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# DEVELOPMENT OF HED@FAIR QUADRUPOLES*

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*Abstract*

Novel experiments to study fundamental properties of high-energy-density states in matter, generated by intense heavy ion beams, will be carried out by the HED@FAIR collaboration at FAIR. For strong transverse focusing a special final focus system, consisted of four superconducting large-aperture high-gradient quadrupole magnets, will be installed at the end of the HED@FAIR beam line. Design and main characteristics of the quadrupole are discussed. Results of mechanical and thermal calculations of main parts of the quadrupole are presented.

## INTRODUCTION

The HED@FAIR collaboration novel experiments [1, 2] to study thermos-physical, transport and radiation properties of high-energy-density matter that is generated by the impact of intense heavy ion beams on dense targets were proposed at FAIR [3]. For strong transverse focusing, a special final focus system (FFS) has to be installed at the end of the HED@FAIR beam line. In order to provide a focal spot of the order of 1 mm, a large focal angle is needed and consequently, four large-aperture high-gradient quadrupole magnets have to be used in the FFS, which IHEP develops at present [4]. This work examines the main characteristics of four wide-aperture quadrupoles, which will be used for focusing the heavy ion beams in these experiments.

A geometry optimization at the infinite permeability approximation $\mu$ and a cylindrical inner radius of the iron yoke was done, using the computer code HARM-3D [5]. Basically, this program uses analytical formulae. In the magnet design, a computer code MULTIC [6] has been employed. This code allows calculating a 3D geometry, taking into account the real dependence of $\mu(B)$ in the iron yoke.

## MAIN REQUIREMENTS TO THE QUADRUPOLE

The required specifications of the quadrupoles are:

- The central integral gradient ($G_0^{int}$) is equal to 36 T;
- The inner diameter of the coil is 260 mm;
- The minimal distance between quadrupole centers of two nearby magnets is 2500 mm;
- The operating mode is DC;
- The radius of the good field quality is $r_0$ = 110 mm;
- The lowest 6-th, 10-th and 14-th harmonics of the field and $b_6^{int}$ of the integral field should not exceed $\pm 2\times10^{-4}$ in geometry optimization; The radius of the good field quality for a geometry optimization is 110 mm;
- The field multipoles $b_n$, $n$ = 6, 10, 14 in the custom magnet are $<2\times10^{-3}$;
- The integral multipole $b_6^{int}$ in the custom magnet is $<2\times10^{-3}$;
- The operating temperature is about 4.4 K;
- The temperature margin has to be about 1 K.

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## 2D GEOMETRY

### General Description

A two-layer quadrupole has a number of advantages over the single-layer one. In particular, it is more technological in manufacturing, easier to manufacture [7] and has half as much a lower operating current. An inter-turn spacer is inserted in the first layer, so the three coil blocks allow one to suppress the first lower multipoles $b_6$, $b_{10}$ and $b_{14}$ in the approximation of the infinitely high magnetic permeability in the iron yoke with a cylindrical internal surface. The coils are enclosed in stainless steel collars that hold all the magnetic forces. The inner iron radius is 160 mm. In order to balance all the forces, acting on the coil and the support system, and to ensure that the offset of any point in the coil is allowed no more than 50 μm, the thickness of the collar should be 35 mm. The cross section of the quadrupole is shown in Figure 1 and the main geometric parameters are presented in Table 1.

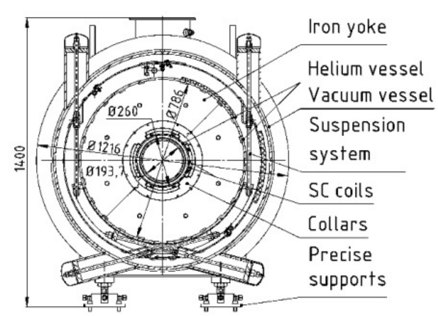


Figure 1: Cross section of the quadrupole.

Table 1: Main Parameters of the Coil Blocks

| Coil blocks | 1 | 2 | 3 |
|---|---|---|---|
| Inner radius, mm | 130 | 130 | 143.75 |
| Initial angle, deg. | 0.2101 | 26.1493 | 0.0572 |
| Final angle, deg. | 19.5735 | 34.0521 | 30.7269 |
| Turn number | 27 | 11 | 47 |
| Maximal field, T | 5.12 | 5.87 | 5.46 |
| Critical temperature, K | 6.44 | 5.84 | 6.16 |

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### *Superconducting Wire*

Preliminary calculations have shown that for these magnets it is possible to use the superconducting wire as described in [8]. The NbTi alloy (Nb-50wt% Ti) multifilamentary composite superconducting wire consists of 162 bundles of filaments in the copper matrix, each of them contains 55 NbTi filaments of 6 µm diameter, so the total number of the filaments is 8910. Each filament is encircled with an Nb diffusion barrier for averting of filament breakings. The bundles are uniformly distributed over the cross section, are surrounded by a copper jacket and have a little copper kernel in the centre of the wire. Table 2 presents the technical parameters of the superconducting wire, where the filling factor $\lambda_s$ is the ratio of NbTi area to the total cross section area of the wire.

Table 2: Characteristics of the Superconducting Wire

| | |
|---|---|
| Superconducting alloy | NbTi |
| Titanium percentage, % | 50±4 |
| Filament diameter, µm | 6 |
| Filling factor, $\lambda_s$ | 0.42±0.02 |
| Copper to non-copper area ratio | (1.39±0.1)/1 |
| Twist pitch, mm | 10±2 |
| Residual Resistance Ratio (RRR) of matrix | ≥70 |
| Critical current at B = 5 T, T = 4.23 K, A | 600±50 |

### *Superconducting Cable*

The keystoned cable of Rutherford type consists of 28 strands of NbTi. The cable length of 138 m was produced with a bare cross-section of 1.62×12.11 mm$^2$. The insulated cable at 100 MPa pressure had 12.7 mm width and 1.71 mm middle thickness. The transposition pitch is 88 mm. The cable insulation consists of three layers of the dry polyimide tape with a thickness of 25 µm and a width of 11 mm. One layer of an epoxidized glass fiber tape about the 68 µm thickness is applied on top of the insulation.

### *Collars*

A stainless steel like Nitronic 40 [9] is quite suitable for the quadrupole production. Nitronic-40 is a high manganese nitrogen strengthened, austenitic stainless steel that combines acceptable low temperature magnetic susceptibility, high strength in the annealed condition, excellent resistance to oxidation at high temperatures, good resistance to lead oxide and a high level of corrosion resistance at ambient temperatures. The alloy is readily weld able. The permeability is 1.0021. Figure 2 shows the dependence of the collar deformations on its thickness at different angles on the outer surface of the collars [10]. The deformation has a maximum value in the plane, where the keys are located, near 20° from the median plane. The optimum thickness of the collar should be chosen so that the radial deformations at the nominal current of 6 kA do not induce harmonics of the magnetic field above allowed limits. In this case, the stresses, arising in the collar, should not exceed the yield strength. The above conditions are satisfied with a collar thickness of 35 mm. So the radius of the iron yoke equals 160 mm.

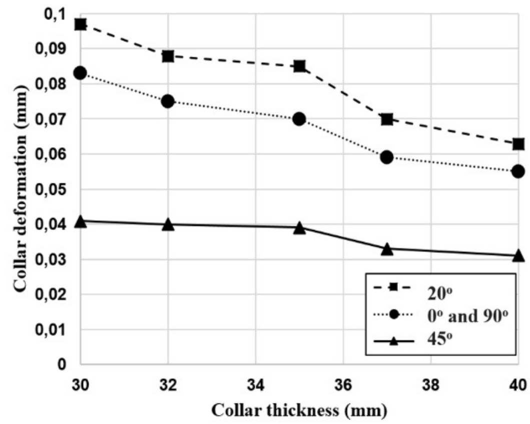

Figure 2: Collar deformation versus its thickness.

### *Iron Yoke*

The carbon amount in steel 2081 [11] provides the low coercive force. The contents of elements in steel 2081 provide the high saturation magnetization of 2.19 T. Since the magnet operates at a constant current, the thickness of the plates is chosen for technological reasons and is equal to 2 mm. The iron thickness is chosen according to Figure 3 [4] and is equal to 200 mm.

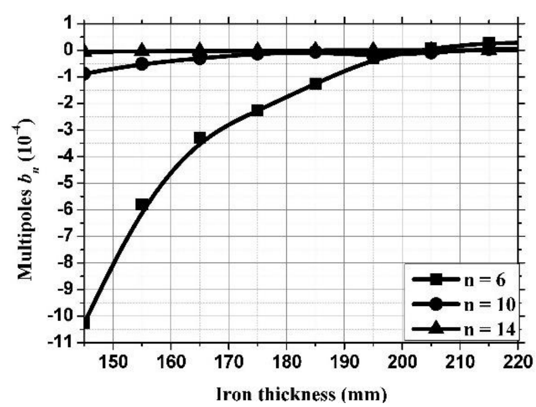

Figure 3: Lower multipoles versus iron thickness.

The rest magnetic parameters are present in Table 3.

Table 3: Main Magnetic Parameters

| | |
|---|---|
| Operating current, kA | 5.73 |
| Storage energy, kJ | 1079 |
| Inner radius of the iron yoke, mm | 193 |
| Thickness of the iron yoke, mm | 200 |
| Turn number/octant | 27-11, 47 |
| Central gradient, T/m | 37.57 |
| Maximal field in the cross section, T | 5.87 |
| Horizontal magnetic force/octant, kN/m | 938 |
| Vertical magnetic force/octant, kN/m | -934 |
| Total magnetic force/octant, kN/m | 1323 |

## 3D GEOMETRY

From technological reasons, the lengths of the layers should be equal. Hence, there is only one parameter - the length of the short block in the first layer, for suppressing

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the integral harmonic $b_6$. If it will be necessary, the integral multipoles $b_{10}$ and $b_{14}$ can also be suppressed by adjusting the coil block angles in the central cross section. An involute of the optimized end parts in the plane $\rho\Theta$-$z$ is shown in Figure 4 (outer surface). The principal parameters of 3D geometry with the cylindrical iron yoke of large magnetic permeability are presented in Table 4.

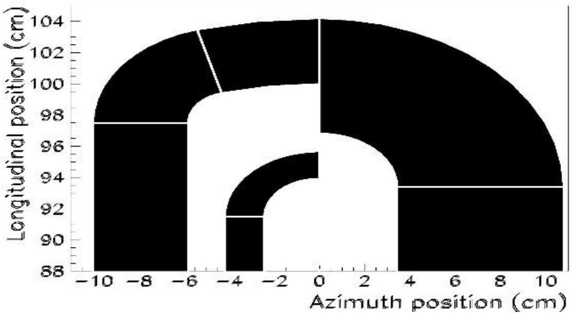


Figure 4: Involute of the optimized end parts (outer surface) in a $\rho\Theta$-$z$ plane: left – the inner layer; right – the outer layer.

Table 4: Main Parameters of 3D Geometry

| | |
|---|---|
| Maximal field in the end parts, T | 5.88 |
| Geometric length of the coil, mm | 1890 |
| Iron yoke shortening, mm | 145 |
| Longitudinal length of the spacer in end parts, *S*, mm | 48.89 |
| Effective length, mm | 1756.8 |
| Critical temperature, K | 5.84 |
| Integral multipole $b_{10}$, $10^{-4}$ | -11.51 |
| Integral multipole $b_{14}$, $10^{-4}$ | -8.71 |
| Horizontal magnetic force in end parts/octant, kN | 30.7 |
| Vertical magnetic force in end parts/octant, kN | -48.5 |
| Longitudinal magnetic force in end parts/octant, kN | 60.3 |
| Total force/octant in the end parts, kN/m | 83.2 |

## QUADRUPOLE PARAMETERS AT QUENCH

The conceptual quench protection circuit with the dump resistor was presented early [4]. The quench detector has the threshold voltage of 0.1 V and the validation time of 10 ms, the time delay of the current breaker is not more than 1 ms. When resistance of the dump resistor is 0.15 Ω and quench occurs at the nominal current of 5730 A in the high field region of the coil, the maximum voltage on the dump resistor will be 860 V and the maximum temperature of the hot spot in the coil will achieve 105 K. Figure 5 shows the maximum temperature and the current decay in the quadrupole coil at quench.

## CONCLUSION

Four wide-aperture superconducting quadrupoles for strong final focusing of energetic heavy ion beams in future plasma physics experiments at FAIR have been developed. The design of the magnets suppressed lower central multipole fields of the 6, 10 and 14 orders as well as the 6 integral harmonic. The quadrupoles have 37.57 T/m central gradient, 260 mm superconducting coil inner diameter and 1.89 m geometric length with the effective length of 1.757 m. The temperature margin is 1 K at 4.85 K outlet liquid helium temperature.

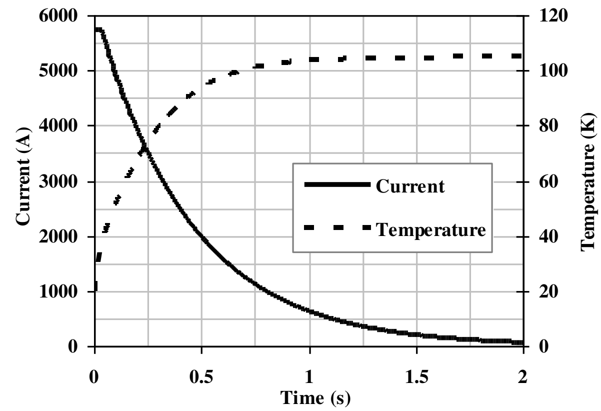


Figure 5: Hot spot temperature and current during quench.

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