# SUPERCONDUCTING MAGNETS FOR USE INSIDE THE HERA EP INTERACTION REGIONS*

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*Abstract*

For the HERA luminosity upgrade, superconducting magnets will be inserted inside the existing H1 and ZEUS experimental detectors. These magnets enable earlier separation of the electron and proton colliding beams than the original HERA design and provide additional interaction region (IR) focusing. Design and production of such magnets is challenging due to detector space limitations, interaction with detector solenoidal fields, large inner synchrotron radiation apertures and stringent field quality requirements. We plan to direct wind ≈1 *mm* cable in dipole, quadrupole, skew dipole and skew quadrupole circuits as discussed in this paper. Recent magnetic field measurements of a short prototype magnet, for quantifying ramp rate effects, are also presented here.

## 1 INTRODUCTION

The HERA collider in Hamburg [1] has two interaction regions (IRs) dedicated to colliding 820 *GeV* protons (p–beam) and 30 *GeV* electrons or positrons (e–beam) at the H1 and ZEUS experiments. In the “Future Physics at HERA” workshop [2] an IR luminosity upgrade has been investigated in great detail. It was shown that an upgrade would improve the HERA research opportunities vastly. The “HERA Upgrades and Impacts on Experiments” group developed a plan for improving the present HERA lattice with new magnets that allows reducing betatron amplitudes ($\beta$–functions) at the interaction point enough to yield a $5\times$ increase in luminosity [3-6].

A key feature is using special magnets inside existing experimental detectors to provide additional e–beam IR focusing and earlier beam separation. To avoid impacting detector performance, the radial space for these magnets is severely restricted. Due to detector solenoidal fields it is not practical to use magnetic materials such as iron to concentrate or shape the magnetic field. A block copper–conductor coil solution was proposed to provide combined quadrupole and dipole fields[7]; however, in machine simulations it was found essential to reduce e–beam chromatic effects by increasing the IR quadrupole gradient. Since a higher gradient was unreasonable for water cooled conductors, a superconducting option was developed.

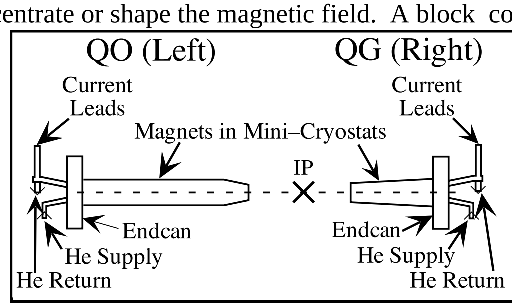


Figure 1: Upgrade Schematic. Magnets inserted 1.75 *m* left of IP (QO) and 1.7 *m* on right (QG). Original HERA layout has ±5.8 m free space. Cryogenic and current feeds are located just outside main detector components.

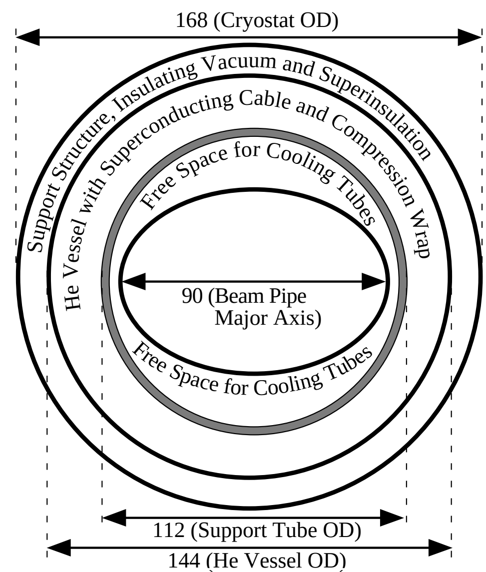


Figure 2: QO Radial Buildup. All dimensions are in *mm.*

## 2 DESIGN CONSIDERATIONS

Because of differing space and aperture requirements to the left and right[1], two magnet designs, denoted QO and QG are required as depicted in Figure 1. QO deflects the e–beam by 8.2 *mr* and QG by 3.5 *mr*. On the e–downstream side, QG needs 120 *mm* horizontal aperture: $20\sigma$ for the e–beam plus room for the QO synchrotron radiation fan.

Without this extra fan, the QO aperture is 30 *mm* smaller than for QG. This is fortunate since QO must fit in a 180 *mm* ID opening defined by an H1 Liquid Argon Calorimeter welding seam. The allowed QO cryostat size, illustrated in Figure 2, is 168 *mm* due to the QO ≈ 5 *mm* center offset and 4 *mr* tilt and to leave space for magnetic shielding near the ZEUS Forward Calorimeter phototubes. 16 *mm* is available radially for He flow, superconductor, and compression wraps and 12 *mm* for cryostat insulating vacuum, superinsulation and the cryostat wall. Beam pipe cooling and He return flow piping uses vac-

[1] Left and right are as viewed from ring center; p–beam goes right to left. Experiments identify left as the “forward side.” Synchrotron radiation goes to right, i.e.e–beam downstream.

uum space between an elliptical beam tube and the circular coil support. The beam tube matches nearby apertures to avoid wake field trapping. QG radial budget is similarly tight.

All cryogenic and superconducting wiring connections, housed in the QO endcan, must be removable to allow sliding the QO cryostat completely inside H1 during installation. Also the QO cryostat is tapered over the last 200 *mm* so as not to obstruct the line of sight from the IP to inner edges of the ZEUS Forward Calorimeter.

## *2.1 Magnetic Field Requirements*

As IR focusing magnets, with e–beam β–functions near ring maxima, QO and QG have stringent field quality goals. The harmonic content of higher order multipoles should be less than 3 to 7 $\times 10^{-4}$ relative to the main component. Four independent magnetic circuits are stipulated for both QO and QG. The required magnetic lengths and strengths are given in Table 1.

Table 1: QO and QG Coil Design Parameters.

| Parameter Description | QO | QG |
|---|---|---|
| Quadrupole Magnetic Length (*m*) | 3.20 | 1.30 |
| Quadrupole Gradient (*T/m*) | 13.0 | 8.50 |
| Dipole Magnetic Length (*m*) | 3.20 | 1.30 |
| Dipole Vertical Field (*T*) | 0.26 | 0.22 |
| Skew Dipole Length (*m*) | 1.55 | 0.60 |
| Skew Dipole Horizontal Field (*T*) | 0.09 | 0.06 |
| Skew Quadrupole Magnetic Length (*m*) | 1.55 | 0.60 |
| Skew Quadrupole Gradient (*T/m*) | 1.20 | 0.80 |

## *2.2 Coil Configuration and Production Issues*

Technology derived from the RHIC corrector program will be used[8]. For RHIC, superconducting wires were ultrasonically bonded to a flat substrate. The completed sheet was then wrapped around a support tube, compressed strongly via a fiber winding layer, epoxy impregnated and cured. This was then repeated and thereby a compact multi–layer conductor structure was built up. However the HERA field quality requirements are more stringent than those for the RHIC correctors and this construction process must accordingly be revised.

Wrapping the flat pattern is susceptible to introducing small angular gaps when the width of the pattern differs from the circumference it is being laid onto. Also it is hard to handle the more than 3 *m* long HERA conductor sheets and avoid small twists and irregularities. These troubles can be avoided if wire is laid down directly on the structure as is done for the RHIC Helical magnets[9]. A winding machine, shown in Figure 3 using ultrasonic bonding technology, has been developed. For a RHIC Helical magnet, a movable head lays down multistrand cable in a twisted slot machined into an aluminum tube. For QO and QG production, the winding pattern is laid directly on an unslotted tube.

Cable placement information comes to the winding machine from the same computer file used for magnetic field calculations. Each cable layer gets its own compression wrap and is cured and sized before adding the next layer. This wrap uses preimpregnated fiber glass, as was used for HERA superconducting correction coils[10]. For

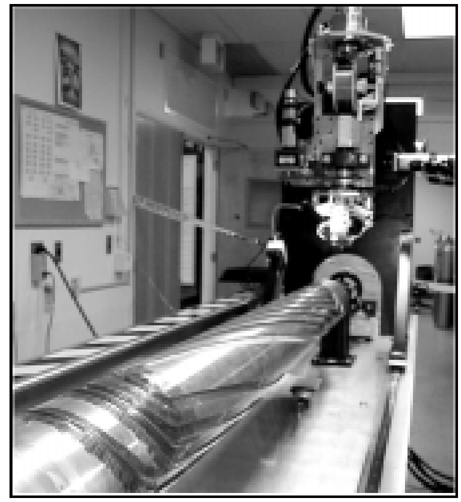

Figure 3: RHIC Helical Magnet Winding Machine.

QO, the main quadrupole has three such layers; for QG two. Next comes a single layer dipole. The outermost cable layer in both magnets is divided longitudinally into skew dipole and skew quadrupole circuits.

The number of layers and cable path, including coil head shape, is optimized to meet HERA magnetic field requirements. Since these magnets contain no magnetic material, warm measurements of field quality can be made after each circuit is complete in order to verify proper conductor placement. The multi–layer magnet assemblies will be cold tested in a vertical dewar.

## *2.3 Cable Issues and Prototype Measurements*

The QO and QG cable has 7 wires wound in the same "6 around 1" configuration used for the RHIC Helical magnets[9]. To ensure more than a factor of 2 operating margin[2], the cable's superconductor ratio is enriched to 1.8:1 (Cu:Super) compared to the Helical specification, 2.5:1. Wire and cable dimensions are kept the same.

During design review an issue regarding current sharing was raised; the 6 symmetric outer conductors experience a different environment than the central conductor around which they are wound. Difference between center and outer conductors might give trouble during ramping[3].

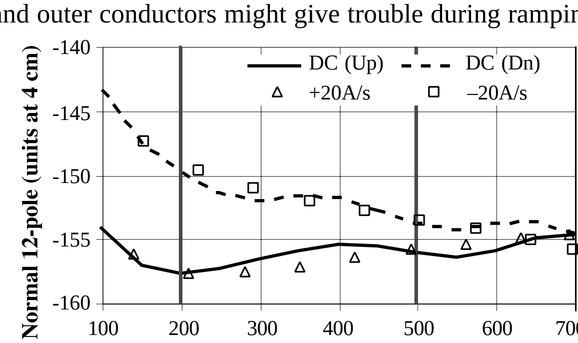


Figure 4: Value of first allowed harmonic, $b_6$, plotted as a function of current. Operating range of 200 to 500 *A* is marked. Note close agreement between 20 *A/s*. ramp and DC. Up–down difference is a measure of magnetization.

[2] Normally synchrotron radiation tails give little heating, but upsets can happen; so $\times 2$ margin specified to avoid quenchs.
[3] Not a concern for DC powered RHIC Helical magnet.

Replacing the central conductor with a copper wire regains symmetry but reduces operating margin 14%. To address this issue, a 0.5 *m*, single layer, test coil was fabricated via the flat wrap technique described earlier. Only the first of the three QO quadrupole layers was put on the support tube; so the test magnet had significant $b_6$ and $b_{10}$ allowed harmonics[4].

Field harmonics were measured during up and down ramping at various rates (DC, 2, 10 and 20*A/s*) with this prototype in a LHe dewar with a 4 *cm* diameter rotating coil. Figure 4 shows a comparison of DC and 20*A/s* for the first allowed harmonic. No effect was seen here or in any other normal or skew harmonics up to the 30–pole. We conclude that for the HERA ramp rate, < 2*A/s*, eddy current driven multipoles are not a concern. The only rate effect hint was that the coil quenched at 1074±10 *A* when ramped at 2*A/s* and 1052±10 *A* at 10*A/s* (i.e. a 2% drop). This prototype showed no training and exhibited a factor 2 margin at short sample.

The up-down difference seen in Figure 4 is a measure of magnetization. The contribution from magnetization is 3.5 units for $b_6$ at 200 *A*, and is smaller for other allowed harmonics. Calculations suggest that a 8μ*m* filament size is small enough to satisfy HERA requirements[11].

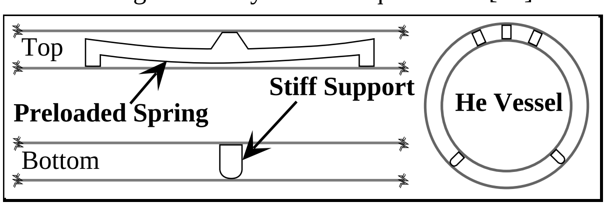


Figure 5: Internal Support Structure (Not to Scale). Note spring supports on top and stiff supports on bottom ensure that cold mass stays centered in cryostat shell.

## *2.4 Cryostat, Beam Tube and Endcan Design*

A special support structure had to be developed to fit in the radial 9 *mm* insulating vacuum space between the He vessel and the inner cryostat wall which did not make too large a heat leak. Our solution, outlined in Figure 5, uses preloaded cantilever springs opposite rigid supports. The spring arms provide a long conduction path for heat to reach the He vessel and the stiff support is a low conductivity G10 plug over a stainless steel tube. The length of the stiff support is such that the magnet aperture is centered in the cryostat when cold. Even when cold, the springs have sufficient preload to prevent the coil head from lifting with the detector solenoid on.

An additional low thermal conductivity support fixes the cold mass both axially and longitudinally at the endcan side, i.e. away from the IP. With this arrangement of fixed and sliding supports, differential contraction between the cold mass and the cryostat is accommodated in a controlled manner and the position of the cold mass can confidently be related to external fiducials.

The primary function of the endcan, shown in Figure 6, is providing cryogenic connections for super critical helium flow to the cold mass, 40°K cooling to the beam pipe and wiring connections for the 4 pairs of stabilized superconducting leads to the magnet circuits. In Figure 6 a

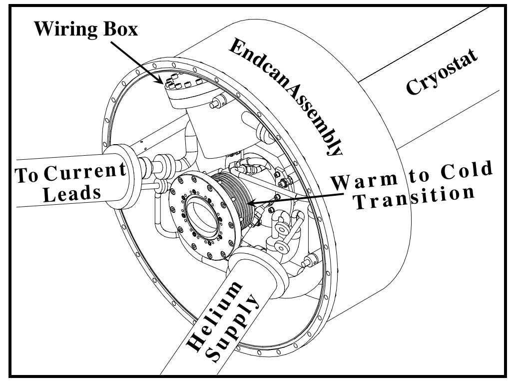


Figure 6: Endcan has 2 fixed plates connected by internal rods. Cylindrical cover shifts for access. 4° and 40°K He are fed via coaxial supply line; return flow and stabilized cable leads go to an external tower with gas cooled leads.

fixed mounting plate is removed for viewing, but in fact it is the cylindrical endcan housing itself which is slid toward the IP for internal access. For QG the cryostat vessel is welded to the endcan plate for magnet support; however, the QO endcan and all connections must be removed during an intermediate H1 installation step.

An internal wiring box pivots to take the differential contraction of lines going to the gas cooled current leads. All cold surfaces and the endcan inner surface are covered with at least 18 superinsulation layers to reduce heat leak.

The elliptical beam tube connects to a circular bellows for making a warm to cold transition inside the endcan. Thin fingers, inside the bellows, give a smooth transition to warm beam pipe and maintain continuity for beam image currents. Since synchrotron radiation heating of the QG beam pipe is possible during upset events, the outside of the stainless steel beam pipe and cooling tubes will be copper coated to conduct excess heat from the midplane.

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[4] European convention: $b_1$ = dipole, $a_2$ = skew quadrupole etc.

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