FULL LENGTH SUPERFERRIC DIPOLE AND QUADRUPOLE PROTOTYPE MAGNETS FOR THE SIS100 AT GSI: STATUS OF THE DESIGN AND MANUFACTURING*

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Abstract

There has been intense design activity on the SIS100 synchrotron at GSI (Darmstadt) during the last years. The SIS100 (part of the FAIR project), will provide acceleration of high intensity U^{28+} and proton beams for 0.5 s with a pulse repetition rate of 0.6 Hz. The accelerator magnetic system has superferric 2 T dipoles of about 3 m length and 32 T/m quadrupoles of about 1m length. The magnet coils are made of hollow NbTi composite cable, cooled with two-phase helium flow at 4.5 K. The lattice is comprised of 108 dipoles and 168 quadrupoles. The inner dimensions of the elliptic beam pipe are 130 x 60 mm^2 for the dipole and 135 x 65 m^2 for the quadrupole. The R&D results obtained from the studies of 1.4 m dipole and 0.4 m quadrupole models were used to estimate the AC losses at 4.5 K for different SIS100 operating cycles. The status of the new magnets design is presented.

INTRODUCTION

It was proposed [1] to use in the SIS100 improved versions of fast cycled, superferric synchrotron magnets, which are similar in design to the Nuclotron magnets in Dubna [2]. One of the main research goals of the collaborative JINR/GSI R&D, started a few years ago, was to minimize the AC power losses in the SIS100 dipole and quadrupole model magnets. Reduction of the total AC power losses by 30 %, compared to the reference Nuclotron dipole, was specified as the aim of the work at the starting point. Intensive theoretical and experimental R&D work was performed in 2001-2005. More then 20 different model magnets were constructed and tested at the Laboratory of High Energies of JINR in Dubna. By the end of 2005, the AC losses at 4.5 K were reduced by a factor of 2.2 and 2.8 for the 4 K yoke dipole and quadrupole respectively. The main steps which have resulted in such a substantial improvement, were reported at EPAC'02, EPAC'04, MT-17, MT-18 and MT-19 Conferences and published in [3 - 7]. Note, at 4K the AC losses of the original Nuclotron dipole (56 x 110 mm^2 beam pipe aperture) amounted to 9 W/m (coil) and 29 W/m (yoke) for the standard cycle (4T/s, 2T, 1Hz; no beam pipe).

THE PROTOTYPES PARAMETERS

The initial parameters, fixed for the design and construction of the first full length SIS100 magnet prototypes, named PDP1 and PQP1 respectively, are presented in Table 1. Note, the values in brackets are considered as ultimate design goal.

Table 1: SIS100 Main Magnet Parameters

	PQP1	PDP1
Maximum dipole field, T	-	1.9 (2.1)
Magnetic rigidity, Tm	-	90 (100)
Quadrupole gradient, T/m	32 (max)	
Beam pipe aperture, mm^2	135 x 65	130 x 60
Effective field length, m	1.1	2.756
Sizes of the window, mm	-	180 x 66
Pole inner diameter, mm	100	-
Ramp rate, T/m·s, T/s	64	4
Cycle length, s	1.8	1.8

The free aperture of both dipoles and quadrupoles of the SIS100 lattice has been increased, in comparison with that of the original Nuclotron magnets. This was motivated by high current beam dynamic problems [8] and the requests of vacuum chamber and magnet coil designers as well.

PDP1 DESIGN APPROACH

The PDP1 design follows the improved nuclotron dipole version. View of the magnet in cryostat and cross section of the yoke are shown in Figure1 and Fig. 2.

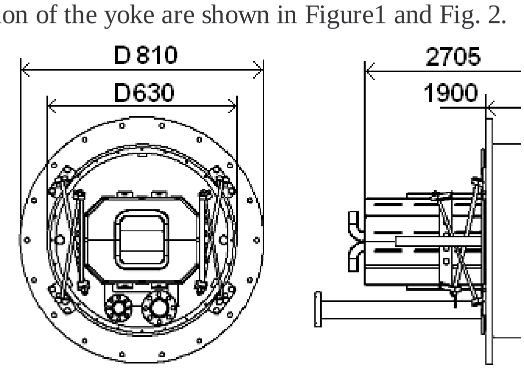

Figure 1: Schematic view of the PDP1 and the cryostat.

The suspension parts provide the fixation of the magnet. The magnet cold mass together with the thermal

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shield at 50 - 70 K is fitted to the external vacuum jacket of 630 mm diameter. The yoke lamination is manufactured from 0.5 mm thick steel and assembled in a packet using stainless steel brackets and 15 mm thick end plates. The brackets have longitudinal cuts to minimize eddy current loss. For the same reason, the end parts of the yoke lamination will have a special design, namely: narrow horizontal slits, as was done at first in the model dipole 4KDP3 [5]. The total mass of the laminations is about 1600 kg.

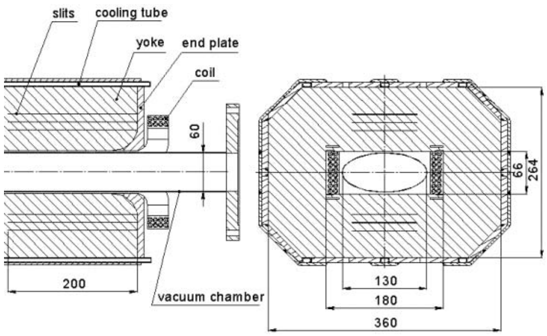

Figure 2: The PDP1 cross section.

The 2D optimization of the magnetic field for the presented yoke profile has been performed based on the following initial conditions: 1) good field horizontal area ($\Delta B/B < \pm 6\cdot10^{-4}$) should be not less then ± 60 mm over the total operation range from injection to the maximum gap field 2.1 T; 2) the hollow cable outer diameter is 6.6 mm, including the kapton electrical insulation of 0.2 mm thickness; 3) the distribution of the coil turns in the vertical direction is equidistant; 4) the cable is comprised of 31 NbTi wires of 0.5 mm diameter each, with ~ 4 µm filaments. Negative shiming and additional slits in the yoke laminations were introduced near the coil top and bottom to satisfy the first condition. As shown in Fig. 3, the specified tolerance for the field nonlinearity is satisfied within about 100% of the beam pipe aperture. Nevertheless, the conditions required to store high intensity beams (close to Coulomb limit) at injection can

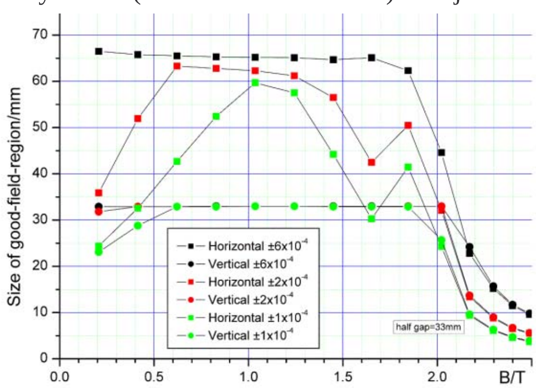

Figure 3: Field nonlinearity in the dipole central part.

lead to even tighter tolerances for the field nonlinearity at low inductions also. Thus, optimization of the magnetic will be continued, including the 3D part. The dipole load line is presented in Fig. 4. As shown, supply current of about 7200 A is needed to reach 2.1 T gap field. The cable quench current safety margin exceeds 30 % in this case.

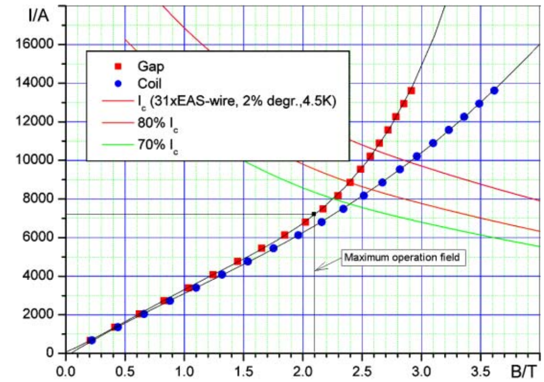

Figure 4: The calculated PDP1 load line and the cable operation current limits in respect to the quench current.

PQP1 DESIGN

The R&D results, obtained for the dipoles, were applied to improve the Nuclotron quadrupole design. The original Nuclotron quadrupole specific AC loss of about 70 W/m was even 40 % higher than for the dipoles. The progress achieved is connected with modification of the yoke. The yoke AC loss contribution was reduced by a factor of 2.8. This result is analyzed in more detailed in [9]. View of the proposed PQP1 magnet in the cryostat is shown in Fig. 5.

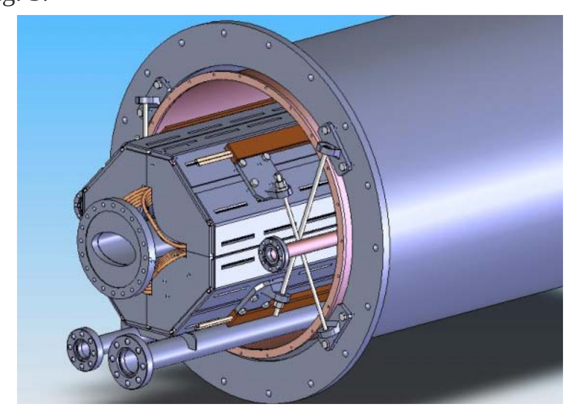

Figure 5: Artistic view of PQP1 magnet.

The basic outer configuration of the PQP1 yoke is similar to that of PDP1. The lamination sheets are produced from the same steel as are those of the dipole. Stainless steel brackets with longitudinal cuts and the end plates provide stacking of the laminations of each quarter of the yoke. The cross section of the lamination is presented in Fig. 6. Narrow slits are used to suppress the eddy current induced by the longitudinal component of the fringe field. Small holes reduce the influence of the iron saturation and partially improve the linearity of the field at maximum current. The coil is manufactured from the same superconductor and hollow cable as the PDP1 and contain 2 x 5 turns per yoke pole. The maximum operating current is higher then for the PDP1 and reaches

7800 A at G = 32 T/m. The field linearity of $\pm 2 \cdot 10^{-4}$ within 100 % of the beam pipe aperture is provided up to a gradient value of 25 T/m and decreases to 50 % of the aperture at maximum specified gradient (G = 32 T/m).

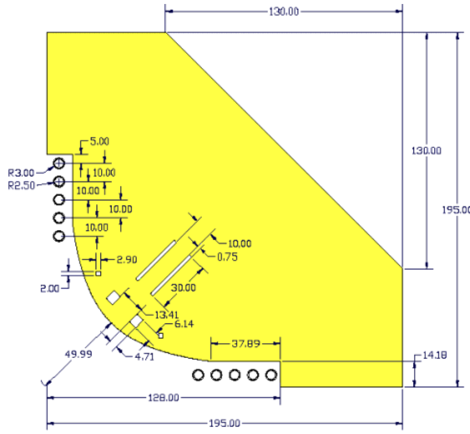

Figure 6: Cross section of the PQP1 lamination sheet.

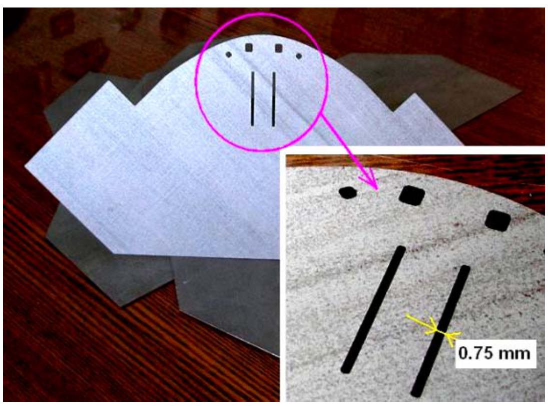

Figure 7: The PQP1 lamination sheet prepared with laser cut machinery.

PREPARATIONS FOR MANUFACTURING

Work on design, fabrication and test of the first full length SIS100 prototype magnets is carried out in collaboration with the BNN and ACCEL Companies (Germany) and FZK research institute in Karlsruhe. Until now, many studies have been performed. Aspects important for the further industrial realization were considered. These are the following: 1). In order to build up a conductor stock for series production, the storage life-time of the Nuclotron cable has to be increased. Two different approaches for alternative insulation concept of the cable were developed. 2). For a precise positioning of the conductor during winding, and to raise the mechanical stability of the winding pack, the use of G11 structural elements was proposed. Samples of the winding pack were manufactured. 3). The winding concept of the coils, especially in the coil-end area, was analysed. The alternative winding scheme and the shape of the structural elements were considerably simplified. 4). Two-dimensional FEM analysis of the mechanical stress field in the magnet was performed. The results indicate that the stresses due to cool down and cycling Lorenz forces are below allowable stresses and the displacement of the coil package is in the range of 0.01mm. The Young's modulus of such a coil sample, before and after one million cycles, showed no difference. The first results have shown that fatigue failure (crack propagation) should not occur in the CuNi helium coolant tube. Nevertheless, the material and the coil sample tests will be continued.

CONCLUSION

Work on the design and manufacture the first SIS100 full-length prototype dipole and quadrupole magnets is in progress. In accordance with our R&D program, a short 1.4 m dipole with the new cross section and the improved coil structure will be manufactured and tested before the full length PDP1 dipole. The optimization of the quadrupole coil design is continuing. Test samples of laser-cut lamination sheets were produced (see Fig. 7). Use of the laser for lamination manufacturing is very attractive during the R&D stage. We are also considering the preparation and test of a short PDP version with separated 4 K / 50 K yoke, to minimized AC power losses in the dipole yoke at 4.5 K.

ACKNOWLEDGEMENT

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