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

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Abstract

The J-PARC Main Ring (MR) is currently working on upgrading the machine power reach to 750 kW by increasing the beam repetition rate from 0.4 Hz to 0.78 Hz. This new operation mode is referred as "1 Hz" operation. The Fast eXtraction (FX) system in MR needs to upgrade to realize 1 Hz operation, and the improvement will be completed in 2021. The present FX Low-Field Septa (FX LF-Septa) which are conventional ones will be replaced with the new septa which is induced eddy current type (FX Eddy-Septa). The first FX Eddy-Septa system, which included the magnets and short pulse power supply (PS), was constructed in 2014. We have been studying the FX Eddy-Septa system to evaluate the stability of the output pulsed current and magnetic gap field since 2014. In winter of 2018, the 1 Hz operation test by using the two Main-chargers was conducted without any problem. The stability of the output pulsed current was 10 ppm. The leakage field was measured along the circulating beam line, and we found that the level of leakage field was still larger than our requirement. The PS has still several issues which must be solved. The switching time of the Main-charger to the Sub-charger must be reduced, the jitter of time lag between two discharge triggers must be eliminated, and the disagreement between the two current monitor systems must be solved.

INTRODUCTION

The J-PARC Main Ring (MR) is being upgraded to increase its proton beam power for T2K experiment to design value of 750 kW by increasing the repetition rate of beam operation from present 0.4 Hz to 0.78 Hz [1]. The new operation mode is referred as "1 Hz operation". We are upgrading the injection system and Fast eXtraction (FX) system of MR for 1 Hz operation [2–5], and the improvement will be completed in 2021. The FX system is used for extracting the beam to the neutrino facility or beam abort dump. It consists of five kicker magnets, Low-Field Septum magnets (LF-Septa) and high-field Septum magnets [6]. The present LF FX-Septa will be replaced with new septa system which includes the septa and their power supply (PS). The present septa are conventional ones, on the other hand the new septa are induced eddy current type (FX Eddy-Septa) [7]. The first Eddy-Septa and new PS were constructed in 2014, then we have been evaluating the quality of the PS and the magnetic field. The new PS consists of two Main-chargers and a Sub-charger of which the maximum output of one unit is

respectively 6.6 kV×5 A and 6.0 kV×0.15 A, a Capacitor-bank (C-bank) of which the total capacitance of the two parallel capacitors is 875 uF, a Switch-bank and a Surge-absorber [5]. The maximum output pulse is 6.6 kV×22 kA, and normal output for beam operation will be 3 kV×11 kA. The output pulsed current consists of fundamental and 3rd harmonic sinusoidal wave, and the pulse width and flat top width of the composite wave is respectively ~800 us and ~10 us. The reproducibility of the peak current pulse by pulse achieved 10 ppm [5]. The magnetic gap field and the field integral, when the output pulsed current was 9 kA, were respectively 0.3 T and 0.47 T·m, which they satisfied our requirement. This paper describes the new results of the 1 Hz operation test and measurement of leakage field along the circulating beam line, and several pending technical issues.

THE 1.0 HZ OPERATION

Since the maximum repetition period of the operation was 2.48 s until summer of 2018, only one Main-charger was used. In order to increase the repetition rate of the operation, the speed of charging to the C-bank is needed to increase. The charging current is proportional to the speed of charging. For instance, when the charging voltage is 3 kV and its rise time is 0.3 s, the charging current is 8.75 A. It is higher than maximum output current of one Main-charger. Therefore, the two Main-chargers were used for 1.0 Hz operation of the PS in Nov. 2018. The repetition rates of the operations were 0.40 Hz, 0.86 Hz and 1.00 Hz. The charging voltage was 3 kV. All operations were continued for ~6 hours without any problem, furthermore the average value of the peak current was able to be kept constant. The reproducibility, of which the definition is r.m.s/average, of the peak current pulse by pulse was also evaluated. The all reproducibilities were 10 ppm. The operation conditions and the results are summarized in Tab. 1.

Table 1: The Operation Condition and Results of the Operations.

Rate [Hz]	rise time [s]	peak current (average) [A]	r.m.s./ave. [ppm]
0.40	0.6	9224.97	10.3
0.86	0.3	9224.97	10.1
1.00	0.3	9224.97	10.1

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MC4: Hadron Accelerators

A17 High Intensity Accelerators
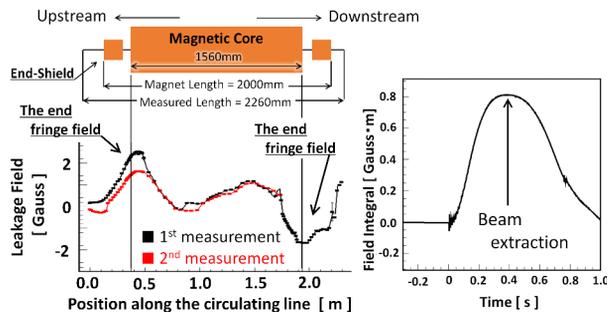
Figure 1: The longitudinal distribution of the leakage field along the circulating line (Left). The time dependent field integrated of the leakage field (Right).

LEAKAGE FIELD MEASUREMENT

The longitudinal distribution of the leakage field and the time dependent field integral (BL) along the circulating beam line of which the range was 2.3 m were measured twice by using a pick-up coil in 2018 (Fig. 1). The charging voltage was 3 kV of which the gap field corresponds to 0.3 T. Our requirement for reduction of the leakage field is below 0.3 Gauss which corresponds to 10^{-4} of the gap field. However, the large leakage field still existed in the magnetic core region and in the end fringe of which the maximum was respectively ~1 Gauss and ~2.6 Gauss. The BL at the beam extraction was ~0.8 Gauss·m of which the bending angle corresponds to 0.001 mrad. We need to reduce the leakage field further, in specially the magnetic shields around the end fringes must be reinforced. Furthermore, an antisymmetric structure across the middle position of the magnetic core was found in the longitudinal distribution. One candidate of the cause of such a large leakage field and the antisymmetric structure is misalignment of the two magnetic cores. It must be symmetrically located across the center of the circulating beam line, however we found the misalignment of their position and direction after first measurement. The horizontal physical aperture of the circulating beam line at upstream and downstream had large discrepancy of maximum 4.5 mm. After correction of the misalignment, we were able to decrease the discrepancy to 1.4 mm. The end fringe field of the second measurement at the upstream reduced to 1.6 Gauss, on the other hand, the leakage field in the magnetic core region did not reduce significantly. Incidentally, we have a plan to install the FX Eddy-Septa in a vacuum chamber in this year. Since the FX Eddy-Septa in the vacuum chamber can be mounted on a base which has precise guides, the leakage field will be able to be measured precisely.

THE PENDING TECHNICAL ISSUES

We have still several technical issues of the PS, and the following items are being discussed how to solve.
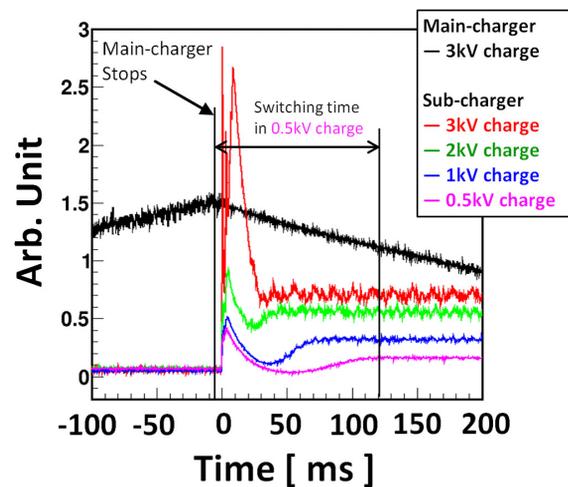
Figure 2: The switching time after optimization of the feedback system of the Main-charger and Sub-charger.

The Long Switching Time

When the charging voltage by using the Main-charger reaches 99.0%~99.9% of the setting voltage, it stops charging, and the Sub-charger starts to charge. The switching time is defined as the time interval between the Main-charger stops and the charging voltage reaches 100% by using the Sub-charger. The switching time was measured in the end of 2018, then it was found that the switching time was longer than our expectation. Furthermore, it depended on the charging voltage, e.g. when the charging voltage was 3 kV and 0.5 kV the switching time was respectively ~65 ms and ~650 ms. The results clearly show that the switching time increases as the charging voltage decreases, therefore the 1 Hz operation is impossible with low charging voltage. The switching time must be reduced to ~50 ms, which is equivalent to the smoothing time of current pattern of the main magnets of MR for 1 Hz operation. Since the switching time is determined by feedback of the Main and Sub-charger, we optimized the feedback system of both chargers. The switching time of ~65 ms and ~650 ms, which were mentioned above, was able to be reduced to respectively ~46 ms and ~126 ms (Fig. 2). However, that is still longer to operate 1 Hz, thus we need to suggest being more informative.

The Jitter of the Trigger Signals

It was found that the peak current of the output pulsed current often jumped ~150 ppm after we solved the problem of the radiative noise [5]. We measured the time lag of the two discharge trigger signals which turn on the two thyristor switches in the Switch-bank and output respectively fundamental and 3rd harmonic wave. The time lag is set to 100 us in normal operation, however we found the time lag had jitter of -0.16 us. Fig. 3 shows the correlation between the peak current (I) and the time lag (t_{lag}) by using a circuit simulation and experimental result. It found that the peak current of both data is propositional to the time
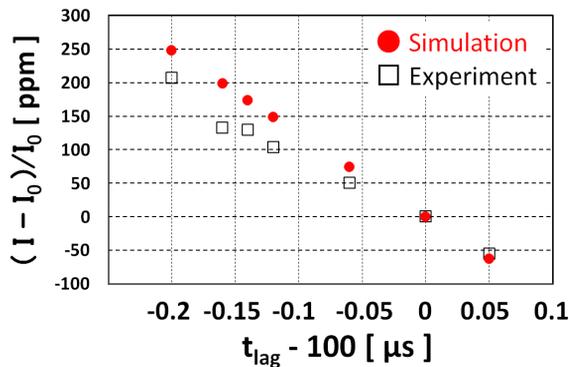
Figure 3: The correlation between the peak current and the time lag which was studied with simulation and experiment. The I_0 means the peak current with the t_{lag} of 100 us.

lag. When the time lag is -0.16 us the variation of the peak current of simulation result corresponds to ~185 ppm, it roughly agrees with experimental result. The result shows the jump of ~150 ppm is caused by the jitter of the time lag. Currently, one external signal is input to the Controller as a discharge trigger for the 3rd harmonic wave. On the other hand, the trigger signal for the fundamental wave is generated by dividing the external signal, and it is delayed with the time lag of 100 us in a counter circuit in the Controller. We guess the jitter was made around the counter circuit. After the modification of the software of the counter circuit, this phenomenon disappeared. However, we do not understand the source of this problem. In order to prevent the recurrence and solve basically, we have a plan to prepare two independent external signals for two discharge triggers which are generated by the scheduled timing system which are used in J-PARC [8]. The stability of the scheduled timing is order of ns, thus we can expect to solve the problem.

Disagreement in Two Current Monitor Systems
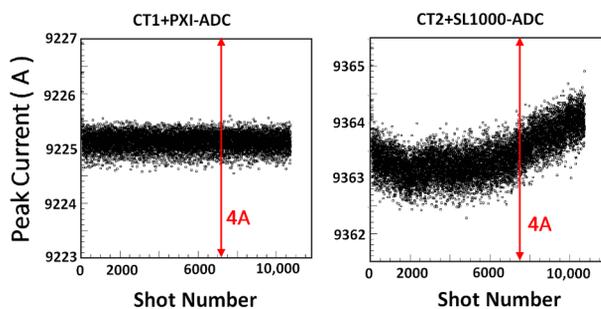
Figure 4: The time variation of the peak current of the output pulsed current by using the different monitor systems.

A current transformer (CT1) which is mounted in the Switch-bank is used for measurement of the output current. The signal of the CT1 input to a 20-bit ADC board of the PXI system (CT1+PXI-ADC) [9] which is a feedback system for long-term stability. In Jan. 2019, we added a new CT (CT2), of which the model is same as

CT1, in the Switch-bank for measurement of output current independently. The signal of the CT2 was input to a 16-bit ADC board of SL1000 which is DAQ system of YOKOGAWA-Denki (C2+SL1000-ADC) [10]. The time variation of the peak current was measured by using the two CTs for cross-check (Fig. 4). The peak current measured by using CT1+PXI-ADC was quite stable during operation. On the other hand, the slow time variation was found in the measurement by using CT2+SL1000-ADC. The results were same even if the two CTs were swapped. We guess the electric and radiative noise, which are generated by many devices of MR and the PS itself, are the cause of the time variation of CT2+SL1000-ADC. This disagreement makes us difficult to determine whether the output current is stable by feedback of the PXI system or not. Our plan for improvement is using of a mineral insulated cable for signal cable or using a copper pipe to protect against the electric and radiative noise.

SUMMARY

We are working on upgrade of the FX low-field Septum magnets for improvement of the beam power of MR in J-PARC. We operated the new low-field Septum magnet power supply with 1.0 Hz and evaluated the stability of the output current. We found the large leakage field and antisymmetric structure in its longitudinal distribution. The issues we need to solve are the long switching time of the Main-charger to the Sub-charger, the jitter of time interval between two discharge triggers, and disagreement in the output current monitor systems.

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