Design of a Twin-Aperture 4 T Curved Dipole Based on High Current Hollow Superconducting Cables for the NICA Collider at JINR

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Abstract. NICA (Nuclotron-based Ion Collider fAcility) is the new accelerator complex currently under construction at JINR. The facility is aimed to provide collider experiments with heavy ions up to uranium with a centre of mass energy up to 9 GeV/u and an average luminosity up to $10^{27}$ cm$^{-2}$s$^{-1}$. The collisions of polarized deuterons are foreseen too. The accelerator complex includes two injector linacs, a superconducting booster synchrotron, a 6 GeV/u superconducting synchrotron (Nuclotron) and a collider consisting of two storage rings. Curved superconducting 4 T Cosine($\theta$)-style dipoles based on a hollow Nuclotron-type cable are chosen for the collider ring lattice. The twin-aperture dipole consists of two vertically assembled cold masses operating at $T = 4.5$ K placed inside a common thermal shield and a common cryostat. The dipole good field aperture is fixed to 60 mm. The maximum cable operating current is about 17 kA. The field ramp is set to 1 T/s.

1. INTRODUCTION

The new project, NICA/MPD, was proposed at the Joint Institute for Nuclear Research in 2006 [1]. The main goal of the project is to study experimentally hot and dense strongly interacting QCD matter at the new JINR facility in the upcoming years [2]. This goal is proposed to be reached by: 1) upgrade of the existing accelerator facility Nuclotron; 2) design and construction of a heavy ion collider with a maximum collision energy of $\sqrt{s} = 9 - 11$ GeV/u and an average luminosity $10^{27}$ cm$^{-2}$s$^{-1}$ and 3) design and construction of particle detectors at the intersecting beams. The realization of the project will lead to unique conditions for the world research activity. The NICA energy region is of major interest because the highest nuclear (baryonic) density can be reached there under laboratory conditions. The generation of intense polarized proton and deuteron beams at the Nuclotron and NICA, aimed at investigating polarization phenomena) gives additional important capabilities to the facility. The maximum c.m. energies of colliding polarized protons and deuterons are planned to reach $\sqrt{s} = 27$ GeV/u and of $\sqrt{s} = 12.7$ GeV/u respectively. The average luminosity should be at the level of $10^{30} \ldots 10^{31}$ cm$^{-2}$s$^{-1}$ in both modes. In addition the possibility to study proton - ion and deuteron – ion head-on and merging beam collisions are under consideration too. The NICA facility with its particle detectors MPD (Multipurpose Particle Detector) and SPD (Spin Physics Detector) has been defined as the flagship project of the JINR for 2010-2016. The proposals of the experiments at the new facility are collected at: http://theor.jinr.ru/twiki-gi/view/NICA/WebHome.

The construction of the new facility is based on the existing buildings. The accelerator chain includes: heavy ion source – RFQ – new heavy ion injector linac – booster ring – Nuclotron – Superconducting
collider rings. Beam cooling systems are foreseen. The design peak kinetic energy of U\(^{92+}\) ions in the collider at the beginning stage was set to 2.5 GeV/\(u\). It was increased later to 4.5 GeV/\(u\) (for gold nuclei). The project presumes in the case continues to operate some of the fixed target experiments. The collider ring is fitted into the existing building if 4 T (or higher field) dipole magnets are used [3].

2. NICA COLLIDER DIPOLE MAGNET

A. General concept

The cross section of the proposed 4 T NICA collider dipole [4] is shown in Figure 1. The dipole consists of two vertically assembled cold masses placed inside a common thermal shield and a common cryostat. A two-layer coil manufactured of hollow NbTi composite cable is used. The coil is cooled with forced two-phase helium flow at 4.5 K. The dipole good field area (\(\Delta B/B \sim \pm 1 \times 10^{-4}\)) is set to a circle of 60 mm diameter. We consider strongly curved magnet as the most suitable option for the NICA collider placed inside the existing building. Therefore a magnet curvature radius of 12 m is necessary. Arranging the magnet apertures vertically saves extra space for the experimental setups in the accelerator hall while the curved magnet minimizes the aperture. The vertical distance between the apertures is mainly given by the collider RF cavities diameter.

![Figure 1. Cross section of the NICA collider dipole: 1 – coil made of hollow NbTi composite cable, 2 – stainless steel collar, 3 - helium coolant pipes, 4 – laminated iron yoke, 5 – thermal shield at 50 – 80 K, 6 – vacuum jacket.](image)

The magnetic field direction must be changeable without strong distortion of the aperture field distribution. The field ramp of up to 1 T/s is considered as desirable parameter.

B. Previous studies

The idea of a straight 4 T dipole based on high current hollow NbTi composite cable was presented first at EUCAS’2001 and published in [4]. That work was stimulated by the desire to find a cost effective approach to construct 4 T, 1 T/s superconducting magnets for the planned SIS200 synchrotron at GSI in Darmstadt. It was assumed that the proposed magnet has a circular aperture of 105 mm diameter and a single layer coil made of hollow superconducting Nuclotron – type cable. The number of turns in the coil is set to 12 or 14. For these cases the cable operating current was calculated to about 36 or 29 kA respectively. The directions of the further work were the following: 1) design and optimization of the magnetic field 2) design of a high current hollow cable. Generating highly homogeneous magnetic fields for Cosine(\(\theta\)) magnets with a small number of coil turns was solved as well [6,7,8]. It was shown that, optimizing the angular distribution of the coil turns and varying the internal boundary of the iron shield allow to reach a field uniformity of \(\pm 1 \times 10^{-4}\) within 75% of the coil aperture over a dynamic range from 0.5 T to 4 T. The results obtained for the case of a single-layer coil show that a similar technique can be successfully applied to optimize a double-layer coil magnet and to reach the needed quality of the aperture field after optimizing the dipole structure. The R&D work on the design of new hollow superconducting cables aimed at operating currents much higher than 6 kA was also started at that time in Dubna. New SC-wires and cable options were proposed, some of them were manufactured and tested. In particular, composite NbTi wire of trapezoidal cross section [9]. Based on that wire a hollow cable with increased current density was
industrially produced and the first Nuclotron-type dipole with a single-layer coil was constructed and tested [10]. The model magnet operating current reached of about 12 kA. Estimates of a very high current cable (up to 50 kA) were performed also. Such cables would completely satisfy the problem of realization of a single-layer 4.5 T curved dipole magnet. Based on that fact, the new version of magnetic system for the FAIR SIS300 synchrotron was proposed [11]. The "old" one was based on a 6 T straight, Cosine(θ)-style, magnet of 2.7 m length. It uses a two-layer coil made of a Rutherford type cable and is cooled by supercritical helium. The basis of the proposed new SIS300 magnetic system are 4.5 T, Cosine(θ)-style, about 7 m long curved magnets utilizing a single-layer coil of a high current hollow cable cooled by a two-phase helium flow.

C. Dipole parameters estimations

To estimate the parameters of the magnet the model presented in Figure 2 was used. The cable design is described in [12], presented at this conference.

![Figure 2](image)

Figure 2. Cross section of the NICA collider dipole internal part (left) and SC cable cross section.

The results of calculations of the magnet central field are presented in Figure 3.

![Figure 3](image)

Figure 3. The dependences of the model dipole central field vs. supply current for different coil and yoke sizes: 1a, 1b - the sizes are shown in Figure 3; 2a,2b – the number of turns in the coil layers are 12/12, internal diameter of iron shield 132 mm and 150 mm respectively. The dependences of the cable critical current are presented also: “trapezoidal-1” from paper [9] and “trapezoidal-2” the new cable described in [12].

The main parameters of dipole magnets are presented in Table 1. The main difference between the versions is the dipole length. The weight of the "v2" magnet version is much less, the cable length necessary for the coil winding is reduced also. From the other hand the number of dipoles is increased and this leads to larger number of magnet end parts, parallel cooling channels etc. The further analysis and optimization of the NICA collider magnetic structure is in progress.
### Table 1: Basic parameters of the NICA collider dipole options

| Parameter                        | Unit | v1     | v2     |
|----------------------------------|------|--------|--------|
| Peak magnetic field              | T    | 3.93   | 3.93   |
| Effective field length           | m    | 3.0    | 1.8    |
| Number of dipoles                |      | 24     | 40     |
| Coil aperture diameter           | mm   | 80     | 80     |
| Magnet curvature radius          | m    | 11.46  | 11.46  |
| Yoke outer diameter              | m    | 0.38   | 0.38   |
| Number of coil turns 1\textsuperscript{st}/2\textsuperscript{nd} layer |      | 14/14  | 14/14  |
| Length of CuNi tube              | m    | ~180   | ~130   |
| Weight of the cold mass          | kg   | ~4500  | ~2700  |

4. NICA REALIZATION STATUS

Modernization of the Nuclotron is one of the key points in the NICA realization. Many of the accelerator systems were improved in 2007-09. These are, in particular: vacuum, RF, magnet power supply and quench detection/energy damp system. Special attention was devoted to the systems that are important for stable, efficient and reliable long term operation of the Nuclotron. The test runs on acceleration heavy ions (Xe or Kr) at the Nuclotron are scheduled for December 2009 – March 2010. The collider installation option which takes into account the space necessary for the assembling and installation of the particle detectors, the collider equipment, part of the existing beam lines, including radiation shield and necessary technological areas of the Laboratory building was designed. The total collider ring length in this case is approximately equal to about 202 m (0.8 of the Nuclotron).

Summary & Outlook

The further R&D work on the NICA collider magnet for 2009-2011 includes: 1) Design of a short (1-1.2 m length) curved single bore model dipole based on a hollow cable (2-layer coil, 80-mm inner diameter, 4 T – maximum central field, 11.46 m curvature radius); 2) Manufacturing of single bore model dipole; 3) Assembling and test of the model dipole, upgrade of the first design, analysis of the results; 4) Full-size twin bore dipole prototype manufacturing and test. Completion of the R&D within 30-32 months from the project approval is planned. Construction so strongly curved 4 T field synchrotron dipole magnets can be realized only with the use of hollow Nuclotron-type SC cable. This is the novel design that can be very useful for different applications.

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