DESIGN AND MEASUREMENT OF MAGNETS AND RF CAVITY FOR THE 1 GEV ELECTRON SYNCHROTRON AT SORTEC

K. Kondo, T. Chugun, M. Kodaira, Y. Yoshiwara and T. Iimura
Keihin Product Operations, Toshiba Corporation,
Suehirocho 2-4, Tsurumi-ku, Yokohama, 203, Japan

S. Nakamura and M. Ohno
SORTEC Corporation, Wadai 16-1, Tsukuba, 300-42, Japan

T. Tomimasu
Electrotechnical Laboratory,
Umesono 1-1-4, Tsukuba, 305, Japan

Abstract

Design and performance of the magnets and RF cavity for 1 GeV electron synchrotron which has been installed in SORTEC are presented.

The precise magnetic field measurement apparatus was developed and applied, then it was shown that magnetic field uniformity $\Delta B/B$ of the dipole magnets was less than 2×10^{-4} and magnetic field gradient uniformity $\Delta G/G$ of the quadrupole magnets was better than 2×10^{-3}.

The shape of RF cavity is re-entrant type and accelerating frequency is 118 MHz. From the characteristic measurement in low power level, Rsh of 1.28 MΩ and Q value of 15,200 were obtained.

Magnet

Dipole magnet design

The design parameters required for the dipole magnets of 1 GeV synchrotron are shown in Table 1. Magnetic field of the magnets is 1.1 Tesla, good field region is ±45 mm, bending radius is 3030 mm and magnet type is rectangular. The synchrotron consists of 12 dipole magnets.

So as to satisfy the magnetic field uniformity in the good field region, the shape of cross section was determined by magnetic field analysis used finite element method. Fig. 1 shows flux line of the dipole magnet obtained by analysis. For widening effective field region, the dipole magnets have shims in the both sides of each pole. Because symmetry of field distribution is better and deformation of iron core is lesser, H-type magnet is adopted.

The synchrotron is operated by 1.25 Hz with rising time of 400 msecond, so the magnets is made of stacked laminated 0.5 mm thickness electrical steel. Reducing the difference of magnetic characteristic among the magnets, electrical steel from the same lot was used for all magnets.

Table 1

Design parameters of the dipole magnets

Core length		1540 mm
Gap height		55 mm
Flux density of gap at injection		0.044 T
at extraction		1.1 T
Bending radius		3030 mm
Bending angle		30°
Good field region		±45 mm
Field uniformity in the good field region		$\leq 5 \times 10^{-4}$
Number of magnets		12
Coil	Main coil	Correction coil
Current	1300 A	60 A
Turns/Pole	20	1
Cooling	Water	Air
Core		
Material		Silicon steel, ^{t}0.5 mm
Shape		Rectangular H-type

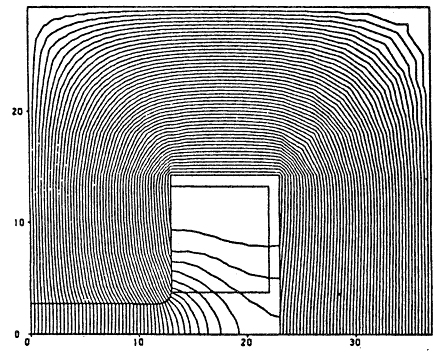

Fig. 1 Flux line of the dipole magnet

Both ends of the magnet were cut by 4 steps which approximated the Rogowski's curve.[1] The Length of laminated core was determined based on the result of magnetic fringing field obtained by field analysis.

Main coils were cooled with water and consist of 40 turns. Correction coils were installed for correcting the difference among the magnets at beam injection, but those were not used.

The assembling accuracy of the magnets was ±0.05 mm at gap and was ±0.5 mm in iron core length.

Magnetic field measurement of the dipole magnets

The magnetic field measurement apparatus shown in Fig. 2 was developed.[2] It has Hall probe as magnetic field sensor and moves on 4 axes (x,y,z,θ). As the accuracy of magnetic field measurement depended on temperature of Hall probe, temperature change was held within 0.1°C. The Hall probe was calibrated by nuclear magnetic resonance method and its accuracy was 1×10^{-4}.

Position reproducibility of the Hall probe was less than 10 μm and magnetic field was measured by personal computer automatically.

Fig. 3 shows a result of the magnetic field uniformity of the magnet. From the measurement results of all magnets, it was confirmed that the magnetic field uniformity $\Delta B/B_0$ was better than 2×10^{-4} in the required good field region and satisfied the specification of the synchrotron.

Fig. 4 shows the comparison of analysis and measurement about magnetic fringing field at the core ends of the magnet. From this figure, it is clear that the analysis value about effective magnetic fringing field length is good agreement with the measurement value.

The deviation of the effective length among 12 magnets was 1×10^{-3}. The dipole magnets for the synchrotron was arranged with the results of magnetic field measurement so that closed orbit distortion was as small as possible.

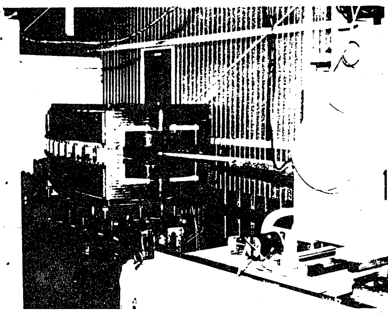

Fig. 2 Field measurement of the dipole magnet by Hall Probe

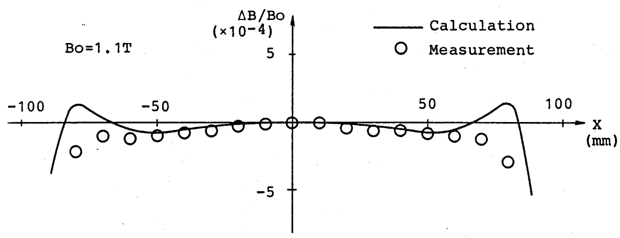

Fig. 3 Radial magnetic field distribution of the dipole magnet

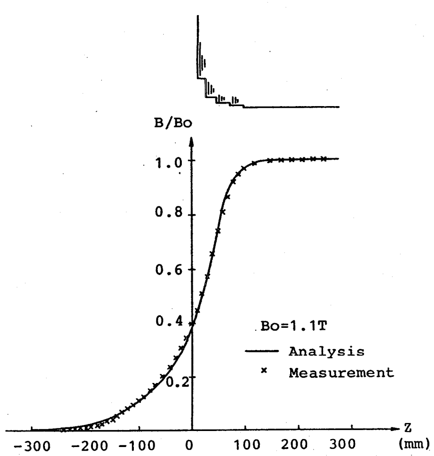

Fig. 4 Beam axial magnetic field distribution of the dipole magnet

Quadrupole magnet design

The design parameters required for the quadrupole magnets are shown in Table 2. So as to satisfy magnetic field gradient uniformity in the good field region, the shape of cross section was determined by magnetic field analysis used finite element method.

The shape of core ends was determinted by integral magnetic field gradient measurement[3] about two kinds of core end model, as shown in Fig. 5. The integral gradient uniformity of case 2 was better than that of case 1, then the shape of case 2 was adopted.

Though the rated magnetic field gradient of the quadrupole focus magnets is different from that of the defocus magnets, these fabrication is same, but these exciting current is changed according to purpose.

Table 2

Design parameters of the quadrupole magnet

Core length	250 mm
Bore diameter	110 mm
Field gradient	5.5 T/m
Good field region	±50 mm
Field gradient uniformity in the good field region	$\leq 2 \times 10^{-3}$
Number of magnets	18
Coil	
Current	585 A
Turns/Pole	12
Cooling	Water
Core	
Material	Silicon steel $^{t}0.5$ mm

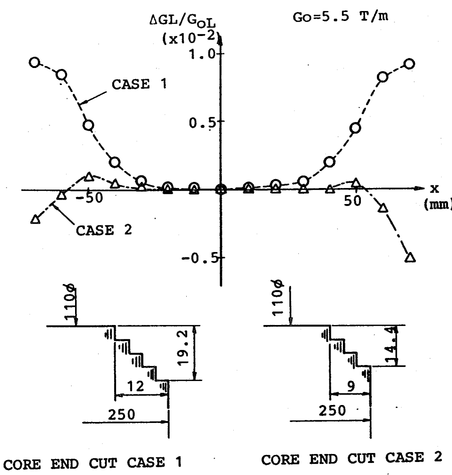

Fig. 5 Radial magnetic field distribution of the quadrupole magnets

Magnetic field measurement of the quadrupole magnets

Reducing the error of position measurement, the integral magnetic field measurement apparatus with long twin coil shown in Fig. 6 was developed and its measurement accuracy was 1×10^{-4}.[4] From the measurement results of all magnets, it was confirmed that the magnetic field gradient uniformity $\Delta GL/G_0L$ was better than 2×10^{-3} in the required good field region and satisfied the specification of the synchrotron.

The magnetic field gradient distribution along beam axis was measured by the magnetic field measurement apparatus with short twin coil. From these measurement, it was known that the effective fringing field gradient length was 53 mm and the deviation among 18 magnets was 2×10^{-3}.

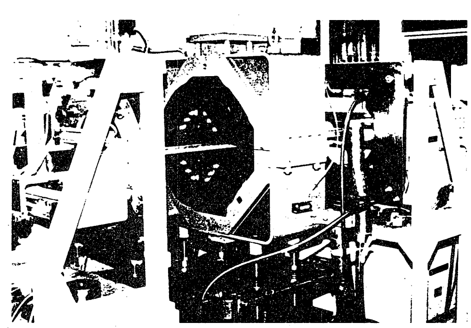

Fig. 6 Field measurement of the quadrupole magnet by long twin coil

RF cavity

RF cavity design

The design parameters of the RF cavity are shown in Table 3. The cavity voltage of 60 kV is necessary to obtaine a reasonable quantum life time. The shape of the RF cavity is re-entrant type and the computer program code SUPERFISH was used to determine the inner structure of the RF cavity.[5] Fig. 7 shows electric line of TM010 like mode in the RF cavity. Considering a few opening are bored, the half of Q value and effective shunt impedance obtained by above program are shown in Table 3.

RF power system has cavity voltage feedback loop. As detuning frequency at beam loading is small, the tuner is not moved by feedback loop, but moved by remote control.[6] It is mainly used to compensate the temperature increase effect.

OFHC copper was used in the body and the electrodes of the RF cavity. The outer surface of the cavity body, the electrodes, the tuner and the input coupler are cooled by water.

Table 3

Design parameters of the RF cavity

Resonant frequency	118 MHz±0.25 MHz
Q value	9400
Effective shunt impedance	0.785 MHz
Cavity voltage	60 kV
Coupling coefficient	1.2
RF power	10 kW

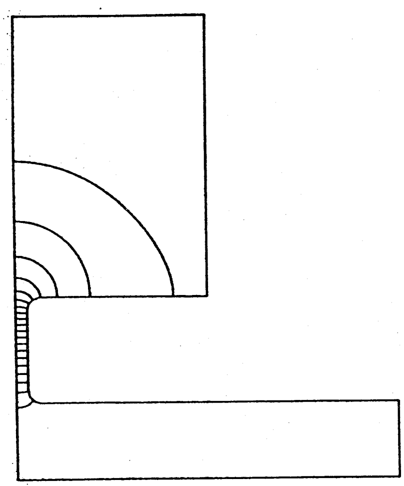

Fig. 7 Electric line of the RF cavity

Measurement of the RF cavity

The low power test in the air was performed by the network analyser. The RF cavity under the measurement is shown in Fig. 8.

Fig. 9 shows the comparison of analysis and measurement about electric field of TM010 like mode along beam axis. From this figure, it is clear that the analysis value is good agreement with the measurement value.

Maximum variation of resonant frequency obtained by the tuner was 580 kHz and satisfied the specification. Now the tuner is situated at 50 mm from the RF cavity surface.

The coupling coefficient between the RF cavity and the input coupler, $\beta = 0$ to 6 was obtained by rotating the input coupler. Now the input coupler is adjusted to be $\beta=1.2$.

Resonant frequency of the RF cavity was adjusted by varying the gap length between the electrodes. The measurement results in the vacuum at 40°C were resonant frequency fr=118.0 MHz, effective shunt impedance R_{sh}=1.28 MΩ and Q=15,200. It was known that the measurement value of R_{sh} and Q was better than the design value.

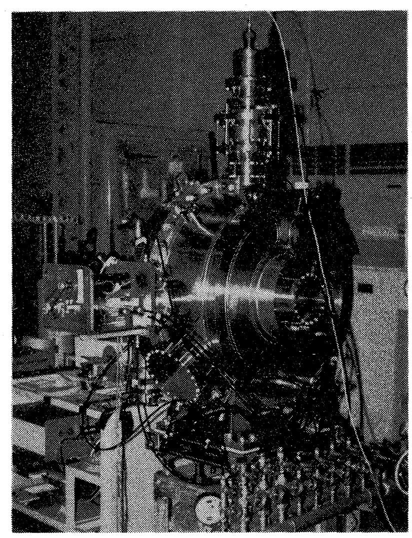

Fig. 8 RF cavity

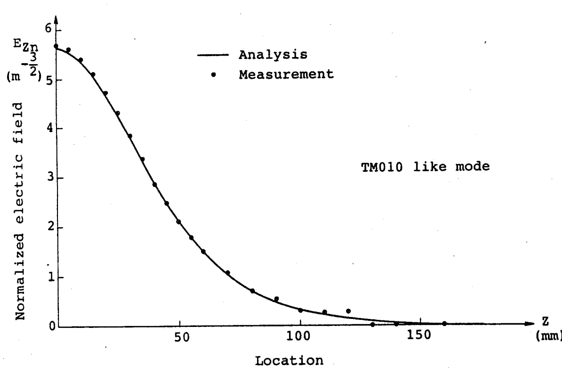

Fig. 9 Electrical field distribution of the RF cavity

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