Impact of the beam pipe design on the operation parameters of the superconducting magnets for the SIS 100 synchrotron of the FAIR project

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Abstract. The SIS 100 accelerator of the Facility for Antiprotons and Ion Research (FAIR) at GSI Darmstadt will be the world’s second fast ramped synchrotron utilising superconducting magnets in heavy ion research facilities. The request for high current Uranium beams requires vacuum of extremely high quality that can be achieved in long term operation only by cold vacuum chambers acting as a cryogenic pump. Its mechanical stable design options are strongly limited by AC loss generation and field distortion problems. Previous R&D indicated that cooling tubes, keeping the vacuum chamber below 15 K, create large additional eddy currents and thus deteriorate the field with a sextupole. This effect is most dominant at the start of the ramp. The ramp rate of the correctors is limited by the maximum available voltage and as by the heat created on the ramp up and the cooling efficiency of the Nuclotron-type cable. Thus we investigate different means to simplify the vacuum chamber design keeping its temperature below 15 K in the area where the highest suction pumping is required with alternative cooling methods as well as on the compensation margin the sextupole correctors can provide. This work was partly supported by the BMBF.

1. Introduction
The SIS 100 synchrotron utilises superconducting magnets providing a field of 2 T (dipole), ramped with a cycle frequency of 1 Hz (4 T/s). The magnets have to be operated at 4.5 K and use the Nuclotron cable (Fig. 1, insert) as its ancestor, the Nuclotron at JINR Dubna [1]. In this cable the superconducting wires are tightly wrapped around a tube which is cooled by a forced two phase helium flow. The magnets create heat when they are ramped due to hysteresis and eddy current effects, which were reduced by a factor of two during previous R&D [2]. Important improvements were also achieved for the magnetic field homogeneity and for the mechanical stability of the coil [3, 2, 4]. The main design issues and operation parameters had been tested on mockups and short model magnets [5, 6]. A decisive step toward series production was to scale these results to larger aperture and increased length of the main magnets, required to realize the challenging beam characteristics and to guaranty its stable long time operation performance. In addition the manufacturing technology must be optimised for industrial conditions and the GSI cryogenic test facility had to be prepared and adjusted for the complex measurements on such magnets [7]. The 3D drawing of the dipole, manufactured by Babcoek Noell GmbH Würzburg
Figure 1. The structure of the Nuclotron cable (top left) and the main features of the magnet design of the first full size dipole. 1 – cooling tube, 2 – superconducting wire (multiflament NbTi/Cu), 3 - Nichrome wire, 4 – Kapton tape, 5 – adhesive Kapton tape, a – cryostat vessel, b – cable and half coil (2 · 4 windings), c – yoke cooling pipes, d – LHe lines, e – suspension rods, f – soft iron yoke, g – bus bars, h – thermal shield (BNG), is given in Fig. 1. Detailed descriptions of the design and of the manufacturing processes are available in [8, 9]. This magnet has been tested since December 2008 and its AC losses were measured [4, 10] next to its magnetic field [11, 12] and the AC losses of the vacuum chamber [10] (see also figure 2).

All these measurements showed that the hydraulic resistance of the cooling tubes in the coil limit the maximum cooling power to slightly less than 45 W, thus this magnet can not be run in the important operation cycles foreseen for FAIR [13] (roughly a triangular cycle form 0.22 - 2.1 - 0.22 T with 0.8 seconds pause (called “2c”) at the lower level and even more intensive ones up to a pure triangular cycle (denoted by \(\backslash\)) as predicted [5, 14].

As high charge state ions (Uranium up to U\(^{28+}\)) will be transported in these machines, the vacuum has to be better than \(10^{-12}\) mbar [15]. So the vacuum chamber has to provide the following functionality:

(i) a cold surface to work as a cryogenic adsorption pump to reach a vacuum pressure better than \(10^{-12}\) mbar operating over 20 years, infinitely refreshable

(ii) minimise the eddy currents induced by the ramped field to an acceptable level so that the field distortion and the dissipated power are tolerable (by geometrical design and material choice)

(iii) be sufficiently mechanical stable to sustain a pressure of 1 bar so that a break of the cryostat pressure will not damage the whole machine

(iv) provide a return path for the beam image current

(v) shield the beam from the outside (skin depth)

The vacuum chamber design was based on [16].
2. Vacuum chamber temperature

Given that the surface temperature of the beam pipe is a major issue for the cryopump performance of the vacuum pipe, first calculations were directed to verify that the temperature is below 15 K, a temperature which was estimated to be cold enough to reduce the residual gas pressure to an acceptable limit.

2.1. Calculated temperature distributions

2.1.1. Chamber in external field

In a first step the vacuum chamber was modelled in ANSYS imposing an external periodically ramped field with 0 - 2 - 0 T and 4 T/s. These calculations were done for the chamber as built by BNG [17] and for the vacuum chamber as built by BINP [18]. The difference between the two vacuum chambers is that the one built by BNG uses cooling tubes, which are soldered to the vacuum chamber, while the one built by BINP uses cooling tubes, which are electrically insulated. The temperature profile calculated for the two is given in Fig. 3. One can see that the temperatures for the one in direct contact are lower by 1 to 2 K than for the latter.

2.1.2. Chamber coupled to the magnet

For the central part of a magnet, the magnetic field and other parameters are typically calculated using a 2D solver (i.e. the part were the magnet’s field is independent from the longitudinal coordinate z and thus $B_z = 0$). For calculating the field on the ramp and for the dissipated power the vacuum chamber must be included into the model. The vacuum chamber is made of an elliptical tube with a thickness of 0.3 mm. Ribs, 3 mm thick, soldered to the tube, reinforce it, so that it can withstand the ambient air pressure. Cooling tubes, soldered to the ribs, cool the vacuum chamber surface to support cryopumping. Therefore a small 3D slice (see Fig. 4) starting from the middle of a rib to the middle between two ribs was created [19].

The end of the magnet’s pole is chamfered to Rogowsky profile and narrow horizontal slits are cut into the laminations in the end to reduce the eddy currents created by the varying $B_z$. 

![Figure 2. The first SIS 100 full size dipole (top) and its vacuum chamber (bottom).](image-url)
Figure 3. The temperature profile for the different vacuum chamber designs

Figure 4. The model of the magnet and the vacuum chamber. The model represents the 2D section of the magnet and one full period of the vacuum chamber.

component. Due to these many components of small dimension (compared to the total magnet length of 3m), a short end model was created enforcing $\frac{dB_z}{dz} = 0$ as boundary condition, to obtain a model which can be solved within reasonable time (see Fig. 5) [20].

The central model was also used to see the impact of the different parts of the vacuum chamber on the cooling (see Fig. 6). The top row shows the magnet and vacuum temperatures while the bottom row shows the temperature inside the vacuum chamber along the ellipse. One can see that the left row (vacuum chamber as designed and built by BNG) gives the lowest temperatures while the vacuum chamber temperature only increases by a few Kelvin along the chamber. If the ribs are left out the temperature increases even more, indicating that a considerable cooling power is provided over the coil pack as well as over the magnet’s yoke, reducing the cooling power available for cooling the magnet itself. The effect of this heat transfer (see Fig. 6(b) and 6(e)) gives a temperature profile not significantly increased with respect to the temperature field.
**Figure 5.** The model of the end section of the dipole magnet and the vacuum chamber. The vacuum chamber is supported by ribs. The separate cooling tubes of the yoke were not modelled.

**Figure 6.** Calculated temperatures. The model with the magnet and yoke temperature is shown for the different configurations in the top row. The temperature along the beam pipe (one quarter starting from the top (small axis) to the right is shown in the bottom row.
Table 1. The average power (in Watts) dissipated in the different components for the different cycles. H – hysteresis loss, E – eddy loss

| cycle | 2a | 2b | 2c | \(\wedge\) |
|-------|----|----|----|-------|
|       | H  | E  | H  | E     | H   | E   |
| yoke  | 0.6| 0.1| 11.8| 0.3   | 23.7| 0.6 |
| brackets | 0.4 | 0.7 | 1.2 |
| endplates | 1.1 | 3.3 | 3.8 | 8.0 |
| yoke  | 0.4 | 0.8 | 1.5 | 2.2   | 3.0 | 4.0 | 5.3 |
| beam pipe central part |  |  |  |  |  |  |
| pipe  | 1.7 | 4.7 | 6.7 | 13.9 |
| tubes | 0.7 | 1.9 | 2.7 | 5.6 |
| ribs  | 0.1 | 0.2 | 0.3 | 0.6 |
| pipe  | 0.3 | 0.7 | 0.9 | 1.9 |
| Total |  |  |  |  |
| magnet centre | 0.7 | 3.9 | 12.2 | 24.5 |
| end   | 1.8 | 6.0 | 9.7 | 18.5 |
| coil  | 8   | 2   | 11  | 22   |
| total | 10.5| 11.8| 32.9| 65.0 |
| vacuum chamber | 2.8 | 7.6 | 10.6| 22.2 |
| total load | 13.2| 19.4| 43.5| 87.1 |

including the effect of the cooling tubes. The power dissipated in the different parts is listed in Table 1 with the different cycles listed in Table 2.

2.2. Measured temperature distributions
The vacuum chamber was inserted into the magnet and the magnet was operated in the different possible FAIR cycles [13] and its loss was measured [10]. The vacuum chamber was also equipped with temperature sensors on the inlet and outlet of the helium flow and on different positions on the chamber. All sensors on the chamber were below the outlet temperature, but close to it and thus only these two are presented in Table 2. The measured temperatures are thus close to the ones calculated.

3. Impact of the vacuum chamber design on the magnetic field
3.1. Theory of new multipole expansions
The optimal design solution for SIS 100 is a curved dipole, which reduces the required aperture, as the dipole magnet follows the beam trajectory [5, 6]. The vacuum chamber is of elliptic shape. Thus the common circular multipole used to describe the field are not straightforward to use.

The multipole expansion in elliptic coordinates \(\eta, \psi\): 
\[ x = e \cosh \eta \cos \psi, \quad y = e \sinh \eta \sin \psi \]
eccentricity is given by [21]

\[ B = B_y + iB_x = \sum_{n=0}^{\infty} E_q \frac{\cosh[n(\eta + i\psi)]}{\cosh(n \eta_0)} \]  

The reference ellipse \( \mathcal{E} \) is \((x/a)^2 + (y/b)^2 = 1 \) \( \Leftrightarrow \eta = \eta_0 \). The expansion coefficients \( E_q \) are derived from a Fourier expansion in \( \psi \) of the field given along \( \mathcal{E} \). These \( E_q \) can be recalculated to circular multipoles

\[ B(z) = B_m \sum_{n=1}^{M} c_n (z/R_{Ref})^{n-1} \]  

using an analytic linear transformation, with \( B_m \) the main field, \( z = x + iy \), \( R_{Ref} \) the reference radius and \( c_n = b_n + ia_n \) the relative higher order multipoles. The \( b_n \)’s and \( a_n \)’s are dimensionless constants. In this paper they are given in units i.e. 1 unit = 100 ppm at a \( R_{Ref} \) of 40 mm. We chose this free parameter such that the relative allowed harmonics \( b_n \) can then be represented as convenient numbers in the order of 1 to 10. Using (2) the field can be interpolated with sufficient accuracy within an ellipse with half axes \( a, b \).

As the dipole magnets are curved, toroidal multipoles were developed, which allow to describe the field in dimensionless local toroidal coordinates [22].

3.2. FEM Calculations

The model presented in 2.1.2 also allows calculating the field within the vacuum chamber. The calculations showed that the field is significantly distorted by the eddy currents within the chamber [20]. The distortion is larger than the magnet distortion itself at the injection field of approximately 0.25 T.

All calculations in 2.1.2 were presented for the now tested straight dipole magnet with a double layer coil (S2LD, see also Fig. 1). As this magnet can not provide the cycles requested for FAIR, the magnet was redesigned to a curved dipole with a single layer coil (Curved Single Layer Dipole, CSLD) [5, 6].

This design was selected as the main dipole for SIS 100 [23]. The same calculations as done with ANSYS were performed using Electra 2D and 3D for the CSLD. The 3D model was similar to the ANSYS model. The difference of the multipoles \( b_3 \) and \( b_5 \) for the transient field, calculated with ELEKTRA 3D, to the static field, calculated with TOSCA 3D, quite match the ones found for the straight dipole (see Fig. 8). In the 2D model the rib was left out. The ELEKTRA 2D model predicts smaller distortions (see Fig. 8(c) and 8(f)) which is to be expected as the eddy flow of 0.1 g/s. \( B_{min} \) ... injection field, \( B_{max} \) ... maximum field \( dB/dt \) ramp rate, \( t_f \) ... flat top time (at \( B_{max} \), \( t_p \) ... injection time, (at \( B_{min} \), \( t_c \) ... cycle time

| \( B_{min} \) [T] | \( B_{max} \) [T] | \( dB/dt \) [T/s] | \( t_f \) [s] | \( t_p \) [s] | \( t_c \) [s] | \( T_{in} \) [K] | \( T_{out} \) [K] |
|-----------------|-----------------|-----------------|----------|----------|----------|----------|----------|
| 2a 0.24         | 1.2             | 4.0             | 0.1      | 0.70     | 1.408    | 5.12     | 15.46    |
| 3a 0.24         | 1.2             | 4.0             | 1.3      | 0.70     | 2.608    | 5.09     | 10.03    |
| 3c 0.24         | 2.0             | 4.0             | 1.7      | 0.68     | 3.408    | 5.14     | 12.66    |
| 4 0.24          | 2.0             | 4.0             | 0.1      | 3.88     | 5.008    | 5.09     | 9.84     |
| 2b 0.24         | 2.0             | 4.0             | 0.1      | 1.0      | 1.4      | magnet can not |
| 2c 0.24         | 2.0             | 4.0             | 0.1      | 0.7      | 1.82     | be operated |
| \( \wedge \) 0  | 2.0             | 4.0             | 0.0      | 0.0      | 1        | in these cycles |

\( B \) is the main field, \( \mathcal{E} \) is a reference ellipse, \( \eta \) is the position of \( (x/a)^2 + (y/b)^2 = 1 \) 

Table 2. The temperature of the vacuum chambers for the different FAIR cycles at helium mass

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currents taking the path over the rib are missing in this calculation. This indicates further that cutting this path can reduce the field distortion considerably.

4. Analytical model
In the next step towards series production the first single layer magnet for SIS 100 shall be built together with the vacuum chamber [5, 14, 24]. So the authors decided to invest the time to make a model of the vacuum chamber which can be solved semi analytically as it is much faster in evaluation and thus easier to handle to optimise the layout.

The vacuum chamber itself is too complicated to model it in one single formula. But the eddy currents can be seen as flowing in the following loops
(i) the tube itself (see figure 9)
(ii) two of the 4 cooling pipes short circuited by the rib (see figure 10)
(iii) one cooling pipe electrically connected to the vacuum chamber over the rib (see Fig 11).

These calculations are based on the following assumptions:
• the external field is a perfect dipole
• the external field is not disturbed by the eddy currents in the loops
• the specific conductivity $\sigma$ is uniform throughout the vacuum chamber
• the field penetrates the full chamber as the skin depth $\delta = c/\sqrt{2\pi\sigma \omega}$, $\Delta << a, b, \delta$

4.1. Estimation of the resistances
The resistance is defined by Ohm’s law (see e.g. [25])

$$R = \frac{V_{ab}}{I} = \left| \frac{-\int_a^b \vec{E} dl}{\int_s \sigma \vec{E} ds} \right|$$

As a first step the difference resistances of the different parts are given. The resistance of a pipe is given by

$$R_{pipe} = \frac{\rho \, l}{(r_o^2 - r_i^2)\pi},$$

Figure 7. The cross section of the curved single layer dipole CSLD.
with $l$ the length of the pipe, $\rho = 1/\sigma$ the specific resistance and $r_o$, $r_i$ the other and the inner radius of the tube. For the cooling tubes one thus get a resistance of $\approx 0.6 \, m\Omega$ for the length of one period.

The resistance of a cuboid is given by

$$R_{\text{cube}} = \frac{\rho l}{wh},$$

(5)

with $w$ its width and $h$ its height. Thus for 1 mm width of the vacuum chamber tube one calculates the resistance to $\approx 33 \, m\Omega$ for the length of one period. The resistance of an elliptic shell with thickness $d$, the radius of the major axis $a$ and the eccentricity $\epsilon$ can be calculated using elliptic integrals of the second kind $E(\psi | \epsilon)$. 

$$R_{\text{ell}} = \frac{\rho l}{ad \left( E(\psi_{\text{min}} | \frac{d}{a}) - E(\psi_{\text{max}} | \frac{d}{a}) \right)}$$

(6)
**Figure 9.** Eddy currents across the tube

**Figure 10.** Eddy currents across the cooling pipes short circuted by the ribs

**Figure 11.** Eddy currents across the cooling pipe and the vacuum tube short circuted by the ribs

| Table 3. Parameters of the vacuum chamber |
|-------------------------------------------|
| Parameter | Value | Dimension |
| specific conductivity | $\sigma$ | 0.5 | $\mu\Omega m$ |
| elliptic tube thickness | $\Delta$ | 0.3 | $mm$ |
| major half axis | $a$ | 65 | $mm$ |
| minor half axis | $b$ | 30 | $mm$ |
| cooling pipes inner radius | $r_i$ | 2 | $mm$ |
| outer radius | $r_o$ | 3 | $mm$ |
| ribs thickness | $b$ | 3 | $mm$ |
| distance | $l$ | 20 | $mm$ |
The resistance of a trapezium is given by

\[ dR_{\text{trap}} = \frac{\rho}{\sigma S(x)} \frac{dx}{b d_1 - \frac{d_1 - d_2}{L} x} \]  

(7)

with

\[ R_{\text{trap}} = \frac{\rho L}{b (d_1 - d_2)} \ln \left( \frac{d_1}{d_2} \right) \]  

(8)

with \( d_1 \) and \( d_2 \) denoting the two parallel sides \( (d_1 > d_2) \) and \( b \) the thickness of the prism. This is used to estimate the resistance of the eddy current loop. The top length \( d_2 \) was set equal to the tube diameter. To estimate \( d_1 \) the tangent to the ellipse was used, that touches the centre of the cooling tube and is nearer to the major axis. Then it was mirrored along the normal on the ellipse, which passes the centre of the cooling tube. These two lines touch the ellipse at \( \psi \approx 0.845 \text{rad} \) and \( \psi \approx 0.233 \text{rad} \). The resistance of this trapezoid is then calculated to 0.1 m\( \Omega \).

4.2. Eddy currents in the vacuum chamber tube

These calculations are based on the results presented in [26]. These calculations are lengthy and only outlined here. For calculating the distortion of the magnetic field as well as the eddy currents and their power the common assumption was used that one has good field penetration and thus no current density \( j_r \) for the tube and no \( j_\eta \) for the elliptic chamber. First the more common case of the thin walled circular cylinder is presented and then for a thin walled elliptic cylinder.

4.3. Eddy currents in a round tube

All the fields are expressed in cylindrical coordinates \( r, \phi, z \) by a vector potential \( \mathbf{A} = (0, 0, A) \). That of the primary field is given by

\[ A_p(r, \phi, t) = -r B(t) \left( \frac{r}{r_1} \right)^n \cos (n(\phi + \phi_0)) / n \]  

(9)

\( n = 1, \phi_0 \) gives a vertical dipole field, \( B_x = 0, B_y = B(t), B_z = 0; \phi_0 = \pm \pi/2 \) gives a horizontal dipole field. For higher \( n \) one gets normal or skew multipole fields. The reaction potential outside the tube must vanish at \( r = \infty \) and is given by

\[ A_o(r, \phi, t) = -ca(t) B(t) \left( \frac{r}{r_1} \right)^{-n} \sin (n(\phi + \phi_0)) / n \]  

(10)

The reaction potential inside the tube must be finite at \( r = 0 \) and is given by

\[ A_i(r, \phi, t) = -cc(t) B(t) \left( \frac{r}{r_1} \right)^n \cos (n(\phi + \phi_0)) / n \]  

(11)

The total potential outside the tube is then \( A_p + A_o \) and inside the tube \( A_i + A_p \).

Now one uses the condition that the normal component of the magnetic induction must be continuous. According to Ampere’s law the tangential discontinuity of the magnetic field is due to a surface eddy current density. It is assumed that the current density is constant in the cylindrical shell in the radial direction. So the surface current density is equal to the volume density multiplied with the thickness \( \Delta \) of the tube. By Ohm’s law the current density is the electrical field times the conductivity \( \sigma \).

\[ B_r |_{r=r_{t+}} - B_r |_{r=r_{t-}} = 0, \quad B_\phi |_{r=r_{t+}} - B_\phi |_{r=r_{t-}} = \mu_0 \Delta \sigma E_z. \]  

(12)
For a linear ramped field \( B(t) \)
\[
B(t) = \begin{cases} 
  B_s \frac{t}{t_0} & 0 \leq t \leq \tau_0 \\
  B_s & \tau_0 < t
\end{cases}
\]
(13)

one obtains the solution for the potential outside
\[
A_o(r, \phi, t) = -\frac{B_s r_t}{n^2 \tau_0} \cos \left( n \left( \phi + \phi_0 \right) \right) \left( \frac{r}{r_t} \right)^n \begin{cases} 
  e^{-\frac{nt}{\tau_0}} \left( e^{\frac{nt}{\tau_0}} - 1 \right) & 0 \leq t \leq \tau_0 \\
  e^{-\frac{n\tau}{\tau_0}} \left( e^{\frac{n\tau}{\tau_0}} - 1 \right) & \tau_0 \leq t
\end{cases}
\]
(14)

and
\[
A_i(r, \phi, t) = -\frac{B_s r_t}{n^2 \tau_0} \cos \left( n \left( \phi + \phi_0 \right) \right) \left( \frac{r}{r_t} \right)^n \begin{cases} 
  e^{-\frac{nt}{\tau_0}} \left( e^{\frac{nt}{\tau_0}} - 1 \right) & 0 \leq t \leq \tau_0 \\
  e^{-\frac{n\tau}{\tau_0}} \left( e^{\frac{n\tau}{\tau_0}} - 1 \right) & \tau_0 \leq t
\end{cases}
\]
(15)

for the potential inside with
\[
\tau = \frac{1}{2} \tau_0 \Delta \mu_0 \sigma
\]
(16)

The current density \( K \) is then given by
\[
K(\phi, t) = \frac{1}{\mu_0} \nabla \times \left( \begin{array}{c}
0 \\
0 \\
A_o(r = r_t, \phi, t) - A_i(r = r_t, \phi, t)
\end{array} \right)
\]
(17)

\[
K_z(\phi, t) = 2 \frac{B_s r_t \tau}{\mu_0 n \tau_0} \cos \left( n \left( \phi + \phi_0 \right) \right) \begin{cases} 
  e^{-\frac{nt}{\tau_0}} \left( e^{\frac{nt}{\tau_0}} - 1 \right) & 0 \leq t \leq \tau_0 \\
  e^{-\frac{n\tau}{\tau_0}} \left( e^{\frac{n\tau}{\tau_0}} - 1 \right) & \tau_0 \leq t
\end{cases}
\]
(18)

The power dissipated can then be calculated by
\[
P = \int_0^{2\pi} K_z^2 R \, d\phi
\]
(19)

with
\[
R = \frac{l}{2 \tau_1 \pi \Delta \sigma}.
\]
(20)

All the exponents contain the time constant \( \tau \) giving the decay rate due to the conductivity of the chamber. The higher the multipole order the faster the eddy currents decay. The chamber does not mix different multipoles. This is to be contrasted with the case of an elliptic chamber.

4.4. Eddy currents: elliptic vacuum tube

These calculations are based on the results presented in [26]. These authors deal with an external field varying harmonically whereas here a ramped field is considered. The calculations are lengthy and only outlined here. For calculating the distortion of the magnetic field as well as the eddy currents and their power the common assumption was used that one has good field penetration and thus no radial current density \( j_r \) for the circular tube and no quasi-radial component \( j_\eta \) for the elliptic chamber are present. The more common case of a thin walled circular cylinder is presented in the previous subsection; here a thin walled elliptic cylinder is treated.

For the elliptic cylindrical coordinates \( \eta, \psi, z \) (\( e \) is the eccentricity)
\[
x := e \cdot \cosh \eta \cdot \cos \psi \quad y := e \cdot \sin \eta \cdot \sin \psi
\]
(21)
the arc element is given by
\[ ds = \sqrt{h_E^2 (d\eta^2 + d\psi^2)} + dz^2 \]  
(22)
with \( h \) the metric coefficient
\[ h_E = e^{\sqrt{\cosh^2 \eta - \cos^2 \psi}} = e^{\sqrt{\sinh^2 \eta + \sin^2 \psi}} := e \ h_r(\eta, \psi) \]  
(23)
The magnetic vector potential \( A \) is defined in Cartesian and in elliptic coordinates by
\[ A = (0, 0, A_p(x, y, t)) = (0, 0, A_p(\eta, \psi, t)) \]  
(24)
with
\[ A_p(x, y, t) = -B(t) \frac{x}{\cosh \eta_0} \]
\[ A_p(\eta, \psi, t) = -B(t) e^{\frac{\cosh \eta}{\cosh \eta_0}} \cos \psi \]  
(25)
The magnetic dipole field induces electric and magnetic reaction fields with coupled multipoles [26]. The total potential is then given by
\[ A(\eta, \psi, t) = A_p(\eta, \psi, t) + A_r(\eta, \psi, t) \]
\[ = -B(t) e^{\frac{\cosh \eta}{\cosh \eta_0}} \cos \psi + \ldots \]
\[ \cdots + \sum_{q=1}^{\infty} [C_{2q+1}^{(1)} \cosh ((2q - 1)\eta) + C_{2q+1}^{(2)} \sinh ((2q - 1)\eta)] \cos ((2q - 1)\psi) \]  
(26)
with \( A_p \) the primary and \( A_r \) the reaction potential. In the interior the reaction field must consist of regular multipoles [21]:
\[ A_i(\eta, \psi, t) = e^{\sum_{q=1}^{\infty} \frac{1}{2q - 1} l_{2q-1} \ \cosh((2q - 1)\eta) \ e^{-(2q-1)\eta_0} \ \cos((2q - 1)\psi)} \ 0 \leq \eta \leq \eta_0 \]  
(27)
In the exterior the field must vanish at infinity (\( \eta \to \infty \)):
\[ A_i(\eta, \psi, t) = e^{\sum_{q=1}^{\infty} \frac{1}{2q - 1} a_{2q-1} \ e^{-(2q-1)(\eta-\eta_0)} + e^{-(2q-1)(\eta+\eta_0)} \ \cos((2q - 1)\psi)} \ \eta_0 \leq \eta < \infty \]  
(28)
Again the normal component of the magnetic induction, \( B_\eta \propto \frac{\partial A}{\partial \psi} \), must be continuous at \( \eta = \eta_0 \); which condition leads to:
\[ a_{2q-1} = l_{2q-1} \]  
(29)
Whereas the discontinuity in the tangential component at \( \eta = \eta_0 \) is equal to the eddy currents
\[ K_z(\psi) = \Delta j_z = H_\psi|_{\eta=\eta_0^+} - H_\psi|_{\eta=\eta_0^-} \]  
(30)
By Ohm’s law the current density is proportional to the electric field, \( j_z = \sigma E_z = -\sigma \frac{\partial A}{\partial t} \)
\[ K_z(\psi) = \Delta j_z = \Delta \sigma E_z = -\Delta \sigma \frac{\partial A}{\partial t} \]  
(31)
thus

\[-K_z = -\frac{1}{\mu_0} B(\eta = \eta_0) + \frac{1}{\mu_0} B(\eta = \eta_0^-) = \frac{1}{h\mu_0} \left[ \frac{\partial A_o}{\partial \eta} |_{\eta = \eta_0} - \frac{\partial A_i}{\partial \eta} |_{\eta = \eta_0} \right] := \frac{dA}{h\mu_0} \]

\[(32)\]

\[A_p, A_o, A_i \text{ are continuous, so is } \frac{\partial A}{\partial t} \text{ thus the current is given by} \]

\[-K_z = \Delta \sigma \left[ \frac{\partial A_p}{\partial t} + \frac{\partial A_i}{\partial t} \right] |_{\eta = \eta_0} \]

\[(33)\]

Equating the last terms of both lines in eq.(32) gives the decisive expression resulting from Ampere’s and Ohm’s law:

\[dA = \mu_0 \Delta \sigma h \left[ \frac{\partial A_p}{\partial t} + \frac{\partial A_i}{\partial t} \right] |_{\eta = \eta_0} \]

\[(34)\]

The left hand side is a simple Fourier series. However, the metric coefficient \( h = e^{h_r(\eta_0, \psi)} \) depends on \( \psi \) and is multiplied with a Fourier series. So it couples multipoles of other order with the given multipole. The interaction of the elliptic chamber with the primary multipole is such that it couples all other odd (even) multipoles to a primary odd (even) multipole. This can be seen and handled computationally by representing the metric coefficient by a Fourier series:

\[h_r(\eta_0, \psi) = \sqrt{\cosh^2 \eta_0 - \cos^2 \psi} = \frac{h_0}{2} + \sum_{n=1}^{\infty} h_{2n} \cos 2n\psi \]

\[(35)\]

The expansion coefficients may be found by numeric integration or expressed through hypergeometric functions [26]:

\[h_{2n} = \frac{1}{\pi} \int_0^{2\pi} h_r(\eta_0, \psi) \cos (2n\psi)d\psi \]

\[= -\frac{(2n-3)!!}{2^{2n-1}n!} k^{2n-1} F_1 \left( \frac{2n-1}{2}, \frac{2n+1}{2}, 2n+1; k^2 \right) \]

\[k = \frac{e}{a} = \text{sech}(\eta_0) \]

\[(36)\]

All the series are inserted into eq.(34) and the resulting system of linear first order differential equations for the expansion coefficients \( l_n(t) \) and \( a_n(t) \) is solved. The task is complicated by the fact that the terms multiplied with \( h \) are the product of two Fourier series. The corresponding decomposition has been accomplished in [26]. So eq.(34) is equivalent to the following matrix equation:

\[ \left( \tau H \cdot D \frac{d}{dt} + I \right) \mathbf{l} = \tau \dot{B}_0(t) \mathbf{b} \]

\[\mathbf{b} = (h_0 + h_2, h_2 + h_4, ..., h_{2n_p-2} + h_{2n_p})\]

\[I = \text{Identity matrix}\]

\[(37)\]

Here we assumed that the system has been cut down to the first \( n_p \) odd multipoles, \( \mathbf{l} := (l_1(t), l_3(t), ..., l_{n_p-1}(t)) \). The decay constant is defined as:

\[\tau = \frac{e\mu_0 \Delta \sigma}{2} \]

\[(38)\]
The matrix $H$ is defined as:

$$H := \begin{pmatrix} h_0 + h_2 & h_2 + h_4 & h_4 + h_6 & \ldots \\ h_2 + h_4 & h_0 + h_6 & h_2 + h_8 & \ldots \\ h_4 + h_6 & h_2 + h_8 & h_0 + h_{10} & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$  \quad (39)$$

and the matrix $D$ is a diagonal matrix

$$D := \text{diag}\left\{ \begin{array}{c} \frac{1 + e^{-2(2n-1)\eta_0}}{2(2n-1)} \end{array} \right\} \quad n = 1, 2, 3, \ldots$$  \quad (40)$$

The above system is decoupled by diagonalising the matrix $H \cdot D$ by an equivalence transformation

$$T^{-1} \left( \tau H D \frac{d}{dt} + I \right) T T^{-1} l = \tau \dot{B}_0(t) T^{-1} b$$  \quad (41)$$

$$T^{-1} H D T = \text{diag}(\alpha_1, \alpha_2, \ldots, \alpha_{np})$$

$$w := T^{-1} l = (w_1(t), w_2(t), \ldots, w_{np}(t))$$

$$\beta = T^{-1} b = (\beta_1, \beta_2, \ldots, \beta_{np})$$

$B_0(t)$, so $\dot{B}_0(t)$, give the time-dependence of the ramped field in the same way as in the circular case:

$$B(t) = \begin{cases} B_s t / t_0 & 0 \leq t \leq \tau_0 \\ B_s & \tau_0 < t \end{cases}$$  \quad (43)$$

Each of the decoupled equations is of the following form:

$$\tau \alpha_i \frac{dw_i}{dt} + w_i = \beta_i \tau \quad 0 \leq t \leq \tau_0$$

$$\tau \alpha_i \frac{dw_i}{dt} + w_i = 0 \quad \tau_0 \leq t \leq \infty$$  \quad (44)$$

The initial condition is: No field for $t \leq 0$ : $l = w = 0$. The corresponding solution of the decoupled system is:

$$w_i(t) = \alpha_i \beta_i B_s \frac{\tau}{\tau_0} \left( 1 - e^{-\frac{t}{\alpha_i \tau}} \right) \quad 0 \leq t \leq \tau_0$$

$$= \alpha_i \beta_i B_s \frac{\tau}{\tau_0} e^{-\frac{t}{\alpha_i \tau}} \left( e^{-\frac{\tau_0}{\alpha_i \tau}} - 1 \right) \quad \tau_0 \leq t < \infty$$  \quad (45)$$

$$l(t) = T w(t)$$  \quad (46)$$

We summarise the results obtained. The potential within the chamber is:

$$A = (0, 0, A)$$

$$A(\eta, \psi, t) = A_p(\eta, \psi, t) + A_i(\eta, \psi, t)$$

$$A(\eta, \psi, t) = -B_0(t) e^{\cos \eta \cosh \eta_0} \cos \psi + e \sum_{q=1}^{np} \frac{2q-1}{2q-1} \cosh ((2q-1)\eta) e^{-(2q-1)\eta_0} \cos ((2q-1)\psi)$$  \quad (47)$$
Here and below the solutions for the \( l_n(t) \) obtained just above must be inserted.

\[
B_\eta(\eta, \psi, t) = \frac{B_0(t)}{h_r(\eta, \psi) \cosh r_0} \cosh \eta \sin \psi + \ldots
\]

\[
\ldots + \frac{1}{h_r(\eta, \psi)} \sum_{q=1}^{n_p} l_{2q-1}(t) \cosh((2q-1)\eta) e^{-(2q-1)r_0} \sin((2q-1)\psi)
\]

\[
B_\psi(\eta, \psi, t) = \frac{B_0(t)}{h_r(\eta, \psi) \cosh r_0} \sinh \eta \cosh \eta_0 \cos \psi + \ldots
\]

\[
\ldots + \frac{1}{h_r(\eta, \psi)} \sum_{q=1}^{n_p} l_{2q-1}(t) \sinh((2q-1)\eta) e^{-(2q-1)r_0} \cos((2q-1)\psi)
\]

These elliptic components may be converted to Cartesian components and combined to a complex field:

\[
B_c(\eta, \psi) = B_y(\eta, \psi) + iB_x(\eta, \psi) = \frac{B_0(t)}{\cosh \eta_0} \left[ \sum_{q=1}^{n_p} l_{2q-1}(t) e^{-(2q-1)r_0} \sinh[(2q-1)(h + i\psi)] \right]
\]

\[
= \frac{B_0(t)}{\cosh \eta_0} \sum_{n=1}^{n_p} e^{2n-1} \left( \cosh[(2n-1)(h + i\psi)] \right)
\]

The expansion coefficients \( e^{2n-1} \) in the second line may be determined from the field given in the first line by their definition as given in [21]. They may be converted into circular expansion coefficients by formulae given in the same reference. So the perturbing multipoles resulting from the eddy currents may be calculated. The resistance of the elliptic annular ring is approximately given by:

\[
R = \frac{l}{A \sigma} = \frac{2l}{\pi(a+b)\Delta \sigma}
\]

* \( l \)...length of tube
* \( A \)...area of crosssections

\[
A = \pi(a_2b_2 - a_1b_1) = \pi \left( (a + \frac{\Delta}{2})(b + \frac{\Delta}{2}) - (a - \frac{\Delta}{2})(b - \frac{\Delta}{2}) \right)
\]

\[
= \frac{\pi \Delta}{2}(a + b)
\]

The eddy currents are found from:

\[
K_z = \frac{dA}{\mu_0 h}
\]

\[
= \frac{1}{\mu_0 e h_r(\eta_0, \psi)} \sum_{q=1}^{\infty} l_{2q-1}(t) \cos((2q-1)\psi)
\]

This surface density current gives rise to loss. The power loss is:
\[ P = R \int_0^{2\pi} K^2 ds \]
\[ = \frac{eR}{\mu_0^2 e^2} \int_0^{2\pi} \frac{h_r(\eta_0, \psi)}{h_r(\eta_0, \psi)} \left( \sum_{q=1}^{\infty} l_{2q-1}(t) \cos((2q - 1)\psi) \right)^2 d\psi \]
\[ = \frac{R}{\mu_0^2 e} \int_0^{2\pi} \frac{1}{h_r(\eta_0, \psi)} \left( \sum_{q=1}^{n_p} l_{2q-1}(t) \cos((2q - 1)\psi) \right)^2 d\psi \]

The total energy due to the loss is:

\[ E_{\text{loss}} = \int_0^\infty P(t) dt \quad (56) \]

\[ P(t) = \frac{R}{\mu_0^2 e} \sum_{j=1}^{n_p} \sum_{q=1}^{n_p} l_{2j-1}(t) l_{2q-1}(t) f_{jp}(\eta_0) \quad (57) \]

\[ f_{jp}(\eta_0) := \int_0^{2\pi} \frac{\cos((2q - 1)\psi) \cos((2j - 1)\psi)}{\sqrt{\cosh^2 \eta_0 - \cos^2 \psi}} d\psi \]

Those coefficients must be evaluated numerically for given \( a \) and \( b \). Analytical expressions for \( l_{2q-1}(t) \) have been found before. So the integration for the energy loss can be done analytically or numerically by one integration as indicated in eq.(56).

4.5. Eddy currents: cooling pipe – ribs – tube

In general, the current of a closed current loop in a magnetic field is described by equation 58

\[ j(t) = -\frac{1}{R} \frac{d}{dt} \int_{A'} B \cdot dA \quad (58) \]

which in our case reduces to

\[ j(t) = -\frac{dB}{dt} \frac{l}{R} |r - r_k| \sin \varphi \quad (59) \]

Here, \( l \) stands for the length of the current loop along the elliptic tube surface and \( |r - r_k| \) describes the width of the current loop, i.e. the distance between the point on the surface of the elliptic tube to the surface of the cooling pipe (see Fig. 13).

\[ r = \epsilon \cosh \eta_0 \cos \psi e_x + \sinh \eta_0 \sin \varphi e_y \]
\[ r_k = (x_0 - r_o \sin \varphi) e_x + (y_0 - r_o \cos \varphi) e_y \quad (60) \]

\( \psi \) and \( \varphi \) are connected by following relation, resulting from geometrical considerations:

\[ \varphi = \arctan \left( \frac{x_0 - \epsilon \cosh \eta_0 \cos \psi}{y_0 - \epsilon \sinh \eta_0 \sin \psi} \right) \quad (61) \]

Special attention must be paid to the discontinuity of the arc tangent at \( \frac{\pi}{2} \), so \( \varphi \) has to be carried on continuously from \( \frac{\pi}{2} \) onwards (see Fig. 12). Fig. 15 shows the value of \( jR \) as a function of \( \psi \). In order to calculate the total current of this current loop, the resistance of this specific loop was computed. Therefor, we took a look at the current loops within the angle interval \([\psi_{\text{min}}, \psi_{\text{max}}]\) defining the points on the ellipse where the tangents of the ellipse and the circle touches the surface of the ellipse. We made an estimate to get an upper bound for the resistance \( R_u \). For the calculation, we split the resistance into three parts:
- $R_1$ - the resistance of the cooling pipe (see Eq. 4)
- $R_2$ - the resistance of the rip connecting the tube with the pipe, approximated by a trapezoid (see Eq. 8)
- $R_3$ - the resistance of the elliptic tube, approximated by a cube with the same width as the trapezoid’s side $d_1$ (see Eq. 5)

This upper bound gives us a value for the resistance of $R_u \approx 2.1 \, \text{m} \, \Omega$ per period. It turned out, that the resistance $R_1$ is small compared to the other resistances. Therefore, this resistance is neglected and the resistance is now split into 2 parts to refine our calculations:

- $R_1$ - the resistance of the cooling pipe (see Eq. 4)
- $R_2$ - the resistance along the elliptic tube. $\rho$ and $l$ are constant in this case, but the Area is a function of $\psi$, hence we had to compute the differential

$$dR = \frac{\partial R}{\partial A} dA \quad (62)$$

$dA$ can be expressed like:

$$dA = ad\sqrt{1 - \epsilon \sin^2 \psi} d\psi \quad (63)$$

with $d$ the thickness of the sheet. This leads to the following expression for the differential resistance (see fig. 14)

$$dR = -\frac{\rho l}{ad} \sqrt{1 - \epsilon \sin^2 \psi} E^2(\psi|\frac{\epsilon}{\eta}) d\psi \quad (64)$$
Table 4. Resistance of different components and the losses in the 4 cooling pipes.

| Part     | decay constant $\tau$ | current | resistance | $\text{loss}_{\text{pipes}}$ |
|----------|------------------------|---------|------------|-----------------------------|
| chamber  | 22 $\mu$s              | 5 A     | 5 $m\Omega$/m |                               |
| tubes    | 5 $\mu$s               | 27 A    | 27 $m\Omega$/m |                               |
| Loop 1   |                        | 0.1 A   | 30 $m\Omega$/m | 2 $mW$/m                    |
| Loop 2   | 2.7 A                  | variable| 265 $m\Omega$/m | 0.8 $W$/m                  |
| Loop 3   | 1.7 A                  |         | 265 $m\Omega$/m | 0.3 $W$/m                  |

Here, $l$ stands for the length of the elliptic tube.

The total current $I$ is now calculated to $I \approx 2.7$ A by integrating $j$ over $\psi$ from 0 to $2\pi$.

4.6. Eddy currents: cooling pipe – rib

We are taking eq. 58 as a starting point again. To calculate the resistance of this current loop, we approximated the parts of the rips using cylinders of the same radius as the outer cooling pipe radius $r_o$. Hence, the total resistance turned out to be $R \approx 5.3$ m$\Omega$ per period. By integrating eq. 58 over the area normal to $\mathbf{B}$, $I$ is evaluated to $I \approx 1.7$ A.

4.7. Comparison to FEM results

In table 4 the eddy current power dissipated in the cooling pipes due to the different loops is $\approx 1.1W$ and roughly 3 W if taking this value for the full magnet length of 2.756 m. This difference could be attributed to the fact that the ANSYS model took solder contacting the pipes and the vacuum chamber into account while the analytical calculations only use the resistance of the cooling pipe.

5. Cooling options for the vacuum chamber

The results presented above show that not only the vacuum chamber itself, but in addition its special cooling tubes create large eddy currents if not properly insulated. Furthermore these tubes require their own, extra cooling circuit making the complex cooling scheme of the accelerator more complicated and less reliable.

To avoid these consequences, the vacuum chamber can be cooled indirectly via heat conduction to the cold mass of the magnet, i. e. the iron yoke and the sc coil. The FEM investigations presented in 2.1.2 show that such an design is feasible.

First ideas and layouts were presented in [27, 28]. The problems of the chambers impedance characteristics and manufacturing technology still have to be solved. In addition the cooling power of the magnet must be sufficient to deal with the significant heat flow coming from the vacuum chamber too. This is an important, qualitative advantage provided by the recently optimized design version CSLD [29, 5, 6] as the hydraulic resistance of the coil is only a quater of the current magnet’s coil for the forced two phase helium flow. An other version of the contact cooling could be a solution similar to that shown in figure 16 using the stabilizing ribs as contact springs.

In any case the optimal beam pipe design minimises the thermal contact resistances between the vacuum chamber and the magnet within the aperture near to the physical limit. The final chamber design must be mechanically stable during the complete life time of the magnet, which has to be carefully analysed too.
6. Conclusion

We discussed the impact of the vacuum chamber on various cooling aspects and on the magnetic field. Analytic solutions for eddy currents in an elliptic vacuum chamber are presented, which can be further extended to the quadrupole. The different sources for the eddy currents were analysed and the analytical estimates for the power dissipated in the cooling tubes compared to ANSYS calculations, which were found to be in the same order of magnitude but different, which can be explained by the solder not being taken into account in the analytical model.

7. Outlook

The sources of losses are well understood and need only known to a precision of one Watt. The field quality has to be described with an accuracy of $\approx 100$ ppm. Thus further steps are required to backup the calculations.

Taking into account that the field created by the eddy currents induced into the vacuum chamber is small compared to field, created by the magnet, the following further steps are being done:

(i) The field within the magnet’s aperture is measured without the vacuum chamber, which quantifies the accuracy of the calculation.

(ii) The FEM model is adjusted until it reproduces the measured field with sufficient quality adjusting the BH curve and the measured mechanical properties of the magnet.

(iii) The vacuum chamber is placed within a conventional magnet of good field quality. Then the field is measured within the vacuum chamber which is now easily accessible.
conventional SIS 18 magnet available at GSI provides a field of appropriate quality and can be ramped faster than SIS 100 and thus eddy currents with the same strength can be produced thus compensating the change of resistivity of stainless steel, which is roughly 3 time higher at room temperature than at cryogenic temperature.

(iv) At last the vacuum chamber is installed in the magnet and the field is sampled within the chamber with a “woodlouse” (see Fig. 17) at different ramp rates at cryogenic conditions and the quality of the model prediction asserted. These final data provide a reliable field information on a geometric extent not reachable by magnetic field probes with the equipment available to the authors.

Considerable currents are created within the cooling tubes, which disturb the magnetic field. These currents have to be compared to the ≈ 8 · 750 A, which are required for the injection field of ≈ 0.22 T. So one gets a ratio between the eddy currents in the tube and the current in the magnet coil of ≈ 7.3 · 10⁻⁴. So an influence is expected and was shown by the FEM calculations.

In the next steps the distortion fields of the different components of the vacuum chamber have to be calculated and compared to the ones calculated by FEM models. Then the cooling layout of the vacuum chamber for the single layer dipole has to be optimized using the analytical formulae and finally crosschecked by a sound ANSYS model as well as by measurements.

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