Opposite Field Septum Magnet System for the Separation of Charged Particle Beams

I. Sakai, Y. Arakaki, M. Tomizawa, Y. Shirakabe, M. Muto, Y. Mori, Y. Ishi, and S. Fukumoto

***Abstract*—The Japan Hadron Facility (JHF) accelerator complex comprises a 50-GeV main synchrotron, a 3-GeV rapid-cycling synchrotron, and a 400-MeV linac. The accelerators provide high-intensity, high-energy proton beams for various scientific fields. These high-intensity, high-energy accelerators, especially the 50-GeV main synchrotron, impose tight demands on the injection/extraction septum magnets for a thin structure, large aperture and high operating field. But to manufacture high field septum magnets on the condition of a large aperture is very difficult because of its extraordinarily strong electromagnetic force due to the self-field. To cope with these tight demands, new design concepts of septa are required. An opposite-field septum magnet system is one of the solutions to realize a thin septa or very high-field septum magnets.**

***Index Terms*—Charged particle beams, magnet, septum.**

I. INTRODUCTION

IN PARTICLE accelerators, various septum magnets have an important roll to separate the charged-particle beams. The conventional septum magnet produces a magnetic field only in the inside of the septum conductor, and there is ideally no magnetic field outside of it. Usually the septum conductor and its support are required to be as thin as possible. But the septum conductor inevitably receives the electromagnetic force produced by the self-field. Therefore, in the case of a high-field septum magnet, the severe electromagnetic force on the septum conductor and leakage flux to outside of the septum are serious problems for designing its structure. To solve these problems, an opposite-field septum-magnet system has been developed for the beam injection/extraction of circular accelerators. A cross-sectional view of the opposite septum magnet is shown in Fig. 1. In this case, the same grade of opposite magnetic field is produced outside of the septum, which is on the side of the circulating beam, by another septum magnet; both septum conductors are mechanically contacted to each other. The electromagnetic force on the septum conductors and leakage flux cancel out each other. Furthermore, the beam-separation angle is twice as large as that of the conventional single septum magnet.

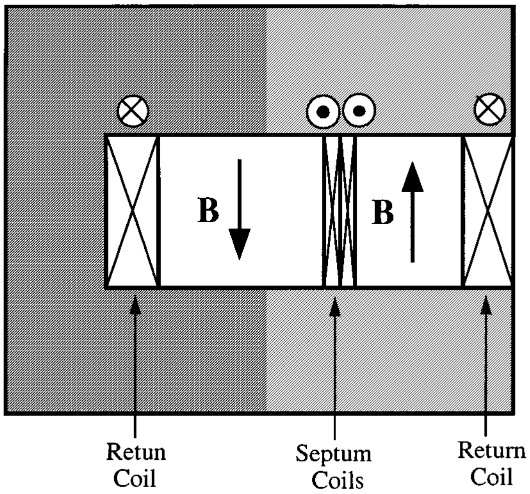

Fig. 1. Cross-sectional view of opposite-field septum magnet.

To use this opposite-field septum magnet for beam injection/extraction for a circulating beam, the magnetic field of the circulating beam side must be compensated by other sub-bending magnets, as shown in Fig. 4. Fortunately, these sub-bending magnets increase the angle of the injection/extraction beam orbit with the circulating beam orbit. To obtain the same injection/extraction angle as that of the conventional septum magnet, we need a half-length opposite-field septum magnet and two quarter-length sub-bending magnets located up-stream and down-stream of the main opposite-field septum magnet.

The opposite-field septum magnet system is useful to realize a thin septum magnet or a very high field septum magnet for beam injection/extraction of particle accelerators. In this paper, we introduce physical fundamentals and technical aspects of the opposite-field septum-magnet system.

II. PRINCIPLE OF THE OPPOSITE FIELD SEPTUM MAGNET SYSTEM

A. Magnetic Field Configuration

As shown in Fig. 1, the opposite-field septum magnet has three conductor blocks in a pole gap. The central conductor forms a septum conductor on which double current flows and makes an opposite magnetic field in both side gaps with both end conductor blocks. These magnetic fields have the same value of opposite signs and face each other across the central septum conductor. For the injection/extraction septum magnet, one side gap is used for circulating beams and the other side gap is used for injection/extraction beams. In the case of equal pole width, the yoke of the magnetic material is unnecessary. But in the case of an unequal pole width, the yoke of the magnetic material must absorb excessive flux.

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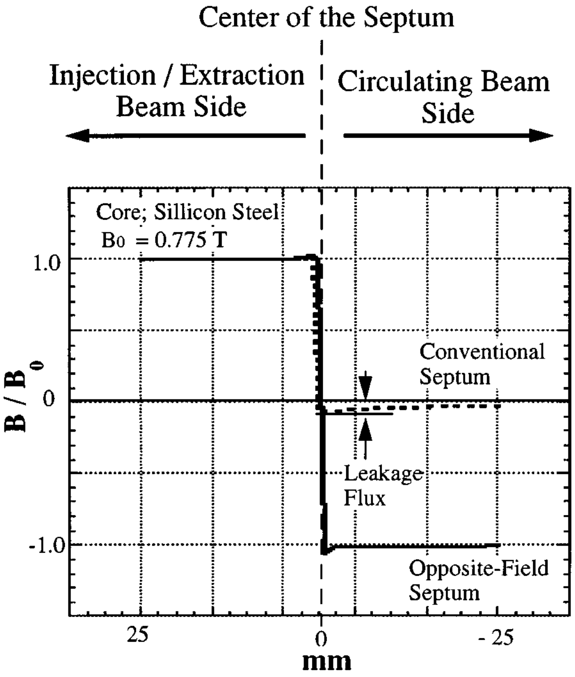

Fig. 2. Comparison of the magnetic field distribution between the conventional septum magnet and the opposite-field septum magnet by a 2-D simulation.

In the any case of normal septum magnets, the magnetic flux inevitably leaks out from the septum because of the finite permeability of the core, especially under high-field operation. The leakage flux can be eliminated by a magnetic shield plate. But the septum thickness is increased for that purpose. On the other hand, in the case of an opposite field-type septum magnet, the leakage flux is canceled out by each other. A comparison of the magnetic field distribution between the normal septum magnet and the opposite-field septum magnet by a simulation using the computer program "Poisson" is shown in Fig. 2, which shows an operation of 0.775 T in the structure of the model magnet. In the opposite-field configuration, the leakage flux from the septum conductor and the electromagnetic force on the septum conductor cancel each other out. We can thus easily obtain a steep septum magnetic field without any magnetic shield. The force-free structure also releases us from serious problems concerning the septum support of normal septum magnets.

B. Opposite Field Septum Magnet and Sub-Bending Magnets System

A schematic layout of the conventional septum magnet and that of the opposite-field septum magnet are shown in Figs. 3 and 4, respectively. The conventional septum magnet produces a magnetic field only inside the septum magnet, and there is no magnetic field outside of it, i.e., there is no magnetic field on the circulating beam orbit. On the other hand, the opposite-field septum magnet makes a magnetic field of opposite sign on the circulating beam orbit.

To use this opposite-field septum magnet for beam injection/extraction, the magnetic field of the circulating-beam side must be compensated by other sub-bending magnets. For perfect compensation, two sub-bending magnets with equal kick angles and values half that of the main opposite-field septum magnets must be settled symmetrically around the septum magnet.

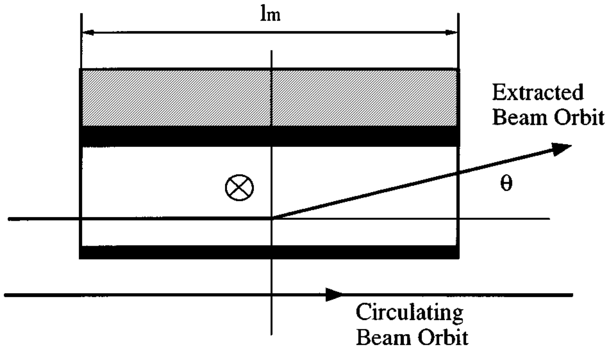

Fig. 3. Conventional septum magnet.

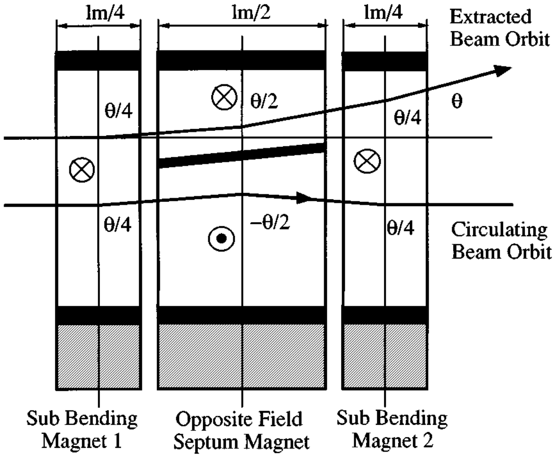

Fig. 4. Opposite-field septum magnet system.

As shown in Fig. 4, the horizontal aperture of these sub-bending magnets covers the injection/extraction beam orbit, so that the injection/extraction angle of the beam orbit with the circulating beam orbit is enhanced to the same amount as the opposite-field septum magnet. To obtain the same injection/extraction angle as the conventional septum magnet, we need only half the length of the opposite-field septum magnet and two quarters of the length of the sub-bending magnets, which are located up-stream and down-stream of the main opposite-field septum magnet. As a result, to obtain the same injection/extraction angle as that of conventional septum magnet with the same magnetic field strength, the total length of the opposite-field septum magnet system is equal to that of the conventional septum magnet, apart from the problem of the longitudinal end-effect and the projection of the coil ends.

III. TRIAL MANUFACTURE OF A THIN SEPTUM MAGNET

The distinctive features of the opposite-field septum magnet are a "force free septum" and a "cancellation of leakage flux." To verify these characteristics, a model septum magnet having a very thin septum (0.3 mm) was made, and experiments involving pulse excitation have been carried out.

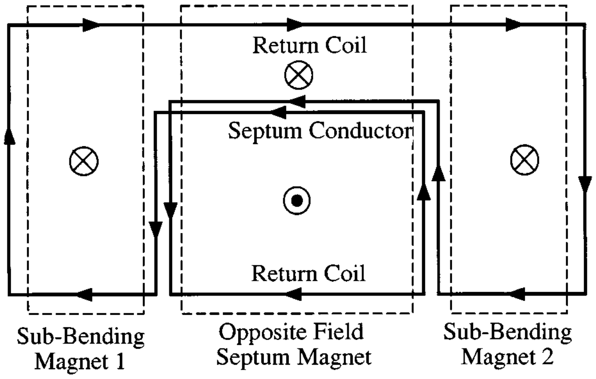

Fig. 5. Schematic layout of the composition of a excitation current using single-power supply.

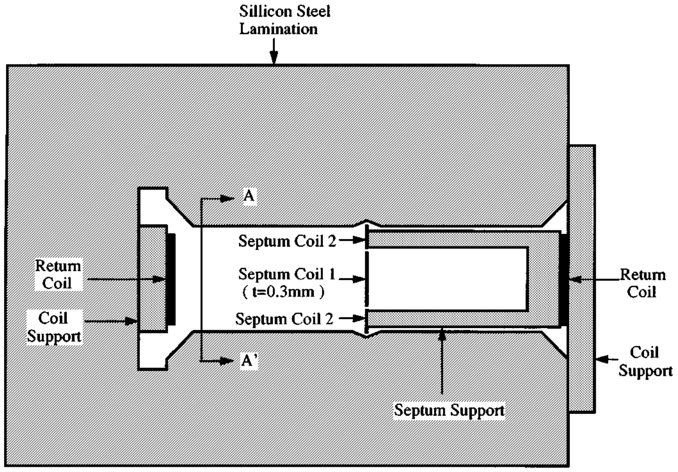

Fig. 6. The transverse cross section of the model magnet.

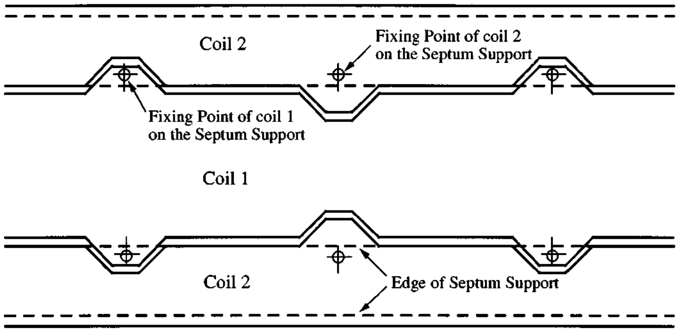

Fig. 7. The external appearance (from A–A′ line in Fig. 6) of the septum conductor of the model magnet.

A. Structure of a Model Magnet

A schematic layout of the composition of excitation-coil circuit using single-power supply is shown in Fig. 5. To make it possible to excite the opposite field septum magnet with a series connection by a single power supply, the central septum conductor must be divided into two parts. The transverse cross section of the model magnet is shown in Fig. 6. In this case, the central septum is divided into three parts. The upper and bottom parts form one conductor and the middle part of the septum forms the other. The thickness of the septum conductors is 0.3 mm. The total height of the upper and the bottom parts is equal to the height of the middle part of the septum so as to realize a uniform current density. These septum conductors are fixed on a horseshoe-shaped insulating support, which enables the injection/extraction orbit to pass in the septum magnet.

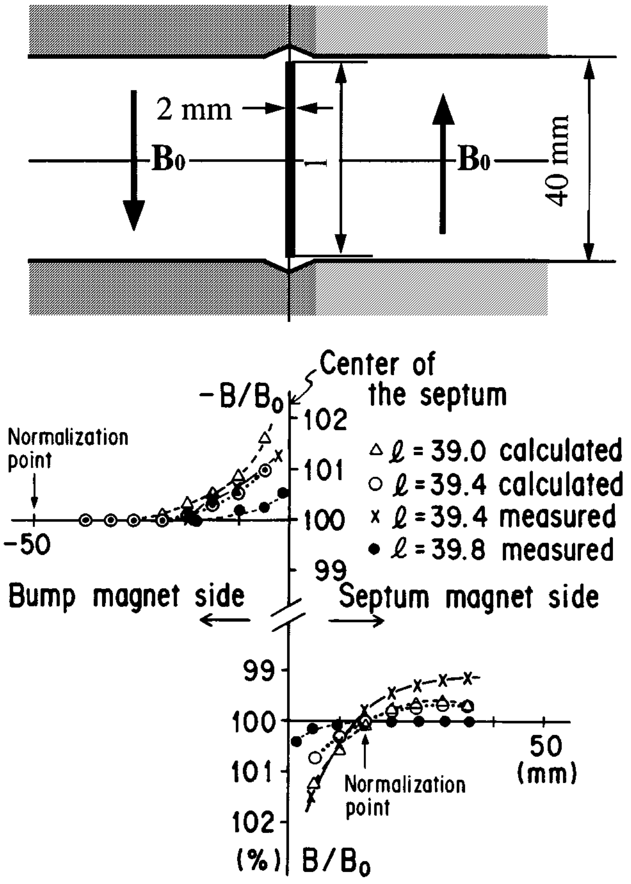

Fig. 8. The magnetic-field distribution of the calculated value by the computer program "Poisson" and the measured values under several conditions.

The external appearance (from A–A′ line in Fig. 6) of the septum conductor of the model magnet is shown in Fig. 7. At the fixing points of the conductor, the edges of the middle conductor and the upper/bottom conductors are alternately shaped, as shown in Fig. 7, to obtain a vertical aperture as wide as possible, and to maintain the uniformity of the magnetic-field distribution. The force free mechanism of the septum conductor and its end structure has been verified trough a pulse-excitation test up to 0.18 T (6 kA).

At the septum conductor, the pole face is notched to make the insulation gap with the septum conductor. As shown in Fig. 6, the notching shape is an equilateral triangle whose width is 10 mm and depth is 2 mm. The longitudinal pole ends are cut along the contour of hyperbolic curve to lamination at the pole end. These cutting effects on the escape any magnetic saturation and eddy current of the field quality must be carefully examined by magnetic-field measurement and computer simulations.

B. Field Quality Near the Septum

An opposite-field type septum magnet has already been developed for both negative-ion charge-exchange injection and

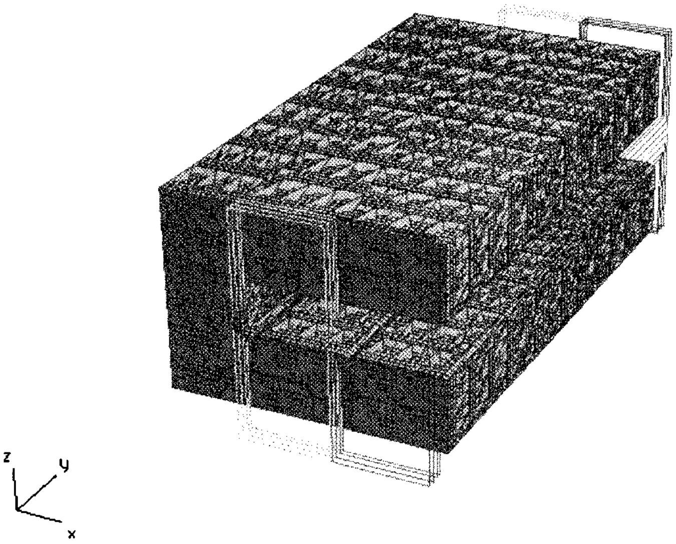

Fig. 9. The layout of an opposite field septum magnet.

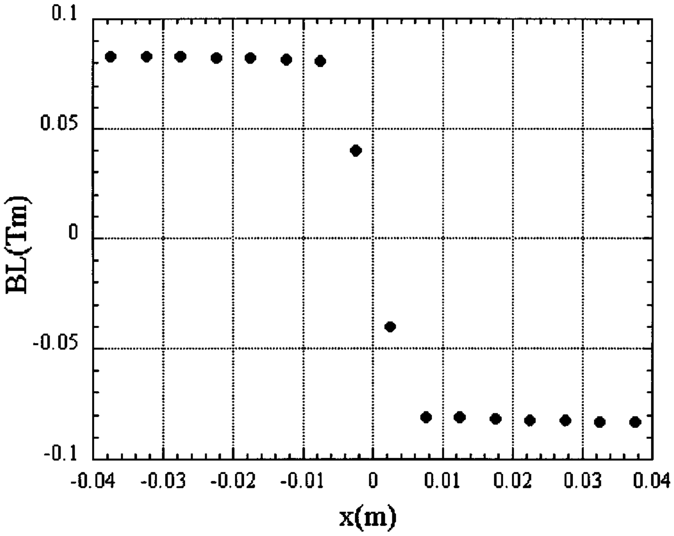

Fig. 10. The effective length of an opposite field septum magnet.

TABLE I

Parameter	Unit	
Maximum Field	T	1.81
Pole Gap	mm	120
Number of Turns (per Pole		32
Maximum Current	A	5406
Maximum Voltage	V	469
Resistivity	mΩ	87
Average Power Loss	W	593
Duty Factor	%	23.4
Conductor Size	mm	7 x 7 -ϕ4.5 (Septum), 7 x 28 -ϕ4.5 (Return)
Total Conductor Length	m	218
Maximum Water Temp. Rise	K	65
Maximum Conductor Temp. Rise	K	85
Total Number of Water Circuits		64
Water Flow	l/min	733
Water Velocity	m/s	6
Water Pressure Drop	MPa	0.3

positive-ion multi-turn injection in our laboratory [1]. At that time, quite the same cross-sectional structure of the core and the single-turn septum was applied, and the optimum shaped of the pole and the size of the septum for a uniform and sharp edge distribution of the magnetic field were carefully examined.

The magnetic-field distribution of the calculated value by the computer program "Poisson" and the measured values under several conditions, which were acquired through optimization process, are shown in Fig. 8.

The notched shape of the pole face, which had the same size as this trial manufacture, was fixed in advance, and the size of the septum conductor was changed by trial and error. The calculated values by "Poisson" were agreed well with the measured value. The field distribution near the septum is very sensitive to the cut-off quantity of the septum. These deformations disturb the field distribution near to the septum. Fortunately, however, regarding the disturbance of the field distribution, the notched pole face and the cut-off septum are complementary to each other. In this way, the optimum shapes of the pole face and the septum conductor were decided, and a field uniformity of less than 1% was obtained [1].

IV. The Calculation of the End Field in an Opposite Field Septum

To inspect the field quality and leakage flux including the end effects, three-dimensional calculation was performed by a finite-element-based program, called "MAFIA." Silicon steel (50RM600) is used as a H–B table. Fig. 9 shows the layout of an opposite-field septum magnet for calculation. The length for the longitudinal direction is 0.4 m. The gap height and width are 40 mm and 75 mm respectively. Two sets of coils are used to generate the opposite field. The magneto motive force is 6 kA turns. The magnetic flux density (B0) is 0.188 T. Fig. 10 shows the transverse distribution of effective length on the median plane. Since the support-metal fittings can not be equipped with the end coil near to the center so as to maintain the thin septum, the force from self field should be taken into consideration. We conform that the end coils in the center push together, and then offset.

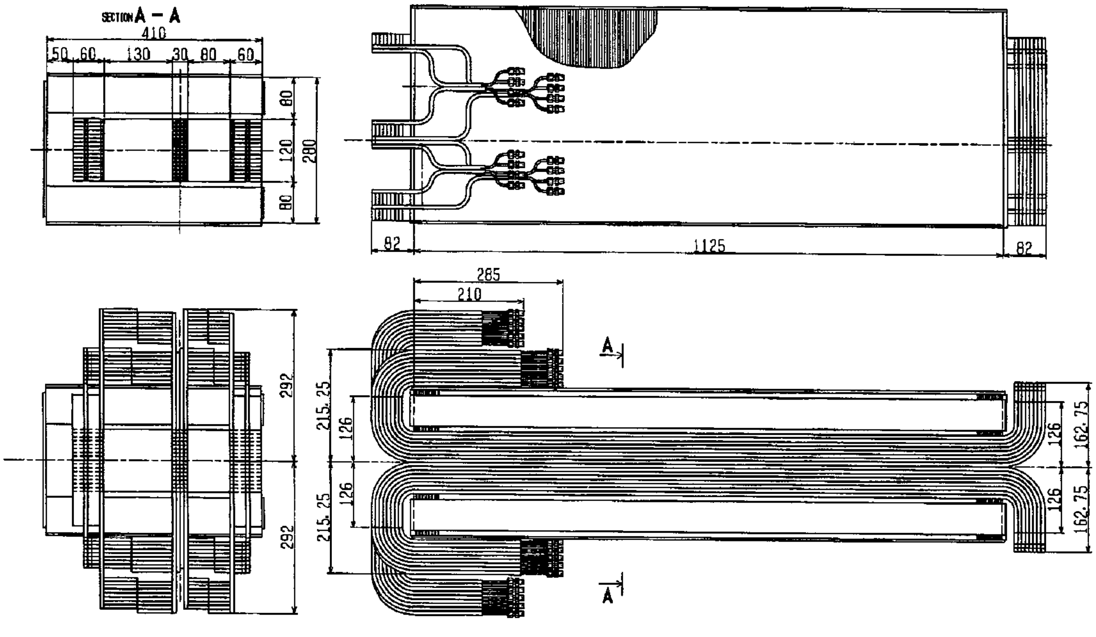

Fig. 11. The overall layout of the magnet.

V. DESIGN OF A HIGH-FIELD SEPTUM MAGNET FOR THE SLOW-EXTRACTION OF 50-GeV PROTON SYNCHROTRON IN THE JHF PROJECT

A. *Requirement for the Slow Extraction Septum Magnet*

The requirements for a high-field septum magnet used to extract 50-GeV protons are as follows: Longitudinal space, 2630 mm; kick angle, = 0.024 rad.; septum thickness, = 30 mm; aperture of septum magnet for extraction, = 60 mm; vertical aperture of main septum magnet and sub-bending magnet for circulating beams, = 120 mm. The acceleration cycle of the 50-GeV proton synchrotron is 3.42 sec and its extraction period is 0.7 sec. The field of the septum magnet must remains on 0.7 sec every 3.42 sec. The tight space, thin septum, large aperture and large kick angle for the beam energy make it hard to realize reliable septum magnets for long-time operation. Moreover, high-duty pulse operation makes it hard to design the cooling system of the conductor.

B. *Structure of a High-Field Opposite-Field Septum Magnet Designed for the Slow Extraction of the 50-GeV Proton Synchrotron*

When the above opposite-field septum magnet is adopted for the slow extraction of a 50-GeV proton synchrotron, although the problem of electromagnetic force is greatly relaxed, coil cooling is still a difficult problem. The overall layout of the magnet and its parameters which we propose are shown in Fig. 11 and in Table I. As shown in Table I, each coil is composed of 64 turns, which are parallel for every turn.

In Table I, although the cooling performance to the average heat loss is shown, since if a practical-condition pulse run is carried out, the time change of the conductor temperature and cooling-water temperature is also taken into consideration. In this case, it is necessary to understand the exact heat-transfer coefficient between a conductor and the cooling water. Moreover, it is also considered to be a subject on manufacturing to maintain the water-flow balance of 64 circuits well; also verification by trial production is required.

VI. SUMMARY

The opposite-field type septum magnet combined with sub-bending magnets has unique features compared with those of normal septum magnets: a force-free structure, cancellation of the leakage flux and a large separation angle. A force-free structure is useful to realize thin septum magnets or high field septum magnets. The current density of the septum is twice as large as that of normal septum magnet, and the combination with sub-bending magnets requires a larger size magnet system. However the separation angle is twice as large as that of a normal septum magnet, and the length of the septum magnet is needed to be half that of the normal septum magnet. Further the force-free structure easily permits pulse excitation for energy saving. As a results, the total power loss of the opposite-field-type septum magnet system is smaller than that of normal septum magnet. The system is the effective solution to realize thin septum magnets and high-field septum magnets.

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