NORMAL CONDUCTING QI AND QJ QUADRUPOLES FOR THE HERA LUMINOSITY UPGRADE

N.Bogatov, E.Bondarchuk, N.Doinikov, V.Ivkin, B.Kitaev, V.Korshakov, N.Maximenkova, V.Muratov, A.Nikiforovski, A.Petrov, Yu.Pusinovich, A.Simakov,
Efremov Institute, St. Petersburg, Russia
B.Parker, BNL, Upton NY, United States
K.Sinram, F.Willeke, G.Woebke, DESY, Hamburg, Germany

Abstract

The Efremov Institute and DESY have designed in collaboration high performance normal conducting quadrupole magnets for the HERA luminosity upgrade[1]. The quadrupole magnets QI and QJ are almost 2m long, they have a pole radius of 37mm and 50mm and must provide a gradient of 27T/m and 18T/m respectively. The requirements for the field linearity is in the order of several $1*10^{-4}$ at a reference radius of 25mm. The space between the coils must be kept free for a synchrotron radiation fun to pass through. Results of detailed design of these magnets are presented and discussed.

1 INTRODUCTION

An upgrade of the HERA straight section is planned in order to increase the design of luminosity by a factor of more than four. Conventional magnets design has to be pushed in order to achieve the ambitions goal.

Four types of normal conducting iron quadrupole magnets are needed for strong and effective low-β-focusing of the proton and the lepton beams in the new interaction region of HERA[2-4]. The magnet design pushs the limits of conventional magnet technology. As a result, field gradients of up to G=30T/m are achieved in large aperture magnets with minimized space requirements for coils, poles and return yokes. The field quality requirements in these magnets are quite stringent. Nonlinearities at radius of 25mm must not exceed a limit of a few units of 10^{-4} in • B/B.

Normal conducting magnets QI and QJ provide low-beta focusing for the HERA lepton beam. The nominal operating energies of the magnets QI and QJ are 12GeV (injection) and 30GeV (luminosity operation). Each magnet should allow operation up to 30GeV and down to 7Gev with no more than a factor two degradation in field quality.

The QI and QJ are a compact fully symmetric high field quality conventional quadrupole magnets. Their specialty is a gap between the coils in the magnet midplane for the synchrotron radiation. To maintain symmetry, the coil geometry is the same in all four quadrants.The value of inductance in the pole ($G*a_0$=1T, a_0 - radius aperture) is quite large. That means iron in the pole fully saturated with B_{Fe}=2-2.3T.

As an initial approximation [5], the profile is taken (for example 1/8 of the magnet) in the following form: the pole generatrix profile with the hyperbolic central part goes tangentially at $x/a_0=1$ to the rectilinear part; then the part is rounded off resulting in the so-called "little shelf" parallel to the midplane. Then the rounded of section transform into an inclined (at an angle of 38^0) rectilinear part. The calculations for the optimization of the pole profile were performed by POISSON [6] and OPERA 2D [7] codes. In case of the QI magnet the influence of harmonics with k=6,10,14 was large and in case of QJ magnet - only harmonics with k=6 (see sections 2 and 3) are important.

The high field quality requires high precision in stamping of the well optimized pole contours and also high precision in magnet assembly. Required stamping and assembly precision are at the level 10-20μm (see section 4). In addition, the magnets have small correction windings which help to assure that the field quality can be achieved over the whole excitation range and to compensate field errors from manufacturing tolerances (harmonics k=3).

2 DESIGN AND FIELD CALCULATION FOR THE QI MAGNET

The 1.88 meter long magnet has a strong gradient of 27T/m at a relatively large pole radius of 37mm. The field errors must be less than $3\cdot10^{-4}$ on a reference radius r=25mm for both, low excitation and high excitation. Fig.1 gives a detailed view of the cross section of magnet QI. The results of the magnet computations are summarized in table 1.

Table 1: Results of quadrupole QI computations. $S=1-f(Aw)/f((Aw)_{max})/2$, $f(Aw)=G/Aw$.

Aw	G	a_6/a_2	a_{10}/a_2	a_{14}/a_2	S
kA	T/m	10^{-4}	10^{-4}	10^{-4}	10^{-2}
1.710	3.097	0.03	0.12	-0.24	0.60
4.275	7.786	-0.06	0.12	-0.24	0.05
8.550	5.580	-0.11	0.12	-0.24	0
10.6875	19.422	-0.16	0.12	-0.24	0.27
12.825	22.704	-0.22	0.12	-0.24	2.85
14.9625	25.267	-0.35	0.12	-0.24	7.33
17.1	27.046	-0.65	0.10	-0.24	13.2

The magnetic properties of steel St_{2081} (μ_{max}=3000, B_s=2T) have been assumed in the field calculations. The maximum field error in whole range of excitation has harmonic content a_6 $\Delta(a_6/a_2)<0.7*10^{-4}$. Harmonics with k=10,14 are almost constant.

The magnet yoke will be produced from laminated magnet steel 0.75mm thickness. and is re-enforced by a rectangular magnet frame made from 10mm thick magnetic steel. This frame is welded to the laminations of the yoke. The mechanical construction is such that the magnet can be separated into two halves easily inside the HERA tunnel to allow for easy installation of the beam pipes. The magnet also has removable pole tips for optimization of the fringe field. The magnet coils are made from rectangular copper conductors with a specific resistance of not more than 17.2m• /mm^2. The coil insulation will be made with vacuum impregnation. Turn-to-ground insulation is designed for a voltage of V=1000V. The coils are water cooled. Despite of the large gradient of 27T/m, the magnet is only 522mm wide. As a result of the high current density in the coil, a large number of the parallel cooling circuits (4 for each coil) is necessary. A pressure gradient of up to 7bar is allowed in each of the parallel cooling circuits. Thermo switches on the conductor detect the temperature of the coil.

The main parameters of the magnet are summarized in table 2.

Table 2: Main parameters of the QI magnet

Parameters	Value
Field gradient, [T/m]	27
Aperture radius, [mm]	37
Magnetic field homogeneity	$3x10^{-4}$
Rated current, [A]	502
Voltage drop, [V]	141
Ohmic resistance of the winding, [•]	0.25
Inductance of the winding, [H]	0.06
Power consumption, [kW]	70.9
Number of the coils per the winding	4
Number of turns per coil	34
Conductor dimensions, [mm]	8x8-∅5
Conductor cross-section area, [mm^2]	44
Hole cross-section, [mm^2]	19.6
Pressure drop per cooling circuit, [bar]	7
Cooling circuits per coil	4
Water speed per cooling circuit, [m/s]	2
Water volume in the cooling system, [l]	12
Water flow per winding, [l/s]	0.64
Water overheating, [K]	31
Cooling system is designed for	
max water pressure, [bar]	21
Magnet length [m]	1.984
Iron length [m]	1.88
Yoke steel weight, [t]	0.98
Winding copper weight, [t]	0.25
Magnet weight, [t]	1.65

3 DESIGN AND FIELD CALCULATION FOR THE QJ MAGNET

The QJ magnet, like the QI, is also compact quadrupole with space in between the coils for the synchrotron radiation fan. The 1.88 meter long magnet has a gradient of 18T/m at a large pole radius of 50mm. The field errors must be less than $1 \cdot 10^{-4}$ for low excitation case and $1 \cdot 10^{-4}$ for high excitation on a reference radius r = 25mm. Fig. 2 gives a detailed view of the cross section of magnet QJ.

The results of the magnet computations are summarized in table 3. The maximum variation in the whole range of excitation has a harmonic a_6 of $\Delta(a_6/a_2)<0.2*10^{-4}$.

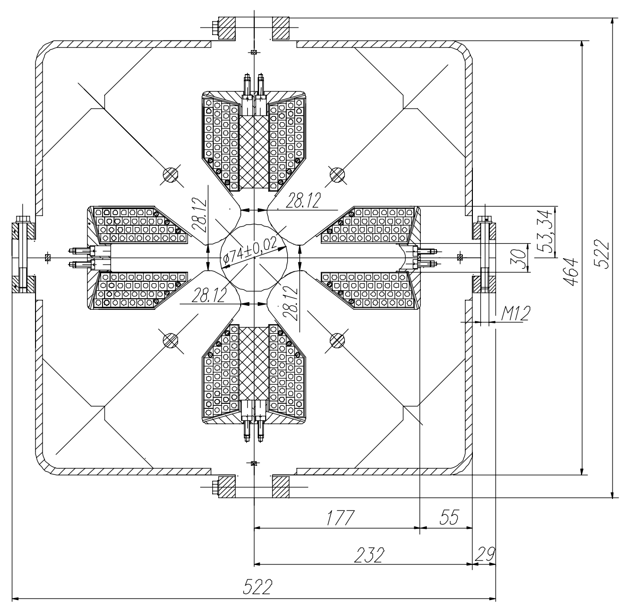

Figure 1: Cross section of magnet QI.

The return yoke of QJ leaves some extra space with a width of 40mm to provide room for distributed pumping. The mechanical construction of QJ magnet has the same features as QI. QJ differs from QI only by its larger aperture of r_{pole}=50mm (pole radius). As a result, it has a large number of turns in the coil and increased number of parallel branches of the water cooling circuit (6 per coil).

The QJ magnet has small correction windings. The main parameters of the magnet QJ are summarized in table 4.

Table 3: Results of quadrupole QJ computations

Aw	G	a_6/a_2	a_{10}/a_2	a_{14}/a_2	S(I)
kA	T/m	10^{-4}	10^{-4}	10^{-4}	10^{-2}
3.5	3.4915	0.16	-0.14	-0.01	0.09
10	9.9842	0.14	-0.14	-0.01	0
15	14.9314	0.10	-0.14	-0.01	0.3
17	16.6843	0.08	-0.14	-0.01	1.7
19	18.17	0.01	-0.14	-0.01	4.2

Table 4: Main parameters of the QJ magnet

Parameters	Value
Field gradient, [T/m]	18
Aperture radius, [mm]	50
Magnetic field homogeneity	$1x10^{-4}$
Rated current, [A]	422
Voltage drop, [V]	155
Ohmic resistance of the winding, [•]	0.34
Inductance of the winding, [H]	0.13
Power consumption, [kW]	65.4
Number of the coils per winding	4
Number of turns per coil	45
Conductor dimensions, [mm]	8x8-∅5
Conductor cross-section area, [mm^2]	44
Hole cross-section, [mm^2]	19.6
Pressure drop per cooling circuit, [bar]	7
Cooling circuits per coil	6
Water speed per cooling circuit, [m/s]	2
Water volume in the cooling system, [l]	16
Water flow per winding, [l/s]	1.04
Water overheating, [K]	20
Cooling system is designed for max water pressure, [bar]	21
Magnet length [m]	2.020
Iron length [m]	1.88
Yoke steel weight, [t]	3.4
Winding copper weight, [t]	0.336
Magnet weight, [t]	3.75

4 QUALITY CONTROL OF THE MAGNETS

The accuracy of the completed quadrupole magnets is achieved by system of close tolerances for the main parts of the magnet (lamination, yoke quadrant, coil, assembled yoke). These tolerances are ensured by the precise manufacturing tooling (i.e. the die, stacking fixture, device for yoke assembly, mandrel and mold for winding and forming of the coils) as well as proper inspection during the main processing operations in content with the quality control program.

The tolerance on the dimensions of the lamination is ±10μ. The first three punched laminations are measured on the coordinate measuring machine with a precision of 3-4μ.

The reference surfaces of the stacking fixture are adjusted with straightness tolerance of 0.01mm at the length of 1m, and are optically measured by autocollimator with a precision of 3-5μ. The aperture (distance between the opposite pole tops) and the symmetry of the pole positions (specified tolerance is ± 0.02mm) will be measured inside the magnet along the entire length by a special gauge with an accuracy of 5-6μ. It consists of an inductance-type gauge, travelling mechanism and electronic data system.

This device is now designed and it will be manufactured by the time of measurement of the first magnets.

The final decision about quality and readiness of the magnets will be made on the basis of acceptance tests and magnetic measurements.

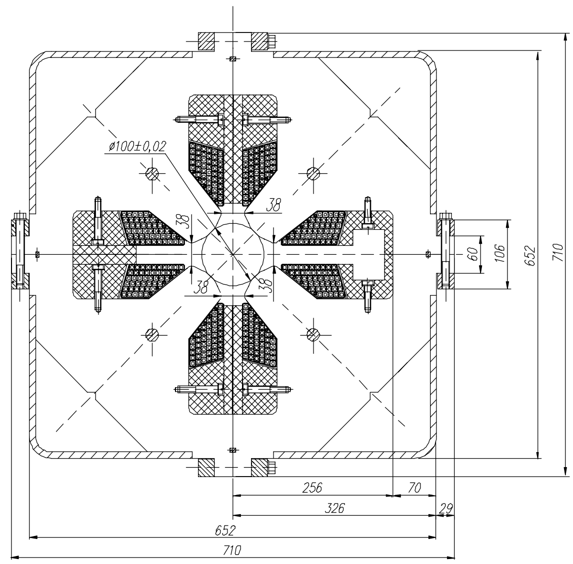

Figure 2: Cross section of magnet QJ

REFERENCES

[1] "Future Physics at HERA", G. Ingelmann, et.al., 1995/96 workshop at DESY, 1996.

[2] "HERA Luminosity Upgrade", L. Suszycki, et.al., DESY workshop working group report, July,1997.

[3] "On Increasing HERA Collider ep IR Luminosity", W. Bartel, et.al., proceedings EPAC'96, June,1996.

[4] "HERA Status and Future Plans", F. Willeke proceedings of PAC'97, Vancouver, May,1997.

[5] K.G. Steffen, High-energy beam optics - N.Y.: Wiley (Interscience), 1965.

[6] POISSON Group Programs. User's Guide, CERN, 1975.

[7] Opera 2D reference manual, VF-01-97-24, Vector Fields Limited, 24 Bankside, Kidlington,Oxford OX5 1JE