ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2022, Vol. 19, No. 4, pp. 397–401. © Pleiades Publishing, Ltd., 2022.

PHYSICS AND TECHNIQUE
OF ACCELERATORS

Solenoid for Spin Physics Detector at NICA from the Nuclotron-Type Superconducting Cable

H. G. Khodzhibagiyan[a], **A. A. Kotova**[a, *], **G. L. Kuznetsov**[a], **D. N. Nikiforov**[a],
M. C. Novikov[a], **and E. V. Sergeeva**[a]

[a] *Joint Institute for Nuclear Research (JINR), Dubna, Russia*

**e-mail: borczova@jinr.ru*

Received January 27, 2022; revised March 1, 2022; accepted March 1, 2022

Abstract—The work is aimed at constructing a superconducting solenoid for Spin Physics Detector (SPD) at NICA project. The design of a superconducting solenoid made of a Nuclotron cable is proposed based on the technology developed at VBLHEP in the production of magnets for the Nuclotron accelerator and the NICA complex. Preliminary calculations of the magnetic field, forces, heat inflows, the maximum temperature of the winding after quench, etc. were performed.

DOI: 10.1134/S154747712204015X

1. INTRODUCTION

The main distinctions between the SPD [1] magnet and the existing and projected magnets for detectors of particles are the design features of the solenoid. The technology using a hollow composite superconducting cable proposed in the Veksler and Baldin Laboratory of High Energy Physics (VBLHEP) and well-proven in magnets [2] of the synchrotron Nuclotron was chosen as the basis for its production. In this case, the winding is cooled due to the circulation of supercritical helium flow in the cooling channels of a hollow cable.

The SPD magnet is designed to create an uniform magnetic field with a nominal induction of 1.0 T in its aperture. The superconducting solenoid will be surrounded by an iron yoke designed to close the magnetic flux and form a magnetic field with the required uniformity.

Requirements to the SPD magnet:

- Maximum field on the solenoid axis—$Bz \leq 1$ T;
- Uniformity of the magnetic field on the axis—$dBz/Bz \leq 0.05$;
- Diameter of the “warm” aperture—3.2 m;
- Solenoid length—3.8 m.

2. SOLENOID DESIGN

The technology using a hollow composite superconducting (SC) cable (see left panel in Fig. 1) proposed at VBLHEP and well-proven in magnets of the Nuclotron was chosen as the basis for the production of the solenoid. VBLHEP has a base for the production of such a cable, which requires only the upgrade of the existing equipment.

Since the solenoid operates at a constant current value, the SC wires can be soldered to the cooling tube, and the tube can be made of copper. Unlike the Nuclotron cable operating in a pulsed magnetic field, the SPD solenoid cable does not have a fixing wire (see right panel in Fig. 1).

A solenoid with an average winding radius of 1.742 m and a length of 3.8 m should have a high uniformity of the magnetic field in the aperture. The SPD winding is planned to be made of 10 coils (see Fig. 2) of 2 sections each. The 0.38 m coil (see Fig. 3) contains 30 turns of a hollow superconducting cable.

The SPD winding of 10 coils is carried out on a mandrel made of stainless steel (SS). Profiled copper inserts are laid below and above of two layers of the coil (see Fig. 4), filling the voids between the turns. At

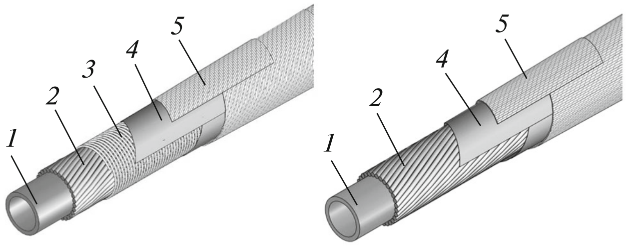

Fig. 1. Hollow SC cable of the Nuclotron (left) and the SPD solenoid (right): (*1*) a tube with a channel for cooling; (*2*) SC wire; (*3*) fixing wire; (*4*) polyimide tape; (*5*) glass fiber tape impregnated with epoxy compound for hot hardening.

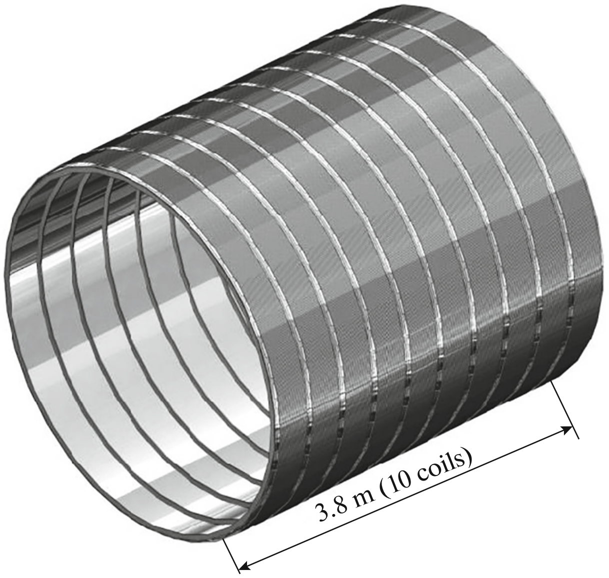

Fig. 2. SPD solenoid made of 10 coils.

the bottom of each layer of the coil, shunts are laid—winding heaters, which are necessary to protect against overheating at quench. A bandage of stainless-steel wire is wound over the coil. After winding of both sections of the coil, the coil is heat-treated in order to polymerize the epoxy compound. The coils are assembled together on a special device. In this case, the mandrels of the individual coils are mechanically interconnected. Then, the helium cooling lines of the solenoid are connected and the electrical connections between the coils are made.

The characteristics of the SPD cable and winding are presented in Tables 1 and 2.

The magnetic and stress calculations have been performed using OPERA simulation software. The value of Bz component equal 1 T at the axis of the magnetic system is achieved by the current in the coils of 5067 A. The variation of Bz at the axis is less than 5%, that satisfies to the requirement to SPD magnetic system. The maximal value of the forces acting between the neighboring coils is 1.36 MN. The pressure

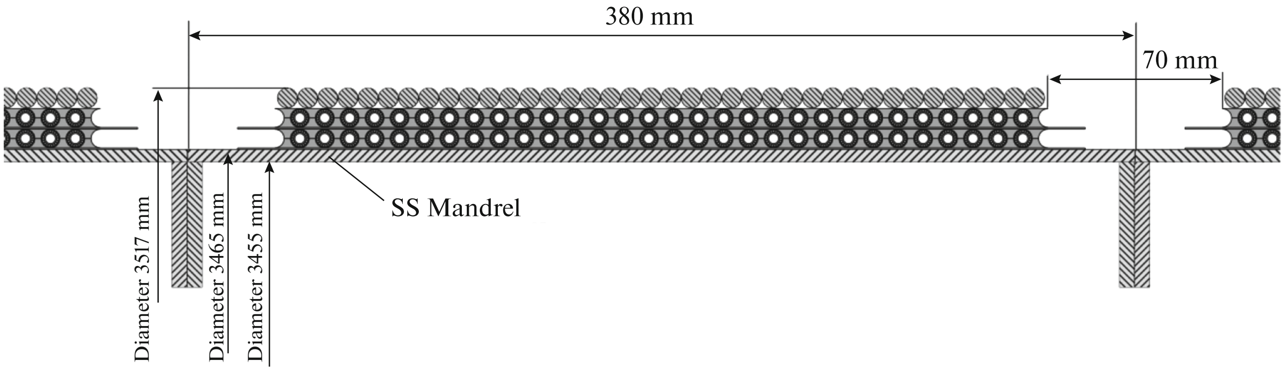

Fig. 3. Cross section of the coil with 2 sections.

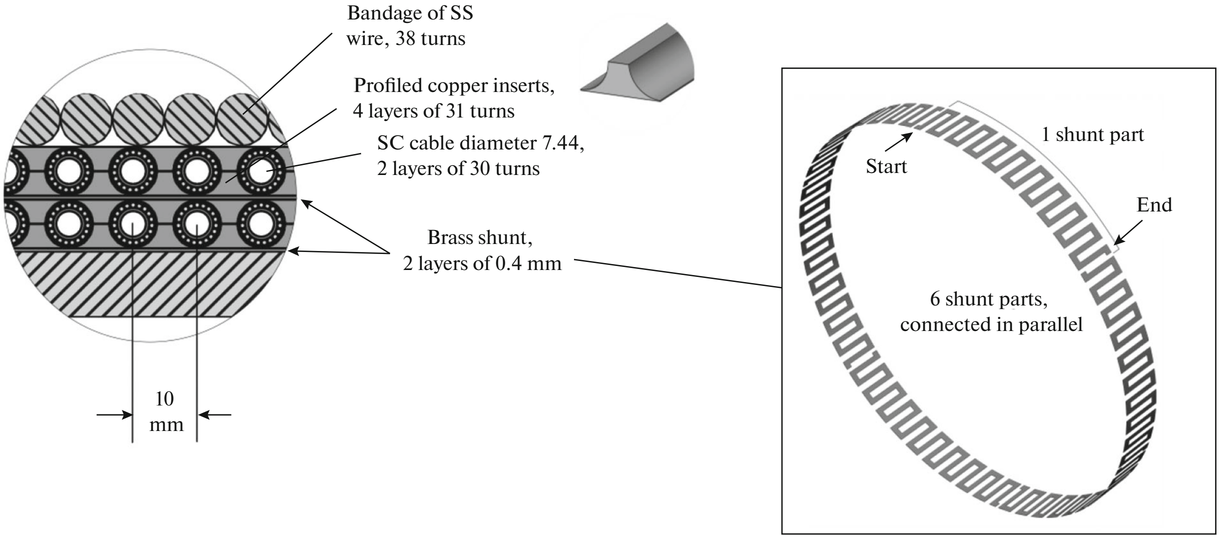

Fig. 4. SPD solenoid coil details.

Table 1. SPD cable characteristics

Cable		
parameter	unit	value
Helium cooling channel diameter	mm	4
Cooling tube outer diameter	mm	5
Cooling tube material		Cu
Number of strands		19
Lay pitch of strands	m	0.1
Diameter with insulation	mm	7.44
Copper sectional area	mm^2	15.77
Superconductor sectional area	mm^2	3.38
Cu/SC ratio		4.66/1
Length in section	m	328.3
Total length in the winding	m	6566
Strand		
Diameter	mm	0.9
Superconductor		Nb–Ti/Cu
(Nb–Ti)/Cu—volumetric ratio		1/2.57
Nb–Ti filament diameter	μm	7
Operational current, $I_{\max}$	A	270
Critical current at 2 T and 4.2 K	A	≥670

Table 2. Main characteristics of the SPD winding

Support cylinder		
parameter	unit	value
Inner diameter	m	3.455
Outer diameter	m	3.465
Material		Steel 12X18H10T
Winding		
Nominal (maximal) magnetic field, B_0	T	1.0
Inner diameter	m	3.465
Outer diameter	m	3.498
Length	m	3.8
Number of layers		2
Number of winding sections		10 × 2
Number of turns		30 × 2 × 10
Operational current, $I_{\max}$	A	5067
Inductance, L	H	1.144
Stored energy at $I_{\max}$, E	MJ	14.7

Table 3. Some characteristics of the SPD solenoid cold mass and cooling system

Cold mass at 4.8 K		
parameter	unit	value
Cu in conductor, $M1$	kg	560
Cooling tube, $M2$	kg	413
Cu inserts in winding voids, $M3$	kg	2402
Brass electrical shunts	kg	162
SS bandage	kg	1670
SS mandrel	kg	2500
Nb–Ti alloy in strands	kg	158
Total	kg	7865
Cooling		
Method	Forced calculation of supercritical helium flow	
Operating temperature	K	4.8
Operating pressure	MPa	0.3
Heat load at operational condition	W	≤40
Heat load at energy input	W	≤74
Nominal He mass flow rate	g/s	16
Number of parallel cooling channel		20
Nominal pressure drops in channel	kPa	≤50
Pressure in cooling channel	MPa	≤3
Cool down time from 300 K to 4.8 K	hour	≥50

of the magnetic field on the solenoid is 0.398 MPa. The details of the magnetic and stress calculations will be given in a separate paper.

3. COOLING SYSTEM

The solenoid winding is cooled by forced flow of supercritical pressure helium inside the cooling channel of the cable. In total, there are 20 parallel cooling channels (10 coils of 2 sections each). Each section of the solenoid is connected in parallel to the supply and return helium headers. The operating temperature of the winding is 4.8 K, the nominal flow rate of liquid helium through the solenoid is about 16 g/s. The cold mass of the solenoid is about 7.9 tons. Cooling of the solenoid is planned by a helium refrigerator with a nominal cooling capacity of 100 W, which will be installed close to SPD. Some characteristics of the cold mass and cooling system are presented in Table 3.

The calculated values of the heat load on the cooling system are shown in Table 4.

Table 4. Calculated values of the heat load on the SPD cooling system

Heat inflow	Unit	Value
Residual gases	W	7.6
Thermal radiation	W	6.2
By suspensions	W	14.4
By current leads	W	11.0
Total	W	39.2

4. QUENCH PROTECTION SYSTEM

Protection of the magnet against overheating at its transition from the superconducting state to the normal state is achieved by solenoid sectioning [3] and uniform dissipation of energy over the whole winding. For this purpose, the winding is divided into 20 electrical sections.

The energy stored in the magnet is dissipated both on the external resistance and on 20 shunts—heaters located on the inner radius of each layer of the winding. The external resistance $Re = 0.04$ Ohm limits the maximum voltage relative to “ground” to ±100 V. The shunts divide the winding into 20 sections, in each of which a shunt made of brass tape is connected in parallel to the winding section (see Fig. 5). The shunt is electrically connected in parallel to the SC cable of its section and has good thermal contact with the SC cable along its entire length, which provides a very high velocity of the normal zone propagation in the winding.

Part of energy released in the winding will be about 54% of the energy stored in the solenoid or 7.9 MJ, and the time constant of the energy dissipation process will be about 13 s, calculated by Eq. (1).

$$\tau_1 = L/\left(R_\mathrm{e} + \Sigma R_{\mathrm{sec\ ave}}\right), \qquad (1)$$

where τ_1—time constant of energy dissipation, s; L—inductance, H; R_e—external resistance, Ohm; $R_{\mathrm{sec\ ave}}$—average resistance of one section, Ohm.

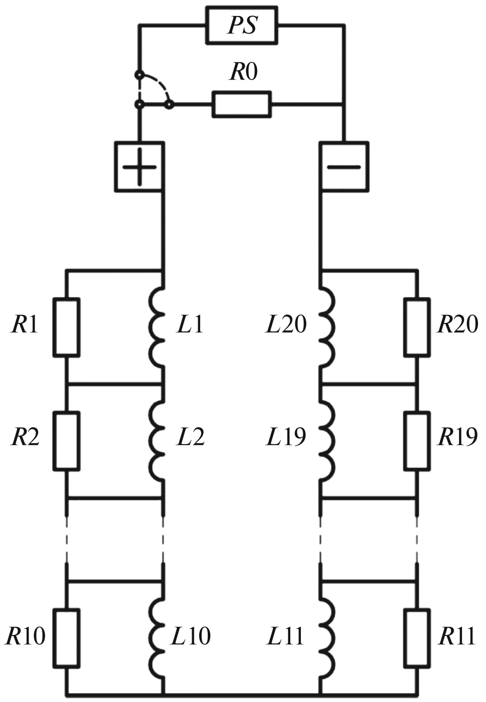

Fig. 5. Electrical connection diagram of the sections.

The estimation of the maximum heating temperature of the winding (at initial winding temperature $T_0 = 4.8$ K) as a result of its transition to the normal state (quenching) is performed under the following assumptions:

– energy released in the solenoid dissipates in superconducting wires, a copper tube and copper inserts;

– normal zone propagation velocity $v = \infty$.

$\Delta T \approx 0.54E/(MC)$, where ΔT—temperature rise after the quench at the point of origin of the normal zone, K; E—stored energy at maximum current $I_{\max}$. $M = M1 + M2 + M3$, where $M1 = 560$ kg is the mass of copper in the SC wire, $M2 = 413.2$ kg is the mass of the copper tube, $M3 = 2402$ kg is the mass of copper inserts. $C = 39.31$ J/(kg K)—the value of the heat capacity of copper at an average temperature of 34.1 K.

$\Delta T \approx 59.8$ K, then the maximum temperature of the winding after quench $T_{\max} = \Delta T + T_0$, $T_{\max} \leq 65$ K.

Table 5. Basic characteristics of the cryostat

Parameter	Unit	Value
Length	m	4.0
Diameter of heat shield at 80 K		
Inner shield	m	3.305
Outer shield	m	3.617
SS vacuum shell diameter		
Inner shell	m	3.175
Outer shell	m	3.767
Number of solenoid supports		24
Mass of vacuum shells	kg	15330
Mass of thermal shields	kg	1340
Total mass of the cryostat	kg	16700

5. CRYOSTAT

The cryostat for the SPD solenoid is being developed. The design of the solenoid suspension system in the cryostat is underway. The basic characteristics of the cryostat are presented in Table 5.

6. CONCLUSIONS

A design of a superconducting solenoid made of a Nuclotron cable is proposed based on the technology developed at VBLHEP in the production of magnets [4] for the Nuclotron and NICA accelerators. The use of this technology makes it possible to produce a solenoid at JINR involving enterprises of the Moscow Region. Calculations show that the solenoid will have the required field quality, the reliable cooling and quench protection system, and maintainability. Less time and money is expected to be spend for producing a solenoid using the Nuclotron technology compared to a commercially available solenoid produced using traditional technology.

ACKNOWLEDGMENTS

The authors are grateful to P.G. Akishin and A.V. Shabunov for the preliminary simulation of the magnetic field and forces acting in the solenoid. Also authors are grateful to V.P. Ladygin for assistance in preparing the article for publication.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. Guskov (for SPD Collab.), “Spin physics detector project at JINR,” in *Proceedings of the 22nd PANIC21 Conference, September 5–10, 2021, Lisbon, Portugal*; arXiv: 2110.08930 [hep-ex].
2. A. M. Baldin, C. A. Averichev, N. N. Agapov, A. M. Donyagin, E. I. D’yachkov, H. G. Khodzhibagiyan, A. D. Kovalenko, L. G. Makarov, E. A. Matushevskiy, and A. A. Smirnov, “Superconducting fast cycling magnets of the Nuclotron,” IEEE Trans. Appl. Supercond. **5**, 875 (1995).
3. M. N. Wilson, *Superconducting Magnets* (Clarendon, Oxford, 1983).
4. H. G. Khodzhibagiyan, N. N. Agapov, P. G. Akishin, et al., “Superconducting magnets for the NICA accelerator collider complex,” IEEE Trans. Appl. Supercond. **24**, 4001304 (2014).