NUMERICAL MODELING AND DESIGN OF A SUPERCONDUCTING SOLENOID GENERATOR OF 6T MAGNETIC FLUX DENSITY

Ion DOBRIN[1], Dan ENACHE[2], Andrei DOBRIN[3], George DUMITRU[4], Radu PINTEA[5], Iuliu Romeo POPOVICI[6], Stefania ZAMFIR[7]

The paper presents the design elements for a superconductor solenoid operating at 4.2K temperature and the numerical modeling of the generated magnetic field. Designed to obtain a 6T magnetic flux density with a very low non-uniformity, of 0.12%, in a well defined area of its center (10 cm^3), the solenoid requires the use of two correction coils placed at its ends. The main coil and the correction coils are also subjected to numerical modeling performed in Comsol Multiphysics. Both windings of the solenoid and of the correction coils are made of superconducting composite wire of the NbTi type and cooled with liquid helium (4.2K). Also, the constructive structure of the solenoid and its related cryogenic elements, necessary for the proper functioning, together with their analysis is described.

Keywords: magnetic field, solenoid, superconductor, numerical modeling, design.

1. Introduction

Many research problems for nuclear and condensed matter physics require the use of high magnetic fields to study specific physical properties of matter and to discover new ones. High magnetic fields could be produced only by the superconducting magnets which usualy require liquid helium for operation at a temperature of 4.2 K.

[1] PhD, Head of Applied Superconductivity Laboratory, National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: ion.dobrin@icpe-ca.ro
[2] PhD student. Eng., National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: dan.enache@icpe-ca.ro
[3] Eng., National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: andrei.dobrin@icpe-ca.ro
[4] Physicist, National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: george.dumitru@icpe-ca.ro
[5] Physicist, National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: radu.pintea@icpe-ca.ro
[6] Eng., National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: iuliu.popovici@icpe-ca.ro
[7] Eng., National Institute for Research and Development in Electrical Engineering – ICPE CA, Romania, e-mail: stefania.zamfir@icpe-ca.ro

Superconducting magnet systems (SMS) operate at low temperatures and the cooling technology is a key concern. Recently, the new cooling cryogen-free technology is increasingly preferred to those using cryogens (liquid helium, liquid hydrogen, or liquid nitrogen) due to its simplier, more compact, and easier to operate modality [1]-[2]. A two-stage Gifford-McMahon (G-M) cryocooler [3] provides the pumping power to cool down the magnet to the working temperature. The cold head (first stage) of a cryocooler has to be situated in a low magnetic field area to avoid degradation of its refrigeration capacity. The degradation of the refrigeration capacity of a cryocooler may be caused by an external magnetic field, which could induce eddy currents into the moving parts (pistons). The generated heat is detrimental to the cryocooler performance. Also, dynamic forces produced by the eddy currents may inhibit the pistons motion, even more diminishing the thermal performance.

This paper presents a 6 T NbTi field winding solenoid designed for material properties measurement in magnetic field environment. The uniformity of the magnetic field is analyzed by numerical simulation in Comsol Multiphysics [4].

The superconducting solenoid ansamble is placed inside the cryrostat that provides safe temperature limits (< 5 K) for the superconducting field winding, and the high temperature superconducting (HTS) current leads. Together with the cryogenic cooling system it is an integrated system.

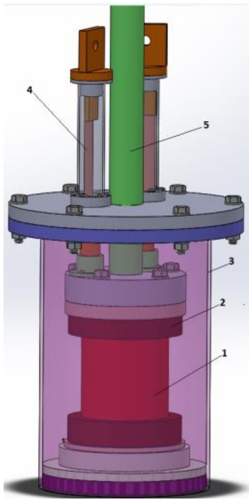
The use of superconducting magnets in research laboratories has become widespread only with the development of the conduction cooling method, using closed cycle refrigerators [3]. Physical properties measurement systems based on so called, conduction cooled magnets or cryogen-free magnet systems are popular commercial experimental tool used to study the physical properties of materials under high magnetic fields and at low temperatures [4,5,6].

2. Design of the solenoid

The 6 T superconducting solenoid designed at ICPE-CA is described in Fig. 1, and its major components are mentioned below:

1. Main superconducting coil(1).

Fig. 2 shows details of the superconducting magnet which is made with NbTi composite wire [2] and wound in solenoid form (see fig.2). The main coil has 80 mm long and the inner diameter of 40 mm.



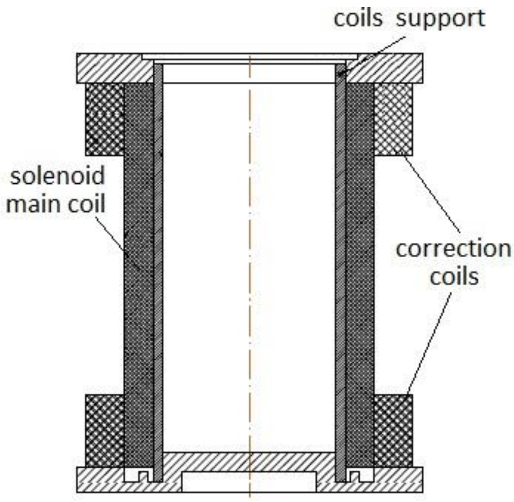


Fig.1. CAD View of the solenoid ensemble.

Fig.2. Superconducting solenoid structure.

Table 1 summarizes the main characteristics of the superconducting solenoidal coil.

Table 1

Solenoid characteristics

Characteristic	**Value**
Wire diameter	0.85 mm
Inner diameter	40 mm
External diameter	58.7 mm
Solenoid length	80 mm
Number of layers	11
Number of turns/layer	118
Total number of turns	1298
Wire length	202 m

The wire produced by Supercon Inc. [7] is 0.85 mm bare diameter, with 54 fillaments (0.075mm diameter) of NbTi, and 1.3 ratio between Copper and NbTi. The NbTi composite wire has a critical temperature of 9.2 K. The dependence of the critical current to the the external magnetic field for the wire, can be observed in Fig. 3. one can observe that for an external magnetic field of ~ 6T, the critical current of the wire is of 500 A. The maximum magnetic field generated inside the solenoid will be simulated and discussed in chapter 3.

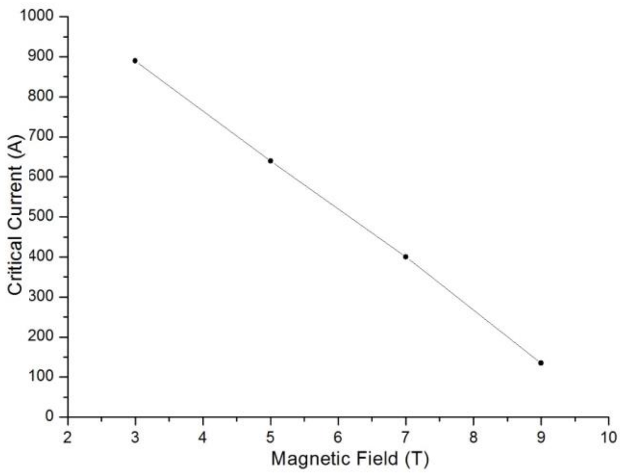


Fig.3. Critical current vs. applied magnetic field for NbTi wire [5]

2. Correction coils (2) are placed at the ends of the main solenoidal coil. They ensure a larger central „good field zone" with a certain higher uniformity of the generated magnetic field. These coils have 15mm long and 59 mm inner diameter. Table 2 shows the characterstics of the correction superconducting coils.

Table 2

Correction coils characteristics

Characteristic	**Value**
Wire diameter	0.85 mm
Inner diameter	58.7 mm
External diameter	68.9 mm
Correction coils length	18 mm
Number of layers	6
Number of turns/layer	21
Total number of turns	252
Wire length	51 m

Both types of superconducting coils are designed and wounded with NbTi composite wire [7]. The coils where impregnated with low temperature epoxi resin EPOTEK type [8].

3.Magnet Cryostat (3) – The superconducting magnet system is housed inside a cryostat made from stainless steel (type 304) material. The cryostat has two important functions: to maintain the low temperature (4.2K) needed for the functioning of magnet and to provide mechanical support for the magnet. The main dimensions are presented below (Table 3).

Table 3

Cryostat geometric characteristics

Characteristic	**Value**
Hight	18 cm
Diameter	12 cm
Inner volume	60 cm^3

4.HTS current leads(4) - The current leads for the superconducting coils are made of HTS tape. They provide the current for the superconducting coils and connect the copper current leads with the terminals of the superconducting magnet. The HTS tape is YBCO type [9] of 12 mm wide and a critical current of 300 A@77 K. Fig. 4 shows a HTS current lead.

Fig.4. CAD view of a HTS current lead.

The thermal flux conducted by the assembled current lead is less than 0.10 W, determined by Comsol Multiphysics [4] simulations.

5. Central channel (5) - The central channel ensures the acces to the magnetic field area inside the central zone of the magnet. There can be placed a sample to be studied in the presence of the magnetic field. The channel is a stainless steel pipe which is vacuumed to a level of 10^{-6} mbar.

A superconducting magnet power source is working with the magnet. This power source is able to supply high currents (0-500 A) to the magnet. The whole system is operated in vacuum conditions so an ultra-high vacuum aggregate is attached with the system. There are temperature sensors (calibrated silicone diodes) [10] mounted at different locations in the system. Cernox sensors [10] are also used at the solenoid level, due to their imunity to high magnetic field conditions.

3. Cryogenic cooling system

The cryogenic cooling of the magnet (fig. 5) is an important part of the magnet design. The usual way for the cooling down of a SC magnet, consists in the use of the liquid helium. Due to the increasing price of the liquid helium, this cooling method became expensive. One way to make less expensive this cooling method is to recover the helium gas. The recovery of the helium gas coming from the liquid helium boiling inside the magnet cryostat, can be performed using a closed cycle cryocooler to recondensate the gas into liquid and his return into cryostat.

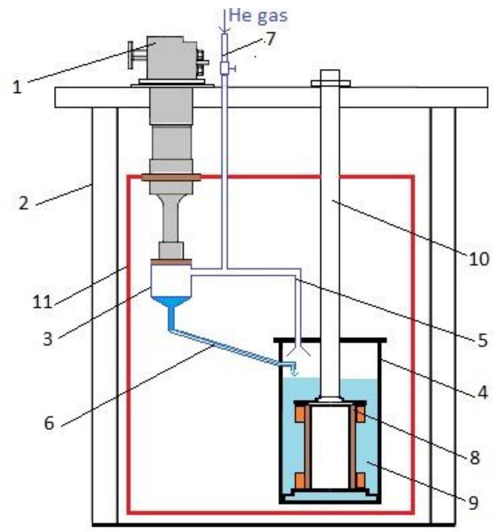


Fig.5. Cryogenic cooling system of the superconducting magnet.

The cryogenic cooling system for the superconducting solenoid consists mainly in the following parts: a cryocooler (1) which is connected with the second stage head (4.2K) to the condenser (3) and with the first stage (50K) at the thermal shield (11). The entire system is placed inside a main cryostat (2). The condenser (3) transforms the He gas into liquid helium, which is passing through the pipe (6) towards the magnet cryostat (4) contributing to the filling with liquid helium, the magnet cryostat. The gaseous helium is recirculated through the return pipe (5) inside the condenser (3). The access of the gaseous helium from outside the system towards condenser is enabled by the access pipe (7). The superconducting solenoid (8) is immersed in liquid helium (9). The central channel (10) enable the access to the central zone of the magnet from outside.

Obviously, the cryocooler is the most important part of the cooling system. It is a Gifford-McMahon close cycle cryocooler [3] having two cooling stages. Stage 1 with a cooling power of 35W at 50 K and the second cooling stage with a cooling power of 1.5 W at 4.2 K. His role is to maintain the necessary level of liquid helium inside the magnet cryostat, ensuring the immersing of the solenoid into the helium bath.

4. Numerical modeling

4.1. Magnetic field

Due to the geometric structure of the superconducting coils assembly used for energy storage, the magnetic field can be analyzed using an axi-symmetric model for numerical simulation. The stationary magnetic field is described by the following equation:

$$\nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times A) = J_\varphi^e, \quad (1)$$

where **A** is the magnetic vector potential (for this model, the angular component is the one used), $\mathbf{J}^e_\varphi$ is the external current density, $\mu_0 = 4\pi \times 10^{-7}$ H·m^{-1} represents the magnetic vacuum permeability and μ_r is the relative magnetic permeability.

Symmetry and magnetic insulation ($\mathbf{n} \times \mathbf{A} = 0$, **n** is the outward pointing normal vector) are limit conditions that have to be imposed to the numerical model.

The mesh consists of 94832 triangular elements with 189997 degrees of freedom. To solve the model, was used a Direct (UMFPACK) stationary solver.

The superconducting winding was considered as a copper winding, but with a very high electric conductivity (10^{19} S/m).

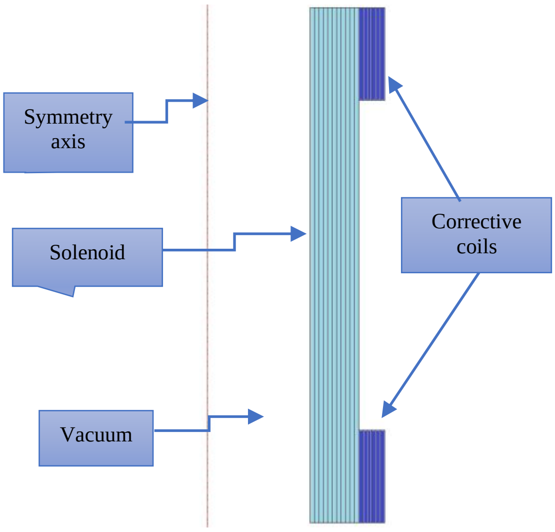


Fig. 6. Geometric model.

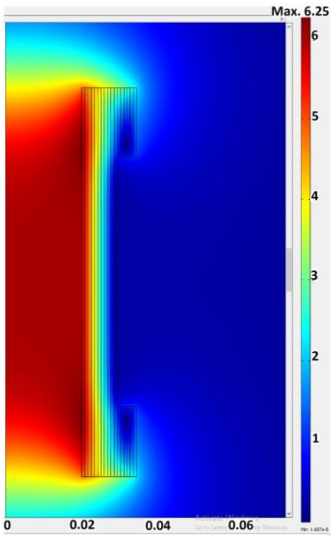


Fig. 7. Color map of the solenoid magnetic flux density.

The magnetic flux density distribution generated by the solenoid is presented in Fig. 7. The color map and the numerical results were performed in COMSOL [4].

The generated magnetic flux density of the solenoid is presented in Figs. 8 and 9. Fig. 8, shows the magnetic flux density generated by the superconducting solenoid main coil alone. Fig. 9 shows a better uniformity and higher values for the magnetic flux density of the solenoid, with the corrective coils contributions. The maximum value of the magnetic flux density (6.25T) can be found at the level of the inner face of the solenoid support. In the center of the solenoid (on the symmetry axis), the magnetic flux density is 6.02T. The non -uniformity (dB/B) of the magnetic field is less than 0.12 % inside a central zone of 30 mm length (fig.10). The load curve of the solenoid, obtained by Comsol simulations at different current values, is presented in Fig. 11. One can see that for a current of 375 A, the targeted magnetic flux density reached in the center of the solenoid was 6T.

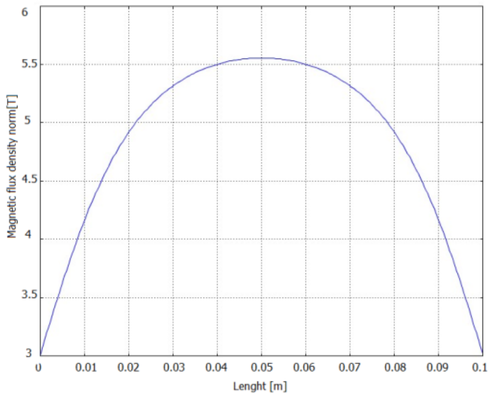


Fig 8. Magnetic flux density in the solenoid center – without corrective coils.

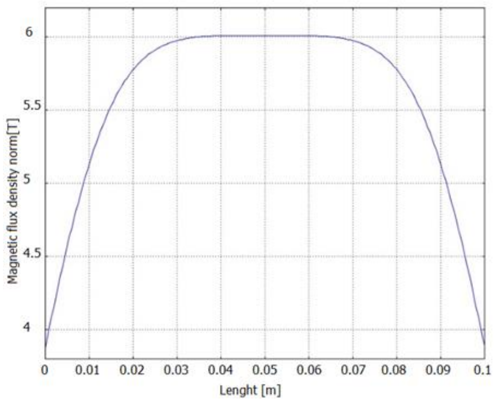


Fig 9. Magnetic flux density in the solenoid center – with corrective coils.

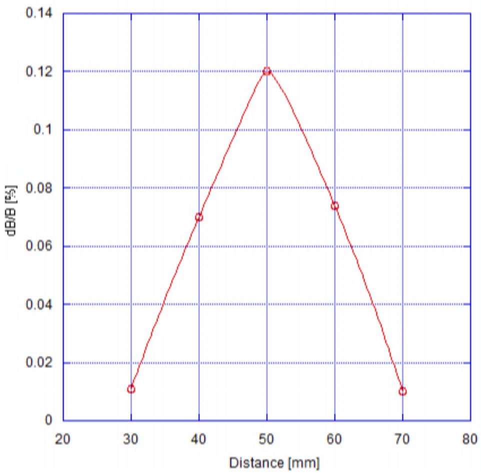


Fig.10. Nonuniformity of the magnetic field on the symmetry axis.

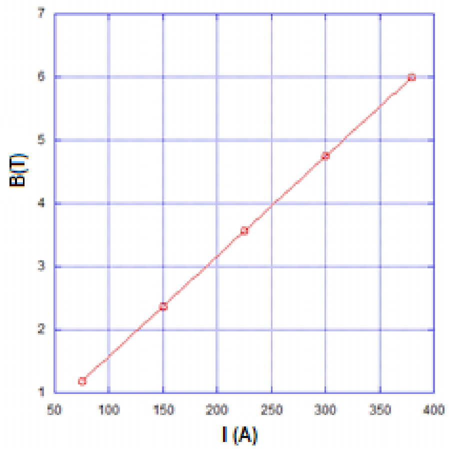


Fig. 11. Load curve of the solenoid.

4.2. Lorentz forces

The magnetic force acting globally on the solenoid body can be expressed in terms of the magnetic flux density by the equation:

$$\mathbf{F} = \frac{1}{\mu_0} \iiint dV(\nabla \times \mathbf{B}) \times \mathbf{B} \tag{2}$$

where, F is the magnetic force, V is the body volume, and **B** is the magnetic flux density.
The "body volume" means the winding volume of the superconducting solenoid.

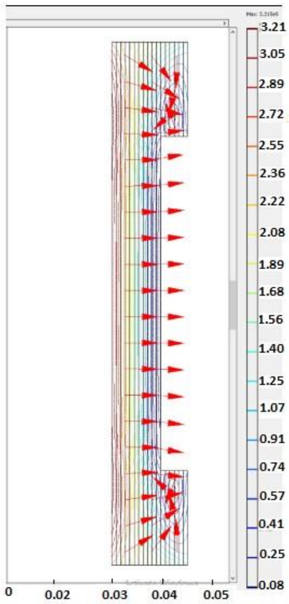


Fig.12. Lorentz force acting on superconducting winding modeling.

Using Comsol Multiphysics software for the volume integral calculation of the Lorentz force, were obtained results summarized in Table 4:

Table 4

Lorentz force in the winding

Force /orientation	Solenoid winding [N]	Correction coils [N]
r	$2.25\ 10^{5}$	$4.68\ 10^{2}$
z	$4.62\ 10^{-4}$	$3.00\ 10^{-4}$
Total	$2.26\ 10^{5}$	$4.69\ 10^{2}$

The Lorentz force has a considerable value acting specially in radial direction.Due to large values (~ 200 kN) of the Lorentz forces, the winding will be glued with epoxy resin for low temperatures range [8]. Epoxy resin impregnation will also reduce the probability of quench producing which is the main reason for Lorentz forces evaluation.

4. Conclusions

A superconducting solenoid made of NbTi wire generating a high magnetic flux density (6T) and high uniformity for a specific central zone of the solenoid was described. A non-uniformity better than 0.12 % of the magnetic field was obtained for 30 mm length zone on the axis of the solenoid. This result was possible do to the presence of the two correction end coils witch were optimized for this purpose. The magnetic flux density of 6 T is obtained for a DC current of 375 A. The evaluation of the Lorentz forces acting on the superconducting winding shows relative high values of ~ 200 KN acting in radial direction. The numerical simulations were performed with Comsol Multyphysics software. The solenoid is cooled down to 4.2 K temperature with a cryogenic circulating system with the condensation of the helium in the liquid phase. This system is using a closed cycle Gifford-McMahon cryocooler with two cooling stages (50 K and 4,2 K). The solenoid will be used for studies on magnetic properties such as magnetic resistivity and magnetization of some materials used in electrical engineering applications (e.g. used for superconducting magnets and rotating superconducting machines).

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