OPERATION OF THE OPPOSITE-FIELD SEPTUM MAGNET FOR THE J-PARC MAIN-RING INJECTION

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Abstract

An opposite-field septum magnet system has been developed for J-PARC main-ring injection. The features of the system are a force-free structure and easy pulse excitation, as well as the possibility of a large-aperture and thin-septum structure [1]. In the case of JPARC main ring injection, a larger beam aperture than the full acceptance of the ring can be obtained at the injection septum magnet for low-loss injection. In this paper we introduce an outline of the opposite-field septum magnet system and methods to eliminate error fields caused by fabrication errors and eddy currents by pulse excitation. The stability of a high current pulse power supply of 48 kA is also discussed.

INTRODUCTION

The concept of the opposite-field septum magnet is shown in Fig. 1. The same grade of opposite magnetic field is produced both inside and outside of the septum. The electromagnetic forces on the septum conductors are cancelled out by each other because of opposite magnetic fields on both sides of the septum. Fast-pulse excitation without any mechanical supports is available due to a force-free structure. The two septum conductors are arranged vertically to make a single line of septum conductors so as to form a thin septum coil. Twice as much as the return current must flow on the septum part. However in the case of low repetition-rate operation, the availability of fast-pulse excitation for power saving makes it possible to realize a much thinner and higher magnetic-field septum structure than the normal septum magnet.

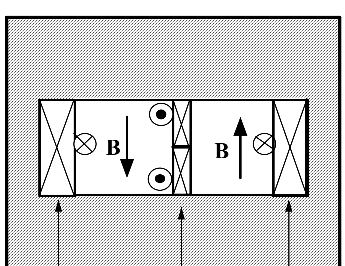

Figure 1: The fundamental concept of the opposite-field septum magnet.

As shown in Fig. 2, the magnetic field of the circulating beam side is compensated by two sub-bending magnets set up-stream and down-stream of the opposite-field septum magnet. These three magnets are connected in series and excited by the same power supply for simultaneous excitation. The beam-separation angle per septum length is twice as large as that of the normal septum magnet with the same magnetic field. The two sub-bending magnets also enhance the injection angle, like a mass-less septum, and also have a role to produce a bump orbit to close the circulating orbit to the septum during the injection/extraction periods. The thin septum structure makes it possible to obtain a sufficient aperture of the septum magnet which reduces the load of the kicker magnets.

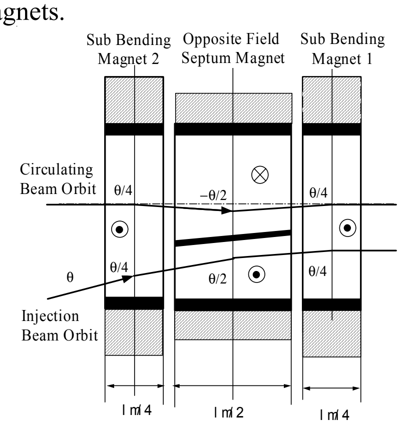

Figure 2: The concept of the opposite-field septum magnet system.

In this paper we describe the structure of the opposite-field septum magnet applied for J-PARC MR injection and how to solve technical problems of the pulse-excited opposite-field septum magnet.

OUTLINE OF THE INJECTION SYSTEM OF THE JPARC MAIN RING

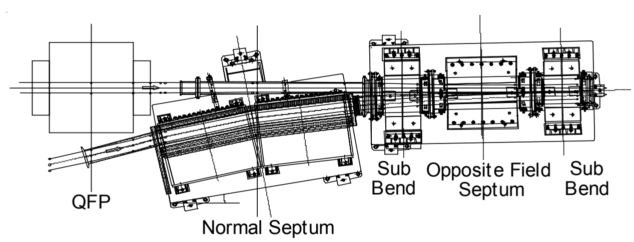

Figure 3: Outline of the injection system of JPARC main ring.

An outline of the injection system is shown in Fig. 3. The thin septum structure (8mm) and the rather high magnetic field (0.60T) of the opposite-field septum magnet is given a sufficient clearance for a high-field (1.36T) normal septum-magnet setting located at the upper stream. In spite of the limited length of the straight section and the restriction of the kicker magnets, the opposite-field septum magnet makes the total injection system simple and compact so as to clear the yoke of the upstream quadrupole magnet.

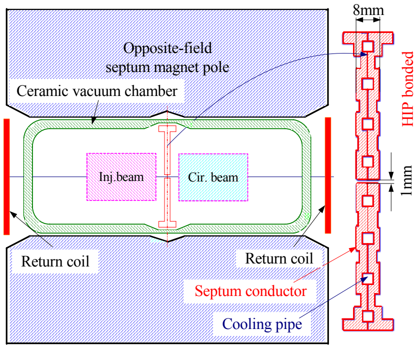

Figure 4: A transverse cross-sectional view of the injection system of JPARC main ring.

The injection beam is shaped to 54π mm mrad by a collimator at the injection beam line. The full acceptance of the injection beam line and the main ring are designed to be more than 81π mm mrad, so as to clear the beam halo of the collimator. Since the opposite-field septum magnet has a thin structure (8 mm), its aperture has 90π mm.mrad, which is larger than the full acceptance of the whole ring for low-loss injection.

A transverse cross-sectional view is shown in Fig. 4. As mentioned above, the two septum coils are arranged vertically to make a single line of septum conductors so as to form a thin septum structure. To decrease the out-gassing rate, the core of the magnet and the return coils are set outside of the vacuum chamber, and only the septum conductors are set inside, which is made by ceramic.

A longitudinal cross-sectional view is shown in Fig. 5. In the septum conductor, four stainless-steel cooling water pipes, which are gathered to one pipe at the end of the conductor, are sandwiched with a copper conductor by the Hot Isostatic Pressing (HIP) technique.

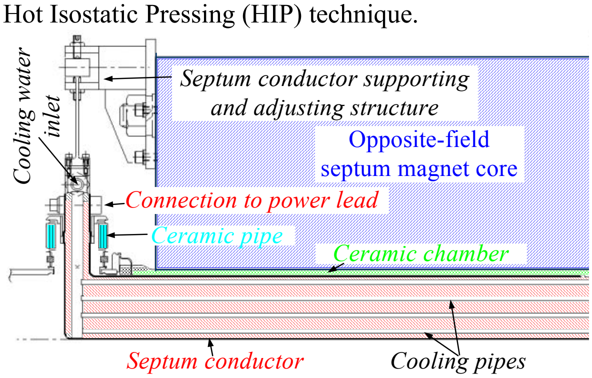

Figure 5: A longitudinal cross-sectional view.

COMPENSATION OF ERROR FIELD

Error Field by Mechanical Errors

Under the criterion of the maximum closed-orbit distortion, which is less than 1 mm, the integrated dipole component of the magnetic field along the circulating beam axis must be suppressed to less than 0.1% of integrated magnetic field of the injection side.

The error fields caused by the fabrication errors and the difference in the effective length of the individual magnets are compensated by a fine adjustment of the gap of the sub bending magnets, which were initially designed to have a variable-gap structure. The ideal gap-width of the sub-bending magnets was obtained by trial and error by changing the gap of the sub-bending magnets while measuring the integrated field using a long coil. Finally, the gap of the sub-bending magnets is 129.5 mm versus 120 mm of the main septum magnet.

Error Field Induced by Eddy Currents

After a fine adjustment of the magnet gap of the sub-bending magnet, residual field errors are caused by eddy currents. Principally, in the opposite-field septum magnet system, the eddy-current fields of the individual magnets are cancelled out by each other. However, disproportion of the eddy-current with the different structures of the cores causes an error field along the circulating beam axis.

At the center of the circulating beam orbit, the dipole component of the integrated error fields caused by the eddy current can be compensated by self-induced back-leg windings of the cores of the magnets, which add an induced magnetic field of the same polarity as the eddy-current field on the core of a lower eddy-current field. In our case, the total eddy-current field of the sub-bending magnets is superior to that of the main septum magnet. Thus, we must set self-induced back-leg windings on the return yoke of the main septum magnet. As shown in Fig. 6, the back-leg windings form a short circuit with septum conductors because it is hard to insert a back-leg coil between the return yoke and the ceramic vacuum chamber. The effect of this short bypass of the main septum conductor is negligible. Because the resistance of the septum conductor is 35 μΩ, on the other hand, the resistance of the bypass is about 72 mΩ, which is 2 x 10^3 times larger than that of septum conductor. The back-leg windings include resistance and inductance to control the current and phase of the induced current, which produces an additional magnetic field to cancel the eddy-current field at the sub-bending magnet. After trial-and-error activity, the values of the resistance and inductance were chosen to be 72mΩ and 12.7 μH, respectively.

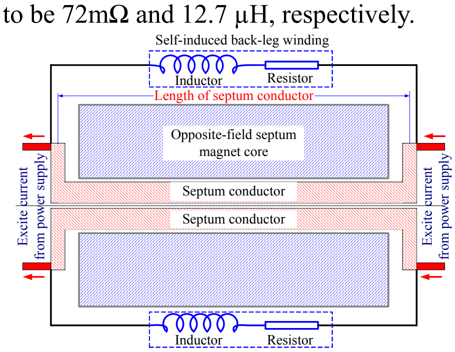

Figure 6: The self-induced back-leg windings to compensate error field induced by eddy current.

The total integration of the error field at the circulating beam side without any back-leg windings was about 1%

of the total kick angle (68 mrad) of the injection side. After compensation with self-induced back-leg windings, less than 0.15% has been achieved. Under this situation, the maximum closed orbit distortion is now less than 1.5 mm.

Compensation of Quadrupole Component

The gap between the septum conductor and the magnetic core is 6 mm in order to insert the ceramic vacuum chamber wall. This larger gap produces a disturbance of the uniform dipole field near the septum conductor. To reduce the disturbance of the dipole field, the shape of the cross section of the conductor is modified to form a uniform current distribution on the septum plane as shown in Fig. 4. Nevertheless, the disturbance of the uniform dipole field near the septum conductor is designed to be less than ±0.3% by a two-dimensional DC analysis by the computer code "Poisson".

The transverse distribution of integrated magnetic field, which were measured by stretch coil along the beam axis, are shown in Fig. 7, which is normalized by the value of the injection side (0.85 Tm). Version 1 in Fig. 7 is a measured data before adjusting, which exceeds ±0.6% and includes quadrupole and higher order components.

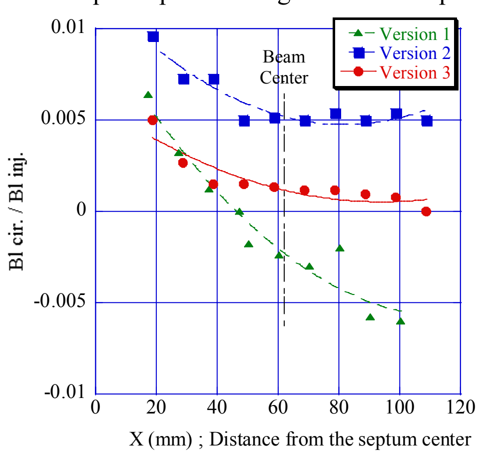

Figure 7: The measured value of transverse distribution of integrated magnetic field.

The measured value before adjusting (Version 1) is well explained by a simulation which included eddy-current effects in the septum conductor itself using "Opera 2D" code [3]. If we had performed the "Opera 2D" simulation before manufacturing, we could have obtained a more precise uniform field distribution near the septum conductor.

The uniformity of field distribution has been improved from Version 1 to Version 3 in Fig. 7 by adjusting the gap of the sub-bending magnets. The quadrupole component has been compensated by a small tilting (±6mrad) of the pole face of sub-bending magnet as Version 3 in Fig. 7.

If we need more precise field uniformity, the septumconductor and magnetic core must both be set inside the vacuum to eliminate the ceramic chamber walls. This in-vacuum-type opposite field septum magnet has been applied for the positive-ion injection for the 500 MeV KEK Booster [2]. However, the laminated magnetic cores increase the evacuating load of out-gassing.

STABILITY OF THE FAST PULS POWER SUPPLY CIRCUIT

The waveform of the pulse excitation current is half-sine wave of which width is 2.5 msec and the peak value is 48 KA for normal operation. The frequency is 25 Hz and the repetition rate is 16 burst every 3.64 sec. The early 12 pulses are used for stability of the intermittent mode operation. The last 4 pulses are used for every two bunch beams injection. (Total 8 bunch beams are injected). The injection system is designed to suppress any emittance growth due to injection errors to be less than 2%. Based this criterion, the stability of the magnetic field is required to be less than 2×10^{-4}. A half sine wave is produced by an LC circuit, and the output current is enhanced by a pulse transformer near to the septum magnet. The output voltage of the power supply is fed back by a direct measurement of the excitation current. The excitation current is measured by CT and digitized by an AD converter. The charging voltage of every repetition cycle is controlled by comparing the measured value and the standard value by a computer.

SUMMARY AND FUTURE PROSPECTS

The opposite-field type septum magnet combined with sub-bending magnets makes it possible to realize a high-field and thin septum magnet useful for the injection/extraction of high-energy accelerators. In the case of the injection septum magnet for the J-PARC 50-GeV proton synchrotron, a larger beam aperture than the full acceptance of the ring can be obtained for low-loss injection. Also, a fore-free structure enables only the septum conductor to be set inside of the vacuum for a low evacuating load. The key technology is how to suppress the error fields of the circulating beam side caused by fabrication errors and eddy currents by fast pulse excitation.

The opposite-field type septum magnet has the possibility to solve difficult problems concerning the injection and fast extraction of high-energy accelerators.

REFERENCES

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