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THE REDUCTION OF THE LEAKAGE FIELD OF THE INJECTION SEPTUM MAGNET IN MAIN RING OF J-PARC

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Abstract

A new injection septum magnet 1 (Inj-SM1) was installed in the Main Ring (MR) of J-PARC in 2016 as an upgrade. We confirmed that the leakage field upstream from the circulating duct of Inj-SM1 was sufficiently smaller than that for the previous Inj-SM1. Nevertheless, we attempted to further reduce the leakage field by using a new magnetic shield to achieve a higher proton beam intensity. In 2017, the first version of the new magnetic shield was produced and installed. The strength of the leakage field with the shield was ≈30% of that without the shield; however, the magnetic field of a quadrupole magnet (QM) upstream of Inj-SM1 was reduced to below the permissible limit, ≈0.1% of the total field integral of the QM, from the point of view of beam optics. Consequently, the first version failed. A second shield, for which the defects of the first version were fixed, was produced in 2018. The strength of the leakage field of Inj-SM1 with the second shield was reduced to ≈30% of that without the shield, while that of the QM was maintained. Thus, we decided to use the second shield for beam operation starting in November 2019. We confirmed that the impact of the leakage field on the circulating beam was 1/20 of that of the previous Inj-SM1.

INTRODUCTION

The J-PARC Main Ring (MR) provides a high-intensity proton beam with an energy of 30 GeV to the neutrino facility [1] or the hadron facility [2]. The present operation cycle is 2.48 s and the maximum beam power to the neutrino facility is 515 kW, which was achieved in March 2021 [3]. To realize the original design value of 750 kW, we will start the operation of the MR with a cycle of 1.3 s in June 2022; this is referred to as 1-Hz operation. The cycle will be further reduced to 1.16 s by 2028 to increase the beam power to 1.3 MW [4]. Over the last decade, the injection magnets in the MR have also been upgraded for 1-Hz operation and a 1.3-MW beam. The high-field injection septum magnet 1 (Inj-SM1), which has a typical field strength of 1.4 T, is used for injecting the proton beam from the rapid cycling synchrotron into the circulating orbit in the MR. The first Inj-SM1 started operation in 2008 (start of the J-PARC MR) and was replaced with the new septum magnet for 1-Hz operation in 2016 [5, 6]. The replacement of the magnet was conducted because it was extremely difficult to further reduce the leakage field of ≈20 gauss around the entrance and exit of the circulating beam duct beside the septum plate. The reduction of the leakage field is an important target for the new septum magnet.

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MEASURES AGAINST LEAKAGE FIELD IN 2015-2016

To minimize the leakage field, magnetic shields, vacuum chambers made of magnetic stainless steel [7], or an eddy current can be used to cancel the leakage field [8–10]. To reduce the leakage field of Inj-SM1, we applied several magnetic shields made of pure iron. The most significant contribution to the leakage field is from an end coil at the beam exit because it is located very close by the circulating beam line. To reduce the leakage field, we covered the entire end coil by a magnetic shield made of silicon-steel (field clamp) (Fig. 1 (top)). This reduced the leakage field to a few gauss [5, 6]. The second most significant contribution is the leakage field that passes through the septum plate. An ideal septum magnet has zero leakage on the outside of the septum plate; however, an actual septum magnet has a small leakage with an order of magnitude that is 0.1% of the gap field. For example, for a gap field of 1.4 T, the strength of the leakage field is ≈14 gauss. Therefore, we covered the circulating duct beside the septum plate by two magnetic shields made of pure iron (outer shields 1 and 2) (Fig. 1 (bottom)). Furthermore, we fabricated a 5-mm-thick circulating duct made of pure iron, which had a dc permeability of ≈8000 emu, in March 2016 [6] (Fig. 1 (bottom)), We measured the time-dependent field integral (BL) of the leakage field along the beam axis in the circulating duct with an applied current of 2,700 A, which is close to the optimal current for beam operation (2,590 A). The maximum value of BL during 0.2 s from the start of beam acceleration was 2 gauss·m. The bend angle of the circulating beam caused by the leakage field was then measured with the 3-GeV circulating beam in December 2016. Based on the measured angle, we obtained a BL value of ≈2.5 gauss·m, which is consistent with the field measurement [6]. The BL of the leakage field of the first Inj-SM1 was ≈30 gauss·m [11], which is 10 times greater than that of the second Inj-SM1. Because our ultimate target for the leakage field is zero gauss·m, we attempted to further reduce the leakage field.

REDUCTION OF LEAKAGE FIELD IN 2017

There was a leakage field of ≈9 gauss upstream from the pure iron circulating duct, where no shield was mounted and the circulating ducts were made of non-magnetic stainless steel [6] (Fig. 2). The origin of the field was the end coil at the injection beam entrance of Inj-SM1. Unfortunately, it was impossible to cover the end coil by a field clamp because of a lack of space. In addition, we could not cover the stainless steel circulating ducts by a magnetic shield because the magnetic field in the circulating ducts includes not only the field of Inj-SM1 but also that of a quadrupole magnet (QM)

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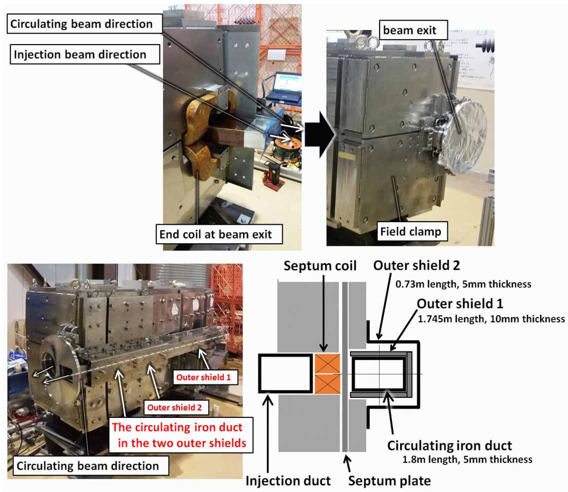

Figure 1: End coil and field clamp at beam exit (top) and several magnetic shields of Inj-SM1.

located upstream of Inj-SM1. The large loss of the leakage field of the QM affects beam optics, which must be corrected using a trim coil mounted in the QM [12]. This correction was not ideal. We thus mounted an additional magnetic shield in the space between the end coil and the circulating ducts. The detailed structure of the additional magnetic shield (Shield-1) was designed using Opera-3D-Tosca in 2017 [13]. The dimensions of Shield-1 were set to 130 mm (width) × 980 mm (height) × 13 mm (thickness) (Fig. 2). We measured the leakage field of each of the magnets with and without Shield-1 using a Hall probe (F.W. Bell, model 8030 [14]). First, we measured the leakage field of Inj-SM1 at three positions from the stainless steel circulating ducts to the outside of the ring. The distances from the center of the beam axis were all ≈160 mm, and those from the surface of the end fringe of the QM, z, were 18, 38, and 82 cm. We had to remount the probe whenever we changed the measurement position because we had only one probe. The reproducibility of the measurement position added some systematic uncertainty (a few percent) to the measured values. The applied current was the optimal pattern for beam injection. The rise, flat top, and fall time were all 0.2 s and the flat-top current was 2,598 A. The measured waveforms of the leakage field are shown in Fig. 3 (top). They indicate that the leakage field at z = 18 and 38 cm was reduced from ≈9 to ≈3 gauss and from ≈3 to ≈1 gauss, respectively. No reduction was found at z = 82 cm because the origin of the leakage found at this position was the induced eddy current field generated on the septum plate, and Shield-1 was not located between this position and the plate. Next, we measured the leakage field of the QM. The results are shown in Fig. 3 (bottom). The leakage field at z = 18 cm on the top of the duct with Shield-1 was 6∼7% lower than without the shield. We found no difference at the three positions on the inside because they were far from Shield-1. The leakage field at z = 25 and 39 cm on the outside (close to Shield-1) was reduced to 33% and 41%, respectively. From these results, the total loss of the BL of the QM caused by Shield-1 was estimated to be 0.3%, which is larger than the permissible limit of ≈0.1% [15]. Thus, we concluded that Shield-1 cannot be used for beam operation.

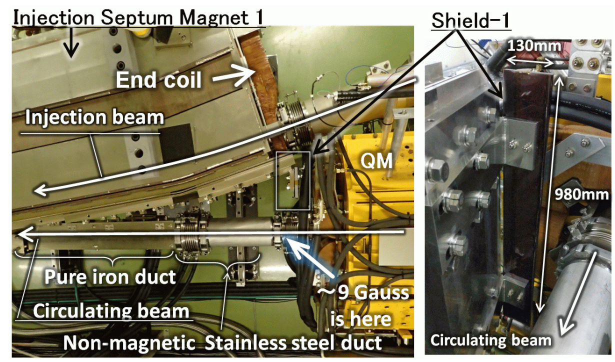

Figure 2: Shield-1 mounted on Inj-SM1 in 2017.

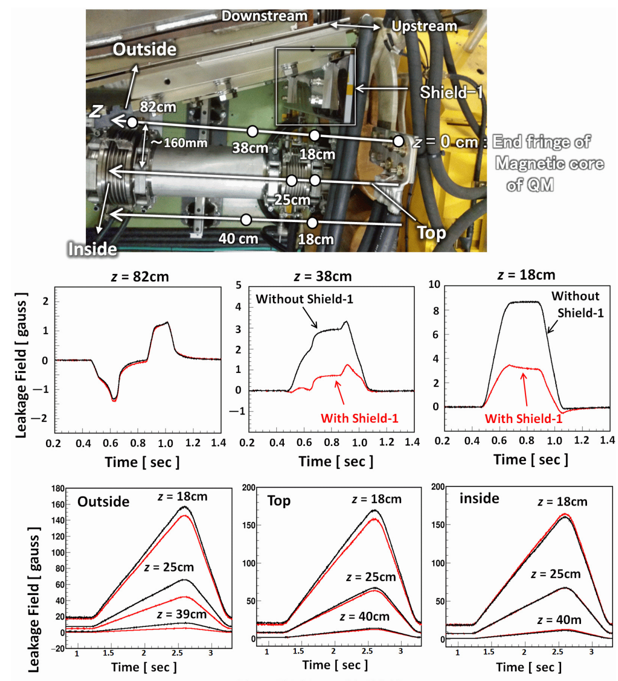

Figure 3: Waveforms of leakage field of Inj-SM1 (top) and quadrupole magnet (bottom) with and without Shield-1 measured in 2017.

REDUCTION OF LEAKAGE FIELD IN 2019

We considered that the cause of the large loss of the leakage field of the QM was Shield-1 being located in front of the magnetic coil of the QM, which obstructed the field of the QM, as shown in Fig. 2. Therefore, we fabricated a new pure iron shield that did not interfere with the QM (Shield-2) in 2018. The dimensions of Shield-2 are 110 mm (width) × 600 mm (height) × 20 mm (thickness) (Fig. 4) . Shield-1 was mounted perpendicular to the septum plate, whereas Shield-2 was mounted parallel to the septum plate so as not

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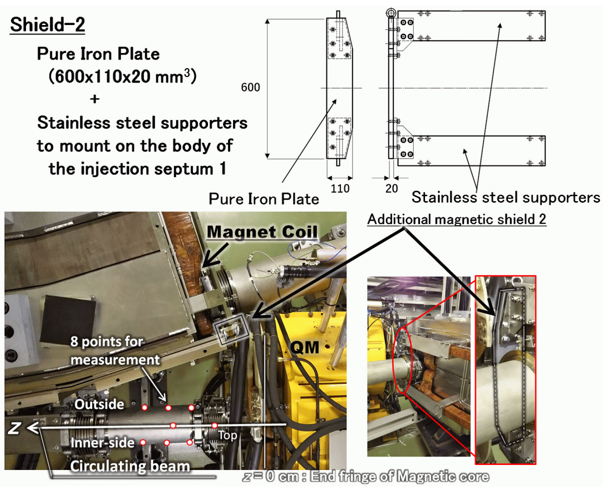

Figure 4: Shield-2 mounted on Inj-SM1 in 2019.

to reduce the leakage field of the QM (Fig. 4). In 2019, we measured the leakage field of Inj-SM1 and the same QM as that measured in 2017. To eliminate the systematic uncertainty caused by the reproducibility of the measurement position, we used eight Hall probes (F.W. Bell, model BH-200), one for each measurement position. The measured waveforms of the leakage field of Inj-SM1 are shown in Fig. 5 (top). The measurement positions on the outside of the circulating ducts were $z = 20.5$, 33, and 52.5 cm. We verified that the leakage field at $z = 33$ and 20.5 cm was reduced to ≈30% of that without Shield-2. Almost no reduction was found at $z = 52.5$ cm for the same reason as that given above. Next, we measured the leakage filed of the QM at the eight positions on the top, outside, and inside of the circulating ducts (Fig. 5 (bottom)). There was no difference between the measurements made with and without Shield-2 at all positions except $z = 20.5$ cm on the inside, where the probe was removed once by accident. From the above results, we found that the leakage field of only Inj-SM1 was reduced by Shield-2. Thus, we concluded that Shield-2 can be used for beam operation. We started to use Shield-2 in November 2019.

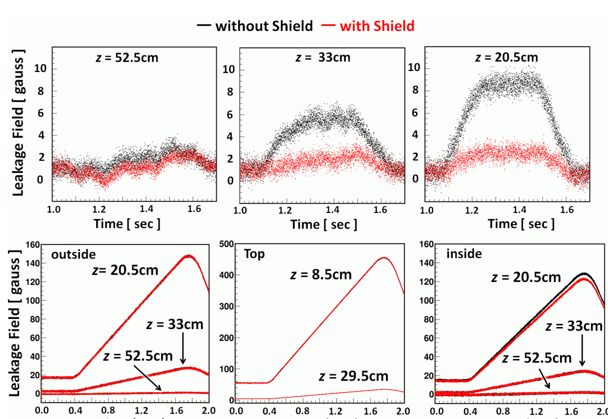

Figure 5: Waveforms of leakage field of Inj-SM1 (top) and QM (bottom) with and without Shield-2 in 2019.

BEAM STUDY WITH NEW SHIELD

Finally, the impact of the leakage field of Inj-SM1 on the 3-GeV circulating beam was measured in November 2019. The time-dependent shift of the beam position with respect to the horizontal direction while Inj-SM1 is excited is shown in Fig. 6. The shift was ≈0.25 mm, which corresponds to a BL of 1.6 gauss·m caused by the leakage field. Thus, we confirmed that the impact on the circulating beam was further reduced by ≈1/3 by Shield-2. The shift of the beam position by the leakage field of the previous Inj-SM1 was ≈5 mm [11], which is ≈20 times higher.

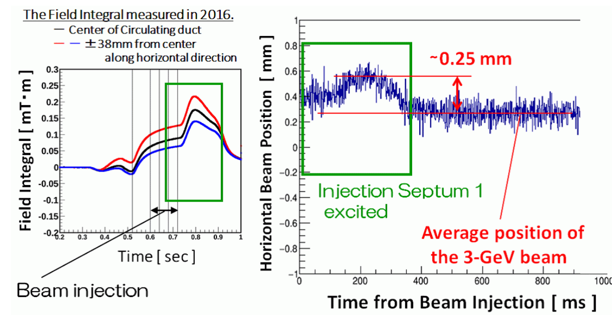

Figure 6: Shift of 3-GeV beam position with respect to horizontal direction caused by leakage field of Inj-SM1 measured in 2019.

SUMMARY

The new Inj-SM1 installed in 2016 reduced the leakage field to 1/10 of that of the previous one with the use of several shields. In 2019, the leakage field was further reduced by ≈1/3 by an additional magnetic shield that does not reduce the leakage field of the QM upstream. The impact of the leakage field on the 3-GeV circulating beam was measured. We confirmed that it was ≈1/20 of that of the previous Inj-SM1.

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