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THE NEW HIGH FIELD SEPTUM MAGNET FOR UPGRADING OF FAST EXTRACTION IN MAIN RING OF J-PARC

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Abstract

The upgrade of the beam power of J-PARC Main Ring to 750 kW by reducing the cycle from 2.48 s to 1.3 s is underway, and the upgrade of the four high-field (HF) septa will be completed by summer of 2023. The operation test of one HF septum, SM31, was conducted in 2020. First trial was 1 Hz operation test, and we confirmed the joule heating at the magnetic coil was lower than limit. Second was magnetic field measurement. We obtained a good linearity between the applied current and the gap field without saturation. The field integral of the gap field was measured to estimate the optimal current for beam extraction, and we found it is 3,400 A. We compared the gap field between in the neutrino line and that in the beam abort line, then we found the longitudinal distributions have a small discrepancy but it was acceptable. The large leakage field was observed around the end-fringes, therefore, in order to reduce the leakage field, we produced an additional duct shield for mounting in the circulating duct in 2022. We verified that the additional duct shield reduced the leakage field to ≈2% of unshielded leakage field. The new SM31 and other two HF septa have been installed in MR by end of May 2022. The beam operation with the new HF septa will be started in June 2022.

INTRODUCTION

The J-PARC Main Ring (MR) provides the high-intensity proton beam with an energy of 30 GeV to the neutrino facility (NU) or the hadron facility. The present operation cycle is 2.48 s and the maximum beam power for Fast eXtraction mode (FX) is 515 kW which was achieved in March 2021 [1]. To realize original design value of 750 kW, we are going to start operation of MR with the cycle of 1.3 s, it is referred to as "1 Hz operation"; moreover, the cycle will be shorten to 1.16 s for increasing the beam power to 1.3 MW by 2028 (1.3MW beam) [2]. The magnets for FX in MR, which are used for switching the proton beam direction to NU or abort dump (ABT) [3], also have been upgrading for 1 Hz operation and 1.3 MW beam, and will be completed by summer of 2023. The four high-field septum magnets (SM) with magnetic field of above 1 T are used, and these magnets are called SM30, SM31, SM32 and SM33 from upstream. To upgrade, the replacement of these septa with new ones is underway. We produced the new septa in 2015, and conducted the operation test of the new SM30 and measured its magnetic field at first in 2018-2019 [3, 4]. Next, we conducted the test operation of the new SM31 in autumn 2020. The aim of the operation test was 1 Hz operation and measurement of the gap field and leakage field. After operation test, two large-sized vacuum flanges made of pure Titanium were weld to the vacuum ducts of the new SM31 in November 2020. In 2021, we produced two additional duct shields which can be mounted in the circulating duct of the new SM30 and SM31 in order to reduce the leakage field further. Regarding the new SM32, unfortunately, the installation in MR was postponed because of a fatal defect in the magnetic coil found in 2021. The new SM33 have been reconstructed with the new beam ducts and removed magnetic cores of SM32 and SM33. The installation of the new SM30, SM31 and SM33 in MR have been completed in May 2022 (Fig. 1). The beam operation with new cycle is going to be started in June 2022. This article focuses on the new SM31. The new SM31 is a bipolar septum magnet as same as the new SM30 [4]. Figure 2 shows the photograph, the specification and applied pattern current of the new SM31. The detail of the operation test in 2020 and the reduction of the leakage field by using the additional duct shield in 2022 will be described.

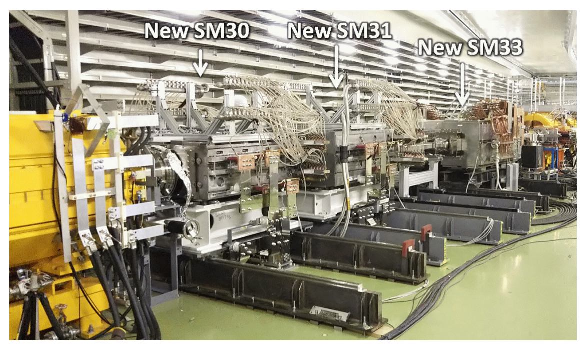

Figure 1: The high-field septa installed in MR in May 2022.

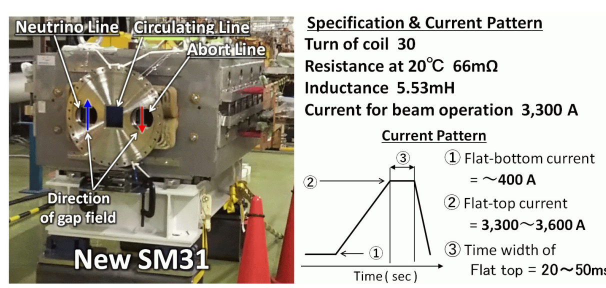

Figure 2: The photograph, the specification and the applied pattern current of the new SM31.

1 Hz OPERATION TEST

In the 1 Hz operation test, the operation cycles which we tested were 1.32 s, 1.28 s and 1.16 s, and the flat-top current

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was 3,600 A. We measured the temperature of cooling water flowed in the magnetic coil by using a radiation thermometer during the operation. The temperature increased approximately 13°C in all cycles which were corresponded with our expected values and it was lower than limit value of 20°C. Consequently, it was verified that the 1 Hz operation has no problem.

MEASUREMENT OF GAP FIELD

The correlation between the applied current and gap field in the NU line which was measured by a Hall probe are shown in Fig. 3. We found no saturation at high-field region, thus we confirmed it has good linearity, however the linear-fit value of the slope was 3.472±0.004(stat) which was 0.8 % lower than design value of 3.501. The possible cause of the lower slope is small leakage of magnetic flux from the magnetic core.

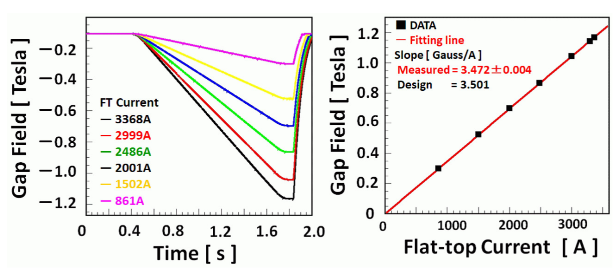

Figure 3: The waveforms of gap field in the NU line (left), and the correlation between the flat-top of the applied pattern current and the gap field (right).

To decide the optimal current for 30-GeV beam extraction, we measured the field integral (BL) along the center of the NU line with the flat-top current of 3,300 A, and the BL was 1.745 T·m. Since the supposed BL for the beam extraction is 1.808 T·m, we estimated the optimal current for beam operation at 3,400 A. Next, we measured the transverse distribution of the BL along the horizontal direction, and the result is shown in Fig. 4. It indicates the BL has an asymmetric sextupole field component, and the difference of the value of the BL between maximum and minimum in the region of ±20 mm which is size of the extraction beam [5] was ≈0.17%. It corresponds to the bending angle of 0.05 mrad for the 30-GeV proton beam. However, since the bending angle is almost same scale of fine-tuning of position and direction of the extraction beam by changing the field strength of the HF-septa, the difference is not serious problem.

Finally, we compared the longitudinal distribution of the gap field between in the NU and in the ABT line with the flat-top current of 3,300 A and 3,400 A (Fig. 5), and found an obvious discrepancy. We presumed the cause of the discrepancy is slight difference of the magnetic cores such as volume, shape and processing. The large asymmetric structure should make the leakage field larger, but that is enough small and the discrepancy is acceptable.

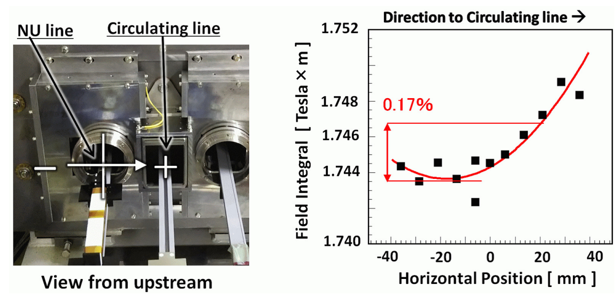

Figure 4: The view of the new SM31 from upstream (left), and the transverse distribution of the BL in the NU line, and the red curve is quadratic fit (right).

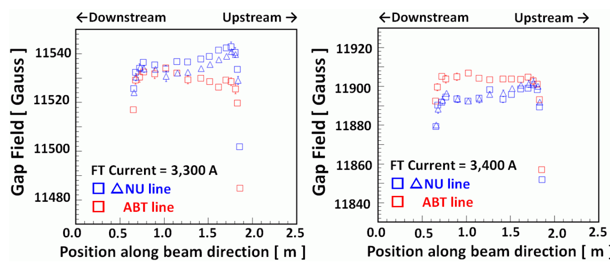

Figure 5: Comparison of longitudinal distribution of the gap field between NU and ABT line with 3,300 A (left) and 3,400 A (right).

MEASUREMENT OF LEAKAGE FIELD

The longitudinal distribution of the leakage field in the circulating duct was measured along the several straight tracks: on the center of the beam-line (center track) which is parallel to the beam direction, on ±10 mm from center track to horizontal direction (10-mm tracks), on ±25 mm from center track (25-mm tracks), and on 18 mm from the inside wall of the duct (18-mm tracks) (Fig. 6). The 18-mm tracks are not parallel to the beam direction because the circulating duct is tapered along the longitudinal direction of which the horizontal size of entrance and exit are respectively 88 mm and 218 mm. The flat-bottom and flat-top of the applied pattern current were 408 A and 3,300 A, respectively. The results shown in Fig. 6 indicate the large leakage field still exists around the end-fringe of the magnetic cores (end-fringe field), especially, extremely large end-fringe field of which the maximum value was 170 Gauss were observed on the 18-mm tracks. We investigated the end-fringe field in detail, and found the cause was magnetic saturation of the septum plates made of iron. Next, the horizontal distribution of the BL which used flat-bottom current (fb-BL) and flat-top current (ft-BL) were also measured along the several tracks (Fig. 7). We found a dipole and quadrupole field component in the both of results, especially, the dipole field component of 1.2 Gauss·m in fb-BL and 1.6 Gauss·m in ft-BL were large and they affect the circulating beam. To reduce the end-fringe field and the dipole field component, the best measures is installation of an additional magnetic shields in the circulating duct.

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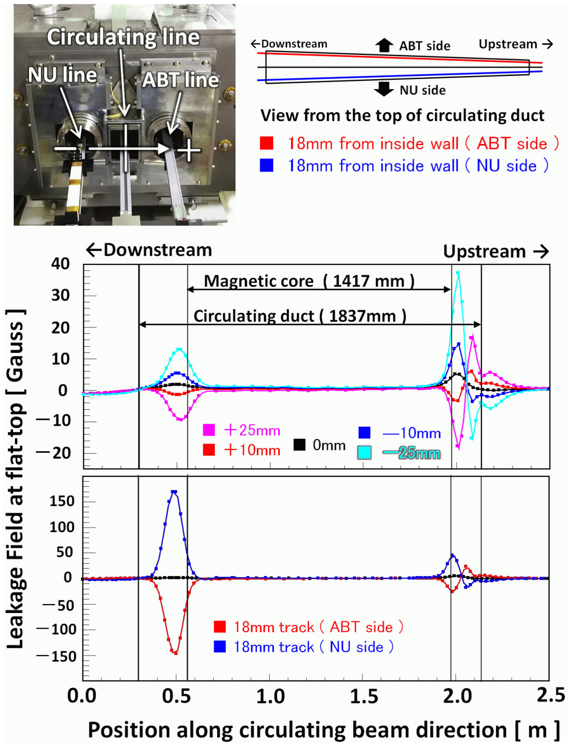

Figure 6: The longitudinal distribution of the leakage field in the circulating duct along the center track, 10-mm tracks, 25-mm tracks, and 18-mm tracks.

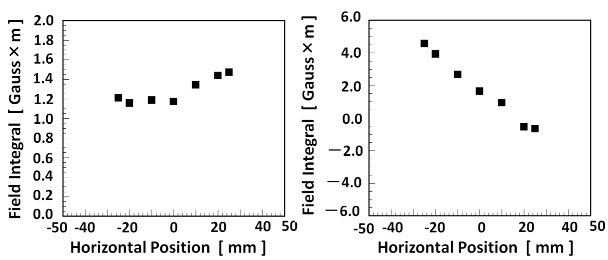

Figure 7: The horizontal position dependence of the BL: fb-BL (left) and ft-BL (right).

AN ADDITIONAL INNER SHIELD

In order to reduce the leakage field in entire area of the circulating duct of 1.837 m length, we decided to produce a duct shield of 1.935 m length and 3 mm thickness made of pure iron (inner shield). The inner shield is also tapered as same as the circulating duct of which the cross section of entrance and exit are respectively 82.2 mm×99.4 mm and 219.6 mm×99.4 mm. The production of the inner shield was completed in March 2022, and we mounted in the circulating duct. After installation of the new SM31 in MR, we have measured the end-fringe field with the inner shield along a 18-mm track of ABT side in May 2022. Figure 8 shows a photograph of the inner shield mounted in the new SM31, and the longitudinal distribution with the flat-top current of 3,960 A. We found that the large end-fringe field was reduced to ≈2% of unshielded end-fringe field, thus we concluded the reduction of the end-fringe field by using the inner shield is a most effective measures.

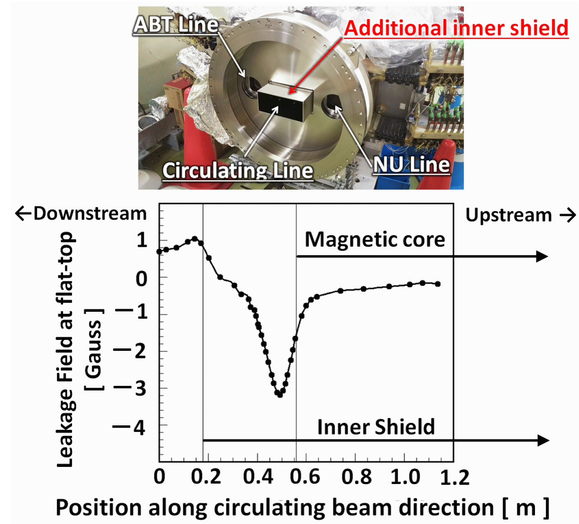

Figure 8: The additional inner shield mounted in the new SM31, viewing from downstream (upper). The longitudinal distribution of the end-fringe field along the 18-mm track with the inner shield (lower).

SUMMARY

We are working on upgrade of the FX high-field septa for increasing the beam power of MR in J-PARC. In 2020, we conducted operation test of the new SM31. The high repetition operation had no problem, and we obtained a good linearity between the applied current and gap field. The longitudinal distributions of the gap field in the neutrino line and abort dump line have small discrepancy, but it was acceptable. On the other hand, we found large leakage field around the end-fringe, and we produced an additional duct shield which is mounted in the circulating duct. The inner shield was installed in March 2022, and we verified the leakage field was reduced to ≈2%. The beam operation with the new high-field septa will be started in June 2022.

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