Superconducting Final Focus Magnets at ILC and Future Colliders

Brett Parker / BNL, January 17, 2020

Venue: IAS2042, 2/F, Lo Ka Chung Building, Lee Shau Kee Campus, HKUST
Outline: Superconducting Final Focus Magnets at ILC and Future Colliders

- IR Magnet† and MDI Lessons from Previous Work
  - HERA-II / BEPC-II IR Magnets and MDI
  - ILC Final Focus Magnets and MDI
  - SuperKEKB IR Corrector Magnets and Cancel Coils

- Some Future IR Magnets and MDI Considerations
  - BNL Electron-Ion Collider (EIC) IR Magnets
  - CERN FCC-ee IR Magnets

†For present usage “IR Magnets” includes Final Focus quadrupoles, Beam Separation Dipoles, Solenoids/Anti-solenoids, Corrector Magnets and External Field Cancel Coils.
For HERA-II IR magnet production we applied BNL ultrasonic coil winding technology to fix the superconductor directly to a support tube.

Fiberglass wrap provides prestress yielding a very compact coil structure with no external collars.

SS-keys in G10 slots centered cold mass in cryostat with compact size but cold spots (i.e. heat load).

Dipole coil in solenoidal field generates torque; this caused magnet center to move during ramp.
For BEPC-II we have just over 25 mm radial space between the inner coil and warm bore and just over 30 mm radial space between the outer coil radius and the outside of the cryostat.

- For BEPC-II we invented Serpentine winding scheme (production efficiency/other benefits).
- Add heat shield / lower heat leak (green field).
- Add local (e.g. SCQ)/integral anti-solenoid coil.
- Had to deal with axial force from anti-solenoid and torques from HDC/VDC dipole correctors.
The cryogenic/power lead connection interface and the physical mounting point (for HERA-II and BEPC-II the “endcans”) needs to be well defined and may require dedicated space outside/inside the experimental detector itself.

Within the warm cryostat shell the cold mass components will shrink and move during cool down; need to define one fixed point where cold mass is fixed and allow other parts to move (bellows, keys in slots etc.)

Any net forces or torques generated in the cold mass eventually have to be brought out to warm supports; the optimization to handle forces without generating large heat loads is not trivial and may require a surprising amount of radial and/or longitudinal real-estate.
For the ILC IR we only need to pass the outgoing highly disrupted beams cleanly on to the beam absorbers.

Main requirement is to shield outgoing beam from any strong external fields... which is done with an active shielding coil.

Main 2.2 m QD0 coil is split in half for low energy optics flexibility and ease manufacturing challenges.

Note there is only a partial anti-solenoid overlapping QD0 (just enough to avoid luminosity loss due to overlapping fields†).
We use 1.9 K pressurized superfluid helium cooling in order not to have “flowing cryogens” (avoid vibrations).
ILC Final Focus Magnets and MDI: Designs

- In order not to have to deal with 40 tons of axial force in the warm-to-cold transition we use a “force neutral” anti-solenoid coil scheme so there is no net force on the cold mass (would take up extra space and add heat load).

- Note in the QD0 R&D prototype shown here, even with thin walled shells, radial space is needed for thermal shield support structure.

- Multiple IR magnets are mounted and kept in alignment on rigid sled structure (note geophones).

- Use shielded bellows for the beam pipe warm-to-cold transitions (IR magnet beam pipes are cold).

- In order to avoid having a large diameter “endcan region,” we need extra longitudinal space to interface with the cryogenic supply line, magnet leads, etc.
The ILC QD0 shows how some of the complexity of the cryogenic interface can be moved further from the experiment (e.g. the Service Cryostat) in order to keep to a minimum diameter cryostat insertion (smaller impact on detector).

Because the present ILC QD0 assumes 1.9K superfluid cooling, the QD0 cryostat has an additional 4K conduction cooled heat shield; the extra radial space this requires is not wasted as it allows a larger outer solenoid coil to balance the axial force generated by the inner anti-solenoid coil.

Unfortunately while the QD0 R&D Prototype parts exist, the idea that 1.9K cooling avoids a significant driving term for vibration has never been tested.

For the FCC-ee, if we use 4.5K in place of ILC 1.9K cooling and don’t (and probably cannot) use a force neutral anti-solenoid coil configuration, the radial space between the cold mass and outer cryostat shell would be reduced... but then we need to deal with large forces and should carefully evaluate possible vibration modes.

MDI for a push-pull IR layout is quite painful!
SuperKEKB IR Correctors and Cancel Coils: Designs

- With 35 correction coils and 8 cancel coils we sometimes hear this referred to as a “complicated system” (criticism implied).
- However there are just enough knobs to allow the operator to adjust each quad’s hor/vert center position and roll angle.
- In addition the operator can make non-linear (normal and skew sextupole and octupole) local optics corrections.
- We could have combined each of the 4 cancel coils on each side into a single multipole coil package, but dead reckoning what the optimum mix of fields would be, before everything was measured, would have been somewhat risky.

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<th>Table 1. Required Field Strengths.</th>
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For external field compensation, the idea was not to cancel the linear ($b_1$, $b_2$) field components, but just include there influence during the optics optimization.

The desired non-linear field profiles were then created by “stretching one Serpentine coil’s end” (now can use dual helical).

Final results for the field profile were actually very good!
• Yes, building in the design flexibility (e.g. knobs for operators or IR opticians) to make beam orbit/optics changes can yield a design that seems “complicated.”

• But having to dead reckon multiple, stringent, magnetic field magnet production requirements can itself be quite costly (i.e. require a lot of contingency to guarantee performance and no errors... the known unknowns) and brings its own risk (... the unknown unknowns).

• The good news is that we still continue to come up with new ideas to make progress on MDI challenges.
EIC IR designs require production of many new challenging magnets (fortunately NbTi seems to be ok and Nb₃Sn may not be needed).

To pass synrad cleanly through rear side electron magnets, we make use of tapered constant gradient quadrupole coils!

A very tough challenge is to always be sure to shield the electron beam from the quite strong hadron magnet fields!

BNL Electron-Ion Collider IR Magnets: Designs

- For the EIC IR design we use tapered coil quadrupoles.
- Thanks to design flexibility of dual helical coil windings we can modify the local field components so as to keep the local quadrupole gradient constant.
- We are halfway in a BNL funded (LDRD) project to wind and test a dual helical tapered quadrupole coil.
- Warm measurements show expected field quality and the target constant gradient.
- Preparations for cold testing are in progress.
- The same dual helical design flexibility that we use to locally adjust the quadrupole strength could also be used to add local admixtures of other field harmonic components (e.g. to buck out magnetic crosstalk between two side-by-side quadrupoles).
Challenge: Deal with magnetic crosstalk between the QC1 IR quadrupoles.

Answer: Use flexible Double Helical coil design to locally adjust QC1 field much like we are doing for the BNL EIC IR.

We could use BNL Direct Wind technology to make double helical coils that by design eliminate magnetic cross talk.

Unlike with SuperKEKB, we must also buck out the $B_1$ term or the zero field path in the quadrupole will be curved! [e.g. then cannot find an orbit path that avoids at least some dipole field]

1.5 cm radius $z \pm 12.5$ cm

Smaller central pipe: 1.0 cm for $z \pm 9$ cm (with taper starting at $z \pm 40$ cm from IP)
An alternative FCC-ee IR magnet design layout that was presented by Anton Bogomyagkov et al. (BINP Group) at 3rd FCC-ee MDI Meeting.

MDI implications of 30 ton net anti-solenoid longitudinal force are very significant; ultimately this has to be managed with support either from the detector or cantilevered. But what about the warm-to-cold transition?

For BEPC-II, a 1.3 ton axial force let to 1.5 W heat load. 30 tons will lead to an even higher load and take up more space. Also how do we handle the torques generated in the cold mass (long lever arm)?

M. Koratzinos, “The idea is to use a stiff skeleton which will replace the very heavy cryostat. All load bearing capability will rely on this skeleton.”

Reduce wall thickness to 4 mm to reduce total weight.
IR Magnet and MDI Lessons from Previous Work
• There is a lot of experience available (find out who to ask).
• And it is easy to overlook (uninteresting) details that can have a significant impact on the final design (e.g. passing forces and torques from cold-to-warm supports).
• Be wary of using “nanometers” and “superconducting magnets” in the same sentence (SuperKEKB vibration work).

IR Magnet and MDI Future Expectations
• Dual helical coil winding is now a key IR magnet technology.
• We will continue to find synergies between future IR design work: ILC, CLIC, EIC, FCC-ee, FCC-eh/LHeC, CEPC and more!
Backup Slides
Multiple main magnet and corrector coils were produced on common support tubes. These tubes are themselves supported from a rigid sled structure inside the cold mass.
The ILC QD0 R&D magnet prototype cryostat is 90% complete and almost ready for insertion of the magnet coils on the “sled assembly.” Finishing the Magnet Cryostat was given higher priority than making the transfer line parts.
ILC QD0 R&D Service Cryostat

Final assembly of the R&D Service Cryostat is now proceeding.

Plan was to test it using a dummy heat load attached to where the transfer line exists.

We would like to mount a geophone alongside the dummy load to characterize sources of vibration.

Transfer line parts drawings do exist but all work has remained stopped due lack of funds.
ILC QD0 R&D Service Cryostat

These pictures were taken in 2014; no additional work since then.