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UPGRADE OF SEPTUM MAGNETS FOR FAST EXTRACTION IN J-PARC MAIN RING

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Abstract

We aim to supply a high-power proton beam of 1.3 MW to the neutrino facility from J-PARC Main Ring (MR) by shortening the repetition cycle to 1.16 s from 2.48 s and increasing the number of particles by 1.3 times. The six septum magnets for fast extraction (FX) need to be replaced to reduce the heat that is generated as a result of shortening the repetition cycle. The replacement of the septum magnets began in July 2021 and was completed at the end of May 2022. The beam commissioning starts in June 2022. We report the details of the replacement work and operation test of the new septum magnets. We found defects in the magnetic coil of the septum (SM32) in August 2021. We decided to postpone its installation to around September 2022 and produce new magnet coils for the SM32. The beam extraction in June 2022 will be performed using a temporary vacuum duct instead of the SM32 magnet, and the extraction beam orbit will be maintained by increasing the magnetic field of the other five septum magnets.

INTRODUCTION

J-PARC MR contributes to the T2K long baseline neutrino experiment by supplying a high-intensity proton beam. The construction of Hyper-Kamiokande is underway on the neutrino detector side, and J-PARC MR on the beam supply side is also updating the equipment to increase the output beam power. An upgrade plan is in progress, which will increase the number of particles and shorten the repetition cycle, and we plan to achieve a MR output of 1.3 MW. The design values of the MR upgrade plan are 1.16 s cycle and 3.3 × 10^{14} protons per pulse [1].

Figure 1 shows the layout of the septum magnets in the J-PARC MR FX section in 2022. The FX section plays the role of beam extraction to the neutrino target and to the beam abort and is realized by providing beam lines on both sides. The details of the updated plan are described in Reference [2]. From the upstream, two EDDY current type septum magnets of about 0.3 T (as low magnetic field magnets) are connected in series with four high magnetic field septum magnets (SM30, SM31, SM32, SM33) of about 1 T. The low magnetic field septum was switched to the pulse excitation type of EDDY septum due to the heat generation problems observed during operation at 1 Hz. We manufactured new magnets for SM30, SM31 and SM32 and introduced ceramic ducts. The flanges of the circulating and the extracting ducts at the up and down streams of SM30 and SM31 and the upstream of SM32 are difficult to separate, so one large flange was welded. If the ducts and flange are all made of metal, a generating eddy current on the ducts by the excitation passes through each other. The large eddy current passes through the ducts as a large loop, resulting in the generation of heat. The loop current on the duct is expected to be several kA, and the heat generation is several tens of kW, which is unacceptable without cooling. We decided to simply use ceramic ducts instead of having a cooling structure in the vacuum ducts. Additionally, we have a plan to manufacture a large aperture QDT (one type of quadrupole magnet in the MR) magnet to expand the beam aperture in the future, and we have shortened the magnet length of the high magnetic field septum to secure the new QDT magnet length.

Two of the power supplies for the EDDY magnets needed to be replaced because of the change to pulse excitation. The EDDY magnet can generate about twice the required magnet field and continue the beam operation even if one unit becomes inoperable. As for the high field septum magnets, their power supplies are reused. The four high magnetic field power supplies are capable of outputting 4.5kA-300V and were manufactured as power supplies that apply with the initial design value of MR 50 GeV acceleration. The MR is currently accelerating to 30 GeV, and

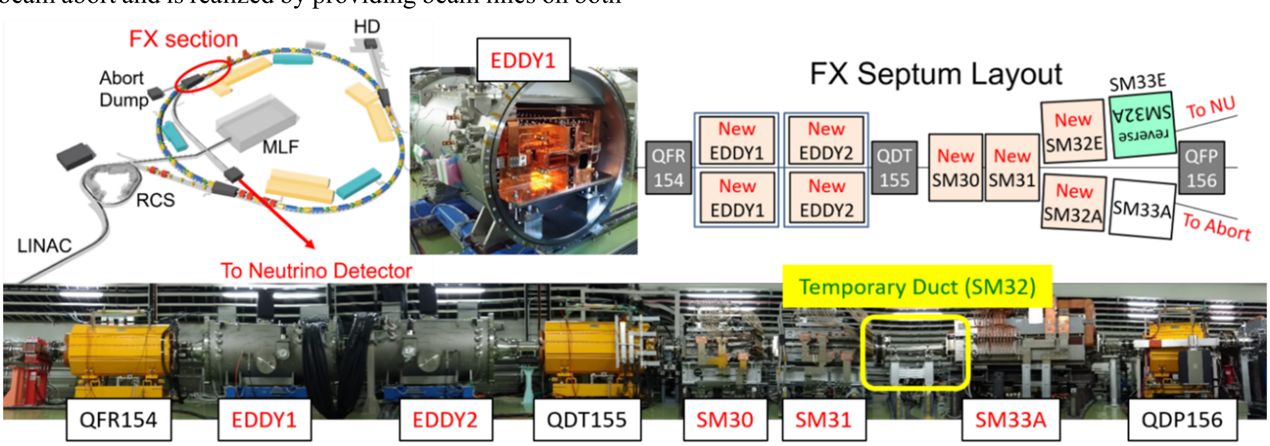

Figure 1: Pictures and schematic layout of the fast extraction septum magnets.

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even with the 1.3 MW upgrade plan, it is not changed. Therefore, the power supply has a large margin, and we also set a higher current tolerance on the magnet side to give a large margin as a high magnetic field output. This makes it possible to continue the beam operation by increasing the excitation current of the other magnets even if one of the septum magnets is broken.

PROBLEMS WITH THE SM32 COIL

Replacement works of the FX septum magnets have been underway since July 2021, but operation tests such as magnetic field measurements have been conducted for several years. We have completed testing of two EDDY magnets [3] [4] and SM30 and SM31 magnets [5] by 2020. The last SM32 septum magnet was planned to be tested in 2021; however, it was postponed after a water leak was detected and found to be the result of cracks in the two coils of copper hollow conductor. While the water leak was stopped with putty and temporarily restored to start the test, discharge was observed from the brazed part of the coil turn. Figure 2 shows photographs of the coil in the problem. The discharge occurred at 1.0 kA current against the rated 3.0 kA. It was thought that the brazing was defective, and it was difficult to repair. We gave up using these coils and decided to make new ones.

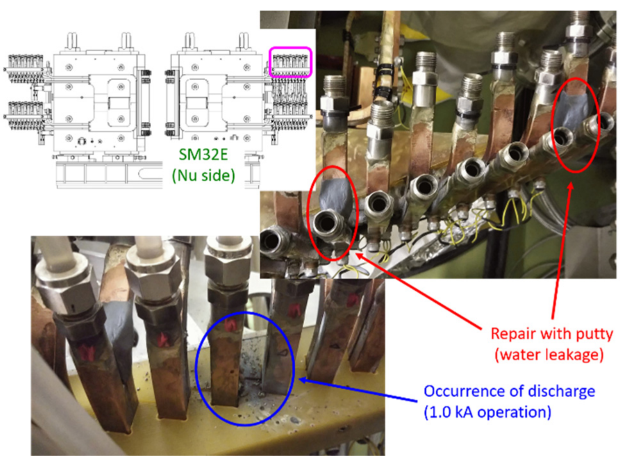


Figure 2: Problems with SM32 coil.

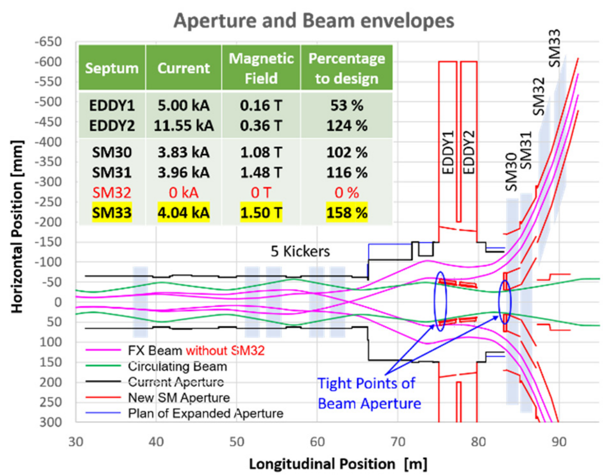
According to the operation plan, a beam test (no beam supply to users) will be conducted in June 2022, and user supply will start in November 2022. July–October is the summer maintenance period, and there will be no beam operation. Since the new coil will not be operational in time for June 2022, we decided to install SM32 in around September and operate the beam in June without the SM32 magnet.

ORBIT STUDY WITHOUT THE SM32

The updated septum magnets are designed so that operation can be continued even if one magnet or power supply is missing. A benefit of changing the low magnetic field septum (FX-EDDY) located upstream to a pulse-excited type, is that it is able to generate a magnetic field that is about twice as high. Failure countermeasures, including other magnets, are described in detail in the proceedings of this conference [6].

Figure 3 shows the extracted beam orbit without the SM32 magnet. If there is no SM32, the amount of excitation of the surrounding septum magnets SM31 and SM33 will be large to maintain the extracting orbit. The magnetic field needs to be about 1.5 T, which is generated by the exciting current of about 4 kA. It has been confirmed that there is no problem by conducting an excitation test up to 4 kA for SM31 and 4.2 kA for SM33. Saturation was measured to be about 3%.

The new SM32 coil is scheduled to be completed in August 2022, but there is a possibility that the coil of the abort beam line side (Abort-side) will not be in time. Here, we plan to operate the user run after November without SM32. Alternatively, we are considering another solution to make room for adjustment by setting the SM32 magnet using only the coil on the neutrino side (NU-side). There is no problem in the calculation and simulation, and we are preparing for that case.



Septum	Current	Magnetic Field	Percentage to design
EDDY1	5.00 kA	0.16 T	53 %
EDDY2	11.55 kA	0.36 T	124 %
SM30	3.83 kA	1.08 T	102 %
SM31	3.96 kA	1.48 T	116 %
SM32	0 kA	0 T	0 %
SM33	4.04 kA	1.50 T	158 %

Figure 3: Beam orbit calculation without SM32.

INSTALLATION AND ALIGNMENT

Since the SM32 septum magnet will not be introduced in time, a temporary vacuum duct was newly manufactured and connected. Additionally, a connecting duct has been introduced between QDT155 and SM30. A partition is set in the vacuum of this connecting duct to prevent the large proton beams from directly hitting the SM30 upstream flange and breaking it if one of the EDDY septum magnets upstream of QDT155 misfires.

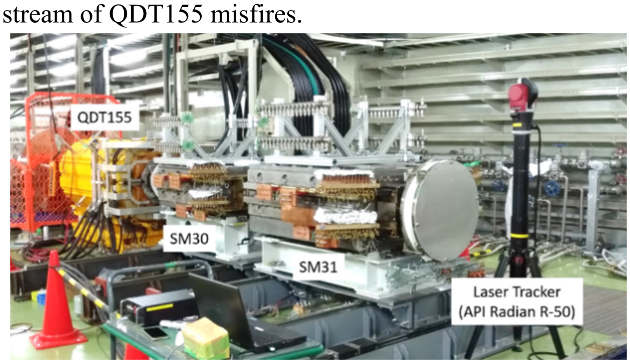


Figure 4: Photograph of the installation work.

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Figure 4 shows a photograph of the installation work. The septum magnets are installed on two rails and pulled out from the beamline so that maintenance can be performed. The rails and magnets were aligned using a laser tracker, and the installation accuracy was about 0.1 mm. The clearance of the beam aperture in design is at least 1 mm, but it may not be maintained due to the accuracy of assembly. Vacuum equipment inserts a bellows duct, but only a deviation of about 0.5 mm can be tolerated. Vacuum connecting is prioritized, but it is important to record the final septum position from the viewpoint of later beam orbit calculation and beam loss estimation.

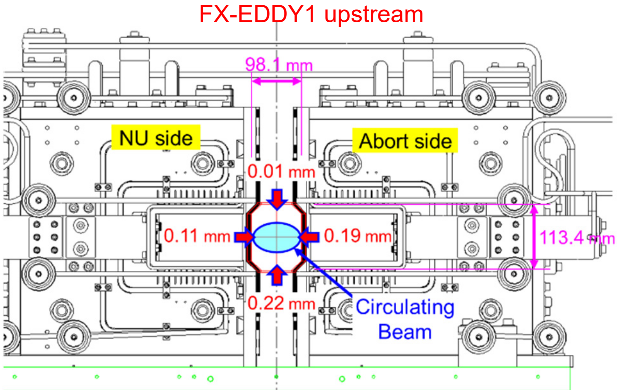

Figure 5: Alignment results of EDDY1 upstream.

Figure 5 shows the septum position upstream of FX-EDDY1 after the alignment. It is significant to secure the aperture of the circulating beam in the place where the orbit clearance of the FX is the least. Although it depends on the tune and the excitation of each quadrupole magnet, it is difficult to maintain the aperture for all the tune candidates. This is an important guideline because the orbit will be adjusted concerning this alignment result. The numerical values in the figure represent deviations from the design values. An inner duct is located in a vacuum to suppress the leakage of the magnetic field. The duct was manufactured as narrow as 0.3 mm, and the result agrees well with the measurement. The center position of the circulating duct was aligned with only a deviation of 0.04 mm, and the installation was performed with good accuracy.

Figure 6 shows the result of the upstream of SM30, which is also a tight position. Similar to FX-EDDY1, an

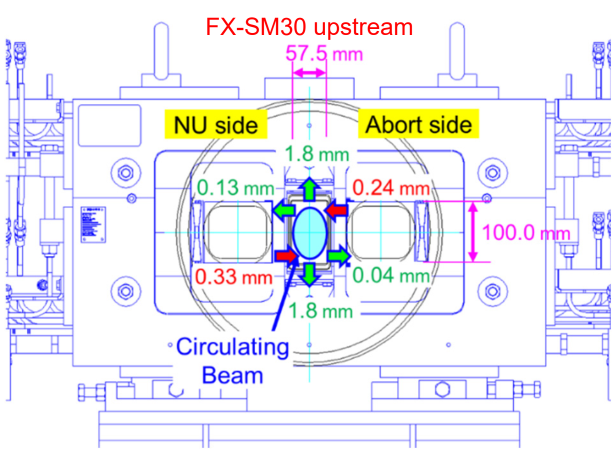

Figure 6: Alignment results of SM30 upstream.

inner duct for suppressing leakage magnetic field was installed in the vacuum. As it is manufactured by welding an iron plate with a thickness of 1 mm in the horizontal direction and 3 mm in the vertical, distortion of about 0.3 mm is allowed. In the case of the upstream of SM30, it is a parallelogram; however, as shown in the figure, alignment is performed in the center position.

BEAM STUDY IN JUNE 2022

Beam operation is scheduled for June 2022 but has not yet started at the time of writing this paper. The operation in June is performed with a 1.36-second repetition cycle, and only the adjustment operation on the accelerator side is performed without supplying to the user. Although there is no SM32 septum magnet, it will be confirmed to extract the beam to the abort at 1 Hz operation using the updated septum magnets. We expect that various results will be obtained, including the beam loss situation.

CONCLUSION

The upgrading work started in July 2021 has been completed, and the beam operation is ready to start. A problem was identified with the SM32 septum magnet that will result in operation in June 2022 being carried out without the SM32 magnet. The beam is extracted to the abort line with the 1.36-second cycle. In the future, we will shorten the repetition cycle to 1.16-second and increase the number of particles to achieve an output of 1.3 MW. The problematic coils of the SM32 magnet will be replaced with new ones. The completion of SM32 is scheduled for around September 2022, and we are preparing for an early introduction.

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