SUPERCONDUCTING CHANNEL MAGNETS WITHOUT STRAY FIELDS

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SUPERCONDUCTING CHANNEL MAGNETS WITHOUT STRAY FIELDS


Résumé - Pour le cyclotron à focalisation par secteurs séparés SuSe, des aimants magnétiques de canal sans champ parasitaire seront élaborés comme injecteurs et extracteurs.semblable à un cable coaxial, un aimant de canal se compose d’un ou plusieurs conducteurs centraux entourés de conducteurs extérieurs sur une surface fermée. Il existe toujours une distribution de courant sur la surface extérieure de telle façon que tout le champ à l’extérieur disparaît à l’exception de petits champs parasitaires, causés par les ouvertures pour le faisceau. Un aimant courbé à supraconducteur est en construction.

Abstract - Superconducting channel magnets without stray fields are developed as injection and extraction elements for the superconducting separated sector cyclotron SuSe. Similar to a coaxial line a channel magnet consists of one or several central conductors surrounded by outer conductors on a closed surface. There always exists a current distribution of the outer conductors, so that the total outside field vanishes except for small stray fields caused by the beam windows. A bended superconducting channel magnet for \( B = 2T \) is under construction.

I - INTRODUCTION

At the Munich Accelerator Laboratory the design of a superconducting sector cyclotron (SuSe) as booster for the existing 13 MV-tandem is studied. SuSe will accelerate protons and heavy ions to maximum energies of 450 MeV respectively 300 MeV/u (for \( Q/A = 0.5 \)) with excellent beam properties \cite{1}. It consists of four sector magnets with a sectorangle of 50° each and two accelerating cavities, positioned in opposing sector gaps and extending into the neighbouring gaps. A top view of the cyclotron is shown in fig. 1, some significant features of SuSe are summarized in tab. 1. Another paper on this conference deals with the superconducting magnet system \cite{2}.

The ions leave the tandem with specific energies of \( E/A \leq 5.5 \) MeV/u. They pass a stripper foil in order to achieve as high charge states as possible, ranging from \( Q/A = 1 \) for protons to 0.16 for U. Then they enter the cyclotron in radial direction in the middle of an intermediate sector. There are some differences to conventional normal conducting sector cyclotrons, which influence the design of the injection system for SuSe fundamentally:

1. Inside the injection radius the valley sectors are totally occupied by the RF-cavities. Therefore no central space is available for injection elements besides in the magnet sectors, where the gap height is 8 cm.

2. Because of the high background field of the sector magnets the magnetic injection elements in this region cannot consist of iron. Thus the elements have to be su-
perconducting with high current densities in order to achieve fields of about 2T.

3. The magnetic injection elements must not have stray fields by two reasons. Firstly these stray fields could cause distortions of the orbits. Secondly there is a certain risk for quenching the injection magnets due to beam heat up. To prevent induced quenches of the big main coils, the magnetic coupling caused by the stray fields has to be avoided.

4. The stray fields of the sector magnets in the intermediate sectors are strongly non-scaling. In order to get similar injection trajectories for different specific charges and final energies respectively, these stray fields have to be compensated along the injection path. These compensating elements must be arranged above or below the orbit plane and must not have stray fields themselves, which would distort the orbits. Therefore screening tubes, either superconducting or of iron, are useless.

### Table 1: Main features of SuSe

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection radius r₁</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Extraction radius r₂</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Maximum field at r₂</td>
<td>4.8 T</td>
</tr>
<tr>
<td>Average field at r₂</td>
<td>2.25 T</td>
</tr>
<tr>
<td>Sector angle per magnet</td>
<td>&gt; 50°</td>
</tr>
<tr>
<td>2 accelerating cavities</td>
<td>TE101 mode</td>
</tr>
<tr>
<td>Resonant frequency range</td>
<td>59...74 MHz</td>
</tr>
<tr>
<td>Harmonic operation modes</td>
<td>,...16.</td>
</tr>
<tr>
<td>Max. accel. volt. per turn at r₁</td>
<td>500 kV</td>
</tr>
<tr>
<td>Max. accel. volt. per turn at r₂</td>
<td>2 MV</td>
</tr>
<tr>
<td>Beam separation at r₁</td>
<td>&gt; 9 mm</td>
</tr>
<tr>
<td>Beam separation at r₂</td>
<td>&gt; 2.5 mm</td>
</tr>
</tbody>
</table>

Fig.1 Top view of the cyclotron. Sc: supercond. sector coil, Y: iron yoke, RF: accelerating cavity.

**II. THE CHANNEL MAGNETS**

To solve all problems listed above, superconducting channel magnets without stray fields are proposed*). These magnets resemble modified coaxial current cables. In the case of a coaxial line the magnetic field between the cylindrical inner conductor and the coaxial outer conductor decreases as \(1/r\). Outside the cable the magnetic field produced by the inner current is just compensated by that of the opposite outer current. Even at the front and the end faces the outside field vanishes, if the connections between the central and the outer cylinder are directed radially (with constant azimuthal current distribution). This can be seen from symmetry arguments and \(\int \vec{H} \cdot ds = 0\). Only at the entrance and exit windows for the beam at the faces the azimuthal current distribution is disturbed, causing only small stray fields of short range.

The field of applications of coaxial magnets is limited by the large field gradient \(\partial H/\partial r\). However, nearly any gradient inside the channel magnet and no stray fields outside are attainable, if the cross sections of the inner and outer conductors are chosen in a proper manner. First this will be shown for straight channel magnets by analogy to electrostatics. Then a more general proof is given for any shape, e.g. curved channel magnets.

If a straight conductor with equidistant charges on it is surrounded by a grounded conducting tube, then the same amount of line charges with opposite sign will arrange on the tube, so that there is no electrical field outside the tube. With $E_x$ and $E_y$ as the field components of the line charges with the longitudinal density $dQ/dz$ at the position $x_i$, $y_i$ one has:

$$\Sigma E^i_x = 0 \quad \Sigma E^i_y = 0$$

(1)

The field components at a position $x$, $y$ are given by

$$E^i_x(x,y) = \frac{dQ/dz}{2\pi \epsilon_0} \cdot \frac{x-x_i}{(x-x_i)^2+(y-y_i)^2} \quad E^i_y(x,y) = \frac{dQ/dz}{2\pi \epsilon_0} \cdot \frac{y-y_i}{(x-x_i)^2+(y-y_i)^2}$$

(2)

The magnetic field components of straight currents are described by analog equations:

$$B^i_x(x,y) = \frac{\mu_0 I}{2\pi} \cdot \frac{y-y_i}{(x-x_i)^2+(y-y_i)^2} \quad B^i_y(x,y) = \frac{\mu_0 I}{2\pi} \cdot \frac{x-x_i}{(x-x_i)^2+(y-y_i)^2}$$

(3)

If the current density is chosen correspondingly to the transversal density of the line charges, then the magnetic field outside the current tube must vanish as in the electrostatic case:

$$\Sigma B^i_x = 0 \quad \Sigma B^i_y = 0$$

(4)

The analogy to electrostatics may serve as a line in designing channel magnets. Another helpful conception is to look at a channel magnet as a superposition of several coaxial lines, each of them without stray fields and no field contributions of the cylindrical outer conductor inside. The precise current distribution can be calculated by a fitting program with the wire positions as variables (within given limits) and the fields as goal of the fit (outside zero, inside the useful channel certain values). As a result of such calculations two channel magnets with rectangular cross sections are shown in fig. 2a) and 2b).

![Fig.2 Cross sections of two channel magnets. B: magnet body, J: jacket, W: beam window. Current density $j=220$ Amp/mm².](image)

Both are suited as septum magnets with a septum of about 1 cm. Here the cross section of the inner conductor equals that of the outer one with opposite current direction. These magnets may be realized by endless winding with the superconducting wire in the inner conductor running in one direction and in the outer conductor in the opposite. If the wires at the faces are led normally to the magnetic field lines, there will be no stray fields even at the ends of the channel magnets (except for the beam windows). In the case of fig. 2a) a constant field of 2T was required in the channel for $7 \text{ cm} < x < 9 \text{ cm}$, in case b) $B(7,0) = 2T$ and a constant gradient $\partial B/\partial x = -0.17 \text{ T/cm}$ for $7 \text{ cm} < x < 9 \text{ cm}$. The gradient mainly depends on the shape of the right bounds of the inner conductor. The current distributions on the rectangular outer conductors demonstrate the analogy to electrostatics as discussed above. In order to get a high field in the useful channel, the inner conductor is arranged asymmetrically. In both cases the overall current density $j=220$ A/mm² is rather modest, thus these channel magnets would remain superconducting even in a background field of $-5T$. Because there is no stray field, there are no forces acting on the channel magnet as a whole in a background field.
The channel magnet of the type as shown in fig. 3a) consists of an inner coil (the two vertical bars) and an outer one, which forms a rectangular frame. On the x-axis at |x| ≤ 1.5 cm the field should be 0.6 T. In fig. 3b) this cross section is approximated by a superposition of four coaxial lines.

In the following it will be shown that for any current loop inside a closed surface of arbitrary shape there always exists a current distribution on this surface, which makes the outside field vanishing. Suppose the surrounding surface is formed by an ideal superconducting foil. By switching on the inner current, surface currents are induced in the foil, which hinder the magnetic flux from penetrating through it. Therefore outside the surface there are no field components $B_n$ normal to the surface. Because $\oint B_n \, ds = 0$ along any closed path on the surface, it must be $B_n = 0$ as well. From this it follows, that especially bended channel magnets with cross sections of the type shown in fig. 2 and 3 are possible. In order to determine the current distributions by means of a fit program in this case, it is advantageous to calculate the fields of ring currents forming a torus. The field of a piece of the torus is not changed, if the wires at the faces from the inner to the outer conductor are led normally to the magnetic field lines.

From the general proof given above it seems obvious to use superconducting foils as outside conductors for channel magnets of the type shown in fig. 3, at least if the background field is modest. During the adjustment of the background field the foils must be normal conducting, of course. In the case of fig. 2 an additional superconducting foil outside the outer conductor can suppress stray fields caused by imperfect positioning of the wires.

To show the feasibility of superconducting channel magnets, the construction of a bended injection element for Suse with a cross section similar to that of fig. 2a) is under way. The outer radius at the septum is 20 cm, the inner radius is 13 cm, the height is 8 cm. The magnet body and jacket are made of a strong aluminium alloy. The superconducting NbTi wires (Vacuum Schmelze, Hanau) with $\phi = 0.4$ mm and the ratio $\text{Cu}/\text{Sc} = 1.35$ have 61 filaments of $\phi = 34 \mu$. The coils are potted.

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