5 Normal Conducting Magnets

5.1 General Description

Six 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. The magnet design is pushing the limits of conventional magnet technology. As a result, field gradients of up to 30 T/m in large aperture magnets with minimized space requirements for coils, poles and return yokes have been designed. The field quality requirements in these magnets are quite stringent. Nonlinearities at a radius of 25 mm must not exceed a limit of a few units of 10^{-4} in $\Delta B/B$.

Almost identical elements are going to be needed for the North and the South interaction region. The two superconducting magnets, QG and QH on the right side of the IR are followed by the normal conducting QI and QJ which provide low-beta focusing for the electron beam. The specialty of QI is that it has a gap between the coils in the magnet midplane for the synchrotron radiation fan. It has a strong gradient of 27 T/m at a relatively large pole radius of 37 mm. QJ is a large aperture magnet with a pole radius of 50 mm. It has the same split-coil feature as QI. The next magnetic elements for the lepton beam are the existing QK-type magnets at 32 m and 45 m. After QJ, the two beams see different magnetic fields and travel in separated beam pipes. The first proton low beta focusing element QM is a vertically focusing septum half-quadrupole with a mirror plate. The magnet is 3.4 m long. It has a 37 mm pole radius, a gradient of 25 T/m and needs the split coil feature as do QI and QJ. Two QM magnets are needed on each side of the IR's. The cut out in the mirror plate which makes room for the lepton beam is a new feature. The challenge of this magnet is to maintain good field quality over the whole excitation range. The next magnets are the also vertical focusing, 1.95 m long QN magnets which have a very large gradient of 30 T/m and small coils which act as a septum between p- and e-beam. There is sufficient space between the return yoke and the coil of these magnets. The radially-inwards space is for the lepton beam and the radially-outwards space is for the γ-beam. The challenge of these magnets is to provide high field quality despite unavoidable saturation effects and to manage the large dissipated power of 124 kW per magnet. Three such magnets are needed on either side of the two IR's. The QN and QM accomplish the first part of vertical focusing of the protons. Horizontal focusing is provided by Q8 and Q9. These are 3.85 m long magnets. Q8 has the same profile as QN but has a larger coil which still leaves enough space for the lepton beam inside the return yoke. Q9 has a minimized return yoke. It is the first magnet at which the electron beam passes outside of the iron yoke. The main parameters of these magnets are listed in table 18. Fig. 42 gives an overview of the magnet system including the longitudinal and transverse space requirements.

5.2 Field Quality Requirements

The nominal operating energies of the magnets QI and QJ are 12 GeV (injection) and 30 GeV (luminosity operation). Each magnet should be good enough to allow operation up to 30 GeV and down to 7 GeV without a factor of more than two degradation in field quality. The operating range of the magnets QM and QN, Q8 and Q9 corresponds to beam energies of 40 GeV to 820 GeV.

Name	Type	L_m (m)	G_{max} (T/m)	R_p (mm)	B_p (T)	# Req.	Comments
QI	Q	1.88	27.	37	0.980	6	Split coil for synchrotron radiation
QJ	Q	1.88	18.	50	0.900	4	Split coil for synchrotron radiation
QM	Q+D	3.40	25.	37	0.925	8	Half-quadr., mirror plate with cut-out
QN	Q	1.95	30.	35	1.050	12	High current density septum coil
Q8	Q	3.85	26	35	0.950	4	Septum coil magnet
Q9	Q	3.85	26	35	0.950	4	Small return yoke
QR	Q	3.00	24.	35	0.840	–	Reuse existing QR magnets

Table 18: *Main parameters of warm magnets of the luminosity upgrade.*

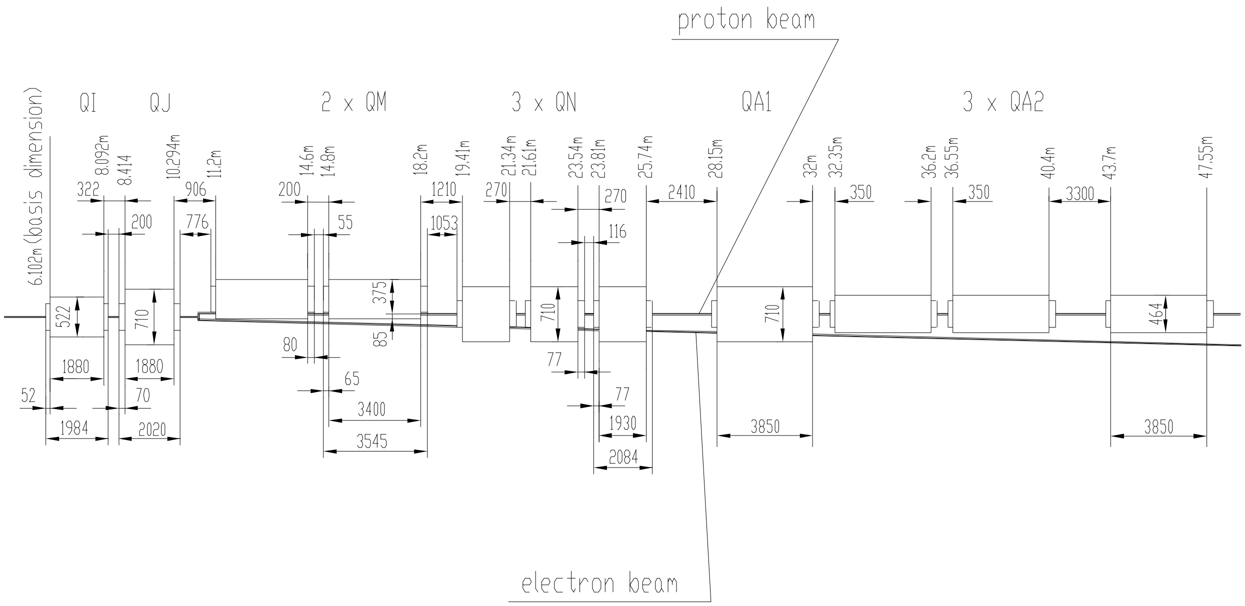

Figure 42: *Overview of the HERA Luminosity Upgrade Rev2.2 Magnet configuration, note the distorted horizontal/vertical scale. (QA1 and QA2 are called Q8 and Q9 in the text.)*

The maximum allowed deviation of the magnetic center of the magnet from the geometric center will be denoted by D. D should not exceed 1 mm for the magnets QI and QJ. The magnet QN is less critical. The field center may deviate as much as 5 mm from the geometric center.

The magnet excitation function, $g(I) = [\int G dl]_I$ is expected to be found within 5×10^{-3} of the predicted value. The design of the magnet should allow to achieve a reproducibility in $g(I)$ of 1×10^{-3}. The gradient in the magnet center should not vary by more than 0.5% for individual magnets in the production process. Saturation and remnant effects are described by

Magnet Name	Reference Radius R [mm]	$\Delta B/B$ low excit. $[10^{-4}]$	$\Delta B/B$ high excit. $[10^{-4}]$
QI	25	3	3
QJ	25	1	1
QM	25	3	3
QN	25	10	3
Q8	25	3	3
Q9	25	3	3

Table 19: *Field error limits of warm magnets.*

a function $S(I)$. Given the definition for $g(I)$ above and its derivative,

$$g'(I) = \frac{d\left[\int G dl\right]}{dI}, \tag{39}$$

$S(I)$ is then given by

$$S(I) = 1 - \frac{g(I)}{g(\frac{I_{MAX}}{2}) + g'(\frac{I_{MAX}}{2}) \cdot (I - \frac{I_{MAX}}{2})}. \tag{40}$$

The function $S(I)$ should be smaller than 0.02 everywhere in the nominal operating range of the magnets.

The quadrupole magnets QI, QJ, QN and QM, Q8 and Q9 need to be accelerator quality magnets. The field quality must be the same or better than that of other quadrupole magnets in HERA. The sensitivity of the beam to non-linear field errors is enhanced in the insertion regions. This has been taken into account and the corresponding field quality requirements are quite demanding.

The field quality will be defined as the maximum deviation of the field from an ideal quadrupole field at a given reference radius R around the beam axis. This definition includes only non-linear field errors.

$$\frac{\Delta B(R)}{B} \equiv Max \left| \frac{\int (B(R,\Phi) - G(R=0) \cdot R) dl}{\int G(R=0) \cdot R dl} \right|, \tag{41}$$

where G is the field gradient,

$$G = \frac{d}{dy} B_y = \frac{d}{dx} B_x \tag{42}$$

and $B(R,\Phi)$ is the radial field at a radius R and azimuth Φ.

5.3 Main Features of the Normal Conducting Magnets

The magnet yokes will be produced from laminated magnet steel. The mechanical construction is such that the magnets can be separated into two halves easily inside the HERA tunnel to allow for easy installation of the beam pipes. The magnets also have removable chambers/end-plates for optimization of the fringe field. The magnet coils are made from rectangular copper

I, kA	G, T/m	$b_6/b_2[10^{-4}]$	$b_{10}/b_2[10^{-4}]$	$b_{14}/b_2[10^{-4}]$	S(I)	F_x, kp/m	F_y, kp/m
1.710	3.097	+0.0357	0.1176	-0.2445	0.0064	3.737	1.514
4.275	7.786	-0.0564	0.1217	-0.2446	0.0005	23.50	9.541
8.550	15.580	-0.1145	0.1233	-0.2446	0	94.11	38.19
10.6875	19.422	-0.1553	0.1233	-0.2445	0.0027	146.9	59.41
12.8255	22.704	-0.2206	0.1233	-0.2442	0.0285	210.2	81.85
14.9625	25.267	-0.3505	0.1203	-0.243	0.0733	364.2	120.1

Table 20: *The results of QI (2-d) magnet computation. The b_n represent the multipole coefficients measured on a radius of 25 mm around the quadrupole axis. Multipole errors are not taking into account the end effects.*

conductors with a specific resistance of not more than 17.2 mΩ/mm^2. The conductor insulation will consist of two layers. An inner layer of 50 μm Kapton film is wrapped by a glass-fiber-epoxy compound. The coils are water cooled. A pressure gradient of up to 7 bar is allowed in each of the parallel cooling circuits. The electrical power necessary to excite the magnets is quite large. Thermo switches on the conductor survey the temperature of the coil. The high field quality requires high precision in stamping of the well optimized pole contours and also high precision in magnet assembly. Required stamping precision is 10 μm and the assembly precision is 20 μm. The coils must be placed with a precision of 100 μm. In addition, most of the magnets have small correction windings which help to assure that the field quality can be achieved over the whole excitation range and which help to compensate field errors from manufacturing tolerances. Each magnet has to undergo a number of tests after assembly. The verification of the field quality is a particularly important issue.

5.4 QI Magnet

The QI magnet is a compact fully symmetric high field quality conventional quadrupole magnet. The specific feature of the QI magnet is the free space between the coils in the magnet midplane to provide space for the synchrotron radiation fan of the electron beam. To maintain symmetry, this coil geometry is kept for all four quadrants.

The QI magnet has an aperture of 37 mm (pole radius) and must produce a gradient of 27 T/m. The field errors must be less than $3 \cdot 10^{-4}$ for low and for high excitation on a reference radius r = 25 mm. The optimization of the pole profile to achieve the required field quality does not represent a particular problem. The results of the magnet computations are summarized in table 20. I is the magnet current times the number of windings, G is the quadrupole gradient, b_n [5] are the multipole coefficients on a reference radius of 25 mm, $S(I)$ is the transfer function parameter defined in the previous section, ($b_2 = 1$), and $F_{x,y}$ are the transverse forces per unit length which act on the coil. The QI magnet is the warm quadrupole which is placed closest to the IP, and which is still surrounded by detector components. The transverse dimensions of this magnet are kept small. Despite the large gradient of 27 T/m, the magnet is only 52.2 cm wide. As a result the current density in the coil is quite large and a large number of parallel cooling circuits (4 for each coil) are necessary. The magnet is 1.984 m long including space for the coil heads. The iron length amounts to l = 1.88 m. The magnet yoke is re-enforced by a rectangular

[5] The b_n are defined as $\int \Delta B dl / \int B dl = \sum_{n=1}^{\infty} (b_n + i a_n)(x+iy)^{n-1}/r_{ref}^{n-1}$

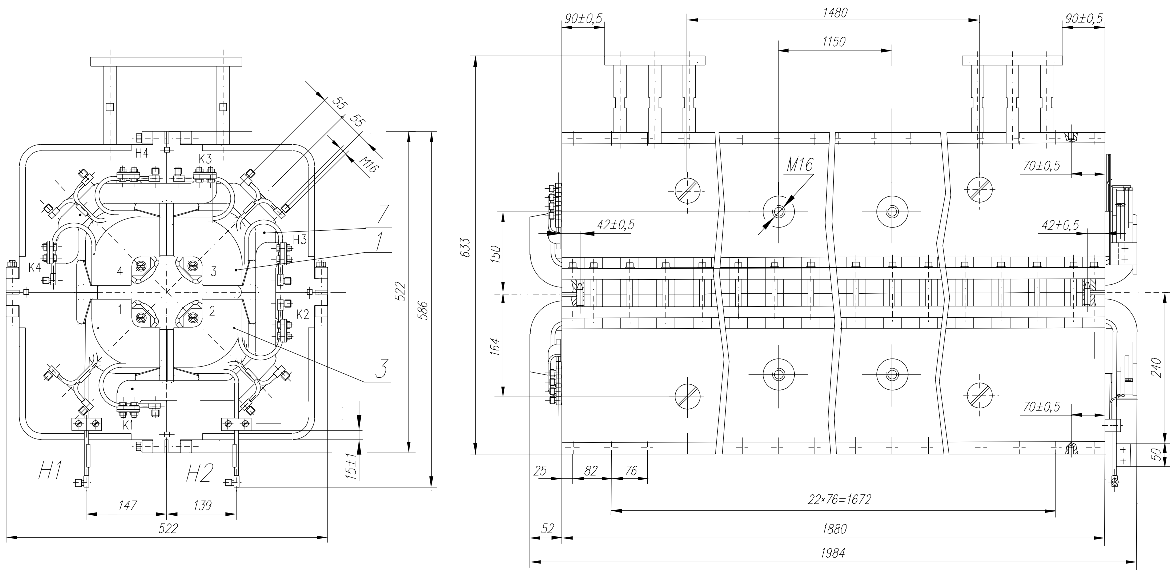

Figure 43: *General view of the Magnet QI. QI is a compact, conventional quadrupole with high gradient, good field quality, a split coil to make room for synchrotron radiation and small transverse dimensions (width 52.2cm).*

magnet frame made from 10 mm strong magnetic steel. This frame is welded to the laminations of the yoke. The magnet can be separated into its quadrants. Quadrants are held together by stainless steel screws at slots at the outside of the return yoke. The space between the coils is filled with glass-fiber-epoxy where the space is not needed for the synchrotron radiation beam. Holes through the upper and lower return yoke are foreseen to provide support for the vacuum chamber. Fig.43 presents the general view of the magnet, Fig. 44 gives a detailed view of the cross section The main parameters of the magnet are summarized in table 21.

Parameter	Value
Field gradient [T/m]	27
Aperture radius [mm]	37
Slot height between the coils [mm]	30
Magnetic field homogeneity at r = 25 mm [10^{-4}]	3
Rated current [A]	502
Voltage drop [V]	141
Ohmic resistance of the winding [Ω]	0.35
Inductance of the winding H	0.06
Power consumption [kW]	70.9
Number of the coils per the winding	4
Number of turns per the coil	34
Conductor dimensions [mm x mm]	8x8
Conductor cross-section area [mm^2]	44
Hole cross-section [mm^2]	19.
Pressure drop per cooling circuit [bar]	7
Cooling circuit per the coil	4
Water speed per cooling circuit [m/s]	2
Water volume in the cooling system [l]	12
Water flow per the winding [l/s]	0.64
Water Temperature Rise [K]	31
Maximum allowed water pressure [bar]	21
Magnet length [m]	1.9844
Magnet iron length [m]	1.88
Magnet width [m]	0.522
Yoke steel weight [t]	0.98
Winding copper weight [t]	0.25
Magnet weight [t]	1.65

Table 21: *Parameters of QI Quadrupole Magnet.*

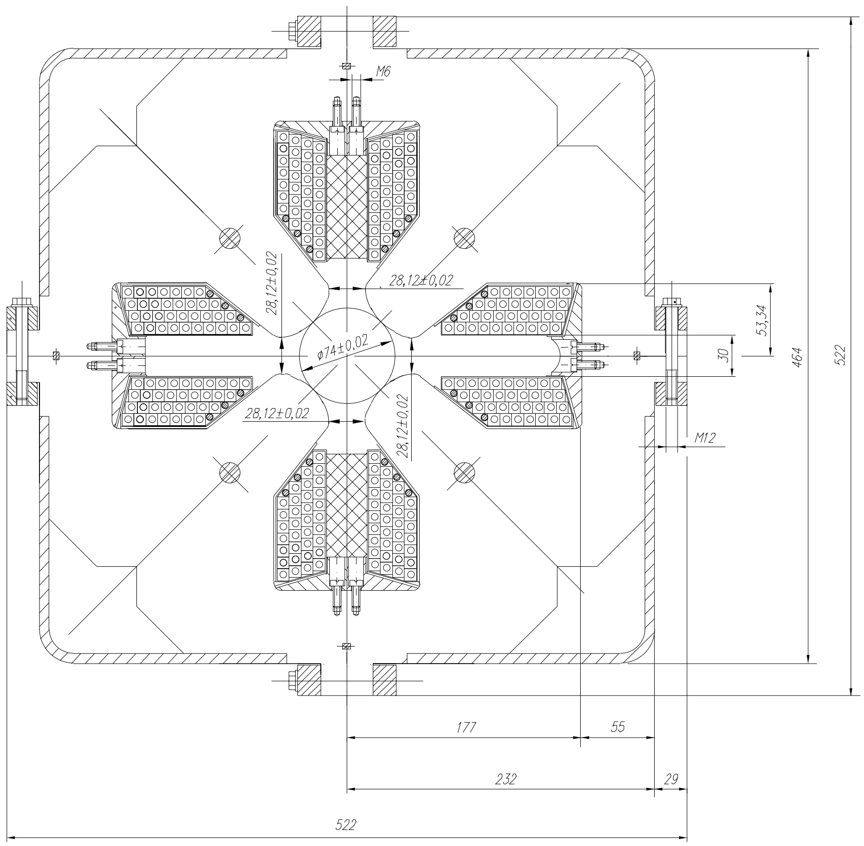

Figure 44: *Cross section of magnet QI. QI is a symmetric quadrupole with a split coil. The aperture radius is* $r_{pole} = 37$ *mm, the space between the coils is 30 mm, the magnet structure is re-enforced by a frame of magnetic steel. The Magnet QI can be separated into its quadrants.*

5.5 QJ Magnet

Like QI, the QJ magnet is a compact quadrupole with space in between the coils for the synchrotron radiation fan.

The QJ magnet has a 50mm aperture (pole radius) and must produce a gradient of 18T/m. The field error must be less than $1 \cdot 10^{-4}$ for the low and for high excitation on the reference radius 25 mm. QJ is a fully symmetric quadrupole lens and there are no problems with field quality. The pole contour has been optimized. The results of magnet computation are summarized in table 22. Table 23 lists the forces on the QJ coil.

I	G_0	b_6/b_2	b_{10}/b_2	b_{14}/b_2	$\sum \lvert b_k/A_2 \rvert$	G_0/I	S(I)	$\lvert F \rvert$
$[kA]$	[T/m]	$[10^{-4}]$	$[10^{-4}]$	$[10^{-4}]$	$[10^{-4}]$	$[T/(m \cdot kA)]$	$[10^{-2}]$	$[10^4 N]$
3.5	3.4915	0.16	-0.14	-0.01	0.31	0.9976	0.09	-
10	9.9842	0.14	-0.14	-0.01	0.29	0.9984	0	-
15	14.9314	0.10	-0.14	-0.01	0.25	0.9954	0.3	-
17	16.6843	0.08	-0.14	-0.01	0.23	0.98134	1.7	-
19	18.17	0.01	-0.14	-0.01	0.16	0.95632	4.2	-

Table 22: *The results of QJ computation.*

I[kA]	19	10	2
Fx [N/m]	376	105	40
Fy [N/m]	206	61	20

Table 23: *Magnetic forces on the QJ coil.*

The transverse space requirements of the QJ magnet do not impose a serious boundary condition. The return yoke of QJ leaves some extra space with a width of 40 mm to provide room for distributed pumps. The mechanical construction of QJ has the same features as QI. QJ differs from QI by its larger aperture of $r_{pole} = 50$ mm (pole radius). As a result, it has a larger number of turns in the coil and an increased number of parallel branches of the water cooling circuit (six per coil). Fig. 45 presents the general view of the magnet, Fig. 46 gives a detailed view of the cross section. The main parameters of the magnet QJ are summarized in Table 24.

Parameters	Value
Field gradient [T/m]	18
Aperture radius [mm]	50
Slot height between the coils [mm]	30
Magnetic field homogeneity [10^{-4}]	1
Rated current [A]	422
Voltage drop [V]	155
Ohmic resistance of the winding [Ω]	0.34
Inductance of the winding [H]	0.13
Power consumption [kW]	65.4
Number of the coils per the winding	4
Number of turns per the coil	45
Conductor dimensions [mm^2]	8x8
Conductor cross-section area [mm^2]	44
Hole cross-section [mm^2]	19.5
Pressure drop per cooling circuit [bar]	7
Cooling circuit per the coil	6
Water speed per cooling circuit [m/s]	2
Water volume in the cooling system [l]	16
Water flow per the winding [l/s]	1.04
Water temperature rise [K]	20
Maximum allowed water pressure [bar]	21
Magnet length [m]	2.020
Magnet iron length [m]	1.88
Magnet width [m]	0.710
Yoke steel weight [t]	3.4
Winding copper weight [t]	0.336
Magnet weight [t]	3.75

Table 24: *Main Parameters of the QJ Quadrupole.*

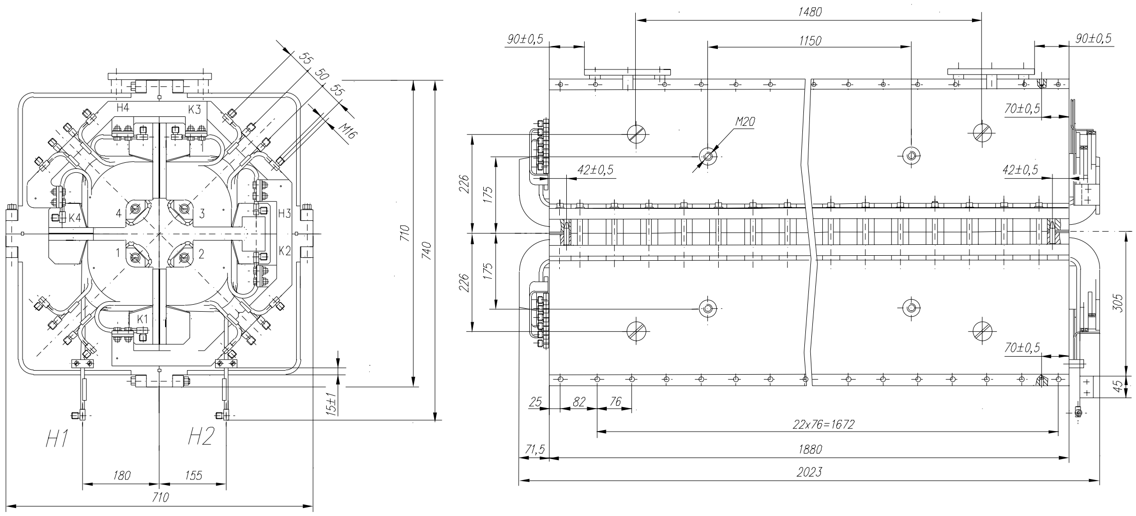

Figure 45: *General view of the Magnet QJ. QJ is a compact, conventional quadrupole with high gradient, good field quality, a split coil to make room for synchrotron radiation and a large aperture.*

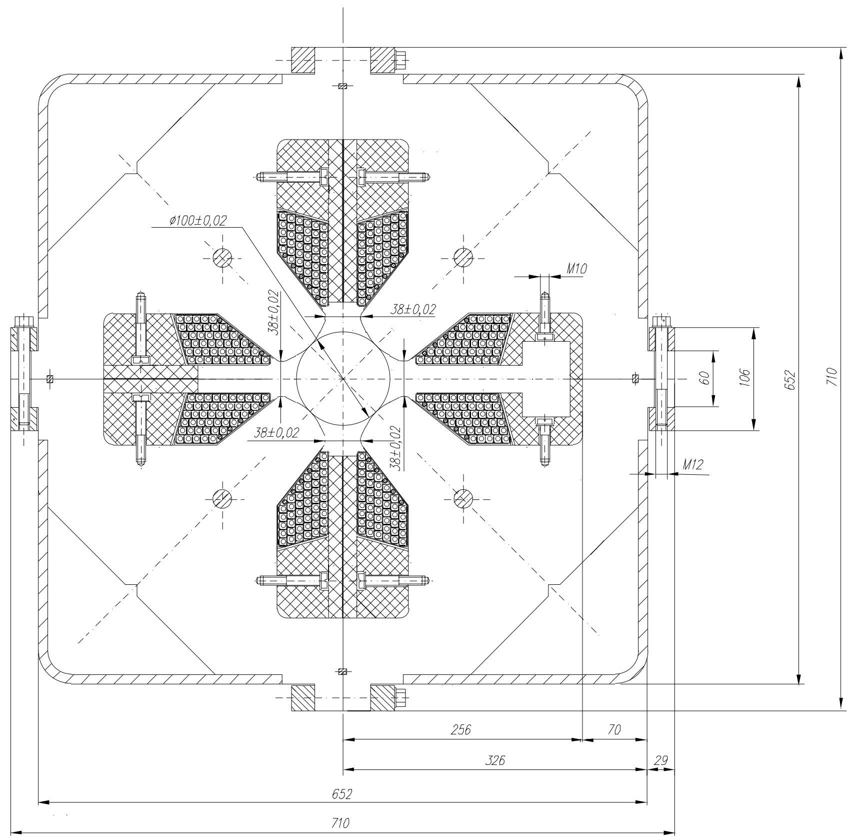

Figure 46: *Cross section of magnet QJ. QJ is a symmetric quadrupole with a split coil. The aperture radius is* $r_{pole} = 50\,mm$*, the space between the coils is 30 mm, the magnet structure is re-enforced by a frame of magnetic steel. The Magnet QJ can be separated into its quadrants.*

5.6 QM Magnet

The QM quadrupole magnet is a septum quadrupole which provides strong focusing to the proton beam and provides a quasi field free region for the electron beam which is as close as 56 mm to the center of the protons. QM is a half-quadrupole. Its mirror plate represents the septum. An ideal mirror plate would provide a quasi perfect quadrupole symmetry. However, there is a deep, triangular-shaped cut-out to provide a field free region for the electron beam close to the magnet aperture. QM has free space between its coils to provide room for the synchrotron radiation fan.

The QM magnet has 37 mm aperture and must produce a gradient of 25 T/m. At both high and low excitation the field error must be less than $3 \cdot 10^{-4}$ on the reference radius of r_{ref} =25 mm. The main feature of QM regarding the field quality is its steel mirror plate with a cut out. This arrangement is a serious distortion of the quadrupole symmetry for the two quadrupole quadrants. The optimum of the opening angle of the triangular cut-out was found to be 90°. The edge of the cut-out at the origin of the half quadrupole is removed, leaving a small septum of 15 mm thickness this way. The mirror plate has a thickness of 85 mm. However, even after optimization, which also has to take into account the field seen by the lepton beam in the cut-out, the field quality is not satisfactory. Without special measures, the non-symmetric geometry leads to strong field imperfections, in particular near the origin. A perfect "knife edge" mirror plate with zero width at the origin would provide a more favorable situation, however, this is be excluded for the sake of mechanical stability. The minimum width of the mirror plate is 5 mm. This helps to provide a field of less than 10 G seen by the electron beam in the cut-out. Furthermore, the steel quality of the mirror plate is an important factor in the field quality consideration. However, high quality, soft magnetic steel with sufficiently large permeability over the whole range is available only in form of thin sheet metal, but not in form of large blocks as would be required for the plate. For this reason, it was decided to add correction windings around the mirror plate to reestablish a symmetric field configuration. Two pairs of coils ("upper"- and "lower" coil) are necessary to obtain satisfactory results. The optimization of QM is performed in two steps. First, the magnet profile is optimized for a perfectly symmetric geometry. In a second step, the effect of the correction windings is added to take into account the effect of the mirror plate. The results of step one of the QM magnet computations are summarized in table 25. The computation taking into account the mirror

-I[A]	G [T/m]	b_6/b_2	$b_{10}/b_2[10^{-4}]$	$b_{14}/b_2[10^{-4}][$	F_x, kg/m	F_y, kg/m
700	1.21	+1.04	-0.496	-0.179	0.7	0.2
16000	25.82	-0.42	-0.494	-0.1.78	263	73

Table 25: *The results of QM magnet computation as full quadrupole magnet.*

plate shows that if steel-10 is used for the plate, we need a current of approximately 60 A in the upper correction coil and about 4 A in the lower correction coil.

The mirror plate is subject to strong magnetic forces. The horizontal force F_x is about 25 kN/m at full excitation. Since the plate is not allowed to move by more than 10 μm under the influence of these forces to assure the field quality, the plate is supported from the magnet poles by bronze support bars. With the help of these supports, the deformation of the mirror plate under the load of the magnetic forces is within the limits of 10 μm. The length of the plate exceeds the length of the iron yoke of the magnet by 35 mm to decrease the stray field on the e-beam trajectory. In addition, the mechanical stability of the mirror plate is improved by a stainless steel reenforcement structure, consisting of an array of massive handles, which are bolted to the plate. The coils are split in the magnet midplane to make room for the synchrotron radiation fan. The return yoke of QM leaves additional space behind the coils for distributed vacuum pumps.

The mirror plate can be removed and the two quadrupole quadrants are then separable. However, for re-assembly, high precision tooling is required. Fig. 47 presents the general view of the magnet, Fig. 48 gives a detailed view of the cross section. The main parameters of the magnet are summarized in Table 26.

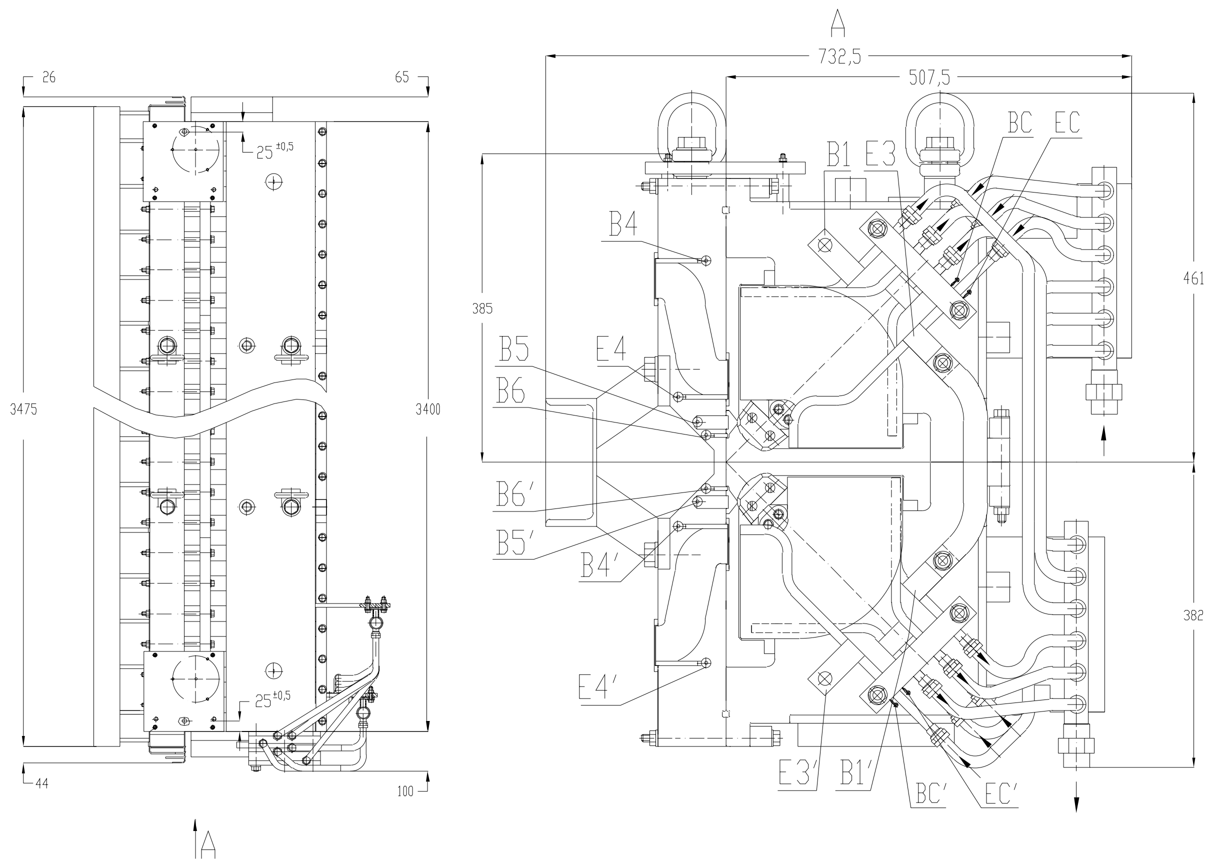

Figure 47: *General view of the Magnet QM. QM is a septum half quadrupole with a cut-out mirror plate.*

Parameters	Value
Field gradient [T/m]	25
Aperture radius [mm]	37
Slot height between the coils [mm]	30
Magnetic field homogeneity [10^{-4}]	3
Rated current [A]	471
Voltage drop [V]	49
Ohmic resistance of the winding [Ω]	0.091
Inductance of the winding [H]	0.175
Power consumption [kW]	23
Number of the coils per the winding	2
Number of turns per the coil	34
Conductor dimensions [mm x mm]	10×12
Conductor cross-section area [mm^2]	97.2
Hole cross-section [mm^2]	19.6
Pressure drop per cooling circuit [bar]	7
Cooling circuits per the coil	3
Water speed per cooling circuit [m/s]	1.35
Water volume in the cooling system [l]	10
Water flow per the winding [l/s]	0.18
Water temperature rise [K]	40
Maximum allowed water pressure [bar]	21
Magnet length [m]	3.585
Magnet iron length [m]	3.40
Magnet width [m]	0.5775
Yoke steel weight [t]	3
Winding copper weight [t]	0.44
Magnet weight [t]	3.75

Table 26: *Main Parameters of the QM Quadrupole Magnet.*

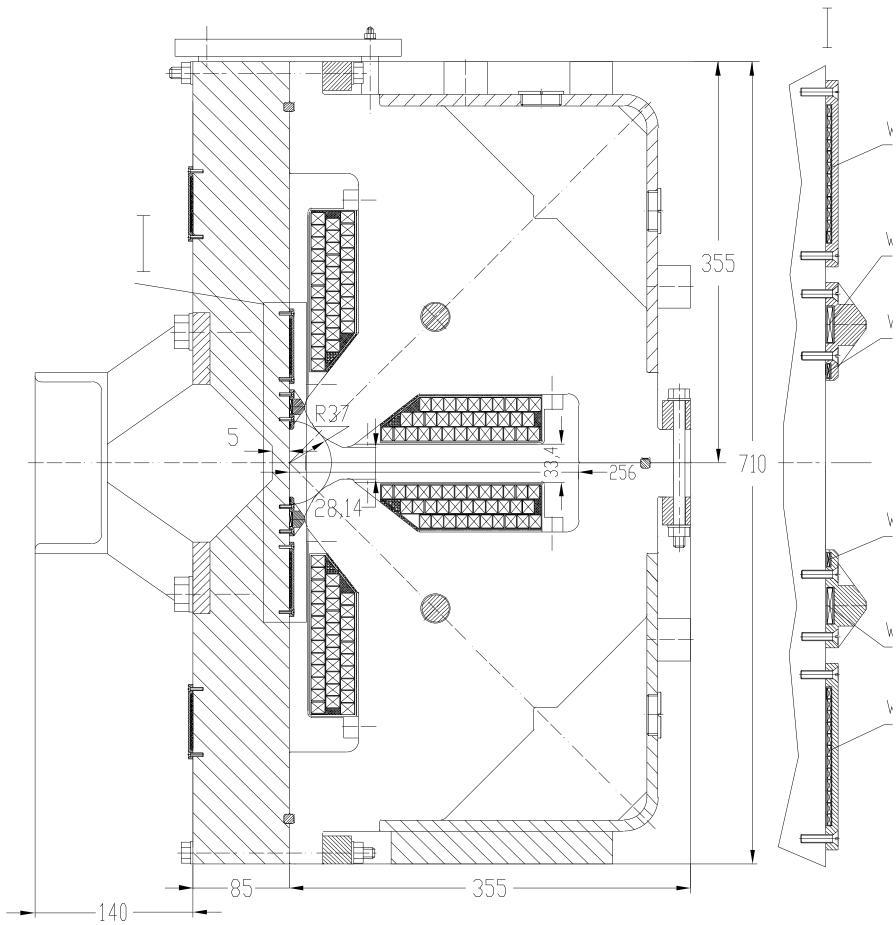

Figure 48: *Cross section of magnet QM. QM is a septum half quadrupole with a cut-out mirror plate. It also features a split coil. The aperture radius is* $r_{pole} = 37\,mm$*, the space between the coils is 30 mm, the magnet structure is re-enforced by a steel frame, the mirror plate is consolidated by stainless steel handles bolted to the plate.*

5.7 QN Magnet

QN is a septum quadrupole magnet with a large current density in each of its coils. It is placed at a distance of 18m from the IP where the proton and electron beam orbit are separated by 130 mm. The profile of this magnet is wide to provide space for the electron and synchrotron radiation beams which pass between the coil and the return yoke of the magnet. The width available for the coil between the two beams is only about 50 mm. In order to achieve a gradient of 30 T/m a current density of $J = 21\,\mathrm{A/mm^2}$ is required (counting only the copper part of the conductor). The coil consists of two parts with slightly different conductor dimensions, a two-layer coil which runs parallel to the side-face of the pole and a one-layer coil which extends along the magnet midplanes. In order to provide the required high field quality, a perfect quadrupole symmetry of the magnet is necessary. Therefore, the magnet laminations have a four-fold symmetry and the coil geometry is identical for all four quadrants. For this reason, QN has a large power consumption of 124 kW (per magnet).

The QN magnet has a 35 mm aperture and must produce a gradient of 30 T/m. The field error must be less than $\Delta B/B = 10 \cdot 10^{-4}$ @ $r = 25\,\mathrm{mm}$ for low excitation in which the magnet is only excited to 5 % of its nominal value and $\Delta B/B = 3 \cdot 10^{-4}$ @ $r = 25\,\mathrm{mm}$ for high excitation. In order to satisfy the stringent field quality requirements the pole profile has been carefully optimized. The magnetic field seen by the electron beam must be less than 20 G with a nonlinear component of less than 5 G. In order to reduce this field to the extent necessary, a plate of magnetic shielding material is inserted between the coil and the e-beam. If the magnetic shielding is inserted only in one quadrant the forbidden harmonics due to the distortion of symmetry increase (odd harmonics, mainly sextupole). To avoid this, shielding is therefore inserted in the other quadrants as well. The shape of these insertions, however, is somewhat different from the screen shape to ease the assembly of the magnet. The results of numerical simulations for a QN magnet with non-perfect symmetry is summarized in table 28. The whole arrangement is optimized and with a satisfactory result.

The results of numerical simulations for a QN magnet of perfect symmetry is summarized in table 27. Table 29 gives the magnetic forces on the coil. There is no free space between the coils in the magnet QN for the synchrotron fan. Therefore the coils must be protected by a synchrotron radiation absorber. There is magnetic shielding material of 9mm thickness between the coil and the vacuum chamber for the electron beam to keep the stray field of the QN magnet at a tolerable level. This stray field is less than 10 G. Fig. 49 presents the general view of the magnet, Fig. 50 gives a detailed view of the cross section. The main parameters of the magnet QN are summarized in Table 30

5.8 Q8 Magnet

Q8 is the first horizontally focusing proton low-β quadrupole. The Q8 quadrupole magnet is a septum magnet like QN, but with a larger coil and with reduced current density. The laminations of QN and Q8 are identical with a pole radius of 35 mm. The coil has a width of 120 mm. The center of the 80 mm wide beam pipe of the lepton beam is at a distance of 262 mm from the center of Q8.

The required field gradient of Q8 is 26 T/m. The iron length of the magnet is 3.85 m. The Q8 field quality corresponds to that of QN. Due to the somewhat lower gradient and the reduced current density, QA is a more conventional magnet. A total field error $\int \Delta B dl / \int B dl <$

Gradient [T/M]	1.4	30
Current [A]	700	16500
B_{pole} [T]	0.46	2.09
Harmonics	low excitation	high excitation
$b_6/b_2[10^{-4}]$	1.79	0.0323
$b_{10}/b_2[10^{-4}]$	0.06354	0.00548
$b_{14}/b_2[10^{-4}]$	-0.8632	-0.852

Table 27: *Harmonics for r=25 mm for perfectly symmetric QN with optimized pole profile.*

Current [A]	700	16500
Gradient [T/M]	1.4	30
Harmonics	Low Excitation	High Excitation
$b3/b_2[10^{-4}]$	-0.108	-0.1367
$b_4/b_2[10^{-4}]$	0.003068	0.00541
$b_5/b_2[10^{-4}]$	-0.002733	0.00470
$b_6/b_2[10^{-4}]$	1.78	-0.01801
$b_7/b_2[10^{-4}]$	0.002064	-0.00329
$b_8/b_2[10^{-4}]$	-0.001505	-0.00122
$b_9/b_2[10^{-4}]$	0.001483	0.00315
$b_{10}/b_2[10^{-4}]$	-0.1748	-0.04070
$b_{11}/b_2[10^{-4}]$	-0.007254	0.00733
$b_{12}/b_2[10^{-4}]$	-0.00725	0.00733
$b_{13}/b_2[10^{-4}]$	0.001647	0.00165
$b_{14}/b_2[10^{-4}]$	-0.84931	-0.8502

Table 28: *The result of magnetic computation for 1/2 QN magnet with optimized pole profile and non-perfect shielding screens, b_n are the multipole components.*

I[kA]	16.5
F_x [N/m]	5200
F_y [N/m]	1630

Table 29: *Forces on QN coil; Force on insertion is 160 N/m.*

Parameters	Value
Field gradient [T/m]	30
Aperture radius [mm]	35
Magnetic field homogeneity [10^{-4}@25 mm]	10
Rated current [A]	1460
Voltage drop [V]	84.6
Ohmic resistance of the winding [mΩ]	51.7
Inductance of the winding [mH]	8.68
Power consumption [kW]	123.6
Number of the coils per the winding	4; 4
Number of turns per the coil	5; 7
Conductor dimensions [mm x mm]	8x10;8.2x10.5
Conductor cross-section area [mm^2]	70.5; 68
Hole cross-section [mm^2]	14.2; 18.1
Pressure drop per cooling circuit [bar]	7
Cooling circuit per the coil	4
Water speed per cooling circuit [m/s]	3.61
Water volume in the cooling system [l]	3.4
Water flow per the winding [l/s]	0.88
Water Temperature rise s[K]	35
Maximum allowed water pressure [bar]	21
Magnet length [m]	2.095
Magnet iron length [m]	1.93
Magnet width [m]	0.708
Yoke steel weight [t]	3.4
Winding copper weight [t]	0.13
Magnet weight [t]	3.6

Table 30: *Main Parameters of the QN Quadrupole Magnet.*

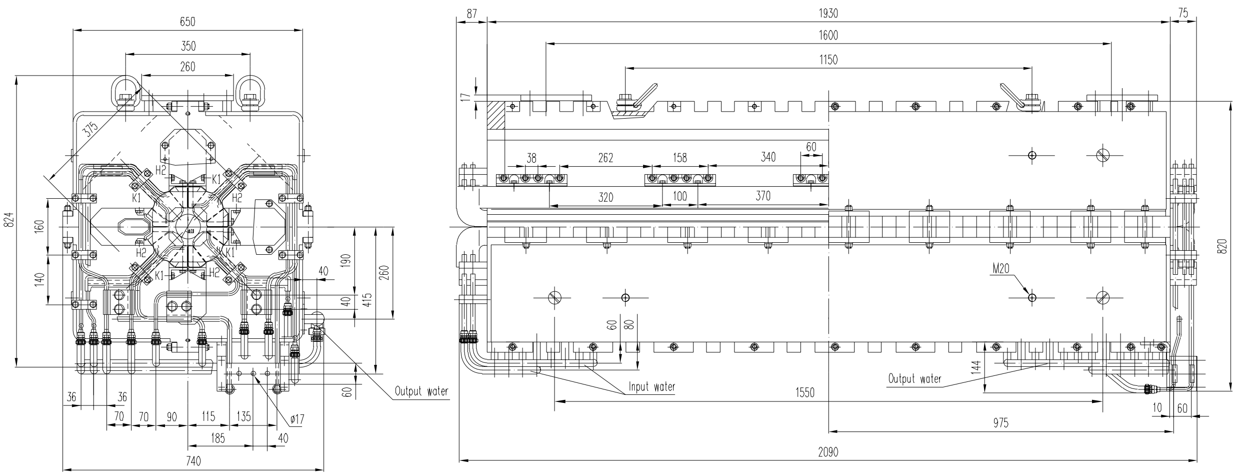

Figure 49: *General view of the Magnet QN. QN is a septum quadrupole quadrupole with a large current density of the coil and a wide return yoke to make quasi field free room for the electron beam.*

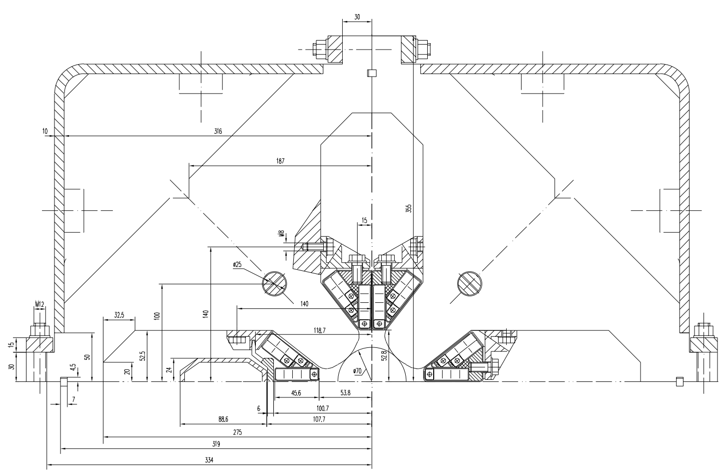

Figure 50: *Cross section of magnet QN. QN is a septum coil quadrupole with 21 A/mm^2. The coil consists of two parts, a two-layer and a one-layer component. The magnet is kept symmetric to preserve high field quality.*

$2 \cdot 10^{-4}$ @$r = 25$ mm can be achieved over the whole excitation range. The field seen by the lepton beam amounts to less than 10 G. The main parameters of the magnet Q8 are summarized in Table 31. Fig. 51 presents the general view of the magnet, Fig. 52 gives a detailed view of the cross section.

Parameters	Value
Field gradient [T/m]	26
Aperture radius [mm]	35
Magnetic field homogeneity [10^{-4}@25 mm]	3
Rated current [A]	470
Voltage drop [V]	137
Ohmic resistance of the winding [Ω]	0.26
Inductance of the winding [H]	0.162
Power consumption [kW]	65
Number of turns per the coil	31
Conductor dimensions [mm x mm]	8.2×10.5
Conductor cross-section area [mm^2]	68
Hole cross-section [mm^2]	18.1
Pressure drop per cooling circuit [bar]	7
Cooling circuit per the coil	5
Water speed per cooling circuit [m/s]	1.9
Water volume in the cooling system [l]	12.5
Water flow per the winding [l/s]	0.17
Water Temperature rise [K]	35
Maximum allowed water pressure [bar]	21
Magnet length [m]	4.07
Magnet iron length [m]	3.85
Magnet width [m]	0.71
Yoke steel weight [t]	7.0
Winding copper weight [t]	0.62
Magnet weight [t]	8.5

Table 31: *Main Parameters of the Q8 Quadrupole Magnet.*

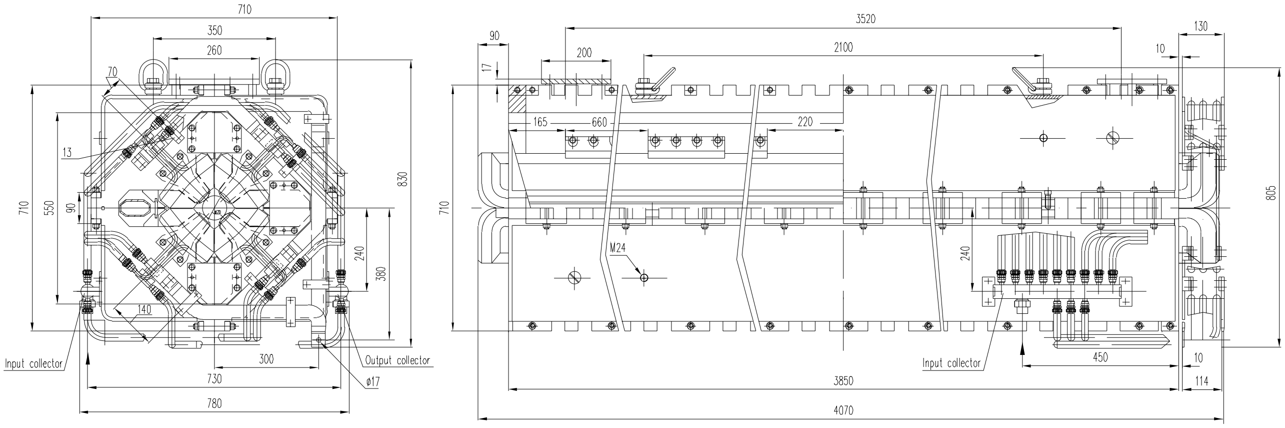

Figure 51: *General view of the Magnet Q8. Q8 is a septum quadrupole quadrupole with a moderate current density of the coil and a wide return yoke to make quasi field free room for the electron beam.*

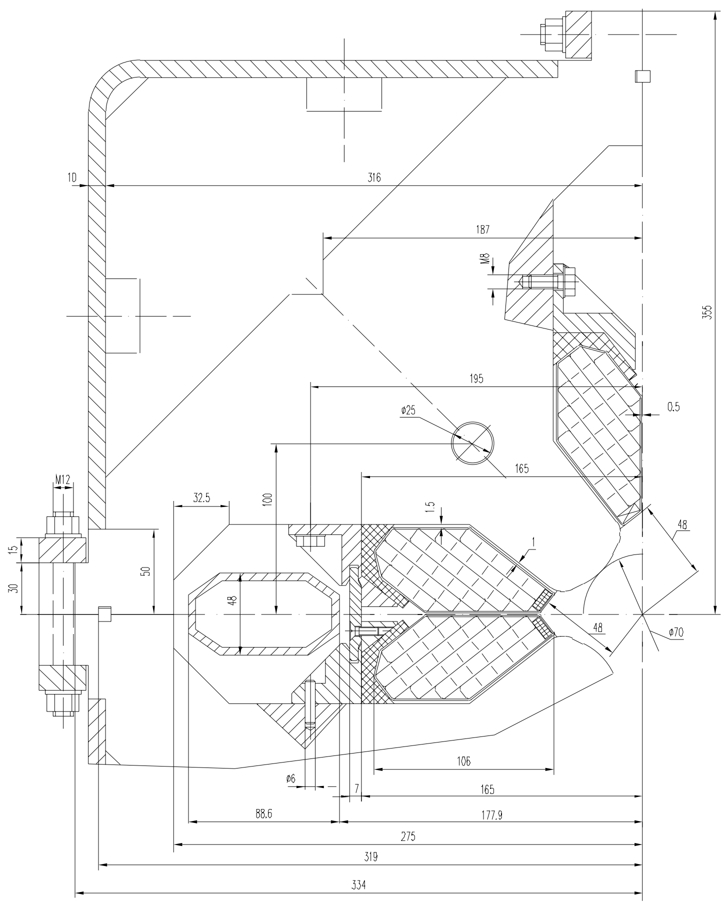

Figure 52: *Cross section of magnet Q8.*

5.9 Q9 Magnet

The Q9 magnet is the first quadrupole with only one beam pipe for protons. The lepton beam passes outside. The Q9 quadrupole magnet has a small return yoke to minimize the width of the magnet. The coil is identical to the Q8 coil. The pole contour is identical to QN and Q8 with a pole radius of $r_{pole} = 35\,\text{mm}$. The lamination profile, however, differs in the narrow return yoke.

The required field gradient of Q9 is 26 T/m. The iron length of the magnet is 3.85 m. The Q9 field quality corresponds to that of QN and Q8. Due to the somewhat lower gradient and the reduced current density, Q9 is a conventional magnet. A total field error $\int \Delta B dl / \int B dl < 2 \cdot 10^{-4}$ @$r = 25\,\text{mm}$ can be achieved over the whole excitation range. The field seen by the lepton beam amounts to less than 10 G, with a strong quadrupole component. The main parameters of the magnet Q9 are summarized in Table 32. Fig.53 presents the general view of the magnet, Fig. 54 gives a detailed view of the cross section.

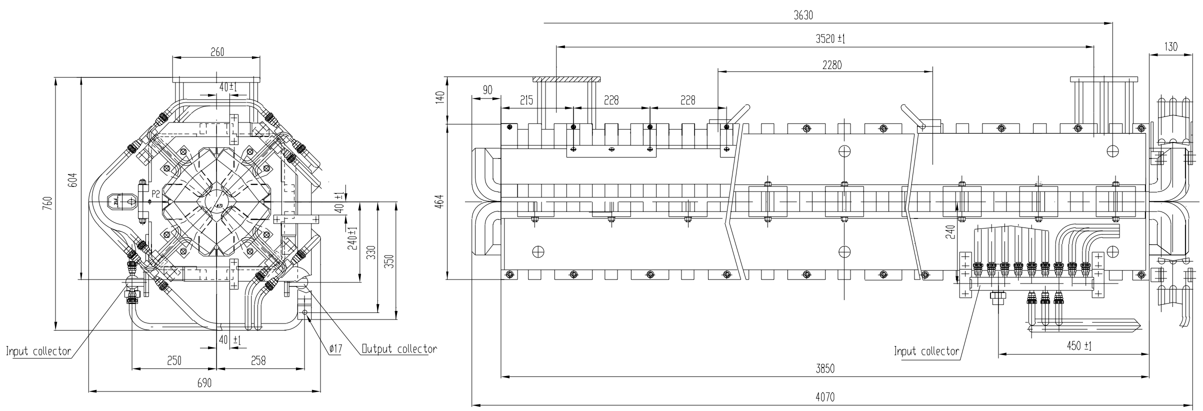

Figure 53: *General view of the Magnet Q9.*

Parameters	Value
Field gradient [T/m]	26
Aperture radius [mm]	35
Magnetic field homogeneity [10^{-4}@25 mm]	3
Rated current [A]	470
Voltage drop [V]	137
Ohmic resistance of the winding [Ω]	0.26
Inductance of the winding [H]	0.162
Power consumption [kW]	65
Number of turns per the coil	31
Conductor dimensions [mm x mm]	8.2×10.5
Conductor cross-section area [mm^2]	68
Hole cross-section [mm^2]	18.1
Pressure drop per cooling circuit [bar]	7
Cooling circuit per the coil	5
Water speed per cooling circuit [m/s]	1.3
Water volume in the cooling system [l]	12.5
Water flow per the winding [l/s]	0.17
Water Temperature rise [K]	35
Maximum allowed water pressure [bar]	21
Magnet length [m]	4.07
Magnet iron length [m]	3.85
Magnet width [m]	0.464
Yoke steel weight [t]	3.24
Winding copper weight [t]	0.64
Magnet weight [t]	4.2

Table 32: *Main Parameters of the Q9 Quadrupole Magnet.*

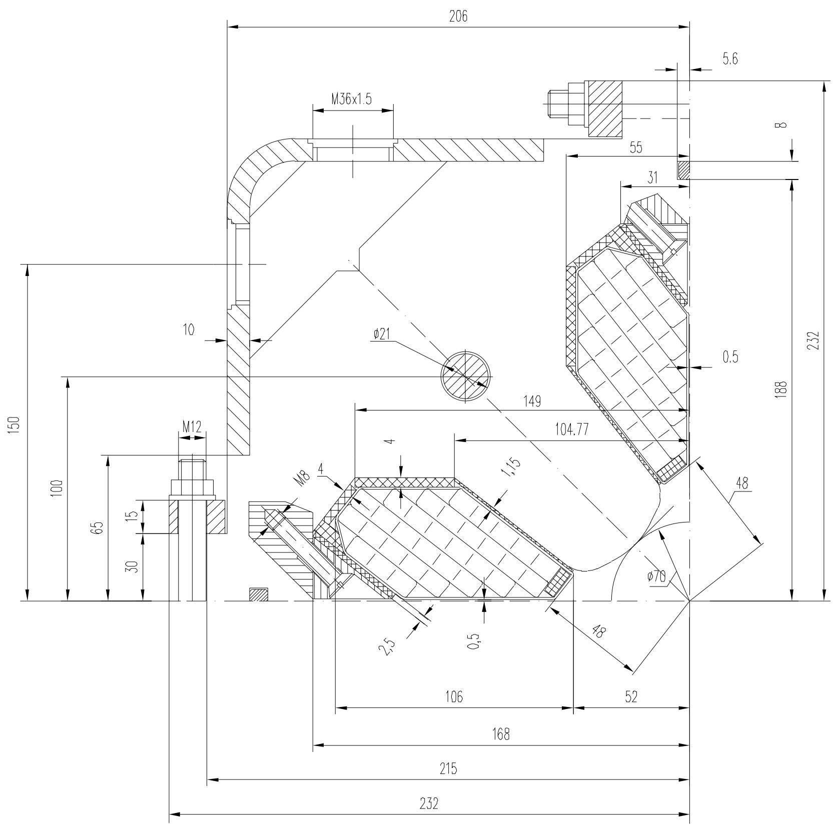

Figure 54: *Cross section of magnet Q9.*

5.10 BQ Magnet

As the orbits for electrons and positrons are not identical, septum-like magnets will be introduced at ± 19.12 m to separate the beams. The requirement was a field strength of $\int Bdl <$ 5 G m (with $l = 66$ cm effective length) at the electron beam position. In addition the field strength at the proton beam position was specified to be 1.34 T. The higher order modes should not drive orbit resonances stronger than one arc bending magnet.

Due to the fact that the magnet will be located very close to the electron beam, a shielding plate of the magnetic alloy Permendur is needed to prevent disturbing field effects on the electron beam. The thickness of the shielding plate was optimized to 23 mm, as a wide gap was required to achieve a good homogeneous b-field at the proton beam position. The distance between the beams is fixed at 128 mm. The current density was set to 9.65 A/mm^2. Fig. 55 shows the geometry of the septum magnet, the beam positions are indicated by shaded ellipses.

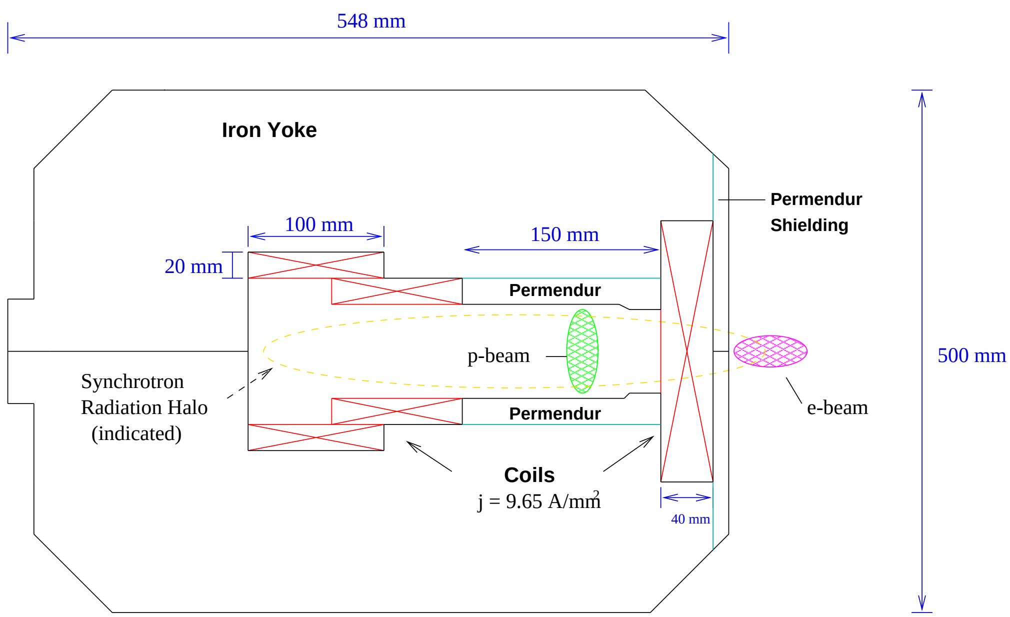

Figure 55: *Cross section of the BQ septum magnet.*

The magnet was designed using the opera-2d program [39] with the solver for nonlinear magneto-static field problems. Because of symmetry conditions only one half of the magnet was taken into account for the calculations. Fig. 56 shows the induced magnetic flux:

Fig. 57 shows the y-component of the B-field along the symmetry axis of the magnet through the gap. It can be seen that the shielding plate works well, because the B-field decreases by an order of 4 beyond the plate.

The pole geometry was optimized in order to get tolerable multipole coefficients. Only the quadrupole coefficient can be compensated by adjusting the optics. The multipoles at a reference radius of 10 mm are shown in Table 33, where the multipoles are normalized to the dipole component.

The final design can be seen in Figure 55, the Permendur layer is 20 mm thick. Additional calculations were made with a pole shim with rounded edges, but there was no improvement.

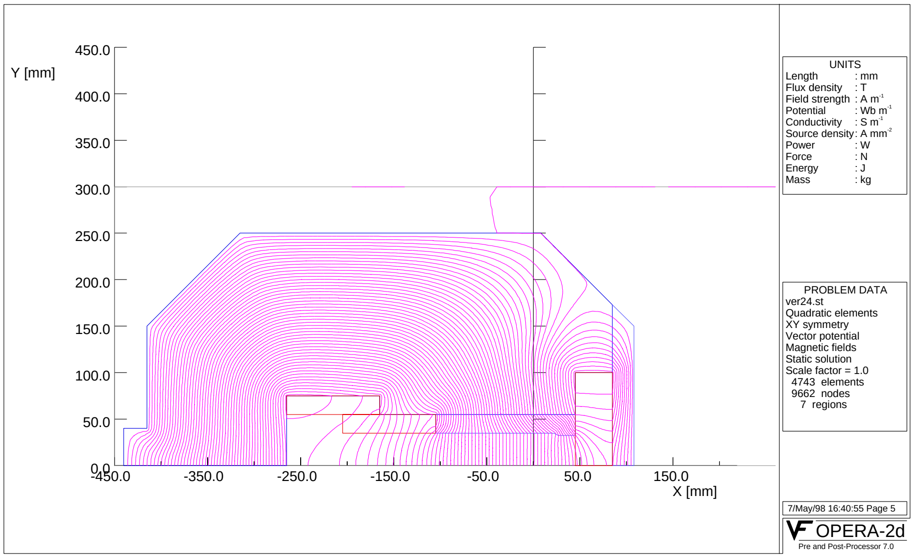

Figure 56: *BQ septum magnet: Induced magnetic flux.*

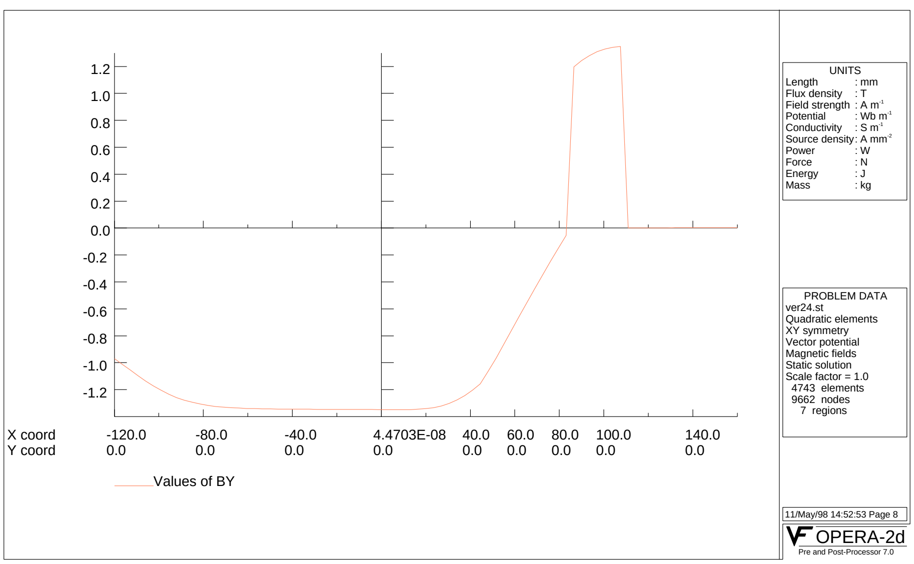

Figure 57: *BQ septum magnet: y-component of the B-field along the symmetry axis through the gap.*

Order n	a_n	b_n
1	0.000	1.00000
2	0.000	0.00098
3	0.000	-0.00010
4	0.000	-0.00030
5	0.000	-0.00017
6	0.000	-0.00005

Table 33: *BQ septum magnet: Multipole coefficients normalized to the dipole component* $(n = 1)$.

5.11 Cooling of Normal Conducting Magnets

It is possible to connect the new magnets and the changed vacuum chambers to the existing distribution tubes. The cooling system will use deionized water with a conductivity of approximately 1 mS/cm. Therefore the only possible materials are stainless steel, copper and bronze (gunmetal). The inlet water temperature is approximately $30° C$. The possible maximum pressure difference between input and output side is 7 bar. The allowed pressure for all connected elements has to be over 16 bar, because the cooling system is a so called PN 16 - system (German standard). The maximum temperature for the magnets has to be $70° C$ to minimize the required cooling water.

With these assumptions it is possible to cool down an additional power of roughly 500 kW per HERA hall. All magnets will be connected in parallel to the distribution tube. If the required pressure difference of the magnet is less than 7 bar, there will be a fitting with an orifice. The vacuum chambers will be connected in series until the maximum water temperature is $70° C$. The pressure difference usually has to fit with an orifice too. To control the water flow through magnets with a power of more than 20 kW there will be a flow meter in the return water line. This measuring device is only a switch and causes a pressure loss of approximately 0.35 bar. It could be necessary to have some changes in the main tubes, because there is not a lot of reserve in the water cooling system any more. Changing the main water distribution in the hall west would save the pump power which is necessary for cooling the new magnets.