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Highlights from SuperKEKB Commissioning for Early Stage of Nano-Beam Scheme and Crab Waist Scheme

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The SuperKEKB electron-positron collider is being commissioned at KEK to study new physics in the B-meson decays. In order to accomplish this purpose, the luminosity of 40 times of the highest luminosity record at KEKB, 8×10^{35} cm^{-2}s^{-1} is necessary. We have applied a novel "nano-beam scheme" to squeeze the beta function at the interaction point (IP) down to 1 mm in the vertical, 60 mm for the HER (7 GeV electrons) and 80 mm for the LER (4 GeV positrons) in the horizontal direction, respectively. We have tested β_y^* of 800 μm finally and performed physics run with data acquisitions by the Belle II detector. The beta function at the IP is the smallest value for the existing circular colliders in the world. However, the design value is 0.3 mm which is still about 1/3 of the achievement. We have also applied a "crab waist scheme" proposed by P. Raimondi et al. to improve the luminosity performance in the nano-beam scheme. The peak luminosity of 2.4×10^{34} cm^{-2}s^{-1} has been achieved which is the highest value in the world. The vertical beam size at the IP of 224 μm was also achieved, which is the smallest beam size for the colliders. The early stage of the commissioning of the nano-beam scheme as well as the crab waist scheme in 2019 run and Spring run in 2020 is presented.

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1. Nano-beam scheme

The luminosity is determined by the beam currents, the vertical beta function at the IP (β_y^*), and the limit of vertical beam-beam interaction (ξ_y) in principle. The benefit of the smaller β_y^* than the bunch length (σ_z) is less obtained for the previous colliders before SuperKEKB [1]. The deterioration of luminosity comes from the geometrical loss which is called an "hourglas" effect. However, the nano-beam scheme overcomes this difficulty by using a small emittance with a large Piwinski angle. The luminosity formula in the nano-beam scheme can be described by

$$L = \frac{N_+ N_- n_b f_0}{2\pi \Sigma_x^* \Sigma_y^*} = \frac{N_+ N_- n_b f_0}{2\pi \phi_x \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\sqrt{\varepsilon_{y+}\beta_{y+}^* + \varepsilon_{y-}\beta_{y-}^*}}, \tag{1}$$

where $N_\pm$ is a particle population in a bunch, n_b is a number of bunches, and f_0 is a revolution frequency. The variable at the IP is denoted by $*$. The Σ_x^* can be written with a half crossing angle, ϕ_x, by

$$\Sigma_x^* = \sqrt{\sigma_{x+}^{*2} + \sigma_{z+}^2 \tan^2\phi_x + \sigma_{x-}^{*2} + \sigma_{z-}^2 \tan^2\phi_x} = \sqrt{\sigma_{x+}^{*2}(1+\Psi_+^2) + \sigma_{x-}^{*2}(1+\Psi_-^2)}, \tag{2}$$

where the Piwinski angle is

$$\Psi_\pm = \frac{\sigma_{z\pm}}{\sigma_{x\pm}^*}\tan\phi_x. \tag{3}$$

In the case of an ordinary collision scheme such as a head-on collision and a small crossing-angle, $\Psi_\pm$ is much smaller than 1. The nano-beam scheme applies a large Piwinski angle larger than O(10), then the luminosity formula becomes Eq. (1). The real horizontal beam size at the IP (σ_x^*) is not present in the formula, however, the effective horizontal beam size can be large. Consequently, the luminosity decreases geometrically. In order to compensate the geometrical luminosity loss due to the effective horizontal beam size, the vertical emittance (ε_y) is required to be small enough.

Figure 1(a) shows the schematic view of the nano-beam scheme. The longitudinal length of overlap region for two colliding beams is called the effective bunch length. When β_y^* is compared with the effective bunch length, the hourglass requirement is modified by

$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} = \frac{\sigma_z}{\Psi}. \tag{4}$$

If σ_z is 6 mm and Ψ is 20, β_y^* can be squeezed down to 300 μm in principle which is much shorter than the real bunch length. In addition to reducing the hourglass effect, the vertex position along the beam axis is also restricted which provides a benefit for the primary vertex reconstruction of physics events.

2. Crab waist scheme

The purpose of the crab waist [2] is to reduce particles collide at the location shifted from the waist position as much as possible. The waist position is defined by the location at the smallest cross section where is the highest density. In addition to the geometrical effect, the crab waist can be expected to reduce resonance lines and a beam-tail due to beam-beam interactions [3]. The waist

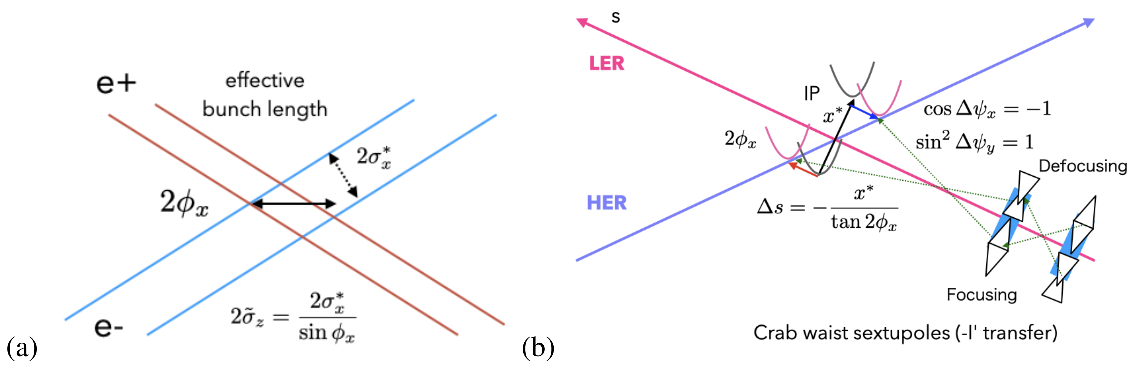

Figure 1: Schematic view of nano-beam scheme (a) and crab waist scheme (b).

position can be shifted by according to the horizontal amplitude when the following Hamiltonian is created at the IP,

$$H_{cw} = -\frac{1}{2\tan 2\phi_x} x^* p_y^{*2}. \tag{5}$$

On the other hand, a crab-waist sextupole can produce the Hamiltonian at the IP as following:

$$H_{cw} = -\frac{K_2}{2}\beta_y^s \beta_y^* \sqrt{\frac{\beta_x^s}{\beta_x^*}} \cos\Delta\psi_x \sin^2\Delta\psi_y x^* p_y^{*2}, \tag{6}$$

where the $\Delta\psi_{x,y}$ is the phase-advance between the sextupole and the IP, s indicates the sextupole. Therefore, the crab waist can be applied by choosing an appropriate phase-advance and beta functions at the sextupole. The phase-advance is adjusted to be almost π in the horizontal and $3\pi/2$ in the vertical direction, respectively. The field gradient (K_2) of the sextupole adjusts the crab-waist ratio from 0 % to 100 %. The schematic view of the crab waist scheme in SuperKEKB is shown in figure 1(b).

The particles in the inner position at the IP are forced by the crab-waist sextupoles and the effect is defocusing according to the horizontal displacement, on the other hand, the outer particles obtain focusing effect from the crab-waist sextupoles which means different α_y^* function is created for each inner and outer particles. As the result of the behavior of the inner and outer particles, the waist position can be shifted along the beam line of the opposite beam due to the crossing angle between two colliding beams. In the case of SuperKEKB, the local chromaticity correction in the vertical direction is utilized to realize the crab waist [4]. There are two pairs of sextupole magnets at each side upper and downstream of the IP to confine the crab waist between them in the interaction region. The phase-advance between two sextupoles in a pair is π and the transfer matrix is -I'. When the different field gradients of $\pm\Delta K_2$ are applied for each sextupole in a pair, the crab waist effect can be induced with keeping the chromaticity.

3. Achievements in 2019 run and 2020 Spring run

Figure 2 shows the operation summary for 2019 run and 2020 Spring run. There are two long shutdowns to maintain both the accelerator and detector. It is found that the luminosity has been improved significantly in 2020 since 2019 run even though the maximum beam currents do not increase. The crab waist has been applied for 2020 Spring run which is expected to reduce the beam-tail and resonance lines induced by beam-beam interactions. The crab waist ratio is 80 % in the LER and 40 % in the HER, respectively.

The horizontal emittance was changed from 1.6 nm to 4 nm to reduce Touschek effect as much as possible. A correction of chromatic X-Y couplings at IP was also tried by using 24 rotatable sextupoles in the LER. The integrated luminosity of 74 fb^{-1} was approximately recorded until 2020 Spring run. The peak luminosity during Belle II data acquisitions (physics run) for each operation period is shown in Table 1.

Classification	2018a/b	2019a/b	2019c	2020a/b
Date start	Mar. 19	Mar. 11	Oct. 15	Feb. 25
Date end	Jul. 17	Jul. 1	Dec. 12	Jul. 1
Period (days)	120	91	57	127
β_x^* (mm)	200 / 100	80 / 80	80 / 60	60 / 60
β_y^* (mm)	3 / 3	2 / 2	1 / 1	0.8 / 0.8
I_{max} (mA)	860 / 800	940 / 840	880 / 700	770 / 660
Crab waist ratio (%)	0 / 0	0 / 0	0 / 0	80 / 40
L_{peak} ($\times 10^{34}$ $cm^{-2}s^{-1}$)	0.26	0.55	1.14	2.40

Table 1: Operation date and period, the minimum beta function at the IP, the maximum beam currents, and peak luminosity under physics run. Left side for the LER and right for the HER to indicate $\beta_{x,y}^*$ and beam currents, and so on. The luminosity does not correspond to the beam currents and the beta functions at the IP.

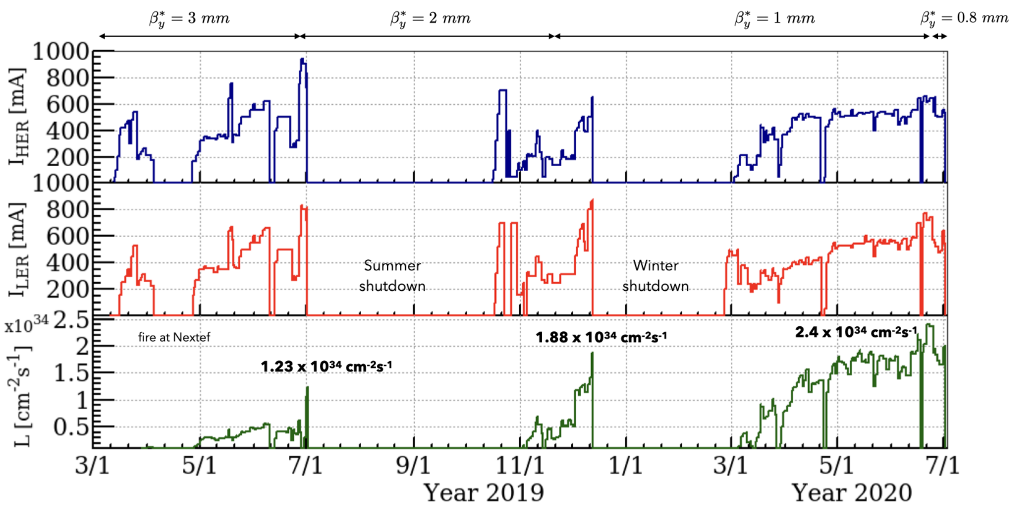

Figure 2: Operation history from 2019 run to 2020 Spring run. The beam current in the HER (top) and LER (middle), and the peak luminosity in a day without a requirement of physics run (bottom).

Figure 3(a) shows a history of β_y^* for various colliders in the world. The β_y^* in the future circular colliders such as FCC-ee and CEPC is 1 or 2 mm which is the same level or larger than the present SuperKEKB operation. This implies that SuperKEKB also plays a role of a challenge for the future colliders. The specific luminosity is shown in figure 3(b) for β_y^*=1 mm and 800 μm. The definition of specific luminosity is

$$L_{sp} = \frac{L}{I_{b+} I_{b-} n_b} \propto \frac{1}{\sqrt{\varepsilon_{y+}\beta_{y+}^* + \varepsilon_{y-}\beta_{y-}^*}}, \tag{7}$$

where $I_{b\pm}$ is the bunch current. If β_y^* and ε_y are constant, the specific luminosity should be constant. Since the specific luminosity decreases gradually as the bunch current product increases, the beam-beam blowup is observed. It is difficult to increase the bunch current product larger than 0.35 mA^2 in 2019 run but it is improved in 2020 Spring run with adopting the crab waist. The specific luminosity increases as squeezing β_y^* when the specific luminosity is between β_y^*=800 μm and 1 mm. In the case of β_y^*=800 μm, the physics run was operated at about 0.3 mA^2 and a stable collision tuning could be performed. The figure shows the specific luminosity in the region larger than 0.4 mA^2, however, the collision tuning is not enough due to lack of the operation time. Therefore, there is a room to improve the specific luminosity at higher bunch current product. The machine parameters achieved during 2020a/b run are shown in Table 2.

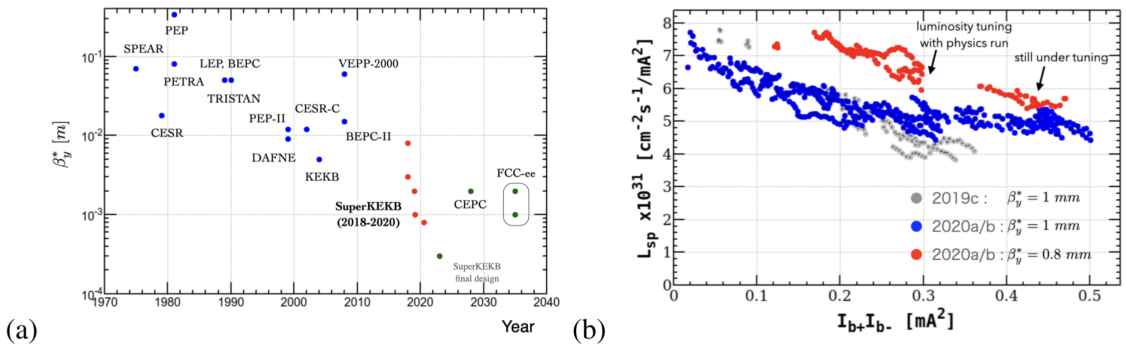

Figure 3: History of the vertical beta function (a) and specific luminosity as a function of bunch current product (b).

4. Conclusions

The beta function at the IP was successfully squeezed down to 800 μm in the vertical direction and 60 mm in the horizontal direction for both the LER and HER. The vertical beam size is 224 nm which is the smallest value for the colliders. The smallest beam size was 700 nm at SLC [5] before SuperKEKB. The peak luminosity is 2.4$\times$10^{34} cm^{-2}s^{-1} which is the world record with β_y^*=1 mm , 712 mA in the LER, and 607 mA in the HER. However, the difficulties such as extremely short lifetime and stability of operation arise significantly. The beam-related background to the Belle II detector and injector performance limit the beam current so far. The contribution of residual beam-gas background is about 50 % in the LER. Therefore, further vacuum scrubbing is necessary to reduce the background. The next target for 2020 Autumn run is 4$\times$10^{34} cm^{-2}s^{-1} and the commissioning to improve luminosity performance has been continued.

	LER / HER	LER / HER	Unit
ε_x	4.0 / 4.6	4.0 / 4.6	nm
β_x^*	80 / 60	60 / 60	mm
β_y^*	1	0.8	mm
I	712 / 607	536 / 530	mA
n_b	978	978	
I_b	0.728 / 0.621	0.548 / 0.542	mA
lifetime	760 / 1270	600 / 1177	sec
σ_x^*	17.9 / 16.6	15.5 / 16.6	μm
σ_y^*	285	224	nm
CW ratio	80 / 40	80 / 40	%
ξ_y	0.039 / 0.026	0.035 / 0.020	
L_{sp}	5.4×10^{31}	6.9×10^{31}	$\mathrm{cm^{-2}s^{-1}}$ /$\mathrm{mA^2}$
L	2.4×10^{34}	2.0×10^{34}	$\mathrm{cm^{-2}s^{-1}}$

Table 2: Machine parameters in Spring run 2020a/b.

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