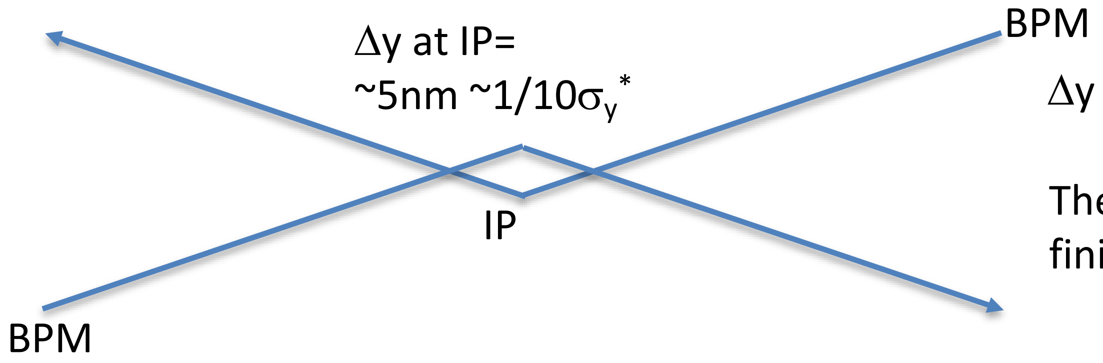
Experience of collision control using beam-beam deflection at KEKB/SuperKEKB

Y. Funakoshi for people working for iBump Feedback

EPOL Workshop 2022.09.26

Two methods for collision control

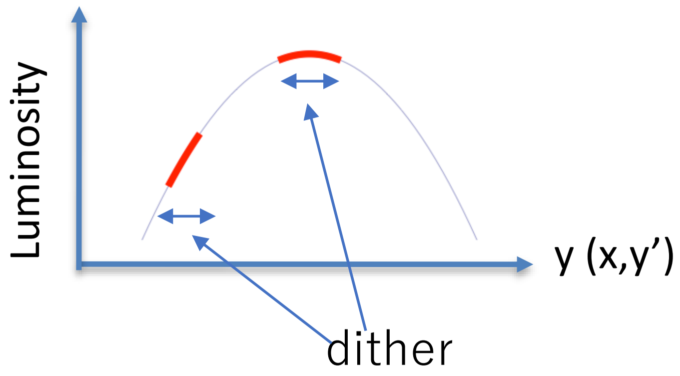
- Beam-beam deflection (SLC, KEKB (y, x), SuperKEKB (y))



Δy at BPM= ~1.3μm

The orbit kink due to beam-beam deflection with finite orbit offset is detected with BPM's near IP.

- Luminosity dithering method (PEP-II (x,y,y'), SuperKEKB (x))



When we dither the beam with some frequency at around the peak of the luminosity, the dithering frequency component of the luminosity change becomes minimum.

Experience of collision control using beam-beam deflection at KEKB/SuperKEKB/~~PEP-II~~

BPM’s for IP orbit feedback

$$k_y = \frac{4p}{b_y^*} x_y$$

BPMs at SuperKEKB should have higher sensitivity than KEKB.

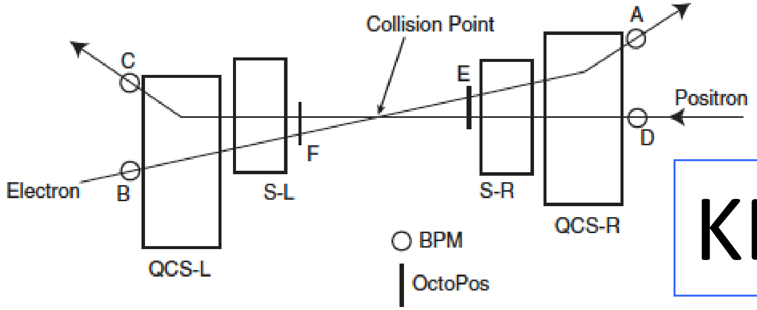
$$Dy' = -\frac{k_y}{2} Dy$$

$$Dy = \frac{s_y^*}{D} = \frac{\sqrt{b_y^* e_y}}{D}$$

$$Dy' = -\frac{2p}{D}\sqrt{\frac{e_y}{b_y^*}} x_y$$

$$Dy^{BPM} \approx \frac{\sqrt{b_y^{BPM} b_y^*}}{2} Dy'$$

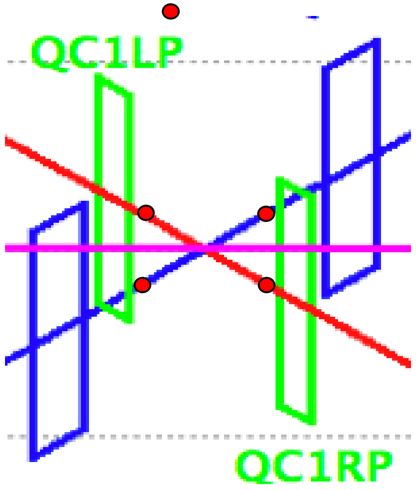
	KEKB	SuperKEKB
$\beta_y{}^*$	5.9mm	0.27mm
ε_y	0.15nm	8.6pm
$\sqrt{e_y / b_y^*}$	1.59 x 10^{-4}	1.78 x 10^{-4}
$\sqrt{b_y^{BPM} b_y^*}$	2.0m	0.5m



KEKB

$\sqrt{b_y^{BPM} b_y^*} » 2.0m$ A,B,C,D: BPM ~2.4m from IP

BPM resolution: ~2μm@1.6A



BPM (l~50cm from IP)

SuperKEKB

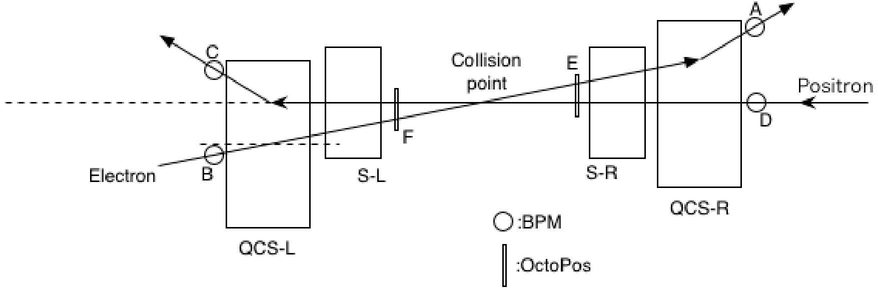
$\sqrt{b_y^{BPM} b_y^*} » 0.5m$

BPM resolution: ~0.2μm@3.6A

Feedback parameter (vertical offset at IP)

$$y_e^A = m_{33}^A y_e^* + m_{34}^A y_e'^{*a}$$

$$y_e^B = m_{33}^B y_e^* + m_{34}^B y_e'^{*b}$$



y_e^* :vertical offset at IP

$y_e'^{*a}$:vertical angle at IP after collision, $y_e'^{*b}$:vertical angle at IP before collision

m^A :transfer matrix from IP to A, m^B :transfer matrix from IP to B

$$\Delta y_e'^* = y_e'^{*a} - y_e'^{*b} = \left(\frac{y_e^A}{m_{34}^A} - \frac{y_e^B}{m_{34}^B}\right) - \left(\frac{m_{33}^A}{m_{34}^A} - \frac{m_{33}^B}{m_{34}^B}\right) y_e^*$$

$\Delta y_e'^*$: vertical beam - beam kick

$$\Delta y_p'^* = y_p'^{*a} - y_p'^{*b} = \left(\frac{y_p^C}{m_{34}^C} - \frac{y_p^D}{m_{34}^D}\right) - \left(\frac{m_{33}^C}{m_{34}^C} - \frac{m_{33}^D}{m_{34}^D}\right) y_p^*$$

Calculated from readings of 4 BPMS

$$\Delta y'^*_{canonical} \equiv \frac{\left(\frac{y_e^A}{m_{34}^A} - \frac{y_e^B}{m_{34}^B}\right)}{\left(\frac{m_{33}^A}{m_{34}^A} - \frac{m_{33}^B}{m_{34}^B}\right)} - \frac{\left(\frac{y_p^C}{m_{34}^C} - \frac{y_p^D}{m_{34}^D}\right)}{\left(\frac{m_{33}^C}{m_{34}^C} - \frac{m_{33}^D}{m_{34}^D}\right)} = \frac{\Delta y_e'^*}{\left(\frac{m_{33}^A}{m_{34}^A} - \frac{m_{33}^B}{m_{34}^B}\right)} - \frac{\Delta y_p'^*}{\left(\frac{m_{33}^C}{m_{34}^C} - \frac{m_{33}^D}{m_{34}^D}\right)} + \left(y_e^* - y_p^*\right)$$

Canonical beam-beam kick (vertical)

$$\Delta y'^{*}_{cannonical} = \frac{\Delta y'^{*}_{e}}{\left(\frac{m^{A}_{33}}{m^{A}_{34}} - \frac{m^{B}_{33}}{m^{B}_{34}}\right)} - \frac{\Delta y'^{*}_{p}}{\left(\frac{m^{C}_{33}}{m^{C}_{34}} - \frac{m^{D}_{33}}{m^{D}_{34}}\right)} + \left(y^{*}_{e} - y^{*}_{p}\right)$$

$$= -\left(\frac{k_{ey}}{m_{ey}} + \frac{k_{py}}{m_{py}} - 1\right)\Delta y^{*}$$

$$= -K_{y}\Delta y^{*}$$

Proportional to IP offset

$$k_{ey} = \frac{4\pi}{\beta^{*}_{ey}}\frac{\xi_{ey}}{2}, \quad k_{py} = \frac{4\pi}{\beta^{*}_{py}}\frac{\xi_{py}}{2}$$

$$\Delta y^{*} = y^{*}_{e} - y^{*}_{p}$$

$$\Delta y'^{*}_{e} = -k_{ey}\Delta y^{*}$$

$$\Delta y'^{*}_{p} = +k_{py}\Delta y^{*}$$

$$m_{ey} = \frac{m^{A}_{33}}{m^{A}_{34}} - \frac{m^{B}_{33}}{m^{B}_{34}}$$

$$m_{py} = \frac{m^{C}_{33}}{m^{C}_{34}} - \frac{m^{D}_{33}}{m^{D}_{34}}$$

In real machine parameters (KEKB)

$$\beta^{*}_{ey} = 6.5\times10^{-3}, \quad \beta^{*}_{py} = 5.2\times10^{-3}$$

$$\xi_{ey} = 0.057, \quad \xi_{py} = 0.074$$

$$k_{ey} = 55.10, \quad k_{py} = 89.41$$

$$m_{ey} = 0.58297$$

$$m_{py} = 0.22968$$

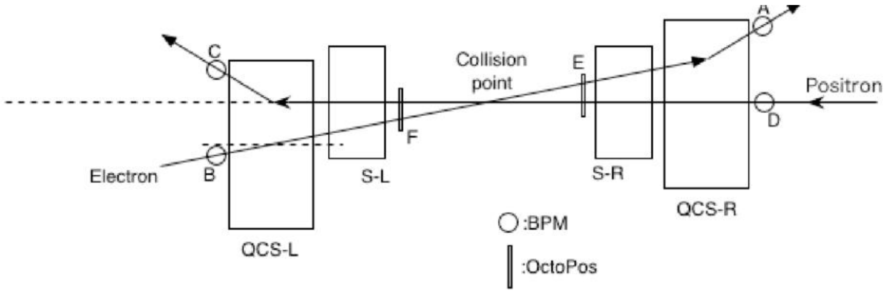
$$\longrightarrow \quad K_{y} = 482.80$$

Horizontal canonical kick is defined and calculated similarly.

Feedback parameter (vertical crossing angle)

$$y_e^A = m_{33}^A y_e^* + m_{34}^A y_e'^{*a}$$

$$y_e^B = m_{33}^B y_e^* + m_{34}^B y_e'^{*b}$$



y_e^* :vertical offset at IP

$y_e'^{*a}$:vertical angle at IP after collision, $y_e'^{*b}$:vertical angle at IP before collision

m^A :transfer matrix from IP to A, m^B :transfer matrix from IP to B

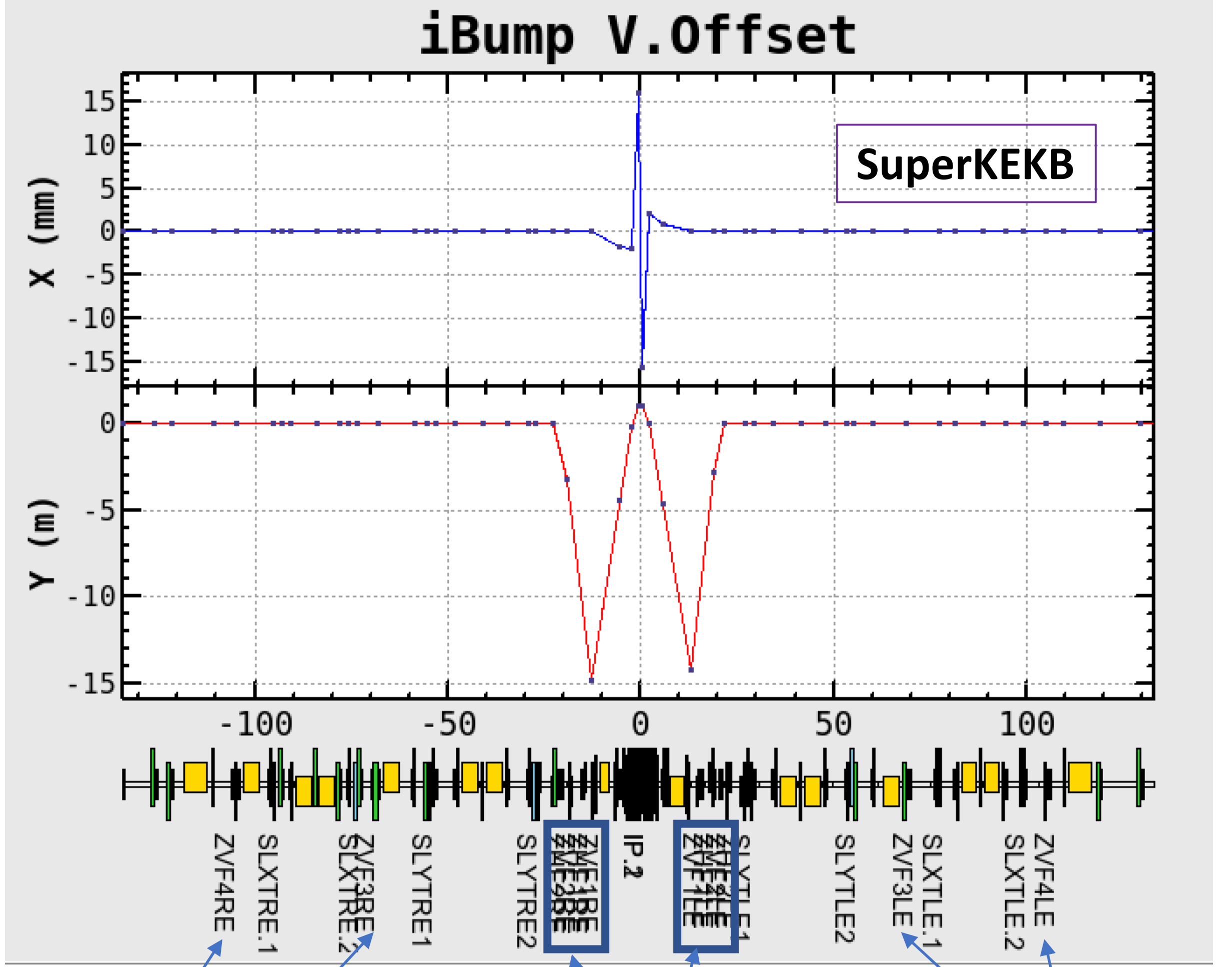
$$\frac{y_e^A}{m_{34}^A} + \frac{y_e^B}{m_{34}^B} = \left(\frac{m_{33}^A}{m_{34}^A} + \frac{m_{33}^B}{m_{34}^B} \right) y_e^* + 2y_e'^{*b} + \Delta y_e'^*$$

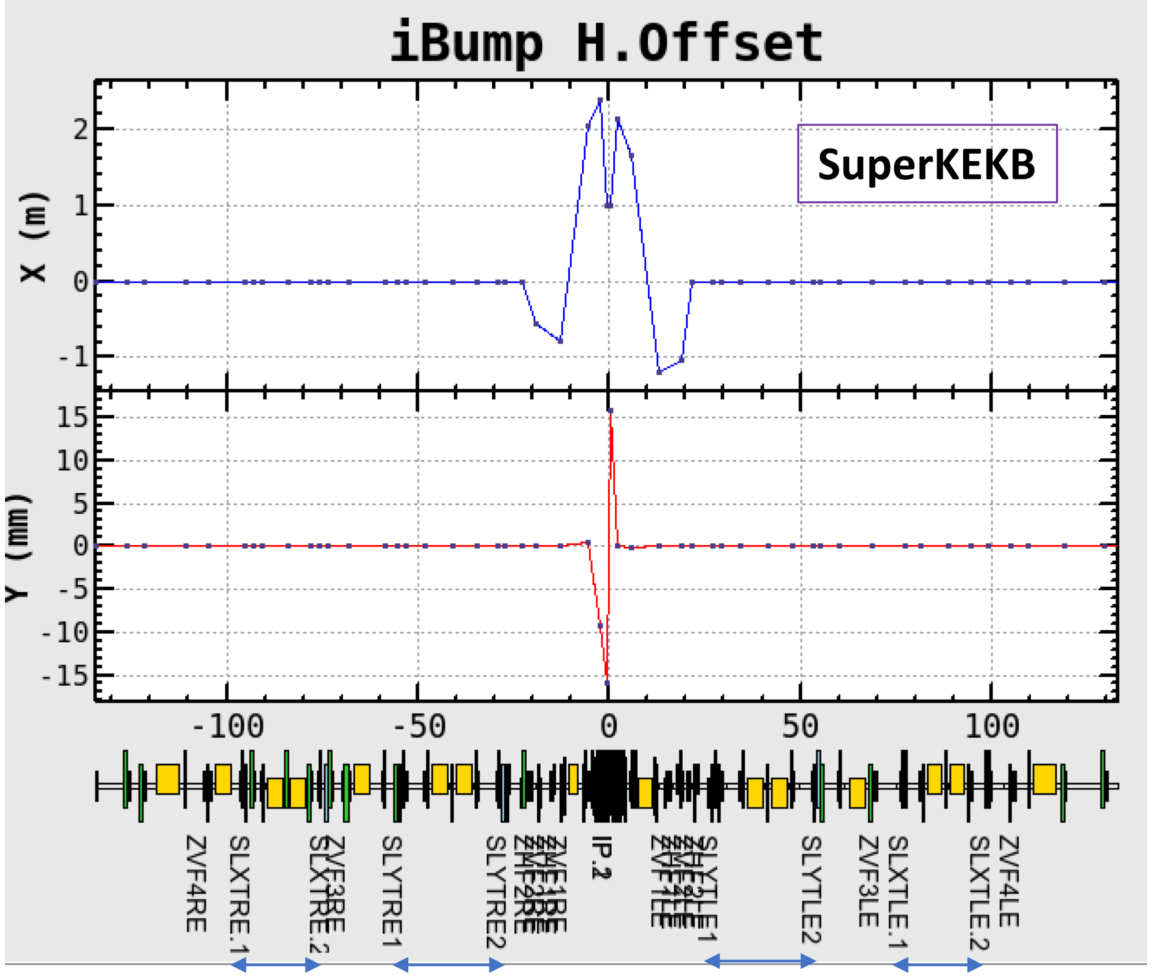
$\Delta y_e'^*$: vertical beam-beam kick

$$\frac{y_p^C}{m_{34}^C} + \frac{y_p^D}{m_{34}^D} = \left(\frac{m_{33}^C}{m_{34}^C} + \frac{m_{33}^D}{m_{34}^D} \right) y_p^* + 2y_p'^{*b} + \Delta y_p'^*$$

$$\theta_{ycanonical} \equiv \frac{\left(\frac{y_e^A}{m_{34}^A} + \frac{y_e^B}{m_{34}^B} \right)}{\left(\frac{m_{33}^A}{m_{34}^A} + \frac{m_{33}^B}{m_{34}^B} \right)} - \frac{\left(\frac{y_p^C}{m_{34}^C} + \frac{y_p^D}{m_{34}^D} \right)}{\left(\frac{m_{33}^C}{m_{34}^C} + \frac{m_{33}^D}{m_{34}^D} \right)} \rightarrow \frac{2y_e'^{*b}}{\left(\frac{m_{33}^A}{m_{34}^A} + \frac{m_{33}^B}{m_{34}^B} \right)} - \frac{2y_p'^{*b}}{\left(\frac{m_{33}^C}{m_{34}^C} + \frac{m_{33}^D}{m_{34}^D} \right)}$$

Steering magnets dedicated for orbit FB (offset)





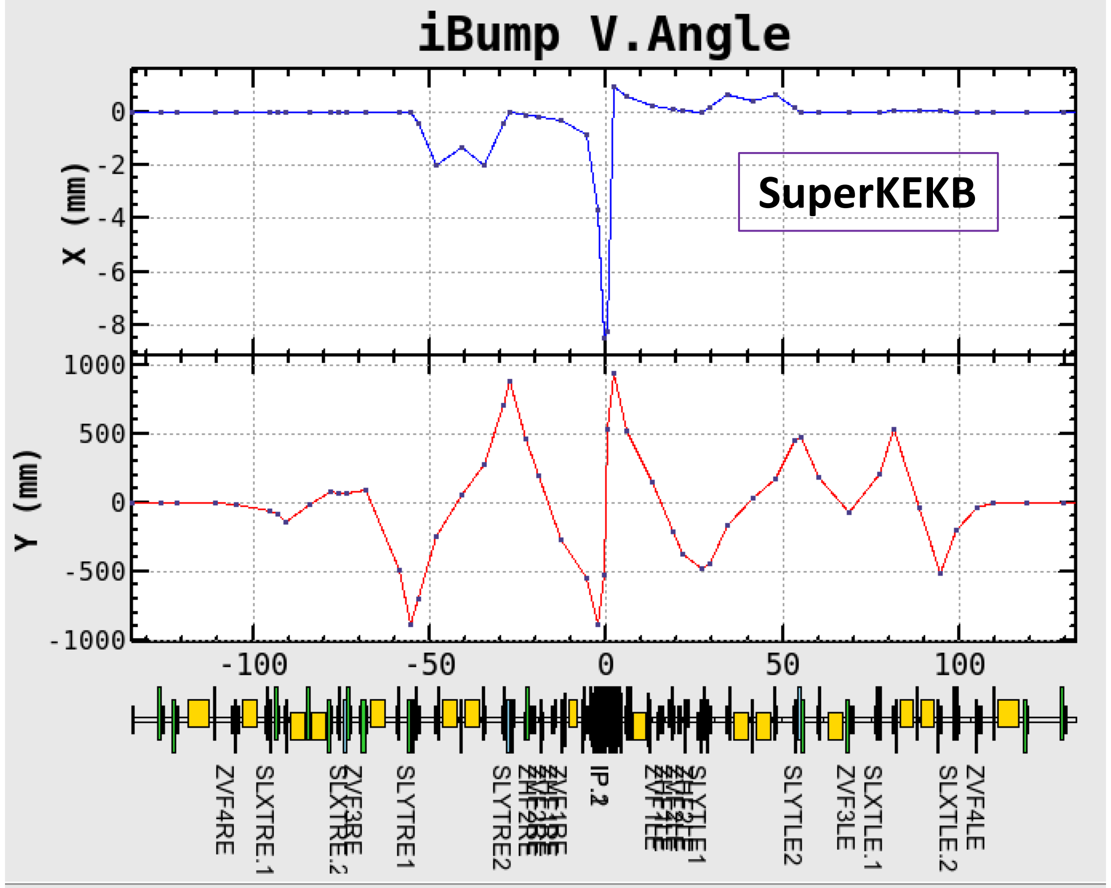
LCCH LCCV LCCV LCCH

Vertical Horizontal/Vertical Vertical

4 horizontal steering magnets
8 vertical steering magnets

100μrad(max) kick angle
@ SUS chamber(5mm^t)

Steering magnets dedicated for orbit FB (v-angle)



For a vertical angle bump, 8 steering magnets are used in order to close the vertical dispersion.

IP orbit feedback

	KEKB	SuperKEKB
IP vertical offset	Beam-beam deflection (used)	Beam-beam deflection (used)
IP vertical angle	used	Not used
IP horizontal offset	Beam-beam deflection (used)	Dithering (not yet used) Slow FB to maintain vertex point is used.

Slow and fast vertical orbit FB

	Slow system	Fast system
Machine	KEKB, SuperKEKB (2018~2021)	SuperKEKB (from autumn 2021)
FB cycle	~ 2 sec (SAD script using EPICS PV's)	32kHz (Dedicated hardware)

Slow feedback system

- Feedback method (linear prediction)

Target value of canonical kick due to BPM offset (obtained by IP offset scan)

$$\Delta y_n = y_n - y_{\text{target}}$$

Canonical kick in n-th FB cycle

$$\Delta y_{n+1} = \sum_{k=1}^{N} c_k \Delta y_{n-k+1}$$

Predicted canonical kick in next FB cycle

$$\begin{pmatrix} \Delta y_{n-1} & \Delta y_{n-2} & \cdots & \Delta y_{n-N} \\ \Delta y_{n-2} & \Delta y_{n-3} & \cdots & \Delta y_{n-N-1} \\ . & . & . & . \\ . & . & . & . \\ \Delta y_{n-M} & \Delta y_{n-M-1} & \cdots & \Delta y_{n-M-N+1} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ . \\ . \\ c_N \end{pmatrix} = \begin{pmatrix} \Delta y_n \\ \Delta y_{n-1} \\ . \\ . \\ . \\ . \\ \Delta y_{n-N+1} \end{pmatrix}$$

N and *M* are determined empirically.
N: 6, *M*: 48
c_k's are determined by the least square method.

$$\Delta y = -G * \boxed{f(\Delta y_{n+1})}$$

Gain factor

Orbit bump height in the next cycle

Orbit offset corresponding to Δy_{n+1}

Performance of slow FB (KEKB)

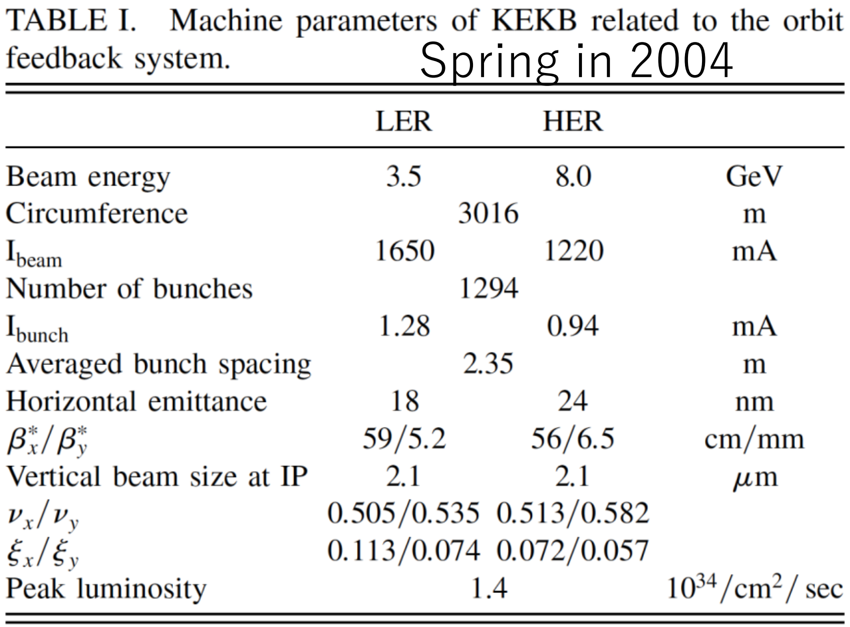


TABLE I. Machine parameters of KEKB related to the orbit feedback system.

Spring in 2004

	LER	HER	
Beam energy	3.5	8.0	GeV
Circumference	3016		m
I_{beam}	1650	1220	mA
Number of bunches	1294		
I_{bunch}	1.28	0.94	mA
Averaged bunch spacing	2.35		m
Horizontal emittance	18	24	nm
β_x^*/β_y^*	59/5.2	56/6.5	cm/mm
Vertical beam size at IP	2.1	2.1	μm
ν_x/ν_y	0.505/0.535	0.513/0.582	
ξ_x/ξ_y	0.113/0.074	0.072/0.057	
Peak luminosity	1.4		$10^{34}/\mathrm{cm}^2/\mathrm{sec}$

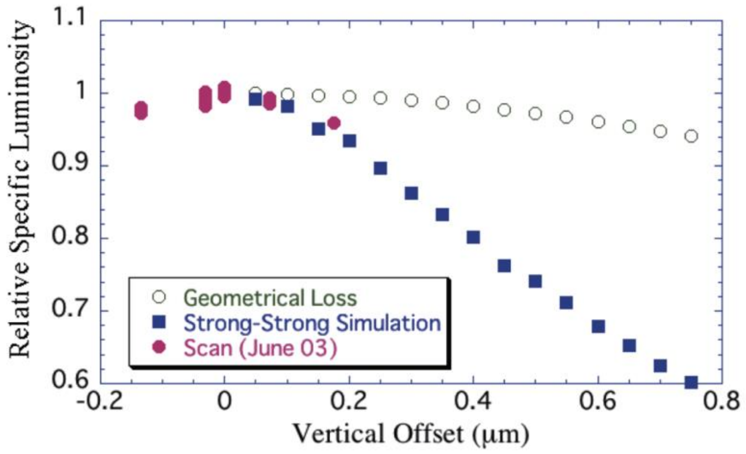
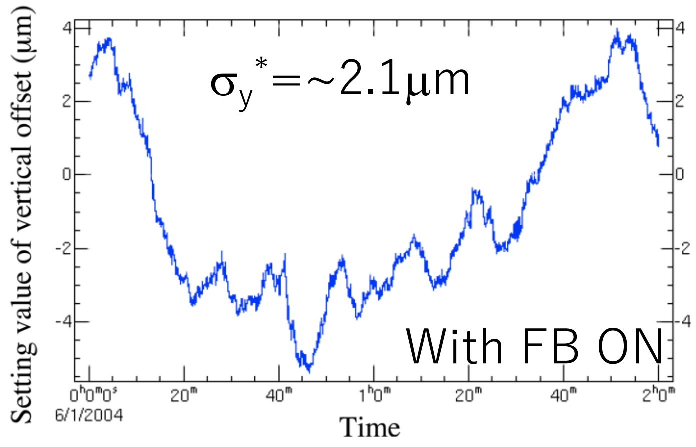


FIG. 5. (Color) Luminosity degradation due to the vertical offset. Both an experimental result and a strong-strong simulation are shown. Also shown is a calculation of a geometrical loss.



σ_y^*=~2.1µm

With FB ON

FIG. 7. (Color) History of the vertical bump amplitude at the IP.

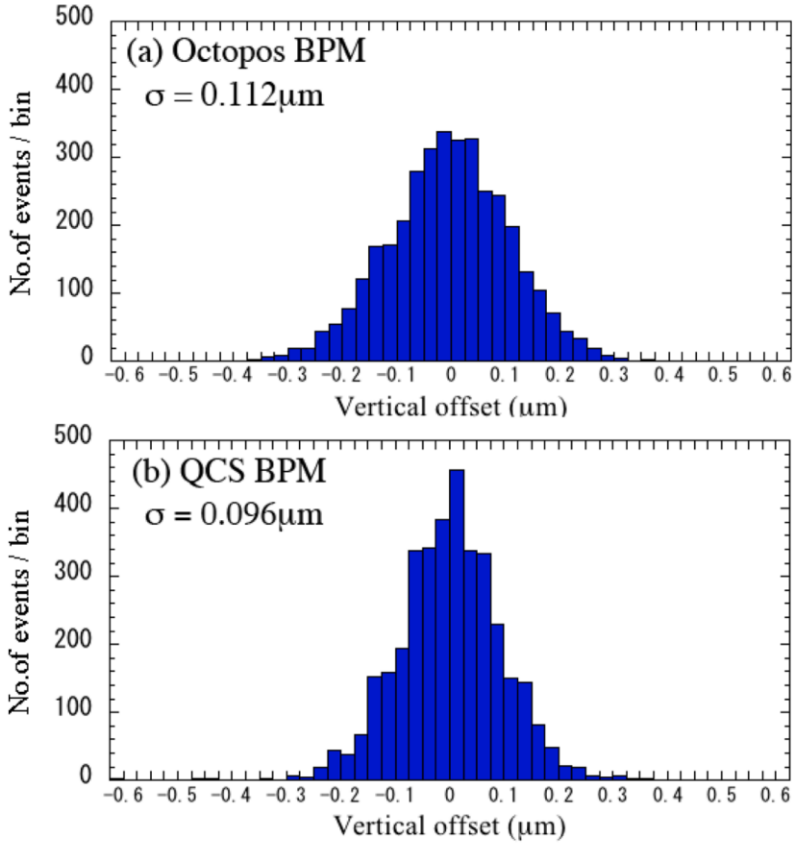
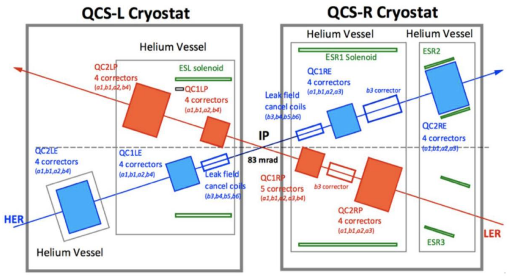
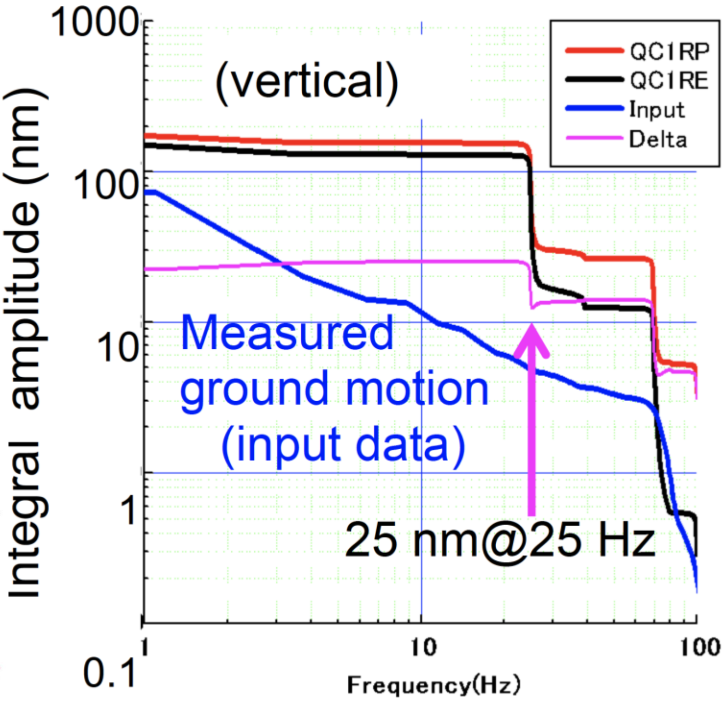


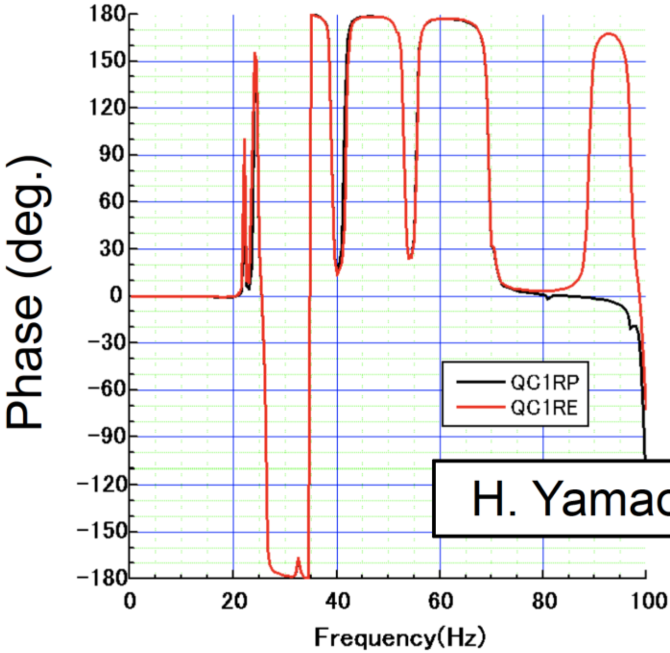
FIG. 10. (Color) The comparison between the feedback with the OctoPos BPMs (a) and the QCS BPMs (b). The abscissa is translated to the vertical offset of the two beams at the IP. The QCS system shows a slightly narrower distribution.

Vertical vibration of QC1RP and QC1RE(simulation)

SuperKEKB







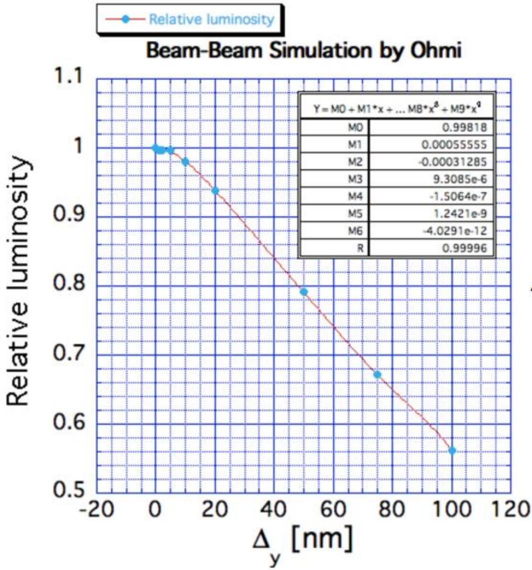
H. Yamaoka

QC1RP and QC1RE vibrate with same phase,

but the amplitude difference still arises: 25 nm at 25 Hz…

Luminosity degradation (based on beam-beam simulation by K. Ohmi)

Frequency (Hz)	24.85	38.93	69.34	99.60
$\Delta y_{IP^*}^{rms}$ (nm)	18.63	1.72	8.29	3.14
$L/L_0^{average}$ (%)	95.4	99.8	99.7	99.7



Orbit change at IP with 1μm offset of QCS magnets

		K1 (/m)	Distancefrom IP [m]	β_Q [m]	β_{IP}[mm]	$\Delta\psi_y/2\pi$	COD@IPfor 1μm Q-offset [μm]	
QC1L	LER	-1.717	0.912	2504.3	0.27	0.24995	-0.7339	>
	HER	-1.142	1.390	5462.4	0.3	0.24997	-0.7684	
QC1R	LER	-1.712	0.912	2567.7	0.27	0.24996	-0.7362	>
	HER	-1.070	1.430	5592.6	0.3	0.24997	-0.7299	
QC2L	LER	0.84161	1.9099	962.2	0.27	0.25004	0.2145	>
	HER	0.65023	2.6799	1923.3	0.3	0.25030	0.2470	
QC2R	LER	0.83924	1.9760	924.6	0.27	0.25005	0.2097	>
	HER	0.55577	2.9449	1806.9	0.3	0.25004	0.2046	

COD $$\Delta y = \frac{1}{2\sin\pi\nu}\sqrt{\beta_Q\beta_{IP}}\cos\left(\pi\nu - |\Delta\psi|\right)\vartheta$$

1μm (QC1 offset) <-> ~0.7μm orbit change at IP

If QCS magnets for both ring move coherently and the vibration amplitudes are same, orbit difference of the two beams much smaller (1/10 ~1/2) than the no—coherent case.

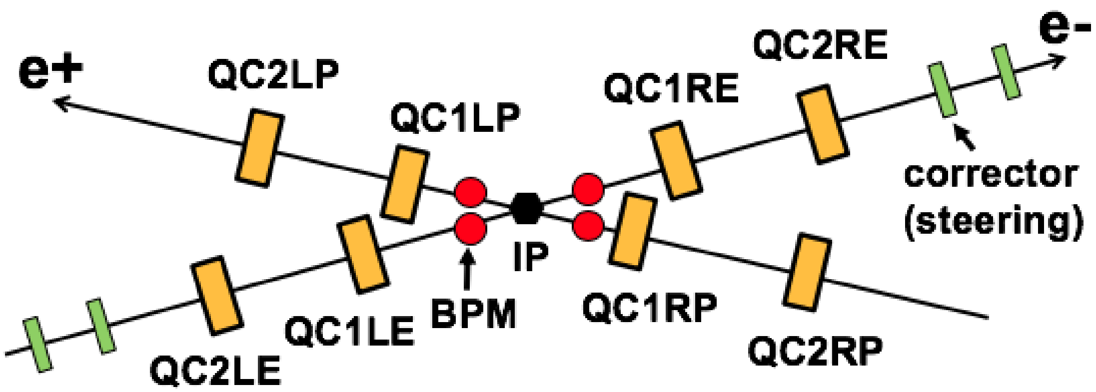
Fast orbit feedback system

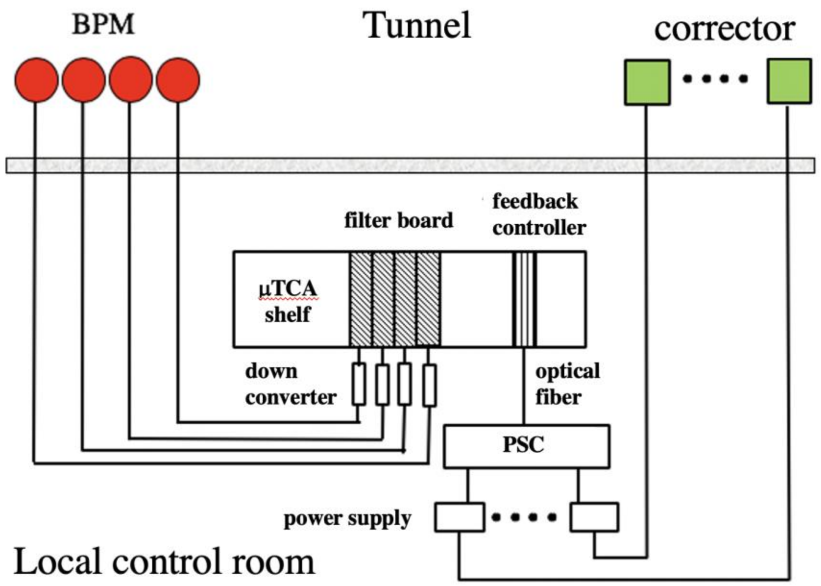
H. Fukuma

Reference: "Orbit feedback system at the collision point by beam-beam kick", H. Fukuma, Lecture note of High Energy Accelerator Seminar OHO2019, 2019, in Japanese

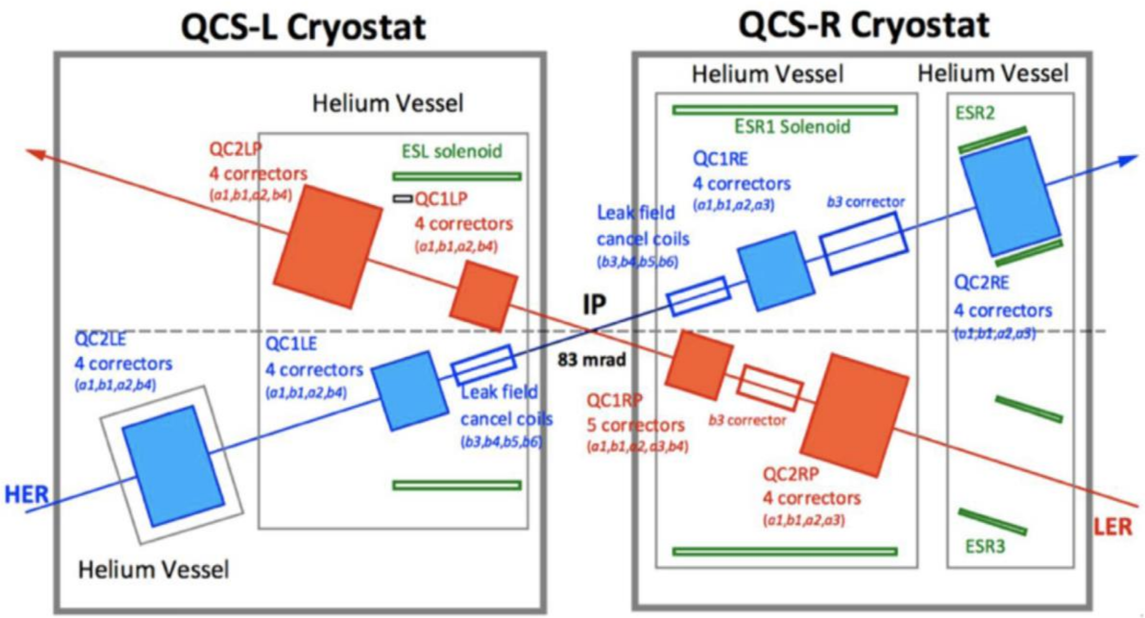
Layout of the fast feedback system

H. Fukuma

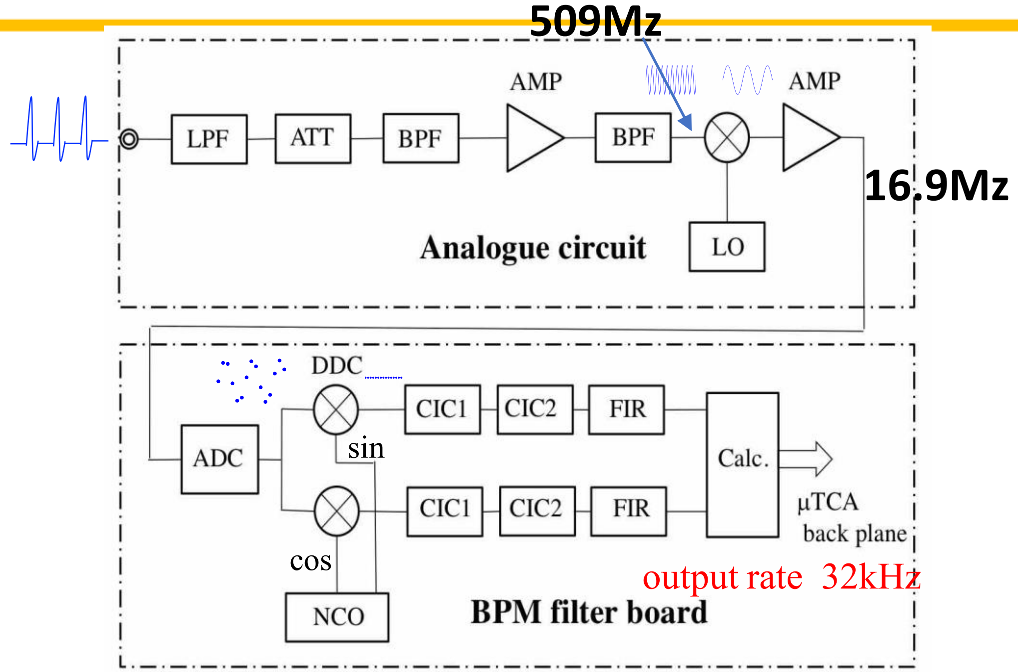




PSC: Power Supply Controller

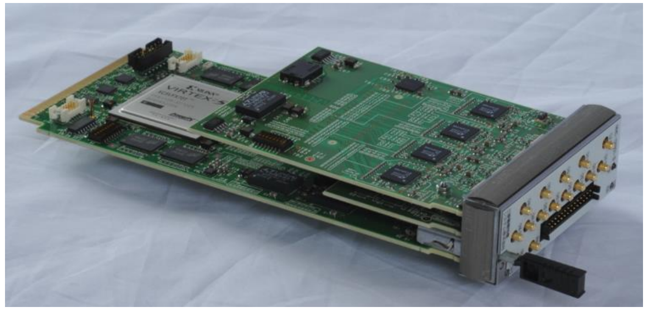


Processing of BPM signal



Block diagram of the detector

LPF: l ow-pass filter, ATT: attenuator, BPF: band-pass filter,
Amp: amplifier, LO: local oscillator, DDC: digital down converter,
NCO: numerically controlled oscillator)

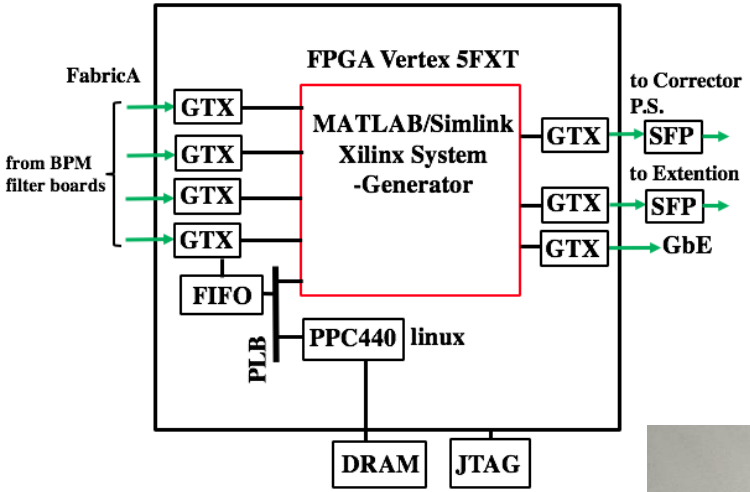


BPM filter board

Feedback controller

- µTCA module
- MATLAB/Simulink
  + System Generator(Xilinx)
- Feedback repetition 32kHz

H. Fukuma



Power supply controller

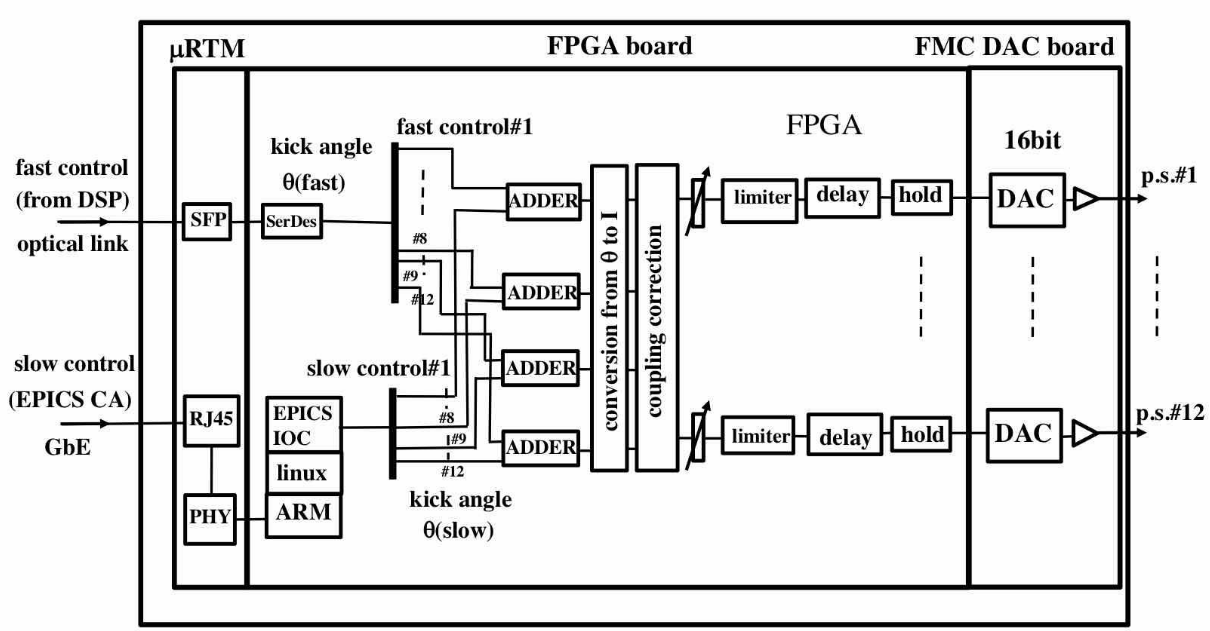
- MTCA .4 module
- Two input channels

  i) From the feedback controller

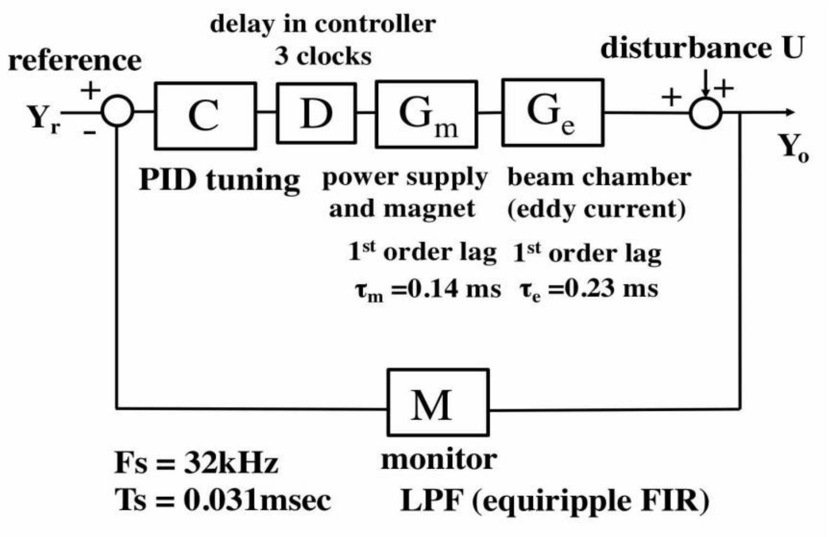
  ii) EPICS channel access

    Slow DC bump
- Built-in EPICS IOC

H. Fukuma



Frequency response of feedback



BPM resolution: ~0.2μm@design current

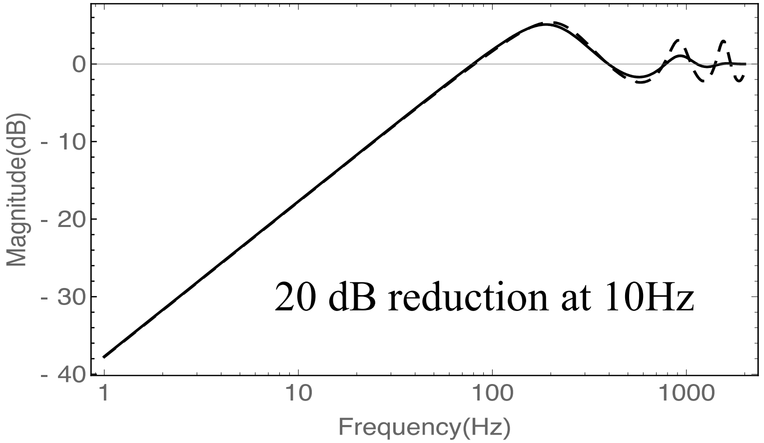
Transfer function(disturbance to the output)

$$H(z)=\frac{Y_o(z)}{U(z)}=\frac{1}{1+C(z)D(z)G_m(z)G_e(z)M(z)}$$

Sampling time(Ts)	31.25μs
Time constant of power supply and magnet (t_m)	0.14ms
Time constant of eddy current of chamber (t_e)	0.23ms
Delay in controller nd	3sample
Taps of FIR N	73

H. Fukuma

$$H(f)=\left|H(e^{-j2\pi fT_s})\right|$$

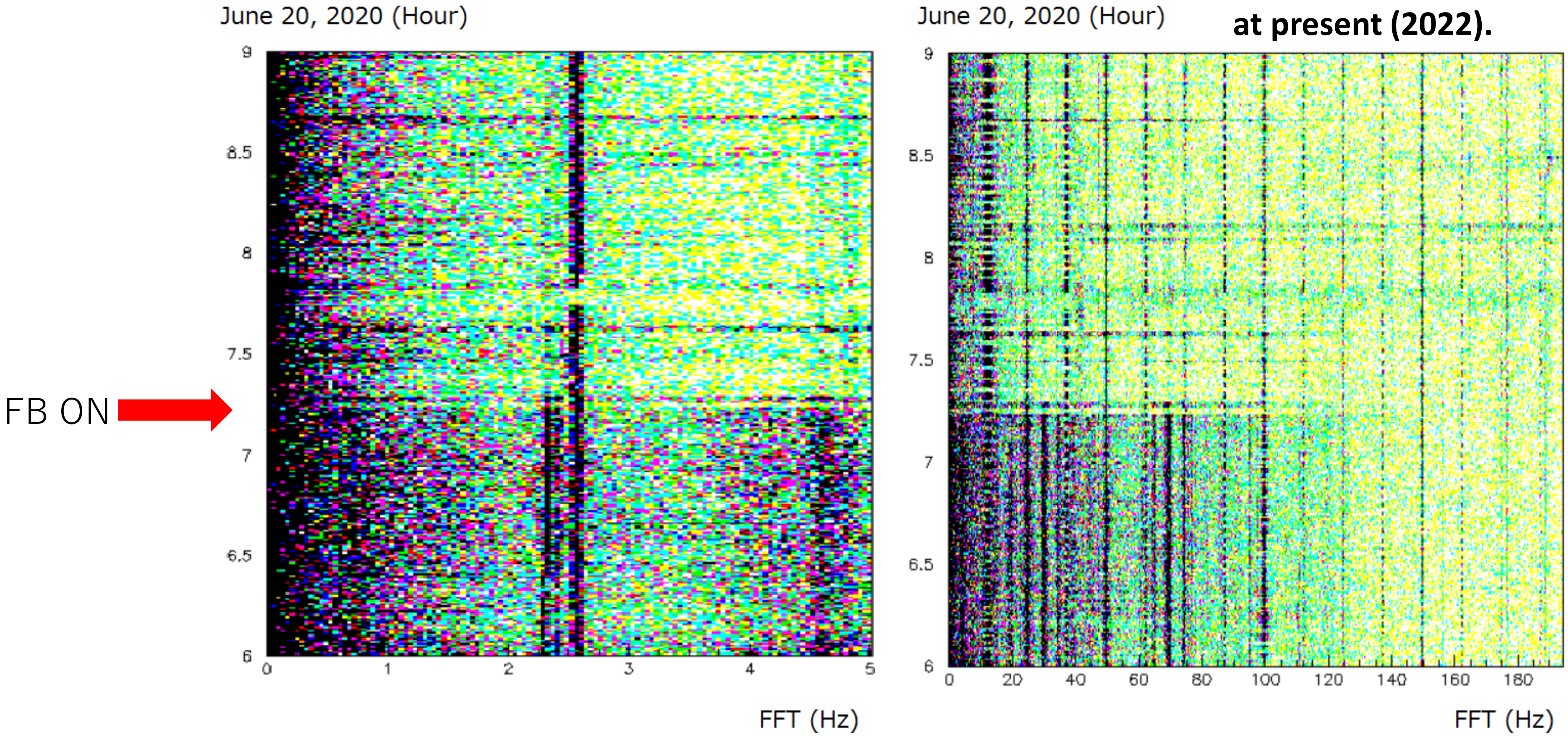


Disturbance rejection by PI control

Effectiveness of fast orbit feedback

Horizontal – FFT , Vertical hour of Time (JST)

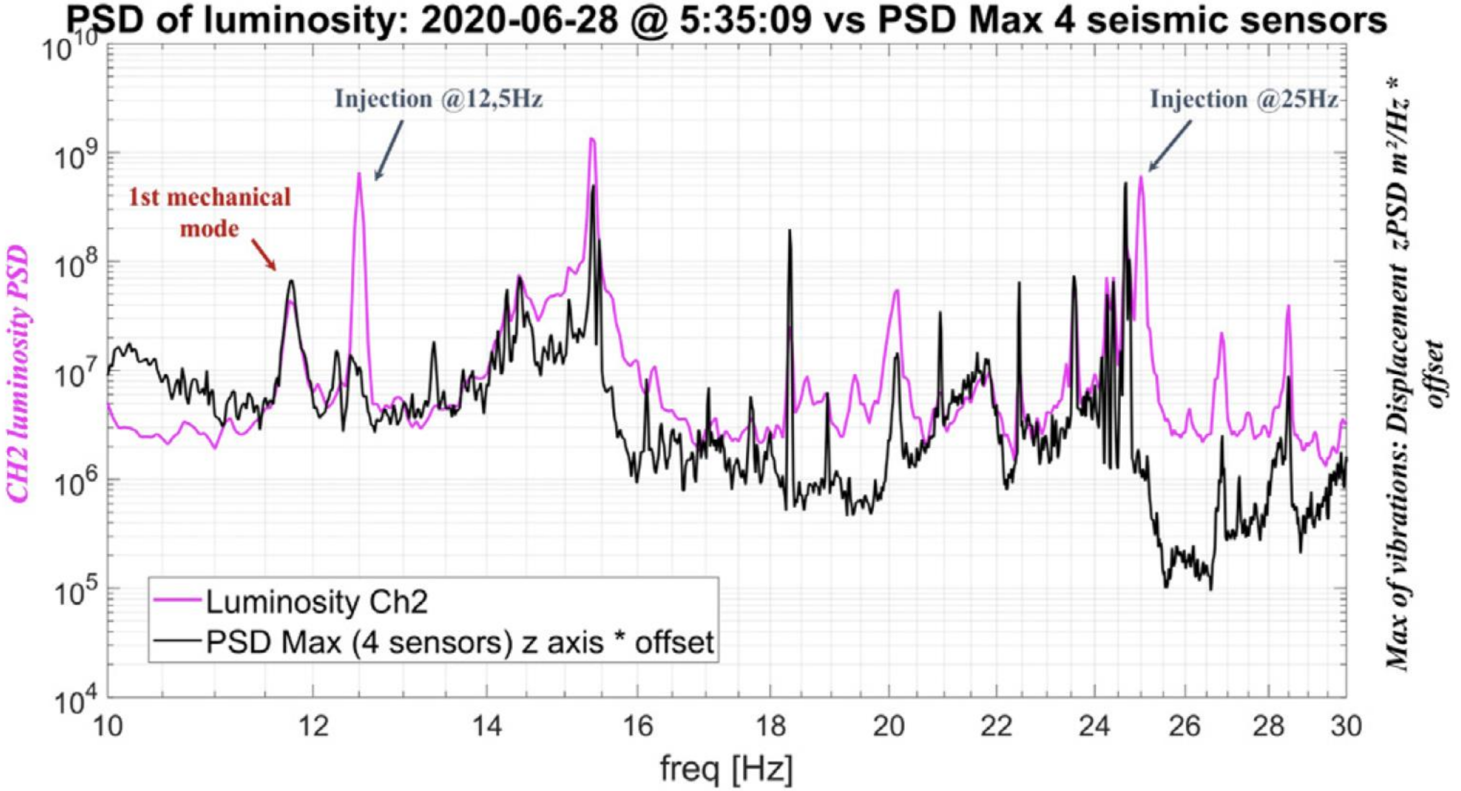
When we switch FB from slow to fast, the luminosity increases by a few percent at present (2022).



S. Uehara

Spectrum of luminosity and vibration monitors

With slow orbit feedback



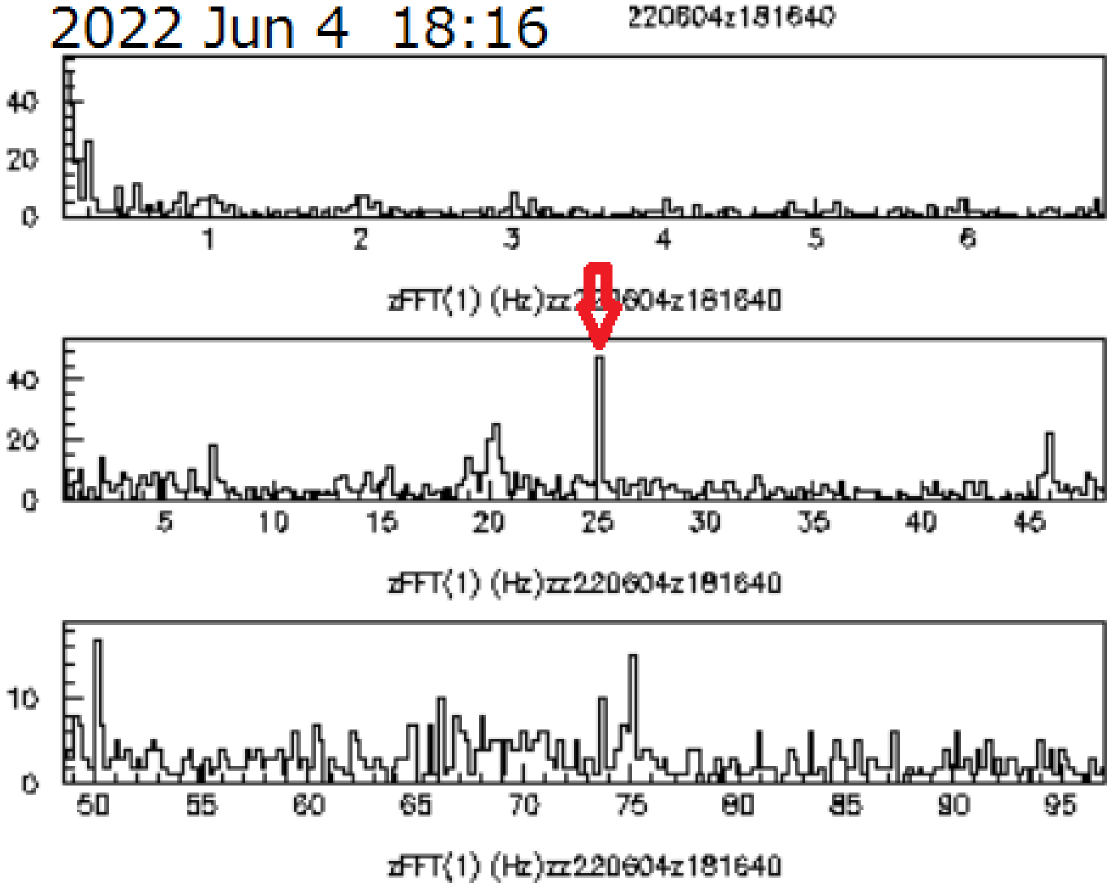
Spectrum of luminosity from fast luminosity monitor

Fast orbit feedback was working.

Injection: LER: 23Hz, HER: 25Hz

S. Uehara

2022 Jun 4 18:16



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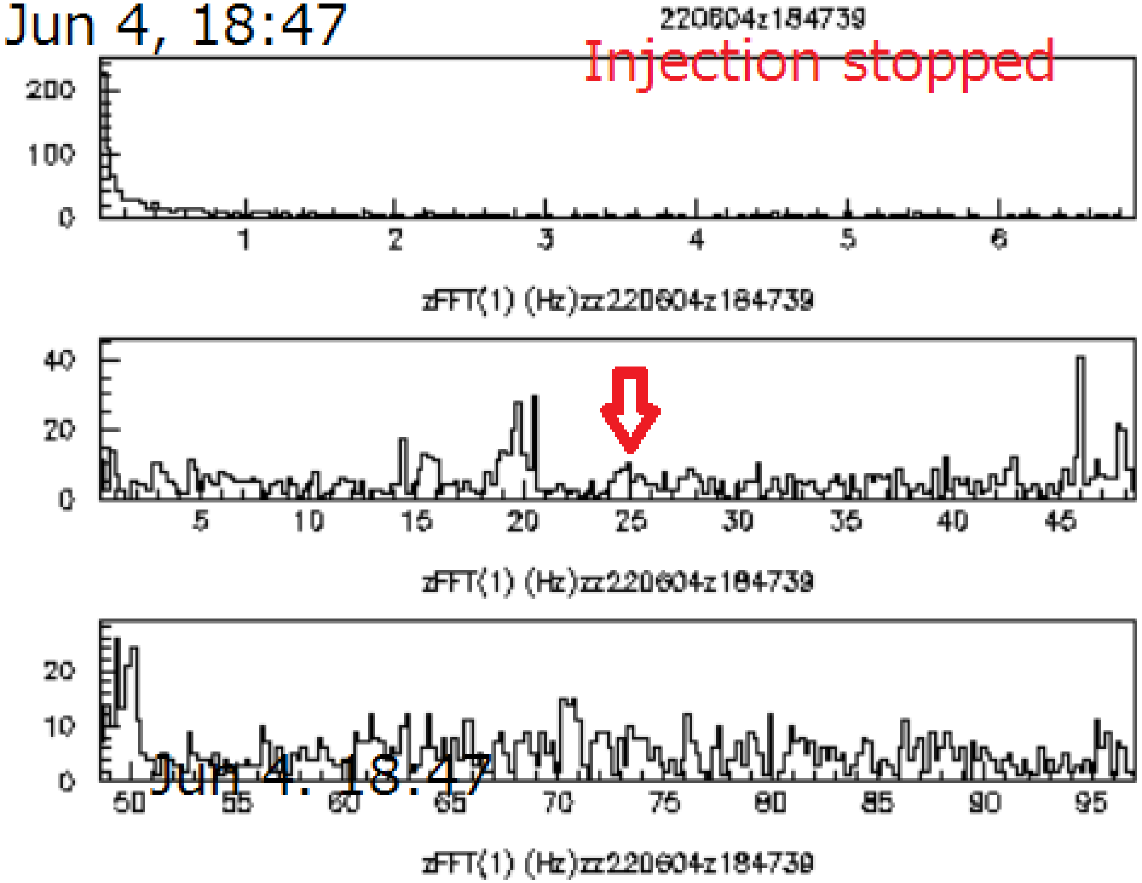
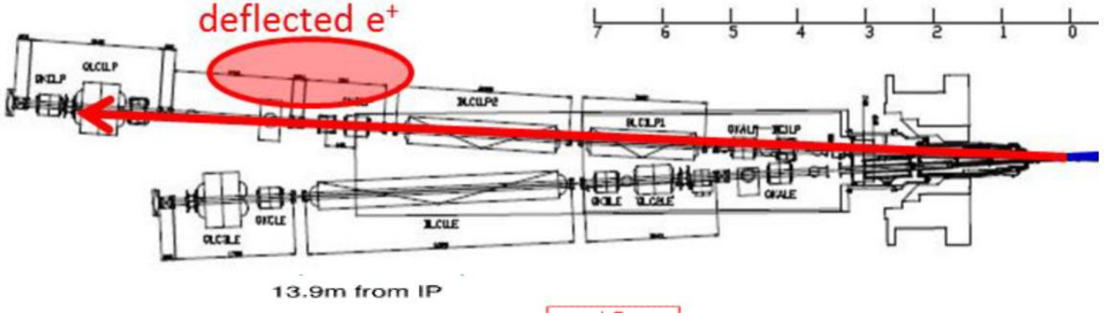


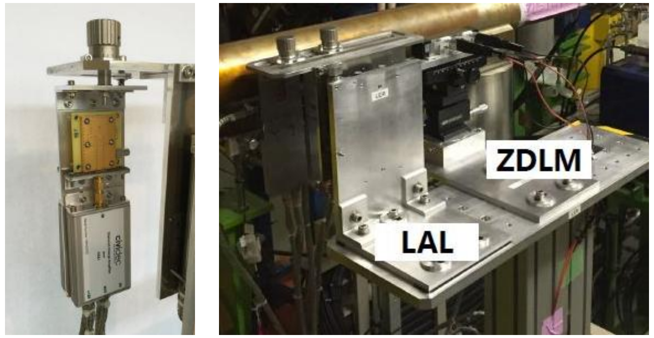
Peaks at around 20 and 50 Hz exist always. Luminosity reduction due to those remaining peaks is less than 5%.

Fast luminosity monitor

- Two complementary techniques developed at LAL and KEK:
  - ~ 5x5x0.5 mm^3 single crystal CVD diamond sensors (CVD DS) pairs coupled to fast charge / current amplifiers (LAL) (LumiBelle 2)
  - Cerenkov detector + scintillator (ZDLM group @ KEK)

positioned together outside of the beam pipe

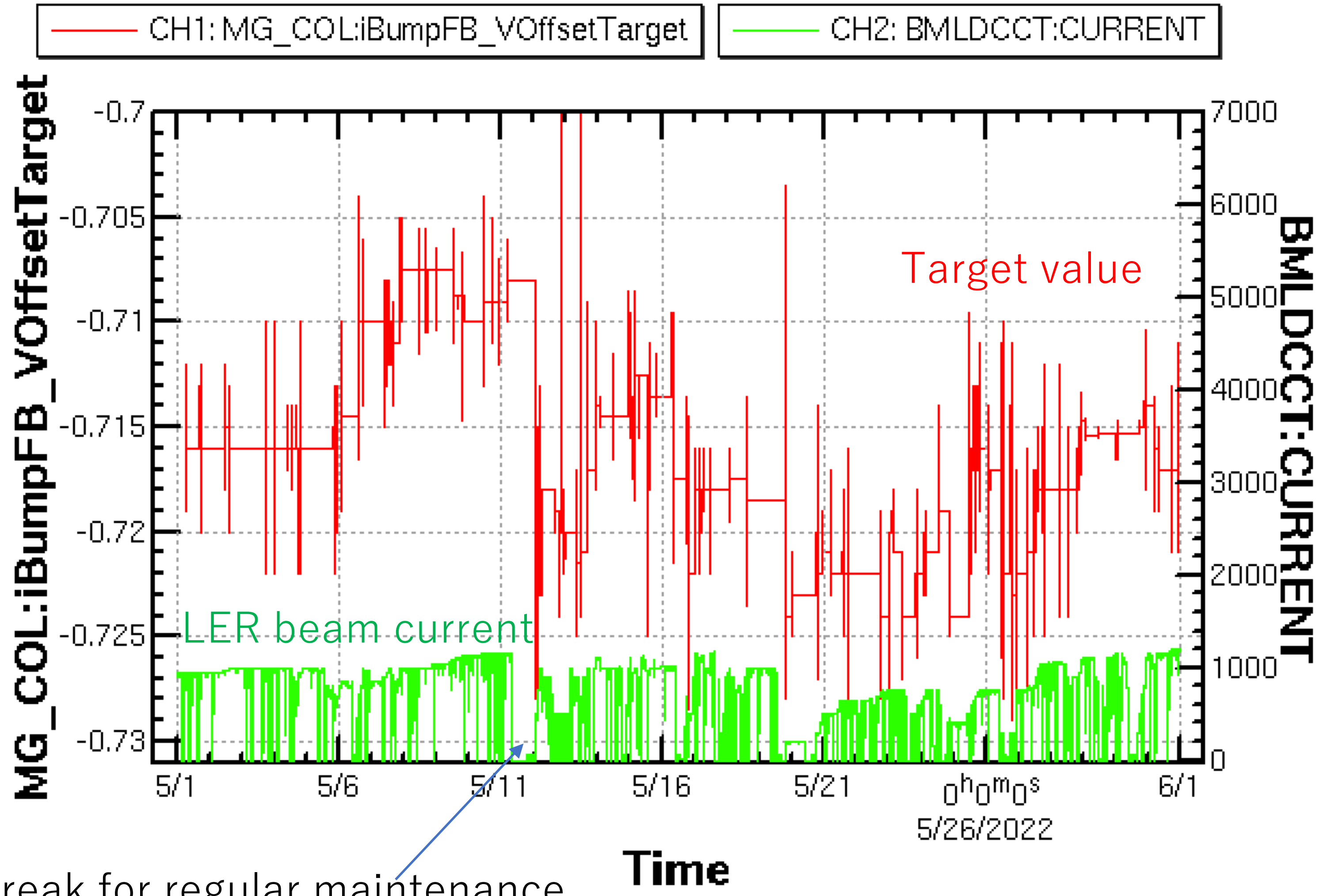




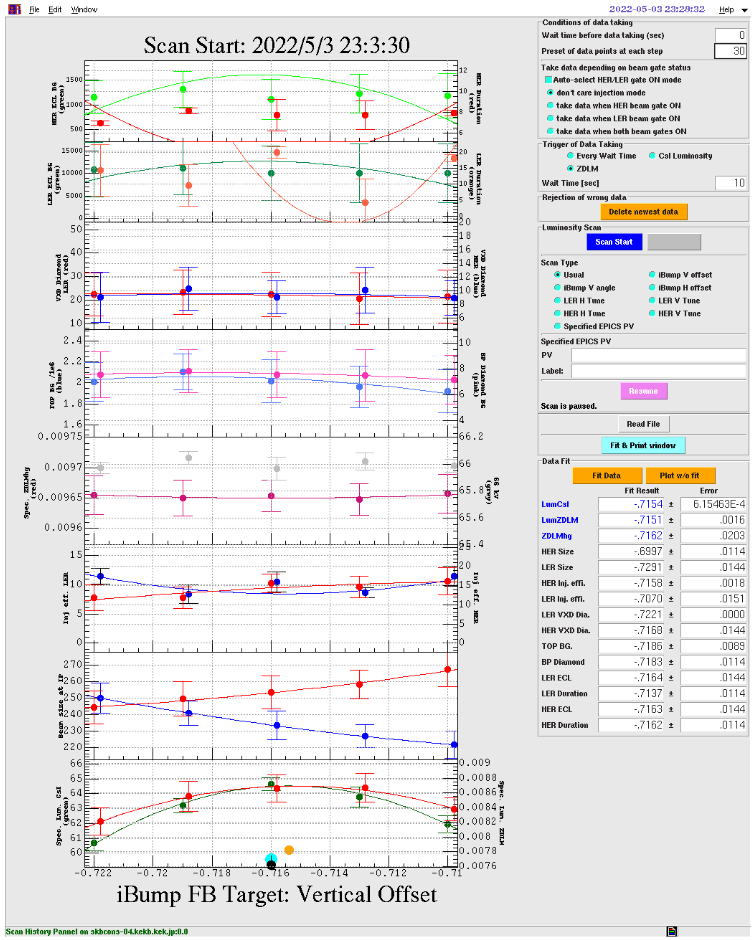
Detects positrons which lost energy due to radiative Bhabha process.

Stability of target value for orbit FB (V-offset)

Target value depends on beam current.



Break for regular maintenance

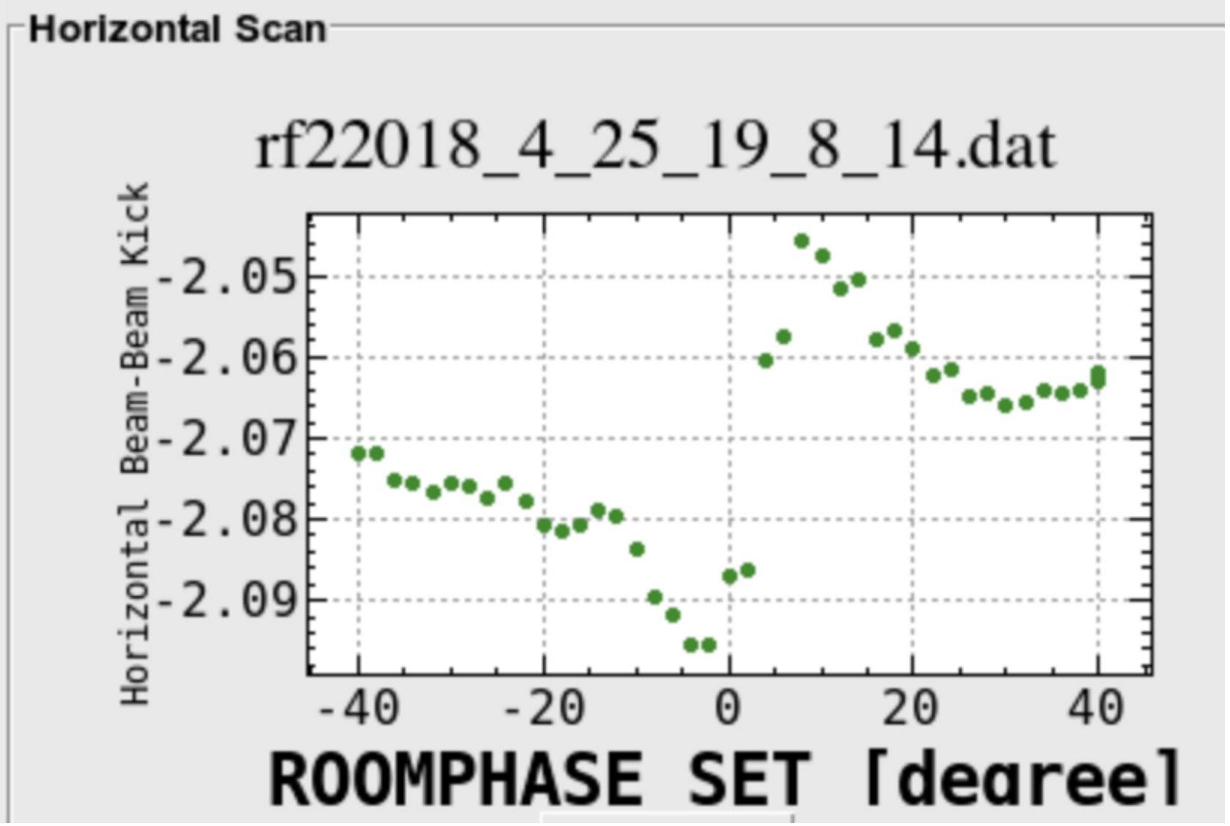


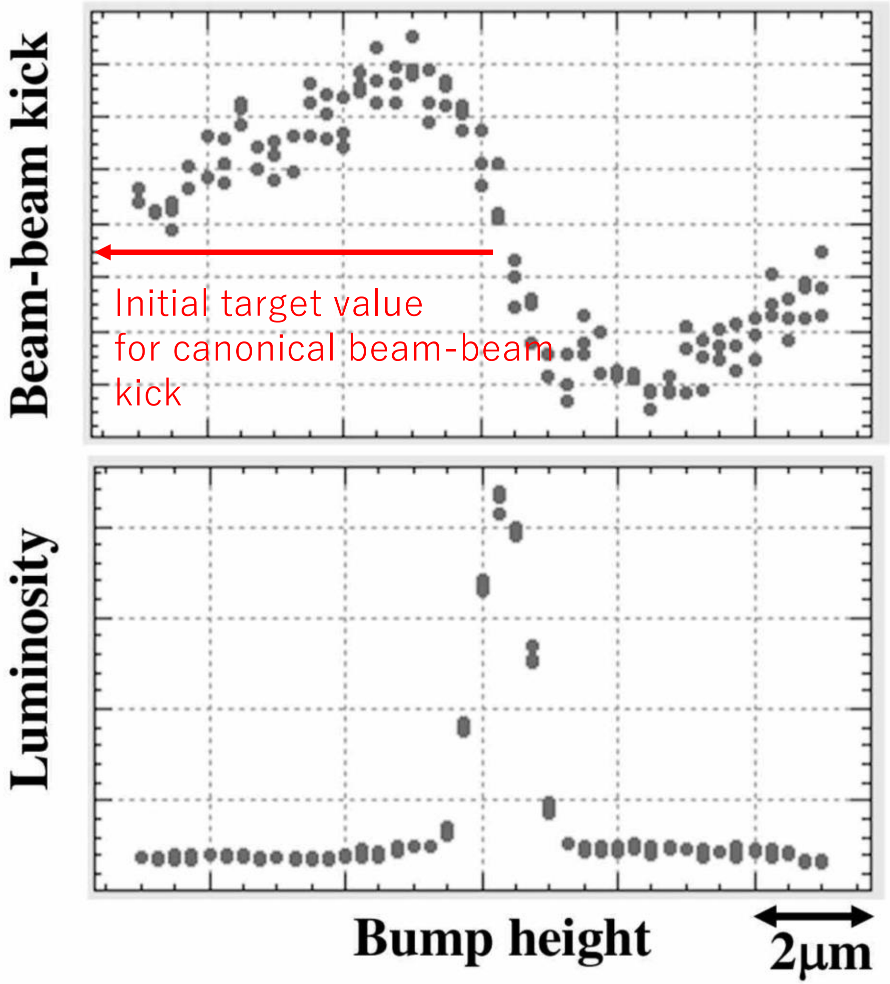
Conditions of data taking
Wait time before data taking (sec): 0
Preset of data points at each step: 30
Take data depending on beam gate status
☐ Auto-select HER/LER gate ON mode
● don't care injection mode
○ take data when HER beam gate ON
○ take data when LER beam gate ON
○ take data when both beam gates ON
Trigger of Data Taking
○ Every Wait Time ○ CsI Luminosity
● ZDLM
Wait Time [sec]: 10
Rejection of wrong data
Luminosity Scan
Scan Type
● Usual ○ iBump V offset
○ iBump V angle ○ iBump H offset
○ LER H Tune ○ LER V Tune
○ HER H Tune ○ HER V Tune
○ Specified EPICS PV
Specified EPICS PV
PV:
Label:
Scan is paused.
Data Fit

	Fit Result		Error
LumCsI	-.7154	±	6.15463E-4
LumZDLM	-.7151	±	.0016
ZDLMhg	-.7162	±	.0203
HER Size	-.6997	±	.0114
LER Size	-.7291	±	.0144
HER Inj. effi.	-.7158	±	.0018
LER Inj. effi.	-.7070	±	.0151
LER VXD Dia.	-.7221	±	.0000
HER VXD Dia.	-.7168	±	.0144
TOP BG.	-.7186	±	.0089
BP Diamond	-.7183	±	.0114
LER ECL	-.7164	±	.0144
LER Duration	-.7137	±	.0114
HER ECL	-.7163	±	.0144
HER Duration	-.7162	±	.0114

Target of orbit FB (v-offset) is scanned typically once per 8-hour shift to trace the change of the optimum value.

IP orbit scan





Initial target value for canonical beam-beam kick

Horizontal (scan RF phase of LER)

Vertical (scan vertical offset at IP)

Summary

- IP orbit feedback (vertical) is indispensable to avoid a luminosity decrease.
- The beam-beam deflection method has been very successfully applied to both KEK and SuperKEKB.
- In SuperKEKB, a fast orbit feedback system has been developed and successfully used in daily physics operation.
  - At present (2022), the luminosity increases by a few percent, when we switch FB from slow to fast one.
  - When we achieve a smaller vertical emittance and/or squeeze IP β_y^* further, the fast orbit feedback may become more important.
- One of annoying issues with the orbit feedback using the beam-beam deflection method is the stability and the beam current dependence of the target value of the canonical beam-beam kick.
  - We have not yet found a method to stabilize the target value.

References

- KEKB:
  - M.Masuzawa, J.W.Flanagan, Y.Funakoshi, K.Oide, “IP ORBITAL FEEDBACK FOR COLLISION TUNING AT KEKB”, Proceedings of EPAC 2000, p1211-1213, Vienna, Austria, June, 2000.
  - Y. Funakoshi, M. Masuzawa, K. Oide, J. Flanagan, M. Tawada, T. Ieiri, M. Tejima, M. Tobiyama, K. Ohmi, H. Koiso, “Orbit feedback system for maintaining an optimum beam collision”, Phys. Rev. ST Accel. Beams 10: 101001, 2007.

- SuperKEKB:
  - Y. Funakoshi, H. Fukuma, T. Kawamoto, M. Masuzawa, T. Oki, S. Uehara, H. Yamaoka (KEK), P. Bambade, D. E. Khechen, D. Jehanno, V. Kubytskyi, C. Rimbault (LAL), S. D. Anderson, S. Gierman, M. Kosovsky, J. Seeman, C. M. Spencer, M. Sullivan, O. Turgut, U. Wienands (SLAC) “Interaction point orbit feedback system at SuperKEKB”, Proceedings of IPAC, Richmond, VA, USA, 2015, MOPHA054.
  - Maurizio Serluca (Annecy, LAPP), Gael Balik (Annecy, LAPP), Laurent Brunetti (Annecy, LAPP), Benjamin Aimard (Annecy, LAPP), Agnes Dominjon (Annecy, LAPP), Philip Bambade (LAL), Sandry Wallon (LAL), Salvatore Di Carlo (CERN) Mika Masuzaw (KEK), Sadaharu Ueharad KEK), "Vibration and luminosity frequency analysis of the SuperKEKB collider", Nucl.Instrum.Meth.A 1025 (2022) 166123

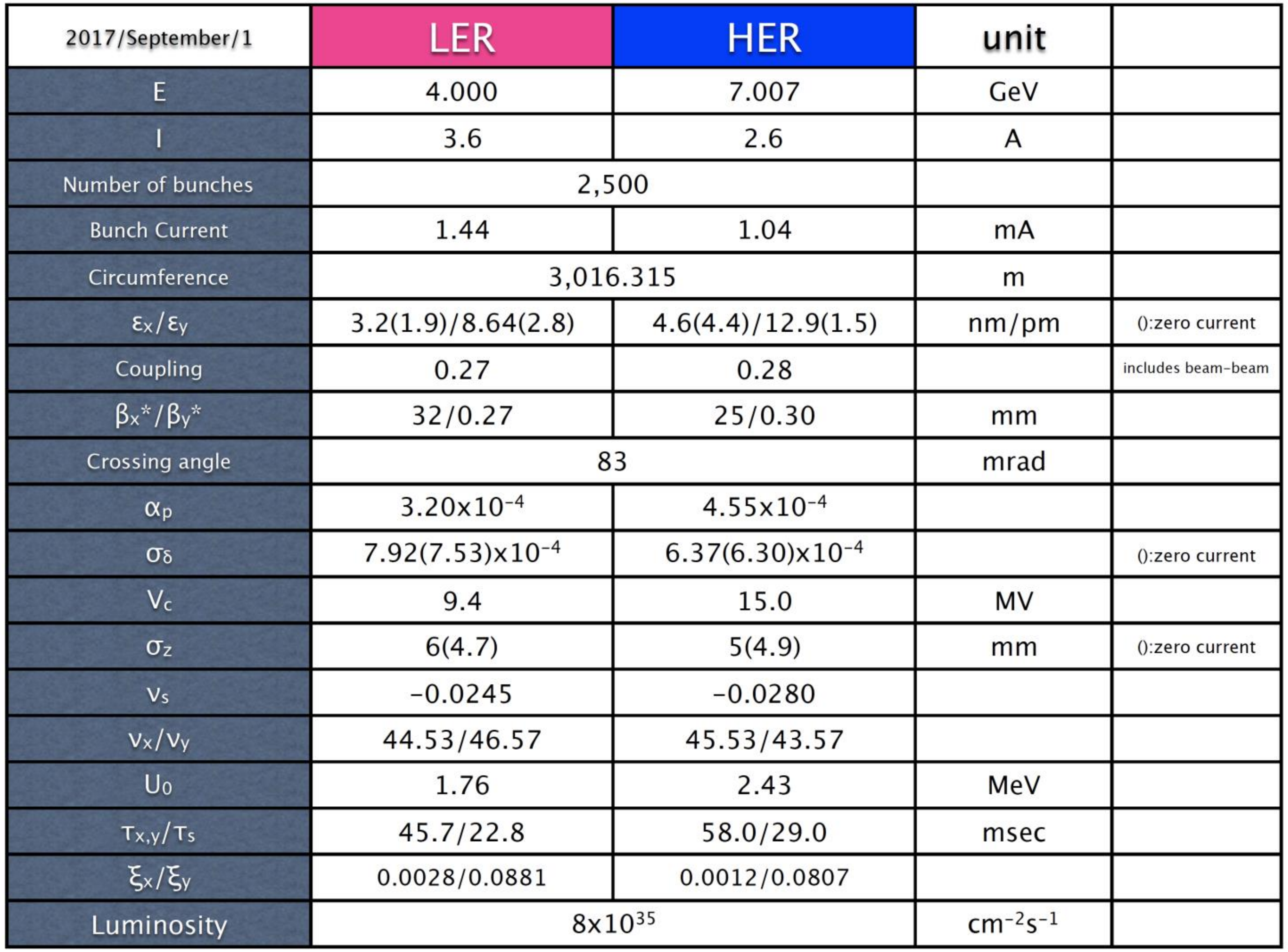
Thank you for your attention!

Machine Parameters of present SuperKEKB

	LER	HER	
Beam Energy	4.0	7.0	GeV
Circumference	3016		m
Crossing angle	83		mrad
Crab waist ratio	80	40	%
Beam current @Maximum Luminosity	1.321	1.099	A
Number of bunches	2249		
Bunch current @Maximum Luminosity	0.5873	0.4887	mA
Total RF voltage V_c	9.12	14.2	MV
Synchrotron tune ν_s	-0.0233	-0.0258	
Bunch length σ_z	5.69	6.03	mm
Momentum compaction α_c	2.98E-4	4.54E-4	
Betatron tune ν_x / ν_y	44.524/46.592	45.532/43.575	
Beta function at IP β_x^* / β_y^*	80/1	60/1	mm
Measured vertical beam size (XRM) @IP σ_y^*	0.224	0.224	μm
Vertical beam-beam parameters ξ_y	0.0407	0.0279	
Beam lifetime	8	24	min.
Luminosity (Belle 2 CsI)	4.65		10^{34} cm^{-2} s^{-1}

SuperKEKB design parameters

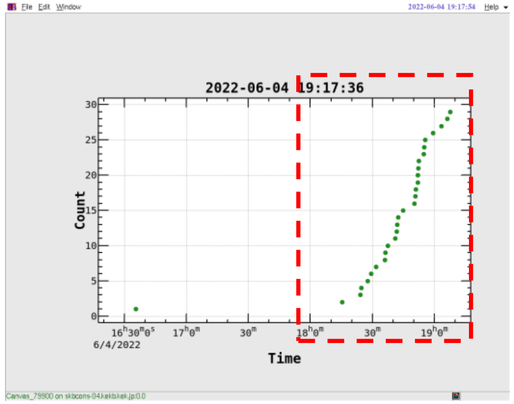
Machine Parameters



2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.20\text{x}10^{-4}$	$4.55\text{x}10^{-4}$		
σ_δ	$7.92(7.53)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$\text{cm}^{-2}\text{s}^{-1}$	

Injection summary

CLAWS count increased.



23:50
Large VXD threshold
300 -> 160