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# *Construction and Operational Experience with a Superconducting Octupole Used to Trap Antihydrogen*

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# Construction and Operational Experience with a Superconducting Octupole Used to Trap Antihydrogen

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***Abstract*—A superconducting octupole magnet has seen extensive service as part of the ALPHA experiment at CERN. ALPHA has trapped antihydrogen, a crucial step towards performing precision measurements of anti-atoms. The octupole was made at the Direct Wind facility by the Superconducting Magnet Division at Brookhaven National Laboratory. The magnet was wound with a six-around-one NbTi cable about 1 mm in diameter. It is about 300 mm long, with a radius of 25 mm and a peak field at the conductor of 4.04 T. Specific features of the magnet, including a minimal amount of material in the coil and coil ends with low multipole content, were advantageous to its use in ALPHA. The magnet was operated for six months a year for five years. During this time it underwent about 900 thermal cycles (between 4K and 100K). A novel operational feature is that during the course of data-taking the magnet was repeatedly shut off from its 950 A operating current. The magnet quenches during the shutoff, with a decay constant of 9 ms. Over the course of the five years, the magnet was deliberately quenched many thousands of times. It still performs well.**

***Index Terms*—Antihydrogen, Direct Wind, Octupole, Superconductivity**

## I. INTRODUCTION

TESTS of CPT (charge/parity/time) conservation are among the most fundamental in physics. One such test is to measure the spectroscopic lines of hydrogen and antihydrogen, affording a matter-antimatter comparison. The ALPHA collaboration recently reported initial success in the accumulation of 38 antihydrogen atoms at the CERN Antiproton Decellerator [1]. These events point the way to high-precision tests of CPT using matter-antimatter comparisons.

The antihydrogen atoms were formed by directing a beam of antiprotons into a plasma of positrons. The low energy portion of the antihydrogen atoms was then trapped in a magnetic well. Deeper wells trap atoms of higher energy and, thus, trap more atoms, leading to the use of superconducting magnets to form the well. The ALPHA well was formed by magnets made by the Superconducting Magnet Division at Brookhaven Lab. The radial wall was generated by an octupole. The axial walls were produced by mirror solenoids located at the ends of the octupole. A description of the design and test of a prototype octupole magnet was recently published [2].

The octupole magnet was made using Magnet Division's Direct Wind facility. This paper reports operational experience with repeated quenching as well as construction details that contribute to its reliability and field quality. Magnets made at the Direct Wind facility have been installed in facilities at the DESY [3], IHEP (Beijing), and J-PARC [4], are being produced for an electron lens at RHIC [5], and are being prototyped as part of the ILC R&D [6], [7]. Another paper to this conference discusses common features of Direct Wind magnets [8].

## II. MAGNET DESIGN

To maximize the field while minimizing the material between the trapped antihydrogen and the detectors, NbTi with a relatively low copper-to-superconductor ratio of 0.9:1 was chosen. For the 0.33 mm diameter strand, the choices for coils made on the Direct Wind machine were a single strand and a six-around-one cable. The cable was chosen to minimize the ramp-down time. Conductor properties are listed in Table I.

TABLE I SUPERCONDUCTOR PROPERTIES

| Property | Value |
|---|---|
| Material | NbTi |
| Cu:SC ratio | 0.9:1 |
| Wire diameter | 0.33 mm |
| Cable type | 6-around-1 |
| Cable diameter | 1.0 mm |
| Cable $I_{ss}$ (4.2K, 5T) | 1.0 kA |

The effectiveness of added layers to the octupole falls off as $r^{-3}$ and adds material. A coil with eight layers was chosen as optimal for these parameters. The coil was wound using a "serpentine" layout [8], which minimizes the axial fields from the octupole.

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The number of turns in each layer was varied to minimize the peak field at the conductor. During the optimization process, it was observed that the peak field was particularly sensitive to the value of the second allowed harmonic, the 20-pole, possibly because it is the harmonic closest to being coherent with the wire spacing. Therefore, the values of both the first (12-pole) and second harmonics were taken into account. The design values of the 12-pole and 20-pole are -11 units and -10 units respectively. (A unit is $10^{-4}$ of the fundamental field at a radius of ~2/3 of the coil inner radius. For the octupole coil, the reference radius is 20 mm.) The number of turns varies from 11 (innermost layer) to 15 (outermost layer). Parameters of the octupole coil are listed in Table II.

TABLE II OCTUPOLE PARAMETERS

| Parameter | Value |
|---|---|
| No. Layers | 8 |
| Total No. Turns | 108 |
| Length | 300 mm |
| Inner Radius | 25 mm |
| Transfer Function | 161 T/m$^3$/A |

In the 2 T background field covering the octupole, the maximum field seen by the conductor was calculated to be 4.04 T. The Lorentz force on the conductor is 4 kN/m. The first layer of the octupole is shown in Fig. 1.

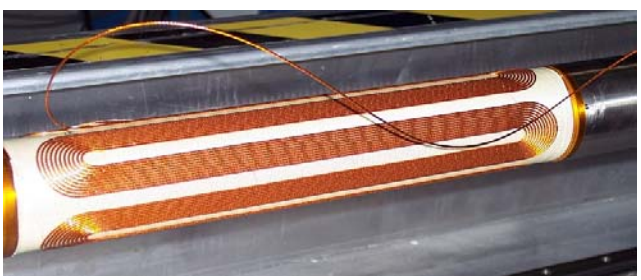

Fig. 1. First layer of ALPHA Direct Wind octupole magnet, with serpentine ends.

## III. MAGNET CONSTRUCTION

The direct wind machine at BNL was built as part of a system developed to wind superconducting coils directly onto a support tube. This is done by using an ultrasonic transducer to embed the wire into B-staged epoxy fiberglass. The winding machine has 11 independently controllable motions and parameters. This allows one machine to have the capability of winding an unlimited number of different coil patterns without making any mechanical changes. The drive head and tail stock of the machine have been fitted with four-jaw chucks to allow tubes of up to 305 mm in diameter to be installed and adjusted to run true. The tail sock is on precision rails which allow its quick adjustment to different length tubes while keeping it centered.

The initial phase of coil winding focuses on conductor placement. To achieve a magnet with low harmonic content, the locations of the wires need careful attention. One big problem is the magnitude of the wire placement accuracy requirement in comparison to the wire geometry and texture. The direct wind conductors are insulated with 12.7 μm Kapton® tape on a 50% overlap, and coated with B staged epoxy for the welding process. Measurement of the wire using mechanical means cannot provide the location accuracy required for the final magnet. This problem is significantly worse for a conductor cable made from 6 strands around 1 center strand (diameter ~ 1.1 mm), as used in the ALPHA magnet. As such, the only practical means for determination of process accuracy is magnetic measurement. Subsequent coil layers can have harmonics introduced to compensate magnetic field errors produced by previous layers.

The error mechanisms and correction schemes are as follows.

1. Support tube location errors. Any bend in the support tube that causes the center of rotation of the tube to deviate in space will cause modulation of the conductor placement. A 101 mm diameter tube with an off- center error of 25.4 μm will create a first harmonic above the fundamental to be on the order of 3 units. A quadrupole wound with this level of inaccuracy will yield a magnetic field with 3 units of sextupole. To achieve harmonics below 1 unit, tube placement accuracies of 2.5 μm would be required. With the substrate wound on the tube, the texture of the substrate prevents accurate measurement of the tube center. To work around this, multiple measurements are taken, and the average location of the tube is determined mathematically along the length of the tube.
2. Support tube out of round errors. As a magnet is built up layer by layer, there will be a tendency of the surface to go out of round. This will also start to modulate the magnetic field by alteration of the wire placement. This error is also measured and compensated in the design of the next layer.
3. Wiring machine mechanical accuracies. All axes which control the conductor placement have encoders capable of 2.5 μm accuracy. The stylus location during rotation is indicated to 12.7 μm repeatability.
4. The wiring file which describes the wire placement can have up to 500,000 points. The straight section is typically defined by points in space every 12.7 mm. At the pole tips where the conductor turns, points are specified at 2 to 5 degree increments depending on the pattern dimensions. Modulation of the pattern for accurate placement occurs at every wiring file point. The modulation includes tube rotation errors, tube out of round compensation, and harmonic modulation to create compensating harmonics.

## IV. CONDUCTOR STABILIZATION

Proper operation of a superconducting magnet requires the conductors to be locked in position to prevent motion due to the electromagnetic force on the conductor. This requirement is complicated by the fact that manufacturing is performed at room temperature, but the magnet is operated at 4.5 K. All materials used must be capable of cryogenic operation without failure. Since the ultrasonic wire bonding mechanism is intended as a wire positioning device only, conductor support must be designed in and applied after a layer of conductor has been placed. All interstitial voids resulting from the bonding of the superconductor into a coil pattern must be filled with a material which matches the thermal contraction of the conductor. G-10, Nomex, and Stycast 2850 filled epoxy are the materials of choice. By design, all internal filler materials and the conductors themselves are placed into compression only. Tension and shear are not allowed within the filler materials.

The reasons for each are as follows:

1. G-10 and Nomex pieces are used to fill large designed-in pattern voids. Pole areas, midplane gaps, and any pattern gaps which are designed in for harmonic modulation are filled with spacers. For 6 around 1 conductor patterns, G-10 is the material of choice. For single 0.33 mm conductor, Nomex (aramid paper) is used. Both materials fill the interstitials, and have the same thickness as that of the insulated conductor, to bring the coil form back to a cylindrical shape for subsequent winding layers.
2. Stycast 2850 FT is the epoxy used for filling interstitial voids which are too small for G-10 or Nomex. This epoxy has several advantages over all other epoxies. It is a matched expansion material by virtue of alumina filler. Typically, this epoxy has a thermal contraction of 25 to 32 ppm/degree C. Normal unfilled epoxies are 60 to 100 ppm/degree C. The hardener used for this is the 24 LV or 23 LV. This hardener allows for a room temperature cure, this being very important for the magnets. The epoxy also has an extremely low cure shrinkage which also prevents the introduction of tension in the final structure.
3. Each lead is stabilized as it leaves the coil pattern by soldering an additional conductor to it.

With the space between the conductors filled, preload is supplied by an S-glass overwrap, which is wound with a tension that is 25% greater than the calculated Lorentz force on the conductor. This construction makes it unnecessary to use steel collars for conductor support, an advantage since the collars would seriously compromise detection efficiency. The coil is wrapped with a B-staged S glass at about 11 kg tension and then cured. The overwrap limits conductor motion under the calculated Lorentz force to about 50 μm.

## V. Quench Performance

Survival of a quench of the conductor requires the timely detection of a quench, dissipation of the resultant energy within the magnet without excessive temperature excursion, and protection of all exit leads against voltages induced by inductive reactance.

1. Quenches are detected via signals from voltage taps in the coil structure. Double layer coils have a center tap to allow difference detection of quenches. When multiple layer coils are used, redundant voltage taps are provided at the coil splice points.
2. During a quench, survival of the coil also requires the mechanical structure be capable of supporting the energy released. The Stycast epoxy used is an excellent material for this by virtue of its alumina filler. The heat conductivity of the epoxy helps transport heat away from a quenching wire distributing it through a coil layer in a timely fashion, and its diffusion velocity helps prevent crazing failure of the epoxy resulting from Von-Mises stresses caused by large thermal gradients.
3. All conductors are double wrapped with Kapton insulation to protect against high voltages which result from fast turn off during a quench. A room temperature voltage standoff of 2 kV was used.

## VI. Operational Experience

The rapid shut-down of the octupole, needed as part of the operation of the experiment, caused the magnet to quench. During five years of operation, the magnet was quenched between 3,000 and 10,000 times. On a daily basis, about 900 times total, it underwent a mini thermal cycle (4 K to 100 K). The octupole's operating current is 950 A. Its short-sample current is estimated to be 1,100 A. During this time, no deterioration of performance has been noted.

## VII. Summary

The performance of the Direct Wind octupole used in the ALPHA experiment has not deteriorated after many thousands of quenches during the several-year course of the experiment.

## Acknowledgment

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