CABLE DESIGN AND RELATED ISSUES IN A FAST-CYCLING SUPERCONDUCTING MAGNETS

A.D.Kovalenko
JINR, Dubna, Russia

Abstract

Hollow superconducting cables for a fast-cycling synchrotrons are discussed. The essential features of the cable designed for the Nuclotron at JINR are presented. New versions of a hollow NbTi superconducting cable are described. The first test results with a cable that has been designed for an operating current of 12 kA at B = 2 T, dB/dt = 4 T/s and pulse repetition rate f = 1 Hz are presented. Further possibilities of using hollow cables both for dipoles with bore field of 4-6 T operating at repetition rate of 0.5 Hz and low field (B=1-1.5T) magnets operating at f = 10-20 Hz are discussed.

1. INTRODUCTION

The Laboratory of High Energies (LHE) of JINR has a long-term experience in design and construction of fast cycling (f = 1 Hz) synchrotron magnets. The first model 2T dipoles based on a cold window-frame yoke and superconducting coil made of hollow composite NbTi cable were constructed and tested at the Laboratory early in the 80's [1]. The R&D work was carried out in accordance with the program of construction the new heavy ion 6A GeV synchrotron, named Nuclotron [2]. The accelerator was built in five years (1987-1992) and put into operation in 1993 [3]. The operating magnetic field of the Nuclotron dipoles is 2T at a ramp rate up to 4T/s and pulse repetition rate f = 1 Hz. The key problem, namely the design of adequate superconducting cable, has been solved at the Laboratory by A. Smirnov with co-authors [4]. The technology for the cable production was well developed. Stable reproducibility of the cable performances has been achieved. The existing equipment at the LHE allows fabrication of about 150 meters of cable per day.

The JINR/GSI collaborative R&D work for the design of new cable options started three years ago. The work is connected with the proposal of construction of a "International Facility for Beams of Ions and Antiprotons at GSI" [5]. The facility consists of several new accelerator rings based on fast ramped superconducting magnets. In particular, 2T dipoles operating at repetition rate up to 1 Hz will be used for the synchrotron SIS100, and 6T dipoles with field ramp not less than 1 T/s should be designed in accordance with the project goal of SIS300. The idea of an SPS upgrade at CERN requires a design of a magnet with at least 4T and field ramp of 4 T/s. In addition, there is a general interest in the design of fast-cycling superconducting synchrotrons operating at f = 10-20 Hz. The concept of a hollow superconducting cable is very promising for all of the cases mentioned above.

2. THE NUCLOTRON CABLE

A general view of the original Nuclotron hollow superconducting cable (HSC) is shown in Fig.1. The main parameters are listed in Table 1. The standard industrial SC wire design of the Bochvar Research Institute [6] was used.

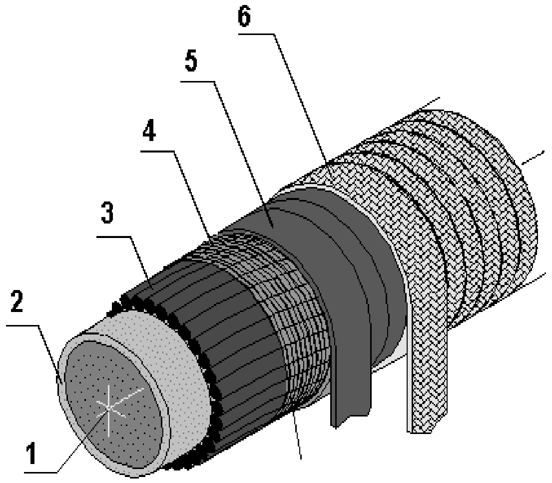

Figure 1. General view of the Nuclotron HSC: 1- two-phase helium, 2-copper-nickel tube, 3- superconducting wire, 4- nichrome wire, 5-kapton tape, 6-glassfiber tape.

Before the final design of the Nuclotron cable, more than 30 different short samples were fabricated and tested. The technology of the Nuclotron cable production and the test results were described earlier [7]. It is important to emphasize two essential features of the design: first, the AC eddy current loss in the cable is very close to the measured one in the SC wire and second, the weak ramp rate limitation (RRL). The dependence of the relative quench current degradation (RRL) on the external magnetic field ramp rate is shown in Fig.2.

Table 1
Main parameters of the Nuclotron cable

Cable diameter with insulation	7 mm
Cooling channel diameter	4 mm
Tube outere diameter	5 mm
SC wire diameter	0.5 mm
Number of the wires	31
Lay pitch of the wires	47 mm
Cu/NbTi ratio	1.38
Number of filaments	1045
Filament diameter	10 μm
Twist pitch of the filaments	5 mm
Minimum I_c per strand at 5 T and 4.2 K	165 A

The optimization of all other parameters was made to obtain the following operating performances at f = 1 Hz pulse repetition rate: quench current higher than 7500 A at B = 2 T and field ramp rate dB/dt = 4 T/s, AC power losses per NbTi volume q = 68 mJ/cm^3 per cycle.

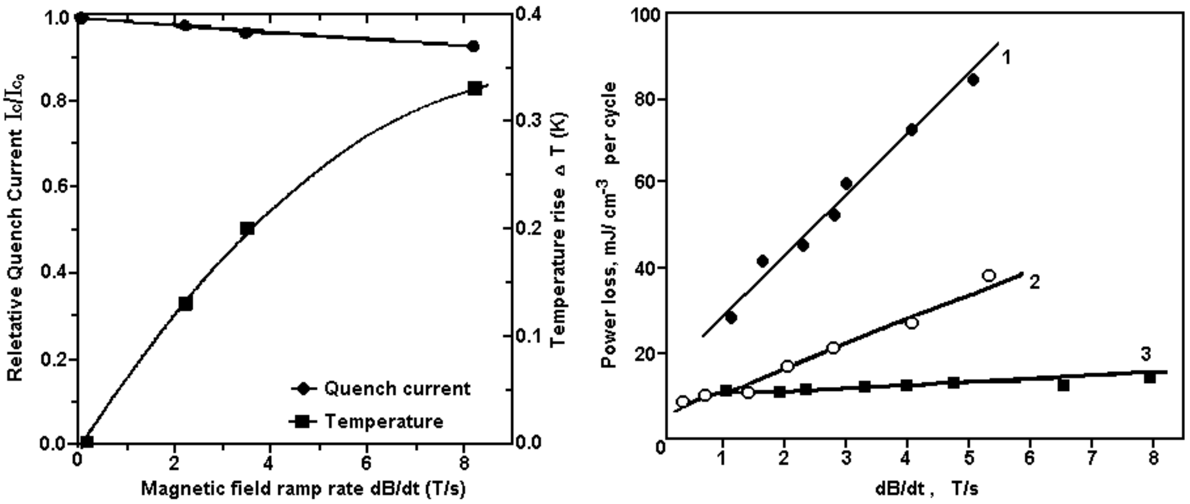

Figure 2. Nuclotron cable (short sample measurements): left diagram – quench current degradation and the superconductor temperature rise versus external magnetic field ramp rate. (I_{co} – critical current at dB/dt=0.1 T/s. The experimental data refer to a short sample): right diagram – the eddy current power loss for different cable samples (Nuclotron cable corresponds to curve - 3).

We emphasize that for a given SC cable and a fixed coolant temperature neither the relative quench current nor the superconductor temperature increase with magnetic field ramp rate depend on the field amplitude. Up to now there are no other SC cables with similar properties. The measured degradation for HSC is only 4.8 %. The stronger ramp rate limitation of the Rutherford cable is caused by higher AC losses and higher thermal resistance between the superconductor and the helium. The comparison of the Nuclotron hollow cable and the proposed several new versions of the "cable-in-conduit", aimed at operating in fast-cycling synchrotron magnets, is presented in [9].

3. NEW OPTIONS OF HOLLOW SC CABLE

As a follow-up of the development described above, it was proposed to use wires of special cross-section (keystoned or trapezoidal) instead of round wires[10]. The main design goal is to increase both the engineering current density as well as the operating current, without loosing the dynamic properties of the cable. A view of the cable cross-section is shown in Fig. 3.

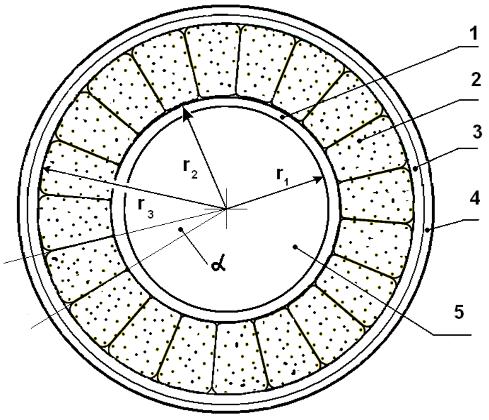

Figure 3. Hollow superconducting cable based on keystoned wires: 1 – copper-nickel tube, 2 – profiled superconducting wire, 3 – nichrome wire, 4 – electric insulation layers, 5 –channel for coolant, α - the wire angular size.

The dimensions of the cable cross-section, number of the wires and the sizes of their cross-sections, cooling channel diameter are optimized for the specified operating conditions. We are planning to carry out R&D works in the following directions:

- design and test the cable (option HSC-K1) for an operating current of 12 kA at B = 2 T, dB/dt = 4 T/s and pulse repetition rate f = 1 Hz;
- investigate the possibility to reach an operating current of 30 kA at B = 6 T, dB/dt =2…4 T/s and pulse repetition rate f = 0.25 …0.5 Hz. (option HSC-K2)

A draft layout of the both cable options, HSC-K1 and HSC-K2 was made. Their main design parameters are listed in Table 2 [11].

Table 2
Main Characteristics of designed HSC-K

	HSC-K1	HSC-K2
Operating parameters:		
- magnetic field, T	2	6
- current, kA	12	30.0
- helium temperature, K	4.6	4.6
- ramp rate, T/s	4	4
AC losses:		
- per NbTi volume, mW/cm^3	45.2	30.1
- per 1 m coil length, W/m	3.8	20.4
Helium channel diameter, mm	4	4.6
Copper-nickel tube diameter, mm	5	5.6
Number of strands	15	12
Strand cross-section, mm^2	0.789	3.62
Cu/NbTi ratio	1.38	1.38
Nb50-Ti50 filament diameter, μm	6	4
Twist pitch of filaments, mm	5	5
Bending nichrome wire diameter, mm	0.2	0.3
Cable diameter with insulation, mm	7.16	10.52
Structural current density, A/mm^2	234	248

The HSC-K1 option is suitable for manufacturing a single-layer winding of the Nuclotron style dipole, whereas the HSC-K2 can be considered as a possible alternative for a fast ramped 6T dipole. The first optimization of HSC-K type cable aimed at the design of a 4T cosine theta style dipole was also done. The results are presented in the next section. Note that both HSC-K1 and HSC-K2 are high current cables, in the range of 12 kA. Nevertheless, SC magnets with an operating current of 12 kA have been designed for the LHC. Much higher operating currents are used in the SC magnet design for ITER research. Other equipment like high current leads, power supplies, etc. have been developed and are available at different laboratories.

3.1 HSC-K1 cable version test results

3.1.1 Manufacturing

Test samples of the cable version were manufactured and tested. For adjustment of tools and mechanics a prototype sample of such HSC was manufactured at the LHE. Fig. 4 presents the photograph of the sample cross-section. The trapezoidal cross-section was prepared by rolling a round 1.05 mm SC wire to the sizes of trapezium 0.73 mm high x 1.21/0.94 mm at the bottom and top sides respectively. The copper-nickel tube was coated with epoxy compound and wrapped with fifteen profiled wires. Winding 0.15-mm diameter synthetic thread under tension in a spiral around the strands provided fixation of the wires and a suitable pre-stress.

The first fabrication experience with the new cable showed that the general idea is feasible, nevertheless, the production technology has to be improved further. The next step was manufacturing of the profiled wire at production stage. The first developed batch was fabricated at the Bochvar Research Institute. A single stacking multifilament composite wire manufacturing process was used. The billet was 130 mm in diameter. The NbTi rods were muffled with 1.5 mm thick Nb barrier and inserted in tubes of Cu–5%Ni-alloy. 127 cylindrical trimetal components were mounted in one hexahedral copper tube. Then 78 copper tubes with NbTi filaments were mounted in a copper shell. The total amount of superconducting filaments in the composite is 10644. The copper non copper ratio in the composite is 1.8. The 1-mm diameter wire was manufactured with 5 intermediate heat treatments at the temperature of 648 K for 24 hours each. The wire was twisted with a pitch of 8 mm. At the final stage of drawing the round wire was keystoned. A view of the resulting cross-section is shown in Fig.5 [12].

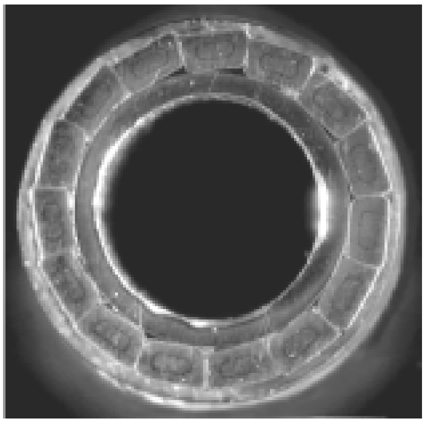

Figure 4. Photo of the HSC-K1 prototype cable (outer diameter is 7.16 mm).

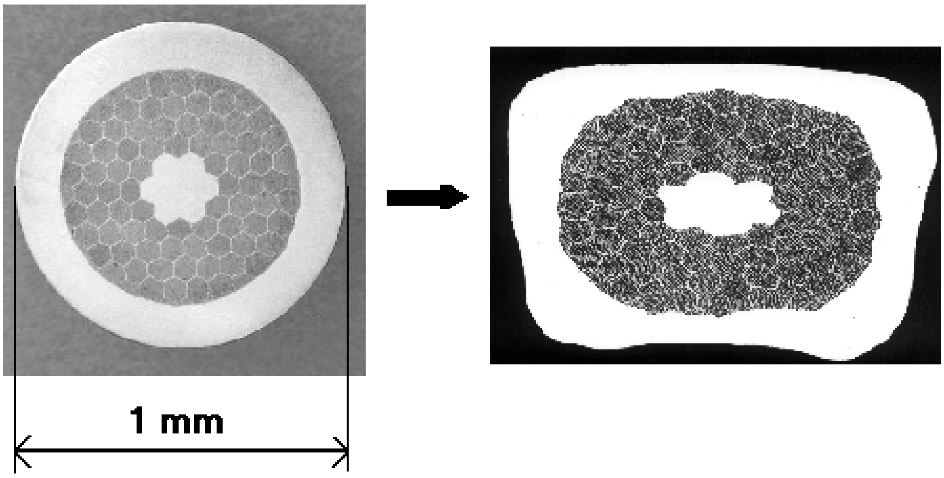

Figure 5. Photos of the HSC-K1 first industrial prototype.

3.1.2 The wire tests

The critical current and AC loss measurements of the wire were performed at the LHE. The dependence of the wire's critical current on external magnetic field is shown in Fig. 6.

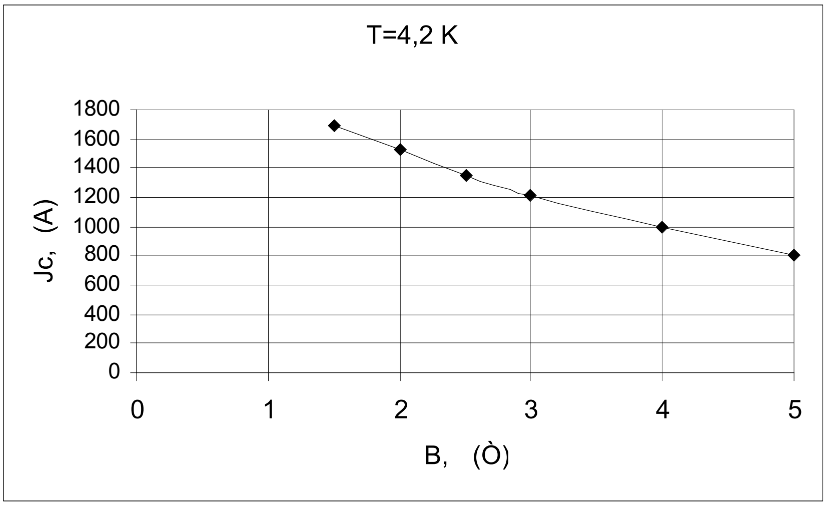

Figure 6. Critical current of keystoned wire versus external magnetic field B at T = 4.2 K.

The measured value is 1400 A at cable operation conditions B = 2 T and T = 4.46 K. Thus the expected critical current of the new cable, consisting of 15 wires, amounts to 21 kA. The AC loss in the wire was measured by calorimetric method. For B = 1.05 T and dB/dt = 2.1 T/s the measured value is about 22.4 mW per cm**3 of the wire. A pilot amount of the new cable was manufactured.

3.1.3 The cable sample test

Actual current leads and the power supply of our test facility are limited to an operating current of 9kA. So we can not excite the new cable directly to 20kA. Thus, it was proposed to test the critical current of the new cable using a closed current loop made of the tested cable itself. The current in the loop is excited by the pulsed magnetic flux in the aperture of the Nuclotron dipole, installed at the existing SC magnet test facility.

The sample tests were performed in October 2003. The magnet was ramped at dB/dt=4 T/s up to B = 2.2 T with pulse repetition rate f = 1 Hz. The current in the magnet winding was measured by a Rogowsky coil, placed at the current lead outside from the cryostat. Both measuring coils were calibrated before the measurements. A 13 kA current, with a 26 kA/s rise time was induced in the sample at the same repetition frequency. No quenches occurred in the sample. During test we could not reach the quench current due to insufficient mutual inductance between the magnet and the tested cable loop. We are planning to repeat the measurements after rearrangement of the test conditions.

4. FAST RAMPED 4T DIPOLE

The concept of hollow superconducting cable can be applied to the design and construction of a fast-ramped 4...6 T dipoles of the future synchrotrons with pulse repetition rate of 0.25...0.5 Hz. It is clear that a "cosine theta" cable arrangement (dipoles and quadrupoles) should be used in this case. A preliminary design of a dipole has been performed.

4.1. Concept of the magnet

A general description of our approach to a fast cycling 4T-magnet was presented in [13]. The magnet has a circular aperture of 100-110 mm. The coil is made with hollow superconducting NbTi cable. It was supposed that a single layer coil will be used. The number of turns in the coil is 12-14; i.e. 6-7 turns per half winding. A larger number of turns is not efficient and limited by available space. The dependence of the magnetic field on the operating current of the magnet is shown in Fig.7. Thus, the cable operating current value should reach of 30 kA. It is possible to reduce the operating current or increase the peak magnetic field with a double-layer coil. The calculations (2D) of the main dipole field were made for different numbers of turns. The angular positions of the turns was chosen to minimize the higher field harmonics.

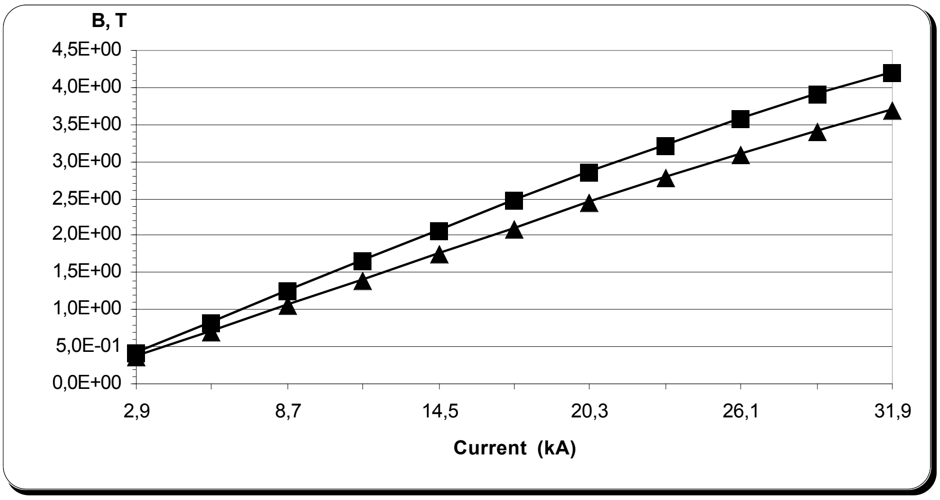

Figure 7. Ddependence of the dipole main field on operating current (for 6 & 7 turn windings).

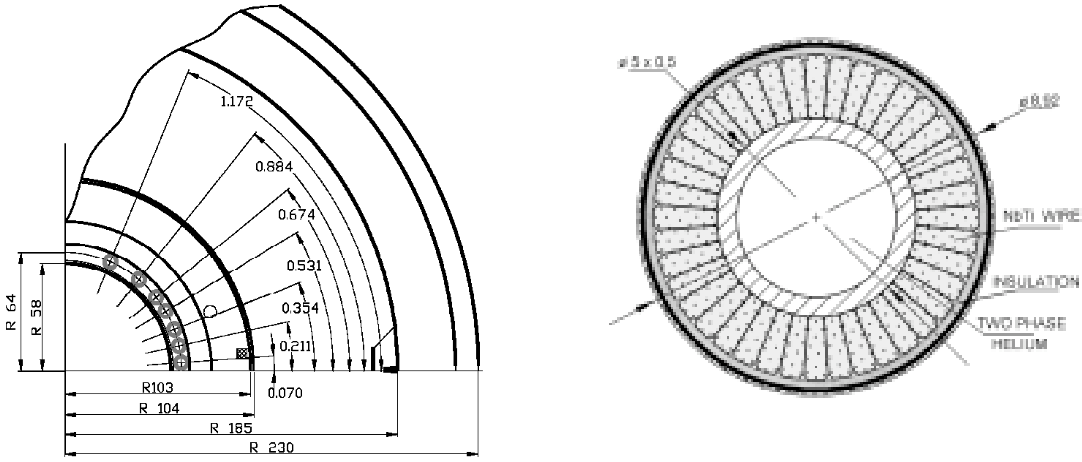

Figure 8. Optimized geometry of the coil for a fast-ramped 4T superconducting dipole magnet and cable cross-section.

4.1.1 Minimization of the cold mass

The magnet cold mass (T = 4.4 K) is limited to the coil and collar only. Cooling of the collar is provided through thermal contacts with the coil. The yoke (iron shield) temperature could stay at the level of T = 50…80 K. A small vacuum gap of 0.5-1.0 mm between them is sufficient. Experimental data on the SIS100 model 2T dipoles tests have shown a number of advantages of such a design concept and practical feasibility [14]. The mechanical characteristics, the strength and the rigidity that are required in the coil and the collars at the force level corresponding to 4 T are well known and feasible.

4.1.2 AC loss, cable & cooling

The main part of the heat load in the magnet comes from the AC loss in the superconducting cable. The static heat flow from the 50 K yoke to the magnet cold mass will not exceed about 1W per meter magnet length. The heat inflow through the yoke support post and suspension parts is negligible as well. The AC power loss caused by the eddy currents in the beam pipe walls is estimated to be about 0.5W/m. We considered the pipe made as a stainless steel tube, 0.5 mm in thickness, for dB/dt =2 … 4 T/s. A new hollow high current cable is under design and test. The first step, namely a new cable operating at 13 kA and B=2.2 T have been made. The critical current of the wire short sample was about 950 A at T = 4.36 K and B = 4 T (see Fig.6.). Thus, taking the number of wires in the cable equal to 40 it will be possible to provide operating a current of 30 kA with about 30 % safety margin. The preliminary cross section of such cable is shown in Fig. 8. The external diameter of the cable is about 8.92 mm including electrical insulation. The calculated AC power loss in the cable is about 1 J/m per cycle at B = 4 T and dB/dt = 4T/s. Note that the averaged value of dB/dt across the cable is about twice less (in the case of a single layer coil). To remove the heat from the coil two phase helium mass flow rate of m = 1.9 g/s should be provided. The helium pressure at the coil inlet depends on the magnet length. For the magnet length of 2.6 m the pressure of p = 1.25 bar is sufficient. Of course, collars with suppressed eddy current power loss are supposed to be used.

4.1.3 The further R&D

A reasonable plan for the future R&D should address the following points:

- reduce the AC power loss in the cable using SC filaments of smaller diameter;
- study possibility of using Nb3Sn instead of NbTi wires;
- test new versions of the cables based on keystoned wires;
- design of a 6 T magnets based on a hollow cable.

5. SUPERFERRIC MAGNET AT REPETITION RATE OF 10-20 HZ.

Our first estimate on the possibility to construct superconducting Nuclotron-type dipole and a cryomagnetic system of a rapid cycling synchrotron (up to 10 Hz) was presented at MT-15 [15]. The extrapolation was based on experimental data obtained for the Nuclotron dipole with a cold iron yoke. Nevertheless, window-frame cold yoke is not optimal design concept for a very fast cycling (f >> 1 Hz) superconducting magnet. Moreover, the results of the recent R&D on SC hollow cables have demonstrated the possibility to produce a cable with much higher operating current and engineering current density compared to that was used for the Nuclotron. A version of superferric dipole magnet with the yoke at T = 50-80 K was also tested successfully. Thus, we can consider superferric H-type magnet with superconducting coils made from a hollow superconducting cable and the yoke at temperature of 50-80K. The cable operating current is chosen in the range of 12…25 kA. Thus, it is possible to obtain a magnetic field of 1.2-1.5 T in a magnet aperture of 55mm x 110 mm (v x h), taking 4 or 2 turns per pole. The external magnetic field in the cable will reach about one half of the field in the magnet gap, i.e. B = 0.6 - 0.75 T. The field ramp in the coils would be respectively dB/dt = 12…15 T/s at f= 10 Hz and dB/dt = 24….30 T/s at f = 20 Hz,. The Nuclotron cable have been tested at B= 2 T and dB/dt up to 8 T/s. We are planning to test the existing cable as well as the new versions at operating conditions suitable for 10-20 Hz superferric magnets.

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