SIMULATION-BASED OPTIMIZATION OF A BENT SILICON CRYSTAL FOR BEAM LOSS REDUCTION IN THE J-PARC MAIN RING SLOW EXTRACTION

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Abstract

To achieve a beam power exceeding 150 kW in the J-PARC Main Ring slow extraction, reducing beam loss at the electrostatic septum (ESS) is critical. As a mitigation strategy, we are optimizing the design of a bent silicon crystal to be installed upstream of the ESS. This paper presents FLUKA simulation studies aimed at maximizing the beam loss reduction effect. We demonstrate that volume reflection is preferable to channeling for our operational conditions; its larger angular acceptance accommodates the substantial vertical beam size and relaxes tight crystal torsion constraints. Furthermore, we evaluated the impact of anticlastic deformation on deflection efficiency for both the (110) and (111) crystallographic planes. Although the (111) plane is more susceptible to performance degradation from anticlastic deformation, introducing a downstream beam diffuser narrows the perfomance gap between the (110) and (111) plans, reducing the overall beam loss to $\sim 30\%$ of the unmitigated case. Based on these results and the practical material availability, we have selected the (111) plane for volume reflection and are proceeding with crystal fabrication for installation during the next maintenance period.

INTRODUCTION

At the J-PARC Main Ring (MR) [1], 30 GeV protons are slowly extracted using a third-order resonance to the Hadron Experimental Facility [2]. Protons accelerated to 30 GeV are extracted over a period of $\sim$2 seconds. The most critical beam qualities required for this slow extraction beam are high beam intensity and temporal flatness during the extraction period.

The performance of the slow extraction at the J-PARC MR has gradually improved since the start of operations in 2009. Figure 1 shows the trend plots of the beam power and spill duty factor for the J-PARC MR slow extraction. In the operation of April 2026, we achieved a intensity of 8.9×10^{13} protons per pulse. With the current repetition cycle of 4.24 s, this particle number corresponds to a beam power of 101 kW with a high extraction efficiency of 99.6%. Although this beam power has almost reached the acceptable limit of the secondary particle production target currently used in the Hadron Experimental Facility, a new rotating target for accepting over 150 kW beam power is under development, and there is a strong demand from physics experiments for a further increase in beam power. One of the challenges that must be overcome to achieve this beam power upgrade is the further reduction of beam loss during the slow extraction. Therefore, we plan to install a bent silicon crystal upstream of the electrostatic septum. A bent silicon crystal is a silicon crystal that has been mechanically and elastically deformed, and it is known to deflect the trajectory of charged particles. Bent silicon crystals have already been put into practical use for beam collimation at the LHC and for beam loss reduction in the slow extraction of 400 GeV protons at the CERN SPS [3, 4]. In this paper, the beam loss reduction effect of a bent silicon crystal for the case of 30 GeV protons in the J-PARC MR was investigated through simulations using FLUKA [5].

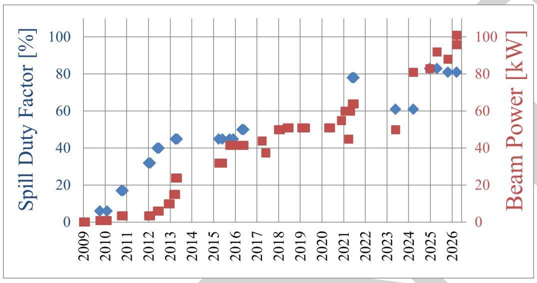

Figure 1: Trend plots of the beam power and spill duty factor for the J-PARC MR slow extraction.

BEAM DEFLECTION EFFECT OF THE BENT CRYSTAL

A bent crystal deflects positively charged particles primarily through two mechanisms: channeling (CH) and volume reflection (VR). In channeling, charged particles are confined within the planar potential created by the crystal planes and deflected along the bent shape of the crystal. While the deflection angle can be controlled by the shape of the crystal, the disadvantage is its small angular acceptance of around $\sim$30 μrad for 30 GeV protons. On the other hand, volume reflection is a phenomenon in which particles outside the channeling acceptance are reflected in the direction opposite to the crystal's bending direction. The deflection angle takes a unique value determined by the crystal structure and cannot be varied; however, since the angular acceptance of VR is determined by the bending angle of the crystal, a larger acceptance can be obtained compared to channeling. Fig-

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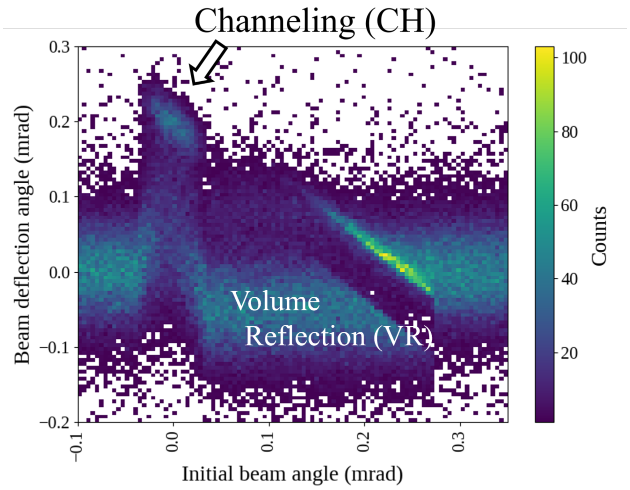

Figure 2: The deflection effect of the bent silicon crystal for 30 GeV protons estimated by FLUKA. Horizontal axis is the beam incident angle, and the vertical axis is the deflected beam angle. The crystal's bending angle and longitudinal length are 200 µrad and 1 mm, respectively.

ure 2 shows the deflection effect of the bent silicon crystal for 30 GeV protons estimated by FLUKA.

We also estimated the beam loss reduction effect of the crystal using FLUKA when it is installed upstream of the electrostatic septum of the J-PARC MR. The optimum bending angle was investigated in the range from 50 to 300 µrad [6]. If we ignore the effect of the vertical beam size described below, a larger bending angle is preferable for both channeling and volume reflection. Table 1 shows the normalized beam loss for the crystal with 300 µrad bending angle. The crystal has a longitudinal length of 1 mm and a transverse thickness of 0.2 mm, and the (110) plane is used for the beam deflection.

Table 1: Normalized Beam Loss Estimated using FLUKA

Configuration	**Normalized Beam Loss**
No Mitigation	100
Channeling	48
Volume Reflection	53

CRYSTAL BENDING METHOD

The crystal is bent using anticlastic deformation. Figure 3 shows a conceptual drawing of the deformation. The beam is deflected according to the curvature whose radius is R_A. A finite primary bending radius R creates a finite anticlastic bending radius R_A through anticlastic deformation. By utilizing anticlastic deformation, interference between the beam and the crystal holder for bending and holding the crystal can be avoided. However, by applying R, the transverse position of the crystal becomes dependent on the vertical position. To increase the bending angle, R_A must be decreased, which requires decreasing R. This consequently increases δx shown in the Fig. 3, leading to a degradation in the beam loss reduction effect for particles located away from the ideal orbit plane in the vertical direction.

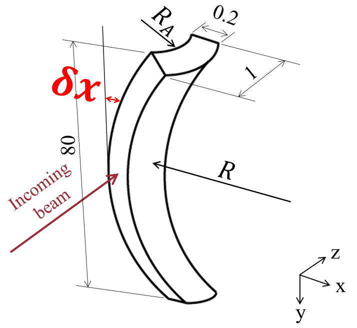

Figure 3: Conceptual drawing of the anticlastic deformation.

To estimate the magnitude of this δx, we carried out finite element method calculations with ANSYS [7]. The deformation behavior of an object is determined by its elastic modulus. Because the crystal is anisotropic, the elastic modulus changes depending on the crystal orientation, which results in the changes of R_A/R depending on which crystal plane is used for deflection and from which direction the beam is incident. The results when (110) plane is used for the beam deflection are shown in Fig. 4. Also, R_A/R can be obtained by $-s_{33}/s_{13}$, where s_{ij} are the components of the 6 × 6 compliance matrix, under the approximation that deformation is small [8]. The R_A/R obtained from the compliance matrix itself is also plotted in Fig. 4, showing good agreement with the ANSYS calculation results. From this result, when using the (110) plane, R_A/R is minimized at $\theta = 0°$, which minimizes the δx. On the other hand, when using the (111) plane for beam deflection, the normal compliance components (the upper-left 3 × 3 submatrix of the compliance matrix) become independent of the beam incident direction; therefore, R_A/R remains constant, with a value of 3.82 obtained from the compliance matrix. Since this is larger than the 2.77 for (110) plane, the effect of δx becomes more significant when the (111) plane is used.

BEAM LOSS REDUCTION EFFECT OF THE BENT CRYSTAL

A large vertical beam size not only degrades the beam loss reduction effect due to the δx but also imposes stricter

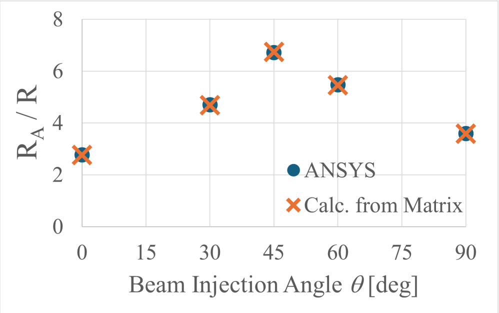

Figure 4: Calculated θ dependence of R_A/R. (110) plane is used for beam deflection. θ is the angle between beam injecion axis and ⟨001⟩ axis.

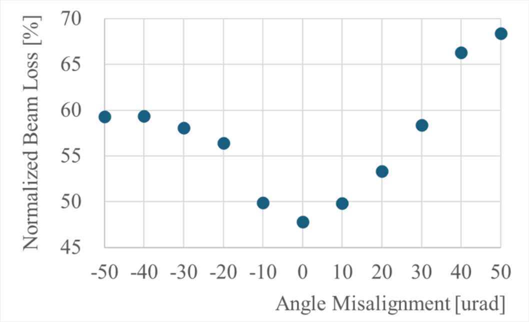

Figure 5: Angle misalignment dependence of the normalized beam loss estimated by FLUKA. The channeling effect is used with (110) plane.

requirements on the torsion of the bent crystal. Therefore, we estimated the impact of the angular misalignment for channeling using FLUKA. The results are shown in Fig. 5. It should be noted that even without any crystal structure, the beam loss is reduced to 73% due to the angle diffusing effect of Coulomb scattering. It can be seen that the channeling effect is almost lost when the angle deviates by +50 µrad. The distribution is asymmetric because particles begin to be reflected by volume reflection when the angle is shifted in the negative direction. To obtain the maximum beam loss reduction effect, the angular deviation must be restricted to within ~±15 µrad. Since the vertical beam size at the crystal position is about 7 mm (1 RMS), this imposes a severe constraint on the torsion of ~2 µrad/mm.

On the other hand, when volume reflection is used and the crystal bending angle is set to 200 µrad, an angular acceptance of ~±80 µrad can be secured, resulting in a torsion requirement of around ~10 µrad/mm. Because this is a feasible value, we decided to adopt volume reflection and evaluated the impact of δx on the beam loss reduction effect with a crystal bending angle of 200 µrad. The results are shown in Fig. 6. Although FLUKA is used for this calculation, care must be taken because the code for calculating the crystal deflection effect for the (111) plane is a pre-release version [9]. In this study, we estimated the beam loss not only for the case where only the bent silicon crystal is installed but also when a beam diffuser is inserted downstream of it. This diffuser has already been installed in MR and is being used for operations for users. As shown in the figure, the beam loss reduction effect begins to deteriorate when δx exceeds ~40 µm.

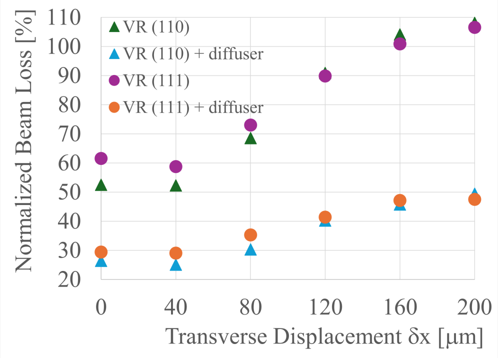

Figure 6: The estimations of δx effect on normalized beam losses estimated using FLUKA. The estimations are for volume reflection using the (110) and (111) planes, both with and without the beam diffuser downstream the crystal.

Table 2: Normalized Beam Loss Estimated using FLUKA Including Finite Vertical Beam Size Effect

Configuration	**Normalized Beam Loss**
No Mitigation	100
VR (110)	57
VR (110) + diffuser	27
VR (111)	66
VR (111) + diffuser	31

Assuming a crystal bending angle of 200 µrad and a longitudinal length of 1 mm, R_A is 5 m. When using the (110) plane, R is 1.8 m using $R_A/R = 2.77$; when using the (111) plane, R is 1.3 m using $R_A/R = 3.82$. The δx corresponding to a vertical beam size of 7 mm are 27 µm for (110) plane and 38 µm for (111) plane.

Assuming a vertical beam profile of a Gaussian with $\sigma = 7$ mm, the beam loss reduction effects obtained by convoluting the beam profile and results of Fig.6 are summarized in Table 2. When the (111) plane is used, the beam loss reduction effect remains smaller than that of the (110) plane due to the combined effects of the smaller R and the inherent difference in the beam deflection efficiency. However, by simultaneously inserting the diffuser downstream of the crystal, the difference between the two is narrowed. Because a wafer with the (111) surface is more readily available, we are planning to fabricate a bent crystal using the (111) plane for beam deflection.

SUMMARY AND OUTLOOK

We investigated the beam loss reduction effect of a bent silicon crystal for slow extraction at the J-PARC Main Ring. We decided to employ volume reflection due to its high tolerance for the angular misalignment of the crystal. The beam loss reduction effect was estimated using FLUKA, taking into account the dependence of the crystal's transverse position on its vertical position caused by anticlastic deformation. The results showed that by inserting a diffuser downstream of the silicon crystal, the beam loss can be reduced to ~ 30% of the case without the crystal and diffuser, regardless of whether the (110) or (111) plane is used. We will now proceed with the crystal fabrication, aiming to install it in the ring during the next summer maintenance period.

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