Optimization of lattice quadrupole magnets for cooler ring, S-LSR

Takeshi Takeuchi\textsuperscript{a,}\textsuperscript{*}, Koji Noda\textsuperscript{a}, Shinji Shibuya\textsuperscript{a}, Hicham Fadil\textsuperscript{b}, Masahiro Ikegami\textsuperscript{b}, Yoshihisa Iwashita\textsuperscript{b}, Toshiyuki Shirai\textsuperscript{b}, Hiromu Tongu\textsuperscript{b}, Akira Noda\textsuperscript{b}

\textsuperscript{a}National Institute of Radiological Sciences (NIRS), 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan
\textsuperscript{b}Institute for Chemical Research (ICR), Kyoto University, Gokasho, Uji-city, Kyoto 611-0011, Japan

Available online 13 August 2004

Abstract

Design of quadrupole magnets for a compact ion accumulation and cooler ring, S-LSR, is presented. By requirements from lattice parameters and spatial boundaries for real installation in S-LSR, quadrupole magnets with relatively short magnetic length but wide horizontal aperture are needed. In this paper, we present results obtained from magnetic field calculations by 2D and 3D modelings, and describe the optimization of a pole face shape and fringing edge (chamfer cut design).

© 2004 Elsevier B.V. All rights reserved.

PACS: 41.85.Lc; 41.20.Gz; 29.20.Dh

Keywords: Beam focusing and bending magnets; Wiggler magnets and quadrupoles; Magnetostatics; Magnetic shielding; Magnetic induction; Boundary-value problems; Storage rings

1. Introduction

An ion storage and cooler ring, S-LSR is being developed by a collaboration between Institute for Chemical Research (ICR), Kyoto University and National Institute of Radiological Sciences (NIRS). S-LSR has two major scientific research scopes, one of which is to develop an accelerator system oriented for downsizing heavy ion cancer therapy accelerators and the other is a realization of a beam crystallization by means of laser cooling [1]. S-LSR is a compact storage ring, consisting of circumference of 22.557 m and a lattice with a superperiodicity of 6, as shown in Fig. 1. Due to a strong radial focusing of bending magnets, S-LSR needs no radial focusing quadrupoles. Ion species stored in S-LSR are tentatively assumed to be proton, $^{12}\text{C}^{6+}$ and $^{24}\text{Mg}^{+}$. 
Although the maximum magnetic rigidity of S-LSR is 1.0 Tm, the assumed energies for H\(^+\), \(^{12}\text{C}^+\) and \(^{24}\text{Mg}^+\) ions are 7 MeV, 2 MeV/\(u\), and 35 keV/\(u\), respectively, at the moment.

2. Requirements for S-LSR lattice quadrupole magnets

S-LSR crystalline mode which is oriented for the laser cooling scheme has a superperiod of 6 and a focusing function of \(-1.5 \text{ m}^{-2}\) [2]. All quadrupole magnets (12 pieces) have the same strength for the focusing function. However, in order to enable a wide range of the available strength for the focusing function, the maximum field gradient of quadrupole magnets is determined to be 5 T/m. By requirements for a compact accelerator, the size of accelerator components should be reduced. Short distances between components are also preferable for S-LSR. Fig. 2(a) shows a view of the distance between the quadrupole magnet and the adjacent dipole magnet. The required useful apertures for S-LSR are \(\pm 100\) and \(\pm 20\) mm in horizontal and vertical directions, respectively. Thus, the bore radius for S-LSR quadrupole magnets is determined to be 70 mm as shown in Fig. 2(b). The specifications for S-LSR quadrupole magnets are given in Table 1.
3. Optimization of the basic design by 2D field calculation

Magnetic fields of S-LSR quadrupole magnets are calculated by 2D magnet static field calculation code, POISSON. The region of the pole with the hyperbola shape which corresponds to equipotential surface of the magnetic potential is limited by the geometrical boundary for the magnet yoke. Thus, we have determined the pole radius and the pole width as 70 and 149 mm, respectively. The required ampere-turn for the field gradient of 5 T/m is 9800 AT per pole. The turn number is determined to be 28 per pole considering the dimension of the hollow conductor used for the coil. The hollow conductor has an area of $8.5 \times 8.5$ mm$^2$ and a hollow diameter of 4 mm. The maximum current density is $6.06 \times 10^4$ A/cm$^2$.

In order to suppress the field gradient error and enlarge the good field region, the optimization of the pole shim design has been made. The following calculations are done in the case of the maximum field gradient of 5 T/m. As the basic design, the hyperbola is extended smoothly to the tangential lines at both sides (Fig. 3(a)) [3]. In Fig. 4, the structure of the field gradient error is shown as the function of the horizontal coordinate of the connected point, $X_c$, between the hyperbola and its tangential line. It is known from Fig. 4, that the useful aperture as large as $\pm 100$ mm in horizontal direction is hardly realized with this basic design. Therefore, we modified the design by connecting the hyperbola smoothly to a circular arc instead of the tangential line as shown in Fig. 3(b). The number of optimizing free parameters in this design increases to 2 from the former design of freedom 1.

As a result of the optimization by the tangential arc, we have obtained a good result for the

| Table 1 |
The specifications for S-LSR lattice quadrupole magnets

<table>
<thead>
<tr>
<th>Maximum field strength</th>
<th>5 (T/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore radius</td>
<td>70 (mm)</td>
</tr>
<tr>
<td>Magnet length</td>
<td>200 (mm)</td>
</tr>
<tr>
<td>Magnet yoke size</td>
<td>$\pm 255$ (mm)</td>
</tr>
<tr>
<td>Maximum excitation current</td>
<td>350 (A)</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>$6.0 \times 10^4$ (A/cm$^2$)</td>
</tr>
<tr>
<td>Turn number</td>
<td>28</td>
</tr>
<tr>
<td>Good field region horizontal/vertical</td>
<td>$\pm 100/\pm 20$ (mm)</td>
</tr>
</tbody>
</table>

![Fig. 3. Design of pole shim. (a) and (b) show the smooth connection to the tangential line and arc of the hyperbola, respectively. The horizontal coordinate of the contacted point is given in a sign of $X_c$.](image)

![Fig. 4. The structure of the field gradient error in the case of the smooth connection to the tangential line of the hyperbola. The horizontal coordinate of the contacted point between the hyperbola and the tangential line is given in a sign of $X_c$.](image)
parameter of the circle radius of 25mm and a centre coordinate of \((x, y) = (10.85, -0.29)\) cm. Fig. 5 shows the structure of the field gradient error for various vertical planes, \(y\). For \(y = 0\), the good field region within the field gradient error of \(\pm 0.3\%\) can exceed \(X = \pm 10\) cm. Also for \(y \neq 0\), the field gradient error for \(y = 0.5\) cm can be about 1%. The maximum magnetic field strength in the iron yoke is found to be 1.2 T, which is considered to be a moderate value.

4. Optimization of integrated field gradient by 3D calculation

4.1. Chamfer end

In practice, beam dynamics of ion beams through the quadrupole magnet is determined by the integrated field gradient, \(G(x)L\), for the present case of the short iron case length of 20 cm. A chamfer cut at both ends of poles enlarges the flat region of the integrated field gradient of quadrupole magnets. The optimization of the cut has been done by using the three-dimensional magnet static field calculation code, TOSCA. The notation of the chamfer cut is illustrated in Fig. 6. The following calculation is also performed for the cases in the maximum field gradient of 5 T/m.

The value of \(\Delta h\) and \(\Delta s\) scaled for the bore radius of 70 mm from the design of Ref. [4] are 4.06 and 1.96 cm, respectively. In order to investigate the effect of \(\Delta h\) and \(\Delta s\) on the integrated

![Fig. 5](image_url)  
Fig. 5. The structure of the field gradient error on the optimized parameters for the smooth connection to the tangential circular arc of the hyperbola. Each curve presents results in vertically planes.

![Fig. 6](image_url)  
Fig. 6. The illustration of the pole. The volume framed by \(\Delta h\) and \(\Delta s\) is linearly cut away. The \(\Delta s\) direction corresponds to the beam axis.

![Fig. 7](image_url)  
Fig. 7. (a) and (b) present the structure of the integrated field gradient error using \(\Delta h\) and \(\Delta s\) as a free parameter, respectively.
field gradient, these are independently changed as free parameters. Figs. 7(a) and (b) present the horizontal distribution of the integrated field gradient error using $\Delta h$ and $\Delta s$ as a free parameter, respectively. In Fig. 7(a), the value in the outer region increases according to the decrease of $\Delta h$. On the other side, the same value increases according to the increase of $\Delta s$, as shown in Fig. 7(b). From these qualitative properties for $\Delta h$ and $\Delta s$, we have tried to optimize. Finally we adopted the values of 8.0 cm and 3.0 cm, respectively, for $\Delta h$ and $\Delta s$. The results in Fig. 8 taking the presence of a field clamp into account, which is located at both sides of the bending magnet as shown in Fig. 2. Figs. 9(a) and (b) show the integrated field gradient error for different vertical planes and allow us to compare between ($\Delta h$, $\Delta s$) = (4.06, 1.96) and (8.0, 3.0)(cm). It seems that the flatness of the integrated field gradient is much better for the case of Fig. 9(b) than the case of Fig. 9(a).

4.2. Excitation and effective length

Fig. 10 shows an excitation curve for the optimized design of ($\Delta h$, $\Delta s$) = (8.0, 3.0)(cm) with the field clamp effect. Squares indicate the field gradients and solid circles show the ratios between the calculated field gradient ($G_{\text{cal}}$) and the value of $G_0 = 2 \mu_0 NI / r_0^2$. It is known that the saturation of the iron is safely avoided up to the excitation value of 5 T/m.

By cutting off the pole with the chamfer cut design of $\Delta h = 8.0$ cm and $\Delta s = 3.0$ cm, it is expected that the effective length of the magnetic field decreases. The effective length, is defined by

$$L_{\text{eff}}^{(x)} \equiv \int G(x, z) \, dz / G(x = 0, z) L$$

\[\text{Fig. 8. The structure of the integrated field gradient error under the presence of a field clamp which is located at both sides of the bending magnet as shown in Fig. 2.}\]

\[\text{Fig. 9. The structure of the integrated field gradient error as a function of the vertical y plane. (a) and (b) are for ($\Delta h$, $\Delta s$) = (4.06, 1.96) and ($\Delta h$, $\Delta s$) = (8.0, 3.0) (cm), respectively. These calculations include the field clamp effect.}\]

\[\text{Fig. 10. The excitation curve for the optimized design of ($\Delta h$, $\Delta s$) = (8.0, 3.0)(cm) with the field clamp effect. Squares indicate the calculated field gradient ($G_{\text{cal}}$) for a current per turn. Solid circles show the ratios between the calculated field gradient and the value of $G_0 = 2 \mu_0 NI / r_0^2$.}\]
which is shown in Fig. 11. Also, results include the effect of the field clamp. In the case of \( \Delta h = 8.0\,\text{cm} \) and \( \Delta s = 3.0\,\text{cm} \), the effective length becomes a little bit shorter compared with the case of \( \Delta h = 4.06\,\text{cm} \) and \( \Delta s = 1.96\,\text{cm} \) but is still larger than the iron case length of 20 cm.

5. Conclusion

The S-LSR quadrupole magnet has been designed by means of two and three-dimensional calculation. For two-dimensional calculation (POISSON), the pole width and the yoke size are determined to be 149 mm and ±255 mm, respectively, for the bore radius of 70 mm. For the design of the pole shim, the smooth connection to the tangential circular arc of the hyperbola was adopted. As a result, the good field region within the field gradient error of ±0.3% can be achieved in the region of ±10 cm in the horizontal direction on \( y = 0\,\text{cm} \). For \( y = 0.5\,\text{cm} \), it is calculated within about 1%.

In order to optimize the structure of the integrated field gradient (GL) for horizontal direction, the design of the chamfer cut was studied by the three-dimensional magnet static field calculation code (TOSCA). The optimized chamfer cut design with the field clamp effect is \( \Delta h = 8.0\,\text{cm} \) and \( \Delta s = 3.0\,\text{cm} \) which satisfies the integrated field gradient error of less than 1%. The fabricated quadrupole magnet for S-LSR is shown in Fig. 12.

References