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Muon Spectrometer Superconducting Magnetic Screen

(Preliminary Design Report)

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Contents:

1. **Introduction**

The first superconducting magnetic screen was constructed and operated successfully at CERN [2]-[4] in 1972 to shield the beam pipe inside the hydrogen bubble chamber located in the magnet. The size of the magnetic volume of the screen was 230 cm in length and 15 cm in diameter. A complete shielding of the magnetic flux was achieved inside the magnetic screen. Preliminary tests showed that small cylinders, built by interleaving sheets of niobium-titanium with high purity aluminum sheets and wire mesh to give access to liquid helium, could shield transverse fields in excess of 2 Tesla, and this arrangement was adopted for the final design [3]. Test results on small cylinders made of Nb_3Sn tape and subjected to transverse external fields up to 4 Tesla indicate that such devices seem to be feasible [2].

The field-free channel through the transverse central magnetic field of a 54-inch aperture magnet was constructed. This flux-free path is a substantial part of the experiment at the Stanford Linear Accelerator Center to measure the electron production of neutral rho mesons. The flux exclusion tube itself is made of Nb_3Sn tape bonded with lead-tin solder to form a rigid tube of laminated superconducting material, approximately four meters long and from 6 to 25 mm in diameter. The shielded transverse magnetic field exceeds 1.5 T [6].

A number of superconducting magnetic screens were constructed in the following years [5]-[8]. To construct the magnetic screen, $NbTi$, Nb_3Sn or Va_3Ga superconducting tape is usually used. A few layers of the tape are wounded on the support cylinder. The superconducting tape is stabilized by the copper tape, which is welded to the superconducting tape. A high purity aluminium tape is used between the layers of the winding.

The authors of [5] used the tape where the vanadium substratum was covered with a Va_3Ga layer. The copper foil was welded to the vanadium tape afterwards. A 99.99% purity $A\ell$ tape was wounded between the layers of the superconductor to reduce the influence of jumps of the magnetic flux. The coil was impregnated with Wood's alloy (low temperature melting alloy). The thickness of the coil was 6.4 mm. It provided the complete shielding of a 10 *kGs* magnetic flux. The measured residual magnetic flux was about 5 *Gauss.* The superconducting magnetic screen could be used to implement the open geometry option of muon absorber [9] which improves background conditions in the muon spectrometer [1].

2. Design parameters

The proposed superconducting magnetic screen has the following substantial differences from those mentioned in the Introduction: first, the shielded volume is rather great (Table 1); second, the influence of the screen on the topography of the magnetic field is significant. The last difference imposes high requirements on reproducibility of this topography (see unit 3.6). The operating conditions of the ALICE Muon spectrometer also impose specific demands on the design of the cryostat and all the subsystems of the screen. A high reliability of the system requires a fast automatic return of the screen to the operating condition in case of the coil quenching.

Table 1: Main parameters of the superconducting magnetic screen

Items	Unit	Value
Aperture diameter	m	0.25 ÷ 0.4
Outer cryostat diameter	m	0.6
Total length of the cryostat	m	6.692
Winding dia. i/o	m/m	0.5/≤0.36
Coil length	m	6.35
Central outer field	T	0.7
Cold mass	t	2.0
Operating temperature	K	4.5
LHe volume	L	80 ÷ 120
Heat loss at 4.5 K	W	5
Heat loss at 80 K	W	40
Power of the refrigerator	W	100
Total cryostat mass	t	2.5
Cooling method	bath	

3. Coil

The basic problem of the construction of the superconducting magnetic screen is to maintain its stability and behaviour with a smooth increase of an external magnetic field. For this, it is necessary to prevent jumps of the magnetic flow and corresponding winding local heating. Naturally, the superconductor tape should be rigidly fixed. Great attention was given to this [6]. The tapes are carefully fixed using low melting soldering. Thermal stabilization is provided with a high purity aluminium tape which covers the superconducting tape with the layer of copper and linings between the superconductor layers (Table2). Under such circumstances, screening currents at the input of the magnetic field are in resistive mode, and the jumps of a magnetic flow are absent or rather small.

3.1. Conductor

The NbTi tape covered with a thin layer of copper is the cheapest and acceptable one appropriate to the value of the shielded field 0.7 T (Table 2). The thickness and width of the tape will be chosen experimentally by testing coil prototype.

Table 2: Conductor parameters

Items	Unit	Value
Superconductingmaterials		*NbTi*
Width of tape	mm	20
Thickness of tape (with *Cu* strips)	mm	0.025÷0.07
Thickness of Aℓ-sheet	mm	0.2
Purity of Aℓ	%	99.995
Layers		20
Impregnatingmaterial	Wood’s alloy	

3.2. Coil structure

Thus, the winding of the screen consists of alternating superconductor layers of copper and aluminum connected electrically and mechanically by soldering. The NbTi tape is reeled up with overlapping, and the number of its layers should be selected experimentally.

3.3 Tooling and technology of the coil winding

The coil could be manufactured at the JINR workshop. A principlal scheme of the winding procedure looks as follows. The basic tube is fixed on the turning machine tool with a remote support. The bobbins with NbTi and Aℓ tapes are placed on the support of the machine tool. The friction brakes built in the bobbin provide a necessary stretch of the tapes. The NbTi tape is covered with solder beforehand. The way of solder local heating should be checked on experimental coils during manufacturing the prototype.

3.4 Electromagnetic forces

The external magnetic field creates a large pressure on the superconducting screen. These forces are transferred to the basic tube. Its deformations and stresses could be calculated using the ANSYS program. Figure 10 shows the magnetic pressure distribution of the ideal diamagnetic cylinder model placed in a homogeneous cross-field [2]. The magnetic pressure is distributed according to the law:

$$p_\varphi = p_{max} \times \cos^2\varphi,$$

$$p_{max} = 16.24 \times B_0^2 \text{ [kgf/cm}^2\text{]}.$$

$$B_0 = 0.71 \text{ [T]},\ \ p_{max} = 8.2 \text{ [kgf/cm}^2\text{]}.$$

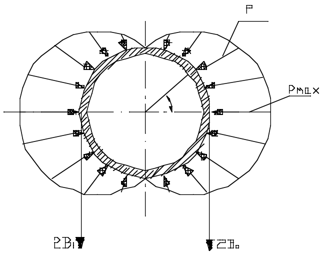

Fig.10. The ideal diamagnetic cylinder in the cross magnetic field [2].

If the magnetic field is not strictly symmetric about the screen axis, side efforts could be the following [2] :

$$\Delta F/\Delta x \cong 21.6 \times R \times (B_{01}^2 - B_{02}^2) \text{ [kgf/cm]}.$$

The estimation and calculation of these forces depends on the technology level of the magnetmanufacturing.

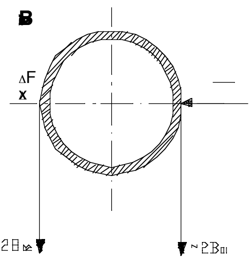

Fig.11. The forces attached to the screen located in a non-uniform field [2].

3.5 Quench of the coil

The processes occurring in the screen winding during its transition from the superconducting to the normal state are apparently investigated not quite enough and are not reflected well in the known literature. Therefore we shall try to make some estimations on the basis of the simplified models.

We consider our screen as a dipole magnet creating inside a field opposite to an external 0.7 T basic field. The energy reserved in this imaginary dipole magnet dissipates in its winding and heats it up during the transition of the screen winding from the superconducting to the normal state. It is possible to achieve that the energy is uniformly distributed in the winding volume. Such a task was successfully accomplished for ultra thin solenoids intended for astrophysical researche [12]. Here the winding made of aluminium-stabilized superconductor, was selfprotected with the help of aluminium strips. The strips lie across the coils and distribute the locally arisen normal zone along the solenoid with a large speed. This is due to a very high thermal conductivity (5kW/(m×K) of high purity aluminium The task of energy uniform distribution in the winding, stored in the magnet, is achieved. Let us estimate the heating of the screen winding.

The specific magnet field energy reserved in the aperture of the imaginary dipole is:

$$e \cong B_0^2/(2\times\mu_0) = 200\ [\mathrm{J}/\ell].$$

We assume that $B_0 = 0.71$ T is presented over a length of 5 m in the volume:

$$V = \pi \times R_{in.}^2 \times \ell = \pi \times 0.25^2 \times 3 = 0.59\ \mathrm{m}^3.$$

Let us assume that the total reserved energy is:

$$E = k \times e \times V = 1.5 \times 200 \times 0.59 \times 10^3 = 177\ \mathrm{kJ}.$$

The weight of the screen winding with a wire bandage is:

$$G \approx \pi \times (R_{out}^2 - R_{in}^2) \times \ell \times (\gamma_{A\ell} + \gamma_{NbTi}) \times 0.5 =$$

$$= \pi \times (0.257^2 - 0.25^2) \times 6.5 \times (2.7+7\ ) \times 0.5 = 0.35\ \mathrm{t}.$$

The weight of the basic tube is:

$G = \pi \times (0.25^2 - 0.235^2) \times 6.5 \times 7.85 = 1.17$ t.

Provided that the winding with a bandage is only heated up:

$E/G = 177/350 \cong 0.51$ kJ/kg.

The specific heat of $A\ell$ and NbTi materials are equal, and the value of E/G is close to $A\ell$ enthalpy at a temperature of 37 K. Heating up to such a temperature is not accompanied by deformations and consequently it is acceptable.

As a result of heating, liquid helium evaporation in the screen cryostat and simultaneously a significant cooling of its thermal shield take place. Approximately 150 litres of liquid helium are required for cooling and filling the cryostat. The restoration time of the screen operating condition could be roughly ~ 1 hour.

3.6 Reproducibility of the magnetic field map.

The topography of the magnetic field is reproduced if the screen "is cleared" from frozen currents which remained from the previous cycle of a joint operation of the magnet and the screen. For its "clearing", it is necessary to lower the magnet current to zero and to supersede liquid helium from the cryostat vessel. After this, the screen winding should be heated up above critical temperature T_c ($T_c \cong 9.3$ K for Nb-50% Ti). Then, it is necessary again to cool-down the winding, to fill the vessel with a winding with liquid helium and to rump smoothly current up to the required value. Further, it is possible to change the current only in the direction of increasing as not fading currents and the distortions of the field topography related to them arise with decreasing the current in the winding . Liquid helium is superseded from the winding vessel through transfer tube 19 (Fig. 6) providing the period of pressure between vessels 3 and 8 with the help of valve 18. The electric heaters located on the screen winding and in liquid helium should be used to accelerate thermal processes.

4. Cryostat

A layout of the cryostat is shown in Fig. 1 and the superconducting winding dimensions in Fig. 2. The cryostat consists of a LHe vessel (*5*,*11*), a vacuum vessel(*1*,*8*,*9*), thermal shields (*2*) with multilayer thermal insulation (*4*) and tubes for liquid (*6*) and gaseous (*3*) helium (Figs.3,4 and Table 1). The vacuum vessel made of stainless steel is a cylindrical shape with two end plates (*8*) (Figs. 3,4). The vacuum vessel should withstand the weight and noncompensated forces between the screen and the dipole magnet.

The external screen vacuum vessel can play the role of basic tube with cylindrical walls 10 mm in thickness. The calculations show (Appendix 1) that the deflection of the vessel under the action of the distributed weight of the screen and absorber does not exceed 0.5 mm (the distance between the supports is 5 m).

To prevent heating the internal vacuum vessel shell by the heated vacuum beam tube, it is necessary to have a gap of a few mm between it and the absorber for a flow of cooling air. The cuts of the spacer ring sides make this gap for passing an air flow. The location of supports (*7*), holding support cylinder (*11*) with superconducting windings (*10*) inside the vacuum vessel is shown in Figs. 3,4. These supports maintain a constant position of the support cylinder during cooling. The thermal isolation part of supports (*7*) consists of a fiberglass cone. The thermal intercept is connected to the radiation shield and carbon fiber cone (Figs. 3,4). The heads of the supports are attached to the vacuum vessel and support cylinder via hinges.

Thermal shields (*2*) made of 1 mm thick copper sheets are attached to the vacuum vessel walls. Gaseous helium at a 5÷80 K temperature flows through tubes (*3*) welded to these sheets. The joints of the radiation shields allow having some thermal deformations. The shields are divided into parts fastened to each other with electrical-insulation plates. This allows one to reduce the influence of eddy currents arising from the changes of the magneticfield.

Multilayer thermal insulation (*4*) consists of double layers of SNT-10 synthetic paper 10 μm thick and AD-1 aluminium foil 10 μm thick. There are 20 double layers of such insulation around the surface of the He vessel (outside and inside) and 80 double layers connected to the thermal shields. The *Scotch 3M-425* thermal conducting aluminium tape is considered for use [10]. It is necessary to study the question on the behavior of various materials which can be used to superisolate the cryostat under the influence of a accelerated particles flow and to choose durable radiating materials.

5. Refrigeration system

5.1 Vacuum System

Due to a large amount of superinsulation material in the thermal shields, the pumping of the volume requires a series of pumps to reach the needed vacuum. An initial vacuum pumping from P=1 bar to P=50 mbar is reached by mechanical pump (*13*) (Fig.5). At the final stage, turbo-molecular pump (*12*) is switched on, and a necessary vacuum of about $10^{-6} \div 10^{-7}$ mbar is reached.

5.2 Cryogenics

A block-diagram of the refrigeration system is shown in Fig. 5.

The safe cool-down of the winding to 4.5 K can be made by a helium flow using the latent heat of helium vaporization and the enthalpy of helium gas. The full cryogenic system requires a helium flow of 0.25 g/s during steady-state operation at 4.5 K assuming heat-leaks into the winding and chimney (Table 3).

Table 3. Refrigeration system and cryostat heat loads (W)

Items	4.5 K	80 K
Helium vessel with coil	4.0	-
Thermal shields	-	30
Chimney	0.2	2
1000 ℓ storage dewar	0.4	-
Transfer line 10 m	0.4	-
Total	5.0	≤ 40
Transfer line 50 m (periodic)	1.6	25

The helium vessel of the cryostat contains a liquid helium amount of 80÷120 liters . This quantity allows one to maintain screen working parameters for a few hours in the case of failure helium supply stopping . The pipes of liquid and gaseous helium are located (Fig.6) in the vacuum pumping pipe near the suspension bracket of the cryostat. A consecutive arrangement of these elements relative to the basic direction of detecting particles reduces the dispersion of particles. The vacuum pump is at a minimum distance from the vacuum vessel. The same time turbomolecular pump is located in this area for an absent-minded magnetic field that is rather convenient to service such a pump. It is required to surround it with a ferromagnetic screen. The liquid helium pipe-line placed between the storage tank and the superconducting screen has its own thermal shield cooled by returned helium gas from the cryostat. Fig. 6 shows that the inlet and outlet helium from the cryostat are separated, but they are in the common vacuum space of the helium pipeline.

6. R & D and prototypes

The history of superconducting screen technology is 20-25 years old, and new better materials are available now. The aims of research work on the superconducting screen are the following :

- to define optimum materials and technology for manufacturing the superconducting screen model on a 1:10 scale ;
- to optimize the design of the superconducting screen ;
- to measure the penetrating ability of the superconducting screen placed in the static and varying magnetic fields ;
- to investigate constructional durability, reliability and the level of possible heating during the quench.

To perform the specified research on the superconducting screen, it is supposed to use a modified transport dewar with a liquid helium volume of 40 litres (Fig.7). The dewar contains helium (*1*) and nitrogen (*2*) vessels. The diameter of dewar neck (*3*) is 70 mm, and appendix (*4*) as a continuation of the helium dewar vessel is attached to the dewar bottom. The length of the appendix is larger than that of the investigated superconducting screen and equals $\cong$ 700 mm. The top part of the vessel neck has inlet (*5*) for inserting