A RESISTIVE COMBINED FUNCTION MAGNET SUITABLE FOR USE INSIDE THE HERA ep INTERACTION REGIONS

B. Parker, BNL, Upton NY, United States
M. Marx, K. Sinram, S.G. Wipf, G. Woebke, DESY, Hamburg, Germany

Abstract

For the HERA luminosity upgrade program [1-4] a normal conducting magnet was investigated for use in the interaction region. We present an unconventional air-coil combined function magnet design which provides both vertical focussing and horizontal bending. A block coil configuration, with midplane conductors omitted on one side, is adopted for providing high field quality, $\Delta B/B = \pm 5\times10^{-4}$ and yet passing synchrotron radiation via a horizontally extended vacuum beam pipe. The design magnetic length is 1.98 m, maximum gradient 7.6 T/m, and average vertical field 0.185T. 2D and 3D field calculations are shown and two solutions for producing the coil heads, forging and selective laser sintering, are discussed.

1 INTRODUCTION

The air coil combined function magnet QG should be located close to the IP, extending from 1.8m to 3.8m, and is inside the H1 and ZEUS experimental detectors as shown in Figure1. In concert with the next combined function magnet QH the QG provides the necessary horizontal bending to separate the electrons from the protons and it also provides an important contribution to the electron focussing so as to help reduce the vertical β-peaks in the downstream electron quadrupoles. Our final design uses a block-conductor configuration as shown in Figure 2. A welding seam inside the H1 liquid argon tank defines the 180mm outer diameter of the magnet support-pipe which contains the magnet collar fixing the coil in a coil trough.

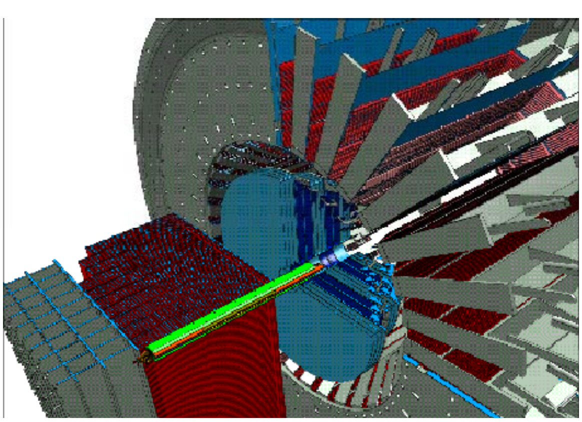

Figure1: Cut away view of ZEUS detector showing QG magnet. QG extends from 1.8 to 3.8m from IP.

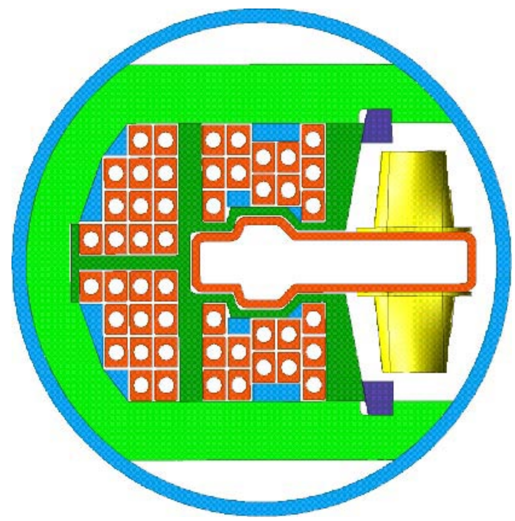

Figure 2: QG magnet cross section

2 COIL DESIGN

The combined function block geometry comes from overlaying the current distribution for a vertical dipole field with that of a normal quadrupole. On one side of the quadrupole the currents add; on the other side they almost cancel; top and bottom there is almost no change. We then discretised the resulting current distribution in an array of rectangular conductors laid out on a grid. Such an arrangement allows dense packing while still permitting layers to be shifted independently. The 2D coil conductor configuration for the magnet was then optimised using OPERA-2D [5].

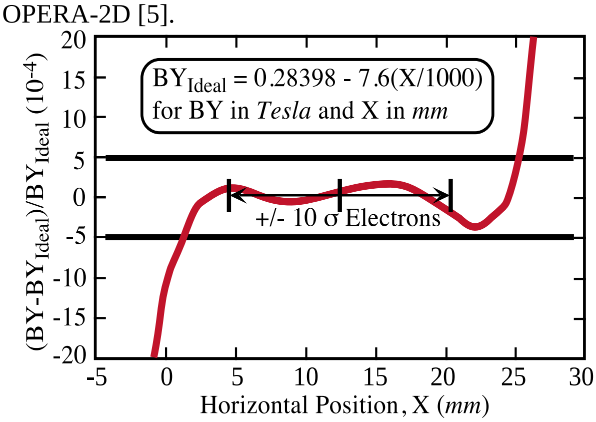

Figure 3: Deviation from linearity of vertical field (BY) at magnet midplane. Fractional difference ΔB/B, in units of 10^{-4}, is plotted as function of horizontal position(X). Design goal of $\pm5\times10^{-4}$ is achieved over a 25mm extent.

2. 1 Coil Optimisation in 2D

Having a large number of very small conductors allows correspondingly fine adjustments to be made to the current distribution but wastes precious space for insulation. Not surprisingly we found that a small number of large cross section conductors yields a higher transfer function but poorer field quality. It was not found possible to meet our field quality goals with fewer than 12 conductors and it was not possible to go beyond 7.6 T/m with more than 18 conductors, while staying below an average effective current density[1] of 20A/mm^2. In order to bootstrap the optimisation procedure an initial guess had to be made for the current distribution. The initial coil configuration approximated a mixture of $sin(\theta)$ and $sin(2\theta)$. Usually 32 to 24 conductors were sufficient to reach a field linearity of 0.5%.

Optimisation was then iterative. The field distribution was calculated for this initial set of conductors and $\Delta B/B$ derived for the magnet midplane, as in Figure 3. Where the field was too high or low, the closest conductor stack was moved up or down, the change noted, and the stack shifted to the better position. Movements of a stack of conductors by 0.5mm had a noticeable effect on the field. After going through all stacks in this way it was sometimes effective to move an entire coil in order to buck out smooth departures from linearity. A sophisticated numerical procedure for automatically optimising conductor placement was not developed because the simple iterative process outlined was adequate to generate solutions for an arbitrary number of conductors.

The solution shown in Figure 3 was not the very "best" which could be achieved in terms of field quality but instead resulted from a compromise with ease of coil fabrication. For the 12 conductor solution shown in Figure 2 only 3 of 10 degrees of freedom were used because conductor edges were lined up to simplify the shape of the coil support H–bars and to permit sliding the completed assembly into the support trough; however, the final compromise placements were all within 0.5mm of their best positions.

2. 2 Coil Head Calculations in 3D

Then the 3D calculations were carried out using the magnetostatic module of the MAFIA[6] program. Once the final placement of the windings at the magnet ends had been modelled in the CAD program I-DEAS[7], it was possible to import the final geometry into MAFIA. Thus the final design could be calculated with the windings at the magnet ends compatible with other requirements such as the position of cooling connections and current leads. The design of the coil ends was not explicitly optimised with a view toward field quality as the mechanical design requirements were deemed challenging enough; however, stretching out the coil heads in order to fit water connections may have helped field quality.

[1] Current density averaged over area of coil, i.e. includes water cooling channel and insulation around conductor.

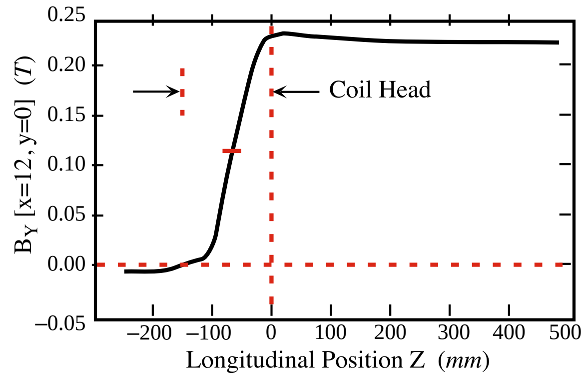

Figure 4: Vertical field (BY) at e-beam center near QG end as a function of distance (Z) from the coil head. Z= 0 is the start of the coil straight section.

Each end of the magnet was calculated separately, using a 50 cm length of the 1.98m magnet. The field differences within the $\pm 15\sigma$ of the electron beam due to the slightly different arrangement of the conductors at each end of the magnet were negligible. Near the ends of the magnet the transverse field varies smoothly as shown in Figure 4.

3 MECHANICAL DESIGN

Due to the presence of the ZEUS and H1 detector solenoid fields, magnetic materials such as iron cannot be used in the QG magnet, and in order to maintain the design field quality of $\pm 5 \times 10^{-4}$ it is estimated that the conductor centers should be within ±0.5mm of their design positions. To achieve this placement goal special attention has been given to the design of the coil internal support structure. As shown in Figure 2 the dimensions of the top and bottom coils are fixed in a H-shaped "coil trough" made from DUROSTONE VEGM-LP[2].

Table 1: Possible coil trough and magnet collar material.

Material	**DURO-STONE**	**DURO-STONE**	**Alu-minium**	**Stainless Steel**
Standard	VEGM-CA	***VEGM-LP***	**AlMg7**	**1 . 4301**
carbon,- ***glass*** content [%]	50	***60***	-	-
Specific gravity [g/cm^3]	1,40-1,65	***1,75-2,10***	2,7	7,9
Radiation length X0 [cm]	≥18,80	*≥11,70*	8,90	1,76
Bending strength [N/mm^2]	450-500	***350-400***	120	490
Tensile strength [N/mm^2]	700	***350***	340	600

[2] Trade Mark: Röchling Haren KG, Postfach 1249, D-49724 Haren

The combined top and bottom coils and the vacuum beam pipe will then be captured in a rigid extruded C-shaped magnet collar made from DUROSTONE VEGM-CA and held in place with clamping bars made from the same material. The VEGM-CA composite material is special in that it has a density lower than aluminium and it is significantly stronger and more rigid against deformation see Table 1.

3. 1 Coil Manufacturing

The coils will be made using a hollow SE-Cu conductor of 10.7x 8mm size with a 5.8mm inner bore for cooling. Tightest bend radius, about equal to the conductor width, would have unacceptable ”keystoning” in standard technique. We investigated manufacturing the coil heads of the first layers with very tight bends by forging or selective laser sintering and then brazing to the straight sections. For tests a company in Hamburg made a sample shown in Fig.5.

Figure 5: Coil head made by forging.

There is no keystoning visible and the cooling channel has almost the original dimension. The advantages of this method are: using the same conductor as in the straight sections, easy brazing, no keystoning. The disadvantages are: different dies for the bends of different layers, high costs. This was the reason we changed to selective laser sintering. The first sample (see Figure 6) made by NRU[3] from bronze powder using our IDEAS IGES file was not satisfactory: very brittle, rough surface and not leak-proof. Then NRU produced a second sample: Selective laser sintered bronze Cu infiltrated.

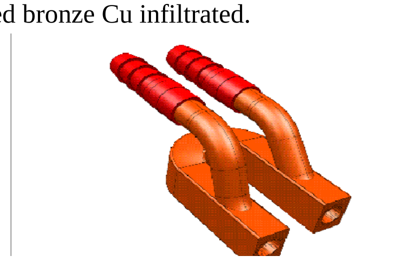

Figure 6: Laser sintered coil head.

This sample showed a better surface and was leak-proof. A third sample of selective laser sintered bronze Cu infiltrated and sealed showed the best results and we think this is a practicable way to produce the coil heads with very tight bends. After the first layers are made as described above, the outer layers are wound conventionally. Then the layers are split vertical and wrapped with glass tape 0.13mm half overlapped. After wrapping the layers are compressed again, the spacers are put in place and the outer insulation is made. To get a stiff, rigid and accurate to size coil body, the coil is vacuum impregnated.

3.2 Magnet Assembly

The two coils are put into the ”coil trough” , then the trough has to be closed by bonding one layer of Kapton on the top and bottom of the coil. The completed coils are shifted into the magnet collar and fixed by clamping one of the H-bars of the trough by bolting the taper gib to the collar. In addition the other H-bar of the trough is fixed by M6 bolts to the collar. After connecting the coils the whole magnet is shifted into the magnet support pipe as displayed in Fig.2 and Fig.7.

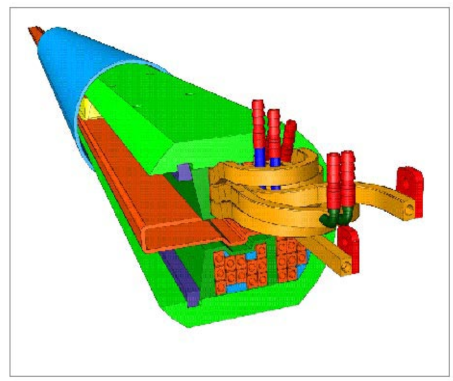

Figure 7: QG magnet half cut with coil head.

4 CONCLUSION

The field calculations show that the field quality can be reached by placing the conductor centers within ±0.5 mm of their design parameters. We think this can be managed by using the described coil trough. Final tests of laser sintered coil heads were very promising. With some additional work we are confident the coil heads with the very tight bends can be made by selective laser sintering, so that the coils can be produced and the combined function magnet can be built.

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[4] ”HERA Status and Future Plans”, F. Willeke proceedings of PAC’97, Vancouver, May, 1997.

[5] Vector Fields Ltd., Kiddington, Oxford, OX5 1JE, England

[6] The MAFIA Collaboration, CST GmbH, Lautenschlägerstr. 38, 64289 Darmstadt, Germany

[7] Stuctural Dynamics Research Corporation; SDRC, 2000 Eastman Drive; Milford, Ohio 45150, USA

[3] NRU Präzisionstechnologie
Stolberger Str. 31 A
D-09221 Neukirchen (Erzgeb.)