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COMPUTER SIMULATION OF THE MECHANICAL BEHAVIOR OF THE FFS SUPERCONDUCTING QUADRUPOLE COIL*

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Abstract

In the frame of the work, carried out at the Research Center of the Kurchatov Institute - IHEP on the development of four wide-aperture superconducting quadrupoles, a mathematical study of the mechanical behavior of the coil block of these magnets was carried out. The quadrupoles are intended for use in the magnetic final focusing system (FFS) of the ion beam in the experiments of the HED@FAIR collaboration [1, 2]. At the design stage of superconducting magnets, it is necessary to perform mathematical modeling to analyze the deformation of coil blocks during the assembly stages, cooling to operating temperature and the influence of ponderomotive forces. The results of computer simulation of changes in the geometry and distribution of forces in the coil block at all these stages are necessary to determine the value of the preliminary mechanical stress in the superconducting coil. The main results of numerical simulation of the mechanics of these magnets are presented in the article.

INTRODUCTION

An international accelerator complex for ions and antiprotons is currently being created (FAIR, Germany, Darmstadt). The HED @ FAIR collaboration will conduct new experiments to study the fundamental properties of high energy density states in matter, generated by intense beams of heavy ions. To carry out these experiments NRC "Kurchatov Institute" - IHEP creates 4 superconducting (SC) quadrupole magnets for the final focusing system (FFS) of the ion beam.

To provide a focal spot of the order of 1 mm, these magnets must have a unique combination of a high magnetic field gradient of 38 T/m and a large inner diameter of the superconducting coil of 260 mm, the operating temperature of the magnets is 4.5 K.

Significant ponderomotive forces arise in the coil of such a magnet, which can transfer it to its normal state. To prevent this transition, the coil is compressed by the bandage with a force sufficient to compensate for the ponderomotive forces. To determine this effort, it is necessary to carry out mathematical modeling of the stress-strain state of the SC coil - bandage system during manufacture and operation.

The main steps taking place with the quadrupole coil block are:

1. Creation of a pre-stressed state under pressure in the coil-bandage system.
2. Fixing the position of the bandage with a key and relieving the press load.
3. Cooling from room to operating temperature.
4. Action on the coil of ponderomotive forces when current is injected into it.

GEOMETRY QUADRUPOLE FFS

Figure 1 shows the cross section of the quadrupole FFS.

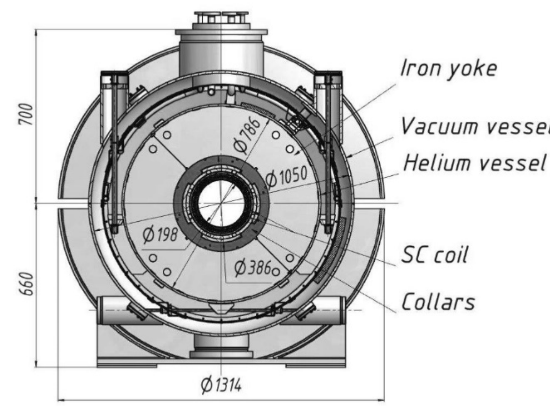

Figure 1: Cross section of the quadrupole FFS.

The main parameters of the quadrupole FFS are presented in Table 1.

Table 1: The Main Parameters of the Quadrupole FFS

Parameter	Value
Operating mode	DC
Inner diameter of the coil	260 mm
Central field gradient	37.6 T/m
Nominal current	5.73 kA
Magnetic field in the coil	5.87 T
Stored energy	1079 kJ
Vacuum vessel length	2400 mm
Vacuum vessel diameter	1400 mm
Cold mass of the quadrupole	~6.5 t
Mass of quadrupole	~10 t

The cold mass inside the helium vessel, with the help of a two-layer superconducting coil, creates a magnetic field, while significant forces arise in the coil, which are compensated by the stainless steel collars (bandage) compressing the coil. Around the collars there is an iron yoke (magnetic shield) made of electrical steel plates. A helium vessel with a cold mass is attached to a vacuum vessel by means of a suspension system; between the walls of the vacuum vessel and the walls of the helium vessel there is a heat shield cooled by a helium flow having a pressure of 13 bar and an inlet temperature of 50 K.

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DESIGN OF THE COIL BLOCK OF THE QUADRUPOLE FFS

The design of the coil block of the FFS quadrupole consists of 4 coils, consisting of two layers of superconducting cable, which are held in a stressed state at a circular aperture by a laminated bandage. The latter is assembled from identical collars so that it forms a periodic structure with two half rings (8 collars in each) in a period. The connection between adjacent collars in one half-ring is provided by a pin. A key is used as a load-bearing element holding the upper and lower half-rings from the collars in the transverse plane.

Collars are made of stainless steel Nitronic 40. Keys, pins are made of stainless steel 316L. The separators are made of brass. The coils are made of Rutherford-type SC cable, consisting of 28 wires with a diameter of 0.85 mm, transposed at an angle of 15 degrees.

RESULTS OF CALCULATING THE MECHANICAL BEHAVIOR OF THE COIL BLOCK IN A QUADRUPOLE FFS

To study the mechanical behavior of the coil block of the FFS quadrupole, a numerical simulation was carried out with the help of computer code ANSYS [3].

The created finite element model in the first quadrant of the coil block is shown in Fig 2. The model is made in the approximation of a solid collar. Keys and pins are not taken into account.

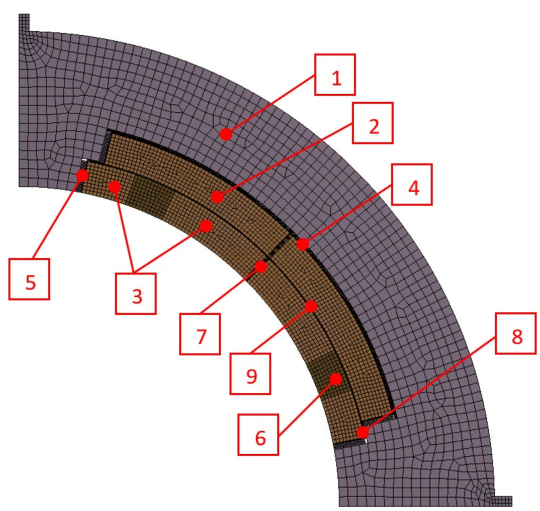

Figure 2: Finite element model in the first quadrant of the coil block. 1- collar, 2- outer coil layer, 3-inner coil layer, 4- protective metal gasket, 5- end metal gasket, 6- separator, 7- body insulation, 8- inner spacer, 9- interlayer gasket.

All contacts between parts were modeled using a sliding contact with a friction coefficient of 0.1. The calculation took into account the mechanical properties of the real superconducting coil. In particular, it was used the measured dependence of the deformation upon the stress of the superconducting coil of the quadrupole FFS, see Fig. 3.

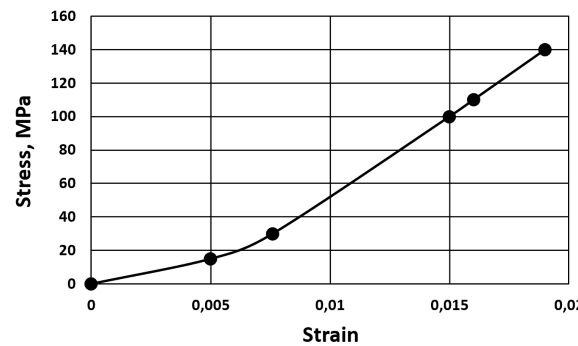

Figure 3: Strain-stress dependence of the superconducting coil of the quadrupole FFS.

Figure 4 shows the magnitude of the stress in the turns of the coil during manufacture and cooling down to 4.5 K. quadrupole FFS.

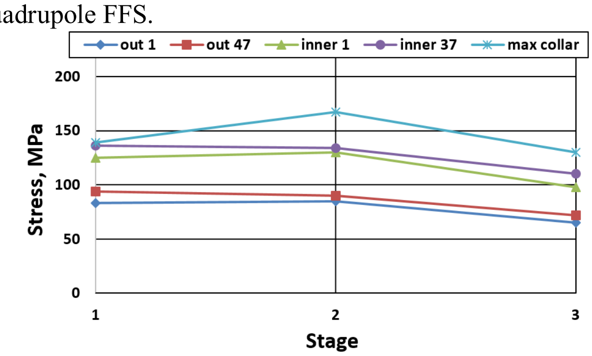

Figure 4: Stresses in the coil at various stages. 1- compression of the coil block with a press, 2- fixing the band with a key and removing the press load, 3- cooling to a temperature of 4.5 K.

RESULTS OF 2D ELECTROMAGNETIC ANALYSIS OF THE COIL BLOCK IN A QUADRUPOLE FFS

As a first approximation of the magnetic properties of the yoke material it was taken the dependence of the magnetic permeability on the magnetic induction for ARMCO steel.

The results of calculation perfomed in code ANSYS the magnetic induction at the current of 5.73 kA in the quadrupole FFS are shown in Fig. 5.

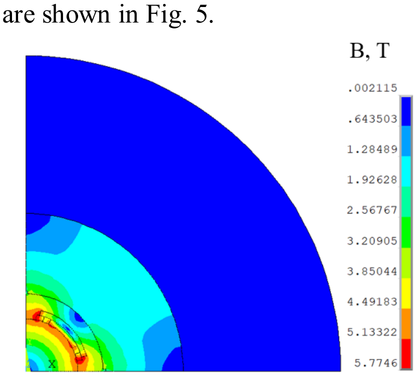

Figure 5: Distribution of magnetic induction for the current of 5.73 kA in the quadrupole FFS.

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The results of calculating the pondemotive forces at the current of 5.73 kA in the quadrupole FFS coil are shown in Fig. 6.

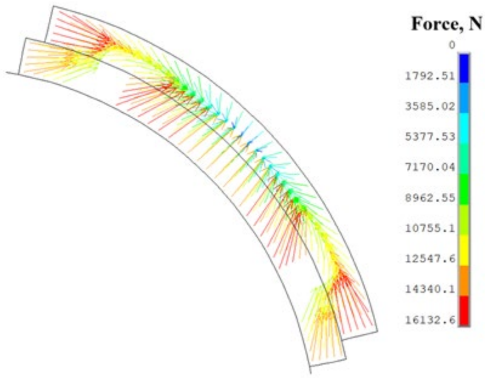

Figure 6: Distribution of pondemotive forces at the current of 5.73 kA in the coil quadrupole FFS.

On the basis of the obtained results of the electromagnetic calculation, it is planned to carry out the calculations of the stress-strain state of the structure of the coil block with the load of the coil by ponderomotive forces, taking into account the previous processes.

RESULTS OF THERMAL- MECHANICAL ANALYSIS OF HELIUM VESSEL QUADRUPOLE FFS

In the process of cooling the cold mass of the quadrupole FFS from a temperature of 290 K to 4.5 K the energy of 5.3×10^8 J must be removed. During cooling, two helium flows are used which is approximately equal in flow rate. One, external, flows through 18 peripheral channels, the other, internal, flows through an internal annular channel. The main amount of the heat of the quadrupole removed during the unsteady cooling mode is contained in the iron yoke. The outer flow is in direct contact with the yoke, whereas between the inner flow and the iron yoke there are two layers of coil with electrical insulation of the SC cable, a layer of body insulation and a layer of stainless steel collars, the thermal conductivity of which is significantly lower than the thermal conductivity of the yoke. As a consequence, the heat transfer from the iron yoke to the outer flow is much greater than the heat transfer from the same yoke to the inner flow.

Therefore, the inner tube will cool faster during the cooling process than the outer shell. As a result, tensile forces will arise in the inner tube, which, at a certain temperature difference between the shell and the inner tube, can cause irreversible deformation of the inner tube. A similar situation is observed during heating, when warm helium is supplied to the cold FFS quadrupole, and compressive forces arise in the inner tube.

In this regard, strength calculations were carried out to determine the permissible difference between the temperature of the outlet end of the outer shell (To) and the temperature of the inlet helium flow (Ti), at which the irreversible deformations in the inner pipe do not yet occurs in the processes of warming and cooling. The results of calculation for the inner tube and for the shell are shown in Fig. 7.

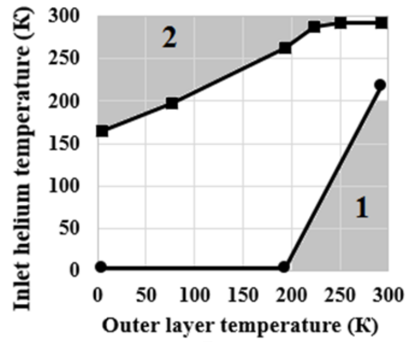

Figure 7: Admissible temperatures of the incoming helium flow Ti at cooling (●) and warming (▪) of the quadrupole as a function of the temperature To of the outlet end of the outer layer. The outer shell is 1.4436 steel, the inner tube is 1.4571 steel. 1 - region of unacceptable temperatures of the input helium flow during cooling. 2 - region of unacceptable temperatures of the input helium flow during warming.

Figure 7 shows that when cooling into a "warm" quadrupole (290 K), the flow of cold helium can be supplied with a temperature of at least 220 K. When the entire outer shell is cooled to a temperature of 280 K, the temperature of the cooling helium flow at the inlet to the quadrupole can be reduced to 190 K, etc. It also follows from this that at a temperature of the entire shell below 190 K, a helium flow can be supplied to the inlet to a quadrupole magnet with a temperature of 4.5 K.

When the cold quadrupole (T≈4.5 K) is warmed up, the initially supplied helium flow should be with a temperature not higher than 165 K. When the outer shell warmed up to 20 K, the temperature of the helium flow at the quadrupole inlet can be increased to 170 K, etc. At a temperature shell 245 K a flow of helium with ambient temperature can be supplied to the quadrupole inlet.

CONCLUSION

A model has been developed and the stress-strain state of the quadrupole FFS coil block has been calculated. The distribution of magnetic induction and ponderomotive forces in the quadrupole coil is obtained. The analysis of mechanical stresses in the helium vessel during the cooling of the superconducting of the quadrupole coil to the operating temperature is carried out and the optimal mode of this process is determined. On the basis of the calculations performed, the drawings of the quadrupole FFS were developed.

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