ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB358

DEVELOPMENT OF LOW-Z COLLIMATOR FOR SuperKEKB

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Abstract

Collimators were installed in the main ring of SuperKEKB to suppress background noise (BG) in a particle detector complex named Belle II. The collimators successfully reduced the BG when the gaps of the collimator were closed. However, in high-current operations (greater than 500 mA), collimator jaws were occasionally hit and damaged by abnormal beams. As a solution to this problem, a low-Z collimator with a jaw made of carbon, which is relatively durable even if it collides with an abnormal beam, has been designed to protect important components.

In this study, we describe the calculation to make a low-Z collimator and its impact on operation.

INTRODUCTION

SuperKEKB is a high-luminosity electron-positron collider with asymmetric energies of 7 GeV (electron, high energy ring: HER) and 4 GeV (positron, low energy ring: LER) [1]. We designed a new collimator to fit the antechamber scheme [2]. The location of the collimators is shown in Fig. 1. See reference [3] ("Report of collimator damaged event in SuperKEKB" in this conference) for a deeper understanding of the motivations of this study.

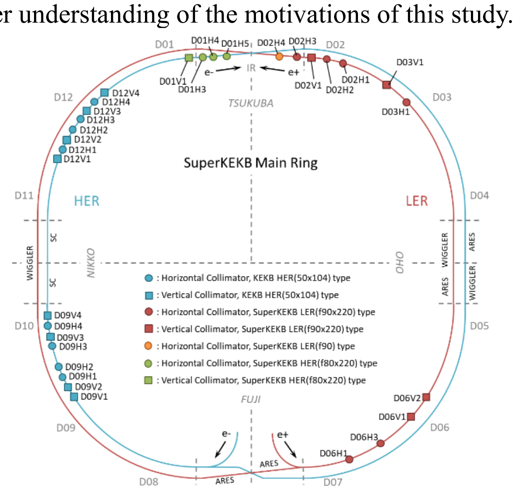

Figure 1: Location of collimators in the main ring of SuperKEKB. The terms H and V in the collimator represent the horizontal and vertical collimators [2].

MATERIAL AND STRUCTURE OF LOW-Z COLLIMATOR JAWS

Selection of the Material for the Collimator Head

To select a suitable material for the collimator head, the maximum temperature and melting point were investigated using FLUKA when the beam was shot into the sample. We observed from the result [2] that carbon had the largest difference between the maximum temperature and melting point. Therefore, carbon was selected as the material for the collimator head. The use of carbon in large hadron collider [4] was also a contributing factor for its adoption.

In SuperKEKB, the beam that was scattered with the residual gas became BG in Belle II, so an ultra-high vacuum state is required. Therefore, we investigated whether outgassing from carbon would be a problem. In the electron/positron ring accelerator, outgassing through photon stimulated desorption (PSD) was the main source of outgases source. We measured PSD as illustrated in Fig. 2 using BL21 at the photon factory. The PSD of carbon (red circles) was found to be at good levels compared to that of copper (black circles).

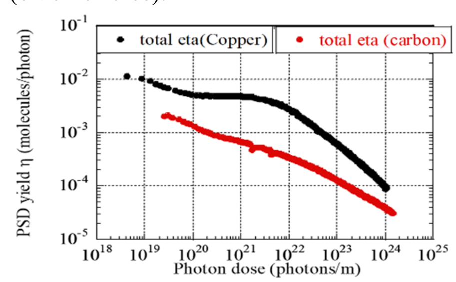

Figure 2: Comparison between PSD of copper and carbon.

Beam Tracking of Scattered Particles

When using carbon as the collimator head, we had to confirm that there is no risk of breakdown of Belle II due to scattered particles by the low-Z collimator. We estimated the Belle II BG for an upgraded jaw with a low-Z material using a newly improved beam-induced BG simulation code [5, 6]. The routine includes a realistic collimator geometry and physics of the beam particle scattering off of collimator jaws. We decided to install the low-Z collimator on the D06V1 collimator to reduce the risk of breakdown of Belle II, because D06V1 is far from Belle II. In D06V1 collimator, before replacing with carbon head, a tantalum head (L = 5 mm) was used, and we confirmed that it was sufficiently effective to reduce BG. L denotes the longitudinal length of the collimator head. From the results [5], we observed that the L of carbon had to be greater than 50 mm to achieve the same effect as tantalum (L = 5 mm). We decided the L of carbon at 60 mm to include a margin because there is a part that is not yet understood regarding injection oscillation. Figure 3 illustrates the results of the absorbed particles in the jaw attached carbon (L = 60 mm). From Fig. 3, we found out that the number of absorbed particles in carbon is small even though carbon is at the tip. This confirmed that carbon does not break easily when used as the collimator head.

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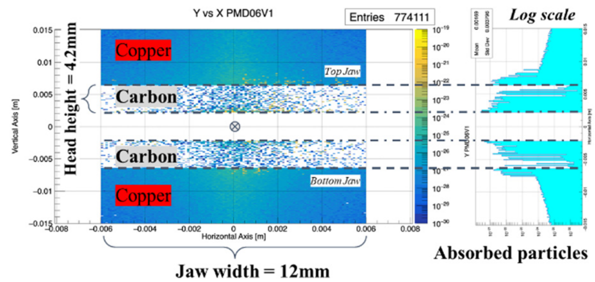

Figure 3: Absorbed particle distribution at the D06V1 jaw attached carbon (L = 60 mm).

Structure of Low-Z Collimator Jaw

To use carbon as the collimator head, it is necessary to satisfy the following conditions. Since collimator head gets heated owing to the resistive wall impedance, the structure of the jaw should have a cooling mechanism. If a gap exists between the body of the collimator jaw and the head, there is a possibility of discharging in the gap, therefore, there should be no gap between the jaw and head of the collimator. We discovered a way to bond copper and carbon as shown in Fig. 4. We designed low-Z collimator jaws, which are installable in the present collimator chamber. D06V1 collimator chamber was installed the main ring of SuperKEKB before 2020a run. Normal type jaws were replaced with low-Z collimator jaws before the 2020c run.

Figure 4: The jaw attached carbon.

Dust Generation from the Carbon

While using carbon in the vertical collimator, it is necessary to select carbon that generates very little dust. If the beam interacts with the dust falling by gravity, this beam loses energy and travels through an abnormal orbit, therefore it can damage important components. The size and the number of dust particles generated from carbon in the liquid were examined. We also examined gamma-irradiated samples (approximately 1 × 106 Gy) to investigate the effects of radiation deterioration of carbon. Figure 5 shows the number of dust particles generated from the samples of carbon and glassy carbon with a carbon coat (GCWC). Glassy carbon is a porous carbon saturated with carbon glass. The sample size was 100 × 100 × 10 mm. In Fig. 5, we observed that GCWC generates less dust than carbon with/without gamma irradiation. The surfaces of carbon and GCWC were measured using an electron microscope [7] and we observed that the surface of GCWC had fewer voids than that of carbon. We surmised that fewer voids were the reason for reduced dust generation. Based on these results, we selected GCWC as the material for collimator head.

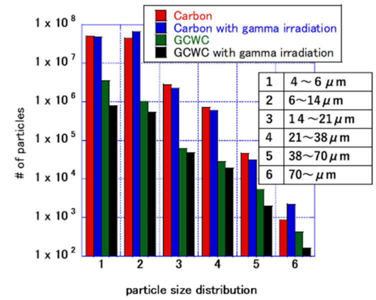

Figure 5: Measurement results of the size and number of the dust particles generated.

Electrical Resistance in the High Frequency Range of Carbon

The bunch length of SuperKEKB LER is approximately 6 mm, thus it has a very high frequency component. Therefore, it is very important to investigate the characteristics of the material used to make components such as collimator heads that are close to the beam. Carbon has the property of passing direct current (DC). However, it has been reported that it has high-frequency absorption characteristics depending on the manufacturing method [8]. We attempted to estimate the skin effect of carbon from the measured Q value using a cavity as shown in Fig. 6. There is a groove in the cavity to separate the degenerate modes. The advantage of this method is that we can measure the electrical conductivity in the high frequency range by simply changing the end plate of the cavity. First, using coppers as end plate, we checked whether the modes could be separated. The measured value of the frequency difference between the modes in which the degeneracy was resolved was 22 MHz, which matched the calculated value as shown in Fig. 7.

From the Q value of TE011 mode measured at 5.04 GHz, the calculated resistance value was 3.33 × 105 Ω · m assuming the characteristics of the skin effect of the metal.

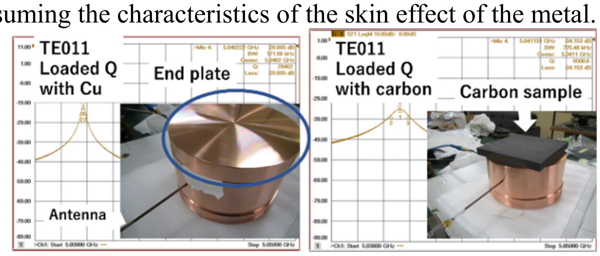

Figure 6: Cavity for measurement of electronic conductivity of the sample.

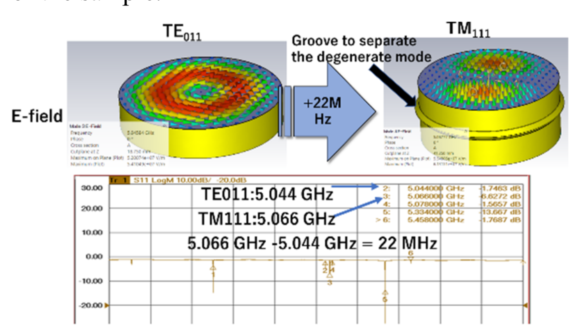

Figure 7: Excited mode in the cavity.

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The calculated value is close to the measured value of the actual DC resistance (approximately 3 × 105 Ω · m). In other words, this carbon sample has high frequency absorption characteristics similar to those of metals from DC to 5.04 GHz, and it can be inferred that high frequency absorption of carbon is not significantly large in high frequency range.

THE IMPACT OF LOW-Z COLLIMATOR ON BEAM COMMISSIONING

BG Reduction and Pressure Change

We conducted an investigation to establish whether the low-Z collimator had any negative effects on BG. From Fig. 8, we observed that BG decreases when the gap of the low-Z collimator was closed. Therefore, we concluded that the low-Z collimator had no negative effect on BG.

The pressure normalized by the beam current (dP/dI) as a function of the beam dose, which is measured using a cold cathode gauge beside the D06V1 collimator, is shown in Fig. 9. We observed that the low-Z collimator jaws did not have any negative effect on pressure.

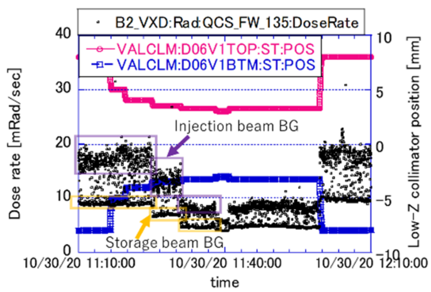

Figure 8: Measured value of BG when the gap of low-Z collimator changed.

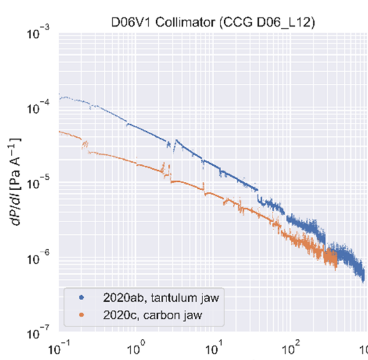

Figure 9: dP/dI beside the low-Z collimator as a function of the beam dose.

Effect of Beam Impedance

It is well known that impedances can cause transverse mode coupling instability (TMCI) and limit the bunch current in storage rings [9]. In SuperKEKB, the main transverse impedance source is the collimators owing to their small gaps. The low-Z collimator (L = 60 mm) has a higher impedance than normal collimators attached to tantalum jaws (L = 5 or 10 mm). We measured the tune shift and observed mode coupling as illustrated in Figs. 10 and 11, respectively, and checked their relation to the gap of the low-Z collimator. We observed that the measured value of the tune shift was consistent with the calculated value. However, the beam size blow-up, which is correlated with bunch current and impedance, was observed earlier than expected. As we learned later, it is probable that this earlier than expected beam size blow-up was due to a tune dependent resonant effect that was in turn caused by the impedance of the low-Z collimator, which dominates other impedances, and thus should be considered as localized. Beam-size blow-up causes a decrease in luminosity. Therefore, the low-Z collimator was removed and we are developing an improved version.

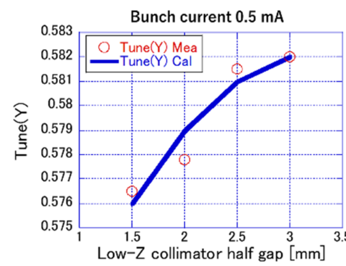

Figure 10: Measured tune shift compared with the estimated values from calculated impedance.

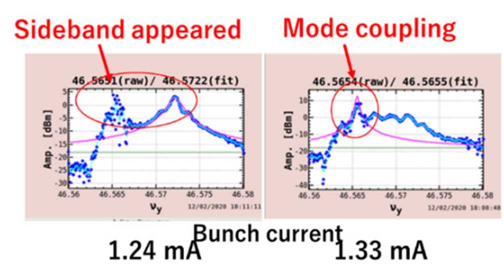

Figure 11: Observation of TMCI phenomenon.

CONCLUSION AND OUTLOOK

We summarize this study as follows:

- To make the low-Z collimator, we performed numerous calculations and measurements. Based on the results, we developed a low-Z collimator using carbon for the SuperKEKB.
- We observed that the low-Z collimator did not adversely affect BG and pressure. However, beam size blow-up correlated with bunch current and impedance was observed earlier than expected.
- As part of future developments, it is under consideration to perform geometry optimization for the purpose of reducing transverse impedance from the low-Z collimator and thereby increasing the TMCI threshold in SuperKEKB.

ACKNOWLEDGMENTS

We thank all the staff of the SuperKEKB accelerator and Belle II detector and Dr. K. Hirano, Dr. Y. Tanimoto, Dr. X. Jin and Dr. M. Hagiwara for their cooperation.

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