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Critical mechanical structure of superconducting high current coils for fast ramped accelerator magnets with high repetition rates in long term operation

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Abstract. The heavy ion synchrotron SIS100 is the core component of the Facility for Antiproton and Ion Research (FAIR) currently under construction at GSI in Darmstadt. It is rapidly cycled with a ramp rate of 4 T/s up to 2 T maximum field and a repetition frequency of 1 Hz. The superconducting coils of the Nuclotron-type magnets utilise a hollow cable cooled with a forced two phase helium flow. These coils must operate reliably over a period of at least 20 years and thus survive $2 \times 10^8$ load cycles. Intensive R&D is necessary to find the optimal solution preventing any possible damage of the coils by the fast pulsing loads over the life time taking into account the complex fine structure of the cable and coil designs as well as its sensitive influence on the field quality, AC loss generation and quench protection. We used FEM codes to analyse critical aspects of various design options and had manufactured coils for detailed mechanical tests. These tests on samples extracted from the coil are: thermal expansion measurements in all three directions on the cable package itself and its composite elements, compression tests and investigation of the Inter Laminar Shear Stress (ILSS). The stress strain behaviour of the cable package was measured along the transversal direction; the most important one to sustain the cycling load by Lorentz forces. A second sample was fatigue tested. Successful integral operation test results for the coil mechanics have been obtained within our first experimental runs on the prototype dipole magnets already started at GSI in the end of 2008.

1. Introduction
The superconducting coil is the key element of any Fast Cycled Superconducting Magnet (FCSM). Due to increasing AC losses with higher ramp rate and repetition frequency their maximal operation parameters are finally limited by the cooling efficiency and mechanical stability of the cable and coil designs. For reliable and optimal solutions the whole complex of the coil package and its constituent parts must be analysed and tested in detail. Compared to a coil design based on the Rutherford cable or on any version of cable in conduit conductor (CICC) the highest operation intensity can be reached using superconducting cables of the Nuclotron-Type (NTC) [1, 2]. In case of moderate mechanical loads but high heat pulses a special NTC can be used [3, 4] combing the large steady state heat removal with direct cooling of the sc strands. The first synchrotron utilizing FCSM for heavy ion research was the Nuclotron...
commissioned at the JINR Dubna in 1993. The SIS100 will be a second generation machine of such type of synchrotron. The results obtained during the R&D phase of the FAIR project are currently under discussion for its second accelerator, the SIS300, for the NICA project at JINR Dubna and the PS2 upgrade at CERN [5, 6, 7]. The NTC can be used both for superferric magnets up to 2 T maximum field and for $\cos(\theta)$-style dipoles at least up to 4.5 T. In this paper we present recent results on theoretical modelling and intensive experimental testing of the mechanical coil structure for the first SIS100 prototype dipole built at BNG Wuerzburg. Some preliminary results and technological consideration were presented in [8, 9, 10].

2. Magnet overview

The principal design elements of the main magnets are shown in figure 1 in form of a rough ANSYS-3D model of the dipole and an OPERA-2D model for the quadrupole. The first prototype dipole has a $2 \cdot 8$ turn whereas the first prototype quadrupole has an $2 \cdot 3$ turn per pole design.

2.1. Nuclotron type cables for main magnets and correctors

The design elements of the standard Nuclotron cable is presented in figure 2, variations of this type, recently under discussion for the corrector magnets, are shown in figure 3 [11, 12]. The strands are individually insulated so that these magnets are low current ones. This is desired as the correctors are powered individually. The design of these magnets is presented in figure 4.

Up to now our tests were made on two design options - for the original Nuclotron dipole coil and its modification for the SIS100 prototype [13]. The following measurements of parts of the cable and of the coil were performed to show that the mechanical properties are adequate and to obtain material data for FEM studies

(i) fatigue crack growth rate of the CuNi material
(ii) thermal expansion coefficients
(iii) tensile strength at 4 K and 300 K
(iv) leak test after mechanical load
(v) G11 material of the coil support structure modulus in different directions
Figure 2. Cable as used for the main magnet. 1 – cooling tube, 2 – superconducting wires, 3 – CrNi wire, 4 – Kapton tape, 5 – glass fibre wire

Figure 3. Low current cable for the correctors. The insulated strands on the left and on the right strands selected for the quadrupole correctors (red ones powered). 1 – CuNi tube, 2 – Kapton, 3 – superconducting wire insulated by enamel, 4 – Kapton, 5 – CrNi wire, 6 – Kapton insulation.

Figure 4. Corrector designs. The left shows the multipole corrector with its different windings (green – quadrupole, blue – sextupole, red — octupole) and the (normal red and skew blue) steerer on the right.

(vi) stress-strain curves before and after 2 million cycles
(vii) leak test before and after 3 million cycles
(viii) thermal expansion coefficients and leak test before and after thermal cycles
(ix) stress-strain-curve after 16 thermal cycles

3. Investigation of the cable mechanics
The following measurements were conducted:

(i) fatigue crack growth rate of the CuNi-material.
(ii) thermal expansion coefficients
(iii) tensile strength at 4K and 300K
3.1. Fatigue test of CuNi material

This investigation is performed using an ASTM proportional compact tension specimen with the size 45 mm · 43 mm · 4 mm and a starting $a/W$ ($a$ is the crack length and $W$ is the width of compact tension specimen, which is 36 mm here) ratio of 0.33. Figure 5(a) shows the pre-cracking of the electro discharge notched specimen at 7 K. From the obtained plots of figure 5 the fatigue crack growth rate of the material CuNi can be computed using a special software to determine the crack length/cycle versus cycle number performance. The results of this computation are shown in figure 6. The determined pre-exponential constant $C$ with $9.28 \cdot 10^{-12}$ (mm/cycle) and the exponent $m = 4.5$ are the so-called Paris constants describing the stage II linear portion of the curve in double logarithmic diagram. The load ratio $(\Delta K_{min}/\Delta K_{max})$ was held constant.

(iv) leak test after mechanical load
(v) G11 material of the coil support structure modulus in different directions
(vi) stress-strain curves before and after 2 million cycles
(vii) leak test before and after 3 million cycles
(viii) thermal expansion coefficients and leak test before and after thermal cycles
with 0.1 during the entire test procedure. The structural analysis following the determined results with the Paris coefficients can be ready applied to the tube enclosed inside the winding pack using the given boundary conditions as follows:

The life of a tube under cyclic loading is estimated by Paris law as given by ASM page 28

\[ a_f = \frac{1}{\pi} \left( \frac{KIC}{\Delta \sigma YS} \right)^2 , \]  

with the input data \( C = m/\text{cycles} = 9.28 \cdot 10^{-15} \), \( Y \) the geometry factor which 1.2 for surface cracks and \( S \) the safety factor set to 2. As initial crack length \( d \) is assumed to 0.2 \( \text{mm} \). The “half size crack” is then \( a_0 = d/2 = 0.1 \text{mm} \). For the fracture toughness \( KIC \) a value of 50 MPam\(^{1/2}\) is assumed as a worst case approximation. The number of cycles \( N_f \) is given by Paris law

\[ N_f = \int_{a_0}^{a_f} \frac{1}{C (YS\Delta \sigma \sqrt{\pi a})^m} \, da \approx 250 \cdot 10^6 , \]  

with \( \Delta \sigma \) to 50 MPa which is 5 times the nominal pressure. So the tube will sustain more than 250 million cycles under the given conditions. These computations show that a crack growth through the wall thickness of the tube during the lifetime of the magnet is more than unlike according to the present findings.

### 3.2. Thermomechanical tests

The stress strain measurements were done on samples (see figure 7), treated differently. The first \( (K_t) \) was annealed in Argon gas, the second \( (K_c) \) was measured after 100 rapid thermal cycles (80 to 300 K) and the third one was measured after annealing and 100 thermal cycles \( (K_v) \) (see figure 8 and table 1). One can see that the stress and strains increase at cold. The tube provides a significant large strength even if mistreated.

### 3.3. Leak rate measurements

The leak rate of the helium tube was tested before cycling with \( F_{\max} = 800 \text{ N} \) (see figure 9), characteristic for the expected Lorentz forces at \( T < 7 \text{ K} \) before and after \( 2.6 \cdot 10^6 \) cycles (see table 2): At a level of \( 10^{-9} \text{ mbar-l/s} \) no impact of the cycling on the leak rate was found for the NiCu-tube of the cable.
(a) at 4.2 K

(b) at room temperature

Figure 8. Stress strain measurements on the CuNi tube.

Table 1. Stress strain parameters for the different measurements. E-modul ... Young’s modulus, $Y_S$ ... yield strength, $UT_S$ ... ultimate tensile strength, $E_U$ ... uniform elongation, $E_T$ ... total elongation.

| Measurement Sample | T [K] | E-modul [GPa] | $Y_S$ [MPa] | $UT_S$ [MPa] | $E_U$ [%] | $E_T$ [%] |
|--------------------|-------|---------------|-------------|-------------|-----------|-----------|
| $K_t$              | 4.2   | 163           | 414         | 792         | 32.1      | 33.1      |
| $K_i$              | RT    | 165           | 250         | 451         | 18.6      | 23.1      |
| $K_c$              | 4.2   | 156           | 385         | 751         | 28.8      | 31.6      |
| $K_c$              | RT    | 154           | 274         | 471         | 21.8      | 29.9      |
| $K_v$              | 4.2   | 161           | 379         | 743         | 21.0      | 21.9      |
| $K_v$              | RT    | 155           | 300         | 498         | 19.7      | 32.2      |

Figure 9. Setup of the leak tests.
Table 2. Leak rate test for cycling with $F_{\text{max}} = 800$ N and $T < 7$ K

| sample   | 1 | 2 | 3 | 4 | 5 | 6 |
|----------|---|---|---|---|---|---|
| before cycling | 1.3 | 1.7 | 92 | 1.5 | 3.3 | 2.8 $[10^{-9}$ mbar l / s] |
| after cycling  | 1.2 | 2.1 | 2.8 | 1.5 | 6 | 3.2 $[10^{-9}$ mbar l / s] |

Figure 10. The FEM model of the Nuclotron cable. On the top right the design of the real cable is shown. The full model is shown in the middle and on the left bottom a zoom of the model start.

3.4. Fatigue Calculations

As the magnet can not be tested on its $2 \cdot 10^8$ cycles, calculations were started to investigate the effects on cycling on the coil pack. The cable in its compound has been modelled in ANSYS in 2D. The results show that the tube will survive 20 years of operation [14]. For further analysis of the thermo-mechanical properties and physical accurate modelling 3D-ANSYS models of the cable were built to study in detail its structural integrity, and first trial calculations were started. We hope to report soon on the mechanical stability of the cable and the stresses and strains it will be exposed to.

4. Mechanical tests on the dipole coil

During the R&D phase the coil design was optimised for industrial cable production and higher coil stability [8, 13, 10]. A coil support structure made of G11 was introduced into the coil package to reduce the "line" forces between the individual cable turns as well as to position them precisely. The mechanical properties of G11 specimens were measured along with the tests on mockups and test coils (see figure 11(b) and figure 12). Several tests were performed on samples extracted from a cable package. These tests are thermal expansion in all three directions $(x, y, z)$ on the cable package itself and G11 material extracted from the test coil after integral testing. Figure 13 presents the thermal expansion results.

Compression tests were performed on the G11 material in all three directions. The compression modulus for G11 is given in table 3. The Inter Laminar Shear Stress (ILSS) was
Figure 11. The cable support structure. The left shows the design and the right shows a sample of the half coil ready for mechanical measurements after a first cool down.

Figure 12. Test of the support structure material.

Table 3. Compression modulus $C_M$ and maximum stress $S_{max}$ of the coil pack

| direction | $C_M$ [GPa] | $S_{max}$ [MPa] |
|-----------|-------------|-----------------|
| x         | 35.2        | 699             |
| y         | 20.9        | 1047            |
| z         | 30.3        | 587             |
investigated for the G11 material too (figure 14, and table 4). The stress strain behaviour was measured in x-direction of the cable package (see figure 11). A second sample was fatigue tested, examining the He-leak before and after thermal and mechanical cycling. The flexural modules was tested as well (see figure 15 and table 4). The method is described in [15].

4.1. Coil Pack Test
The thermal expansion of the coil pack was measured (see figure 16 for the setup) at room temperature and at 7 K (see figure 17). The leak rate before fatigue test was $2 \times 10^{-10}$ to $4 \times 10^{-10}$ mbar·l/s and increased modestly to $5 \times 10^{-10}$ to $8 \times 10^{-10}$ mbar·l/s. The coil pack was stress-strain cycled for $\approx 10^6$ cycles for a force of up to 2 MPa (Lorentz force) and afterwards
destructively tested. For the cycling a compression modulus of 5.8 GPa was found while for the destructive test a compression modulus of 4.8 GPa was found. This gives a movement of less than 5 $\mu$m of the coil windings in the magnet at maximum field.

5. Integral test results for the first prototype dipole magnet
The integral verification of the coil design was tested during measurements on our first BNG prototype dipole at GSI (see figure 18) [9, 16]. The magnet had shown an excellent short training behaviour of the coil, high critical current (near to short sample limit), as well as weak ramp rate dependence. These results are clear experimental proofs that the actual technology for cable manufacturing is sound and ready for serial production.

6. Optimised design for a single layer coil
The obtained results must be adapted and completed for the new curved dipole with a single layer coil [17, 18, 19, 20] and to the other sc magnets of SIS100. The new curved dipole will be equipped with a high current single layer coil as shown in figure 19.

This new design allows more intensive operation cycles of the synchrotron and simplifies the coil mechanics significant too. The dipole will be built next as a pre-series magnet.
Figure 18. The first SIS100 dipole magnet within its cryostat

Figure 19. The cross section of the curved single layer dipole CSLD.

7. Conclusion
Detailed theoretical, numerical and experimentally efforts were successfully completed on cable and coil design during the R&D phase for the SIS100 superconducting magnets. The results show that the coil will survive at least the planned operation period of 20 years under the defined conditions and operation parameters. The first integral test results at the BNG prototype dipole confirm our R&D results showing a stable operation of the coil. The obtained results are useful also for further design work on superconducting high current cable and coils.
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