Superconducting Magnet Rings for MEIC

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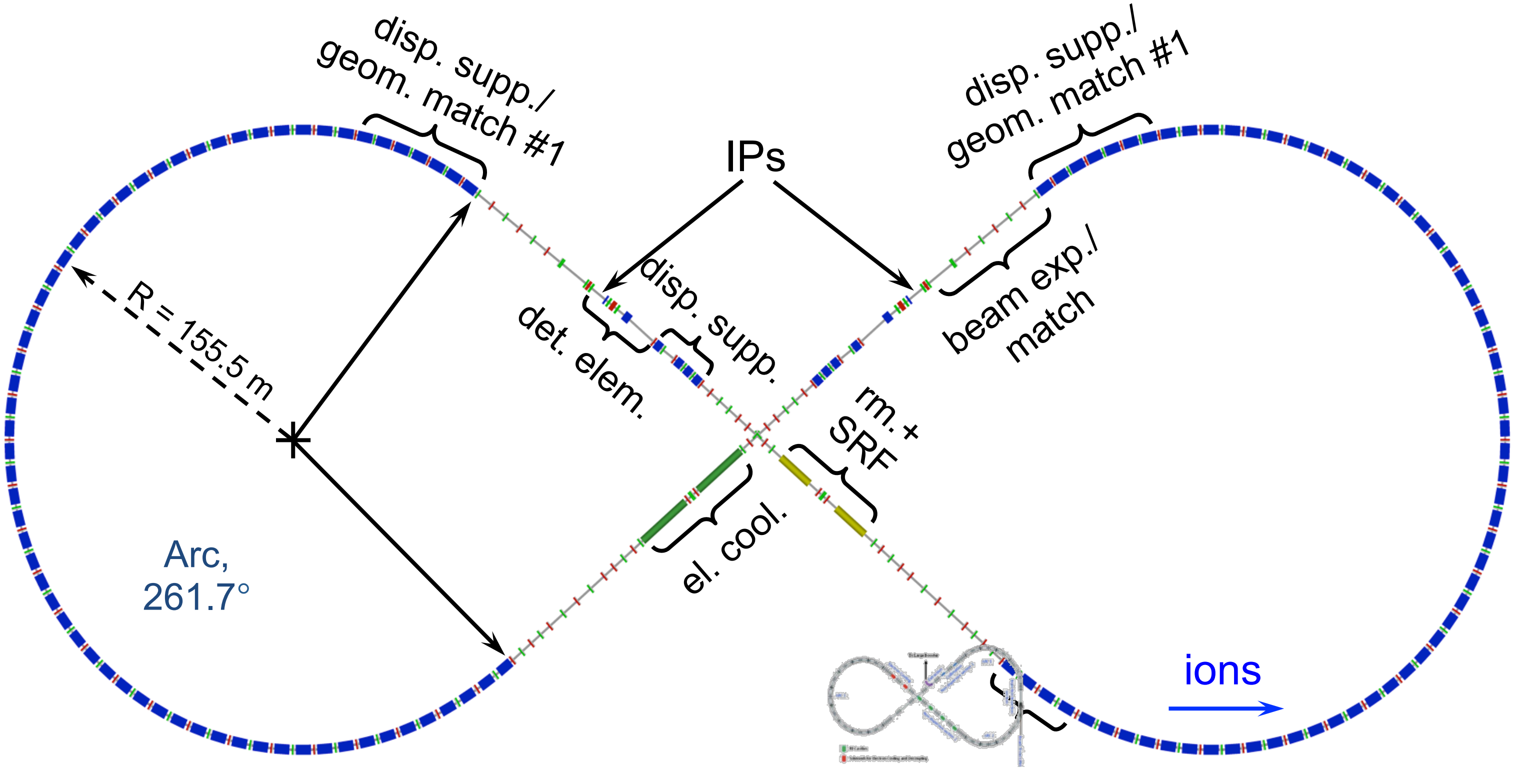


Ion Ring– 128 arc half-cells **Booster – 32 arc half-cells**

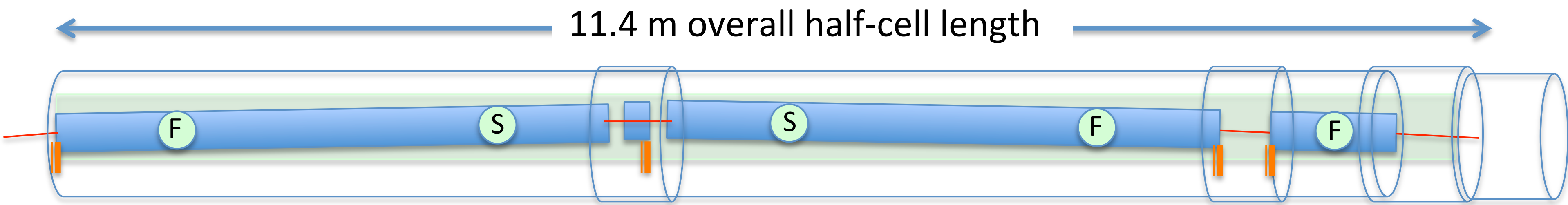
Superferric magnets have been designed for the requirements of arc half-cells:

- Ion Ring: 8-100 GeV protons: 0.25 -- 3 T dipoles, 52 T/m quads
- Booster: 0.2-8 GeV protons: 0.24 – 3 T dipoles, 6 T/m quads

Half-cell cryostat geometry for Ion Ring arcs

Dipole aperture requirement:	betatron amplitude (15 σ) @ injection:	±3 cm
	dispersion of ±0.5% momentum spread:	±1 cm
	sagitta (with 4 m dipole length):	±1.8 cm
		±5 cm
Quad aperture radius requirement:		**4 cm**

Each half-cell contains two 4 m dipoles, one 0.8 m quadrupole, 1 sextupole to correct body sextupole in dipoles (Neuffer):



= leads

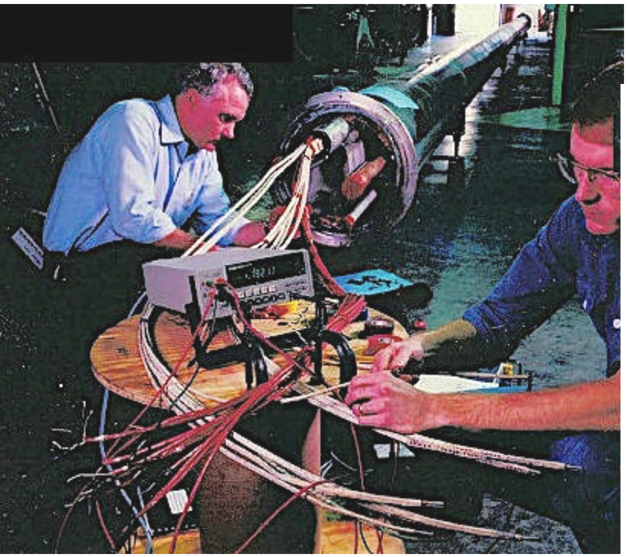
F = fixed anchor to support post

S = sliding anchor to support post

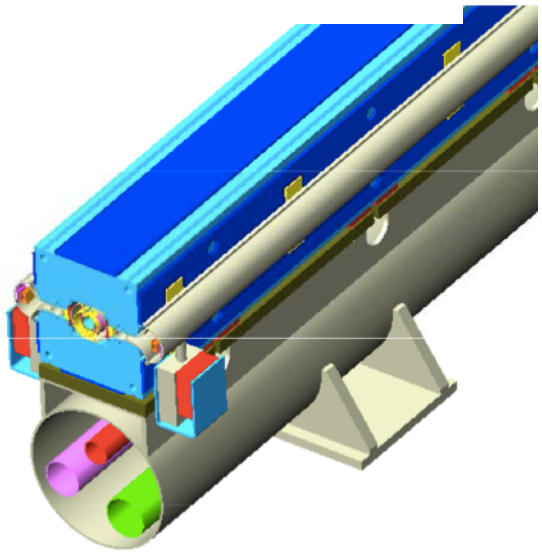
= sliding shroud section of vacuum vessel

Superferric Magnets – Cost Minimum up to ~3 T

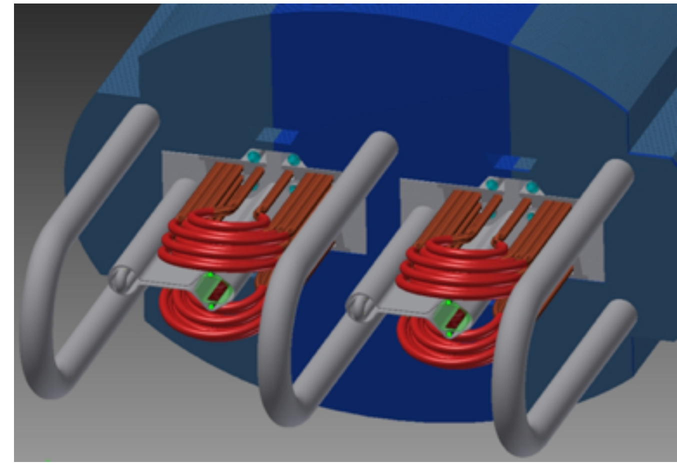
3 T SSC dipole

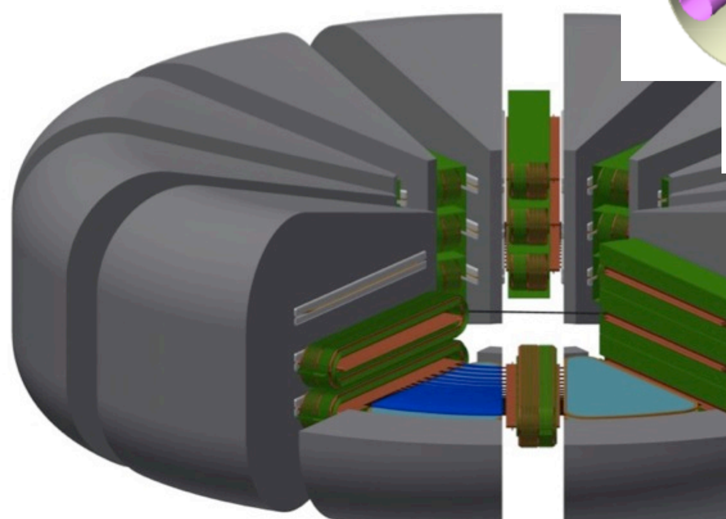


2 T pipe dipole for VLHC



4.5 T for 100 TeV hadron collider

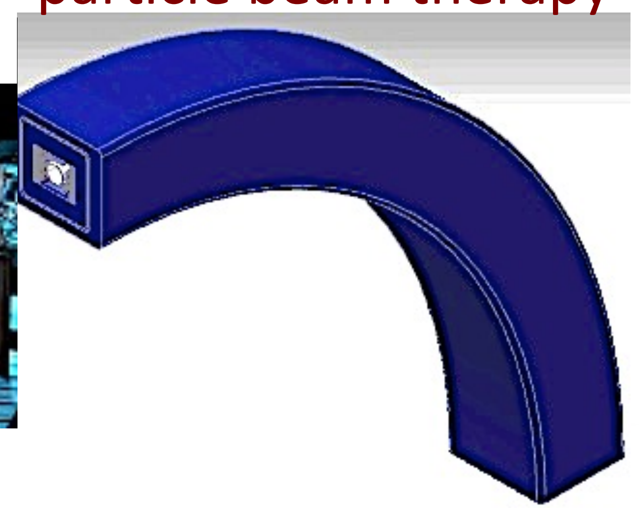




1 T strong-focusing cyclotron

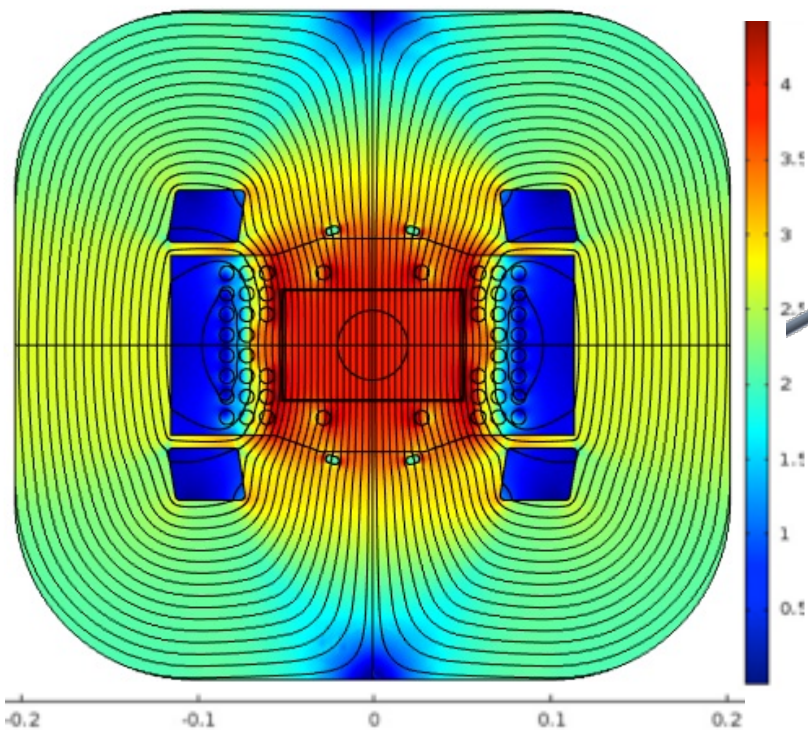
2 T FAIR dipoles

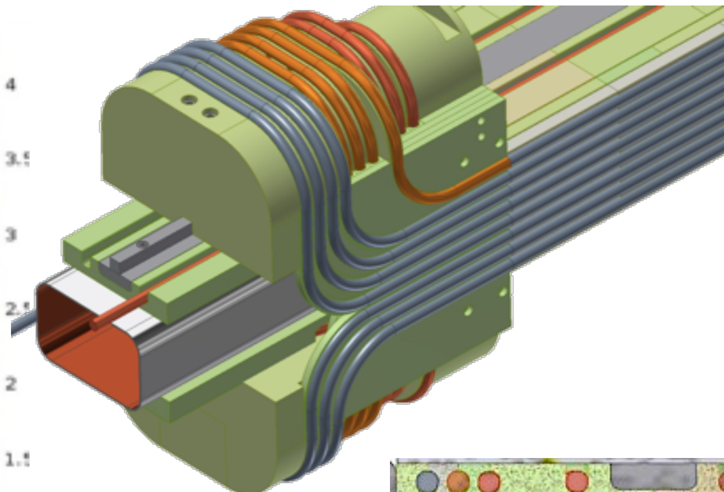
3 T proton gantry for particle beam therapy

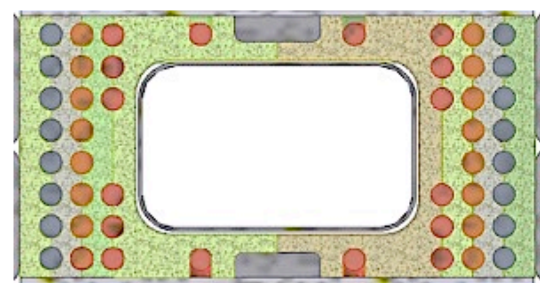


MEIC Arc dipole

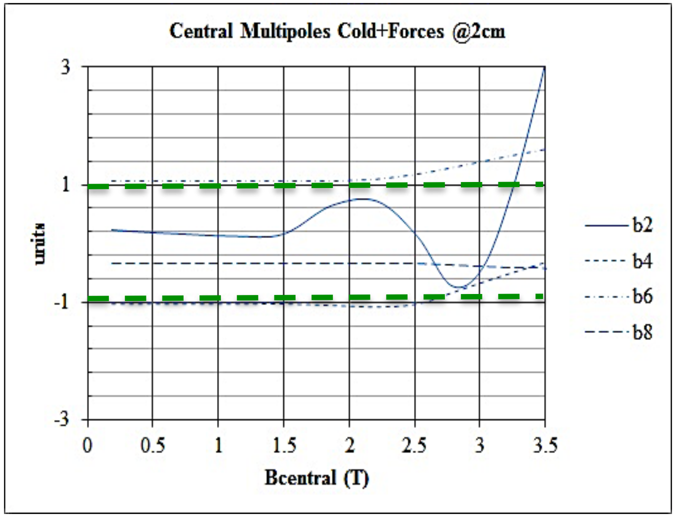
The biggest challenge is to create a 10 cm x 6 cm aperture with the *field quality* needed for high-luminosity collisions with long luminosity lifetime – dynamic aperture

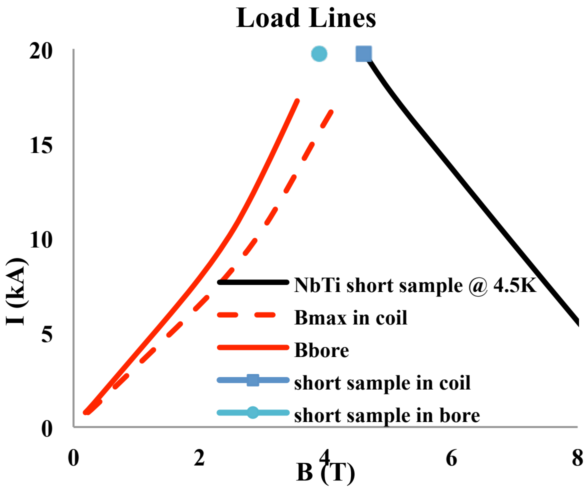






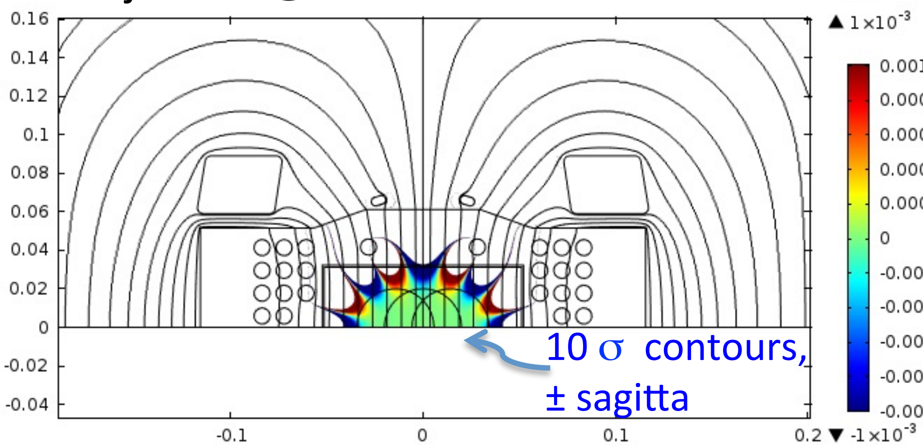
The fields seen by the ion beams…



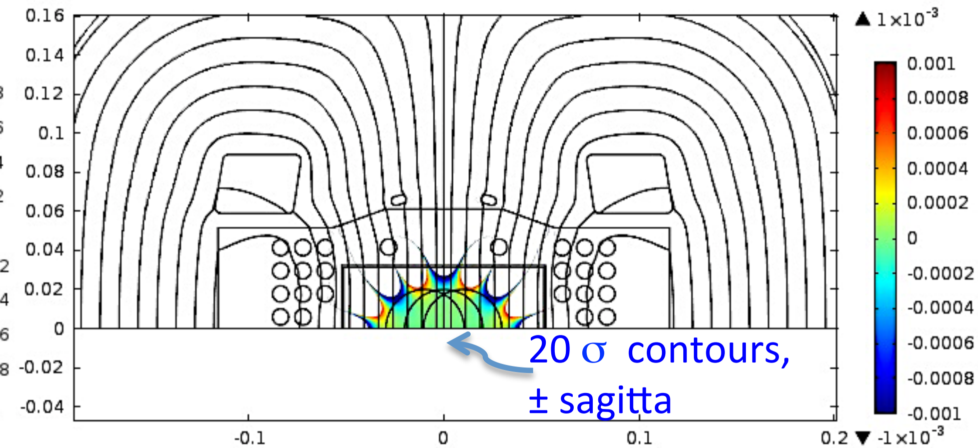


Multipoles vs. field and load lines for MEIC dipole design.

Injection @ 8 GeV

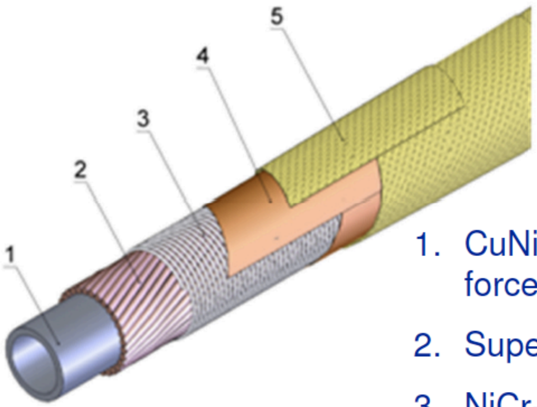


collision @ 100 GeV



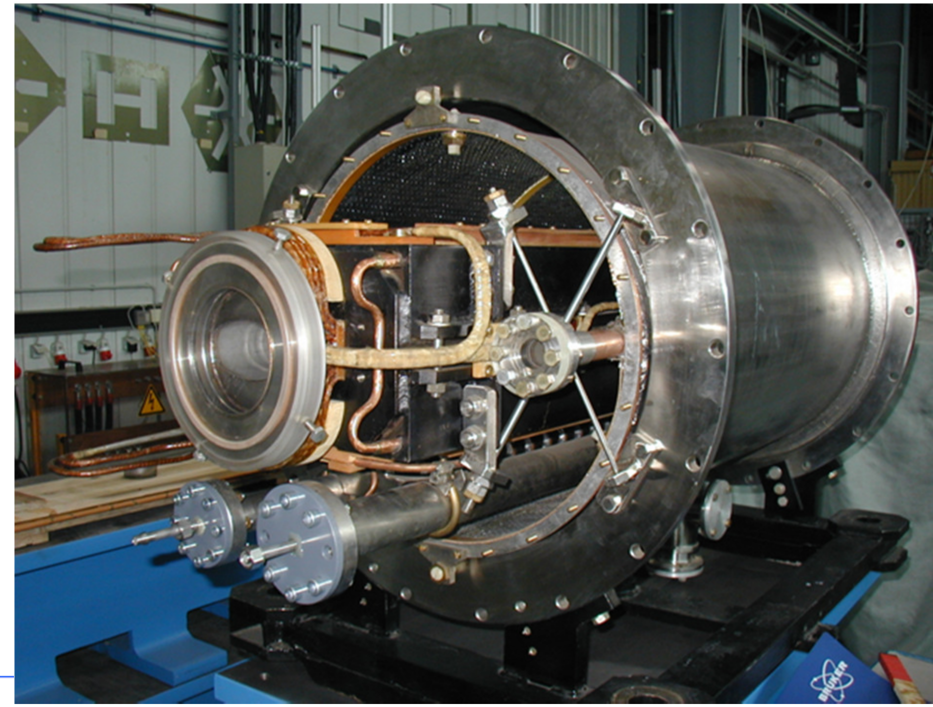
Green is good!

Cable-in-Conduit: Dubna to GSI to MEIC



1. CuNi -Tube cooled by two-phase forced helium flow
2. Superconducting strands
3. NiCr-wire
4. Kapton tape
5. Glassfiber tape

HELMHOLTZ GEMEINSCHAFT GSI FAIR

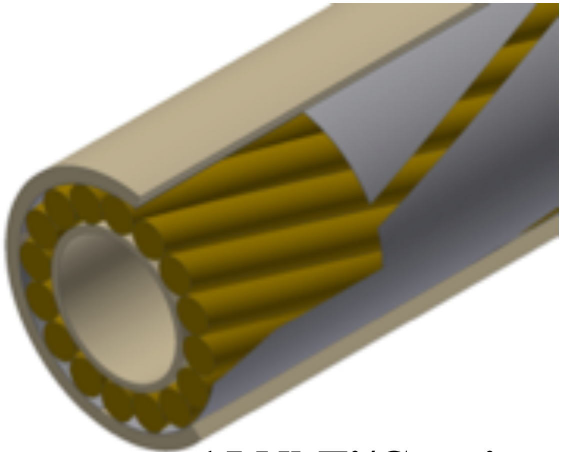


The SIS-100 ring uses superferric dipoles operating at 1.8 T.

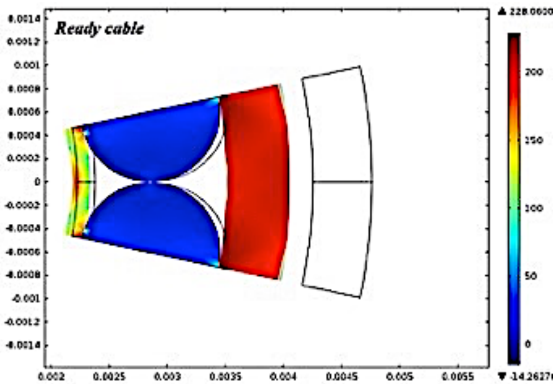
Its conductor is a semi-rigid cable-in-conduit, in which the helium cryogen flows internally so that the magnet is not immersed in liquid helium.

Cable-in-conduit makes a much simpler end geometry for a large-bore dipole. The windings can be supported in a reinforced polymer structure, with tight precision.

We follow the Dubna/GSI CIC strategy with a few improvements for higher-field operation

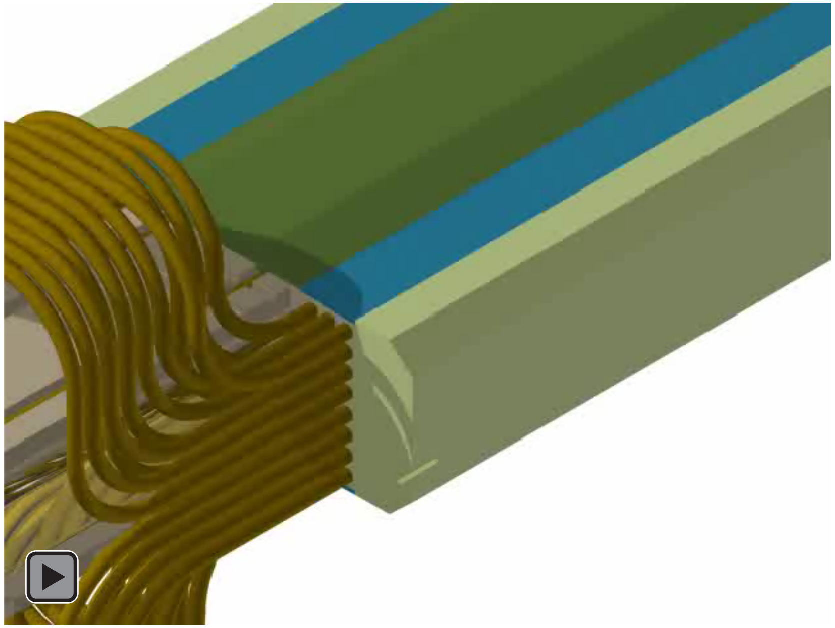


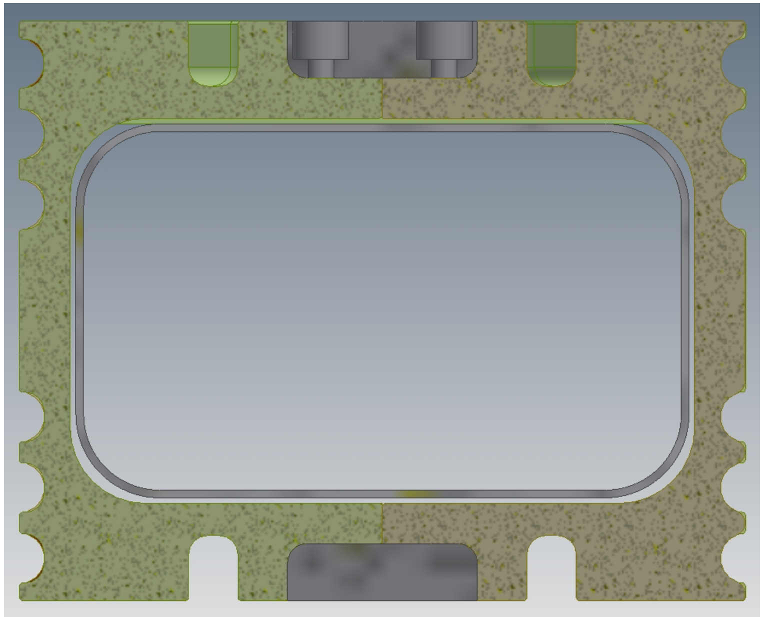
15 NbTi/Cu wires are cabled onto a perforated spring tube.

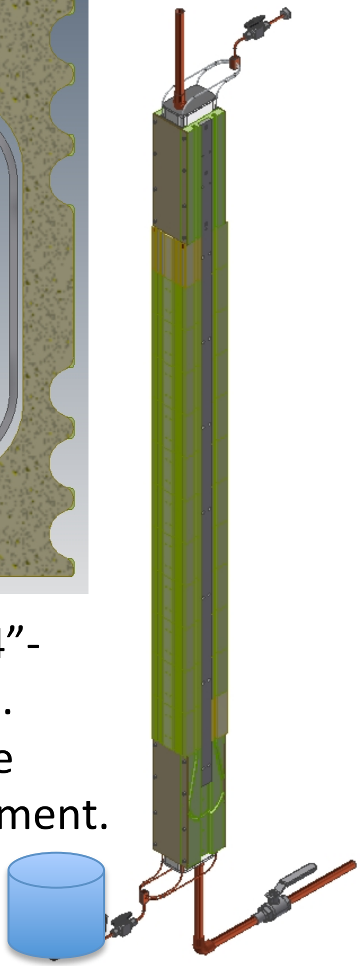


The cable is inserted in a sheath tube, and the sheath is drawn onto the cable to just compress the wires against the spring tube.

Superferric Dipoles: How we build them





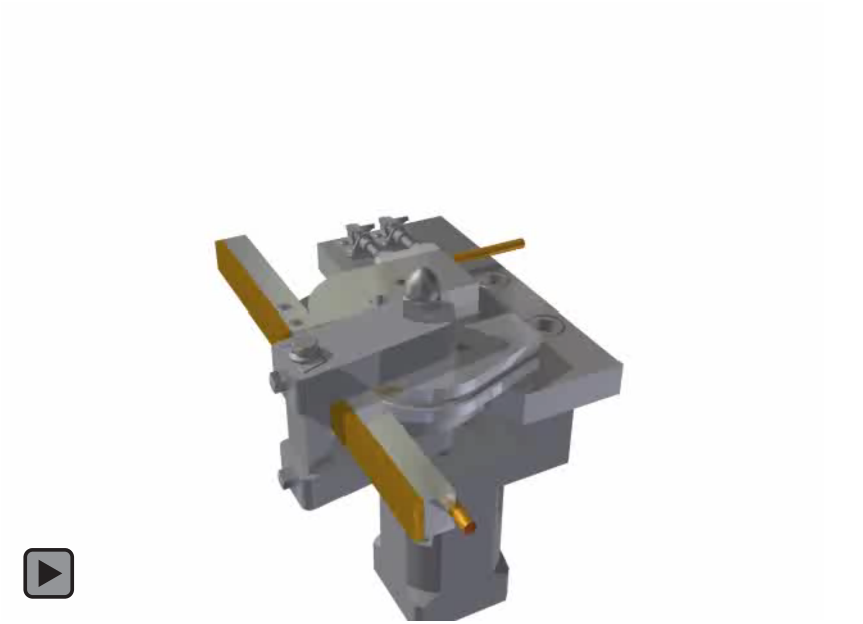


Strategy:

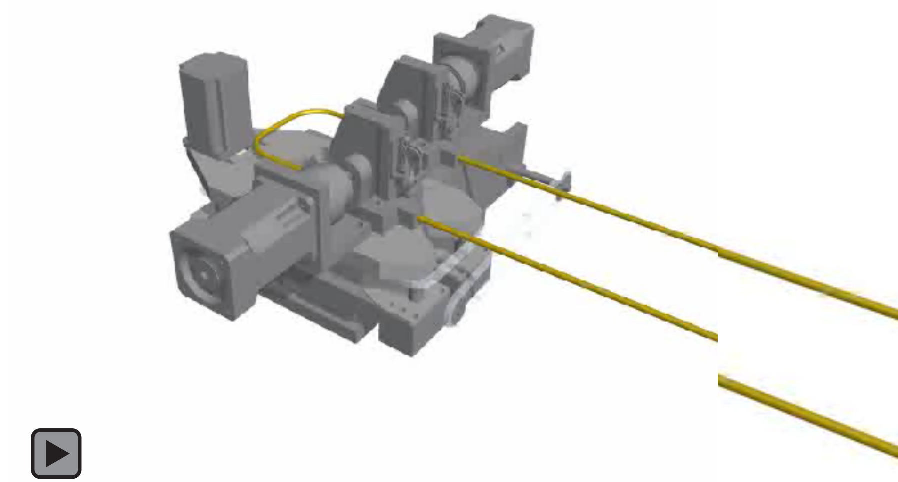
- All cables are positioned sandwiched between layers of precision-machined structure.
- Ends are formed to the side of the dipole, then popped into place in the structure layer.
- Overall coil assembly is preloaded within steel flux return, all windings immobilized.

1. Fabricate inner form segments from 4”-thick G-11 fiber-reinforced epoxy slab.
2. Assemble stack of segments for dipole body, using the CIC channels for alignment.
3. Insert the SS beam tube, seal the ends, and epoxy impregnate the gap between segments and beam tube.

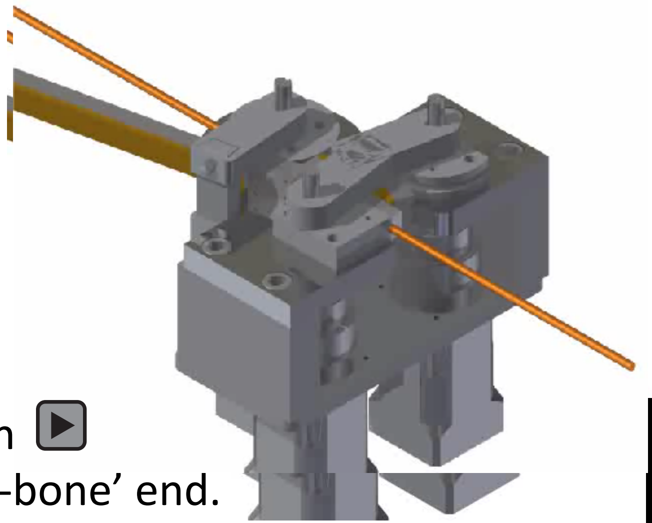
Forming the flared ends requires production tooling



1. Bend a U with the correct horizontal spacing.



2. Bend the U to form a 90° ear, with offset for layer-layer transitions.

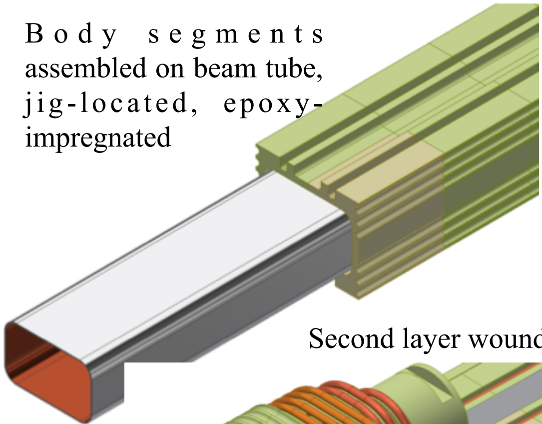


'Odd-man' turn forming a 'dog-bone' end.

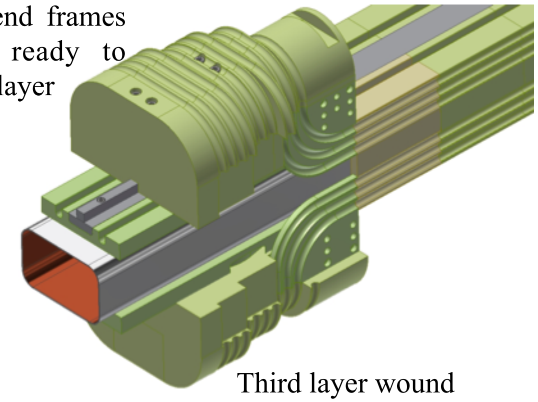
We have validated that bends preserve internal structure, do not damage NbTi wires.

And now for the complete fabrication

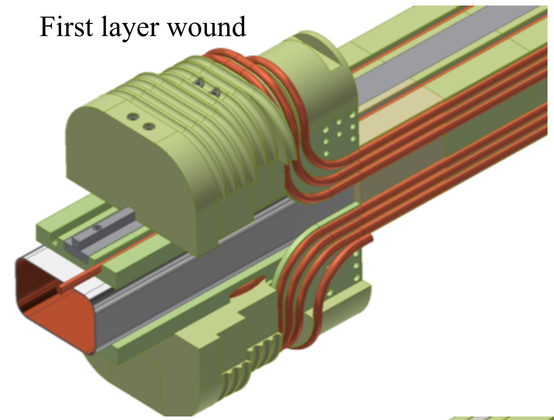
Body segments assembled on beam tube, jig-located, epoxy-impregnated



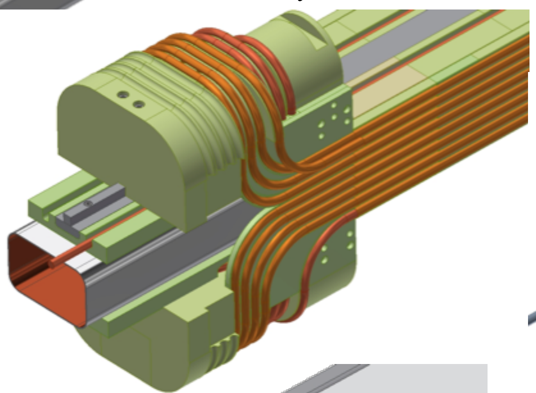
SS bars, end frames installed, ready to wind first layer



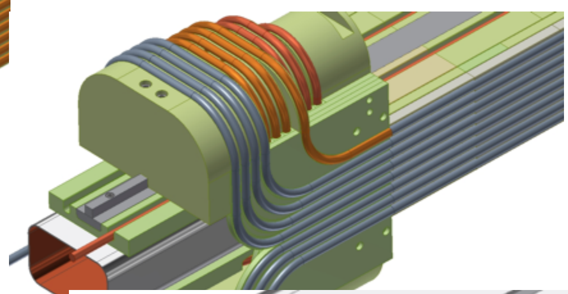
First layer wound



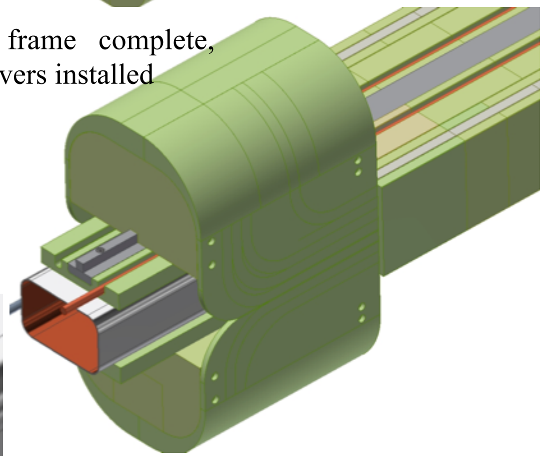
Second layer wound

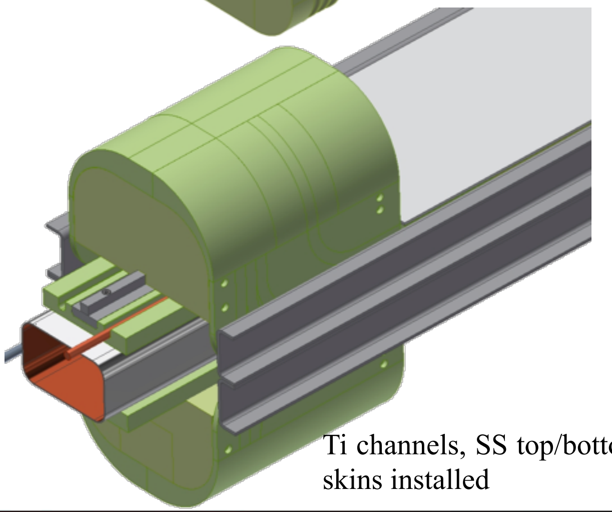


Third layer wound

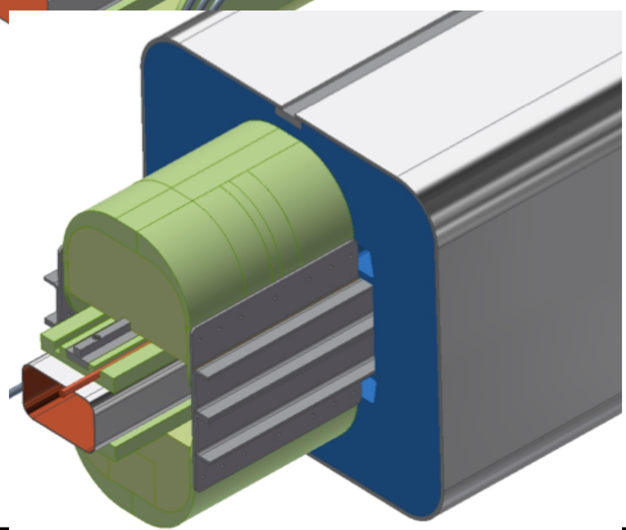


Cable frame complete, End covers installed





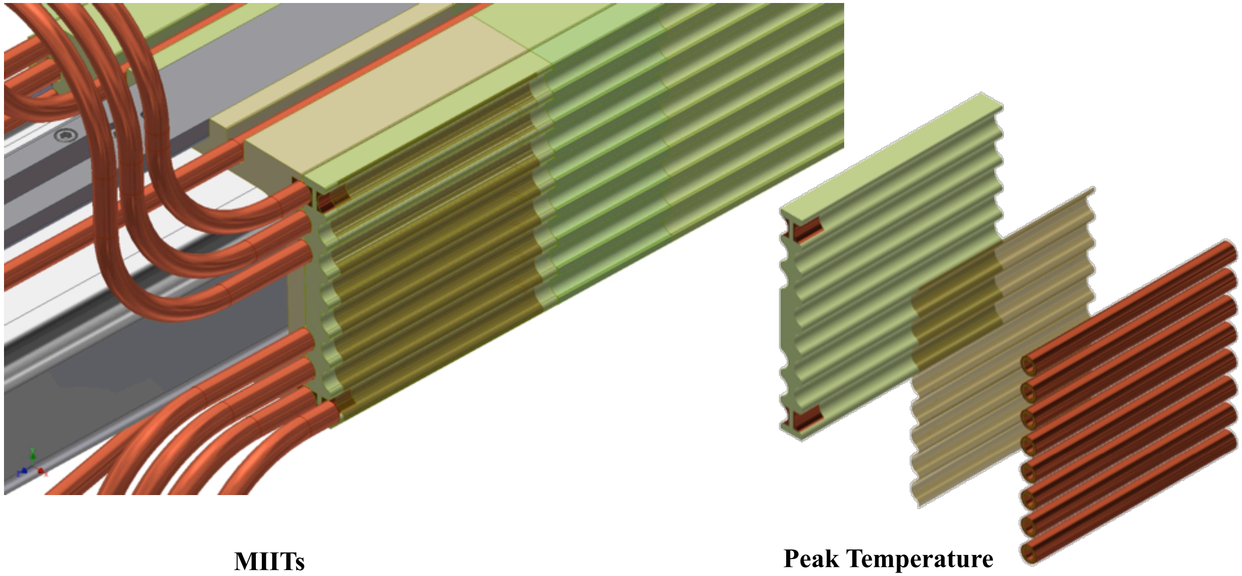
Ti channels, SS top/bottom skins installed

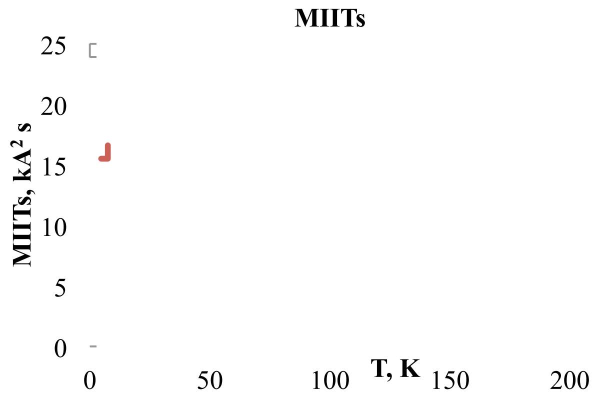


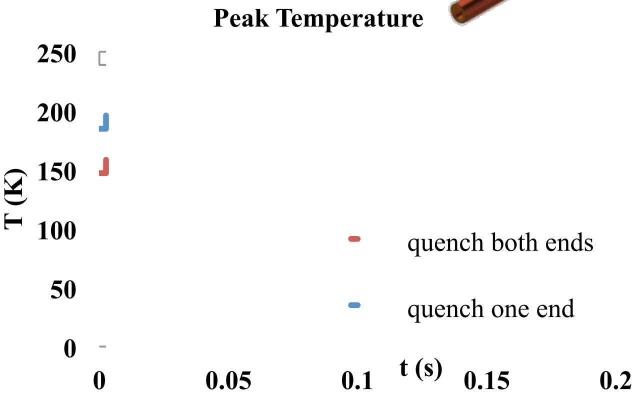
Flux return halves installed and closed, SS shells welded

Quench Protection

Quench heater foils are bonded in a 10 cm end segment of the G-11 structure on both ends of the dipole.
Every cable turn is driven normal in ~10 ms by a current pulse to the heater foils.

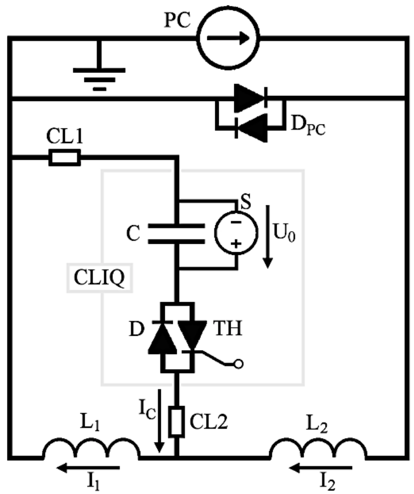


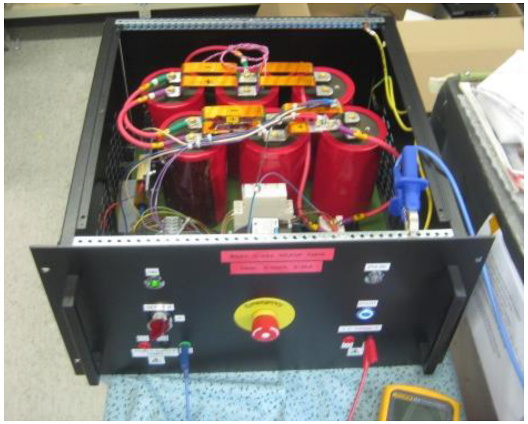


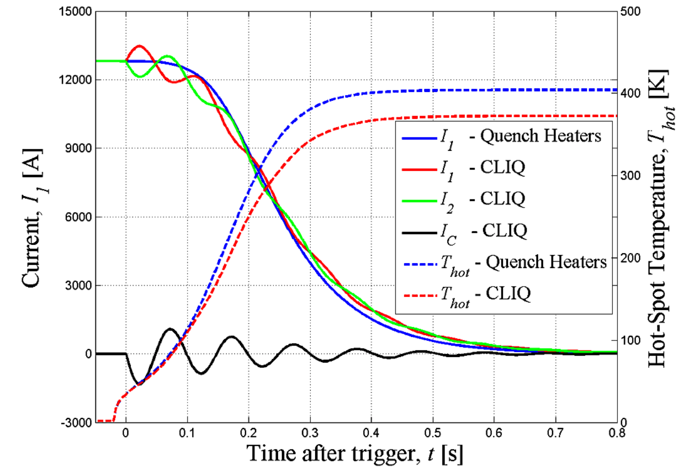


We are evaluating a new quench protection method: CLIQ

Datskov, GSI



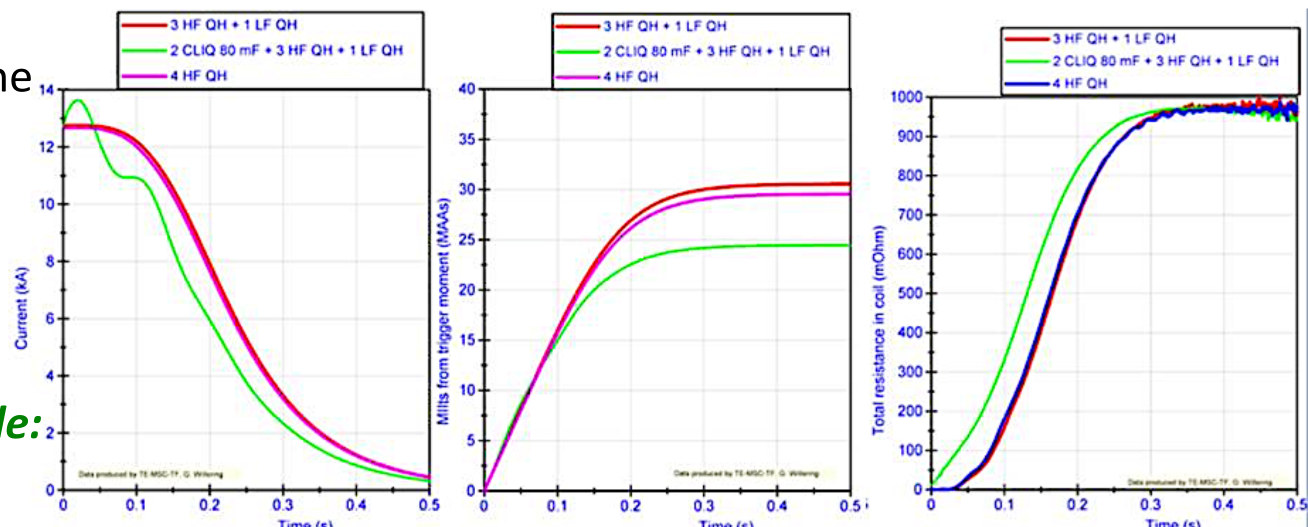




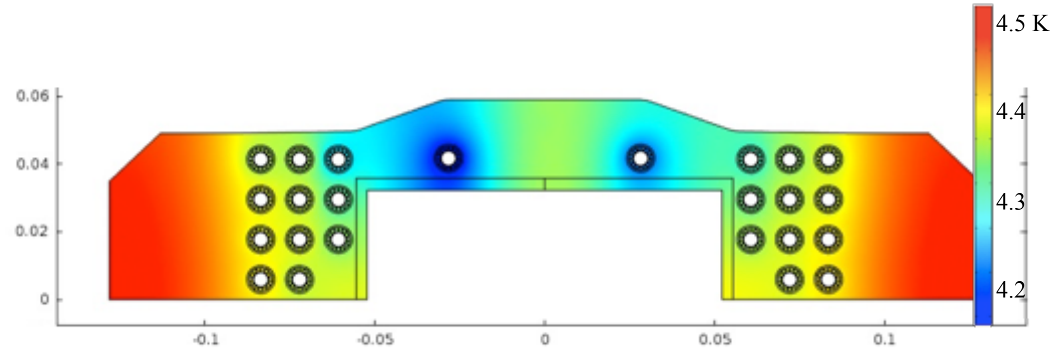
Discharge a capacitor across the inductive circuit of the dipole winding.

It induces distributed AC loss spike that drives quench everywhere in winding.

It works great on an LHC dipole:

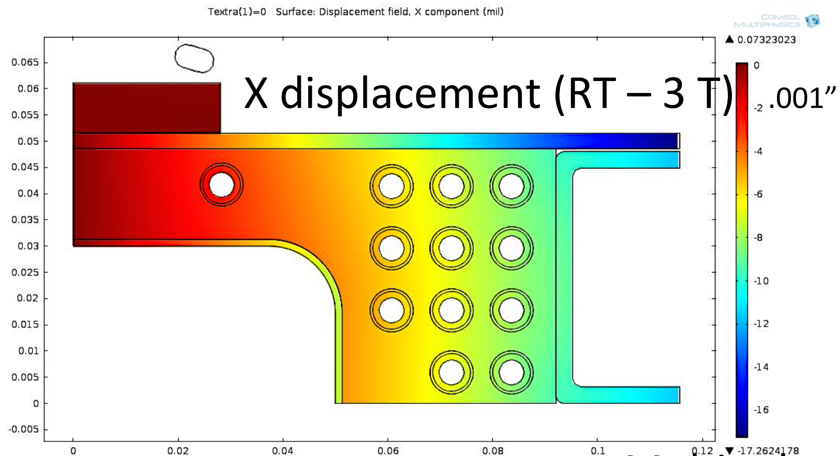


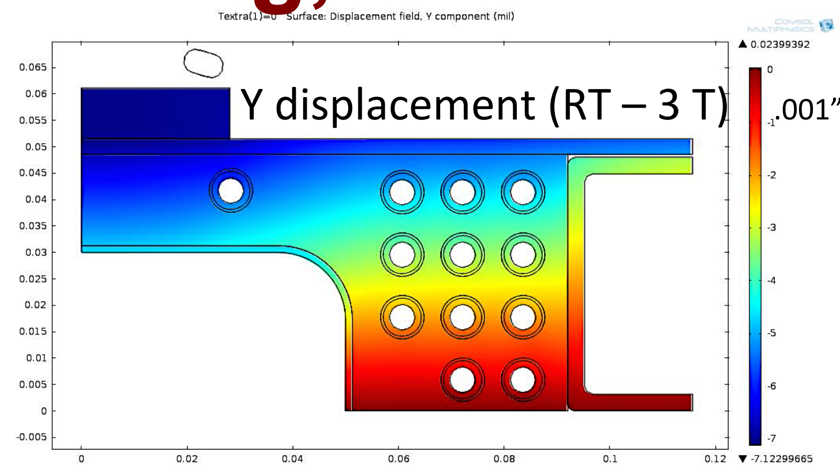
CIC Winding limits temperature rise in event of heat from beam losses



Simulated temperature distribution in the presence of 1 W heat deposition in a MEIC dipole winding.

CIC Structure controls Lorentz stress to prevent coil motion, training, error fields

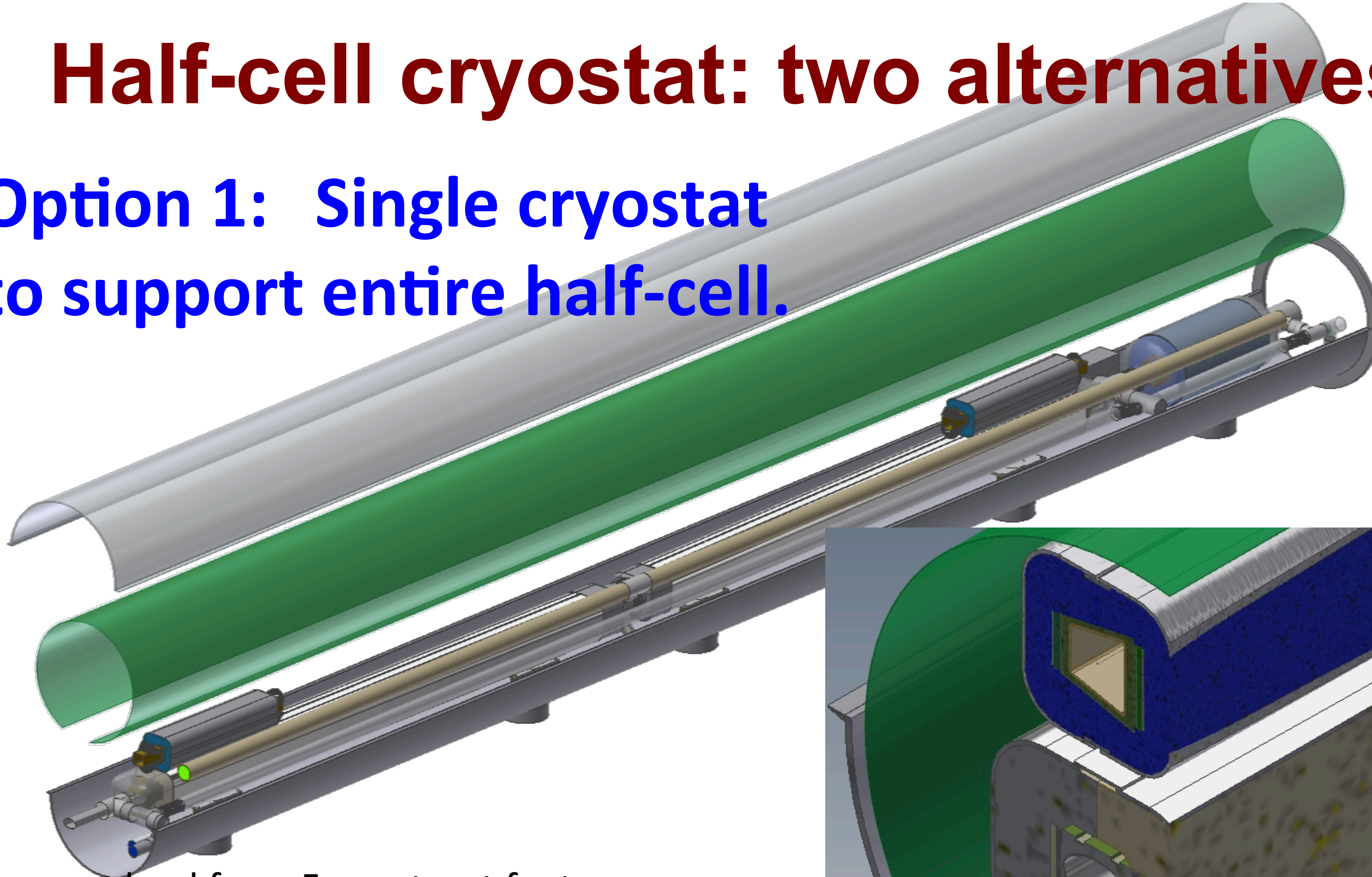




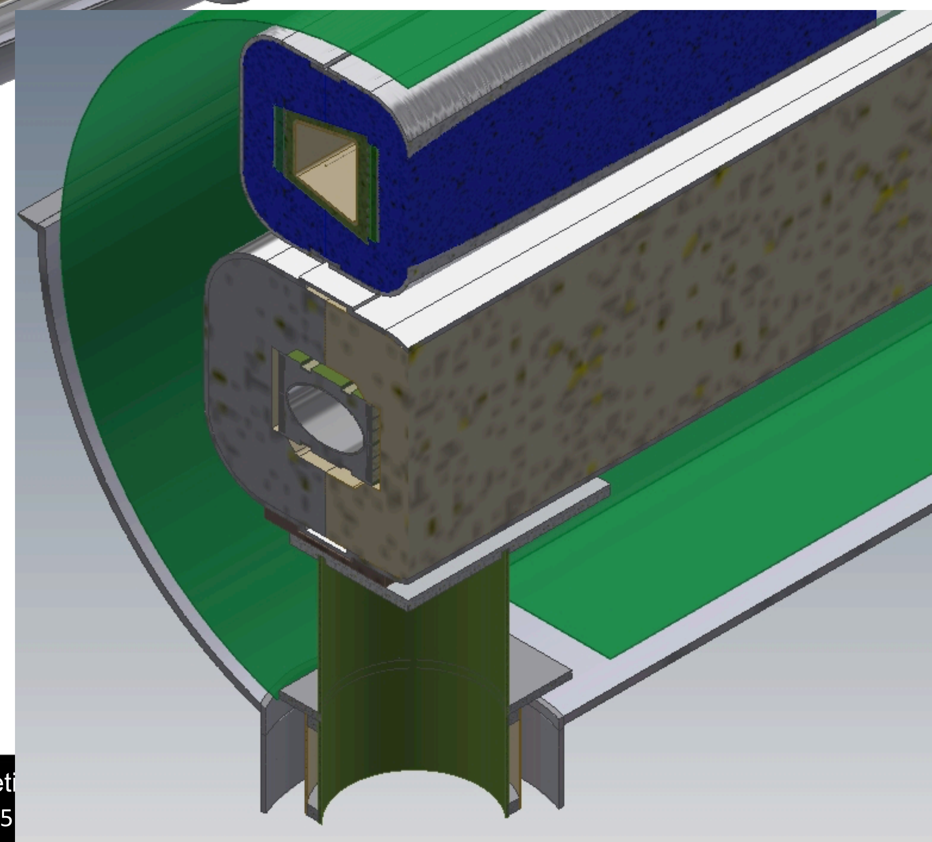
Multipole effects <0.2 units

Half-cell cryostat: two alternatives

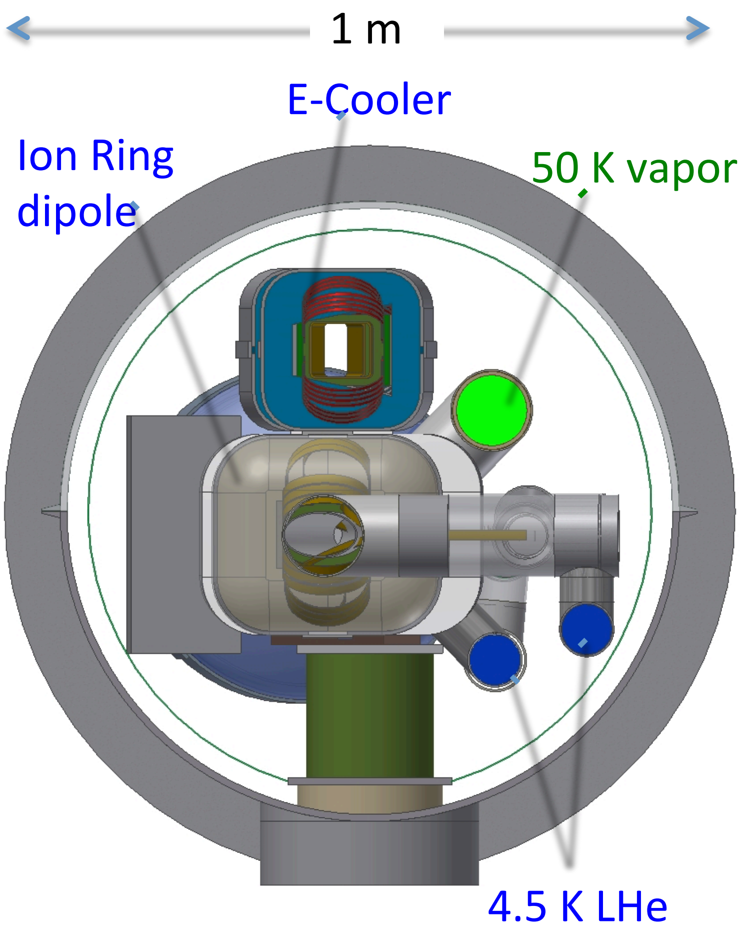
Option 1: Single cryostat to support entire half-cell.

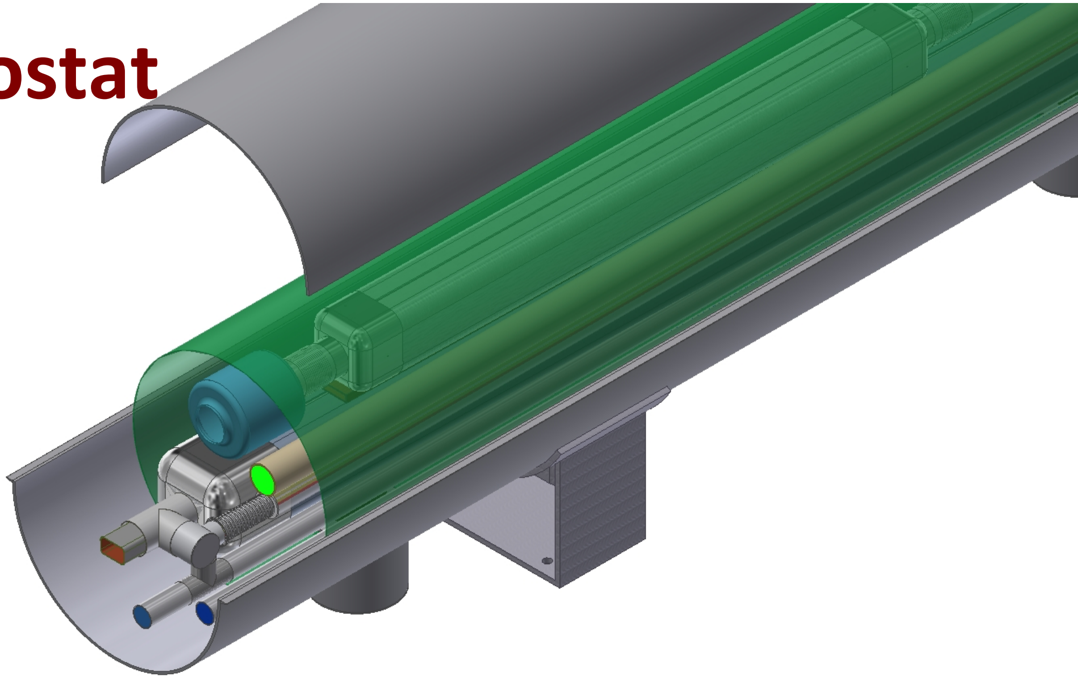


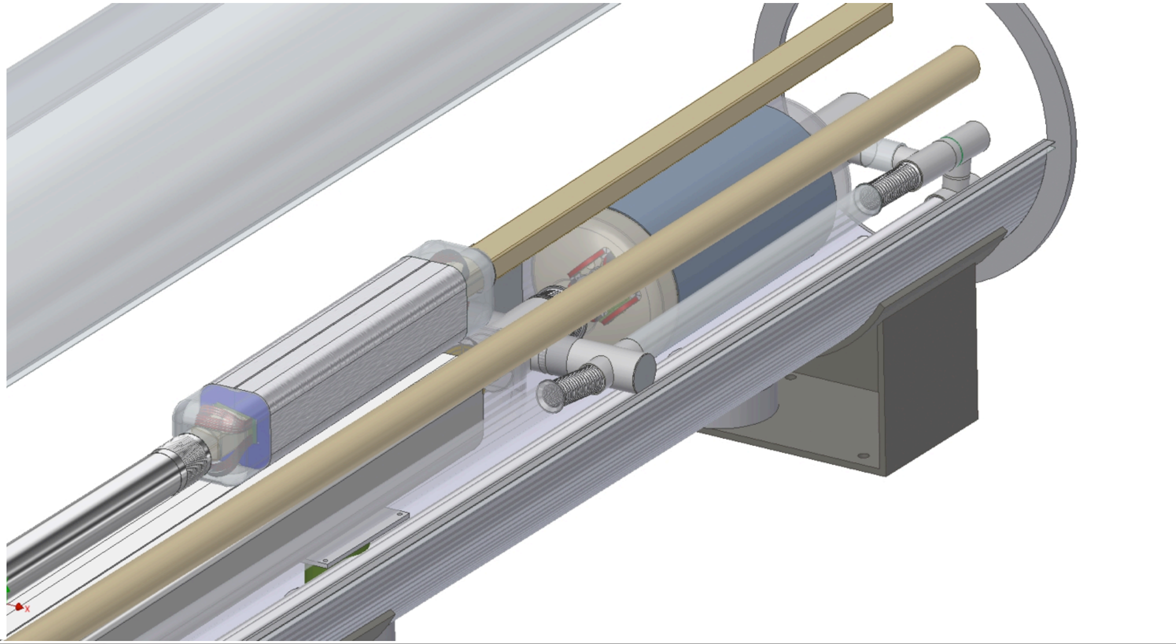
Support load from 5 reentrant feet.
Supports integrate provisions for precise positioning & internal alignment of all elements.
50 K shield, MLI, and top-half shell go on after all alignment. Ports for checking alignments.
Static heat loads ~0.5 W to 4.5 K, 50 W to 50 K.



Detailed views in cryostat







Booster (8 GeV, $\gamma_t = 10$)

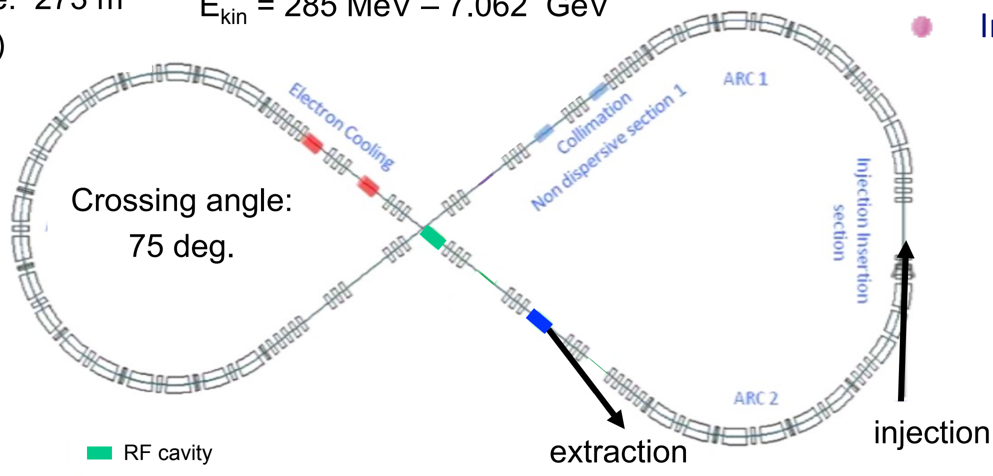
Bogacz

Ring circumference: 273 m (≈ 2200/8)

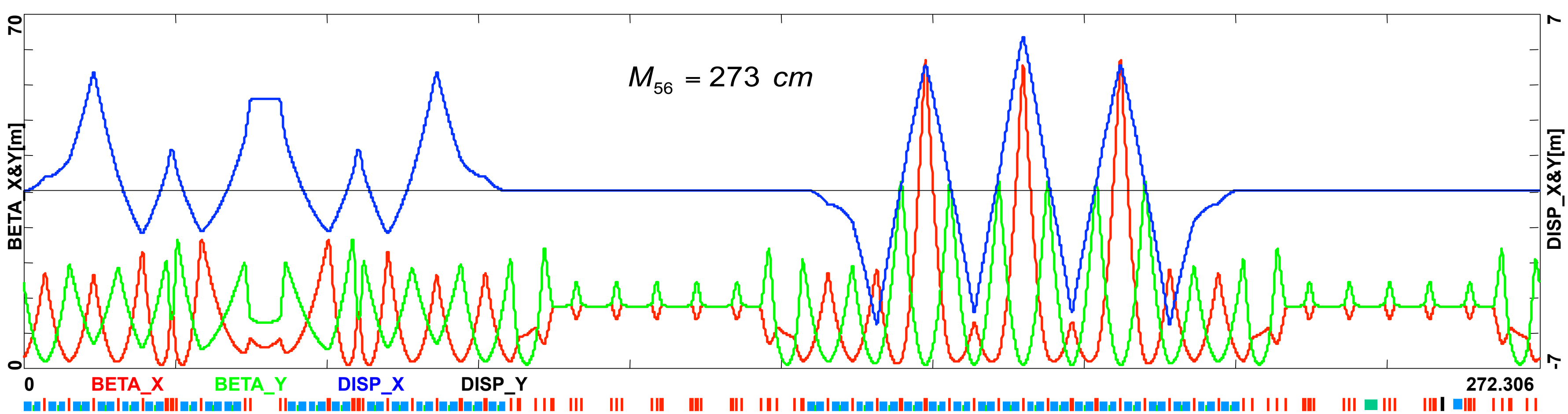
E_{kin} = 285 MeV – 7.062 GeV

$$\gamma_t = \sqrt{\frac{S}{M_{56}}}$$

$$M_{56} = \int \frac{D}{\rho} ds$$



- Injection: multi-turn 6D painting
  - 0.22-0.25 ms long pulses ~180 turns
  - Proton single pulse charge stripping at 285 MeV
  - Ion 28-pulse drag-and-cool stacking at ~100 MeV/u
  - Ion energies scaled by mas-to-charge ratio to preserve magnetic rigidity



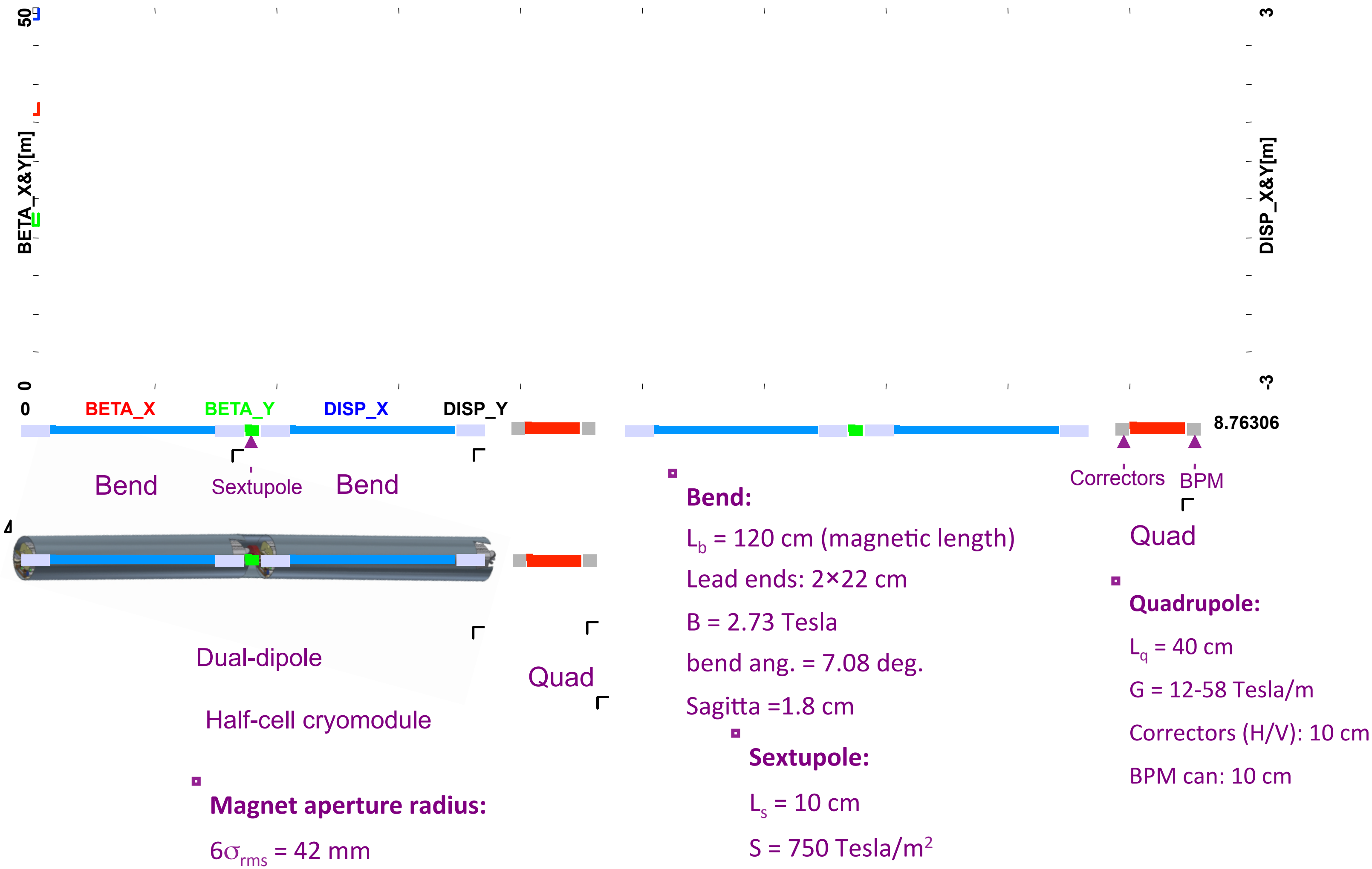
Inj. Arc (255^0) | Straight | Arc (255^0) | Straight (RF + extraction)

Arc Cell – Super-ferric Magnets

For planning purposes we could provide the required fields and apertures for the Booster magnets by building Ion Ring arc dipoles and quads with appropriate lengths:

Dipole 1.2 m **Quad 0.4 m**

It may likely prove to be the case that making the dipoles of a common design is less expensive than making dedicated designs with smaller quad gradient.



Booster arc magnets

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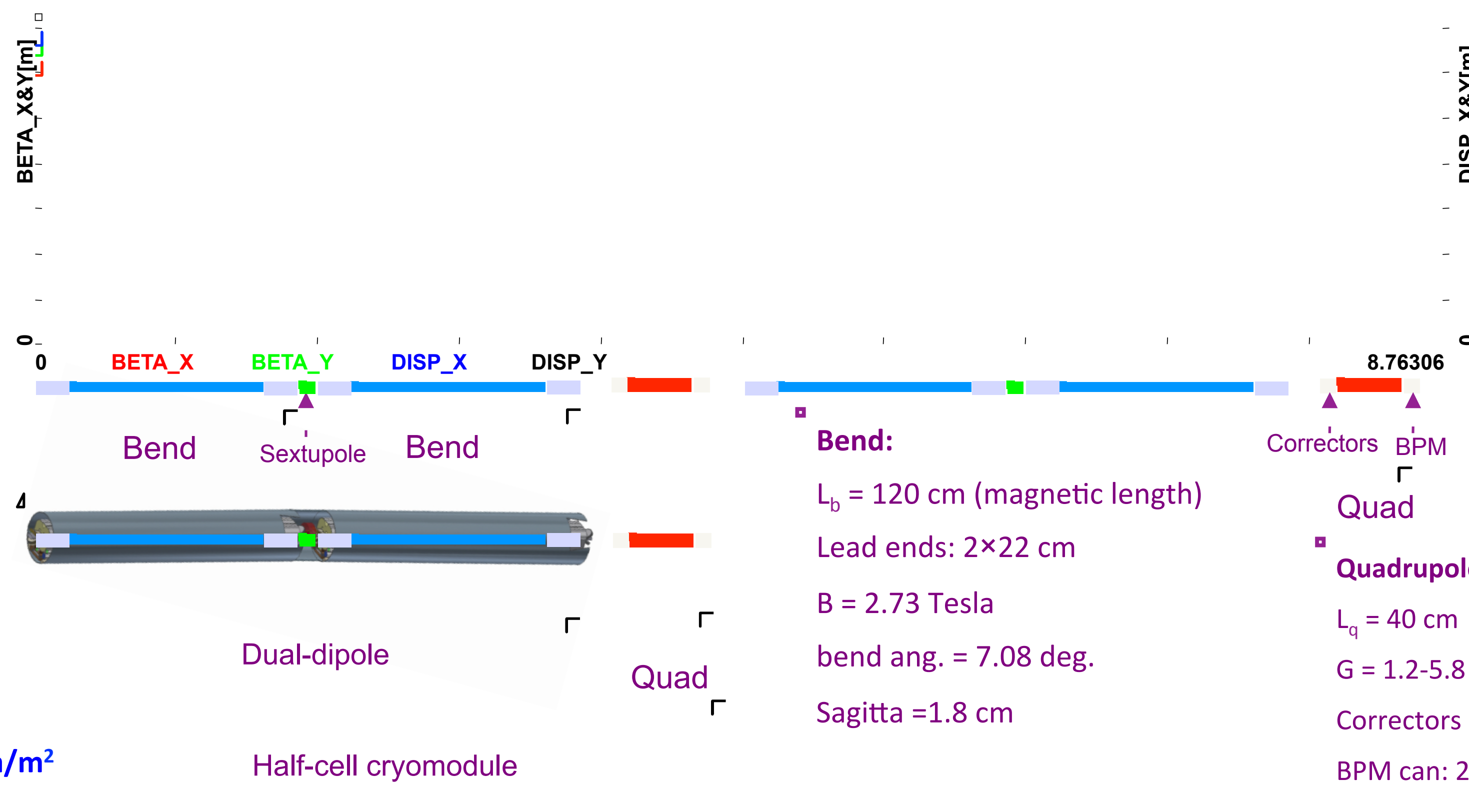


Bend:

L_b = 120 cm (magnetic length)

Lead ends: 2×22 cm

B = 2.73 Tesla

bend ang. = 7.08 deg.

Sagitta =1.8 cm

Quadrupole:

L_q = 40 cm

G = 1.2-5.8 Tesla/m

Correctors (H/V): 20 cm

BPM can: 20 cm

Sextupole:

L_s = 10 cm

S = 750 Tesla/m^2

Cost estimation for a half-cell

- Both top-down and bottom-up direct cost estimation have been done for the superferric magnet systems for the half-cells of the Ion Ring arcs. A top-down analysis was also done for a single-shell cos θ dipole (ala RHIC) with 10 cm bore radius.
- Top-down direct cost estimate for one 4 m dipole (with cryostat):
  - Superferric: **$ 71,087**
  - Cos θ: $135,955
- Bottom-up direct cost estimate for one complete superferric half-cell (2 dipoles, quadrupole, sextupole, cryostat): **$225,968**
- Direct cost for the 128 Ion Ring half-cells plus tooling, field engineering, learning curve for production: **$30,635,421**

Where the $ goes in building dipoles

Eric Willen did a nice analysis of the as-built costs for RHIC dipoles built at Grumman:

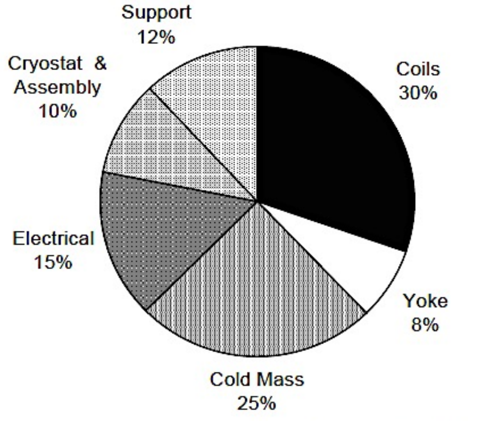


Fig. 9 Labor cost distribution for the production dipoles built by NGC.

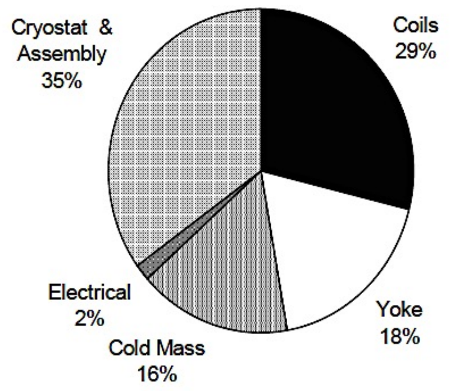
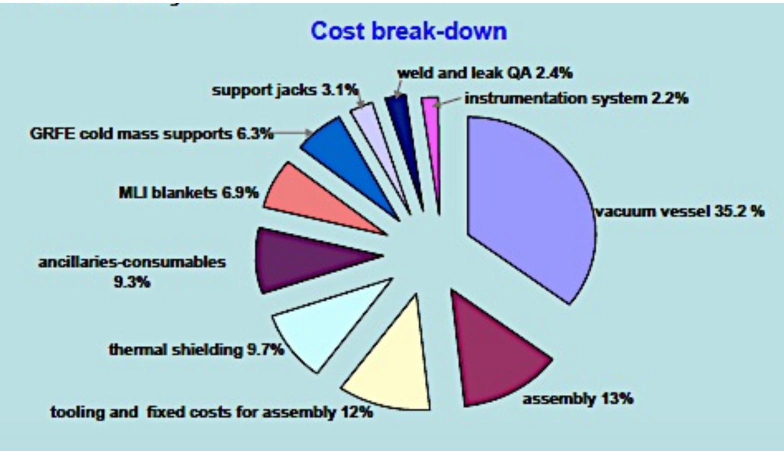
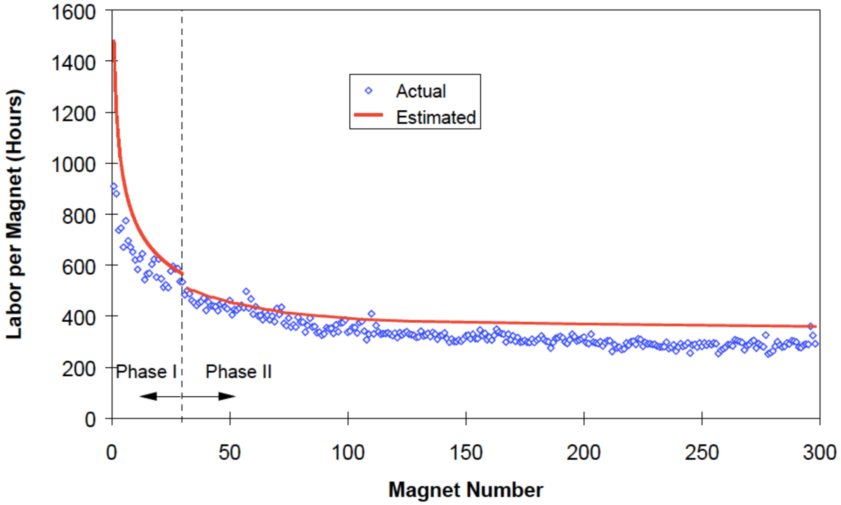


Fig. 10 Material cost distribution for the production dipoles built by NGC.

Vittorio Parma did the same for the LHC cryostats:



Willen also documents the convergence of unit cost during a production run:



R&D for FY2015/16

- Prepare CDR for Ion Ring dipole. ✔
- Fabricate mock-up winding to evaluate fabrication method, precision of location of windings in body and ends. In progress – complete 12/2015
- Design/build 1.2 m prototype of 3 T superferric dipole
  - This is exactly the dipole required for the Booster arcs, and is a short model for the 4 m dipole for the Collider arcs.

  Contract negotiated after Task 2; estimate 10 mo. ARO
- Model the lattice for E-Cooler and Stacker rings that could piggy-back on the Ion Ring dipoles in the same cryostat. Simulate cooling and bunch manipulations. Evaluate benefit in the overall scenario for acceleration, collision in MEIC.

The Accelerator Research Lab is enthusiastic about MEIC and we are working hard to help make it a success