HERA Luminosity Upgrade Superconducting Magnet Production at BNL

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Abstract—**Production of two types of superconducting multi-function magnets, needed for the HERA Luminosity Upgrade is underway at BNL. Coil winding is now completed and cryostat assembly is in progress. Magnet type GO and type GG cold masses have been satisfactorily cold tested in vertical dewars and the first fully assembled GO magnet system has been horizontally cold tested and shipped to DESY. Warm measurements confirm that the coils meet challenging harmonic content targets. In this paper we discuss GO and GG magnet design and construction solutions, field harmonic measurements and quench test results.**

Index Terms—**Accelerator magnets, computer controlled winding, dipole, luminosity upgrade, superconducting cable, quadrupole**

I. Introduction

Our group, the Superconducting Magnet Division at BNL, is producing superconducting magnets needed for the HERA Luminosity Upgrade[1],[2]. Two varieties of magnets, denoted GO and GG, are required for insertion into opposite sides of the H1 and ZEUS experimental detectors. The magnets have different lengths and internal configurations. In addition to the main quadrupole and dipole coil layers, which provide final focusing for electrons and electron proton beam separation, each magnet has skew-quadrupole, skew-dipole and sextupole windings. In order to be compatible with being positioned inside the H1 and ZEUS detector solenoids, without excessive experimental detector shadowing, the magnets are constructed without magnetic flux return yokes and are supported inside thin-walled small-diameter cryostats.

The longer but smaller outer diameter GO cryostat configuration is shown mounted at BNL for horizontal testing in Fig. 1. The cryostat is attached to a larger diameter endcan assembly that provides both support for the cryostat and space for making internal cryogenic and electrical connections to the coldmass. A view inside the endcan is shown in Fig. 2.

A Gatling gun like arrangement of gas cooled leads, set in a compact vertical lead tower assembly, provides magnet excitation and instrumentation connections. These excitation current and signal connections pass to a wiring box inside the endcan via stabilized superconducting leads contained in a flexible extension arm linking the lead tower and endcan. Supercritical helium, which is used to cool the magnet coil layers, and 40°K helium, which is used for cooling the vacuum beam tube, are supplied via connections made at the endcan and returned via connections at the bottom of the lead tower. The lengths and layout of the extension arms between the endcan and lead tower are different for each magnet type and are tailored to fit in available space for each experiment.

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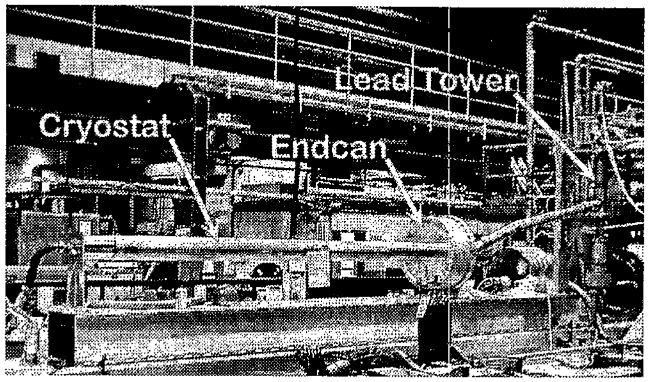

Fig. 1. GO magnet system pictured during horizontal cold testing in the Magcool test facility at BNL. GO consists of a multi-layer superconducting coil assembly, in a mini-cryostat, with a cryogenic feed endcan and semi-flexible extension arm connection to gas-cooled current and instrumentation leads mounted in a compact vertical lead tower assembly.

II. Magnet Production

A. Coil Winding Technique

The main quadrupole and dipole circuits for both magnet types and the GO skew-multipole circuits are wound from superconducting cable consisting of seven 0.33 mm diameter conductors in a six-around-one configuration. For the

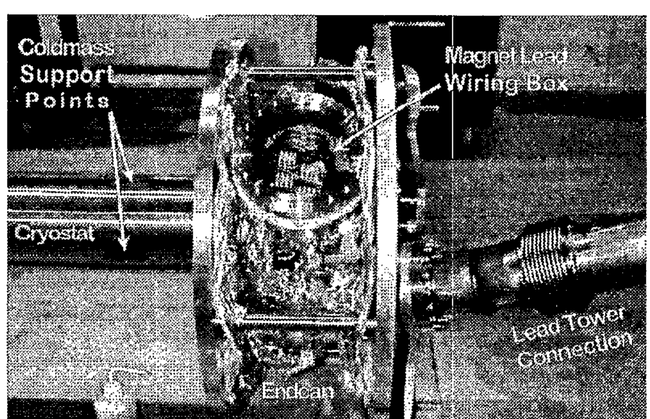

Fig. 2. Endcan with outer cover slid back and wiring box cover removed. Interior parts and cryogenic plumbing are wrapped with superinsulation.

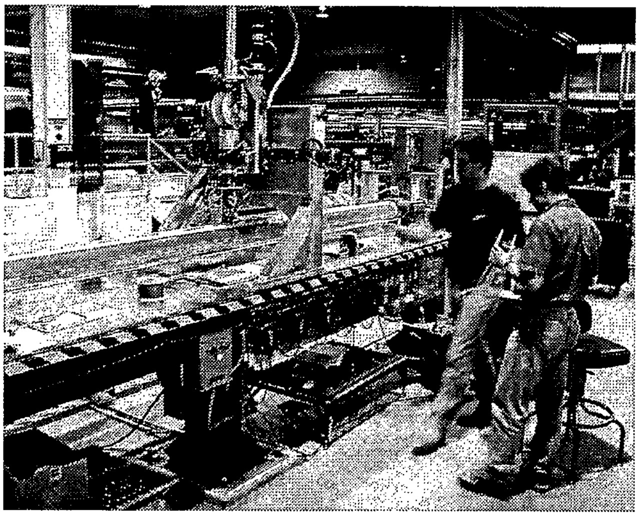

Fig. 3. A GO coil layer being laid down via our computer controlled winding machine. After winding, this layer had its spaces epoxy and G10 filled, was wrapped with s-glass and cured before winding the next layer.

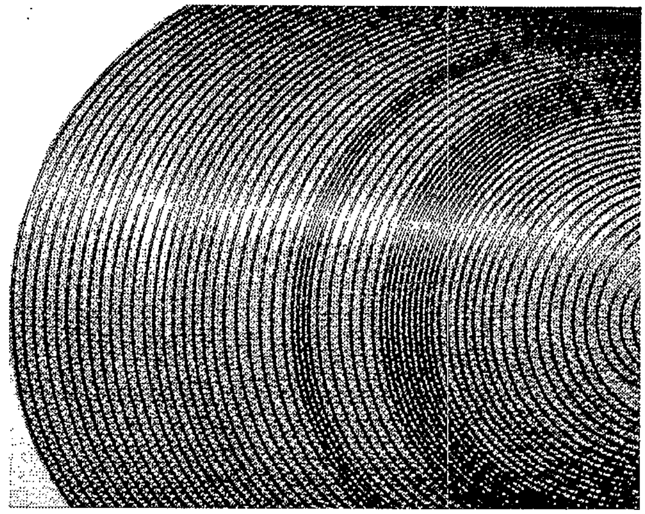

Fig. 4. Close up of GG coil end showing variable wire end spacing used for harmonic correction near coil ends. The 2D cross section is similarly adjusted in the straight section to correct body harmonics.

sextupole layers for both magnets and the skew-multipole layers for GG it was found convenient to use 0.33 mm diameter single strand wire, the same conductor as used for the RHIC corrector program[3],[4]. The choice of a smaller diameter conductor for the sextupole and GG skew-layers saves radial space within the cold mass and also reduces superconductor magnetization effects. Both the six-around-one and single strand conductors were b-stage epoxy coated.

Coils were wound from both cable and single strand conductor via an automatic winding process using a computer controlled winding machine developed in-house, (Fig. 3). Coil winding starts after spiral wrapping a Kapton insulated stainless steel coil support tube with a substrate layer onto which the coated conductor is bonded via localized ultrasonic heating. A close up view near the end of a typical winding pattern is shown in Fig. 4

Our initial coil patterns were composed of separate subcoil windings for each pole, that were then spliced together. For instance a quadrupole winding would have four subcoils with leads at both midplane and pole. These subcoils could be wound with the same handedness and in the same progression, with inside turns followed by outside turns that were almost touching or with field harmonic spacer gaps. Later we developed finer harmonic tuning control by learning to modulate the turn-to-turn spacing in both the magnet ends and straight section. Finally we were able to wind inward after starting from the outer coil pattern edges. Many subcoil splices could then be avoided by winding subcoils in matched pairs, spiraling out from one pole and then spiraling in to the center of the neighboring pole.

B. *Coil Layer Construction*

After each layer was wound we filled the small spaces between conductors with epoxy and the larger gaps, primarily the magnet pole region and any harmonic tuning spacers, with a combination of G10 and epoxy. This epoxy fill was then cured before the layer was wrapped with epoxy impregnated s-glass fiber cord under tension. The s-glass wrap was made to provide coil prestress to minimize conductor motion when the magnet was excited and thereby avoid premature quenches. After applying the s-glass wrap, the layer was cured again so as to have a firm surface for winding the next magnet layer.

In order to help ensure that the coil remained round during curing, each cure was made with the magnet held in four-part clamping fixtures. The machined inner surfaces of this clamping fixture provided a circular reference for curing. Typically, the cured surface had radius irregularities less than ±0.1 mm. Since the coil leads came out from the magnet poles, slots had to be provided in the curing clamps to avoid crushing the leads.

C. *Magnet Construction*

The coil support tube had end flanges welded to it before coil winding started. Once the coil layers were satisfactorily tested, as described later, an outer jacket was welded to these flanges to form the cold mass. Note that the coil support tube is also the inner helium containment wall.

Large transverse forces are expected at the dipole coil ends, due to the interaction of the dipole coil windings with the solenoidal detector field, when the magnet is energized in H1 and ZEUS. These forces are transferred to the outer cryostat body via stainless steel support keys arranged as shown in Fig. 5. The horizontal keys restrain vertical motion and the vertical keys horizontal motion. Differential contraction

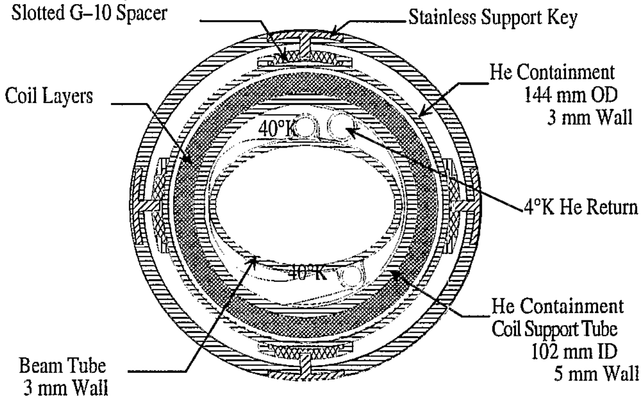

Fig. 5. GO cryostat cross section at internal support location. Stainless steel keys welded to the cryostat wall fix the cold mass center relative to cryostat wall, yet do not restrict longitudinal motion from cold mass contraction.

between the cold mass and the outer cryostat vessel is accommodated since the fixed keys are able to slide in G-10 slotted pieces attached to the cold mass.

III. Coil Tests and Measurements

A. *Warm Harmonic Measurements*

We found it useful to make magnetic measurements of the field harmonics of each layer during production. For the first few magnet layers wound we made harmonic measurements before and after every coil winding and curing step since we were concerned that the conductor might shift during curing and introduce unwanted field harmonics. We found that under the curing procedure outlined earlier, the main change observed for a layer's field was a slight increase in transfer function after that layer's first cure. Later cures and even the subsequent addition of other coil layers with more compression had negligible effect. This behavior is consistent with the wires penetrating deeper into the substrate to a slightly smaller coil radius after the first cure and afterwards staying in place.

Later in production, when we were winding skew-corrector coils where the harmonic goals were not as stringent, we made a test to see if it would be ok to skip some of the intermediate cures. For this test we wound a skew corrector winding before the second cure of the layer directly below it and found it had larger unwanted harmonics than we were accustomed to. An uncured coil layer provides too yielding a surface for winding. After this only the outermost and least critical sextupole coils were wound without full inner layer curing.

The most important use of warm measurements during production was as feedback to make small adjustments to field harmonics before coil winding was completed. In particular the GO main quadrupole magnetic circuit was made up from three separate cable layers connected in series. Once the first quadrupole layer was wound and measured we had the information needed to make changes to the second and third coil layer patterns to counter unwanted harmonics. In this way we were able to both monitor and correct for systematic winding pattern errors and produce magnets with error harmonics much smaller than for an individual layer.

We found that the principal source of coil winding errors was traceable to small support tube axis offset errors and support tube curvature. Offsets manifest themselves as a harmonic modulation of one order higher than the most dominant term. Thus, for a quadrupole winding, an offset introduces otherwise unallowed normal and skew sextupole harmonics. Similarly, for a dipole winding, an offset adds normal and skew quadrupole terms.

Once this was understood we were able to institute a procedure whereby the coil pattern was deliberately modulated during winding to counteract such offset errors. The parameters for this counter-modulation were derived from dial indicator measurements of the support tube. Tube offsets of up to 1 mm were effectively compensated at the level of 8 μm with this technique. The same procedure also allowed us to add desired amounts of any harmonic to cancel errors found in previous winding layers.

B. *Vertical Dewar Tests and Measurements*

Before assembly in their cryostats the GO and GG coils were cold tested in a vertical dewar. Vertical testing for each coil entailed:

- Current ramping to values beyond nominal operation, as indicated in Table I.
- Forced coil quenches, while at operating current, using a nichrome wire heater wrapped around the coil assembly.
- Field harmonic measurements at several current levels.

TABLE I

Nominal Operating and Maximum Test Currents

Circuit	GO magnets			GG magnets		
	Nominal Operation (A)	Max. Test (A) when powered		Nominal Operation (A)	Max. Test (A) when powered	
		alone	with others		alone	with others
Dipole	332	600	400	311	500	500
Quadrupole	505	550	550	500	600	600
Skew Dipole	150	200	180	37	60	60
Skew Quadrupole	150	200	180	37	60	60
Sextupole	20	40	40	16	40	40

At first, each circuit was energized alone to currents shown in Table I. After establishing proper operation of each circuit, the quadrupole and the dipole were set at the maximum safe current (see Table I), and the skew layers were cycled to their maximum test currents. This test was repeated for another polarity of the dipole current, and also for the sextupole circuit energized in place of the skew quadrupole.

None of the coldmasses tested so far (two GO and one GG magnet) exhibited any spontaneous quenches. In order to establish magnet reliability in the event of a machine quench, forced quenches were induced using a heater wrapped around the coil assembly. The energy deposited (kiits) in these quenches was found to be within safe limits.

Magnetic measurements in the vertical dewar were made with a rotating coil system consisting of five tangential windings at a radius of 40.8 mm. The length of the measuring coil was 4.75 m for the GO magnets and was 2.78 m for the GG magnet. Only one circuit was energized at a time. The current was raised in suitable steps (5 A to 20 A) and was held fixed during harmonic measurements. The measurements were made both during the up and the down ramps of the current, and were repeated with the current polarity reversed.

Geometric values of the harmonics were obtained from the slopes of straight line fits to the normal and the skew components of various harmonics measured as a function of current. This procedure eliminates effect of any stray fields on the harmonics. Generally, these harmonics were found to be in good agreement with warm measurements, except for the harmonics allowed by the magnet symmetry. The allowed harmonics show a significant hysteresis and non-linear behavior with current due to superconductor magnetization effects. An example of such a harmonic is shown in Fig. 6 for the normal sextupole term in the main dipole layer of a GO magnet. The direction of current change is as indicated by the arrows. A separation of the "Up" and the "Down" current ramp branches can be clearly seen.

Due to the presence of several concentric layers of magnet circuits with different multipolarities, the magnet symmetry is complex. The coupling of flux from one circuit with the

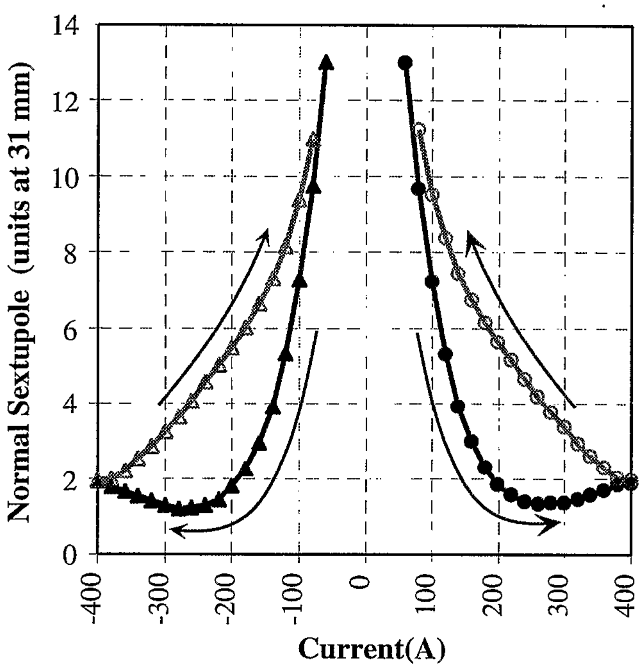

Fig. 6. The normal sextupole harmonic in the dipole layer of the GO magnet QH0103. The values are at a reference radius of 31 mm in "units" of 10^{-4} of the dipole field.

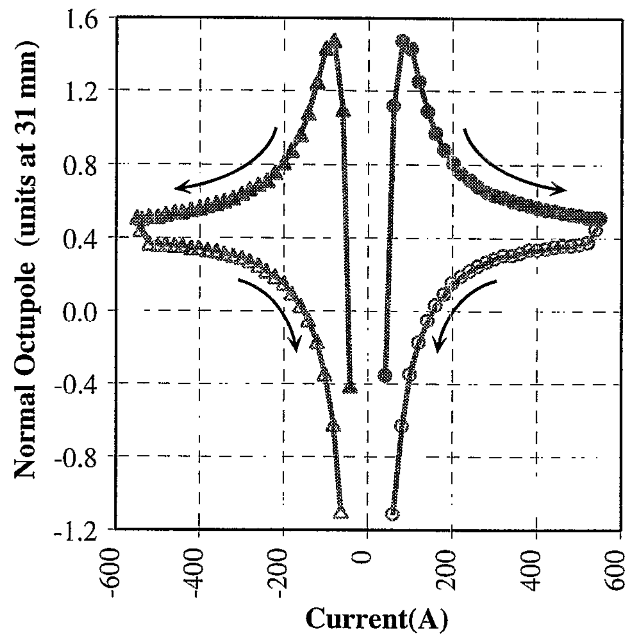

Fig. 7 Non-linear, hysteretic behaviour of the normal octupole term in the GO magnet QH0103. Such a behaviour is not expected for an "unallowed" term in a magnet with only quadrupole symmetry, and is perhaps due to the presence of other layers with different multipolarities. The values are at a reference radius of 31 mm in "units" of 10^{-4} of the quadrupole field.

windings of another circuit can lead to a hysteretic, non-linear behavior in terms other than the usual allowed terms. Such an effect has indeed been observed for a few harmonics. An example is shown in Fig. 7 for the normal octupole term in the main quadrupole magnet.

C. GO Horizontal Testing

While three magnets of each magnet type, enough for two experiments plus a spare, will be produced for the HERA upgrade, only the first unit of each type is to be horizontally tested before shipment to DESY. To date we have had a full horizontal systems test only of the longer GO magnet type. This test was conducted with the GO magnet interfaced to the BNL Magcool cryogenic test system. For this test it was found convenient to cool the inner vacuum beam pipe with liquid nitrogen rather than with 40°K helium as is planned at DESY.

The horizontal test of the first GO magnet system was quite successful. The GO magnet circuits were brought to levels above their respective operating points (the sextupole, was energized just to its current lead limit, 20 A) for an extended period of time and stable operation of both the magnet and current leads was observed.

Due to space limitations, the nichrome heater assembly used to force quenches in the vertical dewar had to be removed; so we were unable to repeat, during horizontal testing, the GO quench measurements. Also, no field quality measurements were carried out during the horizontal tests since it would have been difficult to make accurate harmonic measurements due to the presence of a beam tube with much smaller aperture (see Fig. 5).

D. Determination of Magnetic Center

To facilitate installation of the magnets into the machine, it is important to determine the magnetic axis in reference to fiducials located on the outer surface of the cryostat. A "survey antenna" consisting of a non-rotating coil system was developed at BNL for determining magnetic centers of the RHIC quadrupoles and correctors [5]. We used the same system for determining the magnetic axis of the quadrupole layer in the completed GO magnet. Due to the nature of construction technique used, other layers were found to be concentric with the quadrupole layer within ~0.1 mm based on regular warm measurements. The survey antenna gives the local magnetic center of the quadrupole circuit as a function of axial position. This not only provides an average center, but also gives information about straightness of the magnet. The one GO magnet measured so far showed a bow of about 0.6 mm in the horizontal direction and about 0.35 mm in the vertical direction. This distortion is not expected to significantly impact the magnet performance.

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