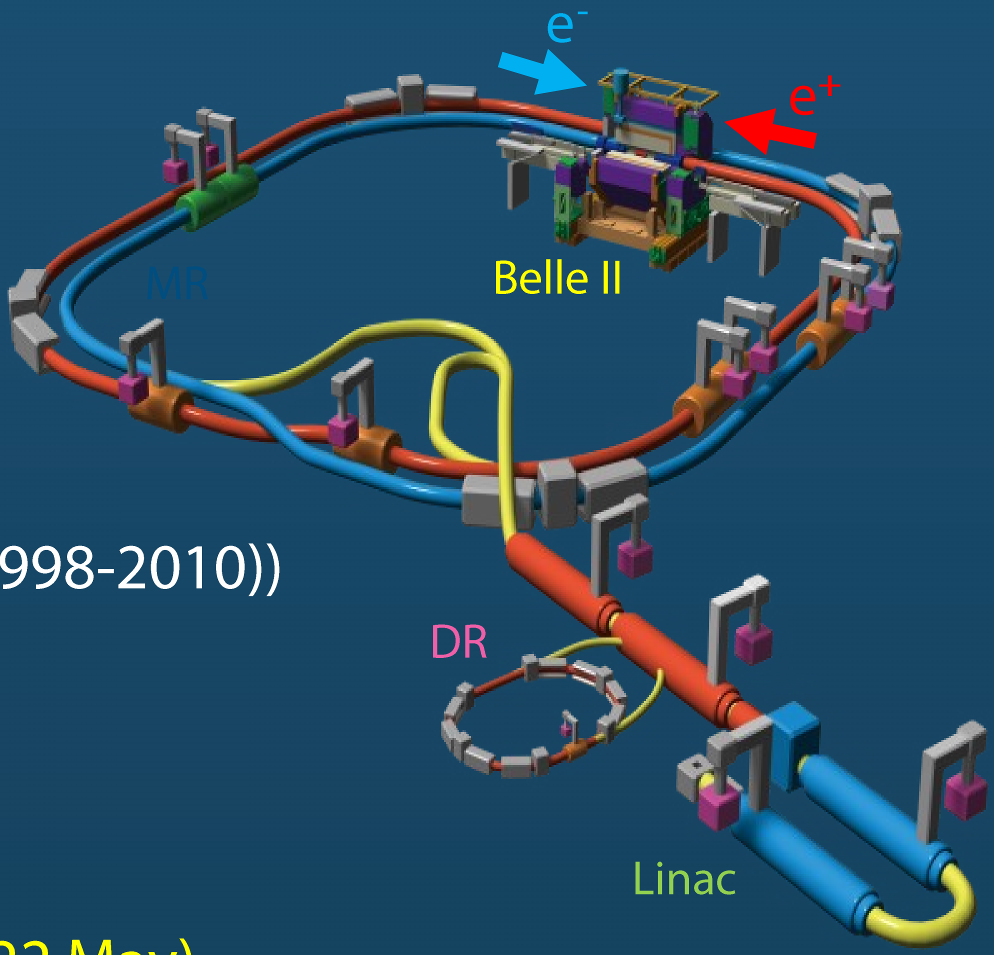
R&D for SuperKEKB and the next generation high luminosity colliders

Gaku Mitsuka (KEK) and John Seeman (SLAC)

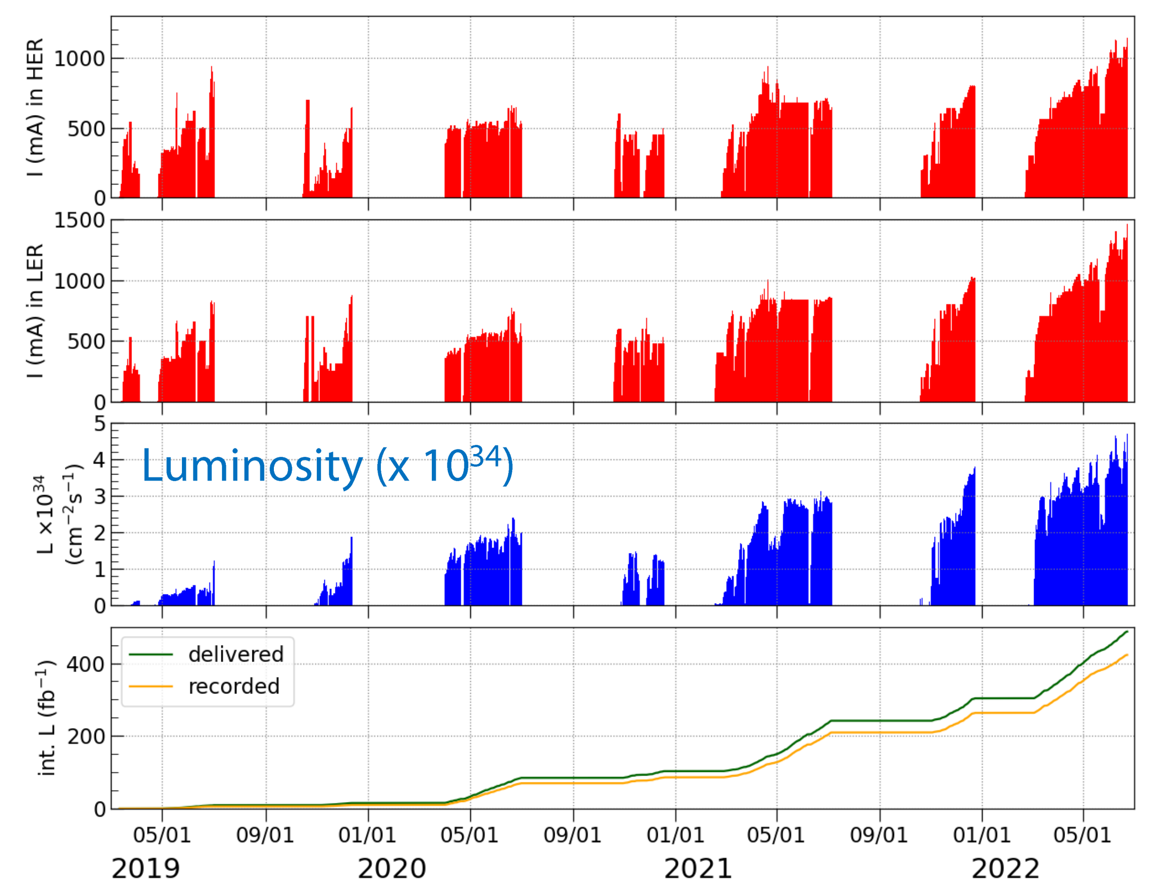
22-23 May 2023, East-West Center

The SuperKEKB e^+e^- collider

- Linac
  - Total length ~700 m
  - Generation and acceleration of e^+ & e^- beam
- Positron damping ring (DR)
  - e^+ energy 1.1 GeV
  - Circumference ~136 m
- **SuperKEKB main rings** (upgrade to KEKB (1998-2010))
  - 7 GeV electron ring (HER)
  - 4 GeV positron ring (LER)
  - Circumference ~3016 m for each
- The Belle II detector (H. Nakayama's talk on 22 May)



Luminosity achievement and future prospect

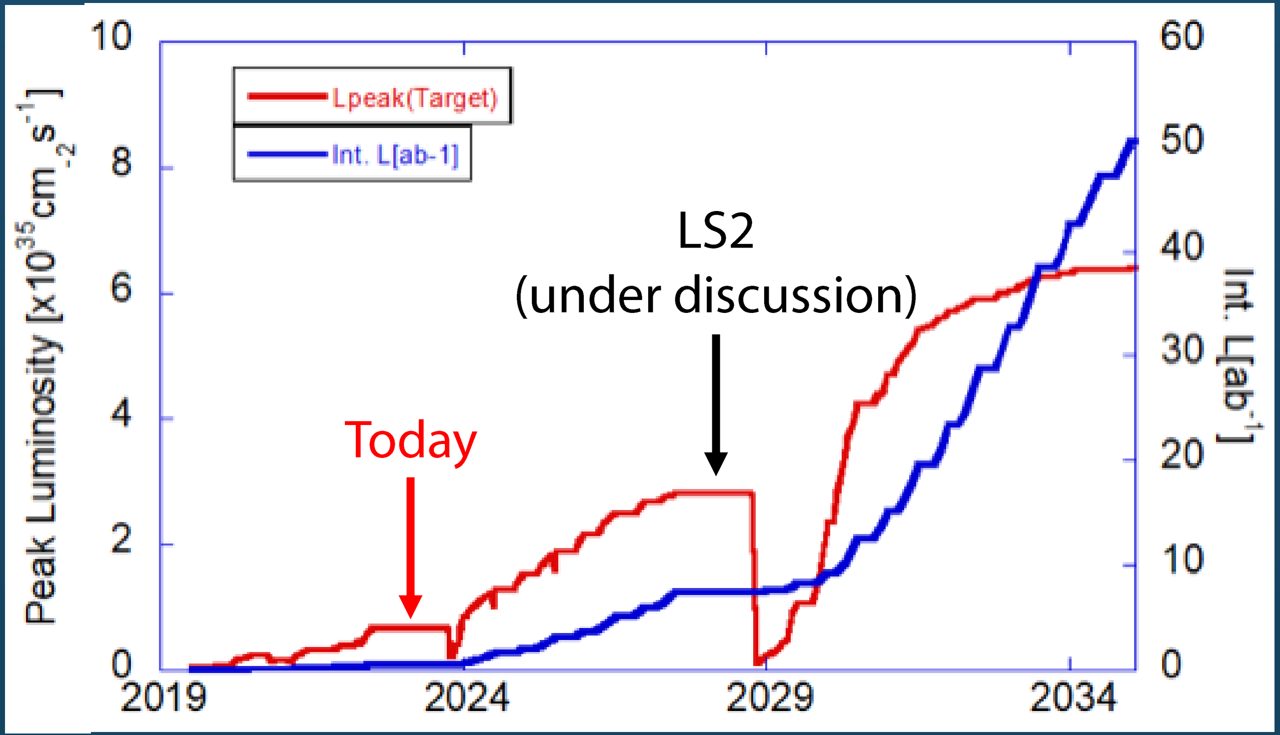

Luminosity (x 10^{34})

The world's highest luminosity in June 2022:

L = 4.65 x 10^{34} $cm^{-2}s^{-1}$ (I_{e+} = 1.46 A, I_{e-} = 1.14 A)

$\int L$ = 424 fb^{-1}

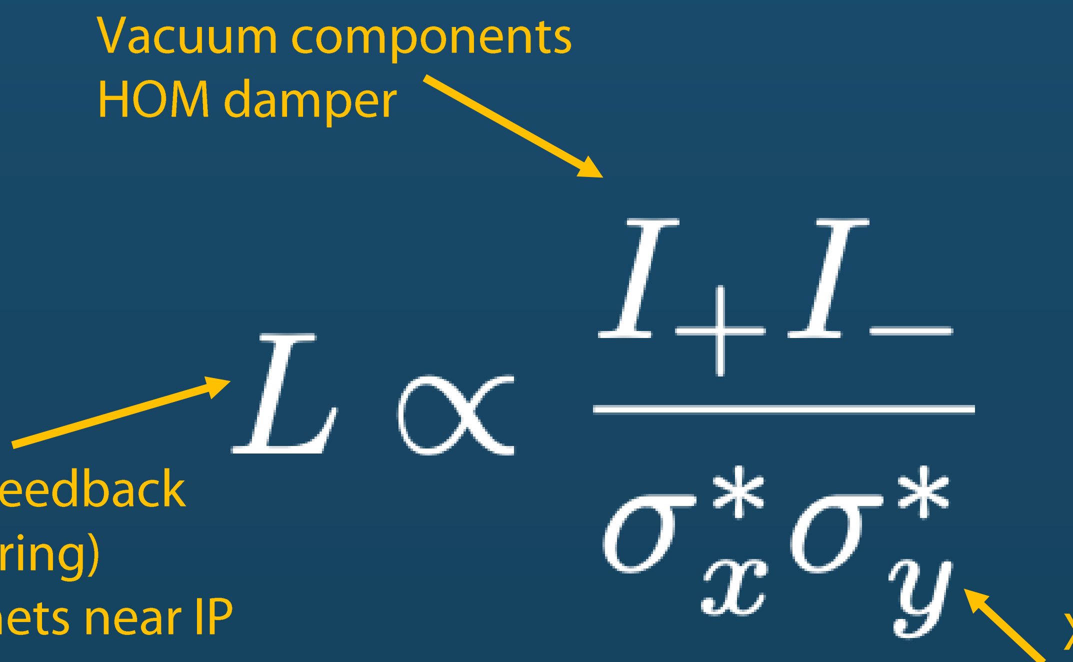
- Long shutdown 1 "LS1" (July 2022 – December 2023)
  Upgrade/maintenance of SuperKEKB and Belle II
- Aiming at 2.4 x 10^{35} $cm^{-2}s^{-1}$ by summer 2026
- 6 x 10^{35} $cm^{-2}s^{-1}$ in early 2030s


LS2
(under discussion)

Today

Research project overview

- Established and succeeded since FY2003
- Labs and universities in US and Japan will jointly develop key technologies/physics models for SuperKEKB and future high-luminosity colliders.
- Human resource development for future accelerators (not only for colliders)



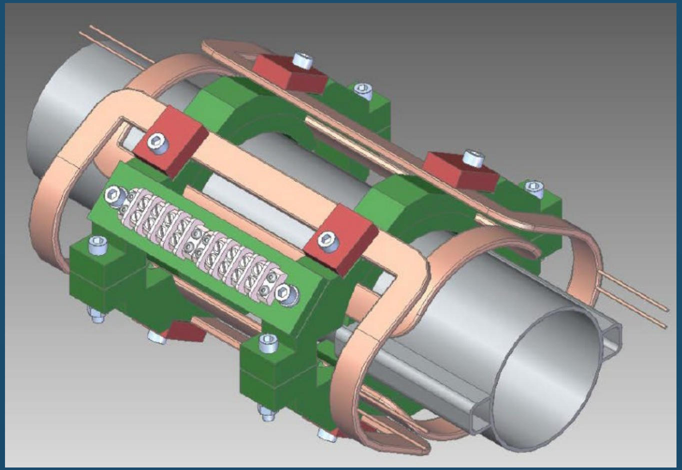
Vacuum components
HOM damper

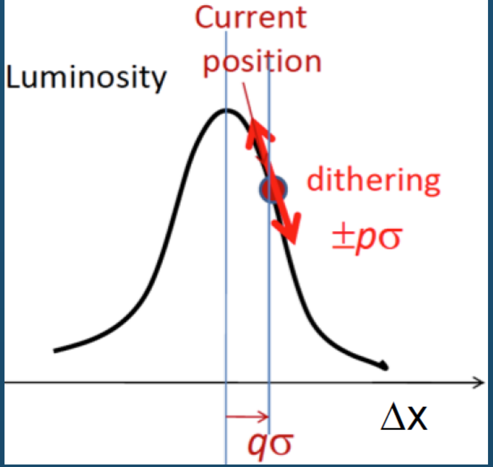
$$L \propto \frac{I_+ I_-}{\sigma_x^* \sigma_y^*}$$

Bunch-by-bunch orbit feedback
IP orbit feedback (dithering)
Superconducting magnets near IP
Accelerator physics

X-ray beam size monitor
Large angle bremsstrahlung monitor

1. Orbit feedback system near the IP (dithering system)





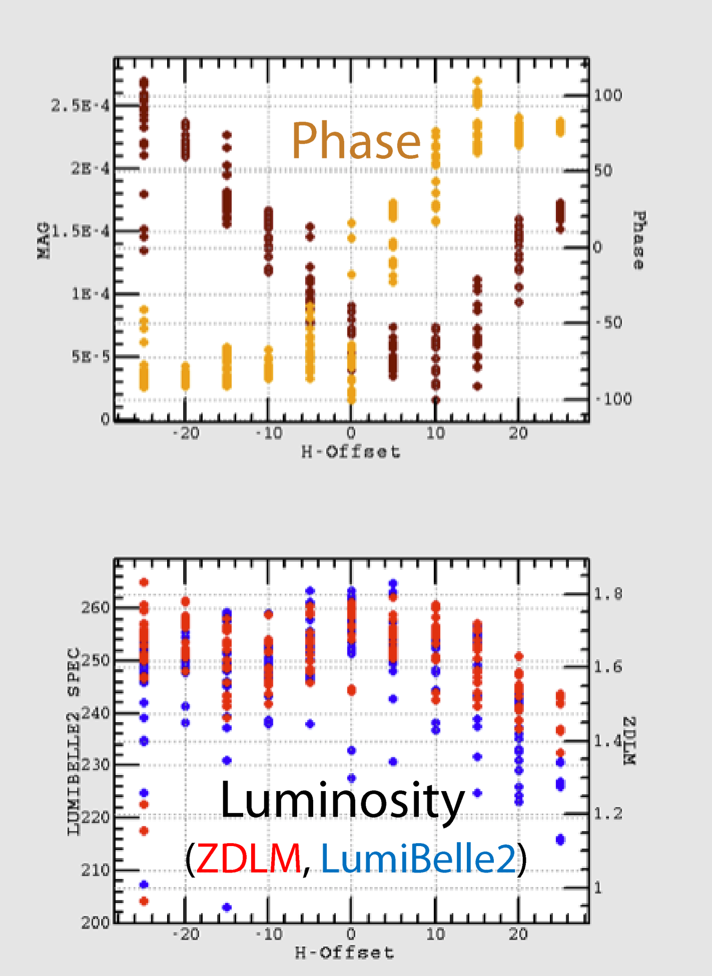
- Dither the horizontal orbit in LER as monitoring a luminosity
- Amplitude of the luminosity fluctuation synchronized with dithering tells us a better direction of the orbit bump for high luminosity
  - Fluctuation decreases as the luminosity approaches the maximum
  - Finally, the phase of the fluctuation flips across the maximum

FY2021-2022 (essentially luminosity campaign)

- No opportunity to study the dithering system

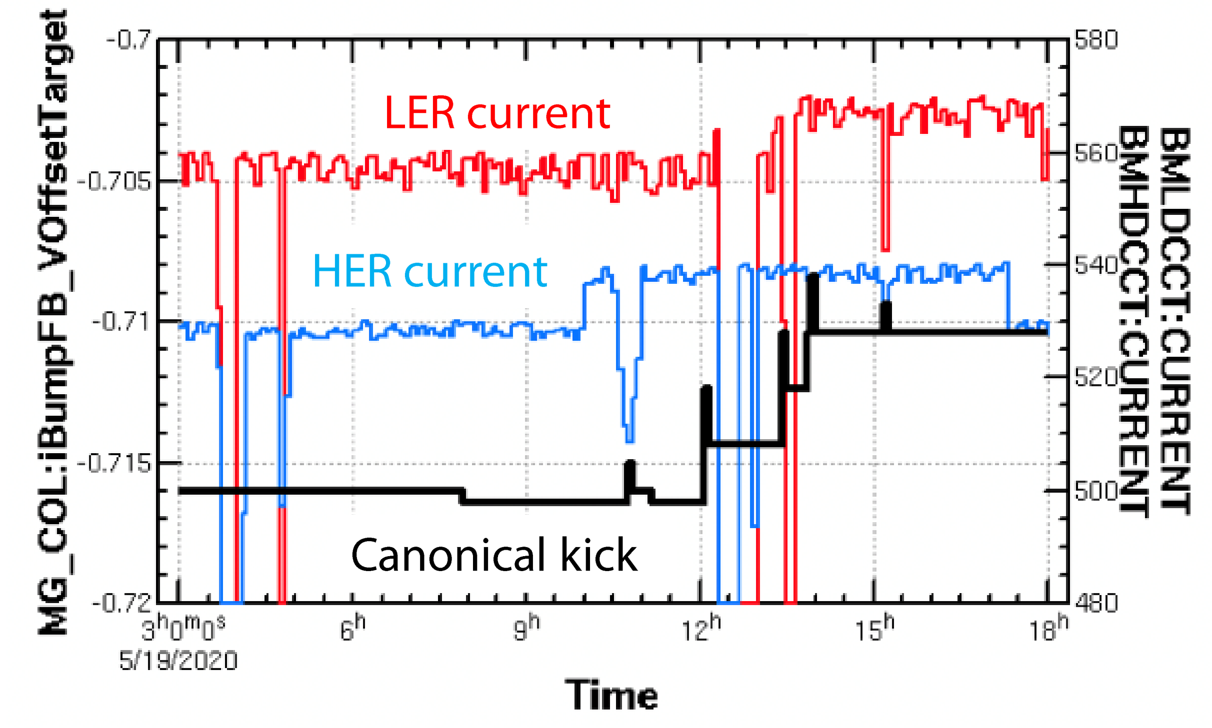
FY2023-

- We will prepare hardware for the vertical dithering system in LS1.



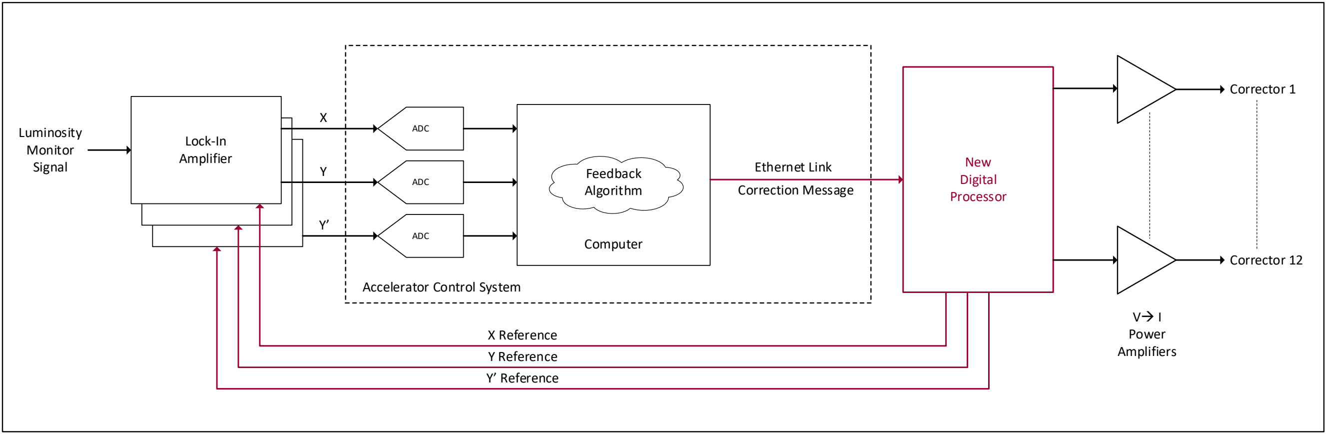
1. Future prospect: 2-axis orbit & angle feedback

Example of the present vertical FB

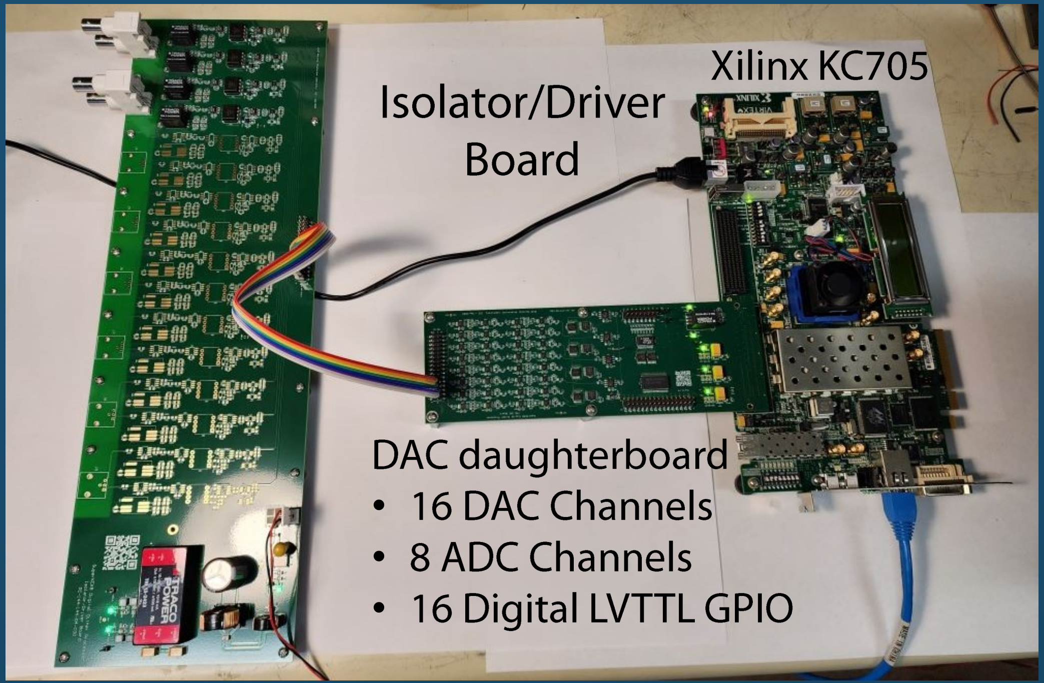


- In the present vertical feedback system (not a dithering system), the vertical orbit is fed back by keeping the strength of the beam-beam canonical kick constant.
- Kick strength optimal for luminosity depends on the stored current; thus needs to be searched and set for each current in situ.
- Dithering system can automatically find the optimal kick strength.

1. Future prospect: Digital Dither Processor upgrade



- A new "Digital Feedback Signal Processor" has been proposed to overcome the issues, suffering from drift, noise and degradation over time due to temperature, aging and sensitivity to noise and power supply variations.
  - The very small amplitudes needed to drive in y and y' are especially sensitive to errors
- It will offer increased flexibility to try out different processing techniques and architectures



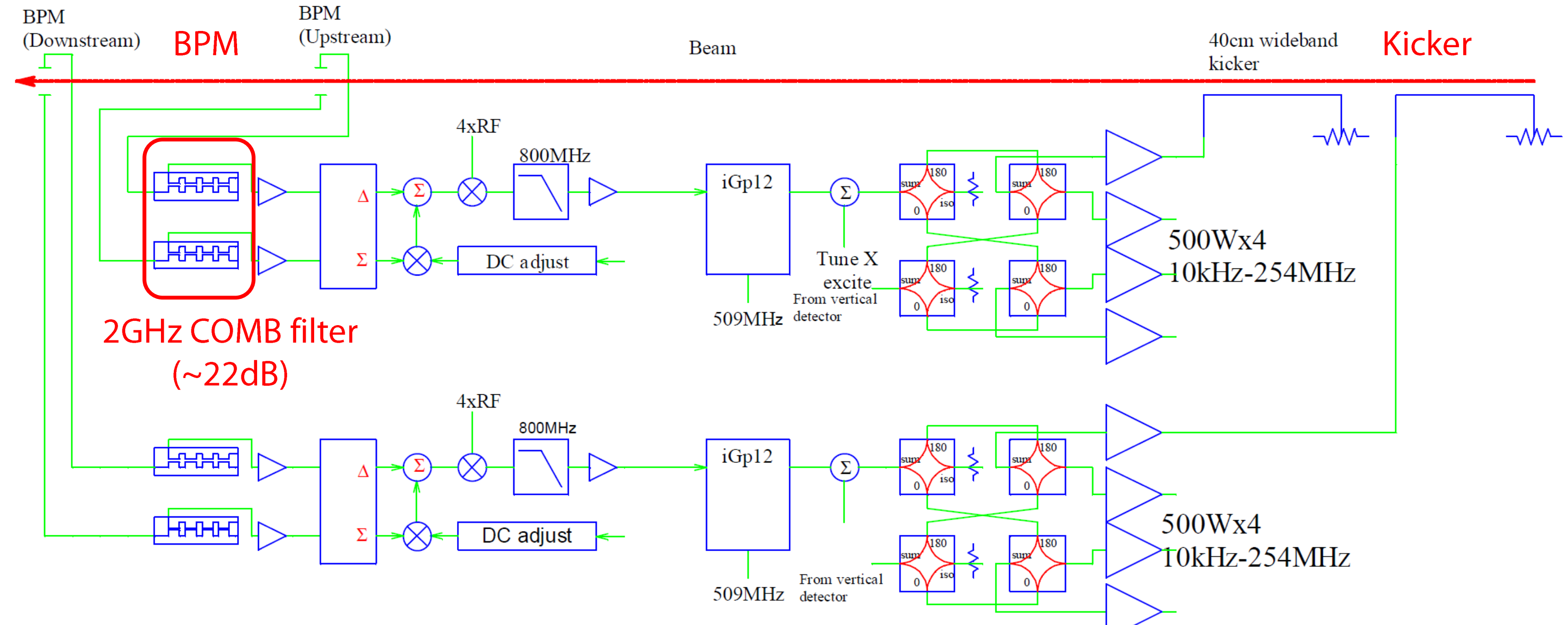
Xilinx KC705

Isolator/Driver Board

DAC daughterboard
- 16 DAC Channels
- 8 ADC Channels
- 16 Digital LVTTL GPIO

- Bring-Up of the I/D board not started yet, FPGA Development ~50% completed
- Nest steps:
  Integration/testing of the sub-components
  Software developments
  - low-level system test
  - migration with orbit FB SW (at KEK)

2. Bunch-by-bunch beam-orbit feedback

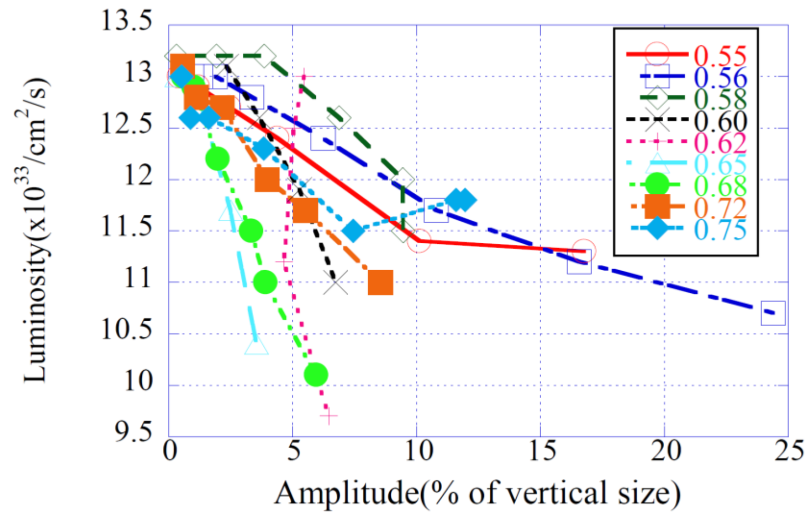


BPM

Kicker

2GHz COMB filter
(~22dB)

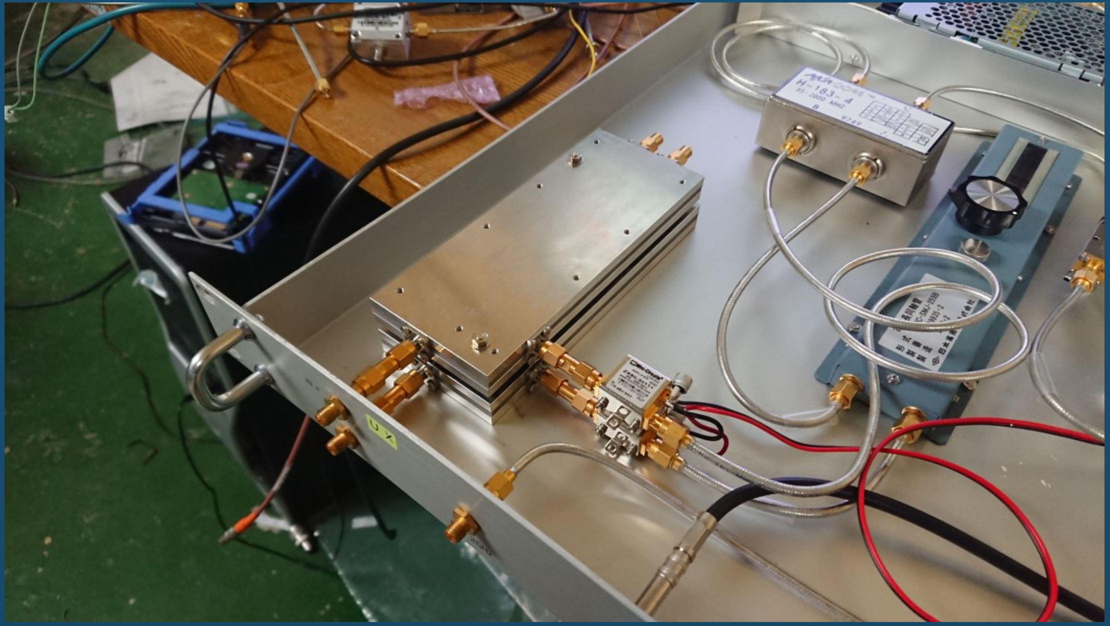
SuperKEKB Transverse Bunch Feedback System

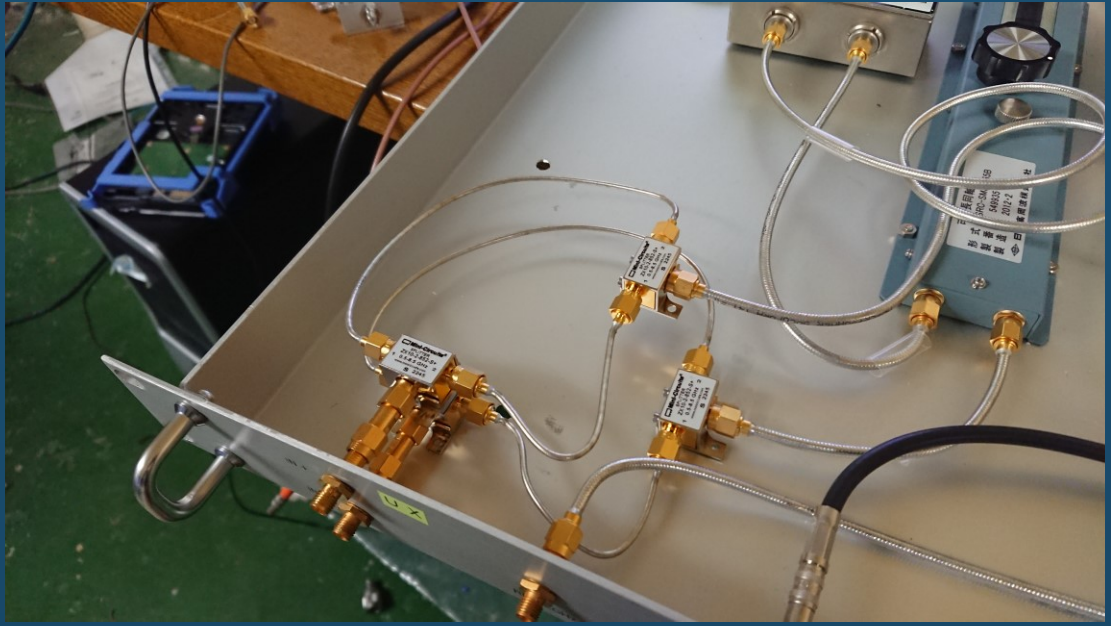


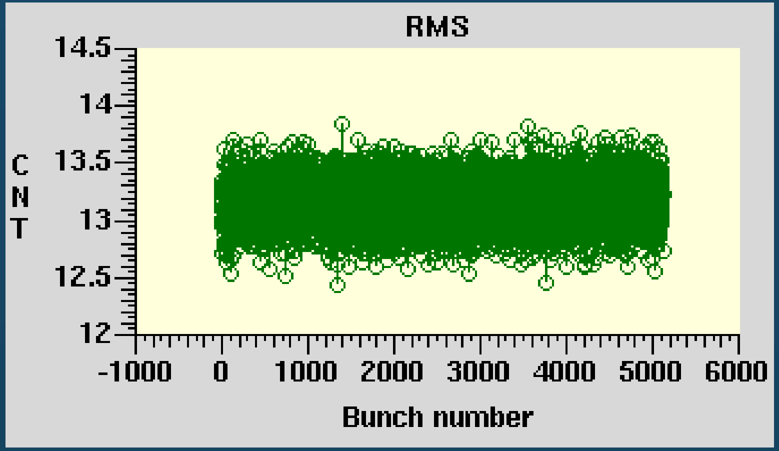
Lessons from KEKB:
Sinusoidal noise signal increases the beam size and degrades luminosity.
(Tobiyama & Ohmi, MOPD73, DIPAC2011)

- Broadband noise in the feedback system could unintentionally excite the beam, especially near vertical tune (+ beam-beam tune shift)
- Reducing the noise in the feedback system is essential.
- Stripline-coupled filter cuts the lower frequency noise
  - Insertion loss (~22dB) causes worse NF upstream of the system.

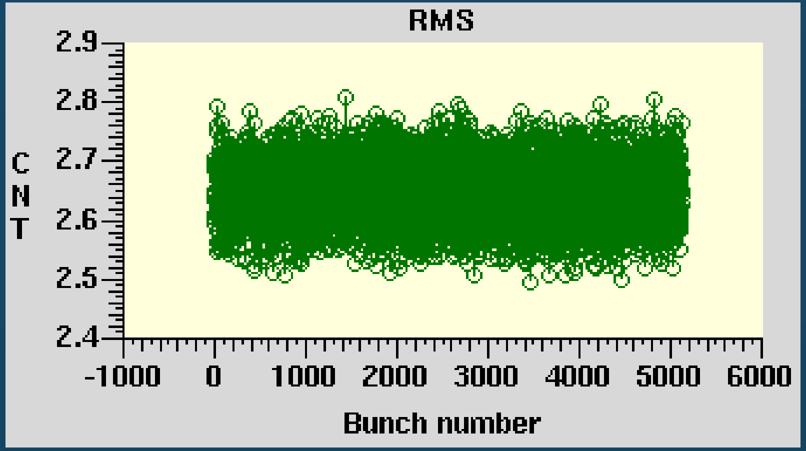
2. Improved noise figure in the feedback detector





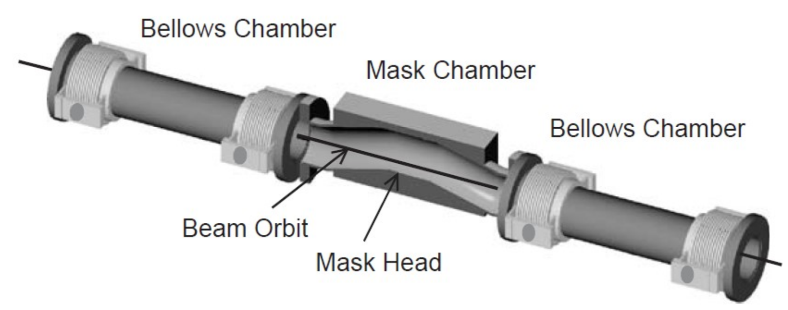


~13.2 counts in ADC of iGp12 (without beam)

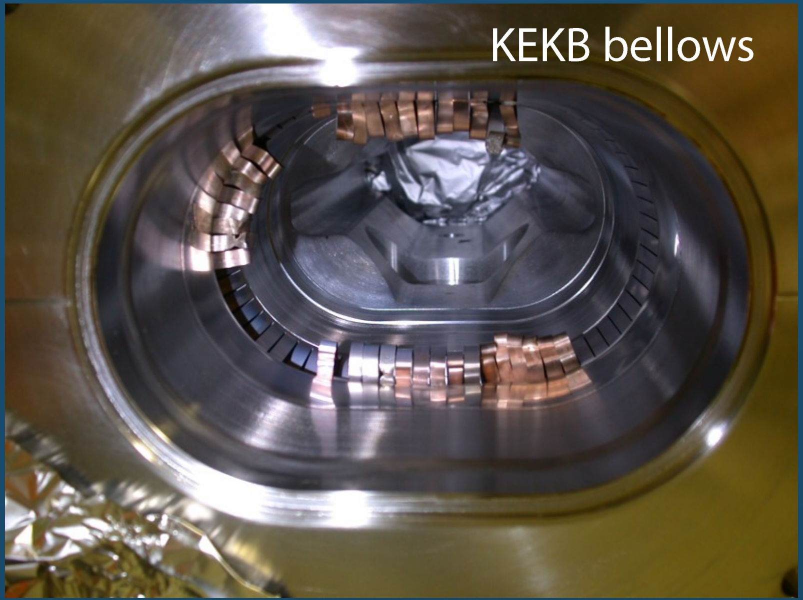


~2.6 counts in ADC of iGp12 (without beam)

3. Vacuum components: lessons from KEKB

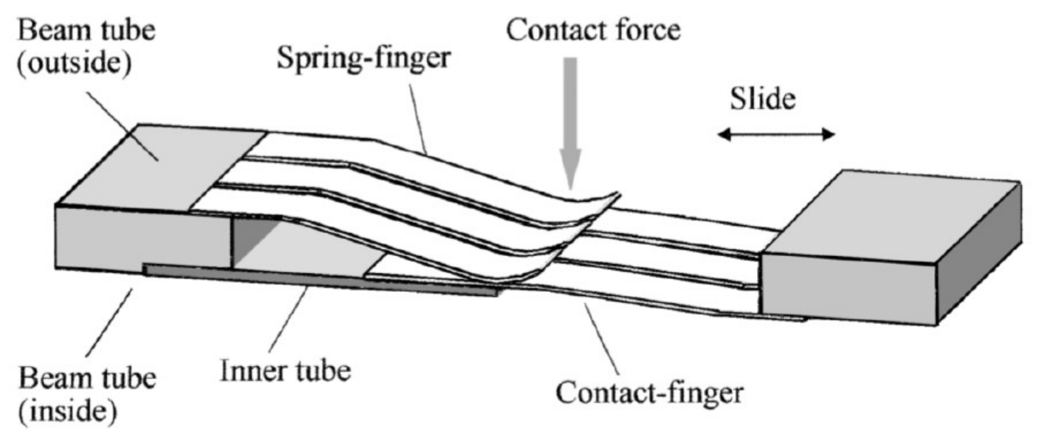


The Higher-Order Mode (HOM) is excited at the mask head where the beam is passing the off-center of the beam chamber.

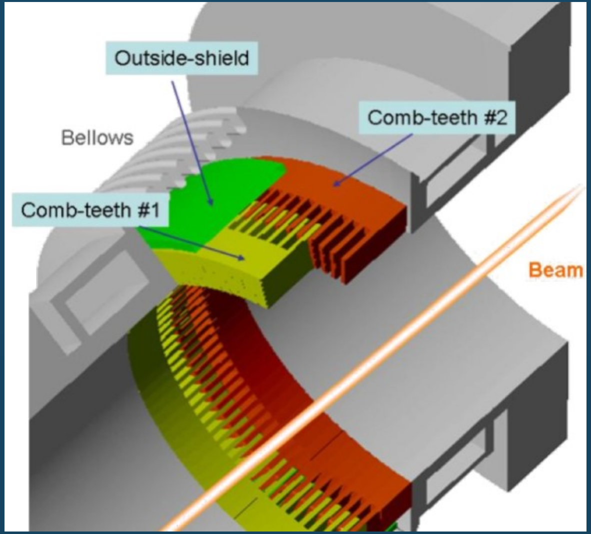


Experience in the KEKB era:

- HOM severely damaged the RF shield of the bellows chamber near an LER V mask.
- HOM leaked from a finger-type RF shield bringing significant heating at a high beam current



“Finger-type” RF shield (KEKB)



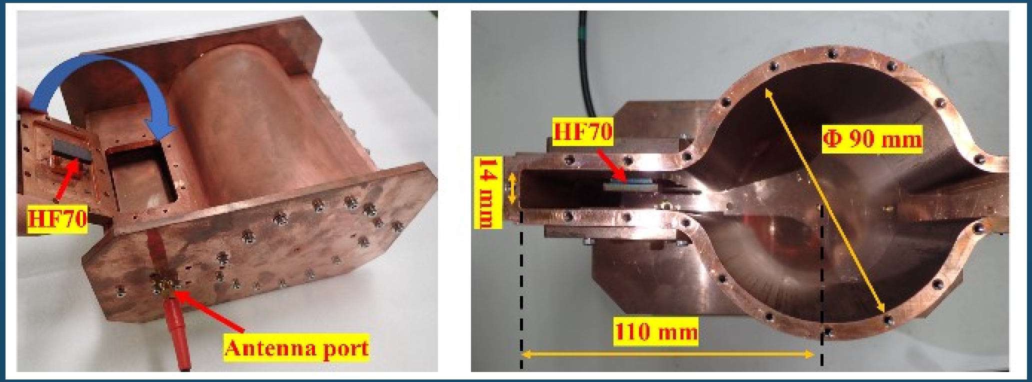
“Comb-type” RF shield (SuperKEKB)

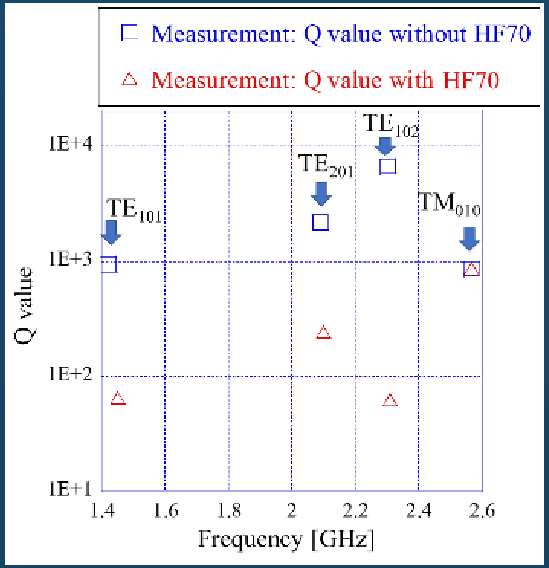
- Mitigating TE-mode HOM leakage
- Thermostable thanks to thick Cu comb teeth
- Low impedance

3. Novel ferrite HOM damper

A new chamber with ferrite tiles to damp strong electromagnetic fields excited at the collimator

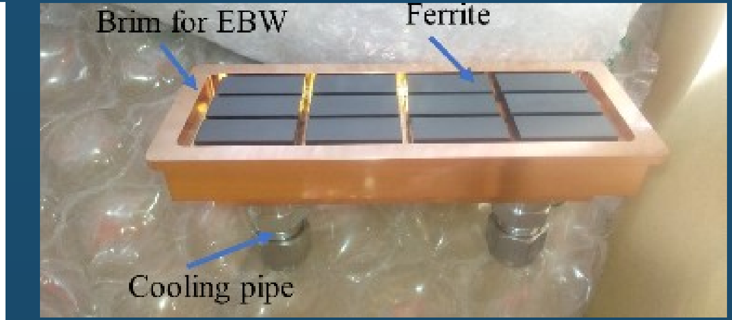
Q-value measurements



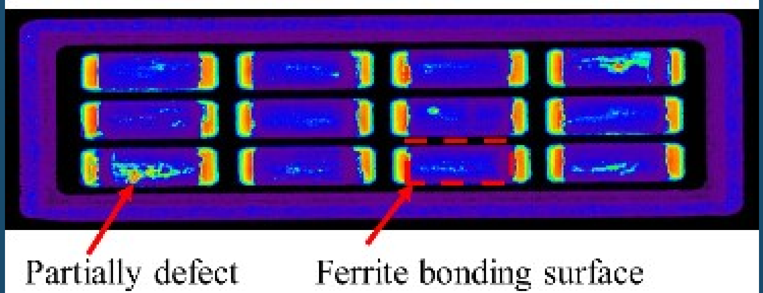


The Q values of the TE modes with HF70 were damped. The Q values of the TM$_{010}$ of the beam acceleration mode were undampened in measurements.

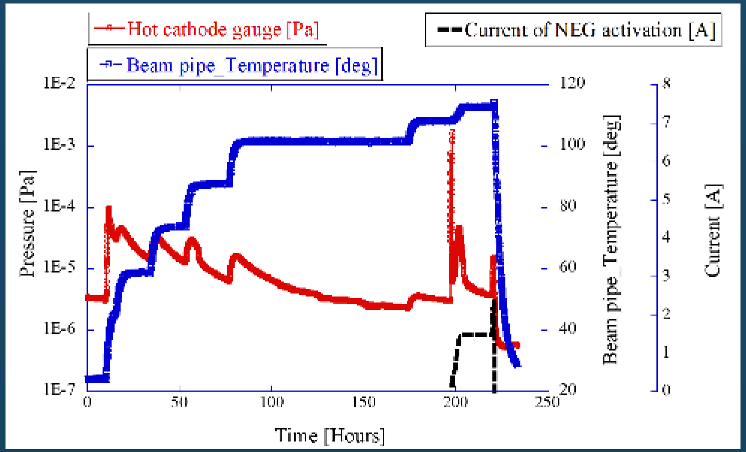
Ferrite bounding test



Ultrasonic test for the bonding soundness check

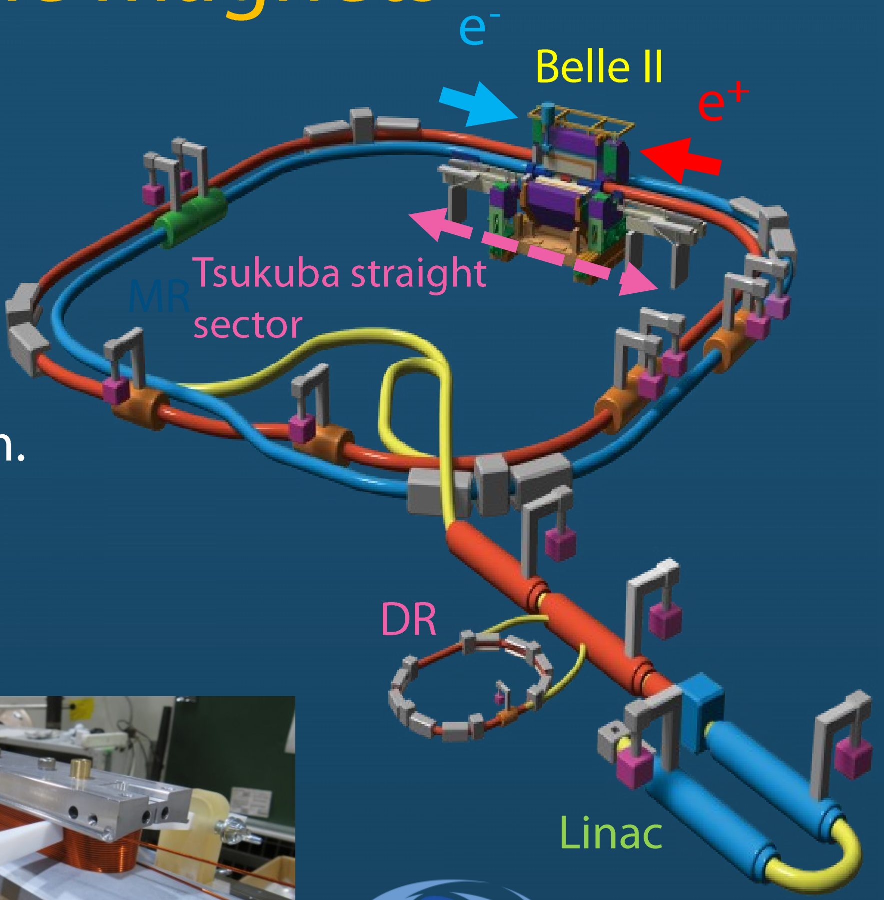


Outgassing rate measurement with prototype chamber



(S. Terui et. al., accepted in NIM A)

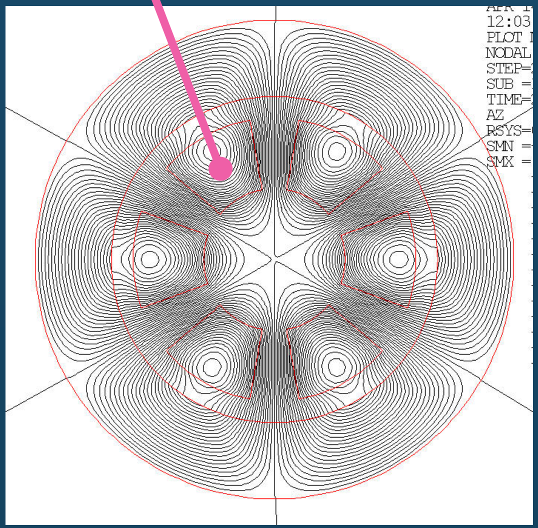
4. R&D of superconducting sextupole magnets

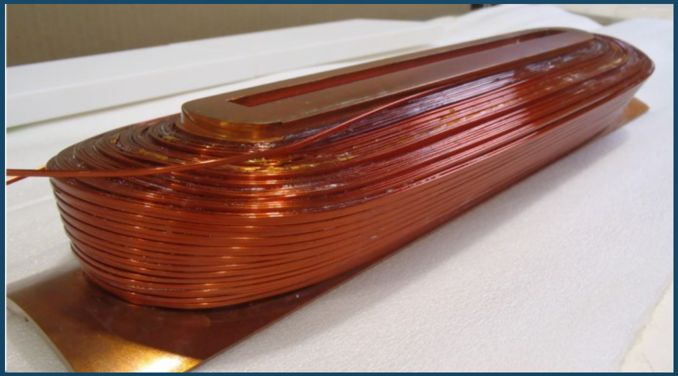


Upgrade of the sextupole magnets in the Tsukuba straight sector
(they work for tuning chromaticity and "Crab Waist.")

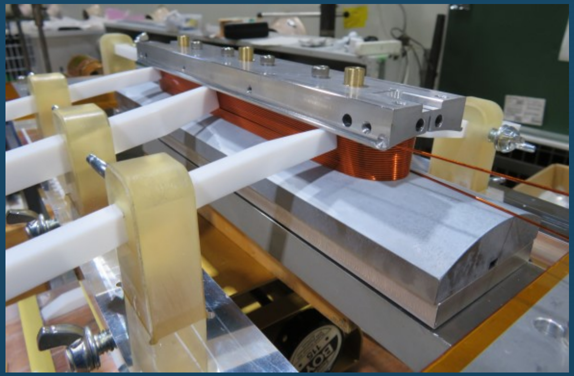
- Replacement of normal sextupole magnets with superconducting sextupole magnets
- The SC correctors can be built in the sextupole magnet system.
    - Enables a quite fine-tuning in the mid-plane phase and at the sextupole center

Superconducting sextupole





Constructed R&D SC coil in JFY 2021



Improved coil production tooling in JFY 2022

Brookhaven National Laboratory

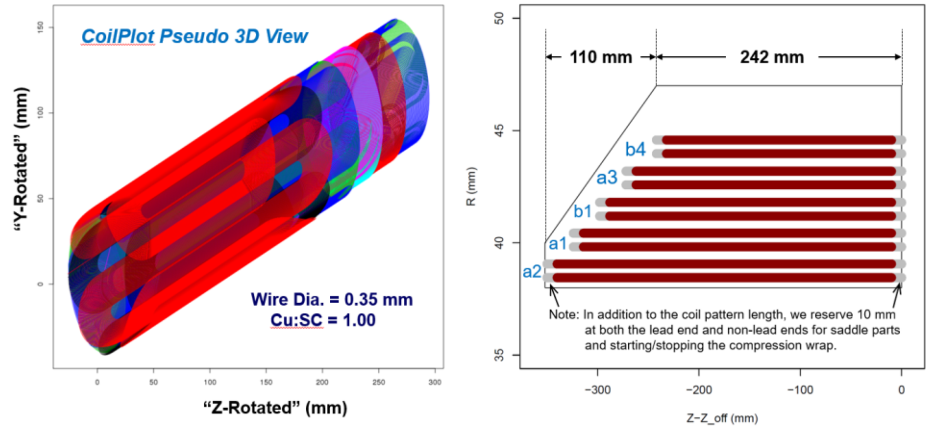
4. R&D of superconducting quadrupole magnets

Remodeling the beam final focus “QCS” system of SuperKEKB

Plan #3: The correctors of QC1P are moved from the inside to the outside of the QC1P magnet

- Quadrupole magnets will be reused.
- Reducing BG on the Belle II detector and SC magnet quench
  - Enlarging the inner diameter of the QC1P beam pipe (R_V=13.5 mm → 18.0 mm)
  - Need to design the SC corrector magnets.

BNL performed the corrector magnet preliminary design in JFY 2021.
Magnet design needs further elaboration.



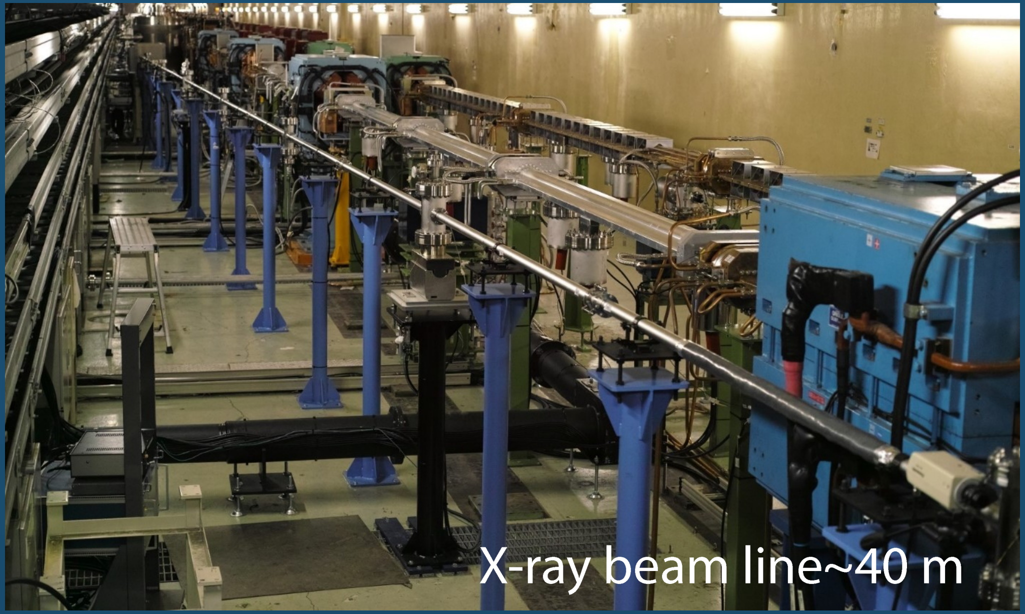
Note: In addition to the coil pattern length, we reserve 10 mm at both the lead end and non-lead ends for saddle parts and starting/stopping the compression wrap.

Plan #8: Big remodeling QCS

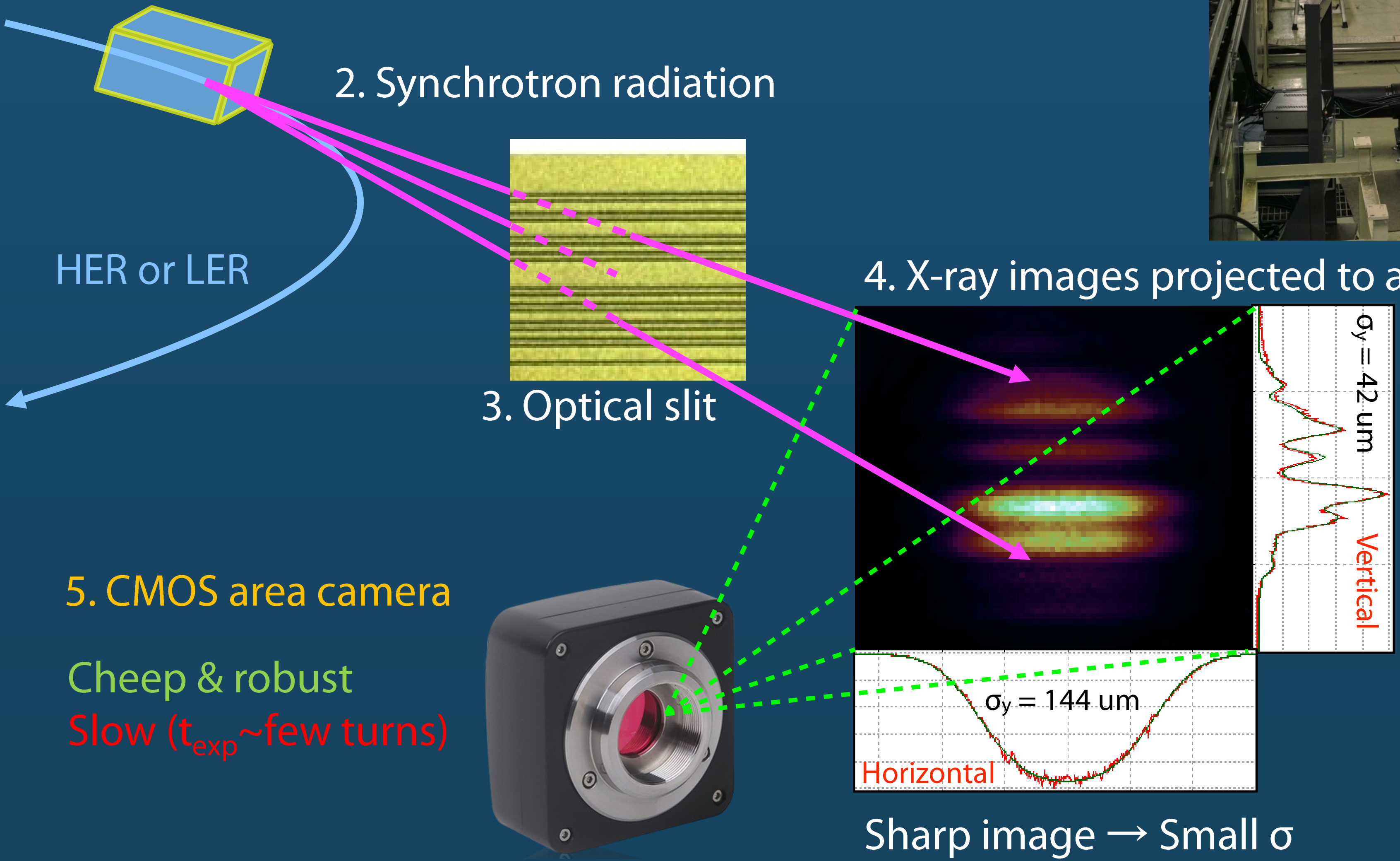
- All superconducting magnets are closer to IP.
- Expanding dynamic aperture for longer beam lifetime
- Need all magnets redesigned and constructed

Brookhaven National Laboratory

5. X-ray beam size monitor



X-ray beam line~40 m



1. Bending magnet

2. Synchrotron radiation

HER or LER

3. Optical slit

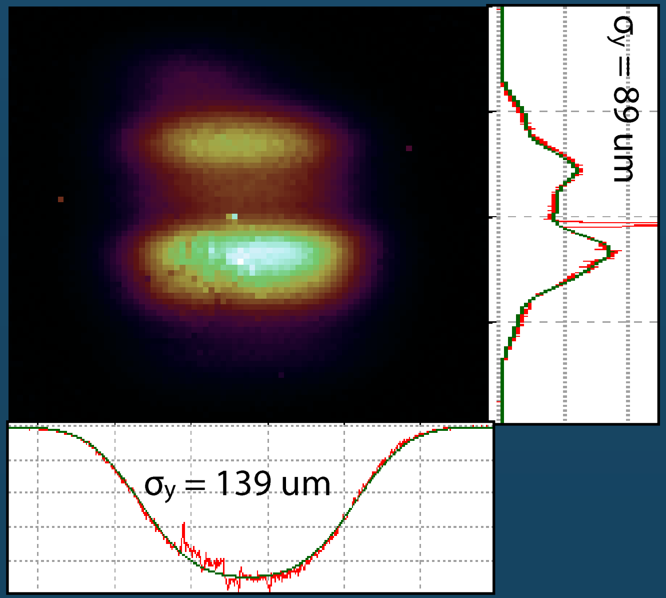
4. X-ray images projected to a YAG/LuAG scintillator

5. CMOS area camera

Cheep & robust

Slow (t_{exp}~few turns)

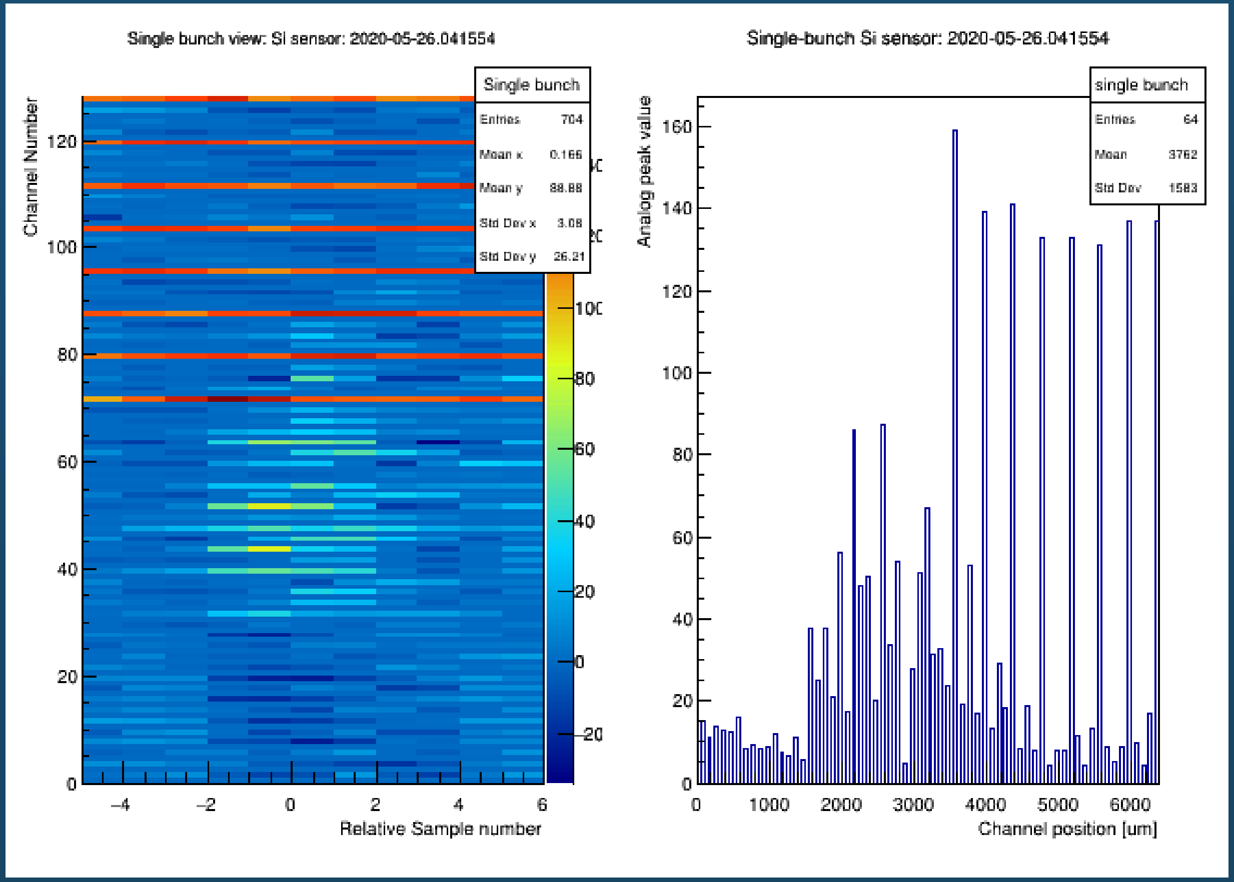
Sharp image → Small σ



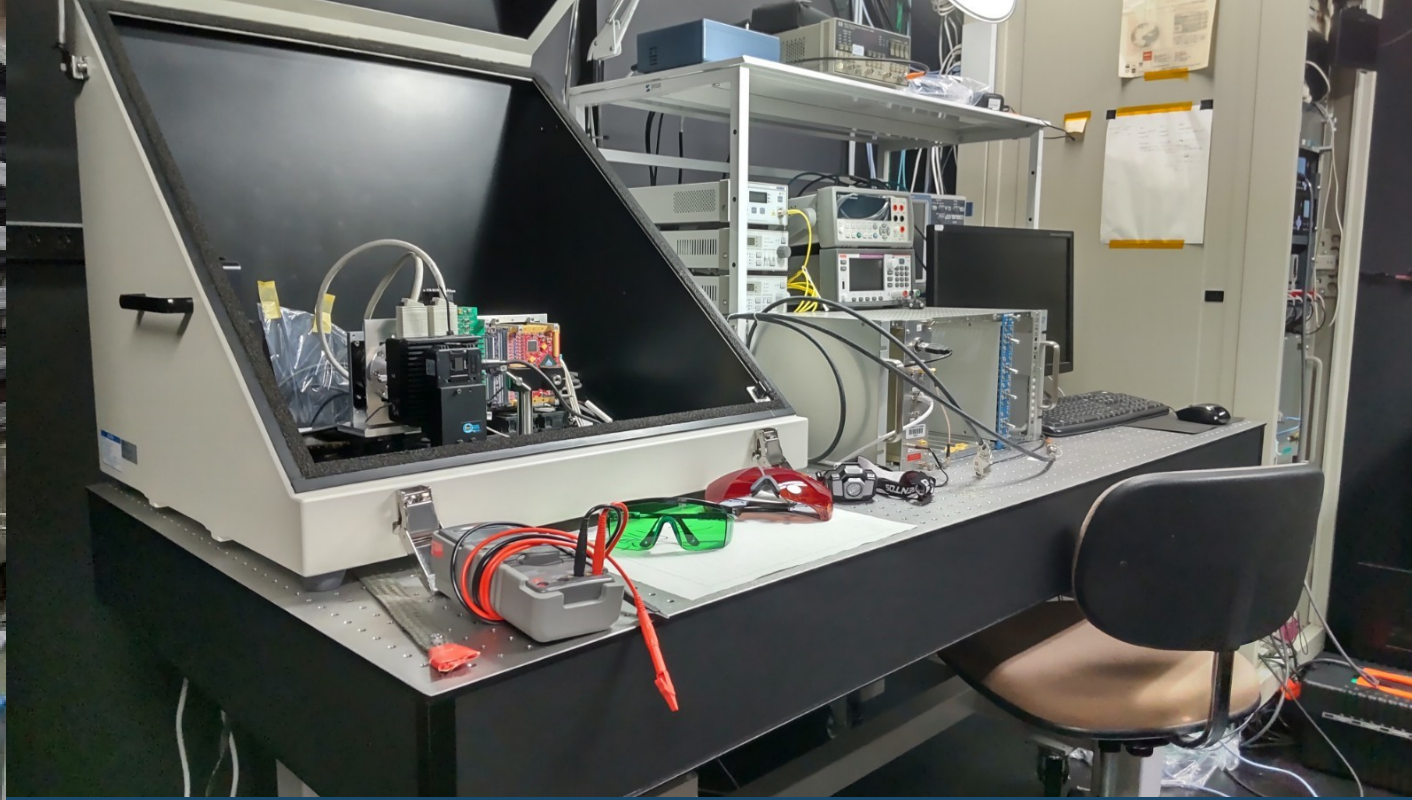
Broad image → Large σ

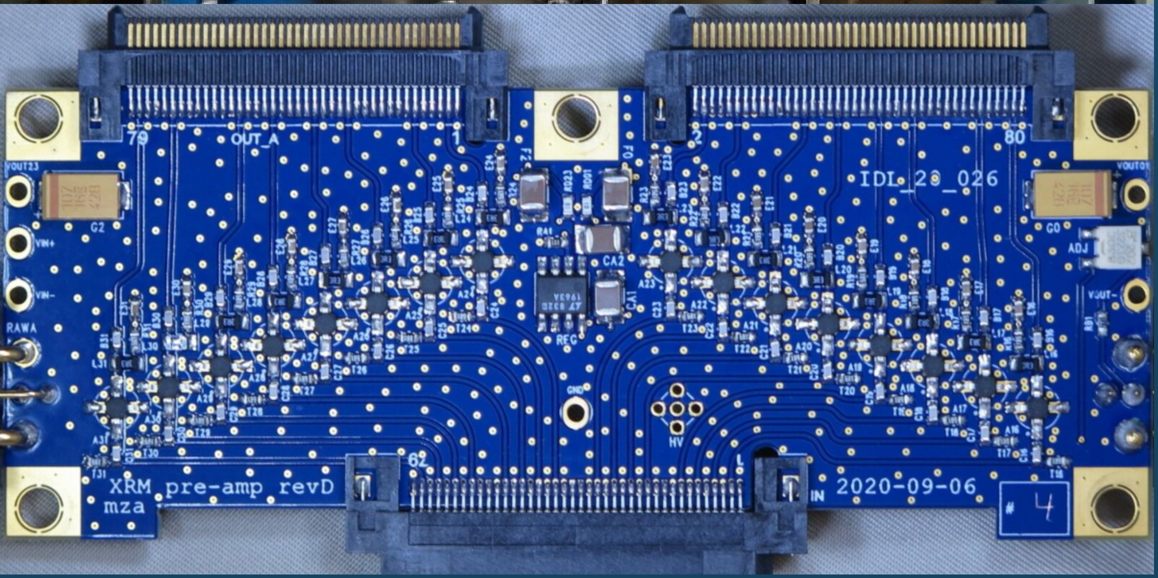
5. Silicon-strip X-ray beam size monitor “SiXRM”

- 50 µm x 128 ch
- 2.7GSa/s ~0.37 ns shorter than 6 ns bunch spacing



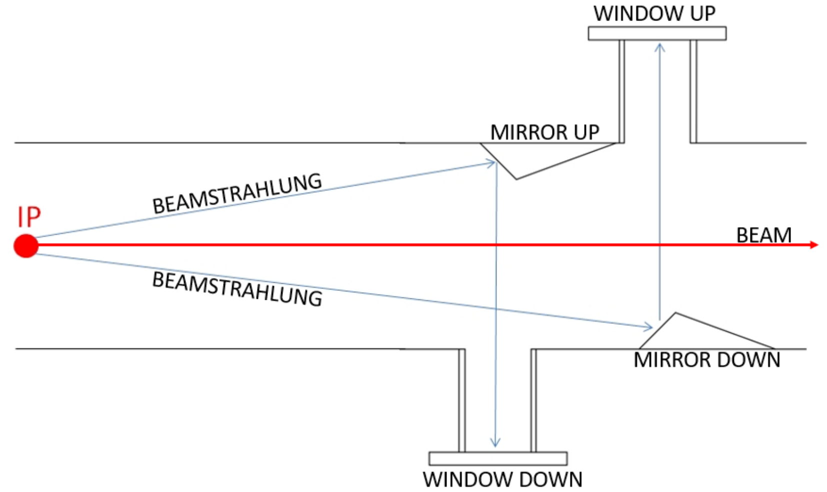
- Successfully catching the signal of one bunch
- Activate every other channel due to a cooling issue
- Oscillation & imperfect ch-by-ch gain calibration



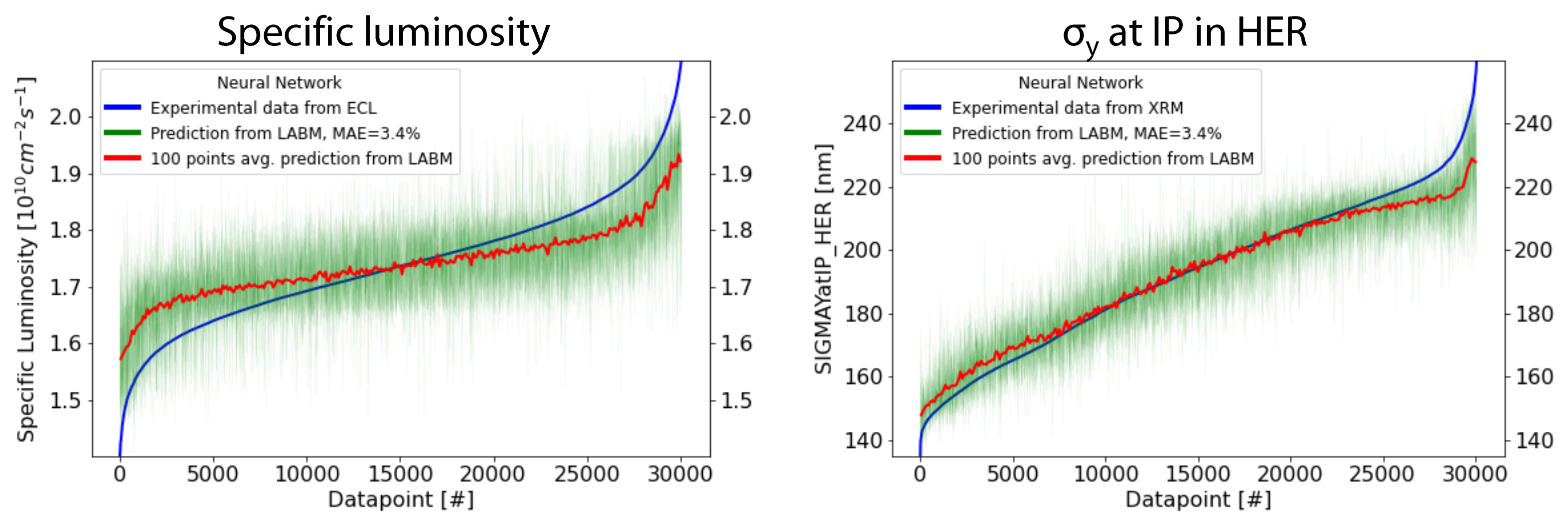


- Revised pre-amplifier initially tested
- FPGA re-programming for better stability
- Channel-by-channel gain calibration
- SuperKEKB beam study (electron cloud, etc.)
- Extension to the horizontal axis, pixel det., RFSoC, etc.

6. Large Angle Bremsstrahlung Monitor



- Bremsstrahlung is the radiation of the particles of one beam due to the bending force of the EM field of the other beam.
- In a recent paper, LABM demonstrates its ability to reconstruct the SuperKEKB beam parameters using the LABM inputs through a neural network approach.
- Nest step is to introduce all the 32 PMTs to analyses.



Specific luminosity

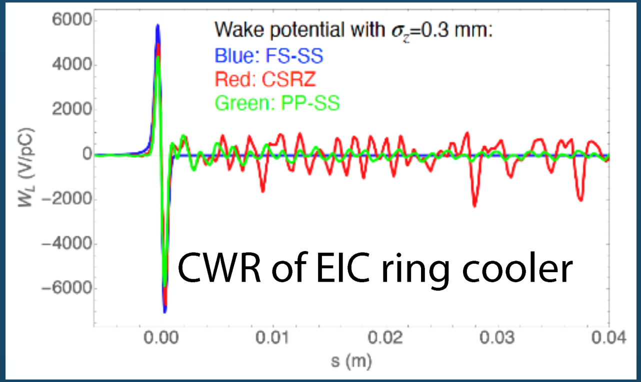
σ_y at IP in HER

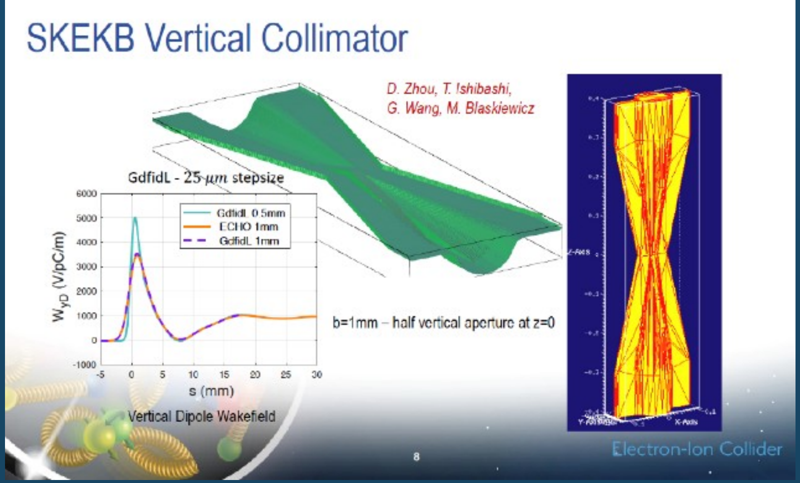
(S.Di Carlo et. al., NIM A 1042 1, 167453 (2022))

7. Accelerator physics

Achievements supported by the US-Japan project:

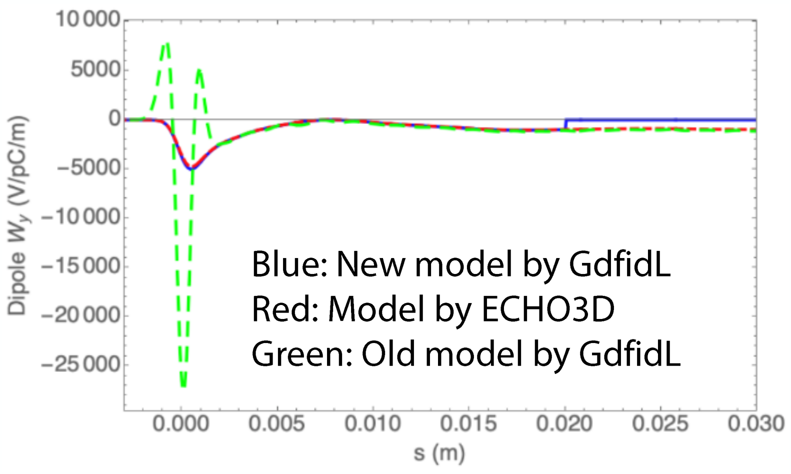
- Theories and numerical simulations of CWR impedance and instability applied to EIC ring cooler
- Impedance modeling for small-gap collimators applied to SuperKEKB
- Optics design with spin rotators for e- polarization
- Nonlinear optics optimization for SuperKEKB

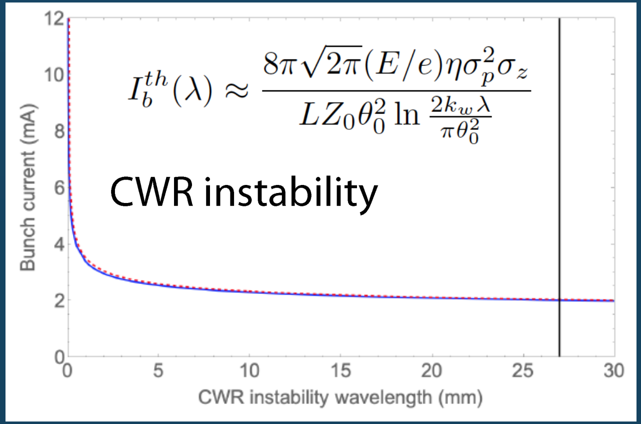




SKEKB Vertical Collimator

D. Zhou, T. Ishibashi, G. Wang, M. Blaskiewicz





US-Japan collaborations create mutual benefits for the success of collider projects in the US (EIC) and Japan (SuperKEKB).

(A. Blednykh et. al., PRAB 26, 051002 (2023))

8. Summary

- SuperKEKB, a luminosity frontier machine, achieved the world's highest luminosity L = 4.65 x 10^{34} $cm^{-2}s^{-1}$ in June 2022.
- We have already started R&D of various components towards our next target
  - 2.4 x 10^{35} $cm^{-2}s^{-1}$ (by summer 2026) and 6 x 10^{35} $cm^{-2}s^{-1}$ (in early 2030s)
- The US-Japan research collaboration has given and will give the significant contribution to the success of SuperKEKB and future high-luminosity colliders.

Acknowledgements:

M. Tobiyama, J. Seeman, R. Ueki, S. Nakamura, T. Oki, J. Dusatko, S. Terui, T. Ishibashi,
N. Ohuchi, Y. Arimoto, M. Andrew, G. Varner, D. Zhou, and many others!

Backup

Many work in the Long Shutdown 1 (2022 Jun - 2023 Dec)

SuperKEKB

- Radiation shield at the IP and other exp. halls
- Radiation shield for the bellows at the IP
- Upgrade of the QCS-cryostat front plate
- Refurbishment of the beam collimators
- Non-linear collimator in the OHO straight section
- Upgrade of the beam-injection line
- Refurbishment of the coupling cavity of the ARES cavity
- Upgrade of the X-ray beam size monitor
- Reinforcement of beam-loss monitors
- Vacuum leak detection for QCS magnet- and service-cryostat
- Replacement of the D5A ARES cavity
- Replacement of the RF input coupler at D08-D, E1, E2
- Upgrade of the MR safety system
- Update of the revolution signal distributor
- Setup of a new NAS system

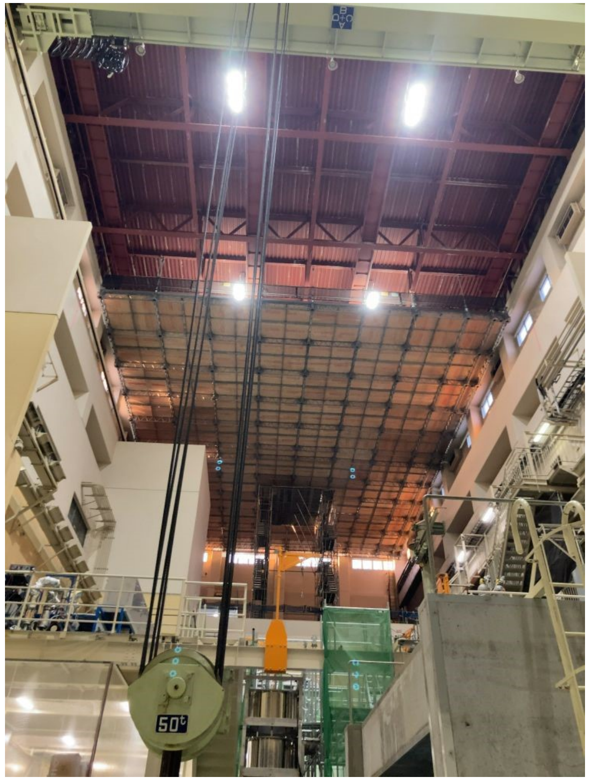
etc…

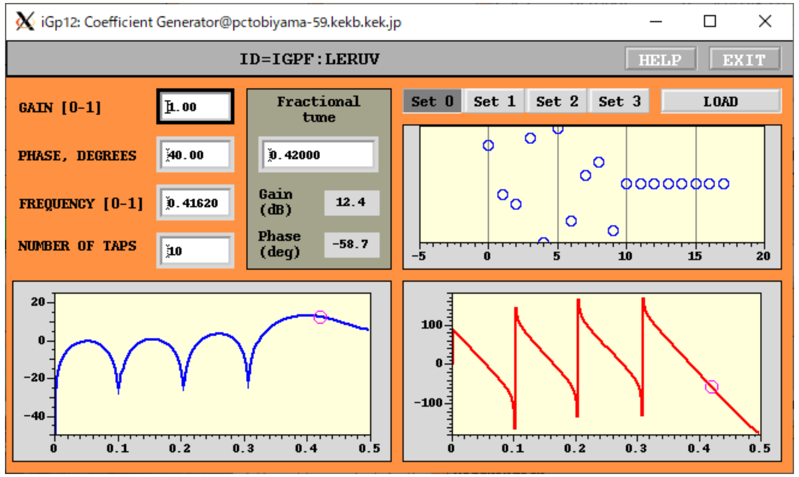
Belle II

- Replacement of the PXD and TOP detectors
- Replacement of the IP chamber

etc…

- Ceiling work at the FUJI and OHO halls.

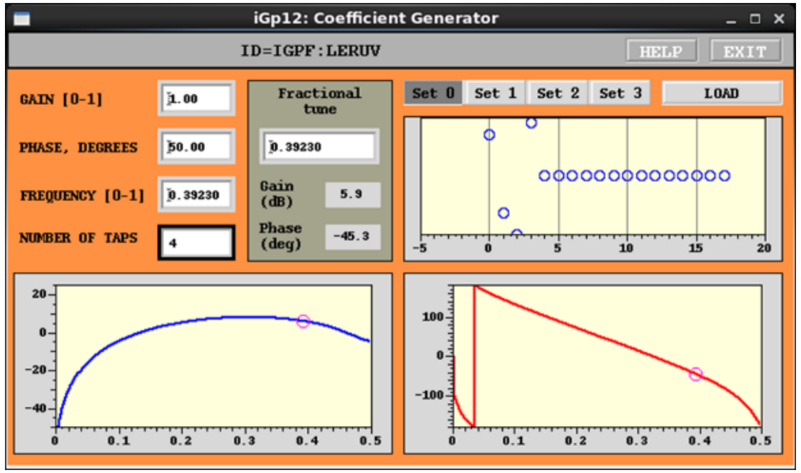



iGp12: Coefficient Generator@pctobiyama-59.kekb.kek.jp

ID=IGPF:LERUV

GAIN [0-1]: 1.00
PHASE, DEGREES: 40.00
FREQUENCY [0-1]: 0.41620
NUMBER OF TAPS: 10

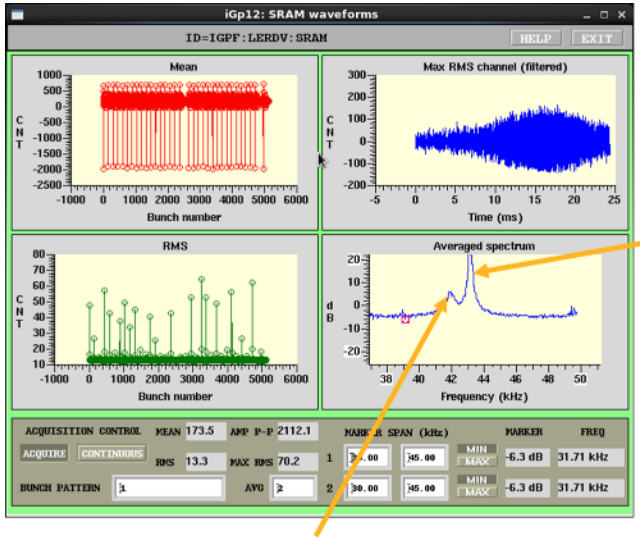
Fractional tune: 0.42000
Gain (dB): 12.4
Phase (deg): -58.7


iGp12: Coefficient Generator

ID=IGPF:LERUV

GAIN [0-1]: 1.00
PHASE, DEGREES: 50.00
FREQUENCY [0-1]: 0.39230
NUMBER OF TAPS: 4

Fractional tune: 0.39230
Gain (dB): 5.9
Phase (deg): -45.3


iGp12: SRAM waveforms

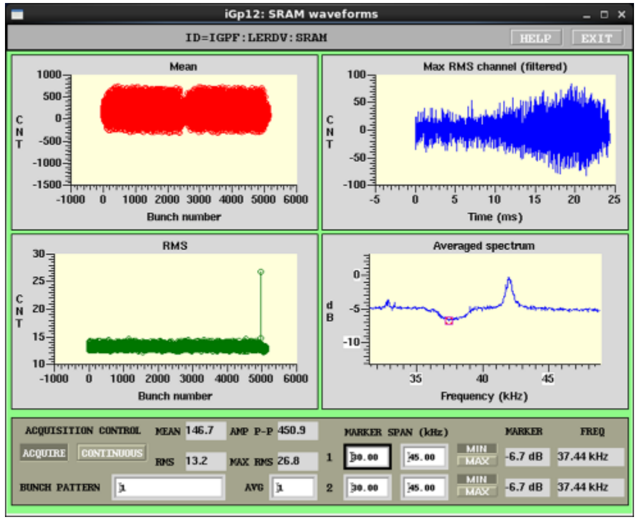
ID=IGPF:LERDV:SRAM

ACQUISITION CONTROL
MEAN 173.5 AMP P-P 2112.1
RMS 13.3 MAX RMS 70.2
BUNCH PATTERN 1 AVG 2

	MARKER SPAN (kHz)			MARKER	FREQ
1	3[illegible].00	45.00	MIN MAX	-6.3 dB	31.71 kHz
2	30.00	45.00	MIN MAX	-6.3 dB	31.71 kHz

betatron +
fs (like) line

normal betatron freq.


iGp12: SRAM waveforms

ID=IGPF:LERDV:SRAM

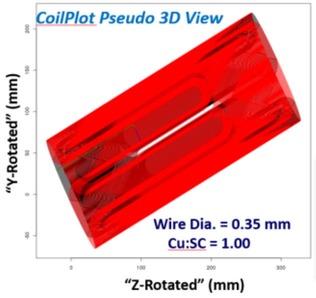
ACQUISITION CONTROL
MEAN 146.7 AMP P-P 450.9
RMS 13.2 MAX RMS 26.8
BUNCH PATTERN 1 AVG 1

	MARKER SPAN (kHz)			MARKER	FREQ
1	30.00	45.00	MIN MAX	-6.7 dB	37.44 kHz
2	30.00	45.00	MIN MAX	-6.7 dB	37.44 kHz

SC corrector magnet design study by BNL

- Multi-types of SC corrector magnets have been studied by the BNL group.
- Corrector magnet for SC sextupole magnet
  - Studies in JFY 2021:
    - The correctors were designed for assembling them in the sextupole magnet bore.
    - Corrector magnet parameters were studied by BNL.
  - **In JFY 2022:**
    - BNL proposed the system design where the correctors are placed in the bore to the outside of the collar.
    - In discussion with KEKB vac. group, it was turned out that the LER magnet design can be used for the HER.
- QCS upgrade
  - The corrector magnet preliminary design of the plan #3 was performed by BNL in JFY 2021.
  - For designing the correctors in the revised plan #3, the magnet system design should be more studied.

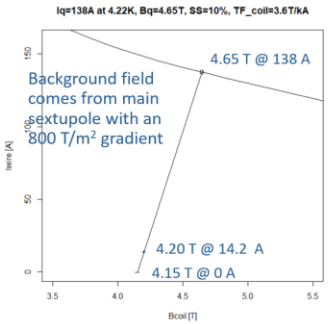
The corrector magnet design study for the sextupole magnet by BNL
Normal quadrupole(b_2) corrector magnet (for correction of the sextupole magnetic center)



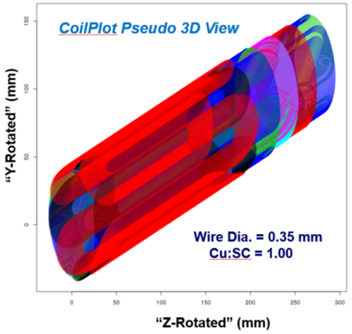
Layer Radius (mm)
71.45
72.06

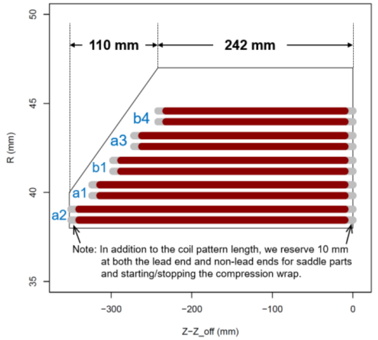
For 0.4*(.25/.225) T/m Gradient, I_{op} = 14.2 A

A b2 coil length of 334 mm yields an effective magnetic length of 225 mm.



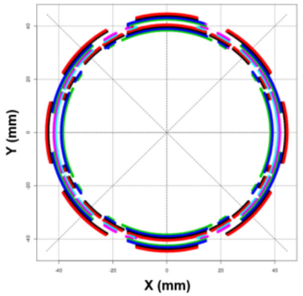
The corrector magnet design study for QCS upgrade plan #3



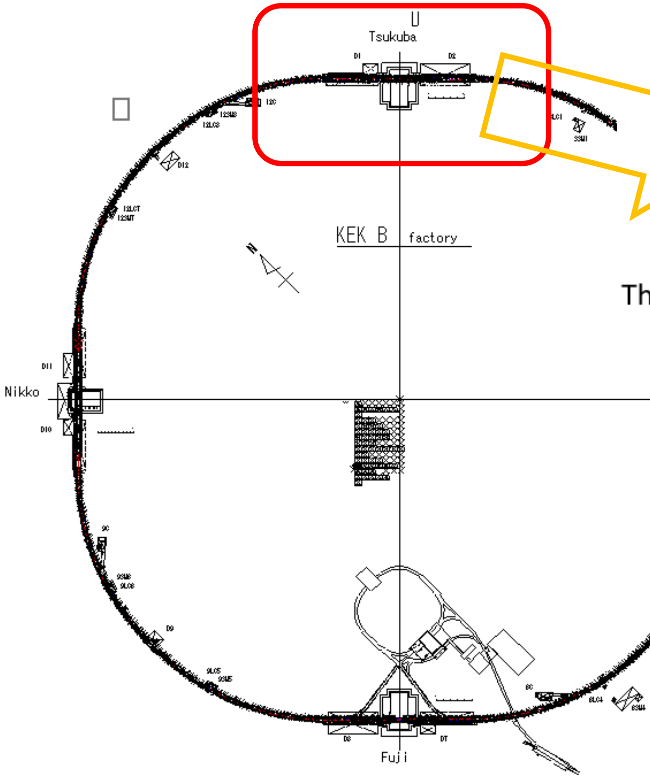


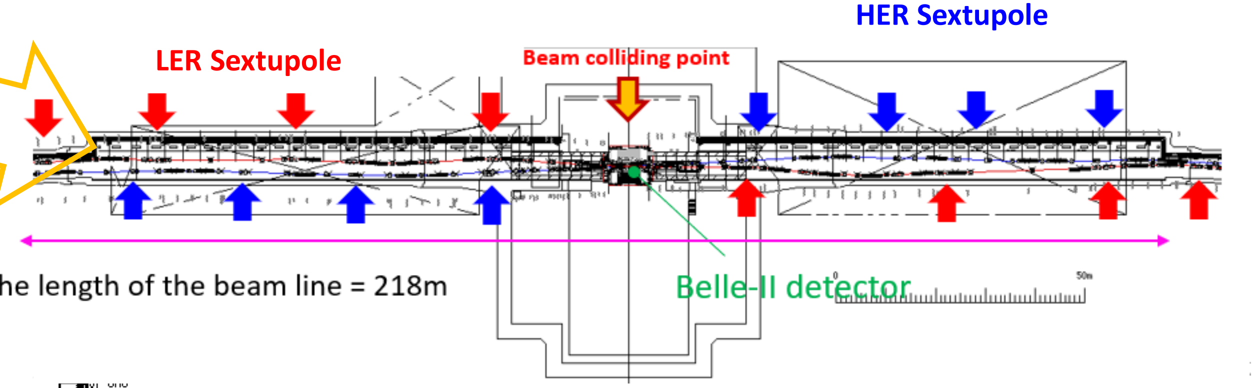
Note: In addition to the coil pattern length, we reserve 10 mm at both the lead end and non-lead ends for saddle parts and starting/stopping the compression wrap.

Corrector Identifyer	Layer Radius	Pattern Length	Magnetic Length	Target Integrated Strength	Current at Target Strength
	(mm)	(mm)	(mm)	Tm, T, T/m, T/m^2	(A)
b4	44.58 43.97	222	190	60	12
a3	43.19 42.58	252	210	5.1	19.3
b1	41.8 41.19	278	155	0.016	46.6
a1	40.43 39.82	304	184	0.016	39.6
a2	39.06 38.45	330	272	0.64	40.7



SC sextupole magnet R&D

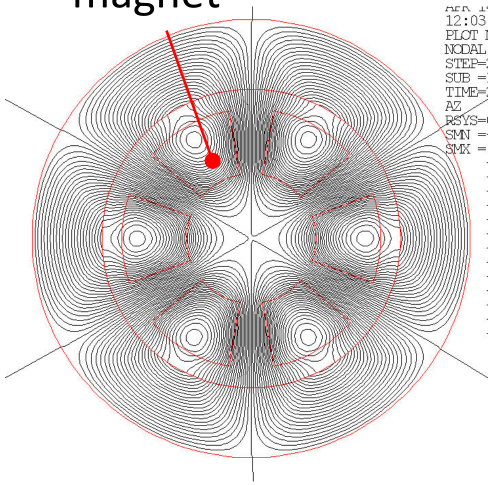




SC sextupole magnet design parameter(LER)

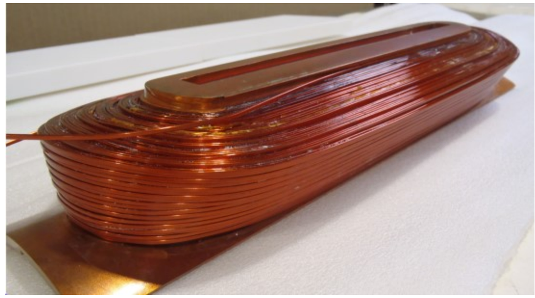
- Inner radius of the coil : R_i=65.2 mm
- Outer radius of the coil : R_o=131.25 mm
- Inner radius of the yoke : R_i=135 mm
- Outer radius of the yoke : R_o=200 mm
- Max. field in the coil : B_{max}=4.73 T
- Field gradient : B''=825 T/m^2

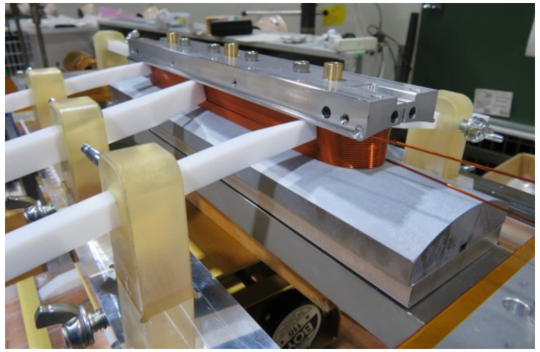
Superconducting magnet



Magnetic flux line of the SC sextupole magnet

Constructed R&D SC coil in JFY 2021





Improved coil production tooling in JFY 2022

Non-linear collimator

- Non-linear collimator is an idea to prevent transverse-mode-coupled instability (TMCI).

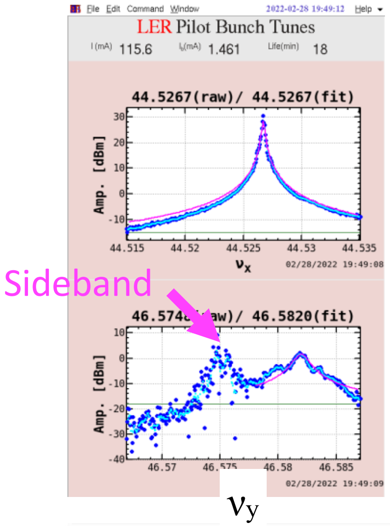
Conventional normal collimator

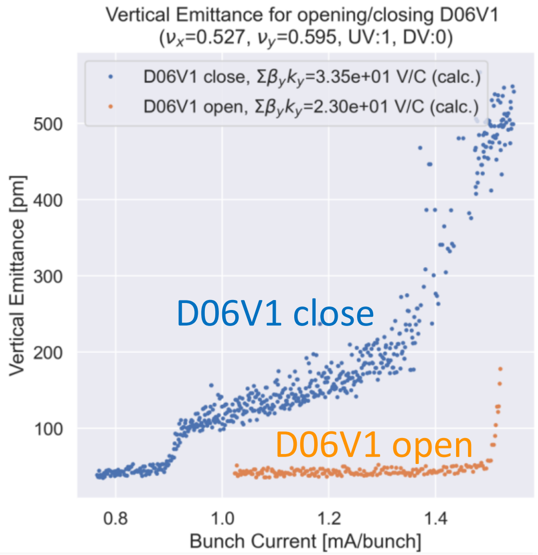
  - Narrow collimators are placed in large-β sections
  - Narrow collimators have a large kick factor k.
  - Increase in βk decreases the TMCI threshold.

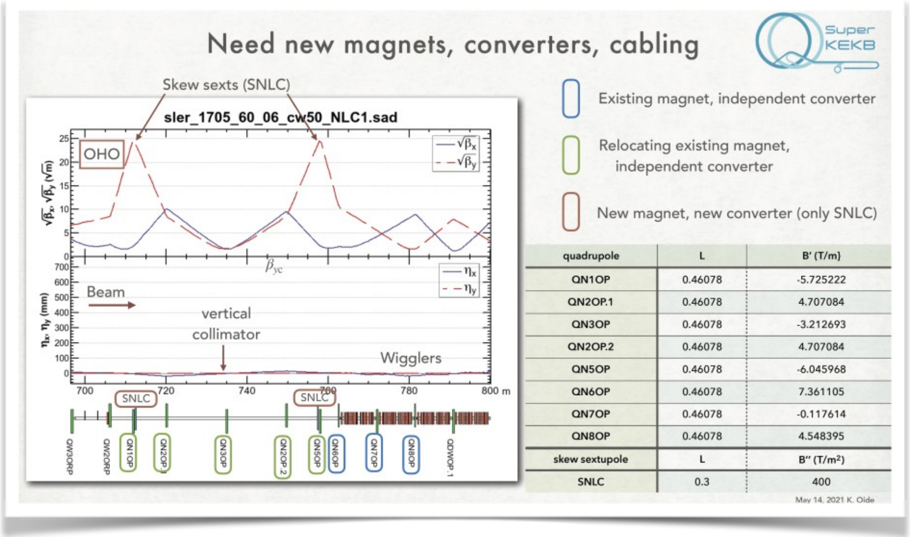
$$I_{\mathrm{thr}} \propto \frac{1}{\sum_i \beta_i k_i}$$

Non-linear collimator

  - Enlarges beam size using a non-linear kick of skew sextupole magnets
  - Enables beam collimation in low-β section and wide collimator aperture
  - βk can be decreased, leading to high TMCI thresholds





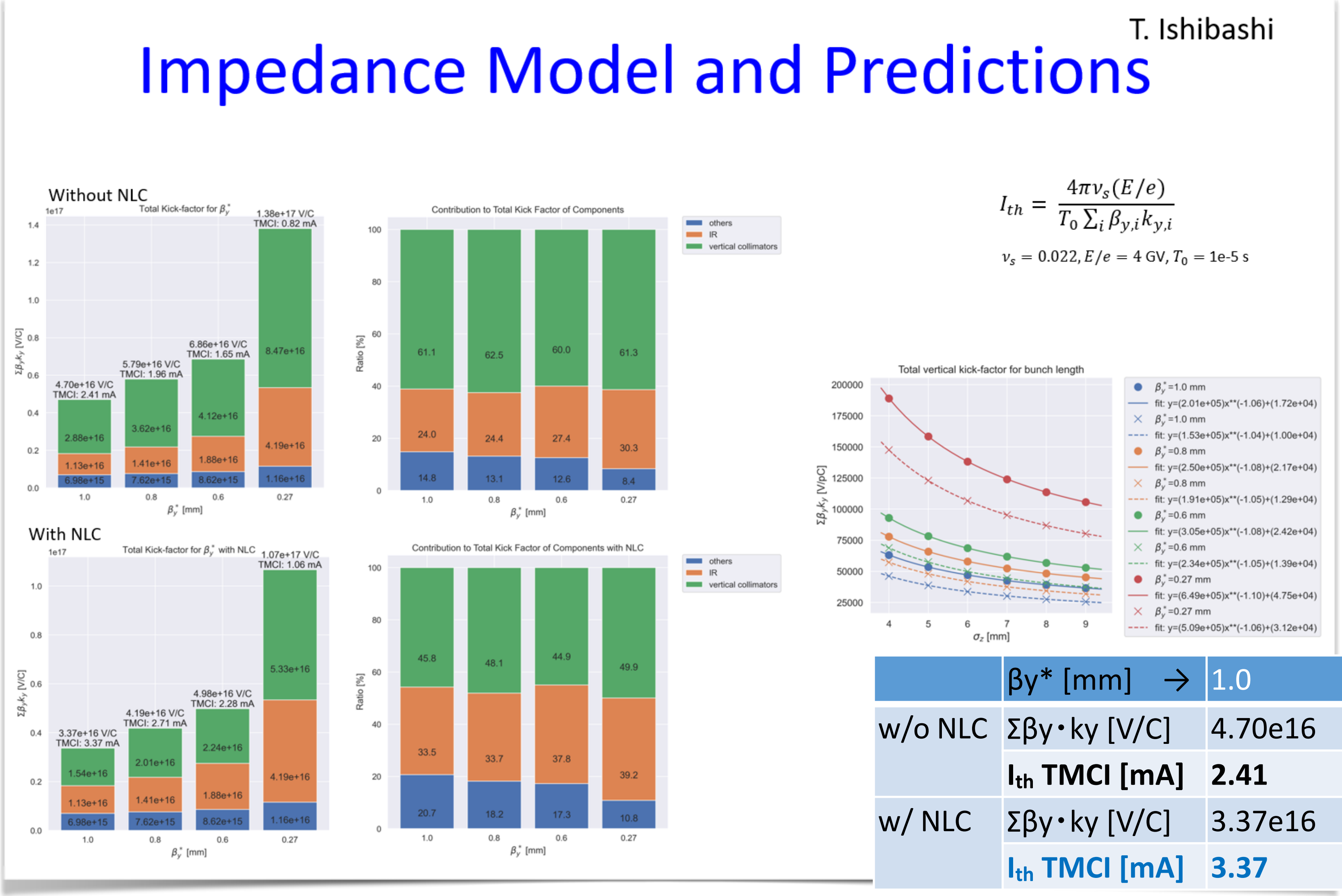


quadrupole	L	B′ (T/m)
QN1OP	0.46078	-5.725222
QN2OP.1	0.46078	4.707084
QN3OP	0.46078	-3.212693
QN2OP.2	0.46078	4.707084
QN5OP	0.46078	-6.045968
QN6OP	0.46078	7.361105
QN7OP	0.46078	-0.117614
QN8OP	0.46078	4.548395
skew sextupole	L	B″ (T/m²)
SNLC	0.3	400

May 14, 2021 K. Oide

Non-linear collimator

T. Ishibashi



Impedance Model and Predictions

$$I_{th} = \frac{4\pi\nu_s(E/e)}{T_0\sum_i \beta_{y,i}k_{y,i}}$$

$\nu_s = 0.022, E/e = 4$ GV, $T_0 = 1\text{e-}5$ s

	βy* [mm] →	1.0	0.8	0.6	0.27
w/o NLC	Σβy・ky [V/C]	4.70e16	5.79e16	6.86e16	1.37e17
	I_{th} TMCI [mA]	**2.41**	**1.96**	**1.65**	**0.82**
w/ NLC	Σβy・ky [V/C]	3.37e16	4.19e16	4.98e16	1.07e17
	I_{th} TMCI [mA]	**3.37**	**2.71**	**2.28**	**1.06**