QUADRUPOLE MAGNET WITH AN INTEGRATED DIPOLE STEERING ELEMENT FOR THE ISIS BEAM TRANSPORT LINE

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Abstract

A refurbishment of beam transport line to the original ISIS target station at the Rutherford Appleton Laboratory has recently been completed. This work involved a slight change to the optics in the area, which included the requirement for extra steering capabilities. Due to the space constraints in the region, a quadrupole magnet with an integrated dipole steering element was developed. The steering dipole consists of four saddle shaped coils situated within the bore of the quadrupole magnet providing a maximum steering angle of 2.5 mrad. This paper outlines the magnetic and mechanical design of the steering element.

INTRODUCTION

The ISIS Facility

The ISIS facility is a Spallation Neutron Source, using neutrons as a probe to investigate the structure of materials at the atomic level. The facility consists of a rapid cycling synchrotron generating 800 MeV protons which are fired at fixed targets to produce neutrons for the instrument beamlines. The accelerator operates at 50 Hz, generating short bunches of protons with an overall beam current of over 200 µA. This current is then directed onto two target stations in separate experimental halls. The fixed targets are both constructed of tungsten clad with tantalum, with the first target station taking four out of every five available pulses, amounting to a total beam power of around 160 kW. The second target station, constructed and first operated 3 years ago, takes 20% of the total accelerated beam, currently amounting to around 30 kW. A graphite target sits in the beam transport line to the first target station, and is used to provide muons to two suits of instruments, giving ISIS further flexibility and greatly enhancing the facility's scientific capabilities. The muon target takes around 2% of the proton beam.

Redesign and Refurbishment of the Target Station One Beam Transport Line

In 2004 construction began on the second target station project. Part of this work involved installing a new beam transport line of around 150 m in length. The beamline is made up of several different types of D.C. magnets. The last six quadrupoles immediately upstream of the neutron target have a relatively large aperture, with a bore diameter of 310 mm. These magnets, designated as "Type Q13", were designed and built by the Budker Institute of Nuclear Physics in Novosibirsk, Russia and upon operation of the new beamline in December 2007, were found to function well.

Shortly after the successful commissioning and operation of these magnets, a new project was instigated to refurbish the downstream end of the synchrotron to target station one beam transport line, with the main focus on the replacement of the beam to target window [1]. This work included a small redesign of the optics in the area to allow for a slight change of positioning for the magnets, ensuring better access to the quadrupoles to facilitate any future maintenance operations. The Type Q13 magnets were selected as being suitable for use in this area. In addition to this, extra steering capabilities were designed into the optic to enable independent control of the proton beam onto both the muon target and the neutron target. Due to the tight space restrictions in the area, it was not possible to accommodate separate steering magnets in the necessary positions to control the beam onto the two targets. It was suggested, therefore, that bias currents could be used to create the required dipole field within some of the quadrupole magnets. This technique involves creating an imbalance of the current in the quadrupole coils, with two coils on one side of the magnet having a greater current and, hence, more ampere-turns than the opposite pair. This effectively pushes the magnetic centre away from the mechanical centre, aligned to the beam, adding a dipole component to the magnetic field causing the beam to be deflected, or steered. It is normal, when designing and building quadrupole magnets, to strive to achieve the best possible accuracy in the manufacture of the magnet steel and coils, to eliminate any errors that would result in such dipole fields. This method of biasing the current on a pair of coils results in other unwanted harmonics being generated, producing a very poor field quality.

A new approach was, therefore, developed, using separate coils placed within the bore of the quadrupole to generate the required dipole field. This technique gave several important advantages. First, the design and positioning of the coils could be optimised to improve the field quality of the magnet when the dipole field was required, eliminating some of the higher order harmonics. Secondly, the separate coils enabled independent power supplies to be used, simplifying the control of the two magnetic fields. Third, this approach allow the dipole elements to be inserted in any Type Q13 magnet, ensuring that a spare generic Type Q13 magnet could be fitted with the dipole steering coils, and be inserted into the beam transport line in the event of a failure to an existing operational magnet. For these reasons, the conceptual design for the separate dipole insert coils was adopted, and a detailed magnetic and mechanical design was developed.

DIPOLE INSERT DESIGN

Magnetic Design

The concept for the design of the dipole insert consists of a pair of coils to drive the main dipole component, and a second, smaller pair to balance out the higher harmonics caused by the shape of the quadrupole pole pieces. Both coils are saddle shaped, and run through the bore of the magnet occupying unused space between the main quadrupole coils and the cylindrical vacuum vessel. This concept was simulated in the OPERA 3D code from Vector Fields. Figure 1 shows the arrangement of the coils inside the magnet. The main quadrupole coils have been removed for clarity.

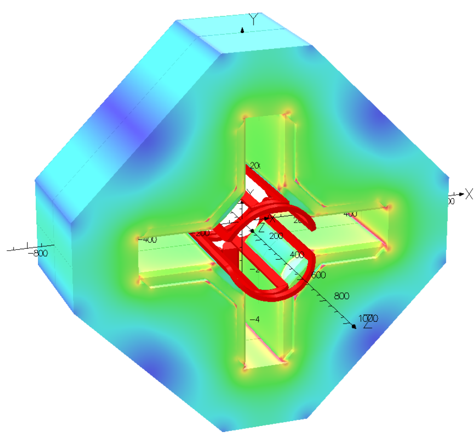

Figure 1: Dipole insert coils as modelled in OPERA 3D, with main quadrupole coils removed for clarity.

The specification for the inserts required a dipole field to give a maximum deflection of 2.5 mrad. For protons with an energy of 800 MeV, this translates to a field integral requirement of around 12.5 Tmm. Since the dipole insert coils were being integrated into a known magnet, the magnetic length was effectively set by the existing steel at 615 mm. The required peak field within the central part of the magnet was therefore calculated to be 20 mT.

An estimation of the required ampere turns to produce this field was made by applying Ampere's law. However, since the shape of the steel inside the quadrupole is relatively complex, the simulations using OPERA 3D were used to verify the result.

Once the required ampere turns were obtained, the magnetic field quality was optimised by adjusting the geometry of the coils. The angular positions of the windings were tuned to give the best possible field quality. Figure 2 shows the calculated homogeneity of the field integrals, as simulated by OPERA 3D, up to the maximum good field radius of 120 mm.

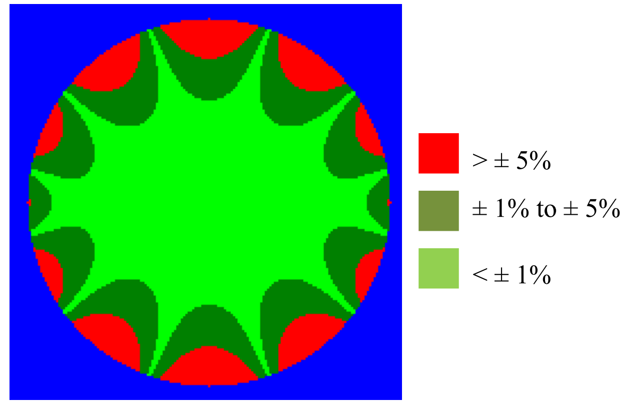

Figure 2: Calculated integrated field quality for the dipole insert coils, showing percentage deviation from the central field integral.

Although the field quality may appear to be quite poor, it should be noted that it is substantially better than the resulting field quality from a magnet with bias currents on the main quadrupole coils. Since the dipole field is only a small fraction of the main quadrupole field, the errors, when normalised to the quadrupole, are less significant.

Mechanical Design

Once the magnetic design had been finalised, the task of designing the physical dipole insert began. A previous project which involved the procurement of bi-polar power supplies for different steering magnets had already been completed. It was decided that these power supplies would be suitable to drive the dipole inserts. The maximum current output of these power supplies was ±125 A. Given the required ampere-turns, the number of turns for each coil was calculated, ensuring the maximum operating current was just below the 125 A limit of the power supply.

The conductor cross section was selected from the standard available sizes of copper extrusions and the total dissipated power was calculated. The cooling channel was sized to ensure the total head loss of water was not greater than the maximum 3 Bar pressure differential that the existing circuit was capable of delivering, without further modification.

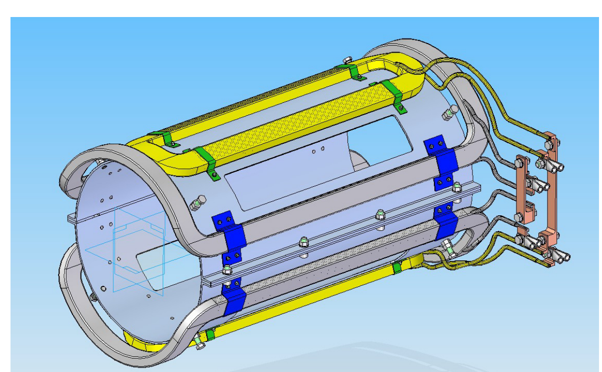

Figure 3: CAD model showing the mechanical design of the dipole insert coils.

The maximum field gradient that the Type Q13 magnet is able to produce is 8.2 Tm^{-1}. This translates to a field of around 1.35 T in the location of the dipole coils. When the coils are energised with their maximum current, a significant Lorentz force is generated. The supports for the coils were evaluated to ensure the expected loads were managed, with the forces effectively reacted back to the vacuum vessel, to which the coils were mounted. Figure 3 shows the design of the dipole insert, constructed using Solid Edge Computed Aided Design software.

Magnetic Measurements

The quadrupole and dipole inserts were both manufactured by the Budker Institute of Nuclear Physics. The magnetic measurements were also carried out at the institute. The measurements included assessments of the magnetic length, the multipole harmonic content and current verses field linearity. An array of hall probes spaced at known transverse positions was passed longitudinally through the bore of the magnet on the median plane. This gave both a measurement of the magnetic length and an assessment of the field quality of the magnet. A rotating harmonic coil was also used to obtain the multipole content of the magnetic field. These measurements were taken at various different current levels of both the quadrupole and the dipole insert.

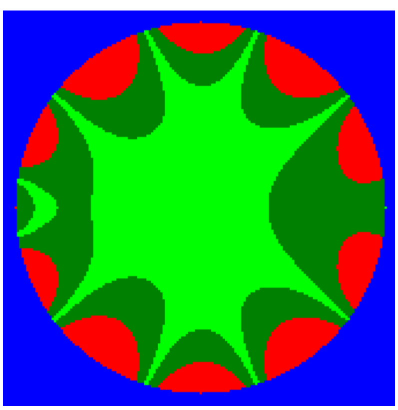

Figure 4: Measured integrated field quality for the dipole insert coils, showing percentage deviation from the central field integral.

Figure 4 shows the measured integral field quality, reconstructed from the rotating coil method. The measurements were taken with the dipole current at 100 A, and zero current in the main quadrupole coils. It can be seen that the measured field errors compare relatively well to those predicted by the simulations made during the design phase. A small amount of quadrupole and sextupole exist in the magnet. The sextupole is probably caused by a slight error within the tolerances of the manufacturing and installation processes. It is possible that the quadrupole is due to the remnant field in the quadrupole steel. A calculation shows that this level of quadrupole field could be generated depending the exact coercivity of the steel used.

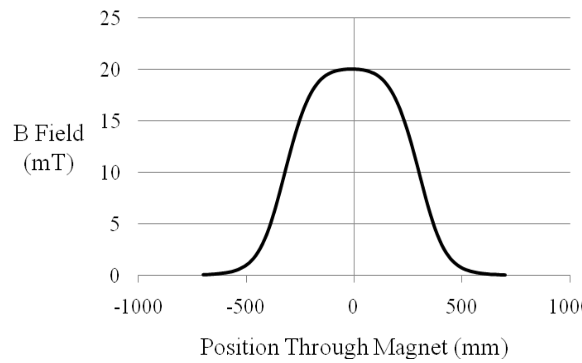

Figure 5: Measurement of the dipole field along the central axis of the quadrupole.

Figure 5 shows the magnetic field produced by the dipole insert along the main axis of the quadrupole. This measurement was taken with the dipole coils energised to their maximum current and no power on the main quadrupole coils. From this measurement the magnetic length of the dipole insert was calculated to be 628 mm. Although this was slightly longer than the predicted effective length of 615 mm, the agreement with the simulation was generally good, considering the variation in the field integrals in the good field region.

SUMMARY AND CONCLUSIONS

A dipole insert for a large aperture quadrupole magnet has been successfully designed. The magnetic measurements agree well with the predicted values obtained from the simulations performed using the OPERA 3D software. The field errors generated by the dipole insert are relatively small when normalised to the quadrupole field. The manufacture of the magnets by the Budker Institute of Nuclear Physics has been completed. The magnets have been installed in the ISIS Target Station One beam transport line and operate as expected.

REFERENCES

[1] S D Gallimore et al., Remote Handling Equipment and Techniques for the Replacement of the ISIS Proton Beam to Target Window, TUPS048 Proc. IPAC11, San Sebastian, Spain.