Basic Acceptance Tests on Q35 Quadrupoles.

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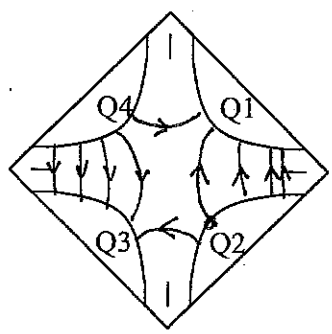
The quadrupoles under test was mounted in the magnet test area and flushed for about 18 hours. The resistance to ground was just under 1000 M ohms which is unusually good, however, the water feed pipes were long lengths of plastic and short insulated feeds would give a lower value.
Initially, problems were encountered with powering the quadrupole as it had been set up for power feeds from opposite sides rather than the same side. The quadrupoles were reconfigures by replacing an insulated spacer in the pipe assembly with a conducting one.

The quadrupole was marked up to simplify test measurements.
Drafting tape was placed on the pole pieces and the centres of the quadrupole pole pieces were marked out. The accuracy would have been ±2mm

The quadrants were labelled 1, 2, 3 and 4, clockwise when viewed from the end where the water feed comes in, as shown in Fig. 1.



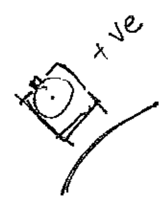


Fig. 1. Schematic view of the quadrupole as viewed from the water-feed end.

The measurements were made with a transverse Hall probe and a Hirst type GM05 gaussmeter,
The hall probe was mounted in the centre of each pole in turn. The probe was 8 mm above the surface of the pole in the orientation (+ve) shown in Fig. 2, and 2 mm above the surface in the converse orientation (-ve).
For these measurements, the position with the hall probe placed with its lock button facing towards the centre of the magnet was defined as the +ve position, the converse being the –ve position. This gave a +ve reading when the field was as shown in the Fig. 2.
Measurements of each pole for +ve and –ve positions were taken at 200A and 400 A

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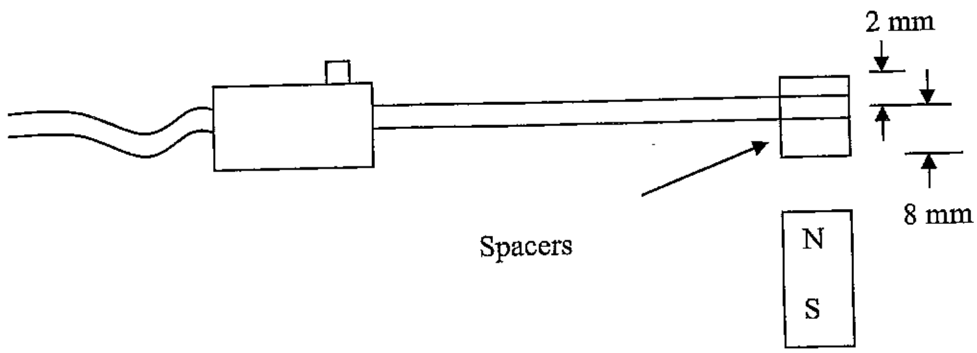


Fig. 2. Schematic representation of the hall probe +ve orientation.

Initially, a clamp meter was used to determine the current. This was found to be erratic, so first a shunt meter was used, and then a high precision power supply, reputed to be accurate to a few parts per million.
The polarity used to power the quadrupoles was normally +ve to the front conductor in quadrant 2. Quadrupole 9015.5 was powered in the opposite sense
To check the calibration of the hall probe, A comparison was made with a recently calibrated hall probe. At -409 mT on hall probe used, the reference hall probe read -408 mT

Results

The results are tabulated below

Quad S.No. 9015/8 Tested 20 Nov 2007

Command currrent (A)	shunt current (A)	volts across coil (V)	Command currrent (A)	Clamp current (A)	volts across coil (V)	Command currrent (A)	Clamp current (A)	volts across coil (V)
0	0	0		200			400	
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1			Q1	198.7	-205.2	Q1	399	-416
Q2			Q2	-198.4	205.8	Q2	-401	413
Q3			Q3	198.6	-205.4	Q3	399	-415
Q4			Q4	-198.6	205.9	Q4	-401	412

For the test of Quad 9015.8, the shunt current was used as a reference value. It was later found that this was slightly erratic

Quad S.No. 9015.5 Tested 29 Nov 2007

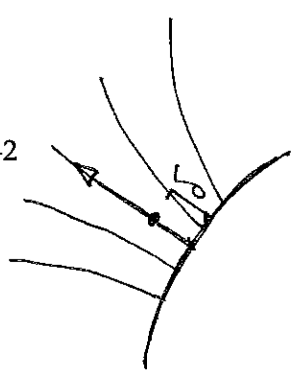
Command currrent (A)	Shunt current (A)	volts across coil (V)	Estimated current (A)	Shunt current (A)	volts across coil (V)	Estimated current (A)	Clamp current (A)	volts across coil (V)
0	0	0	202.7	201	30.64	404.3	400	61.62
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1			Q1	-205.6	213.4	Q1	-411	423
Q2			Q2	205.9	-212.5	Q2	408	-424
Q3			Q3	-204.6	213.3	Q3	-406	423
Q4			Q4	205.9	-212.8	Q4	409	-426

Note in Quad S.No 9015.5 the polarity was reversed and the estimated current was derived from the shunt current using a calibration factor determined from later tests

Quad S.No. 9222.4 Tested 5 Dec 2007

Command current (A)	Shunt current (A)	volts across coil (V)	Estimated current (A)	Shunt current (A)	volts across coil (V)	Estimated current (A)	Shunt current (A)	volts across coil (V)
0	0	0	196.7	195		396.3	392	
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1			Q1	197	-206	Q1	400	-416
Q2			Q2	-199	206	Q2	-401	412
Q3			Q3	200.2	206.4	Q3	400	-412
Q4			Q4	-199.6	207.5	Q4	-404	414

For the test of Quad S.No. 9222.4, the estimated current was derived from the shunt current using a calibration factor determined from later tests



Quad S.No. 9116.1 Tested 21 Feb 2008

Command current (A)	Shunt current (A)	volts across coil (V)	Command current (A)	Shunt current (A)	volts across coil (V)	Command current (A)	Shunt current (A)	volts across coil (V)
0	0	0	200	198.3		400	395.7	
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1	0.611	-0.339	Q1	202.2	-207.8	Q1	404	-421
Q2	-0.28	0.6	Q2	-202.2	209.8	Q2	-405	418
Q3	0.6	-0.32	Q3	202.8	-208.1	Q3	403	-418
Q4	-0.35	0.633	Q4	-202.3	210.7	Q4	-405	421

Note, the command current is reputed to be accurate to a few parts per million

Oddball Quad S.No. 153-1 Tested 27 Feb 2008

Command current (A)	shunt current (A)	volts across coil (V)	Command current (A)	shunt current (A)	volts across coil (V)	Command current (A)	shunt current (A)	volts across coil (V)
0	0	0	200	198.3	30.2	400	395.7	62.2
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1	0.62	-0.36	Q1	202.8	-209.2	Q1	403	-419
Q2	-0.32	0.6	Q2	-202.9	206.4	Q2	-406	414
Q3	0.59	-0.34	Q3	203.7	-208.9	Q3	404	-420
Q4	-0.35	0.62	Q4	-203.9	209.7	Q4	-406	417

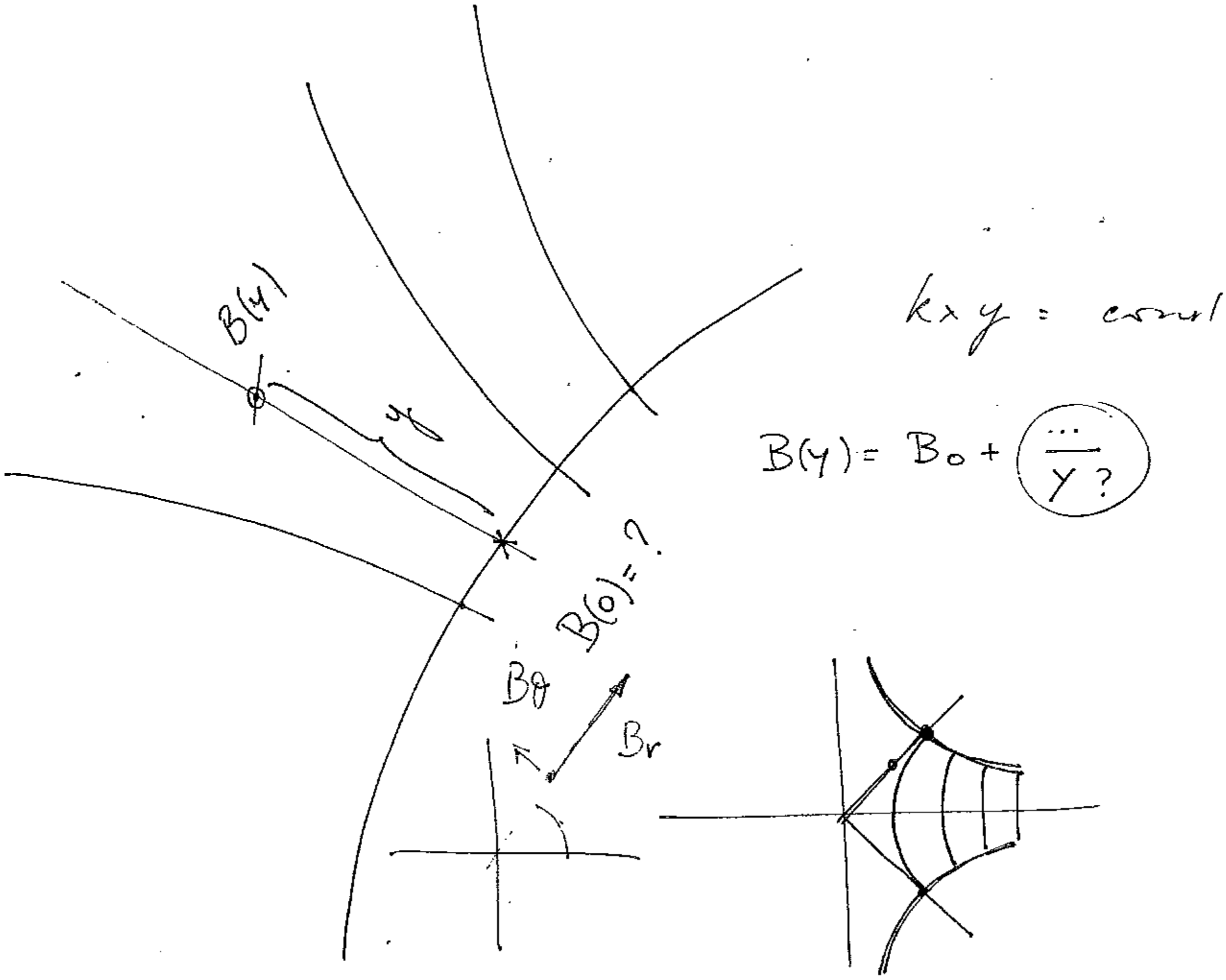
Quad S.No. 9268.2 Tested 10 March 2008

Command current (A)	Shunt current (A)	volts across coil (V)	Command current (A)	Shunt current (A)	volts across coil (V)	Command current (A)	Shunt current (A)	volts across coil (V)
0	0	0	200	198.3	30.52	400	395.7	61.7
Field mT	Norm	Invert	Field mT	Norm	Invert	Field mT	Norm	Invert
Q1	-0.13	0.2	Q1	202.2	-208.9	Q1	403	-418
Q2	2.2	-1.8	Q2	-202	209.6	Q2	-405	417
Q3	0.02	-0.005	Q3	202.3	-209.9	Q3	403	-418
Q4	-0.001	-0.02	Q4	-202.3	209.6	Q4	-405	417

Note: Quad S.No. 9268.2 was tested without mirror plates

Conclusion

The quadrupoles appear to work appropriately and the fields appear to be consistent to better than 1% between the quadrupoles.



$$B_r(r,\theta,s) = \frac{\sin m\theta}{m!} \sum_{p=0}^{\infty} (m+2p)\, G_{m,2p}^{(s)}\, r^{2p-1}$$

m

$\binom{m}{n} = \frac{m!}{n!(m-n)!}$ $\quad G_{m,0}(t) = \mu_0 I_c \frac{(2m-1)!}{R^m 4^m (m-1)!} \sum_{k=0}^{m>0} (-)^k \frac{m+k+1}{2k+1}$

$m = 1$

$$G_{1,0} = \frac{\mu_0 I_c \; 1!}{R4 \; 0!} \sum_{k=0}^{1} (-)^k \left(\frac{k+1}{2k+1}\right) f_{2k+1}(t) \binom{1}{k} \quad f_{2k+1}(t$$

$\binom{1}{0} = \frac{1!}{0!\,1!} = 1$

$\binom{1}{1} = \frac{1!}{0!\,1!}$ $\quad = \frac{\mu_0 I_c}{4R}\left[f_1(t) - \frac{2}{3} f_3(t)\right.$

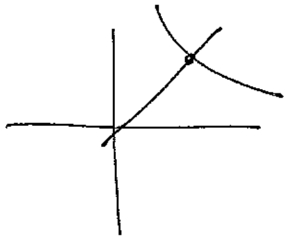
$$B_r(r,\vartheta,s) = \frac{\sin(\pi/2)}{2!} \sum_{p}^{q} {}_p(2+0) \cdot$$

$\theta = 45° = \frac{\pi}{4}$

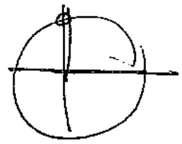
$p = 0$

$m = 2$

$$\cdot\ G_{2,0} \cdot r^{2-1}$$

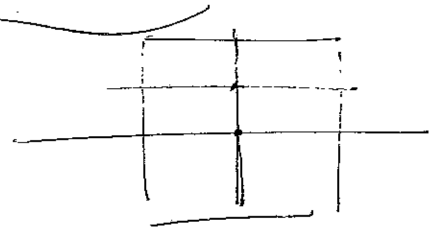


$$B_r(r,\vartheta,s) = \frac{1}{\cancel{2}} \cancel{2} \cdot \frac{\mu_0 I_c}{8R^2} \cdot$$



$$\cdot\ r \cdot \Big[9 f_1(t) - 8 f_3(t) + 3 f_5(t) \Big]_{s-z_L}^{s+z_L}$$

$$= \frac{\mu_0 I_c}{8R^2} \cdot r \cdot \underbrace{\Big[18 f_1(z_L) - 18 f_3(z_L) + 6 f_5(z_L) \Big]}_{8.0079} \simeq \mu_0 I_c \frac{r}{R^2}$$



$$f_n(t) = \left(\frac{t}{\sqrt{R^2+t^2}} \right)^n \qquad s = \phi$$

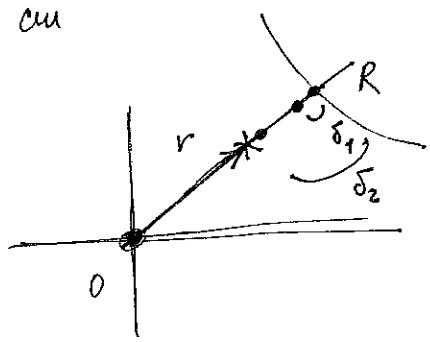
$$f_1(t) = \frac{t}{\sqrt{R^2+t^2}} \qquad f_1(z_L) - f_1(-z_L) = 2 f_1(z_L)$$

$$f_3(t) = \frac{t^3}{\left(\sqrt{R^2+t^2}\right)^3}$$

$R = 10.15$ cm

$z_L = 42.5$ cm

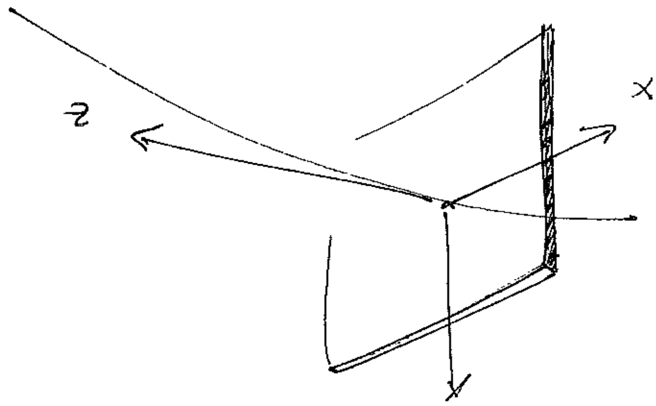
$$f_5(t) = \frac{t^5}{\left(\sqrt{R^2+t^2}\right)^5}$$



$$f_{2n+1}(t) = - f_{2n+1}(-t)$$

$$B_0 = B_r(r=R) = \frac{\mu_0 I_c}{R}$$

$$B_0 \cdot B_r(r = R-\delta_1) = \frac{\mu_0 I_c}{R^2}(R-\delta_1)$$



$J_0 = 400\,A$

$\delta_2 = 8\,mm$ $\delta_1 = 2\,mm$ $\delta_0 = 0\,mm$

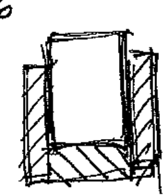
404 mT 421 mT

$$B_r = \frac{\mu_0 I_c}{R^2}(R-\delta) = B_0\left(\frac{R-\delta}{R}\right) = B_0\left(1-\frac{\delta}{R}\right)$$

$$B_0 = \frac{\mu_0 I_c}{R}$$

$B_0 = 429.46\ mT$

$$B_r(\delta=2) = B_0\left(1-\frac{2}{101.5}\right) = B_0 \cdot 98.03\,\%$$



$$B_r(\delta=8) = B_0 \cdot 92.12\,\% = 404\ mT$$

$$\Rightarrow B_0 = \frac{404}{0.9212} = 438.57\ mT$$