DC SEPTUM MAGNET FOR BEAM EXTRACTION

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Abstract

A septum magnet with DC excitation has been fabricated for slow beam extraction at TARN II. Its gap height, core length and septum thickness are 25 mm, 1 m and 9 mm, respectively. At the maximum excitation current of 2500 A in 4-turn septum coils, corresponding to the magnetic field of 5 kG, the current density amounts to 78 A/mm². Measured temperature rise in the air is less than 27 ℃ at the septum coil under the condition that a flow rate of cooling water is 2.4 ℓ/min per each coil. This is well below the tolerance for DC operation although a little higher temperature rise is anticipated for real application in a vacuum chamber. The measured field homogeneity in the aperture is better than 0.8%. The leakage field strength at an entire region outside of the septum is less than 0.24% even at its largest point, which is considered to have no significant effect on the circulating beam.

Introduction

A heavy-ion synchrotron/cooler ring, TARN II has been constructed at Institute for Nuclear Study, University of Tokyo and beam experiments have been started since the end of 1988[1]. A slow beam extraction system for TARN II, which utilize a third order resonance has been studied in preparation for biomedical irradiation with high-energy (several hundreds MeV per nucleon) heavy-ion beams. The equipment for the extraction has been constructed assuming the beam energy between 150 MeV/u and 350 MeV/u for ions with charge to mass ratio of 1/2 and between 150 MeV and 1100 MeV for proton. Thus the maximum magnetic rigidity to be treated is 6 T·m. In the system, the beam whose amplitude has increased enough to exceed a certain size (75 mm) by a perturbation due to a non-linear sextupole field is deflected by an electrostatic deflector(ES) at first and then further deflected by a septum magnet(SM) located about 11 m downstream from ES. In order to avoid a collision of the injected beam with the septum of SM, the septum thickness should be smaller than the distance between the extracted beam and the circulating beam envelope. The condition to enlarge the available space for the septum coil has been searched so as to enable DC operation of the septum magnet. In Fig. 1, an extracted beam trajectory is shown for the most severe case of 1.1 GeV proton, where the deflection angle of the extracted beam is the smallest as 5.3 mrad, together with a beam envelope of the injected beam. After calculations for various conditions, it is found that the septum thickness is required to be within 9 mm. To produce a deflection angle of 85 mrad as is the case in Fig. 1 by the septum magnet of 1 m in length, its field strength is required to be 5 kG. The main specifications are given in Table 1. In the present paper, the design and fabrication procedure of the septum magnet is described together with its excitation characteristics.

Table 1

Specifications of the Septum Magnet

Maximum Field Strength	5	kG
Maximum Ampere-Turn	10000	AT
Number of Turns	4	T
Maximum current	2500	A
Septum Thickness	less than 9	mm
Core Length	1	m
Magnet Aperture (Gap x Width)	25 x 60	mm²
Field Homogeneity (in the aperture)	within 1	%
Deflection Angle	85	mrad

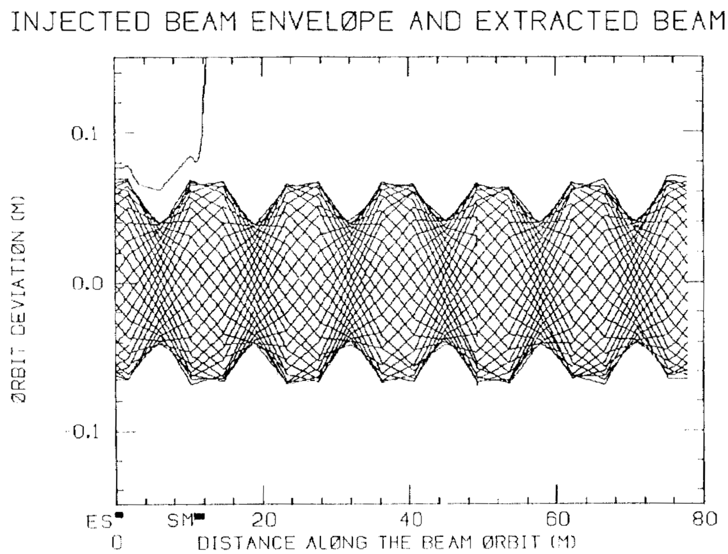

Fig. 1. The injected beam Envelope over the whole circumference and the extracted beam trajectory of TARN II.

Design of the Septum Magnet

At TARN II, the vertical emittance of the injected beam is assumed to be 15π mm·mrad, which is expected to decrease to $\sim 5\pi$ mm·mrad after acceleration up to 150 MeV/u. The vertical beam size is ±6.3mm in this case. On the assumption of the usage of the magnet in a vacuum chamber with consideration of the possible closed orbit distortion and clearance between the extracted beam and the magnet pole-face, the gap height is determined to be 25mm, which requires 10000 AT to realize the field strength of 5 kG. The horizontal size of the extracted beam is 20 mm at the septum position. In addition to this, 10.4 mm is required as the sagitta of the magnet. Considering the possibility of utilizing this septum magnet also for a fast extraction with a full aperture kicker magnet in future, the horizontal aperture is decided to be 60 mm.

A hollow conductor of the cross sectional area of 7x7 mm² with a hole of the size of 4x4 mm² for cooling water is used in 4 turns as the septum coil. In this shape, the current density amounts to 78 A/mm² for the maximum excitation current of 2500 A. The return current is fed to the coil with larger size as shown in Fig. 2(a) to reduce the current density to a usual size (8.4 A/mm²). The electrical insulation is made with ceramic coating for the return coils and with Kapton foils and sheets for septum coils, which might lower the bakable temperature below 300 ℃. As the resistence of each septum coil is estimated to be 0.55 mΩ, the power dissipation is 3.4 kW at each coil in case of DC operation. In the condition that the velocity of the cooling water is set to be 2.5 m/sec, the temperature of the water is to be raised by 20 ℃ if all the heats are taken away by the water. Here a parallel water path is assumed for each coil. In addition to this, there are temperature difference between the

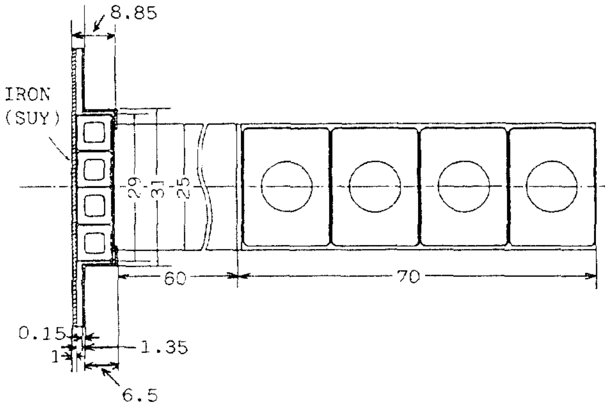

Fig. 2.(a) Cross sectional view of the septum coils and the return coils. The septum thickness is 8.85 mm. An iron plate of 1mm in thickness, which is magnetically insulated from the iron core, is attached to the septum coils to suppress the leakage field level.

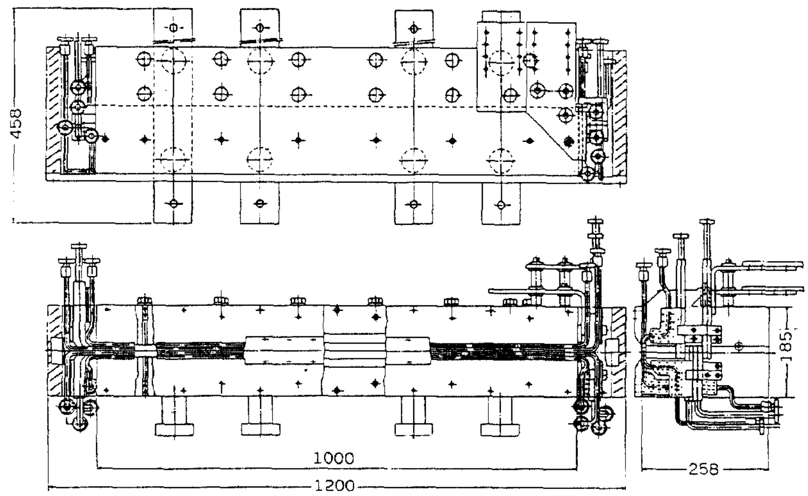

Fig. 2(b) The drawing of the mechanical design of the septum magnet. The shaded portions are the shielding blocks of iron which have the same cross section as the iron core.

cooling water and the conductor surface of the coil and the temperature gradient in the coil-conductor itself, which are calculated to be 15 ℃ and 1 ℃, respectively for the maximum excitation current of 2500 A. The correlation between the calculated temperature rise at the septum coil and the excitation current is shown by a solid line in Fig. 3. Thus the maximum temperature of the coil is expected to be less than 66 ℃ even if the temperature of the input water amounts to 30 ℃, which is considered well in a torelable limit. After experimental check of the validity of the calculation used therin by a scaled model test[2], the septum magnet is decided to be made for DC excitation. Accordingly the core is made of solid iron (soft magnetic iron-C2504 in Japanese Industrial Standard), which is preferable from both points of view of degassing rate and fabrication precision to a laminated core for AC excitation.

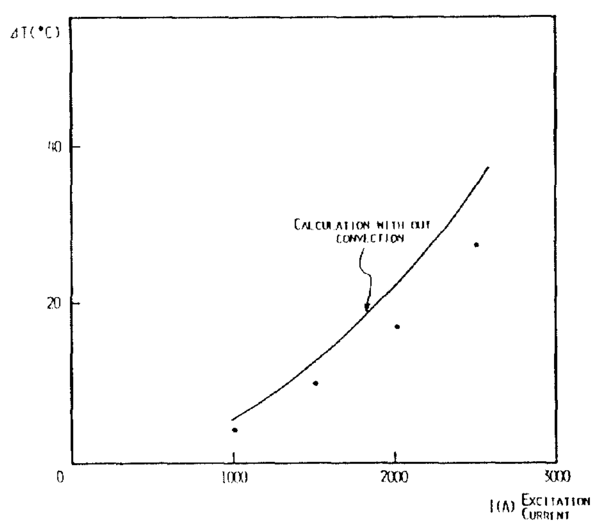

Fig. 3. The correlation between the temperature rise and the excitation current. The solid line shows the calculation without convection and black circles represent the measured data in the air.

Another emphasis is made to suppress the leakage field outside the septum because it might affect the nearby injected beam if the septum magnet is excited with DC mode. The iron core shape and coil position relative to the iron core are optimized with use of the computer code TRIM[3]. The leakage field is further suppressed by adding a thin iron plate(1 mm in thickness) just outside the septum coil(Fig. 2(a)). It should be noted that this iron plate must be insulated-magnetically from the iron core[4]. The calculated field structure is shown in Fig. 4. As the above calculation is made in two dimensional way, it is forseen that the fringing fields at both ends of the magnet come round the septum coil to the outer side region in case of a real magnet with three dimension. For the purpose of suppressing such an effect, a shielding iron block of 30 mm in thickness is attached at each end of the magnet as shown in Fig. 2(b) by shaded portions. An overall view of the fabricated septum magnet before attachment of shielding blocks at both ends is shown in Fig. 5.

Excitation Characteristics

Temperature Measurement

The temperature rise is measured under the condition that the flow rate of the cooling water is

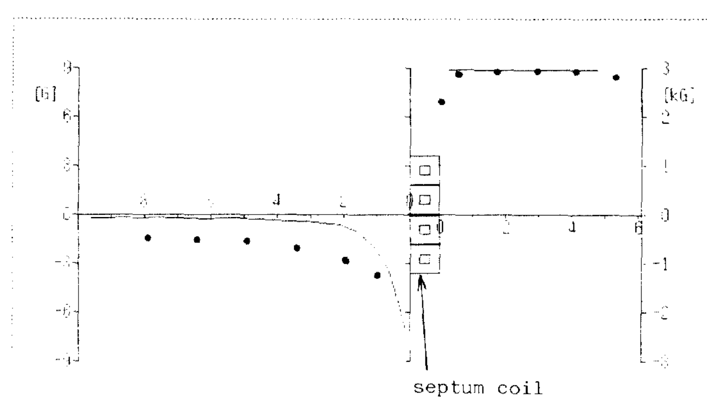

Fig. 4. The structure of the magnetic field on the median plane at well inner part of the iron core. Black circles show the calculated values and the solid line represents the measured results along the line 20 cm inner from the core end.

2.4 ℓ/min (corresponding to the water velocity of 2.5 m/sec) per each coil and the input water temperature is kept 19 ℃. The measurement was performed in the air. The results are plotted in Fig. 3 by black circles. The measured temperature rise is 27 ℃ even for the DC excitation of 2500 A. The reason why the measured values are systematically a little lower than the calculated ones is considered to be due to the fact that a heat flow due to convection exists in the condition of this measurement, which is not taken into account in the calculation. Although the temperature rise is considered to increase to the calculated one in real installation in a vacuum vessel, the DC operation of this septum magnet is warranted with regards to the temperature rise.

Field Measurement

The field structure of the septum magnet is studied by using a hall-probe with the dimension of 3x5 mm², which has been calibrated with use of an NMR. The position of the probe can be controlled automatically by a personal computer (PC9801), which is connected to a driving stage in two directions consisting of two ball screws and two pulse motors. The resolution of the positioning is 25μm. To prepare for the beam extraction of α particle with kinetic energy of 150 Mev/u at the first operation, the field measurement has been performed at the excitation current of 1500 A (corresponding to 3 kG) at first. The field mapping is applied in the horizontal plane and its results are displayed on a CRT. A typical example is shown in Fig. 6. It is known from the figure that the leakage field in the outside region of the septum is well suppressed in the Y region larger than 27 cm although the peak of the leakage field observed in the Y region between 20 cm and 27 cm (corresponding to the region between the iron core and the shielding block) is also small as 5 G. Thus it is found that the shielding blocks attached to both ends of the magnet (locating at the Y region between 27 cm and 30 cm as indicated by two arrows in Fig. 6) play an important role to suppress the protrusion of the fringing fields at the entrance and exit coming round the septum coil to the outside region. The measured results at the positions 20 cm inside from the core end (corresponding to Y = 0 cm in Fig. 6) are compared with the calculated values in Fig. 4. Measured field homogeneity in the region

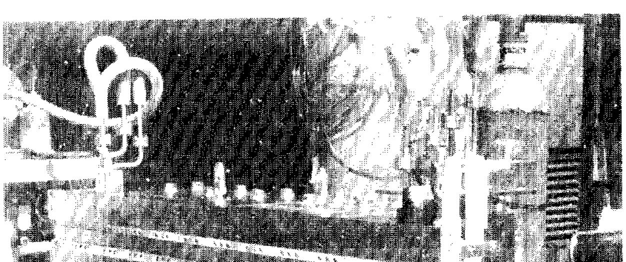

Fig. 5. An overall view of the fabricated septum magnet. This picture is taken before the attachment of the shielding blocks at both ends so as to show the coil end.

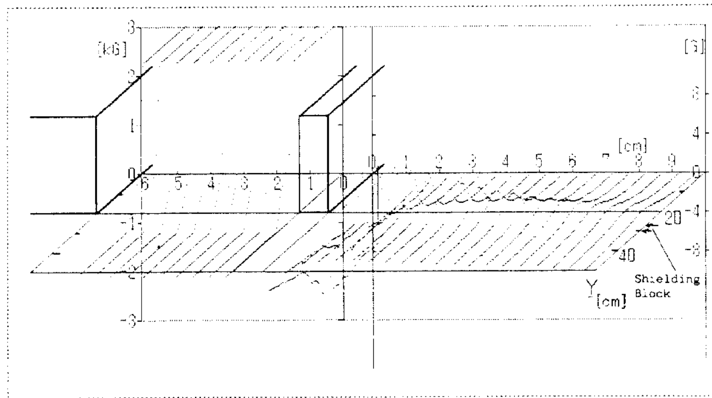

Fig. 6. Three dimensinal display of the measured field structure taken with the excitation current of 1500 A. X and Y directions correspond to the directions perpendicular and parallel to the magnet axis respectively.

between the septum and return coils are better than 0.8% and the leakage field strength outside the septum is less than 0.24% of the inner field strength even at the largest position 2 mm outside from the suptum surface as shown in Fig. 4. From the result of field measurements, this septum magnet is found to have a sufficient characteristics for real application with DC mode also from the viewpoint of leakage field into the occupied region by the circulating beam.

Aknowledgement

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