THE STRASBOURG SUPERCONDUCTING COIL CYCLOTRON PROJECT


Centre de Recherches Nucléaires, B.P. 20, 67037 Strasbourg Cedex, France

Abstract. - A project for a superconducting coil compact cyclotron which allows to accelerate ions to energies up to 80 MeV/A from a 16 MV MP Tandem is presented. Some specific points are emphasized: the injection, the magnetic field configuration, the bunching and the beam transfer from the Tandem.

The Strasbourg project\(^1\) consists of a superconducting coil, \(K = 560\), compact cyclotron. Ions from the 16 MV MP Tandem of the Centre de Recherches Nucléaires in Strasbourg will be stripped inside the cyclotron before being accelerated. Conclusions of prospective studies\(^1\) have shown that energies of 10 to 80 MeV/A for light ions and 5 to 16 MeV/A for the heaviest are needed. A careful examination leads to the conclusion that a 3 sectors \(K = 560\) compact cyclotron with superconducting coils corresponds the best to this choice. The following table and Fig. 1 give the main characteristics of the project. A working group has been constituted which made detailed studies on the following points: calculation of the magnet configuration leading to isochronism, injection and stripping, mechanical structure of the magnet and mounting of the machine, superconducting coils, cryostat and cryogenics, bunching and beam transfer from the MP. The study of the RF system and computer control have also begun:

\[\text{Effective bore length limit: } K = 310 \text{ to 700 } 0.1 \text{ to } 0.24\]

\[\text{Focusing limit: } E_{\text{foc}} = 170\]

\[\text{RF low energy limit: } n/\lambda = 5 \text{ MeV/amu}\]

<table>
<thead>
<tr>
<th>Injection</th>
<th>16 MV MP Tandem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils</td>
<td>3 sectors</td>
</tr>
</tbody>
</table>

**Iron**
- Pole diameter: 180 cm
- Hill iron gap: 8 cm
- Average optical constant: \(2 \text{ rad} / \text{m}\)
- Total weight: 200 t
- Extraction radius: 82 cm

**Field**
- Max central field: 4.6 T
- Min central field: 2.45 T
- Max average field: 4.6 T
- Extraction radius: 4.6 T

**RF System**
- 3 buses
- Frequency range: 22 to 50 MHz
- Vessel numbers: \(2,3,4\)
- Die voltage: 100 kV
- Max total RF power: 230 kW

**Superconducting wires**
- 2 sections (inner 60 cm, outer 40 cm)
- Max total Ampere-turns: 5.7 \(10^6\)
- Effective stored energy: \(4 \times 10^7\)

**Field trimmers**
- 67 pairs of trim coils
- F: 30 kHz

**Extraction system**
- One turn extraction with \(n = 1\) excitation
- 2 Electrostatic deflectors
- Magnetic channels

**Beam characteristics**
- \(\pm 20 \text{ to } 45 \text{ MeV/amu}\)
- \(10^{-7} \text{ to } 10^{-13} \text{ A}\)
- \(127\) ± 12.4
- \(127\) ± 12.4

\[\begin{align*}
\text{Coil} & \quad 2060 \text{ mm} \\
\text{Outer diameter} & \quad 2416 \text{ mm} \\
\text{Distance between coils} & \quad 120 \text{ mm} \\
\text{Overall coil height} & \quad 512 \text{ mm} \\
\text{Inner coil height} & \quad 307 \text{ mm} \\
\text{Outer coil height} & \quad 206 \text{ mm} \\
\text{Double pancakes per coil} & \quad 15 \\
\text{Turns per double pancake} & \quad 80 \\
\text{Total current per coil} & \quad 1220 \\
\text{Insulation between pancakes} & \quad 2 \text{ mm} \\
\text{Nominal current} & \quad 2380 \text{ A} \\
\text{Maximum rated current} & \quad 3200 \text{ A} \\
\end{align*}\]

\[\begin{align*}
\text{Apparent maximum current} & \quad 3200 \text{ A/m}\text{.} \\
\text{Total ampere-turns} & \quad 5.7 \times 10^6 \text{ A} \text{t} \\
\text{Maximum stored energy} & \quad 49 \text{ MJ} \\
\text{Maximum field at the conductor} & \quad 4.6 \text{ T} \\
\text{Cu resistivity at } 4.5 \text{ K} & \quad 3.10^{-8} \text{ Ohm} \text{cm} \\
\text{Critical current at } 4.5 \text{ K} & \quad 3045 \text{ A} \\
\text{Maximum working point} & \quad 4.6 \text{ T} \\
\text{Conductor weight} & \quad 9 \text{ t} \\
\text{Coil and cryostat weight} & \quad 15 \text{ t} \\
\end{align*}\]

In the following we give more details about the superconducting coil, the injection, the magnetic field configuration and the beam transfer.

**Superconducting coil**

\[\begin{align*}
\text{Inner section} & \quad 1860 \text{ A} \\
\text{Outer section} & \quad 2380 \text{ A} \\
\text{Inner section} & \quad 2380 \text{ A} \\
\text{Outer section} & \quad 870 \text{ A} \\
\end{align*}\]

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* Internal reports have been written on all this subjects and are available on request.
Injection parameters

Injection geometry has been chosen to enhance high energies-high intensities for light ions from $^{12}\text{C}$, leading to the following figures:
- Common steering point 2.5 m from the center
- Stripping in a hill and injection "with the spiral" allowing to have most of the injection path near along the median line of a valley where the field is low and nearly does not vary
- Minimum entry angle into the field as small as possible.

From that the main parameters are:
- Steering distance 2.5 m
- Steering angle $\pm 1^\circ$
- Stripping position 15.5 to 20.3 cm
- Entry angle 10 to 25°
- Charge state ratio 2.85 to 3.95
- Energy gain 17 to 32.5

Detailed calculations from an analytical description of the actual (calculated) field given by the magnet configuration described below give the injection limitations as shown on Fig. 2. These limitations are somewhat restrictive for high energy intermediate and heavy ions and mainly for low energy light and intermediate ions keeping the best for light-high energy ions.

Magnetic field configuration

Several possible configurations have been studied, ending with the final design described below (Fig. 3). The criteria are dictated essentially by the need to obtain good isochronous fields together with adequate focalization for the whole ion range with optimized excitation for main and trim coils. Spacing and mechanical requirements, particularly severe in such a compact cryogenic cyclotron in which the housing space for injection, extraction and acceleration components is so small, are to be carefully examined as well.

For each configuration the resulting magnetic field has been determined as already done elsewhere by the combination of two separate contributions, the one from the components with cylindrical symmetry, the other from the iron pole tips. For several values of the intensities $I_a$ and $I_b$ in each pair of superconducting coils the relaxation method (code POISSON) has been used to calculate two different field maps. The first one corresponds to the field produced by the coils together with the main part of the iron which is cylindrically symmetric: the yoke, the two end rings and the cylindrical poles generated by the valley profile. The second calculation is also for cylindrical symmetry and for the same iron part with addition of pole pieces with the same axial profile as the pole tip in a hill stretched out over to $2\pi$. The actual average field value is between those two results and is obtained by a combination of the two field maps with a weighting factor depending on the hill width. The azimuthally variable field component given by the spiral pole tip has been calculated with a specially written code, using the uniform magnetization approximation.

Isochronism and betatron oscillations frequencies have been studied for twelve different ions: from $^{12}\text{C}$ up to $^{238}\text{U}$ and for final energies near the maxi-
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![Graph](image)

**Fig. 4** Upper part: Calculated field compared with theoretical isochronous field. Lower part: Residual field defect with trim coil corrections.

The average field is the nearest to isochronism have to be determined. Such a calculation is done from the following grid: The average field value has been computed with POISSON code for a set of equally spaced current densities covering the overall range: \( I_a = 1100, 1800, 2500 \) and \( 3200 \text{ A/cm}^2 \) for the coil nearest to the median plan (inner coil); \( I_b = -1000, -300, 400, 1100, 1800, 2500 \) and \( 3200 \text{ A/cm}^2 \) for the farthest one (outer coil). From this grid the average field value for a given ion has been derived by interpolation using a least squares fit method to minimize isochronism defects. From that result corrections have been made setting trim coil currents to compensate these defects. As an example the average field for \( ^{58}\text{Ni} \) is shown on Fig. 4 while Fig. 5 shows \( V_r \) and \( V_z \) for \( ^{12}\text{C} \) at two different energies.

Such a method has been used optimizing main coil dimensions and iron geometry: pole tip azimuthal profile (angular width and spiral constant), valley axial profile near the extraction radius and central region configuration. The trim coil array has been chosen taking into account the residual field differences from the isochronous field.

Resulting main characteristics for the coils and the iron geometry are listed in the following table.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner coil cross section</td>
<td>352 cm²</td>
</tr>
<tr>
<td>Outer coil cross section</td>
<td>358 cm²</td>
</tr>
<tr>
<td>Median plane distance</td>
<td>6 cm</td>
</tr>
<tr>
<td>Valley gap (progressively)</td>
<td>70 cm</td>
</tr>
<tr>
<td>RF holes</td>
<td>22.6 cm up to ( z = 56 ) cm</td>
</tr>
<tr>
<td>Radial position</td>
<td>49 cm</td>
</tr>
</tbody>
</table>

Beam matching and injection system

Using most of the present experimental facilities has been our aim but we could not avoid the usual apparent complexity of the transfer line and of the bunching system shown in Fig. 6.

![Diagram](image)

**Fig. 6** Lay out of the facility (MP on the left and experimental areas above are out of scope). The time structure is obtained by a double drift buncher \(^5,6\) positioned on the low energy platform placed upstream of the MP Tandem and operating on the RF frequency. The efficiency of such a buncher
is about 65%. The dimensions of this system have been determined according to Hinderer's formulation (Fig. 7). A high energy buncher placed roughly in the middle of the transfer line provides an upright emittance ellipse at the cyclotron injection stripper and a pulse width of ± 3°.

The platform voltage is varied so as to compensate partially the variations of the effective lengths between the terminal of the MP and the cyclotron. Fig. 8 shows how the mean position of the H.E. buncher was determined.

The third section is similar to the Chalk River\textsuperscript{8} line and is destined to the emittance and dispersion matching. Another but more expensive solution has been proposed based on the use of variable lengths as suggested by F. Hinterberger\textsuperscript{9}.

References
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