A New Dipole Bending Magnet with Improved Magnetic Field Distribution

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Abstract

We propose a new design for dipole bending magnets which has improved magnetic field distribution. The present bending magnet controls the flow of the magnetic flux by introducing some vacant portions in the magnet pole. This dipole magnet realizes better magnetic field distribution in a wide range of magnetic field strengths. We have investigated these dipole magnets using two-dimensional numerical analysis. In this paper, the principle of the design and examples of calculated results will be presented.

1 Introduction

It is necessary that bending magnets for synchrotrons provide good magnetic field distributions for various magnetic field strengths, which change from low to high values, for beam acceleration. In order to obtain good distributions at various magnetic field strength values, i.e. in wide dynamic range, magnet pole shape has been studied.

Generally, the saturation effect of the magnet pole deforms the magnetic field distribution at high magnetic fields. The magnet pole shape has, therefore, been designed to achieve good magnetic field distribution in the required good field region, especially at high magnetic fields. Unfortunately, the pole shape designed for high magnetic fields with iron saturation tends to bring about deterioration in the quality of the magnetic field distribution at low magnetic fields without saturation. These characteristics have limited the dynamic range of bending magnets in synchrotrons.

Based on these conditions, we propose a new type of dipole bending magnet which has improved magnetic field distribution. A new design concept is based on the control of the flow of the magnetic flux in the magnet pole with use of vacant portions, hereafter called air slots, introduced in the magnet's iron core. This new concept was originally proposed for the development of combined function bending magnets[1], and we have investigated the possibility of applying it to a dipole bending magnet by numerical analysis.

The concept for the improvement of magnetic field distribution is described in section 2, and a comparison of the designs and calculation results of the conventional shim-type and the new air-slot-type magnet are described in sections 3 and 4.

2 Improvement of magnetic field distribution

In the conventional dipole bending magnet, application of shims to the magnet pole face has been considered an effective way of improving the uniformity of magnetic field distribution at high magnetic field. However, the shape of shims for very high magnetic fields often exerts a bad influence on the field distribution at low magnetic fields, and the shape for low magnetic field is not suitable for high field. In order to obtain good uniformity in a wide range of magnetic field strengths, it is necessary to cure this problem. Therefore, we propose a new design for dipole bending magnets to improve magnetic field distribution at various magnetic field strengths.

The scheme for improving magnetic field distribution by introducing air slots in the magnet pole is shown in Fig. 1. The magnetic susceptibility of the air slots in the magnet poles is much lower than that in the iron core. Without the air slots, the perimeter of the iron

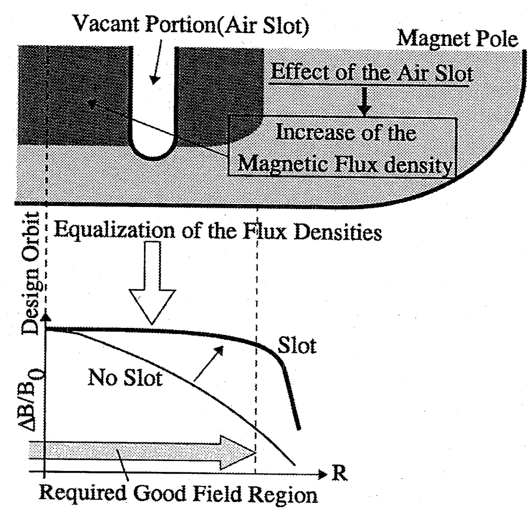

Fig. 1 The scheme of improvement of magnetic field distribution by introducing air slots into the magnet pole

pole saturates earlier than the central area as excitation goes up, and thus the magnetic flux density on the median plane around the perimeter does not keep up with that of the central area. Because of this effect, the magnetic flux density immediately decreases off center and the magnetic field distribution gets worse. On the other hand, introducing air slots in the iron core leads to an increase of the magnetic flux density in the iron region around the air slots. At high magnetic fields, therefore, if the position and shape of the air slots are adjusted to equalize the magnetic flux densities in the whole pole iron, the magnetic field distribution can be flattened as shown in Fig. 1. At low magnetic field where the iron doesn't saturate, the effect of air slots is very small and the magnetic field distribution is controlled only by the shape of the pole surface.

This new concept may be useful for improving the dynamic range of the magnetic field and extending the good field region size.

3 Designs of Bending Magnet

As an example of the magnet design, we assume the magnets for a compact proton synchrotron that accelerates proton beams from 7MeV up to 270MeV[2]. The mean radius and the circumference of the synchrotron are about 3.5m and 22m, respectively. So the curvature radius of the bending magnet is 1.4m. The minimum magnetic field strength is 0.273T for beam injection and the maximum is 1.808T for extraction. The good field region is determined based on our analysis of the beam size in the synchrotron. The required magnetic field uniformity in the good field region is ±0.04%. The specifications of the magnets are listed in the Table 1.

Table 1
Specification of the dipole magnet

Minimum Magnetic Field(T)	0.273
Maximum Magnetic Field(T)	1.808
Curvature Radius(m)	1.4
Bending Angle(degree)	60
Gap Height(mm)	56
Good Field Region(mm)	±50
Required Magnetic Field Uniformity(%)	±0.04

Based on these specifications, magnet shape is determined with use of the computer code PANDIRA. The air-slot-type pole magnet is shown in Fig. 2, and as a reference, the conventional shim-type is shown in Fig. 3

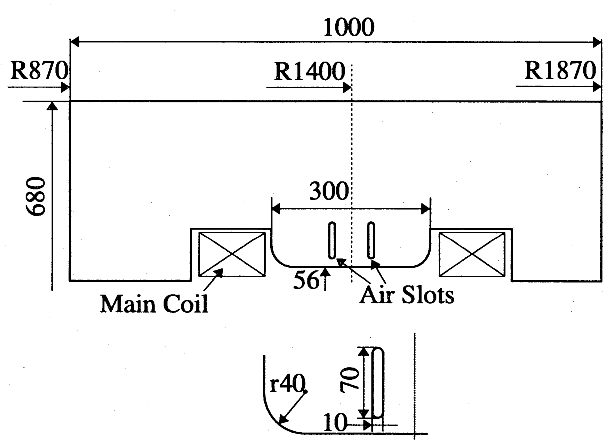

Fig. 2 Cross-sectional view of the air-slot-type magnet

The pole width of the air-slot-type magnet is 300mm and quarter circles are used to prevent the local edge effect at both ends of the pole. Air slots have race-track shape with 70mm height and 10mm wide. The width of shim-type pole is 340mm and the height of the shims is 0.8mm.

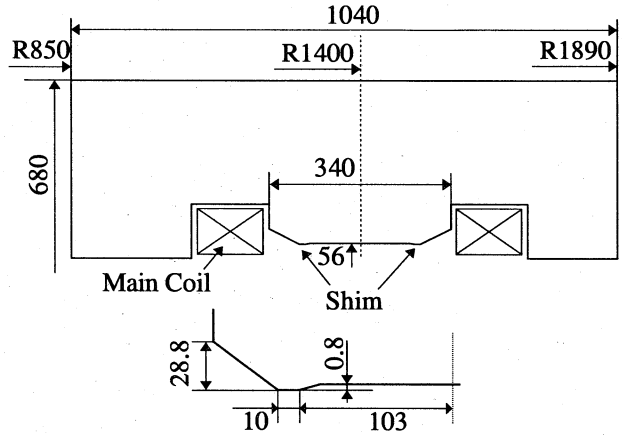

Fig. 3 Cross-sectional view of the conventional shim-type magnet

4 Calculation results

Figures 4 and 5 show two-dimensional magnetic field distribution of the air-slot-type magnet and the shim-type, respectively. They are calculated with use of the computer code PANDIRA. The horizontal axis shows the radial distance from the design orbit and the vertical axis shows the deviation of the magnetic field strength from the value on the design orbit(R=0). The packing factor was assumed to be 0.90 in both cases.

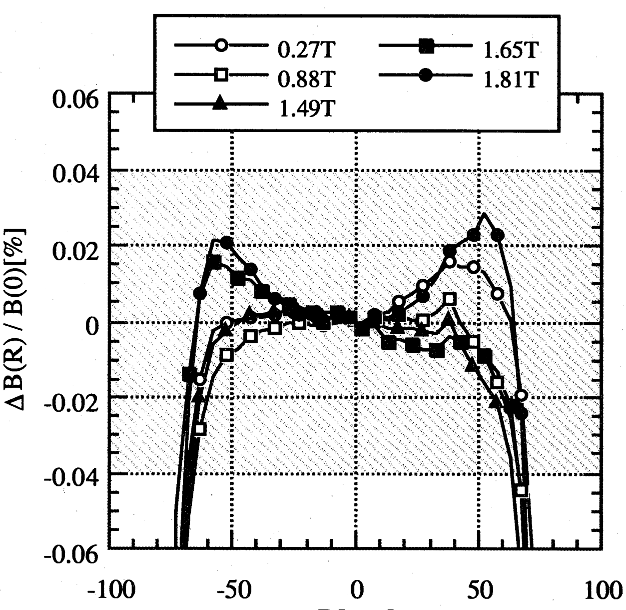

Fig. 4 Two-dimensional magnetic field distribution of the Air-slot-type magnet

As shown in Fig. 4, the good field region width is over ±60mm, and the magnetic field distribution does not change very much from 0.27T to 1.8T. The position, width and height of the air slots are adjusted to flat-

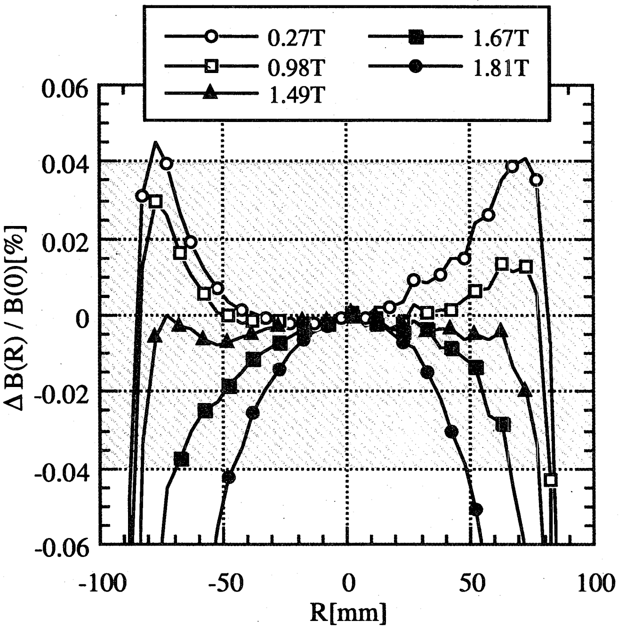

Fig. 5 Two-dimensional magnetic field distribution of the conventional shim-type magnet

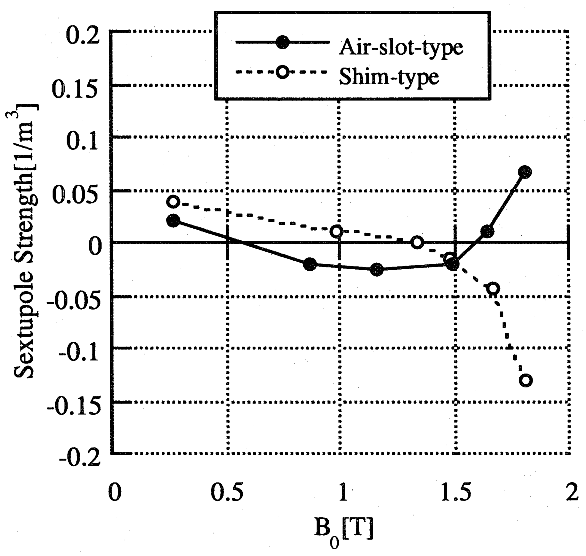

Fig. 6 Dependence of calculated sextupole strength on magnetic field strength, B_0, at design orbit

ten the magnetic field distribution in all magnetic field ranges.

Figure 5 shows that the required field uniformity in good field region of ±50mm wide is barely obtained up to a magnetic field of 1.8T. The distribution at 1.8T is deformed because of the saturation of iron. On the other hand, at a magnetic field strength of 0.27T, the distribution is deformed by the effect of the pole face shape, especially of the shims. If the shim height and position are optimized for the magnetic field distribution at 1.8T, the required uniformity of the field distribution at 0.27T cannot be achieved. So it is difficult to obtain the pole shape which can achieve the uniformity in required value from 0.27T to 1.8T.

Comparing results of these calculations, the field uniformity of the air-slot-type magnet is much better than that of the shim-type at low magnetic fields. These results indicate the dynamic range can be extended to low magnetic field in the case of the air-slot-type magnet. The injection energy of synchrotrons can be lowered than that of synchrotrons using conventional magnets.

To compare the qualities of the magnetic field distribution, we estimated the nonlinear components, mainly the sextupole, for the shim-type and air-slot-type bending magnet. Figure 6 shows the behavior of the sextupole strength in the good field region of ±50mm. At 1.8T, the absolute value of the sextupole strength in the air-slot-type is one-half of that in the shim-type. From this estimation, it is found that the air slot is effective in controlling the magnetic field distribution, especially at high magnetic fields where the iron core saturates.

In both cases, we calculated three-dimensional magnetic field distribution using the computer code TOSCA. The calculated results were consistent with the above results.

5 Conclusion

We presented a new dipole bending magnet which improves the magnetic field distribution by introducing some vacant portions in the magnet pole. These portions, called air slots, control the flow of the magnetic flux especially at high magnetic fields, so that a good field distribution can be obtained in a wide range of magnetic fields because of air slots.

We calculated the magnetic field distribution in a magnetic field range from 0.27T to 1.8T for a compact dipole magnet(curvature radius 1.4m) by using two-dimensional numerical analysis. The results showed that the qualities of the magnetic field distribution at all the magnetic field strengths are better than these in the conventional shimmed pole magnet.

References

[1] M. Tadokoro et al., "A Combined Function Magnet for a Compact Synchrotron", Proc. 1996 Part. Accel. Conf., Vancouver., in press.

[2] K. Hiramoto et al., "A Compact Proton Synchrotron for Cancer Treatments", Proc. 1996 Part. Accel. Conf., Vancouver., in press.