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BNL Direct Wind Superconducting Magnets

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***Abstract*— BNL developed Direct Wind magnet technology is used to create a variety of complex multi-functional multi-layer superconducting coil structures without the need for creating custom production tooling and fixturing for each new project. Our Direct Wind process naturally integrates prestress into the coil structure so external coil collars and yokes are not needed; the final coil package transverse size can then be very compact. Direct Wind magnets are produced with very good field quality via corrections applied during the course of coil winding. The HERA-II and BEPC-II Interaction Region (IR) magnet, J-PARC corrector and Alpha antihydrogen magnetic trap magnets and our BTeV corrector magnet design are discussed here along with a full length ILC IR prototype magnet presently in production and the coils that were wound for an ATF2 upgrade at KEK. A new IR septum magnet design concept for a 6.2 T combined-function IR magnet for eRHIC, a future RHIC upgrade, is introduced here.**

***Index Terms* — Coil Winding, Interaction Region, Magnet Production, Serpentine, Superconducting.**

I. BNL Direct Wind Basic Information

THE Brookhaven National Laboratory (BNL) Direct Wind magnet production process draws from experience making correctors for the Relativistic Heavy Ion Collider (RHIC) project where a conductor pattern was bound to a flexible substrate sheet and the whole sheet was wrapped around a tube [1]; wrapping the support tube brings intrinsic challenges.

- If the support radius is slightly different than planned, the coil pattern will not match the tube circumference.
- Even with the correct radius the pattern could be placed askew with opposite pattern edges not lining up.

Both lead to magnetic field errors. RHIC used independent nested support tubes for different corrector layers and RHIC pattern lengths were short so harmonic errors were small and met the corrector magnet tolerance specification. The Hadron-Electron Ring Accelerator Luminosity Upgrade (HERA-II) brought challenges that led to BNL Direct Wind [2].

- HERA-II IR magnet field harmonic requirements were much more stringent than those for corrector magnets.
- The long 3.5 m HERA-II coil pattern lengths would have been difficult to handle and wrap precisely.
- The HERA-II IR design called for many overlapping, multi-functional coils of different field multipolarities.

With tight IR radial space, independent coil support tubes were not feasible; however, with all the coils being placed directly on top of each other it would have been hard to control the radial build up and circumferential matching for the outer coil layers.

So for HERA-II we developed a new computer controlled winding machine where we first wrapped substrate on a support tube and then bonded the coil pattern to this substrate. Pattern bonding was done using a winding head supported in a gantry that traversed the length of the tube while the tube itself rotated about its axis. With this setup, pictured in Fig.1, a coil pattern is put on the tube without an intermediate transfer step. During the course of winding the conductor stays in place because both the substrate and the insulated conductor are b-stage epoxy coated. Conductor is payed out, ultrasonically heated, and by rapidly cooling through conduction the copper in the conductor under the winding head for a temporary conductor to substrate bond. Note this preliminary conductor attachment is not intended to be strong enough to hold against large Lorentz forces but only to keep every conductor turn tacked in place during the subsequent production steps. Presently we have two conductor options:

- single strand 0.4 mm diameter wire conductor or
- round cable ≈1 mm diameter that is made up from seven conductor strands in a 6-around-1 configuration.

Once the desired coil winding is placed on the tube, we fill large pattern gaps that occur at the poles, the coil ends and the material spacers, with matched alumina filled expansion epoxy. Note that the filler pieces closely match the conductor thickness. Nomex™ paper [3] is used for single wire layers

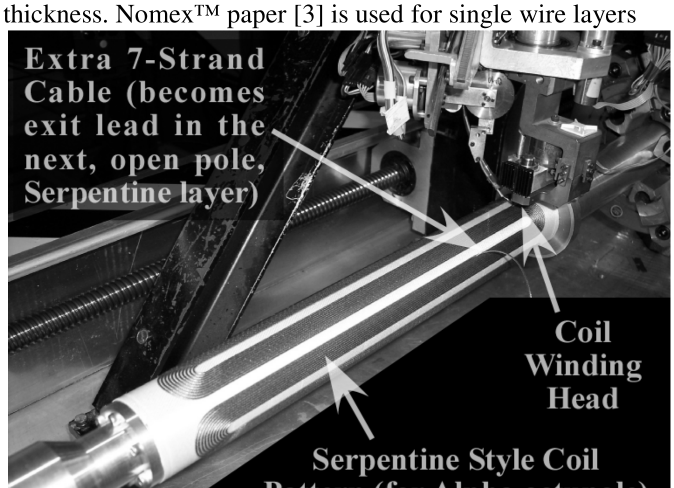

Fig. 1. BNL Direct Wind production of a Serpentine style octupole coil.

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and 1 mm thick G-10 for seven-strand cable for a smooth surface with no large interstitial epoxy filled regions. The epoxy filled coil is then cured at low temperature to set the conductors in place.

Next we provide coil prestress by wrapping the structure with s-glass fiberglass roving under tension. The wrapping tension and number of turns per unit length are adjusted counter the expected electro-mechanical forces calculated for the coil under operating conditions. By applying prestress during production we avoid a large buildup of stress in outer layers for a compact structure, which withstands large Lorentz forces, without using extra space for an external collar or yoke. The coil support tube reacts against applied prestress and to stay within the tube material's elastic range, we use an appropriate inner support tube wall thickness. These magnets can fit into very tight radial spaces inside a high energy physics experimental detector. The support tube serves for cold mass helium containment and sometimes also as the vacuum beam pipe.

II. Coil Topology and Serpentine Winding Patterns

After HERA-II we were faced with IR magnet production for the Beijing Electron Positron Collider Luminosity Upgrade (BEPC-II) [4]. While the IR quadrupole integrated gradients were similar for both projects; BEPC-II needed larger diameter quadrupole coils, had much shorter magnetic lengths and an aggressive production schedule. Producing the large number of coil layers needed for BEPC-II with the coil topology inherited from the RHIC corrector days looked very challenging; so we created a new Serpentine style coil winding topology [4], [5].

We use "planer pattern" to denote a coil winding, such as RHIC correctors, for patterns drawn in a spiral manner upon a flat substrate without crossing another turn. Planar patterns trap coil leads at poles. For the BEPC-II eight-layer quadrupole coil package it was very unattractive to have to bring all the trapped leads to the outermost surface and then to have to make a large number of splices to connect all the subcoils together.

A natural way to reduce the number of subcoil lead splices is to combine two planar coil layers in a dual-layer planar coil pattern, shown in Fig. 2, where we start winding at the coil pack midplane and spiral inward on successive turns towards the pole region. Upon reaching the pole we must stop and fill pattern gaps with G-10 and epoxy, wait for the epoxy to cure, apply fresh substrate and only then can we continue winding. Winding picks up in the same direction as before but now atop previous conductor. From the pole we continue outwards to the coil midplane where we drop down to the bottom layer and spiral inward again to a second pole. At the pole we stop, fill and cure and then finish by winding outward in the second layer back to the midplane. This procedure yields a pair of coil poles that have side-by-side entrance and exit leads at their common coil pack midplane.

Doing the above once is enough for a dipole coil but for coils of greater multipolarity, N, where $N=2$ for quadrupole, $N=3$ sextupole etc., we must repeat this sequence N-1 additional times and then splice together leads from different subcoil pairs. For the BEPC-II eight-layer quadrupole we would start and stop sixteen times with a lot of time is spent curing epoxy. For the Alpha antihydrogen trap octupole we wanted to reduce the number of subcoil splices for better reliability under frequent quenches during running with rapid deliberate shutdown [6]-[8].

Our Serpentine solution became obvious once we took into account that we actually wind on a cylinder and are not restricted to a single flat sheet. For a support tube, when we go around 360º we return back to the start and can lay down a new turn. The fundamental trick, illustrated in Figs.1 and 3, is to reverse the conductor bend direction at every coil pattern end. With oscillating end geometry, Serpentine coils have no net inward or outward spiral and independent of coil multipolarity later turns can always be laid down next to earlier ones. Another difference, with respect to planar coil pack's spiral pairs, is that a Serpentine style coil pack can have an odd number of turns; we can adjust the coil turn number by half a turn per pole, something very useful when designing coils with a small number of turns. But our most important consideration is production efficiency; we can wind a complete coil layer at a single go and only stop once to do G-10 placement, epoxy filling and curing.

Serpentine coils do not look like spiral planar windings and their poles are open at one end. Serpentine field quality optimization is correspondingly different. By inspection we see that a Serpentine coil with fixed end turn spacing, all the straight section conductor lengths are identical across the coil pack. It should not be a surprise then that, independent of angle, every Serpentine turn contributes on an equal footing to the field integral and the integral field harmonics very closely body. The planar pattern spiral geometry forces turns closer to

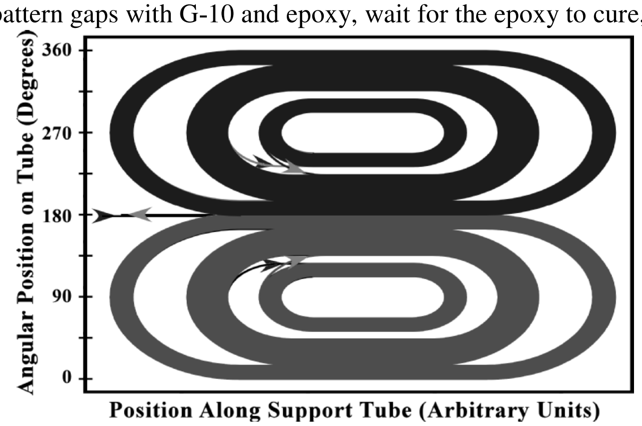

Fig. 2. Dual-layer Planar Dipole Coil Winding Pattern.

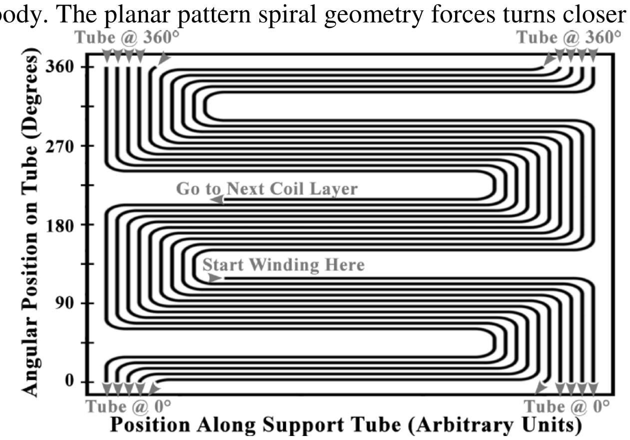

Fig. 3. Quadrupole Single Layer Serpentine Winding Pattern.

the pole to be shorter than turns further away. Planar patterns have an extra angular dependence with turn length, correlated to turn number, which for short magnets causes the integrated harmonics to differ from the 2-dimentional field result and should be accounted for when optimizing the magnet ends; however, a simple Serpentine pattern, with no end tuning spacers and fixed end spacing, will automatically have integral field quality the same as from a very fast and simple 2-dimentional magnetic model optimization.

Serpentine coils wound with uniform end spacing have end field fall-off that tends to be smoother than obtained with planar patterns that use end harmonic tuning spacers. This in turn translates to Serpentine magnets having lower peak end fields. For the Alpha antihydrogen trap octupole Serpentine winding helped to avoid magnetic “holes” in the end field regions where more energetic trapped particles could leak from the trap [6].

Because every Serpentine layer turn wraps around the support tube in the same direction, a net solenoidal field is generated. Accordingly we often wind Serpentine patterns in dual-layer pairs to be able to wind around the tube the same number of times in both directions. Note we are free to use quite different coil patterns in the dual-layers and once created a combined function Serpentine magnet by winding a dipole pattern atop a quadrupole one with no net winding number around the tube. We thereby avoided generating solenoidal end fields [5].

Dual-layer Serpentine patterns also give new options for current lead management. If we start winding at a pole’s closed end and leave spare un-bonded conductor, as in Fig.1, when we finish winding at the now open pole in the next layer we can pair this extra conductor with conductor exiting from the last turn and thereby bring out a coil exit lead pair without having to use any extra radial space. A similar trick is used to pass leads from one coil completely through a second coil on the same tube without taking up extra radial space by entering at an open pole and waiting for the next layer’s open pole to exit [5].

III. BNL Direct Wind Production Technique

Immediately before we wind a coil layer we characterize the substrate surface at several longitudinal locations to learn how the local tube diameter, center offset and tube ovality varies along the length of the tube. With these data we can then make small adjustments to the coil pattern just before it is wound. With a fresh machined tube surface we should only to have to make a tube offset correction. But when winding on top of a thick stack of previous coil layers it can be difficult to precisely predict the radial buildup and sometimes the surface we are about to wind upon have become slightly out of round. When striving to meet aggressive field harmonic goals, such tube imperfections would drive noticeable levels of error harmonics if left uncorrected. Our ability to make local tube offset corrections means that we do not go to extraordinary lengths to perfectly align the tube axis with respect to the winding machine and then benefit from faster turnaround. This correction algorithm also enables coil winding on curved support tubes and on long slender flexible support tubes where the tube center sometimes strays from the winding machine’s axis of rotation [2], [5].

We also have capability to modulate the conductor placement on-the-fly during coil winding for a means to introduce a small, arbitrary admixture of field harmonic components, including otherwise unallowed components, to the coil pattern. When winding Serpentine coil patterns one coil pack is forced to be different from all others in that layer due to the need to connect a given turn number, n, to turn $n+1$. This $n+1$ change breaks coil symmetry and introduces small unallowed harmonics[1] that we easily correct with our on-the-fly harmonic addition scheme.

Our capability to add harmonics is especially useful when winding coils comprised of many layers. During the course of production we will make warm magnetic measurements of coil layers wound so far and if we find a small error that we want to correct, we then add the appropriate counter harmonic term in later layers. Occasionally when we look to make either large magnitude harmonic correction or add a complex mixture of intermediate scale harmonics, these corrections are made iteratively offline to the “wiring file,” the point-to-point description of the path of the conductor in space which is passed to the winding machine control software. By iterating and checking our correction results in offline analysis, we look to eliminate correction crosstalk, which sometimes occurs with large harmonic content changes, before committing to winding a coil layer. In most cases this offline iteration is not needed and we simply use on-the-fly correction.

IV. Some Direct Wind Highlights and Future Prospects

Limited IR radial space provided the major constraint for our HERA-II IR magnet designs. We had to fit quite different upstream and downstream magnet configurations into two quite different experimental detectors H1 and ZEUS. In the end we ended up having to wind some coils on tapered coil support tubes but still managed to satisfy the HERA-II IR magnet field quality specifications [9].

For BEPC-II in addition to an aggressive production schedule, challenging IR magnet field quality requirements, tight radial and longitudinal space constraints to integrate many coil layers of different multipolarity, we had to intermix a multi-section antisolenoid coil into the main coil package for local detector field compensation [4].

For the Japan Proton Accelerator Research Complex (J-PARC) we first produced a set of normal and skew-quadrupole correction coils that fit in the very limited radial space between the main combined function magnet coil and the beam tube. The “normal focusing” corrector was given the correct small admixture added dipole integrated field to decouple it’s flux coupling to the main combined function field so as to avoid a large inductive energy transfer to the corrector during a main magnet quench. In the end J-PARC only required dipole and skew-dipole correction and we produced conduction cooled magnets that were placed in the interconnection region between adjacent main magnets [10].

[1] Planar patterns also have intrinsic turn n to $n+1$ issues for each subcoil.

Production of the wide variety of correction coil packages, each with many individual coil layers, needed for the canceled BTeV project at Fermilab was a good match to BNL Direct Wind capabilities. For optimal BTeV production efficiency we initially intended only to wind dual-layer Serpentine coils, but during design optimization we realized that we could easily combine planar and Serpentine coils for winding odd numbers of layers in regions where radial space was especially tight, by first winding a planar pattern and then bringing its trapped lead out in a later open Serpentine end [5], [11].

Experience operating the Alpha antihydrogen trap magnet is presented elsewhere in this conference [8]. Here we note that our Serpentine style coil winding scheme permitted fine, half a turn per pole, incremental step adjustment of the Alpha octupole coil that was used to maximize the octupole gradient while minimizing the addition to the coil peak field caused by higher order allowed harmonics. Serpentine windings also proved advantageous for maximizing the magnetic well trap depth by through favorable end field geometry [6].

We developed compact actively shielded coil structures for the International Linear Collider (ILC) IR magnets in order to permit disrupted beam exiting from IR to pass cleanly just outside the coil through the cold mass and thereby reduced the ILC total crossing angle from 20 to 14 mrad [12]-[14]. We have tested short model magnets to benchmark performance inside detector solenoid and found that the coil directly reached conductor short sample operation while in a 6 T solenoidal background field [13]. Next we refined our techniques and successfully wound ILC final focus magnet prototypes on the full length "spaghetti like" 3.5 m support tubes that are only 20 mm in inner diameter, [15]. We plan to horizontally test this full length ILC IR magnet prototype with 1.9K, pressurized superfluid He-II in a systems test and look to characterize its cryostat, cold mass and eventually its magnetic field center stability [16].

The quadrupole and sextupole coils we produced and magnetically measured for the final focus upgrade of ATF2 at KEK demonstrate how the BNL Direct Wind production harmonic adjustment procedure has been used to reach field harmonics of 49 parts per million at 10 mm reference radius. This is much better than the existing ATF2 conventional final focus magnets and suggests the future possibility of using them to test pushed optics focusing regimes of interest to the ILC and Compact Linear Collider (CLIC) [16], [17].

For the Electrons in RHIC collider (eRHIC) IR layout, with a 10 mrad total crossing angle, the closest quadrupole should let the incoming electron beam pass through a low field region before colliding with a hadron beam of either protons or ions. The hadron beam IR optics make use of strong combined function fields and the IR magnet aperture is greatly expanded to allow neutrons and off-momentum charged particles to be separated from the circulating hadrons and to be detected further downstream. A tailored combination of co-wound Serpentine style dipole and quadrupole coils, having a 6.2 T peak field strength, provides a "low field sweet spot" near the coil package where with a simple passive shield the field seen by the e-beam is reduced to a fraction of a Gauss with 52 mm separation between the electron and hadron beams [18].

SUMMARY AND FINAL ACKNOWLEDGMENT

BNL Direct Wind magnet production has already been enabling for many challenging physics projects and looks to have a promising future. This paper is dedicated to the father of BNL Direct Wind, Pat Thompson, whose dedication and spirit of technical innovation was only surpassed by a willingness to mentor and support others. Pat, you are missed.

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