Solenoid for Polarized Particle Detector SPD NICA from the Nuclotron-type Superconducting Cable

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Introduction

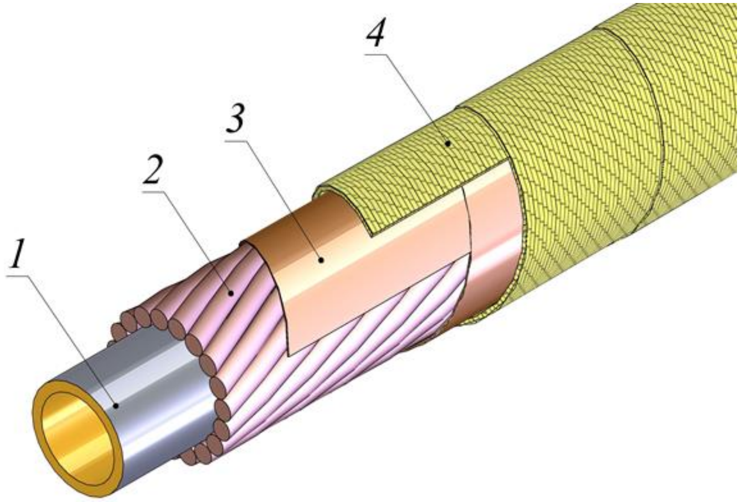
- The SPD magnet is designed to create a uniform magnetic field with a nominal induction of 1.0 T in its aperture. The superconducting solenoid will be surrounded by an iron yoke designed to close the magnetic flux and form a magnetic field with the required uniformity.

Magnet requirements:

- **Maximum field on the solenoid axis - $B_z \leq 1$ T**
- **Uniformity of the magnetic field on the axis - $dB_z / B_z \leq 0.05$**
- **The diameter of the "warm" aperture – 3.2 m**
- **Solenoid length - 3.8 m**

Solenoid Design

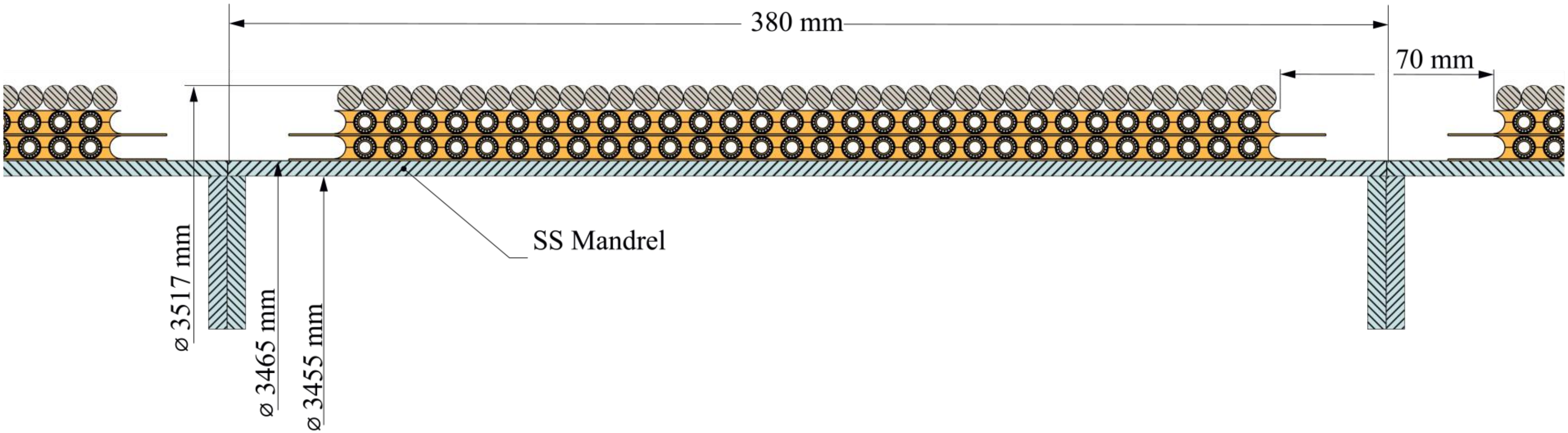
The technology with the use of a hollow composite superconducting cable, proposed at the VBLHEP and well-proven in the magnets of the Nuclotron, was chosen as the basis for the manufacture of the solenoid. VBLHEP has a base for the production of such a cable, which requires only the modernization of the existing equipment.



Hollow SC cable of the SPD solenoid: 1 - a tube with a channel for cooling; 2 - superconducting wire; 3 - polyimide tape; 4 - glass fiber tape, impregnated with epoxy compound for hot hardening.

Solenoid Winding

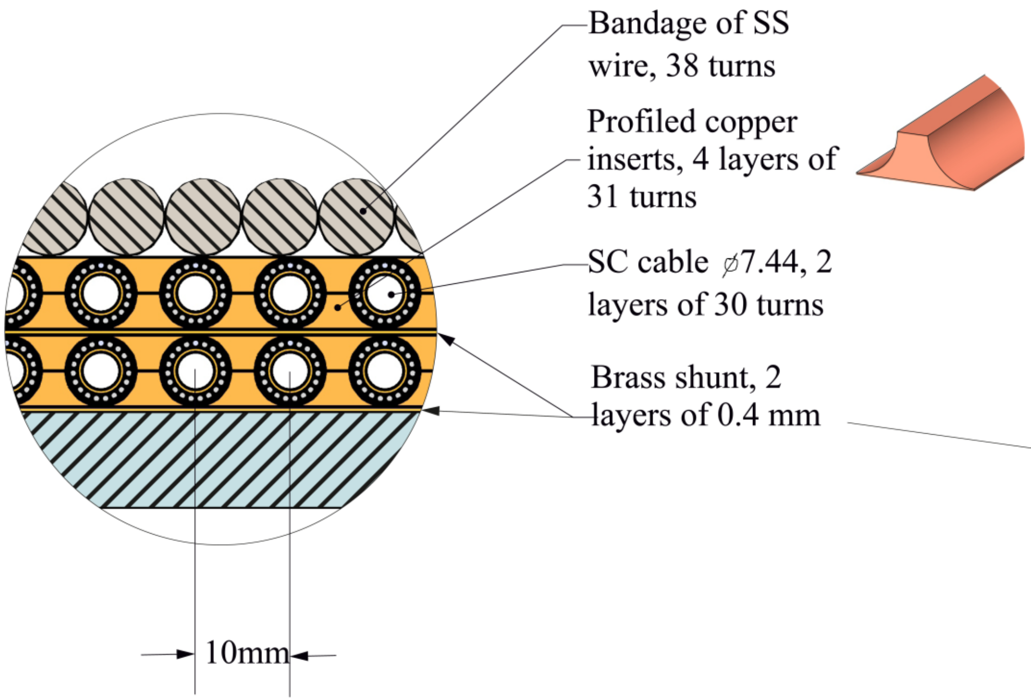
A solenoid with an average winding radius of 1.742 m and a length of 3.8 m must have a high uniformity of the magnetic field in the aperture. The two-layer winding is planned to be made of 10 coils, 2 sections each. The 0.38 m coil contains 30 turns of hollow superconducting cable.

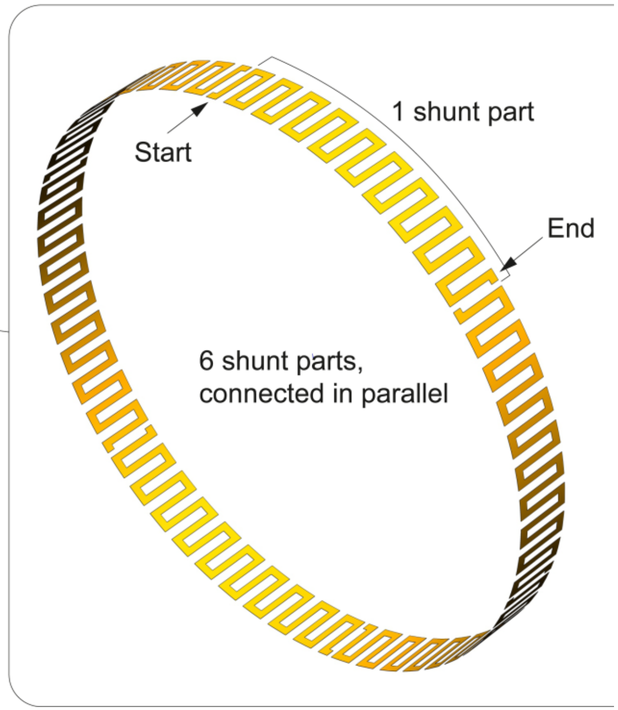


Manufacturing of coils

Winding of 10 coils is carried out on a mandrel made of stainless steel. Profiled copper inserts are laid below and above each layer of the coil, filling the voids between the turns. At 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 assembly of the coils among themselves is carried out on the 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.

Solenoid coil details





Winding cable characteristics

Cable		
Helium cooling channel diameter	m	$4 \cdot 10^{-3}$
Cooling tube outer diameter	m	$5 \cdot 10^{-3}$
Cooling tube material		Cu
Number of strands		19
Lay pitch of strands	m	0.1
Diameter with insulation	m	$7.44 \cdot 10^{-3}$
Copper sectional area	m^2	$15{,}77 \cdot 10^{-6}$
Superconductor sectional area	m^2	$3{,}38 \cdot 10^{-6}$
Cu/SC ratio		4,66/1
Length in section	m	328,3
Total length in the winding	m	6 566
Strand		
Diameter	m	$9.0 \cdot 10^{-4}$
Superconductor		Nb-Ti/Cu
(Nb-Ti) / Cu – volumetric ratio		1 / 2,57
NbTi filament diameter	μm	7
Operational current, I_{max}	A	270
Critical current @ 2T and 4.2K	A	≥ 670

Main characteristics of winding

Support cylinder		
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		2 * 10
Number of turns		30 x 2 x 10
Operational current, I_{max}	A	5067
Inductance	H	1.144
Stored energy @ I_{max}, E	MJ	14.7

Cooling system

The solenoid winding is cooled by a supercritical pressure helium flow which is forced through the cooling channel of the cable. There are a total of 20 parallel cooling channels. 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 from a helium refrigerator with a nominal cooling capacity of 100 W, which will be installed close to the SPD.

Cooling system

Calculated heat load

Heat inflow		
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

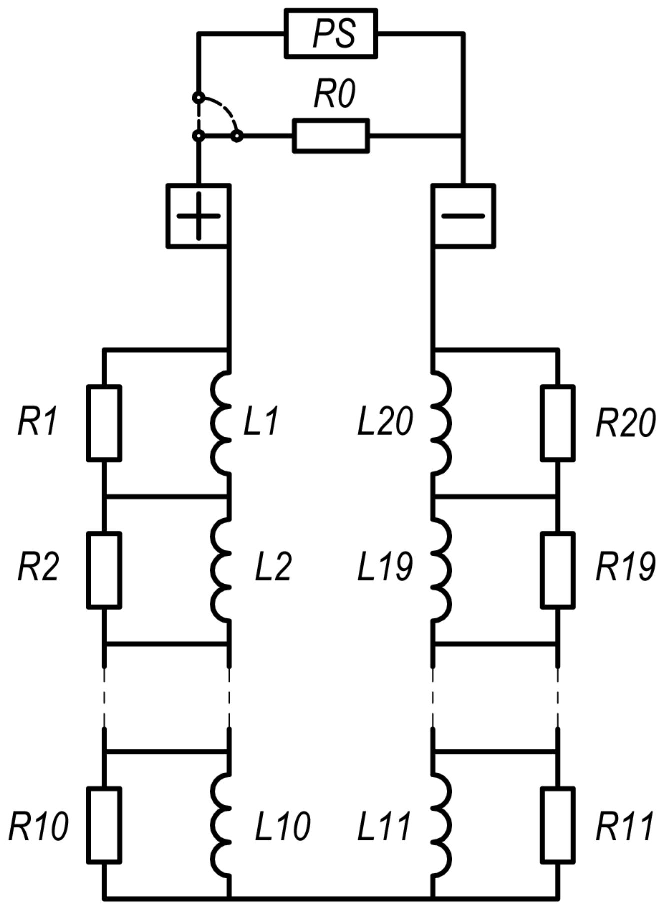
Cooling system

Cold mass at 4.8 K		
Cu in conductor, M_1	kg	560
Cooling tube, M_2	kg	413
Cu inserts in winding voids, M_3	kg	2 402
Brass electrical shunts, M_4	kg	162
SS bandageM_5	kg	1670
SS mandrel, M_6	kg	2 500
Nb-*Ti* alloy in strands, M_7	kg	158
Total	kg	7 865
Cooling		
Method		Forced circulation of supercritical helium flow
Operating temperature	K	4.8
Operating pressure	MPa	0.3
Heat load at operational condition	Вт	≤ 40
Heat load at energy input	W	≤ 74
Nominal *He* mass flow rate	kg/s	$16 \cdot 10^{-3}$
Number of parallel cooling channels		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

Quench protection system

Protection of the magnet against overheating at its transition from the superconducting condition to the normal state is achieved by solenoid sectioning 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. External resistance R0 = 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 parallel to the winding section. 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.



Quench protection system

The part of energy released in the winding will be about 54% of the energy stored in the solenoid or 7,900 kJ, and the time constant of the energy dissipation process will be about 13 s. The estimation of the maximum heating temperature of the winding as a result of its transition to the normal state (quenching) is made under the following assumptions:

- the energy released in the solenoid dissipates in superconducting wires, copper tube and copper inserts;
- normal zone propagation velocity $v = \infty$.

$\Delta T \approx 0{,}54\ E / (M \cdot C)$, K

where: E - stored energy at maximum current Imax;
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, **T max ≤ 65 K**

Cryostat

The basic characteristics of the cryostat

Length	m	4.0
Diameter of heat shield at 80 K: Inner shield Outer shield	 m m	 3.305 3.617
SS vacuum shell diameter: Inner shell Outer shell	 m m	 3,175 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

Thank you for your attention