Overview of Phase 1 Commissioning

Y. Funakoshi for SuperKEKB Commissioning Group

Accelerator Laboratory, KEK

2016.06.13@21th KEKB Review

SuperKEKB

- **Upgrade project of KEKB B-factory**
  - Search for new physics beyond the standard model at B-meson regime
- **e^- - e^+ two-ring collider consisting of**
  - Injector (Linac): *L* ~600 m
  - Damping ring (e^+): *C* ~100 m
  - Main ring (MR): *C* ~ 3016 m
    - HER: 7 GeV e^-, 2.6 A
    - LER: 4 GeV e^+, 3.6 A
  - Belle-II detector
- **Design luminosity**
  - 80 x 10^{34} $cm^{-2}s^{-1}$
    (~40 times of KEKB)

SuperKEKB Commissioning Phases

2016 Feb. ~ June

Phase 1
w/o QCS and Belle II

basic machine tuning
vacuum scrubbing
Optics tuning
BKG study

~2017 Autumn (~ 5month)

Phase 2
w/QCS and Belle II
w/o Vertex detector

DR commissioning
BKG study
Luminosity tuning
Target luminosity:
1×10^{34} cm^{-2} s^{-1}

~2018 Autumn

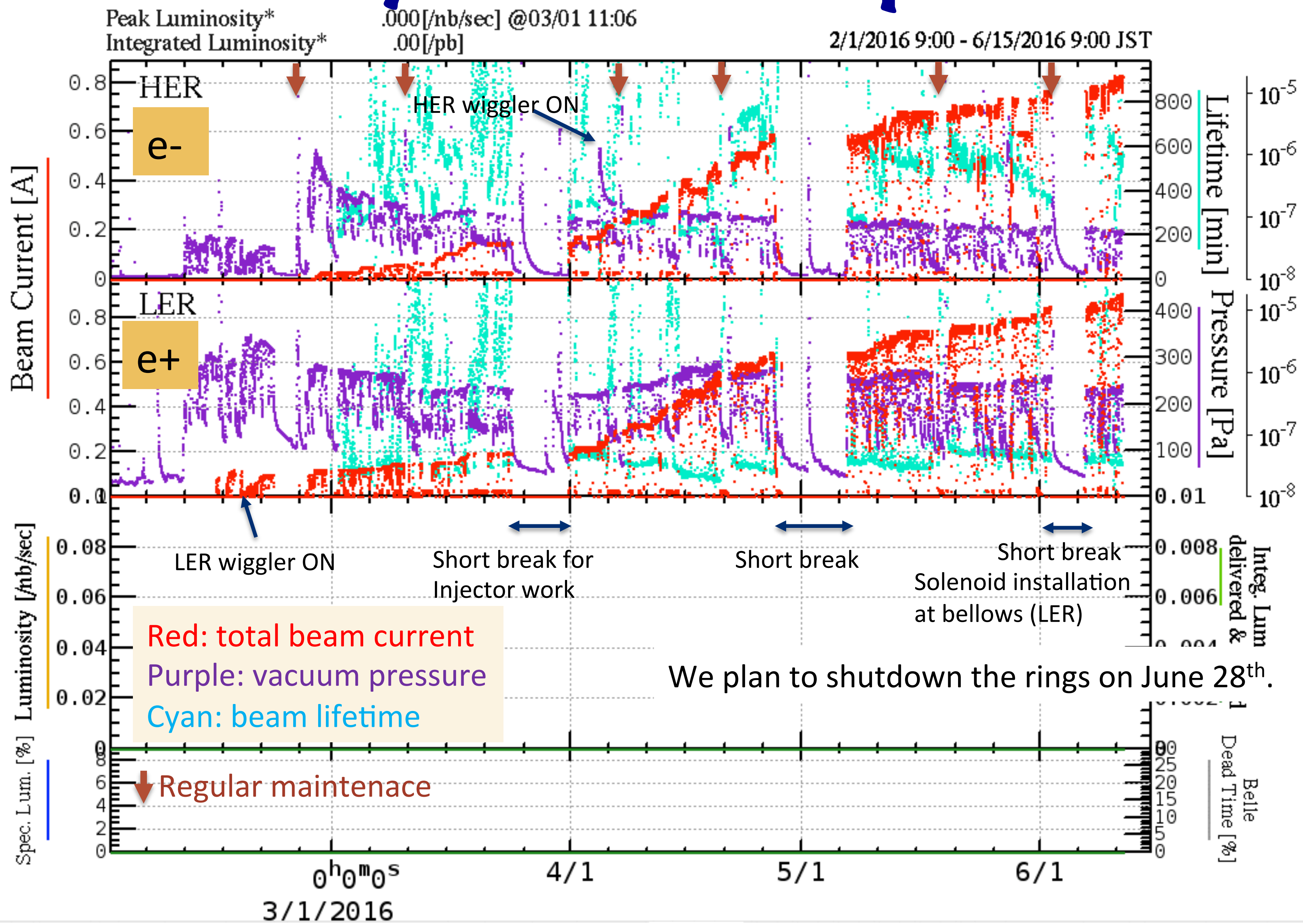
Phase 3
w/ full Belle II

Physics Run
Luminosity tuning

Mission of Phase 1 operation (Feb. 2016 ~ June 2016)

- Startup of each hardware system
- Establish beam operation software tools
- Preparation for installation of Belle-II detector
  - Enough vacuum scrubbing
    - Request from Belle II group: ~1 month vacuum scrubbing with beam current of 0.5~1A (360~720Ah).
  - Beam background study with test detector (named Beast)
- High beam current operation
  - Find/solve problems associated with high beam current operation
- Optics study w/o IR (no detector solenoid)
  - Low emittance tuning
- Other machine studies

History of Phase 1 operation



Machine parameters in Phase 1

	LER	HER	Units	
Beam energy	4.000	7.007	GeV	
Beam current	910 (~40)	830 (~40)	mA	(): optics correction
# of bunches	1576	1576		
Bunch current	0.58	0.52	mA	
Hor. emittance	1.8	4.6		Zero current
Momentum compaction	2.45×10^{-4}	4.44×10^{-4}		
Energy spread	7.5×10^{-4}	6.3×10^{-4}		
Total V_c	7.56	12.45	MV	
Bunch length	4.6	5.3	mm	Zero current
ν_s	-0.019	-0.025		
Tune ν_x/ν_y	44.59/44.63	45.57/43.61		
U_0	1.76	2.43		Wiggler ON
$\tau_{x,y}/\tau_x$	46/23	58/29		Wiggler ON

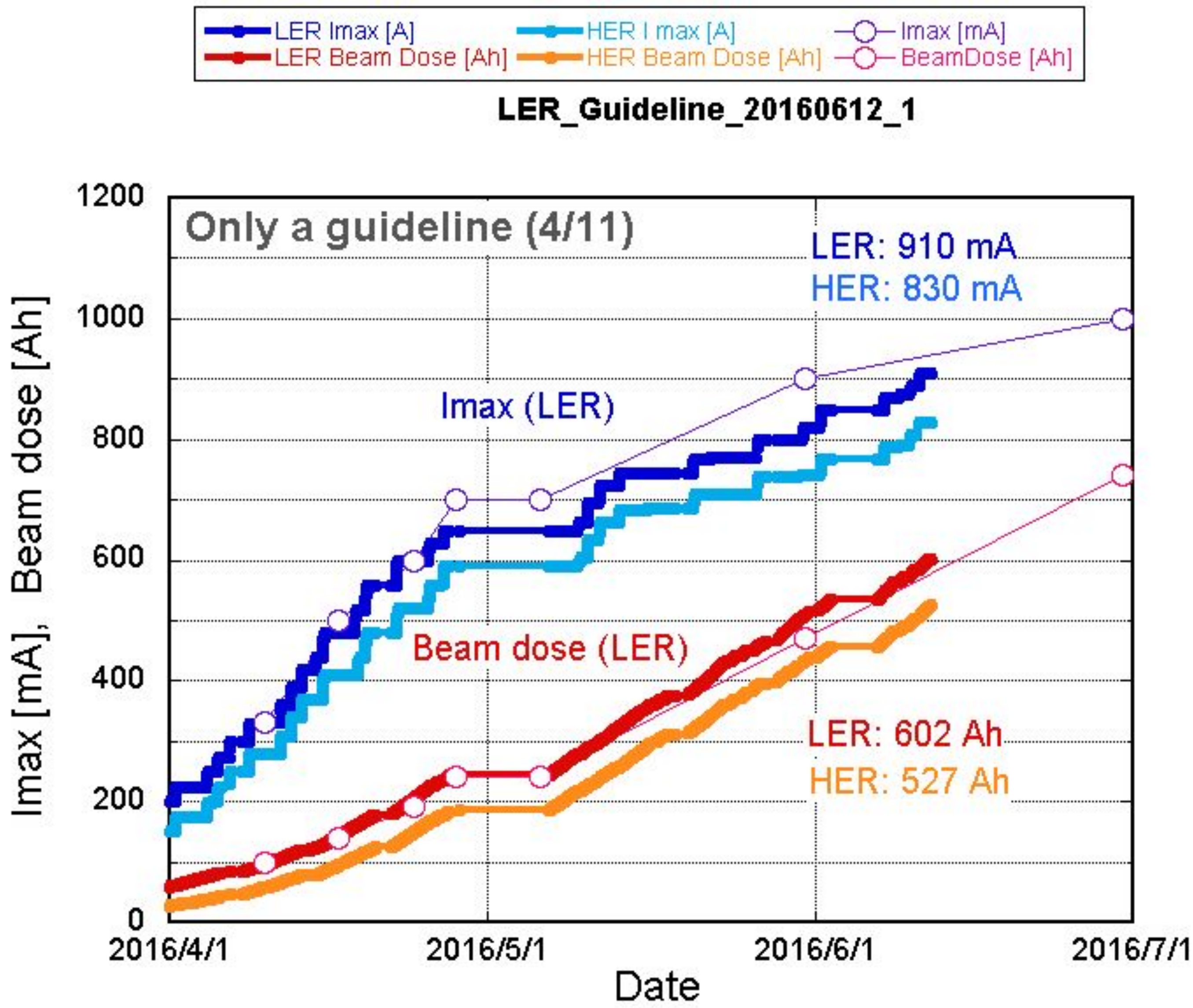
as of June 12th

Machine parameters in Phase 3

2011/July/20	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)/11.5(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	3.25×10^{-4}	4.55×10^{-4}		
σ_δ	$8.08(7.73)\times10^{-4}$	$6.37(6.31)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0247	-0.0280		
ν_x/ν_y	44.53/44.57	45.53/43.57		
U_0	1.87	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

Y. Suetsugu

Guideline for vacuum scrubbing and achievement as of June 12th



Request from Belle II group: ~1 month vacuum scrubbing with beam current of 0.5~1A (360~720Ah).

Startup of SuperKEKB (3 months)

- Much faster startup than KEKB
  - KEKB beam currents achieved after first 3 months
    - LER: ~300mA, HER: ~200mA (540mA, 300mA: 4 months)
  - SuperKEKB beam currents achieved after first 3 months
    - LER: ~650mA, HER: ~590mA (820mA, 740mA: 4 months)
- Compared with KEKB...
  - Each hardware component has been upgraded with experiences at KEK and has worked fine (RF, Magent, Vacuum...)
  - The bunch-by-bunch feedback system has more effectively suppressed instabilities.
  - Operational tools (such as closed orbit correction system) has worked fine based on experiences at KEKB.

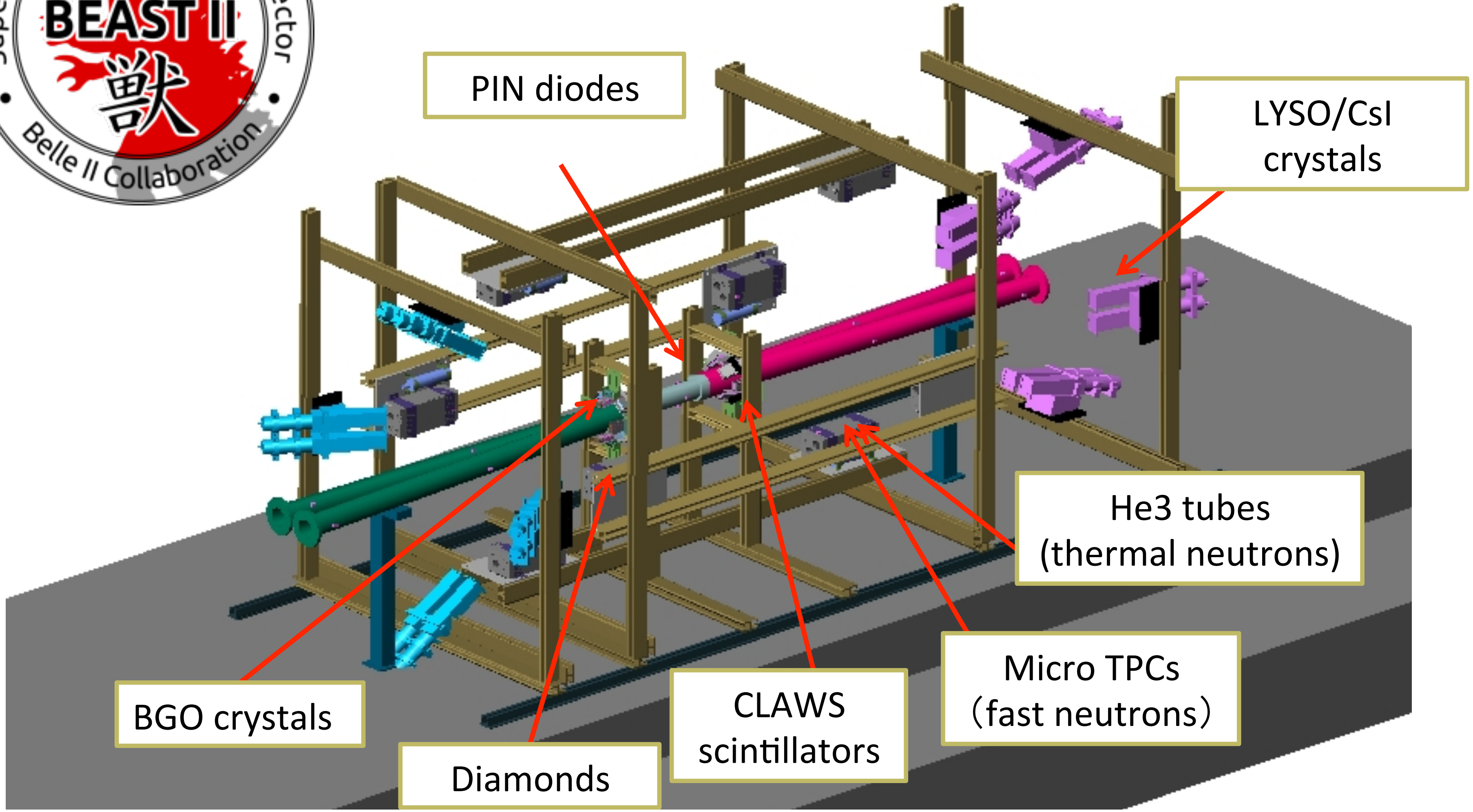
Beam background study using Beast detector

- Touschek background
  - Change vertical beam size by using ECK (Emittance Control Knob)
- Vacuum background
  - Vacuum bump study
- Injection background
- Collimator study

Details are given in the talk by H. Nakayama.

H. Nakayama

BEAST Phase1 sensors at IP



Various measurements (fast charged particle, high-energy photons, thermal/ MeV neutron, dosimetry, etc..) to **validate beam loss simulation**

Issues with high beam currents

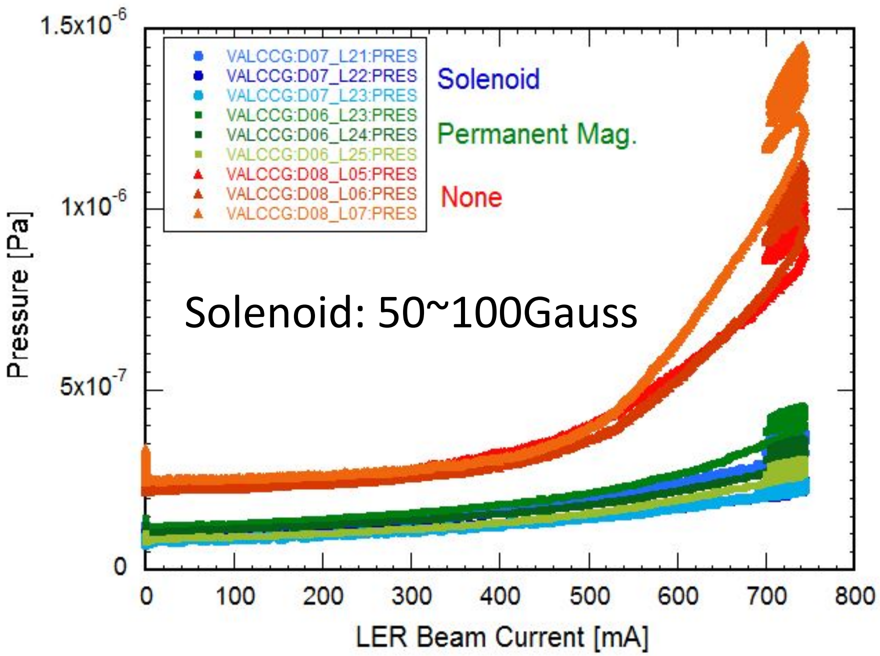
- Nonlinear vacuum pressure rise as function of beam current (LER)
- Vertical beam size blowup as function of beam current (LER)
- Frequent beam aborts associated with vacuum burst (LER)
- Longitudinal coupled bunch instability (LER)
  - Instability was first observed around 660mA. The mode number is ~600. We needed the use of longitudinal feedback system to suppress it. The source of the instability is still unknown. At KEKB, we never needed the longitudinal feedback system.
- Longitudinal coupled bunch instability (HER)
  - Sometimes, detuned cavities induce the instability due to the fundamental mode. -1 mode damper was set up to suppress the instability.
- Hardware troubles due to the high beam currents
  - Vacuum leakage by the direct hit by the beam at bellows near the abort kickers (HER) (Suetsugu's talk)
  - Damage to the feedthrough of the transverse FB kicker (LER) (Tobiyama's talk)

Y. Suetsugu

Nonlinear pressure rise against beam current in LER

- The pressures at whole LER ring showed the nonlinear behavior against the beam current.
- The behavior is quite similar to that of electron currents measured at aluminum parts without TiN coating.

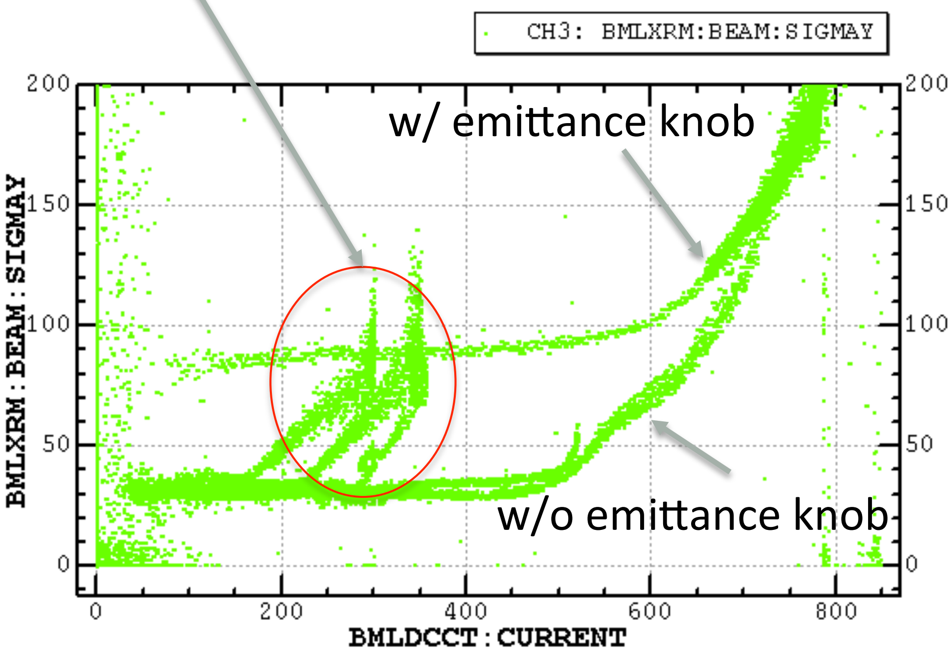
- We have aluminum bellows chambers along the ring without TiN coating. The bellows chamber has a length of 0.2 m and located every 3 m on average. Number of such bellows chamber is 810.
- Countermeasure
  - Installation of solenoid magnets at th bellows.
  - We have installed permanent solenoid magnets at all of bellows chambers during short break (June 02-05)



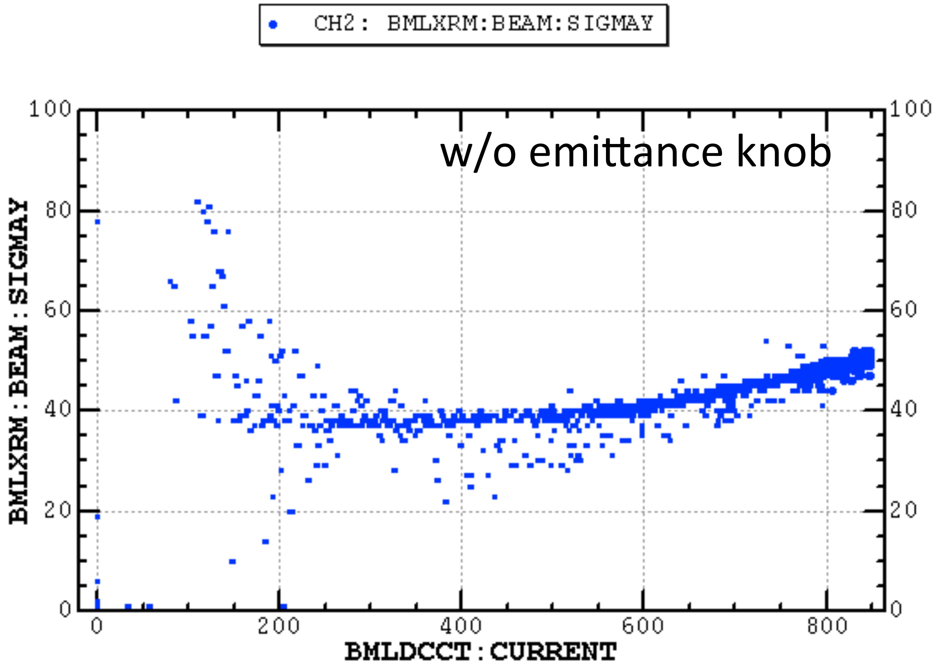
More details are discussed in the talk by Y. Suetsugu .

LER vertical beam size blowup

Blowup study with shorter bunch spacing



3.06 spacing (1576 bunches)



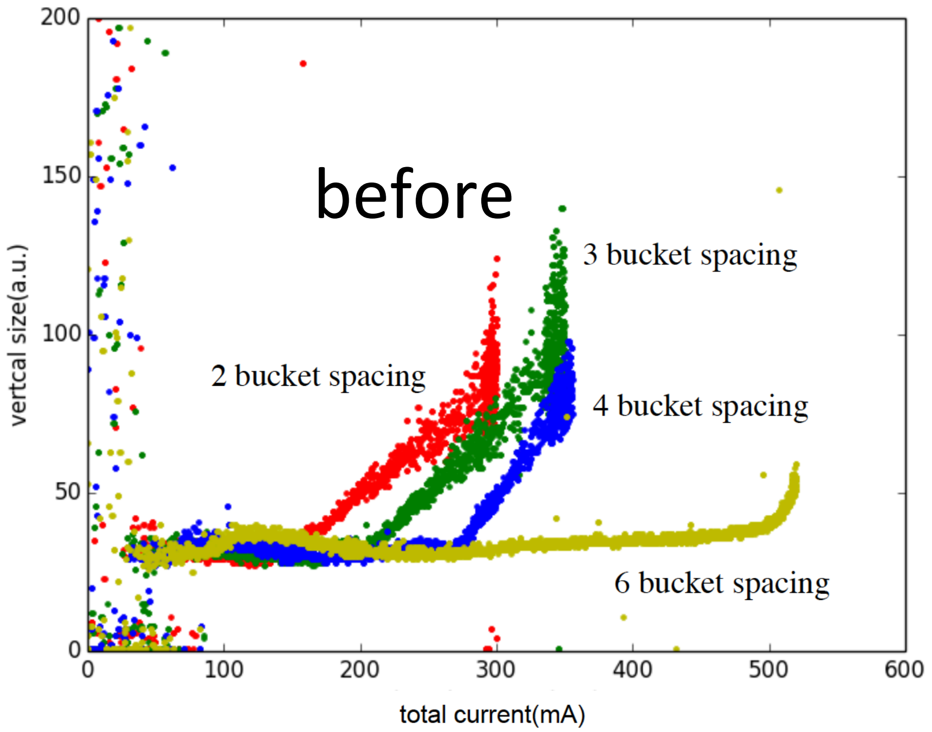
3.06 spacing (1576 bunches)

June 1st (before installation of solenoids at bellows chambers)

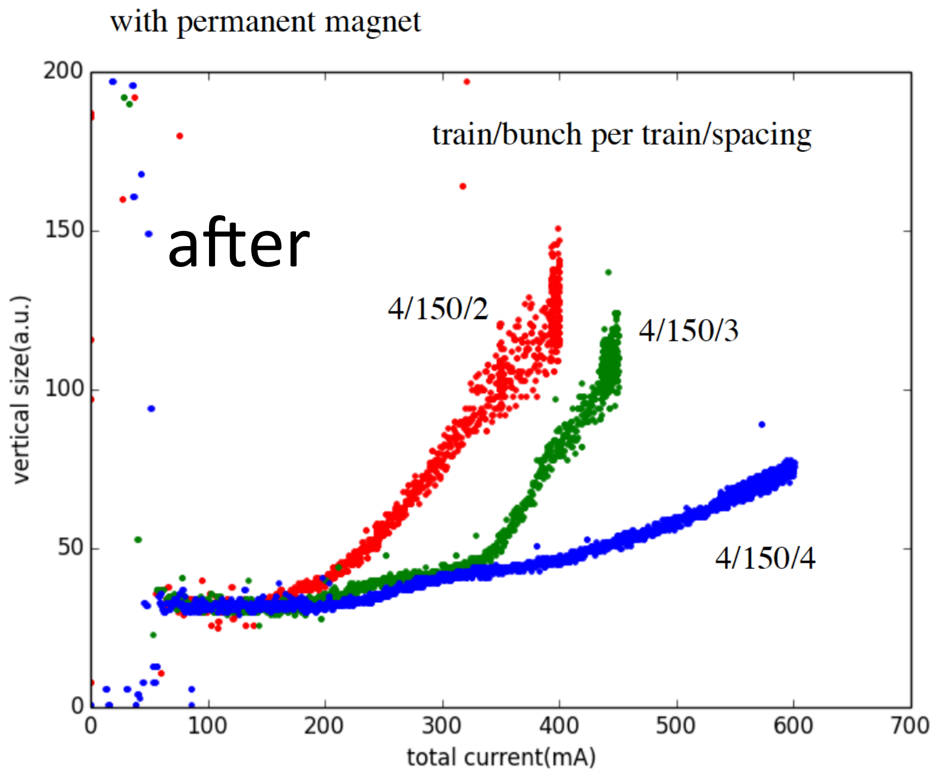
June 6th (after installation of solenoids at bellows chambers)

One of the motivation of installing solenoids was to check their effects to the beam size.

Blowup study



June 1st (before installation of solenoids at bellows chambers)



June 8th (after installation of solenoids at bellows chambers)

The solenoids at bellows were effective to raise the blowup threshold by a factor 1.5.
The electron clouds seem to be responsible for the beam blowup.
We may need more solenoids for higher beam operation.

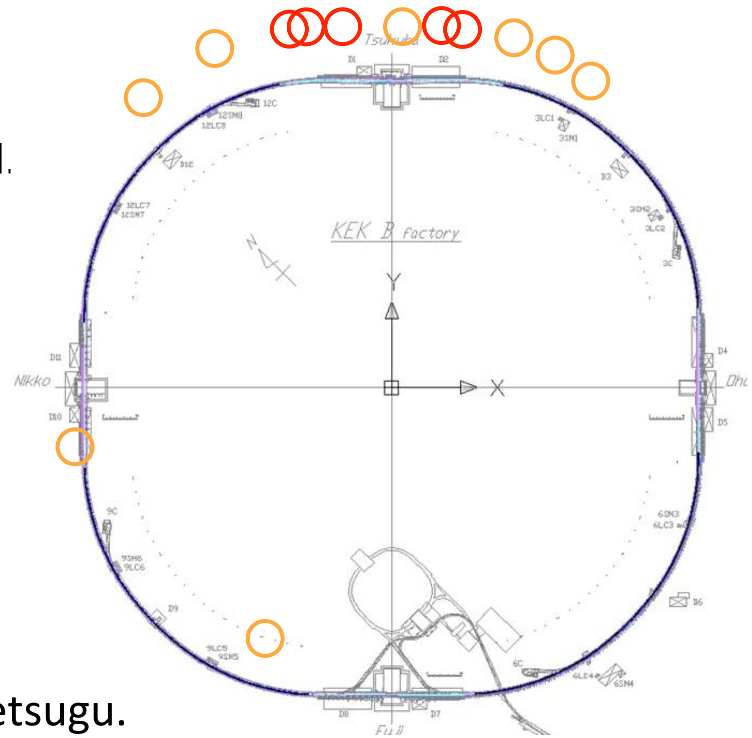
More details will be given in the talks by Y. Suetsubu and K. Ohmi.

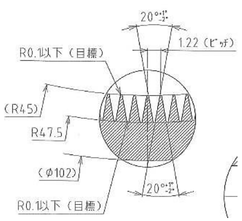
Vacuum burst in LER

Y. Suetsugu

Pressure bursts accompanying beam loss in LER

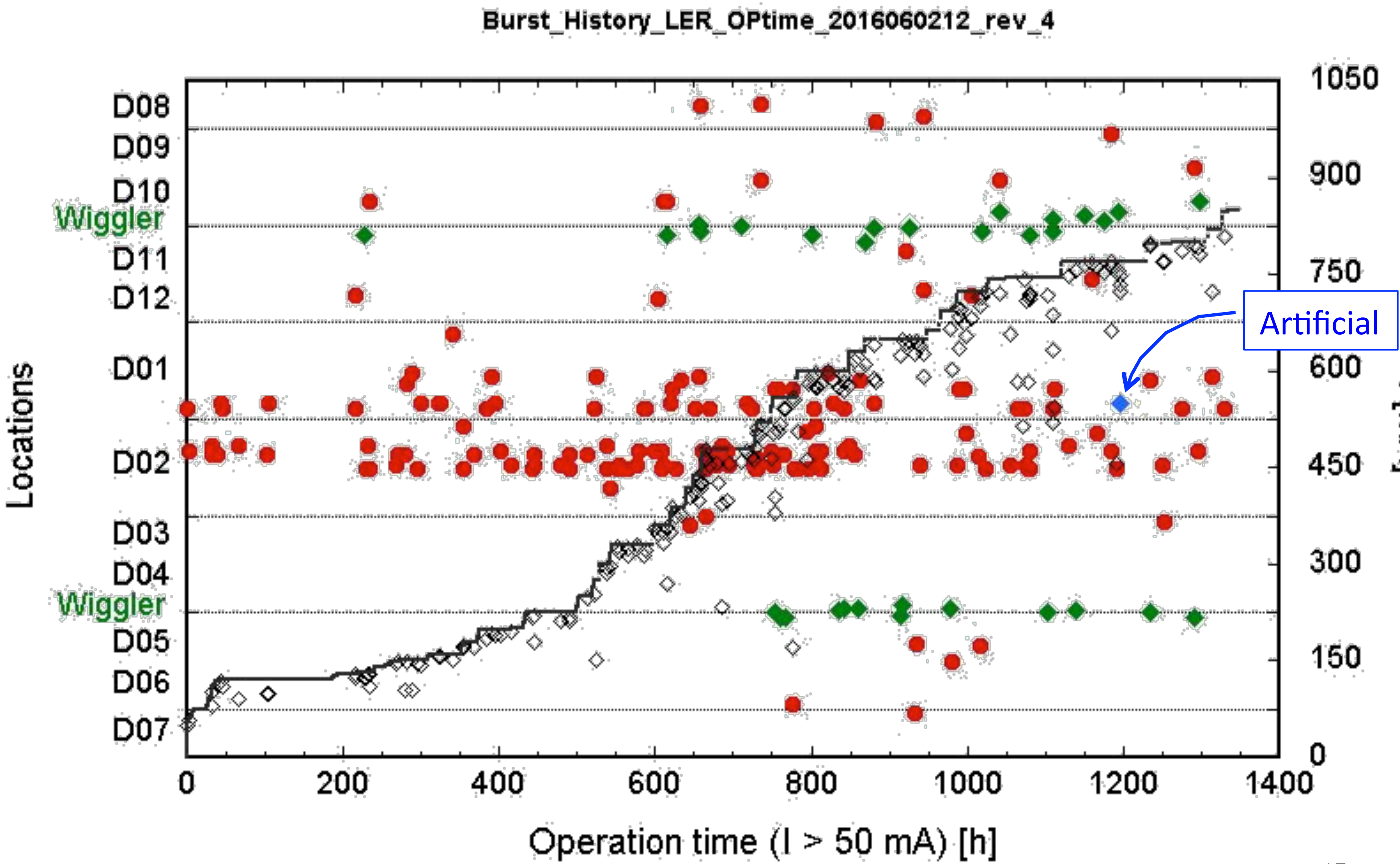
- One big concern is that beam aborts accompanied by localized pressure bursts have been frequently observed from the early stage of the commissioning in the LER.
- The beam loss monitors trigger the beam aborts.
- Frequent pressure bursts have occurred near or inside the aluminum beam pipes in dipole magnets.
  - Our beam pipes for dipole magnets have a groove structure as a counter measure against electron cloud effects.
- The beam current where the bursts occurred has Increased gradually.
- The reason for the pressure bursts is not well understood.
- Possible causes are the discharge at poor electrical contacts by the wall current and the collision of dusts (small particle) with circulating beams. A knocker against vacuum chamber could reproduce the vacuum burst. This result seem to support the hypothesis that the burst is induced by dust particles.





More details are discussed in the talk by Y. Suetsugu.

Locations of vacuum burst in LER

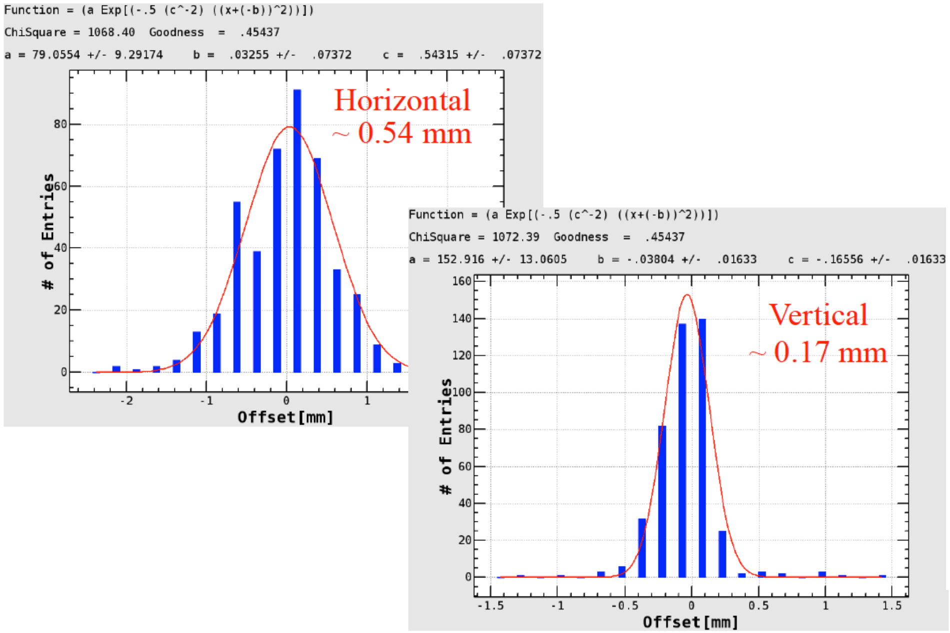


Optics corrections

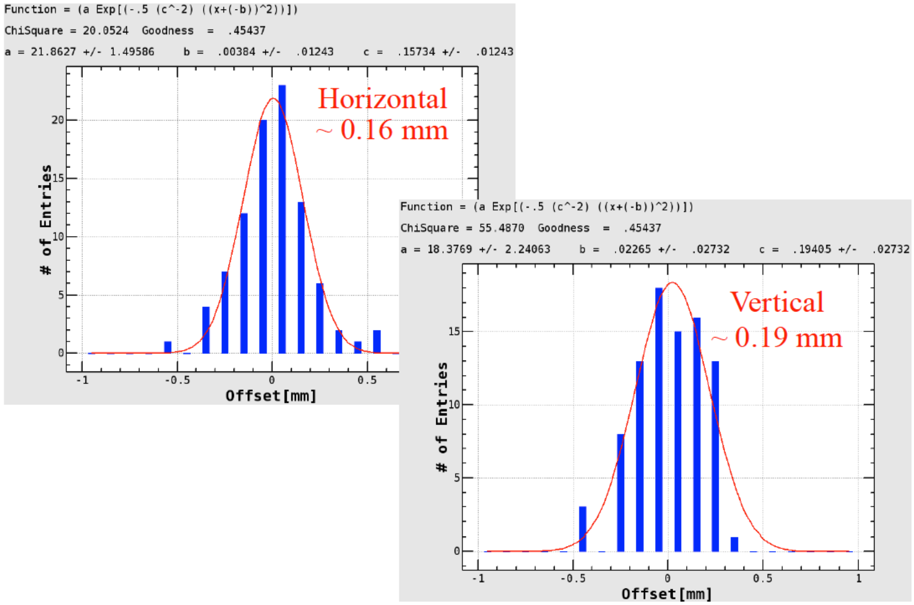
- Base measurements for hardware system check
  - BPMs
    - BPM check with beams (orbit bumps) -> We found mis-connection or mis-cabling of BPM cables with ~>20 BPMs.
    - Gain calibrations of BPMs have been done with beams.
    - Quad-BPM measurements (to measure difference between field center of quadrupole magnets and the center of near-by BPM) have been almost finished.
  - Steering magnet
    - Check with beams (orbit bumps) -> We found an error with the excitation curve of steering magnets.
  - Closed orbit correction system
    - Closed orbit correction is a basis of optics correction. A reliable closed orbit correction system has been established based on the above measurements and modifications.

Beam based BPM offset measurement (Quad-BPM, SextBPM)

LER Quadrupole Offset Distribution



LER SextBPM



Ring circumference

- From the orbit measurement, we can know the ring circumference.
  - LER: $C_{Measurement} - C_{Design}$ ~2.0mm (Cir: 3016m)
  - $C_{LER} - C_{HER}$ ~ 0.2mm (LER chicane can adjust +/- 3mm)
  - Magnet group has done a good job in the alignment work.

Method of optics correction

- At SuperKEKB, we follow the method successfully used at KEKB.
- Optics corrections on X-Y coupling, dispersions and beta-beat are done iteratively.
- Since there are not enough single path BPMs, we rely on conventional BPMs.
- For the measurements of X-Y coupling and beta-beta, orbit responses are measured with single kicks by steering magnets.
- For the measurement of dispersion, we use a usual RF phase frequency change.

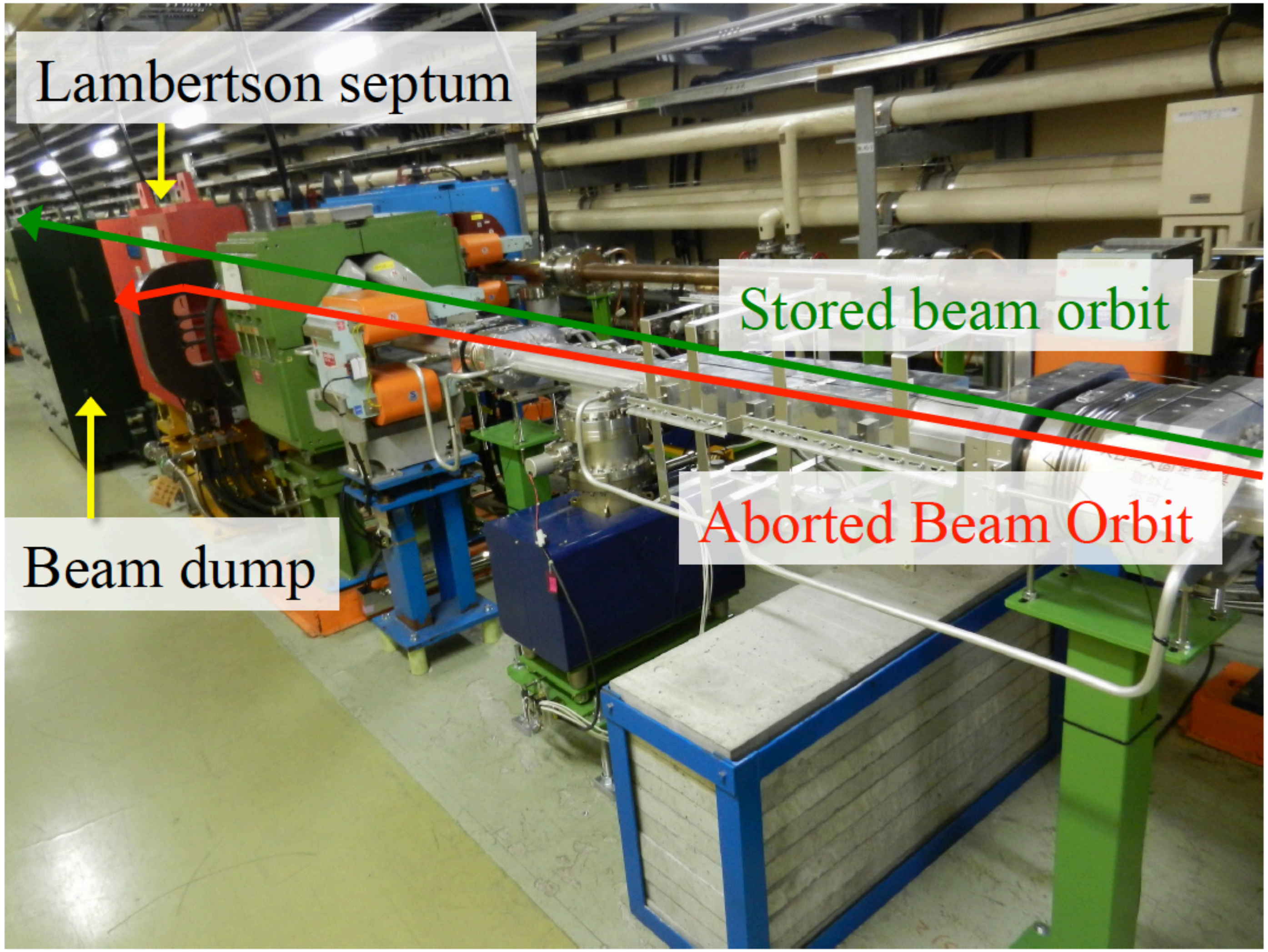
Details are given in the talk by H. Sugimoto.

Highlight of low emittance tuning

- The X-Y coupling correction and dispersion correction are important to get a low vertical emittance.
- While the HER corrections went well, we encountered a difficulty in the LER corrections.
  - The obstacle of the corrections was leakage magnetic field from the Lambertson septum magnets whose main component is skew-Q.
    - We have made two countermeasures against the problem.
      - The use of skew-Q coils of the SF magnet nearby the Lambertson. (downstream of the Lambertson septum)
      - Installation of permanent skew-Q magnet in the upstream of the Lambertson septum.

Leakage Field from Lambertson Septum

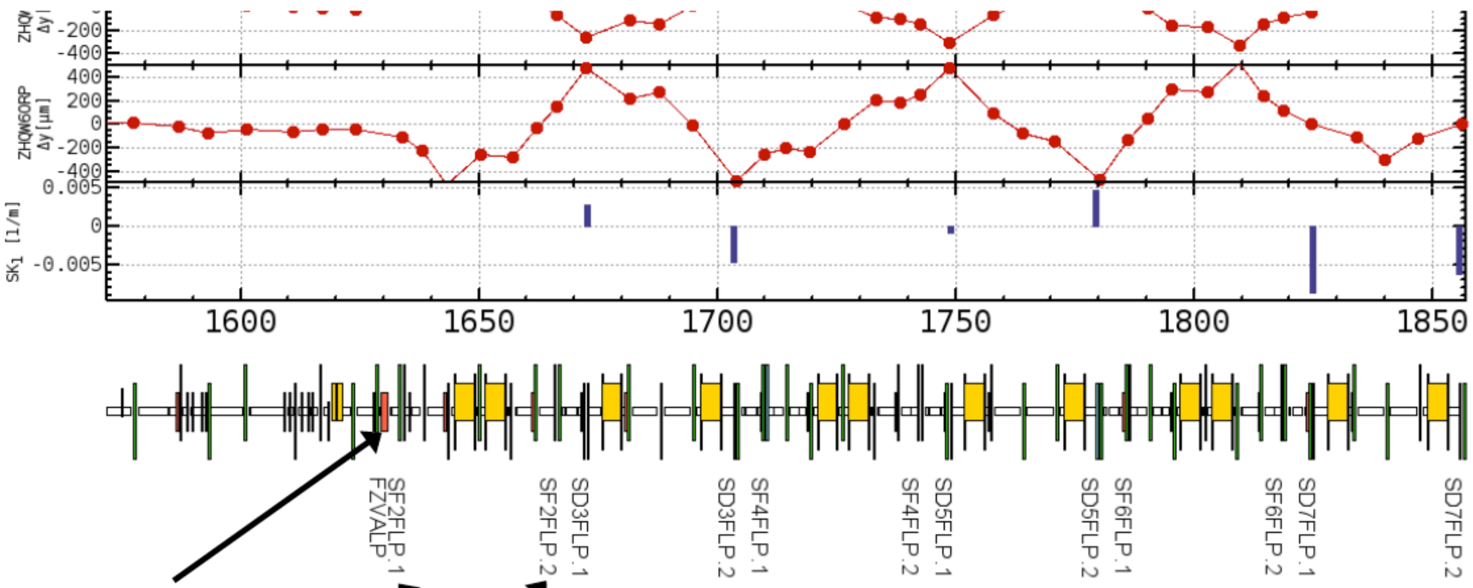
- A Lambertson septum is used to deliver aborted beam to a beam dump.
- This magnet creates unexpected leakage field to stored beam line.



H. Sugimoto

Add Skew Correctors

- All focusing (SF) and defocusing (SD) sextupole magnet have skewQ coil.
- As for Phase 1, Power supplies (PS) for skewQ are prepared only for SD magnets.
- We activate skewQ coils of one SF pair near the septum by using standby PS.



Lambertson septum

Activate those two skewQ coils installed in SF magnets.

XY-Coupling Correction

H. Sugimoto

- Correction with the additional skewQ coils.
- The vertical leakage orbit is effectively reduced.

Measurement:

Vertical leakage orbit induced by independent 6 steering kicks.

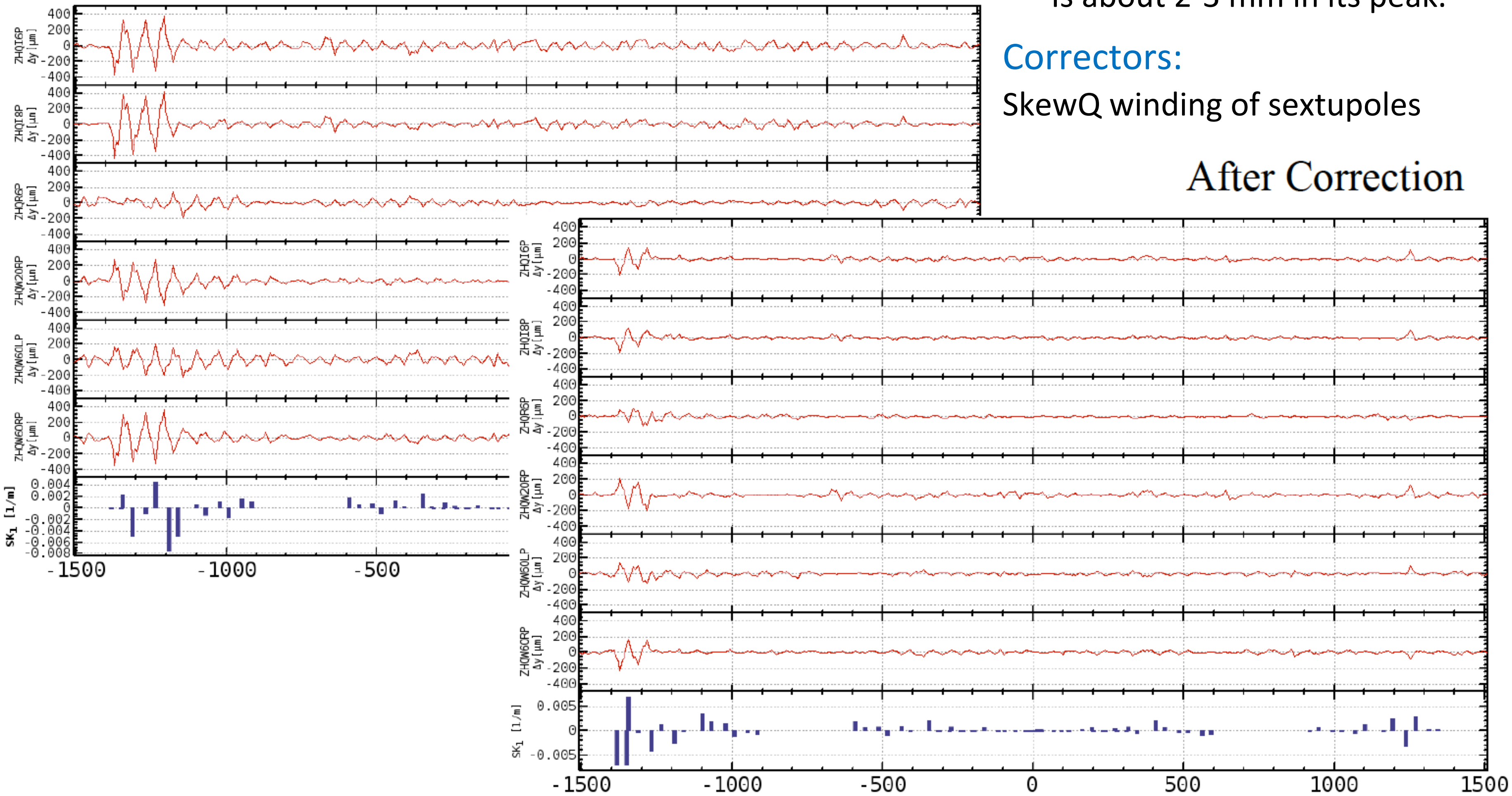
- Induced horizontal orbit amplitude Is about 2-3 mm in its peak.

Correctors:

SkewQ winding of sextupoles

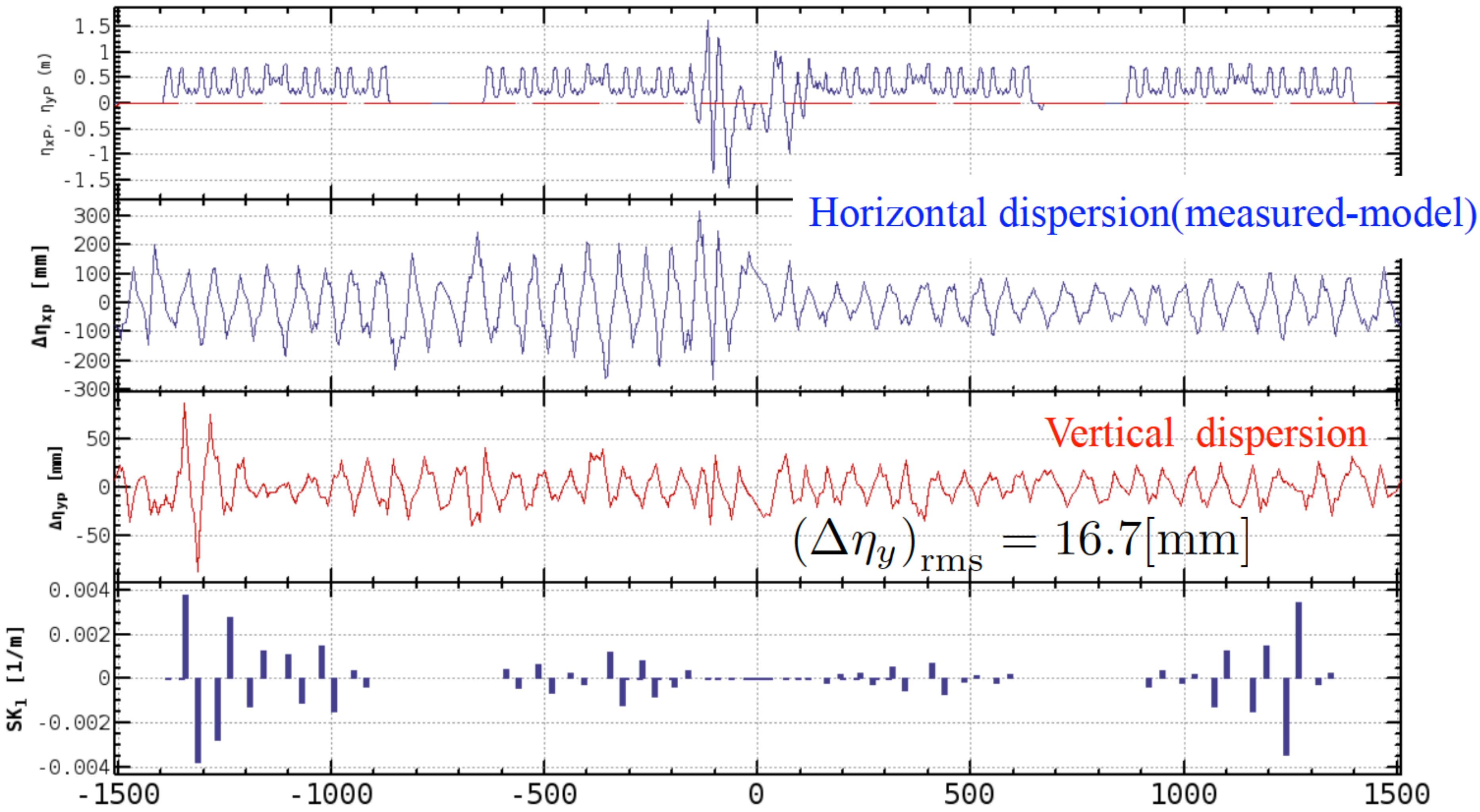
Before Correction

After Correction



H. Sugimoto

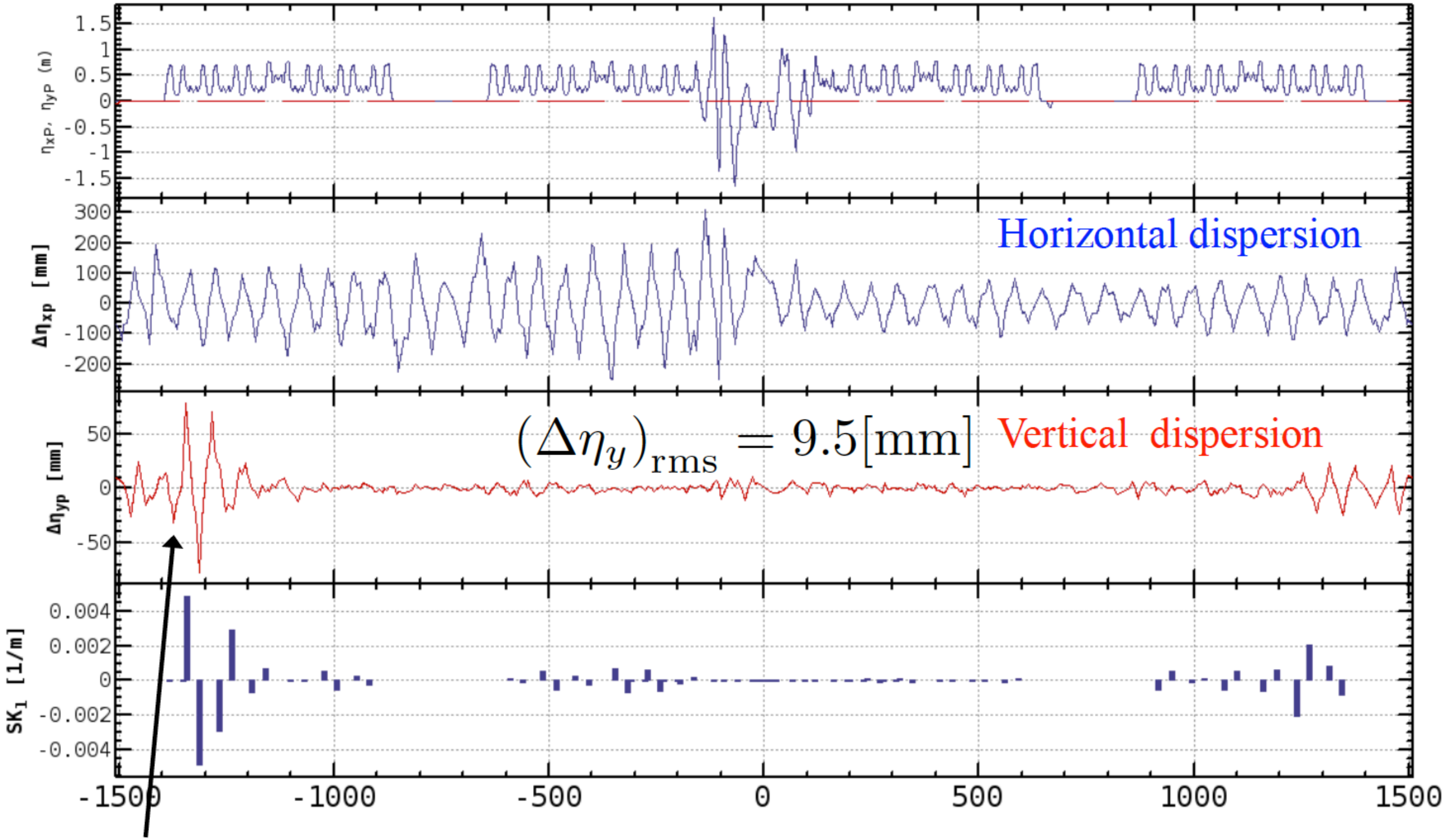
LER Vertical Dispersion *Before* Correction



Correctors:
SkewQ winding of sextupoles

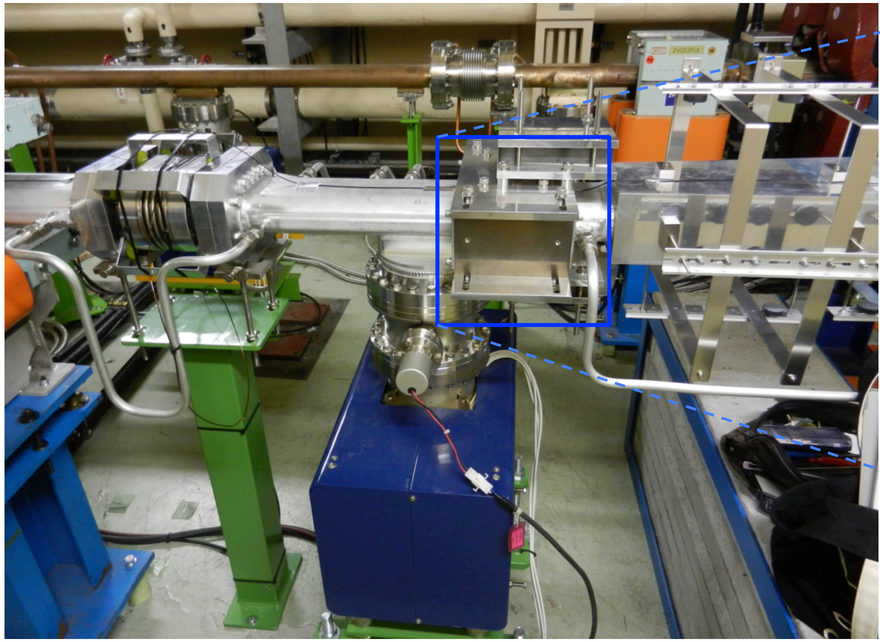
LER Vertical Dispersion *After* Correction

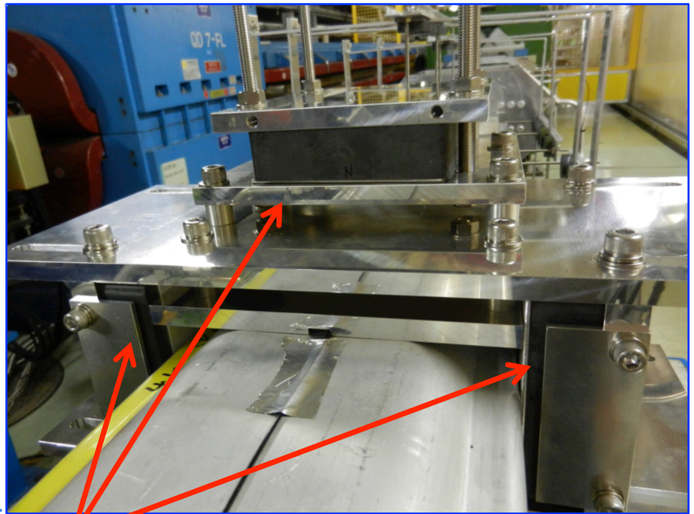
H. Sugimoto



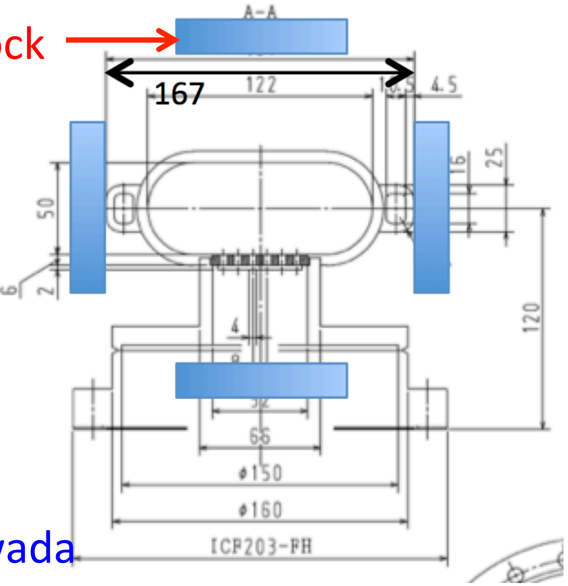
- This peak is not correctable due to hardware limit of SkewQ corrector strength.
- We have a plan to enforce SkewQ correctors.

The skew quadrupole magnets to cancel the leakage field from the Lambertson





Ferrite block



Ferrite block

Size: 100 x 25.4 x 150 (mm)

B ~ 550 (Gauss)

r = 85.5 (mm)

→ SK1 = - 7.7e-3 (/m)

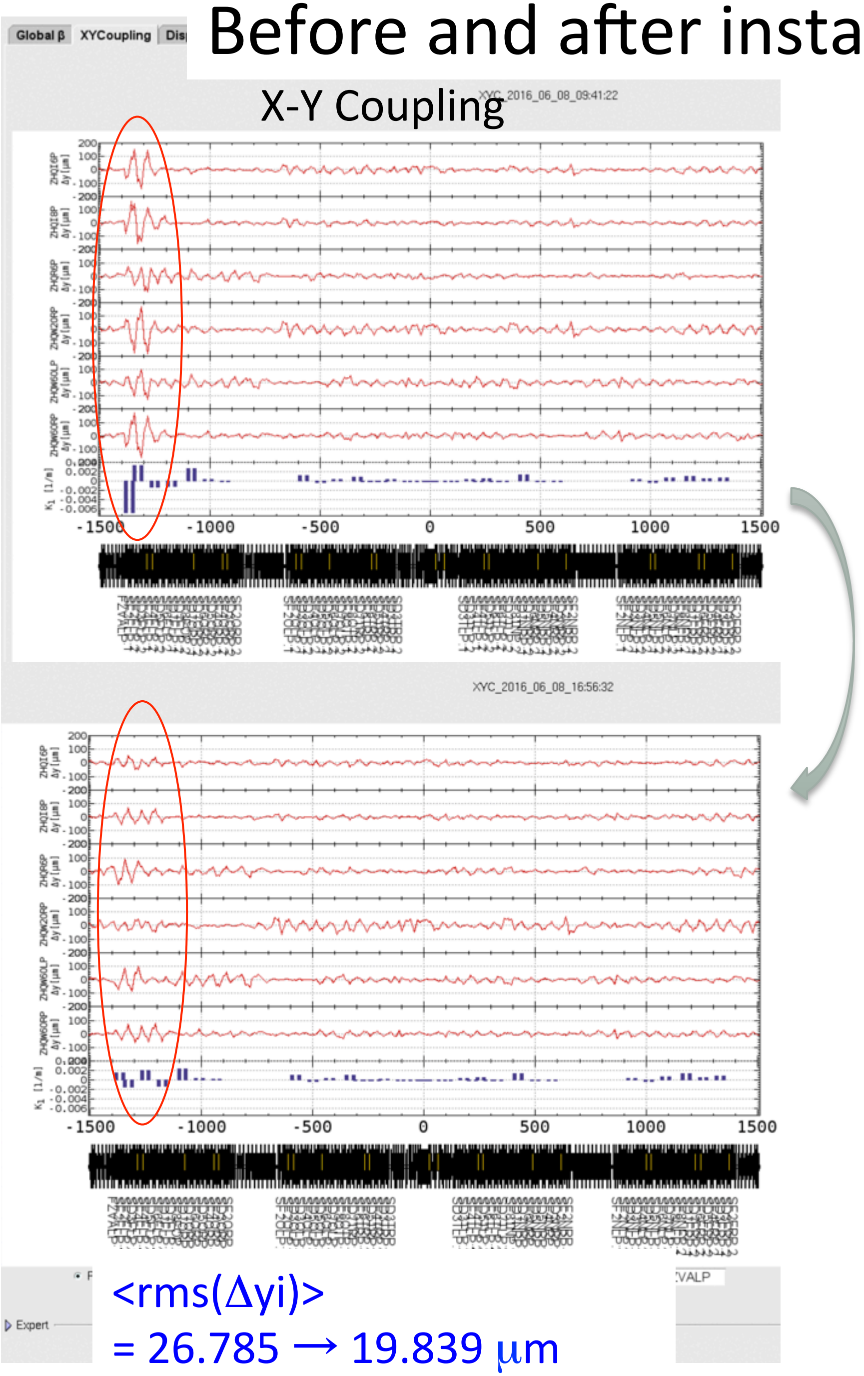
which is adjusted the requirement from optics.

N. Iida, M. Kikuchi, K. Kodama, T. Mimashi, T. Mori, T. Tawada

Before and after installation of Ferrite blocks

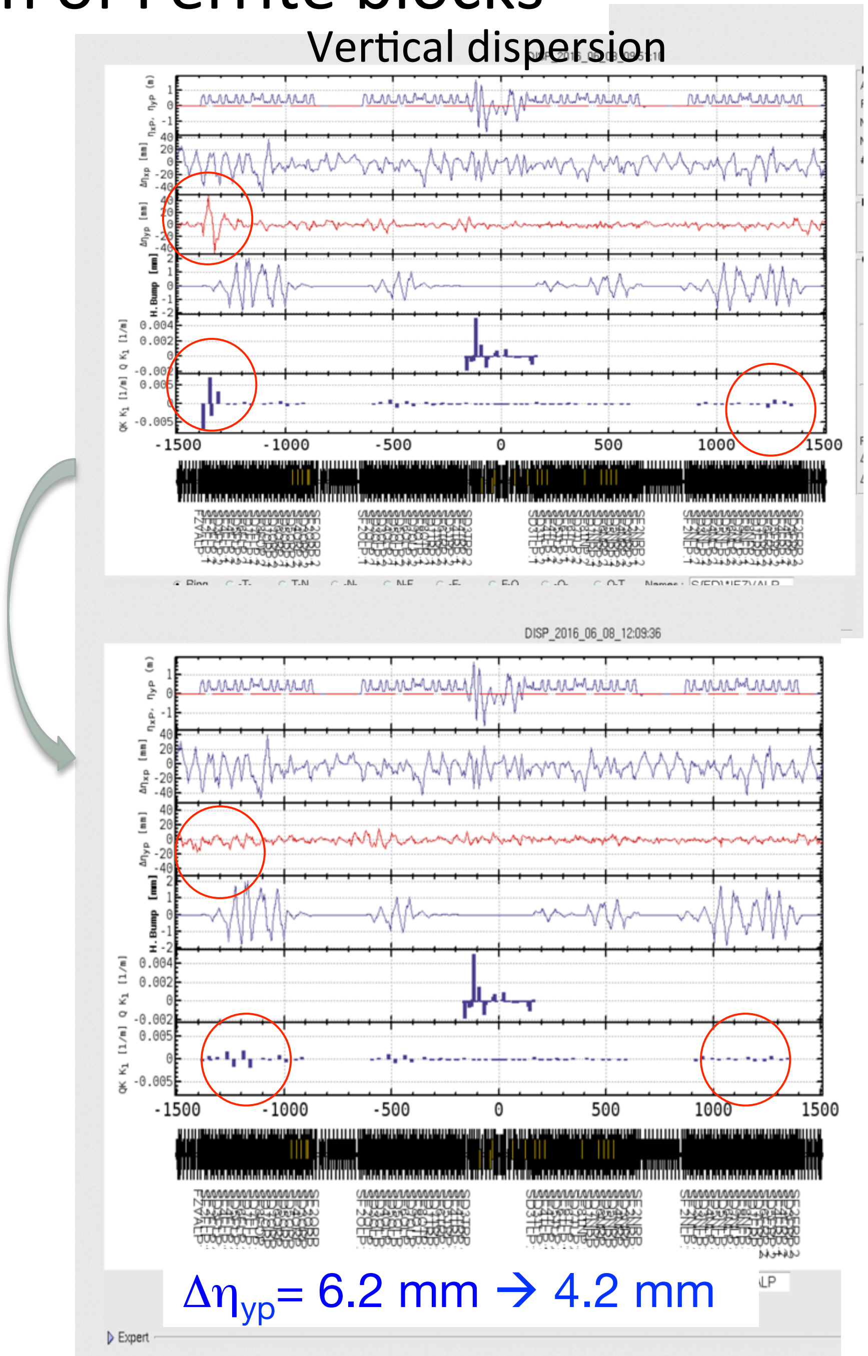
H. Sugimoto

X-Y Coupling



<rms(Δyi)>
= 26.785 → 19.839 μm

Vertical dispersion



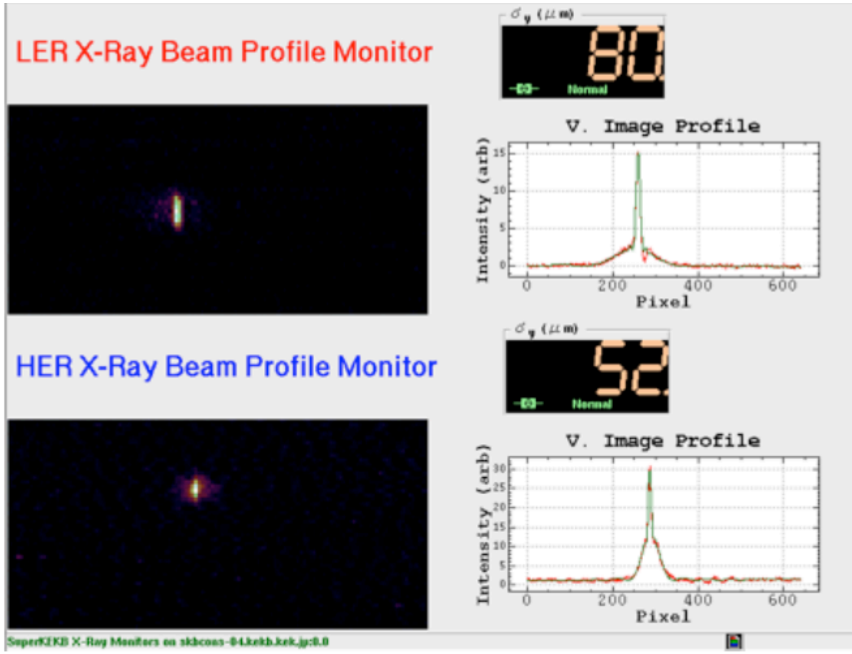
$\Delta\eta_{yp}$ = 6.2 mm → 4.2 mm

Present status of linear optics corrections

Items	LER	HER	KEKB typical value (LER)	Unit
X-Y coupling average of rms (Δy_{1-6})	19.8	7.7		mm
H. Dispersion rms (Δh_x)	14.8	16.1	10	mm
V. Dispersion rms (Δh_y)	4.2	4.8	8	mm
Beta-x rms ($\Delta b_x/b_x$)	4.9	4.3	6	%
Beta-y rms ($\Delta b_y/b_y$)	5.3	3.7	6	%

More details will be discussed in the talk by H.Sugimoto.

Beam size measurement by using X-ray monitor



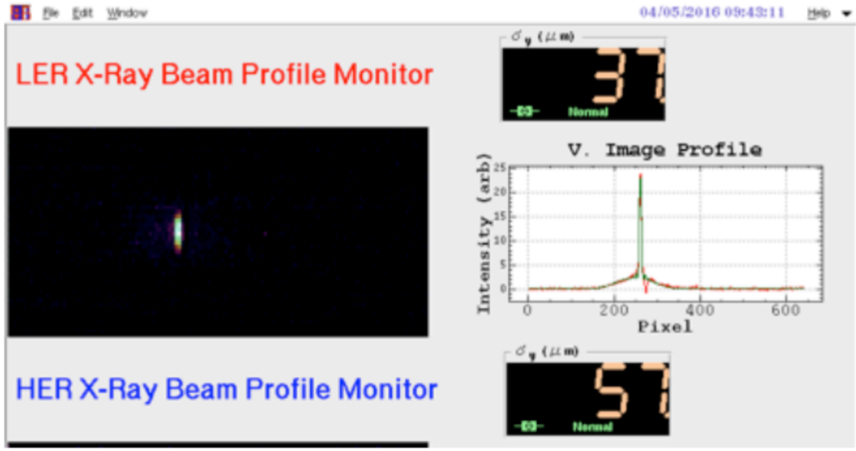
March 23rd, 2016

ε_y = 96pm (by = 67 m @source)

$\varepsilon_y/\varepsilon_y$ = 5.3% (ex = 1.8nm)

ε_y =356pm (by = 7.7 m @source)

$\varepsilon_y/\varepsilon_y$ =7.7 % (ε_y= 4.6nm)



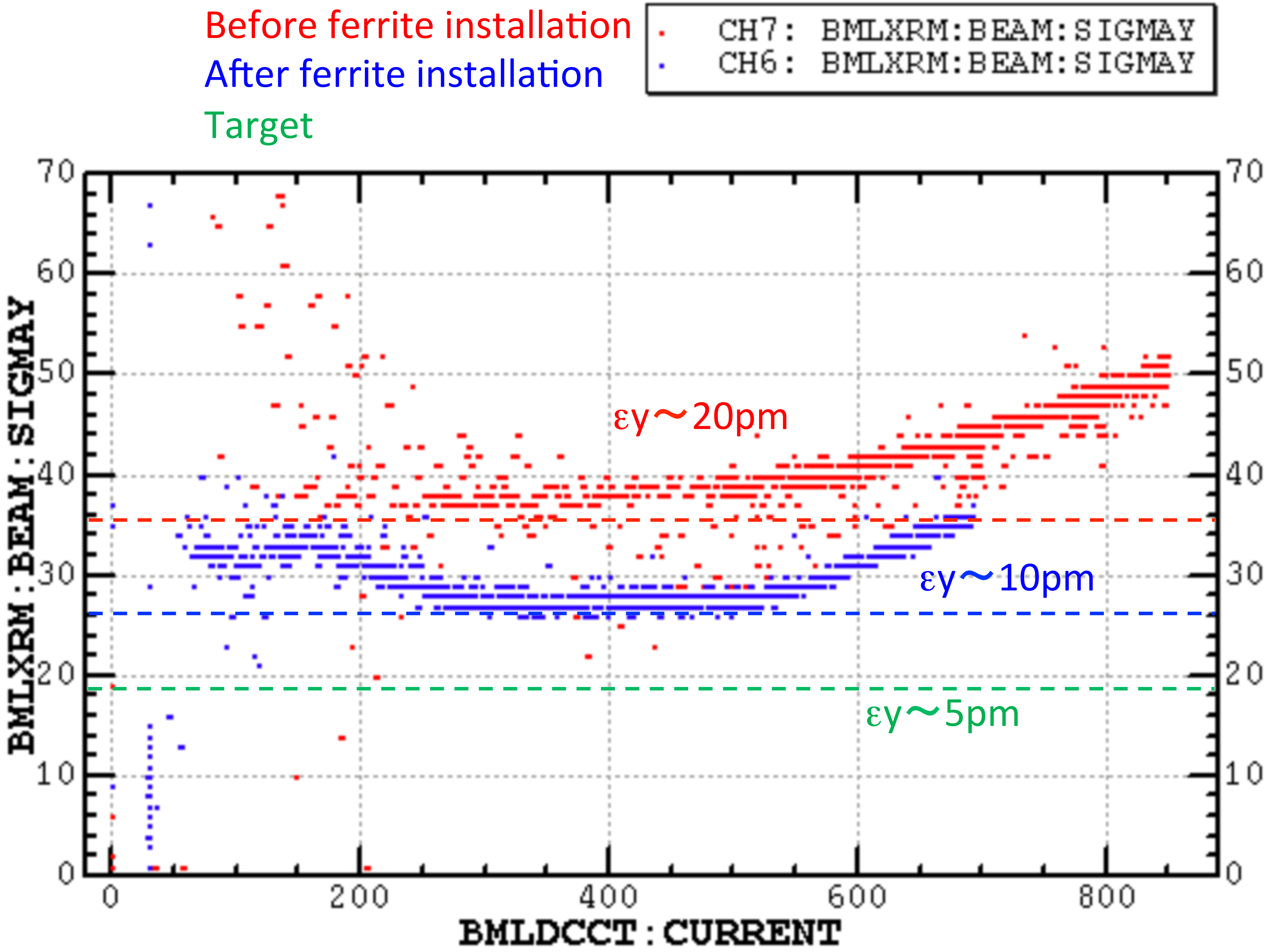
April 5th, 2016

ε_y = 20pm (by = 67 m @source)

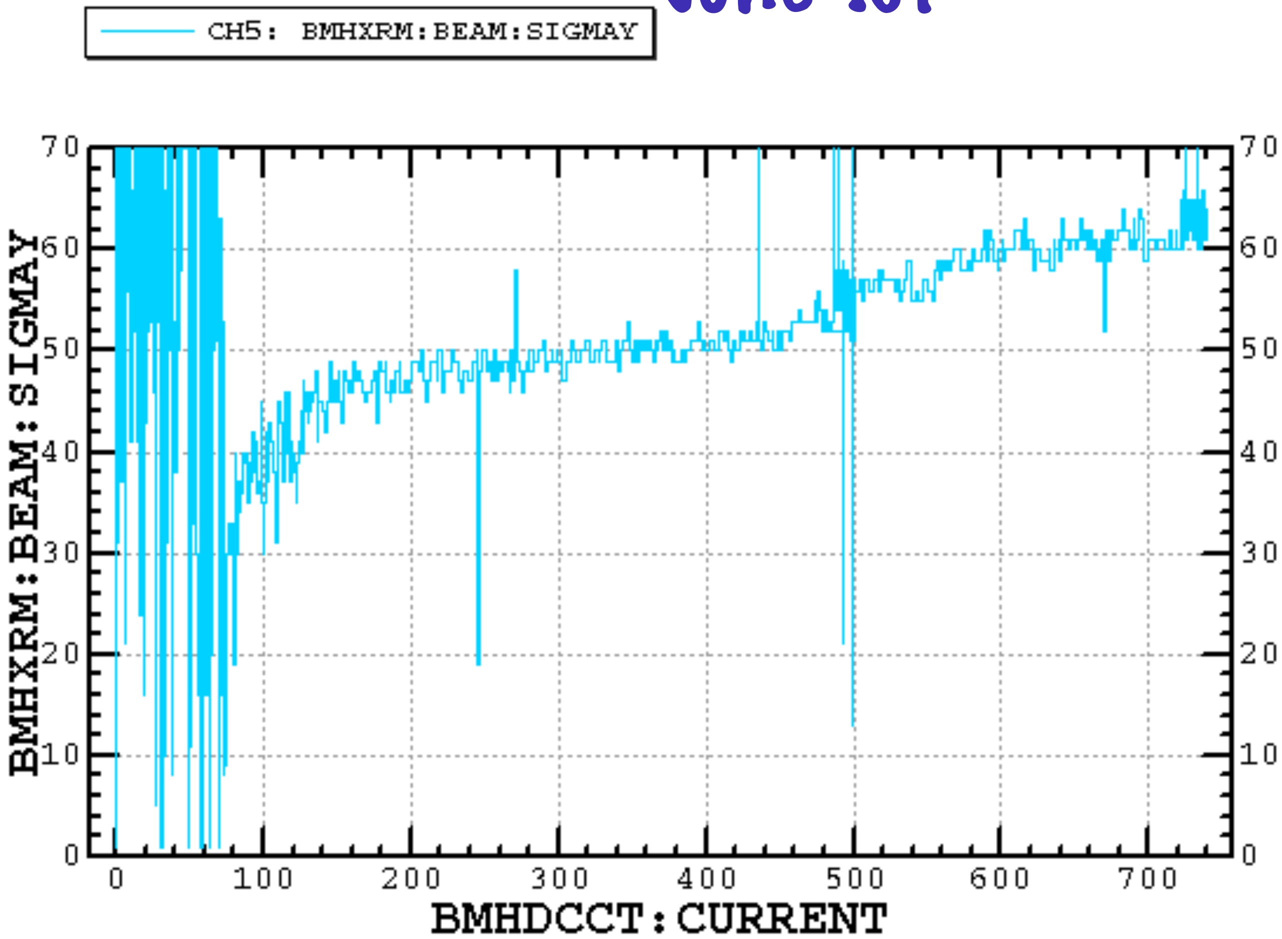
$\varepsilon_y/\varepsilon_y$ = 1.1% (ex = 1.8nm)

Target vertical emittance (LER) in Phase 1 is ~5pm.

Vertical beam size measurement (after permanent skew-Q installation)



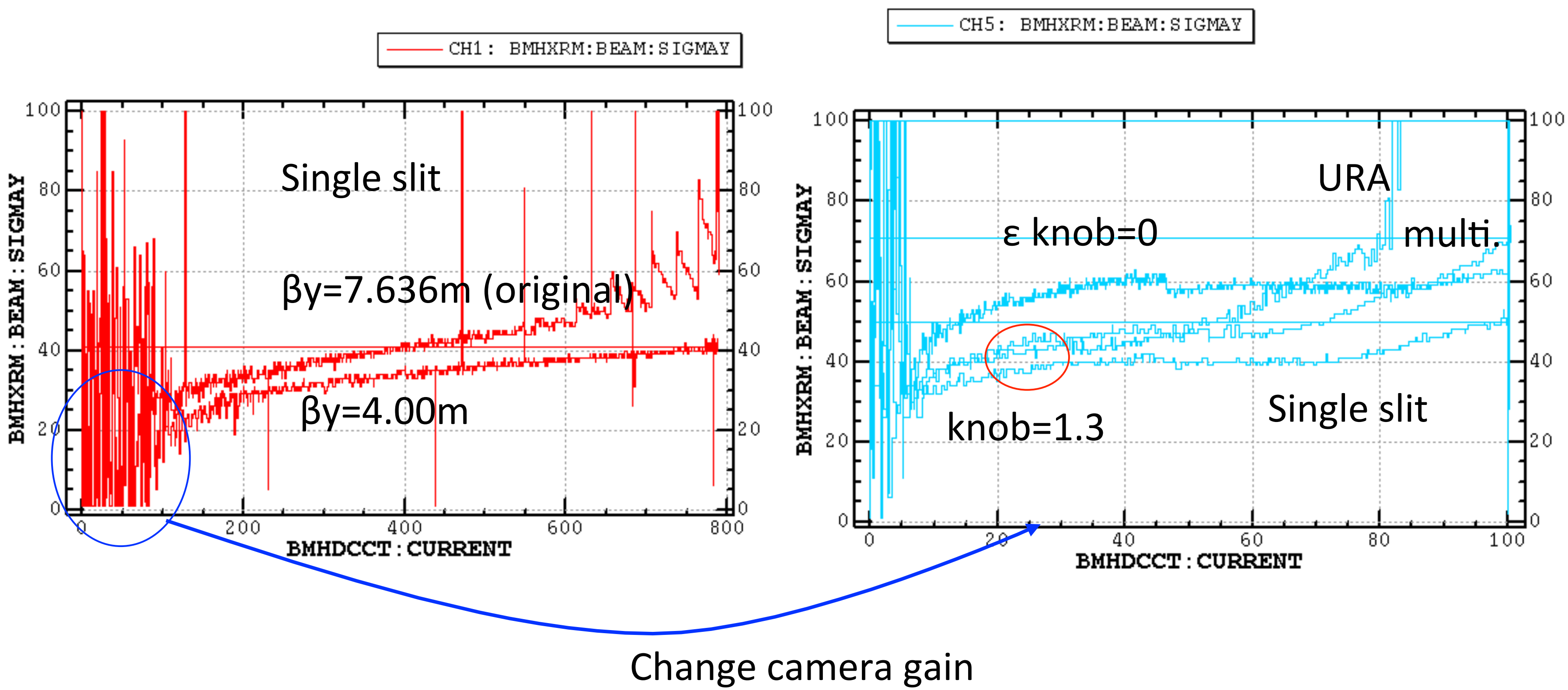
HER Beam size measurement by using X-ray monitor June 1st



HER σy@source point = 40μm? -> εy=210pm

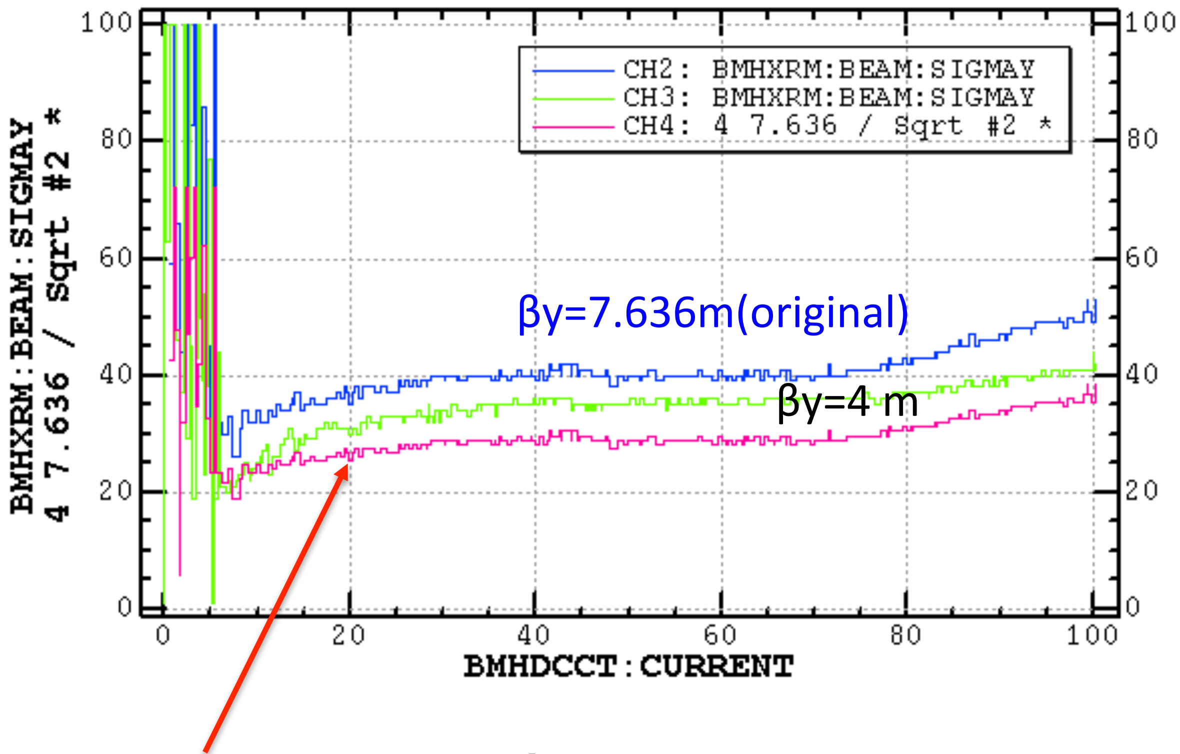
This vertical emittance is inconsistent with optics correction results.

HER X-ray monitor study (June 9th)



The current dependence of HER vertical beam size seems to be fake.

HER X-ray monitor study (June 9th)



Data with βy =7.636 x $\sqrt{4}/7.636$

The measured beam size does not scale the beta function.
Is there any offset in the measurement such as coupling from horizontal size?

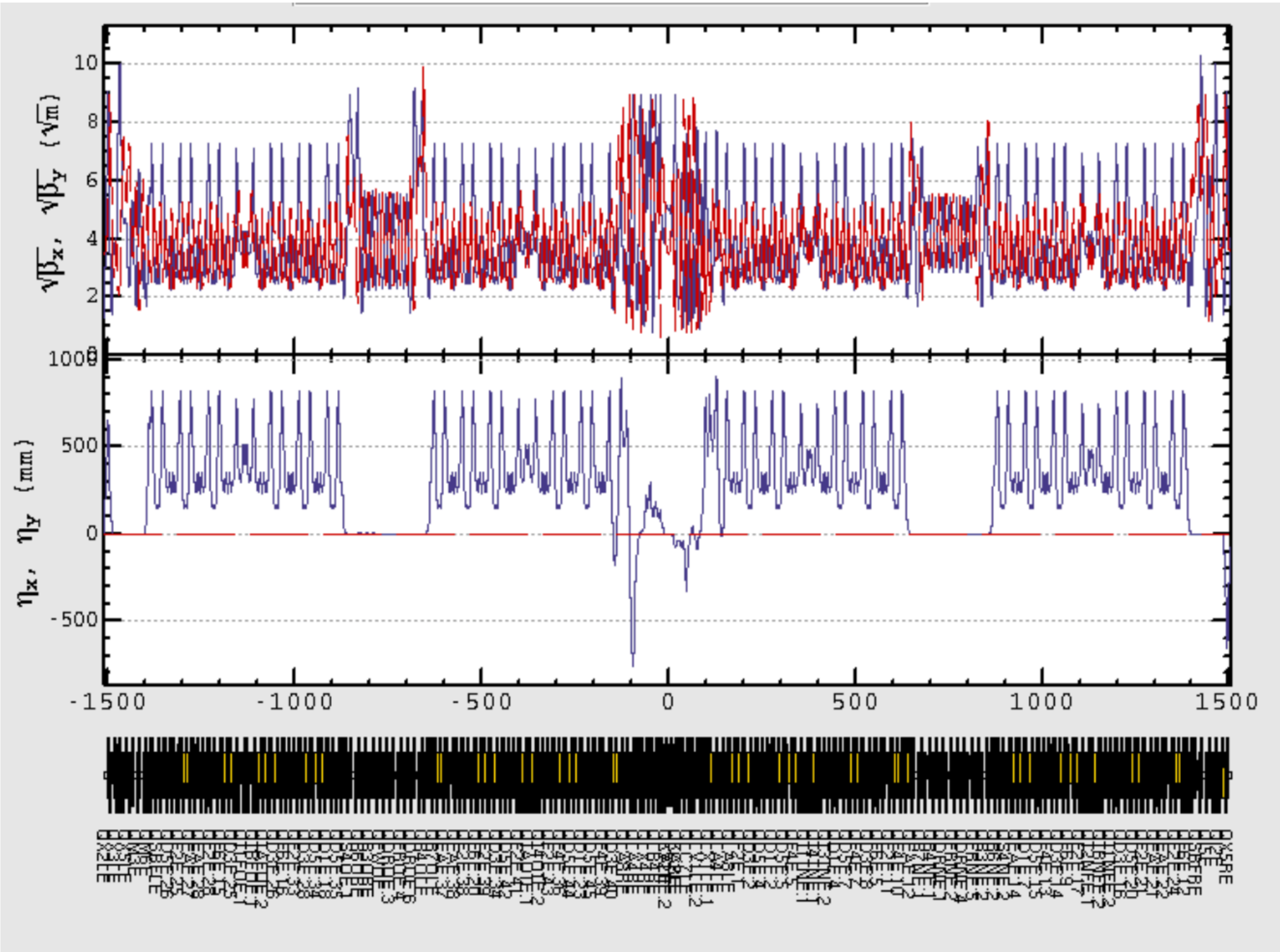
More details are given in the talk by J. Flanagan.

Summary

- After 5 year's upgrade work from KEKB, Phase 1 operation of SuperKEKB (w/o Belle-II detector and IR) started in Feb. 2016 and on the way.
- The startup of SuperKEKB operation is relatively smooth thanks to experiences at KEKB.
- In preparation for installation of Belle II detector in Phase 2, vacuum scrubbing is being done and beam background study has been done with Beast detector.
- The optics correction study is going on energetically.
- The LER low emittance has been much improved by the correction of leakage field of Lambertson septum.
- The calibration of X-ray monitor is an important tuning item.
- We observed the vertical beam size blowup in LER. The source of the blowup seems to be the electron clouds.
- Injector has worked stably. For Phase 2 and 3 operation, we will need more improvements.

SPARE SLIDES

HER Phase 1 Lattice

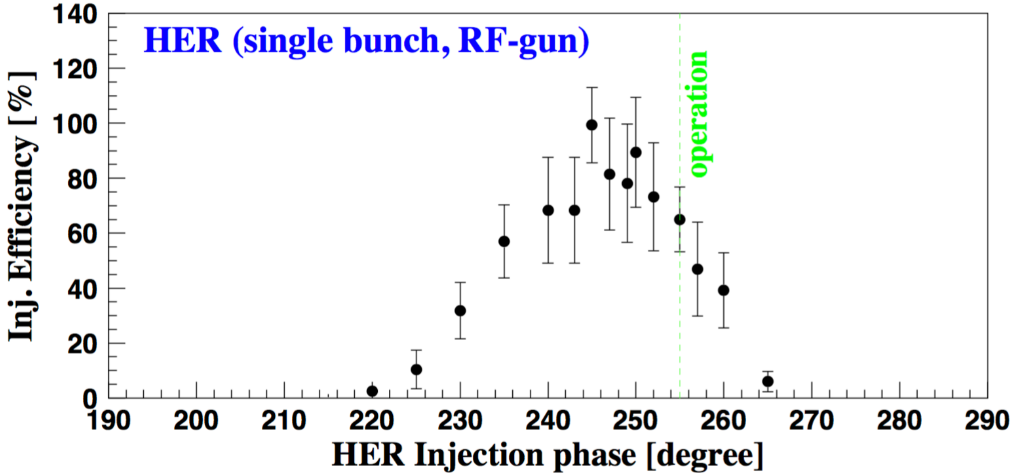


Injection phase vs efficiency

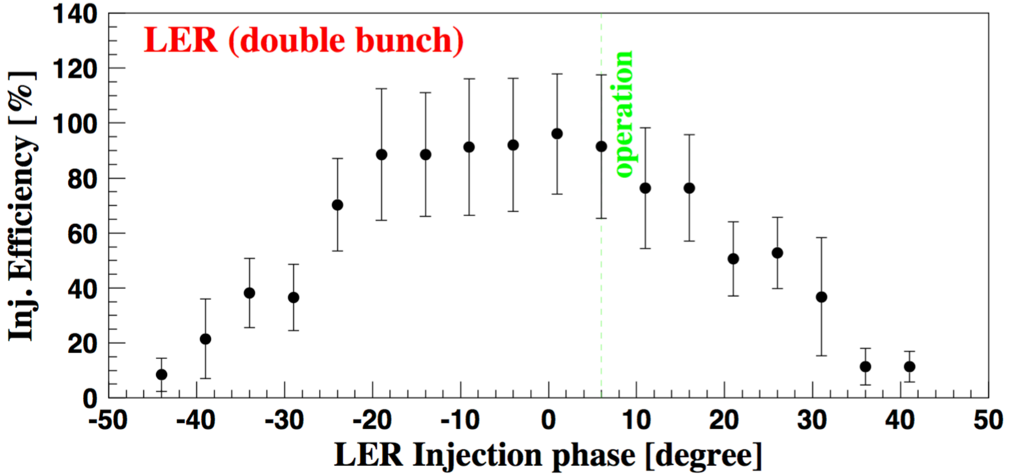
Error bar: RMS in 100 shots.

入射位相を変えながら入射効率を測定した。

測定時の電流
HER: 40~95 mA
LER: 40~90 mA



・現在の設定値は最適な位相からずれている
HER変更: 255° → 245°
LER変更: 6° → -5°

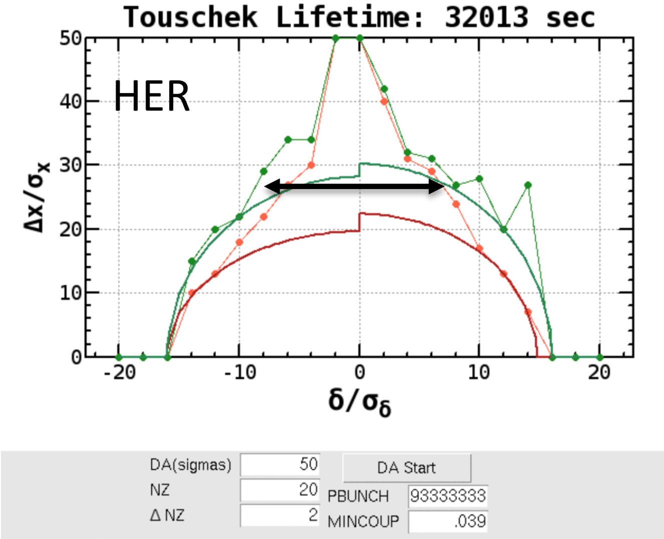


HER: $\Delta\phi_{full}$ = 45 deg. → 14 σ_δ ↔ 28 σ_δ (model);); 16 σ_δ @ x/ σ_x > 25
LER: $\Delta\phi_{full}$ = 80 deg. → 28 σ_δ ↔ 32 σ_δ (model)

see next page

Comments

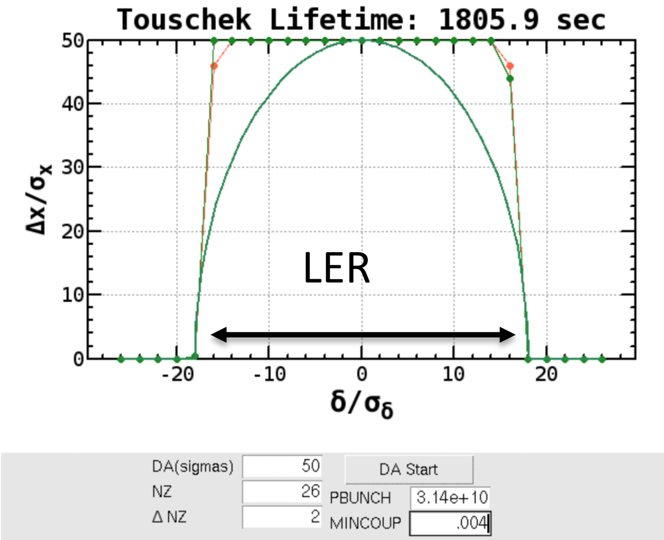
- HERのε_yは、本当に巨大なのか？ (really big ?)

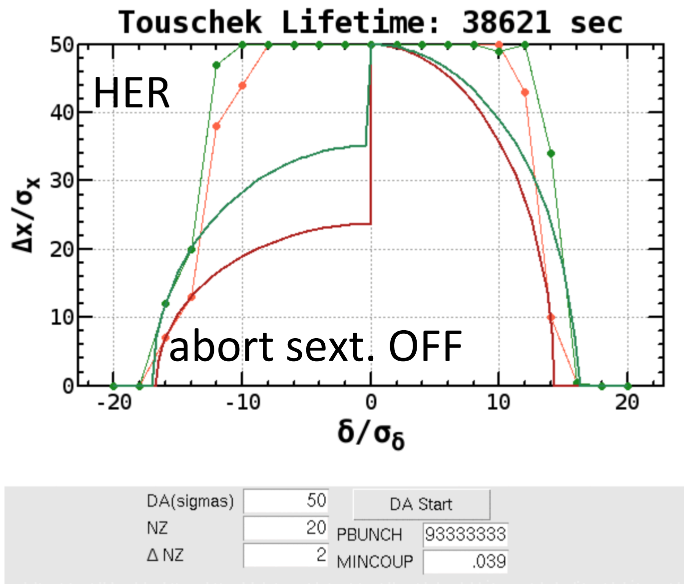


Touschek lifetime ~530 min
when ε_y =180 pm ($\varepsilon_y / \varepsilon_x$ = 3.9 %)

σ_y = 37 μm @ X-ray

HERのoptics測定からは推測できない (see next)





abort sextをOFFすればoff-momentumの横方向の口径はかなり大きくなる。

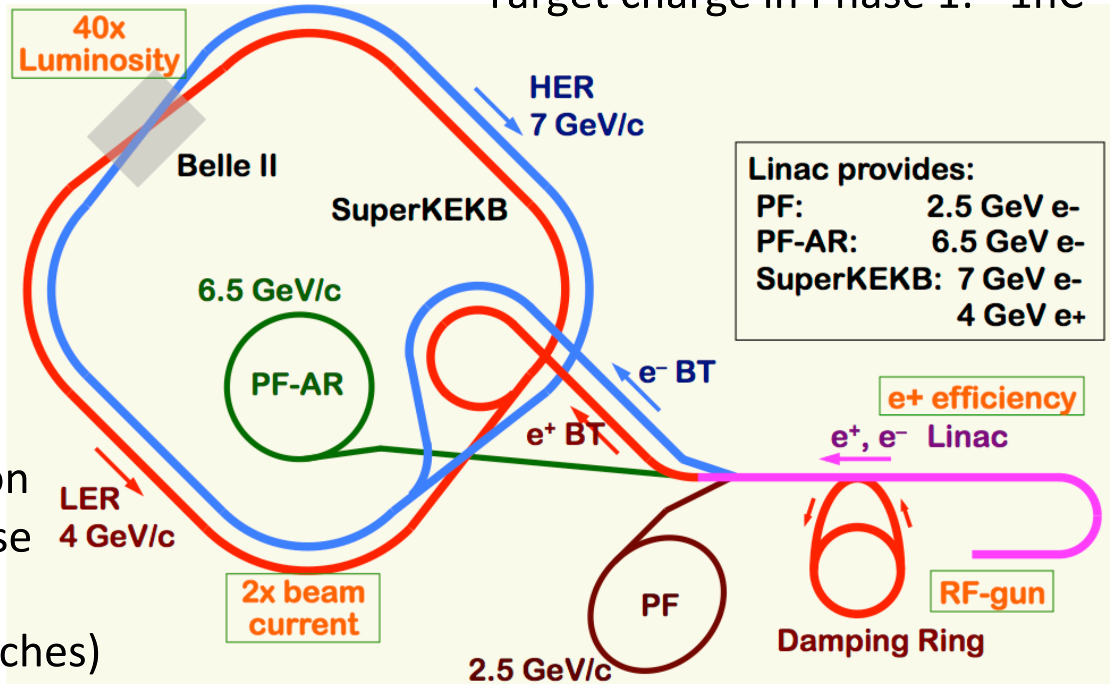
Injector Status

- Requirements to Linac
  - Higher charge for electron and positron
  - Lower emittance for electron and positron
- Linac challenges
  - Low emittance and high intensity e-
    - high-charge RF-gun
  - Low emittance e+
    - damping ring
  - Higher e+ beam current
    - new capture section with flux concentrator
  - Emittance preservation
    - precise beam control
- Status in Phase 1
  - RF gun: still under development
  - Damping ring: under construction
  - Flux concentrator: in practical use
  - Charge at end of BT
    - e-: ~0.6nC, e+:~0.6nC (2bunches)
  - Dedicated machine study for injector: 1 day / week

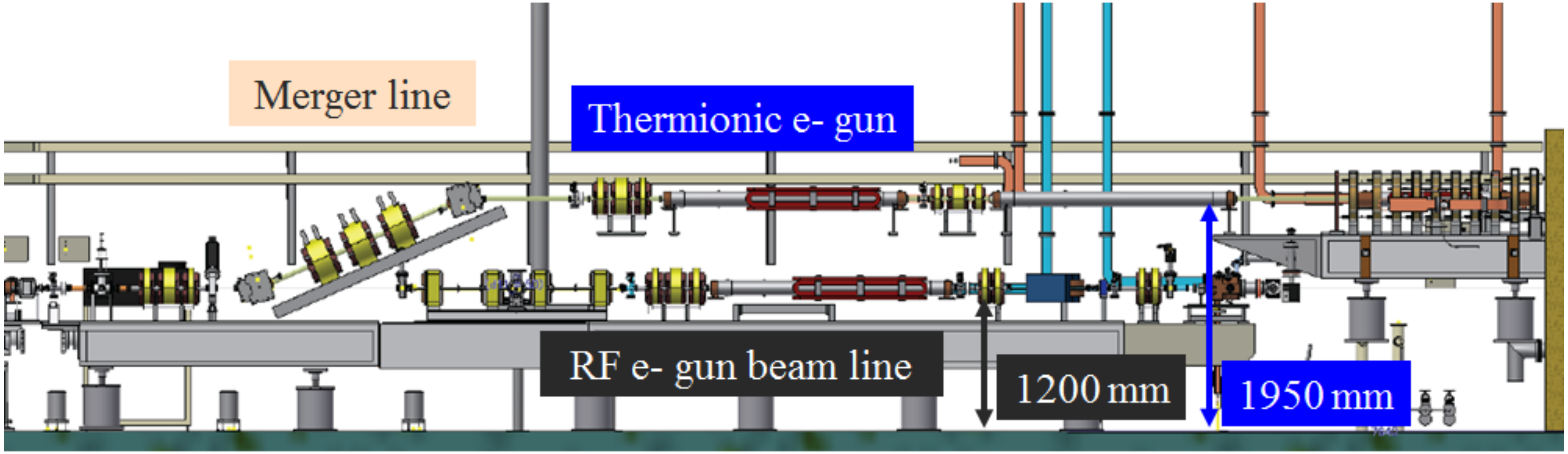
SuperKEKB requirements (Phase 3)

	KEKB (e+/e-)	SuperKEKB (e+/e-)
Charge [nC]	1/1	4/5
Normalized emittance[μm]	2100/300	100/50 (H)
		20/20 (V)

Target charge in Phase 1: ~1nC

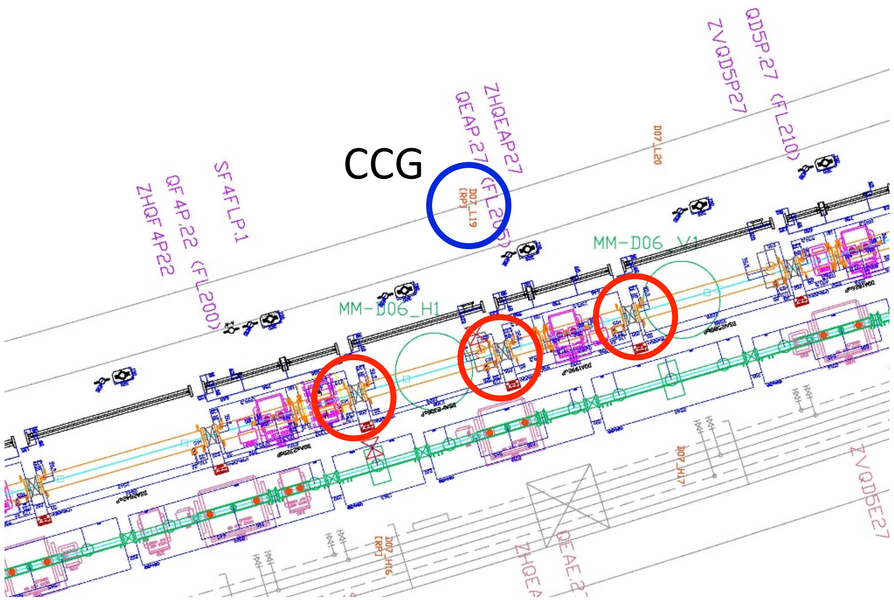


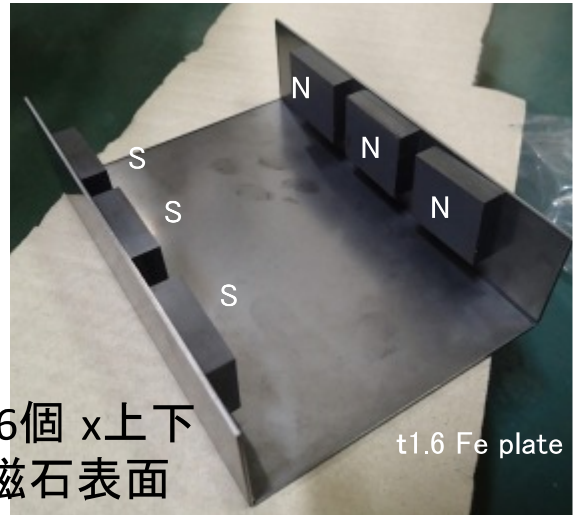
Layout of electron gun (Thermionic DC gun and photo-cathode RF gun)



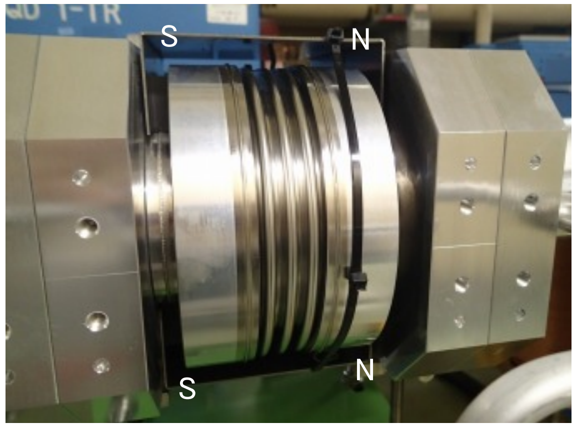
予備実験(4/25)

- 南トンネルの 3個のベローズに「永久磁石」を取り付けて、圧力の振る舞いを調べた。





30 x35 x6個 x上下
970G@磁石表面



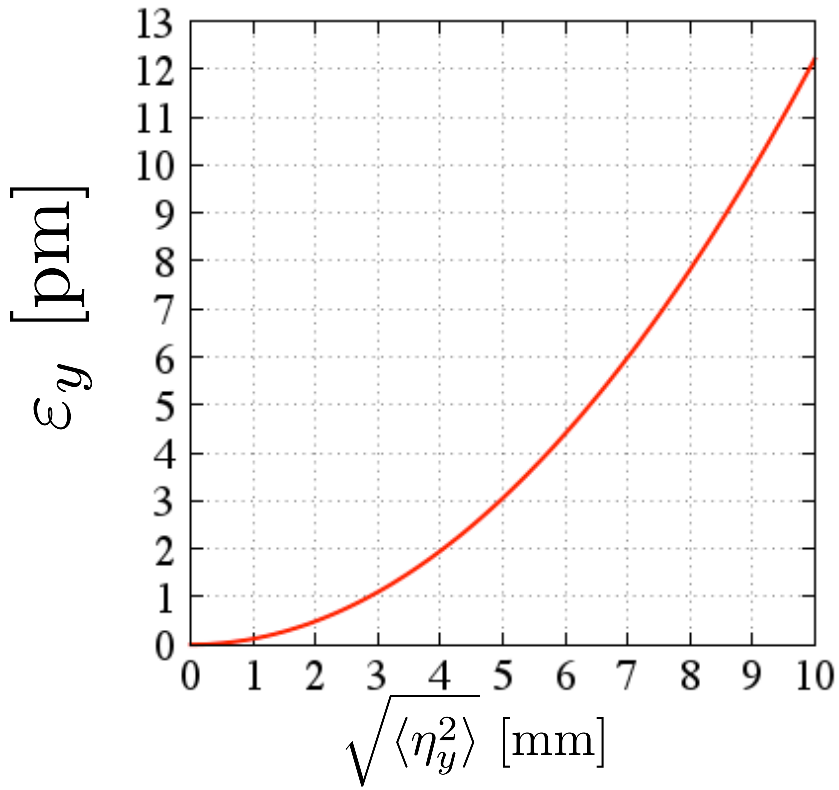
ベローズ内部表面で
中央付近Bz = 60～120 G
磁石の真下で極性反転

Vertical Emittance and Dispersion

$$\varepsilon_y \sim \frac{2J_z\sigma_\delta^2}{\beta_y}\langle\eta_y^2\rangle$$

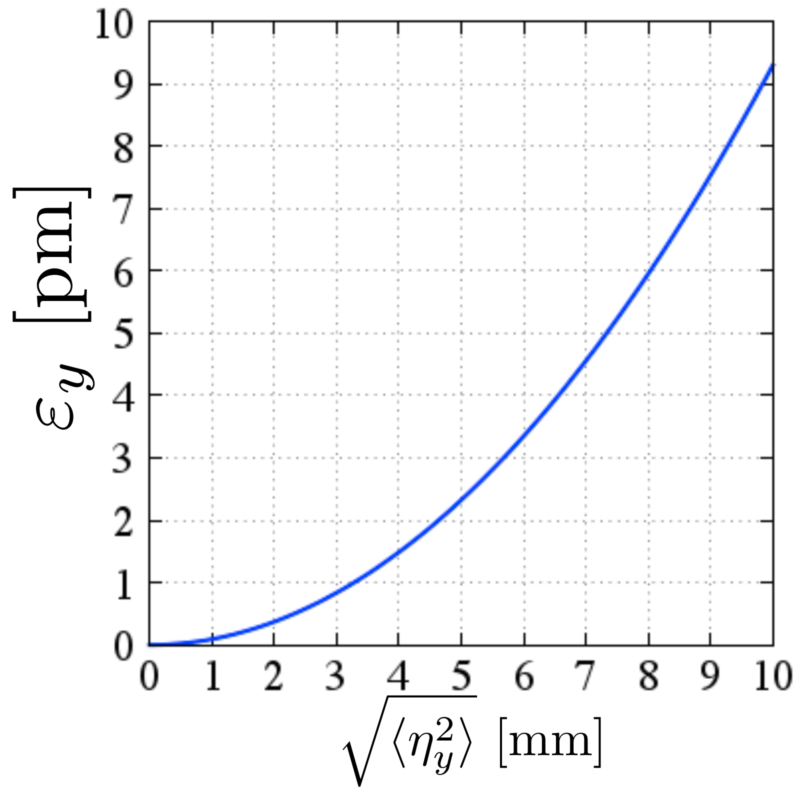
LER

$J_z \sim 2$
$\beta_y \sim 20$ [m]
$\sigma_\delta \sim 7.7 \times 10^{-4}$



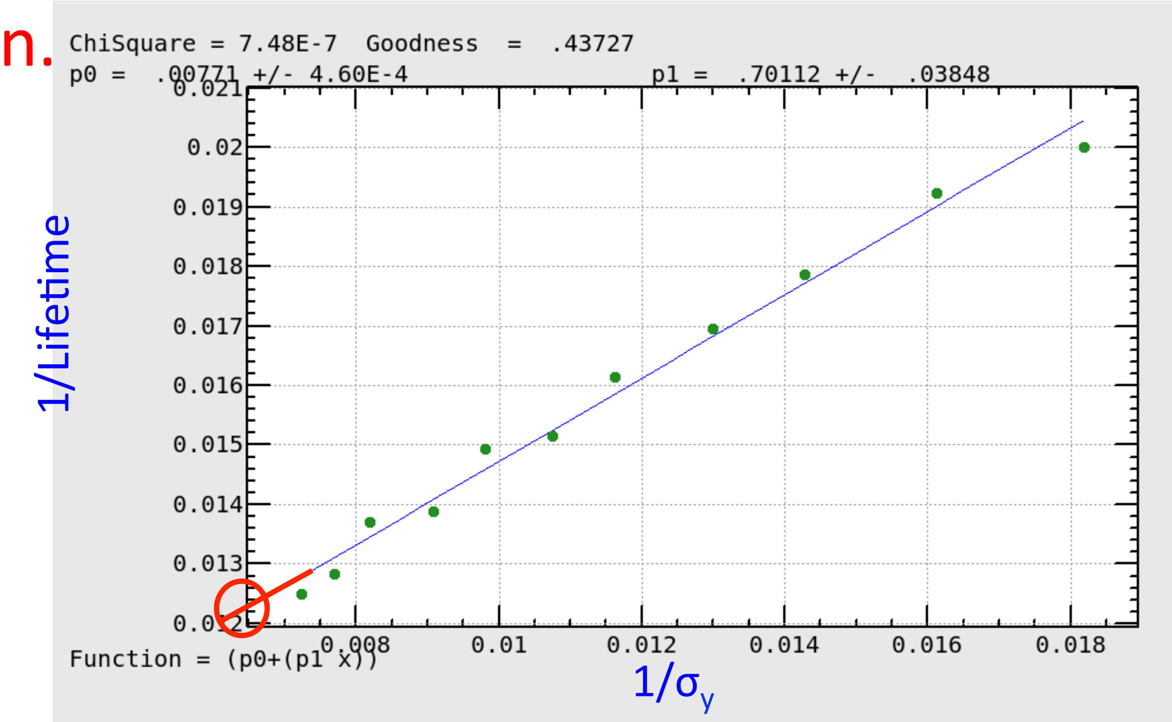
HER

$J_z \sim 2$
$\beta_y \sim 17$ [m]
$\sigma_\delta \sim 6.3 \times 10^{-4}$



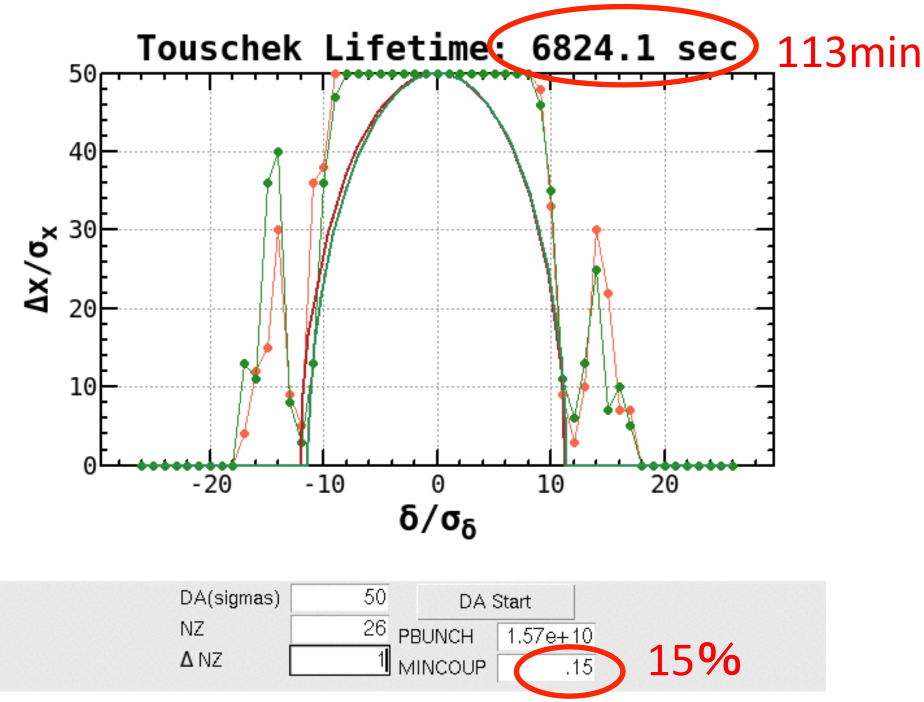
Beam lifetime from vacuum and Touschek effect

- Change vertical beam size -> Lifetime measurement
- Lifetime from vacuum: 129.7 min. @(350 mA, 1576 bunches)
- Actual lifetime: 75min. -> Touschek Lifetime:177 min.

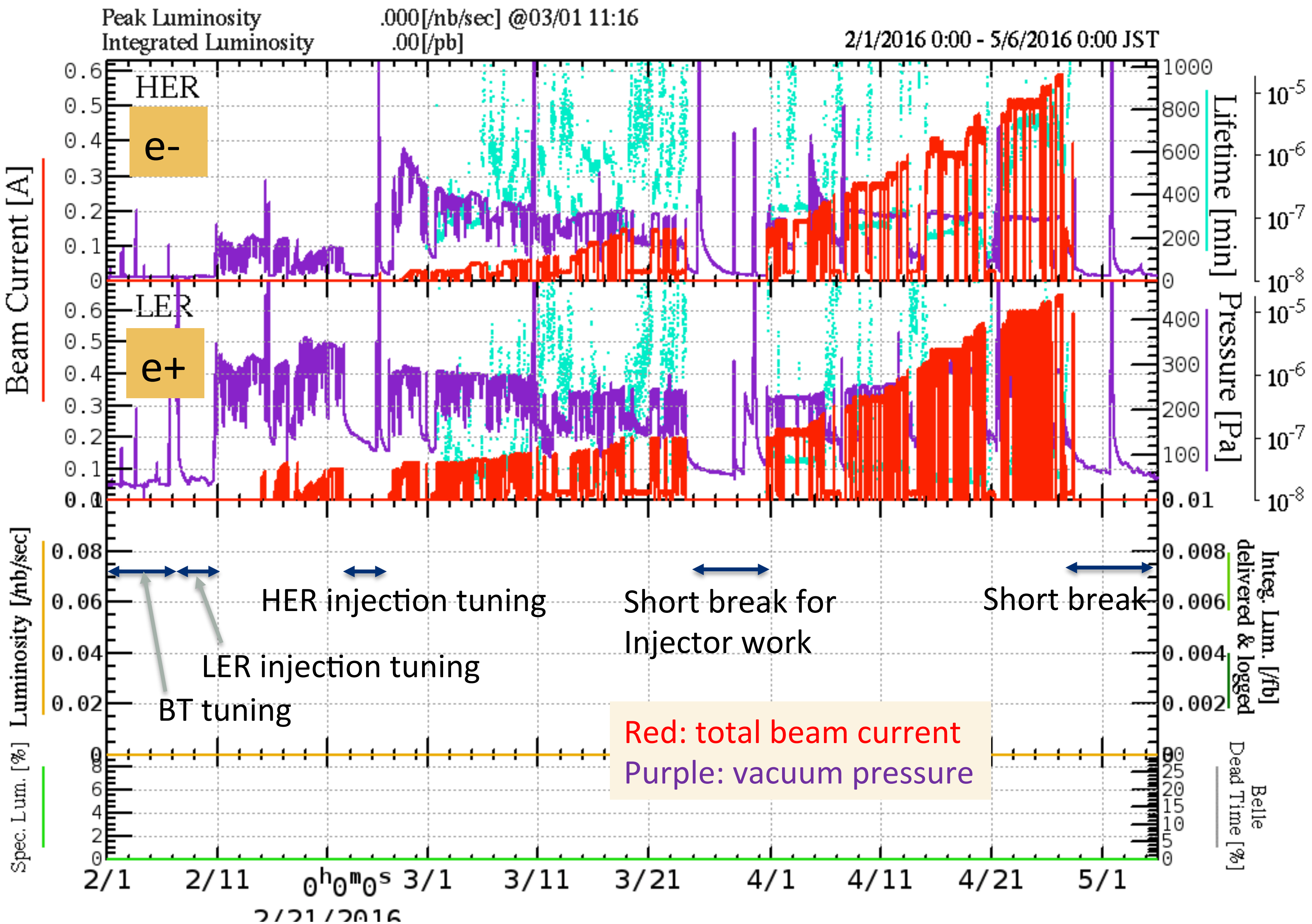


Touschek lifetime from simulation

- $\varepsilon_y/\varepsilon_x$ = 15%, I_b = 0.25 mA
- Lifetime from simulation: 113 min.



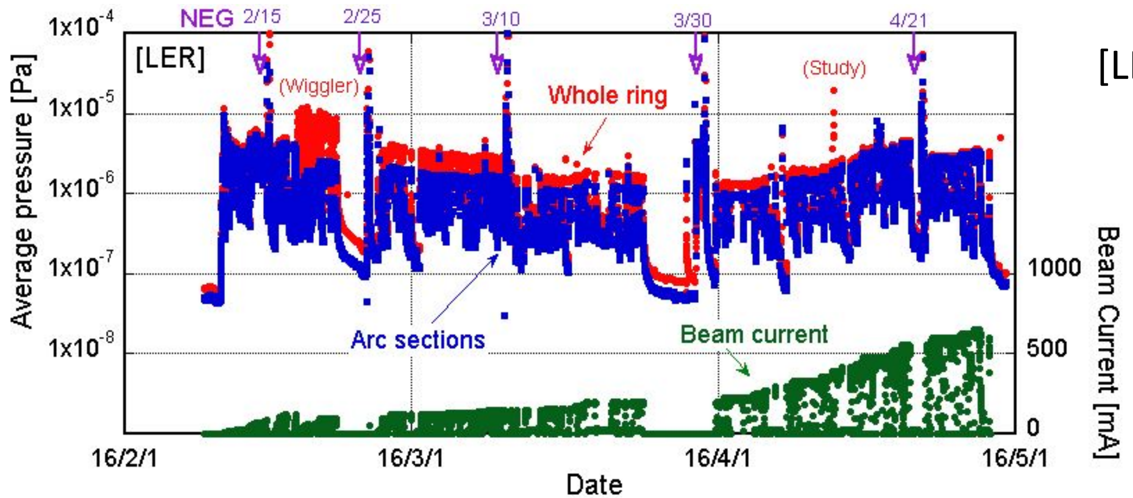
History of Phase 1 operation



History of vacuum scrubbing

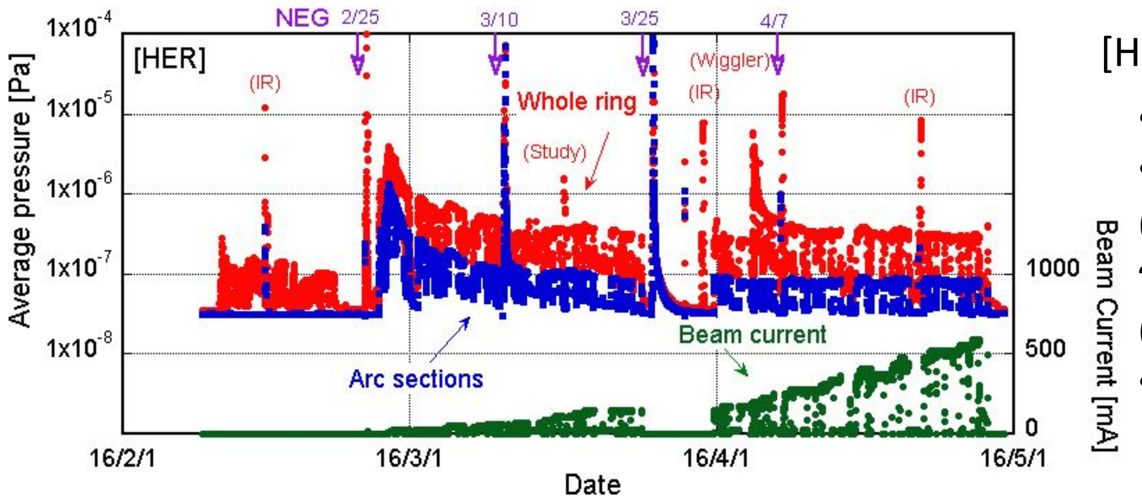
Y. Suetsugu

- **The beam currents and average pressures (2016/4/30)**



[LER]

- Max. Beam current: 650 mA
- Avg. Pressure ~ 3x10^{-6} Pa
- Life time ~ 60 min.



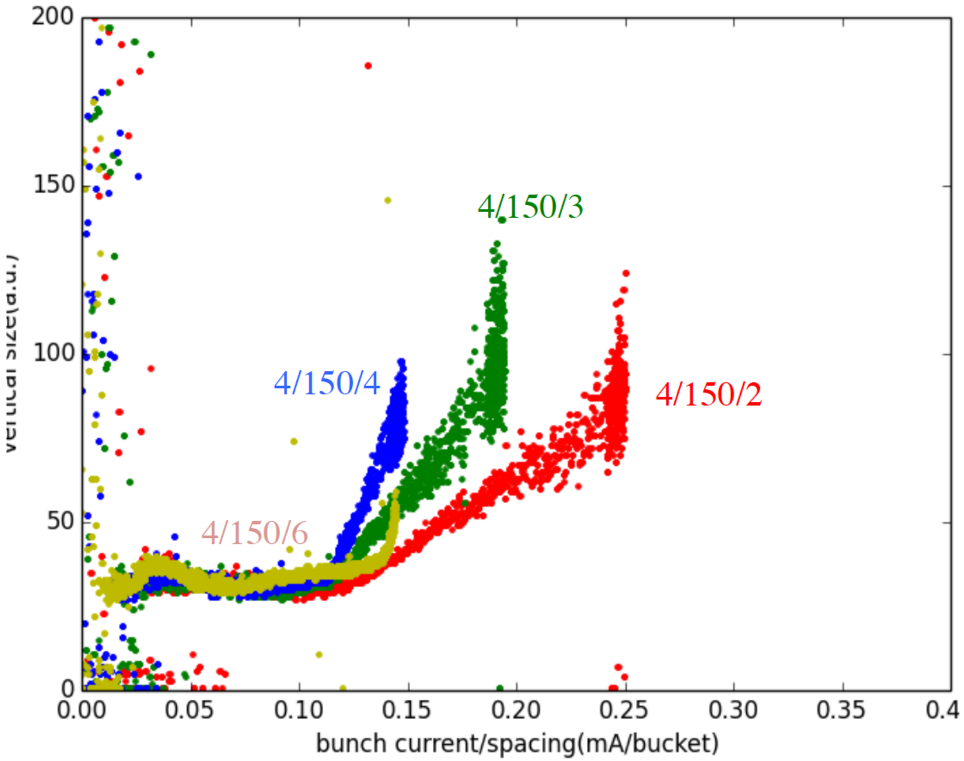
[HER]

- Max. Beam current: 590 mA
- Avg. Pressure ~ 3x10^{-7} Pa (whole ring) ~ 1x10^{-7} Pa (arc sections)
- Life time ~ 600 min.

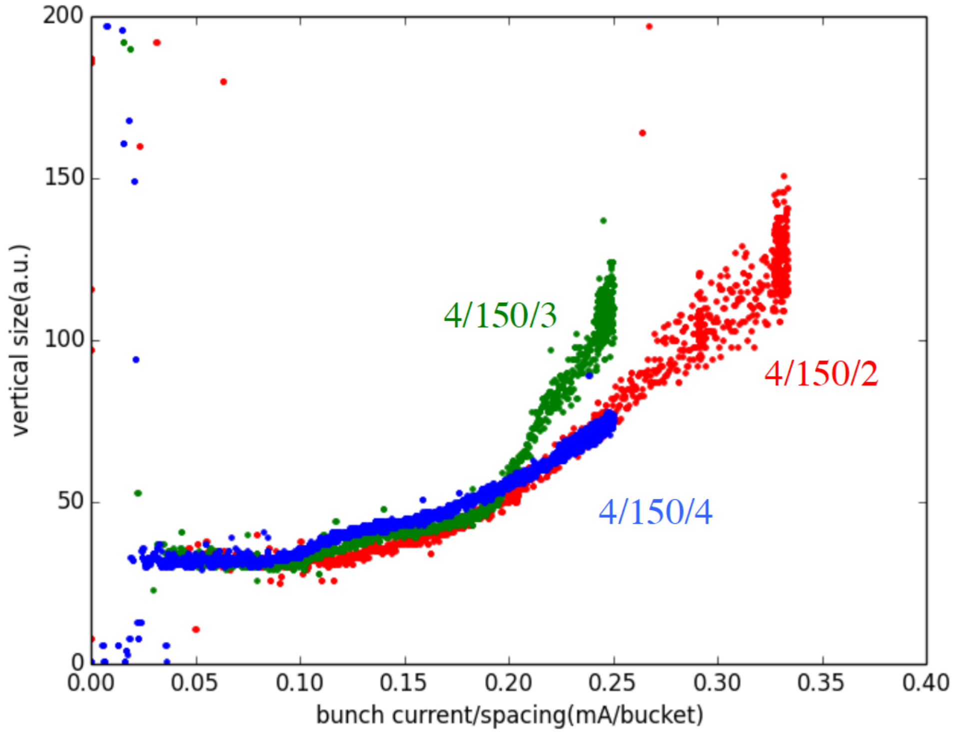
Request from Belle-II group: ~1 month vacuum scrubbing with beam current of 05~1A.

Blowup study

w/o permanent magnet



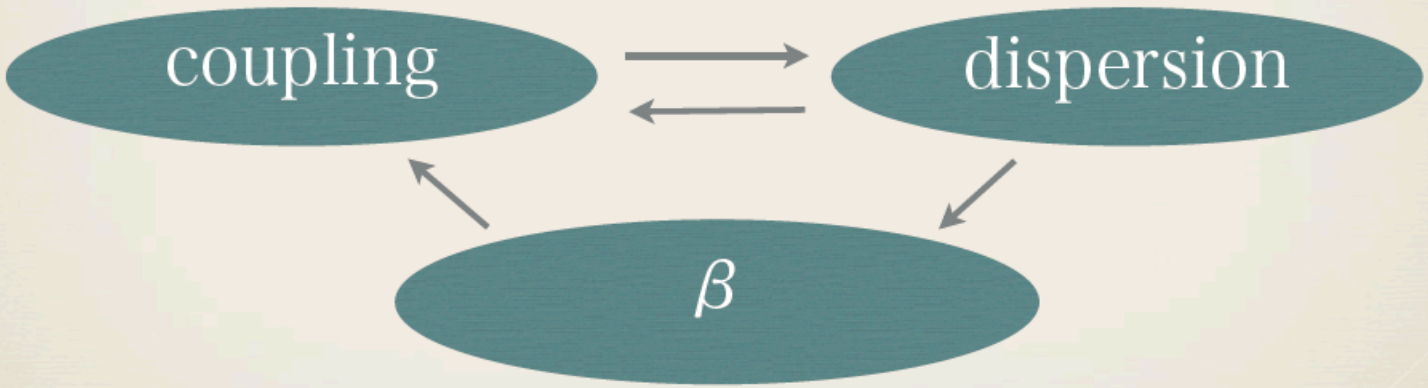
with permanent magnet



Iteration

2008_06_19_19_06_29fop	Fill-Length Optimization
2008_06_19_19_06_32luh	Beam Collision Panel
2008_06_19_19_09_12XY_Coupling	MeasOptHER
2008_06_19_19_12_59Dispersion	MeasOptHER
2008_06_19_19_18_27XY_Coupling	MeasOptHER
2008_06_19_19_21_34Dispersion	MeasOptHER
2008_06_19_19_22_29Dispersion	MeasOptHER
2008_06_19_19_23_29Dispersion	MeasOptHER
2008_06_19_19_31_36Global_Beta	MeasOptHER
2008_06_19_19_38_29Global_Beta	MeasOptHER
2008_06_19_20_16_46_amsad8	amsad8 screen capture
2008_06_19_20_34_16_amsad8	amsad8 screen capture

* A loop of coupling, dispersion, β corrections takes **30-60 minutes** per ring to converge. (1 correction takes 3.5 to 7 minutes)



* We do not have to solve the entire problem at once by a single big matrix.

* Although these corrections are not independent, their cross-talks are smaller than the diagonal parts, so the iteration converges quickly.

Machine study to be done in May and June (>30 shifts)

- More optics study
- X-ray monitor calibration
- LER beam size blowup
- Longitudinal/transverse bunch-by-bunch feedback system
- Beast background study
- Impedance measurement
- Rotational sextupole magnet
- Dithering coils
- Beam transport line study
- Linac study (RF gun etc.)