A HYBRID QUADRUPOLE DESIGN FOR THE RAL FRONT END TEST STAND (FETS)*

C. Plostinar, STFC/RAL/ASTeC, Chilton, Didcot, Oxon, UK
M. Clarke-Gayther, S. Jago, STFC/RAL/ISIS, Chilton, Didcot, Oxon, UK.
P. Davis, Trinity College, University of Oxford, Oxford, UK

Abstract

The Front End Test Stand project being constructed at Rutherford Appleton Laboratory (RAL) aims to deliver a high current (60 mA) H^- chopped ion beam, at 3 MeV and 50 pps. The main components of FETS are the H^- ion source, the Low Energy Beam Transport line (LEBT), the Radio Frequency Quadrupole (RFQ), the Medium Energy Transport (MEBT) line with beam chopper, as well as a comprehensive set of diagnostics. Space restrictions in the MEBT line place constraints on component length and drive the requirement to identify compact component configurations. A description is given of a novel compact hybrid quadrupole magnet, whose design is based on the concentric combination of a permanent magnet quadrupole (PMQ) and a laminar conductor electromagnetic quadrupole (EMQ). Simulations of magnetic field distribution 3D are presented, and possible applications and further developments are discussed.

INTRODUCTION

Triggered by the growing interest for High Power Proton Accelerators (HPPA), the Front End Test Stand project at Rutherford Appleton Laboratory has experienced major developments over the last few years [1]. It is hoped that at least two future projects will benefit from the FETS R&D: a high intensity proton machine as the driver for a future neutrino factory and a possible MW upgrade of the ISIS Spallation neutron source.

For these MW range projects, high quality beams are essential. Significant technical development is necessary, especially at the front end of the accelerator where low energy (2.5 – 3 MeV) beam chopping at high duty cycle (1 – 10%) is required to minimise beam loss and the induced radioactivity at injection into downstream circular accelerators. This is why, the primary goal of FETS is to demonstrate a high quality, high current, chopped beam.

One of the key components of FETS is the MEBT line. It consists of a series of quadrupoles, RF buncher cavities, and a novel “fast-slow” beam chopper system [2].

In order to minimize emittance growth, halo formation and subsequent beam loss in the downstream linac, the MEBT optical design must be as short as possible, imposing the necessity of compact beam-line components.

* We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, Contract No. RII3-CT-2003-506395).

THE HYBRID QUADRUPOLE

Electromagnetic quadrupoles (EMQs) produce high magnetic fields which can be adjusted by varying the current flow in the conductors and have traditionally been the optimum choice for focussing elements in particle accelerators. More recently, an increased number of accelerators have adopted permanent magnet quadrupoles (PMQs) based on rare earth materials for transporting and manipulating the beam. PMQs offer the advantage of a compact design with high field gradients. However, EMQs are preferable to PMQs due to the fact in EMQs the magnetic field can easily be adjusted while in PMQs the field cannot be changed once they have been installed, except by complicated mechanical means.

For the FETS MEBT line a hybrid quadrupole option is under investigation. The main aim is to address the requirement for a compact design, combined with a (limited) ability to adjust the field gradient. The hybrid quadrupole will be a concentric combination of PMQ and laminar conductor EMQ types (Lambertson quadrupole). It has been shown that relatively small magnetic fields can be obtained by etching the coil’s turns on a flexible printed-circuit board [3]. The circuit board is rolled to form a cylinder that will provide a quadrupole field. By placing this structure inside the aperture of a PMQ, one can adjust the magnetic field by varying the current in the laminar conductors. The resulting structure is a very compact adjustable PMQ.

THE PMQ DESIGN

In order to analyse the achievable field gradient and the field homogeneity of a PMQ, a 3D model has been created in Opera Vector Fields [4]. The model is based on a PMQ developed by Aster Enterprises [5] for the Spallation Neutron Source (SNS) DTL in Oak Ridge, Tennessee. It consists of 16 magnet pieces made of samarium cobalt (Sm_2Co_{17}) equally spaced at an angle of 22.5^o and with an interior radius of 16.3 mm. Each magnet has an individual easy-axis direction, which increases by $67.5\ ^o$ from one to the next (Figure 1).

Several factors have also been considered in choosing Sm_2Co_{17} as the preferred permanent magnet material:

- It has a high magnetic strength for its size.
- It has a high resistance to radiation damage.
- It has a very good reversible temperature coefficient (-0.03%/°C), shows a high resistance to demagnetisation and performs very well even at higher temperatures (350 °C) [6].

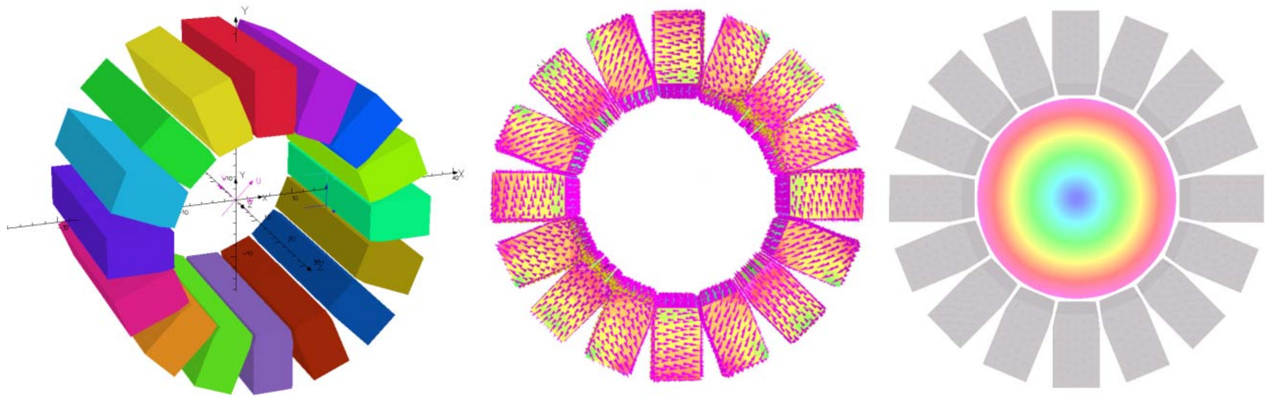

Figure 1: Left: The 3D model of the PMQ. Centre: The magnetisation direction in the magnetic material. Right: The magnetic field inside the PMQ aperture (B_{mod}).

For the purpose of this analysis we have used several BH curves to describe the magnetic performance and capabilities of Sm_2Co_{17} with the remanence (the residual flux density) B_R varying from 1.02 – 1.07 T and the coercivity H_C varying from 764 – 820 kA/m.

First simulations indicate that a gradient of ~ 34 T/m is easily achievable thus confirming the simulations previously made simulations with Pandira and Opera 2D [7]. The field gradient deviation is ±0.75% (±0.45% on the median plane) while the field deviation is ±0.1% (0.05% on the median plane) for a good field region radius of 12 mm. The field and the field gradient homogeneity on the median plane can be seen in Figure 2.

The Fourier harmonics analysis of the integral field indicates the presence of small higher order components which are uncharacteristic for a quadrupoles field. We have reasons to believe that this is due to the fact that in the Opera model a very coarse mesh has been used in order to reduce the simulation time and this will be further investigated.

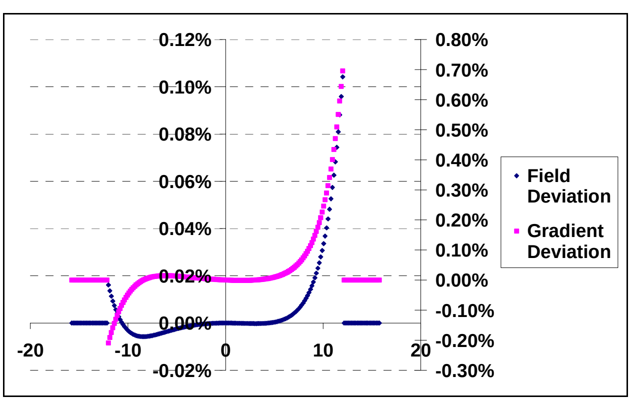

Figure 2: The deviation of the magnetic field and of the magnetic field gradient for the PMQ model.

THE LAMINAR EMQ DESIGN

For the laminar design we are interested in finding the current distribution over a cylindrical surface which will produce a quadrupole field. In order to achieve this, the current density distribution has to have a cos(2θ) azimuthal dependence [8]. In practice this is realized by etching a conductor following a rectangular spiral path on a flexible printed circuit board. Only the current flowing in the conductors parallel to the magnet axis (active conductors) will contribute to the axially integrated magnetic field. The cos(2θ) current distribution is obtained if the semi-length of the active conductors is [9]:

$$z(\theta) = \frac{L}{2}\left[1 - \left|\sin(n\theta)\right|\right]^{1/2} \qquad (1)$$

where L is the magnet length.

Using a CAD package, a double sided printed circuit board has been designed, each side consisting of 104 active conductors (26 conductors per coil). The upper side of half a quadrupole can be seen in Figure 3. A further 3D model based on the CAD design has been created in Opera (Figure 4) in order to study the magnetic properties of the laminar EMQ.

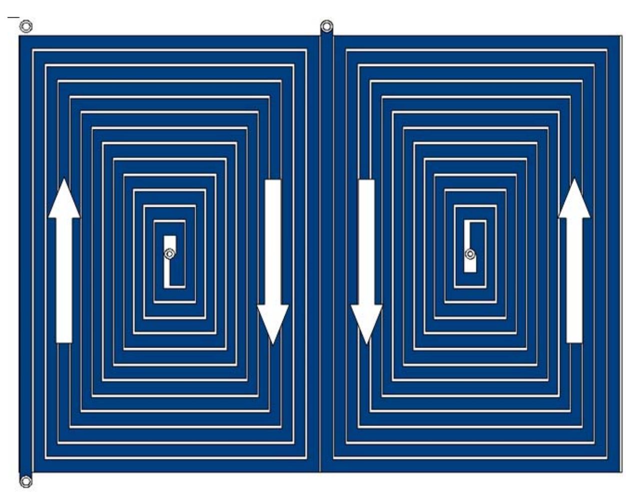

Figure 3: The upper side of the printed circuit board for one half of the quadrupole. The arrows indicate the current direction in the active conductors.

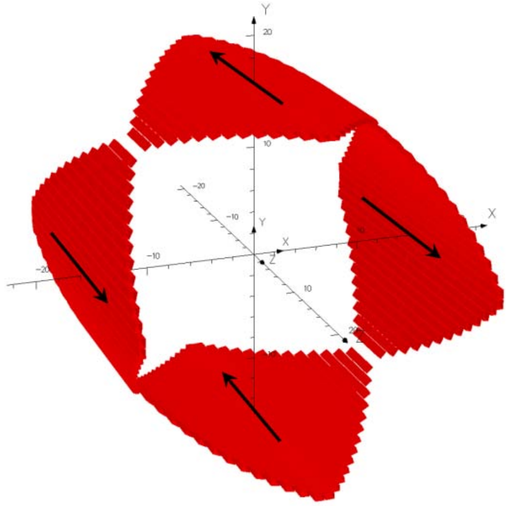

Figure 4: Opera 3D drawing of the printed circuit quadrupole. Only the active conductors have been modelled. The arrows indicate the current direction in the conductors.

As expected, the field quality is lower than for the PMQ model. This is caused by the inevitable geometrical asymmetries introduced by the spiral shape of the conductors. For a current density of 10 A/mm^2 a field gradient of 0.18 T/m is achievable. However, for the FETS requirements, filed gradients up to five times higher are required and in order to achieve this range of adjustment, multiple circuit board layers or conductors capable of carrying larger current densities must be utilised.

For a good field region radius of 12 mm, the field deviation is ±2% (±1.66% on the median plane) and the maximum gradient deviation is of ±9.5% (±5.2% on the median plane). For the FETS requirements the reduced field quality of the laminar EMQ is not of real concern as this will only be responsible for a fraction of the total quadrupole field. The deviation of the magnetic field and of its gradient on the median plane can be seen in Figure 5 and in Figure 6 we present a contour plot showing the magnetic field deviation in the good field region.

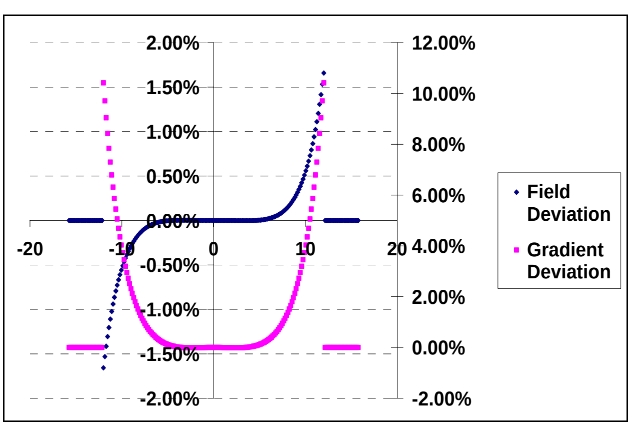

Figure 5: The deviation of the magnetic field and of its gradient for the EMQ laminar model (median plane).

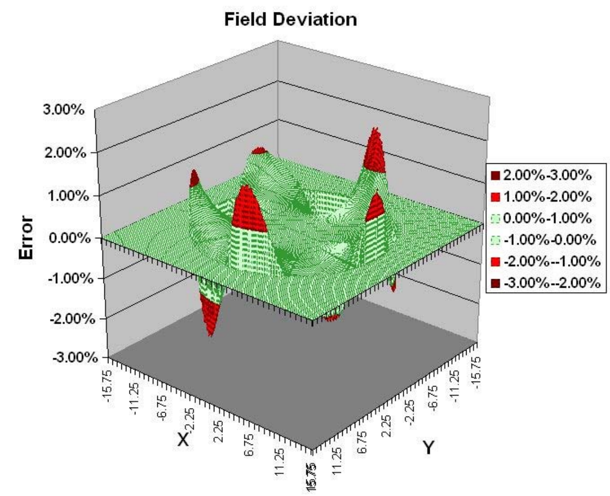

Figure 6: The deviation of the magnetic field and of its gradient for the PMQ model.

CONCLUSIONS

A compact hybrid quadrupole design to be used in the Front End Test Stand is under development at RAL. The new quadrupole will offer more design options for the MEBT line and at the same time we are investigating the possibility of using these hybrid quadrupoles for the DTL section of a future RAL linac. An experimental setup is in preparation to verify the accuracy of the simulation codes by measuring the achievable range of field adjustment and field homogeneity of an existing PMQ – laminar quadrupole, combination. Also, the relatively high current density in the conductors requires an estimation of the cooling requirements in the laminar EMQ which is now under way.

REFERENCES

[1] A. Letchford et al., “Status of the RAL Front End Test Stand”, Proceedings of EPAC’08.
[2] M Clarke-Gayther, “Fast-Slow’ beam chopping for next generation high power proton drivers”, Proc. of PAC’05, Knoxville, USA.
[3] Robert T. Avery et al., “Printed-Circuit Steering Coils’, Proc. of PAC 1971, Chicago, USA.
[4] Opera Vector Fields http://www.vectorfields.com
[5] Aster Enterprises http://www.asterenterprises.com
[6] R. F. Holsinger, “Permanent Magnet Beam Transport”, Proc of PAC’95, Dallas, USA.
[7] C. Plostinar et al., ‘‘Re-bunching RF cavities and hybrid quadrupoles for the RAL Front End Test Stand (FETS)”, Proc. of EPAC’06, Edinburgh, Scotland.
[8] T. F. Godlove et al., “Printed-Circuit Quadrupole Design”, Proc. of PAC’95, Dallas, USA.
[9] W.W. Zhang et al., “Design and Field Measurements of Printed-Circuit Quadrupoles and Dipoles”, Phys. Rev. Special Topics – Accelerator and Beams, Vol. 3, 122401 (2000).