THE DEVELOPMENT OF A NEW LOW FIELD SEPTUM MAGNET SYSTEM FOR FAST EXTRACTION IN MAIN RING OF J-PARC

T.Shibata*, K.Ishii, T.Sugimoto, H.Matsumoto, KEK, Tsukuba, Japan
K.Fan[1], HUST, Wuhan, China

Abstract

The J-PARC Main Ring are working on improved beam power to 750 kW by shortening the repetition period from 2.48 s to 1.3 s. The low-field septum magnets in the fast extraction beam line will be replaced by new magnets around 2020. We constructed a test-bench of a new magnet which are induced eddy current type and a new power supply in 2014. We were in trouble with the periodic radiative noise which had effect on the stability of output current. We tried to protect against the radiative noise, and finally we were able to solve the problem.

In March 2018, we introduced a new Sub-charger system instead of the Dropper which broke down in 2016 due to difficulty of its tuning. Since the scheme of the Sub-charger is simpler than that of Dropper, we can expect to operate stably. The stability of output current requires below 100 ppm, and we confirmed the Sub-charger system satisfied that. We measured the horizontal distribution of the field integral of the magnetic gap field, and the flatness was 0.04%/50 mm which is much smaller than that of current low-field septum magnets.

INTRODUCTION

For increasing the beam power of Main Ring (MR) in J-PARC for Fast eXtraction (FX) to 750 kW, the repetition period of beam operation must be shortened to 1.3 s from 2.48 s of which is current value [1]. We are on upgrade of most injection and FX magnet systems [2–4]. We are planning to replace the current two Low-Field Septa (LF FX-Septa) and their Power Supplies (P.S.) due to several reasons [5,6]. First, the current LF FX-Septa are conventional type, which use hollow conductors for the septum coil, have a problem with a durability of insulator on the surface of the septum coil by its vibration. Second is that the large leakage quadrupole field still exists in the circulating beam line. Another is we need large aperture than current one to reduce the radioactivation by collision with beam halo of which will increase the intensity in future upgrade.

The new LF FX-Septa, which are induced eddy current type and be called Eddy-Septa (Fig. 1), have the advantage of the current LF FX-Septa [6] to solve above problems. The Eddy-Septa have no septum coil, but they have thin septum plate, thus, there is no longer problem with the durability of the septum coil. In addition, the aperture can be expanded larger than current's one. Second is that the leakage field on the circulating beam line can be reduced below 10^{-4} of the gap field by induced magnetic field which is generated by eddy current on the surface of the septum plate. Furthermore,
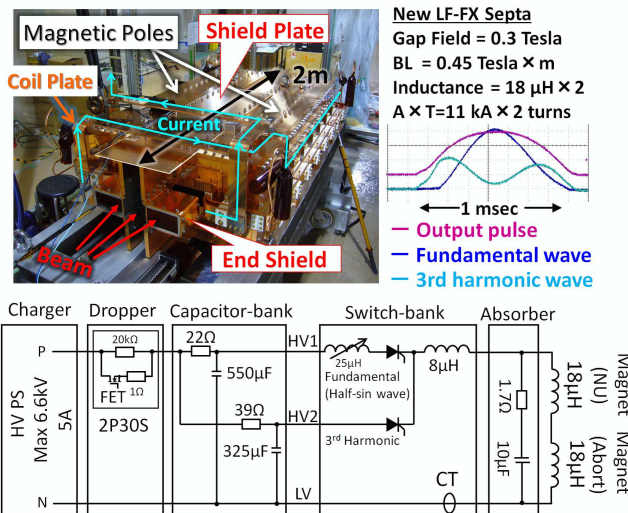
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* tatsunobu.shibata@j-parc.jp

Figure 1: The photograph of the magnet (upper) and the circuit diagram of the Power Supply (lower) for new Eddy-Septa. This P.S. outputs pulsed current.

since the Eddy-Septa need a short-pulsed current of which the time width is ~1 ms, the effect on the circulating beam by the leakage field should be small. In fact, an induced eddy current magnet is already used in the injection beam line in MR [7].

The circuit diagram of the new P.S. of which the maximum output is 6 kV×22 kA is shown in Fig. 1. It consists of Chargers, a Dropper, a Capacitor-bank, a Switch-bank, and a Surge absorber [6]. The several Chargers of which the maximum output is 6.6 kV×5 A can be operated by parallel connection for quick charging. A Dropper receives the charging voltage from the Chargers, and charges to capacitors precisely by dropping the charging voltage about 10%. A Capacitor-bank has two parallel capacitors of which the capacities are respectively 550 uF and 325 uF, and the two switch groups in a Switch-bank allow the accumulated charge in each capacitor to discharge at difference timing. The shape of each output pulsed current is respectively fundamental and 3rd harmonic sin-wave.

Thus, we can adjust the flatness at the flat-top of 10 μs of the output pulsed current to 10^{-4} by superimposition of these two sin-wave. The charging voltage is controlled by an ordinary analog feedback system for high stability and reproducibility below 100 ppm. In addition, a precise digital feedback system is also introduced to suppress the long-term drift of the output current.
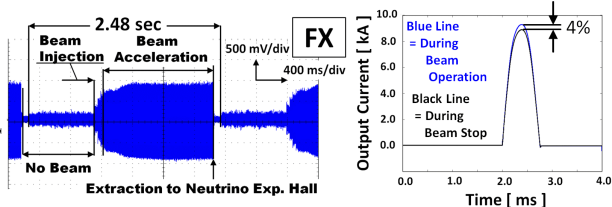
Figure 2: The periodic radiative noise in the V_{ref} signal (left), and the comparison the waveforms of the output current with before and after the measures (right).

A test-bench of the first Eddy-Septa system have been constructed in a power supply building in MR area in 2014, and we have been studying its performance. Two Eddy-Septa systems will be completed around 2020.

STATUS OF THE NEW POWER SUPPLY

Protection Against Radiative Noise

The periodic radiative noise, of which was synchronized with the beam operation in MR, was observed in the power supply building in 2016 [6] (Fig. 2). In 2017, the same radiative noise was detected near the entrance of the sub-tunnel [1] in the other power supply buildings in MR area. We infered that the source of the radiative noise is wake field which was generated by the proton beam in MR, and it traveled through the sub-tunnel to ground and released into the power supply building. Since the P.S. for Eddy-Septa was located near the entrance of the sub-tunnel, the radiative noise had major effect to the P.S. We found that an analog reference voltage (V_{ref}) signal, which is sent from the control unit to the Chargers and determines the charging voltage, was affected by the radiative noise. First, we measured the reproducibility of output current pulse by pulse during the beam operation in MR in Oct. 2017, the result was $\pm$r.m.s/average = $\pm0.1\%$. Furthermore, Fig. 2 shows the approximately 4% jump by the radiative noise. The V_{ref} signal had to be protected against the noise.

We had taken some measures to protect the V_{ref} cable against the radiative noise. A toroidal coil filter with the FINEMET-core was introduced, and a route of the wiring and the grounding of the V_{ref} cable were optimized, and it was covered with aluminum foils. After taking the above measures, we measured the reproducibility again during beam operation in MR in Dec. 2017. As the result in Fig. 3, we were able to improve on the reproducibility to $\pm0.024\%$, and reduce the jump of the current to approximately 0.3%. Although the results did not satisfy our requirement of which is below 100 ppm. we were able to understand the effect on the P.S. by the radiation noise.

The New Sub-Charger System Development

Since we had several experiences in breakdown of the Dropper during 2014-2016, the Dropper was removed re-

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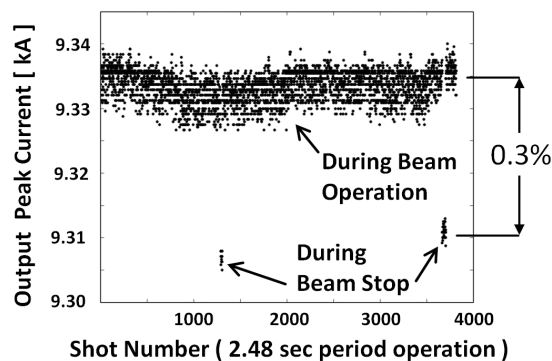[1] The sub-tunnel is an aisle to connect power or signal cables between ground and MR tunnel.

Figure 3: The time variation of the output current with protection the V_{ref} cable against the radiative noise.
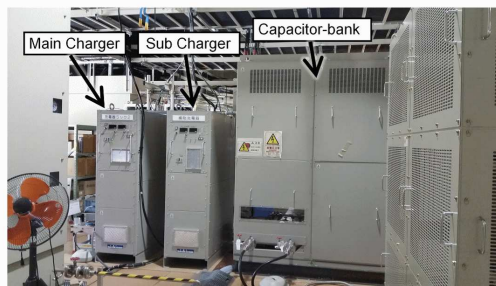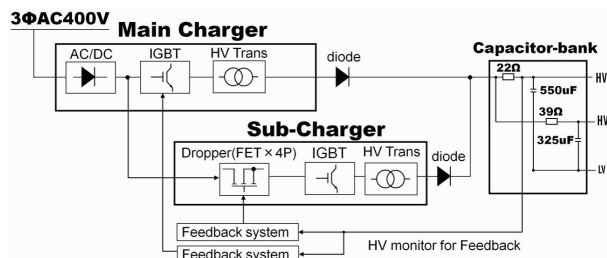
Figure 4: The schematic diagram (upper) and the photograph (lower) of the new Sub-charger system.

gardless of its high stability of the charging voltage. Then, we have decided to introduce a new charger system by using a Sub-charger in 2017. The detail of the problem with the Dropper and the necessity of a Sub-charger system have been described in [6]. The construction of a Sub-charger, of which the maximum output is 6 kV$\times$0.15 A, was completed in March 2018. The schematic diagram and the photograph are shown in Fig. 4. The tuning of the Sub-charger system is easier than that of the previous one. The accuracy of the charging voltage with previous one was determined by the Dropper. However, it was quite difficult to tune 60 FETs of which are 30 series and 2 parallel connection in the Dropper. On the other hand, the Sub-charger has only 4 parallel FETs to be tuned. The procedure of the charging with the Sub-charger system is as following. First, the Main-charger charges to the capacitors directly, and stops when the charging voltage reaches 99%~99.9% of the setting voltage. After that, the charging is continued to 100% by the Sub-charger which is connected in parallel to the Main-charger. Accordingly, the accuracy of charging voltage is determined by the Sub-charger. The diodes are used to the output line of

all chargers, for protection against the return current when breakdown of the chargers or Capacitor-bank. The charging voltage are controlled by a feedback system by monitoring the charging voltage to Capacitor-bank. To solve the problem in the radiative noise, we changed the method of V_{ref} signal from analog voltage to a serial communication, and fiber-optics are used for all the control signals from the controller unit to the chargers. We were able to achieve 20 ppm of the stability at flat-top of the charging voltage by tuning the Sub-charger in March 2018. The stability of the output current was measured during the beam operation in MR by using the Sub-charger system. Fig. 5 shows the time variation of the output current of which the Y axis is the difference from average current divided by average current. The reproducibility was ±10 ppm (70 ppm pk-pk), and there was no jump by the radiative noise, then the Sub-charger system satisfied our requirement.
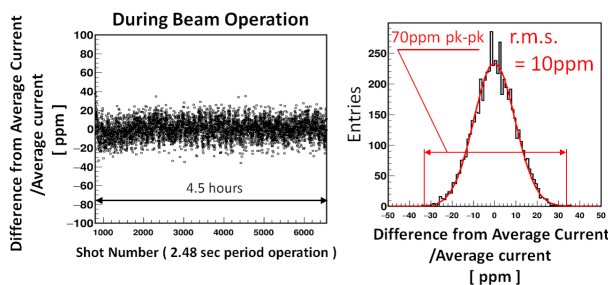

Figure 5: The time variation of the output current (left), and its distribution (right).

MAGNETIC GAP FIELD MEASUREMENT

We measured the magnetic field and its field integral in the gap space in Feb. 2018. A pickup coil was used for sensor of the magnetic field [6]. The position of the coil on th rail located along the beam direction was measured by a laser rangefinder with the accuracy of approximately ±0.5 mm. The gap field distribution along beam direction at the center of the gap space is shown in Fig. 6. The measured magnetic field in the gap was approximately 0.3 Tesla which was same as that of the current LF FX-Septa.

We also measured the field integrals and their flatness along horizontal direction, then the position of the track was varied in the range of -30 mm to +20 mm with reference to the center of gap. The result is shown in Fig. 7. The field integrals were higher than typical value of the current LF FX-Septa of 0.44 Tesla×m. The flatness was within approximately 0.04%/50 mm, which was smaller than that of current one by 1 or more orders of magnitude.

SUMMARY

We presented the status of the new FX LF-Septa, of which is Eddy-Septa type. We were able to solve a problem with the radiative noise synchronized with beam operation in MR which caused the instability of the output current. We have
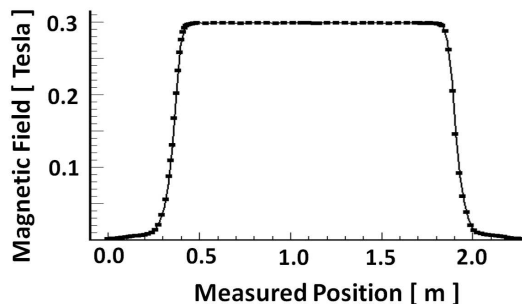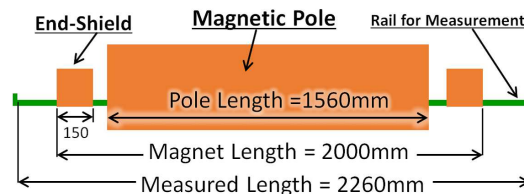

Figure 6: The position distribution of the gap field along a track at the center of gap.
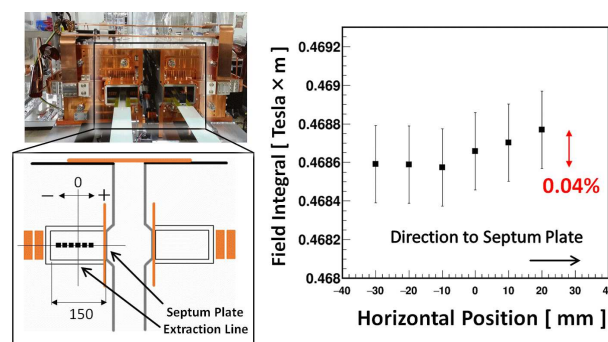

Figure 7: The horizontal distribution of the field integral along the beam direction.

constructed a new Sub-charger system instead of the Dropper in March 2018. The gap field distribution was quite good compared to the current one.

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