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THE NEW EDDY CURRENT TYPE SEPTUM MAGNET FOR UPGRADING OF FAST EXTRACTION IN MAIN RING OF J-PARC

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Abstract

As part of the goal of increasing the beam power of the Main Ring for Fast eXtraction (FX) in J-PARC to 750 kW, we have been evaluating new FX low-field septa of induced eddy current type (Eddy-septum) since 2014. To reduce the leakage field in the circulating line of the eddy-septa, new pure iron duct-type magnetic shields were produced in July 2021, and in March 2022 we verified that the leakage field was greatly reduced . The construction of the two eddy-septa and their power supplies was completed in May 2022. Beam operation with a new 1.3-s cycle will be started in June 2022.

INTRODUCTION

The J-PARC proton accelerator experiment laboratory consists of a 400-MeV LINAC, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 50-GeV Main Ring (MR). The MR is a proton synchrotron that receives the 3-GeV proton beam from the RCS, accelerates it to an energy of 30 GeV, and extracts it 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 the original design value of 750 kW, we are working towards operating the MR with a cycle of 1.3 s in June 2022 [2], referred to as "1 Hz operation". The cycle will also be reduced to 1.16 s to increase the beam power to 1.3 MW by 2028 (1.3 MW beam) [2]. The magnets for FX (FX magnets) in the MR, which are used for switching the direction of the proton beam to the NU or the abort dump (ABT), have been in the process of being upgraded for 1 Hz operation and 1.3 MW beam for a decade, and this will be completed by summer 2023. The FX magnets consist of five kickers, two low-field septa (LF-septa) and four high-field septa [3]. The upgrade includes an improvement of the power supply for the kickers and replacing the septa with new ones. During a long-term shutdown of the MR in 2021–2022, the two LF-septa was removed from the beam line and the new septa were installed. The construction of two sets of power supplies for the new septa was completed in May 2022. This article focuses on the upgrade of the LF-septa system.

FX LOW-FIELD SEPTUM MAGNET

The previous LF-septa, removed in 2021, had a conventional configuration with a thin septum coil. The typical gap field for the previous LF-septa was 0.3 T, and the applied current waveform had a time width of ~1.5 s, the same as that for the high-field septa. Each previous LF-septum consisted of two septa, located symmetrically with respect to the beam axis, one used for NU extraction and the other for ABT extraction, with a circulating beam passing through the space between the two septa. These septa were mounted in a vacuum chamber, because the extraction lines were not sufficiently separate from the circulating line, and there was no space to mount a beam duct.

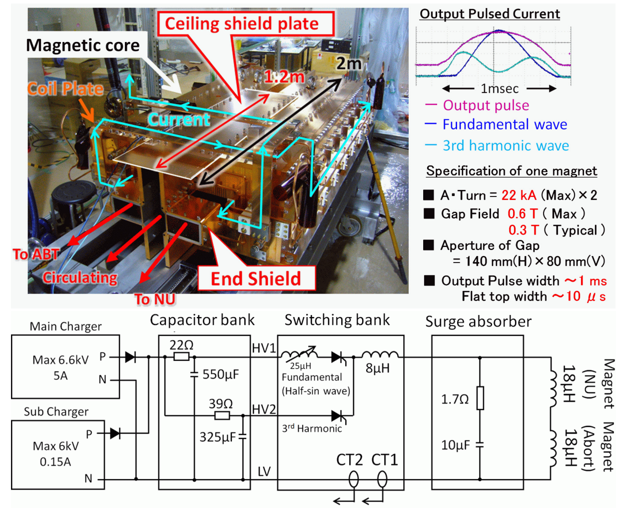

Figure 1: Photograph of eddy septum magnet (upper left), waveform of output pulsed current and specifications of eddy septum system (upper right), and circuit diagram of pulse power supply (lower).

The new LF-septa are induced eddy current type (eddy-septa) (Fig. 1) [4, 5]. We will use two eddy-septa, mounted in two vacuum chambers, as in the case of the previous LF-septa. The eddy-septa have developed in some electron and proton accelerators in the world except J-PARC: e.g., the injection/extraction of synchrotron SOLEIL [6, 7], the injection of SSRF storage ring [8, 9], the extraction of SPS in CERN [10]. The upstream and downstream eddy-septa are called Eddy-1 and Eddy-2, respectively. The most significant feature of an eddy-septum is that it can greatly reduce the leakage field compared to the previous LF-septa. Since the configuration of an eddy-septum is based on a C-type bending magnet, it does not have a septum coil but has a thin copper plate on the opening side of the magnetic core (septum plate). The applied current waveform for an eddy-septum is a short-pulse half-sinusoidal wave. When the short-pulse current is applied to the eddy-septum, the pulsed leakage field penetrates the septum plate, inducing an eddy current in the septum plate that cancels the leakage field. Other advantages of eddy-septa for high-power beam operation include: (1) a zero-Gauss leakage field during beam injection

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and acceleration because they are excited only during beam extraction, (2) a wider horizontal aperture of the magnetic gap due to the lack of a septum coil, which constrains the aperture, (3) lower possibility of vibration damage to the insulator on the septum coil and (4) lower joule heating in the magnetic coil and core due to the short-pulse current. However, the power supply (PS) must be replaced because that for the previous LF-septa cannot supply the short-pulse current. The PS has been under development since 2014 in the electric building along with the other power supplies for the FX magnets [3, 11–14]. One septum PS consists of two main chargers, a sub-charger, a capacitor bank, a switching bank and a surge absorber (Fig. 1). The main chargers charge the capacitor bank with a maximum charging voltage of 6 kV and the switching bank then discharges the capacitor bank with a maximum output power of 6 kV×22 kA. The output short-pulse current has a full and flat top width of ~800 µs and ~10 µs, respectively. It is a composite of a fundamental and a 3rd harmonic sinusoidal wave, to optimize the flatness of the flat top region of the waveform by adjusting the difference between each discharge time.

HISTORY OF DEVELOPMENT OF EDDY-SEPTA

The most significant technical goals regarding the magnets are achieving the expected gap field and an extremely low leakage field in the circulating line. We measured the field integral (BL) of the gap field with a charging voltage of 3 kV, which is half the maximum value, and obtained 0.449 T·m. Since the BL for one of the previous LF-septa for 30-GeV beam extraction was 0.44 T·m, we determined that the optimal charging voltage for 30-GeV beam extraction is ≈3 kV. In addition, we confirmed good linearity between the BL and the charging voltage in the range from 2 to 4 kV without any saturation. When the bending angle is fixed, the extraction energy is proportional to the BL, that is, the charging voltage. Therefore, we can estimate the optimal charging voltage for any extraction energy. In 2019, we measured the uniformity of the BL along the horizontal direction in the gap space, and obtained a gradient of 0.15%/47 mm, which was smaller than the value of 0.8%/44 mm for the previous LF-septa [14], showing that the uniformity was improved. We started taking measures against field leakage in the circulating line in 2014. First, a copper ceiling plate with a thickness of 5 mm was mounted on top of the magnetic core to shield against the induced field generated in the bus-bar coils over the magnetic cores [3]. We measured the longitudinal distribution of the leakage field in the circulating line and found that a leakage field of 3–4 Gauss and 10 Gauss still existed in the magnetic core region and the end-fringe of the magnetic core (end-fringe field), respectively [14], indicating that we need to further reduce the leakage field by using an additional shield.

REDUCTION OF LEAKAGE FIELD IN CIRCULATING BEAM LINE

First, to reduce the end-fringe field, in 2019 we produced a rectangular trial duct made of pure iron with a length of 0.3 m. The duct was mounted on the end-fringe of the magnetic core, which allowed the end-fringe field to be reduced to below 4 Gauss. Then, in 2020 we produced a pure iron rectangular duct with a length of 2.3 m to reduce the leakage field for the entire circulating line. To prevent beam loss, we optimized the thickness of the side to 1 mm and that of the top and bottom to 3 mm. The leakage field at the center of the circulating line with the duct shield was reduced to ≈0 Gauss and the end-fringe field to 2 Gauss. The time-dependent BL is ≈0 Gauss·m at beam extraction. Based on these results, we decided to use a pure iron duct shield for beam operation. The actual duct shields for Eddy-1,2 were designed in 2021. A length of 2.244 m was used, where the length of the vacuum chamber is 2.254 m, The thickness is the same as that for the trial version. The cross-sectional shape was chosen to be an octagon to fit the shape of the circulating line. The actual duct shields are tapered along the longitudinal direction because the two eddy-septum magnetic cores have horizontal apertures that become narrower from the entrance to the exit. We optimized the inner dimensions of the duct shield using the SAD [15] beam simulation program. The inner width at the entrance and exit for Eddy-1 were set to 98.1 mm and 84.6 mm, and those for Eddy-2 were set to 83.4 mm and 74.4 mm, respectively. The inner height of the duct shield was set to 116.4 mm, larger than the size of the circulating beam. Figure 2 shows the duct shield for Eddy-1.

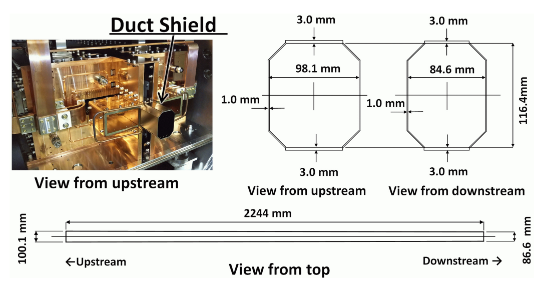

Figure 2: Location and illustration of duct shield for Eddy-1.

The production of the duct shields was competed in July 2021 and the shield for Eddy-2 was mounted in the circulating line in January 2022. In March 2022, the longitudinal distribution of the leakage field in the duct shield with V_{FT} of 3 kV and 4.5 kV was measured along three tracks: in the center of the duct shield (center track), parallel to the beam direction, and at ±26 mm from the center track in the horizontal direction (±26-mm tracks). The measurement results together with the leakage field without the duct shield measured in 2019 are shown in Fig. 3. The field strength in the region of the magnetic cores on all tracks were reduced to below 0.1 Gauss. In addition, the end-fringe field of ≈10 Gauss was also reduced to a few Gauss, although we found that the end-fringe field had an asymmetric distribution with

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respect to 0 Gauss due to the magnetic field generated by the current passing through the bus bars over the magnetic cores. The time-dependent BL on the center track without any duct shield reached 1 Gauss×m, and was reduced to ≈0.2 Gauss×m using the duct shield. The maximum BL values with V_{FT} of 3 kV and 4.5 kV on the −26-mm track were 0.4 and 0.6 Gauss×m, respectively. Thus, we verified that the duct shield strongly reduced the leakage field. The duct shield for Eddy-1 was mounted in April 2022.

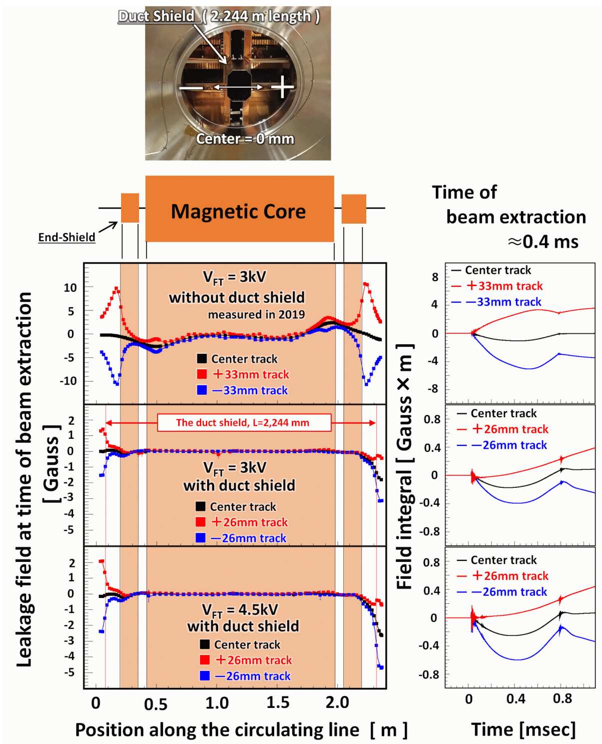

Figure 3: Leakage field and BL without any duct shields measured in 2019 (top) and with duct shield measured in 2022 (middle and bottom).

INSTALLATION OF EDDY-SEPTA SYSTEM IN MR

Both eddy-septa were mounted in the vacuum chambers and installed in the MR, and construction of the two PS sets for the eddy-septa was also completed in the electric building by the end of April 2022. We conducted the first operational tests of the Eddy-2 system, followed by the Eddy-2 system, with a maximum V_{FT} of 4.5 kV. Upgrading of the LF-septa system, including the construction of all of the eddy-septa systems, was completed in May 2022. Figure 4 shows photographs of the PS and the vacuum chambers that the septa are mounted in. Beam operation with a cycle of 1.3 s will be started in June 2022, and a high-power beam will be provided to the NU from November 2022.

Figure 4: Photograph of PS for Eddy-1 (upper) and Eddy-1,2 installed in the MR (lower).

SUMMARY

As part of the upgrade of the FX septa to increase the beam power of the MR in J-PARC, the low-field septa are being replaced with eddy-septa. New additional duct shields were produced and mounted in the circulating line in 2022, and we verified that the leakage field was greatly reduced. The installation of the eddy-septa and the power supplies was completed at the end of May 2022. Beam operation with the new 1.3-s cycle will be started in June 2022.

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