Mini-Workshop: Accelerator - Machine Detector Interface for Future Colliders

Venue: IAS2042, 2/F, Lo Ka Chung Building, Lee Shau Kee Campus, HKUST

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY | HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

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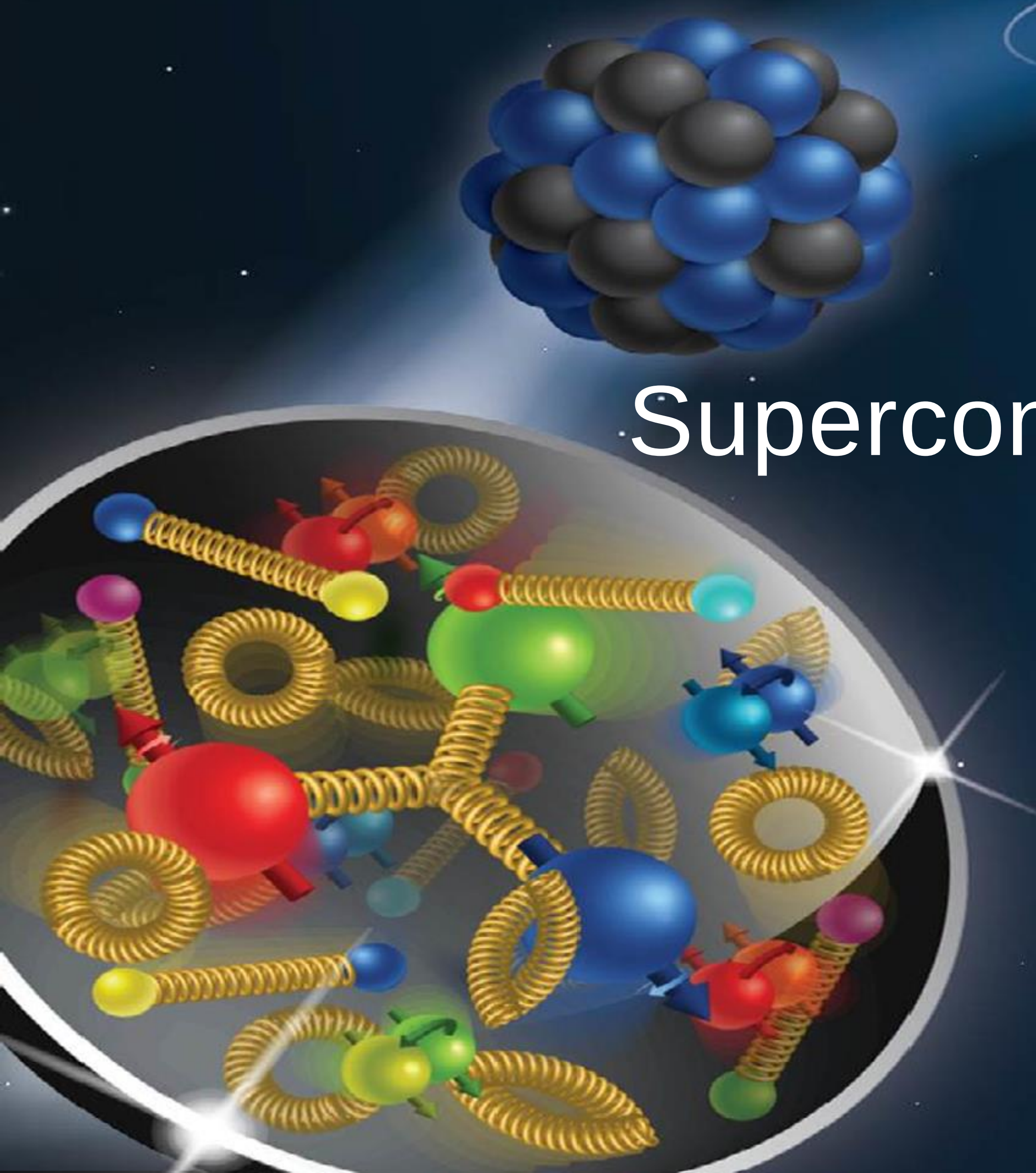
High Energy Physics



Superconducting Final Focus Magnets at ILC and Future Colliders

Brett Parker / BNL, January 17, 2020

Electron Ion Collider – EIC

BROOKHAVEN NATIONAL LABORATORY

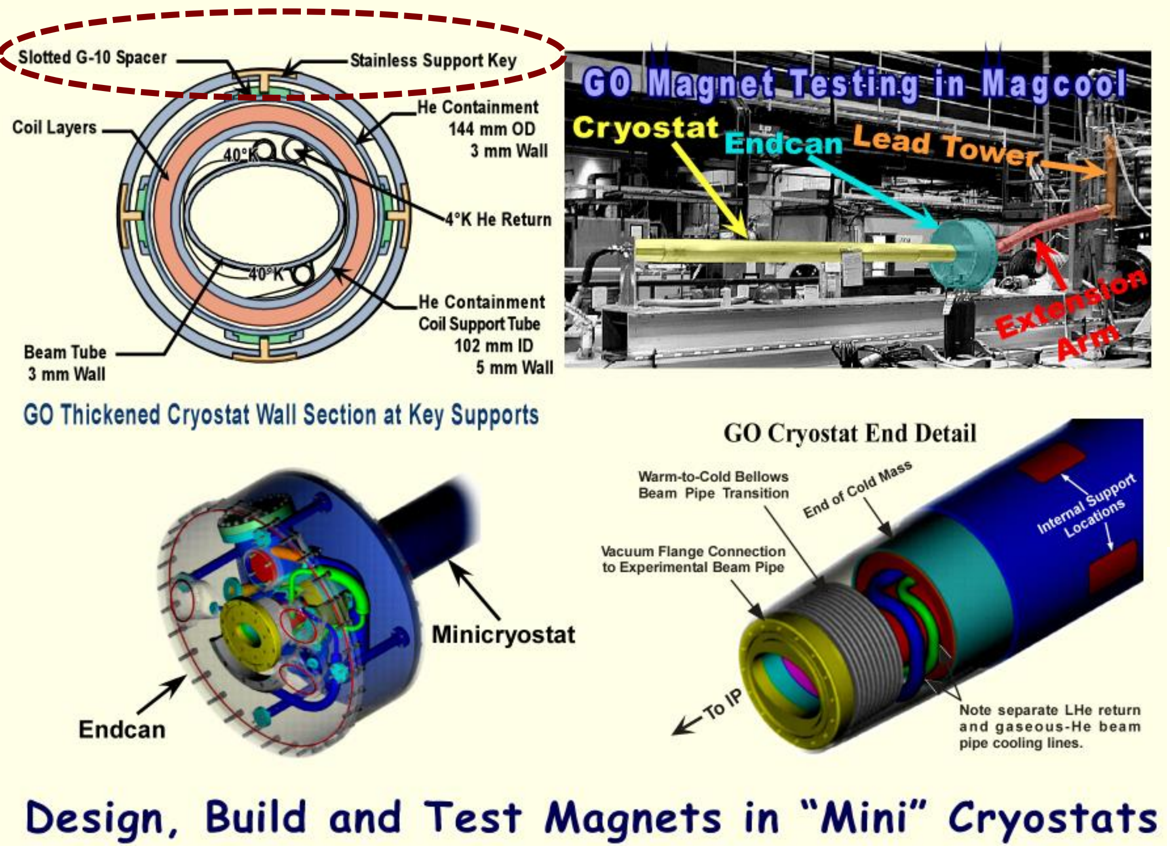
U.S. DEPARTMENT OF ENERGY | Office of Science

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.

HERA-II / BEPC-II IR Magnets and MDI: Designs



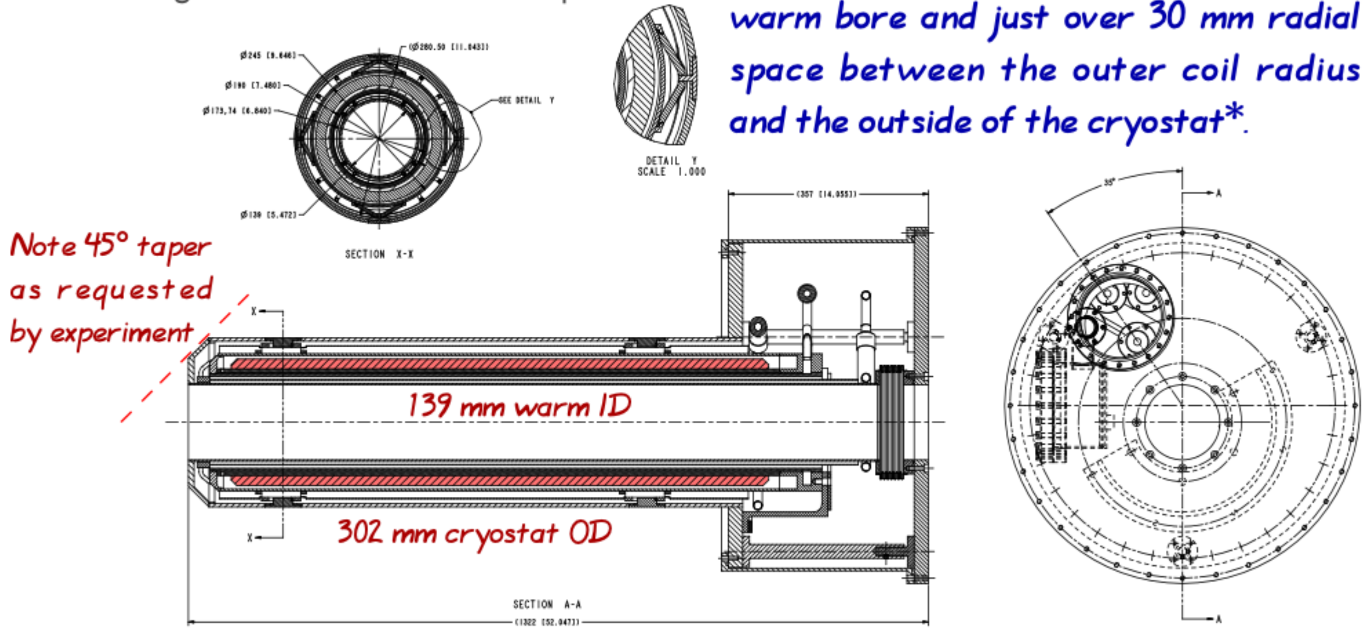
- For HERA-II IR magnet production we applied BNL ultrasonic coil winding technology to fix the super-conductor directly to a support tube.
- Fiberglass wrap provides prestress yielding a very compact coil structure with no external collars.

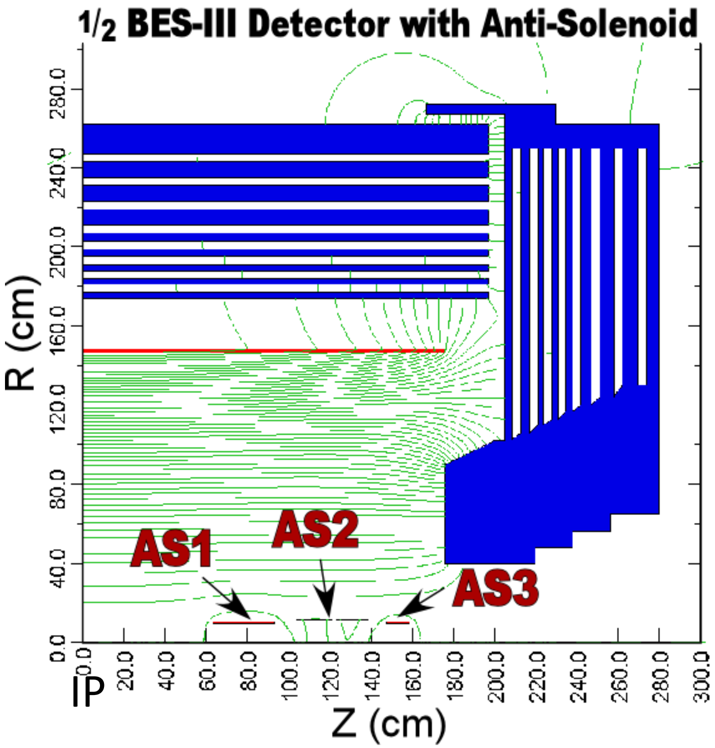
- SS-keys in G10 slots centered cold mass in cryostat with compact size but cold spots (i.e. heat load).
- Dipole coil in solenoidal field generates torque; this caused magnet center to move during ramp.

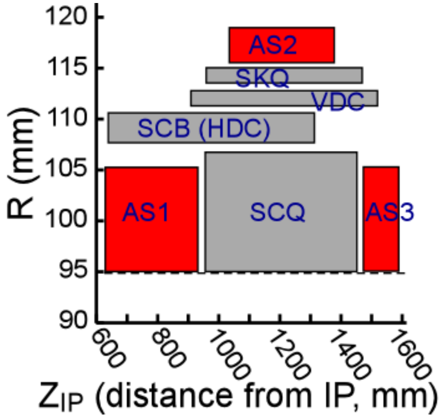
HERA-II / BEPC-II IR Magnets and MDI: Designs

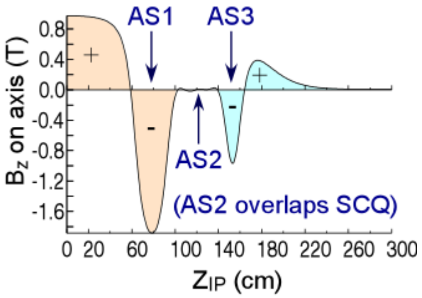
Unlike HERA-II, the BEPC-II magnets have inner/outer gas cooled heat shields plus LHe cooling on both sides of the coil pack.

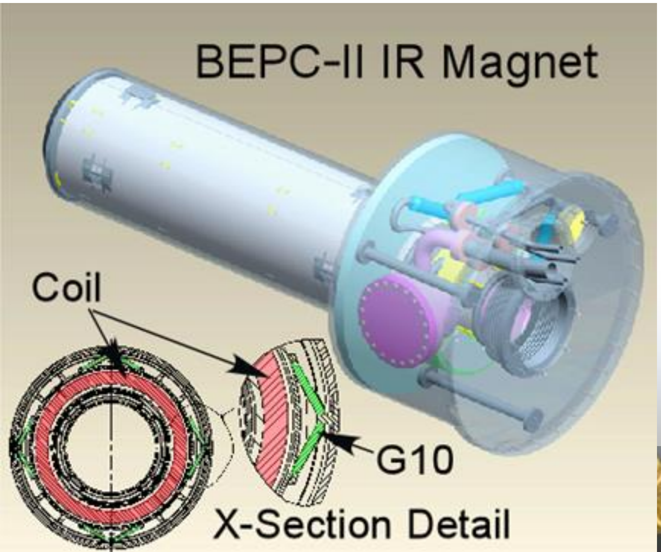
For BEPC-II we have just over 25 mm radial space between the inner coil and warm bore and just over 30 mm radial space between the outer coil radius and the outside of the cryostat.*









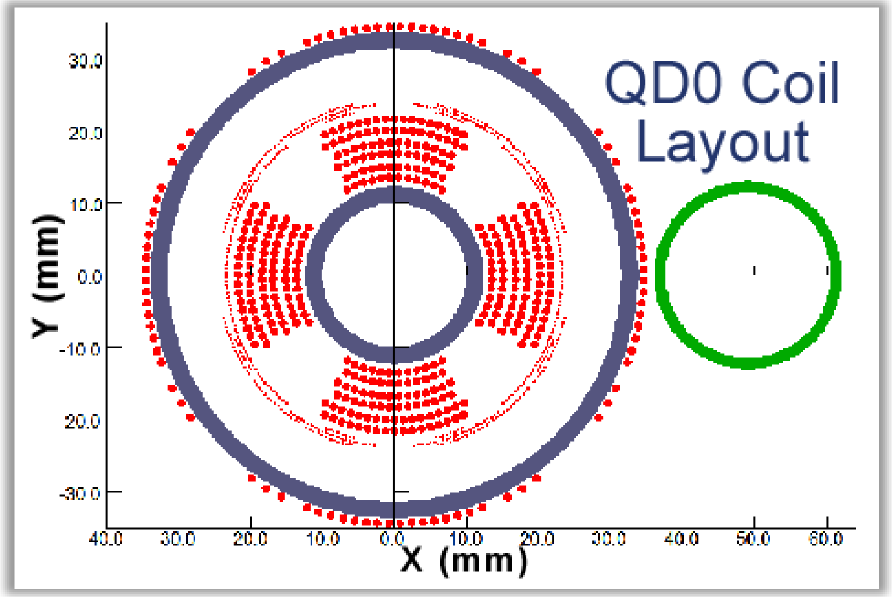


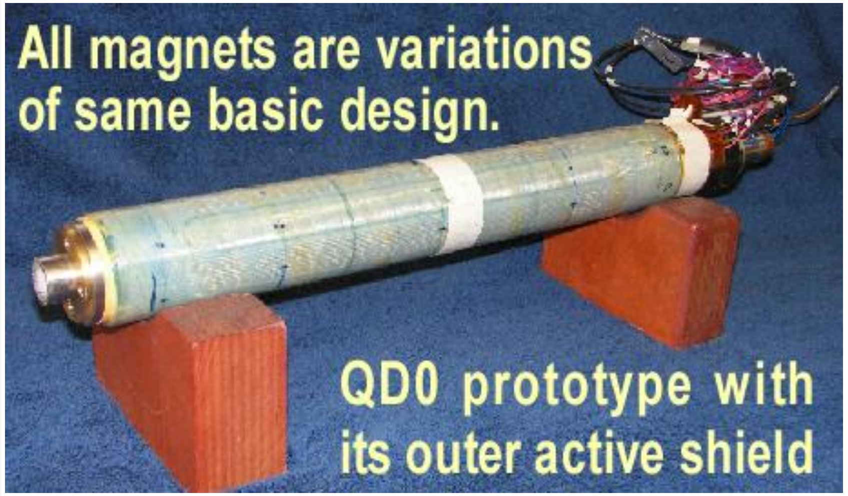
- For BEPC-II we invented Serpentine winding scheme (production efficiency/other benefits).
- Add heat shield / lower heat leak (green field).
- Add local (e.g. SCQ)/integral anti-solenoid coil.
- Had to deal with axial force from anti-solenoid and torques from HDC/VDC dipole correctors.

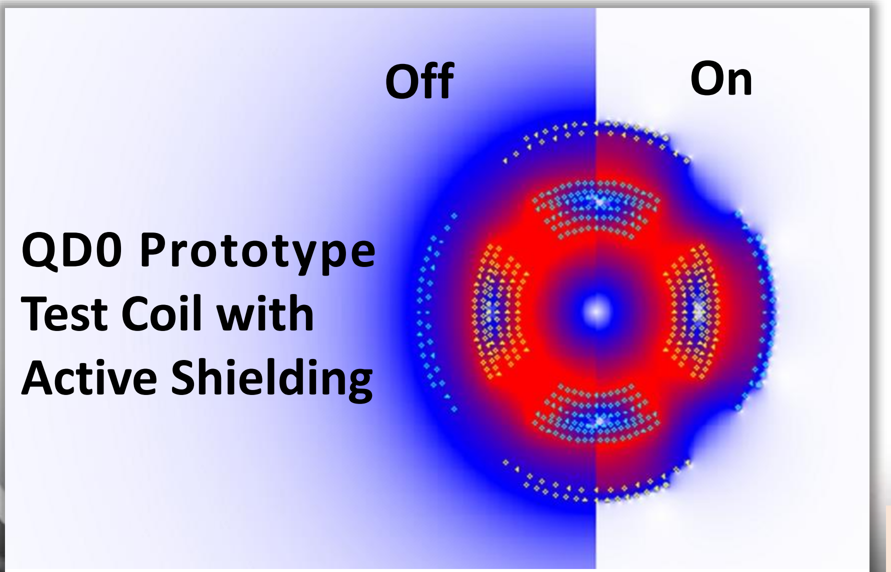
HERA-II / BEPC-II IR Magnets and MDI: Lessons

- 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.

ILC Final Focus Magnets and MDI: Designs





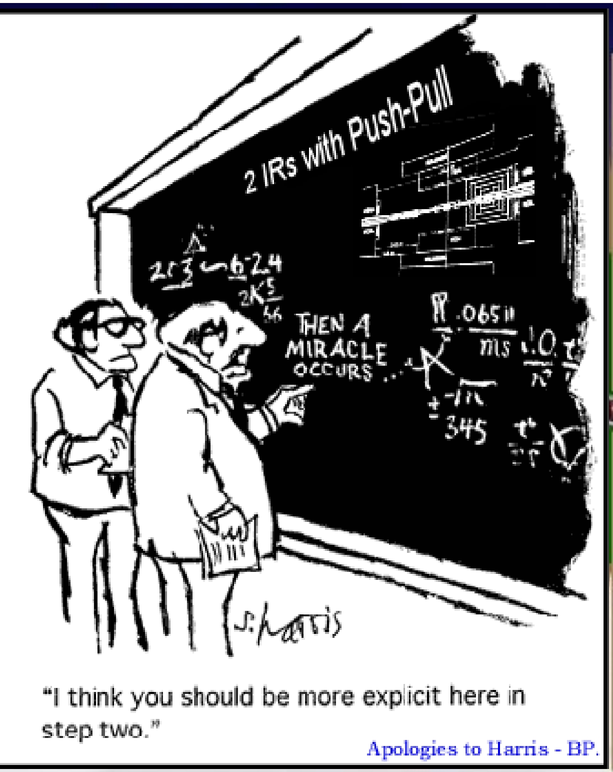


QD0 with Active Shield Off/On

- 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 too overlapping fields†).

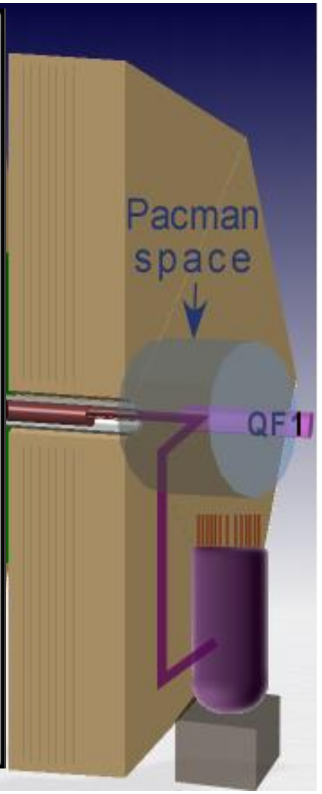
†Y. Nosochkov and A. Seryi, "Compensation of Detector Solenoid Effects on the Beam Size in a Linear Collider," Physical Review Special Topics - Accelerators and Beams, **DOI: 8. 10.2172/829740**.

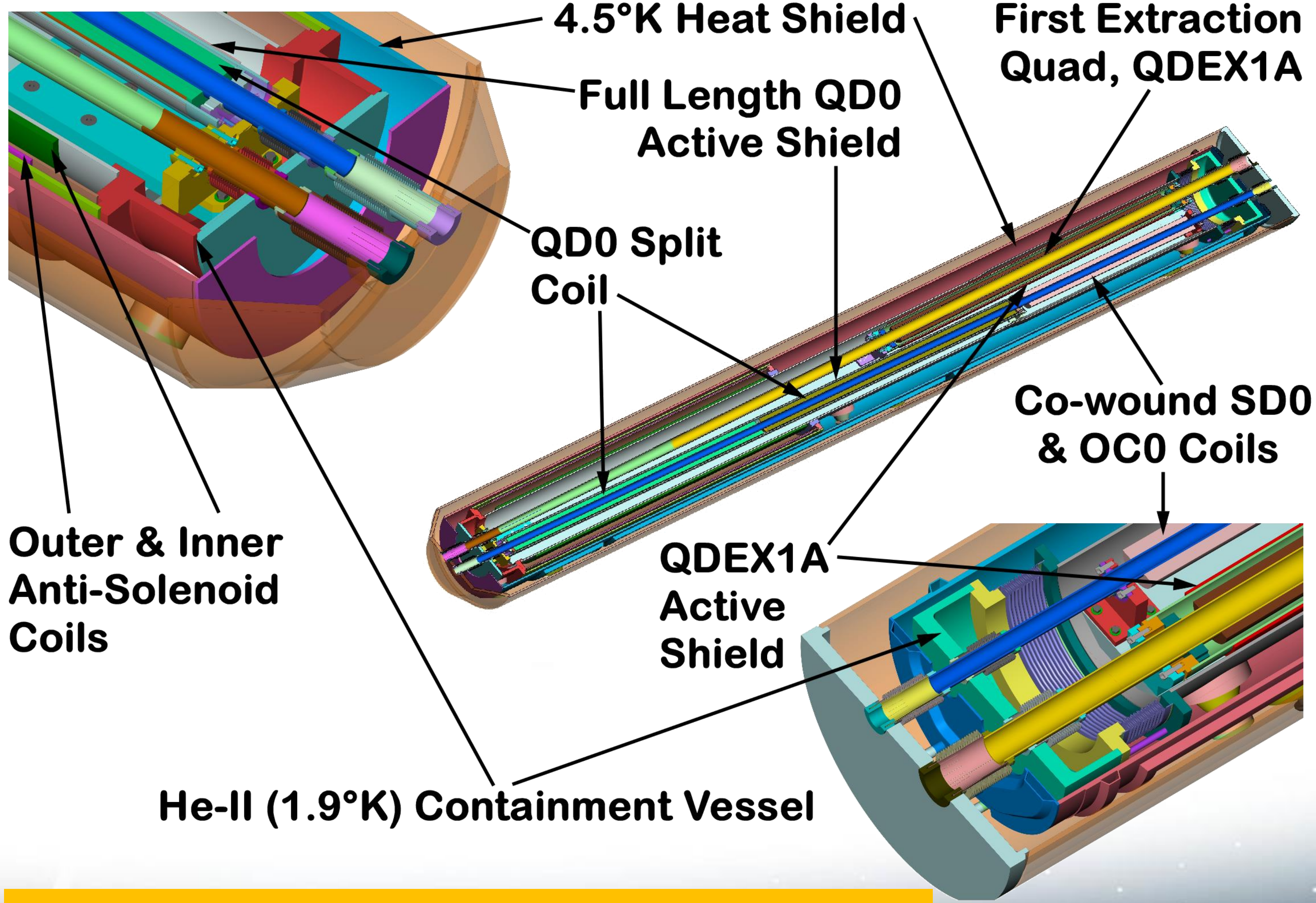
ILC Final Focus Magnets and MDI: Designs

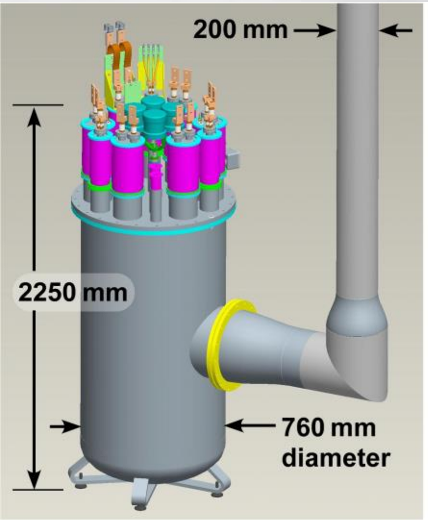


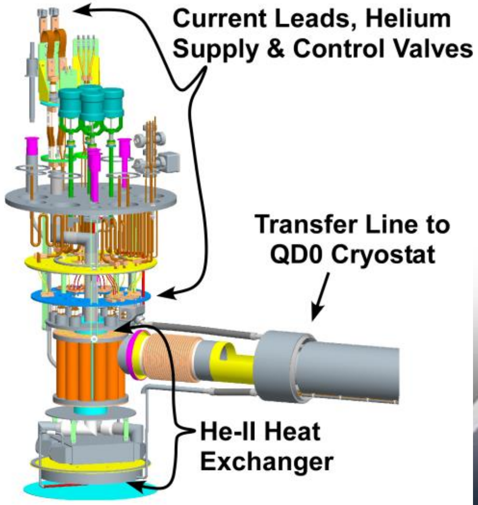
"I think you should be more explicit here in step two."

Apologies to Harris - BP.





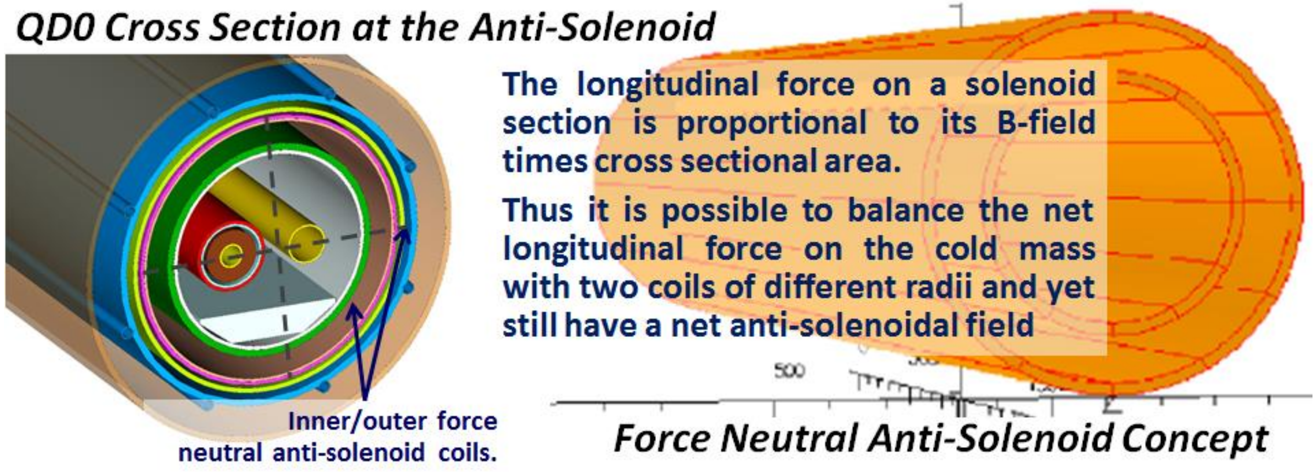


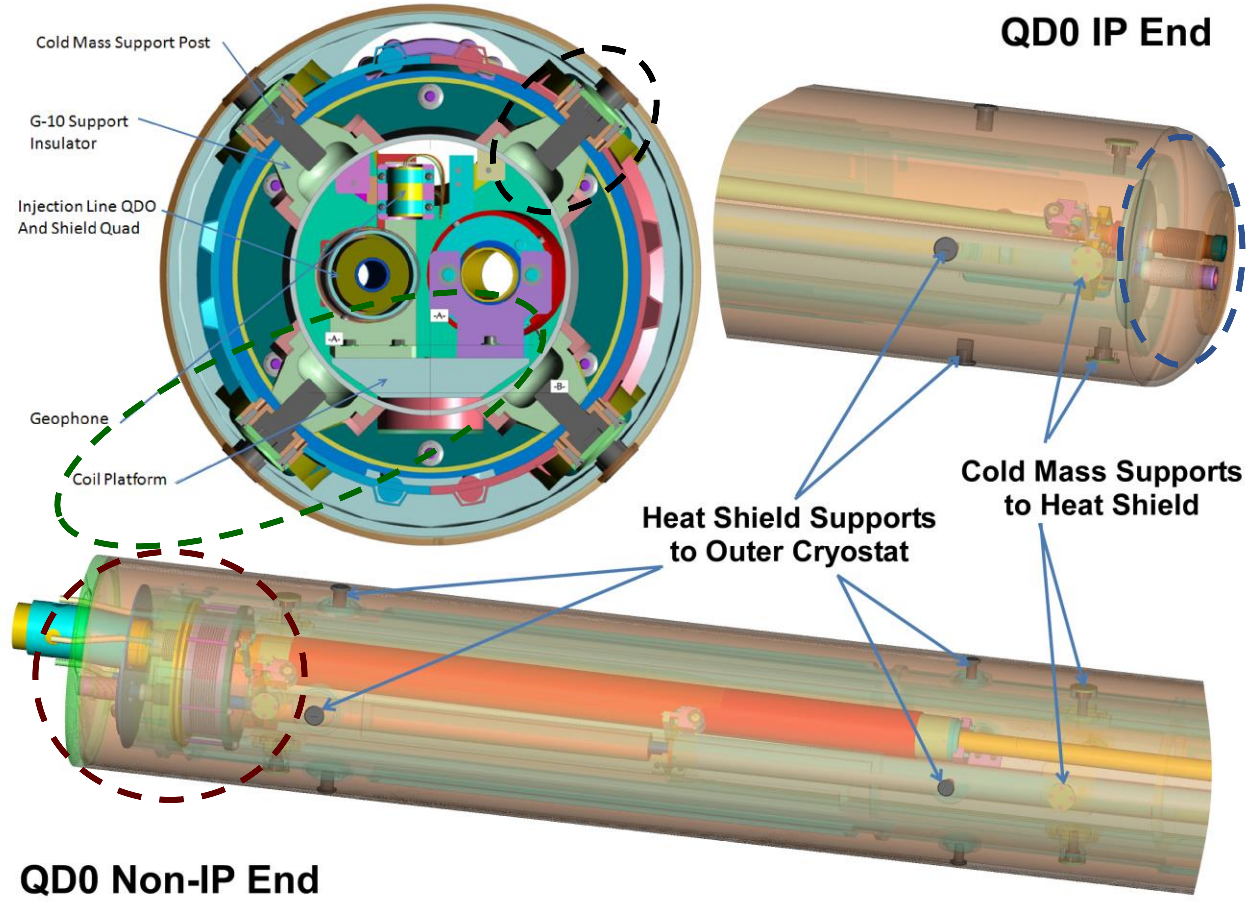


We use 1.9 K pressurized superfluid helium cooling in order not to have "flowing cryogens" (avoid vibrations).

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.

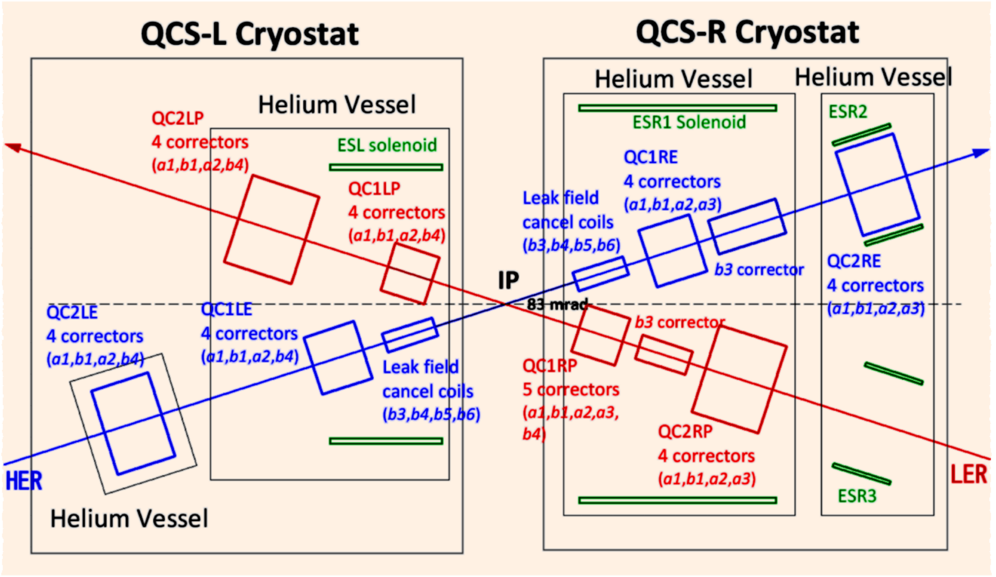
ILC Final Focus Magnets and MDI: Lessons

- 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

SuperKEKB IR Corrector & Cancel Coil Overview

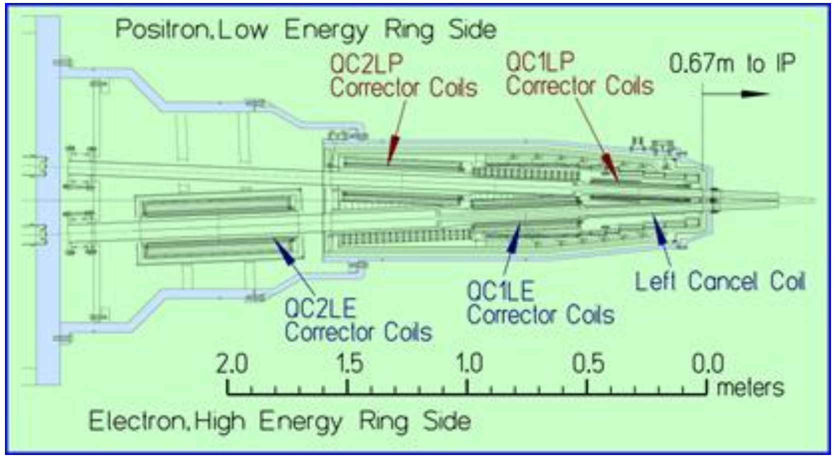
- For a 40-fold b-factory luminosity increase, the current SuperKEKB upgrade at KEK uses nanobeam optics that requires production of new superconducting IR quadrupoles.
- 35 correction coils and 8 cancel coils are integrated inside/outside and before/between main quadrupoles to precisely control IR magnetic fields and ensure good beam lifetime.
- We use BNL Direct Wind to make these coils in order to satisfy demanding production requirements that go well beyond specifications typical for corrector magnets.



- Large 83 mrad total crossing angle permits High Energy Ring (**HER**) **Electron** and Low Energy Ring (**LER**) **Positron** separation in independent warm beam pipes.
- Magnets are in Left/Right cryostats thrust deep into upgraded Belle-II experiment in a **combined detector and compensation coil solenoidal field**.
- Except for the closest in **QC1PL/R** magnets, the IR quadrupoles have magnetic yokes.
- **QC1P** external field would perturb **HER** optics if not dealt with via **"cancel coils."**
- Correctors come in wide range of apertures, multipolarities, lengths and field strengths.

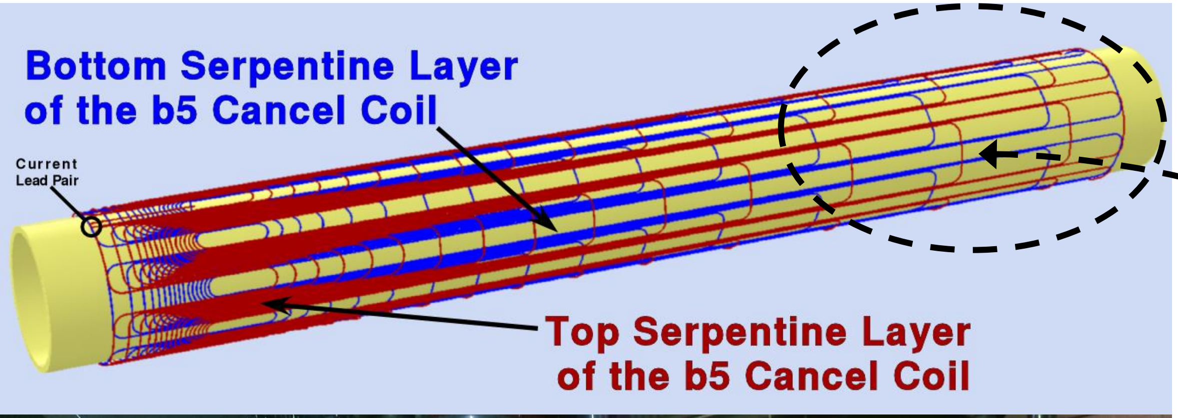
Table 1. Required Field Strengths.

Magnet	R_r mm	A_1 T•m	B_1 T•m	A_2 T	A_3 T/m	B_3 T/m	B_4 T/m^2
QC1RP	10	0.016	0.016	0.64	7.6	17.2	60
QC2RP	30	0.03	0.03	0.31	1.36		-
QC1RE	15	0.027	0.046	0.75	7	27	-
QC2RE	35	0.015	0.015	0.37	1.5		-
QC1LP	10	0.016	0.016	0.64	-	-	60
QC2LP	30	0.03	0.03	0.31	-	-	60
QC1LE	15	0.027	0.046	0.75	-	-	60
QC2LE	35	0.015	0.015	0.37	-	-	60

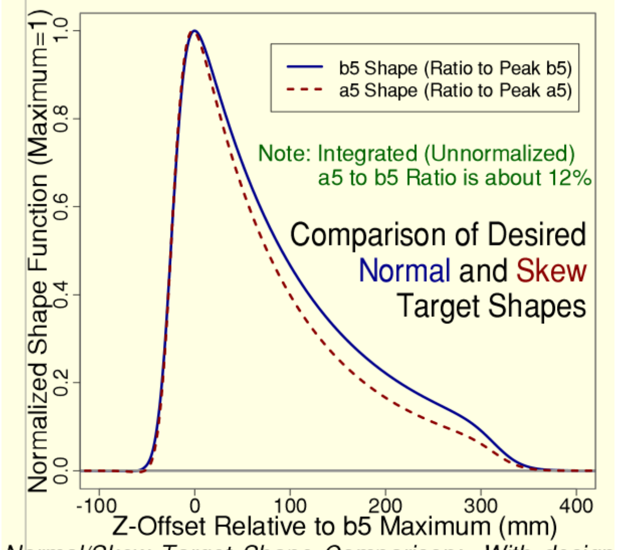


- With 35 correction coils and 8 cancel coils we sometimes hear this referred to as a "complicated system" (criticism implied).
- However there are just enough knobs to allow the operator to adjust each quad's hor/vert center position and roll angle.
- In addition the operator can make non-linear (normal 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.

SuperKEKB IR Correctors and Cancel Coils: Designs



- 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!

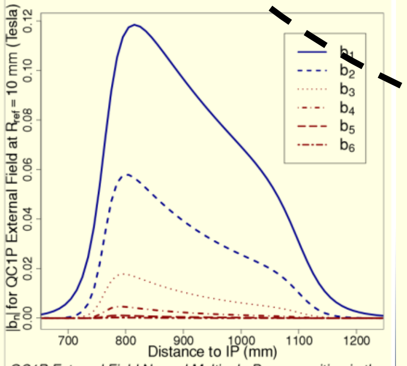


Normal/Skew Target Shape Comparison: With design beam line quad offsets and rotation b5/a5 external field shapes differ so cannot get a5 from b5 via a coil rotation.

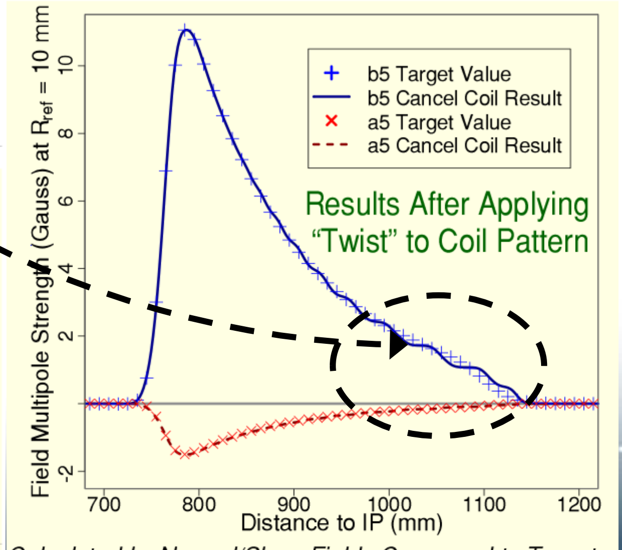
SuperKEKB External Field Cancel Coil Design Motivation

Studies indicate that beam lifetime is sensitive to fairly small magnetic field errors, so our SuperKEKB corrector designs look to keep local magnetic field errors below a few gauss at appropriate reference radii. But the QC1P external field leaking over into the HER aperture greatly exceeds this goal if not deal with via dedicated field cancel coils.

- Dipole and quadrupole (**b_1, b_2**) linear terms are not dangerous and can be incorporated into the optics optimization.
- But non-linear sextupole and higher order terms (**b_3-b_6**) do need to be bucked out.
- Because beam line separation varies with distance from the IP, the cancel coil fields also must vary along the HER beam line.
- Fortunately the cancel coils' external fields fall quite rapidly & do not impact the LER.
- We create cancel coil field profiles from coils that are basically "nothing but ends" and then adjust their end turn spacings.



QC1P External Field Normal Multipole Decomposition in the HER Aperture as a Function of IP Distance for R_{ref} = 10 mm.

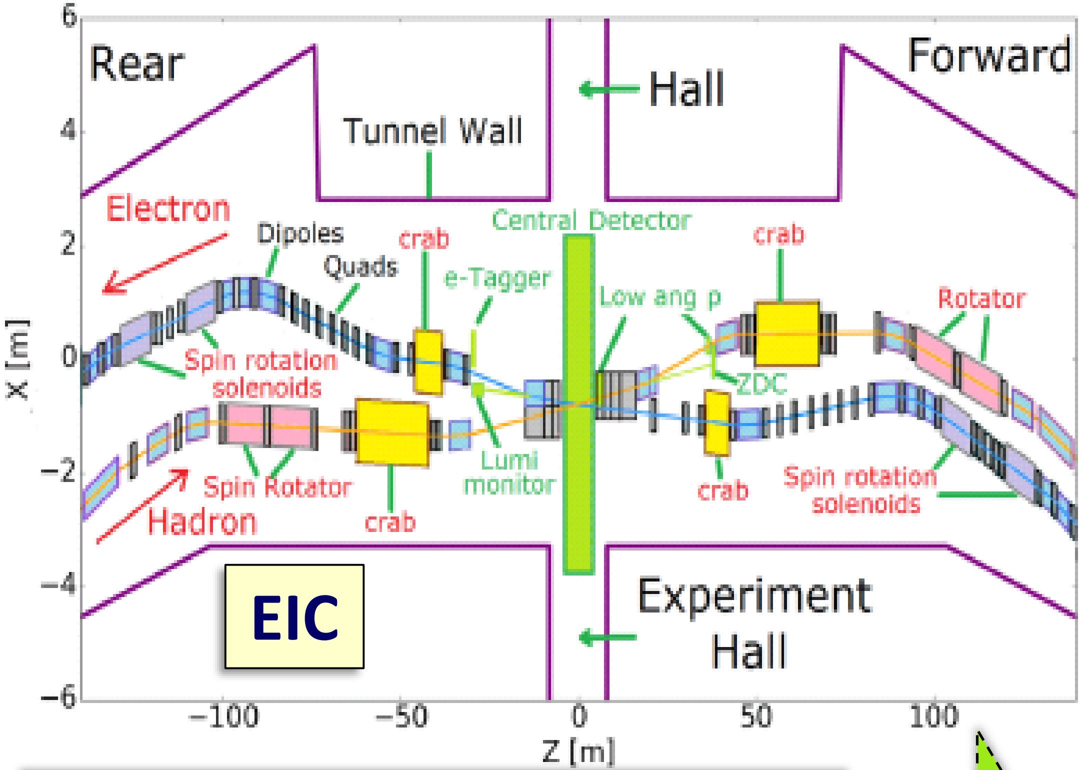


Calculated b5 Normal/Skew Fields Compared to Targets.

SuperKEKB IR Correctors and Cancel Coils: Lessons

- 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.

BNL Electron-Ion Collider IR Magnets: Designs

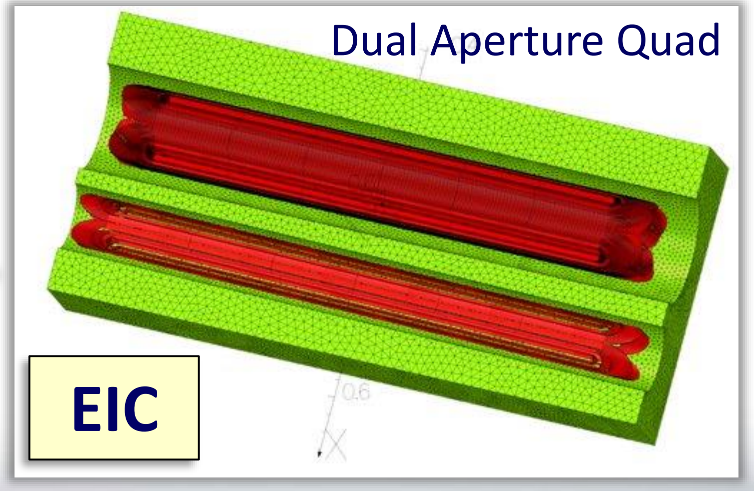


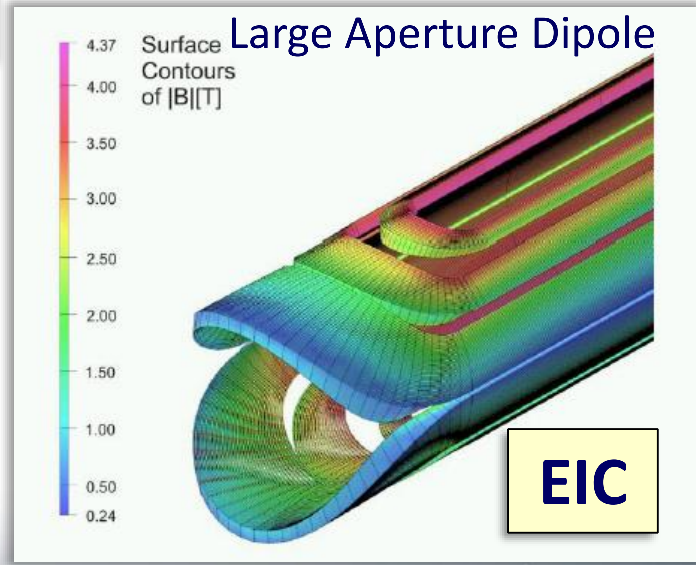
EIC IR designs require production of many new challenging magnets (fortunately NbTi seems to be ok and Nb_3Sn may not be needed).

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!

Dual Aperture Magnets





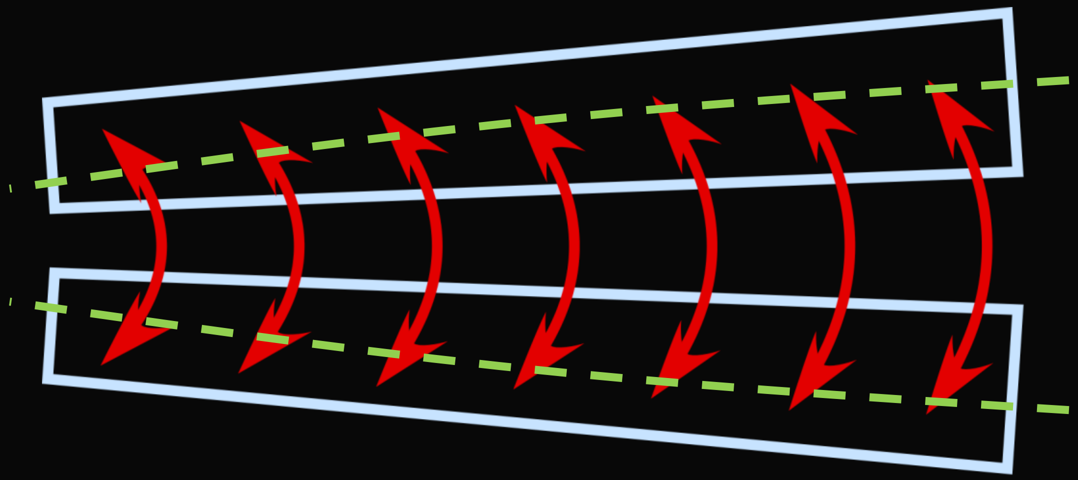
H. Witte, B. Parker, and R. Palmer, “Design of a Tapered Final Focusing Magnet for eRHIC,” IEEE Trans. Appl. Supercond., vol. 29, issue 5, pp. 1-5, Aug. 2019. doi: 10.1109/TASC.2019.2902982.

BNL Electron-Ion Collider IR Magnets: Designs

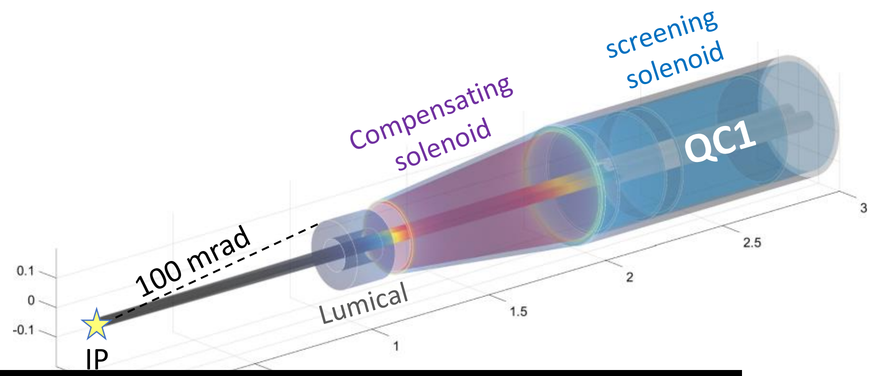
- For the EIC IR design we use tapered coil quadrupoles.
- Thanks to design flexibility of dual helical coil windings we can modify the local field components so as to keep the local quadrupole gradient constant.
- We are half way in a BNL funded (LDRD) project to wind and test a dual helical tapered 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).

CERN FCC-ee IR Magnets: Discussion

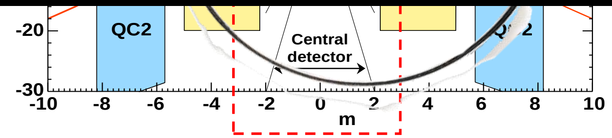
Challenge: Deal with magnetic crosstalk between the QC1 IR quadrupoles.

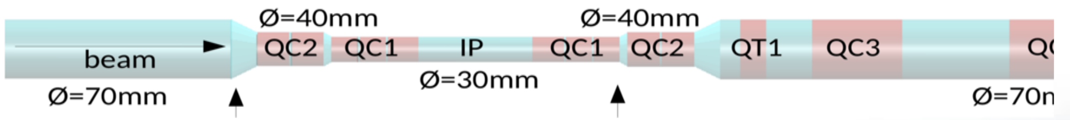


Answer: Use flexible Double Helical coil design to locally adjust QC1 field much like we are doing for the BNL EIC IR.



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]



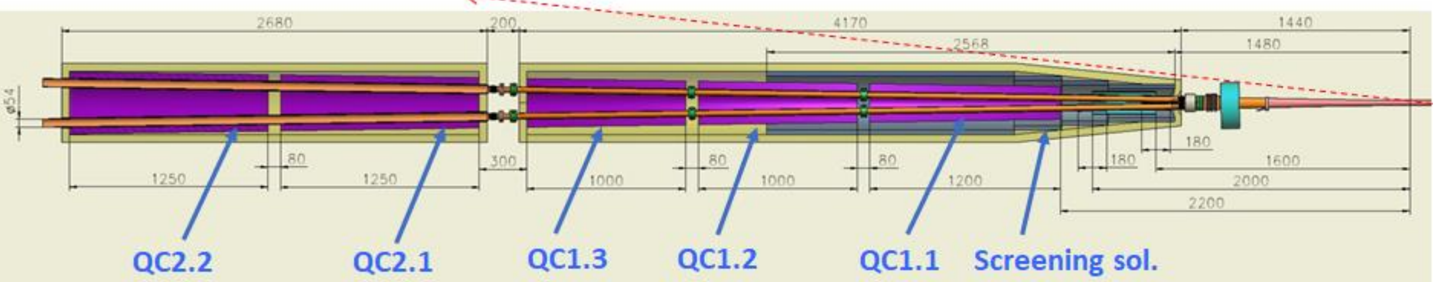


1.5 cm radius z ± 12.5 cm

Smaller central pipe: 1.0 cm for z ± 9 cm (with taper starting at z ± 40 cm from IP)

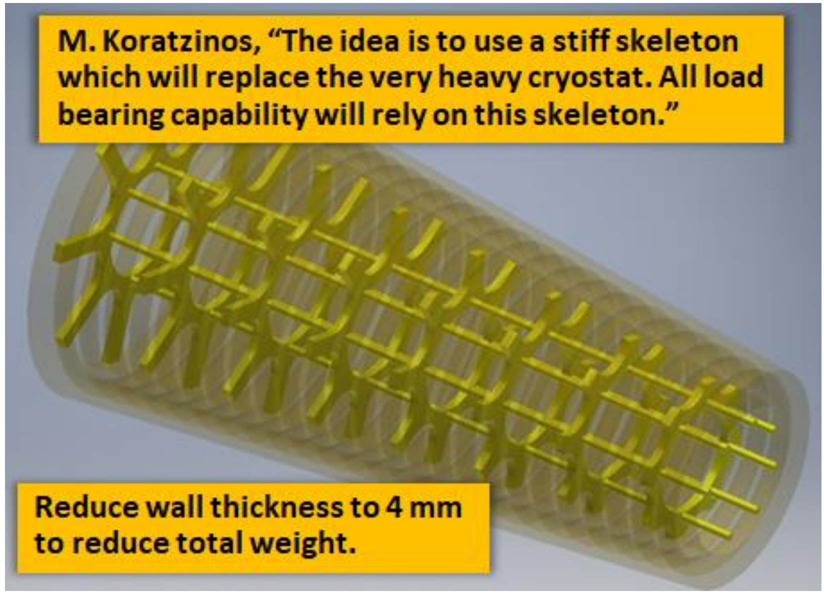
We could use BNL Direct Wind technology to make double helical coils that by design eliminate magnetic cross talk.

CERN FCC-ee IR Magnets: Discussion



An alternative FCC-ee IR magnet design layout that was presented by Anton Bogomyagkov *et.al*. (BINP Group) at 3rd FCC-ee MDI Meeting.

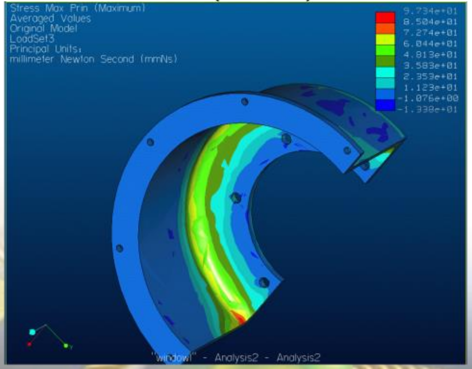
Two IR magnet FCC-ee concepts for a final focus magnet layout.



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?

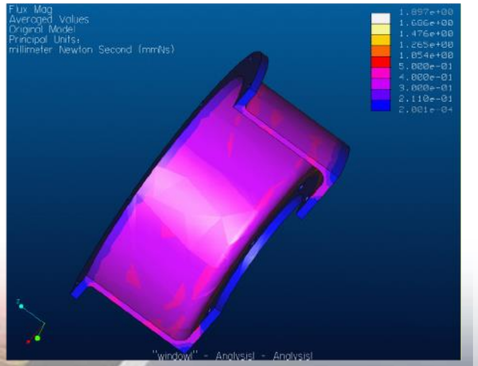
Axial Restraint axial stress (MPa)

- 13KN applied load away from IP
- Max stress = 97MPa



Axial Restraint heat flux (mW/mm)

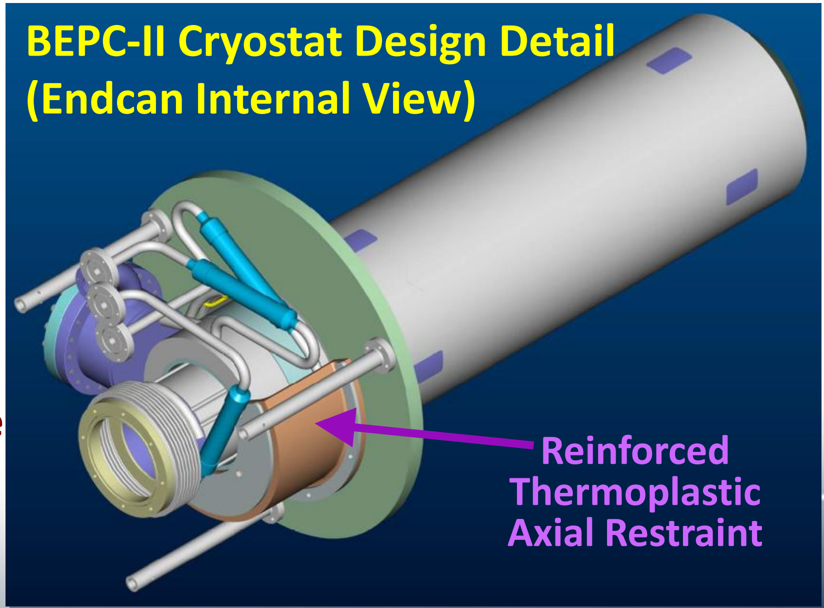
- Ultem 2400 polyetherimide glass reinforced thermoplastic
- k = 0.22 w/m-C
- 300K – 4K heat load
- 1.5 W total heat load



BNL Modeling by Andy Marone for BEPC-II Support Structure.

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)?

BEPC-II Cryostat Design Detail (Endcan Internal View)



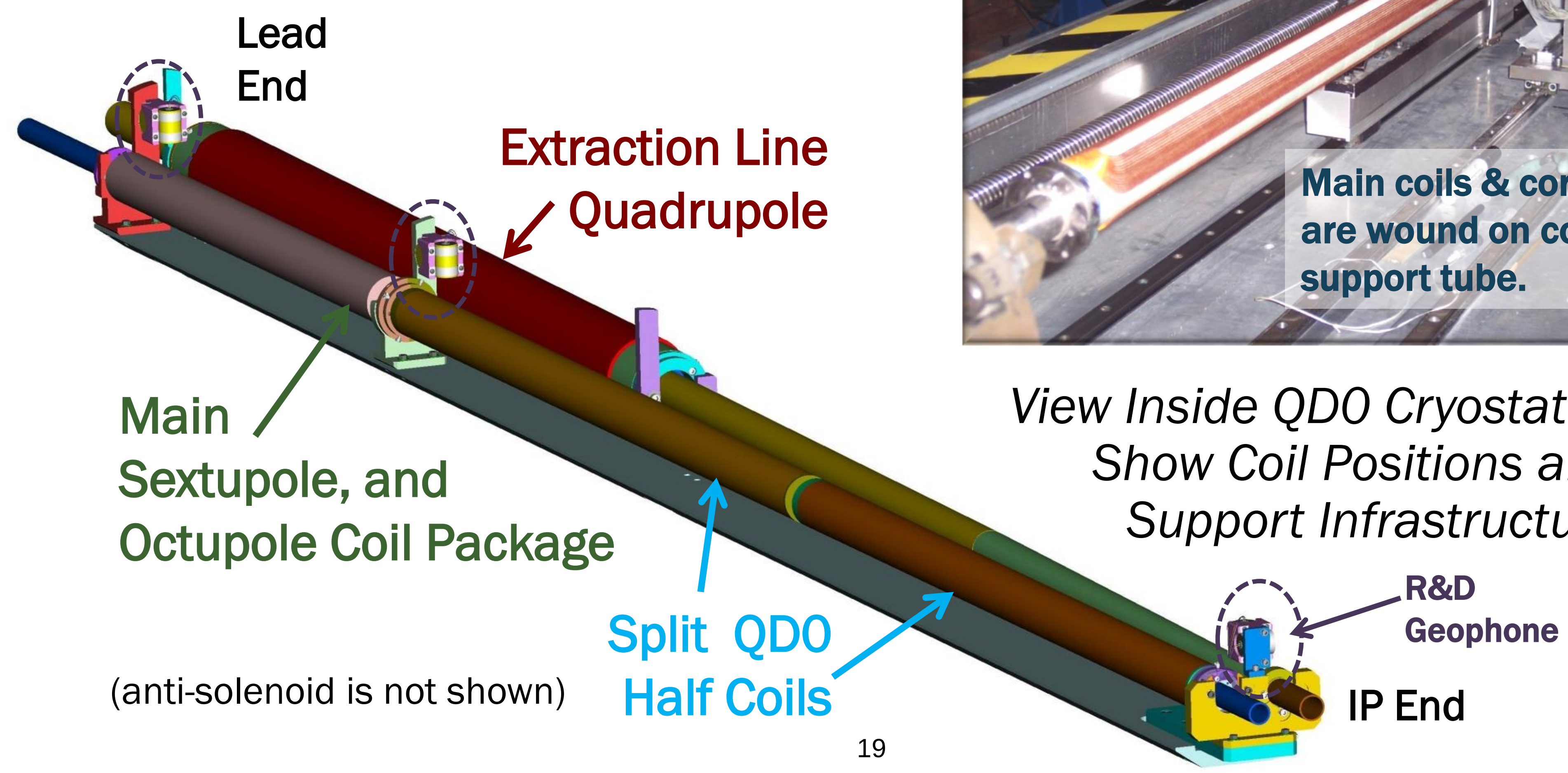
Summary: Superconducting Final Focus Magnets at ILC and Future Colliders

- 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

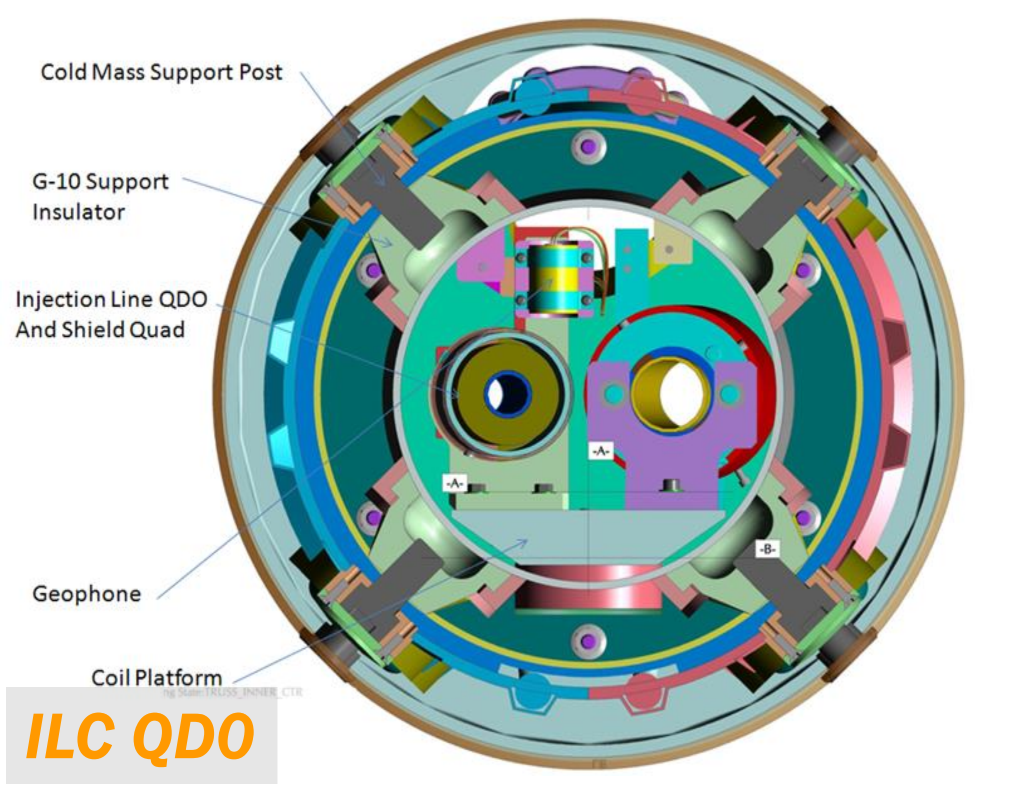
ILC QD0 Magnet Coil Configuration

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.



View Inside QD0 Cryostat to Show Coil Positions and Support Infrastructure

ILC QD0 R&D Magnet Cryostat

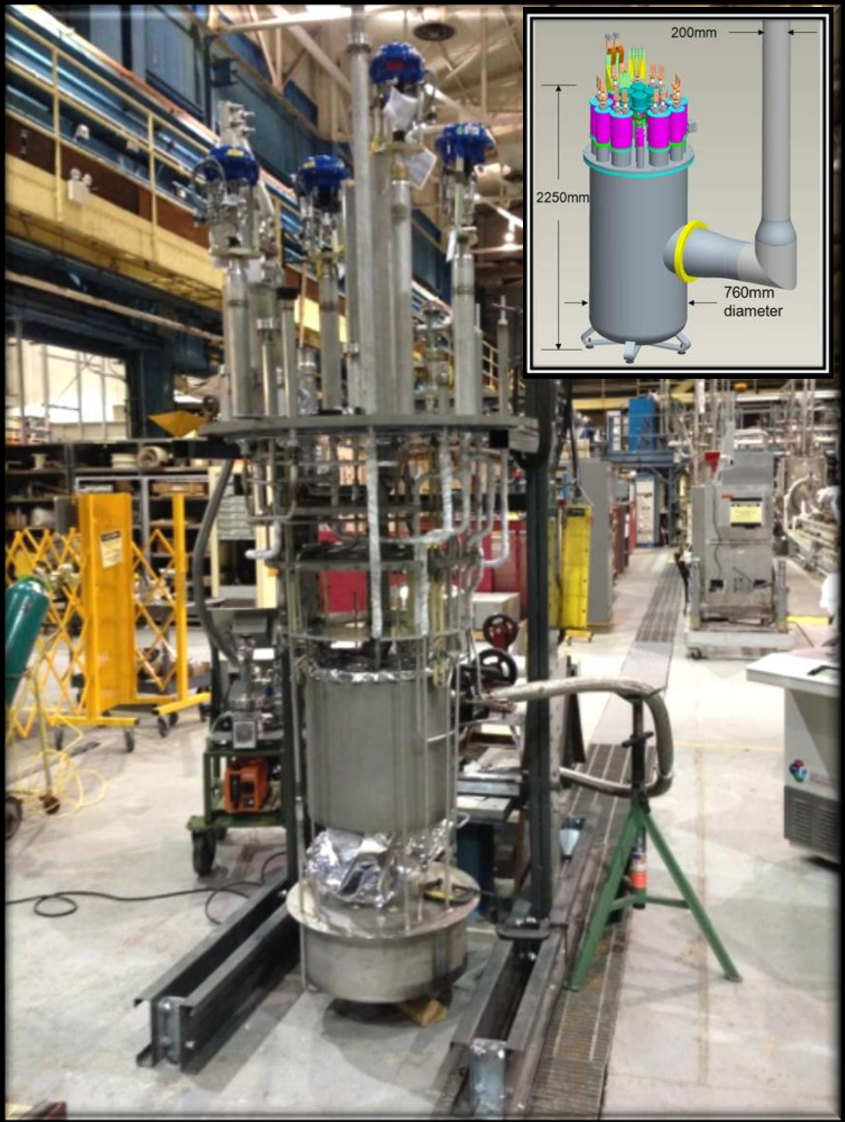


The ILC QD0 R&D magnet prototype cryostat is 90% complete and almost ready for insertion of the magnet coils on the "sled assembly."

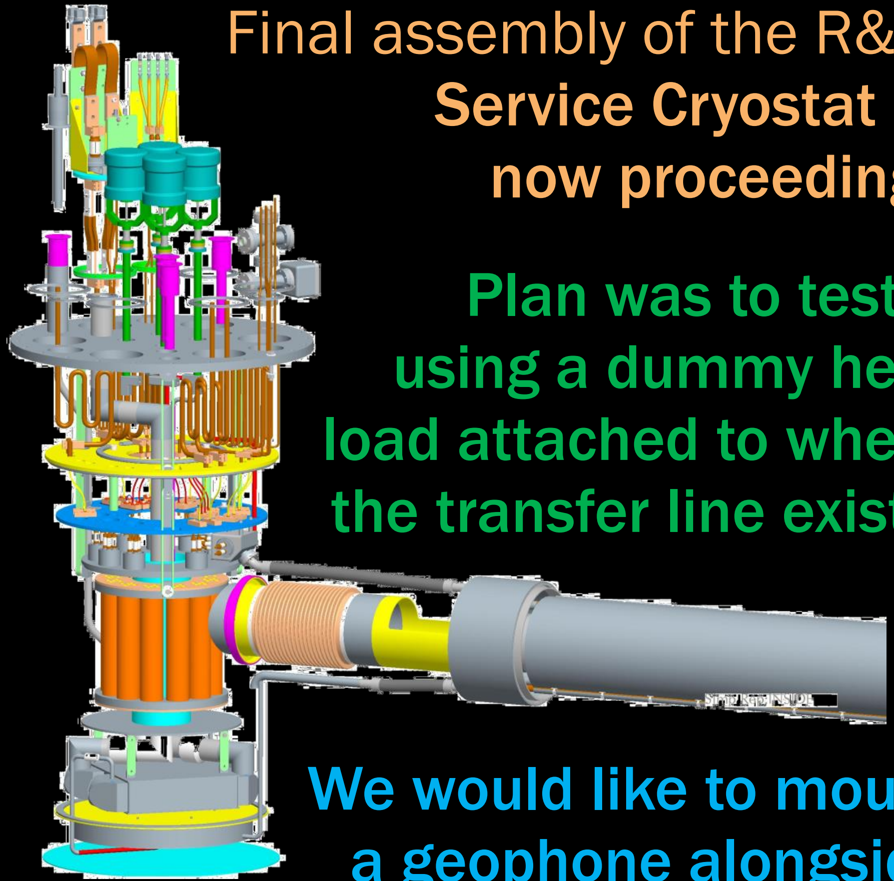
Finishing the Magnet Cryostat was given higher priority than making the transfer line parts.

ILC QDO R&D Magnet Cryostat Assembly

ILC QD0 R&D Service Cryostat



ILC Service Cryostat undergoing final leak testing before assembly with outer vessel.



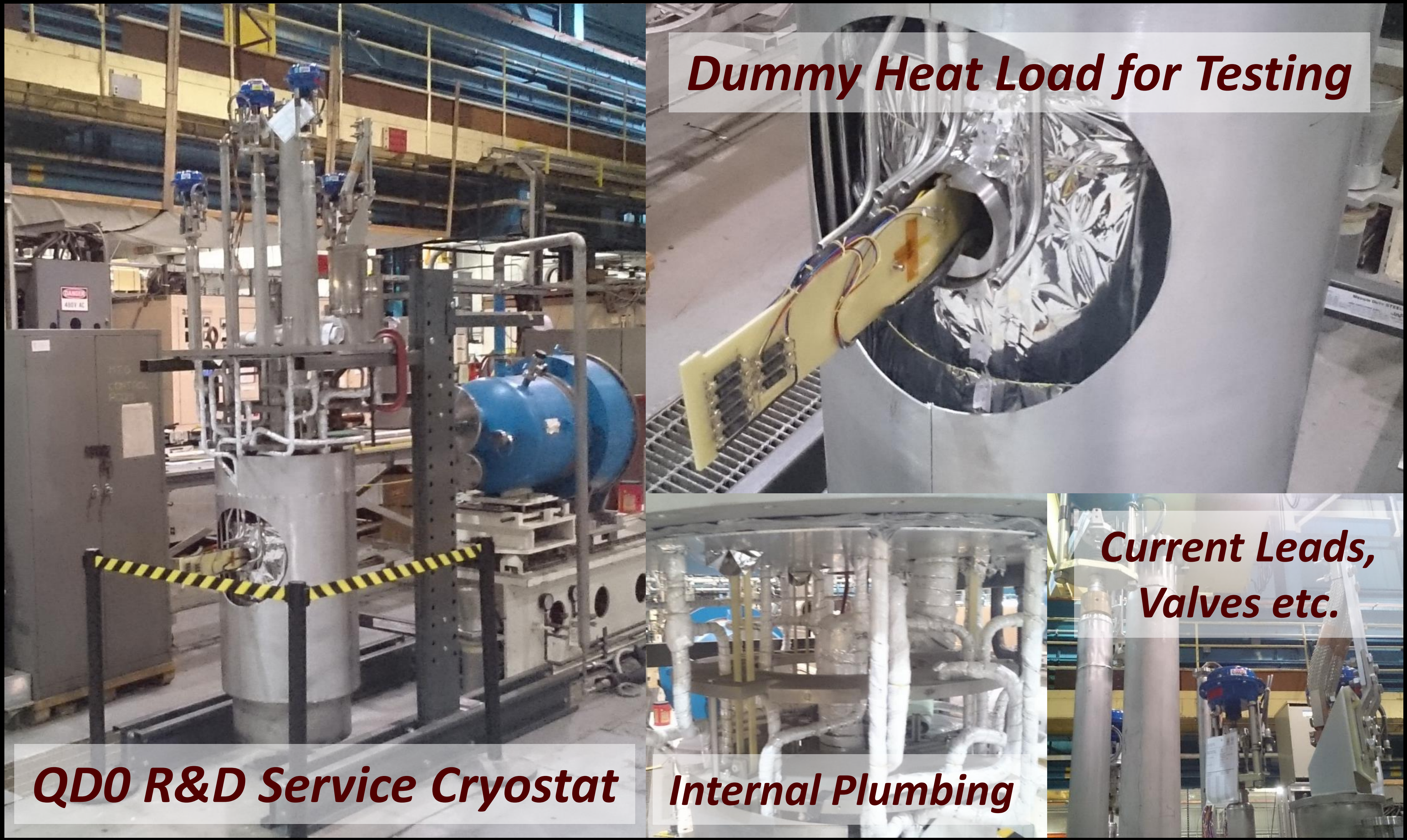
Final assembly of the R&D **Service Cryostat is now proceeding.**

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.