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Design and Study of New Cables for Superconducting Accelerator Magnets: Synchrotron SIS 100 at GSI and NICA Collider at JINR*

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Abstract. Recent data from the design of new optimized options of NbTi composite wires and hollow cables for fast cycling synchrotron SIS100 at GSI and NICA collider at JINR are presented. The SIS100 new cable is proposed to be used for manufacturing of single-layer coil for dipole magnet with maximal amplitude of pulsed magnetic field up to 2 T. The cable should provide continues pulsed operation at the current amplitude of I = 13 kA and magnetic field ramp rate of dB/dt = 4 T/s. The results of experimental study of energy losses in the new wire and cable samples for SIS100 magnets are presented. The design cable parameters for the NICA 4 T dipole magnet are fixed at the level of I = 17 kA and dB/dt = 1 T/s. The status of the work is presented and discussed.

1. Introduction
The synchrotron SIS 100 is the core component of the international Facility of Antiproton and Ion Research (FAIR) to be built at GSI Darmstadt. The aim of the FAIR project [1] is to provide high intensity primary and secondary beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics. This requires an upgrade of the existing GSI accelerator facility and the construction of a new accelerator complex. It consists of 2 synchrotrons in one tunnel, SIS100, SIS300, and several storage rings. SIS100 will accelerate ions and protons at a high repetition rate at about 1 Hz. The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions up to uranium [2]. It includes a new 6.2 MeV/u linac, a 440 MeV/u booster, the upgraded SC synchrotron Nuclotron and a collider consisting of two SC rings. The cables for the SIS100 magnets and for the NICA collider magnets are based on the Nuclotron-type cable. It is a hollow composite NbTi superconducting cable cooled with a two-phase helium flow.

2. Cables design
The cable for SIS100 magnet with a single-layer winding [3] should operate in a pulse mode with a current amplitude of 13 kA, a magnetic field ramp rate of 4 T/s, and a frequency up to 1 Hz. Low losses in the wires and in the cable are an important condition for successful operation of SIS100. New wires and the cable intended for the SIS100 magnets have been developed and investigated [4–6]. The basic characteristics of the cable for the SIS 100 magnets are presented in Table 1. The wires were...
designed in a way that the matrix to superconductor ratio was about 1.5. Two different approaches were followed: a conventional double stacking (DS) approach with 397 multiplied by 84 elements and a single stacking plus cold bonding (SS+CB) approach. For the later, the initial layout of 3132 multiplied by 7 elements could not be drawn to the final wire size and therefore the production was stopped. Instead a 3132 multiplied by 5 wire with additional copper in the centre was produced without difficulties. To increase the stability of the magnets and to minimize the AC losses during the operation of the magnets, the filament diameters of the wire was made to about 3 µm. This requires a CuMn inter-filamentary matrix for avoiding proximity coupling between the filaments, which would increase the losses again. Wires for the SIS100 magnets were manufactured at the Bochvar Institute and have the following main characteristics: a critical current density of 2400 A/mm² at 5 T and 4.24 K; a “n” parameter of 30; an effective value of the filaments diameter D_{eff} of 6.4 microns, and D_{eff}/D ratio of 1.56. The properties of these wires are described in [7] more detail. The cross section of the cable for SIS100 magnets is presented in Figure 1. The superconducting cable contains a 5.7 mm diameter copper-nickel tube, inside which a two-phase helium flows. This tube is wrapped with 23 superconducting wires, 0.79 mm in diameter, with a strand’s transposition length of 50 mm. A 0.2-mm diameter Ni-Cr wire is spirally wound around the superconducting wires with a tension of 10 N. Such a design provides a good thermal contact of the superconducting wires with the cooling helium flow [8, 9].

Figure 1. Cross section of the SIS100 (left) and NICA collider (right) cables: 1 - copper-nickel tube, 2 - composite NbTi wire, 3 – wires binding by Ni-Cr wire, 4 - electrical insulation.

The cross section of the cable for the NICA collider magnets [10] is presented in Figure 1 (right). A 4 mm diameter copper-nickel tube wrapped with 12 superconducting wires. The cable for the NICA collider magnet will be made using the Nuclotron cable machine and the experience gained earlier in manufacturing a cable from wires with a cross-section in the form of a curvilinear trapezium [6]. The cross-section of the wire will be drawn to trapezoidal form at the final stage from the round wire to increase structural current density in the cable. The cable for the NICA collider magnet will be made using the same machine and the experience gained earlier at manufacturing cables from wires having cross-section in the form of a trapezoid. Some characteristics of the cable for the 4 T NICA magnets are presented in Table 1.

| Parameter                        | Units | SIS100 | NICA |
|----------------------------------|-------|--------|------|
| Cable diameter with insulation   | mm    | 8.26   | 8.00 |
| Cooling channel diameter         | mm    | 4.7    | 3    |
| Number of the wires              |       | 23     | 12   |
| Wires cross-section area          | mm²   | 11.3   | 22.4 |
| NbTi cross-section area           | mm²   | 4.51   | 10.1 |
| Operating current at 4.5 K       | kA    | 13 @ 2T | 16.6 @ 5T |
| Structural current density at 4.5 K| A/mm² | 191 @ 2T | 259 @ 5T |
| Critical current at 4.5 K        | kA    | 20.7 @ 2T | 23.1 @ 5T |
| Critical to operating current ratio|       | 1.59 | 1.39 |
3. Experimental study of AC losses in wire and cable samples

The instrumentation for AC losses measurements of short samples of superconducting wires and cables (without transport current) was designed and constructed at Laboratory of High Energy Physics JINR. The scheme of instrumentation is shown in Figure 2. The superconductor sample is placed inside a vertical cryostat. The superconducting dipole magnet is used for generating a pulsed magnetic field. The pulses had triangular shape. The amplitude of the field as well as the field ramp rate can be changed from 0 to 2 T and from 0.05 to 6 T/s respectively. The magnetic field was directed perpendicular to the longitudinal axis of the samples. The measurements were carried out at 4.2 K using the calorimetric method. The AC losses are calculated from the energy balance.

![Figure 2. Setup for AC loss measuring in short samples of superconductors: 1 – cryostat for liquid helium; 2 – power supply; 3 - heat exchanger for helium from calorimeter; 4 - liquid helium level gauge; 5 – pressure regulator; 6 – superconducting dipole magnet; 7 – flow meter; 8 – liquid helium input valve; 9 – electric heater; 10 – sample of superconductor; 11 – Hall transducer; 12 – calorimeter; P1 - pressure gauge.](image)

The calorimeter consists of two coaxial tubes. The inner tube with a diameter of 18 mm is filled with liquid helium, in which a sample of the superconductor, an electric heater, and a level gauge are placed. The pressure regulator and gas flow meter are used to determine the vaporization heat of helium in the calorimeter at constant pressure. The AC losses can be measured in a range from 10 to 600 mW. It is possible to change the sample position in space by rotating the calorimeter around its axis. Basic parameters of the setup are presented in Table 2.

**Table 2. Basic parameters of the setup for measuring the AC losses**

| Parameter                                | Value   |
|------------------------------------------|---------|
| Peak magnetic field T                    | 2.0     |
| Maximum ramp rate T/s                   | 5.0     |
| Minimum ramp rate T/s                   | 0.05    |
| Maximum rate of heat release mW         | 600     |
| Minimum rate of heat release mW         | 10      |
| Heat inflow mW                          | ≤ 15    |
| Internal diameter of the calorimeter mm  | 18      |
| Maximum length of the samples mm        | 330     |
| Accuracy of the measurement %           | 10      |

A short cable sample for the SIS 100 magnets have been produced using the Nuclotron cable machine [8] after it was adapted to the sizes of the cable for SIS100 magnets. The AC losses of the cable were measured. The main characteristics of the wire for the SIS 100 cable sample are presented in Table 3.

**Table 3. Main characteristics of the wire used for the SIS 100 cable sample**

| Wire diameter (mm) | Number of filaments | Filling factor of NbTi | Filament diameter (µm) | Filament twist pitch (mm) |
|--------------------|---------------------|------------------------|-------------------------|---------------------------|
| 0.79               | 15660               | 0.40                   | 4.0                     | 8.0                       |
The experimental dependence of the AC losses on the magnetic field ramp rate $dB/dt$ for the cable sample is presented in Figure 3. The losses are measured powering the external magnetic field to 1.05T using unidirectional triangular pulses. This value corresponds to the average value of the magnetic field in the coil of the SIS 100 magnet, when the field in the aperture of the magnet is approximately 2.1 T.

![Figure 3](image)

**Figure 3.** AC losses per 1 cm$^3$ of Nb-Ti in cable sample for SIS100 magnets as a function of the magnetic field ramp rate at $B_m = 1.05$ T.

The experimental data show that the hysteresis loss is less than 50% of the total losses in the sample at $B_{max} = 1.05$ T and $dB / dt = 2$ T / s. Eddy currents between the wires are practically absent in cables of this type. The eddy current losses between filaments, having a twist pitch of 8 mm, are major contributors to the AC loss in the cable sample. The results from these measurements show reduced losses compared with the original Nuclotron cable [11] and thus one can expect that with further optimized wires (e.g. 3 µm filament twist pitch ~ 6 mm) the AC losses in the superconducting winding of the SIS 100 dipole at $B_{max} = 2.1$ T, $dB/dt = 4$ T/s, and $f = 1$ Hz could be 6 W, which is a reduction by a factor of 4 compared to the original design.

**Conclusion**

- New superconducting cables for 2 T SIS100 magnets and 4 T NICA magnets are designed.
- The AC losses in the cable sample for the SIS 100 magnets have been measured.
- The further reduction of the AC loss in the wire and the cable can be reached reducing the filaments size and twist pitch. The AC loss in the cable of the SIS100 magnets could be reduced by a factor of 4 compared with the loss in the cable of the original Nuclotron design.

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