DESIGN OF THE QUADRUPOLE MAGNETS FOR THE DIAMOND SYNCHROTRON SOURCE

N.Marks, J.A.Clarke and D.J.Holder, ASTeC, CLRC Daresbury Laboratory, Warrington WA4 4AD, U.K.

Abstract

The 3 GeV synchrotron source, DIAMOND, will be a low emittance electron storage ring with a 24 cell lattice, providing beam-lines from insertion devices and bending magnets. The lattice requires 240 quadrupole magnets divided into ten families, each family having different aperture and strength requirements. The specifications have been rationalised into two magnet cross sections and three lengths to meet the requirements of all quadrupoles in the lattice. The paper provides information of the choice of these geometries, together with data from two dimensional finite element modelling. Each quadrupole will have an individual power supply and the parameters of the common current and voltage specification, which will meet the requirements of all quadrupoles, are presented.

1 SPECIFICATION OF PARAMETERS

1.1 Determination of Inscribed Radius

The specification of the quadrupole inscribed radius is determined by the geometry of the vacuum vessel containing the circulating electron beam. The relevant parameters for determining the inscribed radius are given in Table 1. These are based on beam stay-clear dimensions defined elsewhere [1]; the vessel dimensions correspond to a smooth, uniform profile vacuum vessel around the complete lattice.

Table 1: Parameters determining quadrupole inscribed radius.

horizontal beam stay-clear (total)	80 mm
vertical beam stay-clear (total)	34 mm
internal tolerance clearance (total)	2 mm
vessel wall thickness	3 mm
external tolerance (assembly & location)	3 mm
resulting quadrupole inscribed radius	37 mm

The outer dimensions of the octagonal vessel which will be used in, including the necessary space for assembly and clearance, together with the 37 mm inscribed radius hyperbolic pole are shown in Fig 1.

1.2 Quadrupole Parameters

There are a total of 240 quadrupole magnets, split into ten families, required for the DIAMOND lattice. The length, number and horizontal and vertical good gradient half aperture for each family are given in Table 2.

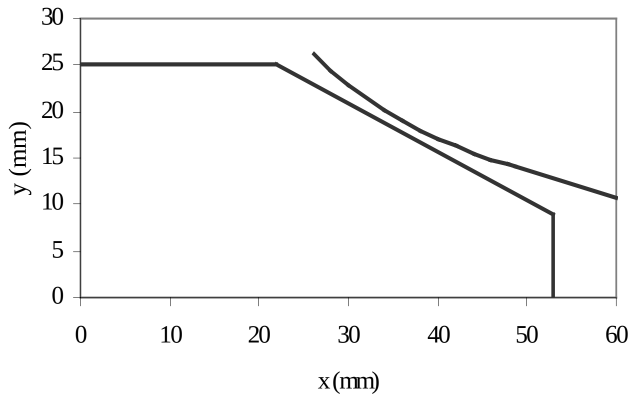

Figure 1: Cross-section showing outer dimensions of the storage ring vacuum vessel (including tolerances) and the R = 37 mm quadrupole magnet pole surface.

Table 2: Parameters of ten quadrupole families

Family	**Magnetic length (m)**	**No. per family**	**Horiz. good gradient (mm)**	**Vertical good gradient (mm)**
Q1AB	0.4	36	±36	±16
Q2AB	0.4	36	±20	±16
Q1B	0.4	36	±25	±12
Q2B	0.6	36	±25	±12
Q3B	0.3	36	±25	±12
Q1AD	0.4	12	±36	±16
Q2AD	0.4	12	±20	±16
Q1D	0.4	12	±25	±12
Q2D	0.6	12	±25	±12
Q3D	0.3	12	±25	±12

It is uneconomic to adopt an individual design for each of the families identified in Table 2. It can be noted that the families fall into two groups: the small number of magnets (48) which require 36 mm half aperture, which will call for very broad poles, and the remaining much larger number of quadrupoles (192) which need either 20 mm or 25 mm half aperture and which can be satisfied with a single cross-section design with a narrower pole width. Thus, it is proposed to have two quadrupole cross sections; the broad pole design being described as ‘W’ (for wide) types, and the more conventional magnets designated ‘N’ (for narrow) types. The ‘N’ types are required in three different magnetic lengths (0.3, 0.4 and 0.6 m), and the length specifications are therefore described by the letters ‘S’,‘M’ and ‘L’ (short, medium, and long). The 'W' types are all 0.4 m, 'M' length magnets.

To provide for a wide range of operational tune points, the maximum quadrupole strengths for all families are specified as:

$$g = 17.5 \text{ T/m};$$

with 'good gradient' within the apertures defined as :

$$-0.1\% \leq \Delta g/g(0) \leq 0.1\%.$$

The resulting audit for different quadrupole types is given in Table 3.

Table 3: Parameters of proposed four types of quadrupole.

Type	No. required	Magnetic length (m)	Horizontal good gradient (mm)	Vertical good gradient (mm)
WM	48	0.4	±36	±16
NL	48	0.6	± 25	±12
NM	96	0.4	± 25	±16
NS	48	0.3	± 25	±12

1.3 Steel Specification

Non-linear finite element investigations of the quadrupole gradient quality and amplitude were performed using the steel B/μ curve specified for the dipole steel and described elsewhere [2]. The steel data used corresponded to the 'parallel to rolling direction' values.

2 LARGE APERTURE ('W' TYPE) QUADRUPOLES

2.1 Pole Geometry

A pole geometry which would generate the required quality of field was developed and modelled. The pole follows the equation:

$$xy = R^2/2$$

out to $x = 49.2$ mm;

with a linear tangent extending to the pole corner at $x = 60$ mm.

From the pole corner, the pole receded at an angle of: 45° out to $x = 70.0$ mm.

The pole was then broadened, with each side diverging at an angle of: 10° to the pole centre line.

This broadening had been found to be necessary at gradients of 17.5 T/m to prevent saturation in the pole root.

The magnet was modelled in four-fold symmetry, with a back-leg thickness of 60 mm; the cross section of one-quarter of the 'W' quadrupole, as used for the finite element modelling, is shown in Fig. 2.

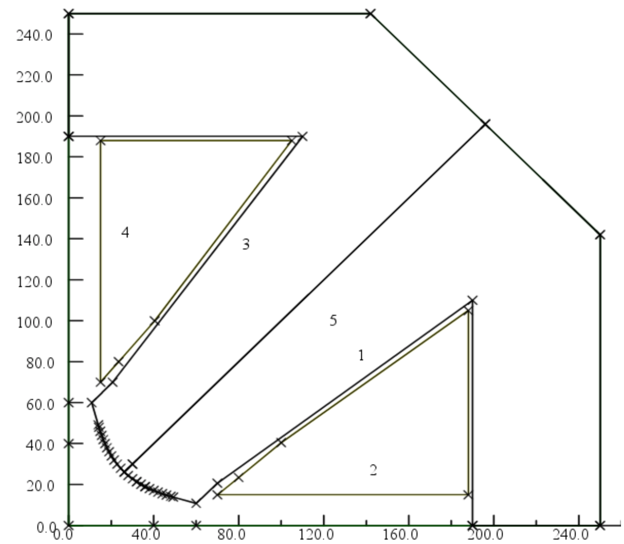

Figure.2: One quarter geometry used for modelling the 'W' type quadrupole; areas 1 & 3 are high permeability steel; areas 2 & 4 are conductor.

2.2 Gradient Quality

Non-linear exploration of the gradient quality was performed on the one-quarter geometry of Fig. 2 using the two-dimensional f.e.a. code, OPERA. Results are shown in Fig 3, where the homogeneity in the gradient of the vertical field (dH_y/dx) is plotted as a function of horizontal position (x) for five vertical positions within the good gradient region.

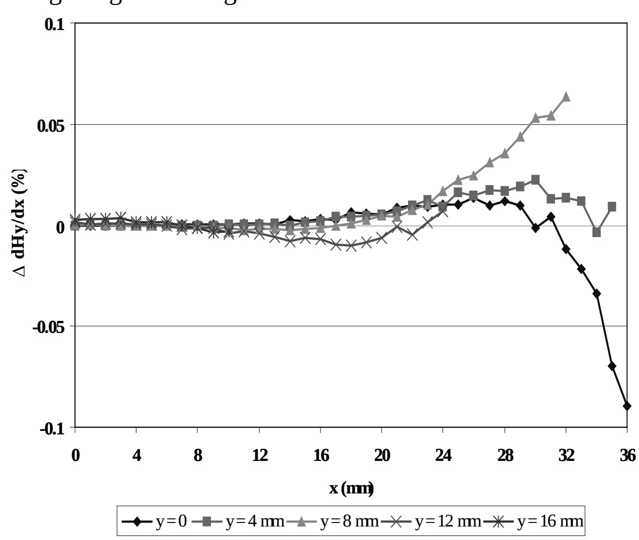

Figure 3: Homogeneity of the field gradient in the 'W' type quadrupole expressed as a percentage of the variation from dHy/dx at the origin (0,0), as a function of x, at differing vertical positions (y = 0, to y =16 mm); the data extends over the whole 'good gradient' ellipse.

The quality complies with the 'good gradient' specification throughout the required transverse region. On the y = 0 axis the predicted gradient has the quality indicated in Table 4.

Table 4: Gradient quality predicted for the 'W' type quadrupole on the y = 0 axis.

Δ dHy/dx (%)	at x value (mm)
+ 0.015	26
0	31
-0.09	36

3 LOW APERTURE ('N' TYPE) QUADRUPOLE.

3.1 Pole Geometry

A narrower pole was developed for the 'N' type quadrupole, producing the geometry described below. The pole followed the equation:

$$xy = R^2/2$$

out to $x = 37.3$,

with a linear tangent extending to the pole corner at:

$$x = 48 \text{ mm}.$$

From the pole corner, the pole followed an angle of:

$$45°$$

out to $x = 57.0$ mm.

The pole was then broadened, each side diverging at an angle of:

$$10°$$

to the pole centre line.

As with the 'W' type quadrupole, this widening of the pole was necessary to prevent saturation in the pole root.

3.2 Gradient Quality

The gradient quality predicted by non-linear modelling using OPERA is shown in Fig. 4; this again shows the homogeneity in gradient of the vertical field within the good gradient region. The gradient quality on the y = 0 axis is given numerically in Table 5.

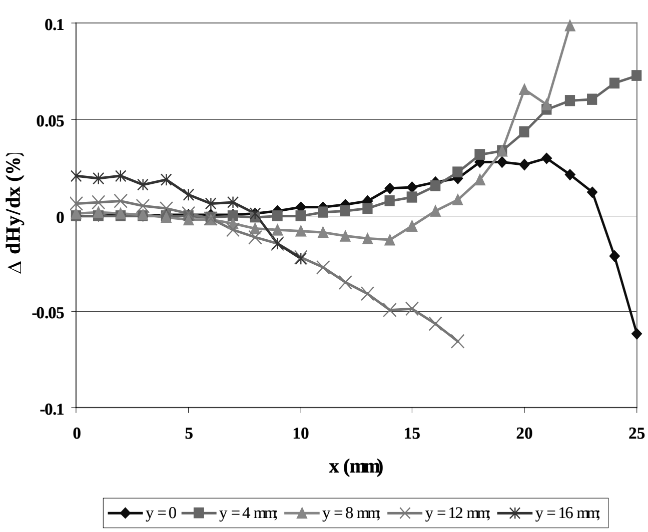

Figure 4: Homogeneity of the field gradient in the 'N' type quadrupole expressed as a percentage of the variation from dHy/dx at the origin (0,0), as a function of x, at differing vertical positions (y = 0, to y =16 mm); the data extends over the whole 'good gradient' ellipse.

Table 5: Gradient quality predicted for the 'N' type quadrupole on the y = 0 axis.

Δ dHy/dx (%)	at x value (mm)
+ 0.03	20
0	23
-0.06	25

4 POWER SUPPLY REQUIRMENTS

4.1 Coil Parameters

Whilst the 'W' and 'N' type magnets have differing cross-sections, both types have the same amplitude specification, they will operate at the same current density and the constraints imposed by power supply economics indicate that they will have the same maximum operating current. The coils on the two types of magnet will therefore have the same cross-section and winding geometry but with different overall widths and three different lengths. The common parameters of the coils for the 'W' and 'N' type quadrupoles are given in Table 6.

Table 6: Coil data for 'W' and 'N' type quadrupoles.

minimum amplitude linearity	97%
total Amp-turns per pole	9818 At
number of turns per pole	54
operating current at 17.5 T/m	182 A
current density in copper	3 A/mm^2
conductor cross section	60 mm^2
conductor dimensions	10.1mm x 7.5mm
water cooling tube diameter	4.5 mm
maximum water temperature rise	10°C
maximum water pressure drop	5 bar

To provide full flexibility for the operation of the lattice, all quadrupoles will have a separate power supply. The four types of magnet have the same current ratings but differing voltage and power requirements. However, a single rating power supply design will be specified for general use, simplifying procurement and the provision of spares [3]. The quadrupole power supplies will have the ratings shown in Table 7.

Table 7: Ratings of individual quadruple power supplies.

Current rating	200 A
Maximum power output	6 kW
Current stability	1:10^5

5 REFERENCES

[1] N. Wyles et al, "Defining the DIAMOND Storage Ring Apertures", these proceedings.

[2] N.Marks et al, "Magnetic Design of the Dipole Magnets for the DIAMOND Synchrotron Source", these proceedings.

[3] S.A.Grifiths et al, " A Power Converter Overview for the DIAMOND Storage Ring Magnets", these proceedings.