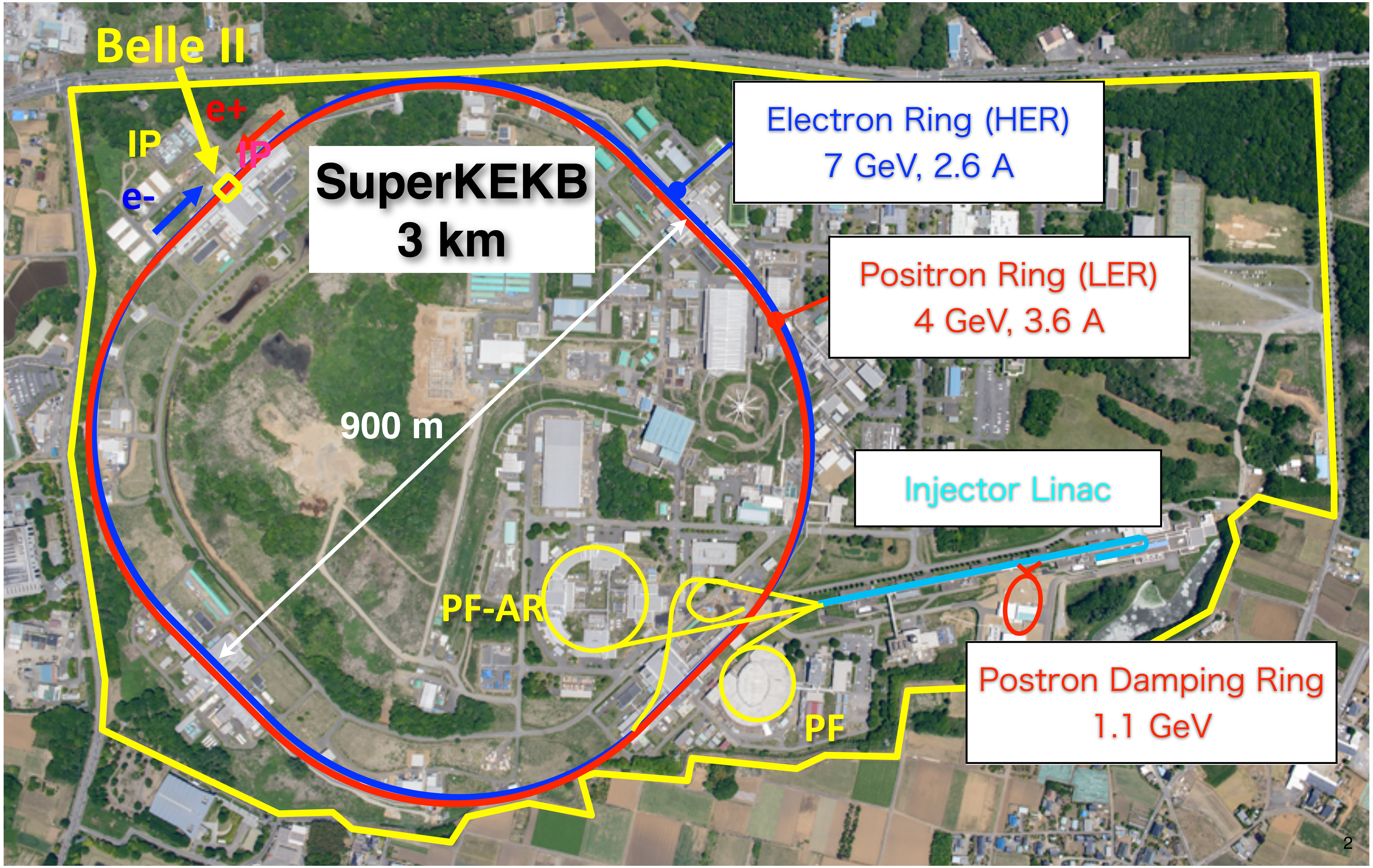
Status of SuperKEKB

Y. Ohnishi / KEK

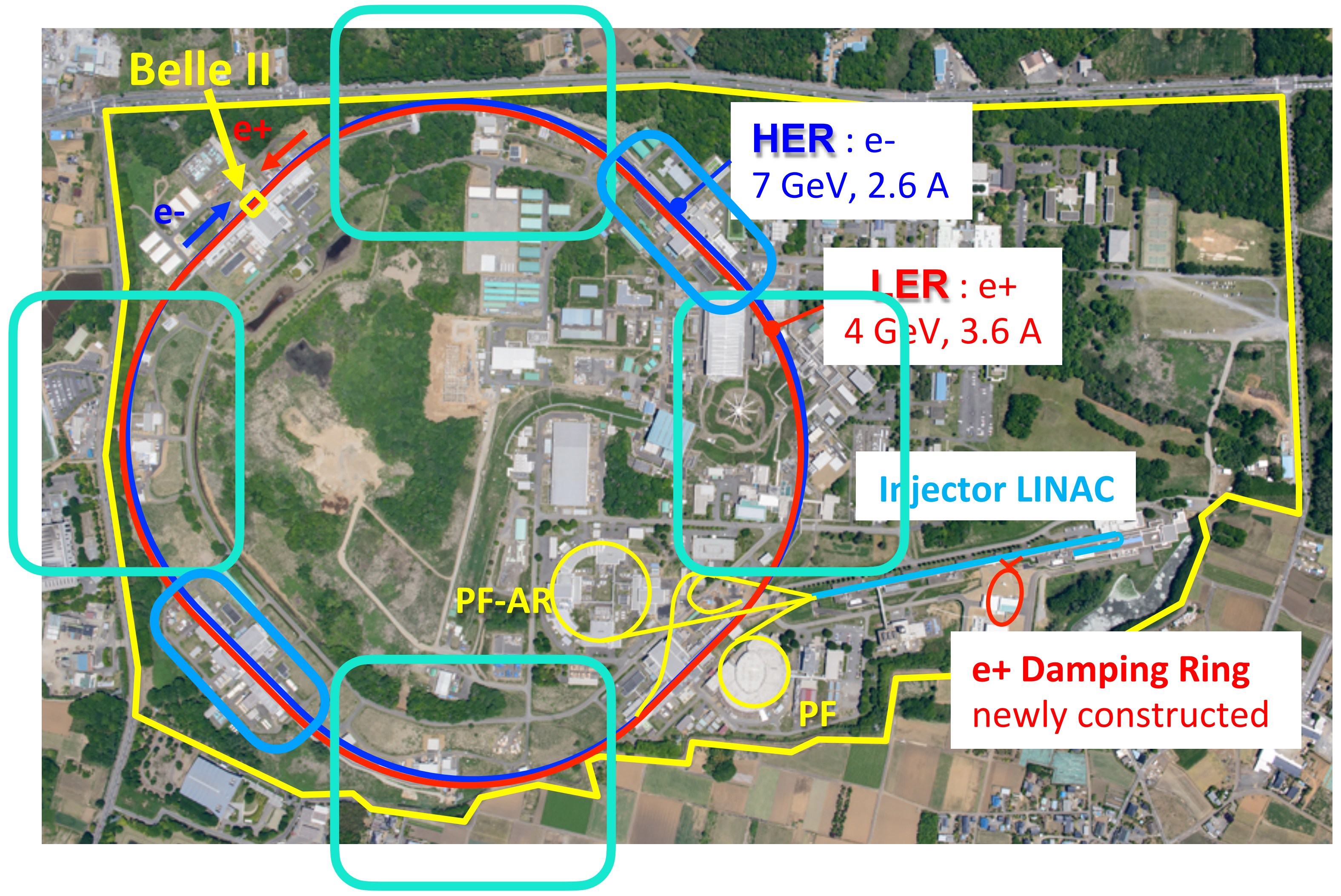
On behalf of SuperKEKB Commissioning Group

SuperKEKB at KEK, Japan

Target luminosity : 8 x 10^{35} cm^{-2} s^{-1} The numbers are the final design values.



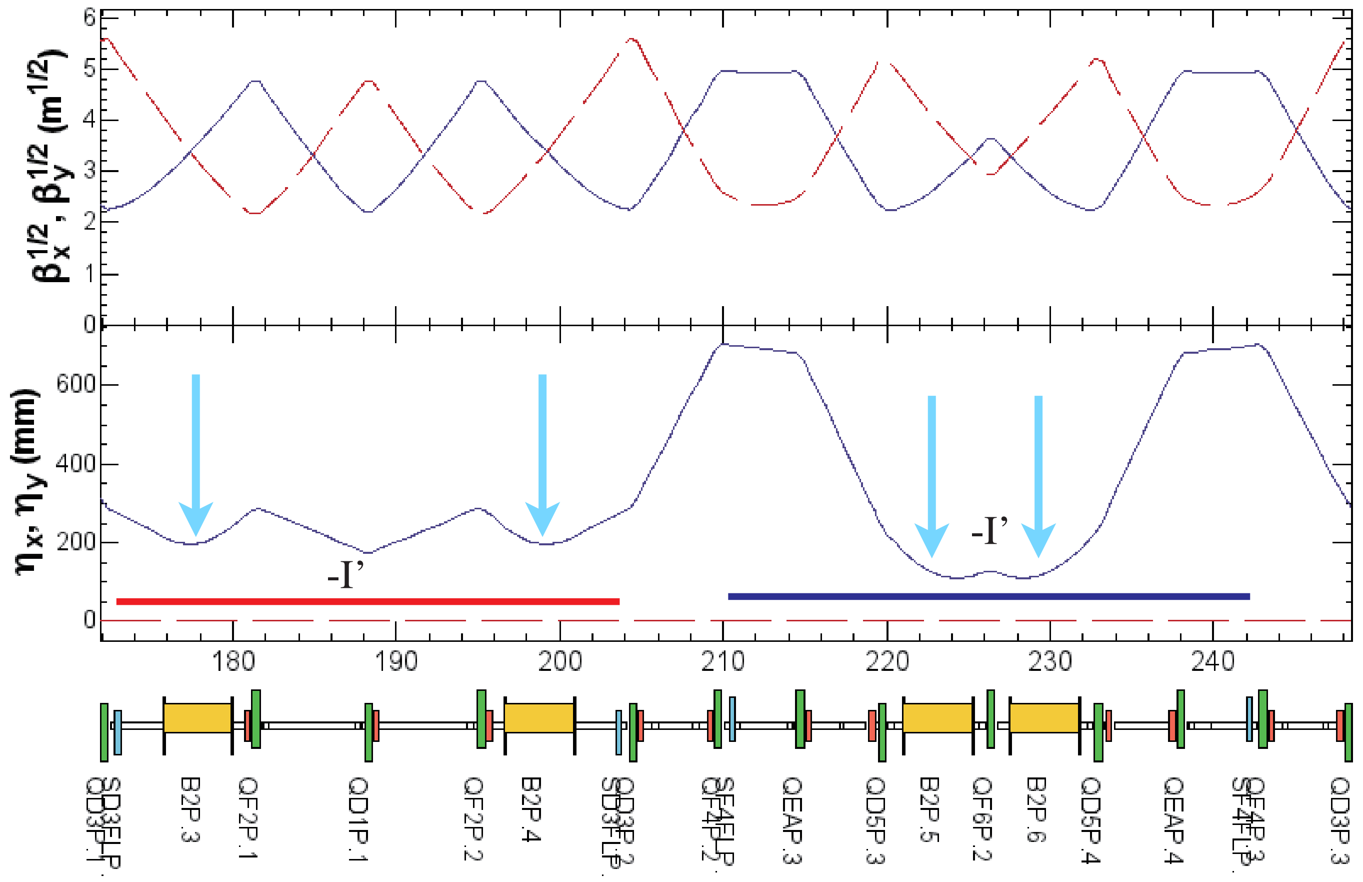
Arc Lattice: To Make Emittance Small



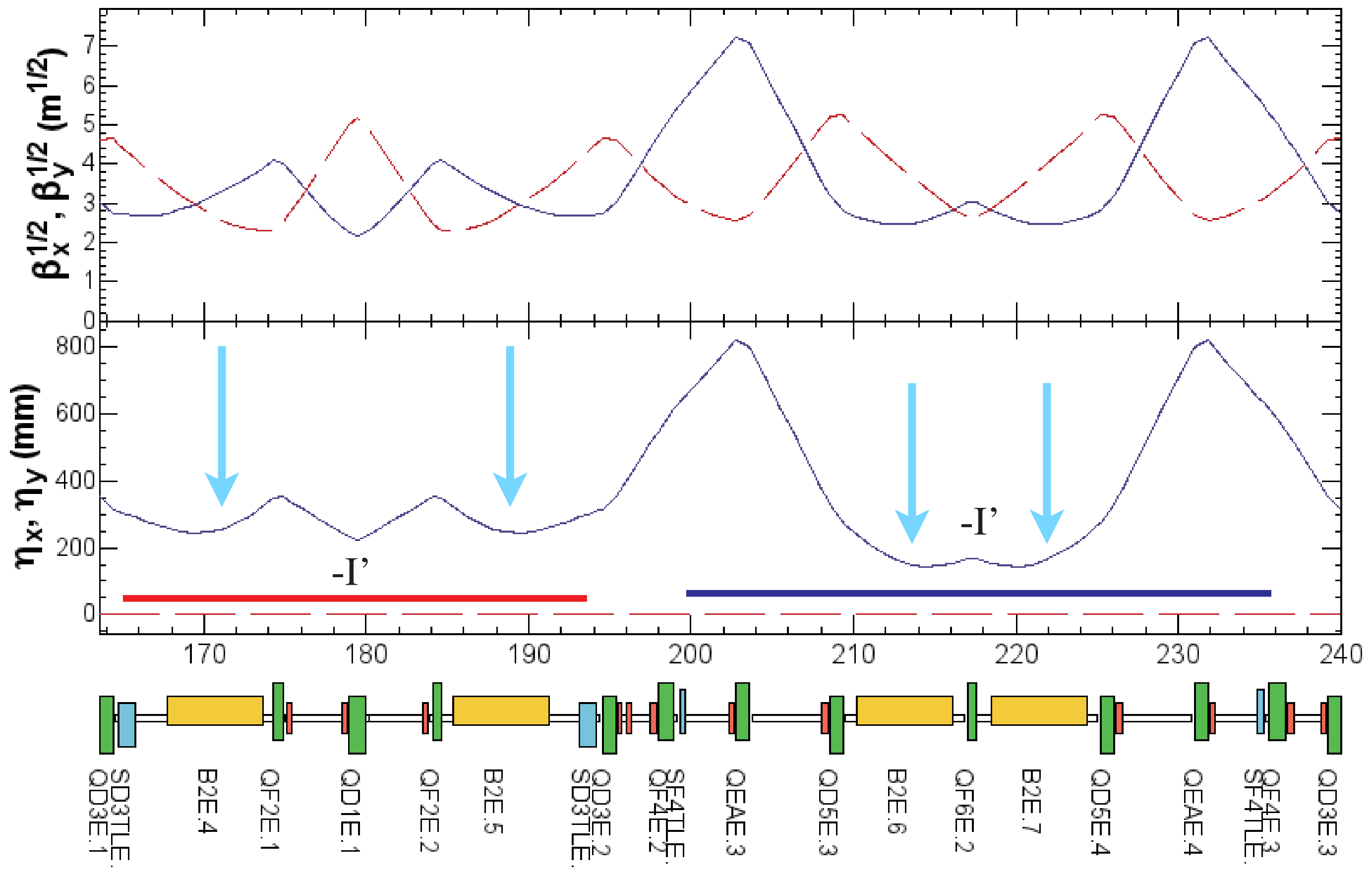
4 arcs + 4 straight sections

Arc Lattice (Normal Cells)

LER ε_x = 4 nm



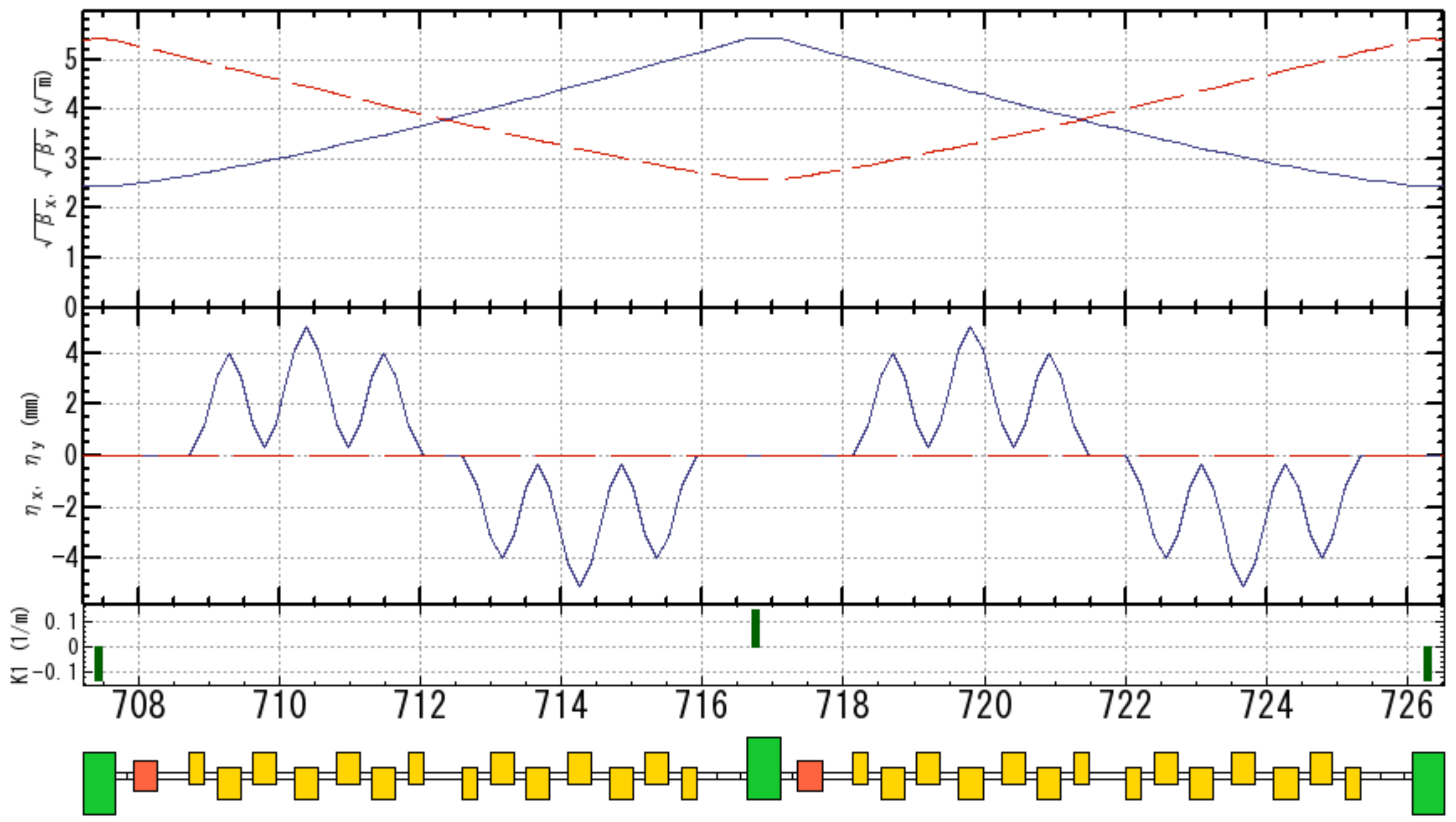
HER ε_x = 5 nm



non-interleaved sextupoles

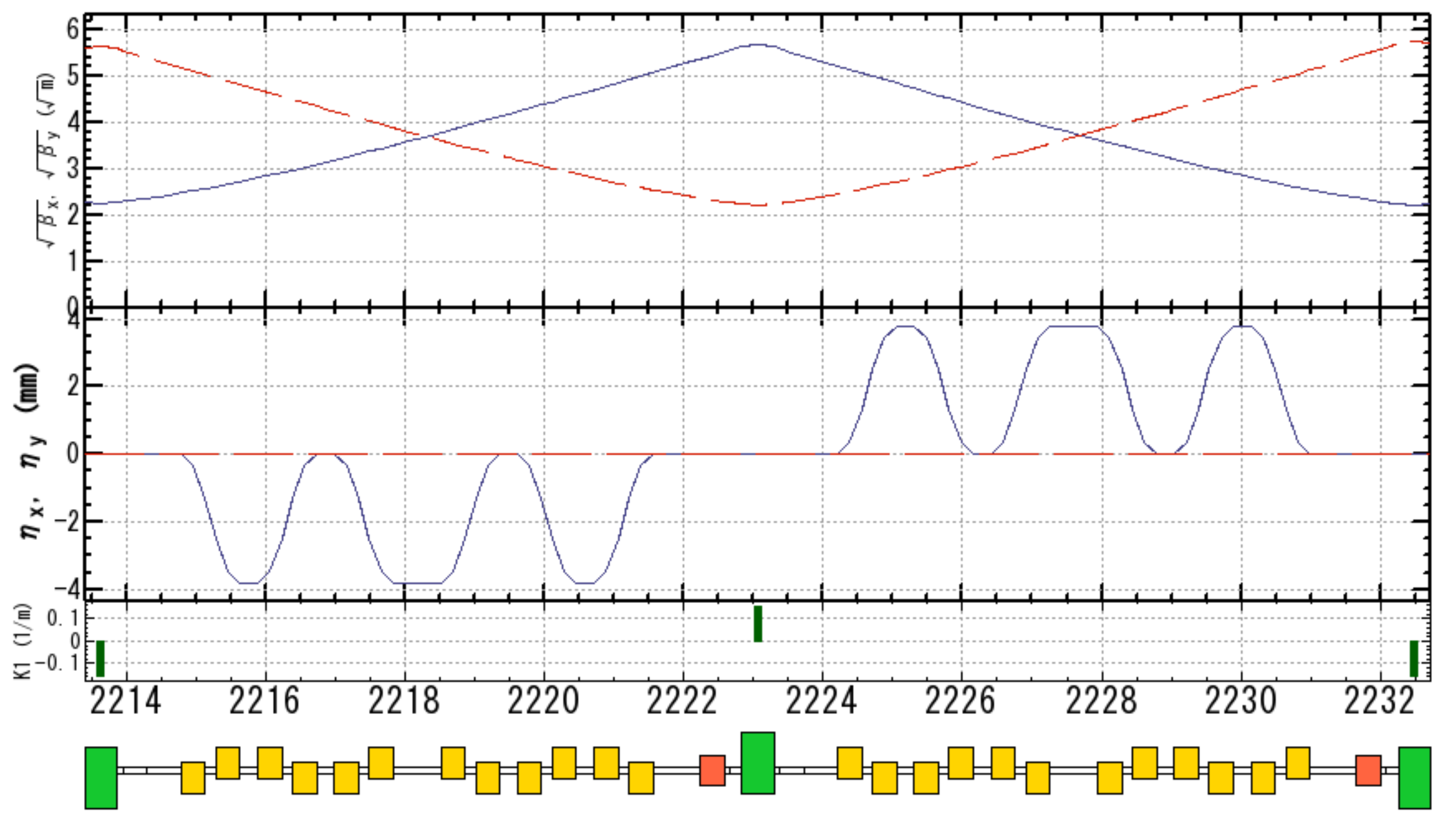
Wigglers are also used to make low emittance.

LER



ε_x = 1.9 nm (arc+wiggler)

HER

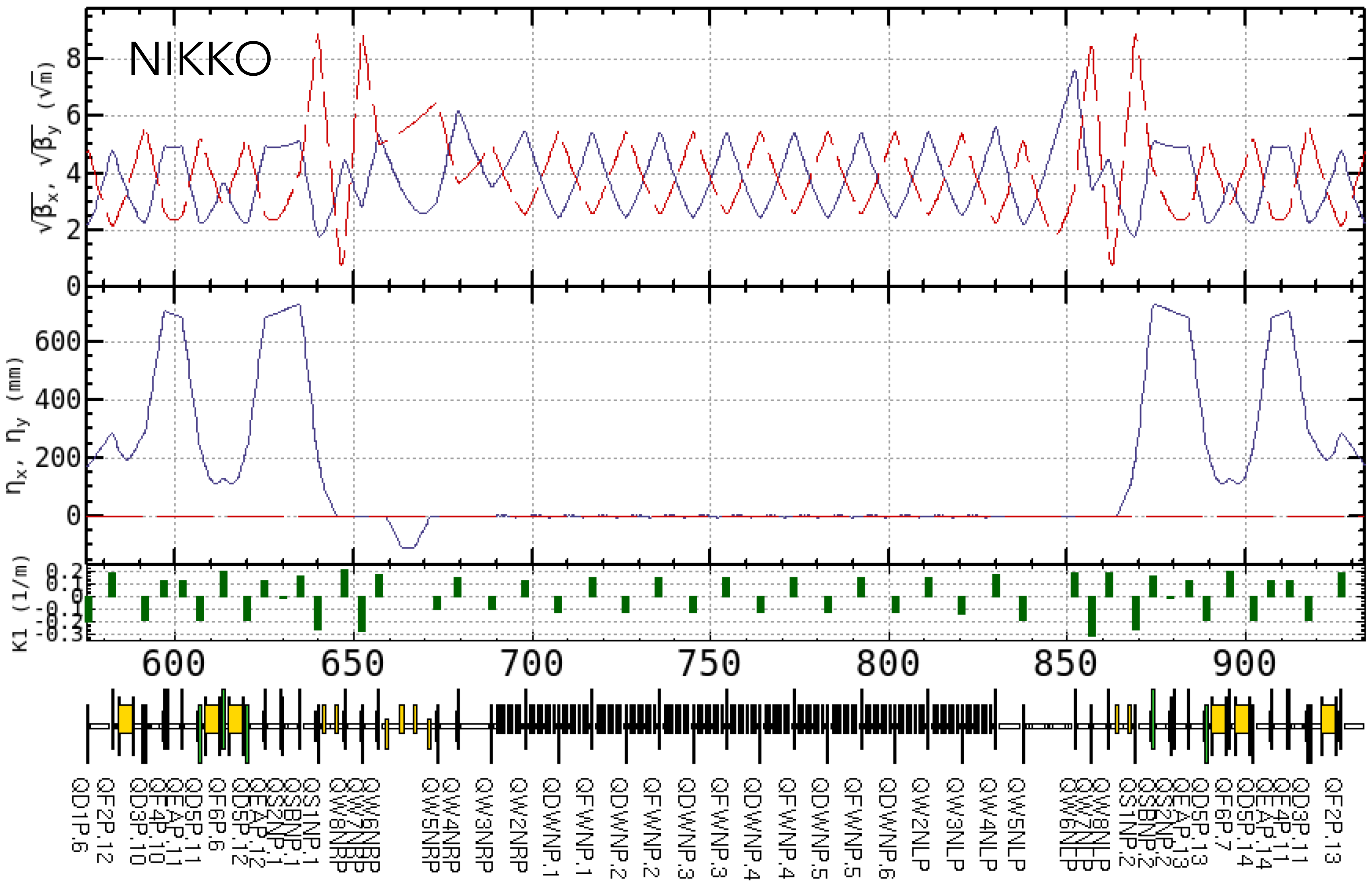


ε_x = 4.4 nm (arc+wiggler)

$$\beta_x^*/\beta_y^* = 80\ mm/1\ mm \qquad \Psi = \frac{\sigma_z}{\sigma_x^*}\tan\phi_x \qquad \beta_y^* > \frac{\sigma_z}{\Psi} = \frac{\sigma_x^*}{\phi_x}$$

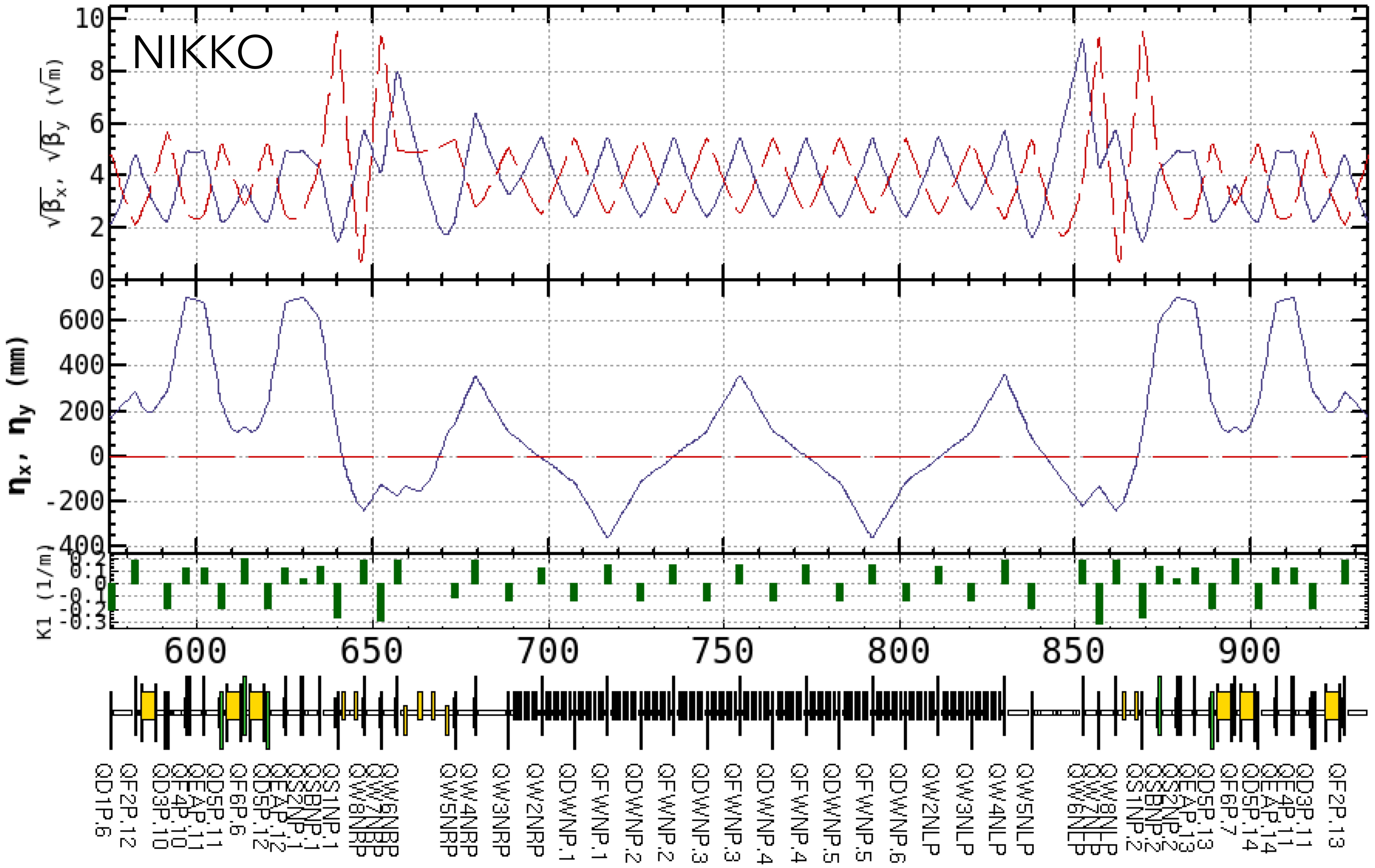
w/o intra-beam
(σ_z = 5.5 mm)

ε_x = 1.6 nm $\Psi = 20$



1704_80_1_A_YO4

ε_x = 4 nm $\Psi = 12.8$

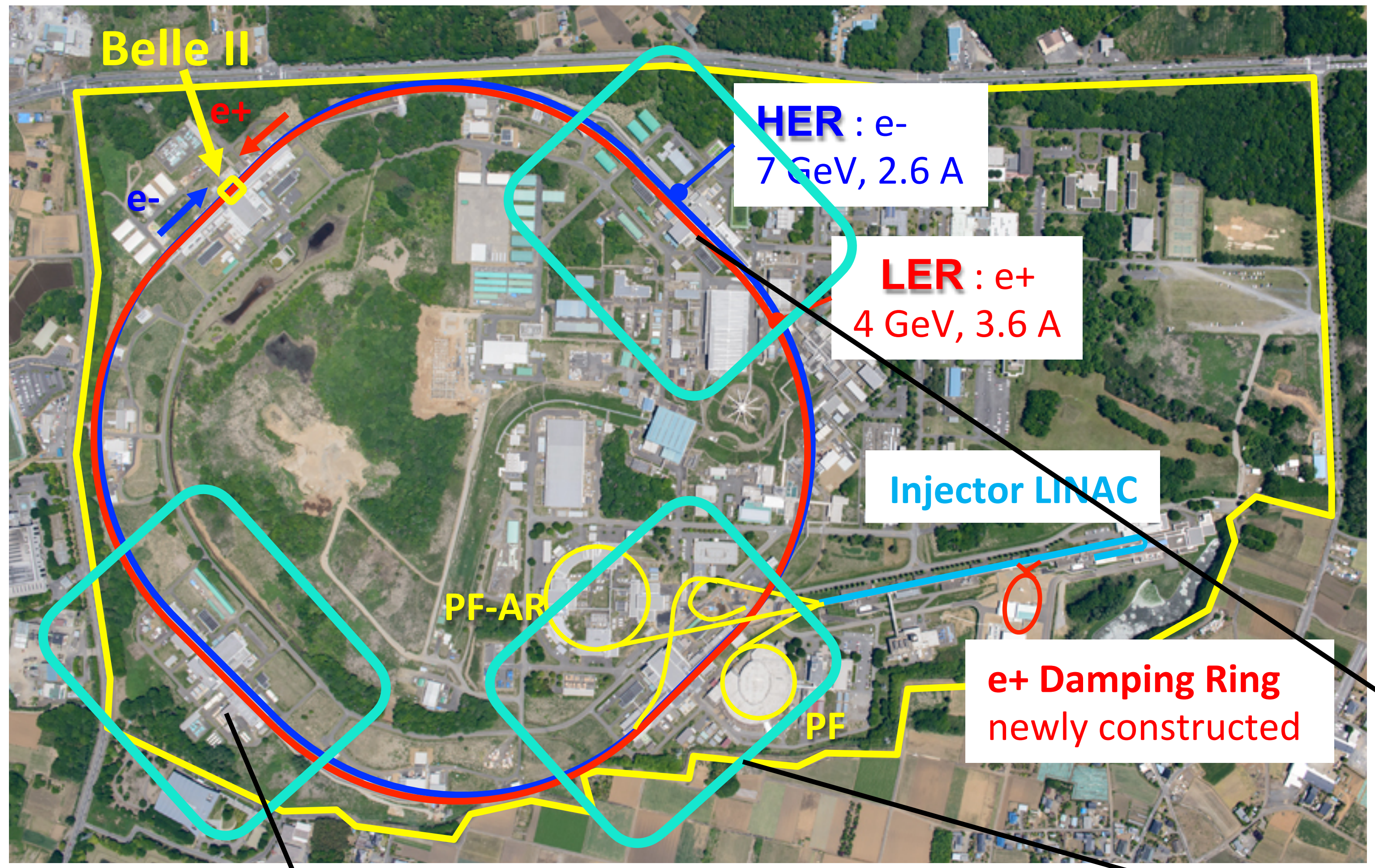


1705_80_1_CW00_HE_2

In order to make Touschek lifetime longer, the emittance can be optimized.

Larger emittance is preferable as long as the nano-beam scheme is OK.

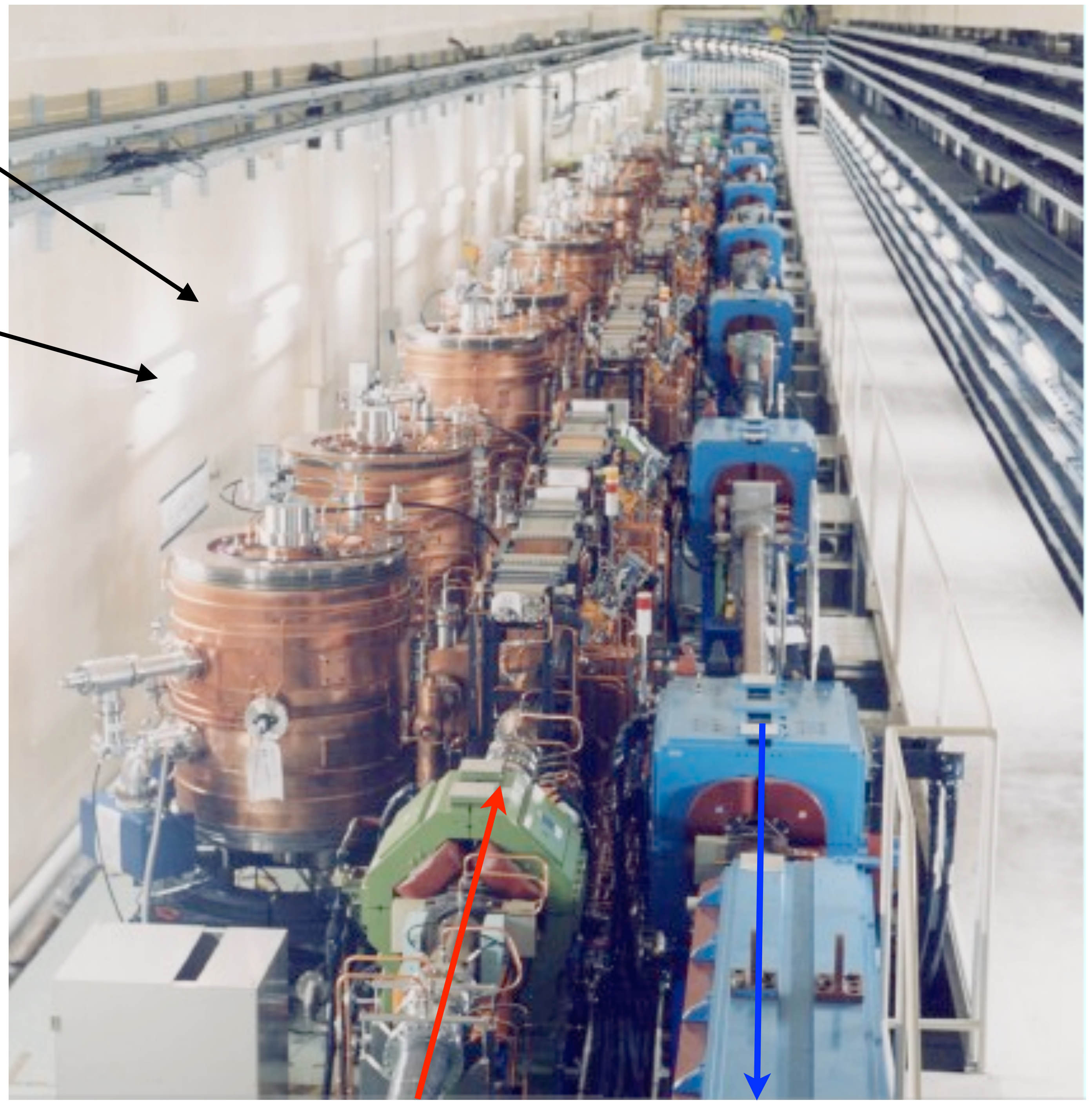
4 arcs + 4 straight sections



To compensate energy loss due to synchrotron radiation, 10〜15 MV of accelerating voltage is necessary.

Normal ARES：30 units

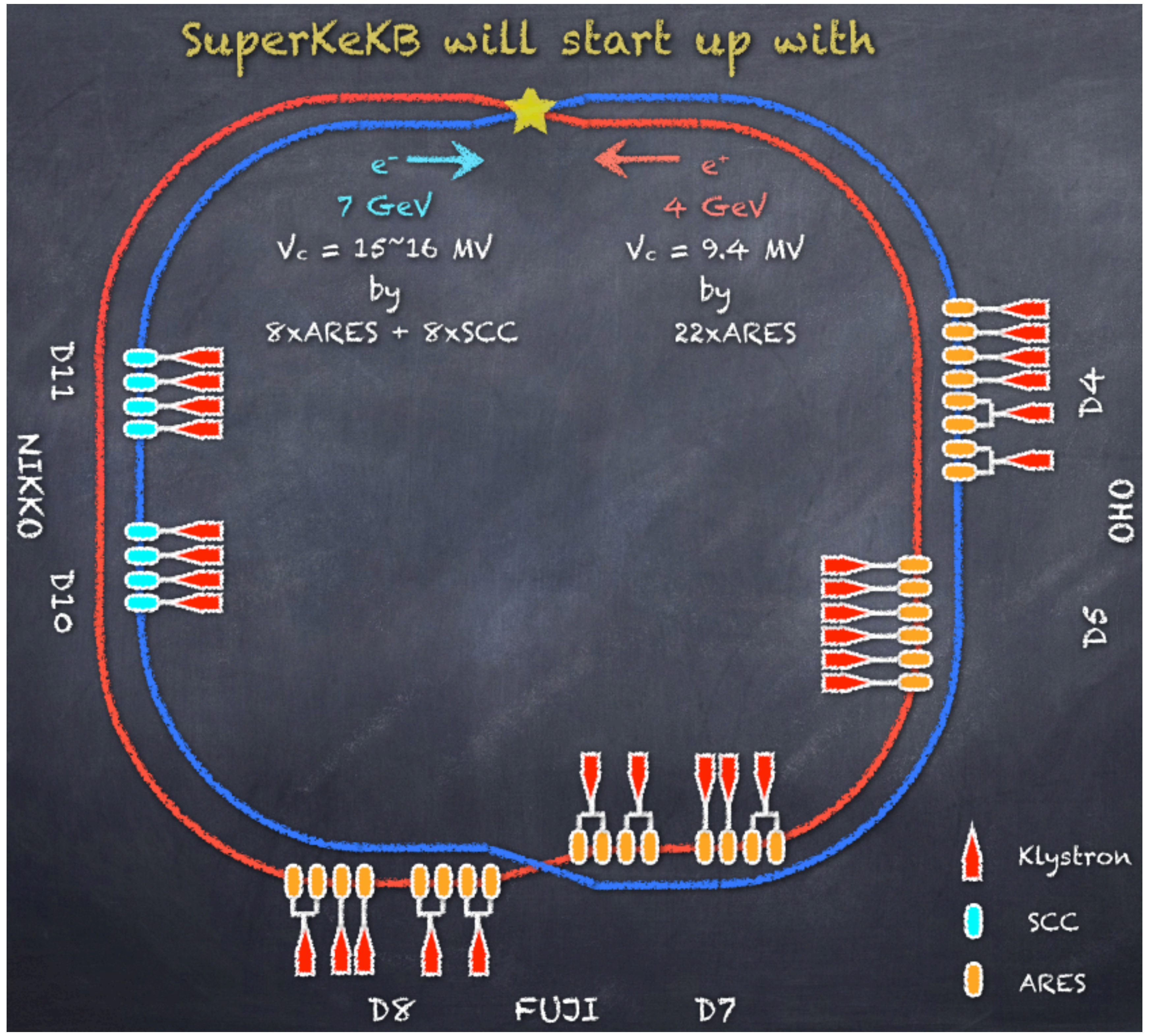
22 for LER, 8 for HER



0.5 MV / cavity

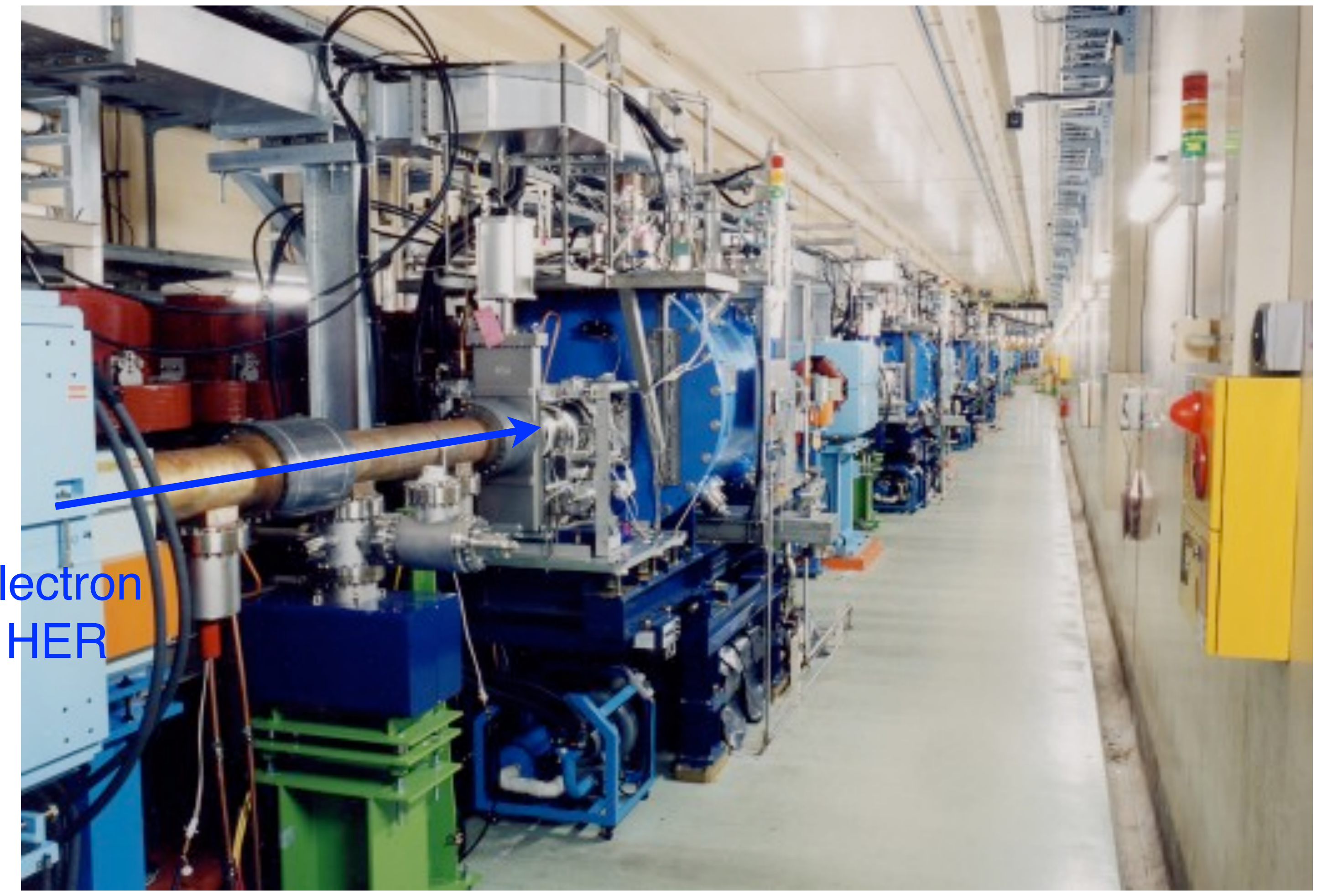
positron, LER

electron, HER



Superconducting Cavity：8 units

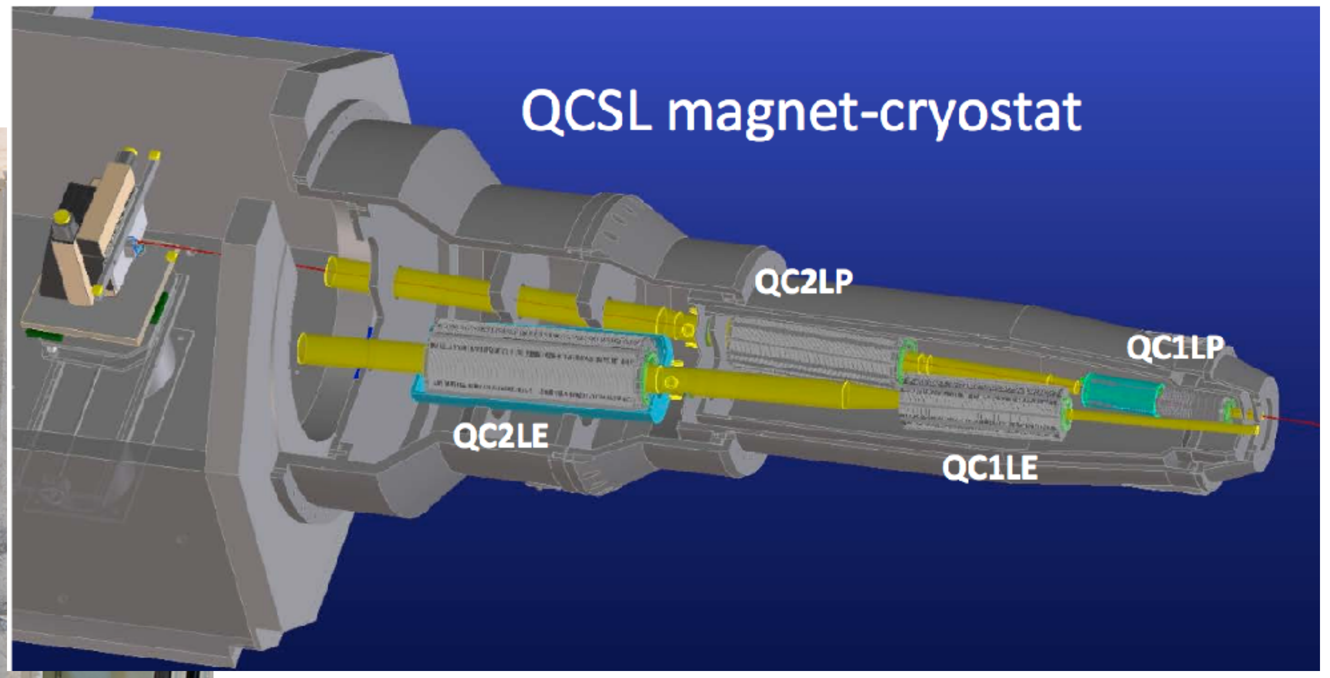
only for HER



1.5 MV / cavity

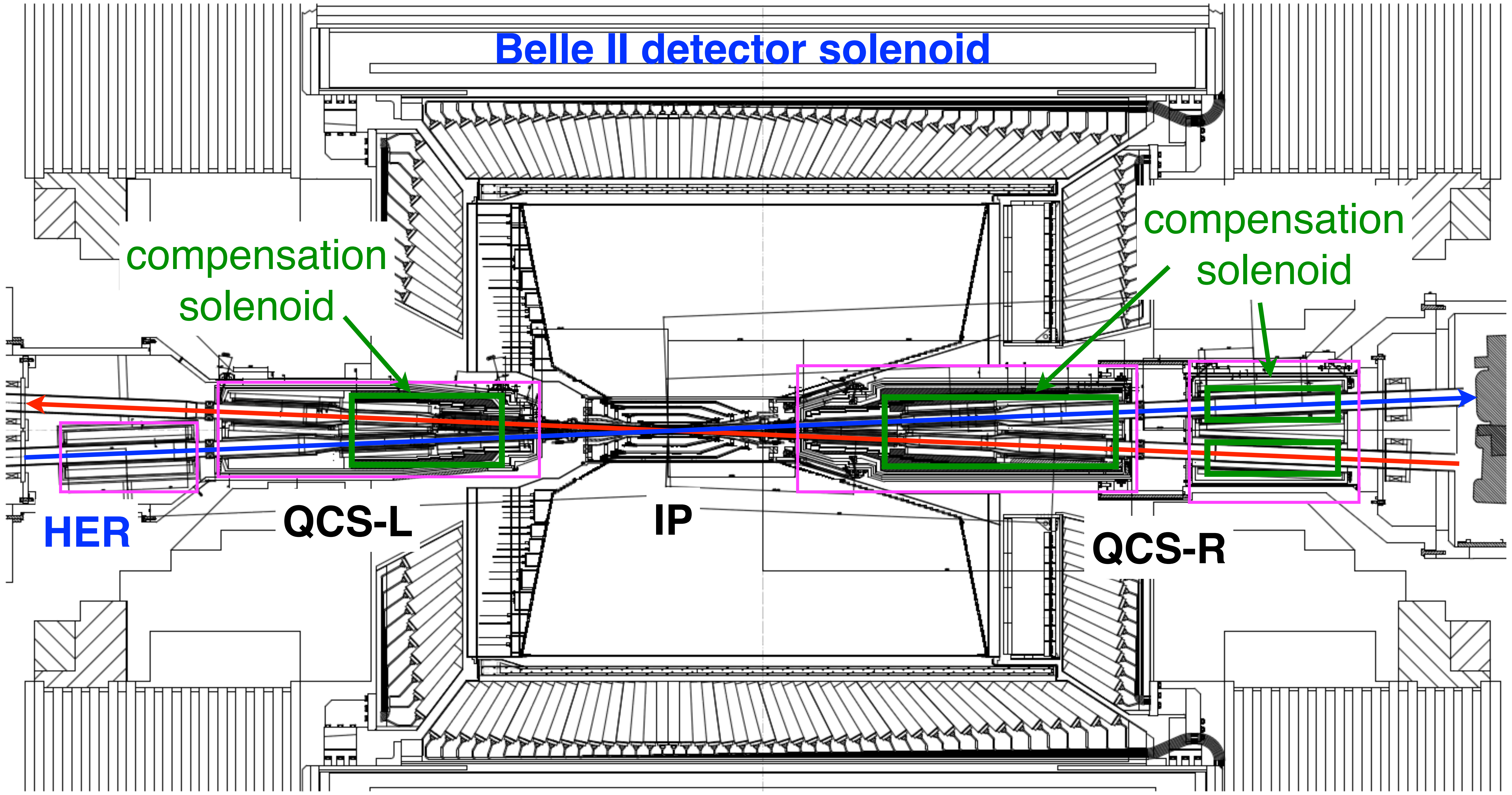
Interaction Region: Superconducting Magnets

Superconducting Magnets

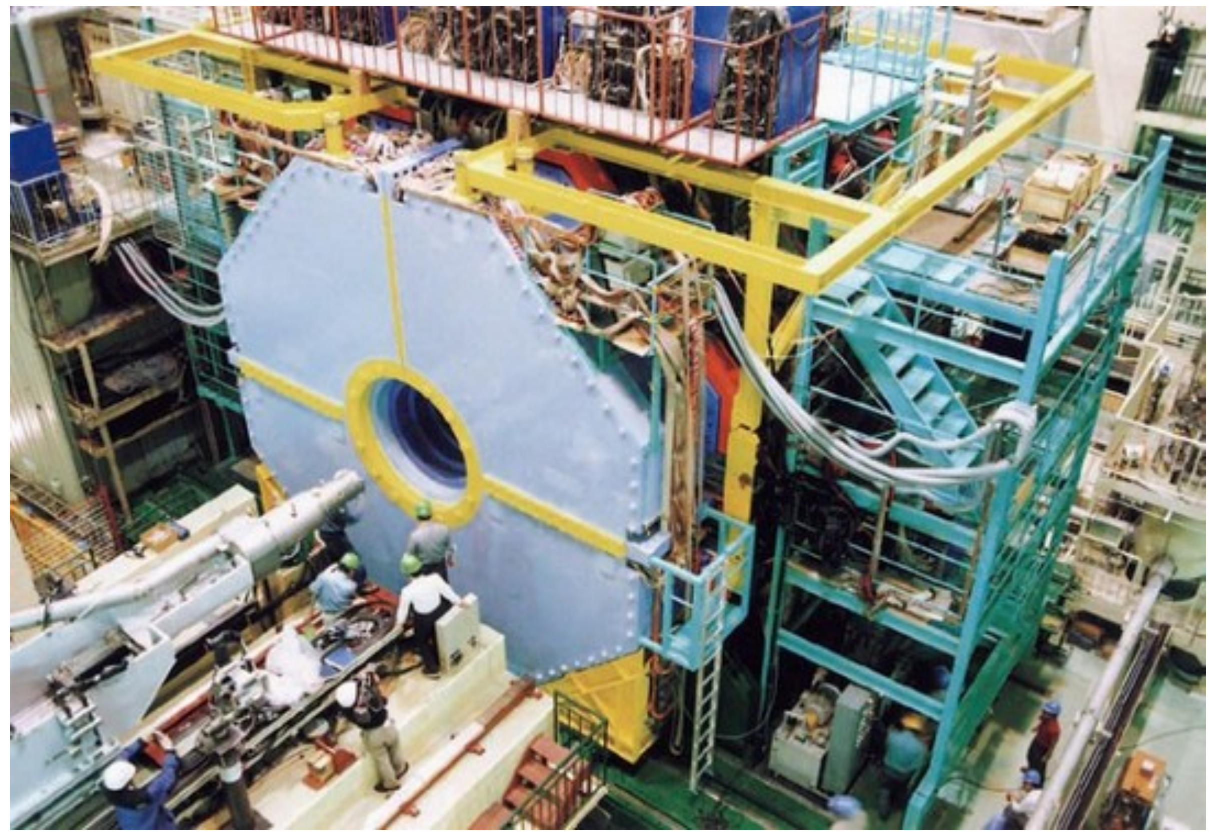


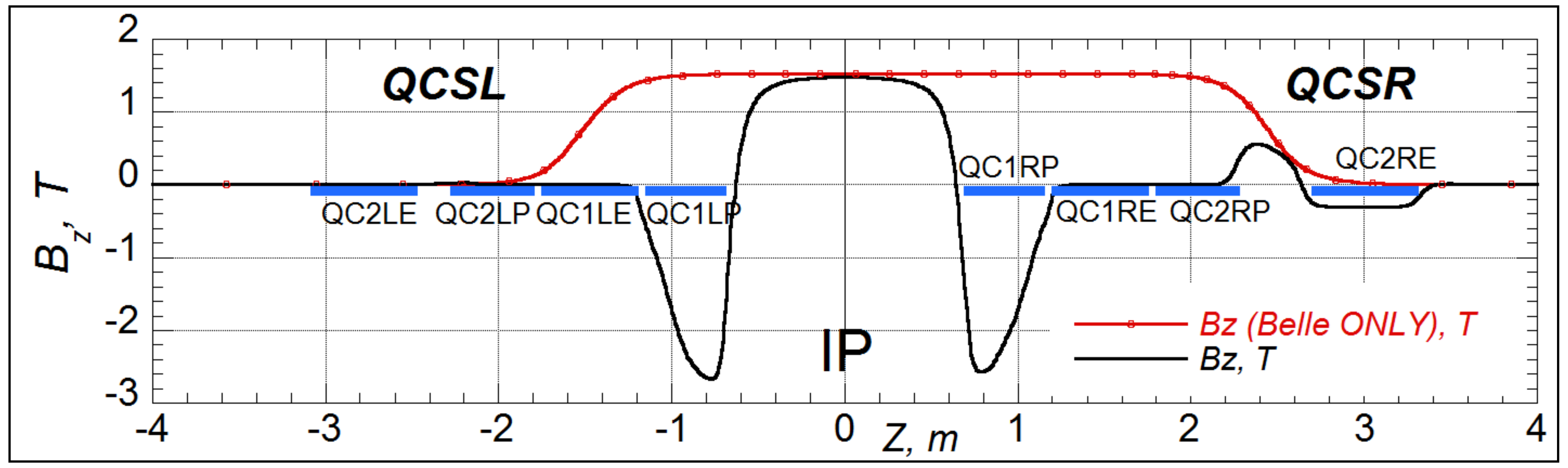
4 quadrupoles (QC1, QC2)
+ 16 corrector coils
+ 4 cancel coils (for leakage field)
+ anti-solenoid
for the left side

1.5 Tesla detector solenoid



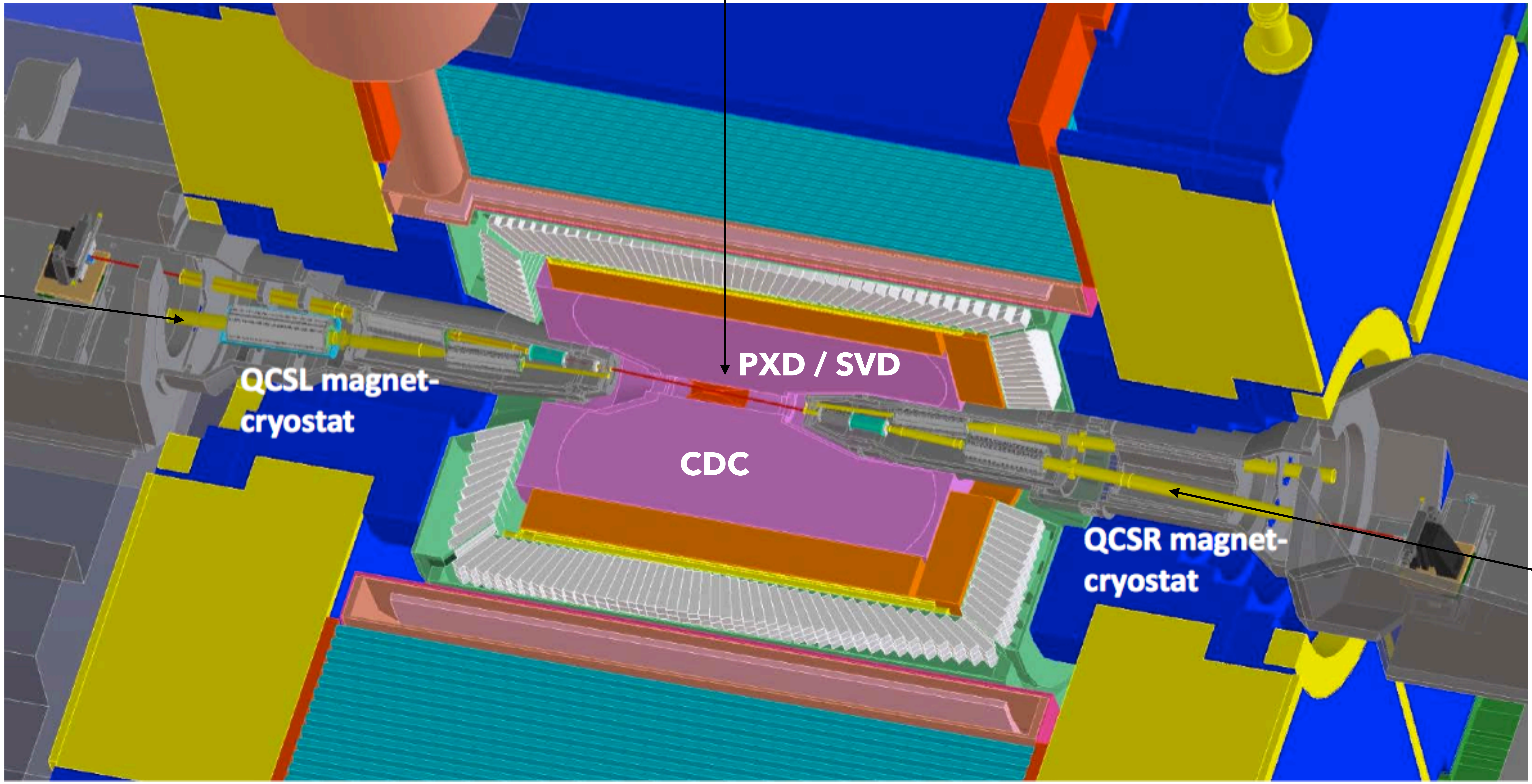
BROOKHAVEN NATIONAL LABORATORY





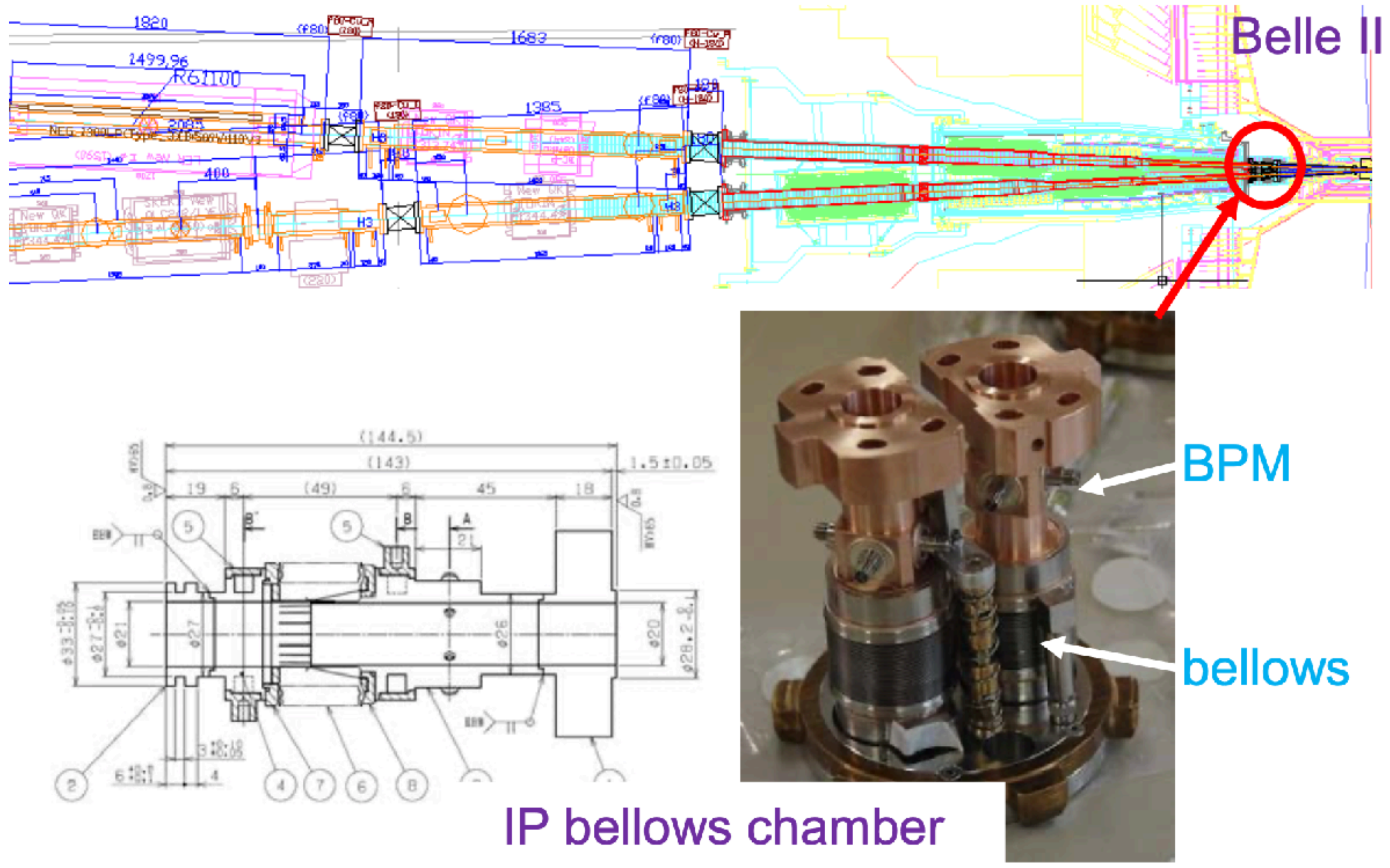
Final Focus and Belle II Detector

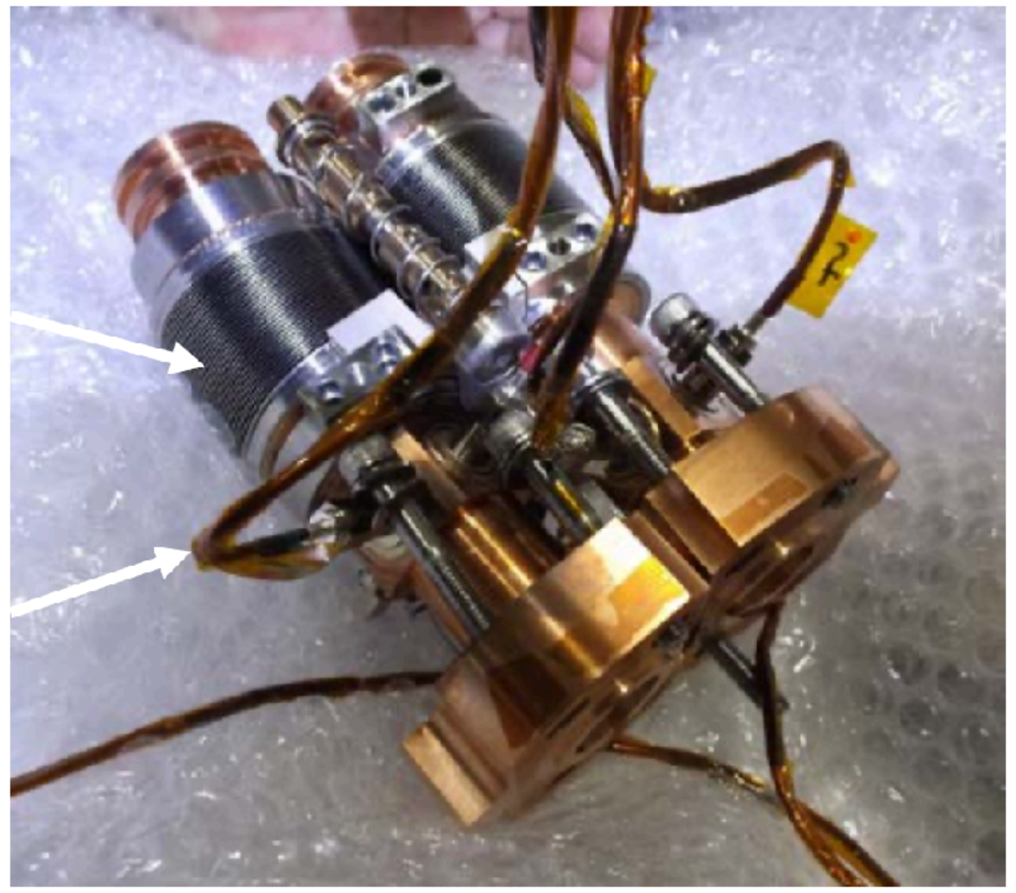
The horizontal crossing-angle is 83 mrad to realize the nano-beam scheme and separation of two beams.

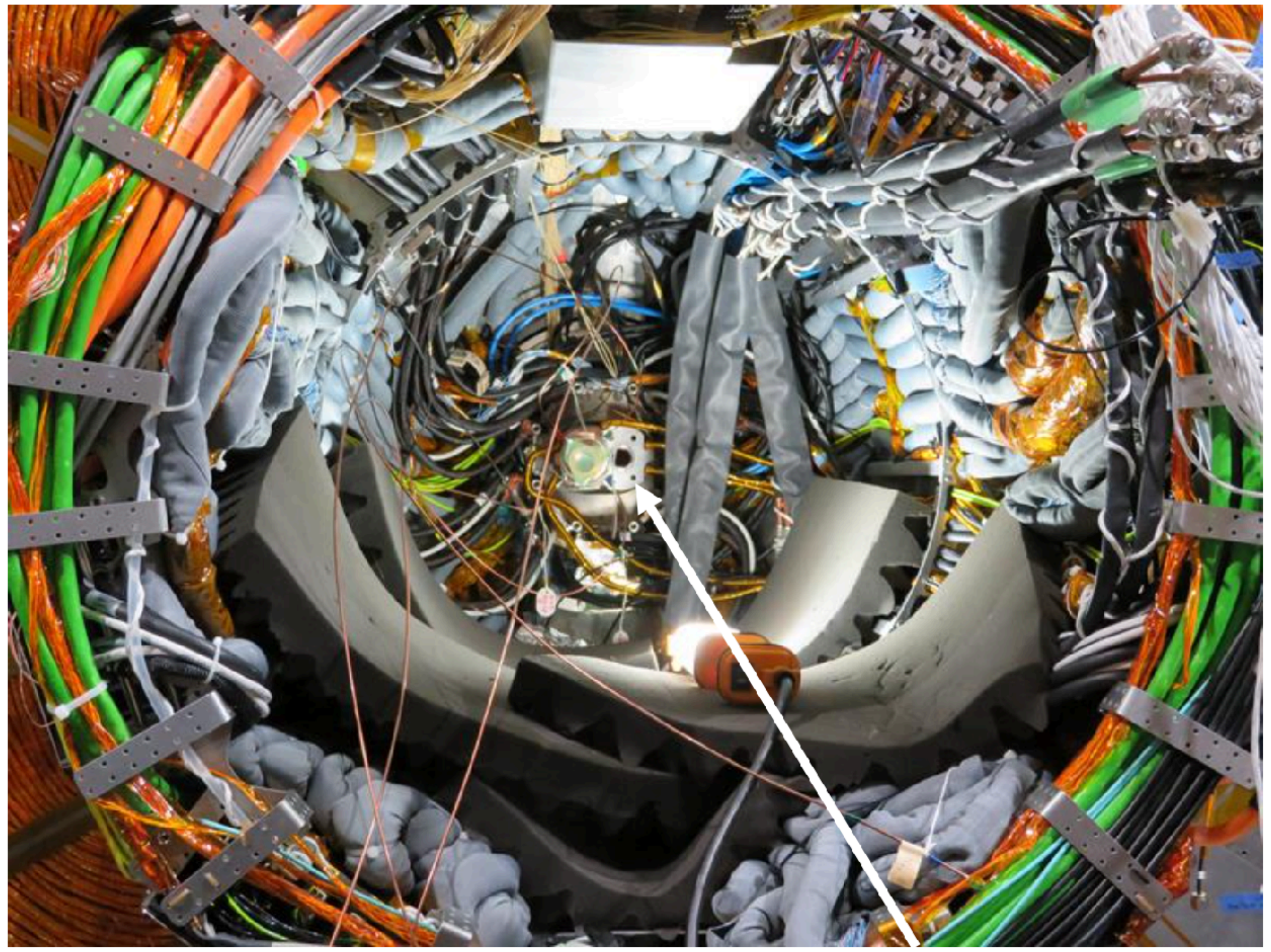


1.5 T detector solenoid and compensation solenoid within the cryostat of the final focus system

Connection Between QCS and Belle II Detector

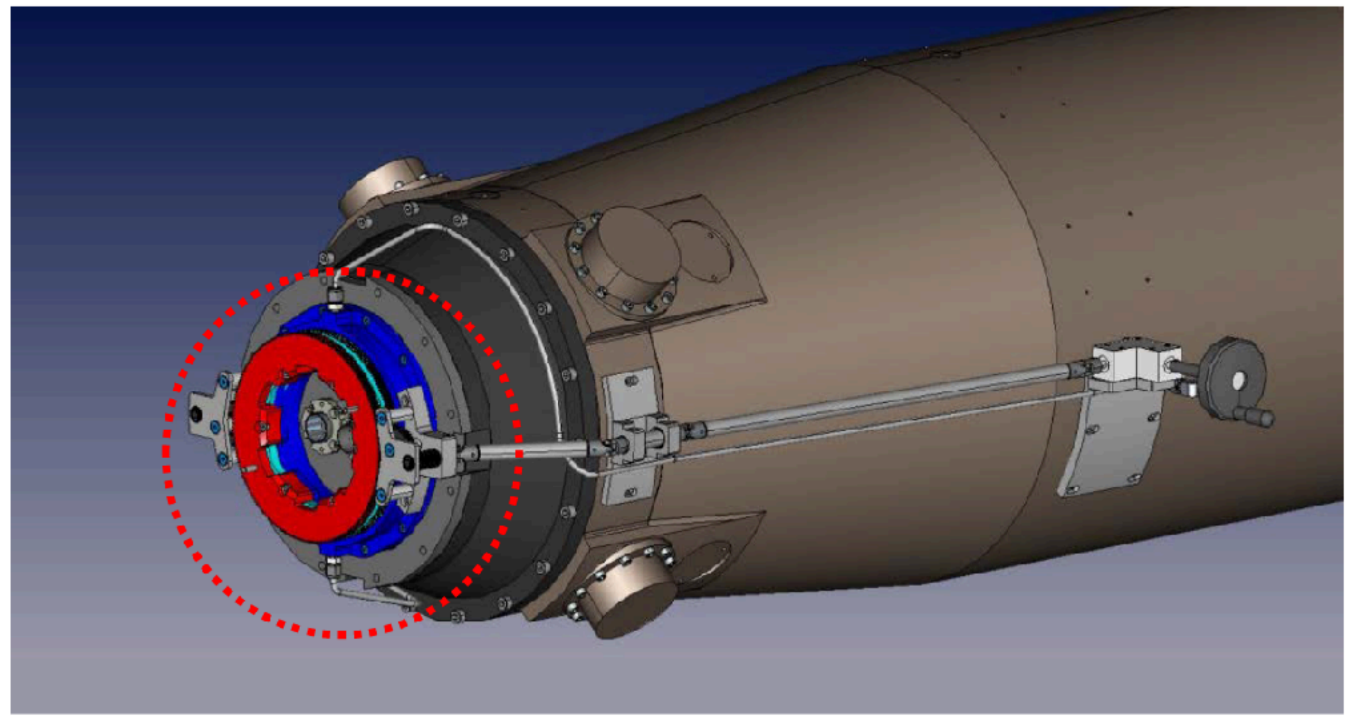




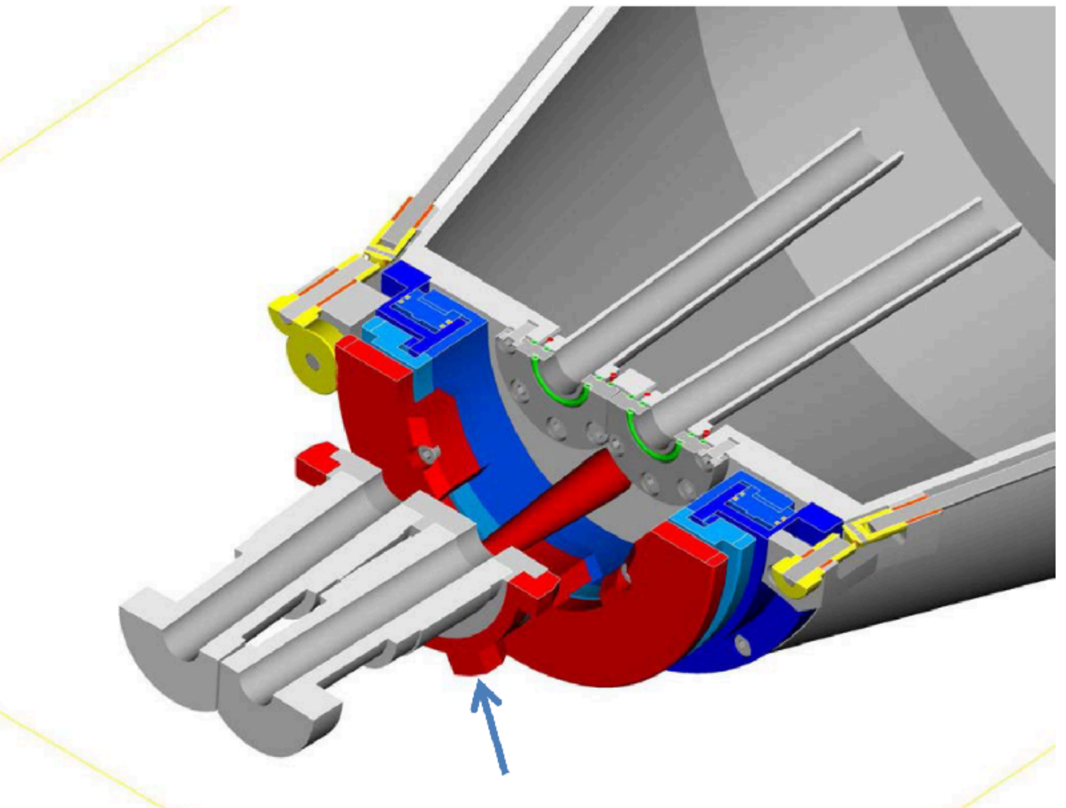


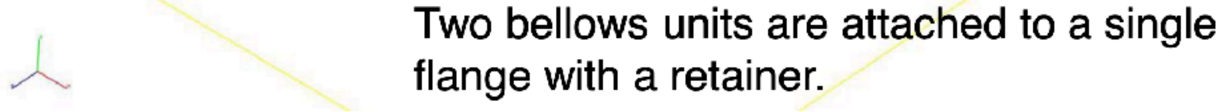
Bellows chamber

RVC



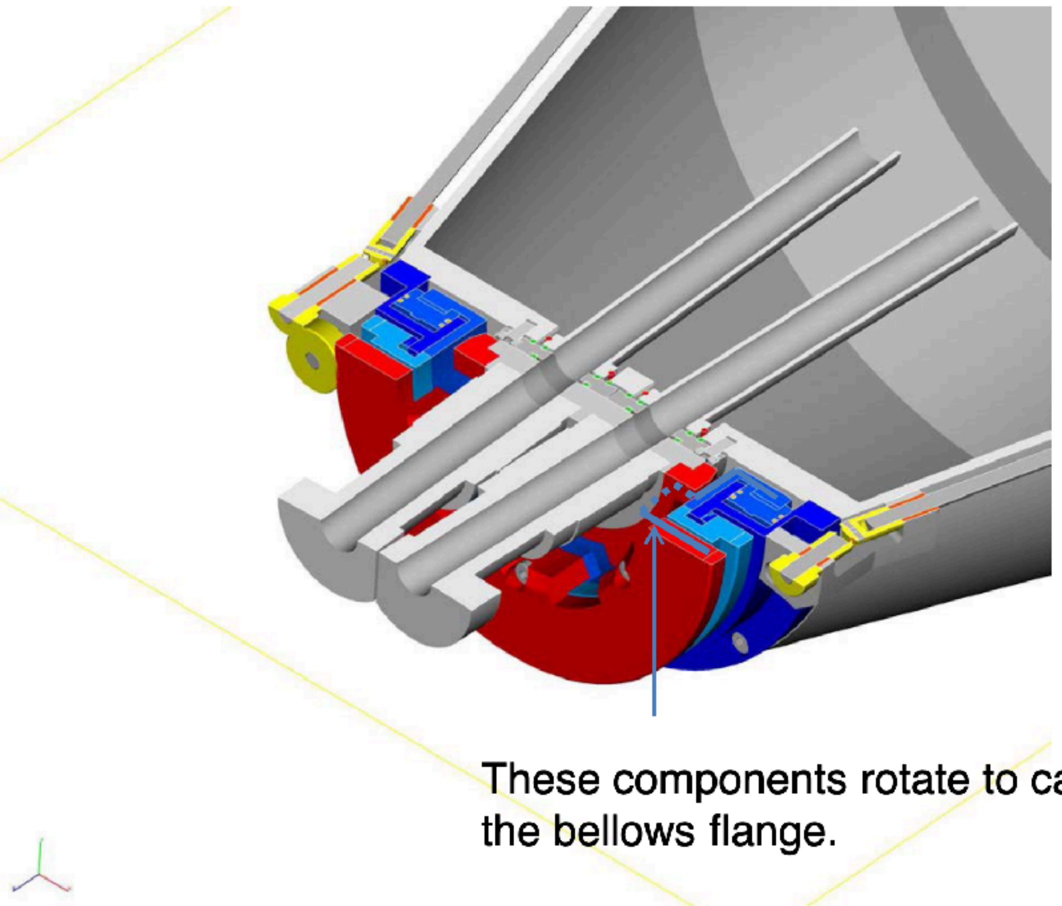
RVC is a mechanism introduced by Belle group to disconnect QCS from VXD by a remote manipulation.
RVC was designed and produced by DESY.

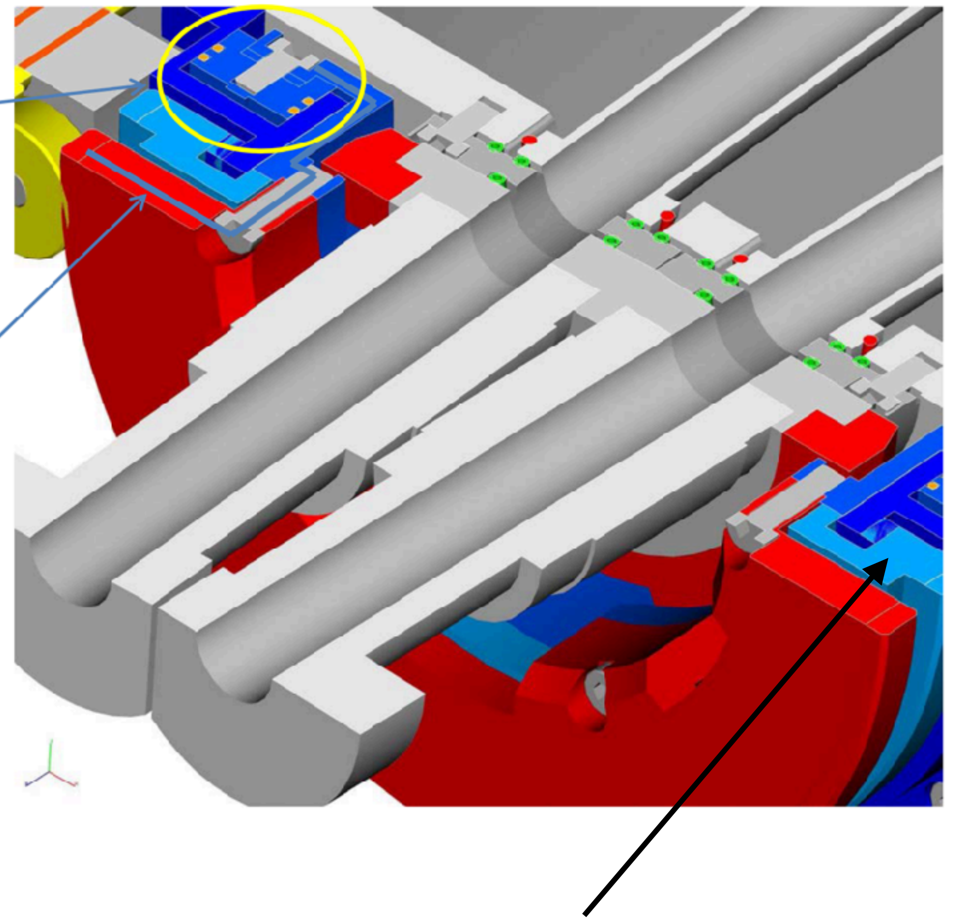




RVC on the new QCS head

Photo by DESY





Luminosity

General formula:

$$L = \frac{N_+ N_- n_b f_0}{2\pi \Sigma_x^* \Sigma_y^*}$$

$$= \frac{N_+ N_- n_b f_0}{2\pi \phi_x \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\sqrt{\varepsilon_{y+}\beta_{y+}^* + \varepsilon_{y-}\beta_{y-}^*}}$$

$$\Sigma_x^* = \sqrt{\sigma_{x+}^{*2} + \sigma_{z+}^2 \tan^2\phi_x + \sigma_{x-}^{*2} + \sigma_{z-}^2 \tan^2\phi_x}$$

$$= \sqrt{\sigma_{x+}^{*2}(1+\Psi_+^2) + \sigma_{x-}^{*2}(1+\Psi_-^2)}$$

$$\simeq \phi_x \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}$$

$$\Psi_\pm = \frac{\sigma_{z\pm}}{\sigma_{x\pm}^*}\tan\phi_x$$

$\sigma_{z+} = 4.6\ mm \quad \sigma_{z-} = 5.1\ mm$ (zero current)

Vertical emittance is important.
X-Y couplings and vertical dispersion affect the vertical emittance.

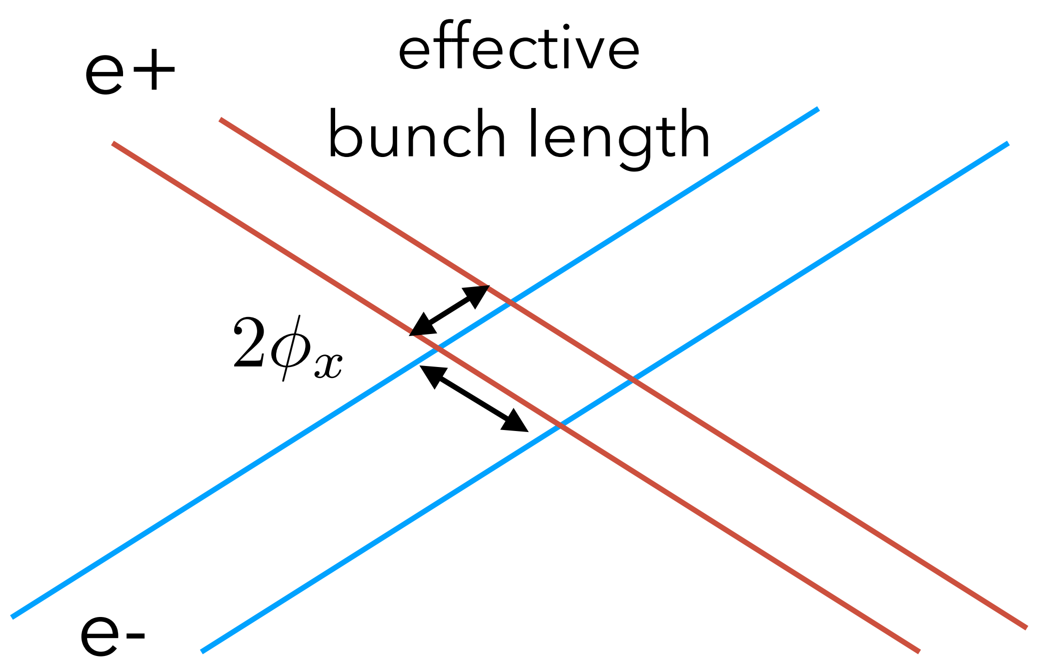
Nano-beam scheme Piwinski angle : $\Psi_\pm = 10 \sim 19 >> 1$

Bunch lengthening is important.
For instance, impedance affects bunch lengthening.

To avoid **hourglass effect**:

$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} = \frac{\sigma_z}{\Psi}$$

$$\sigma_x^* = \sqrt{\varepsilon_x \beta_x^*}$$



Horizontal emittance : $\varepsilon_{x+} = 2\ nm$ *(4 nm)*
$\varepsilon_{x-} = 4.6\ nm$

$\beta_{x+}^* = 80\ mm / \beta_{x-}^* = 60\ mm$ $\quad \tilde{\sigma}_{z+} = 305\ \mu m / \tilde{\sigma}_{z-} = 400\ \mu m$ *(431 μm)*

Definition of specific luminosity

$$L_{sp} = \frac{L}{I_{b+} I_{b-} n_b}$$

Definition of beam-beam parameter (here)

$$\xi_{y\pm} = \frac{2 e r_e \beta_{y\pm}^*}{\gamma_\pm I_\pm} L$$

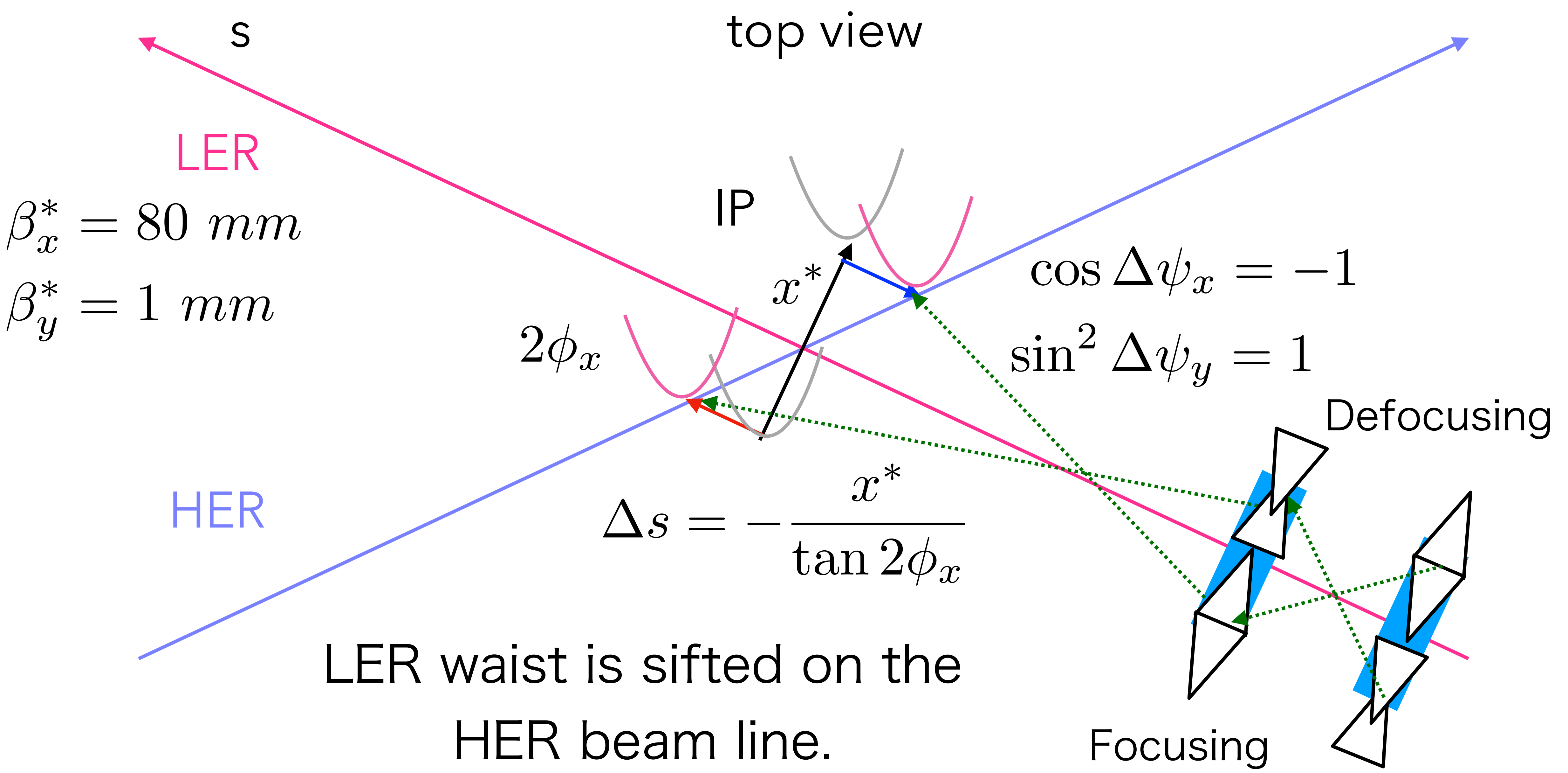
Crab Waist

Waist shift :

$$\begin{pmatrix} \tilde{y}^* \\ \tilde{p_y}^* \end{pmatrix} = \begin{pmatrix} 1 & \Delta s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y^* \\ p_y^* \end{pmatrix}$$

$$\tilde{y}^* = y^* - \frac{x^*}{\tan 2\phi_x} p_y^*$$

$$H_{CW} = -\frac{1}{2\tan 2\phi_x} x^* p_y^{*2}$$



LER waist is sifted on the HER beam line.

Crab waist sextupoles (-I' transfer)
(opposite deviation from the reference field for each)

On the other hand, Hamiltonian of sextupole :

$$H = \frac{K_2}{6}(x^3 - 3xy^2)$$
$$= \frac{K_2}{6}\beta_x^{3/2} X^2 - \frac{K_2}{2}\sqrt{\beta_x}\beta_y XY^2$$

IP to CW sextupole :

$$\begin{pmatrix} X, Y \\ P_{X,Y} \end{pmatrix} = \begin{pmatrix} \cos \Delta\psi_{x,y} & -\sin \Delta\psi_{x,y} \\ \sin \Delta\psi_{x,y} & \cos \Delta\psi_{x,y} \end{pmatrix} \begin{pmatrix} X^*, Y^* \\ P_{X,Y}^* \end{pmatrix}$$

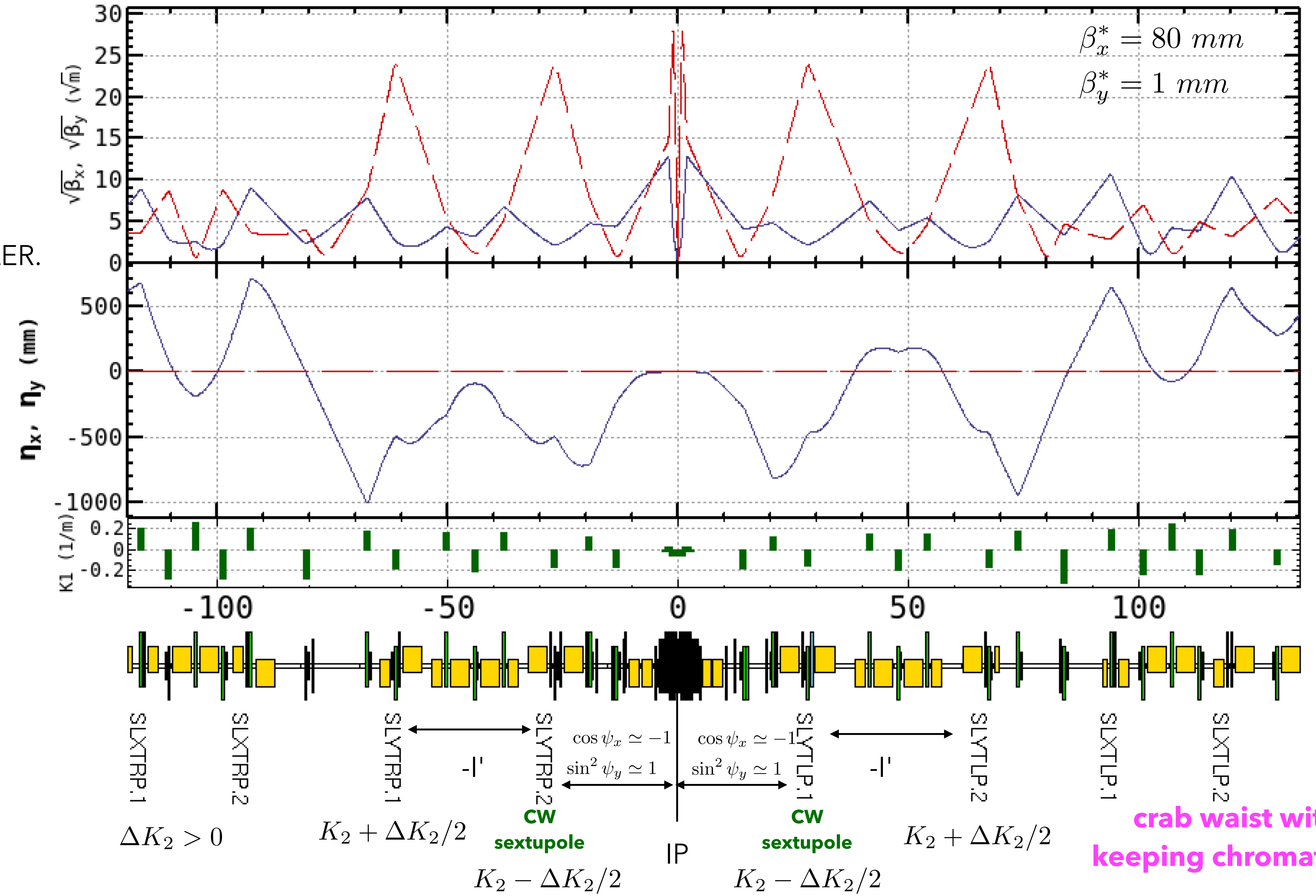
$$H_{CW} = -\frac{K_2}{2}\beta_y\beta_y * \sqrt{\frac{\beta_x}{\beta_x^*}} \cos \Delta\psi_x \sin^2 \Delta\psi_y x^* p_y^{*2}$$

References: **P. Raimondi et al., SuperB CDR, 2007**
K. Oide et al., ICHEP 2016

Crab Waist Lattice in LER

FCC-ee style
Crab Waist
(K. Oide)

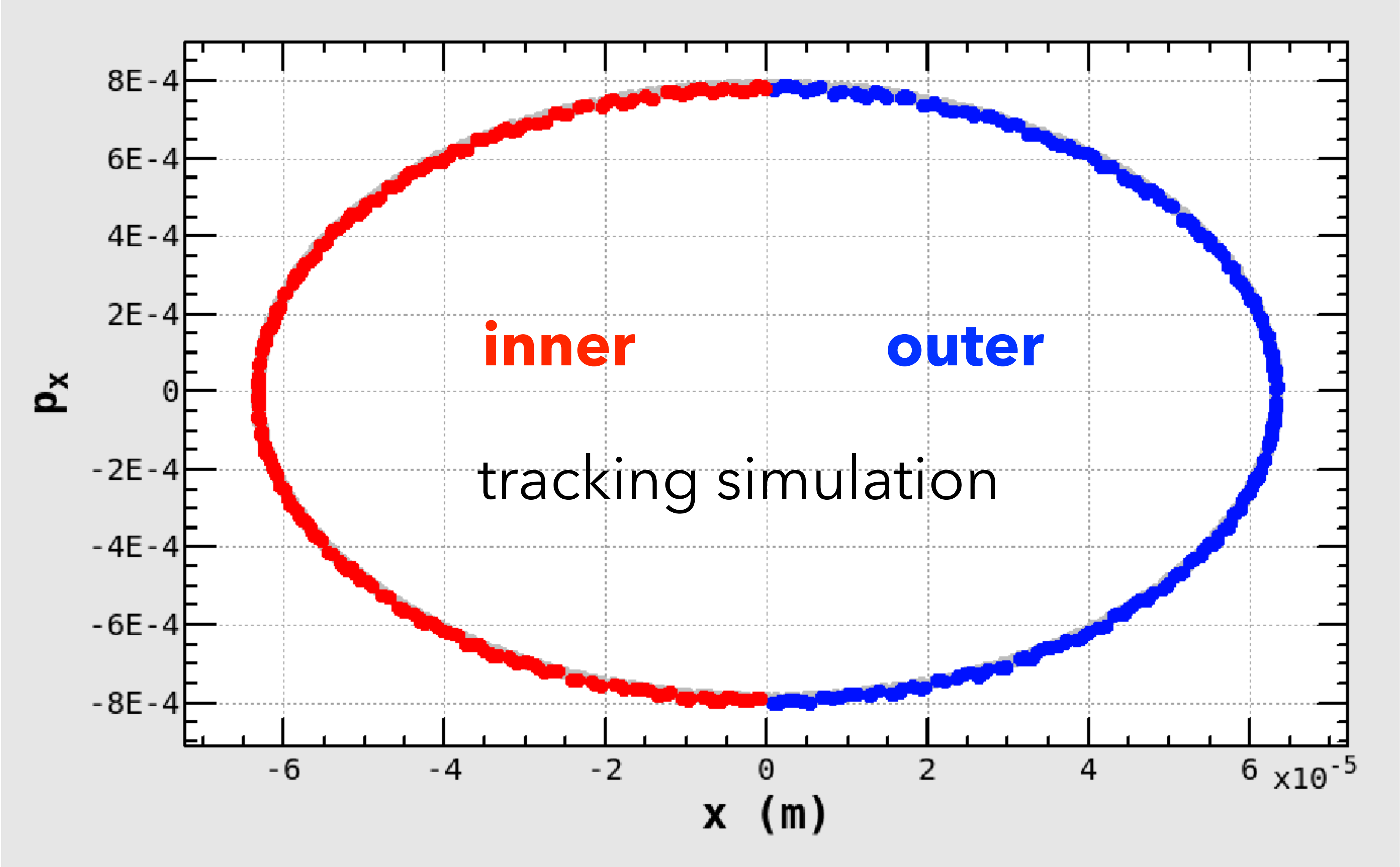
HER is similar to LER.

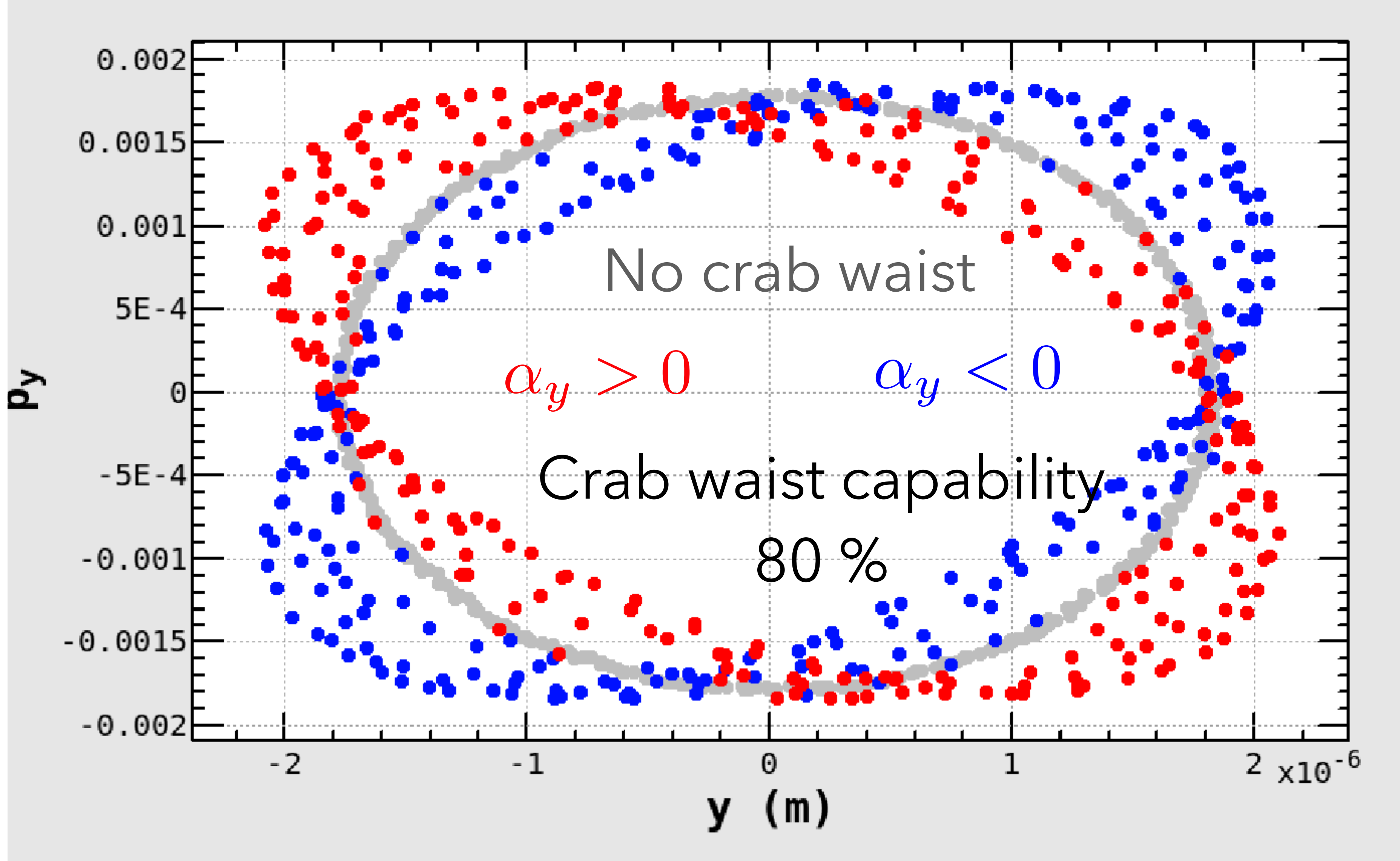


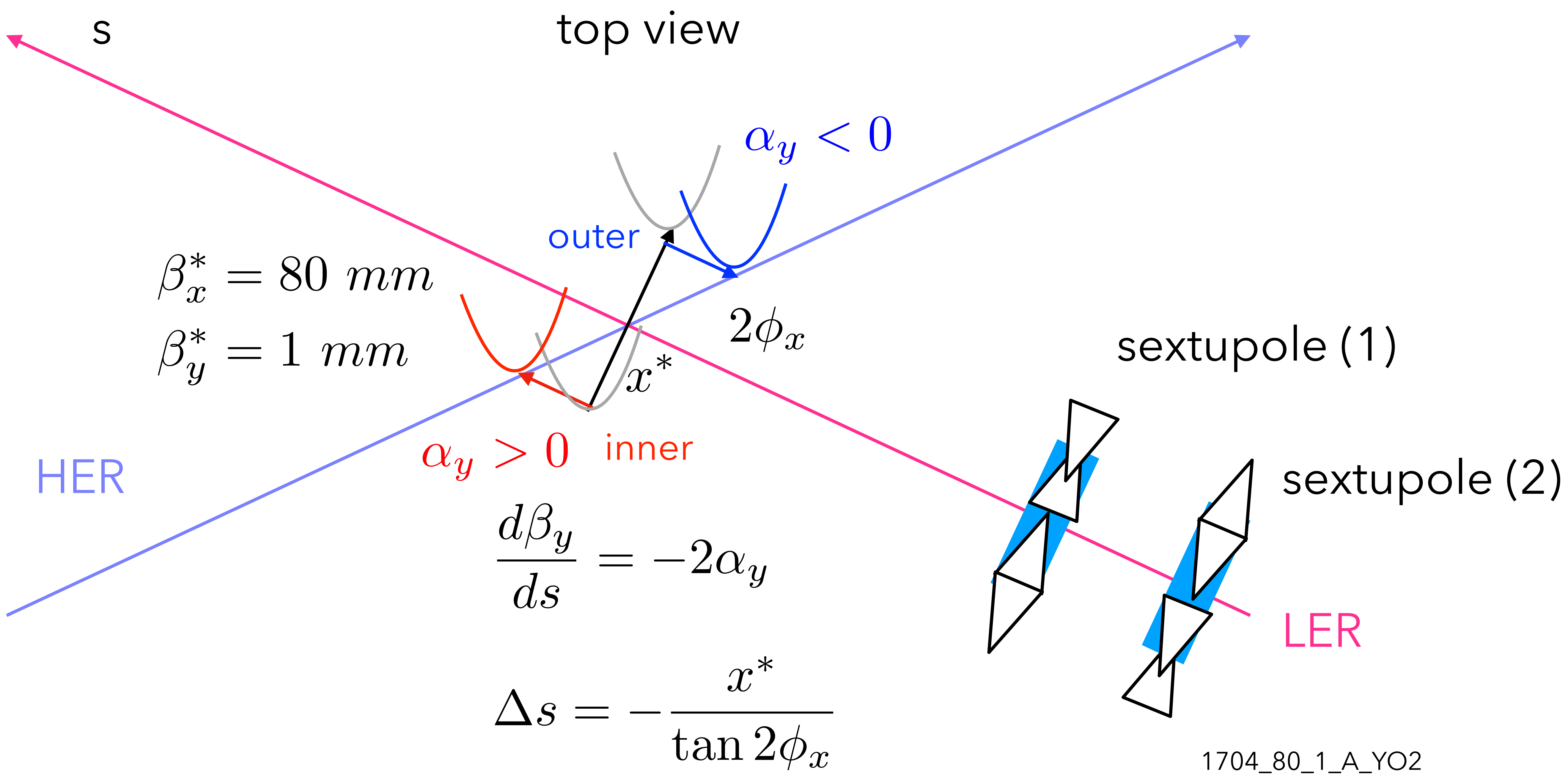
crab waist with keeping chromaticity

Phase Space at IP in LER

Interaction point (s = 0)







CW sextupole	L-side	R-side	Unit
$\beta_{x\ (sextupole)}$	5.66	5.52	m
$\beta_{y\ (sextupole)}$	525	521	m
$\cos\Delta\psi_x$	-0.992	-0.988	
$\sin^2\Delta\psi_y$	1.0	1.0	
$K_{2\ (SLYT\{LR\}1/2)}$	1.327 / 3.526	1.226 / 3.478	1/m^2

Crab waist capability 80 %

- Phase1 operation (2016.Feb. ~ June);
  - Vacuum scrubbing, low emittance beam tuning, and background study for Belle II detector installation
  - w/o final focusing system (QCS) and Belle II detector
- Phase2 operation (2018.Mar. ~ July);
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD)
  - Demonstration of nano-beam collision scheme
  - Study on background larger than at KEKB due to much lower beta functions at IP.

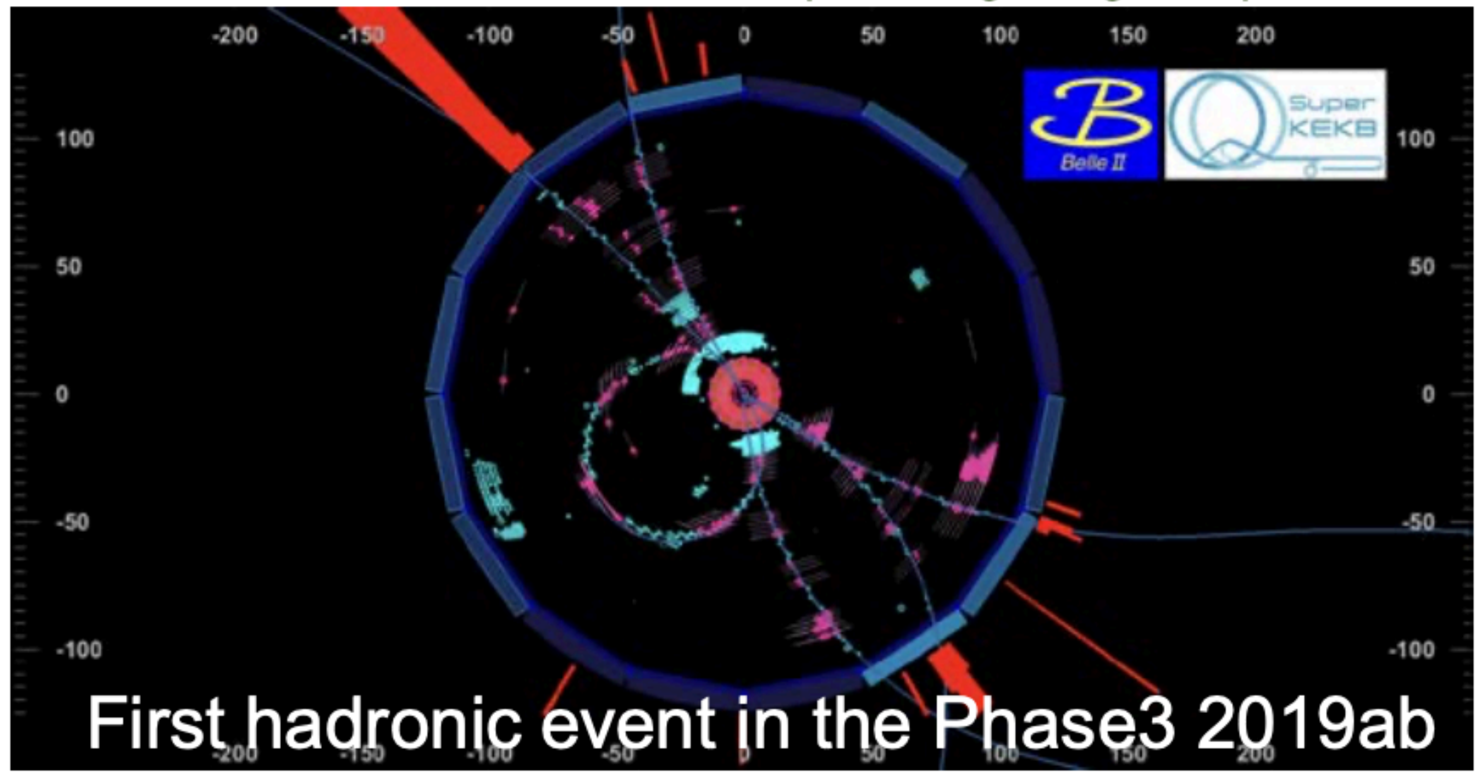
- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector.
  - Phase3 2019ab (2019.3~7)
    - "Status of Early SuperKEKB Phase-3 Commissioning" by A.Morita (WEYYPLM1) @ IPAC'19 (2019.5.22)
  - Phase3 2019c (2019.10~12)
  - Phase3 2020ab (2020.2~)
  - ✓ New nomenclator of each run of Phase3

"Phase3 YYYYxx"

Calendar year ↑ YYYY

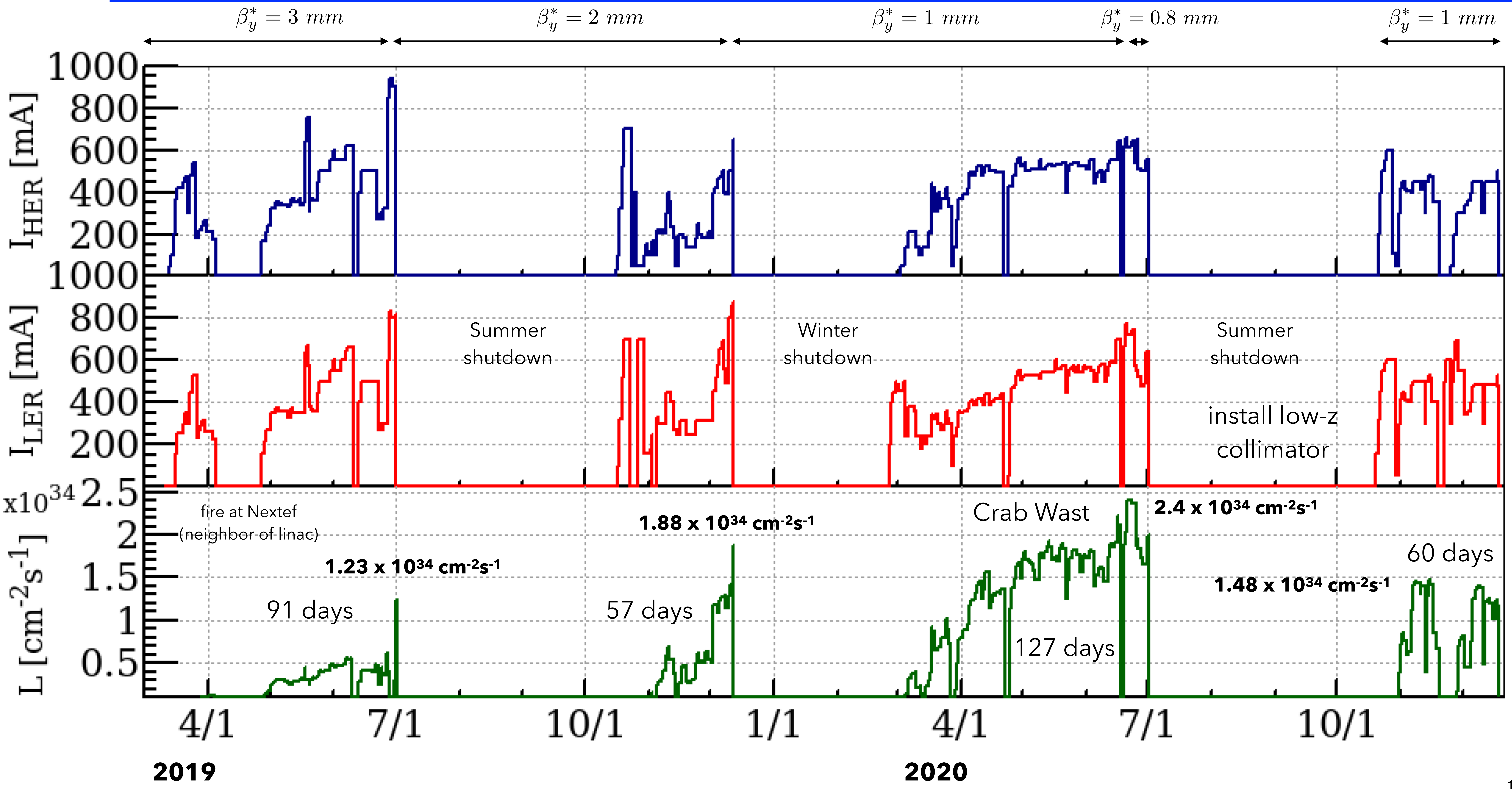
xx:
- a : Winter shutdown - March
- b : April - Summer shutdown
- ab : Winter shutdown – Summer shutdown
- c : Summer shutdown – Winter shutdown

April is beginning of Japanese fiscal year.


First hadronic event in the Phase3 2019ab

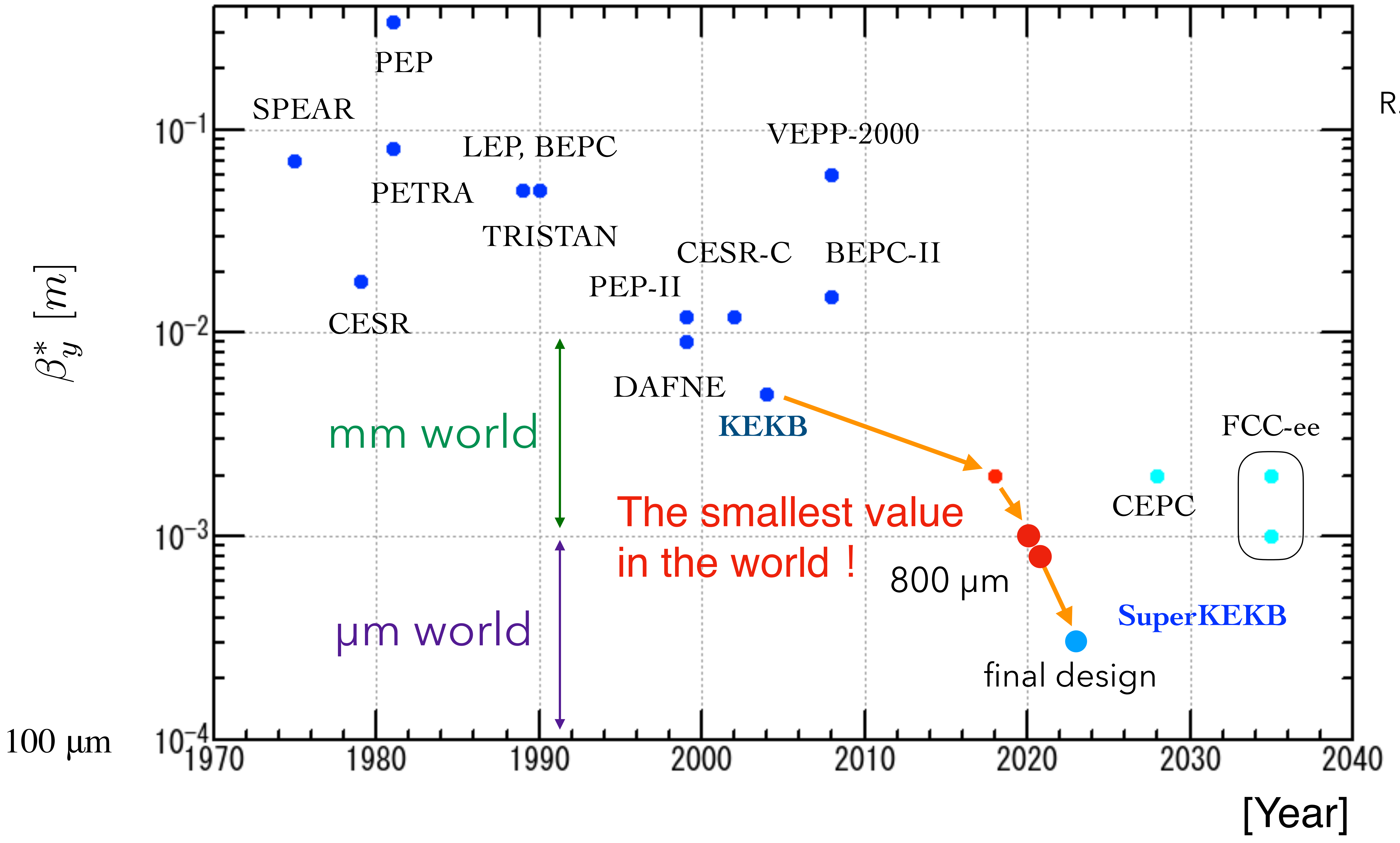
K. Shibata et al., IPAC 2020

History of Phase 3



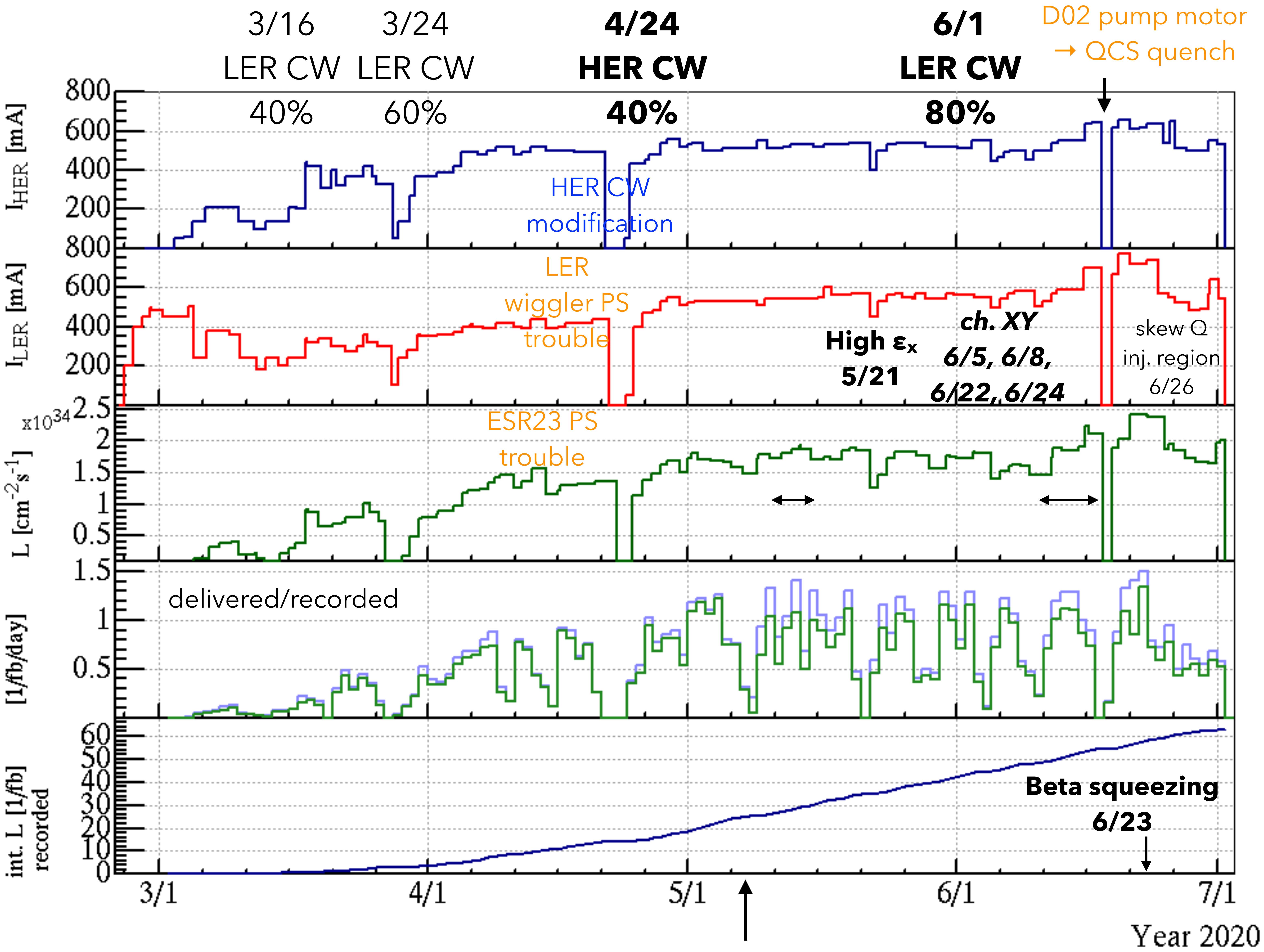
History of Vertical Beta Function at the IP

The β_y^* at SuperKEKB, 800 μm is the smallest value in the world.
The vertical beam size at the IP, 0.22 μm is also the smallest value for colliders.



σ_y^* = 0.7 μm at SLC
"SLC - THE END GAME"
R. Assmann et al., EPAC2000

Machine Operation in 2020ab



Remarks : Online luminosity does not include trigger-veto dead-time before May 7.

LER started on Feb. 25

HER started on March. 2

Max. current
LER : 770 mA
HER : 660 mA

Peak luminosity : 2.4 x 10^{34} $cm^{-2}s^{-1}$

Int. luminosity/day : 1.346 / 1.498 fb^{-1}

5/11-5/14 off-resonance

6/10-6/17 off-resonance

LER :

$$\beta_x^*/\beta_y^* = 80\ mm/1\ mm$$
$$\rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

HER :

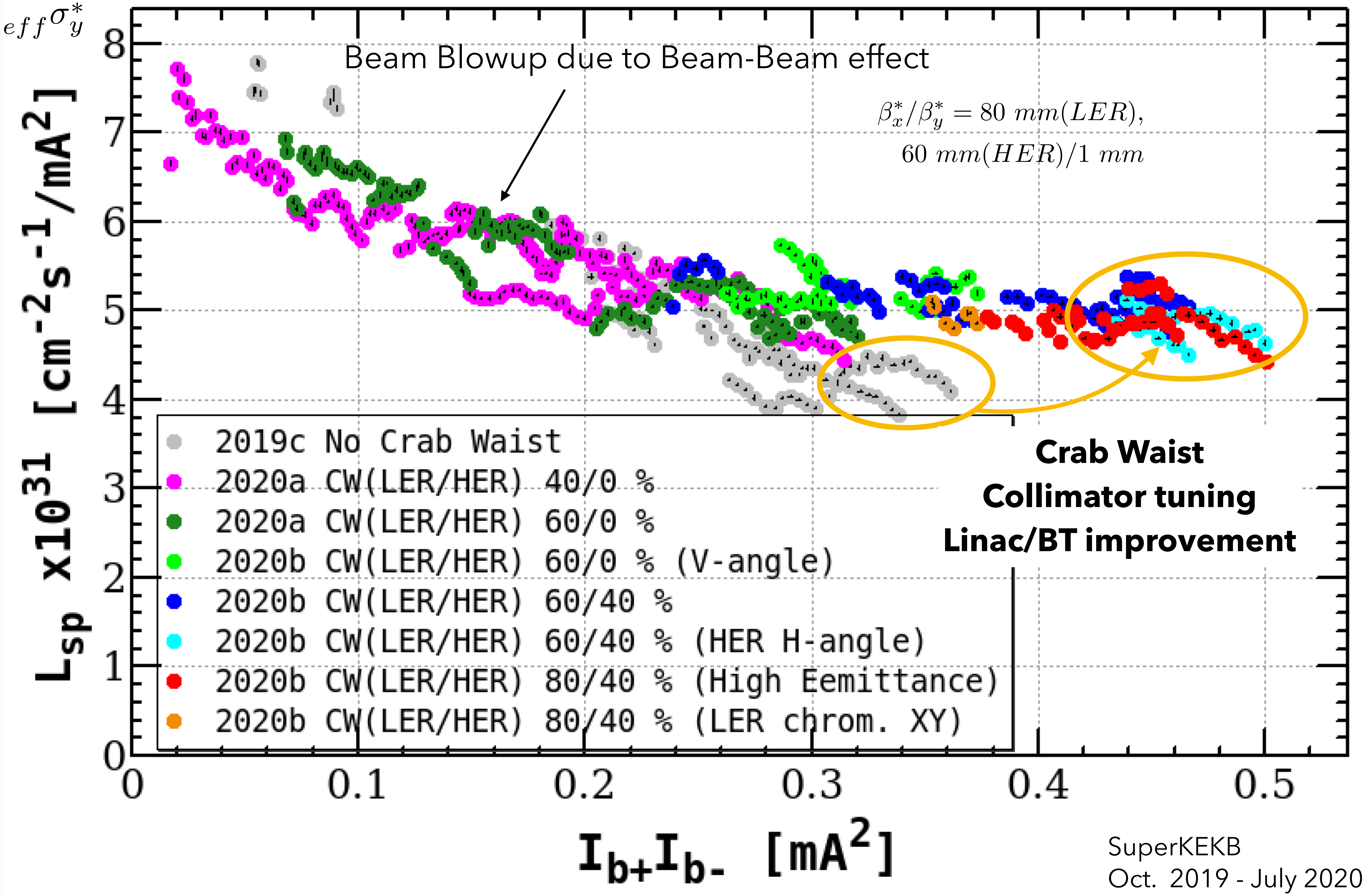
$$\beta_x^*/\beta_y^* = 60\ mm/1\ mm$$
$$\rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

History from Phase 2 to Phase 3

	Phase 2 2018a/b	Phase 3.1 2019a/b	Phase 3.2 2019c	Phase 3.3 2020a/b	Remarks
Date	**March 19 - July 17 2018**	**March 11 - July 1 2019**	**Oct. 15 - Dec. 12 2019**	**Feb. 25 - July 1 2020**	
Operation time (days)	120	91 (fire : 21)	57	127	~ 6 months per year
Beta Function at IP (mm)	LER : 200 / 3 HER : 100 / 3	LER : 80 / 2 HER : 80 / 2	LER : 80 / 1 HER : 60 / 1	LER : 60 / 0.8 HER : 60 / 0.8	The minimum horizontal / vertical value
Beam Currents (mA)	LER : 860 HER : 800	LER : 940 HER : 840	LER : 880 HER : 700	LER : 770 HER : 660	The maximum values during the operatation
Peak Luminosity ($cm^{-2}s^{-1}$)	**2.62×10^{33}** → double	**5.50×10^{33}** → double	**1.14×10^{34}** → double	**2.40×10^{34}**	w Belle II
	5.55×10^{33}	1.23×10^{34}	1.88×10^{34}	-	w/o Belle II

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma^*_{x,eff}\sigma^*_y}$$

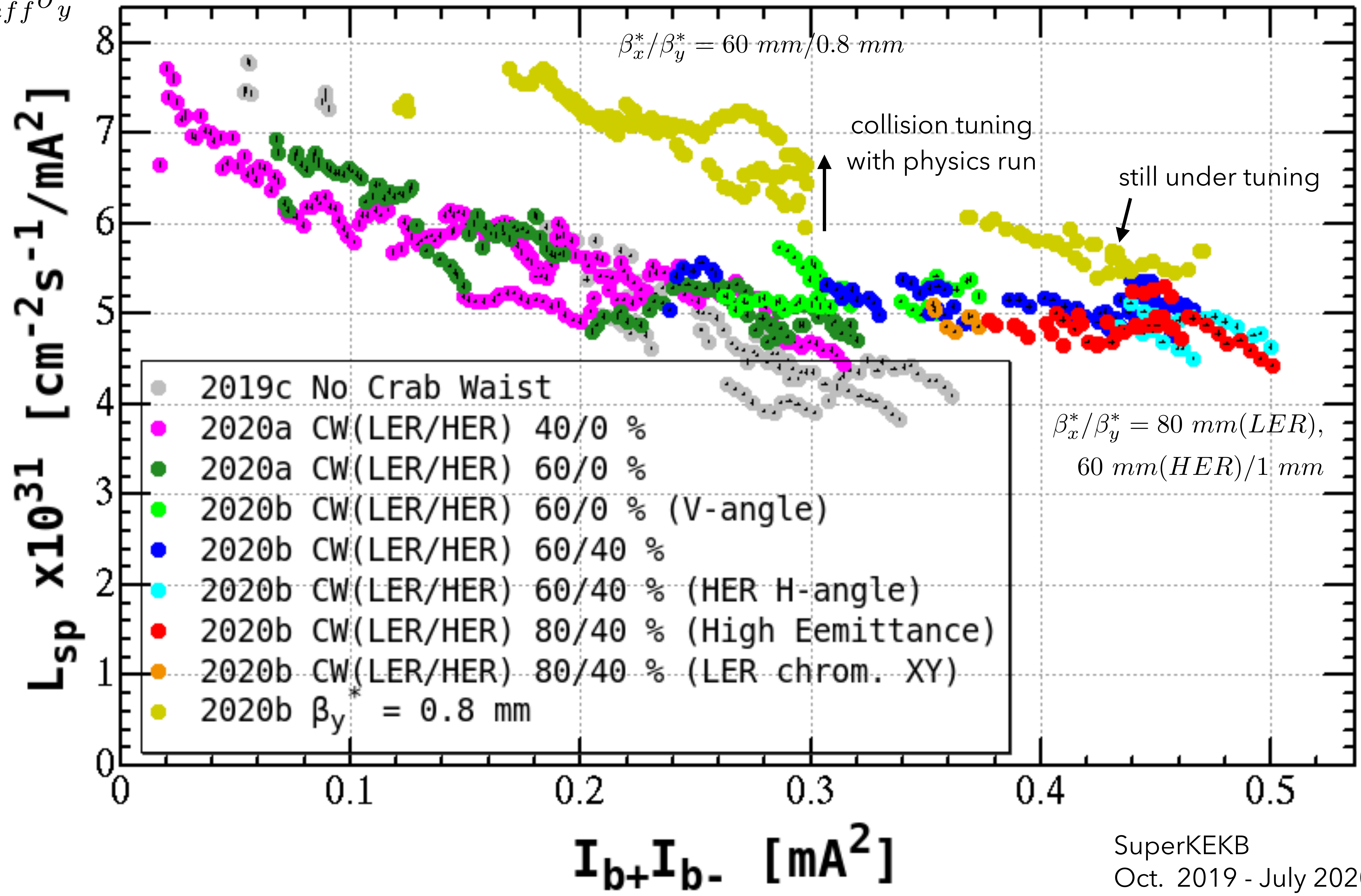
$\beta_y^* = 1\ mm$



SuperKEKB
Oct. 2019 - July 2020

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma^*_{x,eff}\sigma^*_y}$$

$\beta^*_y = 1\ mm$ and $0.8\ mm$

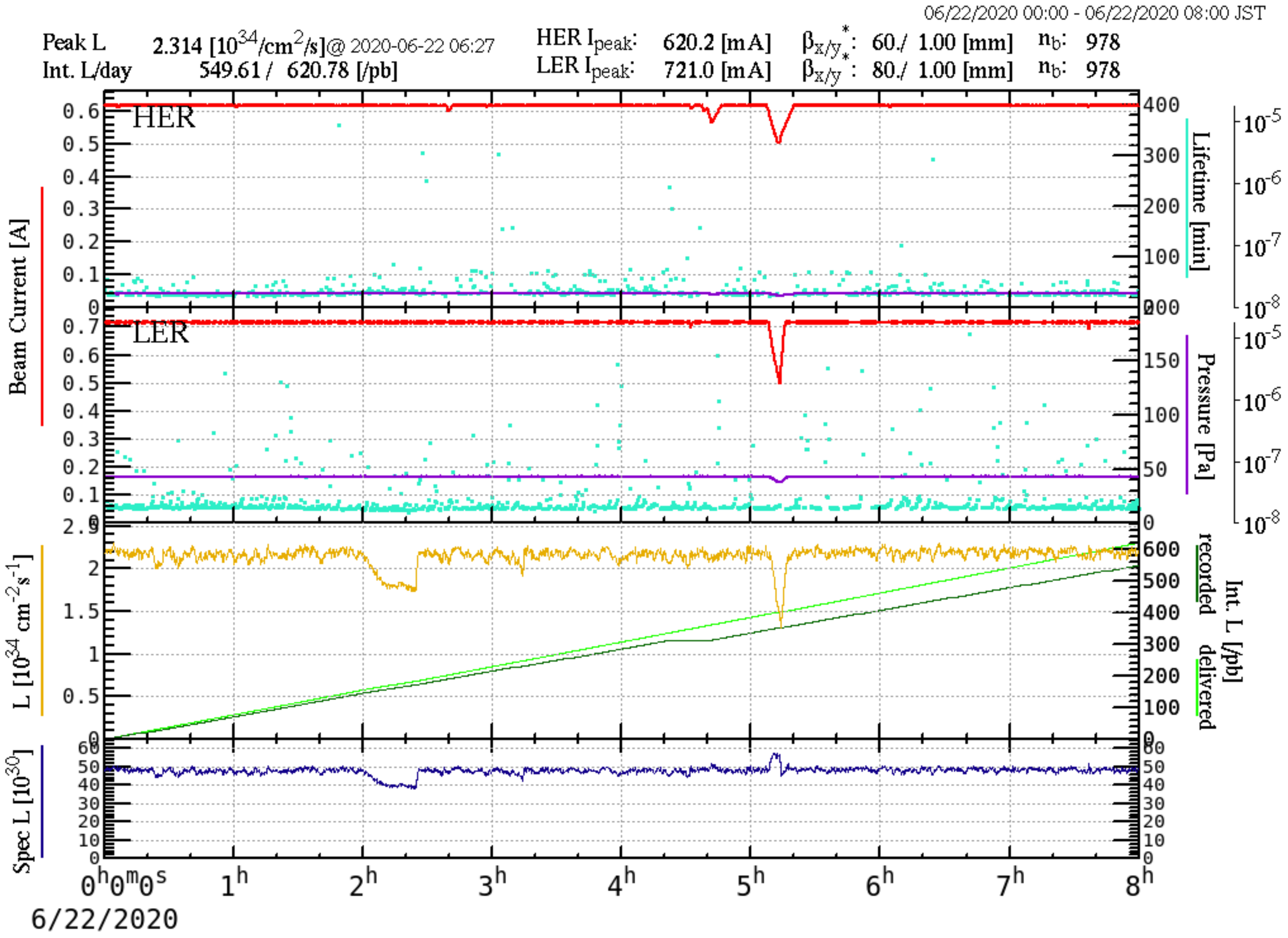


SuperKEKB
Oct. 2019 - July 2020

Best Shift

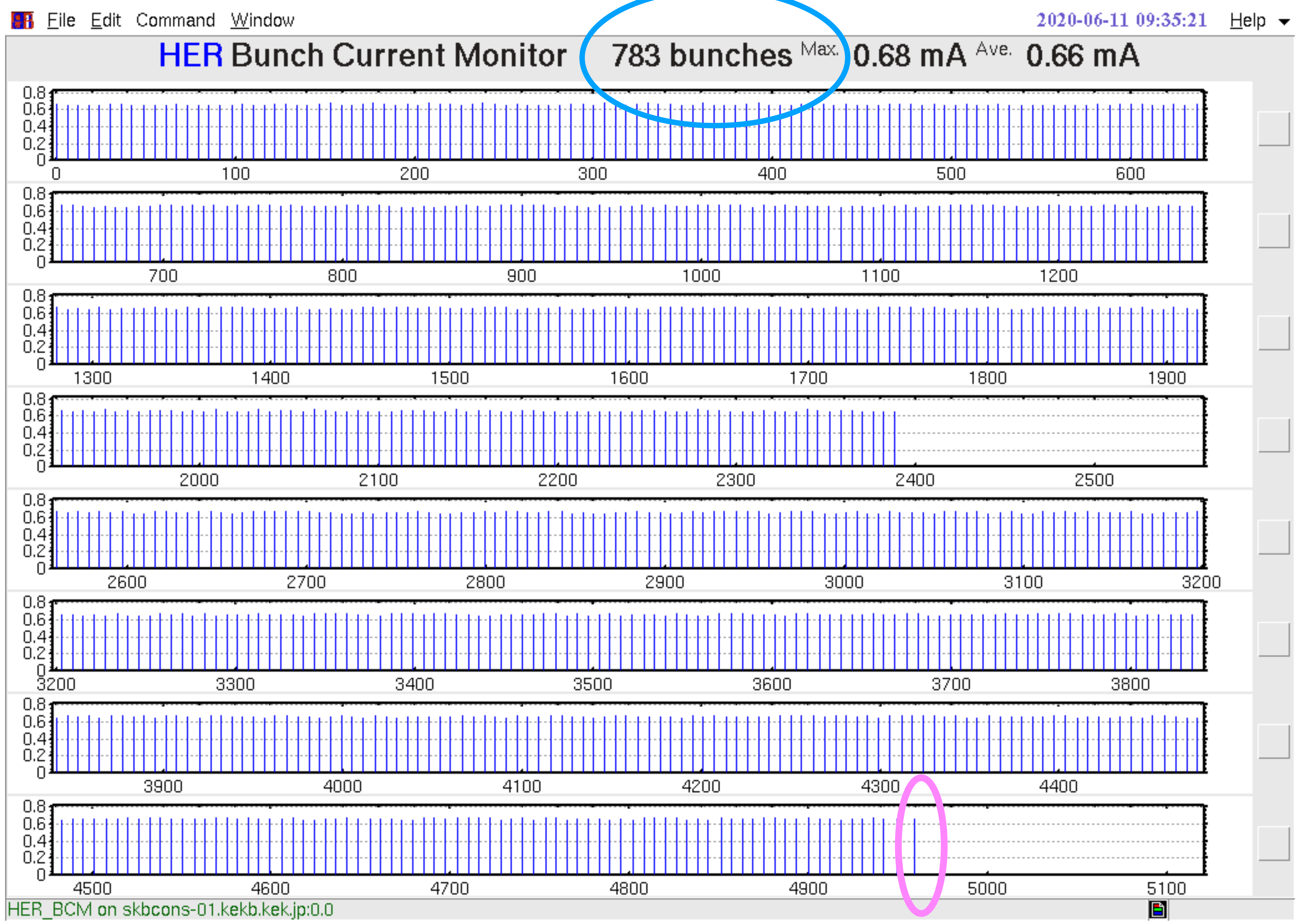
Continuous injection (top-up) has been successfully working to keep beam currents.

shifter : M. Nishiwaki



549.6 pb^{-1}/ 620.8 pb^{-1} (89 %)

Two abort gaps are prepared to make abort trigger fast.



pilot bunch
to measure tunes

pilot bunch
to measure tunes

Comparison between Machine Parameters

	KEKB : June 17, 2009		SuperKEKB : June 21, 2020		SuperKEKB : July 1, 2020		SuperKEKB : final design		Unit
Ring	LER	HER	LER	HER	LER	HER	LER	HER	
Emittance	18	24	4.0	4.6	4.0	4.6	3.2	4.6	nm
Beam Current	1637	1188	712	607	536	530	3600	2600	mA
Number of bunches	1585		978		978		2500		
Bunch current	1.03	0.750	0.728	0.621	0.548	0.542	1.44	1.04	mA
Horizontal size σ_x*	147	170	17.9	16.6	15.5	16.6	10.1	10.7	μm
Vertical cap sigma Σ_y*	1.33		0.403		0.317		0.079		μm
Vertical size σ_y*	0.940		0.285		0.224		0.048	0.062	μm
Betatron tunes ν_x / ν_y	45.506 / 43.561	44.511 / 41.585	44.523 / 46.581	45.531 / 43.577	44.525 / 46.581	45.531 / 43.574	44.53 / 46.57	45.53 / 43.57	
β_x* / β_y*	1200 / 5.9	1200 / 5.9	80 / 1.0	60 / 1.0	60 / 0.8	60 / 0.8	32 / 0.27	25 / 0.30	mm
Piwinski angle	0	0	10.7	12.7	12.3	12.7	19.3	19.0	
Beam-Beam parameter ξ_y	0.129	0.090	0.0389	0.0261	0.0345	0.0199	0.0881	0.0807	
Specific luminosity	1.71×10^{31}		5.43×10^{31}		6.90×10^{31}		2.14×10^{32}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.11×10^{34}		2.40×10^{34}		2.00×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$
Remarks	Crab crossing		Crab waist (80 %, 40 %)		Crab waist (80 %, 40 %)		-		

Damage of Movable Collimators

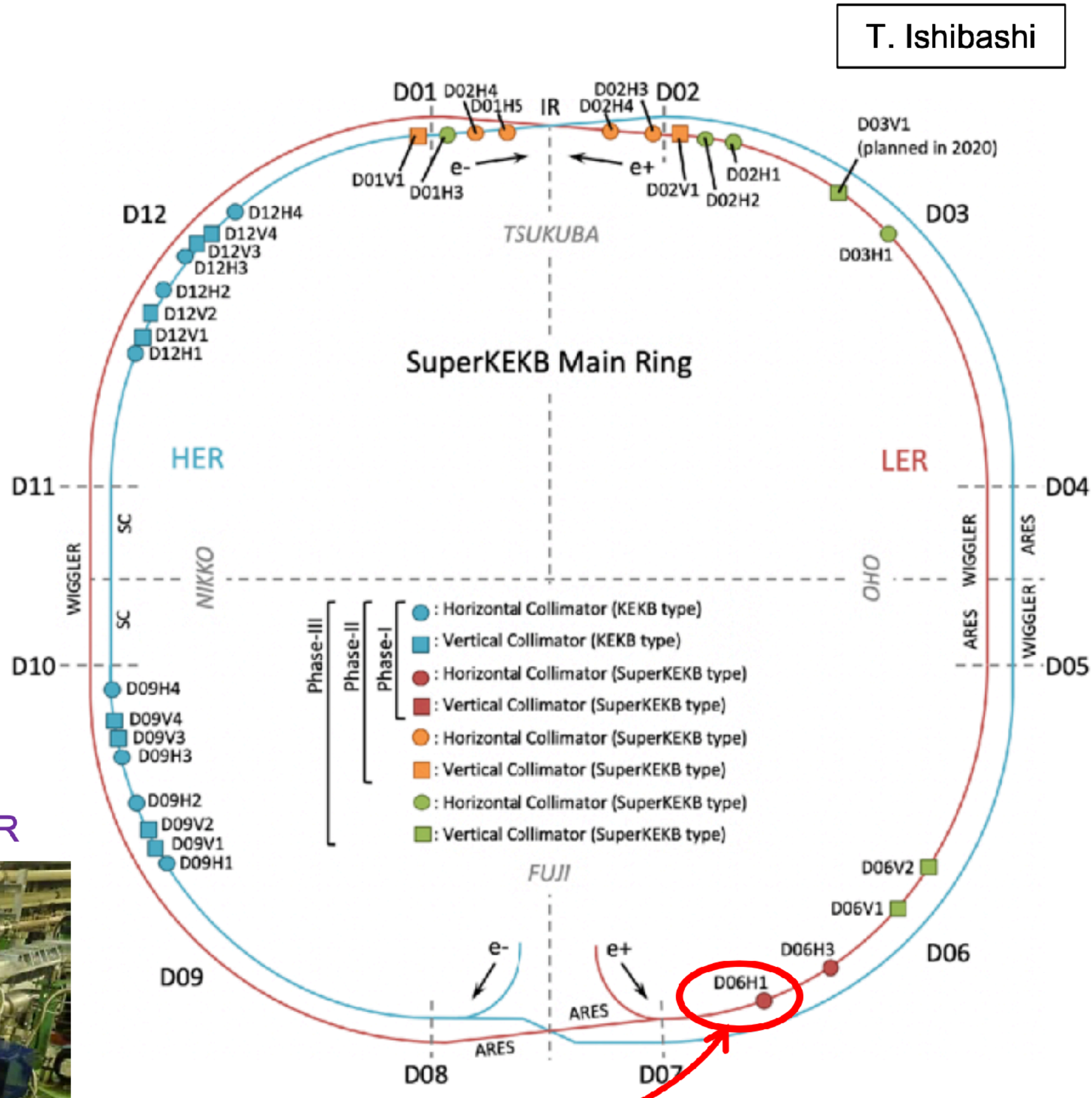
K. Shibata, IPAC 2020

- Replacement of damaged collimator head;
  - One of LER collimator head was damaged during Phase3 2019c.
  - 4 collimator heads were damaged in total so far.
    - ✓ LER : D06V2 (Phase3 2019c), D02V1 (Phase3 2019ab), D02V1 (Phase2)
    - ✓ HER : D01V1 (Phase2)

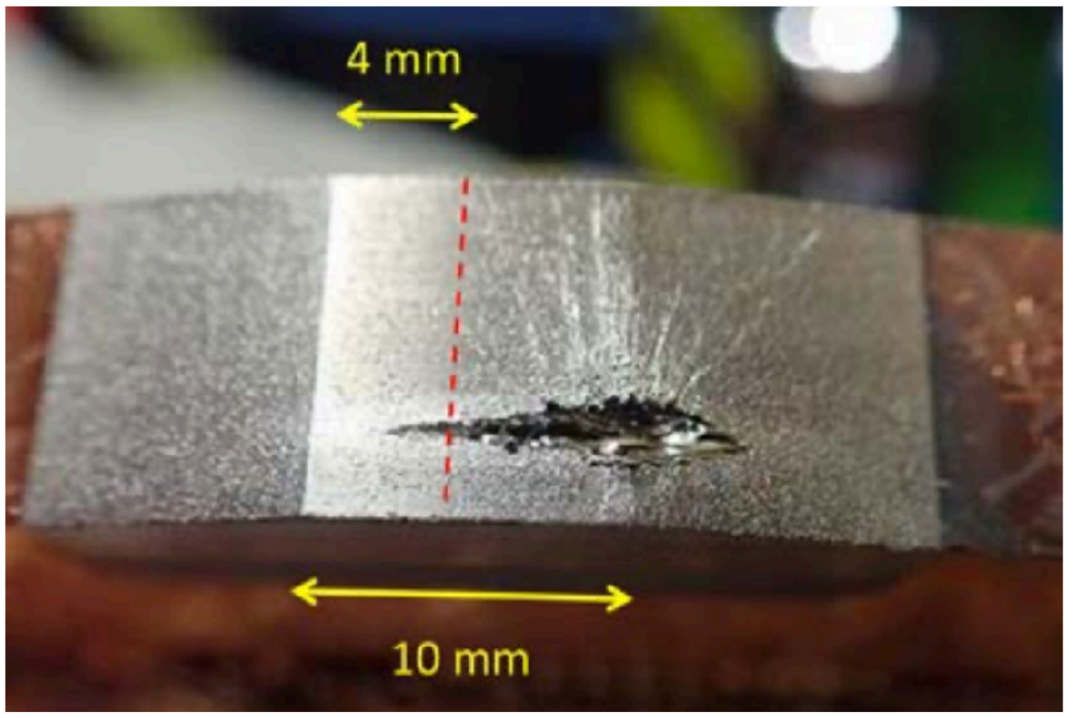
➢ Robust collimator is required in order to increase beam current.
  - R&D of Low-Z collimator has been tested in 2020c.
  - Short Ta head was set to D06V2 in a chain of low-Z collimator R&D.

- Installation of new vertical collimator (D06V1) in LER.

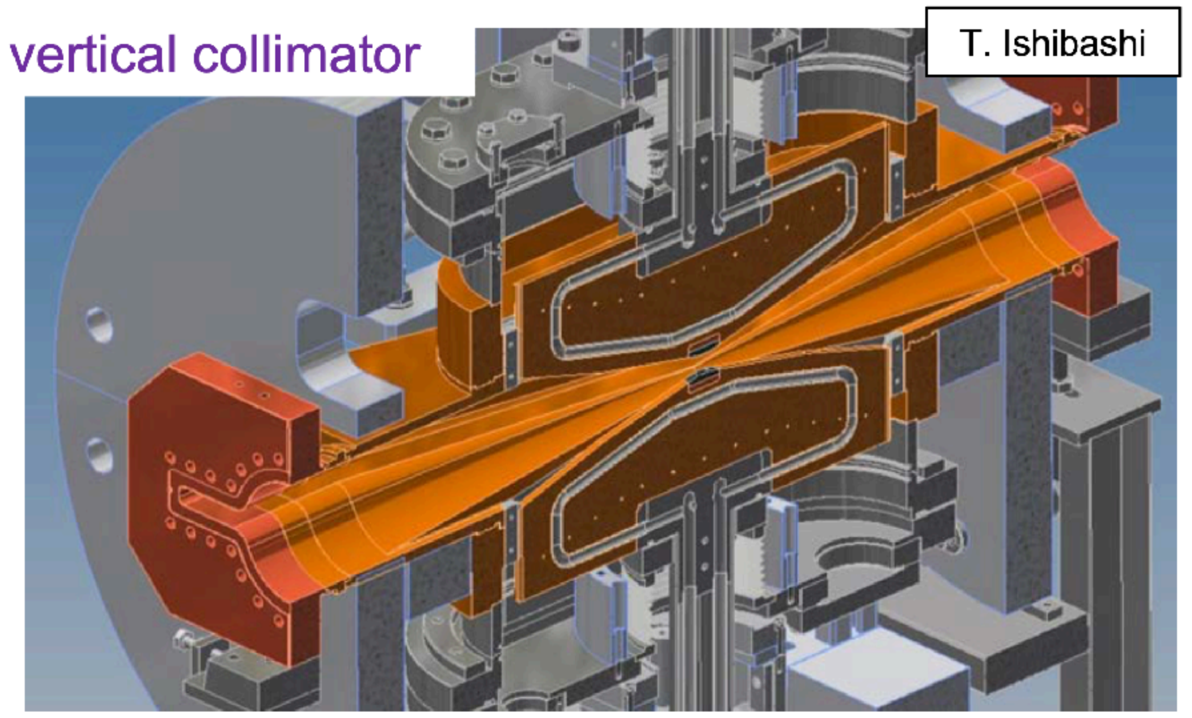
➢ Reduction in BG by a factor of 2.5 is expected by a simulation.



Damaged head



vertical collimator



New vertical collimator in LER

Ref. H. Nakayama et al.,
#6 17:40- Wed. 20 January IAS

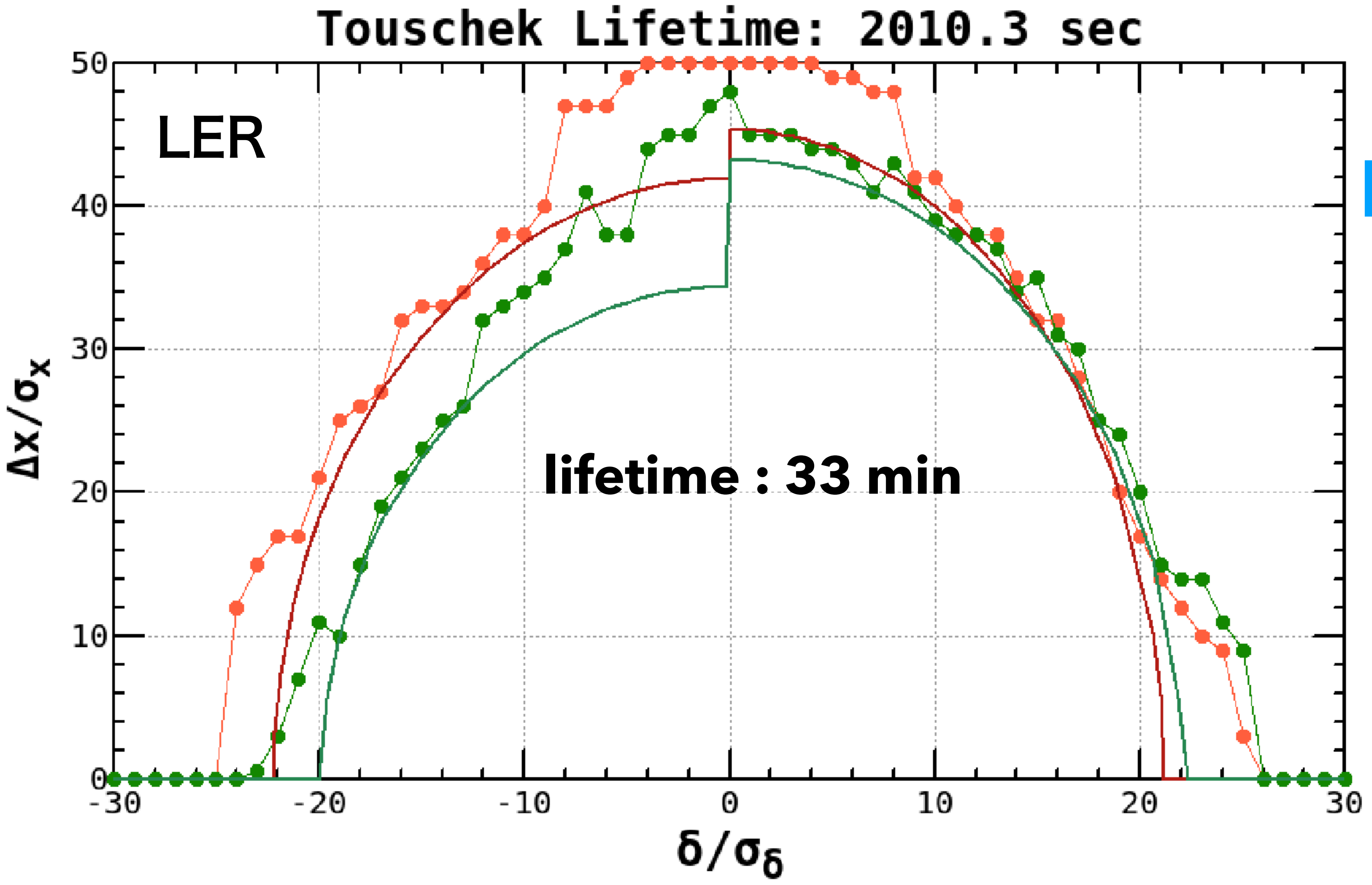
Dynamic Aperture and Touschek Lifetime in LER

Tracking simulation(Synchrotron oscillation : ON, Radiation damping : OFF)

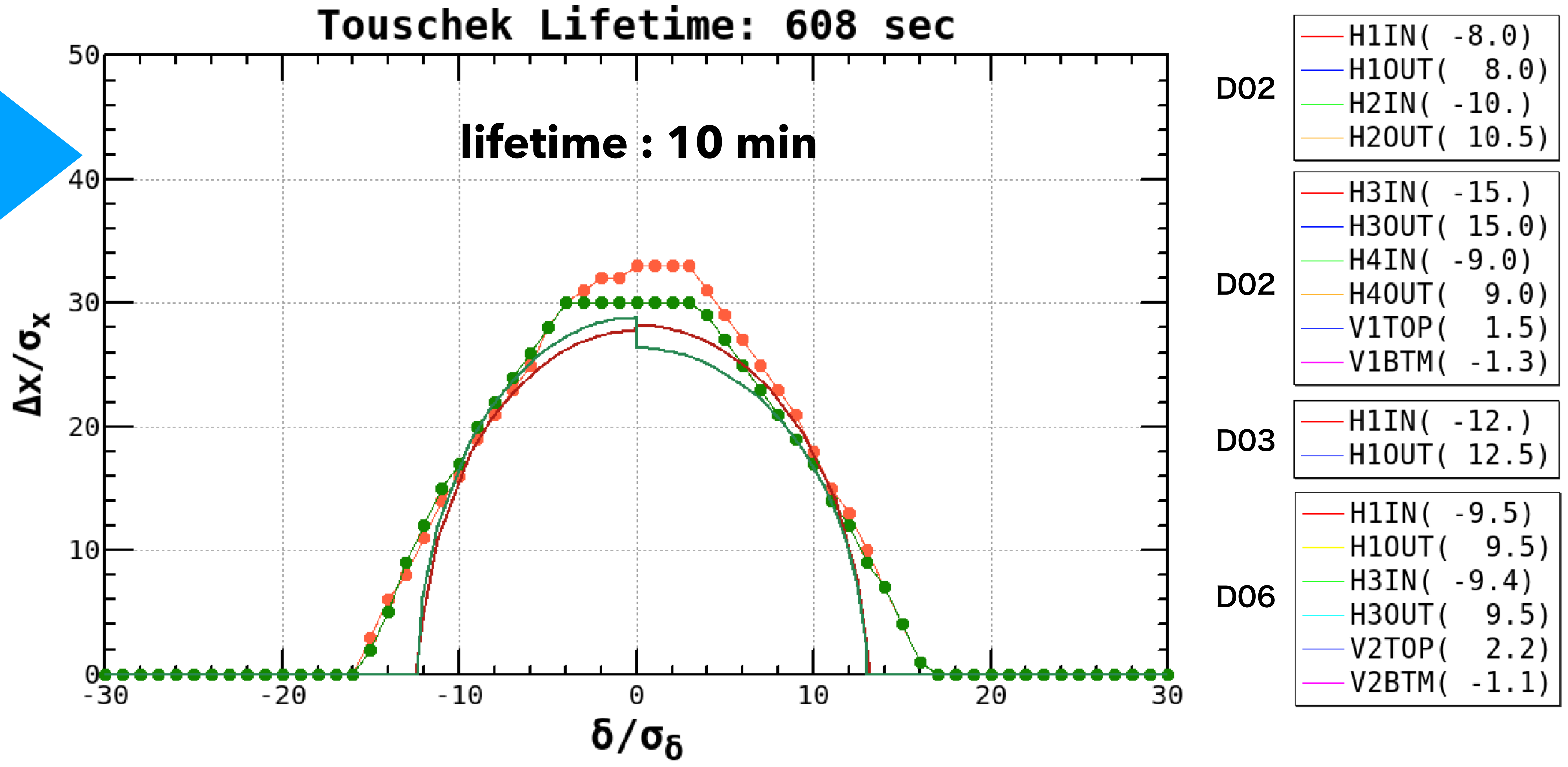
β_x^* = 80 mm / β_y^* = 1 mm
I_b = 0.51 mA/bunch
$\varepsilon_y/\varepsilon_x$ = 0.6 %

400 mA / 783 bunches

QCS aperture only w/o collimators



QCS aperture with collimators

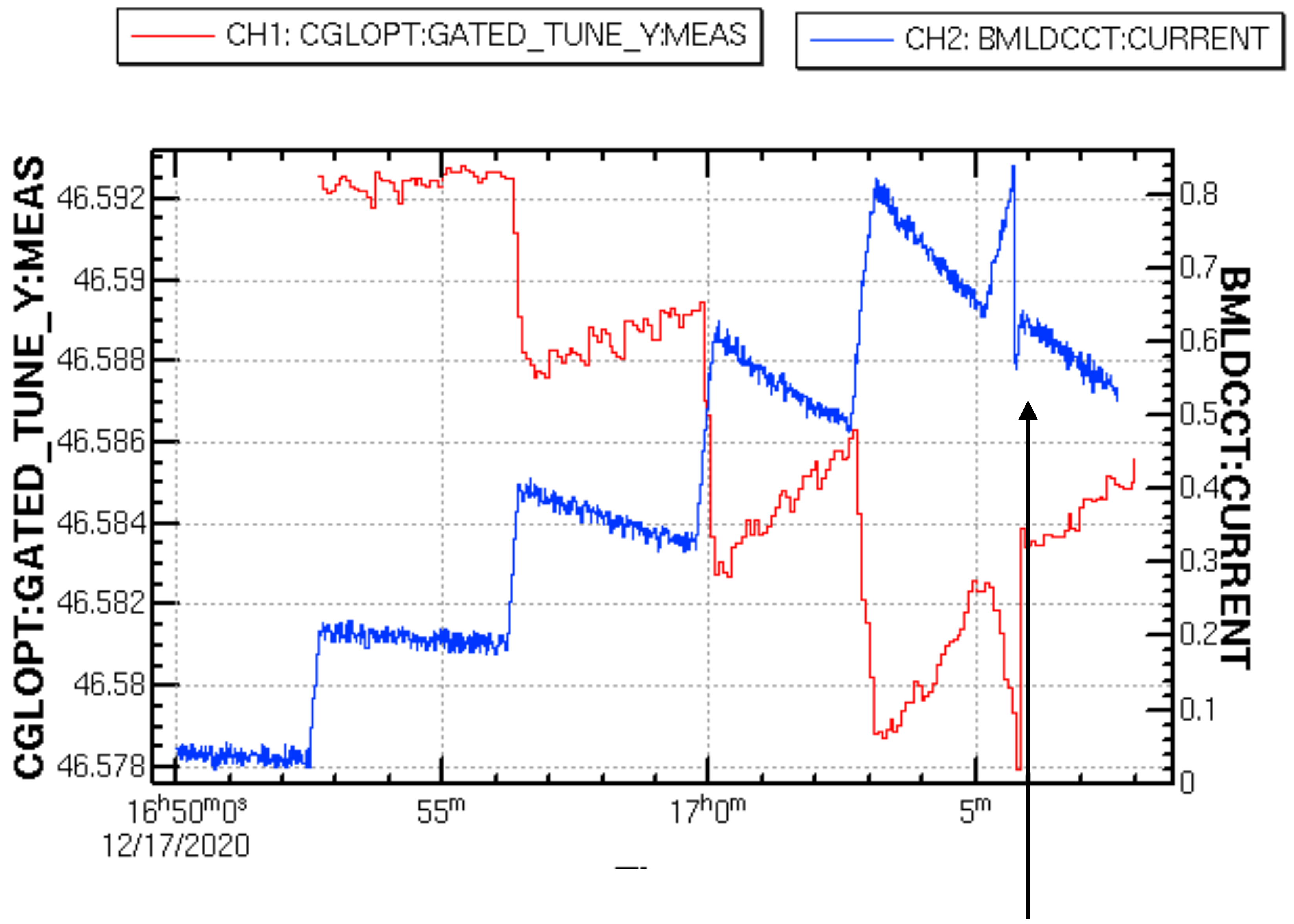


The simulation result is consistent with the measurement (total ~6 min).

- Touschek lifetime in the LER for β_y^* = 1 mm(0.5 mA, 0.6 % coupling) is about 30 min for QCS aperture only. The design lifetime is estimated under this condition (w/o collimators) !!!
- Horizontal collimators determine the dynamic aperture in the LER.
  - Collimators in the dispersive region restricts momentum acceptance
- Even though the horizontal collimators are full open (26 mm), the vertical collimators(~1.5 mm) also reduce the dynamic aperture. Touschek lifetime is 10 min at most which is consistent with the measurement.
- The collimator apertures are optimized to reduce BG with keeping lifetime as much as longer.

Single Bunch Tune Shift and TMCI in LER (2020c)

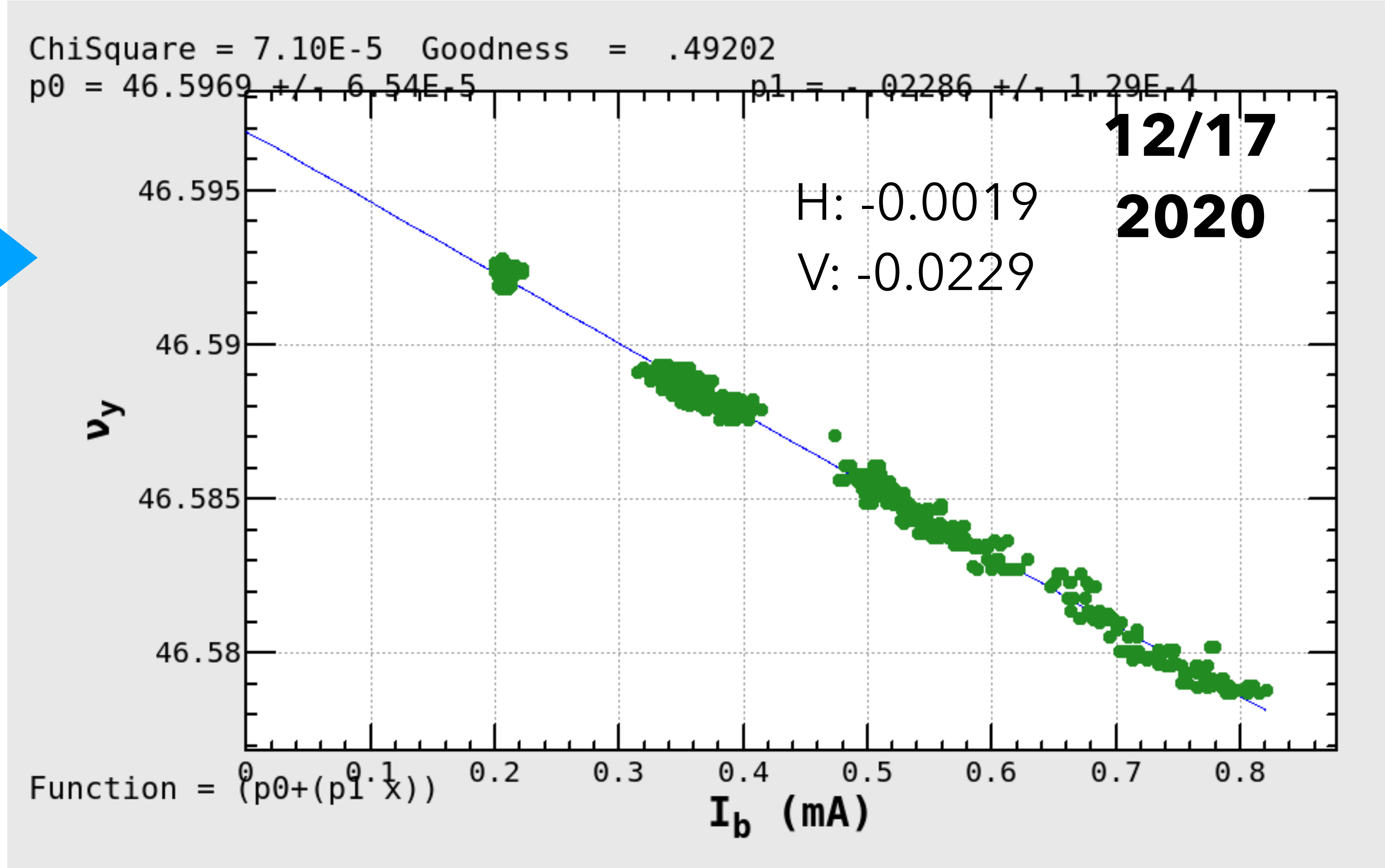
vert. tune



single bunch current

Tune shift is same as synchrotron tune

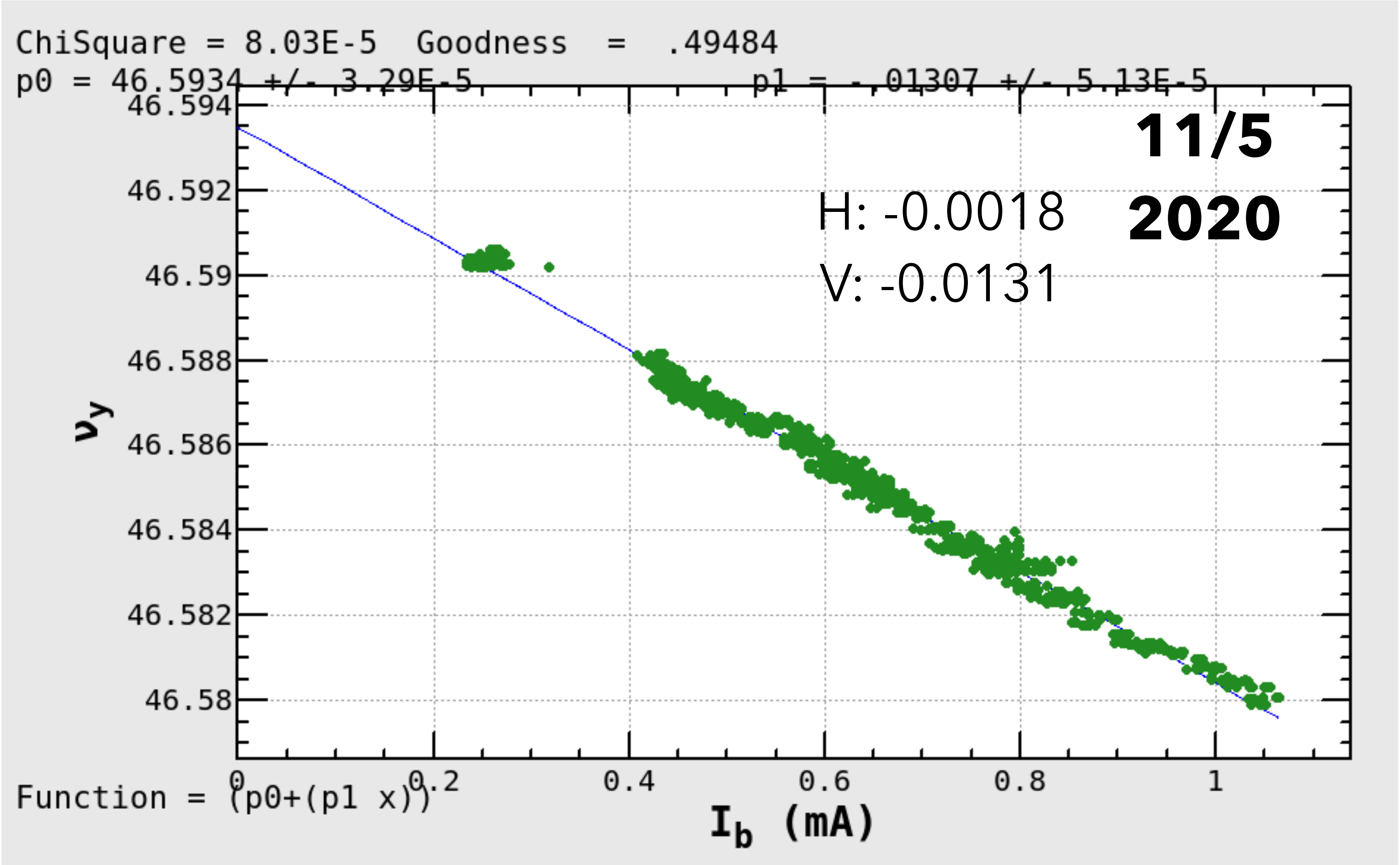
$$\nu_s = -0.0235$$



Beam current can not be stored larger than 0.8 mA/bunch.

2020	11/5	12/17
D02V1 (mm)	1.52 / 1.2 (1.36)	1.68 / 1.2 (1.44)
D03V1 (mm)	2.0 / 1.98 (1.99)	0.68 / 1.38 (1.03)
D06V1 (mm)	3.2 / 3.2 (3.2)	2.7 / 1.2 (1.95)
D06V2 (mm)	2.2 / 1.9 (2.05)	2.28 / 1.85 (2.07)

← carbon head



TMCI

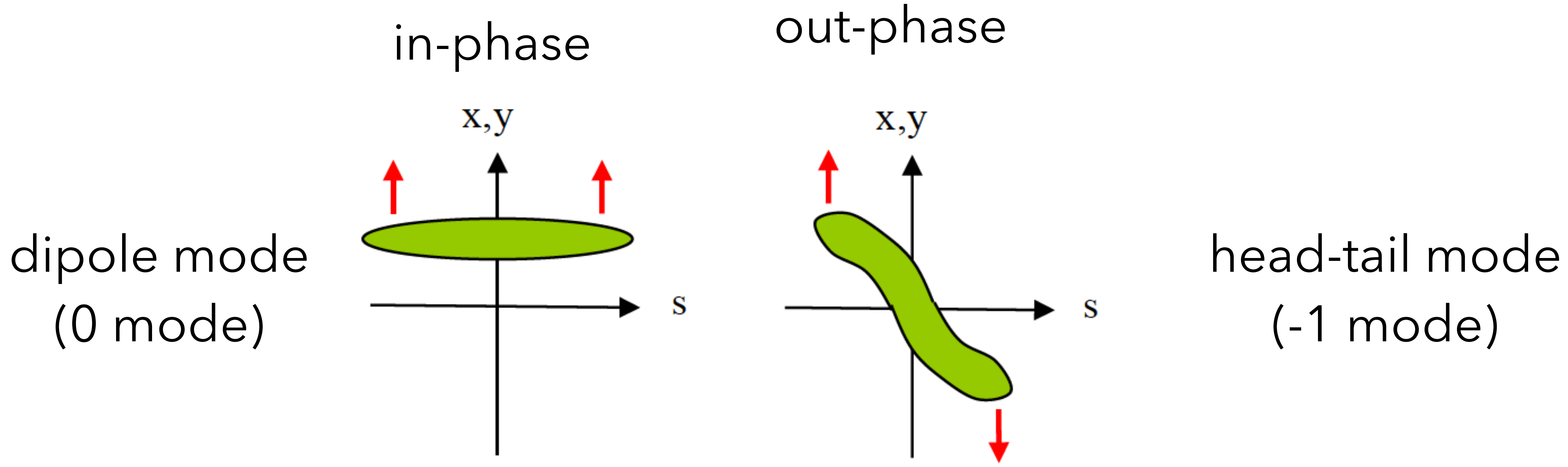


Figure 1: Snapshots of beam oscillations when the head and the tail of a bunch oscillate in phase (left) and out of phase (right).

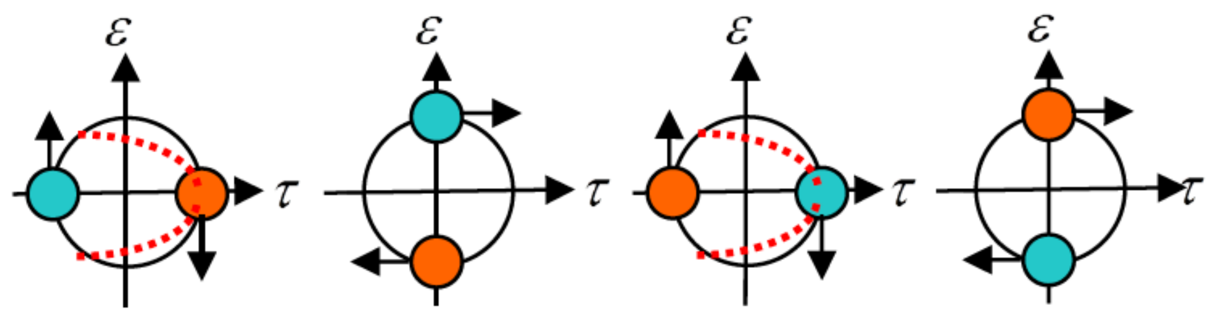


Figure 2: Position of the two particles in the synchrotron phase space and wake fields at every quarter of the synchrotron oscillation. The wake fields are denoted by the red dashed lines.

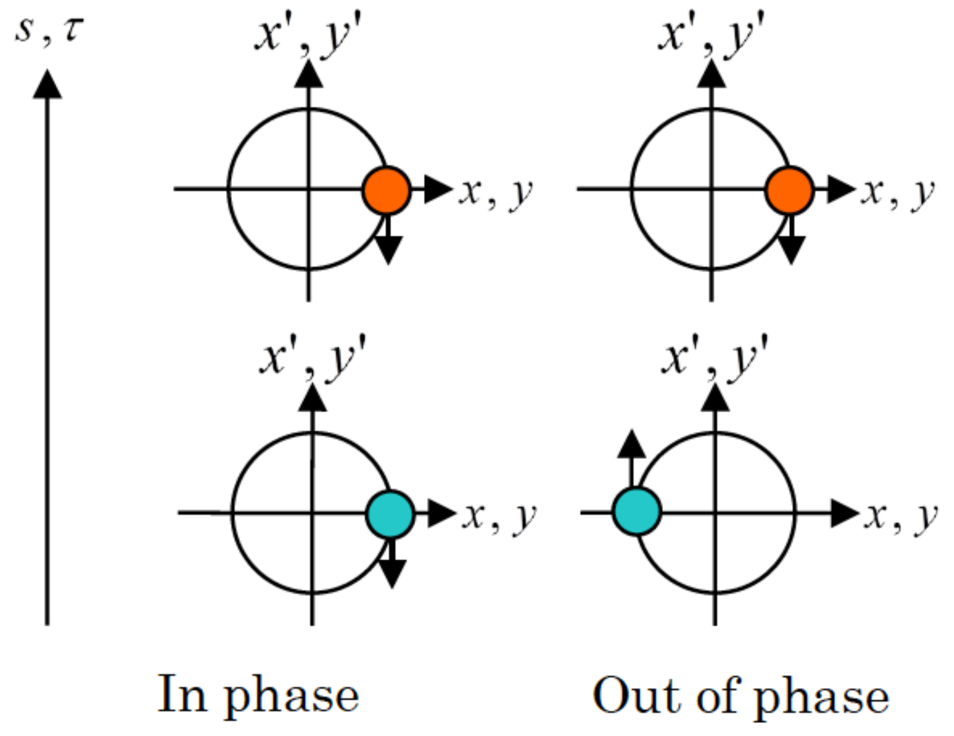
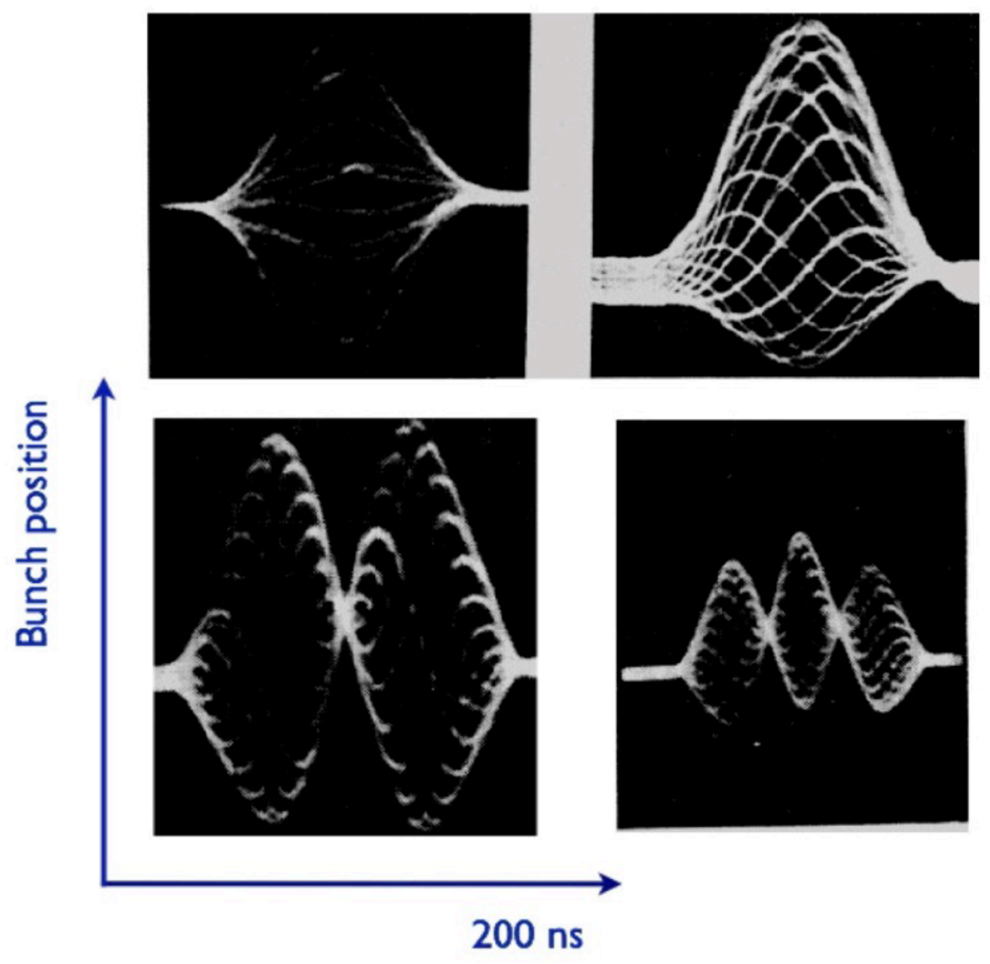
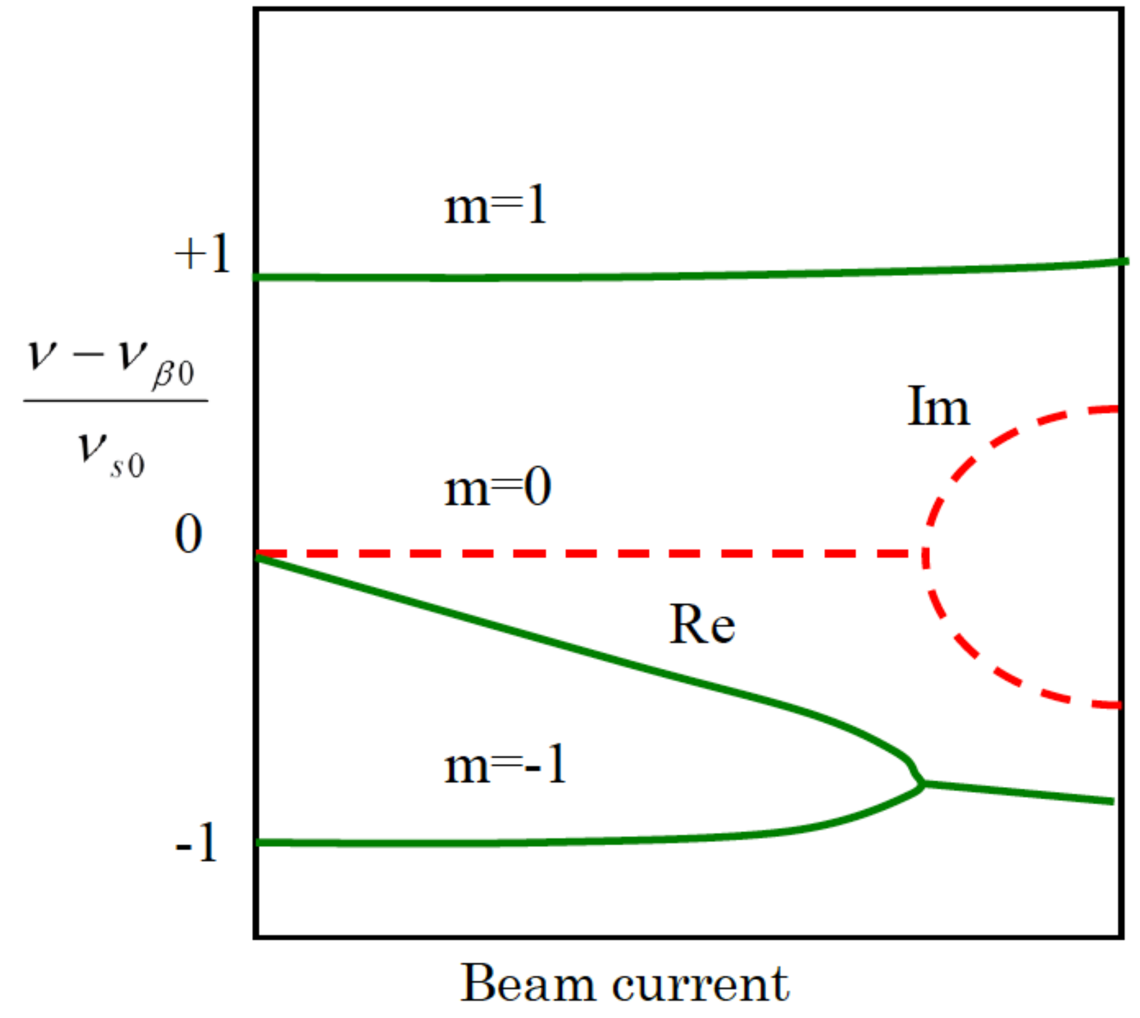


Figure 3: Two modes in which the head and the tail of the bunch oscillate in phase (left) and out of phase (right).





Y. H. Chin, ICFA69

Figure 9: Typical behavior of coherent tune shifts as a function of the beam current. The real and the imaginary parts of the tune shifts are denoted by the solid and dashed lines. When the two tune shifts merge, the imaginary part of the tune shift (the growth rate) starts to increase rapidly.

- Transverse single bunch instability
  - Head-tail instability related to chromaticity
  - Strong (Fast) head-tail instability=Transverse Mode Coupling Instability

  - BBU as seen in Linac > stabilization due to the synchrotron motion

- A. Chao, M. Tigner, p121

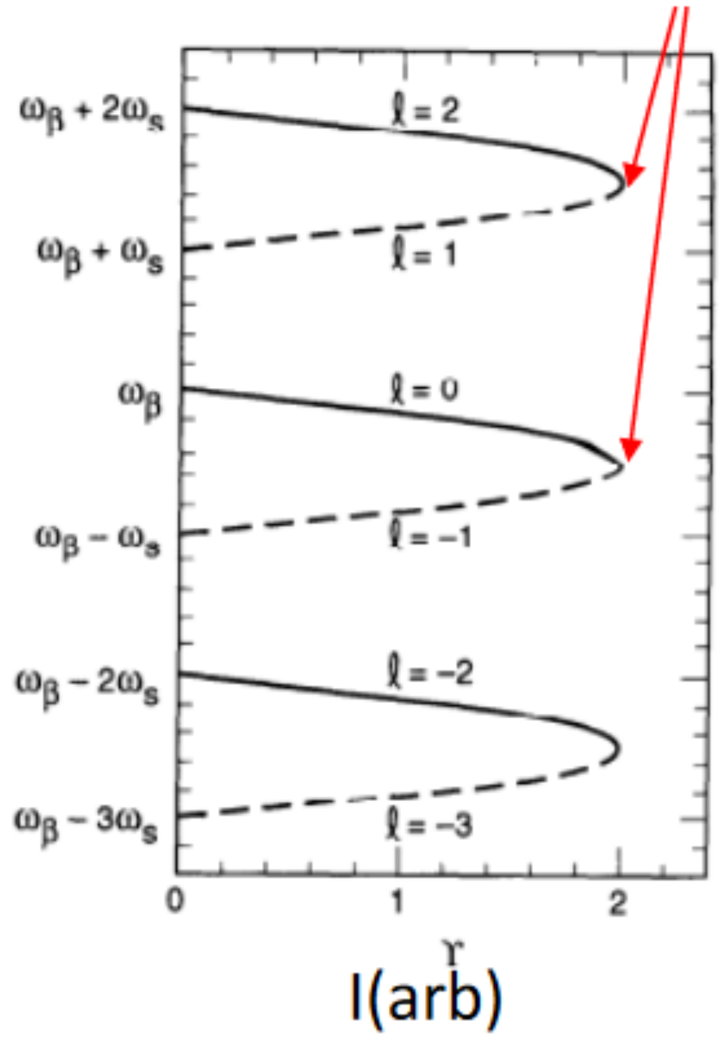
$$I_{th} = \frac{2\pi\nu_s E/e}{\sum_i \beta_i Z_{\perp i}} F(\sigma_z) \qquad F(\sigma_z) \approx 1 \text{ for short bunches}$$

$$I_{th} = \frac{C_1 f_s E/e}{\sum_i \beta_i \kappa_{\perp i}(\sigma_z)} \qquad C_1 = 8 \text{ or } 2\pi$$

$$\kappa_\perp(\sigma_z) = -\frac{i}{2\pi}\int_{-\infty}^{\infty} d\omega Z_\perp(\omega) e^{-\omega^2\sigma_z^2} \qquad \Delta\nu_\beta = \frac{Ne^2}{E}\frac{\sum_i \beta_i \kappa_{\perp i}(\sigma_z)}{4\pi}$$

Two particle model using constant wake (Chao's text)

Unstable at this current



Experiment at SLAC (Chao's text)

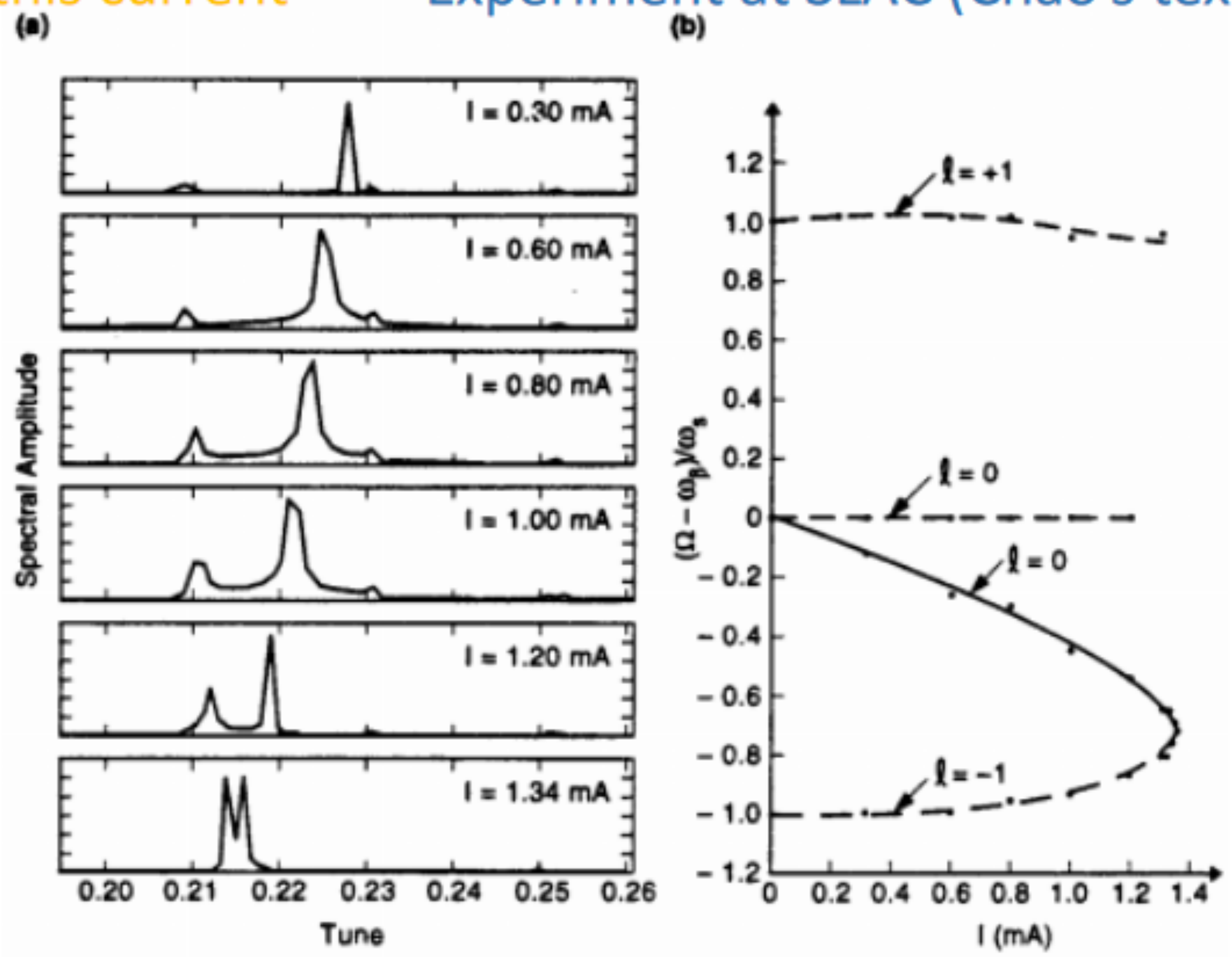
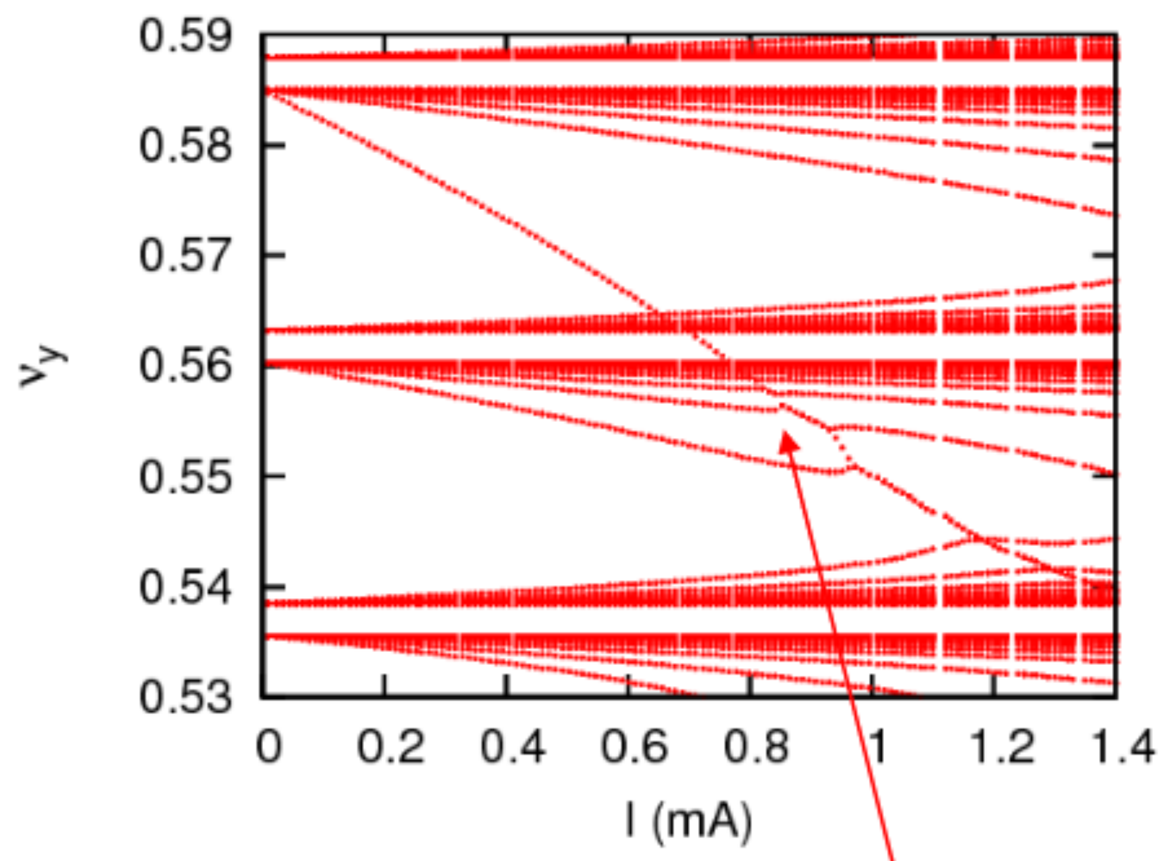
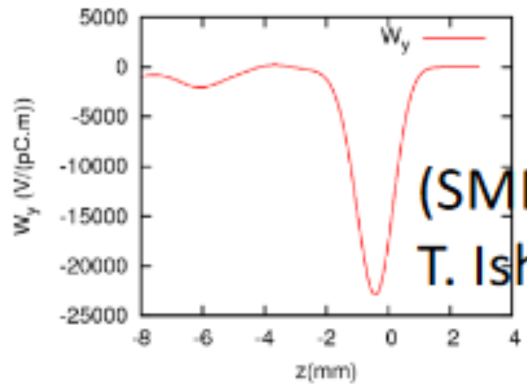


Figure 4.16. Simulation of the strong head-tail instability for the PEP storage ring. (a) Spectrum of the beam center of charge showing the collective modes for several beam intensities. (b) Mode frequencies $(\Omega - \omega_\beta)/\omega_s$ versus the average beam current $I = Ne/T_0$. (Courtesy Steve Myers, 1992.)

SuperKEKB using a collimator impedance model



Unstable at this current

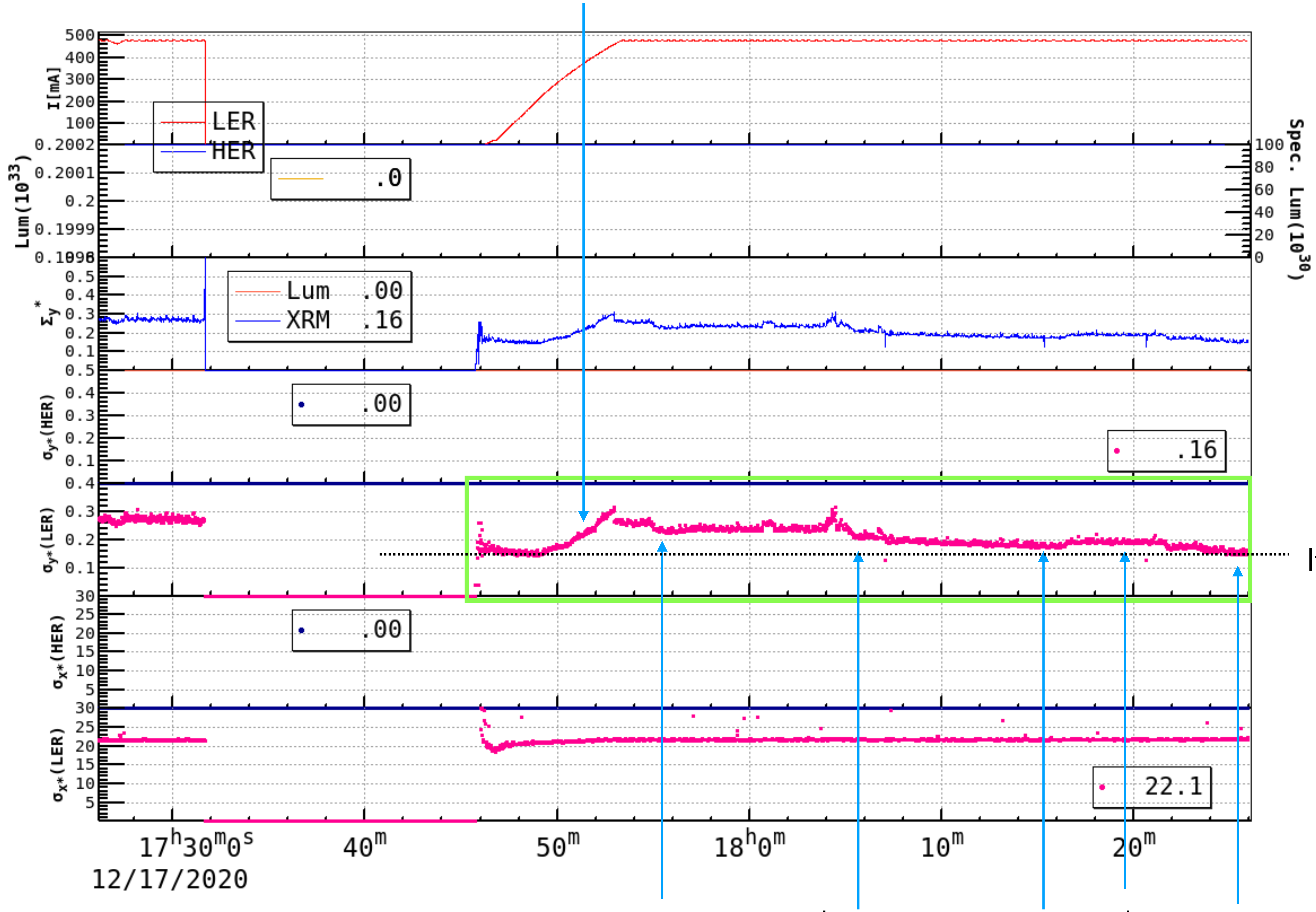


(SMM_V2_Wz_Wx_40.dat, T. Ishibashi,2016)

TMCI has been observed at many accelerators since 1967. (VEPP-2, ADONE, ...) LEP, PEP, ESRF, SOLEIL, NSLS-II propose various technologies to overcome TMCI.

Impedance Budget and Collimator Aperture in LER

Beam size becomes large as increasing beam current at the single beam in the LER



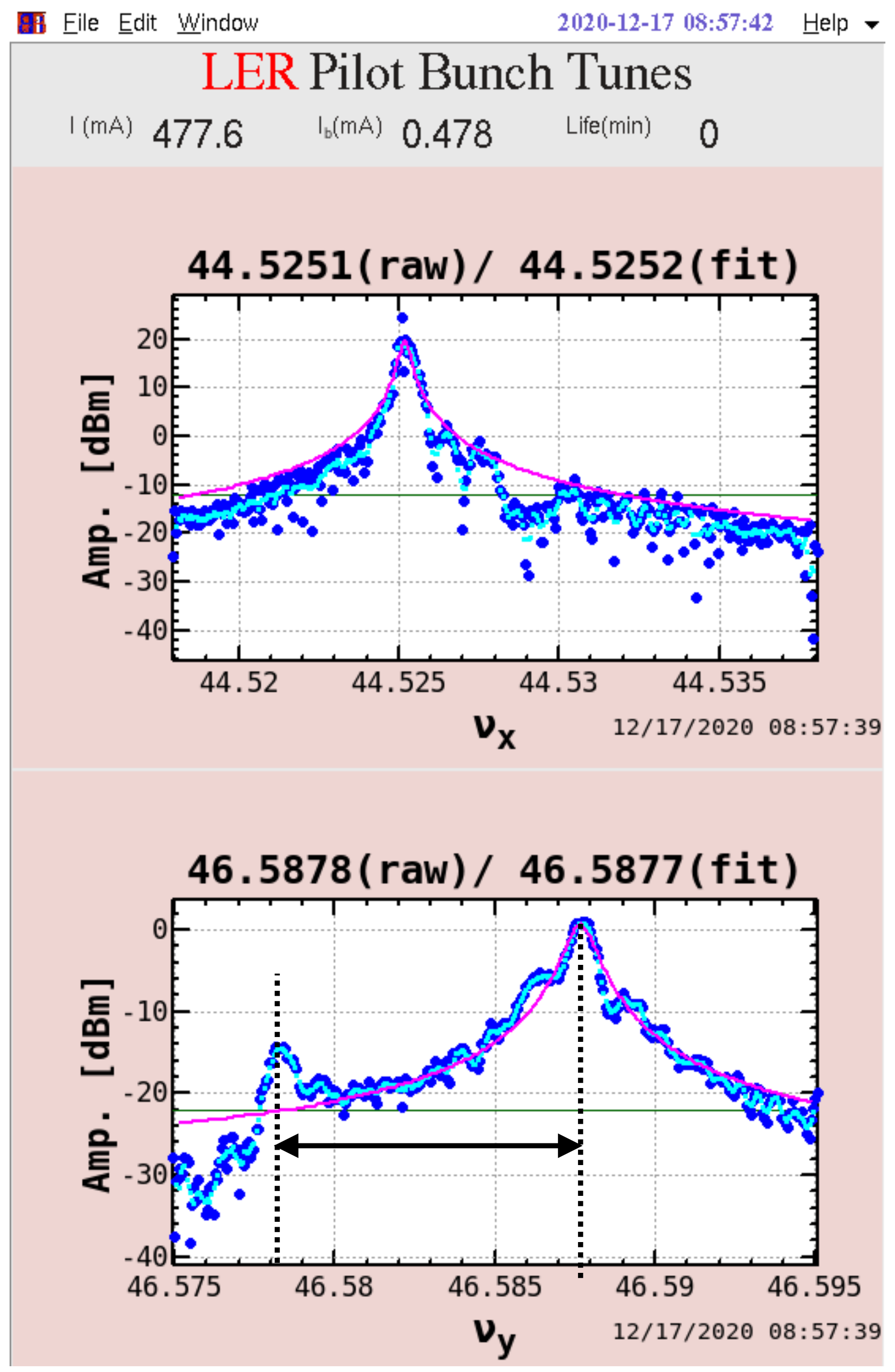
BxB FB gain adjusted

change tune

open D03V1

close D03V1

open D06V1



dipole motion
+ head-tail motion

If D06V1 is opened, the beam size is back.
(Background increases.)

The impedance effect: D06V1 > D03V1

D03V1 : *Tl* head
D06V1 : carbon head

Summary

- The peak luminosity of **2.4 x 10^{34} $cm^{-2}s^{-1}$** with Belle II data acquisition is the world record.
- The vertical beta at the IP, **0.8 mm** is the smallest value in the world. Beam size at the IP is also smallest.
- SuperKEKB applies a really large Piwinski angle, O(10). The crab waist has been adopted in the both rings together with the nano-beam scheme.
- The **crab waist scheme** seems to work successfully. Especially, it is effective at higher bunch current.
- The rotatable sextupoles have been utilized to correct chromatic X-Y couplings in the LER. The effort will be continued to the following operation. This may help to reduce beam-beam blowup.
- RF system works well and provides stable operation; LER max. current is 770 mA and 660 mA in HER in 2020ab.
- Collimators in the LER: .We have to consider TMCI threshold. Pure carbon head (low-Z) is NG due to large impedance.
- Difficulties arises significantly such as extremely short beam lifetime, stability of operations, and so on. Sextupole and octuple tunings have to be performed to improve lifetime issue if the dynamic aperture affects it. The linac performance will be a key issue to overcome the short lifetime. Impedance issue is still open question.
- Beam background (TOP counter, PMT lifetime) and injector performance limit the beam currents so far. (H. Nakayama, #6 Wed., 20 January)
    - Beam background comes from stored (residual gas, Touschek) and injected beam. 50 % for LER beam-gas events
- The target for the next run is 4 x 10^{34} $cm^{-2}s^{-1}$ by increasing beam currents.