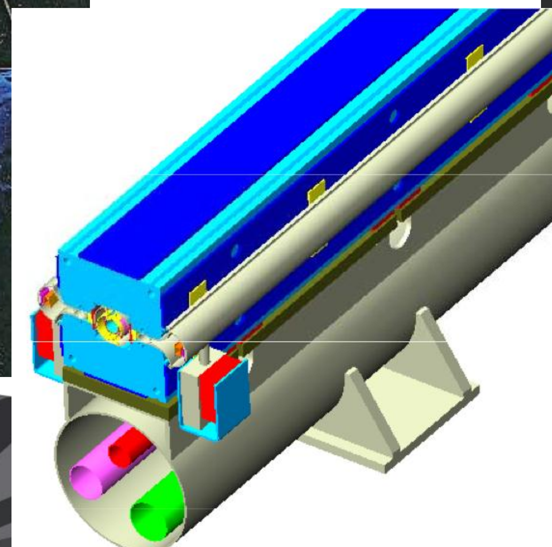
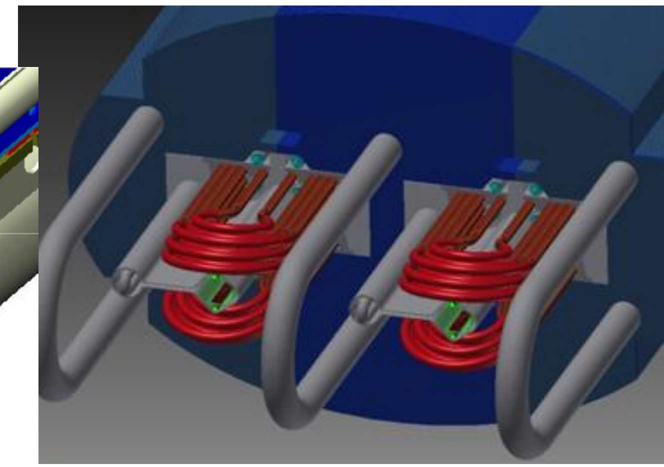
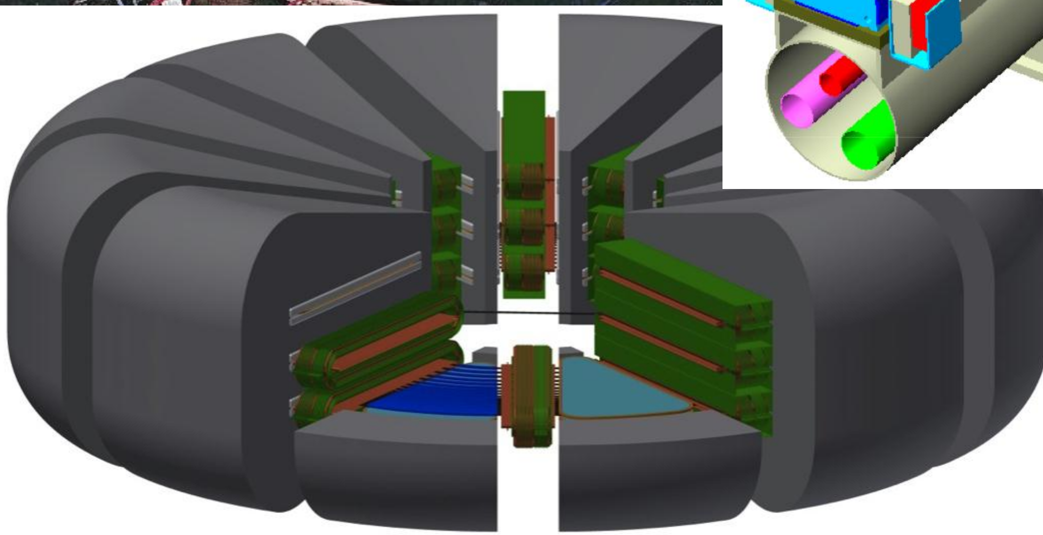
Superferric Magnets for Fun and Profit

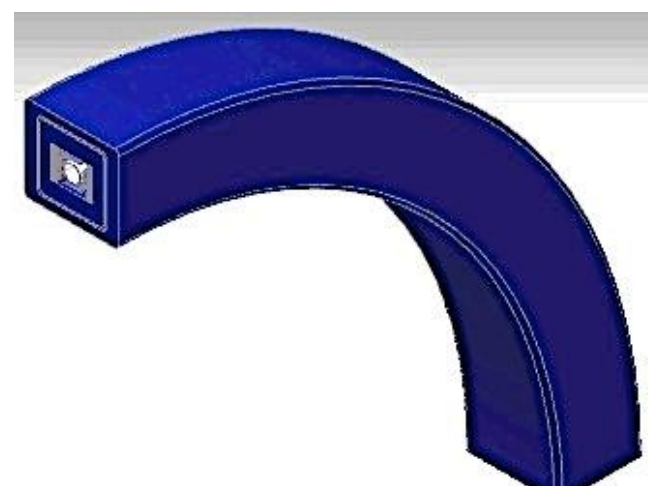
Peter McIntyre

Texas A&M University



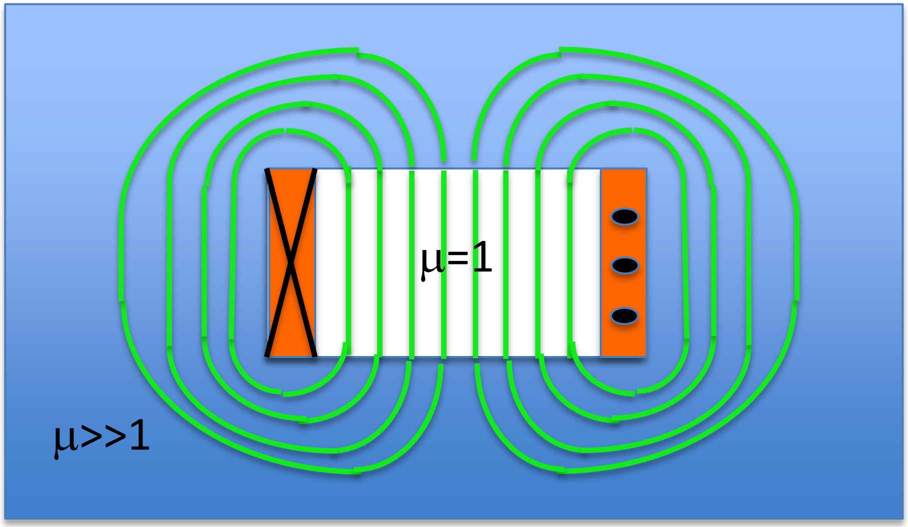






What makes a superferric dipole?

Ampere's Law: $$\oint \frac{\vec{B} \cdot \overrightarrow{d\ell}}{\mu(r)} = NI$$



You must supply current to drive magnetic flux across the vacuum gap in the steel.
But the rest of the path is almost free…

Boundary conditions

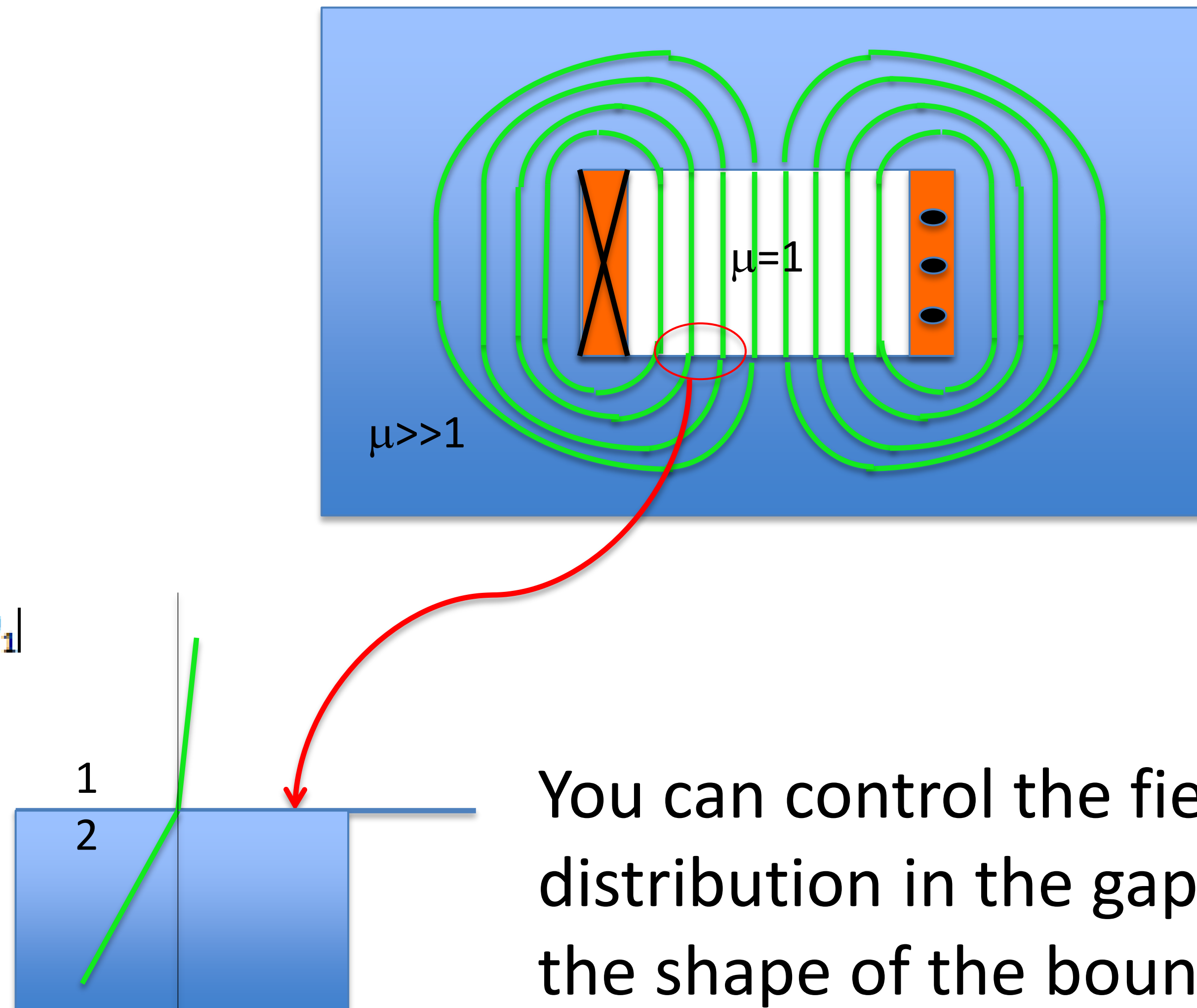
$$\oint \frac{\vec{B}\cdot\overrightarrow{d\ell}}{\mu(\vec{r})} = NI$$

$$B_{\perp 1} = B_{\perp 2}$$

$$H_{\parallel 1} = H_{\parallel 2}$$

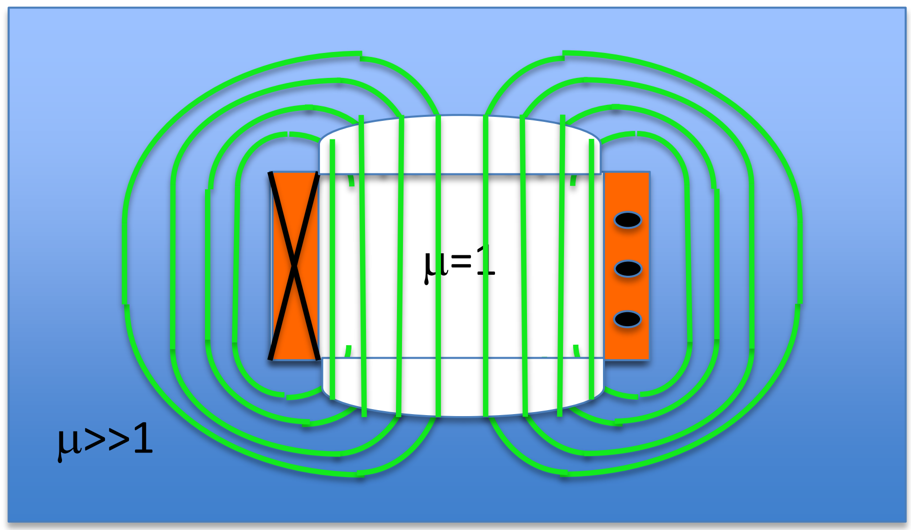
$$\vec{B} = \mu\vec{H}$$

$$\tan\theta_2 = \mu\tan\theta_1$$



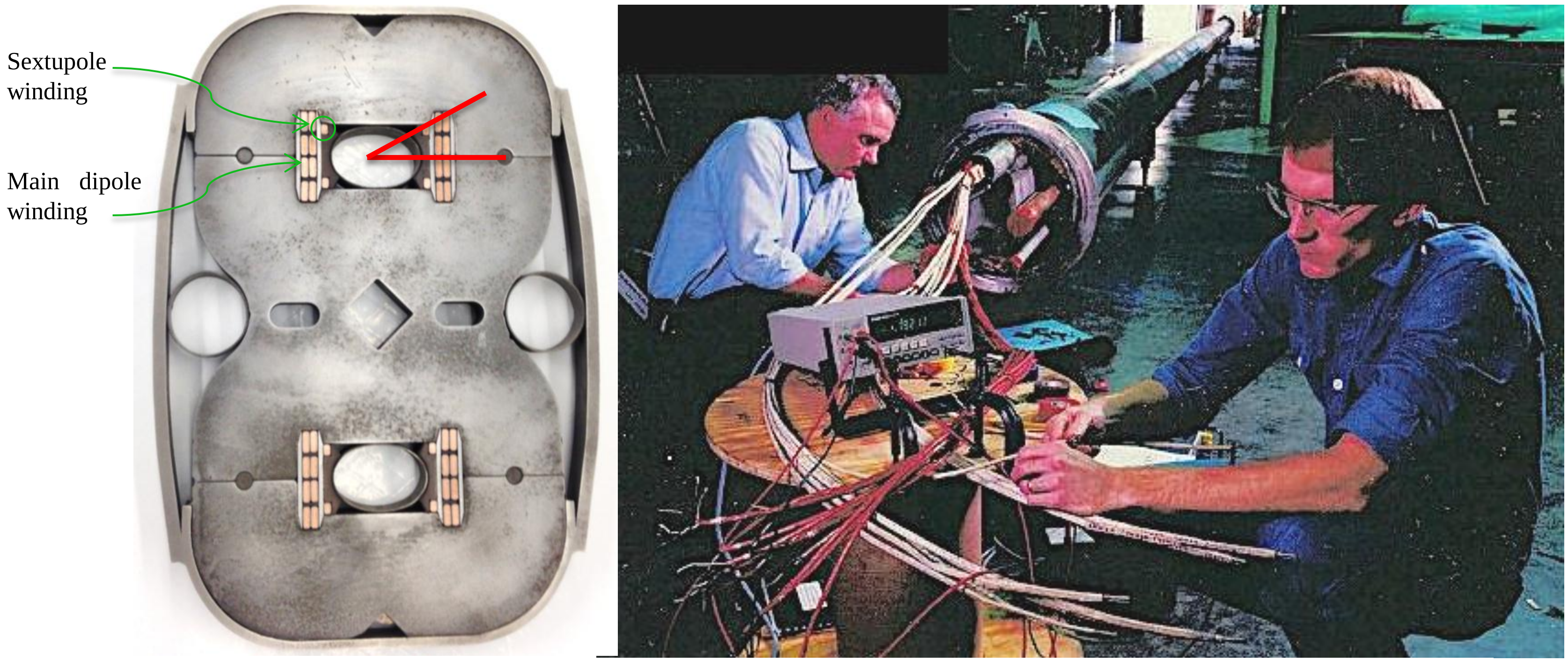
You can control the field distribution in the gap using the shape of the boundaries.

The Danby Trick



If you want to push field beyond the saturation of steel (~1.7 T), move the steel boundary away from the gap until it is in a location where field has reduced to ~saturation.
Curve the boundary so that the boundary condition now gives the desired pure dipole.

Correction windings



Superferric SSC dual dipole: a) cross-section of dual dipole, showing window-frame dipole winding and corner sextupole winding; b) successful testing of 35 m long dual dipoles made at General Dynamics – the longest superconducting magnets ever built.

Multipoles: $\vec{B}(r,\theta) = \sum_n (\hat{x} + i\hat{y}) r^{in\theta}$

Suppose you want to kill an unwanted multipole, e.g. *sextupole*
Place a current element where that multipole is max, others are min

Superferric SSC: kill sextupole, decapole *at all field values*

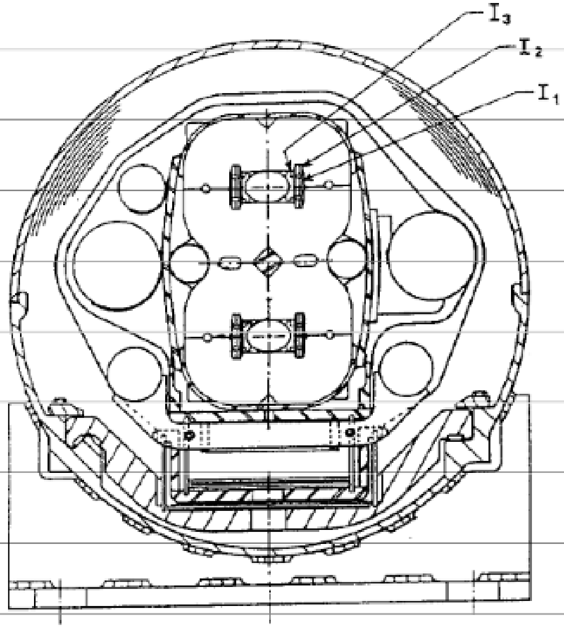


Figure 2: The 2-in-1 3 Tesla superferric magnet is enclosed in a vacuum chamber of 16 3/4'' O.D. The iron is 1/16'' laminations. The two magnet channels are magnetically independent. The gap of the magnet is 1 inch. The good field is greater than 2 cm diameter. The support in the figure is made of 2 concentric fiberglass cones, one between 10°K and 80°K and the other between 80°K and 300°K. There is a support every 24 feet. The small pipes are for liquid helium and nitrogen and the larger ones for helium gas. Sixty layers of superinsulation are between 80°K and 300°K.

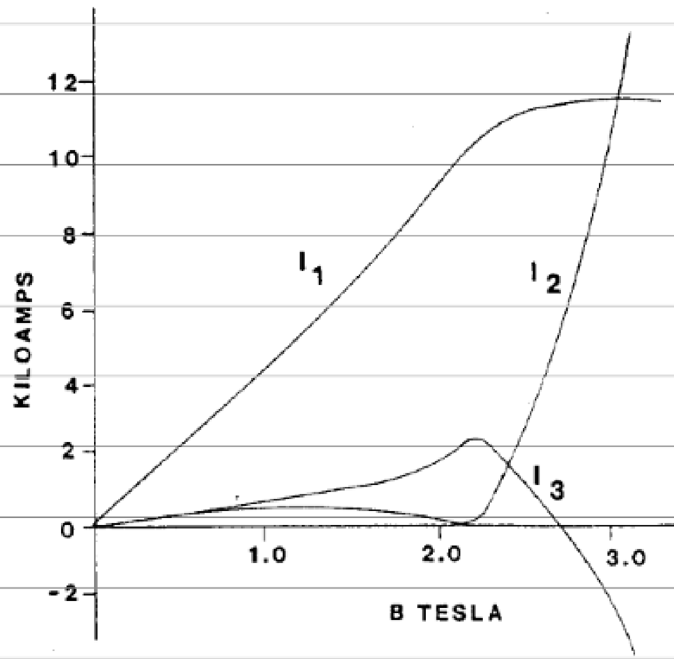
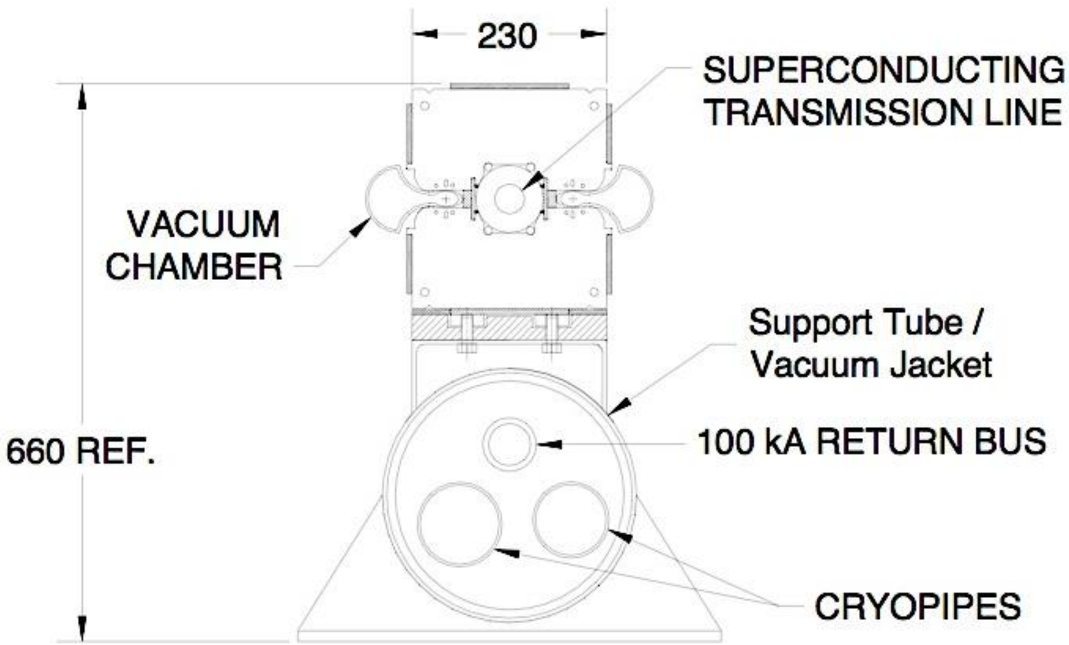


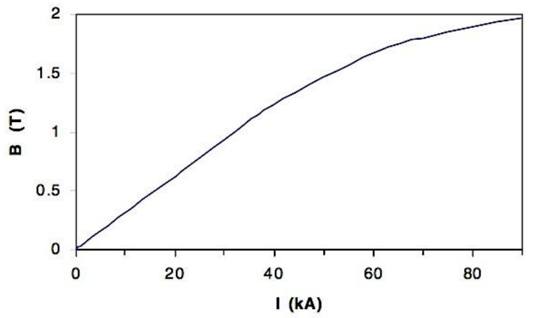
Figure 3: The 3 independent currents as a function of magnetic field.

Foster's pipe dipole

Transmission Line Magnet



- 2-in-1 warm iron warm bore superferric
- alternating gradient (no quads)
- 100kA Transmission Line
- all-piping cryogenic system



- 1.966 Tesla (=20 TeV) at 87.5 kA.
- Transmission line design current is 100 kA.

Using holes to correct saturation multipoles

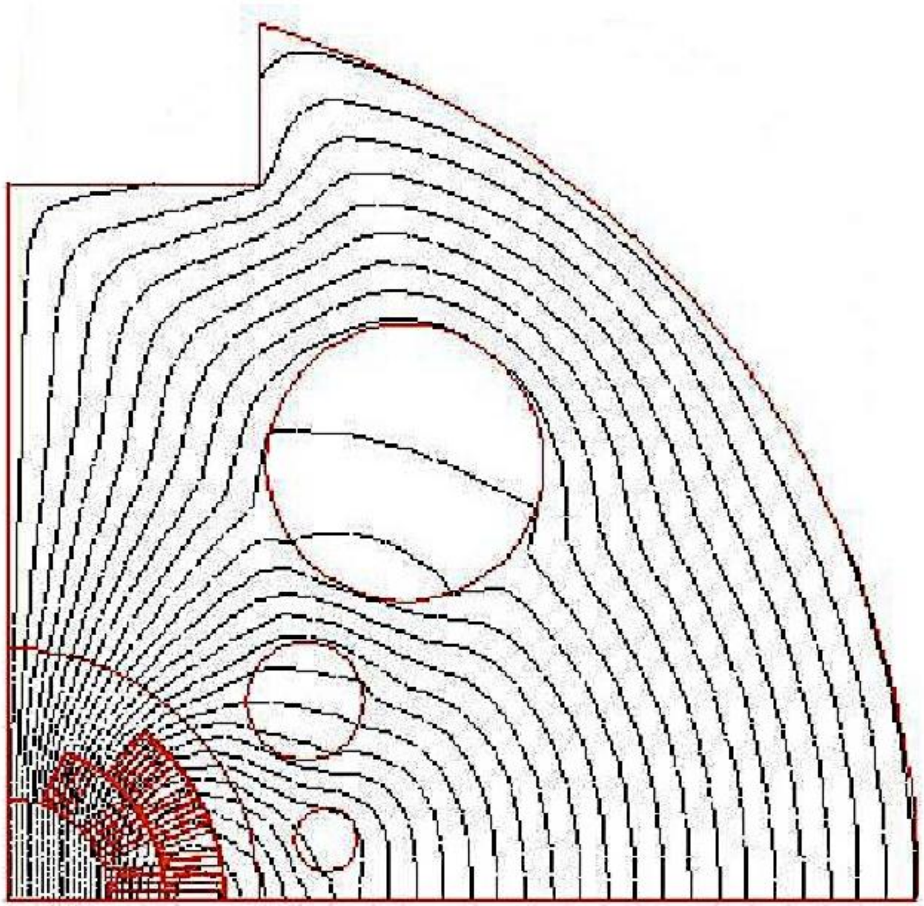
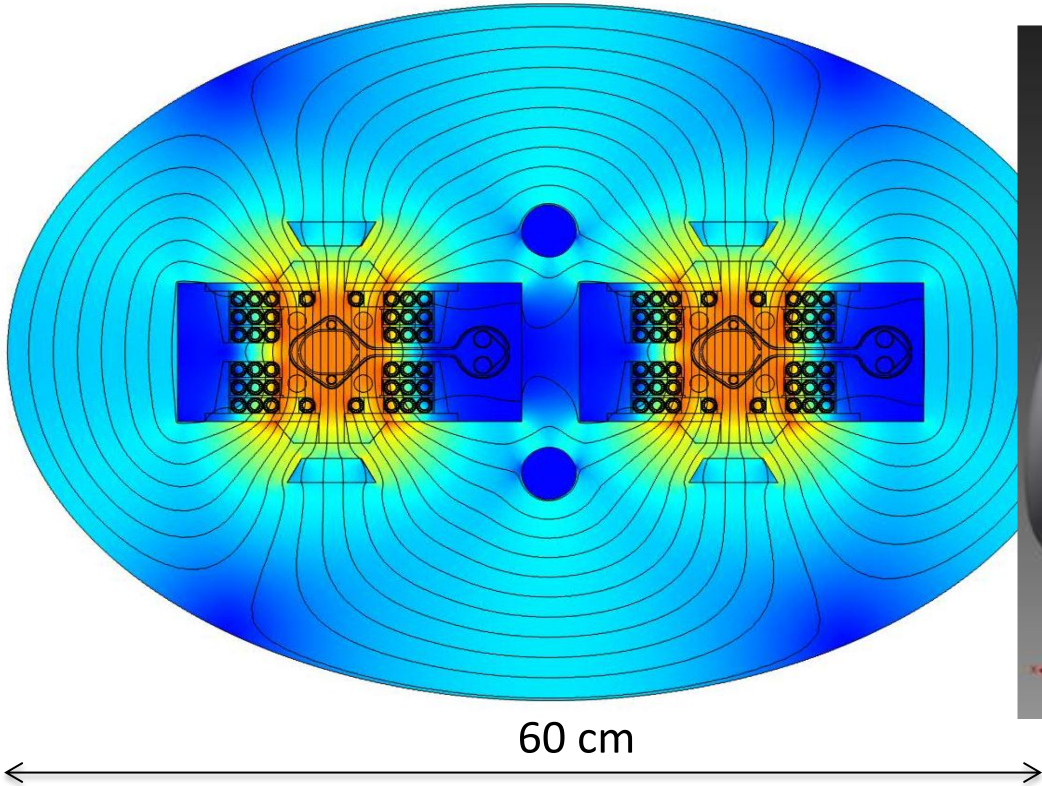
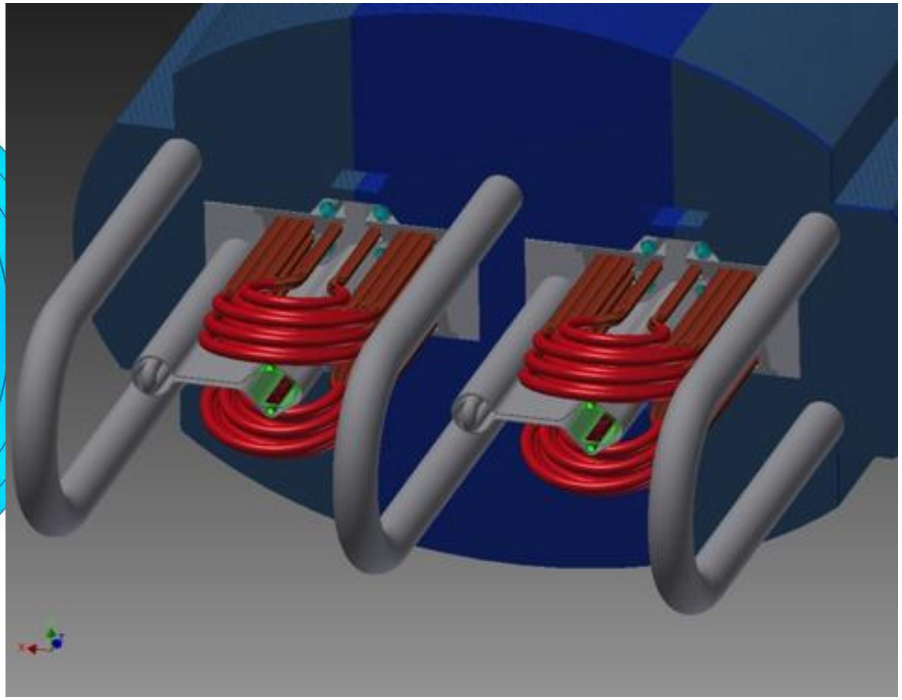


Figure 3. Geometry of the 50-mm bore design with semi-optimized yoke hole configuration and flux lines at 18 kA.

4.5 T ‘Superferric’ Dipole for 100 TeV Hadron Collider

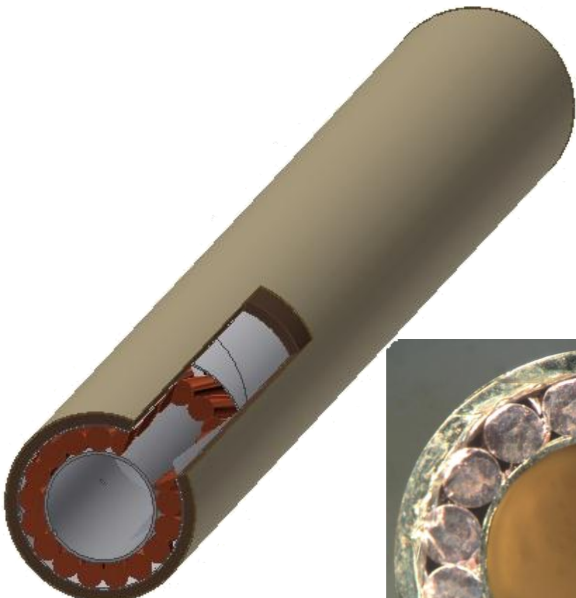


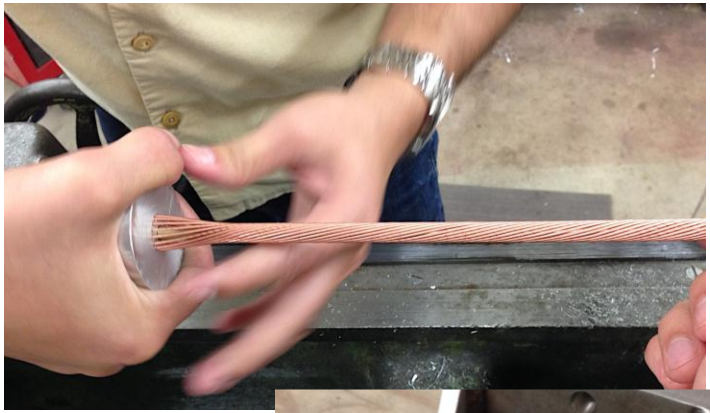


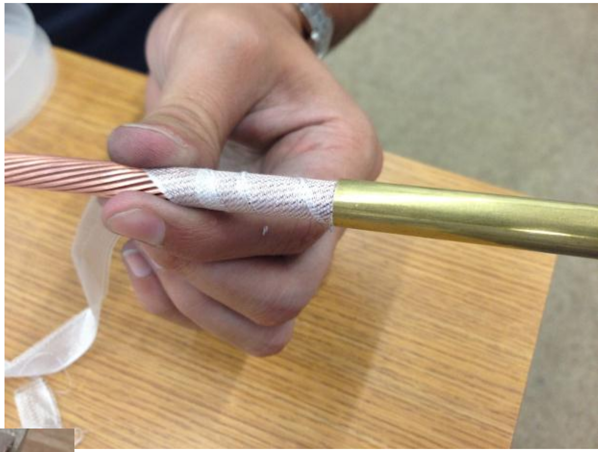
- 4.5 Tesla dipole field
- C-dipole: synchrotron radiation passes into a second chamber where it is absorbed at 150 K.
- Refrigeration is 100x more efficient, so heat load not a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns total, wound from 2 pieces of round cable-in-conduit.

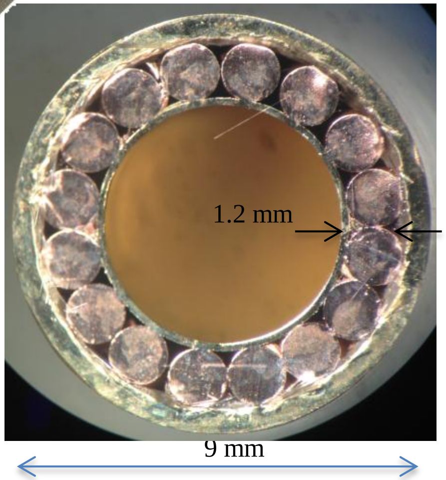
NbTi cable-in-conduit

- Improve upon the CIC conductor developed by Dubna for FAIR:

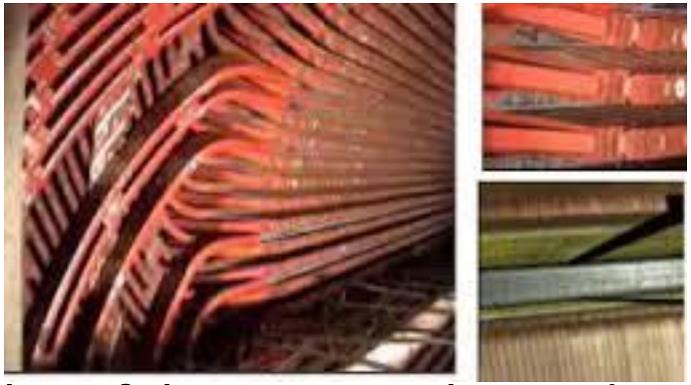






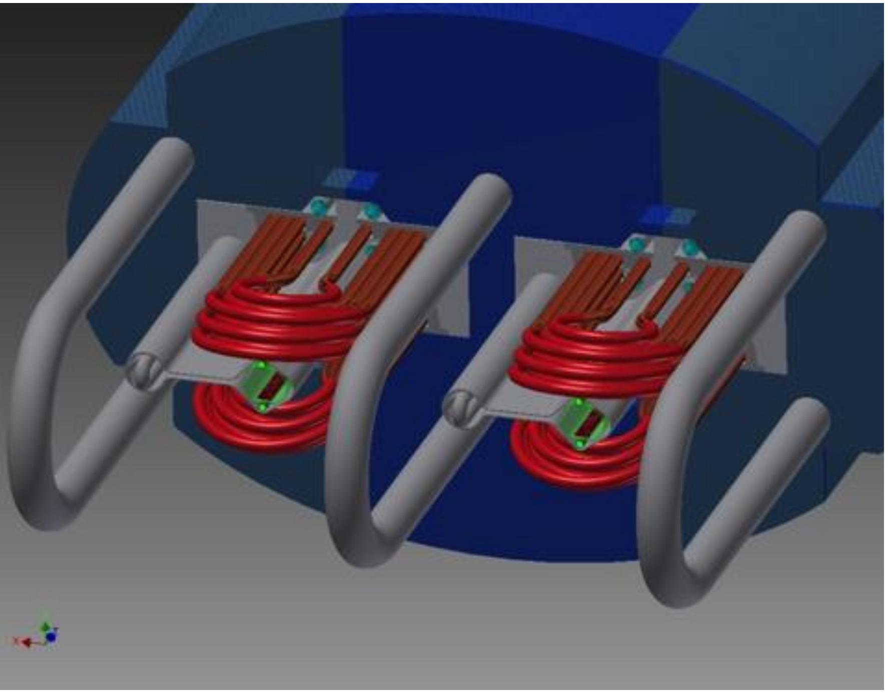


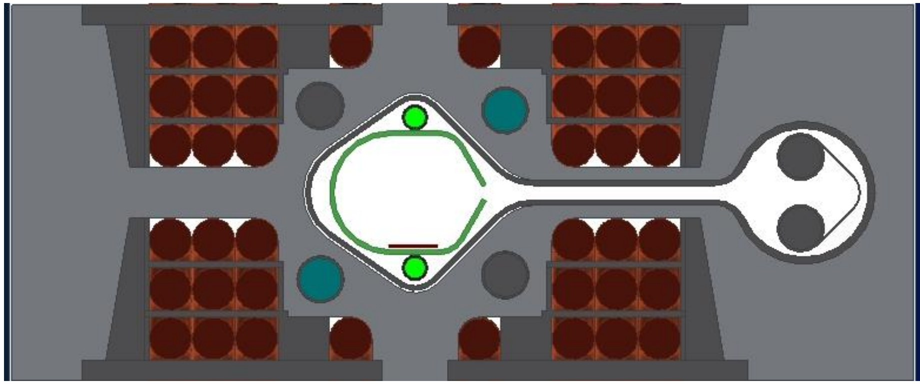
Motor and generator industries routinely manufacture large shaped windings like those of the CIC C-dipole.



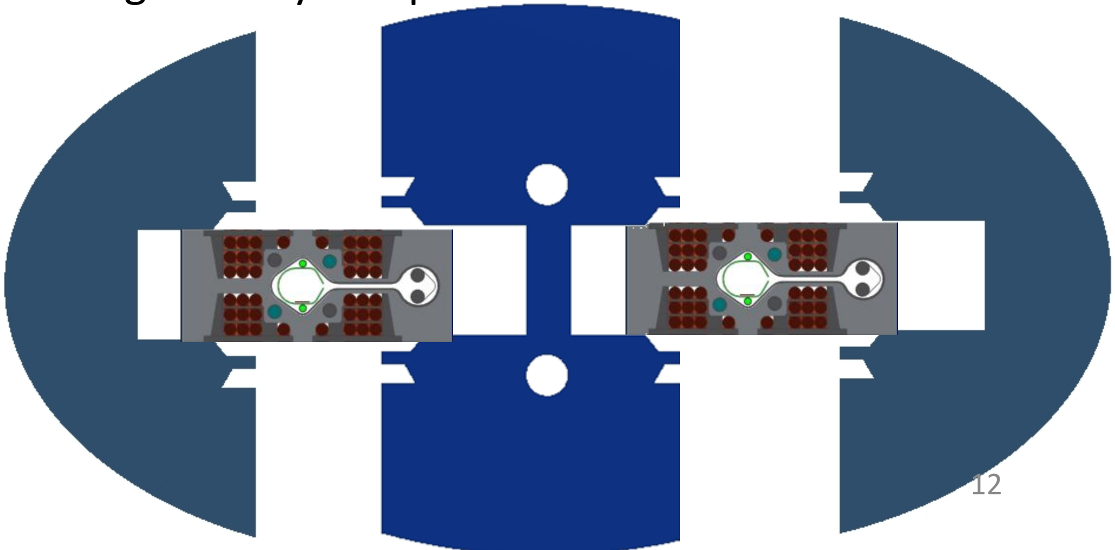
They fabricate each winding in a single-fixture sequence: wind onto peg-pattern forms, bend ends of each layer using hinged platens.

Manufacture of the dipole





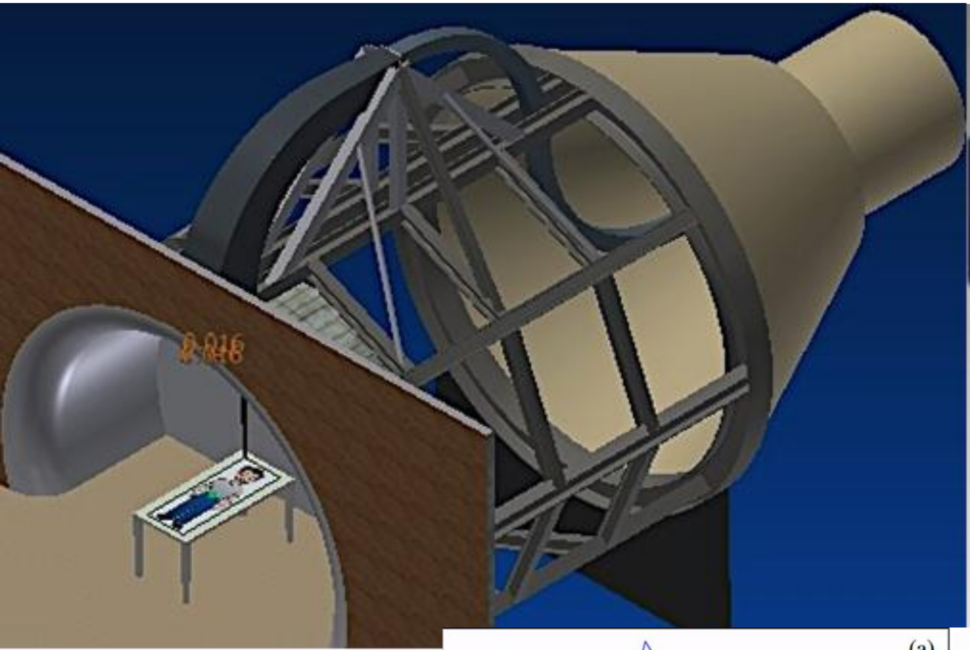
2. Insert half-windings into one-piece lamination stack, insert wedges, compress/weld to preload and seal.
3. Vacuum-impregnate windings to lock coil geometry and preload.

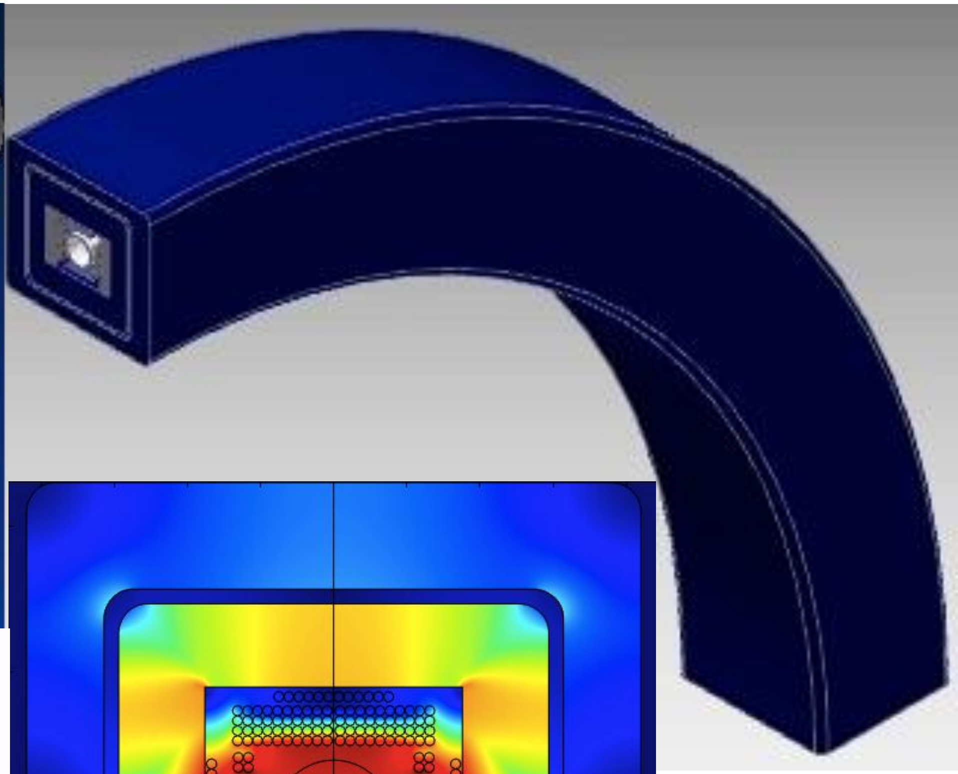


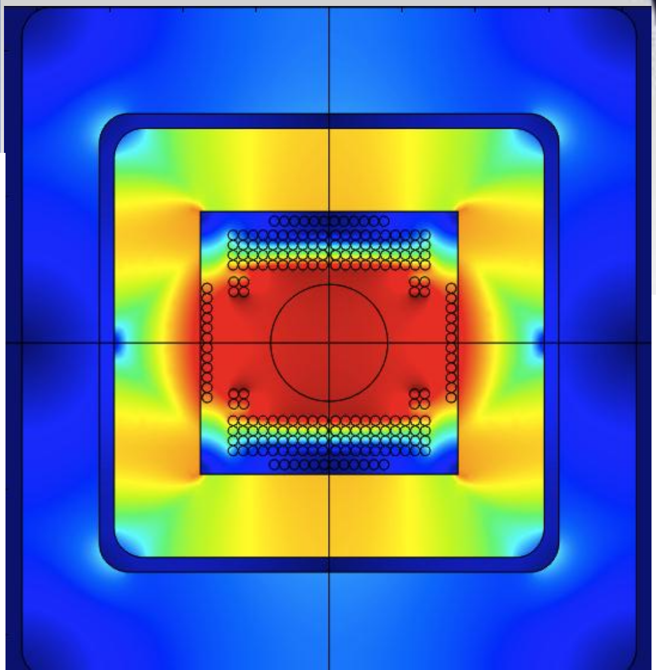
1. Wind racetrack pancake windings for top/bottom halves - bend ends 90°.

4. Install winding assemblies into flux return assemblies, compress and weld.

Combined-function (dipole+quad) elements for Proton/ion beam therapy gantries



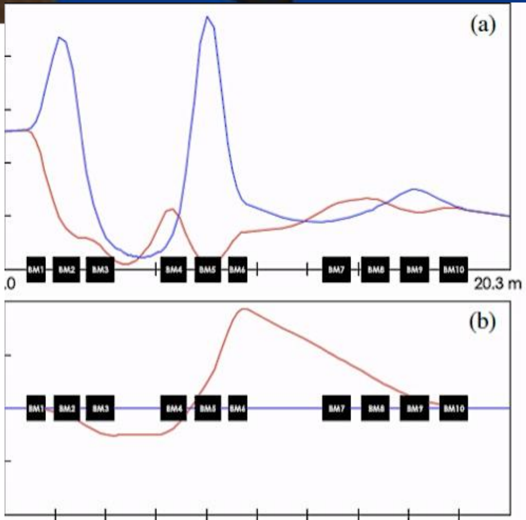




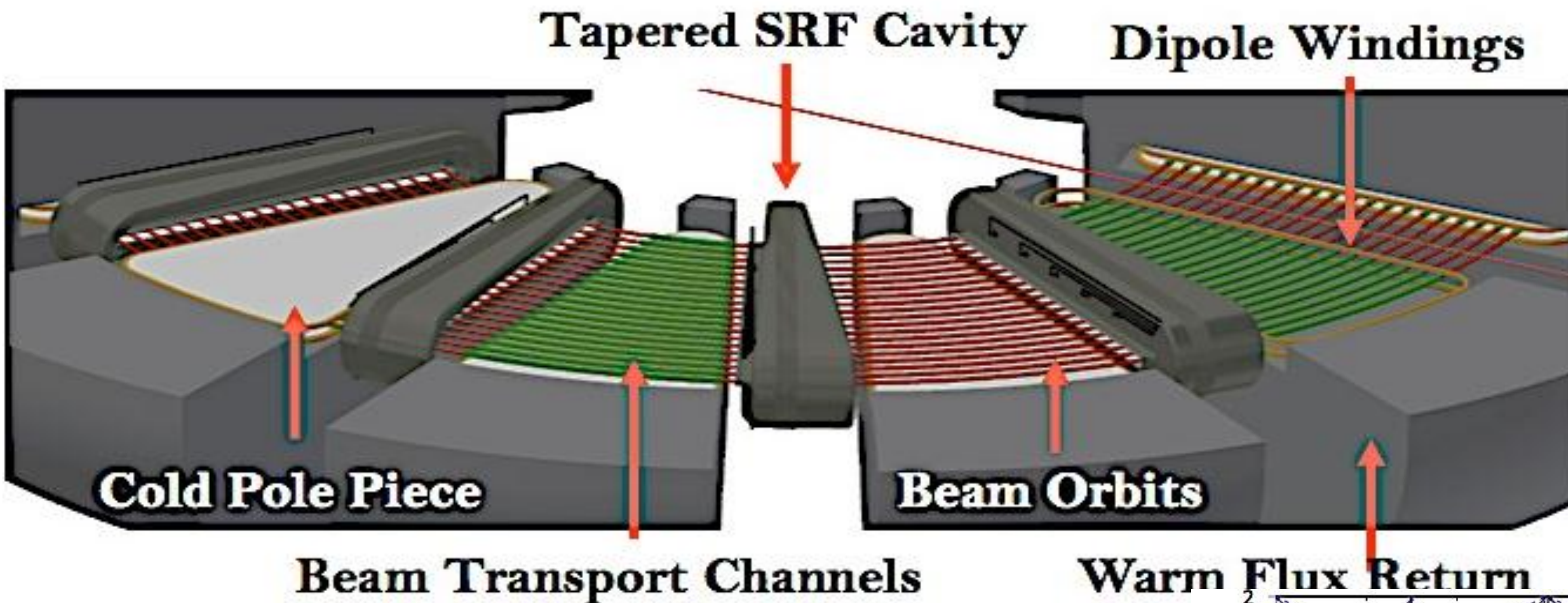
MgB$_2$ CIC windings

operating @ 15 K

give 2 T and 3 T versions.



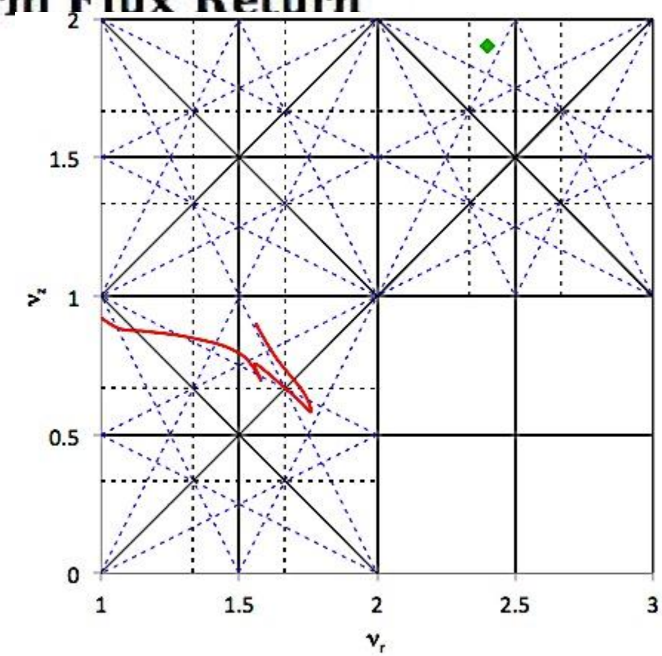
Superferric Strong-Focusing Cyclotron



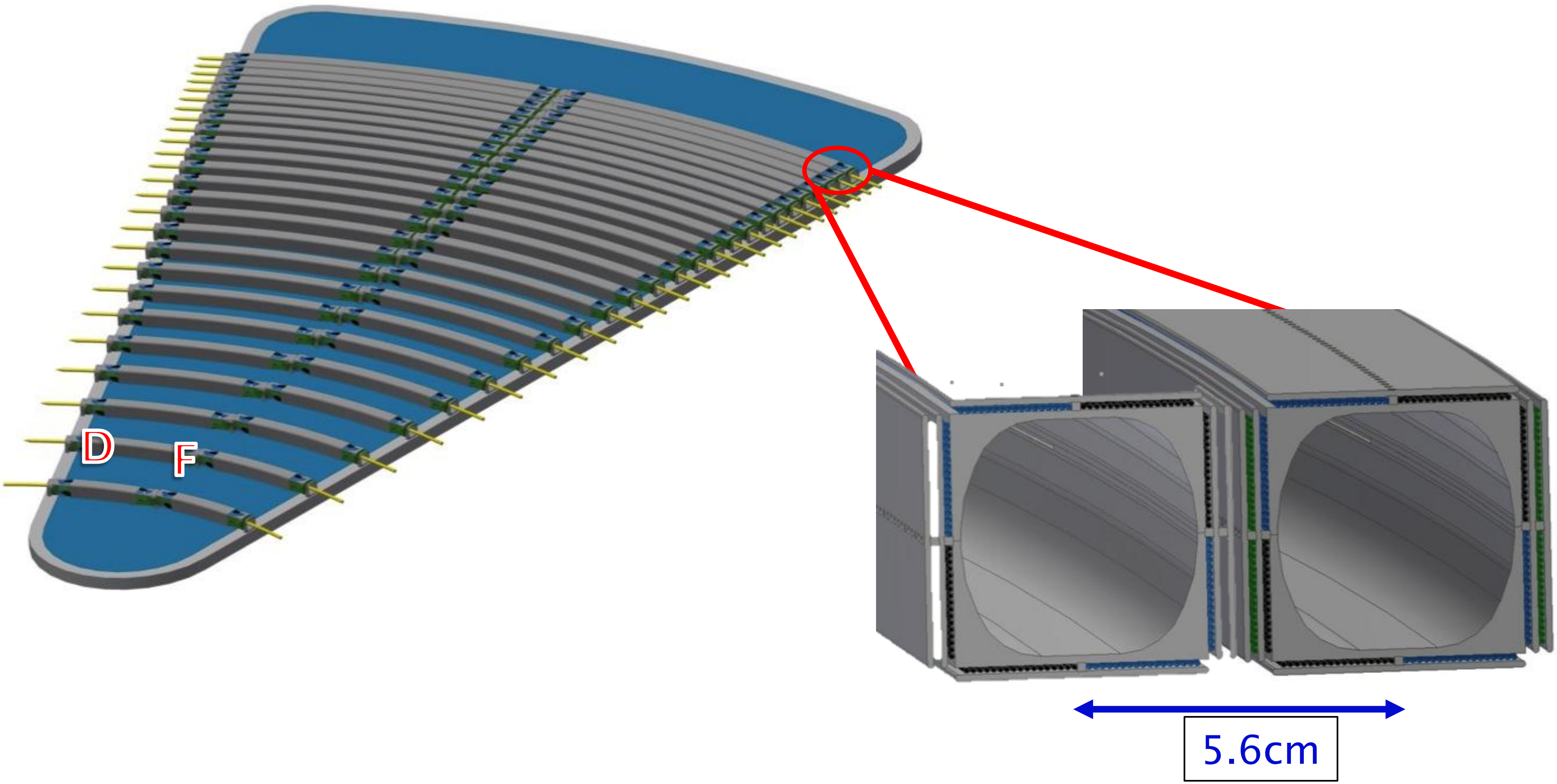
10 mA CW protons @

100 MeV for isotope production,

800 MeV for ADS destruction of TRU



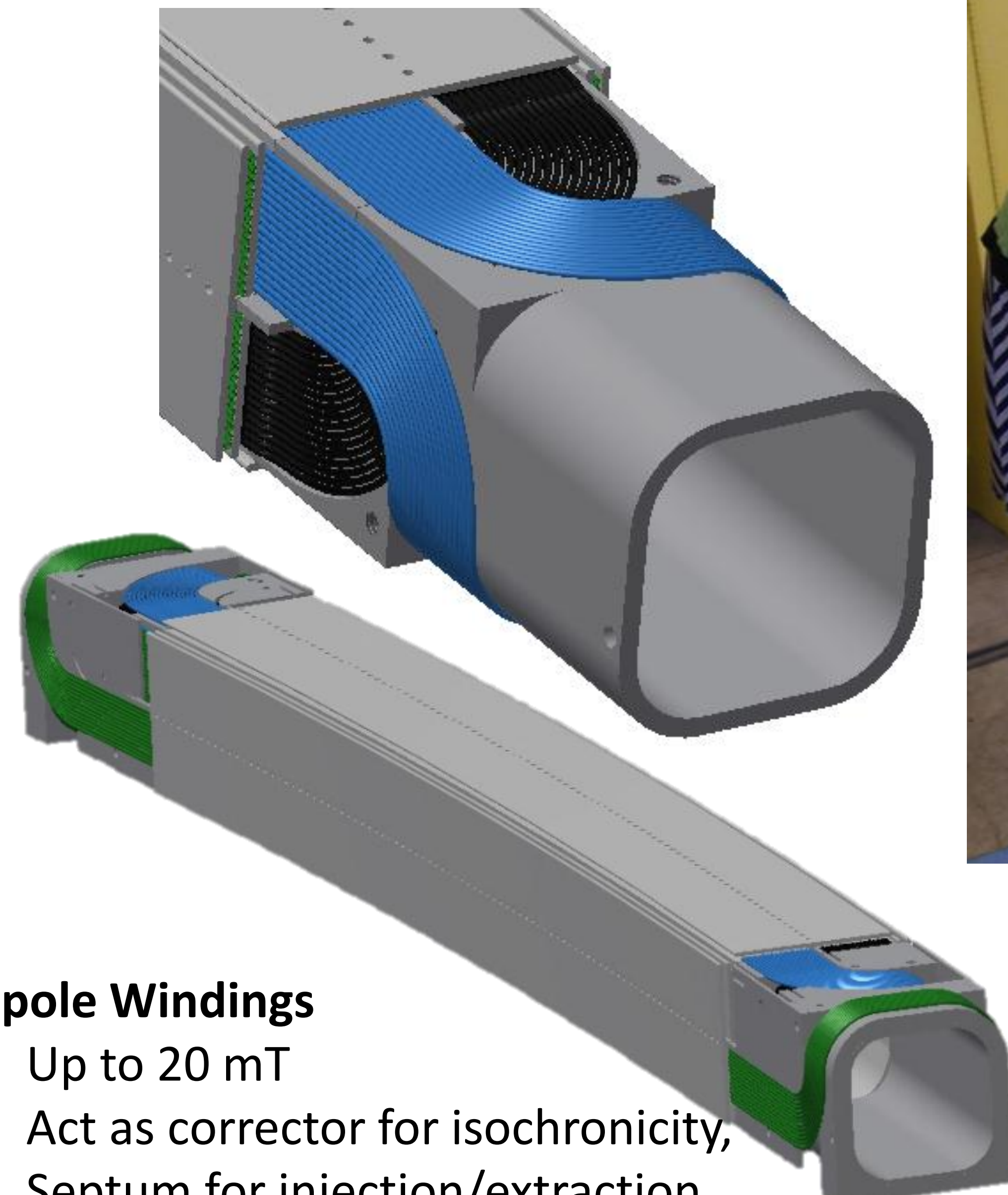
F-D doublet on each orbit, each sector



BTC dimensions are set by the requirements for beam separation at extraction.

>80% of horizontal aperture is useful for orbits.

MgB_2 windings on beam transport channels



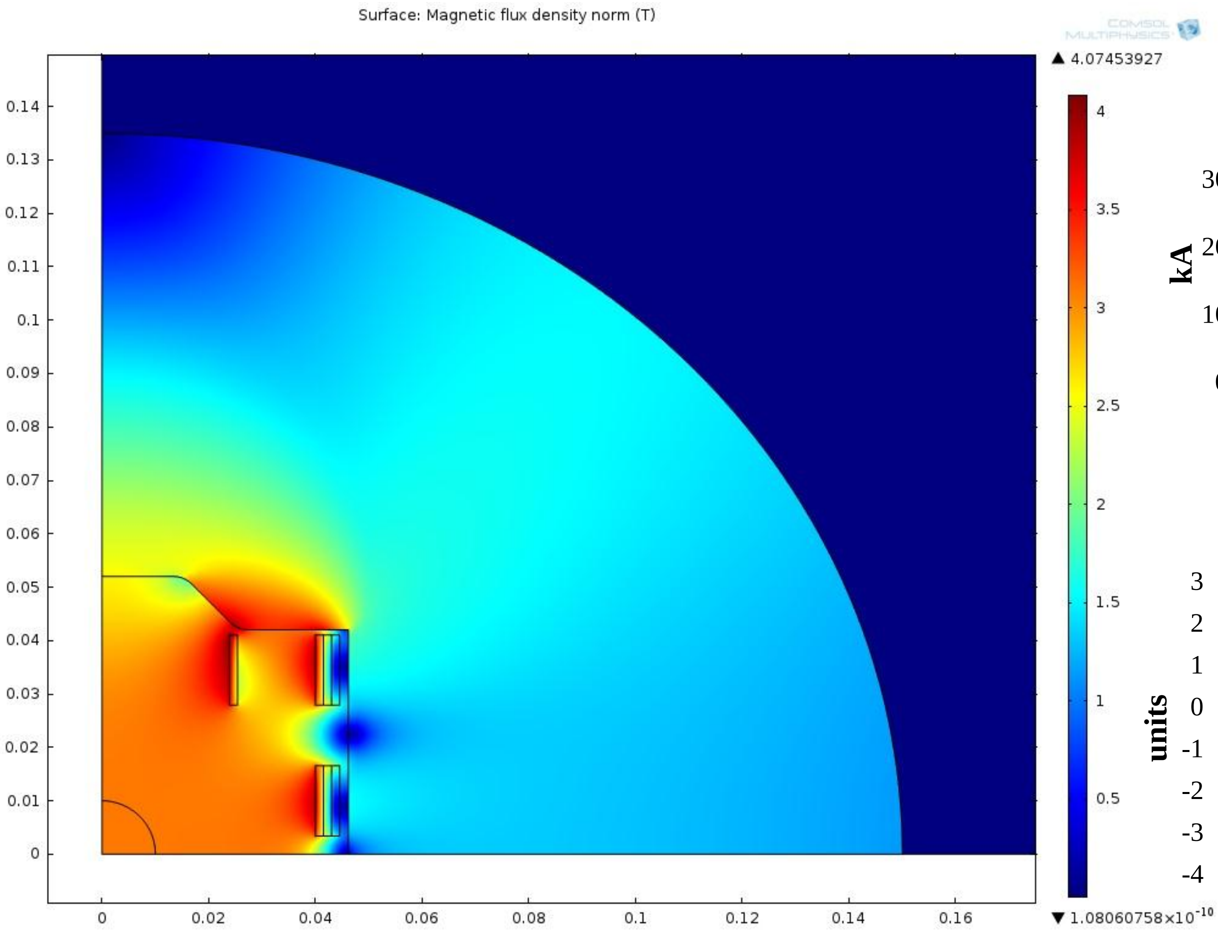
Quadrupole Windings

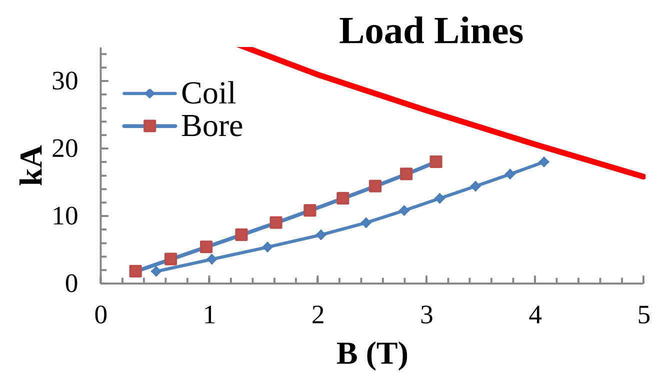
- Up to 6 T/m
- Panofsky style
- Alternating-gradient focusing
- 6 families provide tune control

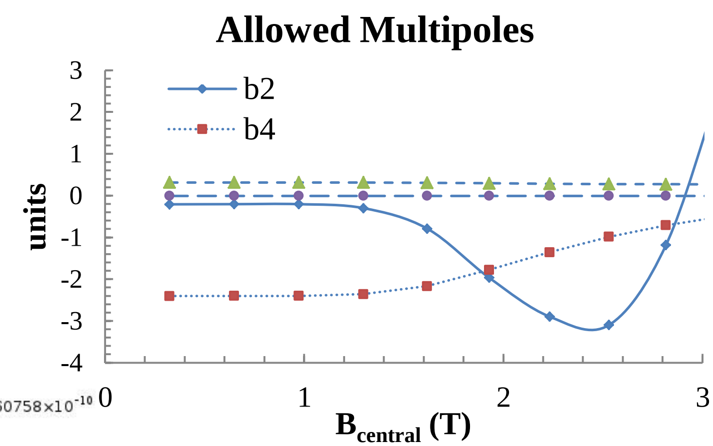
Dipole Windings

- Up to 20 mT
- Act as corrector for isochronicity,
- Septum for injection/extraction

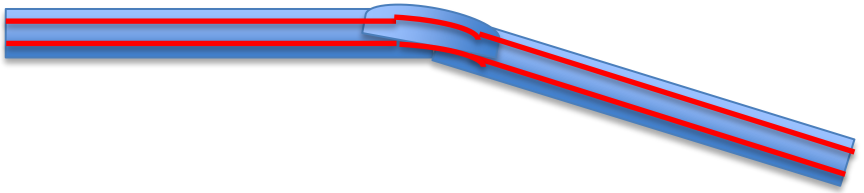
Now for protons & ions @ MEIC…







If you want long magnets with a lot of sagitta…



Needs CIC cable, not Rutherford cable