RESULTS OF MECHANICAL ANALYSIS OF WIDE-APERTURE QUADRUPOLE NODES FOR HED@FAIR EXPERIMENTS*

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Abstract

In the frame of collaboration with FAIR, the IHEP will develop and fabricate superconducting wide-aperture quadrupole magnets with the following parameters: the inner diameter of the coil is 260 mm; the integral field gradient is 66 T. The results of strength calculations of the most important components of these quadrupole magnets are presented in the article. Dependence of strains on the stresses of a superconducting cable for a quadrupole is presented. The stress-strain state of the collars is analyzed; the mechanical analysis of the helium vessel and the vacuum vessel of the superconducting quadrupole magnet is carried out.

INTRODUCTION

Novel studies on the fundamental properties of high-energy-density (HED) states in matter, generated by intense heavy ion beams, will be carried out by the HED@FAIR collaboration at the new accelerator Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [1-3]. In order to provide a strong transverse compression of energetic ion beams at the target, a special final focus system (FFS) will be used. This FFS has to provide a focal spot size of the order of 1 mm. Therefore, a large focal angle is required and consequently, wide-aperture high-gradient quadrupole magnets are employed in the FFS. This paper presented results of strength calculations of the most important components of these quadrupole magnets of the HED@FAIR FFS.

In the frame of collaboration with FAIR, the IHEP will develop and fabricate four superconducting wide-aperture quadrupole magnets with the following parameters: the inner diameter of the coil is 260 mm; the integral field gradient is 66 T. In accordance with these requirements, the design of the magnets, described below, has been developed and analyzed.

REQUIREMENTS TO THE QUADRUPOLE

The main requirements to the quadrupole magnet are: DC operating mode; the coil inner diameter is 260 mm; the minimal distance between quadrupole centers of two nearby magnets is 2.5 m; the integral of field gradient is 66 T. Additional requirements to the quadrupole magnet are: the radius of the good field quality is 110 mm; the field multipoles $|b_n|$, n = 6, 10, 14 are less than 2×10^{-4}; the integral multipole $|b_6^{int}|$ is less than 2×10^{-4}; the temperature margin is about 1 K.

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MATERIALS

It is possible to use the superconducting wire [4] for these magnets. The NbTi alloy multifilamentary composite superconducting wire consists of 8910 filaments of 6 μm diameter; the critical current density at 5 T, 4.2 K is 2.4 kA/mm^2.

The stainless steel Nitronic 40 is suitable for collars production. The collars is fastened with key, made of steel Nitronic 40. The mechanical properties of the Nitronic 40 steel, which will be used for collars and key, are presented in [5]. Particularly, yield strength is 450 MPa at 300 K and is 1390 MPa at 4.2 K.

It is proposed to use steel 1.4429 as material for the helium vessel, in which the yield strength is 280 MPa at 300 K [6]. The vacuum vessel will be produced with steel grade 1.4404, in which the yield strength is 220 MPa at 300 K [6].

GEOMETRY QUADRUPOLE

Figure 1 shows the cross section of the quadrupole.

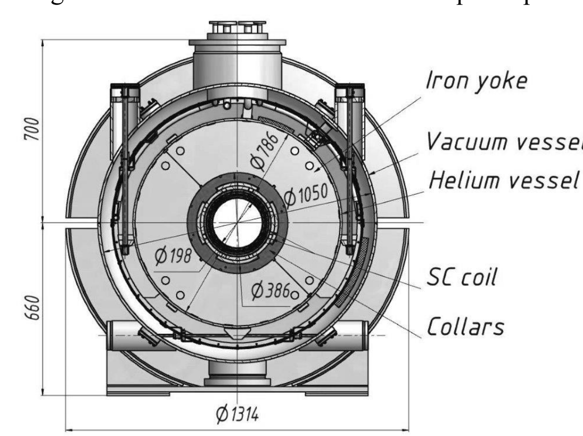

Figure 1: Cross section of the quadrupole.

The main part of the quadrupole is a superconducting coil, consisting of two layers. To ensure reliable and stable operation, it is squeezed by collars made of stainless steel, which have the necessary strength and rigidity to retain the magnetic forces that occur at current input. The coil together with the collars and the iron yoke, are placed inside the helium vessel. Through the helium vessel liquid helium is circulated, to support the coil in the superconducting state. The helium vessel is suspended on a special suspension system inside the vacuum vessel.

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SUPERCONDUCTING CABLE

Cable samples were made and their properties were investigated for fabrication of the superconducting coil. The Rutherford type cable is transposed from 28 NbTi wires and has a trapezoidal cross section. The bare cable has the width of 12.35 mm and the midline thickness of 1.54 mm. The transposition pitch is 88 mm. The packing factor, which is the ratio of the total area of the wires to the trapezium area of the cable, is 0.835.

The insulation system has to provide gluing the coil turns together to give the coil a rigid shape and to facilitate its manipulation during the subsequent steps of a magnet assembly. The cable insulation for the quadrupole consists of three layers of the dry polyimide tape (tape thickness is 25 µm and a width of 11 mm). One layer of epoxidized glass tape of 100 µm thickness and 10 mm width was applied on top of the insulation of the dry polyimide tape.

Exceeding the dimensions (oversize) is necessary to ensure that the cable dimensions should coincide with the required parameters at the applied pressure of 100 MPa.

RESULTS OF MEASURING MECHANICAL CHARACTERISTICS OF THE SUPERCONDUCTING CABLE

The cable stack sample consisted of 47 pieces of the insulated cables of 170 mm length, which were placed in a special device, alternating the narrow and wide sides of the trapeziums. The cable stack was compressed on the press to a predetermined pressure, after which it was heated to a temperature of 150°C during 5 hours to polymerize the compound. The sample of 100 mm length was cut from the obtained sample to measure the dependence of deformation from of the applied pressure. The load was created by a hydraulic press with a piston diameter of 100 cm².

Figure 2 shows the results of measuring the oversize of a cable. Cable stack samples had the rectangular and equilateral trapezoid cross-section. It is seen that the applied pressure affects the thickness of the cable.

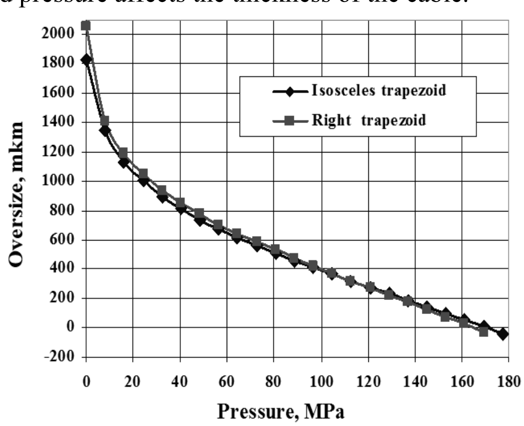

Figure 2: Oversize of cable samples relative to the caliber versus pressure on the sample.

Figure 3 shows the Young's modulus of these samples. The Young's modulus was calculated in accordance with Hooke's law. It can be seen that the obtained results are practically the same for these samples.

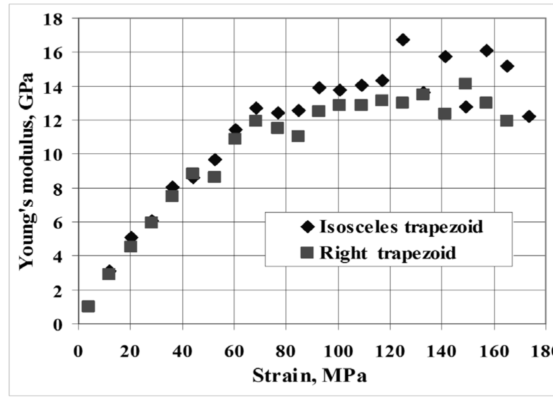

Figure 3: Dependence of Young's modulus of cable samples on the applied pressure.

For technological reasons, a cross-section in the form of an equilateral trapezium is more preferable.

COLLARS

Collars of the superconducting coil are one of the most crucial nodes of the superconducting quadrupole magnet. The collars must have sufficient stiffness and strength to balance the forces on the coil side. The coil is crimped by the collars made with pairwise plates of 1.6 mm thick, compressing the coil alternately in the vertical and horizontal directions, after which the collars are fixed by dowels. At this stage of the magnet assembly the pressure on the collar in the tangential direction is 100 MPa according to calculations. The pressure on the collar in the radial direction is assumed to be 7.7 MPa and in the tangential direction is 20 MPa at the nominal current of 6 kA. A strength calculation was performed with help of ANSYS [7] program to determine the strains and stress of the collar plates during the assembly and operation of the magnet. The general view of the collar calculation model is shown in Fig. 4.

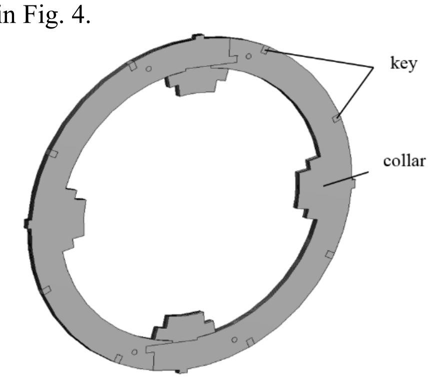

Figure 4: General view of calculation model of collars.

The maximum deformation of the collar plates during collaring was 0.087 mm in the radial direction and are located in the region of the poles. The maximum deformation of the collar plates during current input was 0.075 mm in the radial direct and are located in the region of the median plane.

The maximum stress in the various elements of the collar for the stage of the collaring and the stage of the nominal current injection are presented in Table 2 in MPa.

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Table 2: The Maximum Stress (MPa) in the Various Elements Collar at Collaring and Nominal Current

Elements	Collaring	Nominal current
Collar key region	105	240
Collar pole region	140	200
Collar joint region	180	190
Key	110	200

The collar thickness in the radial direction is 35 mm and provides a sufficient rigidity. Figure 5 shows the dependence of the collar deformations on its thickness on the outer surface of the collars.

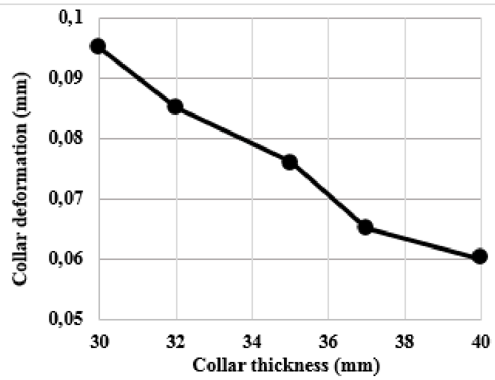

Figure 5: Collar deformation as a function of its thickness.

The maximum stress in the various elements of the collar for the stage of the nominal current injection. The values of the deformations, indicated above, are admissible, because the nonlinearities of the magnetic field, that arise in this case, remain within the specified limits.

HELIUM VESSEL

The helium vessel is a container, made of stainless steel, parts of which are connected by welding. The main junctions of the vessel are the half-shell, torospherical bottoms, inner tube. A superconducting quadrupole cold mass of 6500 kg is installed inside the helium vessel. The thickness of the shell, the bottoms of the helium vessel is 8 mm, the thickness of the inner tube is 6 mm. A finite element model was created with help of ANSYS [7], to which a combination of loads from a double weight of a quadrupole magnet of 13000 kg and a load of a test pressure of 18.6 bar was applied.

The maximum stress is 190 MPa on the inner surface of the bottom of the helium vessel. The stress in the shell of the helium vessel and the inner tube do not exceed 100 MPa. The maximum deformation is 0.66 mm and is located on the spherical part of the bottom of the helium vessel. The calculations showed that the developed design of the helium vessel has sufficient rigidity and strength at its testing and operation.

VACUUM VESSEL

The main node, perceiving the mass of the superconducting quadrupole magnet and protecting it from the environment, to create a heat-insulating vacuum, is a vacuum vessel. It consists of a half-shell, torospherical bottoms, necks, bundle tube, technological branch pipes and stiffening ribs of the shell. A vacuum is maintained inside the vacuum vessel during the magnet operation. The vacuum vessel must resist loads from the double weight of the superconducting quadrupole magnet (13000 kg), as well as the outside atmospheric pressure of 1 bar at an operation. The thickness of the shell, bottoms and edges of the vacuum vessel is 10 mm, the thickness of the inner tube is 4 mm. In the ANSYS [7] program a strength calculation of the vacuum vessel was carried out with the loads, indicated above. The maximum stress is 100 MPa and is located in the place of attachment of the branch pipe of the helium vessel supports to the shell.

The maximum deformation is 0.35 mm on the nozzle of the support of the helium vessel and is directed towards to the central transverse axis of the magnet. The calculations showed that the developed design of the vacuum vessel will provide reliable and safe operation at the testing and operation of the superconducting quadrupole.

CONCLUSION

Superconducting quadrupole for the HED@FAIR beam line in the FAIR project have been developed. The technology of production of superconducting cable has been worked out, a sample of superconducting cable has been manufactured and their mechanical properties have been studied, the cross-sectional shape of the cable for making quadrupole coils has been chosen. The values of deformations and stress in the developed design of the collar at the stages of collaring and at nominal current are permissible. The calculations showed that the developed design of the helium and vacuum vessels will provide reliable and safe operation at the testing and operation of the superconducting quadrupole.

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