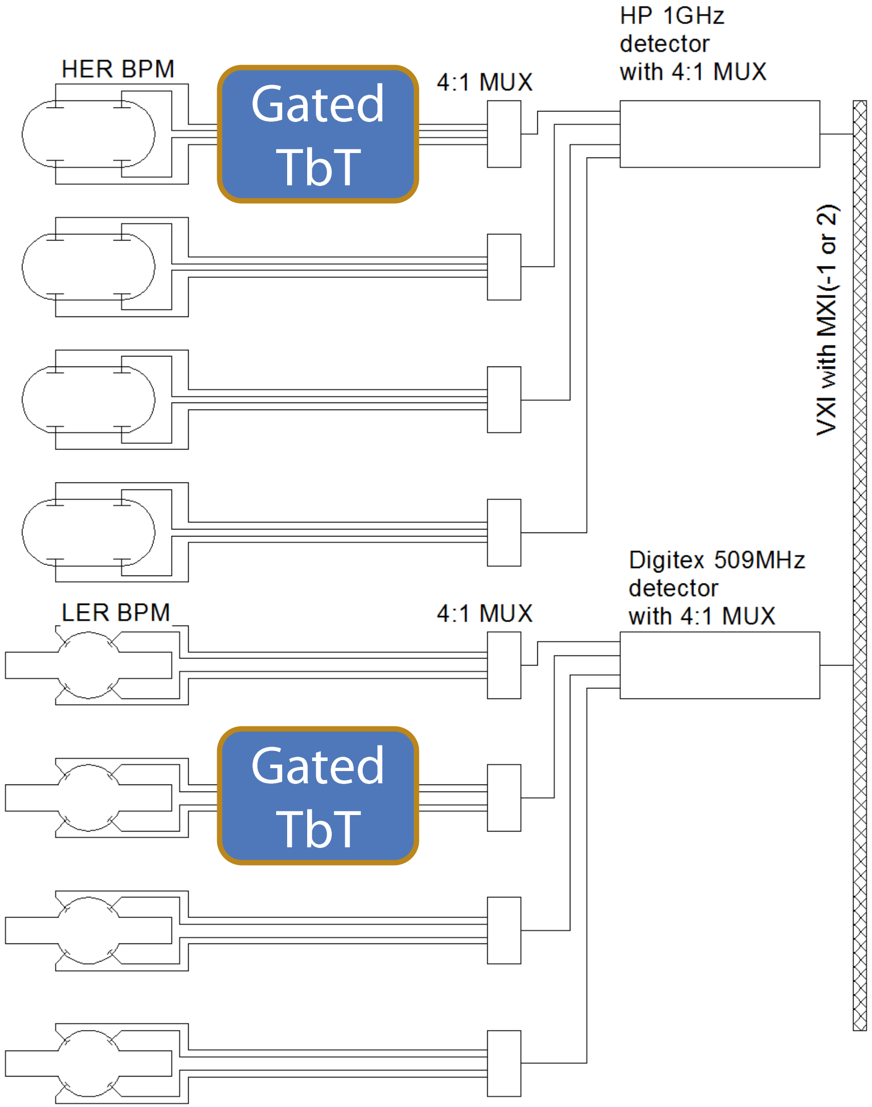




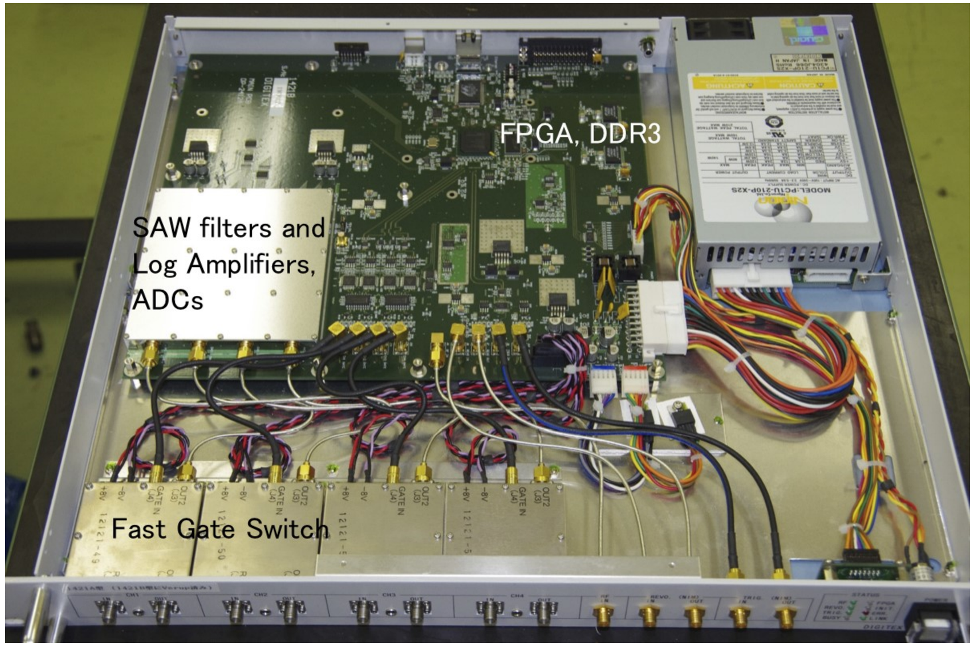


- 97% of the KEKB HER arc-sector beam pipes are re-used in SuperKEKB HER.
- BPM system in KEKB, including the 1 GHz narrowband detectors, is re-used in SuperKEKB HER to reduce cost.
- Since the LER BPM chambers were replaced with new ante-chambers (to prevent electron clouds), new BPM blocks and button electrodes were designed and fabricated.
- We newly developed the 509 MHz narrowband detectors to meet the ante-chambers cut-off frequency bellow 1 GHz.

BPM detector circuits

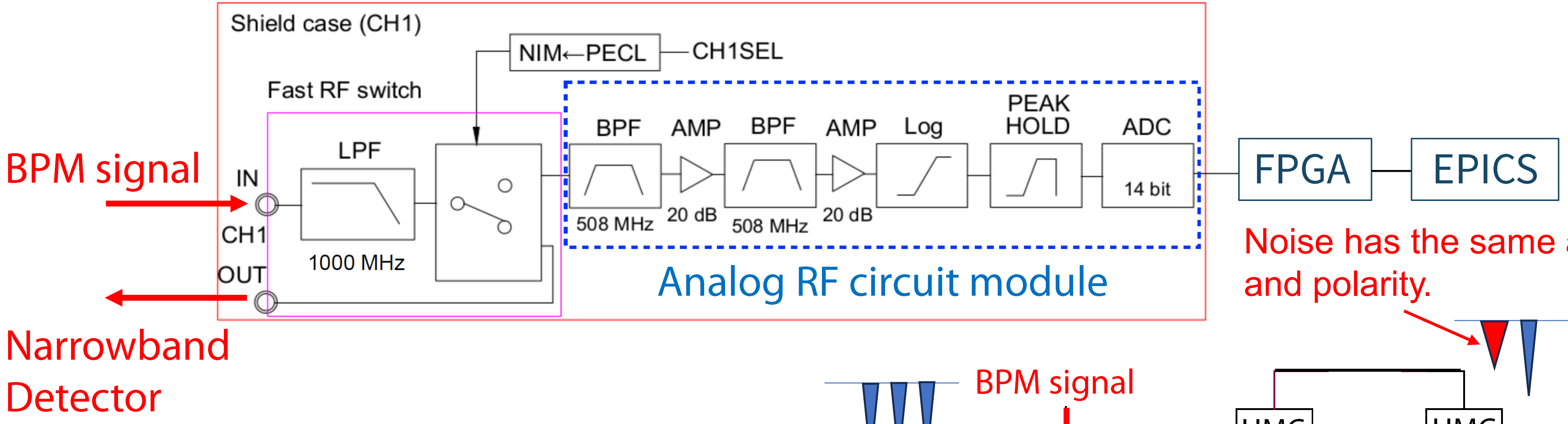


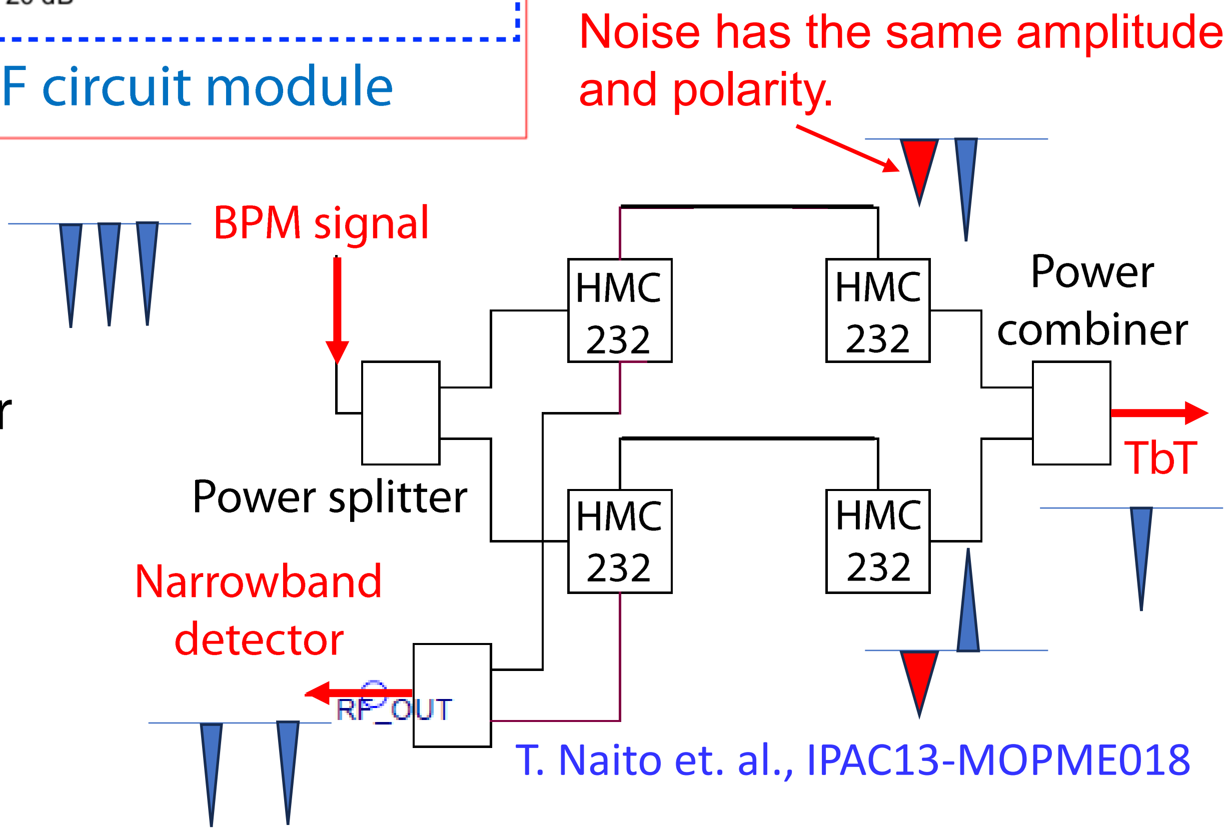
- 1 GHz (reuse of KEKB) detectors in HER (466)
- 509 MHz new detectors in LER (444)
- Gated turn-by-turn detectors (70 for each ring)
  - Measurements for betatron X-Y coupling
  - Measurements for beam optics in beam collisions



- RFSoC-based BPM detector (R&D using ZCU111)

Gated turn-by-turn BPM detector



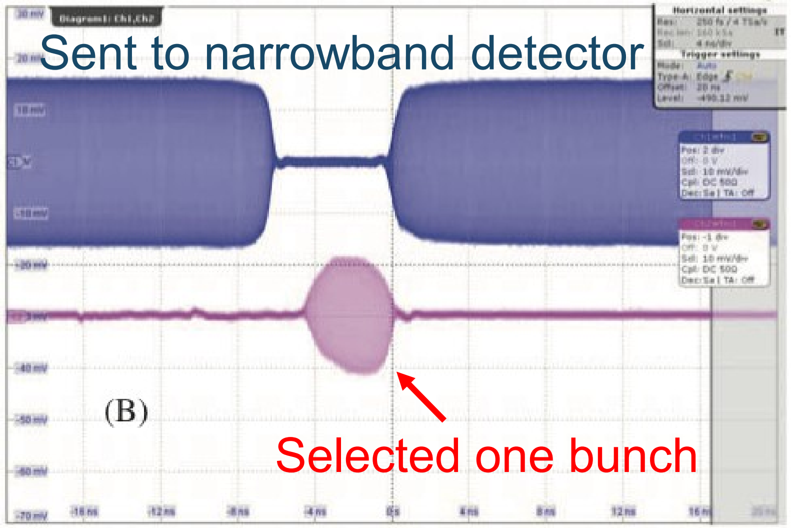


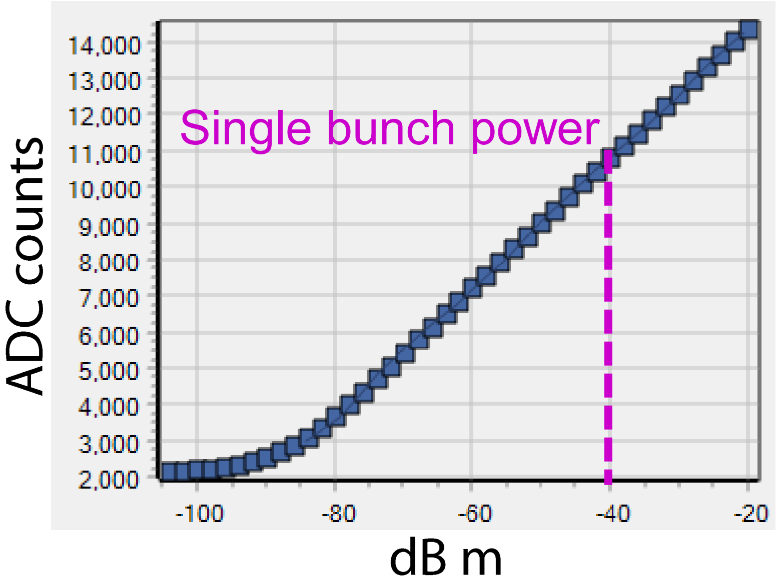
T. Naito et. al., IPAC13-MOPME018

Requirements for the fast gating switch

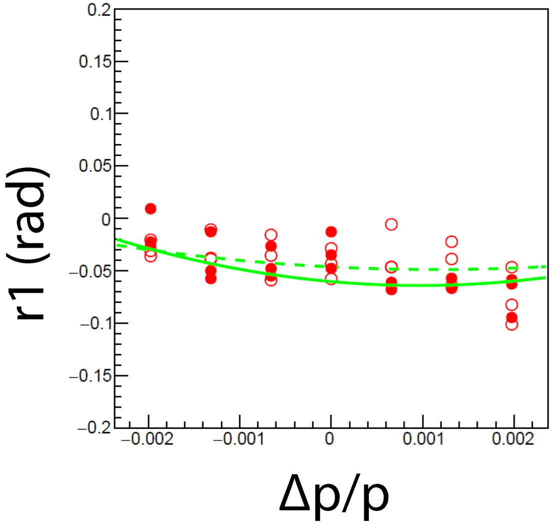
- Good isolation from the storage beam power (70 dB larger)
- Short rise/fall gating time for the minimum bunch separation of 4 ns.
- Gate switching noise to be harmless to the narrowband detector.

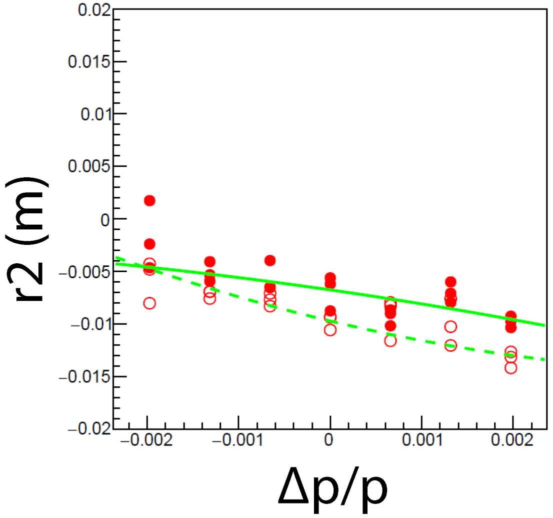
Performance of the gated turn-by-turn detector





30 June 2021 in LER





- Isolation: 80 dB
- Insertion loss: 4 dB
- Switching noise: 2 mVpp
- Rise/fall time: 0.6 ns

- Linearity [-80 dBm, -20 dBm]

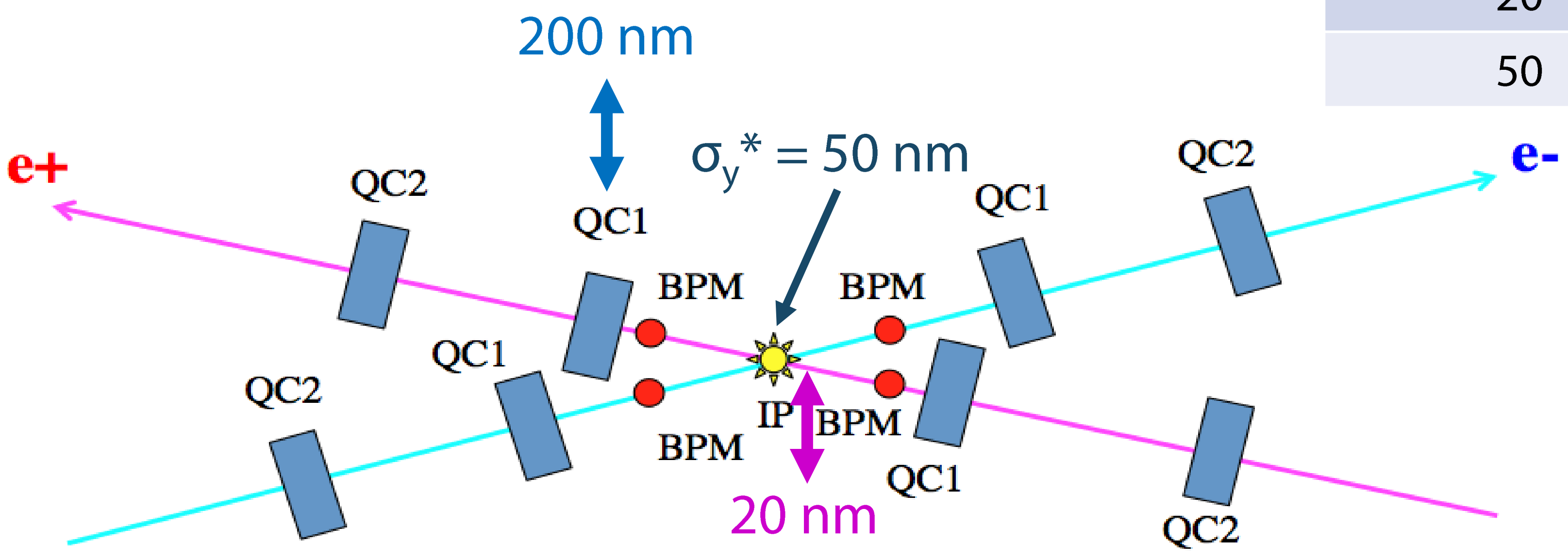
$$\sigma_y^{*2} = \varepsilon_y \beta_y^* + \varepsilon_x \beta_x^* \left(\frac{r_2^2}{\beta_x^{*2}} + r_1^2 \right) + (\eta_y \sigma_\delta)^2$$

- Gated turn-by-turn BPMs give essential contribution to σ_y* minimization through the chromatic X-Y coupling optimization.

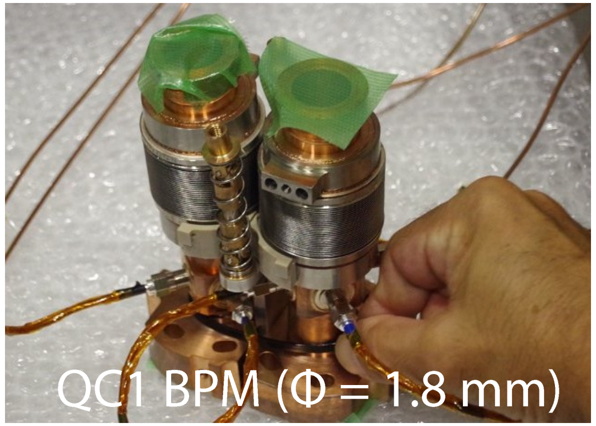
Beam-orbit feedback at the interaction point

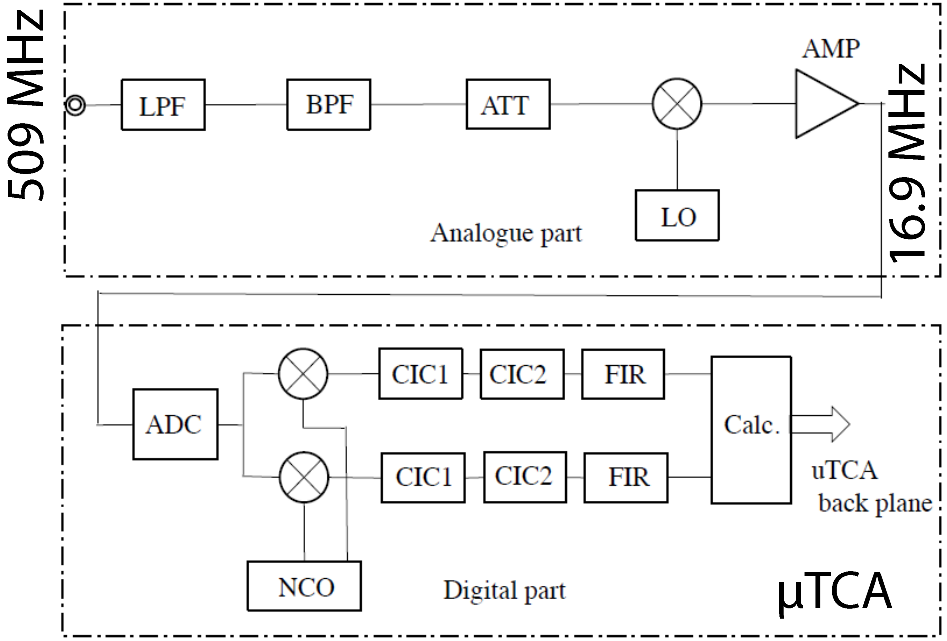
- **Beam-orbit feedback system** is necessary to compensate for the oscillation of the interval between two beam orbits at the interaction point.
- Considering the QC1 quadrupoles vibrating ~200 nm (at ~O(10 Hz)), beam orbit interval at the interaction point would be 20 nm.
- The interval ~20 nm corresponds to 40% of the designed $\sigma_y^* = 50$ nm.

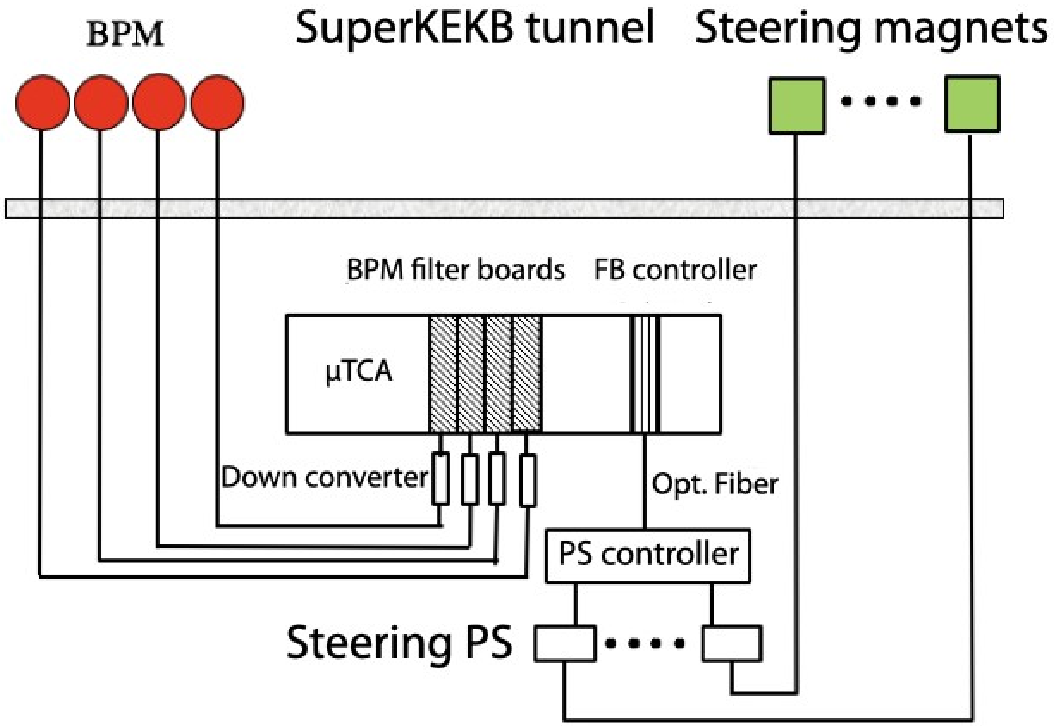
Vibration/σ_y^* (%)	Lum. degradation (%)
20	2
50	10

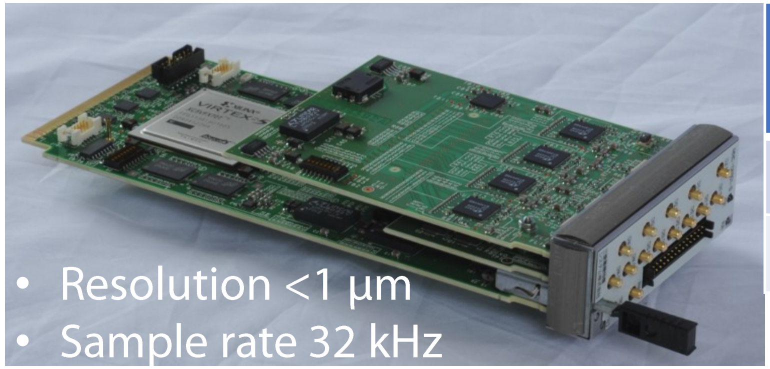


Feedback detectors and controllers



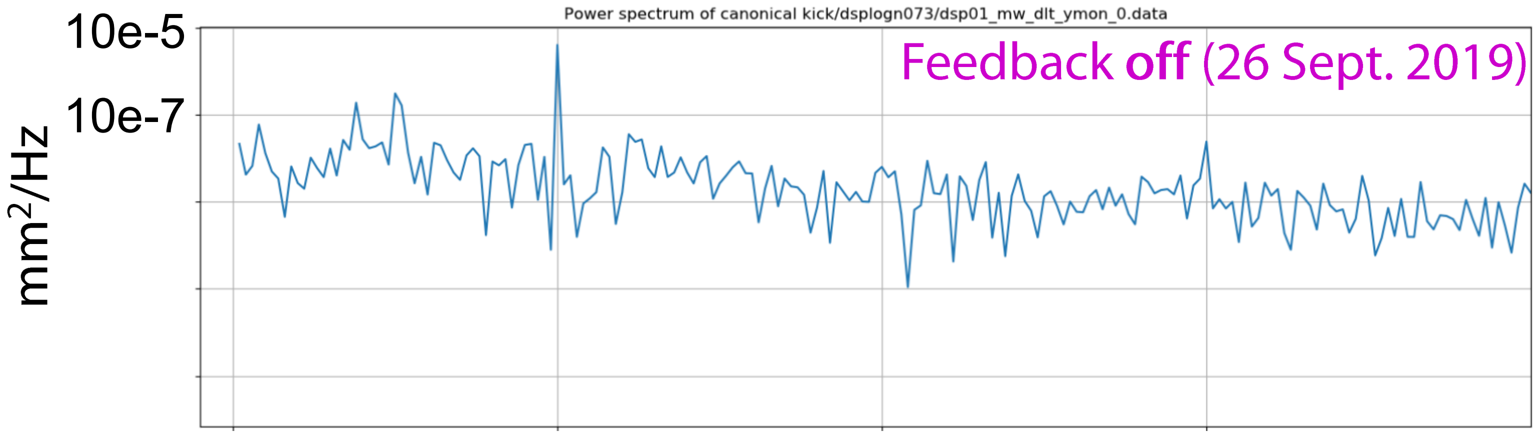


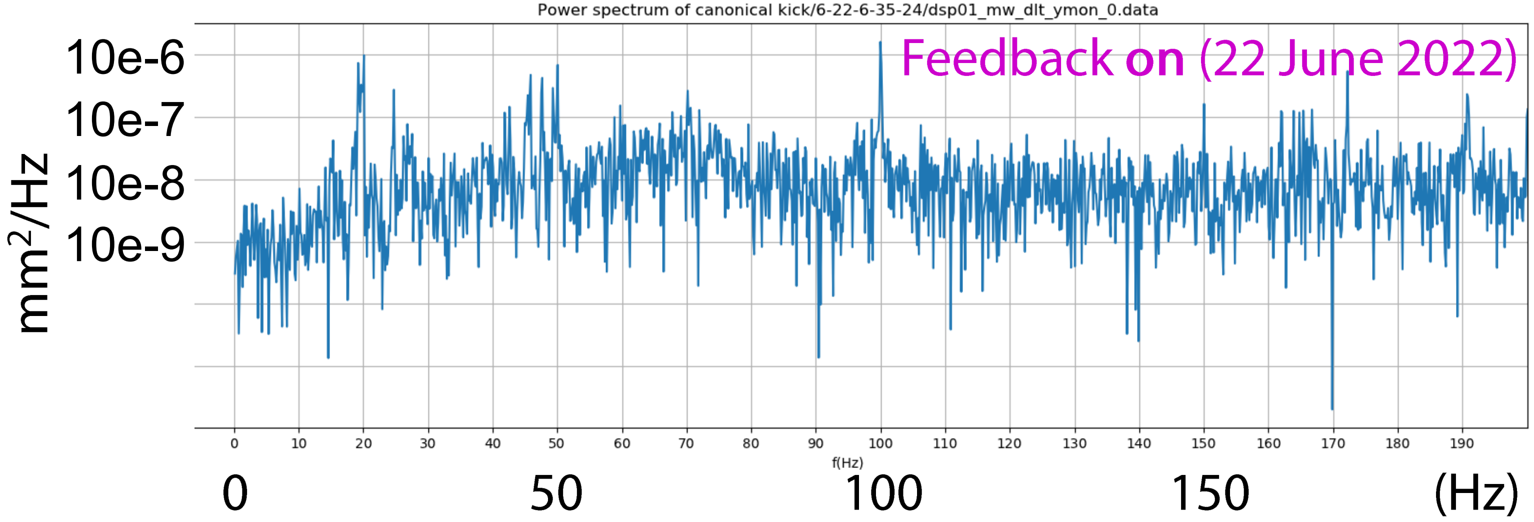




Interval at IP (nm)	Vibration at BPM (µm)
50 (= σ_y^*)	50
5 (= $\sigma_y^*/10$)	5

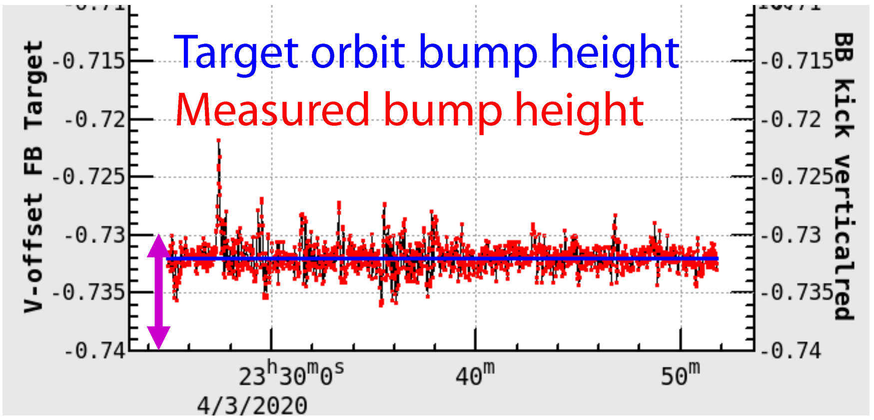
Feedback performance



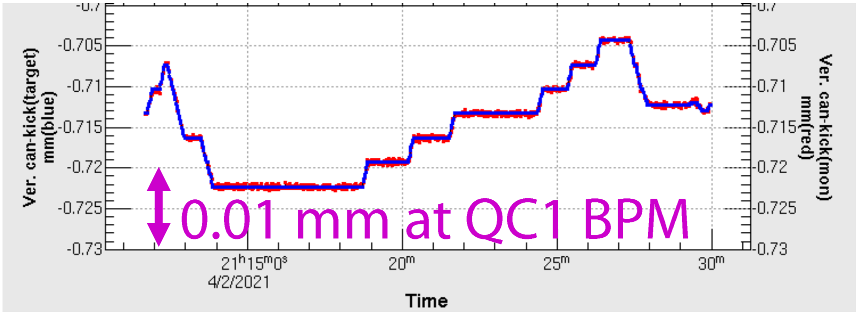


Feedback ON reduces the amplitude from 0 to 50 Hz by ~20 dB.

KEKB-era feedback



Excellent traceability!



Summary and prospects

- X-ray beam size monitor:
  Renovation is ongoing though, the X-ray interferometer is promising to measure $\sigma_y < 10\ \mu m$.
- Synchrotron radiation extraction mirror:
  Excellent performance confirmed below 1 A, keep paying attention to what happens above 1 A
- Gated turn-by-turn BPM detector:
  Utility and online analysis software R&D is ongoing toward a "handy tool"
- Beam-orbit feedback system at the interaction point:
  Testing the FIR with a smaller tap number to get a greater reduction gain
- Sudden beam loss (not presented today):
  Yet another challenge for integrated luminosity, stop by TUP002.