BNL-94492-2010-JA

Magnetic Field Measurements of an HTS Retrofit Synchrotron Dipole

J. Muratore, J. Escallier, G. Ganetis, A.K. Ghosh, R.C. Gupta, P. He, A. Jain, P. Joshi, P. Wanderer, M. Fee and M. Christian

Submitted to the IEEE Transaction on Applied Superconductivity

December 2010

Superconducting Magnet Division

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of Science

DISCLAIMER

Magnetic Field Measurements of an HTS Retrofit Synchrotron Dipole

J. Muratore, J. Escallier, G. Ganetis, A. K. Ghosh, R. C. Gupta, P. He, A. Jain, P. Joshi, P. Wanderer, M. Fee and M. Christian

***Abstract*—A copper coil dipole magnet from the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (BNL) has been retrofitted by HTS-110 Ltd with coils made from Bi-2223 wire and a self-contained cryogenic cooling system, while keeping the magnet's original iron yoke. This modified bending dipole, which is the first such known retrofit HTS-based accelerator magnet, provides the benefits of a compact coil design to accommodate space-limited experimental issues and a significant reduction in power costs as compared to the original copper magnet. In order to validate this modified design for use in the synchrotron, a detailed magnetic field map has been measured using a multiple-Hall probe assembly and transporter system. The results are discussed in this paper, along with the performance of the closed circuit cryogenics system in keeping the coils below 45K.**

***Index Terms*— high temperature superconductor, HTS, Bi-2223 tape conductor, superconducting magnets, accelerator magnets, magnetic field measurements.**

I. INTRODUCTION

There are presently more than 75 synchrotron light source facilities worldwide and these are continuing to increase in number and beam energy. Recent examples of upcoming new light sources are National Synchrotron Light Source II (NSLS II), being constructed at Brookhaven National Laboratory (BNL) in New York, USA, and MAX IV, to be built at MAX-lab in Lund, Sweden. With increasing beam energy, it is necessary to build larger circumference storage rings with more magnets and/or manufacture magnets with stronger magnetic fields. The room temperature copper coil magnets presently being used in light source synchrotrons require a large cost in electrical power and cooling water, and future storage rings with more and/or stronger magnets will result in even higher costs. There is clearly a strong incentive to find ways to reduce such costs.

One solution to reduce such costs would be to use magnets built with coils wound with high temperature superconductor (HTS) wire. The recent development of reliable and practical wire made of HTS has made it possible to manufacture magnets with HTS coils instead of copper and benefit from the greater current densities (about 150 times that of copper) and the more compact size of the coils, which would allow more room for experiments or beam line equipment. The main cost in electrical power comes from the refrigeration of the HTS, which is about ⅓ the resistive power consumption of the copper coils. The payoff is in lower energy costs, stronger magnetic fields due to greater current carrying capacity, elimination of cooling water systems, more compact size, and greater efficiency of operation. Furthermore, for magnets presently in use in some accelerators, it is actually possible to replace the copper coils with HTS coils. This provides an added advantage of reusing the same iron yoke and supports of the original magnet, while reproducing the original field.

In order to demonstrate the feasibility of such a scheme, a prototype of an HTS accelerator dipole was made by retrofitting a spare VUV (vacuum ultraviolet) storage ring bending dipole from the NSLS at BNL by replacing the copper coils with HTS coils. The HTS coils were contained in a compact cryostat and conductively-coupled to a small closed loop cryogenics system, while keeping the original iron yoke. This paper describes this specialized magnet, believed to be the first of its kind for an accelerator, and discusses the results of detailed magnetic field measurements made after the retrofit process, and compares these data to measurements performed on an NSLS VUV storage ring copper magnet, a prototype built and measured in late 1979.

II. DESCRIPTION

The VUV storage ring bending dipole is a C-type magnet with two double-layer, multiturn copper pancake coils, mounted on a yoke assembled from 1.5 mm thick steel laminations, grouped in eight blocks shaped like parallelograms, and arranged to provide a bending angle of 45^0 and bending radius of 1.9099 m along the particle orbit path of arc length 1.50 m. The pole gap is 55 mm and pole face width 155 mm. The distance between the coils is 80 mm. More details of the construction and characteristics have been presented elsewhere [1], [2]. Fig. 1 shows a side view drawing of a VUV ring bending dipole. These magnets are presently operated at 1.41 T central field and 1639.2 A for 0.808 GeV beam energy. The resistance of the coils is 0.00486 Ω, so at the operating current the power consumption is 13.1 kW.

The spare NSLS VUV ring bending dipole was sent to HTS-110 Ltd of Lower Hutt, New Zealand, where the yoke was retrofitted by replacing the copper coils with a pair of HTS

Manuscript received 3 August 2010. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.
J. Muratore, J. Escallier, G. Ganetis, A. K. Ghosh, R. C. Gupta, P. He, A. Jain, P. Joshi, and P. Wanderer are with Brookhaven National Laboratory, Upton, NY 11973 USA (phone: 631-344-2215; fax: 631-344-2190; e-mail: muratore@bnl.gov).
M. Fee and M. Christian are with HTS-110 Ltd, 69 Gracefield Road, Lower Hutt, New Zealand

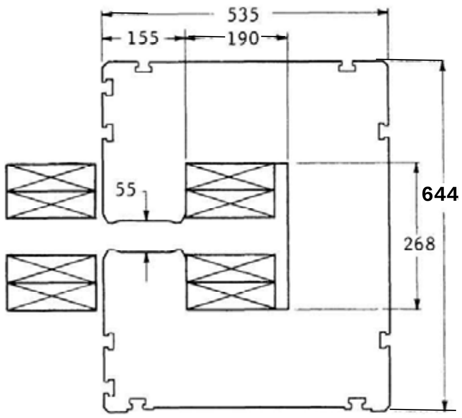

Fig. 1. Side view of a VUV storage ring bending dipole [1]. Units are mm. It is not shown in the drawing that the distance between the coils is 80 mm.

coils on the original yoke, to provide the same central field. Fig. 2 is a photo of the original dipole with copper coils, and Fig. 3 shows the retrofitted dipole with HTS coils and cryocooler cold heads. The HTS coils consist of two double-layer, multiturn pancakes wound with BSCCO-2223 multifilament composite wire manufactured via the powder-in-tube process by American Superconductor Corporation of Devens MA USA. It is High Strength Plus wire and is in the shape of a tape 4.3 mm wide and 0.270 mm thick and clad with 0.05 mm thick stainless steel. Insulation consists of 50 µm epoxy-impregnated nomex paper on the sides of the tape, G10 between the layers, and fiberglass on the top and bottom of each coil. This conductor has an engineering critical current density J_e of 124.40 A/mm^2 (77 K, self field). BSCCO comprises 40% of the composite volume, with the rest mainly silver. Each pancake coil layer has 158.75 turns, except for the bottom layer of the lower coil, which has 159.25 turns. Fractional turns are due to the crossover between layers. This gives the lower coil a total of 318 turns and the upper has 317.5 turns. The missing 0.5 turn in the upper was designed to allow the two leads to come out on opposite ends and balance the heat load between the two cryocooler heads. This decreases the cooling cost. According to calculations, the field uniformity is not compromised by this asymmetry in turns [3]. The superconducting leads are composed of the same HTS conductor but with copper backing, and are joined to full copper leads for the cold-to-warm transition to the external current terminals.

Each coil is mounted in a compact aluminum cryostat kept under vacuum and is sandwiched between copper plates which provide the conductive thermal coupling to a cryocooler system. This system consists of two Gifford-McMahon AL125 cold heads driven by a CP830 compressor (cooling capacity 70W at 50K) from Cryomech Inc, Syracuse, New York USA and is a He closed loop system designed to maintain the coils at a temperature in the range 39 – 45 K in the cryostat. The retrofitted magnet is designed to provide 1.386 T central field at 111.2 A compared to the 1639.2 A that the original copper magnet requires [4]. The power consumption required by the cryorefrigerator is 3.9 kW [5], resulting in a 70% reduction in power consumption compared to previously stated power of the original copper dipole. Furthermore, as can be seen in the photos, the distance between the two coil packs has been

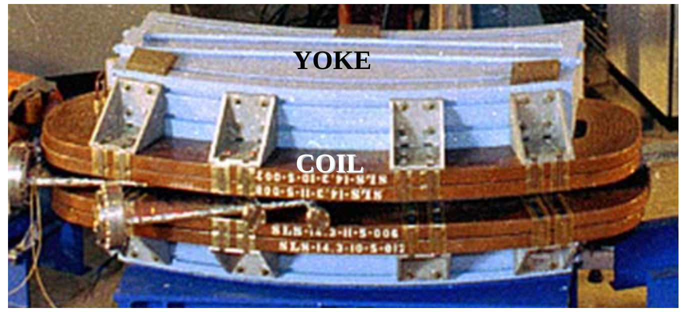

Fig. 2. Photo of VUV storage ring copper coil dipole at NSLS.

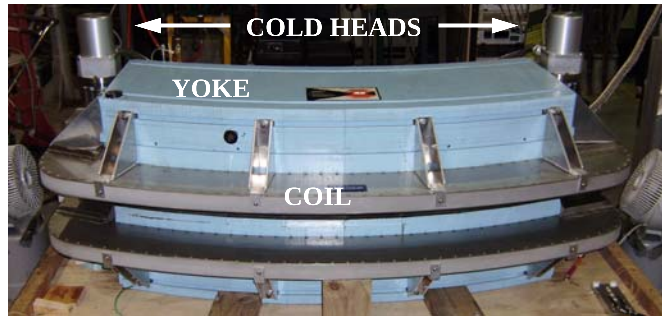

Fig. 3. Photo of retrofitted HTS coil dipole for VUV storage ring.

significantly increased, from 80 mm in the copper magnet to 145 mm in the HTS. This widens the aperture for beam line equipment. After running the retrofitted dipole at the design field, HTS-110 sent it back to BNL to be more extensively tested at 41 K (nominal) at the Superconducting Magnet Division (SMD).

III. EXPERIMENTAL DETAILS

In order to detect a possible quench of the superconductor before damage could occur, the coils were equipped with four voltage taps which were used to monitor the upper and lower coil voltages and the splice between the coils. Also, room temperature taps were added at the external power terminals to monitor the two leads (including the copper). Temperatures were monitored by six sensors: at the inside and outside of each coil and in each cryocooler cold head. These are CCS/D3 (carbon-ceramic/grade D3) sensors from Temati of Oxford UK. They exhibit less than 1% error in magnetic fields of less than 6 T, and they are calibrated to an absolute accuracy of approximately ± 0.2-0.3 K in the range of interest for this magnet, 10-77 K.

The magnet was energized by a Suncraft Electronics Model 440 150A/20V bipolar power supply. Since the focus of the testing was magnetic field measurements, there were no plans to purposely quench the magnet and possibly incur degradation to the conductor. Up to the maximum test current of 113 A, no quenches were expected, but it was still necessary to incorporate a quench protection system, which was borrowed from the Relativistic Heavy Ion Collider at BNL. This consisted of an energy extraction circuit and quench detector (QD) circuitry monitoring the upper and lower coil voltage difference, which should always be nominally zero in the superconducting state, and the voltage on the leads, which, due to the copper section, is a linearly increasing value during ramps. During testing, the voltage thresholds for tripping the QD were set to 12 mV and 50 mV for the coil voltage difference and lead voltages, respectively. These thresholds were chosen as a compromise between false trips due to noise and an acceptable detection time. When the QD trips, there is a 16.67 ms delay (1 power line cycle), which acts to verify that the voltage is not a transient event, then the QD output signal level drops to shut off the power supply. At the same time, it opens an IGBT switch in the energy extraction circuit containing a 0.5 Ω dump resistor, which is divided by a voltage tap in order to limit the voltage generated in the coil during a quench event to less than 35 V. This was done as a safety precaution because 100 mA leakage to ground had been detected at 35 V during hipot testing at 41K. The cause of this ground fault has not been determined, but it did not pose an issue during testing with the protective measure already mentioned. During testing, signals were continuously monitored at a sampling rate of 60 samples/s and voltage resolution of 300 μV, and included the upper and lower coil voltages, coil voltage difference, lead voltages, splice voltage, and power supply current. In the event of a QD trip, these signals would be captured at the time of the event for analysis. The total time range of capture was 50 s, with 25 s before the QD trip and 25 s after the trip. It should be noted that there were no quenches during the course of the testing.

Before cooldown, a turbomolecular pumping station with a liquid nitrogen cold trap was used to bring the cryostat down to a vacuum of about 10^{-6} mbar (7.5 x 10^{-7} Torr) before the cryocooler compressor was started. Cooldown to the nominal operating temperature of 41 K took about 18 hours. Once the temperature reached the nominal operating value, cryopumping began and the turbopump was shut down. The cryorefrigeration system kept the temperature stable at nominal for about 5 days and then the turbopump was turned back on to address a 1 K rise of temperature, possibly due to a minor leak or out-gassing due to o-ring seals. Since this magnet is a prototype, o-rings were used in many places where there would normally be welds, so as to gain quick access to the coils if needed. Therefore some out-gassing or leaking is possible during operation of the magnet. The cryogenics system therefore performed to specifications, as described in the HTS-110 documentation [4] with magnet and cold head temperatures maintained at 41 - 42 K and 36 K, respectively, and the turbomolecular pump turned off after reaching those operating temperatures and occasionally started up again. Out-gassing or leaking during cryopumping seemed to be a small effect, however, and the pump was needed only occasionally while cold to keep temperatures stable over long periods of operation. A 1K increase during magnet powering can be attributed to heating in the copper leads. This increase in temperature was expected and was well within the safety margin.

Magnetic field measurements were performed with an assembly of three Model MPT-141 Hall probes from Group3 Technology Ltd of Auckland, New Zealand. These probes have a range up to 3T, with resolution 10^{-6} T above 0.3T and 10^{-7} T below, and good accuracy with a small maximum error of ±(0.01% reading + 0.006% full scale). The assembly was mounted on a fixture designed to slide on a rail installed along the arc of the pole face. The three Hall probes were aligned linearly and perpendicular to the arc and measured the field at three positions on the median plane between the pole faces: at the central curved axis of the particle orbit and 30 mm transversely to each side of the axis, toward the inside and outside, in order to cover most of the 68 mm "good field" region [1] and validate field uniformity, which in principle should repeat that of the original copper dipole magnet.

The ramp rate was 0.5 A/s or less for all tests. It was kept this low to limit voltages generated by the high inductance of 2.5 H of the HTS dipole. (In comparison, the inductance of the copper magnet is about 7 mH). The test plan included several sets of measurements. A test to measure the transfer function and the hysteresis was performed at the magnet center position by taking measurements at discrete steps from 0 to 113 A, and back to 0. Axial scans with the Hall probes were done along the entire pole face arc in increments of 1.0 cm, and then 0.5 cm after passing each end, because of the rapid decrease in field after leaving the pole face. A scan was done at the original design operating field of 1.2 T (89.27 A), since the only available data from the copper dipoles was from the prototype at that field taken in late 1979 before installation of the magnets in the NSLS [2]. The results of the present tests can then be compared with that original data. A scan was also done at the present operating field of 1.4 T (113.39 A).

IV. RESULTS

Fig. 4 shows a plot of magnetic field vs. distance for 1.2 T operation along the beam path central axis and the two displaced paths at ±30 mm. As can be seen, the three plots show no significant divergence and it is clear that the "good field" region of homogeneity extends to at least ±30 mm to each side of the beam path central arc. This agrees with the value for the original magnets as stated in [1]. In fact, the uniformity at ±30 mm is within ±0.35% of the central axis value at magnet center. This is seen in Fig. 5, which shows the data between the pole ends in a more detailed scale. Fig. 6 shows an appropriately scaled and cropped version of the central axis data from Fig. 4, plotted with the data for the VUV ring dipole prototype [2], and it can be seen that the agreement is reasonably good. The gradual decrease in field from the magnet center (exhibited in both old and new data) has been attributed to iron saturation in the yoke ends [2].

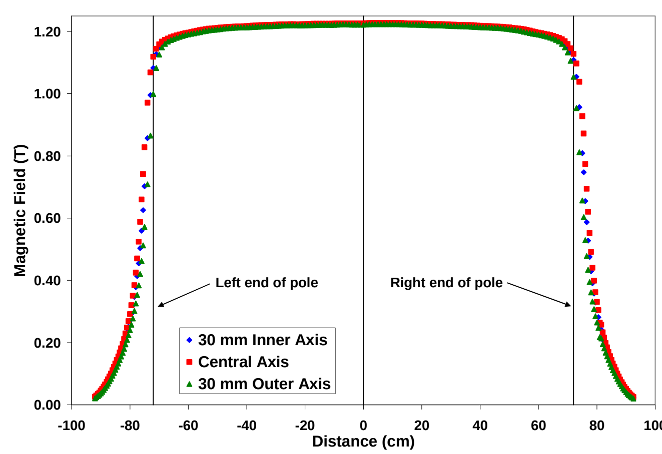

Fig. 4 Scans of magnetic field vs. distance along the beam path central axis and the two adjacent axes. The operating field here is 1.2 T.

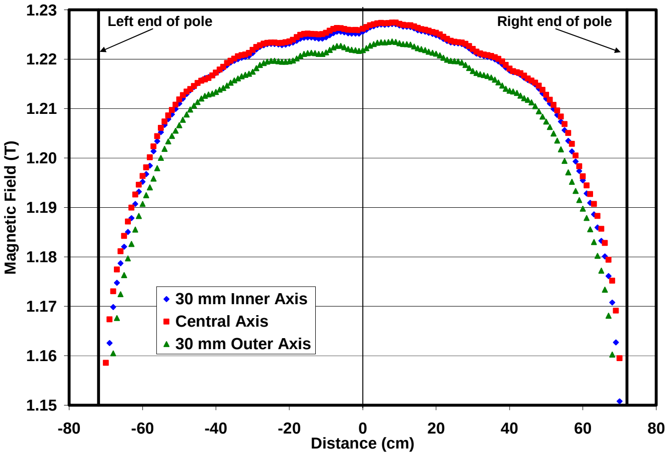

Fig. 5. Plot of magnetic field scans with enlarged scale showing degree of field uniformity for the three scan axes across the pole face width.

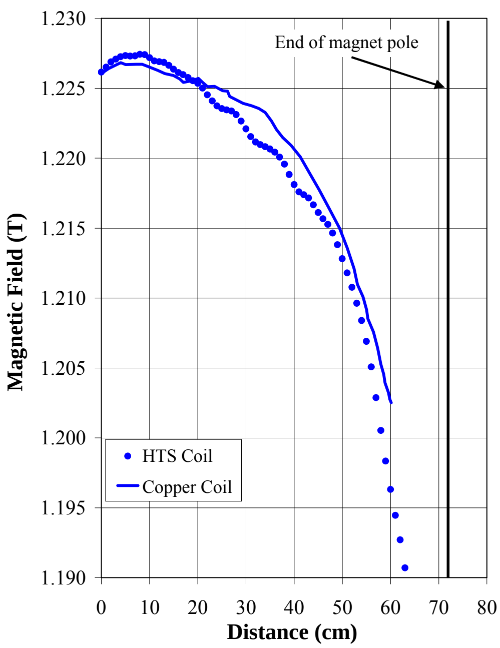

Fig. 6. Plot showing magnetic field vs. distance along the beam path for 1.2 T operation for both the HTS retrofitted dipole and an original copper VUV ring dipole.

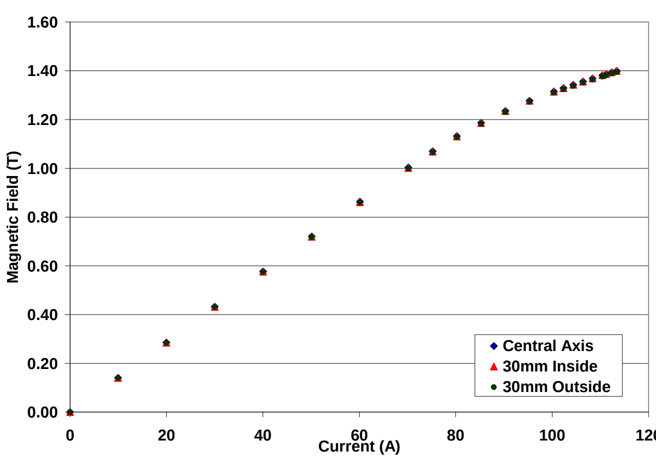

Fig. 7. Magnetic field vs. current measured in the retrofitted HTS dipole.

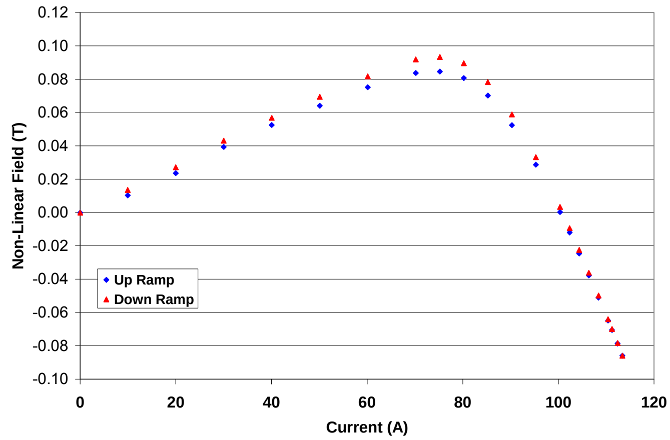

Fig. 8. Plot showing the hysteresis and iron saturation in the magnetic field measurement loop to 113 A after subtracting out the linear component.

Fig 7 shows a plot of magnetic field vs. current for the three axes. It is again evident from this data that the field is reasonably uniform over the 60 mm of measured pole face. This data is from the up ramp of the measurement cycle to the present operational field of 1.4 T (113.39 A) and back to 0. Also, this data agrees with the data from testing at HTS-110 before shipment to BNL [4]. The measured hysteresis from the measurement cycle was too small to be shown at this scale, so the data were adjusted by subtracting out a linear fit to the data points. Fig. 8 shows this adjusted data. As can be seen, the dominant non-linear contribution is from the saturation of the iron yoke. The hysteresis is a small effect, with the hysteresis loop having its largest width of 0.0089 T at 80.25 A.

V. CONCLUSIONS

As shown in the last section, the results of the magnetic field measurements have verified that the HTS-retrofitted version of the NSLS VUV storage ring bending dipole performs the same as the original copper magnet did and supplies the nominal central field for proper operation at 0.808 GeV. Importantly, it does this at only 30% of the former magnet's power consumption and with more space between the coils. In addition, the compact closed loop cryorefrigerator, with occasional turbopump operation, successfully kept the coils at 41 K for about three weeks, indicating that the cryostat and refrigerator system were never compromised and exhibited no signs of significant leaking or out-gassing of materials in the cryostat. In light of these results, this project was successful in validating the retrofitting of copper magnets to HTS-based magnets, as well as the feasibility of using such HTS-based magnets in accelerators.

ACKNOWLEDGMENT

The authors thank John Cintorino, Sebastian Dimaiuta, William McKeon, Daniel Oldham, Andrew Sauerwald, Daniel Sullivan, and Frank Teich for their expert technical assistance, without which these tests could not have been done. Thanks also go to Michael Harrison for supporting this project.

REFERENCES

[1] J. Galayda, R. N. Heese, H.C.H. Hsieh, H. Kapfer, "The NSLS Magnet System", *IEEE Trans. Nuclear Science*, Vol. NS-26 No. 3, pp. 3919-3921, June 1979.
[2] J.N. Galayda, L. N. Blumberg, R. N. Heese, H.C.H. Hsieh, "Beam Optical Properties of the NSLS Dipoles", IEEE Trans. Nuclear Science, Vol. NS-28, No. 3, June 1981.
[3] M. Fee, "Feasibility study for High Temperature Superconductor retrofit of VUV-ring dipole magnets", HTS-110 Limited, 69 Gracefield Road, Lower Hutt, New Zealand, 10 September 2006.
[4] Operating Manual for HTS Retrofit Synchrotron Dipole, HTS-110 Limited, 69 Gracefield Road, Lower Hutt, New Zealand.
[5] Cryogenic Refrigerator: Installation, Operation and Routine Maintenance Manual, Cryomech, Inc., 113 Falso Drive, Syracuse, New York 13211, USA.