DESIGN AND OPERATION PARAMETERS OF THE SUPERCONDUCTING MAIN MAGNETS FOR THE SIS100 ACCELERATOR OF FAIR

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Abstract

SIS100, the worlds second large scale synchrotron for ion research, will use superferric magnets. The dipoles are of the window frame type, whose aperture was chosen as an optimum balance between the achievable field quality and AC losses at cryogenic temperatures. Analogous design optimisation was done for the quadrupole and corrector magnets as well. We present the design of the main magnets, estimate their operation parameters and define the crucial aspects to be experimentally analysed before series production, e.g. precise magnetic end field optimisation.

INTRODUCTION

The heavy ion synchrotron SIS100, the core component of the Facility of Antiproton and Ion Research (FAIR) at GSI, will provide beams with high currents. Its superferric magnets, creating the bending and focusing fields, require to be built of small size to obtain economic operation still allowing a 1Hz operation cycle.

The small aperture of these magnets next to the small yoke requires special measures to meet the target field quality in the magnet ends. So a dedicated insert is to be used to improve the dipole end field quality.

The 1Hz operation requires a ramp rate of 4T/s for the dipoles; only the new designed high current Nuclotron cable can provide sufficient cooling power. The quadrupole design was changed from a 6 turn to a 3 turn coil design and can now use the same cable, thus making the magnet production more economic.

DIPOLE

The size of the yoke dipole can be significantly reduced for superferric magnets as Ampere-turns are cheap. Superconducting magnets, operated in a continuous fast ramped cycle, require that any AC loss is reduced to a minimum by using a small yoke together with a coil head fitting tightly around the vacuum chamber. The small yoke and magnet aperture makes it difficult to create good field quality at the same time.

Reference Measurements on SIS18

Magnet Resonances of a high current machine can lead to beam loss due to the Laslett Tune Shift. SIS18, the synchrotron for high current heavy ion beams with a rigidity of up to 18 Tm, is operating and its beam performance if known. A spare dipole is available, so its magnetic field was remeasured to see which field distortions are bearable.

Table 1: Harmonic field content of the SIS18

I [kA]	B_1 [T]	b_3	b_4	b_5 [units]	b_6	b_7	b_8
2	1.0480	-5.72	0.01	-1.61	0.57	-1.25	-0.28
3.5	1.7236	-2.74	0.67	-1.72	1.13	-0.84	-0.42

The field quality of SIS100, even of elliptic aperture, is studied using circular harmonics calculated from elliptic ones; these were not available for SIS18. Therefore a separate measurement was made and elliptic and circular multipoles calculated so that its field quality can be compared to the one of SIS100 given that the beam performance of SIS18 is known. It was mapped on an ellipse in the longitudinal mid plane of the magnet. The data showed a deviation of $\pm$ 2 units matching the design criteria (1 unit = 100 ppm). The end was mapped on the surfaces of a box (x = $\pm$ 77.5 mm, y = $\pm$ 30 mm, z = $\pm$500 mm, R_0^{SIS18} = 65 mm; y... vertical, z ... tangential to beam, x...xyz $\rightarrow$ right hand coordinate system) and the field was recalculated to an elliptic cylinder. These data were used as basis to calculate elliptic harmonics and then the corresponding circular harmonics [1]. (Multipoles following the curvature of the beam are local toroidal-elliptic multipoles [2]; the results given there allow quantifying the artifacts of the used approach). The measurement was performed with one hall-probe measuring the vertical field B_y thus the assumption was used that no skew harmonics exist (as $\mathbf{B}(\mathbf{z}) = \sum_{n=1}^{\infty} \mathbf{C_n} \left(\mathbf{z}/R_0^{SIS18}\right)^{n-1}$ and $\mathbf{C_n}\mathbf{z}^m = r^m[B_n \cos(m\phi) - A_n \sin(m\phi) + \mathrm{i} A_n \cos(m\phi) - \mathrm{i} B_n \sin(m\phi)]$ with $\mathbf{C_n} = B_n + \mathrm{i} A_n$ and $m = n - 1$). The obtained multipoles were scaled in such a way that it was assumed that the field errors in the middle (magnet length $\approx 2.3\,m$) are far less and only the end harmonics need to be taken into account. Thus Table 1 shows the field distortion of the total field. One can see that the sextupole is significantly larger than 2 units.

End Optimisation

The end field of the SIS100 magnet contributes significantly to the total field distortion. Therefore its distortion had to be reduced, especially the sextupole as the SIS100's foreseen working point is near to a 3$^{\mathrm{rd}}$ order resonance.

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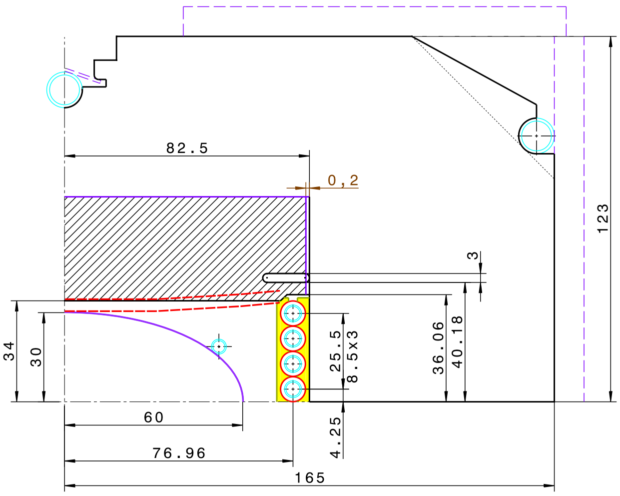


Figure 1: The sextupole superimposed on the pole surface of the SIS100 dipole lamination. The hatching indicates the insert. The red dashed line indicates the superimposed sextupole shape.

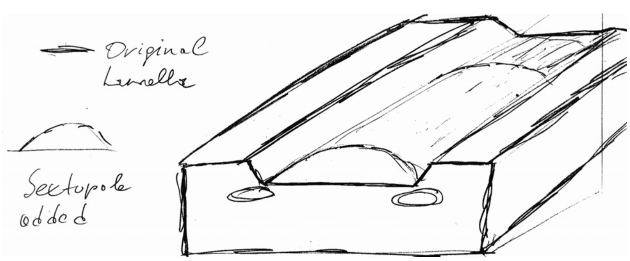


Figure 2: Continuous end profile surface

Thus the Laslett tune shift can easily create beam loss.

An appropriate hypothesis for the field formation of a magnet end is: the $\cos\theta$ model for the coil end loop itself next to its image currents and the field forming of a conventional magnet. Only the currents in z create distortion fields contributing to the harmonics, thus only the part of the end loop pointing in z creates distortion fields. The coil head itself creates a large positive sextupole as typical for an air coil magnet (e.g. [3]), as its contributing current are below the angle of 30° (asserted by FEM calculation moving the coil head far apart from the magnet yoke end). Calculations with enlarged coil end loop showed only modest field improvements. Therefore the loss minimised end coil loop does not need to be changed [4].

So the sextupole needs to be diminished. End fields of air coil magnets show large higher order harmonics which were compensated with a layout with opposite harmonic content further down the longitudinal axis (e.g. [3]). Here a negative sextupole is required. Combined function magnets are dipoles with a superimposed quadrupole. A dipole with a sextupole component requires that the pole surface is changed to some parabola (see Fig 1) with a smooth connection to the regular dipole profile (see Fig 2). This insert is foreseen for the 1st article of the now to be ordered SIS100 dipoles. The insert requires a little gap ($\approx$ 0.2 mm) on the sides to the laminations so that it can be removed. FEM calculations using an end model, similar to [5], showed that the gaps do not add additional field distortions. This is no surprise as the insert was made larger than the aperture. Further the saturation hole forces most of the flux to circulate above and thus it is nearly perpendicular to the inserts gap.

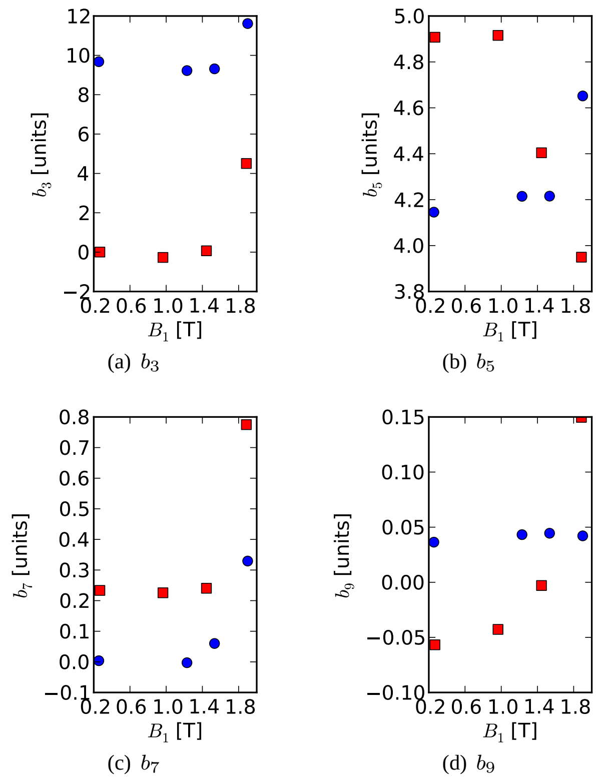


Figure 3: Influence of the insert on the field quality. Blue. . . original design, red. . . optimised shape.

These FEM calculations (see Fig. 3, R_0 = 40 mm) show that a shape can be made giving a zero sextupole in the end up to $\approx 1T$ and a factor of two smaller error at nominal field. So the field error is expected to be comparable to SIS18. The higher order harmonics can be optimised slightly changing the shape of the parabola.

QUADRUPOLE

The large AC losses, created in the 1 Hz triangular cycle for the SIS100, required that the dipole will be build using a single layer coil with a high current cable [6]. A single cable design for all SIS100 main magnets is advantageous for economical benefits. Further the quadrupoles can be built of smaller size, their hydraulic resistance can be adjusted to the dipoles and the coil windings can be packed in a reinforcement structure as used for the dipoles. A quadrupole with 2 turns per pole was investigated first, but it only provided 0.5 K temperature margin, which was considered as too little. A quadrupole design with three turns (see Fig. 4)

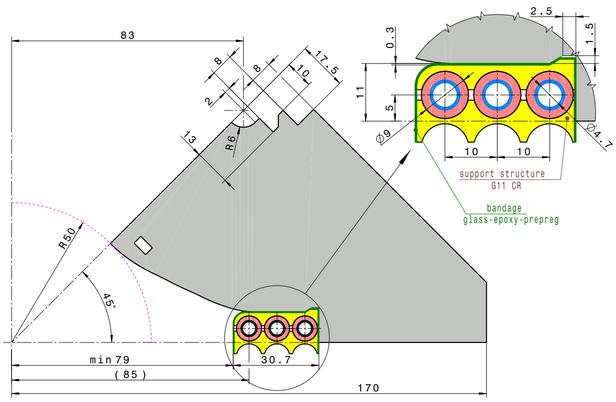
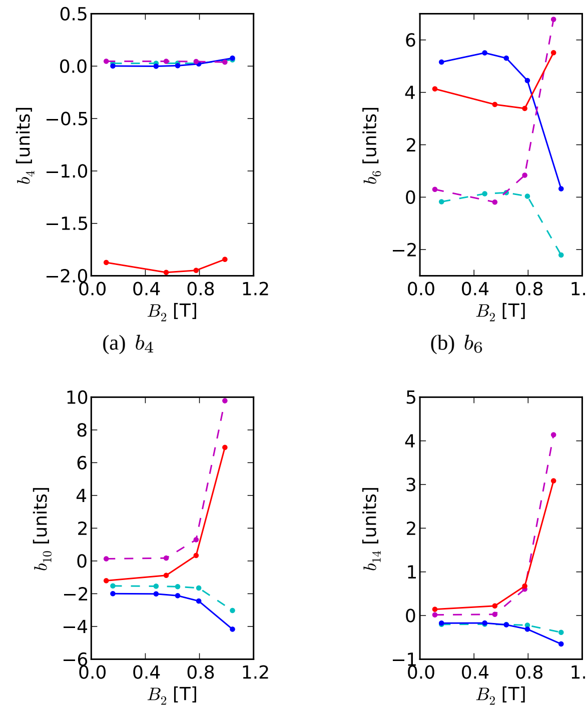


Figure 4: Lamination of the 3 Turn quadrupole



(a) b_4 (b) b_6

(c) b_{10} (d) b_{14}

Figure 5: Comparison of the central and the total field quality of the 3 turn (central — dashed cyan line, total solid blue line) to the 6 turn (central — dashed magenta line, total solid red line)

gives a temperature margin of $\approx$ 1K. Its operation current is $\approx$ 10.8 kA for the nominal gradient of 27 T/m. An AC loss of $\approx$ 40 W is expected for the 1 Hz operation mode.

The field quality was calculated with TOSCA and compared to the 6 turn quadrupole [7] originally foreseen for SIS100. The currently obtained harmonics b_{10} and b_{14} (see Fig 5) are slightly higher than for the 6 turn, but can be made comparable.

The 6 turn quadrupole used a different cable with a smaller diameter. This gives a much larger hydraulic resistance. The bus bars for the quadrupoles must also be mounted within the hydraulic cycle of the dipoles. Further quadrupoles with separately insulated cable [8] are required in the injection and extraction beam lines. Therefore this 3turn design further simplifies the design of the SIS100 machine as: 1.) the same iron geometry can be used for the high and low current quadrupoles, 2.) the same wire and cable as for the dipole can be used (no extra development), 3.) only one type of HTS current leads is required and only one type of bus bars and voltage breakers in the dipoles, quadrupole doublets, bypass lines, feed in lines, superconducting links, current lead boxes (simpler design and less costly) 4.) the quench measurements made on dipoles can directly be used for the quadrupole and 5.) only one single type of superconducting joints is need.

CONCLUSION

SIS100 is now approaching the realisation stage with the dipole magnet series to be ordered. Beam loss calculations showed that the end is of concern, thus the end is made of a parabolic shape which adds a negative sextupole compensating the "air coil" sextupole contribution of the coil head end.

A quadrupole with 3 turns allows using the same cable for dipoles and quadrupoles.

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