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DESIGN OF A FAST CYCLED LOW LOSS 6T MODEL DIPOLE COOLING AT 1.9K

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Abstract

The option being considered for the FCC-hh high energy injector is a superconducting synchrotron replacing the CERN SPS. The new machine would operate in a cycled mode also to feed experimental areas, much like the SPS nowadays. Due to this specific cycled operation, innovative design and development approaches is required to cope with the AC losses in the superconducting cables and iron yoke. The research joins experience accumulated at CERN and JINR in the design and operation of large systems operated at 1.9 K and in fast ramped and cycled magnets respectively. Minimization of the cycling power losses is particularly important. Total thermal losses should be limited to tentatively < 2 W/m at 4.2 K equivalent. The magnet design, and the results of preliminary tests on a candidate NbTi-wire for building a model magnet are presented and discussed.

INTRODUCTION

The Joint Institute for Nuclear Research (JINR) jointed to the Future Circular Collider (FCC) design study group leading by CERN [1] in fall 2014. After discussion on the scope of the Collaboration the Parties came to common point of view that the exploratory phase will take the design and construction of original 6 T cycled dipole operated at 1.9 K. Special attention should be paid to minimization of the total power losses in the coil, yoke and in the magnet overall. Thus, a long-term CERN and JINR experience in the design and construction of the world largest magnetic system, LHC, operating at 1.9 K [2] and the world first fast-cycled superferric ion synchrotron, Nuclotron, [3] respectively, should be resulted in novel object – low loss 6 T synchrotron. The first step is a model dipole magnet with the parameters shown in Table 1.

The magnetic field of 6 T level looks not very problematic in comparison with 8.36 T (LHC) or especially with 16 T dipole field planned for the FCC. Moreover design efforts have been contributed to the 6T dipole for the SIS300 synchrotron of the FAIR complex at GSI [4,5], nevertheless some important advantages can be reached in the considered case.

The magnetic field homogeneity should correspond to usual synchrotron tolerances i.e. the order of 5·10e-4 within the beam area limited to 70% of the aperture and the field range between 0.12 and 6.0 T.

Table 1: Main Specification for Model Dipole

Parameter	Unit	Value
Central field	T	6.0
Aperture	mm	80
Coil temperature	K	1. 9
Field ramp	T/s	0.2 – 0.5
Coil conductor		Nb/Ti/Cu
Thermal losses	W	< 2 W/m at 4.2 K.

GENERAL CONCEPT

Basic advantage of a magnet operating at 1.9 K is the possibility to increase current density in the conductor. The data obtained from the tests of the first LHC model dipole have been demonstrated the Ic increase by a factor of 2 [6]. Well-tested one-layer coil RHIC dipole [7] generates 3.4 T field within 80 mm aperture at 4.2 K and 5000A supply current. Thus, it was reasonable to estimate feasibility the constructing of 6 T one-layer coil cooling at 1.9 K for the dipole [8,9]. Conceptual cross-section of the dipole is shown in Fig. 1. The cold mass at 1.9 K includes the coil, stainless steel collar and some part of laminated yoke.

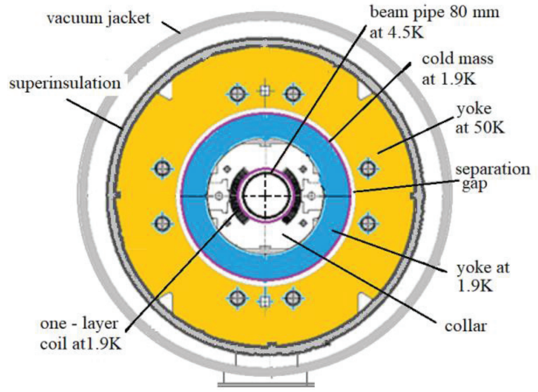

Figure 1: Conceptual cross-section of the magnet.

The 1.9K cold mass including current transport lines is placed inside a welded stainless steel vessel, electrically insulated from it and having low heat transfer support posts. The main part of iron yoke is kept at 50K and separated from the 1.9K cold mass with a small gap. Support and alignment is also provided by means of a low heat transfer mechanical system. The proposal of cosine theta type magnet with separated cold mass (4.2-4.5)K/(50-80)K was considered in [10,11] and was tested

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experimentally at 2T Nuclotron-type model dipole in the context of the SIS100 dipole R&D [12]. The 50K cold mass is assembled inside special support frame taking also the necessity of minimization eddy current loss into account. It is wrapped by a superinsulation. Model dipole is installed in the cryostat at the support post and is aligned by the support strings.

CONDUCTOR, CABLE, COIL

One can expect much less power losses in the coil and better heat transfer from the winding. The parameters above mentioned are resulted from reduced NbTi amount (higher I_c @1.9 K), adequate filament size and twist pitch; optimal number of coil turns (I_m ~13 kA); separation of the yoke onto 1.9 K (smaller part) and the rest one at 50 K, minimization of the cable loss and optimization of the coil shape. The conductor parameters for start option were fixed practically to the following: NbTi filament diameter –3.2 μk, filament twist pitch – 8 mm, wire diameter – 0,81 mm, Cu/nonCu – 1.38. The conductor was manufactured by the Bochvar Institute (Moscow). The wire critical current measured by the manufacturer at 6 T, 4.2 K was about 400 A. The measurements at 1.9 K over the field range from 6 to 10 T and at 6 T, 4.2 K (reference point) were performed at CERN. The data are shown in Fig. 2.

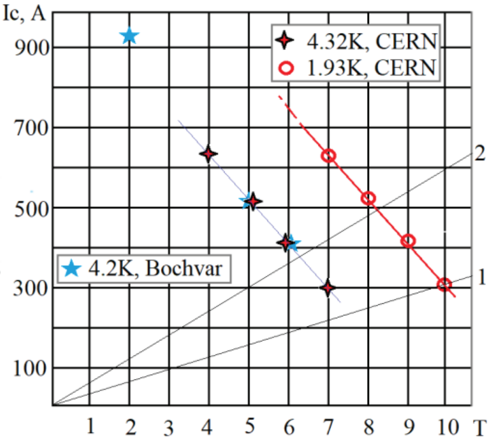

Figure 2: Critical current data measured at CERN and by the wire manufacturer (October-November 2018).

As it follows from the measured data, one can expect the increase of I_c at 1.9 K, with respect to 4.2 K, by a factor of 2. The load lines corresponding to different peak field at the coil turns multiplied by a factor 1.3 (30% margin) are shown at the plot also.

It is clear that optimization of the coil configuration can give minimum difference between a gap field (B_{gap}) and maximum field at the coil (B_{coil}). Several configurations of the winding, the first of all classical cos(θ) and a block-coil design as well, were considered to do that. Finally, the option that provide B_{coil}/B_{gap} ratio of 6.4T/6.0T was found (Fig. 3).

Taking I_c = 500 A per wire. (30% margin on Bcoil) and thickness of SC-cable with electrical insulation 1.71 mm, we obtain possible number of turns n = 29 for a half of the winding and supply current of I_o = 11.16 kA at B_{cent} = 6.0 T. Thus the number of wires in cable can be limited to 24 and the cable cross section should be of 9.82x1.71 mm^2.

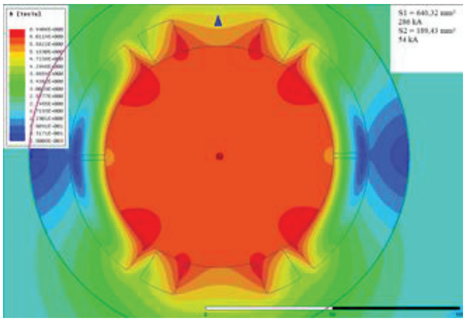

Figure 3: Coil turns distribution of the model dipole.

POWER LOSSES

To estimate the expected power losses in the model dipole we use experimental data that have been collected over the period of the Nuclotron and the SIS100 dipole R&D. A large number of models were prepared and tested at the JINR Laboratory of High Energies aimed at the reducing of power losses in the Nuclotron-type magnets. A summary plot of the tests is shown in Fig. 4.

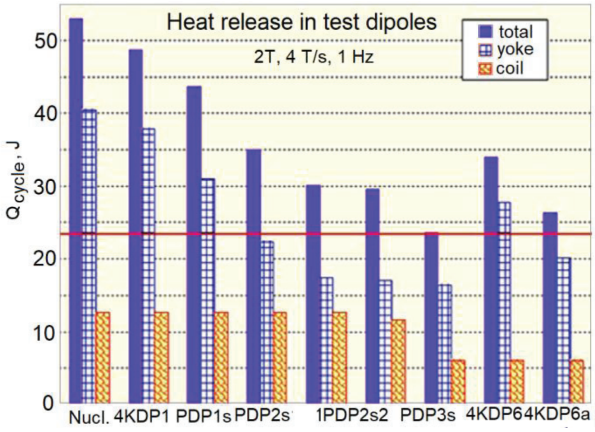

Figure 4: Summary plot of AC loss measurements for different modifications of the Nuclotron dipoles.

Basic parameters that define the difference between the Nuclotron-type dipole magnet models from the current case are the following: the magnetic field amplitude $\mathbf{B_m}$, SC filament diameter $\mathbf{d_f}$, the filament twist pitch $\mathbf{l_p}$, cycle repetition rate **f**. We extrapolate the measured losses to the expected ones using the following scaling: 1) coil magnetization loss $P_h \sim d_f{\cdot}B_m{\cdot}f$, coil matrix loss $P_e \sim (B_m{\cdot}f{\cdot}l_p)^2$; 2) iron magnetization loss $P_y \sim B_m{\cdot}f$, iron eddy current loss $P_e \sim (B_m{\cdot}f{\cdot}\delta)^2$, where δ - iron lamination thickness. The data obtained for the model 4KDP6 (the last column in Fig. 4) were taken as a reference. View of the magnet is shown in Fig. 5. The total AC loss at 2T, 4 T/s, 1 Hz was 33.9 J per 1.4 m long dipole per cycle.

The dependence of the losses on dB/dt was fitted as: P_{mag} = 17.1 + 4.2 dB/dt (J/cycle) from the measured data. The loss components were the following: P_{coil} =2.51+0.71 dB/dt; P_{yoke} = 14.5 + 3.49 dB/dt J/cycle respectively.

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Comparison of the 4KDP6 and 6T model dipole is presented in Table 2.

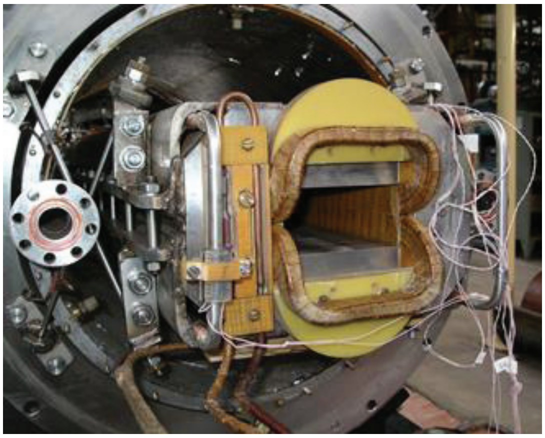

Figure 5: View of the model dipole 4KDP6.

Table 2: Comparision of the 4KDP6 and 6T Model Dipole

Parameter	**2T, 4 T/s**	**6T 0.2 T/s**	**6T 0.5 T/s**
Peak field, T	2	6	6
Pulse rep., Hz	1.0	0.016	0.04
Filament dia., µk	4.2		
Twist pitch, mm	12	7	7
Coil aperture, mm	120x56	Ø90	Ø90
Iron thickness, mm	0.5	0.5	0.5
Cu/nonCu	1.38	1.56	1.56
Power loss, W/m:			
coil hysteresis	2.51	0.09	0.23
eddy current	2.84	0	7
Yoke:			
magnetization	14.6	0.5	
eddy current	14.0	0.56	3.5
Total, W/m	33.96	1.19	5.10

CONCLUSION

Different options of SC magnets were considered. The expected power losses extrapolated based on the measured data from the Nuclotron-type magnets have shown possibility of limiting the losses to the specified level. Nevertheless, careful design of 1.9K cold mass is necessary. Near future work (2019) will be focused on the manufacturing and tests of cable samples, design and preparation of a test coil samples and technical design of model dipole.

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