

SMALL-BETA COLLIMATION AT SUPERKEKB TO STOP BEAM-GAS SCATTERED PARTICLES AND TO AVOID TRANSVERSE MODE COUPLING INSTABILITY

H. Nakayama, Y. Suetsugu, K. Kanazawa, Y. Ohnishi, Y. Funakoshi, K. Ohmi, D. Zou, KEK, Japan

Abstract

At SuperKEKB, beam particles which are Coulomb-scattered by the residual gas molecules change direction and will be eventually lost by hitting beam pipe inner wall. Due to large vertical beta function and small beam pipe radius just before IP, most of Coulomb-scattered particles are lost there and are very dangerous for the Belle-II detector. To stop such particles before the IP, vertical collimators are installed in the ring. However, such vertical collimators should be placed very close (few mm) to the beam and therefore induce transverse mode coupling instability. To avoid beam instability and achieve collimation at the same time, we need to install vertical collimators where vertical beta function is SMALL, since maximum collimator width determined by aperture condition is proportional to $\beta^{1/2}$, and minimum collimator width determined by instability is proportional to $\beta^{2/3}$. We present our strategy to stop beam-gas scattered particles and simulated loss rate in the interaction region. We will also show dedicated vertical collimator design to achieve less instability.

BEAM-GAS COULOMB SCATTERING

Beam particles scattered elastically (Coulomb-scattered) by remaining gas molecules are travelling off-orbit and might be lost by hitting beam pipe inner wall if deviation is too large. When beam particles are scattered at $s = s_1$, the deviation (y_2) at $s = s_2$ in vertical direction is expressed as follows:

$$y_2 = \theta_y \sqrt{\beta_{y,1} \beta_{y,2}} \sin(\psi_{y,2} - \psi_{y,1}) \quad (1)$$

where θ_y is Coulomb scattering angle in vertical direction, $\beta_{y,1}, \beta_{y,2}$ are vertical beta function at $s = s_1, s_2$ and $\psi_{y,1}, \psi_{y,2}$ are phase of vertical oscillation at $s = s_1, s_2$. Here we consider only vertical direction of Coulomb scattering because vertical deviation is larger than horizontal deviation and therefore Coulomb-scattered beam particles are mainly lost by hitting vertical beam pipe inner wall.

Since SuperKEKB beam pipe radius is smallest in the interaction region (IR) and SuperKEKB vertical beta function β_y is also largest in the whole ring at the interaction region, Coulomb-scattering beam life time is determined by the beam loss at the interaction region. The critical scattering angle ($\theta_{c,1}$) at $s = s_1$ can be expressed as follows:

$$\theta_{c,1} = r_{\text{IR}} / \sqrt{\beta_{y,1} \cdot \beta_{y,\text{IR}}} \quad (2)$$

where r_{IR} and $\beta_{y,\text{IR}}$ are beam pipe radius and vertical beta function at the interaction region where β_y is maximum.

Then inverse beam life time τ_R^{-1} is express as follows:

$$\tau_R^{-1} = cn_G \sigma_R = cn_G \frac{4\pi \Sigma Z^2 r_e^2}{\gamma} < \frac{1}{\theta_c^2} > \quad (3)$$

where c is the light speed, n_G is particle density, σ_R is cross section, ΣZ^2 is sum of squared atom numbers in remaining gas molecule, r_e is classical electron radius, γ is Lorentz factor of beam particles.

Compared to the KEKB, SuperKEKB maximum vertical beta function becomes larger (600m \rightarrow 2900m), averaged vertical beta function also becomes larger (23m \rightarrow 50m), and beam pipe radius at the maximum vertical beta function becomes smaller (35mm \rightarrow 13.5mm), These lead to ~ 90 times shorter SuperKEKB Coulomb beam life time (> 10 hours $\rightarrow \sim 30$ minutes).

From the view point of detector group, Coulomb-scattered beam particle is one of dangerous detector background sources, together with Touschek-scattered particles, electrons/positrons from radiative Bhabha process at collision point, etc. (see [4] for more details). Coulomb background is especially dangerous because all the beam losses are concentrated inside detector and simulated beam loss rate is several order higher than acceptable level. To protect our detector, we need to install a collimator upstream of the interaction region so that Coulomb-scattered particles are stopped by the collimator and will not reach the detector.

CONDITIONS FOR COLLIMATOR POSITION

The collimator position should satisfy following conditions on β_y at the collimator position and collimator (half) width d .

Firstly, collimator should be close enough to the beam orbit, so that scattered particles which might reach detector without collimator should be completely stopped by the collimator. In other words, collimator physical aperture ($d/\sqrt{\beta}$) should be smaller than (or at least same with) that of the interaction region:

$$d/\sqrt{\epsilon\beta} \leq r_{\text{IR}}/\sqrt{\epsilon\beta} \quad (4)$$

where ϵ is emittance of the ring. Therefore the maximum collimator width d_{max} is condition is expressed as follows: $d_{\text{max}} \propto \beta^{1/2}$.

Secondly, since our collimator width is rather narrow (few mm), collimator should not be too close to beam orbit in order to avoid the Transverse Mode Coupling Instability (TMCI), or called fast head-tail instability. According to

[3], threshold bunch current (I_{thresh}) is expressed as:

$$I_{\text{thresh}} = \frac{C_1 f_s E / e}{\Sigma \beta_y k_y (\sigma_z)} \quad (5)$$

1. Beam bunch current should be smaller than I_{thresh} to avoid TMCI. Kick factor of collimator with rectangular window can be analytically calculated as:

$$k = 0.215 A Z_0 c \sqrt{\frac{\theta_{\text{slope}}}{\sigma_z d^3}} \quad (6)$$

2. Using those two equations, minimum collimator width d_{min} is expressed as: $d_{\text{min}} \propto \beta^{2/3}$.

In order to satisfy both of above two conditions, β_y at the collimator position should be SMALL, which is different from the usual situation in which we are not worrying about TMCI and we try to find larger β or η position for the collimator.

In addition to aperture and TMCI conditions, oscillation phase at the collimator should be almost equal to that of interaction region, in order to stop the particles which might be lost in interaction region. We also need enough space (1.5m) along the beam line to install a collimator.

In the latest optics design of SuperKEKB, we can find a good position for the collimator which satisfies all of conditions shown above, fortunately. Figures 1 and 2 show the condition for the collimator width d and vertical beta function β_y for both rings. Allowed region is shown as area hatched with green lines. For the SuperKEKB Low Energy Ring (LER), the downstream end of the drift space element called “LLB3R”, which is 82 m upstream of IP, is a candidate position, with $\beta_y = 125$ m and allowed width is $2.23 \text{ mm} < d < 2.81 \text{ mm}$. For the SuperKEKB High Energy Ring (HER), the downstream end of the drift space element called “LTLB2”, which is 61 m upstream of IP, is a candidate position, with $\beta_y = 123$ m and allowed width is $1.74 \text{ mm} < d < 2.26 \text{ mm}$.

BEAM LOSS RATE AND LIFE TIME

Using Eq. 1-3, we sum up the beam loss rate from the scattering in each beam line element, at the interaction region and at the vertical collimator. For the multi-turn simulation, phase advance of $\psi/2\pi = 44.57$ (43.57) for LER (HER) per turn is taken into account. By summing up the loss rate up to 100 turns, we can calculate the total loss rate and therefore the Coulomb beam life time.

Table 1 shows the loss rate at the interaction region, total loss rate, and the Coulomb beam life time for various collimator width. Thanks to the vertical collimator, loss rate in the interaction region can be significantly reduced from $\mathcal{O}(10^2)$ GHz to <0.1 GHz, which is tolerable for the detector. However, the loss rate is sensitive to the collimator

¹ $C_1(\sim 8)$ is constant, $f_s(=2.13\text{kHz})$ is synchrotron frequency, E is beam energy, e is unit charge, k_y is kick factor of collimator and σ_z is longitudinal bunch length.

² $A(\sim 1)$ is constant, $Z_0(=377\Omega)$ is impedance of free space and $\theta_{\text{slope}}(\sim 0.063)$ is the slope angle of collimator.

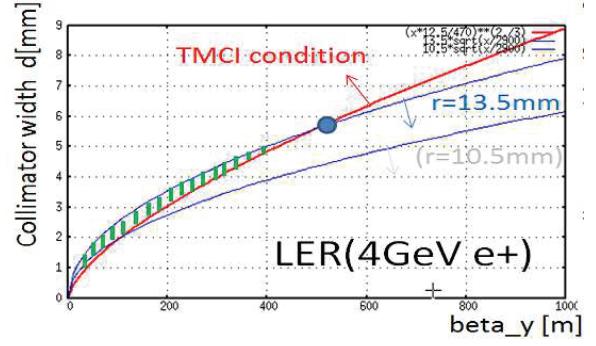


Figure 1: Aperture condition and TMCI condition on collimator width d and vertical beta function β_y in LER. Allowed region is shown as hatched area with green lines.

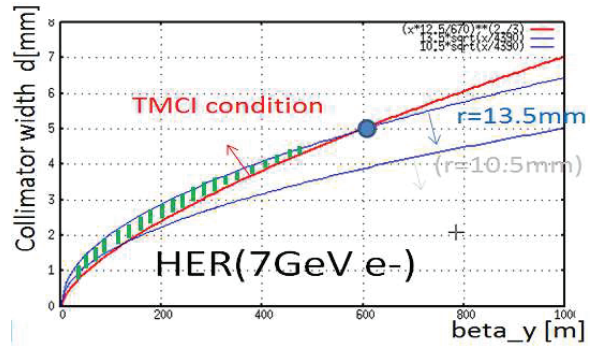


Figure 2: Aperture condition and TMCI condition on collimator width d and vertical beta function β_y in HER. Allowed region is shown as hatched area with green lines.

width, so the careful alignment scheme is necessary. Including the possible safety margins, we decide to set LER collimator width to be 2.6 mm and HER collimator width to be 2.2 mm. Estimated Coulomb beam life time is 1.7×10^3 sec for LER and 3.6×10^3 sec for HER.

Table 1: Loss rate at the interaction region R_{IR} , total loss rate R_{tot} , and the Coulomb beam life time τ_{Coulomb} for various collimator width d .

LER			
d [mm]	R_{IR} [GHz]	R_{tot} [GHz]	τ_{Coulomb} [sec]
2.50	0.05	141.8	1594.8
2.60	0.09	131.0	1724.9
2.70	0.24	121.4	1860.2
2.80	1.65	111.4	2000.5
2.90	11.48	100.8	2014.3
HER			
d [mm]	R_{IR} [GHz]	R_{tot} [GHz]	τ_{Coulomb} [sec]
2.20	0.001	45.2	3615.2
2.30	0.357	41.0	3951.3
2.40	7.99	33.0	3985.9

BEAM INSTABILITY ESTIMATION BY TRACKING SIMULATION

The discussion so far is based on Eq. 5 which assumes Gaussian bunches and broad-band resonator impedance, and Eq. 6 which assumes rectangular shape of collimator window. In this calculation, we perform more realistic calculation with dedicated collimator design and tracking simulation study based on impedance calculation of the collimator.

Figure 3 shows the dedicated collimator head design to achieve low-impedance characteristic. Inner aperture is flat only around the narrowest point and most of other region is kept cylindrical.

Impedance calculation of this low-impedance collimator with 2.4 mm width is shown in figure 4. Taking into this impedance calculation result, we perform the tracking simulation and investigate the vertical beam size blow-up after up to 3000 turns. As shown in figure 5, vertical beam size is stable up to 5 times higher than design bunch current.

Therefore we conclude our collimator setting strategy is confirmed for the LER, with several safety margin. The calculation for the HER is ongoing.

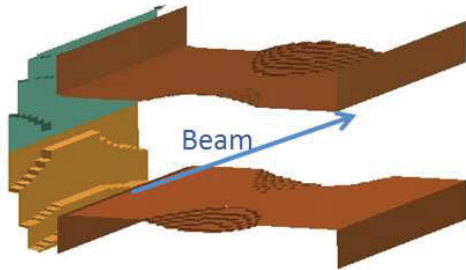


Figure 3: Low-impedance design of collimator head shape.

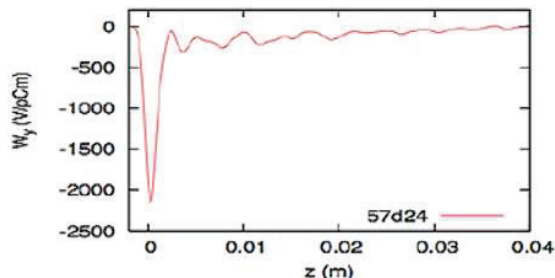


Figure 4: Calculated impedance of low-impedance collimator with 2.4 mm width.

COLLIMATOR DESIGN R&D

In this section, we report the current status of collimator design R&D work. Note that these are preliminary and details are not fixed yet.

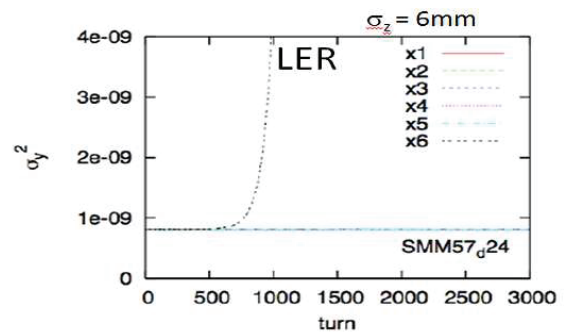


Figure 5: Vertical beam size blow-up after up to 3000 turns based on the tracking simulation with $x1 \sim x6$ of the design bunch current.

Figure 6 shows half-cut model of 3-dimensional drawing of vertical collimator. Surface of collimator head material is tungsten, and collimator body is copper. Collimator is cooled by water flow path ~ 1 cm from collimator surface. We plan to use SiC on both end of collimator as HOM absorber. Central part of the collimator might be designed to be replaceable, in order to prepare for the possible damage on the collimator head.

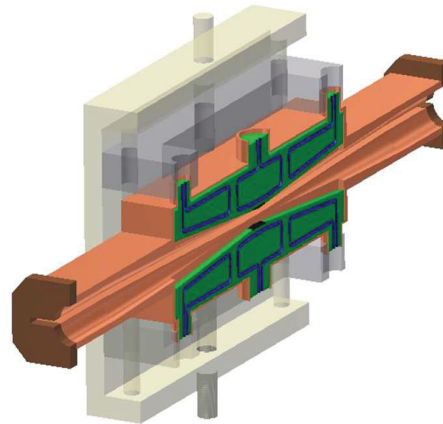


Figure 6: Half-cut model of 3-dimensional drawing of vertical collimator.

REFERENCES

- [1] P. Raimondi, talk given at the 2nd SuperB workshop, Frascati, 2006.
- [2] Belle II Technical Design Report, <http://xxx.lanl.gov/abs/1011.0352>
- [3] "Handbook of accelerator physics and engineering", p.121.
- [4] H. Nakayama, "Beam background and MDI design for SuperKEKB/Belle-II" (poster TUPPR007 in this conference).