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https://agenda.infn.it/event/21199/overview

Advanced Technology Research Office
Superconducting Magnet Division
Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY

Direct Wind Magnets for the ILC, SuperKEKB, FCC-ee and the Electron-Ion Collider

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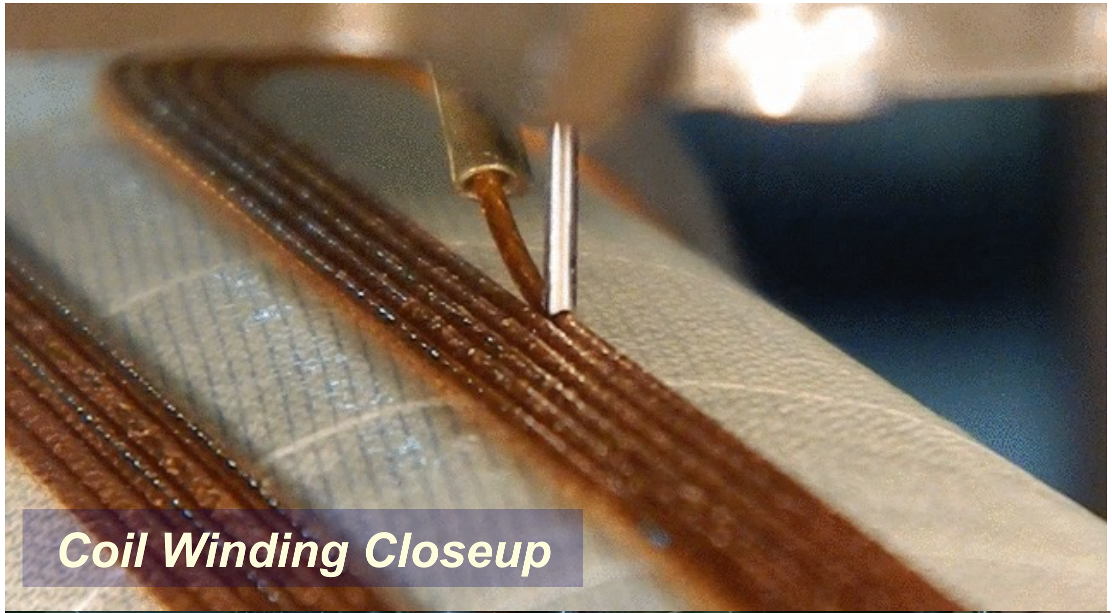
Contribution to WG10, IR Magnet Technology
Wednesday, September 14, 2022

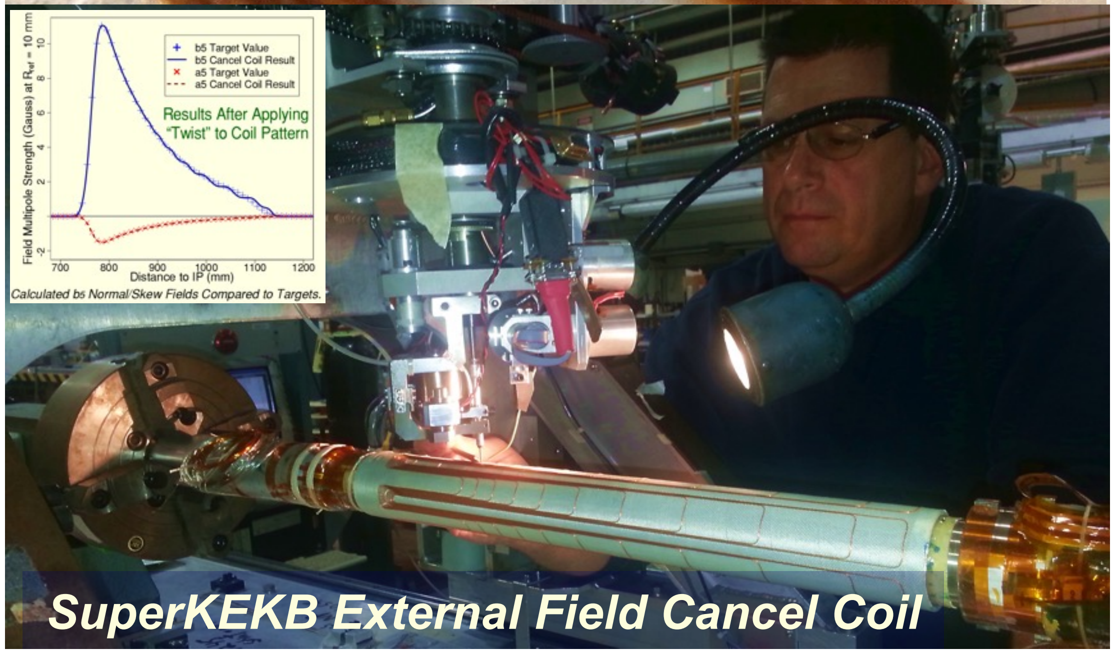
@BrookhavenLab

- Review motivation and development of BNL Direct Wind.
- Compare / contrast Planar and Serpentine Patterns.
- Show ILC QD0 Direct Wind active shielding configuration.
- Compare / contrast Serpentine and Double Helical (CCT) approaches for performing localized field profile tailoring.
- Propose using Direct Wind for making FCC-ee IR correctors.
- Show some future applications for SuperKEKB and the EIC.

1. Temporarily bind round conductor/cable to a substrate covered support tube.
2. Fill empty space in coil pattern with G10/Nomex/epoxy.
3. Wrap with fiberglass roving under tension to provide prestress after which cure the epoxy.
4. In multilayer structures, make magnetic field harmonic measurements that are then used to fine tune ultimate field quality by adjusting later coil windings.



Coil Winding Closeup



Calculated b_5 Normal/Skew Fields Compared to Targets.

SuperKEKB External Field Cancel Coil

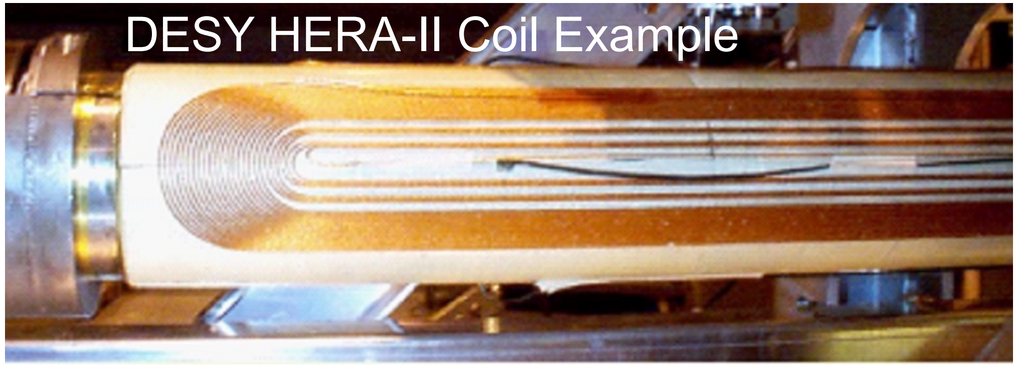
Direct Wind followed RHIC corrector production where wire was bonded to a flat substrate and wrapped around a support tube.

But it was not practical to accurately wrap 3+m long HERA-II coils and we started winding directly on to substrate covered tubes.

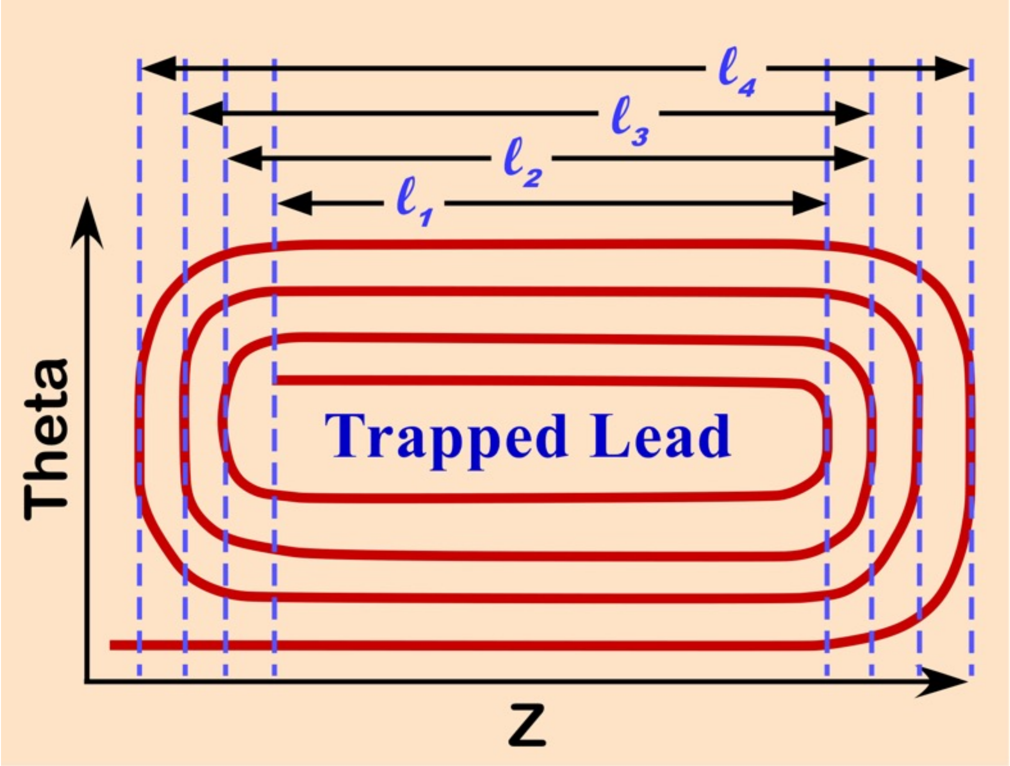
After laying down a layer, gaps are filled with G10 and epoxy and then tightly wrapped with fiberglass roving against Lorentz forces.

Note we must deal with leads coming from the pole regions unless we wind one pole immediately atop the current pole.

But to “double-layer” these planer poles, we would have to start and stop winding many times to fill spaces and wait for many low-temperature epoxy cures.

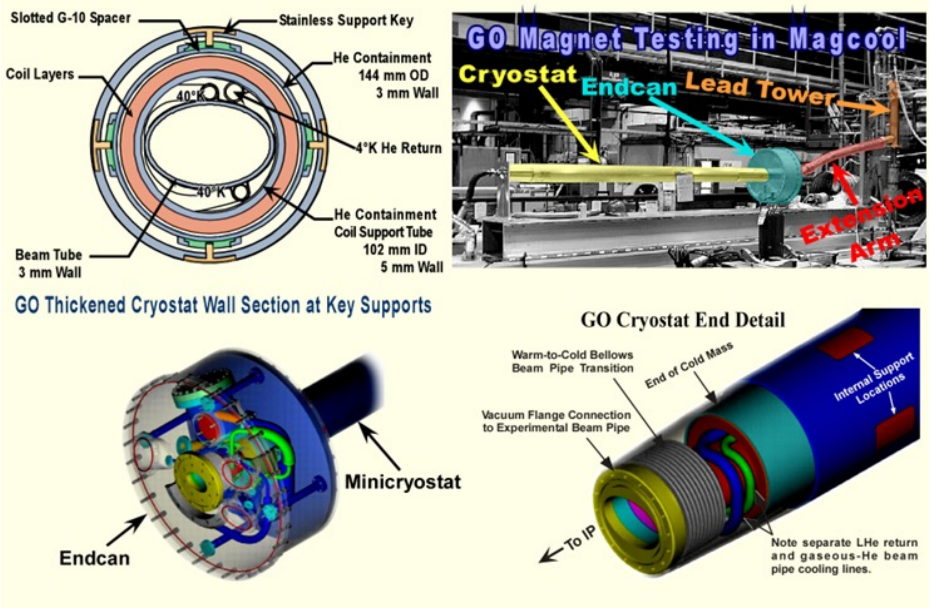


Have correlation between turn angle and length.



Planer Coil Winding Topology

HERA-II IR Magnet Production with a Very Thin Cryostat



For BEPC-II we had to pack more in less space; the main 8-layer BEPC-II quad coil would have been very slow if we had wound it as sets of planar coil pole patterns (start/stop and wait for epoxy).

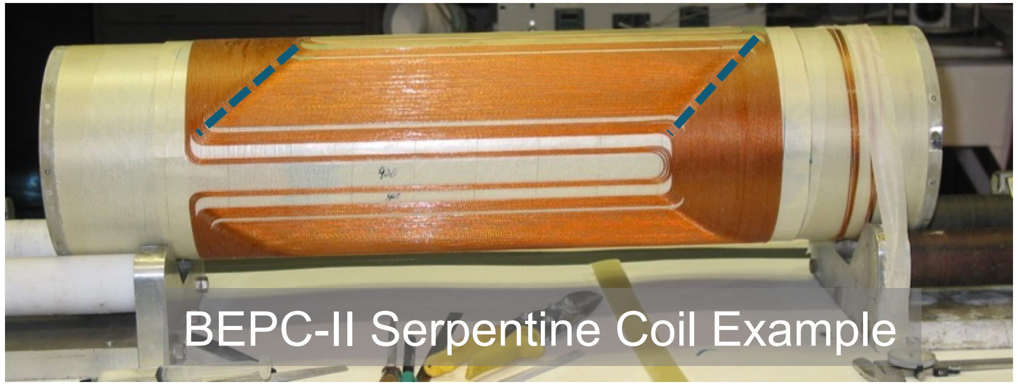
But by alternating conductor bend directions at each end, we could go around the tube and wind all the poles for one layer.

With this Serpentine geometry we wind layers in opposite pairs to eliminate solenoidal end fields.

Closed pole ends in one layer are open in the next, so we can bring current leads out naturally together (saves radial space).

Note that, with the exception of some small $N \rightarrow N+1$ effects, we automatically see integral harmonics same as in the 2D body.

All the turns in the coil pack are the same length independent of angle (same integral weighting).

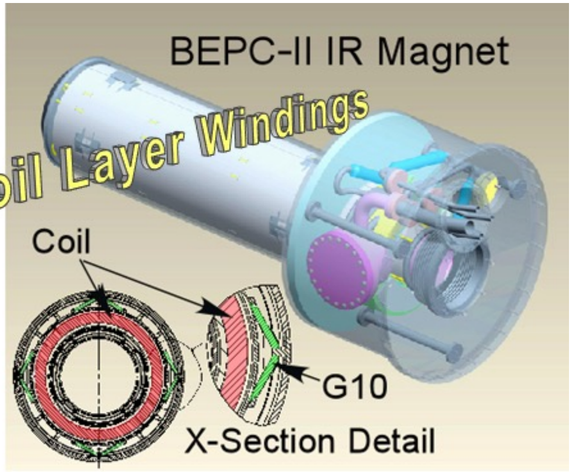


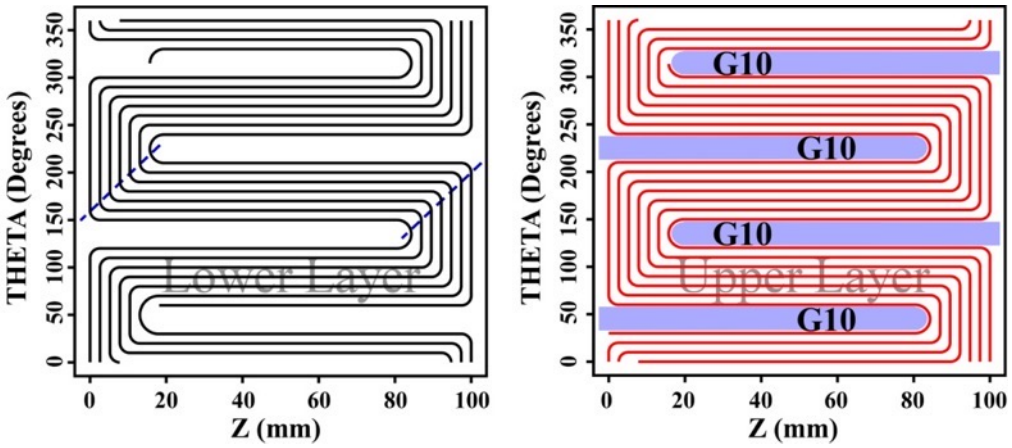
Wind two opposite layers to cancel solenoid term.

Integral harmonics are same as body harmonics.

Leads exit second layer open pole (not trapped).

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





BEPC-II IR Magnets: 2X Aperture, 1/7 HERA-II Coil Lengths

Serpentine Coil Winding Topology

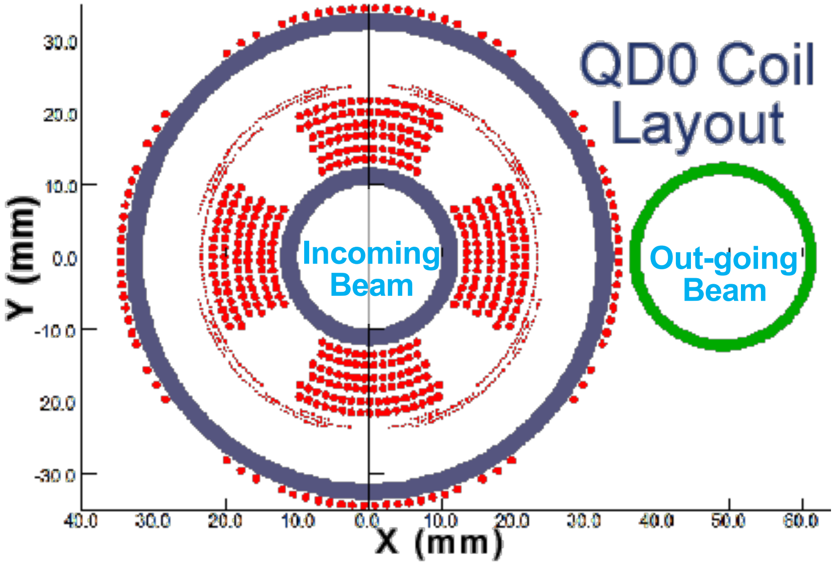
The ILC Final Focus QD0 quad is inside 3 to 5 T solenoidal fields for ILD and SiD; QD0 cannot have a magnetic yoke (has only a partial anti-solenoid).

At 500 GeV CM, QD0 gradient is 140 T/m and its external field is canceled by an active shield coil (with larger radius and opposite smaller gradient).

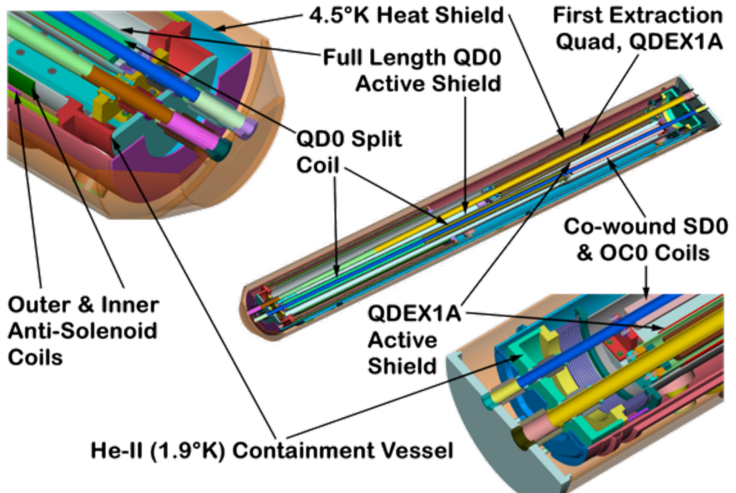
Note the anti-solenoid has different radius inner/outer coil in order that the cold mass not see net longitudinal force (e.g. force neutral anti-solenoid).

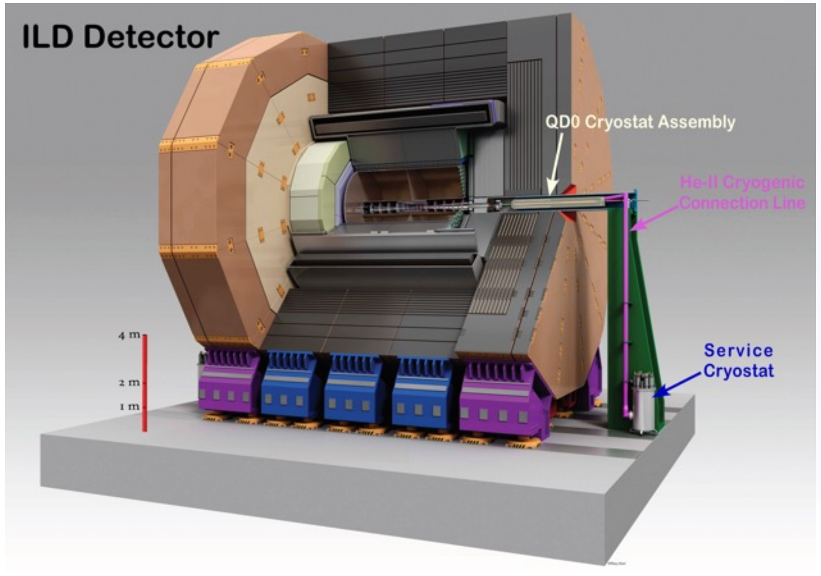
BNL has fabricated (90% complete at end of TDR) a full-length QD0 R&D prototype along with its Service Cryostat (QD0 cryogenic feed interface).

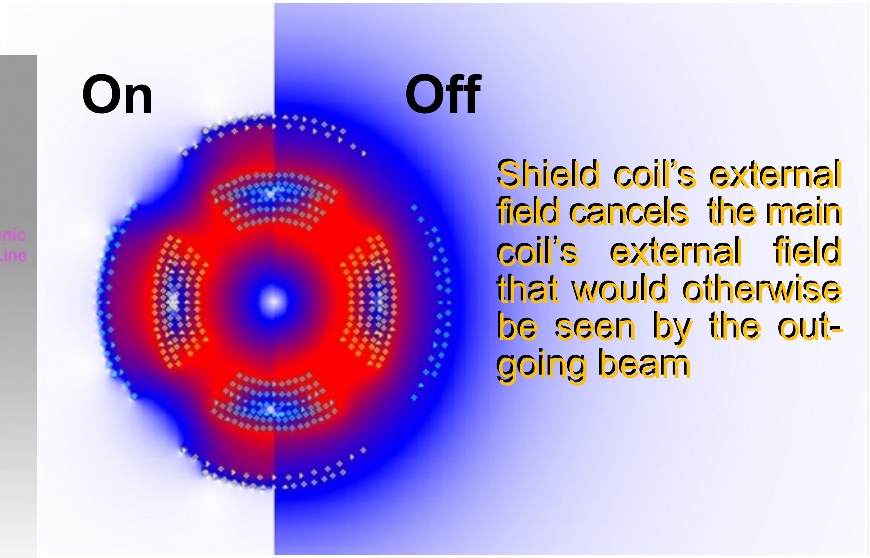
We request funding (ILC IDT WP-16) to complete the QD0 R&D assembly and do cold vibration stability measurements during ILC pre-lab phase.



ILC QD0 Coil with Active Shield







We use 1.9 K pressurized superfluid helium cooling in order not to have "flowing cryogens" (avoid vibrations).

QD0 with Active Shield On/Off

While the IR magnets for the BNL Electron Ion Collider (EIC) are outside the detector solenoid, the small, 25 mrad, crossing angle means that there is very little space for magnetic yoke material between the electron and hadron beams and excitation coils.

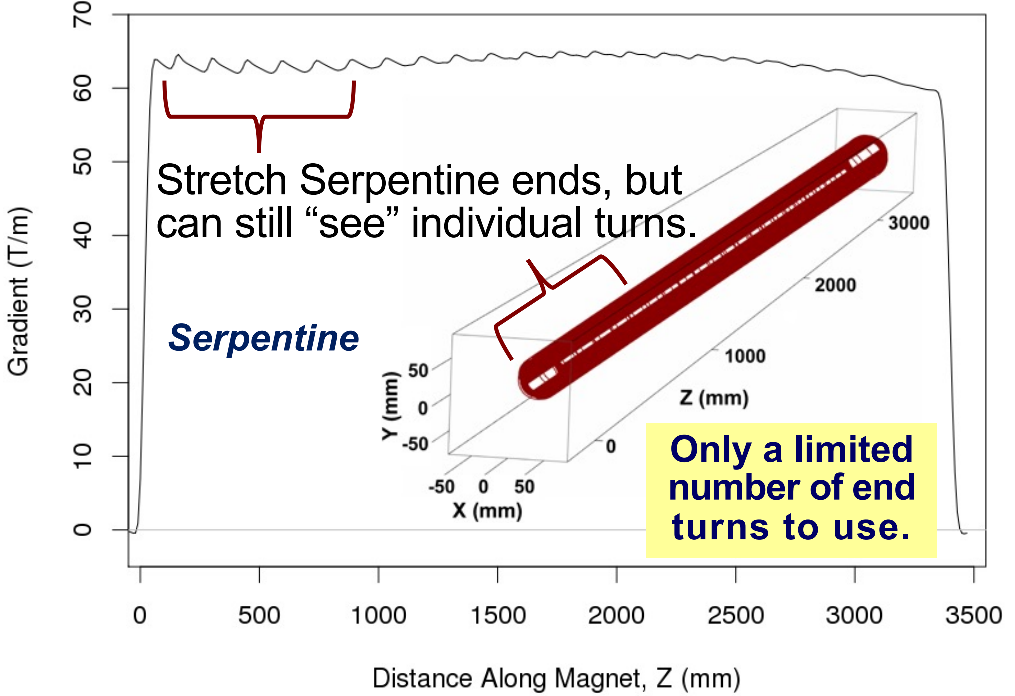
In order to fit some yoke in the tightest spacing at their IP ends, for some magnets we use "tapered coils" (change size along magnet).

With Serpentine coils we could tailor the resulting field profile along the magnet, much as was done for SuperKEKB Cancel Coils, but we find greater design flexibility using Double Helical (CCT) coils.

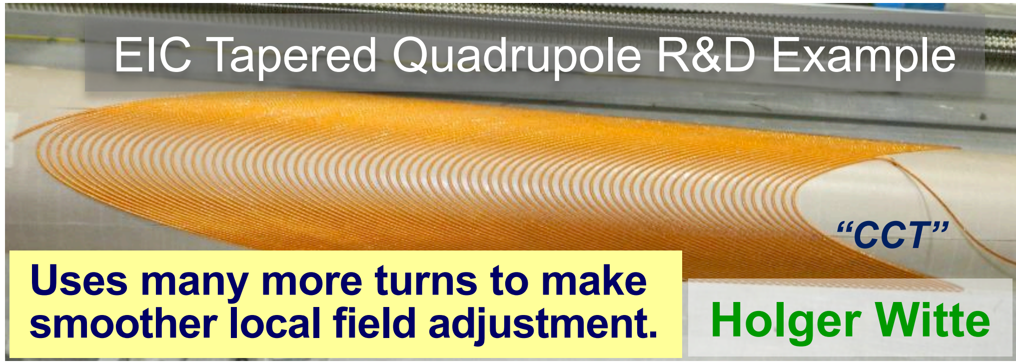
As with Serpentines, Double Helical coils are wound in layer-pairs to eliminate unwanted solenoidal fields; local position modulation of the "solenoid-like" turns allows very fine local field profile adjustment.

During Direct Wind R&D development, we wound and successfully tested (went to short sample) a tapered Double Helical quadrupole magnet with a constant gradient along its length.

Serpentine/Double Helical coil patterns represent opposite extremes of similar fundamental winding topologies; both have advantages for different magnet applications.

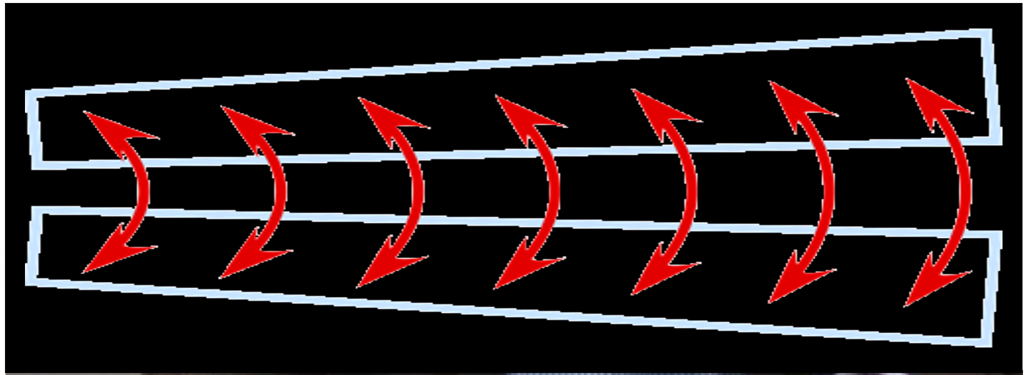


Constant Gradient Tapered Serpentine Coil



Constant Gradient Tapered Double Helical

Self-Consistent Side-By-Side FCC-ee IR Coils



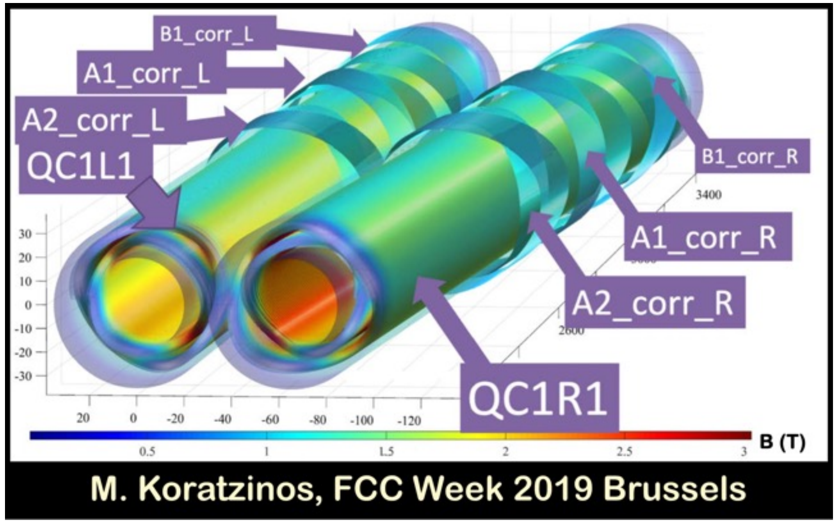
The FCC-ee IR magnet beamlines are very close with no magnetic yokes possible for shielding and have local field adjustments to self-consistently correct for the external field from the other beamline. This is accomplished by placing conductors in groves in a Double Helical (CCT) coil topology.

The FCC-ee IR magnet baseline uses Canted Cosine Theta (CCT / Double Helical) to locally deal with the external field cross talk between the side-by-side coils for two closely spaced beamlines.

The FCC-ee CCT geometry coils utilizes superconductor cables supported in grooves unlike the Direct Wind technique described so far.

For the FCC-ee IR magnets it seems promising to fabricate the main coils via the baseline conductor in grove technology but use Direct Wind to produce thin-layered side-by-side corrector coils that nest outside the main coils (groves are not as space efficient for positioning very small diameter corrector coil wires).

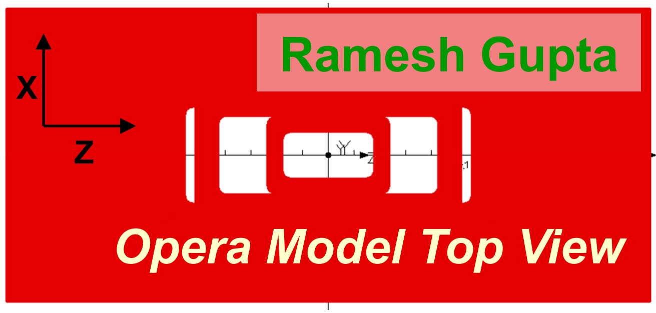
The corrector magnet design study is part of an ongoing FCC-ee IR magnet optimization including anti-solenoids and other MDI issues.



FCC-ee Side-by-Side IR Magnets

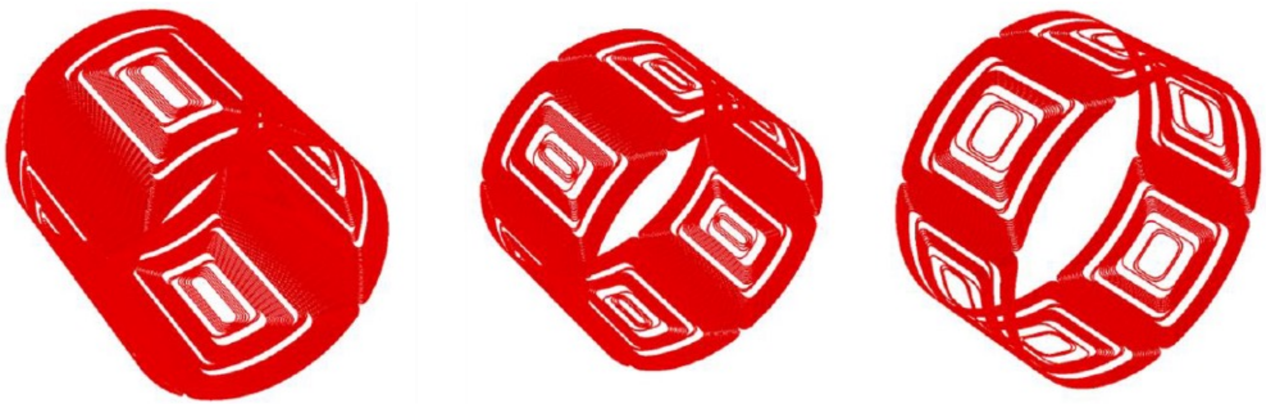
In the optimum integral design, midplane turns extend full length and contribute maximum to the field. The cosine theta distribution is obtained in an integral sense:

$$I(\theta) \cdot L(\theta) \;=\; I_o \cdot \; L_i(\theta) \propto I_o \cdot L_o \cdot \cos(n\,\theta)$$



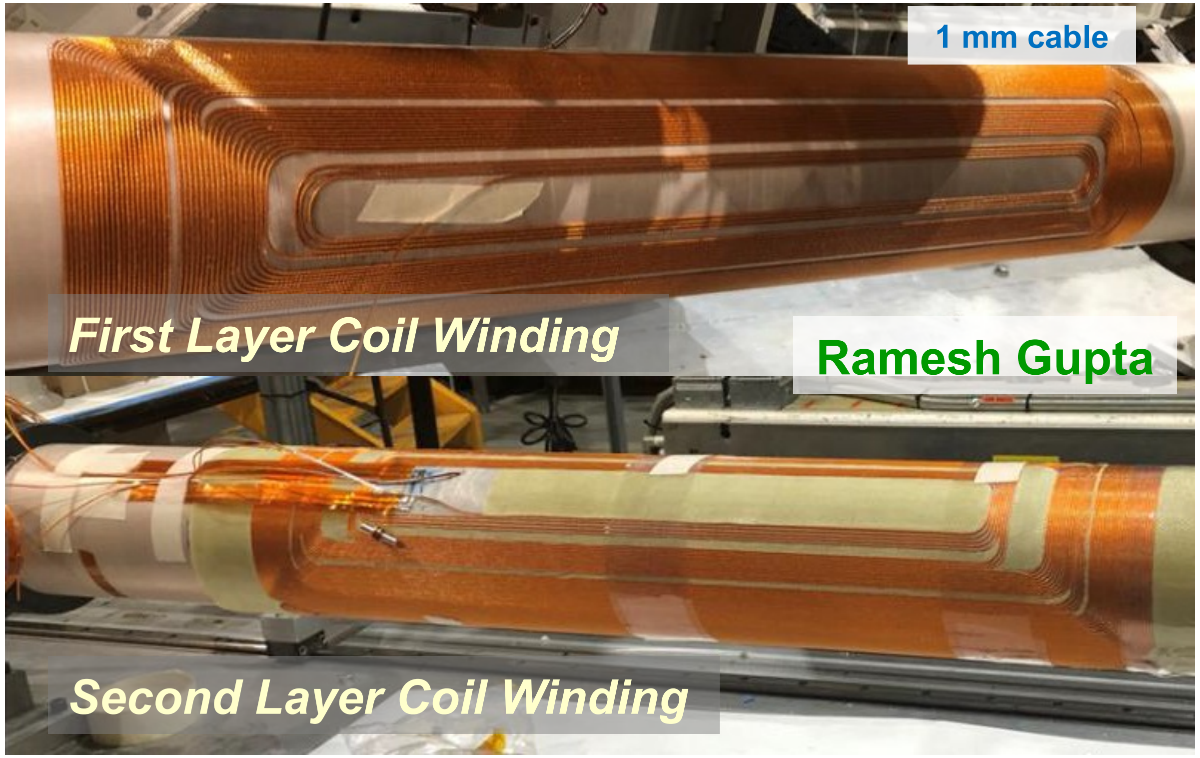
Optimum Integral Direct Wind Short Dipole Design

The *optimum integral design* provides a unique solution for building short magnets, with dipole coil lengths less than their coil diameter, quadrupole coil length less than their coil radius and sextupole coil length 2/3 of their coil radius, etc. Such short superconducting magnets are otherwise not possible with a comparable integral field for the same coil length and coil thickness.



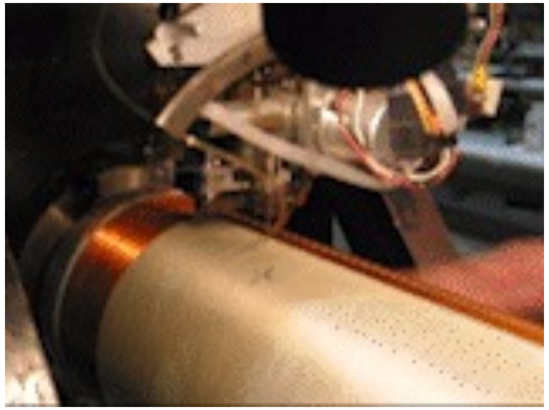
Ramesh Gupta

Optimum Integral Quad, Sextupole and Octupole Coils

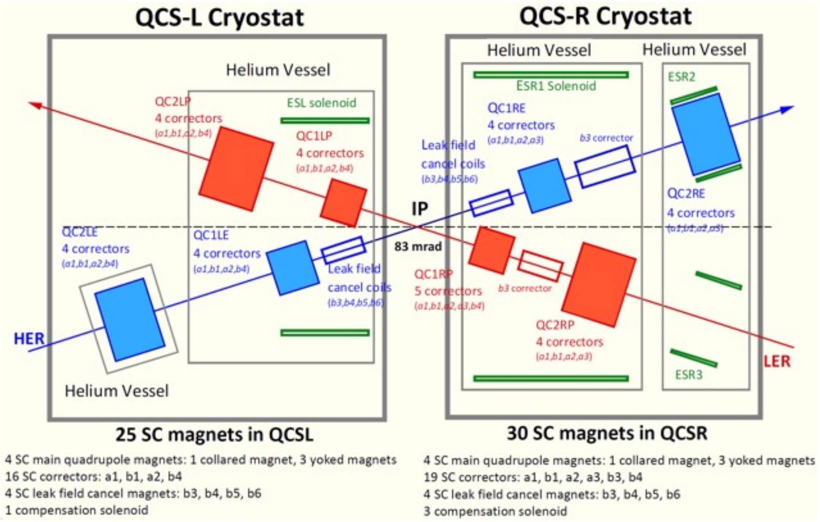


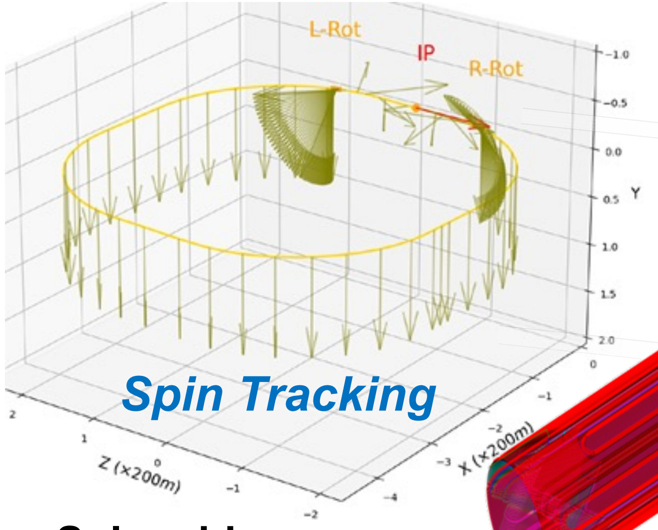
STTR† EIC Optimum Integral R&D Coil Production

†Small Business Technology Transfer Program



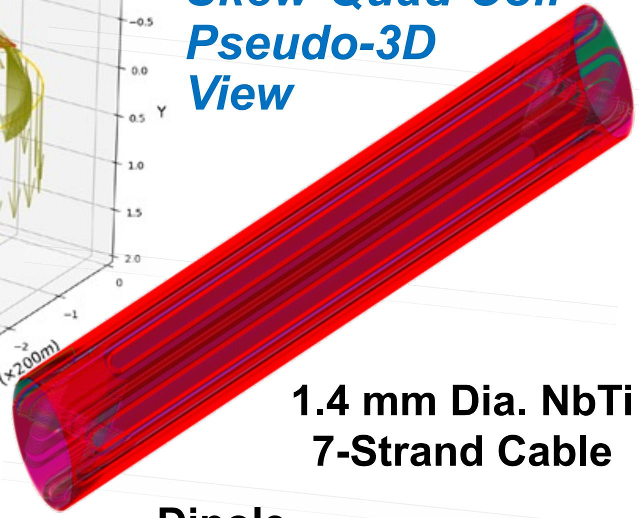
Direct Wind Corrector for the SuperKEKB IR





Spin Tracking

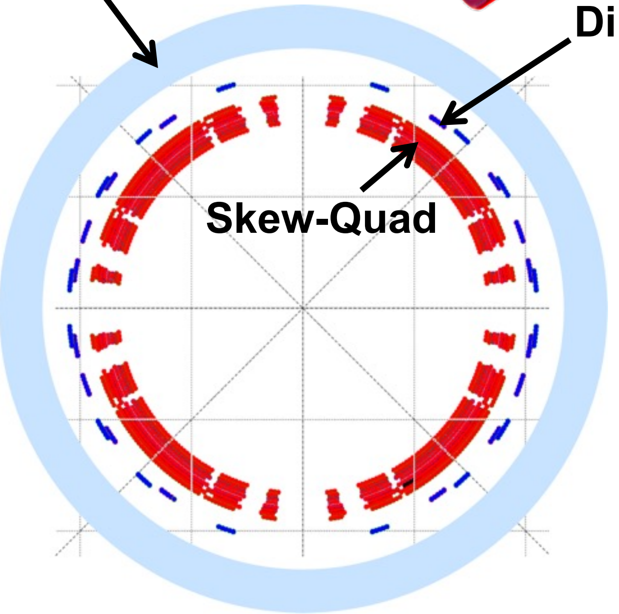
Skew-Quad Coil Pseudo-3D View



1.4 mm Dia. NbTi 7-Strand Cable

BNL wound the 43 corrector and cancel coils for the SuperKEKB Upgrade.

Have US/Japan collaboration funding to explore increasing IR aperture at a critical point with a new corrector package and to wind correction coils for a possible new superconducting LER Crab Waist sextupole.



Solenoid Field 4.85 T
Skew Gradient 24 T/m
Dipole Field 0.2 T

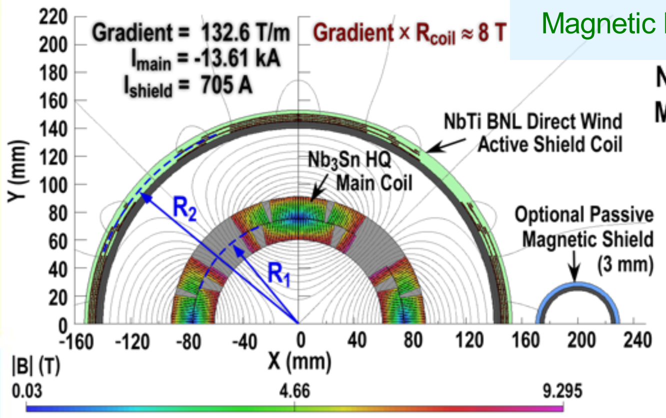
Combined Field @ Skew-Quad is 6.15 T
I_{op} = 729 A
I_q = 1050 A
for 69% Short Sample

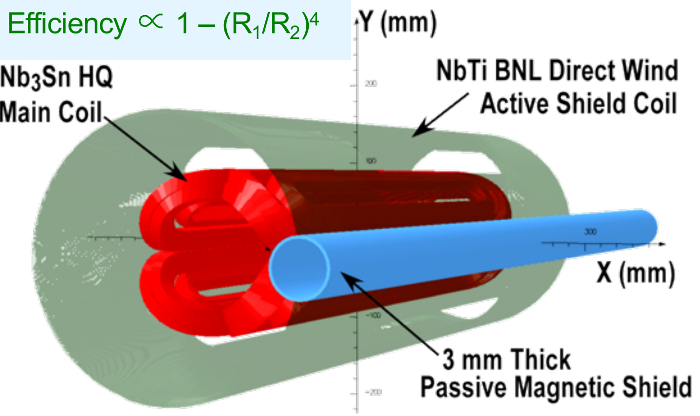
Coil Cross Section at Skew-Quad Center

Another interesting prospect allows Belle II to explore a new spin physics frontier by having longitudinally polarized electrons at the IP. We want to do this, without moving magnets in the tunnel, by replacing pairs of warm dipoles on either side of the IR with new superconducting multifunction, standalone spin rotator magnets.† These spin rotator modules overlay solenoidal field on the existing dipole bend and a set of integrated skew-quadrupoles correct the local optics coupling. BNL Direct Wind is a natural candidate for producing the required multi-function magnetic field configuration.

†This multifunction coil configuration was first proposed by Uli Wienands/ANL.

Magnetic Efficiency $\propto 1 - (R_1/R_2)^4$





High Gradient Nb_3Sn Quad with an NbTi Active Shield

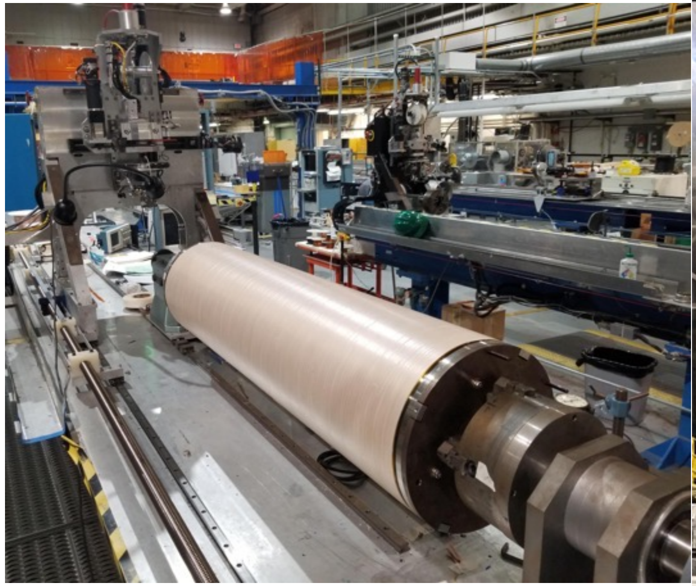
Active shielding is not just for the ILC QD0…

For colliders, such as the EIC, where we need to get a much lower energy beam past a high-field magnet, the magnetic yoke is so highly saturated that there is no effective shielding effect at the low energy beam ($\mu \approx 1$).

Here a Direct Wind active shield coil is intended to cancel the external field from a much stronger Nb_3Sn quadrupole.

In this way it is possible to have fields of a few gauss just outside a 9 T coil structure.

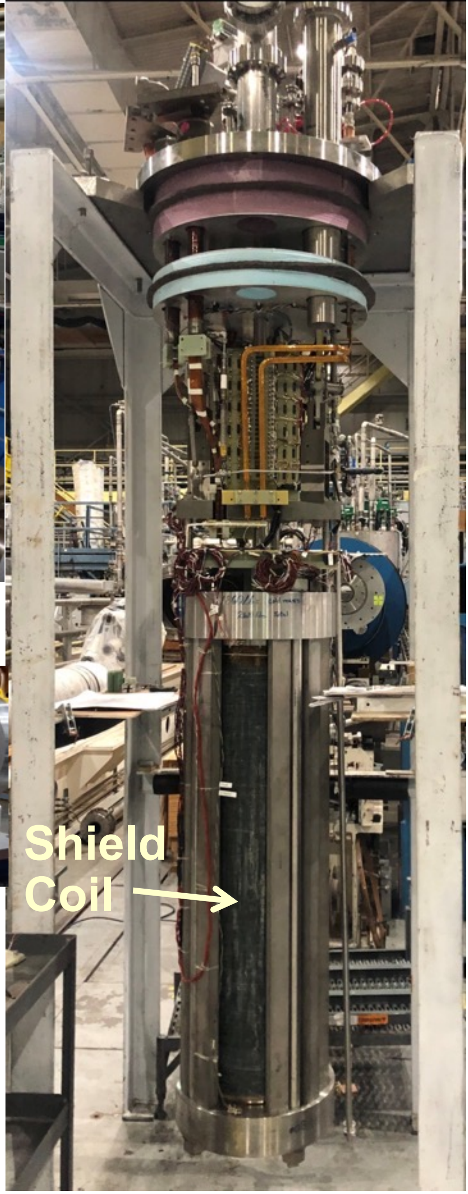
We look to test this magnet configuration soon.



NbTi Direct Wind Shield Coil

Nb_3Sn Quad Coil from LARP

We extracted Nb_3Sn coils from a previous LARP quad and placed them in a new, more compact (no magnetic yoke), structure to provide necessary coil prestress.



Cold Test Ready

We need B-field to detect charged particles coming from the EIC IP that pass just outside the hadron beam tube in B0 spectrometer; so how can we also get the electron beam safely through this B0 spectrometer field?

Note the spectrometer field is maintained constant independent of the hadron beam energy (e.g. no ramping).

Wind a combination of main hadron quadrupole and dipole coils to produce a combined-function field that is zero at the e-beam axis.

A weak e-dipole finishes correcting integrated field seen by e-beam.

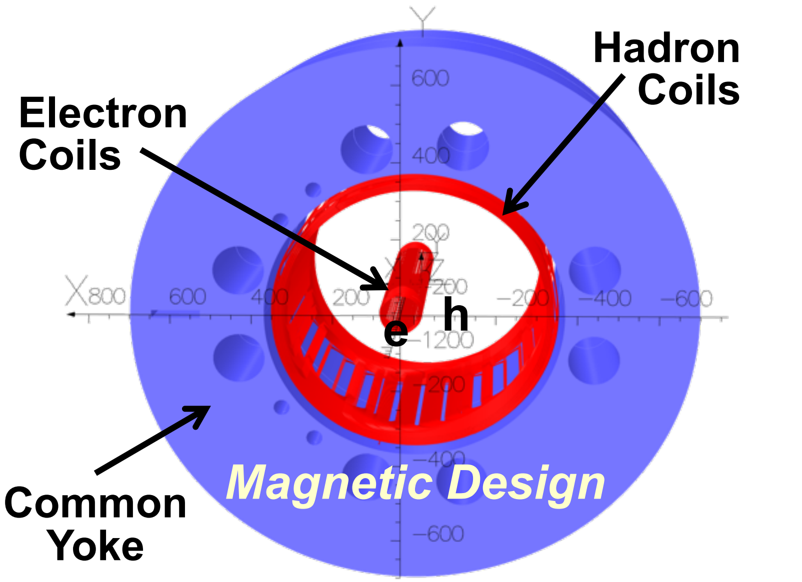
Hadrons see 1.3 T average field while electrons only a few gauss.

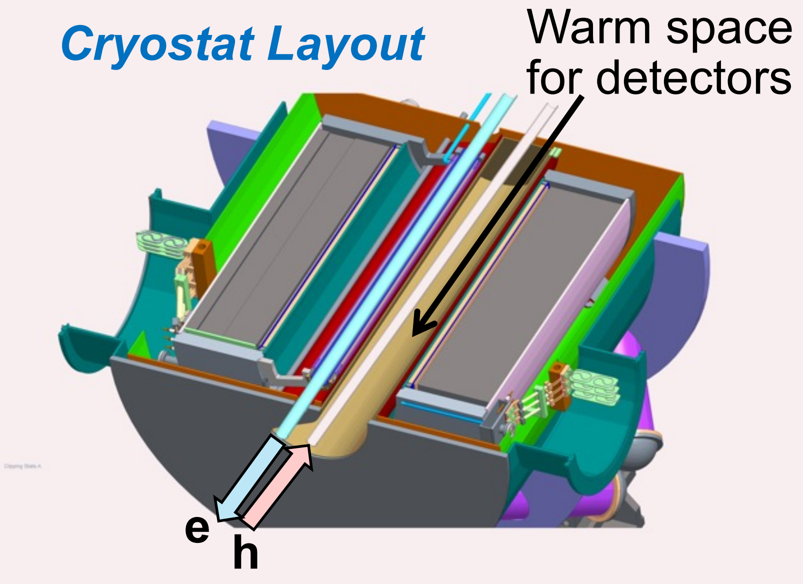
Main coil gradient is close to defocusing needed for 10 GeV electrons.

At other electron energies (e.g. 18 and 5 GeV) an electron gradient tuning coil either adds to or partially cancels the main coil gradient.

The B0 hadron beam pipe is inside a warm space and is surrounded by experimental detectors.

Put first e-quad inside the B0 hadron spectrometer.





EIC B0 Forward Spectrometer

Thank you to the organizers of eeFACT2022 to have the chance to report on the efforts of many people in the BNL Direct Wind team… and for your kind attention. B.P.