Future Directions for X-ray beam size monitors at the SuperKEKB e^+e^- collider

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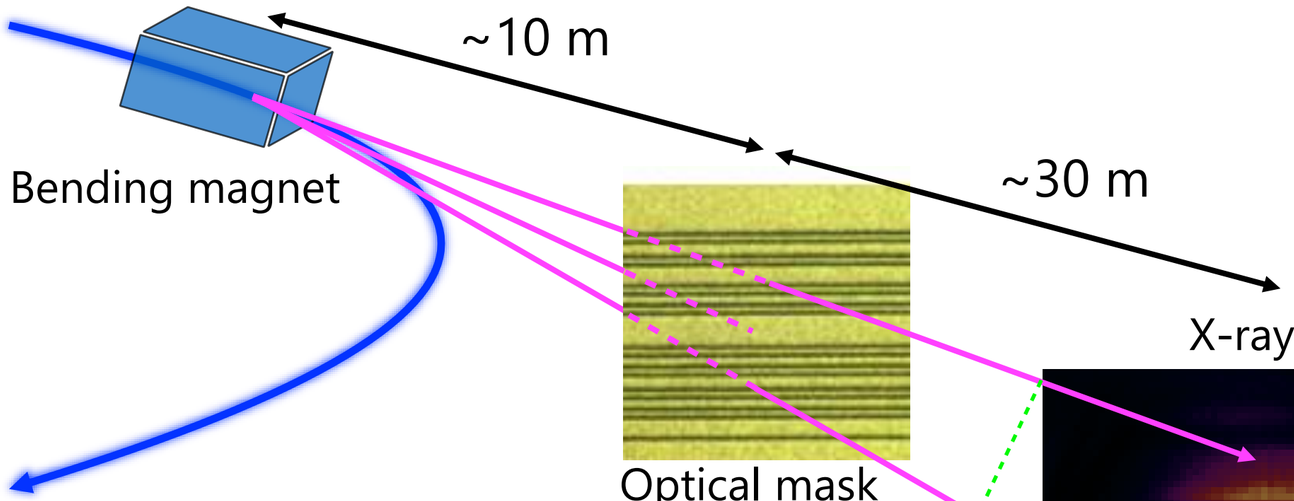
Beam size measurements at SuperKEKB

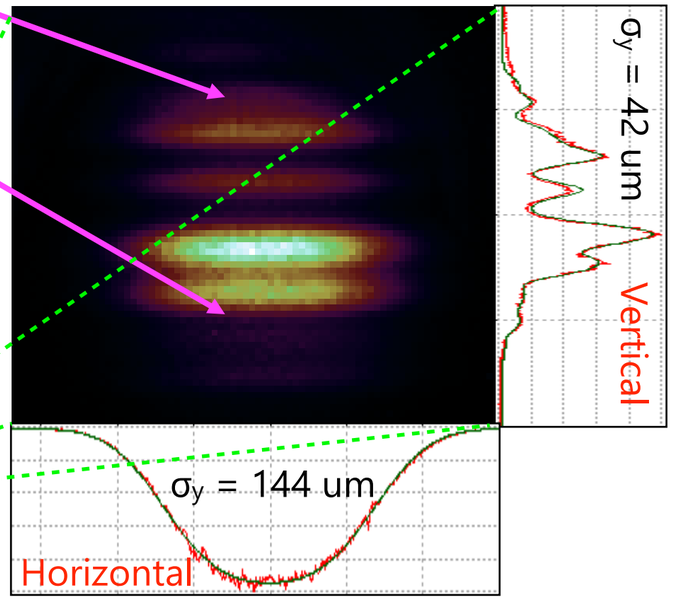
Wavelength	X ray (~0.1 nm) Since SuperKEKB	Visible light (~500 nm) Since KEKB era		
Monitor	X-ray monitor	Interferometer	Gated camera	Streak camera
Sensitivity	X, Y	X, Y	X, Y	Z
σ_{min}	X : ~ 130 μm **Y : ~ 10 μm**	X : ~ 200 μm Y : ~ 40 μm	X/Y : ~100 μm	Z : ~0.5 mm
Precision	X : ~ 5 μm **Y : < 1 μm**	X : ~ 3 μm Y : < 1 μm	X/Y : ~100 μm	Z : ~0.5 mm
Meas. rate Analysis rate	~ 300 Hz < 100 Hz	~ 10 Hz ~ 0.5 Hz	~1 Hz Offline	Manual Offline

Same idea as a X-ray pin-hole camera

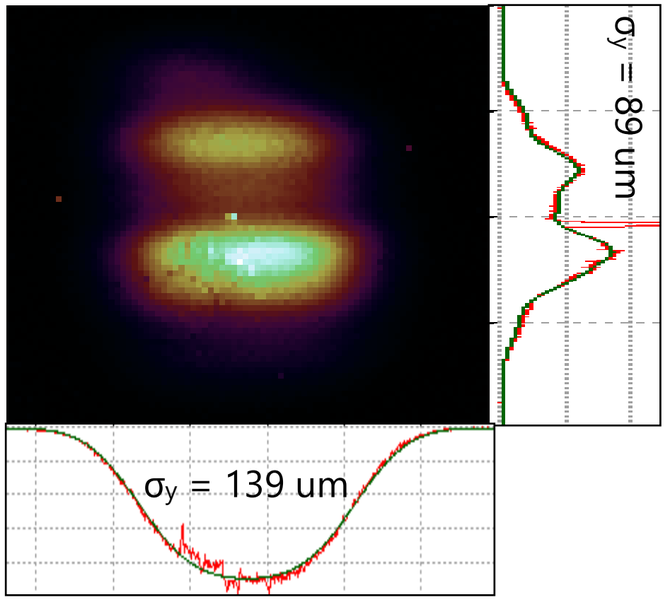


Optical mask
Au coating on CVD diamond substrate

X-ray images projected to a YAG/LuAG scintillator

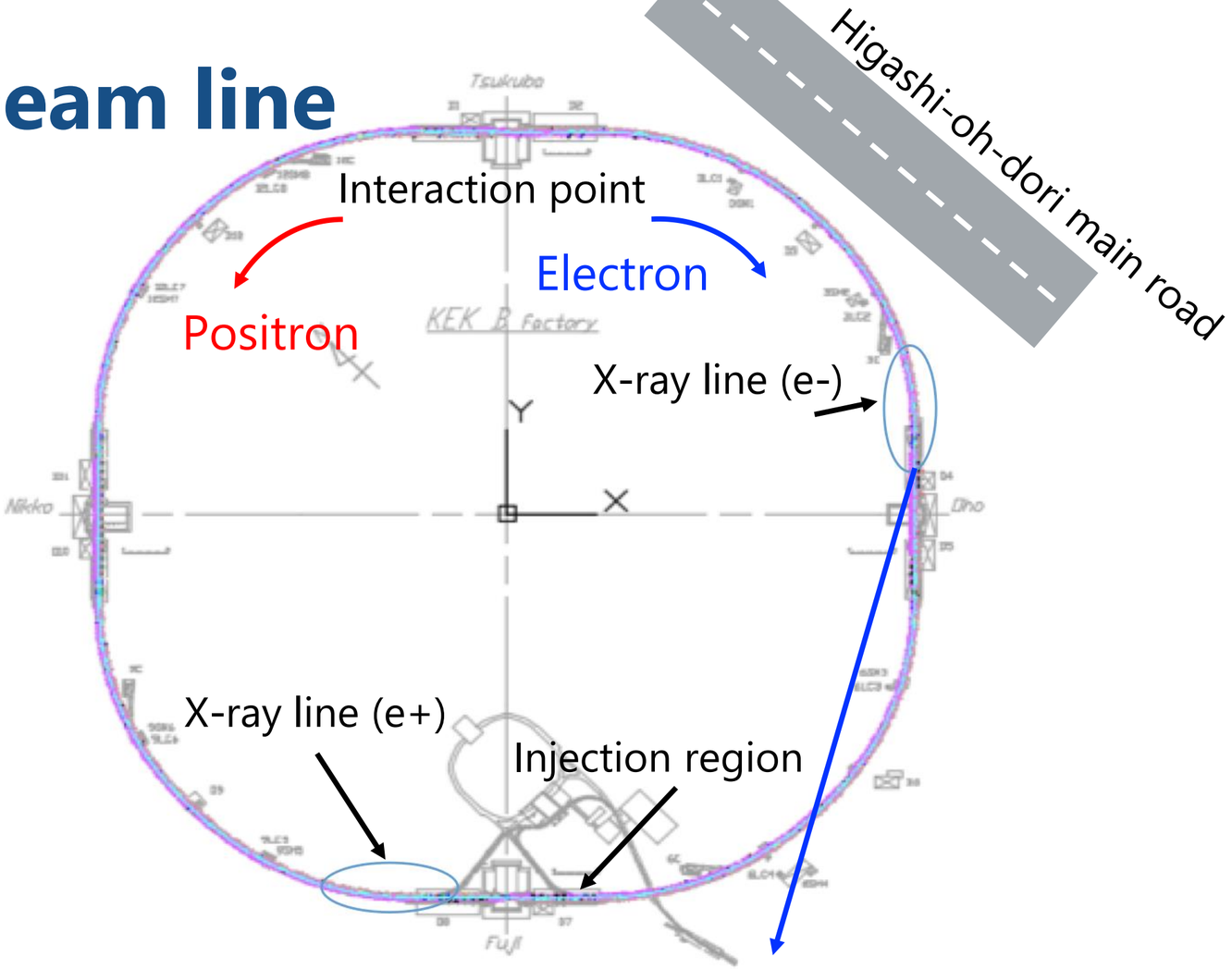


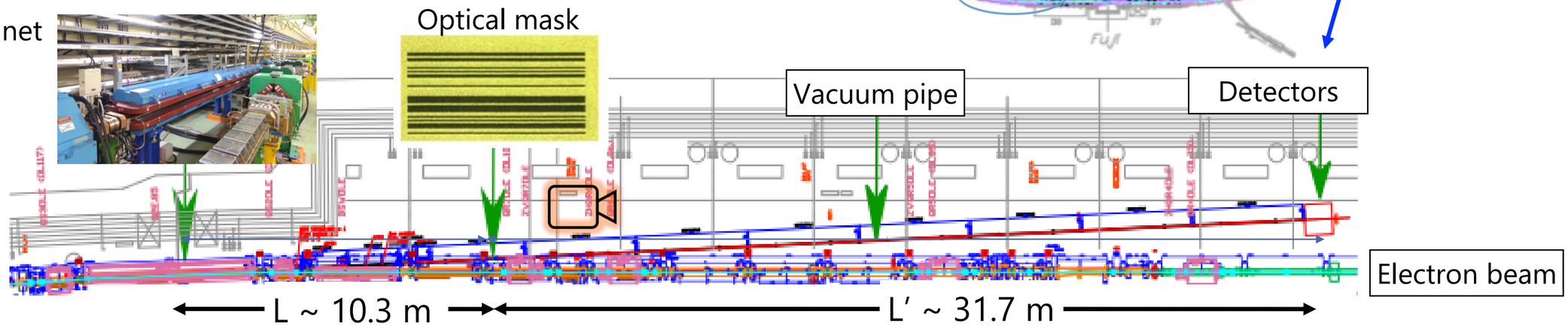
Sharp image → Small σ



Broad image → Large σ

The SuperKEKB X-ray beam line





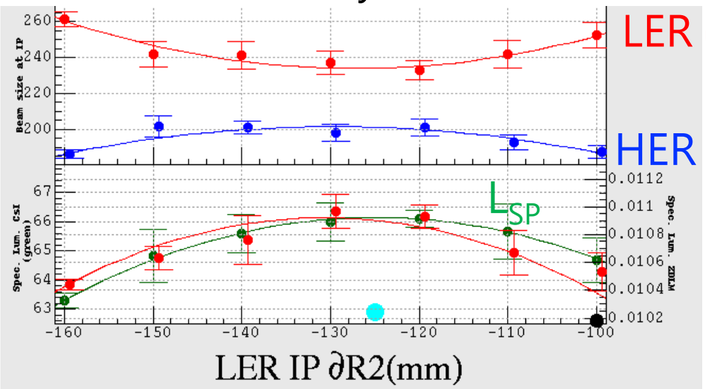
Present status of the X-ray beam size monitors

Vertical beam size measurements in Phase 1 and 2.

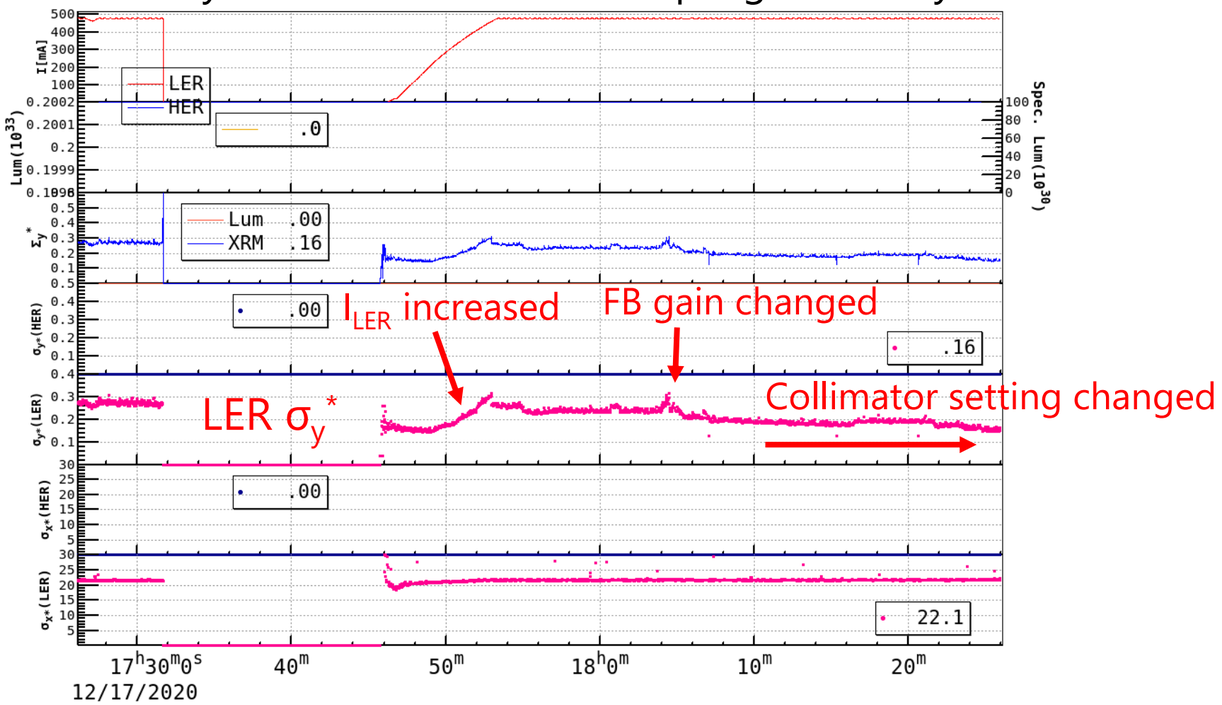
Parameter	Phase 1 (2016/2-6)		Phase 2 (2018/3-7)	Unit
	LER	HER	HER	
σ_y optics estimation	~25	~9 (*)	~9	μm
σ_y measured	21.56 ± 2.9	16.93 ± 0.75	12.35 ± 0.39	μm
σ_s (inferred PSF)	15.63 ± 2.9	31.58 ± 0.72	6.6 ± 0.73	μm

(* Note that $\beta_{y,HER}$ was 7 m throughout Phase-1 and at Phase-2 study, and was 28 m for other periods.)

Luminosity scan



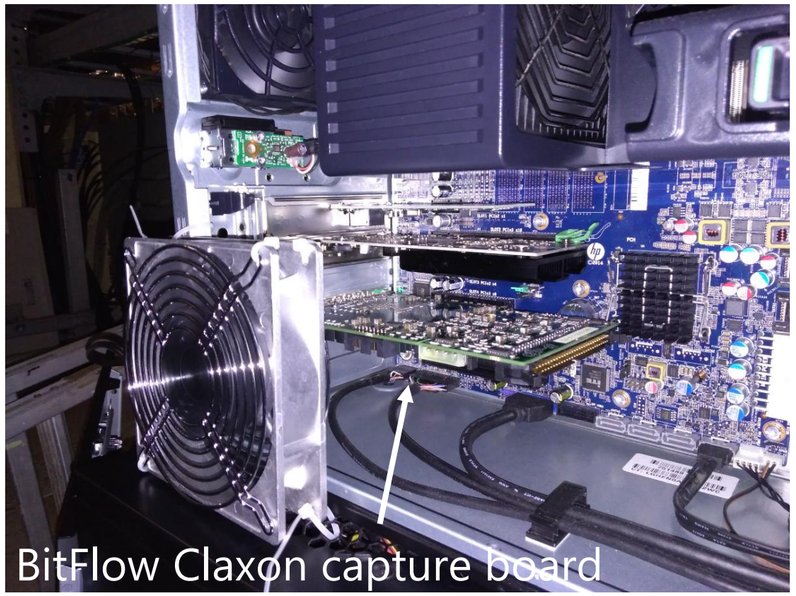
Study on transverse mode coupling instability

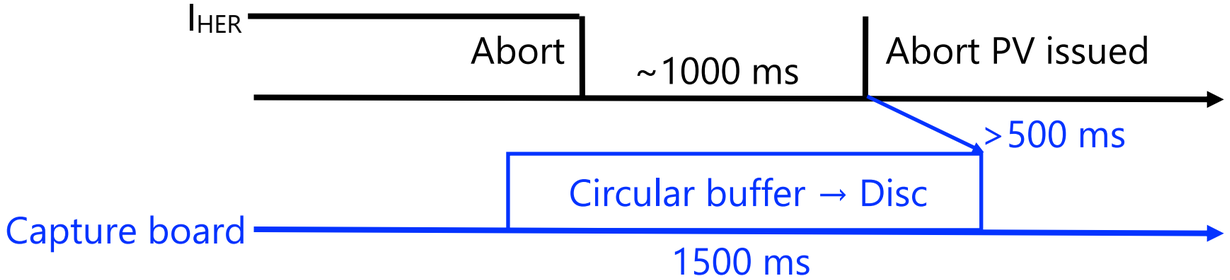


- Achieved the targeted minimum σ_y (~10 μm) in the commissioning Phase 1 and 2, though need to calibrate the monitor in case of σ_y < 20 μm anyway
- "Workhorse" in daily beam operation such as luminosity scans and beam studies

Future direction 1: Abort diagnostics

- ~70% of beam aborts at SuperKEKB are not synchronized with beam injection and their causes are hardly understood.
- If exist, beam sizes' oscillations and/or blows up may contain ample information on how beam losses followed by beam aborts occur.
- Introduced fast area cameras working with 100 kHz (~f_{rev}) in HER and LER, and recorded the last ~(10^3) turns data immediately before beam abort



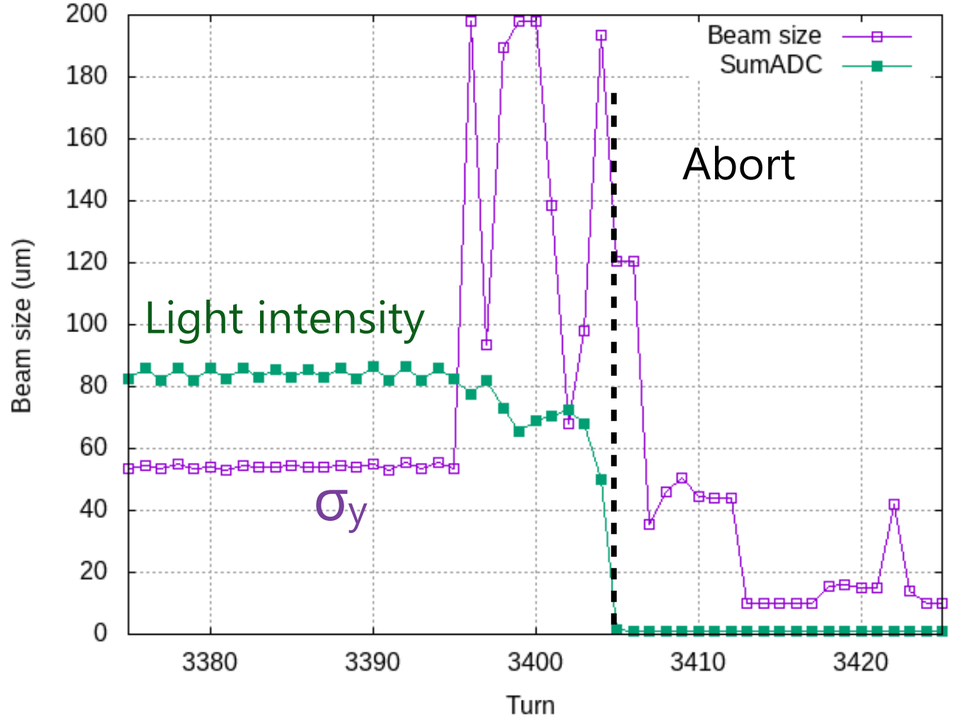


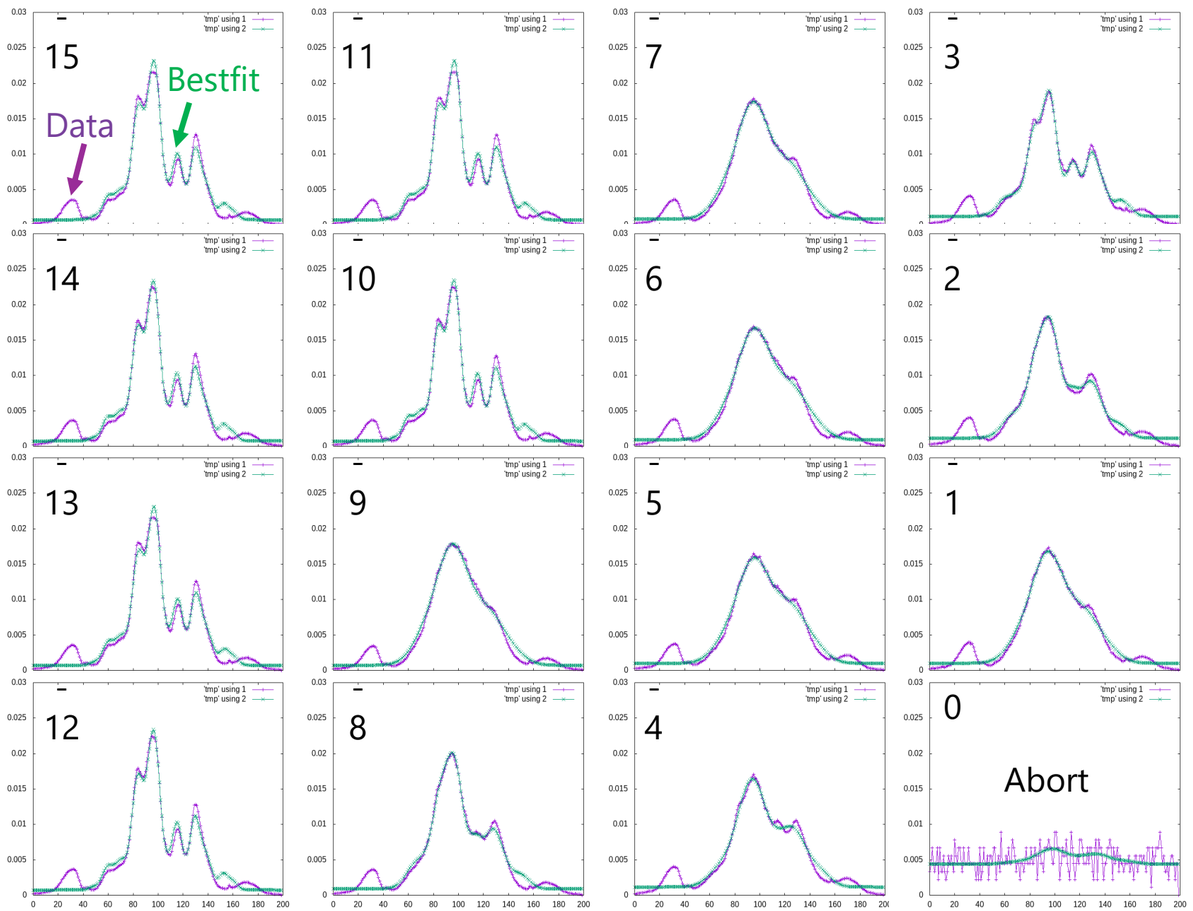
Improvements since 2021 fall run

- Revolution-trigger-synchronized shutter open/close enables focusing on exactly same bunches over many turns.
- 2 ns step delay interleaved into the trigger system

σ_y oscillation before HER beam-loss abort

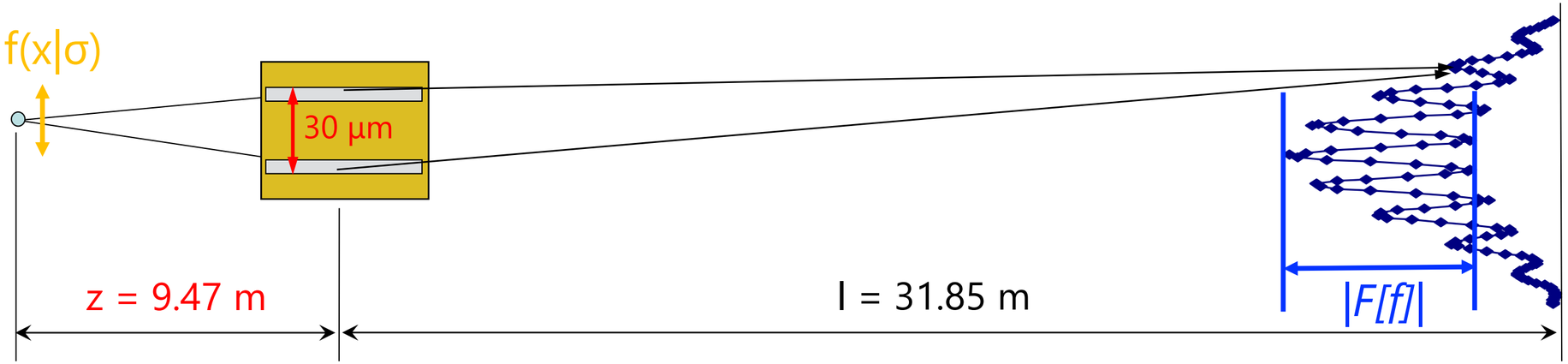
HER_20210420_03.43.13 (817 mA + 837 mA)





- σ_y starts oscillated 15 turns before a beam abort.
- Scenario hypothesis : beam orbits and/or angles of few hundreds bunches within 1 μs exposure somehow changed incoherently for each, and accordlingly beam sizes (not necessarily bunch sizes) get “visibly” larger.
- Further discussions need beam orbit/size deconvolution (aka. unfolding) using the both bunch oscillation recorder and X-ray monitor data.

Future direction 2: X-ray interferometer



- Essential idea of the present X-ray monitor at SuperKEKB is geometric optics (i.e., X-ray image is mostly independent of a X-ray wavelength if no absorber material.)
- Can a wavelength be used as additional information? ⇒ Interferometer with spatial coherence
- **Peak-valley height F is a function of "source size/wavelength". Equivalently one can extract source size in units of wavelength.**
  ⇒ Far small beam size can be measured using X ray ~ 0.1 nm compared with visible light ~ 500 nm.

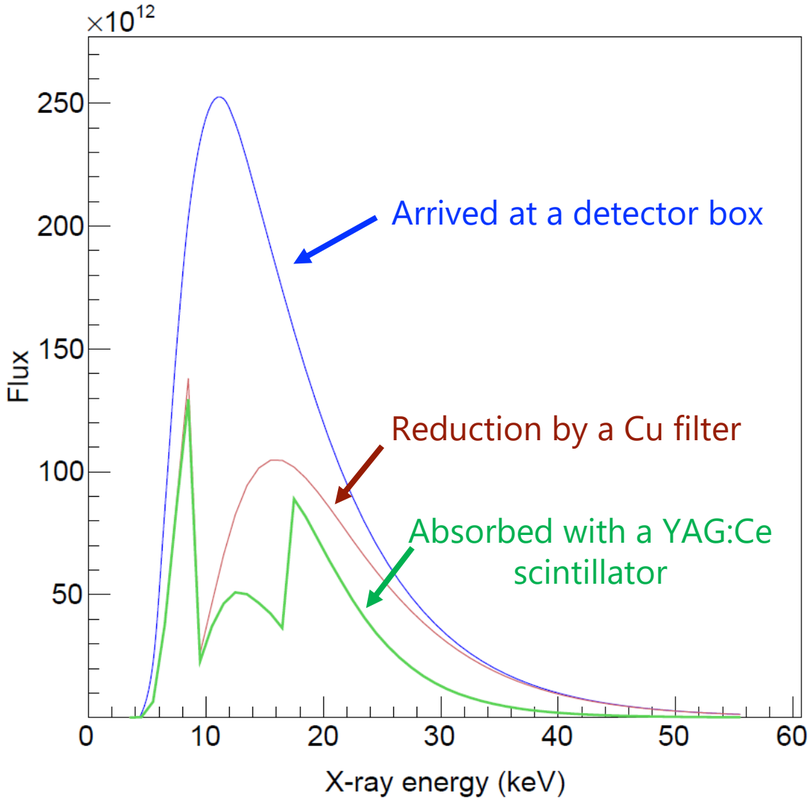
$$F[f] = \frac{\int_R e^{-i2\pi s x} f(x|\sigma)dx}{\int_R f(x|\sigma)dx} \rightarrow e^{-2(\pi\sigma s)^2} e^{i\delta} \quad \left(s = \frac{d}{z\lambda}\right)$$

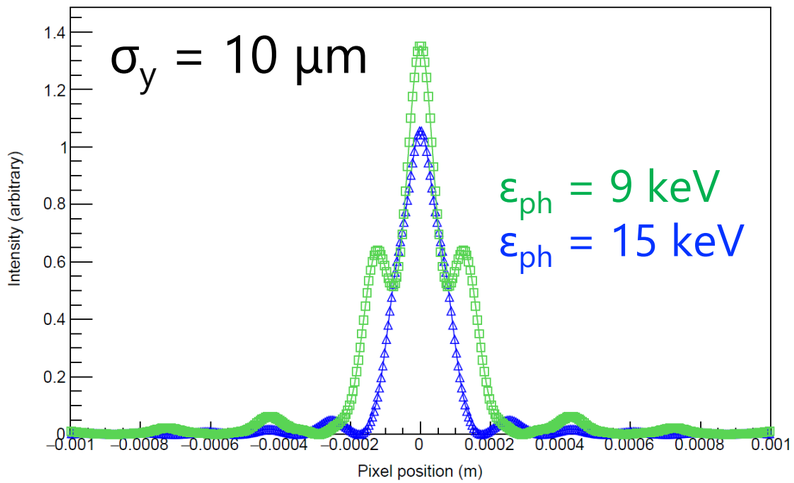
Provided properly scaled distance (z) from a light source to a mask and a slit separation (d), a X-ray interferometer will be a good testbench for FCC-ee beam size measurements.

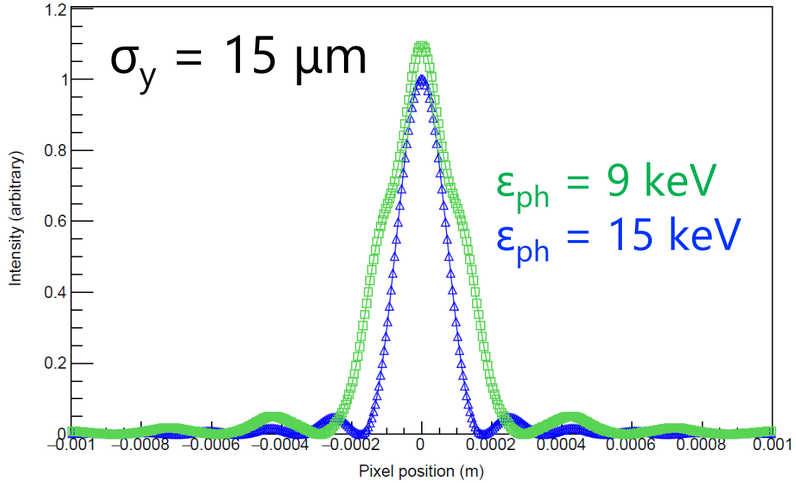
	SuperKEKB	FCC-ee
Beam size σ_y	< 10 μm	< 10 μm [1]
Slit separation d	30 μm	300 μm
Source-mask z	~10 m	~100 m

[1] Thibaut Lefevre, FCCW 2019, Brussels

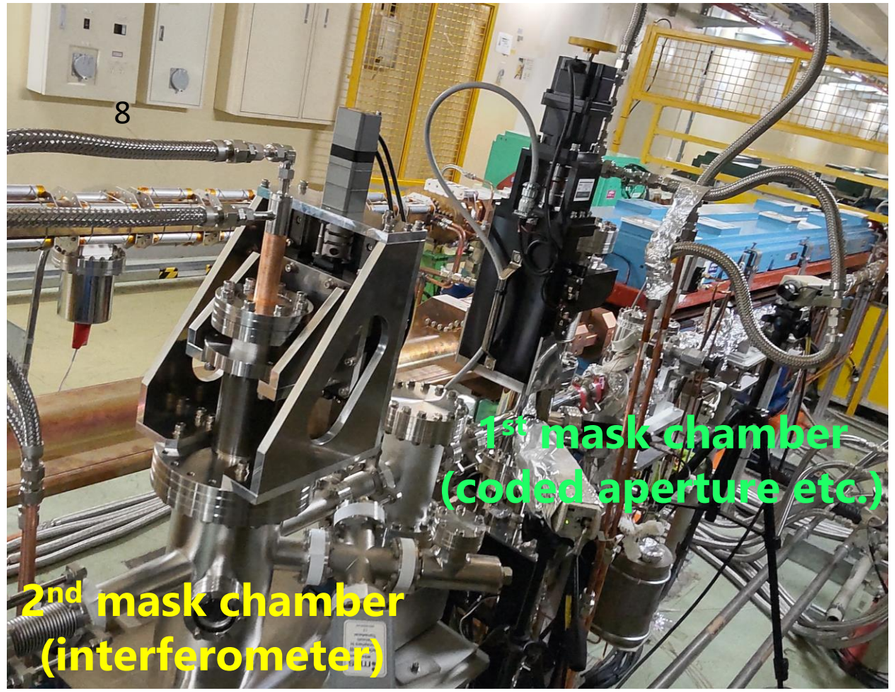
Simulated interference fringes





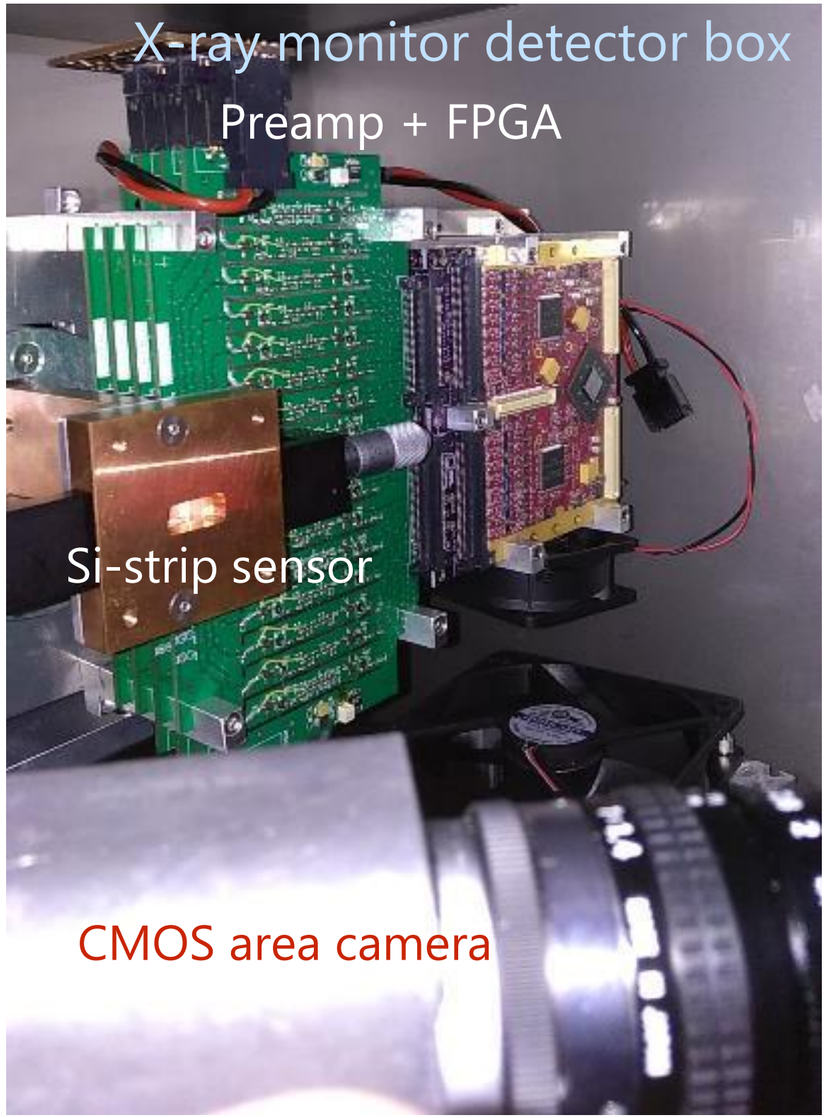


(https://advacam.com/camera/advapix-tpx3)



- σ_y = 10 μm is measurable if X-ray > 10 keV can be well reduced.
- Hard to measure σ_y > 15 μm
- **Test measurements planned in the 2021 fall run**
- X-ray energy spectrum measurements are planned too using the CERN's Timepix technology.

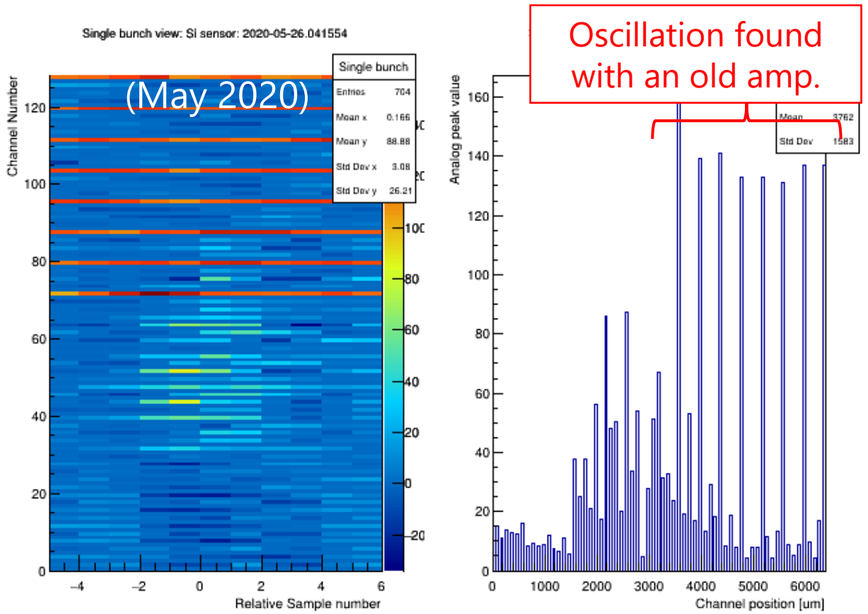
Future direction 3: Bunch-by-bunch measurements



SuperKEKB X-ray monitor's optical detectors

1) CMOS area camera
→ Cheep and simple but generally slow
"Live streaming" suitable in daily beam operation
2) SiXRX: Si-strip sensor and ultra fast amp. + FPGA
→ 2.7 Gsps enables bunch-by-bunch measurements.
Special detectors for beam studies (e-cloud, TMCIs, etc.)

- FPGA codes under upgrade
  → Debug, simplification, to work with new Vivado…
- Test measurements with new sensor+new amp. soon



Summary

X-ray beam size monitors meet SuperKEKB's requirements:

- Measurement range at σ_y = 20-200 μm
- Confirmed measurable down to ~10 μm with a special optics configuration
- Precision achieves $\delta\sigma_y$ < 1 μm at σ_y < 50 μm.

Three future directions:

- Beam abort diagnostics by looking at possible σ oscillation and/or blow up immediately before beam aborts
- X-ray interferometer towards precise measurements near σ_y ~ 10 μm
- Bunch-by-bunch measurements enabling e-cloud, TMCI and other studies