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UPGRADE OF J-PRAC FAST EXTRACTION SYSTEM

K.Fan#, K. Ishii, N. Matsumoto, T. Sugimoto, T. Shibata, H. Matsumoto, KEK, Tsukuba, Japan
Y. Kawaguchi, Nichicon, Japan

Abstract

The J-PARC main ring (MR) fast extraction (FX) system has two functions: to deliver a high power beam to the neutrino experimental facility and to dump the beam at any time in case of hardware failures. The present FX system consists of five bipolar kickers and eight bipolar septa. In order to raise the beam power to the design limit, both the beam intensity and the repetition rate will increase gradually. The FX system needs to be upgraded to satisfy the new requirements. The upgrade includes FX orbit optimization and new design of devices. Firstly, two high performance eddy current septa have been designed and fabricated. Then downstream high field septa are redesigned and using ceramic beam pipe to eliminate eddy current effects, which meets the requirement of high repetition rate operation. A new large physical aperture quadrupole is needed to accommodate high intensity beam. In order to evaluate the beam loss in the new system, realistic 3D beam tracking is studied.

INTRODUCTION

The J-PARC MR is being upgraded to increase its beam power to the design limit by increasing the beam intensity and the operation repetition rate, which will impose high requirements to the FX system. The present FX system consists of five kicker magnets (K1~5) and eight septa as shown in Fig. 1. The septa system consists of four low-field septum magnets (SM11/12/21/22) installed in two vacuum chambers, and four high-field septa (SM30~33) installed outside of vacuum. The FX system has two functions: extract normal beam at 30 GeV to the neutrino experimental target, and abort beam at any energy to the garbage when the interlock system is fired. Thus, all the kickers and the septa are designed to be able to generate bipolar magnetic fields to realize the two functions.

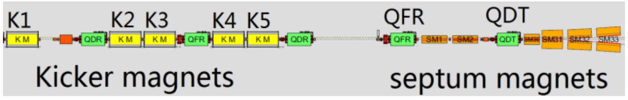

Figure 1: Layout of entire FX system.

The FX system was originally designed for 50 GeV proton beam extraction working with very low repetition rate and low beam intensity. In the future high beam power operation, however, the existing FX system may present several problems, which include, 1) low stability of the low-field septa in high repetition rate operation due to mechanical configuration, 2) large beam losses due to the insufficient physical aperture of quadrupole, and 3) large leakage field of high-field septa in high repetition rate operation due to loop eddy currents. These problems will increase the beam loss particularly at the injection period and at the start of acceleration.

To realize the high beam power operation, we must not only fix the problems of the existing systems, but also need to develop new system to deal with the potential problems that may arise in high beam power operation. Thus, a new FX system is being upgraded.

NEW FX SYSTEM

The new FX system will change the configuration at downstream to improve the performance and to make enough space for the quadrupole upgrade. The upgrade includes: a) use two long eddy current septa to replace the present four low-field conventional septa, b) design new quadrupole with large physical aperture to accommodate high intensity beam, and c) design new high field septa at downstream. The layout of the new FX at downstream is shown in Fig. 2, in which 5 kickers located upstream of QFR are not shown.

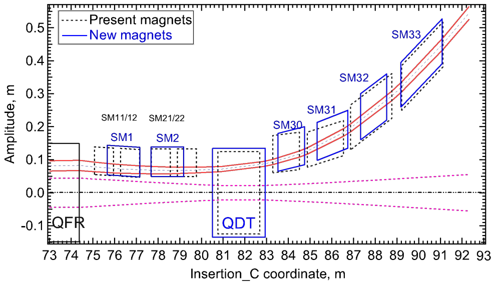

Figure 2: New FX system configuration at downstream.

Eddy Current Septum Design

The existing low-field septa are located in the between of two quadrupoles (QFR and QDT), which consists four conventional multi-turn septum magnets. They have relatively large leakage field and low operation stability due to its mechanical structure [1]. Two new design eddy current septa SM1 and SM2 are the first subject of the upgrade project to replace the existing four septa. Eddy current type septum permits thinner passive septum improving the mechanical stability. Since they are excited only at the extraction energy, the leakage field effects can be neglected. One major concern of the new eddy current septum is the possible particle losses of the extracted beam at higher beam power due to its narrow beam separation in the x-direction. Thus the septum is required to be designed as thin as possible. However, the eddy current septum must produce field with long flat top period (>5 μs) to accommodate all extracted beams in

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#kj.fan@kek.jp

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MR ring. To ensure the flatness of the top field the excitation current pulse width must longer than 1 ms, which not only requires thick eddy current septum to prevent eddy current diffusion but also makes gap field quality worse. To deal with these difficulties, a novel design of using superposition a 3rd harmonic to a fundamental sinusoidal pulse is adopted [1,2].

To reduce eddy current septum thickness further without affecting the gap field quality, the septum plate is divided into inner and outer parts, which is shown in Fig. 3. Furthermore, a thin magnetic shield is added on the septum to suppress the leakage field.

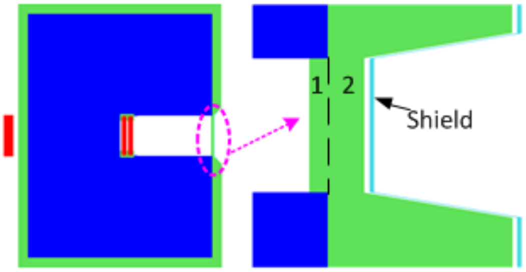

Figure 3: Eddy current septum structure.

The new septa are designed with a large physical aperture so that it can accommodate the extracted beam of 70 πmm.mrad. As a consequence one of the detrimental effects is the large end fringe field that will impair the circulating beam. End field clamps are implemented that can reduce the fringe leakage field greatly, Fig. 4 shows the new eddy current septum in field test.

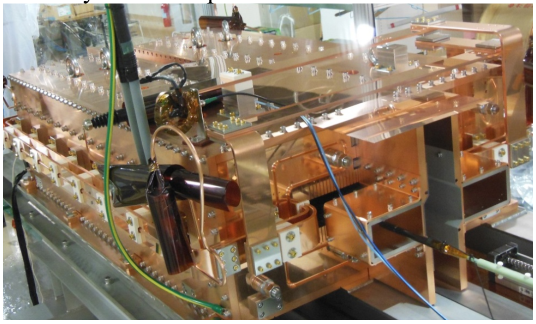

Figure 4: Eddy current septum in test.

Large Aperture Quadrupole Magnet (QDT)

The acceptance of QDT155 was designed for the low intensity proton beam with energy of 50 GeV. However, the extracted beam energy reduces from 50 GeV to 30 GeV, while the beam intensity will increase nearly double to realize the beam power of 720 kW. The extracted beam emittance is expected increase a lot due to the space charge effects, which may exceed the acceptance of the Q magnet. In order to examine the physical aperture of the QDT155, we need to track a realistic particle distribution through the 3D model. The x-values at the QDT155 exit is most critical to the operation since the extracted beam has its crest in the y-direction and could be lost due to a limited vertical aperture there. This can be seen from the Fig. 5, where the available vertical apertures including the vacuum chamber thickness are plotted. It shows clearly that high intensity beam with 10 π emittance will hit on pipe if the incident beam exits from the QFR with an initial angle of 0.55°. To avoid beam loss, the reference trajectory is preferred to closer to the QDT center, which requires less kick angle of the low-field septa, however, it creates difficulties for downstream high-field septa.

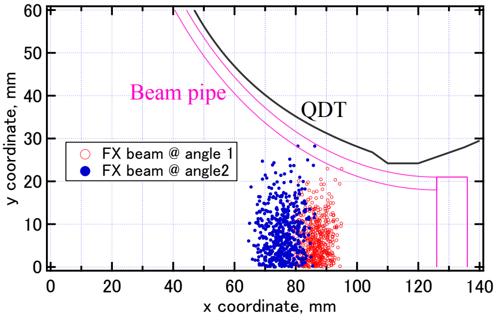

Figure 5: Limitation of Q magnet aperture.

In order to eliminate any beam losses, the physical aperture is increased from 150 mm to 220 mm, which creates challenges for magnet design. One important design task is to eliminate material saturation at pole tip. The magnet length has to be increase 500 mm to reduce the required gap field. However, the lattice symmetry is broken if only one QDT is changed that leads to beam loss. Beam optics study shows that three QDTs are needed at least to ensure beam quality. The cross section of the new QDT is shown in Fig. 6. Large aperture creates another problem that the extracted beam will suffer significant high order field components due to large fringe field.

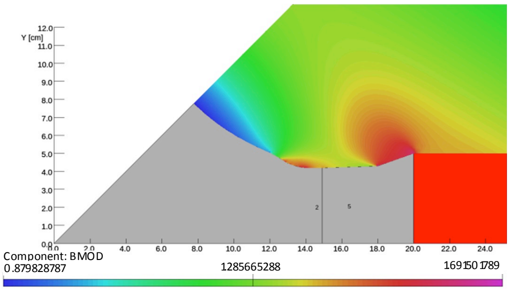

Figure 6: Magnetic field in Q magnet pole.

Existing High-field Septa Problem

The FX system was original designed for the extraction of 50 GeV proton beam, which requires very high field integral. Four large-size high-field septa are mounted in a limited space. Since the operation repetition rate is only 0.3 Hz, the eddy current effects were overlooked and stainless beam pipe was used to save cost. However, the compact installation space makes the circulating beam pipes and extraction beam pipe electrical connected. It provides a loop path for the eddy current, which magnifies the eddy currents effects during the acceleration period [2]. The eddy current effects will become severe in future high repetition rate operation.

The new design of the high-field septa becomes shorter to make more clearance to separate individual septum. One important improvement is using ceramic pipe to improve gap field quality and to eliminate eddy current effects on circulating beam. The 3D model of high field septa is shown in Fig. 7, among which the old SM33 will be reused.

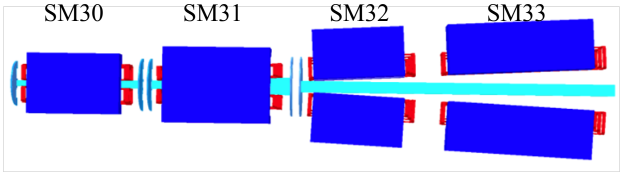

Figure 7: FX high-field septa layout.

SM30/31 Design

The SM30 and SM31 have the similar structure. Two septum magnets generate opposite field for beam extraction and abort beam are integrated in one big magnet core due to narrow beam separation, which is shown in Fig. 8. This configuration has the benefit that the core provides path for leakage field, which can reduce the leakage field greatly in the middle of the circulation beam pipe.

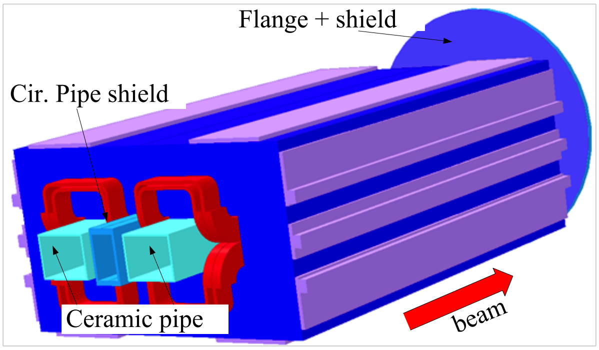

Figure 8: Bipolar septum in one magnetic core.

However, at the magnet end the large fringe field exists due to the large physical aperture and the end coils. The fringe field will penetrate to the circulating beam region creating significant leakage field as shown in Fig. 9. In order to prevent the leakage fields impair the circulating beam magnetic shield is needed to reduce the leakage. Shield plates are added to the circulating beam pipe and the flange. Figure 9 compares the shield effects.

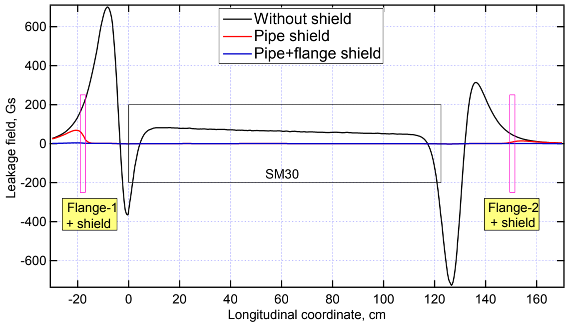

Figure 9: Leakage field suppression.

SM32 Design

The SM32 consists of two independent septum magnets because of the large beam separation as shown in Fig. 10, in which only 1/4 magnet is shown due to symmetry. This configuration leads to relatively large leakage field compared with the one unit core type septum SM30, thus special care is needed to design shield structure for the circulating beam pipe.

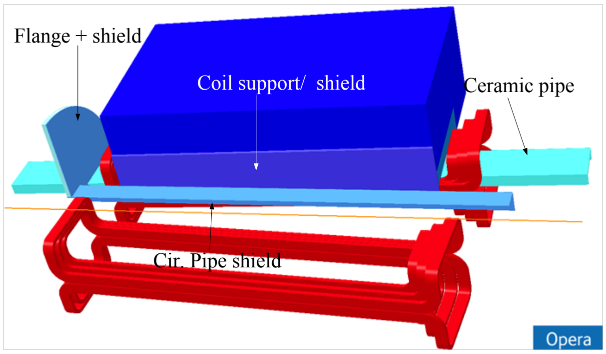

Figure 10: SM32 structure.

By optimization the shield configuration, the leakage field can be suppressed greatly. The main components of the leakage field integral are quadrupole and octupole, which can be reduced one order lower after shield. Figure 11 compares the multi-pole components of the leakage field integral with and without shield.

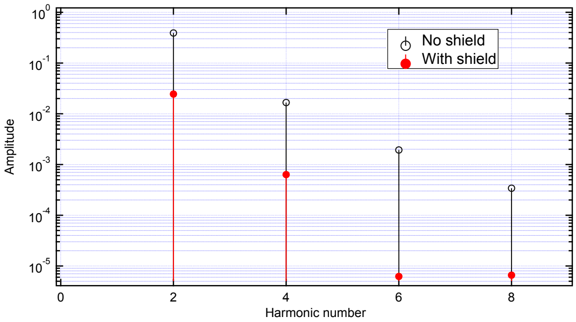

Figure 11: Leakage fields suppression by shield.

SUMMARY

In order to realize high beam power operation, the existing FX system needs to be upgraded. The highlights of the FX system upgrade are the follows: 1) Superposition of 3rd harmonic to generate enough flattop field for the eddy current septum. 2) Realistic reference particle trajectories through the model are produced to examine design parameters. 3) Magnetic fields on the reference trajectories and their harmonic contents are accurately calculated for the study of particle beam dynamics. 4) Ceramic beam pipes are implemented to ensure the high gap field quality in high repetition rate operation.

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