Highlights from SuperKEKB Commissioning for early stage of Nano-Beam Scheme and Crab Waist Scheme

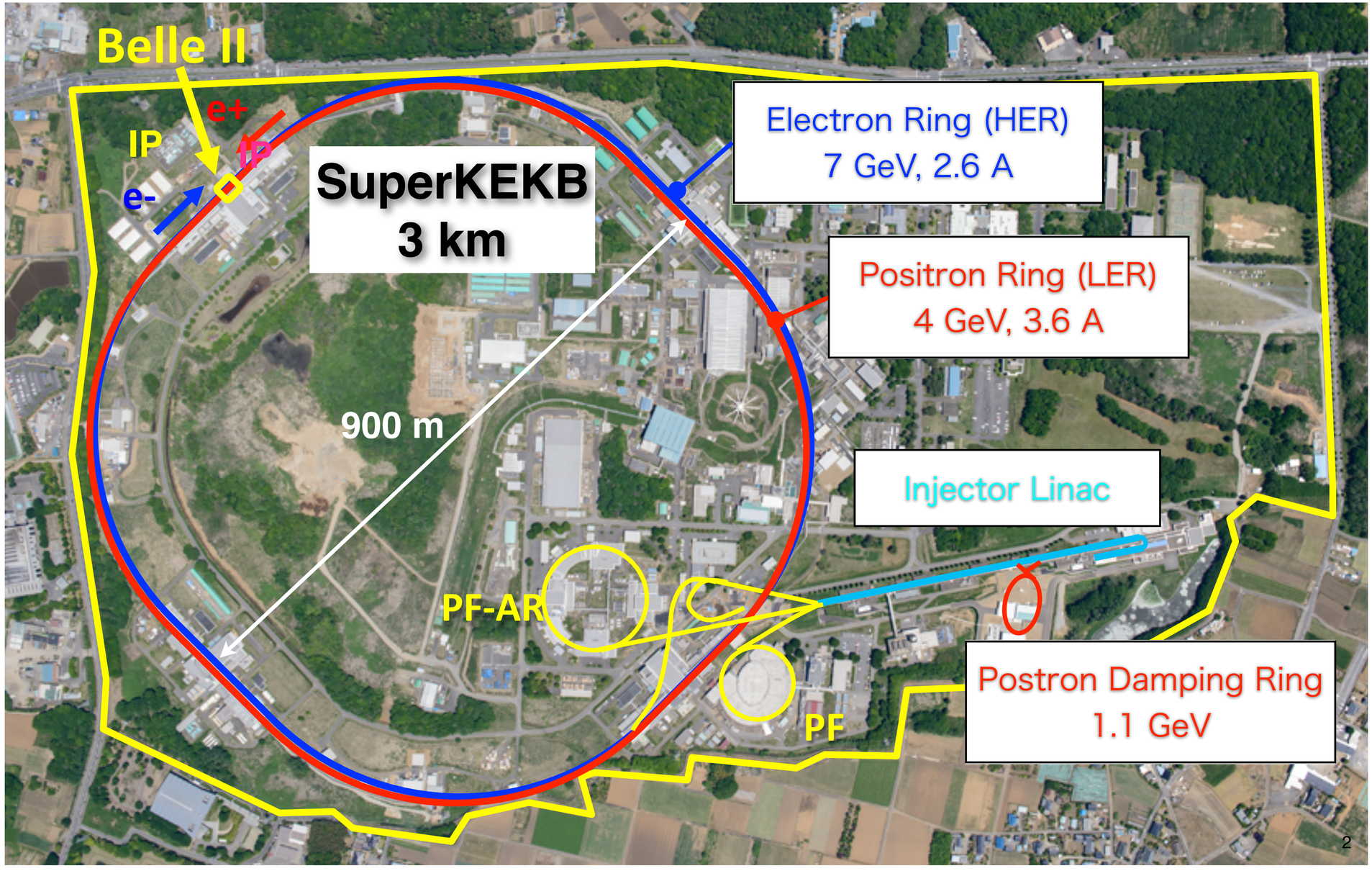
ICHEP 2020 | PRAGUE

Y. Ohnishi / KEK

On behalf of SuperKEKB Commissioning Group

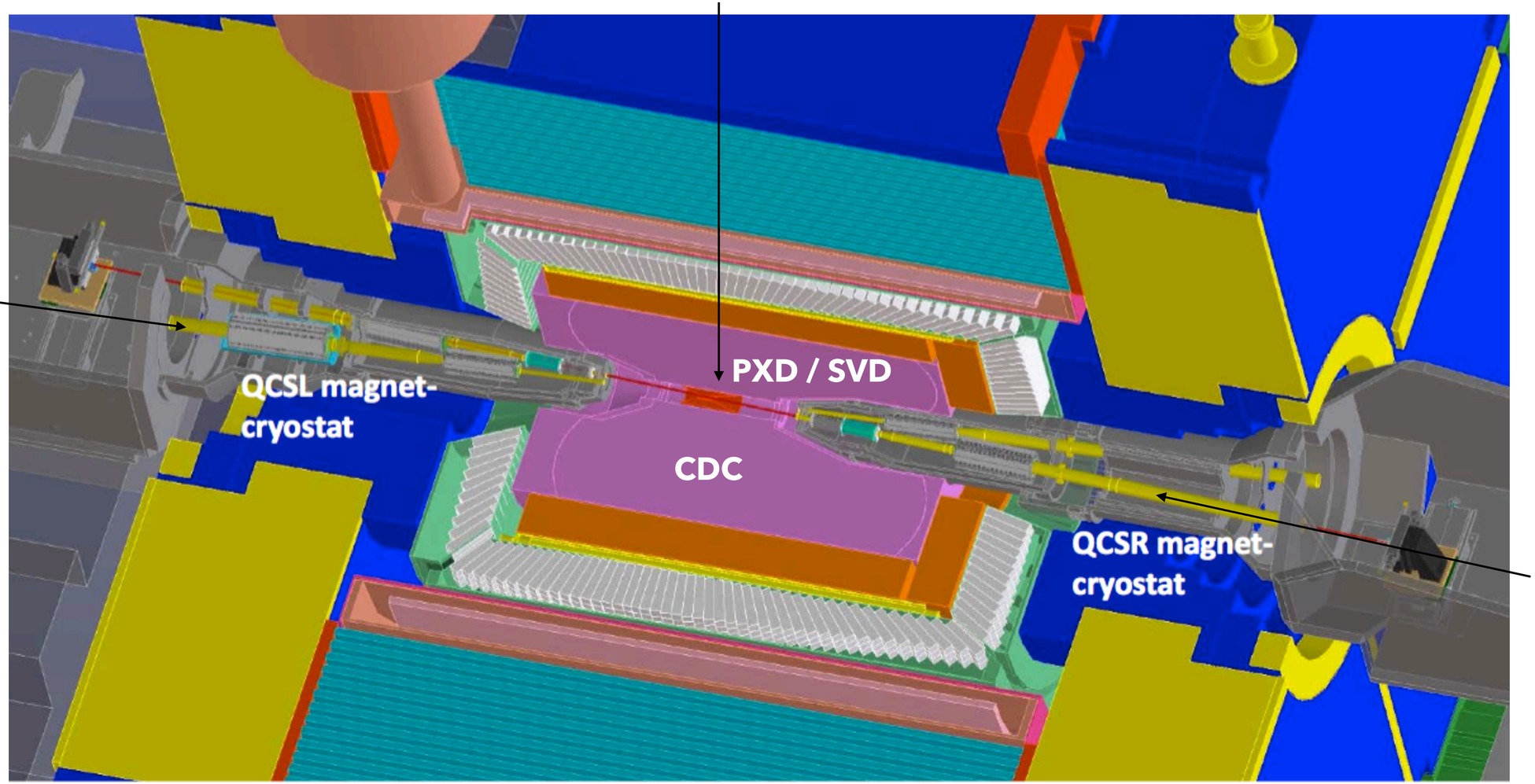
SuperKEKB at KEK, Japan

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



Final Focus and Belle II Detector

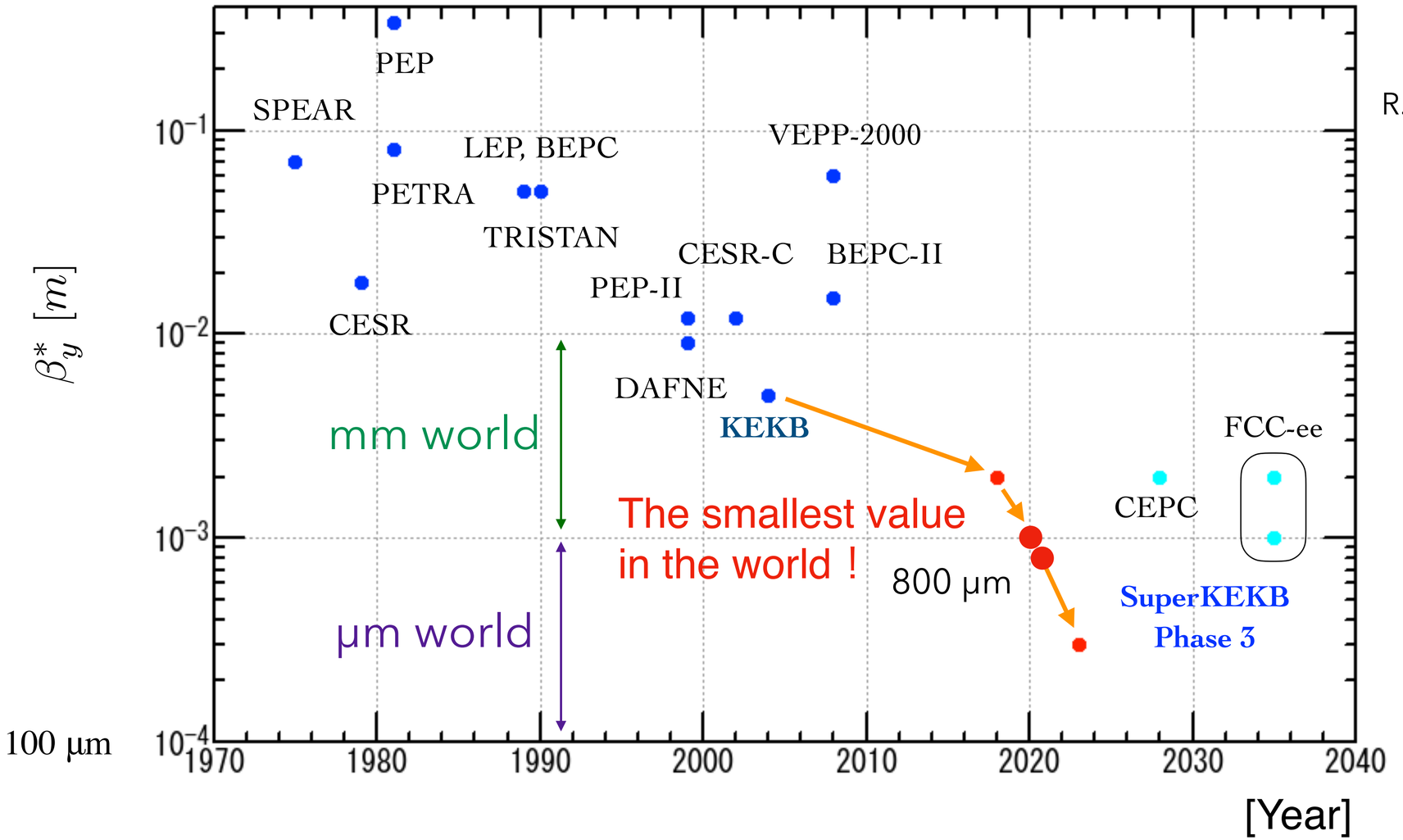
The horizontal crossing-angle is 83 mrad to realize the nano-beam scheme and separation of two beams.



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

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

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.

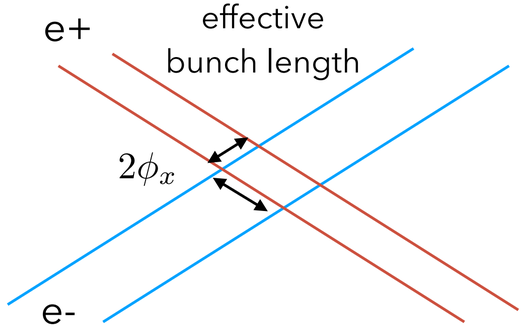
Nano-beam scheme Piwinski angle : $\Psi_\pm = 10 \sim 19 >> 1$

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)

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

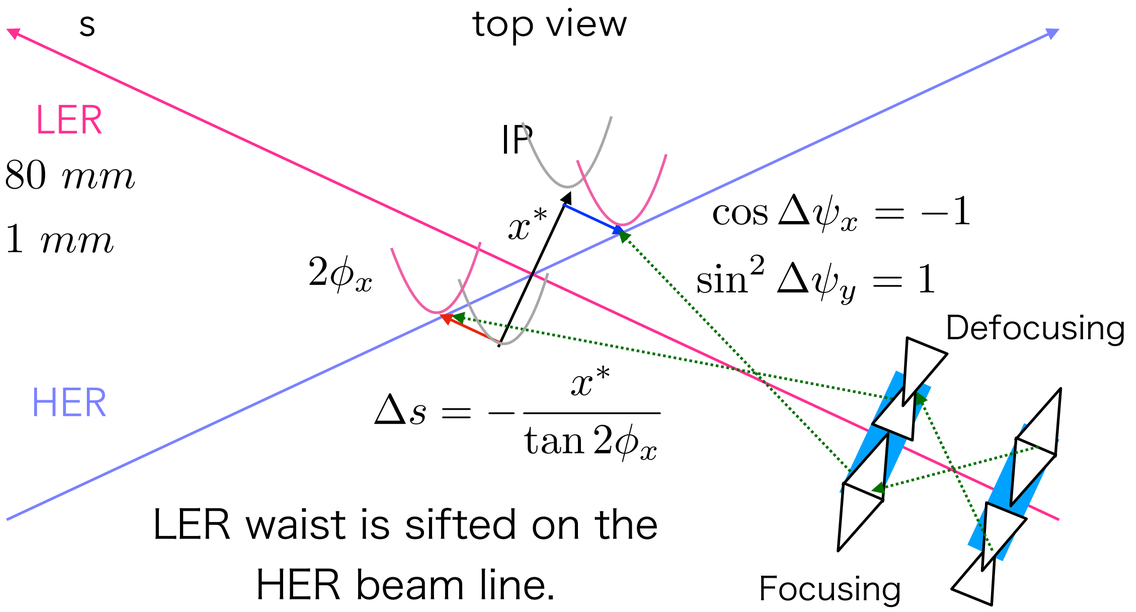
Crab Waist

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 :

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

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

IP to CW sextupole :

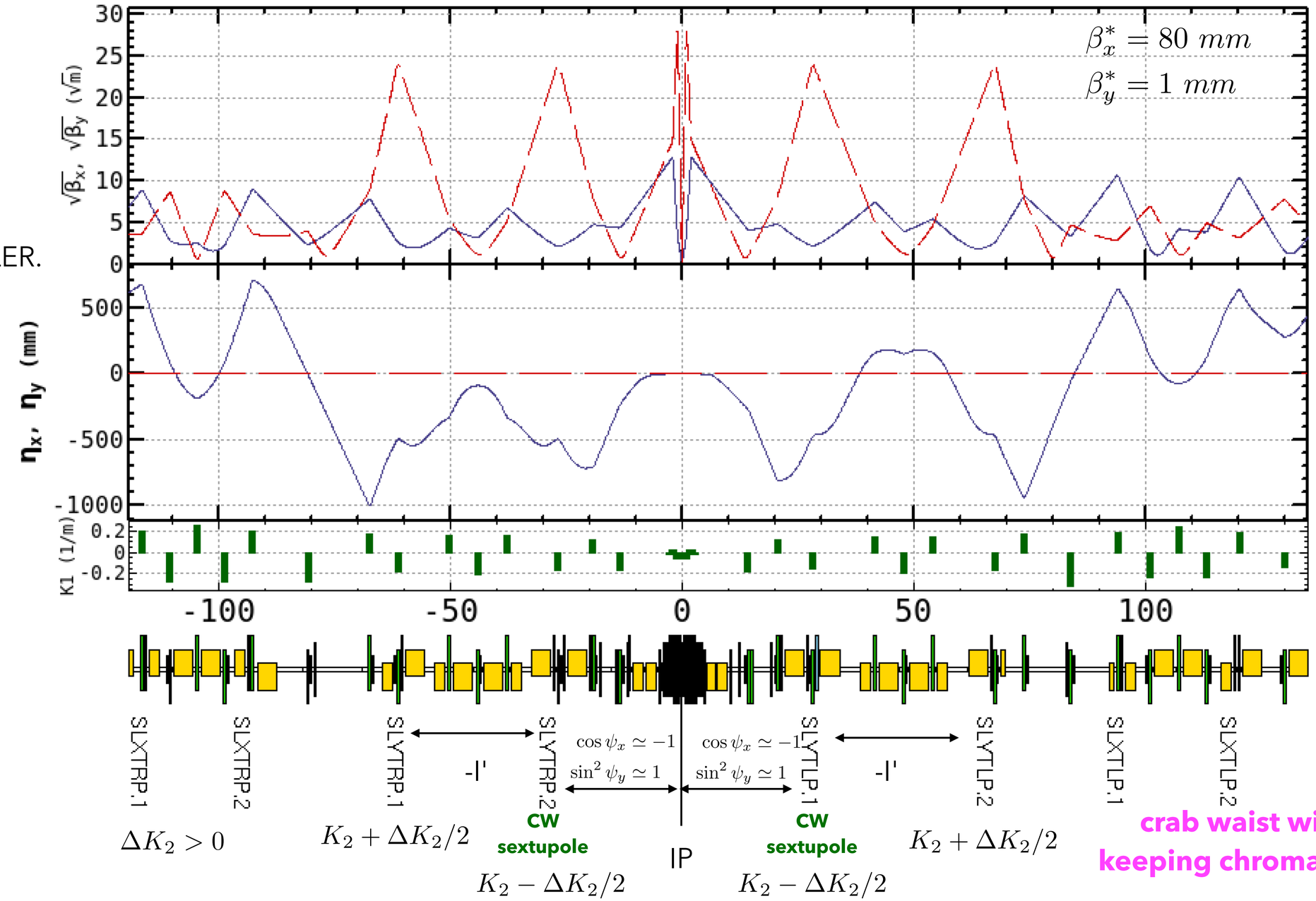
$$\begin{pmatrix} X, Y \\ P_{X,Y} \end{pmatrix} = \begin{pmatrix} \cos\Delta\psi_{x,y} & -\sin\Delta\psi_{x,y} \\ \sin\Delta\psi_{x,y} & \cos\Delta\psi_{x,y} \end{pmatrix} \begin{pmatrix} X^*, Y^* \\ P^*_{X,Y} \end{pmatrix}$$

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

Crab Waist Lattice in LER

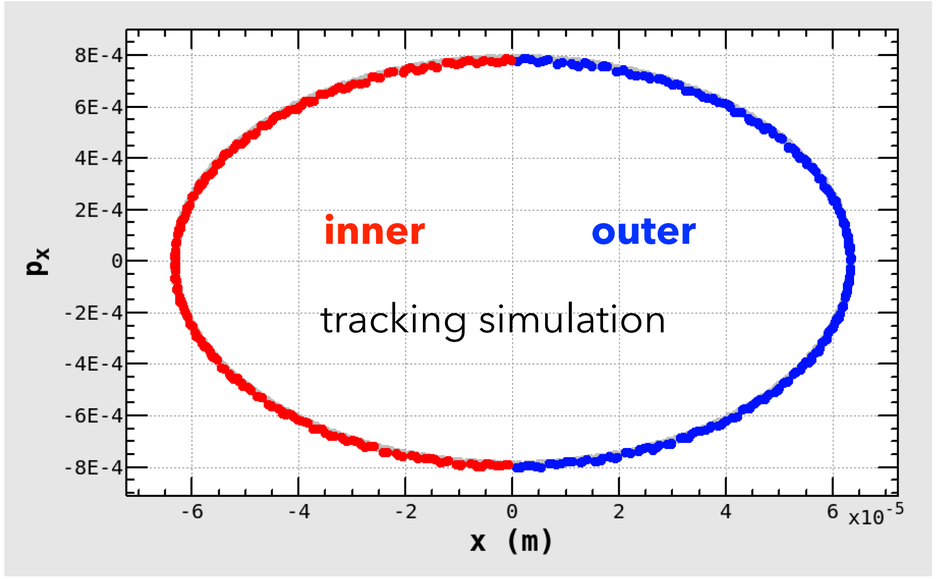
FCC-ee style
Crab Waist
(K. Oide)

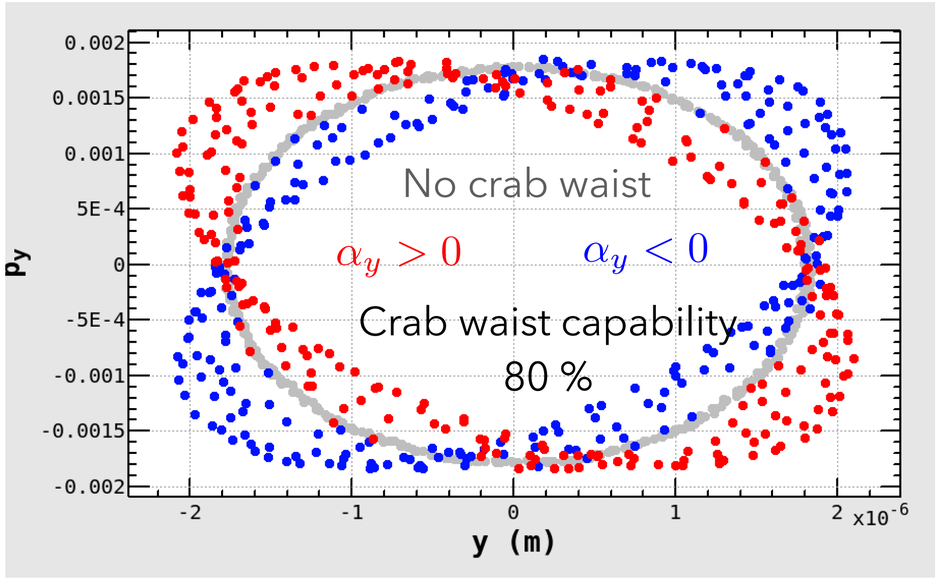
HER is similar to LER.

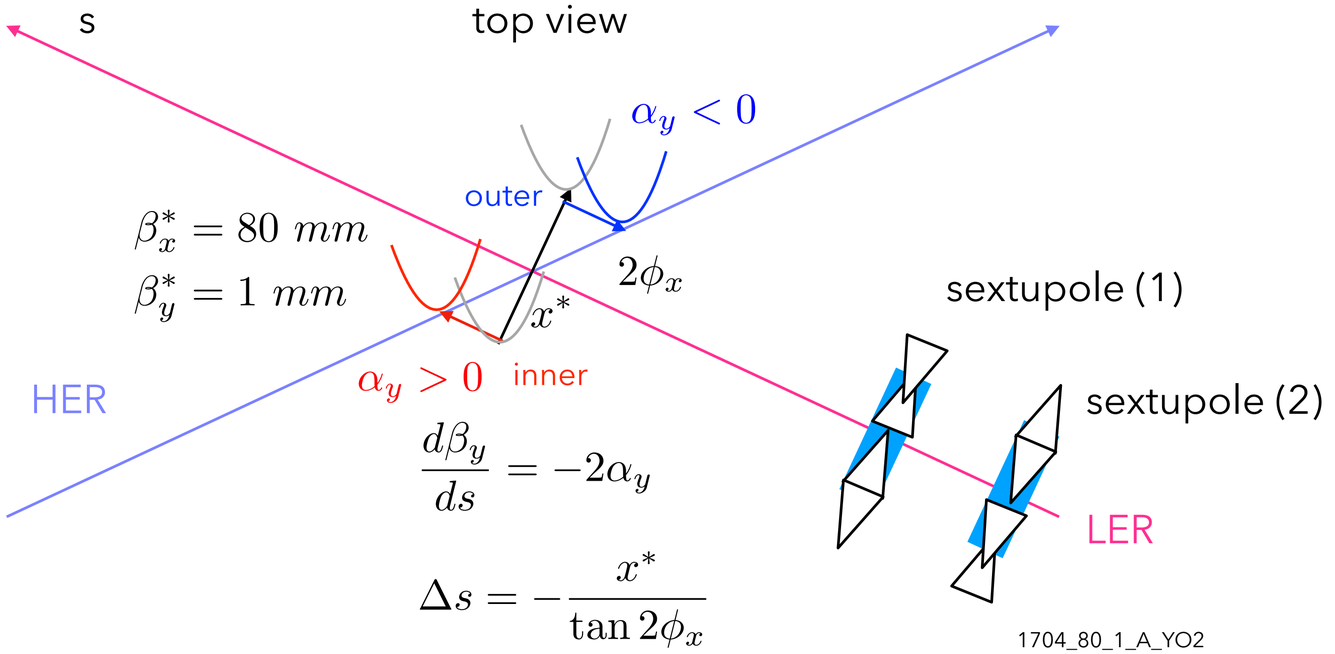


Phase Space at IP in LER

Interaction point (s = 0)



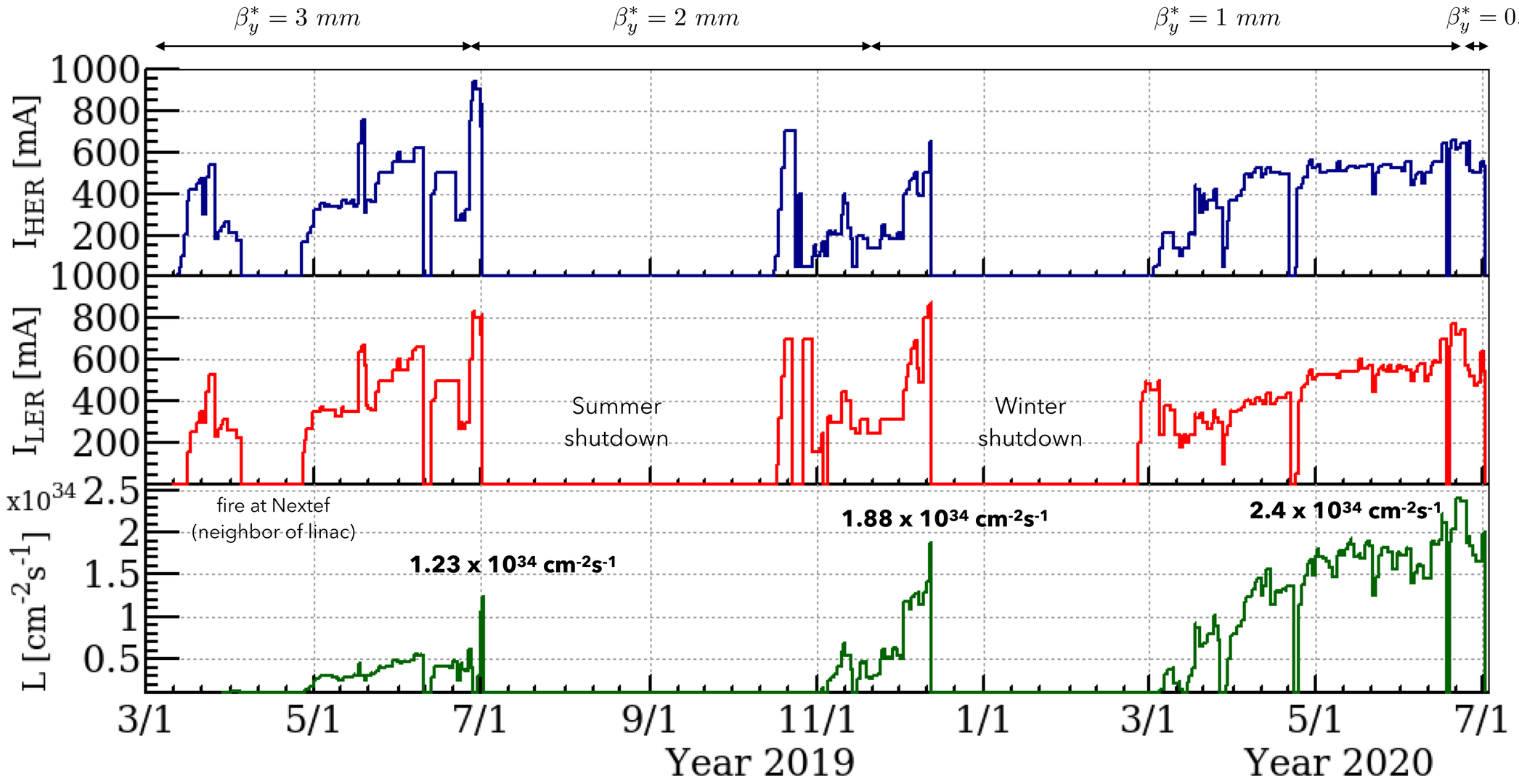




CW sextupole	L-side	R-side	Unit
$\beta_{x\ (sextupole)}$	5.66	5.52	m
$\beta_{y\ (sextupole)}$	525	521	m
$\cos\Delta\psi_x$	-0.992	-0.988	
$\sin^2\Delta\psi_y$	1.0	1.0	
$K_{2\ (SLYT\{LR\}1/2)}$	1.327 / 3.526	1.226 / 3.478	1/m^2

Crab waist capability 80 %

History of Phase 3



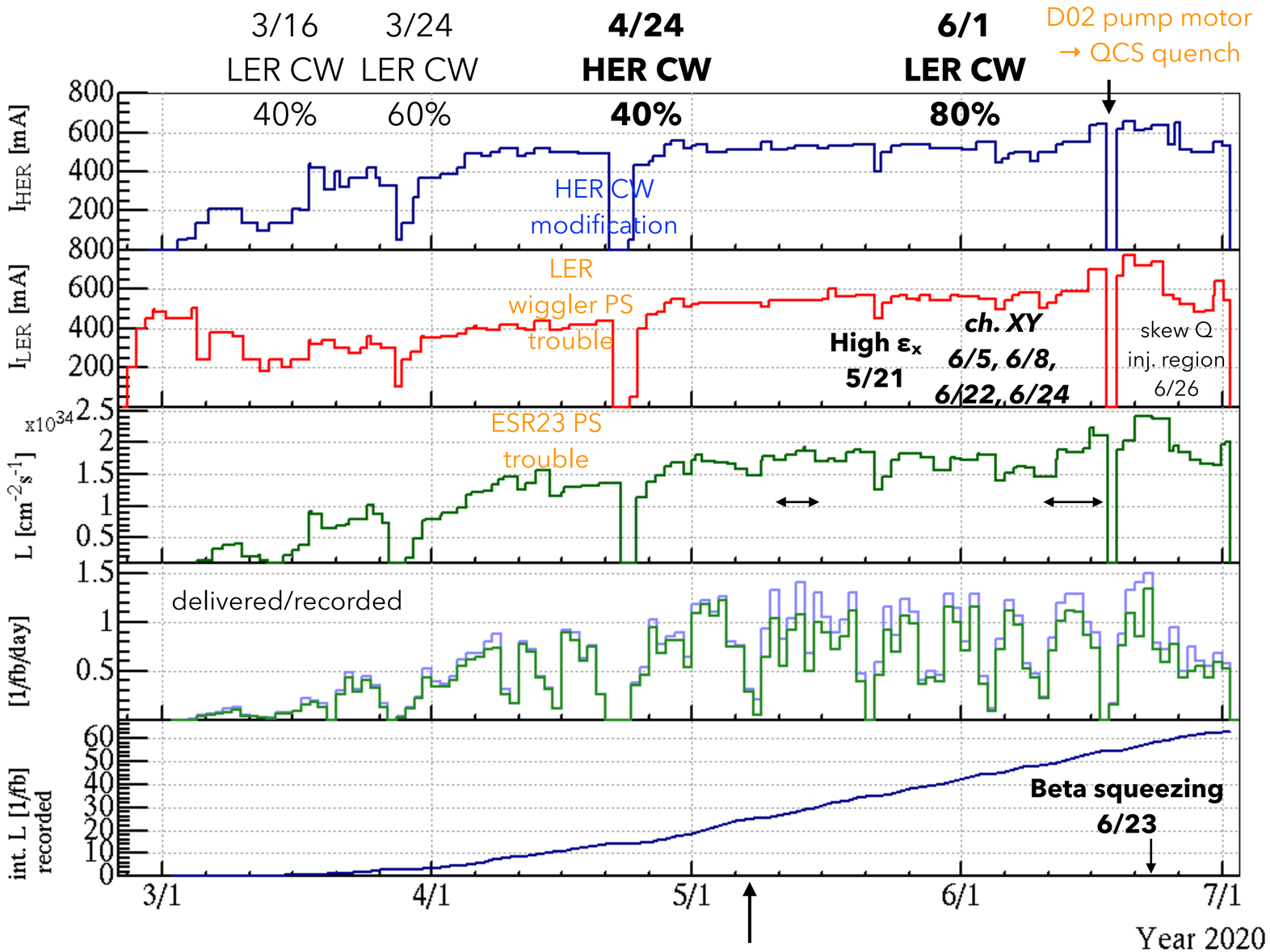
91 days

57 days

127 days

~ 9 months in total

Recent Operation Summary



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 :

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

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

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

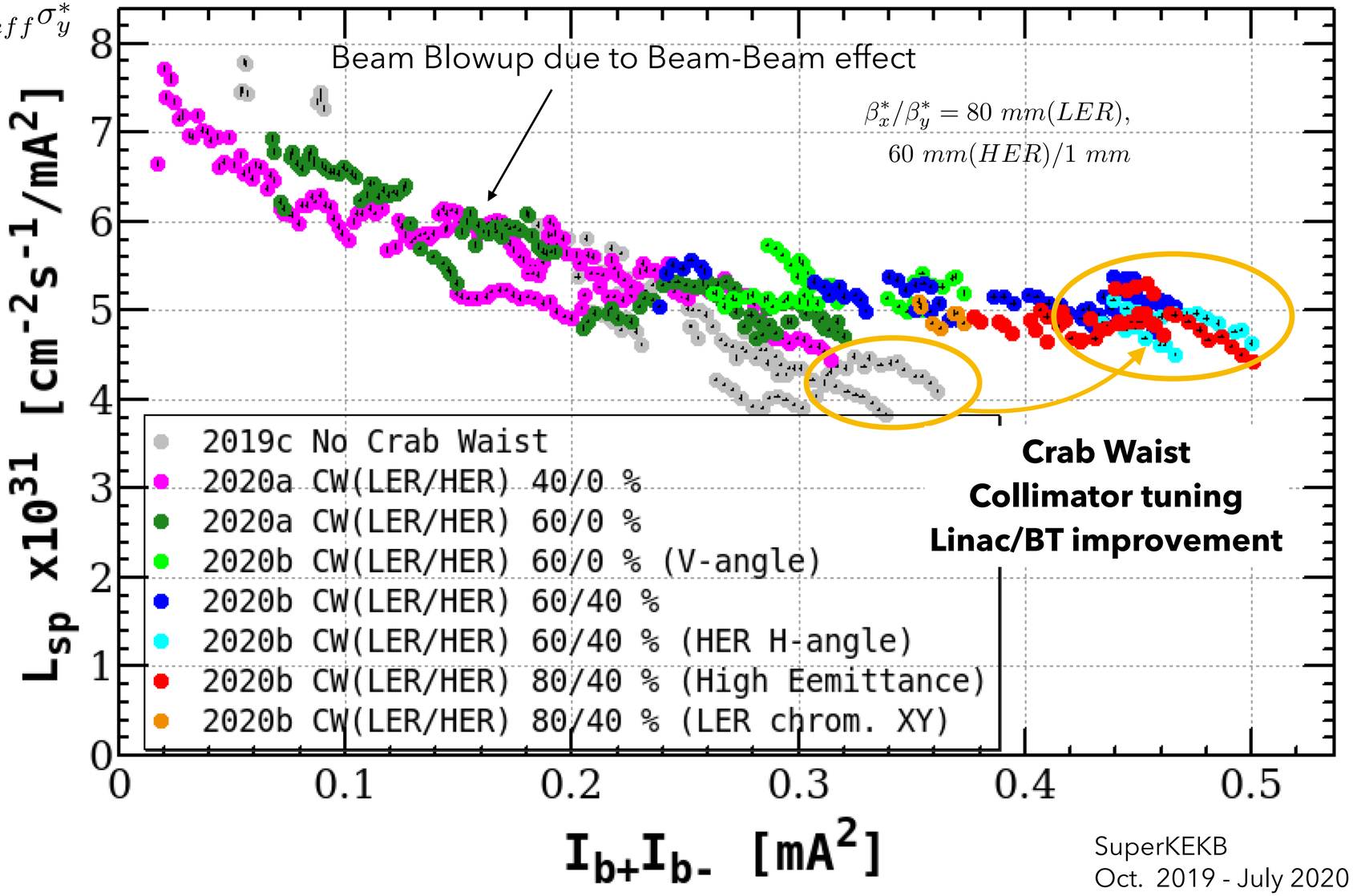
History from Phase 2 to Phase 3

	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

Specific Luminosity

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

$\beta^*_y = 1\ mm$

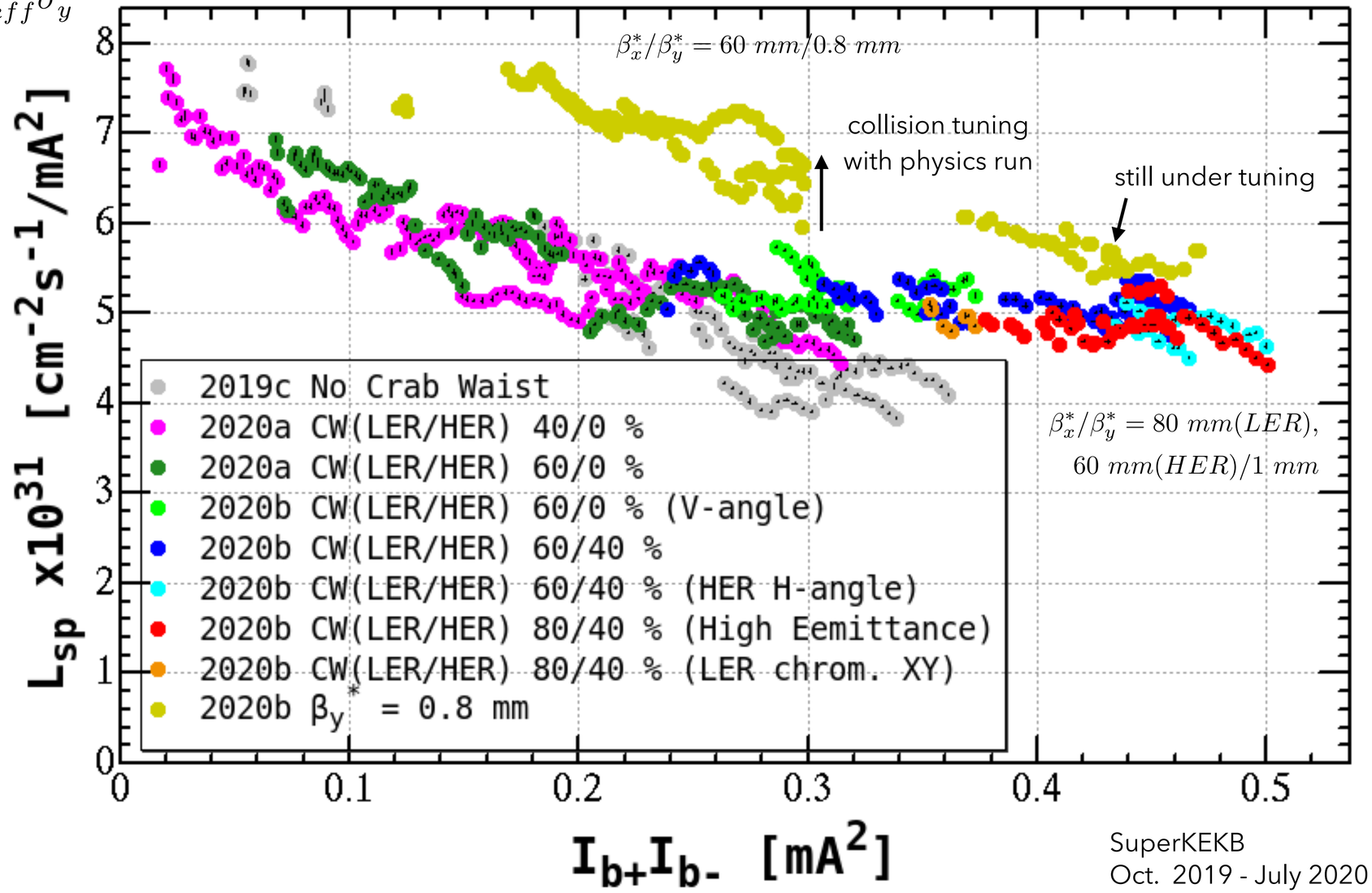


SuperKEKB
Oct. 2019 - July 2020

Specific Luminosity

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

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

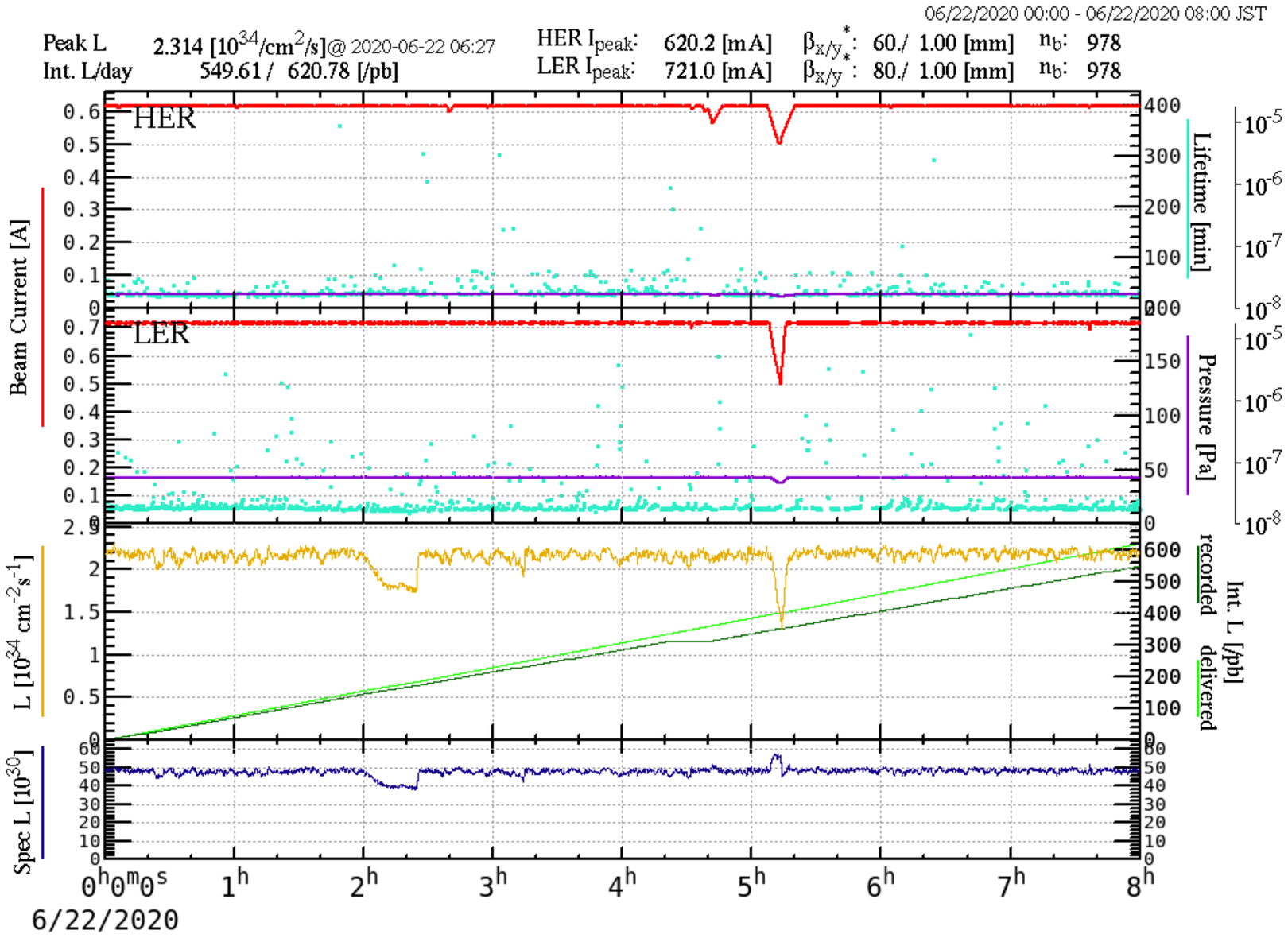


SuperKEKB
Oct. 2019 - July 2020

Best Shift

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

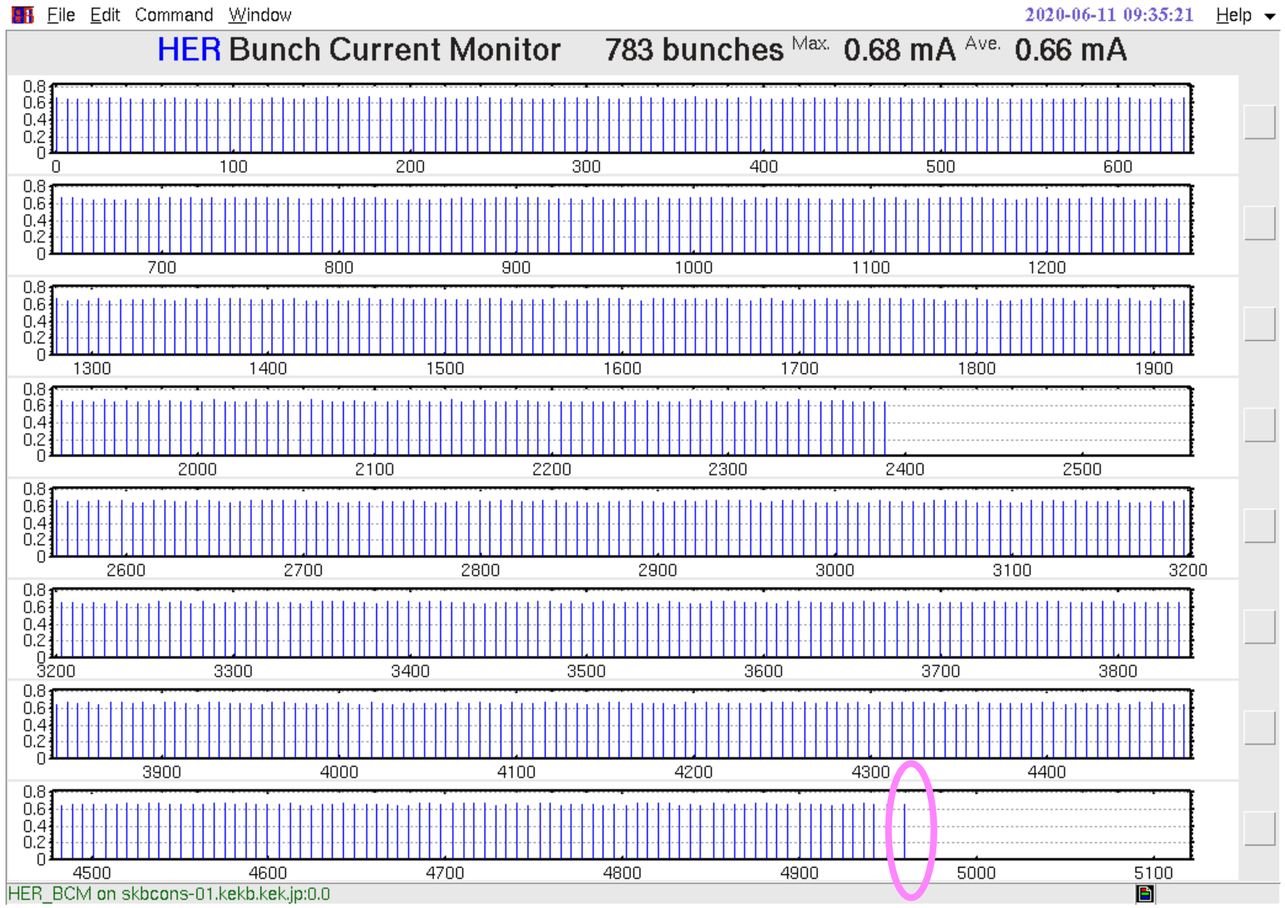
shifter : M. Nishiwaki

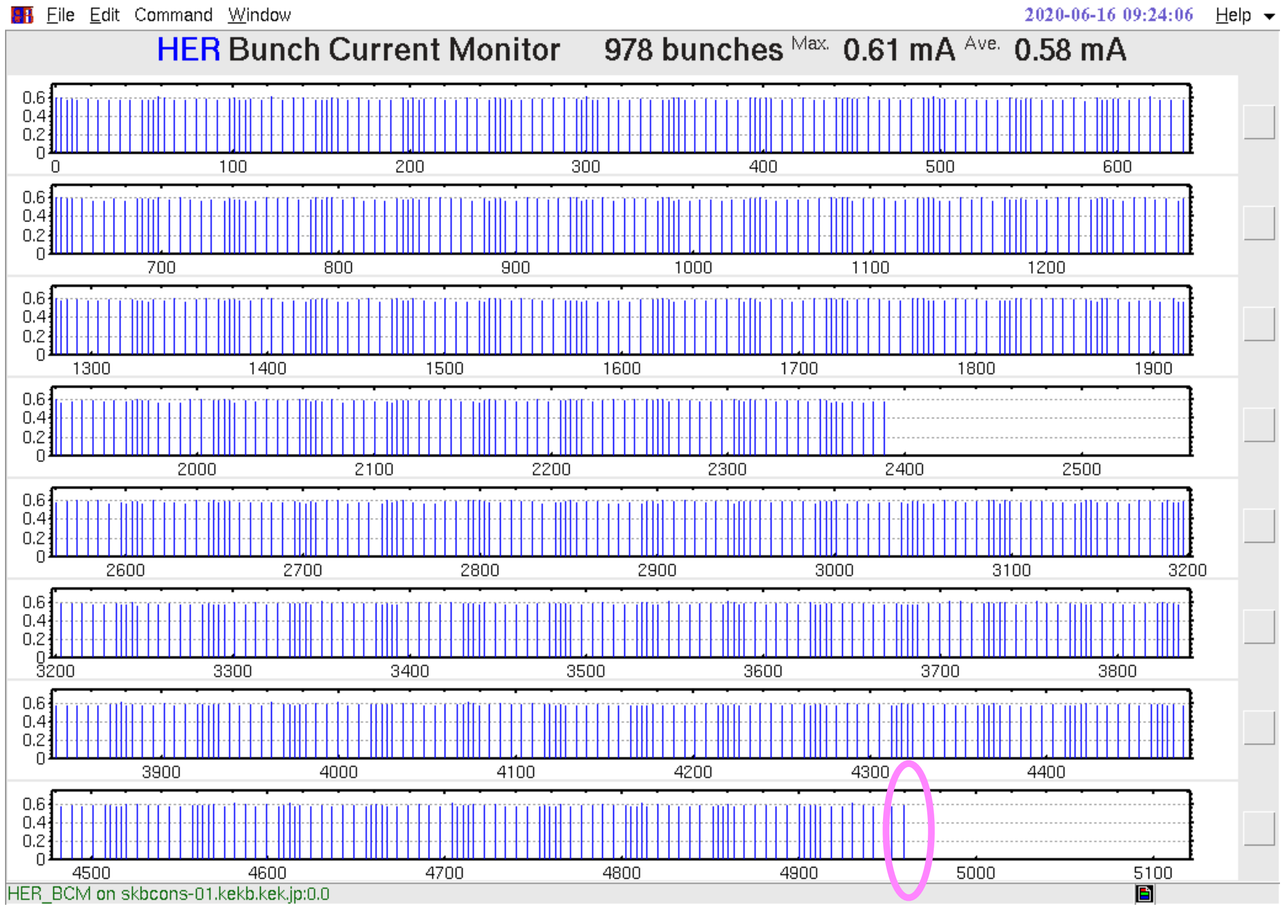


549.6 pb^{-1}/ 620.8 pb^{-1} (89 %)

Fill Pattern

Two abort gaps are prepared to make abort trigger fast.





pilot bunch
to measure tunes

We switched 783 bunches to 978 bunches for physics run in June.

We will increase bunch number gradually as well as total beam currents.

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		Crab waist		-		

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.
- Collimators works well to reduce detector background. More precise adjustment system will be necessary soon.
- However, 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 for the next Autumn run to overcome one of the difficulties. Impedance issue is an open question.
- Beam background (TOP counter, PMT lifetime) and injector performance limit the beam currents so far.
  - Beam background comes from stored (residual gas, Touschek) and injected beam. 50 % for LER beam-gas events
- The target for the next Autumn run is 4 x 10^{34} $cm^{-2}s^{-1}$ by increasing beam currents. We consider to achieve 10^{35} $cm^{-2}s^{-1}$ until the end of 2021.