LARGE APERTURE QUADRUPOLE MAGNETS FOR ISIS TS-1 AND TS-2

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Abstract

The ISIS pulsed neutron and muon source at the Rutherford Appleton Laboratory has two target stations TS-1 and TS-2. Budker Institute of Nuclear Physics developed, produced and delivered seven type Q13 quadrupole magnets with an aperture diameter of 310 mm for TS-2 beam transfer line. Later an additional three quadrupoles with integrated dipole coils were developed and delivered to ISIS TS1. To improve the field quality across the full current range a special pole profile and end chamfer were designed using the MERMAID code. The magnetic field map was measured by a set of Hall probes. Moreover, BINP produced a rotating coil with radius 120 mm for field quality measurements.

MAGNETS FOR TS-2

The Type Q13 Quadrupole Magnet is a major component of the TS-2 EPB, a single pass beam transport line [1]. It is a normal conducting D.C. magnet manufactured from steel yokes and four identical moulded coils.

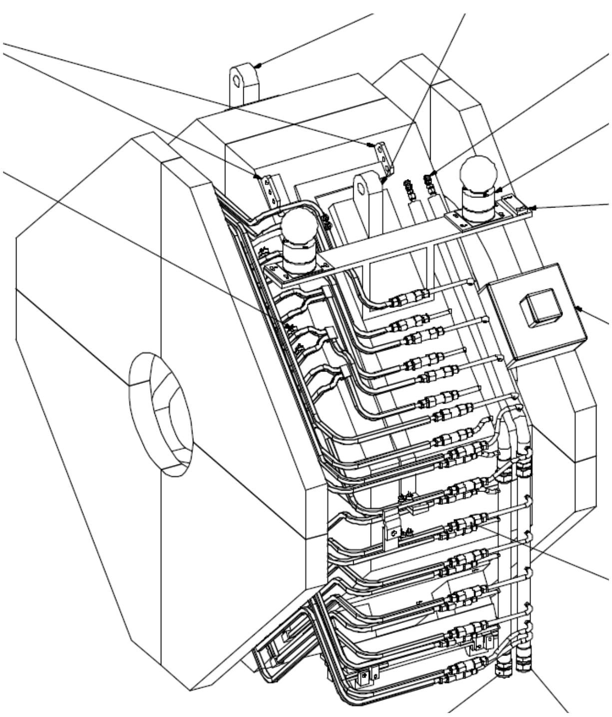

Figure 1: Initial design.

The parameters detailed below are the outcome of an initial design study developed at RAL.

Table 1: Initial Parameters

Aperture Diameter	310 mm
Effective Length	500 mm
Peak Field Gradient	8.2 T/m
Min Field Gradient	2.0 T/m
Good Field Region (GFR)	120 mm
Integrated field gradient within GFR	±0.5%
Number of Turns per Pole	80
Maximum Current	1070 Amps
Maximum Magnet Resistance at 30°C	0.11 Ohm
Maximum Voltage Drop	118 Volts
Maximum Power Dissipation	126 kW
Cooling Water Temperature Rise	20°C
Maximum Cooling Water Flow Rate	90 L/min
Maximum Pressure Drop	4 Bar
Maximum Mass of Magnet	6.0 tonnes

DESIGN CALCULATION

The initial design included two steel end plates of 60 mm thickness located on both side of quadrupole magnet for achievement good field quality.

The magnetic design has been carefully recalculated at BINP using the MERMAID code. Calculations have shown significant dependence of field quality from current due to steel saturation. Field quality was around 2% at GFR through field gradient range. Adding of lateral magnetic steel end plates reduces the field gradient by 2% and also reduces effective magnetic length and integrated field gradient by 10% at the same current. It was decided to design magnets without end plates. Therefore the maximum integrated field gradient 0.5*8.2 T/m = 4.1 T can be achieved on the less current and consequently the problem caused by saturation was reduced. Other profit is reducing power dissipation per magnets on 40% from 126 kW to 77 kW in order to have integrated field gradient 4.1 T.

However the field quality of magnet without end plates is sensitive to magnets placed nearby. Quadrupoles are used in triplet with distance between quadrupole centres of 1000 mm. The calculation shows the field quality changes no more than $5*10^{-5}$ and the effective magnetic length and therefore integrated gradient are reduced only on 0.4%.

Before steel arriving to BINP workshop it was estimated the risk of magnetic property difference of a waited steel from calculated. For this in calculation with MERMAID code was input steels with a bit different magnetic properties. Independent on steel quality the field quality can be achieved better than 1% on the range from 1 T to 4.1 T by means of end chamfer angle tuning.

The designed parameters are listed in Table 2.

Table 2: Q13 Magnet Parameters

Aperture Diameter	310 mm
Yoke Length	490 mm
Magnetic Length	570 mm
Field Gradient at 880 Amps	7.2 T/m
Integrated gradient at 880 Amps	4.1 T
Maximum Current	1000 Amps
Magnet Resistance at 20°C	0.10 Ohm
Power Dissipation at 880 Amps	77 kW
Magnet Weight	5.4 tonnes

MAGNETS FOR TS-1

After commissioning TS-2 the upgrade of TS-1 has started. Three new large aperture quadrupole magnets were produced, each magnet having an individual vacuum vessel to allow easy replacement. This arrangement matches the modern design of the proton beam to target station 2.

The quadrupole magnet is required to focus and de-focus the 800MeV proton beam. To improve control of the proton beam position, a dipole steering magnet was designed to sit inside one of the quadrupole magnets. The geometry of the coils for this steering magnet was carefully designed using computer simulations to use the steel poles of the surrounding quadrupole magnet to produce a dipole field. This hybrid magnet allows both the quadrupole and dipole magnetic fields to be individually controlled, giving a high degree of flexibility in a compact space. The beam spot can now be steered independently onto the main neutron-producing target and onto the intermediate muon-producing target which lies upstream of the neutron target. The design of quadrupole magnets with steering magnet is shown in Figure 2. The steering dipole consists of four saddle shaped coils situated within the bore of the quadrupole magnet providing a maximum steering angle of 2.5mrad. Besides the dipole field harmonic b1 each couple coils produce on the quadrupole yoke also higher odd harmonics b3, b5, b7 and so on. By selecting the numbers of turns in each couple coils the harmonics b3 can be significantly reduced.

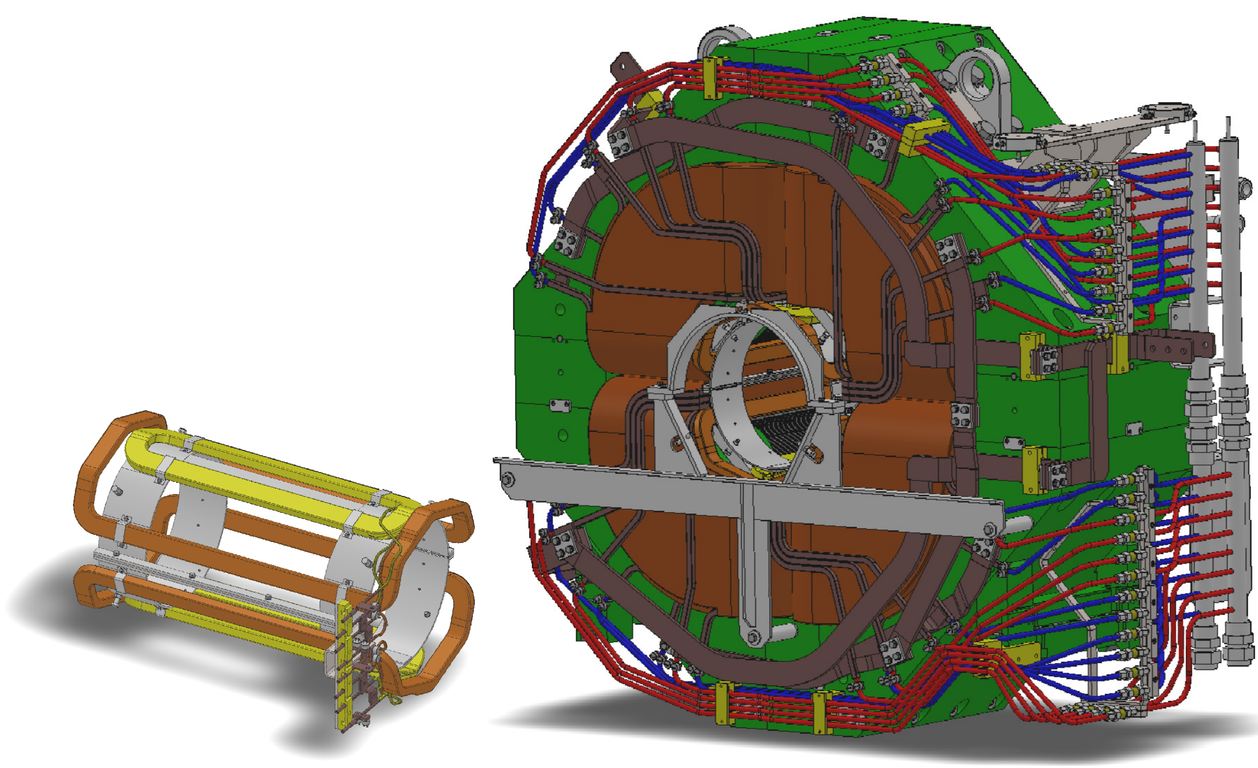

Figure 2: The Q13 type quadrupole magnets with dipole steering magnets.

MAGNETIC MEASUREMENTS

The magnets were measured by set of hall probes. Moreover rotating coil with radius 120mm has been produced.

On the figure 3 an excitation linearity of field gradient in the magnet centre verse current is shown. Linearity is defined as: $\frac{G(I)}{I} \Big/ \frac{G(200A)}{200A} - 1$

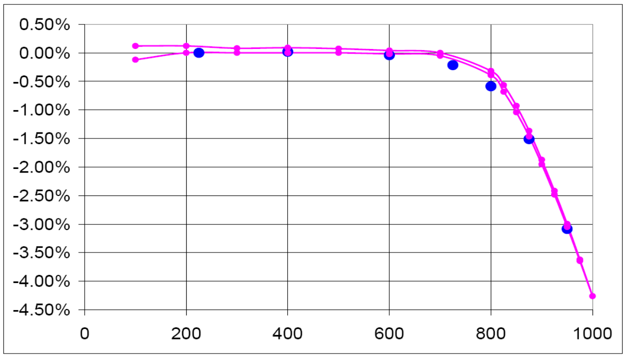

Figure 3: Excitation linearity of field gradient in the magnet centre verse current. Blue – calculated before production with MERMAID 3D code, red – measured results.

On the figure 4 the results of measurements for steering magnet in quadrupole magnet by rotating coil system are presented. Harmonics are normalized on the main harmonics of steering coils B1. Higher harmonics became insignificant when quadrupole magnet switch on.

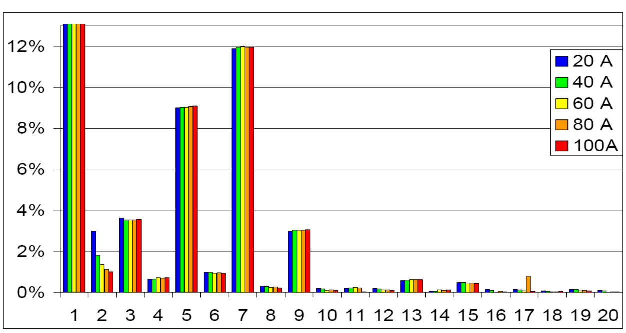

Figure 4: Normalized harmonics B_n/B_1 for different current of steering coils in switch out quadrupole.

FIELD HARMONIC B6

As it is know for quadrupole magnet a steel saturation leads to the dependence of field harmonic B_6/B_2 on current. Saturation takes place on pole yoke corners where magnetic field concentrates. One contribution is in 2D on the corner where pole hyperbole is cut. Second contribution is on the corners of end chamfer. In the type Q13 magnet design all corners was rounded as soon as possible. Nevertheless saturation for magnet remains significant.

Usually a quadrupole end chamfer is adjusted on one current where B_6 should go throw zero. For Q13 type magnet the end chamfer has been adjusted on the maximum current (red line on the figure 5).

On the Q13 type quadrupole magnet each coil is attached to the yoke pole by stainless steel bracket by stainless steel M12 bolt placed near centre of end chamfer. Replacement all stainless steel bolts on the magnetic steel bolts leads to reducing field harmonic B6 on the all current range without deterioration other harmonics (blue line on the figure 5). A saturation of magnetic bolts near at end chamfer centre compensates a saturation of corners on the pole yoke and therefore improves field quality.

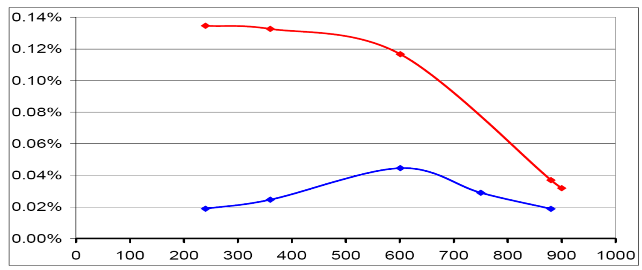

Figure 5: Field harmonics B_6/B_2 verse current. Red – magnet with stainless steel bolt. Blue – quadrupole with bolts from magnetic steel.

On the modern circular accelerator the field quality requirement becomes stronger and now it is around less $2*10^{-4}$ for quadrupole field harmonics B3/B2 and B4/B2. It becomes comparable with B6 harmonic changing due to saturation. Designing of end chamfer with a little hill in the chamfer centre can help further field quality improvement.

CONCLUSION

BINP developed, produced and delivered the seven quadrupole magnets of Q13 type to ISIS TS2. Also BINP produced thirteen the type M24 an M26 dipole steering dipoles of large aperture. Magnets have been delivered in April 2007 and installed. First protons have been delivered to the Second Target Station in December 2007. After that the additional three quadrupoles with dipole steering coils were developed and delivered to ISIS TS1 in June 2010. These magnets have been installed during a six-month shutdown at ISIS from August 2010 to February 2011 and now its work under beam.

REFERENCES

[1] J. Thomason, “Upgrade To ISIS For The New Second Target Station”, EPAC’08, Italy, 2008, THXG03, p. 2902; http://www.JACoW.org.