Progress in the Design of a Fast-Cycling Cos− style Dipole based on High Current Hollow Superconducting Cable

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Abstract. The progress in the design of a fast-ramped, fast-cycling Cos− style 4 T dipole based on high current hollow superconducting cable is presented. New results obtained in the optimization of both the 40 kA hollow cable and the magnet coil structures are discussed. Experimental data from recent tests of the model dipole coil made from the NbTi keystoned wire are reported. The joint optimization of the angular distribution of the coil turns and the internal shape of iron boundary makes it possible to achieve a relative non-linearity of the magnetic field better than \(5 \times 10^{-4}\) within 82\% of the coil aperture over a dynamic range from 0.3 T to 4.5 T. The diameter of the new hollow cable is 8.92 mm. It consists of 40 keystoned NbTi composite wires and a 3mm bore coolant tube. The designed operating current is 40.1 kA at 4.5 T. Full scale tests of the model dipole coil will be performed after completion of the necessary test facility upgrade. The actual maximum of 11.4 kA for the operation current is limited by the power supply and current leads of the test stand. The new current leads aimed at a current of 20 kA have been designed and manufactured.

1. Introduction
The concept of a fast-ramped fast-cycling 4 T superconducting Cos− style dipole based on a single-layer coil made from hollow NbTi cable was first presented at EUCAS2001 [1]. The main advantages of the new concept are much better cooling conditions of the superconductor and much less inductance of the magnet winding compared with the traditional dipole based on Rutherford cable. The R&D and prototyping work in this direction is continued at the LHE JINR since that time. One of the main research goals is the design and fabrication of a superconducting cable operating at 35 kA, 35 kA/s and gap magnetic field of 4 T and higher. Moreover, it is extremely important to reach the highest current density in a cable without losing its good cooling conditions. We continue to explore the concept of an NbTi hollow cable cooled with two-phase helium flow. It is typical for the cable type proposed and used for the Nuclotron 2 T, 4 T/s superferric magnets [2]. Nevertheless, the suggested new design makes it possible to improve substantially the cable performance. The first optimization results for the magnetic field in the magnet aperture were presented at EUCAS’03 [3]. An attempt was made to suppress the higher harmonics of the magnetic field in the
aperture by means of a proper angular distribution of the coil turns. A mathematical model and special computer code were developed and used for this purpose [4]. The best obtained result was a relative nonlinearity of the magnetic field of $\Delta B/B \geq 5 \times 10^{-3}$ within 75% of the magnet aperture at $B = 4$ T. The further improvement of the magnetic field quality was limited by insufficient flexibility in the choice of the coil turns angular position and large dynamic range of the operating field values as well. The new optimization step was made with the help of a newly developed mathematical model and computer code [5] that made it possible to include the inner shape of the ferromagnetic boundary into the process of optimization.

2. Cross section and field optimization
The optimized cross section of the dipole (one quarter) including the coil turn positions and the ferromagnetic yoke is presented in figure 1. The initial conditions were as follows. The cable outer diameter not exceed 9 mm, free aperture diameter $\approx 104$ mm, radial position the centers of the coil turns - 57 mm, $B/H$ curve of the ferromagnetic is the same as for the Nuclotron.

![Figure 1. Optimized cross section of 4 T dipole: 1 – coil made from hollow superconducting cable, 2 – ferromagnetic inner boundary, 3 – non magnetic collar, 4 – laminated ferromagnetic yoke.](image)

The optimization process is based on a computer search for optimal angular positions of the turns and for an internal shape of the yoke inner profile which provide the minimum difference of the field vertical component at a circle of $R = 40$ mm compared $R = 0$. The mathematical model was described detailed in [4, 5]. Additional fictitious current coils were introduced for imitation of the yoke. The optimization results are shown in figure 2.

![Figure 2. The results of 4 T dipole optimization: left plot – the dependencies of the gap magnetic field and the field sextupole component on supply current; middle plot – relative inhomogeneity of the field along horizontal axis; right plot – the field map, obtained with the ANSYS.](image)

The sextupole nonlinearity was suppressed to about $\pm 1 \times 10^{-7}$ of the main field within 75% of the magnet aperture over dynamic range from 0.5 T to 4 T. Direct field calculations of the optimized dipole were
performed using the ANSYS computer code. The obtained results (see figure 2) confirm the excellent quality of the aperture field after the optimization of the dipole structure.

3. Optimization of the hollow cable

The calculations have shown, that the operation current of the cable should be about 35 kA for a magnet field of 4 T (see figure 2). The space available for the optimal distribution of the coil turns (figure 1) leads to the needed cable engineering current density of about 440 A/mm². For the original Nuclotron cable the same parameter extrapolated to B = 4 T at 4.5 K would not exceed 75 A/mm², i.e. the difference reaches a factor of 6. Several possibilities to solve this problem were considered and partially have been tested experimentally: 1) increase of the outer cable diameter; 2) reduce the cooling channel diameter; 3) increase the percentage of the superconductor in the total cross section of the cable; 4) decrease the operation temperature of the superconductor; 5) optimize the magnet design to maximum field to current ratio B/I; 6) use a wire made from other superconducting material (Nb₃Sn, MgB₂). A comparison of three new hollow cable versions (KWAT1, KWAT2, and KWIT1) designed in accordance with the mentioned above possibilities 1 - 4 is presented in Table 1.

| Parameter                                      | Units   | KWAT1 | KWAT2 | KWIT1[6] |
|------------------------------------------------|---------|-------|-------|----------|
| Cable diameter with insulation                 | mm      | 7.34  | 8.92  | 8.92     |
| Cooling channel diameter                       | mm      | 4     | 3     | 3        |
| Number of the wires                            |         | 15    | 40    | 40       |
| Wires cross-section area                        | mm²     | 12.0  | 37.2  | 35.3     |
| NbTi cross-section area                         | mm²     | 4.29  | 16.8  | 15.9     |
| Percentage of NbTi in cable cross-section      | %       | 10.1  | 26.9  | 25.4     |
| Critical current density @ 4.5T, 4.5K          | A/mm²   | 2070  | 2960  | 2960     |
| Operating current at T=4.5 K                   | kA      | 12 @ 2T | 40.1 @ 4.5T | 40.1 @ 4.5T |
| Structural current density at T=4.5 K          | A/mm²   | 223 @ 2T | 504 @ 4.5T | 504 @ 4.5T |
| Critical current at 4.5 K                      | kA      | 17.4 @ 2T | 49.6 @ 4.5T | 47.1 @ 4.5T |
| Critical to operating current ratio             |         | 1.45  | 1.24  | 1.17     |

It is obvious, that the calculated parameters of the KWAT2 and KWIT1 version are satisfy our design goal. The new cable’s cross section is shown in figure 3. The further increase of the KWAT2 critical current up to 53 kA is possible for example by means of decreasing the operating temperature to 4.3K. The optimization of the dipole to a maximum B/I ratio can reduce the needed operation current. Nevertheless, additional sextupole correction windings should be added to the main dipole coil.

Figure 3. Cross section of the KWAT2 (a) and KWIT1 (b) cables: 1 - copper-nickel tube, 2 - composite NbTi wire of keystoned profile, 3 – wires binding by, 4 - electrical insulation.

4. Model cable test results

The KWAT1 version has been manufactured and tested as real dipole coil in the Nuclotron-type dipole. The R&D stages from keystoned wire fabrication at the Bochvar Research Institute (Moscow)
to the first 50 m of the cable production LHE JINR as well as the first coil from KWAT1 and it’s tests were described in [7,8,9]. The maximum cycle operation current of 11.4 kA obtained in the July 2005 tests was limited not by the cable but by the test bench capabilities. The standard operation limits of the LHE test facility were: supply current of 6 kA, current ramp rate of 12 kA/s at an inductance of 1mH. The power supply upgrade performed in 2004-2005 made it possible to increase the current by a factor of two. New and more powerful current leads have been designed, manufactured, installed and have passed the first tests. Nevertheless, the desired goal of 15-20 kA at pulse operation was not reached. Thus the second tests of a KWAT1 coil were performed with existing but upgraded current leads. The geometry of a single-layer 8 turn winding made from KWAT1 corresponds to the 1.4 m long Nuclotron window frame yoke. The sizes of a window are 126mm x 59 mm. The coil was separated from the yoke window by a gap of 2 mm similar to the 80 K yoke magnet version [10]. A stable operation of the magnet at dB/dt = 4 T/s, f = 0.5 Hz was observed up to the supply current of about 10700 A. The first quench occurred at a current of 11400 A after more than ten cycles. The quench was initiated by the current leads. No normal zone was detected in the coil.

5. Summary & outlook
The optimized version of a 4T “Cos – style” dipole with the aperture of 104 mm was developed based on a new mathematical model for the magnetic field calculations and a new approach to high current hollow NbTi composite multifilament cable manufacturing. The experimental tests of the KWAT1 cable version have verified the possibility to increase the operation current to about 12 kA, i.e. by a factor of 2 compared to the original one. Thus, the constructing feasibility of a single – layer 2 T, 4 T/s, superferric window-frame dipole magnet was confirmed as a by-product of the R&D. Preliminary calculations had shown the technical possibilities to reach peak magnetic fields up to 4.4-4.6 T at field ramp rates of 3 – 4 T/s, based on a single-layer dipole with the coil made from high current hollow cable. These topics will be analyzed in more detail in the future.

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