The Serpentine Coil Design for BEPC-II Superconducting IR Magnets

Prepared by Brett Parker
Brookhaven Superconducting Magnet Division

To be presented at the "Mini-Workshop on BEPC-II IR Design" held 12-16 January 2004 at IHEP/CAS, Beijing, P. R. China.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

January 12, 2004
Upton, NY, USA

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

"Serpentine Coil Design for BEPC-II Superconducting IR Magnets."

The design and production of the superconducting IR magnets for BEPC-II presents special challenges, compared to HERA-II, that are driven by the fact that the BEPC-II coils have a much shorter aspect ratio (length/diameter). For example the BEPC-II quadrupole, SCQ, needs multiple conductor layers to ensure adequate integrated strength and all the BEPC-II coils require much special attention to compensate coil-end harmonic effects. It is not found practical to wind the BEPC-II in the same manner as HERA-II coils. To this end a new "serpentine" style winding technology was developed for BEPC-II to fully address these concerns.

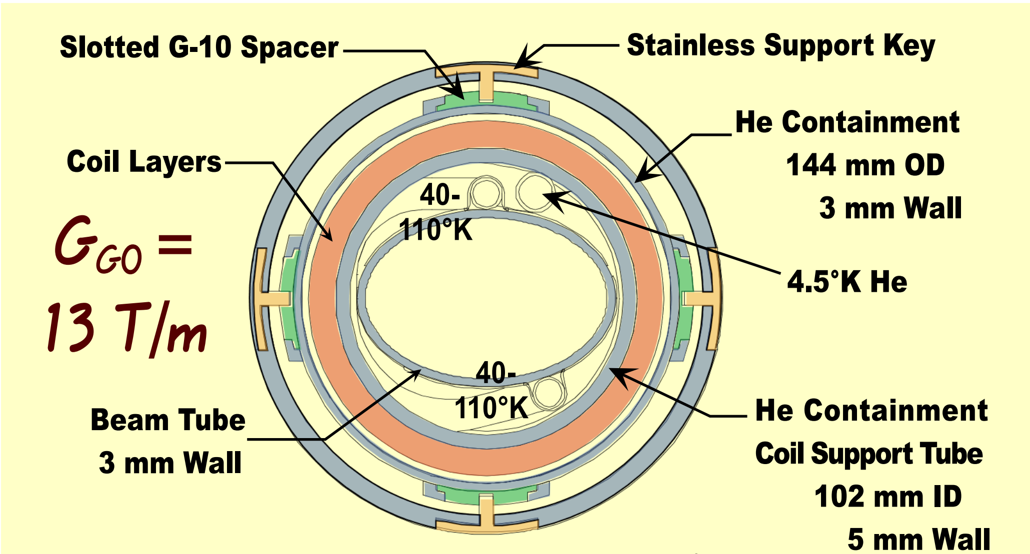
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Presentation Outline:

- Historical Outline of the Previous Work.
  - Review HERA-II Upgrade IR Magnet Design.
  - Highlight BEPC-II Upgrade IR Magnet Issues.
- Winding Technology Issues and Solutions.
  - Challenge of Winding Short Multi-Layer Coils.
  - Outline Standard Approach and its Shortcomings.
  - The New "Serpentine Coil Winding Solution."
- Review Present Status and Future Plans.
  - The First Serpentine Style Test Coil Winding.
  - Vacuum Impregnation and Quench Test Results.
  - Second SCQ Serpentine Test (Correct Harmonics).
  - Show the Final BEPC-II Serpentine Coil Designs.

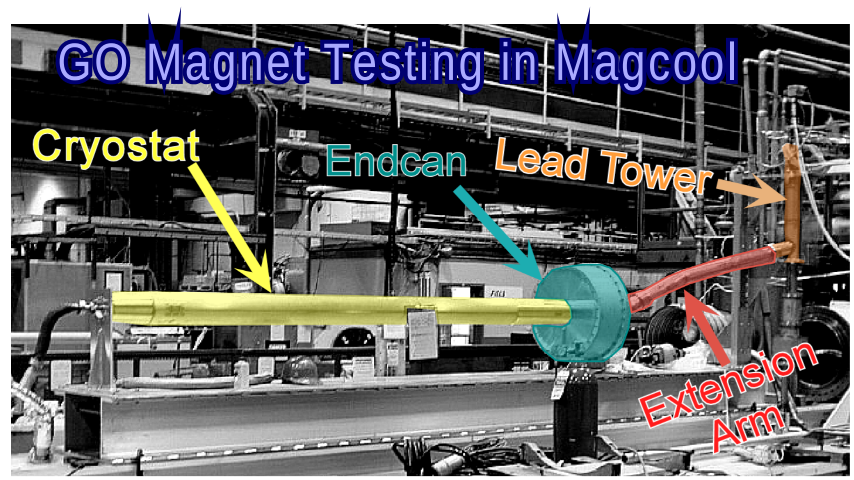
Brookhaven National Laboratory
Superconducting Magnet Division

Visual Summary of HERA-II Luminosity Upgrade Magnet Production.



GO Cryostat Cross Section

H-Dipole, Quad, V-Dipole, Skew Quad & Sextupole coils fit inside a very tight radial envelope!



BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

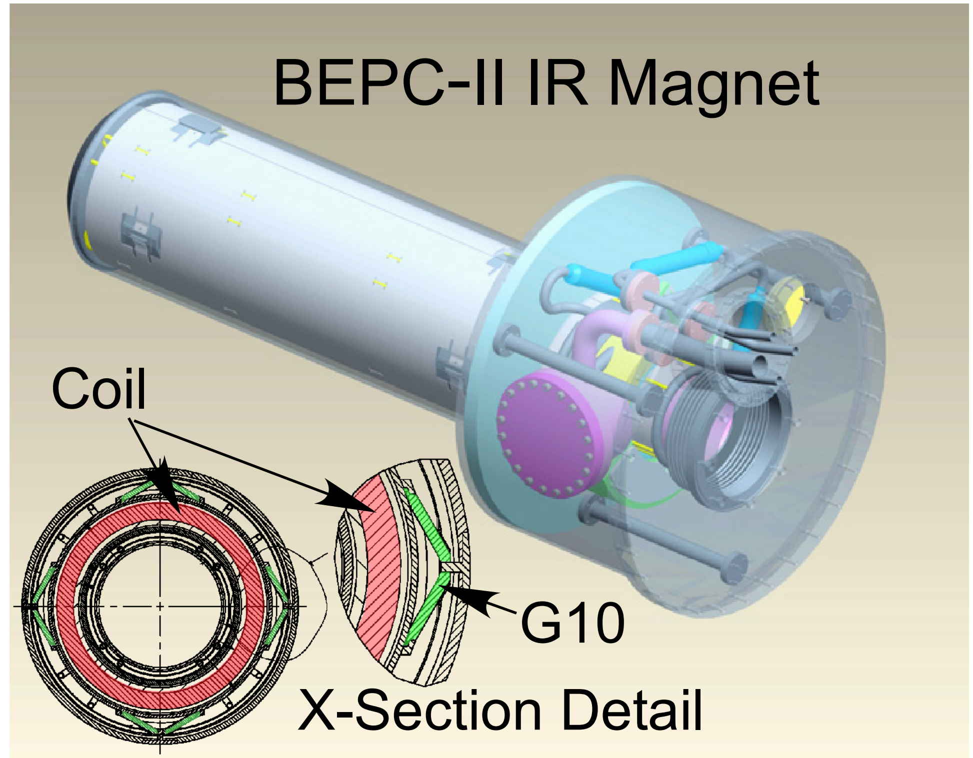
Some Relevant HERA-II Magnet Production Highlights.

- Both single strand wire and seven strand round cable ultrasonically were bonded to coil support tube forming “direct-wind” coil pattern. Gaps in layer pattern filled in with G10 and epoxy before applying fiberglass wrap for prestress.
- Mix and match coil types; each receiving own prestress.
- Field harmonic measurements (warm) and corrections incorporated throughout coil production. So multilayer coils have the best harmonics.
- HERA-II leads came from pole region. Inconvenient for a multilayer structure (so BEPC-II will use dual-layer windings).
- HERA-II did not leave enough radial space for heat shields and cold mass supports (BEPC-II provides more space).

IR Magnets for the BEPC-II Luminosity Upgrade at IHEP, Beijing, P. R. China.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Name	Function	Layers*	Conductor
SCQ	Main Quad	8	7 strand cable
SCB (HDC)	Hor. Dipole	2	7 strand cable
VDC	Vert. Dipole	2	1 strand wire
SKQ	Skew Quad	2	1 strand wire
AS1	Anti-Solenoid	6	MRI wire
AS2	Anti-Solenoid	2	MRI wire
AS2	Anti-Solenoid	6	MRI wire



Compared to HERA-II, the BEPC-II magnets have almost double the aperture but only 1/7 the length. The radial budget does give more space for the cryostat (…that is used to provide a warm bore tube, inner and outer heat shields and LHe cooling flow on both sides of a thicker coil pack).

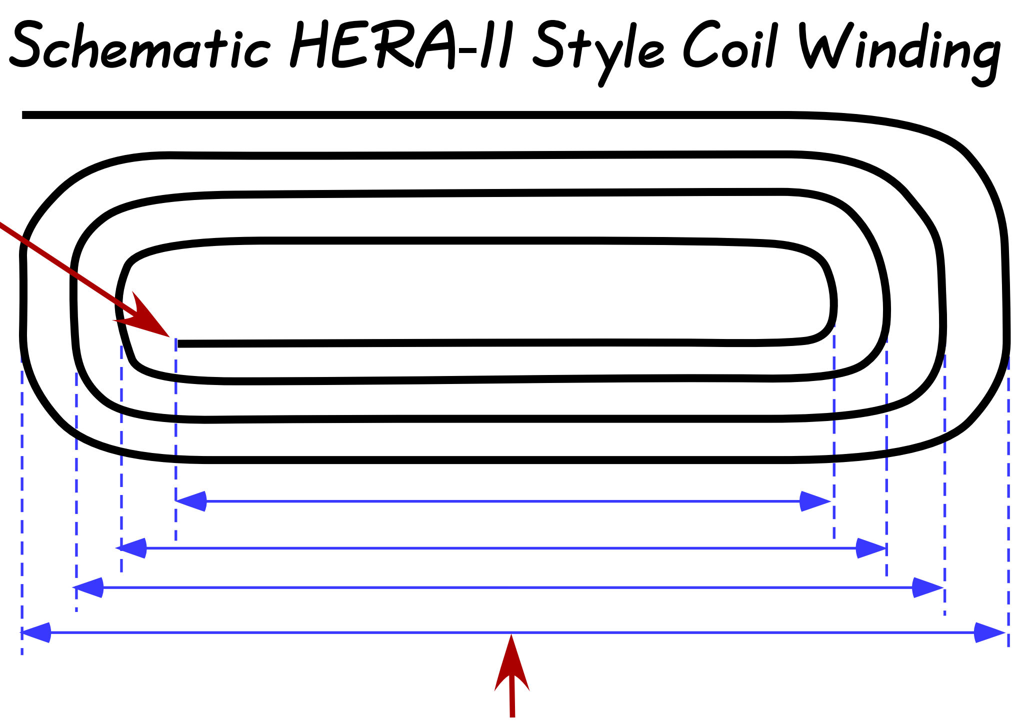
***Note each BEPC-II cold mass has a total of 28 winding layers.**

Issues Stemming From Standard Coil Winding Technique (i.e. HERA-II Lessons).

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

BEPC-II cold mass is much more complicated than HERA-II. So had to look for ways to improve coil structure. Initially we tried simple extension to double-layer coils, but discovered significant issues....

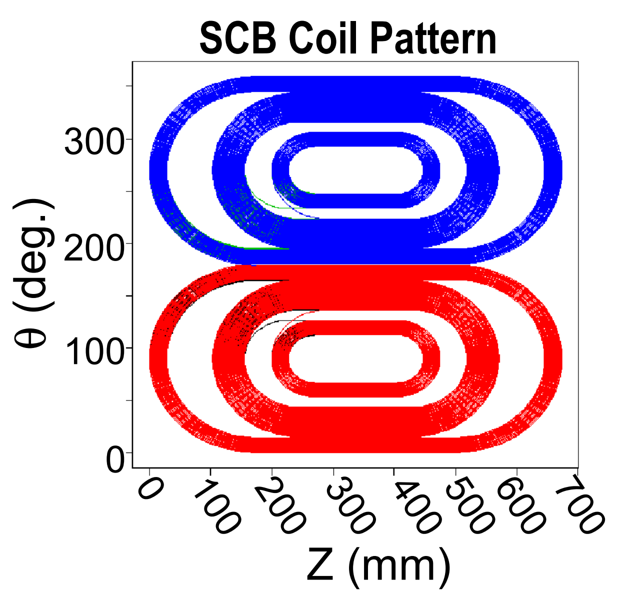
The return lead is trapped inside the coil winding near the pole.



For a short coil the change of straight section length with turn number makes it very hard to achieve good harmonic quality ("...ends are important").

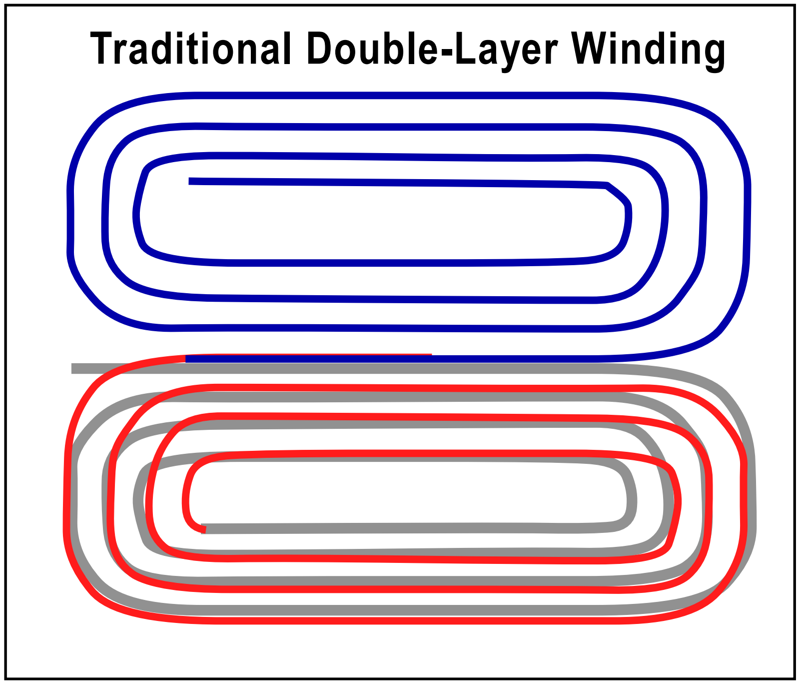
The Original BEPC-II "Dual-Layer Coil Winding" Design Solution.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division



Traditional Double-Layer Winding Steps:

Wind first base coil (gray) then stop to insert G10, and substrate etc. Then continue winding in same direction in second layer (red) before dropping down to the first layer and winding next pole (blue). Stop and repeat as needed.



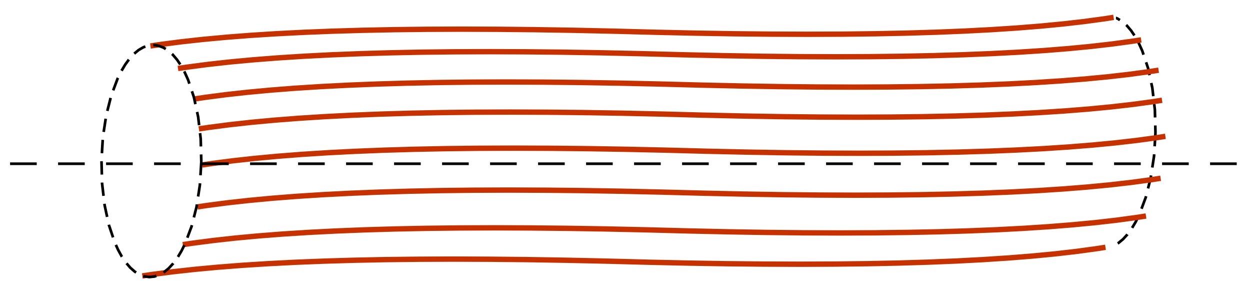
- *For a quadrupole we have to stop/restart four times per double layer (slows processing)!*
- *Harmonics "swing rapidly" near end spacers (|B| varies strongly off-axis in the end region).*
- *And it is still very difficult to ensure good integral harmonics (turn length correlation).*

New serpentine pattern offers a better solution....

BROOKHAVEN NATIONAL LABORATORY Superconducting Magnet Division

Deliberately Provocative observation:

Imagine that every turn takes the same shape in its path in space independent of angle.



Then each turn gets the same longitudinal integral weighting with the consequence that the integral harmonics are the same as that given by the 2D cross section!

The Serpentine Winding Solution.

For a “flat pattern” it is not possible to keep the winding paths the same without crossing wires, but winding on a tube opens up new topological possibilities.

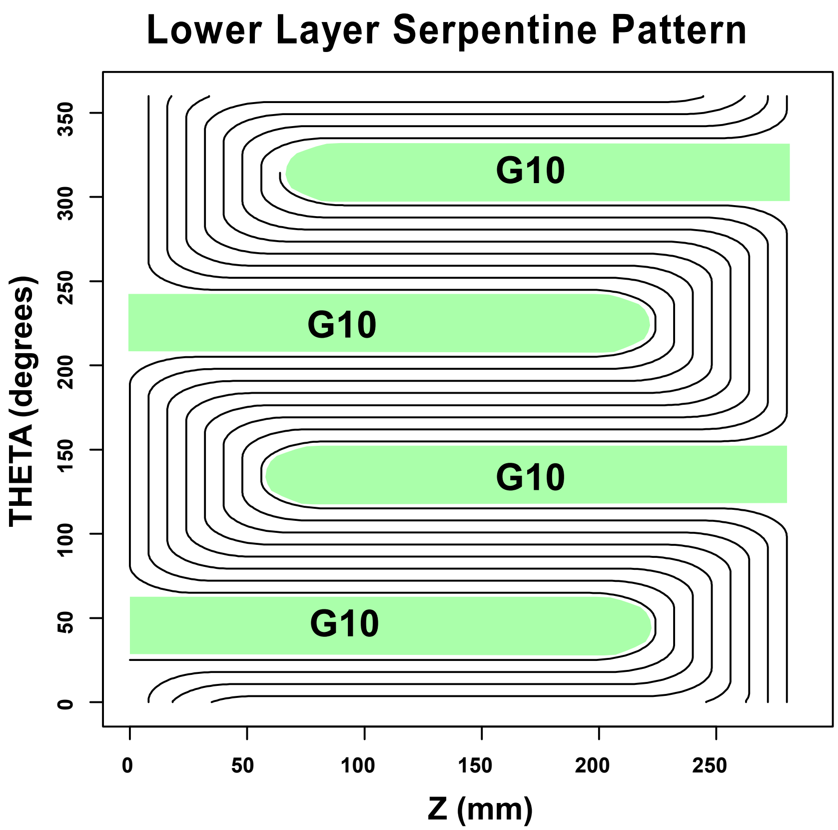
By allowing the pattern to wind around the support tube it is possible to lay successive turns next to each other without having to cross wires.

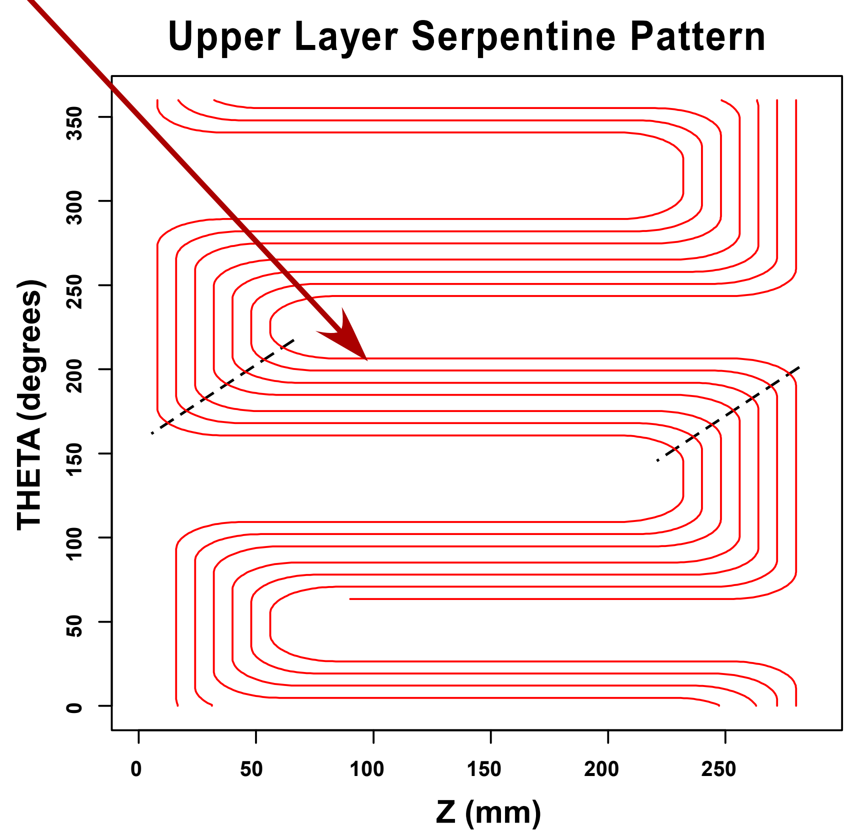
This is the serpentine winding principle.

The Serpentine Dual-Layer Coil Winding.

Brookhaven National Laboratory
Superconducting Magnet Division

The lengths of turns in the conductor packs are identical.





First lay down continuous pattern that wraps around the support tube. Fill in spaces with G10 and lay down substrate for upper layer.

The upper serpentine layer winds around the tube in the opposite direction (covering lower layer's open ends).

Some Observations Relevant to Dual-Layer Serpentine Coils.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

- The serpentine pattern winds around the support tube in opposite directions in the two layers and we are careful to wind the same number of times in each direction in order not to generate a net solenoidal field.
- However with the above constraint in mind the patterns in the two layers are allowed to be quite different.
- There is a small, but easily corrected, lead pack asymmetry that arises from the need to connect turn N to turn N+1 .
- The present *AddHarmonic* harmonic correction procedure works well because 3D problem is effectively reduced to 2D.
- We have developed serpentine coil configurations that allow easy access to current leads without taking up extra radial space (this is a spinoff of KEK-JPARC winding work).

BROOKHAVEN NATIONAL LABORATORY Superconducting Magnet Division

Building Up Experience with Serpentine Coil Windings.

Our serpentine winding proceeds as follows:

- Do entire first layer, fill gaps before adding new substrate.
- Do second layer, fill gaps then do a vacuum impregnation.
- Do fiberglass compression wrap and cure for next layer.

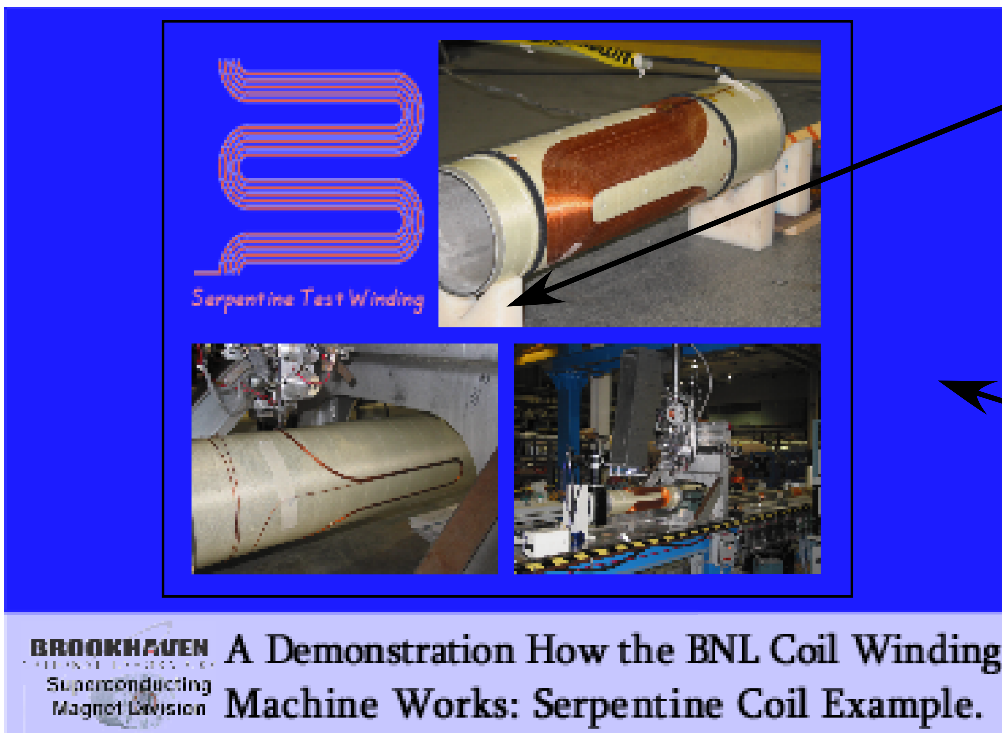
We decided to do a BEPC-II prototype winding to test our new serpentine software and get feedback on vacuum impregnation technique.

Our first serpentine winding test was made with a very simple pattern that did not include features (no 2D cross section spacers or constant radius end turns) needed to achieve good harmonic quality but it did give us a chance to get experience and look out for show stoppers (none found!).

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

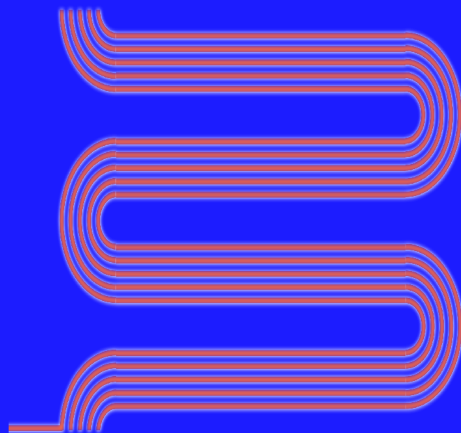
Serpentine Movie Viewing Instructions.

The next viewgraph is linked to a 5 minute movie showing the winding of the second layer of our first test serpentine coil. The link is to a quicktime format movie file, serpentine_movie.mov, which should be put in the same directory as this presentation. Note Acrobat Reader version 4 or greater has built in support for such quicktime movies.



When it is over this box the curser should change from a pointer to a movie icon. Click here to start movie and bring up the quicktime movie controls.

Click outside the box or hit "Esc" when you are ready to move on to the rest of this presentation.



Serpentine Test Winding

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

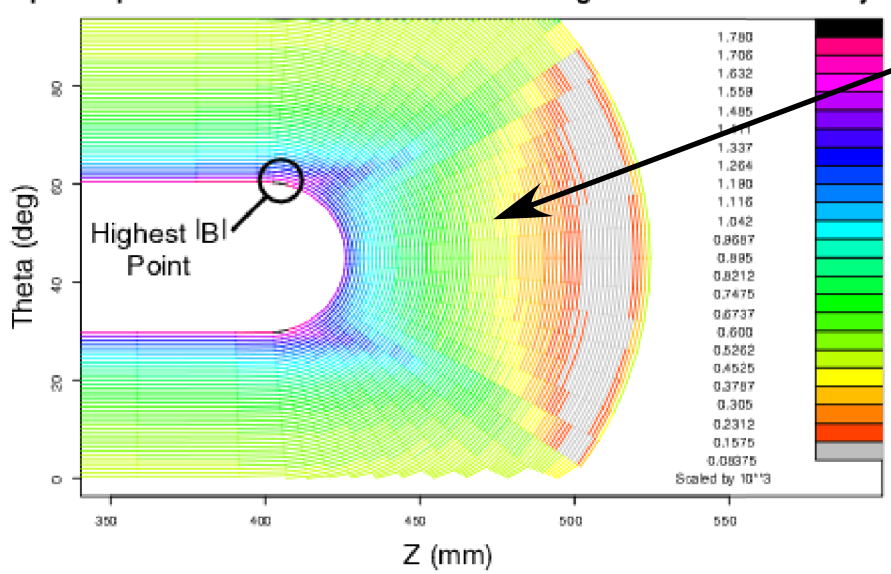
A Demonstration How the BNL Coil Winding Machine Works: Serpentine Coil Example.

Analysis of First Serpentine Test Coil.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Our *Coilfield* code calculates the field contribution from each wiring segment defined in the winding pattern. By convention wiring segments are kept shorter than 0.5" (12.7 mm) and span no more than a 3° arc. *Coilfield* is used to calculate central and integral harmonics and transfer functions. We also can place the coil in a background field and calculate the total field, force and torque on each wire segment.

|B| per ampere of excitation current for wire segments in lower coil layer.



Plot of total field at each wire segment in the wiring file with the highest field point shown in black.

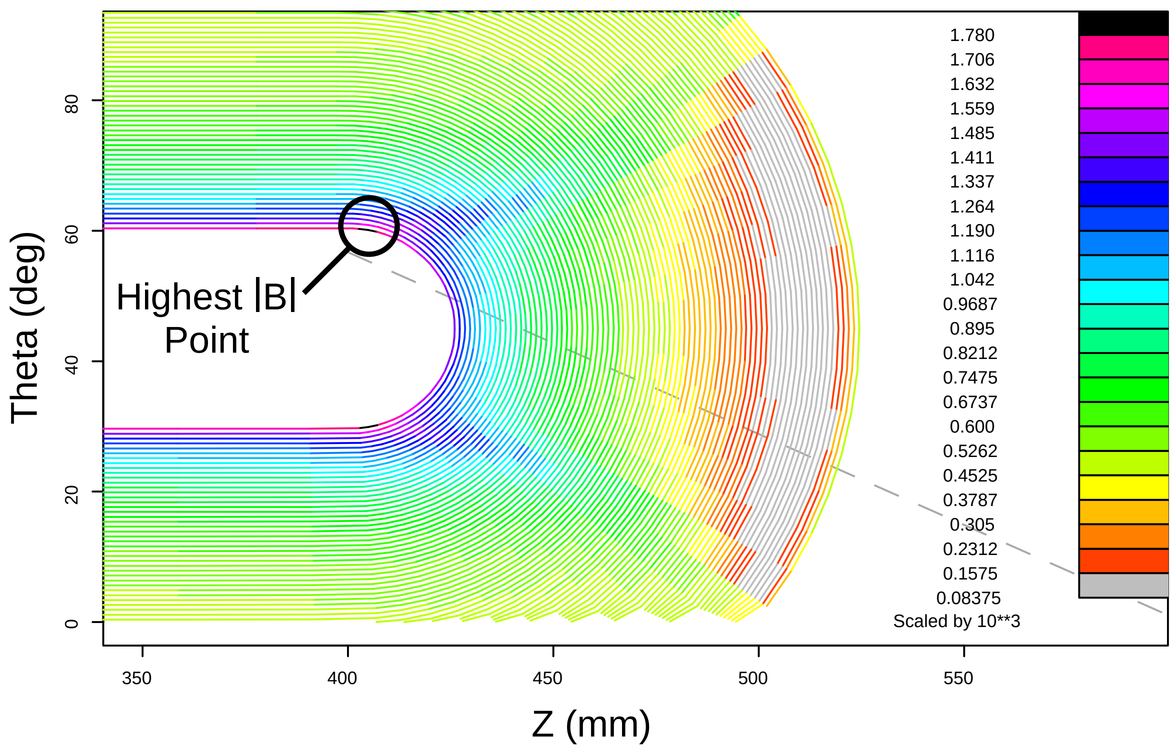
Trivia:

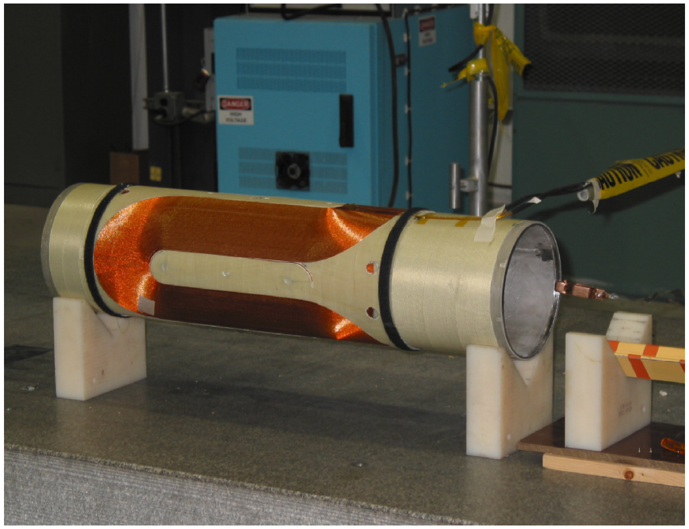
Note that for the eight winding layers for SCQ, such a calculation involves close to a quarter of a million wire segments.

A Test of the New Serpentine-Style BEPC-II SCQ Coil Winding Pattern.

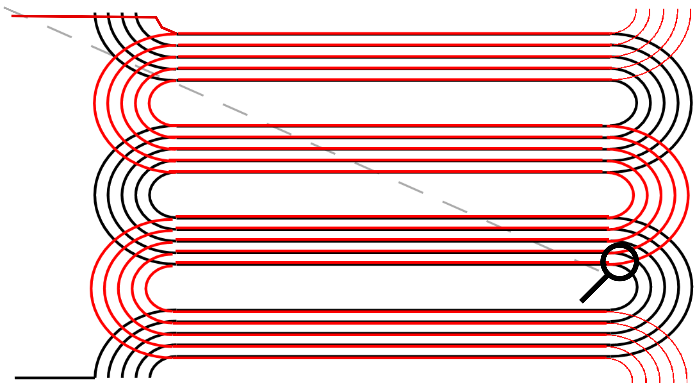
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

|B| per ampere of excitation current for wire segments in lower coil layer.





Warm coil testing before vacuum impregnation was done and the fiber-glass prestress wrap was added.



Double-Layer Winding Schematic.

Test winding quenched at 911 A which is 90% of cable short sample*.

*Note a different cable with different superconductor to copper ratio & higher short sample will be used for the actual BEPC-II SCQ magnet.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Serpentine Winding Technique: Improvements Made after First Test.

- First crude vacuum impregnation fixture had extra space beyond coil ends that filled with epoxy. This area developed visible cracks upon cooldown. Waste space reduced in final fixture and unavoidable spaces will be filled with fiberglass weave to avoid crack propagation.

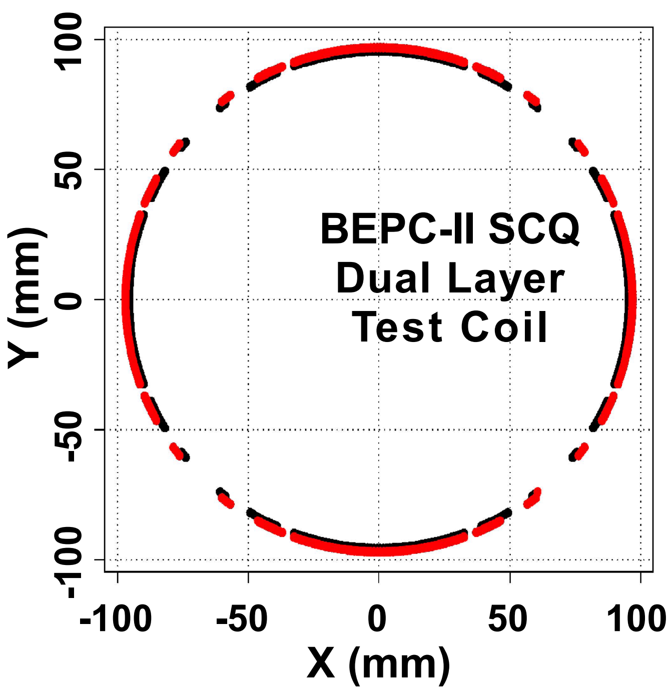
- Serpentine coil design software has been upgraded to handle 2D harmonic tuning spacers, end spacers (not used) and constant radius bends (needed to keep path length constant). Now have enough “knobs” to be able to provide desired harmonics.

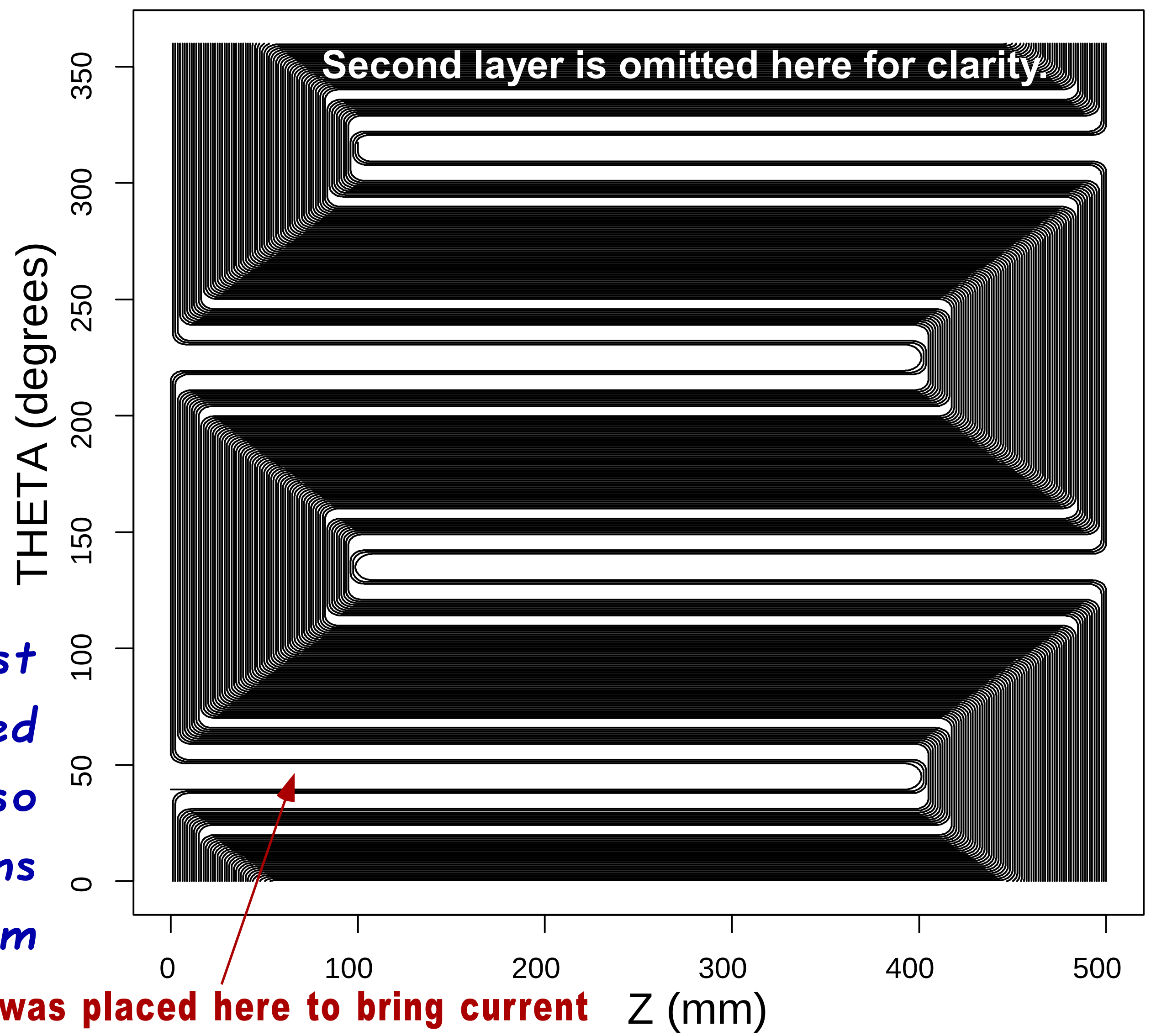
- With the first test winding we realized that more attention was needed on how to bring out coil leads. Lead scheme has been improved in subsequent design iterations. Now have a robust solution.

Next we decided to try to wind a harmonically correct SCQ using the above improvements.

The Next Step: Wind a Proper Serpentine BEPC-II SCQ Test Pattern (Bottom Layer).

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division





The second serpentine test winding has features needed for proper harmonics. Also worked out lead connections and improved the vacuum impregnation fixture.

Tube was placed here to bring current lead down and out via the gap in first layer.

Knowledge Gained with the Second Serpentine BEPC-II SCQ Test Winding.

The field quality is generally very good - certainly far better than the first coil. The only notable harmonics are -3.7 units of skew sextupole, +2.1 unit of skew octupole and +1.5 unit of normal decapole (all at a reference radius of 50 mm). All other harmonics are about or below one unit. This field quality is similar to what we can typically achieve for a single layer coil.

I believe this test coil can be declared a success as far as field quality goes. - Animesh Jain, 22 December, 2003.

In order to prepare a path for getting the return current lead out from the second layer a teflon tube was run alongside the input lead on the bottom layer. It was then a simple matter to run the current lead through this tube, passing under the second layer's end turns, to the outside.

Later we realized that swapping the layer winding order allows to bring out both leads via the pole gap in the second layer (see figures next few pages).

BROOKHAVEN NATIONAL LABORATORY Superconducting Magnet Division

Comment on Field Harmonic Experience.

In a discussion of the previous results with Animesh Jain I (BP) learned that while I had become accustomed during HERA-II production to expect single layer winding errors would be smaller than 2 units (i.e. > 2 x 10^{-4} fractional error with respect to fundamental) upon occasion, when there were major changes in the winding procedure, we saw single layer errors as large as 4 units (scaled to BEPC-II).

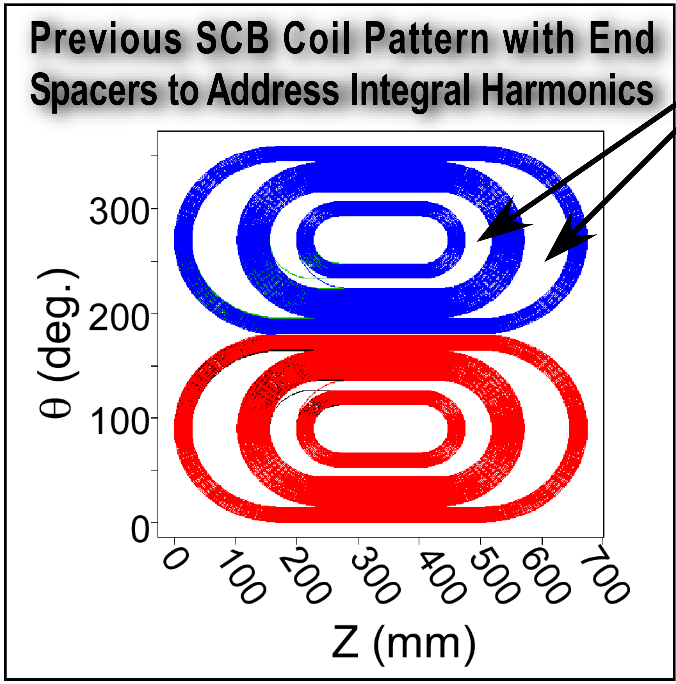
For a multilayer coil winding, experience show that the final achievable error level can be reduced at least inversely to the number of windings so for the four double-layer SCQ coil we can expect an error pedestal of about 1 unit. Since SCB, VDC and SKQ are single windings their error limits remain higher.

Note: By design all magnets, SCQ, SCB, VDC and SKQ have zero design integral harmonics. Final harmonics are thus dominated by production.

Comparison of Serpentine Results with the Previous BNL BEPC-II Design.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Up to this point we have not had a chance to make detailed comparisons for all the BEPC-II coils; however, from spot checks we see the following trends:



Serpentine coils tend to have much smoother off-axis field behavior when compared to the traditional flat pattern coils with end spacers. In particular we avoid large field swings that occur crossing the spacers shown in the coil pattern on the left.

So far we find that serpentine coils tend to have lower peak fields than their flat pattern equivalents but more detailed comparisons are needed to see if this holds up more generally.

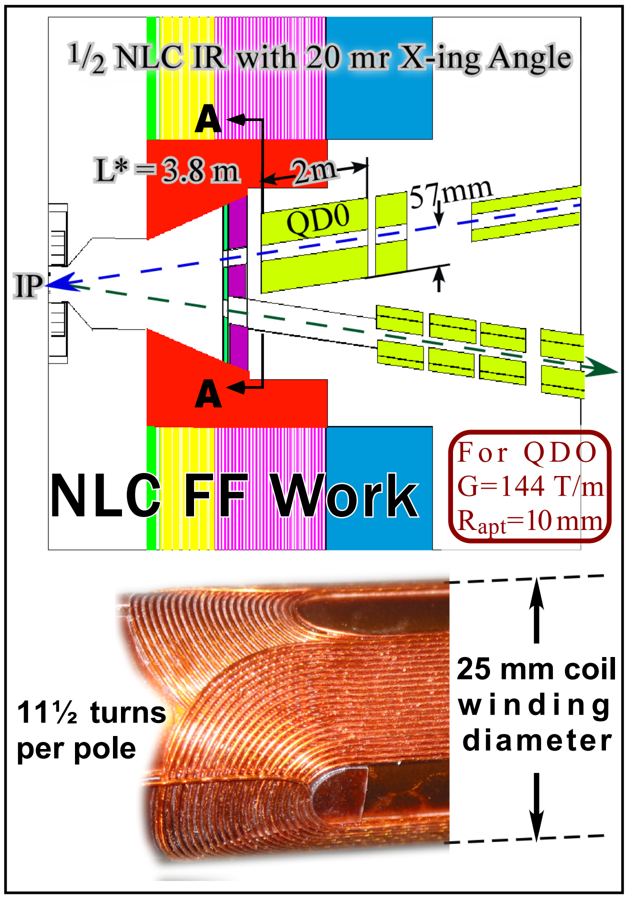
***AddHarmonic* works much better for short serpentine coils than it does for flat patterns (more "2D").**

Serpentine coils are by far much easier to adjust to zero harmonics. For the very short BEPC-II coils we find that the end turns contribute significantly to the fundamental harmonic. Simply modifying end spacers was not enough but we had to keep changing the 2D cross section. Serpentine coils require only 2D optimization rather than much harder 3D.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

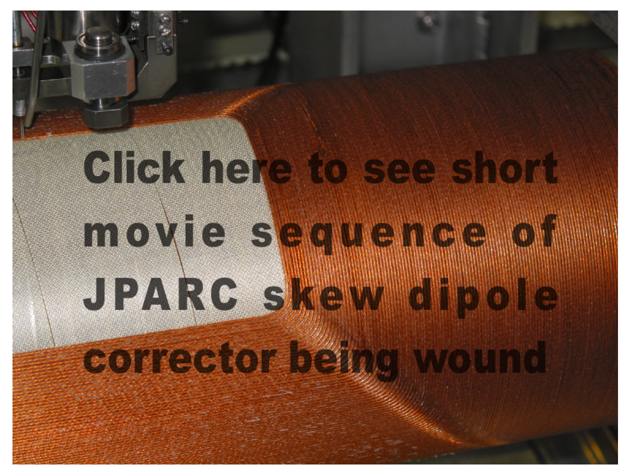
Useful Synergy with Other Ongoing BNL Coil Production Activities.

The BEPC-II magnet production program has benefited greatly from work in progress to produce a superconducting NLC final focus prototype and work to produce combined-function and skew dipole correctors for the KEK JPARC project.



For NLC FF work we developed and wound 1.8 m nested-serpentine quadrupole prototype using single strand wire. Along the way we learned to design coils with an odd number of turns in the coil pack (new design freedom) and how best to get the leads out. This work is applicable to the VDC and SKQ correctors which will be wound as nested-serpentines.

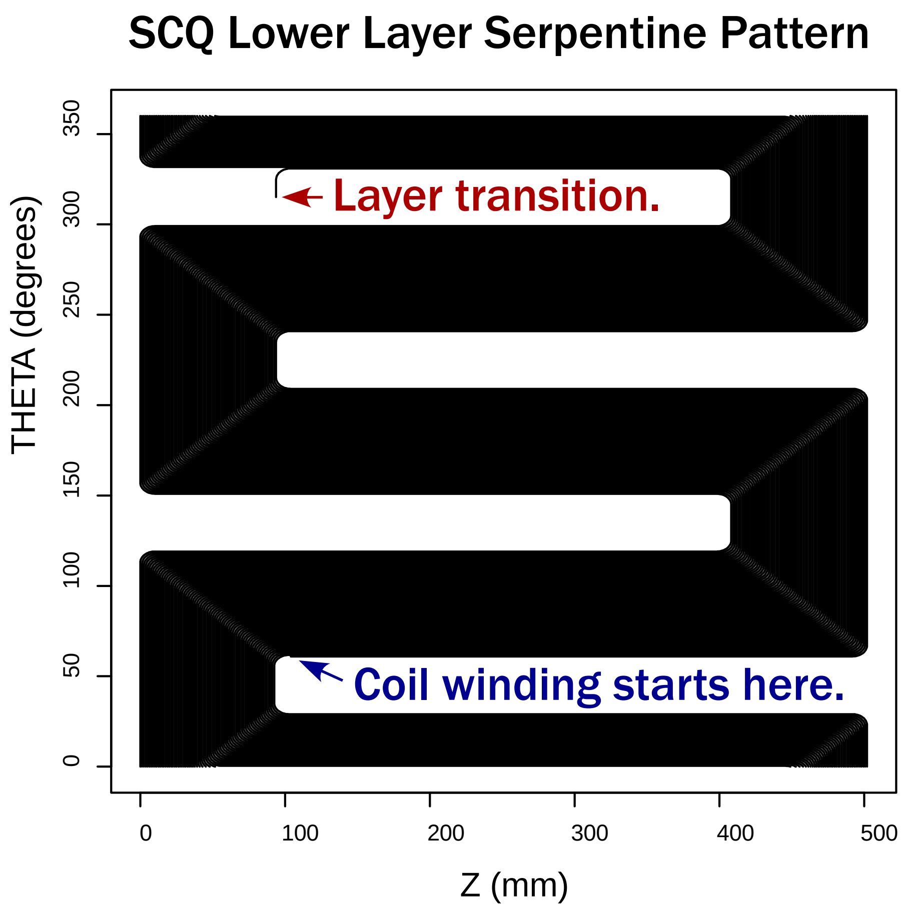
For JPARC we make 600 mm long skew-dipole and combined function correctors. Here we realized that production goes better if the bottom layer is kept simple with harmonic spacers only on the upper layer (a good lesson for BEPC-II).

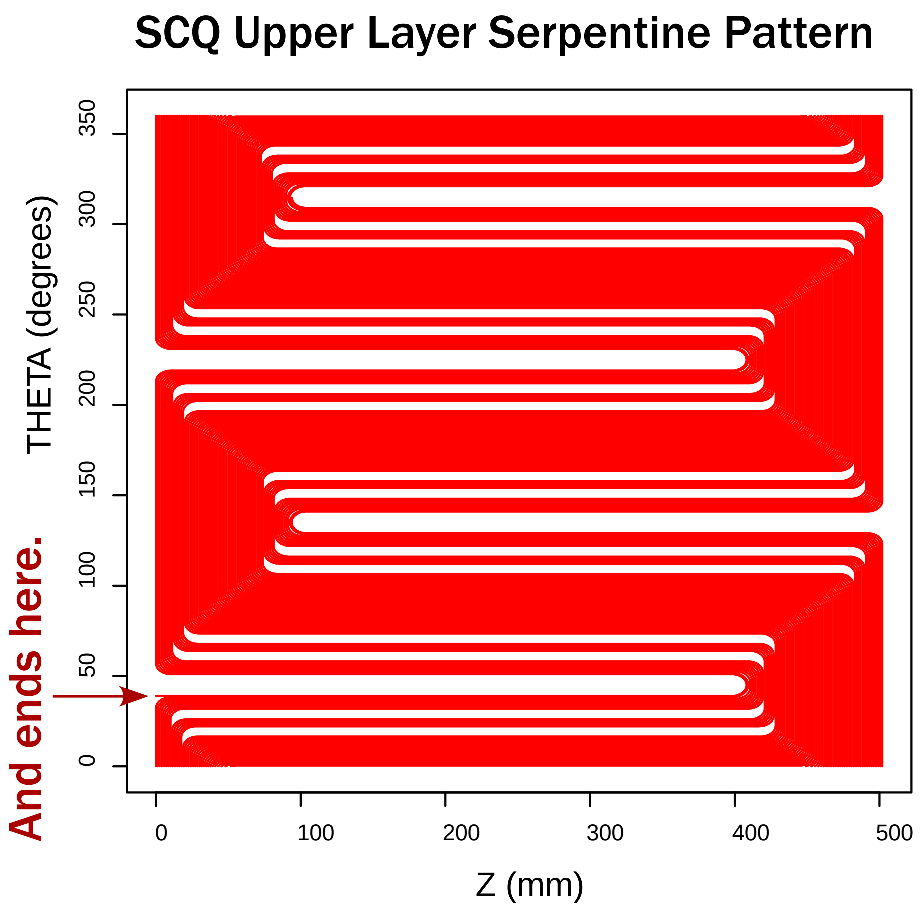


Quicktime Movie: jparc_skewdipole.mov

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Final "Tweaking" of the SCQ Coil Pattern.



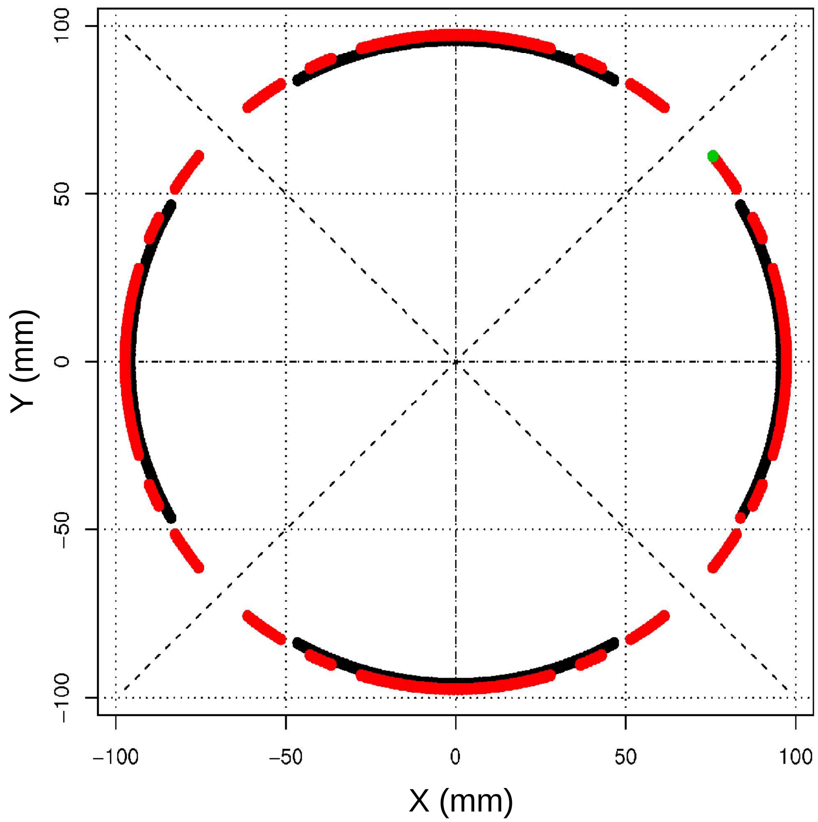


Harmonic tuning spacers are now only placed in the second layer.

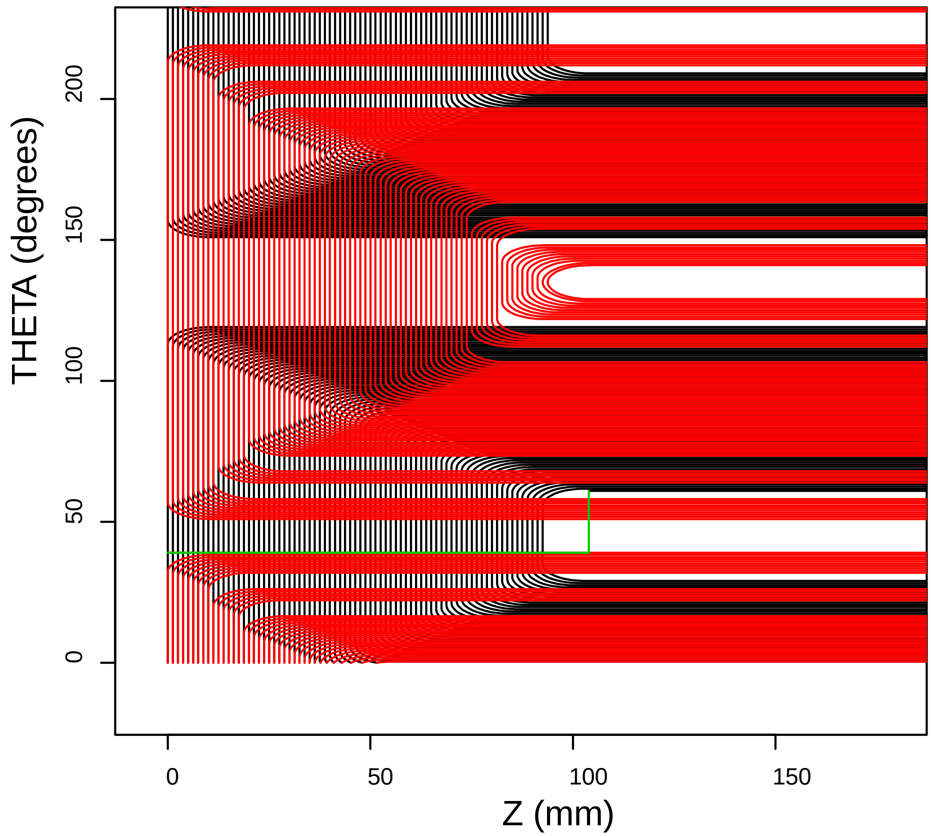
Brookhaven National Laboratory Superconducting Magnet Division

Final "Tweaking" of the SCQ Coil Pattern.

SCQ First Double-Layer Cross Section



SCQ Serpentine: Close Up at Lead End



Keeping the bottom layer pattern simple (no spacers) reduces the time the coil stays on the winding machine and we find good harmonic solutions with fewer total spacers. Starting winding at the pole allows the input lead to be brought out next to the exit lead in the gap in the second layer.

Summary of BEPC-II SCQ, SCB (HDC), VDC and SKQ Serpentine Coil Designs.

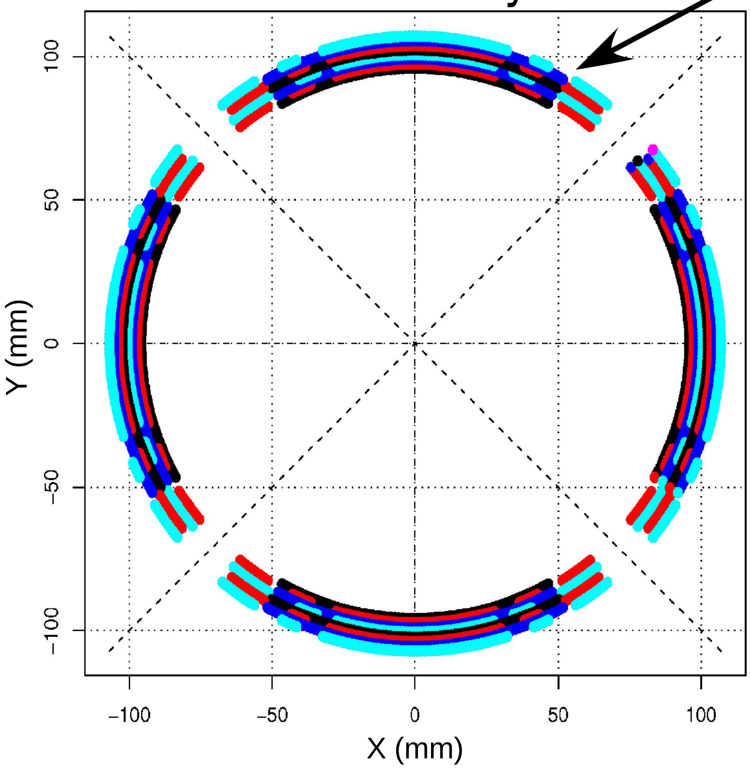
With the next four viewgraphs we quickly review the final proposed serpentine winding patterns for the BEPC-II IR magnets. The SCQ and SCB cable magnets build upon JPARC experience and the VDC and SKQ single strand corrector coils will be wound similar to the NLC FF quadrupole as nested-serpentine coil patterns.

Note for SCQ special attention has been given to how to connect leads from the four double-layers together with the result that the AS3 coil should be slightly shortened in order to assure that adequate space would be present for SCQ lead splices. This resulted in a minor reoptimization of all the antisolenoid coils, AS1-3, which will be reported in a separate presentation.

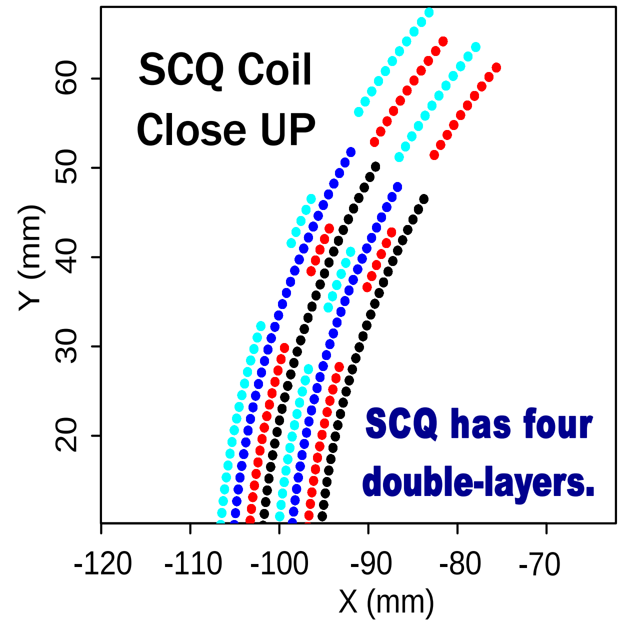
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

The “Final” Multi-Layer SCQ Coil Pattern.

SCQ Final Cross Section with Four Double-Layers

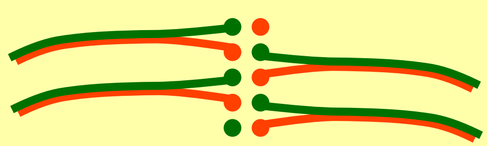


Original SCQ pattern had two harmonic tuning spacers in every layer; present design only two in every other layer but achieves better solution. Since coil features now do not line up as much in different layers, result has reduced peak field.



Each double-layer has two leads that exit next to each other from the coil pack. It is then a simple matter to make pigtail splices (wires alternating clockwise and counterclockwise azimuthally to save longitudinal space) to connect up the different layers. Thus these splices are done outside the main coil pack where they can be reliably made up.

View towards coil lead end

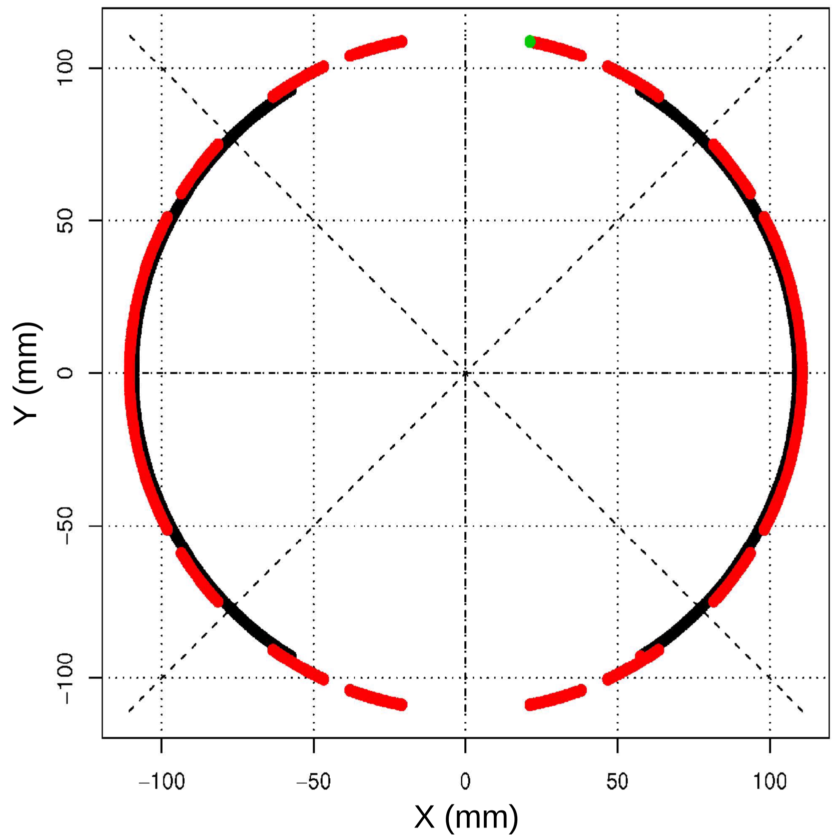


SCQ Wiring Schematic

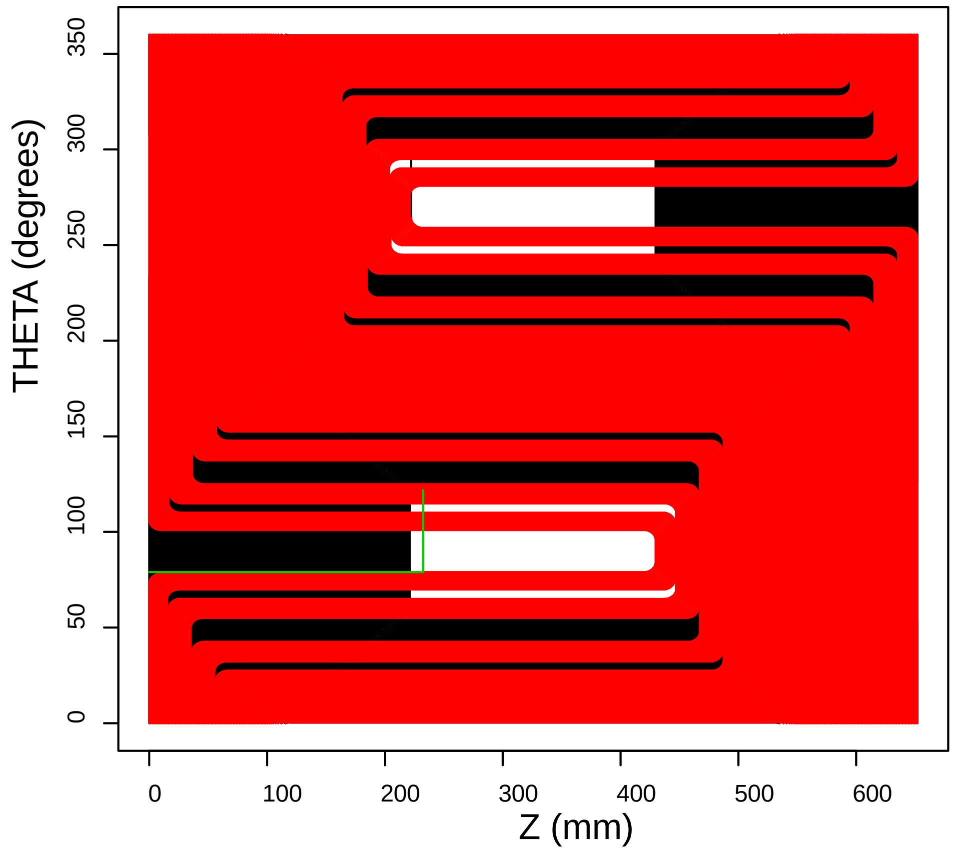
The “Final” SCB Serpentine Coil Pattern.

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

SCB Final Serpentine Cross Section



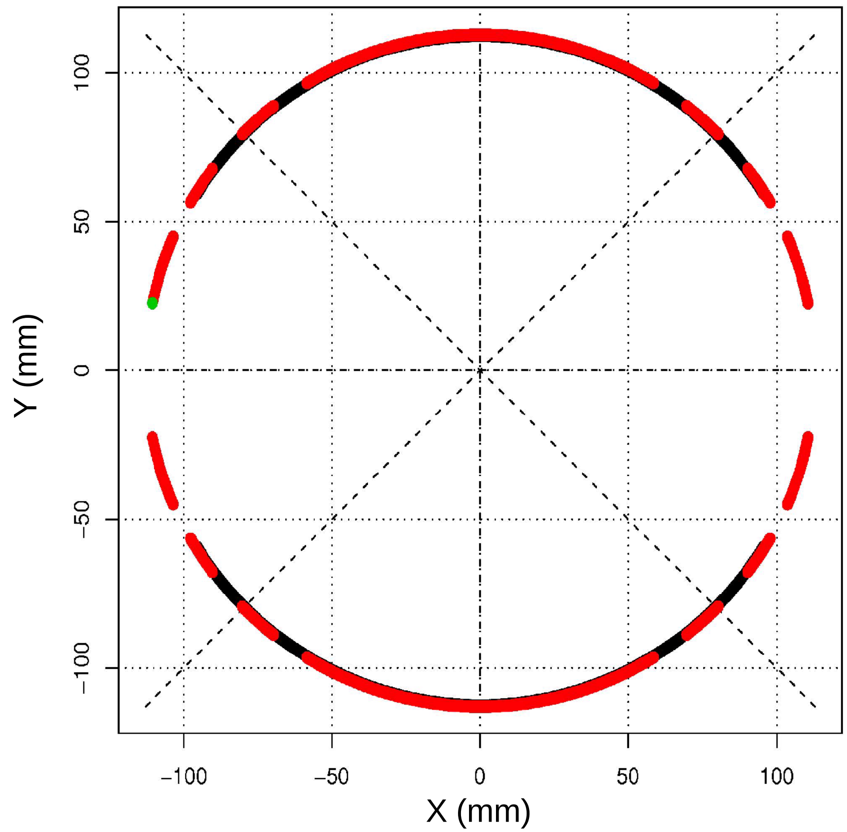
SCB Final Serpentine Winding Pattern



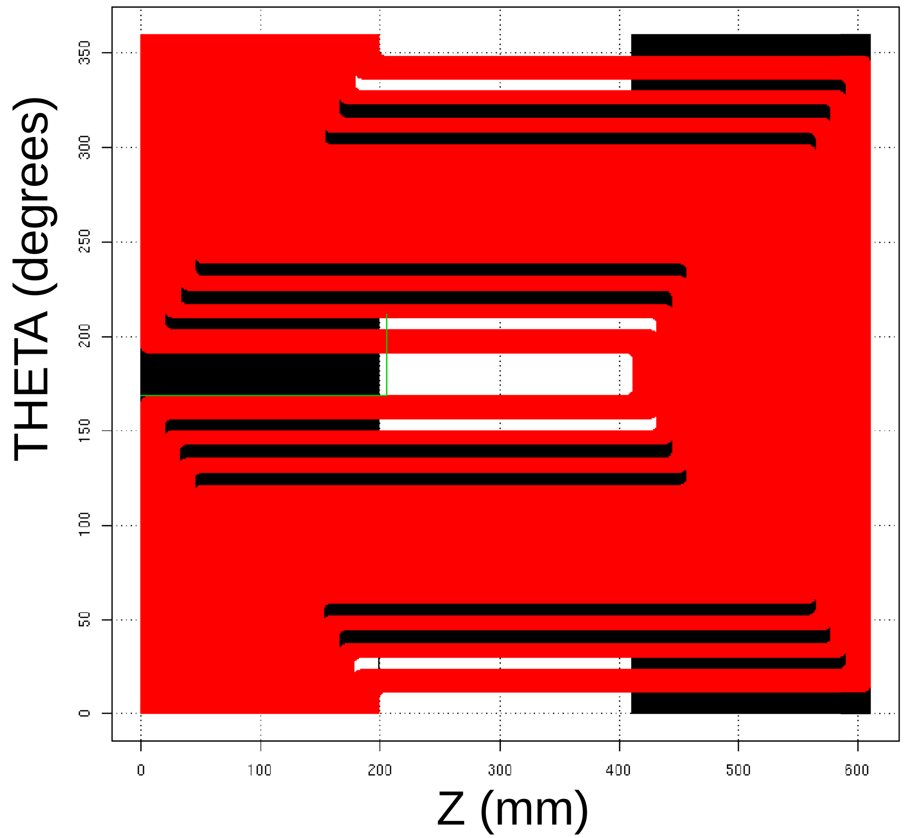
Like SCQ the SCB coil is wound from seven strand cable. Here three spacers in the upper layer are sufficient to ensure good harmonics. Note that dipole ends are naturally longer than quadrupole ends so SCB has even less “straight section” than SCQ and has to be wound longer than SCQ in order to have the same magnetic length.

The “Final” VDC Serpentine Coil Pattern.

VDC Final Serpentine Cross Section



VDC Final Serpentine Winding Pattern

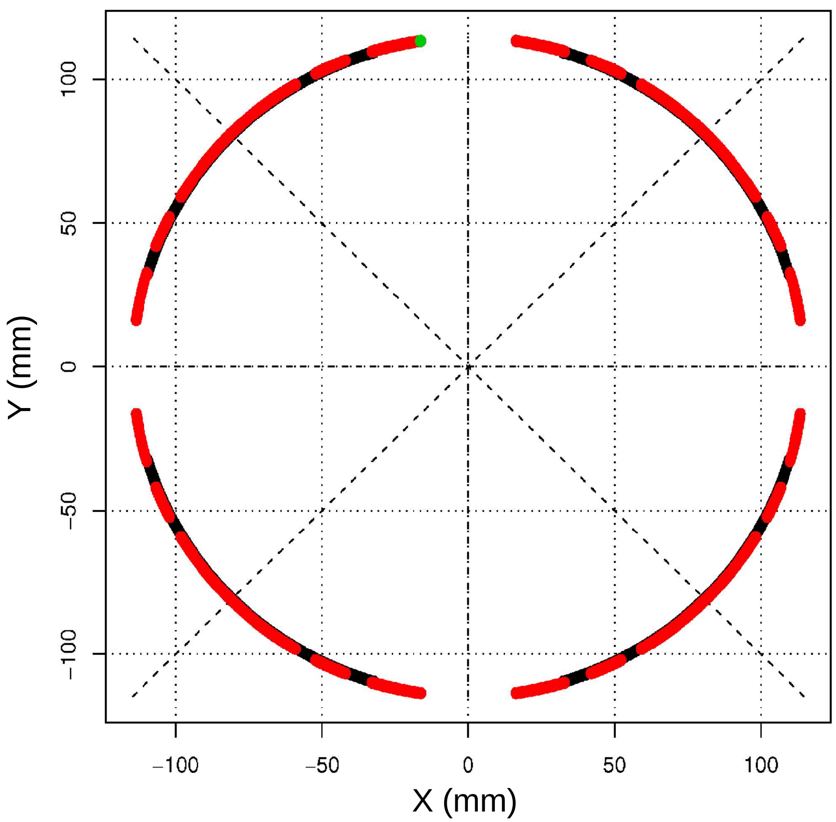


VDC is wound using single strand wire and as with SCB three spacers in the upper layer are adequate for tuning design harmonics. The actual winding pattern is a nested-serpentine, as was done for the NLC FF quadrupole, where the conductors in the second layer are constrained to lie in the “grooves” atop the lower layer turns. As was done for HERA-II spacers are filled in with Nomex.

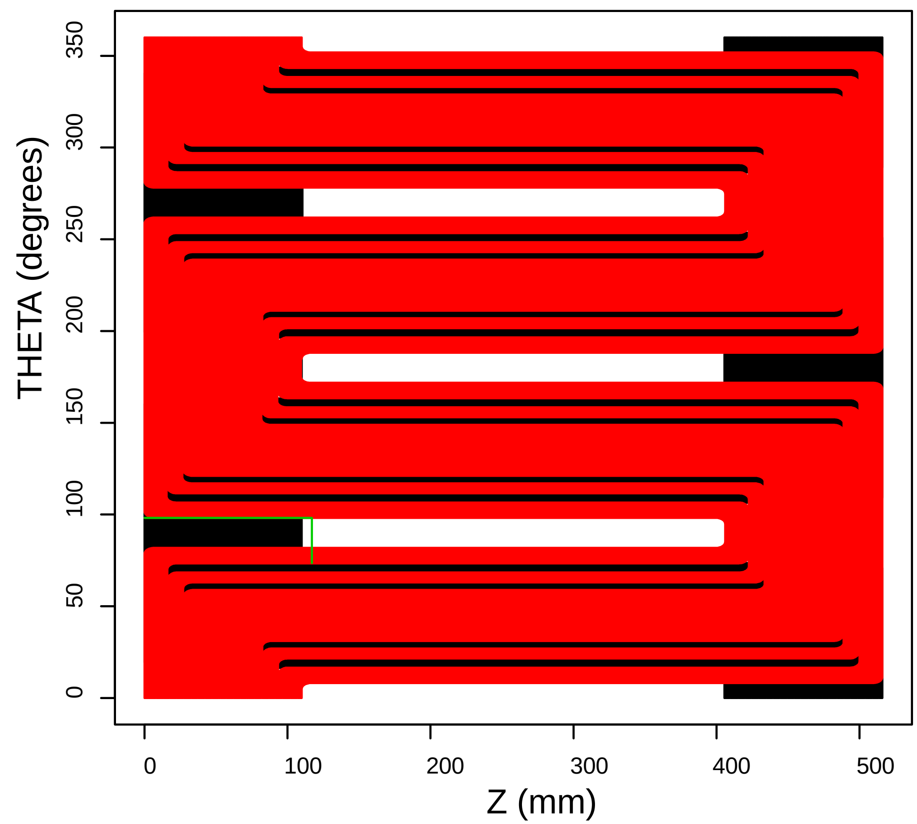
The “Final” SKQ Serpentine Coil Pattern.

Brookhaven National Laboratory
Superconducting Magnet Division

SKQ Final Serpentine Cross Section



SKQ Final Serpentine Winding Pattern



SKQ is also wound in a nested-serpentine pattern from single strand wire and only two spacers are needed in the upper layer for desired design harmonics.

Serpentine Coil Design for BEPC-II Superconducting IR Magnets: Summary.

Serpentine style coil winding has matured just in time to be useful for the BEPC-II superconducting IR magnet coil production.

Serpentine patterns offer many advantages for short aspect ratio magnets including the ability to correct SCQ harmonics during production using existing *AddHarmonic* software.

This gives us confidence to meet BEPC-II goals.

The End of the Beginning…