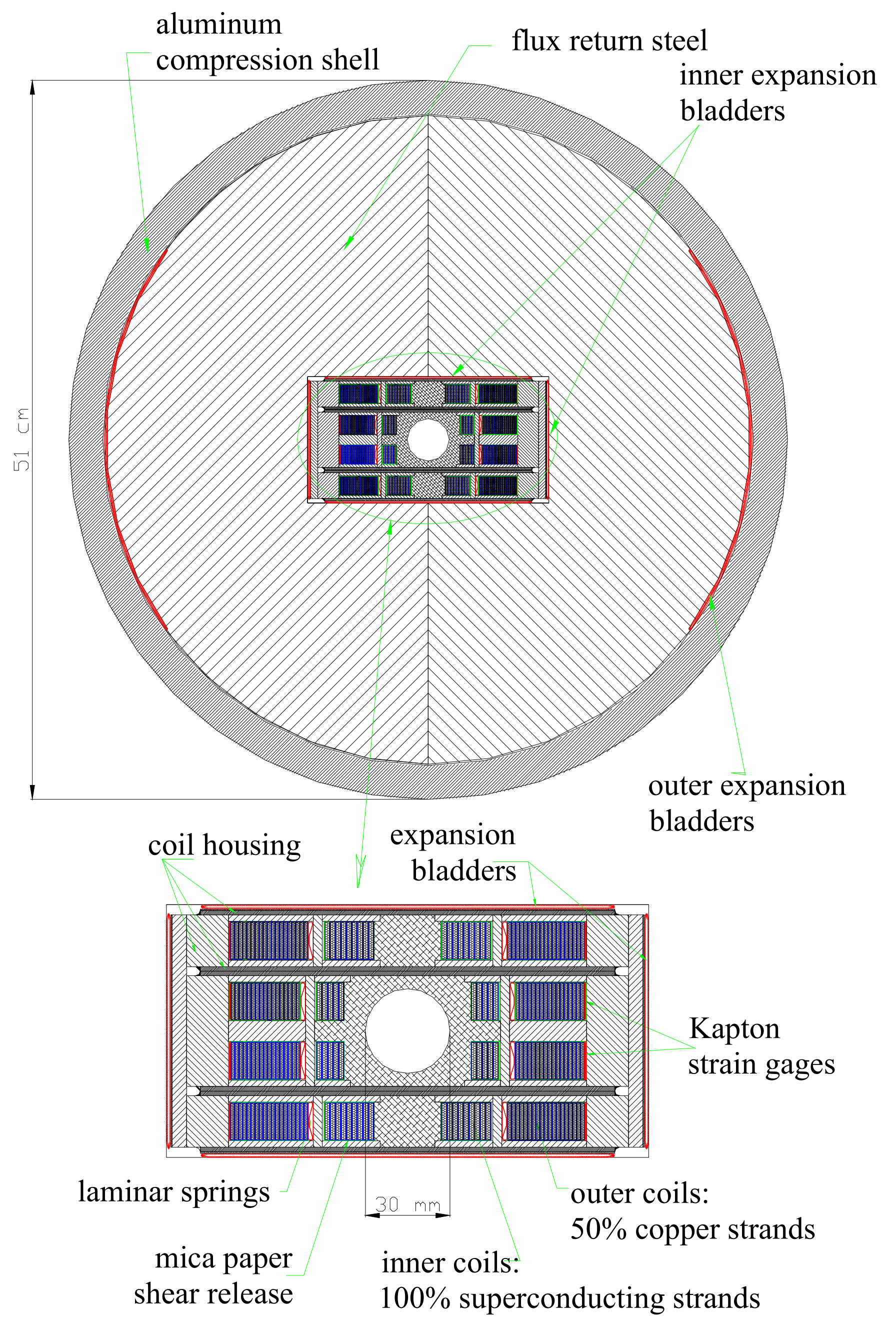
12 Tesla Hybrid Block-Coil Dipole for VLHC

Raymond Blackburn, Nicholai Diaczenko, Tim Elliott, Rudolph Gaedke, Bill Henchel, Ed Hill, Mark Johnson, Hans Kautzky, Peter McIntyre, Al McInturff, and Akhdior Sattarov

Texas A&M University



aluminum
compression shell
flux return steel
inner expansion
bladders
51 cm
outer expansion
bladders
coil housing
expansion
bladders
Kapton
strain gages
laminar springs
30 mm
outer coils:
50% copper strands
mica paper
shear release
inner coils:
100% superconducting strands

Motto for high-field dipoles:
keep it simple, stupid!

The problems for Nb_3Sn high-field dipoles:

- Conductor is fragile – wind & react, degradation under Lorentz loading
- Filaments are fat –persistent current multipoles, snap-back
- Preload is immense – how to assemble?
- Conductor is expensive – 10 x NbTi

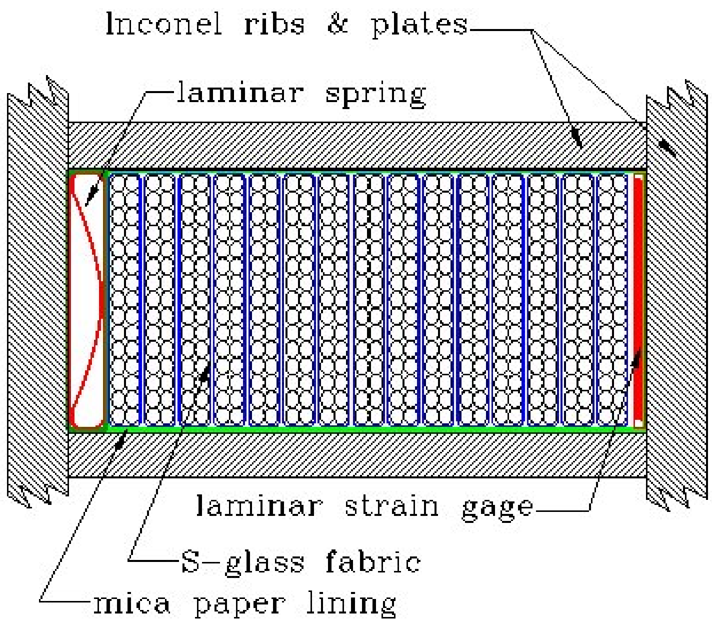
Block-coil designs enable us to address these problems

- Stress management: limit coil stress
- Racetrack pancake coils

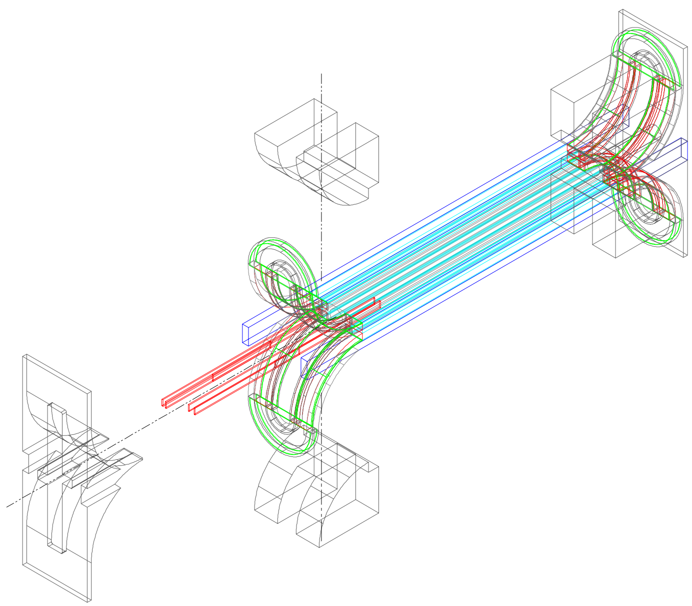
  (bend ends up/down on center layers)
- Close-coupled steel reduces amp-fac, suppresses persistent-current multipoles
- Simple assembly, preload using expansion bladders
- Conductor optimization – least superconductor of any high-field design!

Stress management

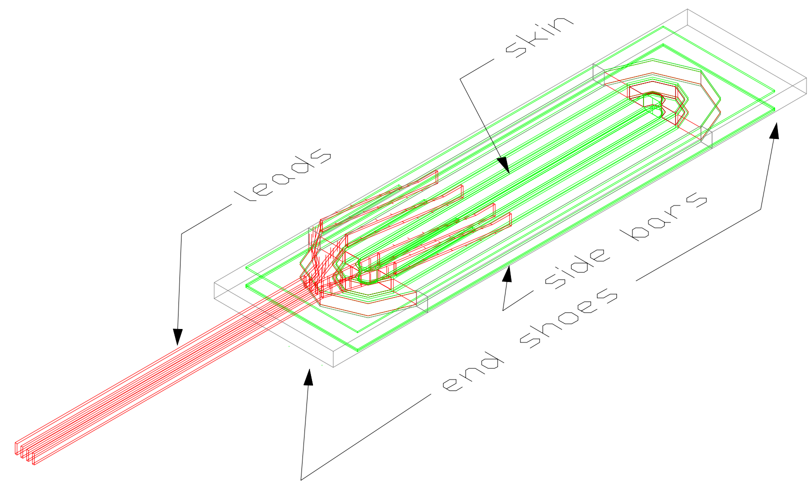
- Each block within the coil controls stress so that it cannot accumulate from inside blocks to outside blocks:



Pancake coils are compartmentalized so that they are easy to build, and control axial stress internally



Center double pancake



top/bottom single pancakes

We have built a NbTi practice dipole to test fabrication, assembly issues

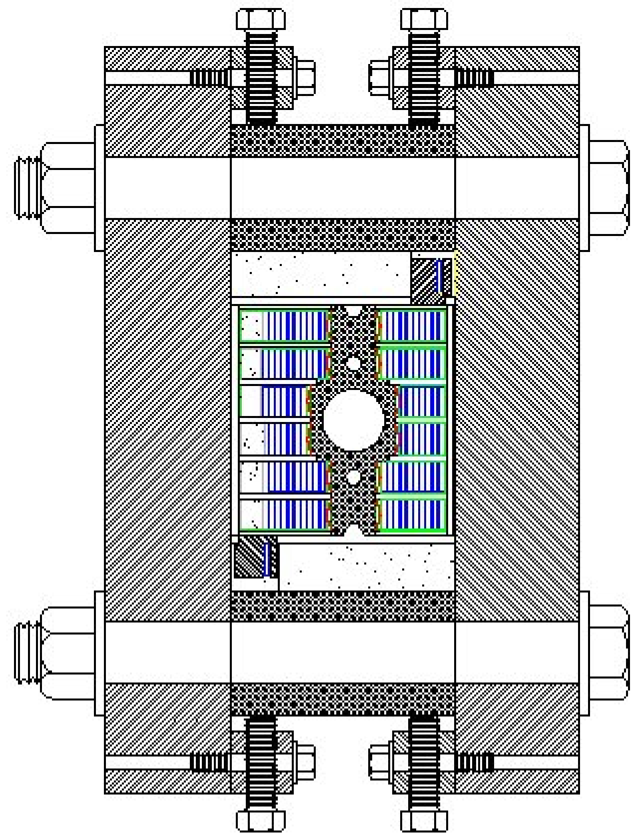
7 Tesla short-sample field

6 layers

Single-block pancakes

Ends planar

Ribs, plates, springs, shear release, S-glass insulation, strain transducers as will be used in Nb_3Sn models.

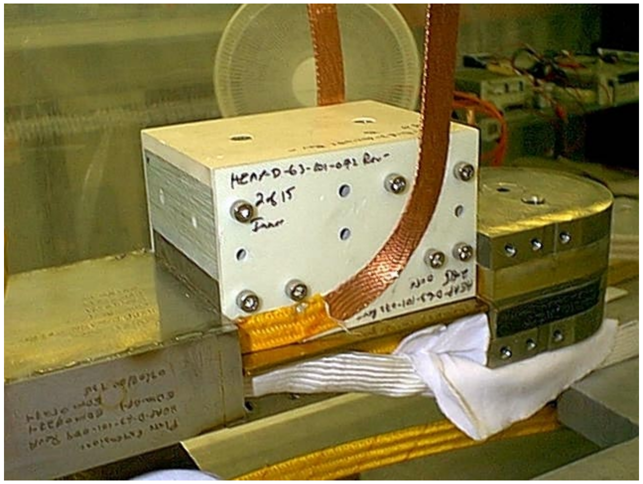


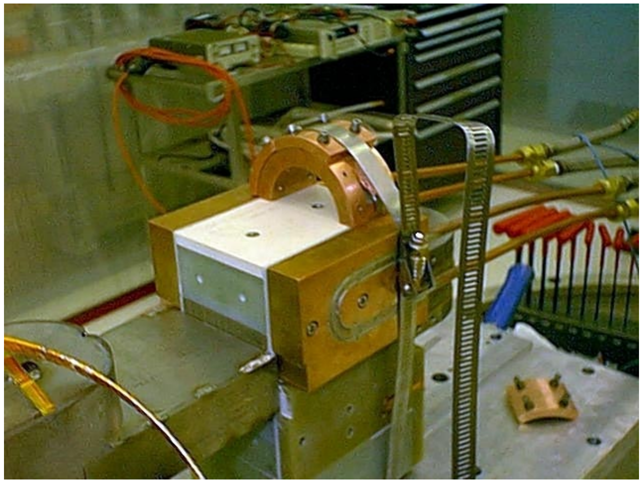
Coil winding

- Winding uses simple tooling, fixtures
- Tolerances held to .002”
- Transitions, leads made with S-bends

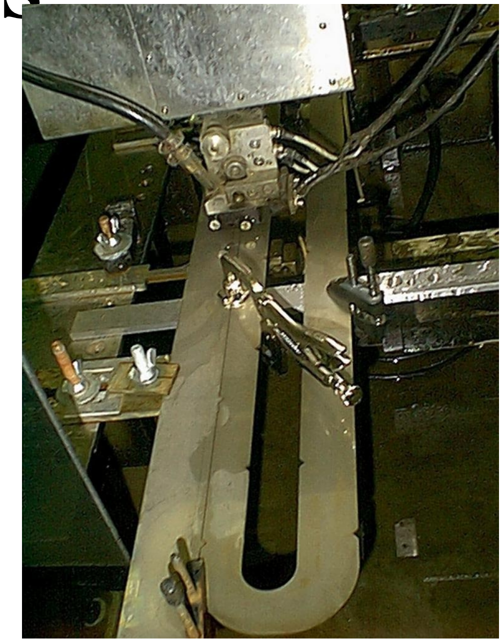
Splice joints

- Splices were made as horseshoe, 4” overlap
- Heaters control temp
- Splice rigid on coil end
- For Nb_3Sn we will make straight splices

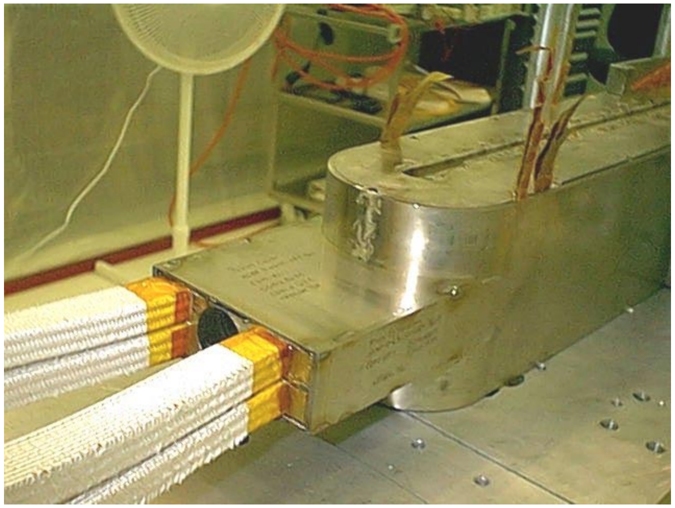




Ribs & plates control stress both transverse and axial

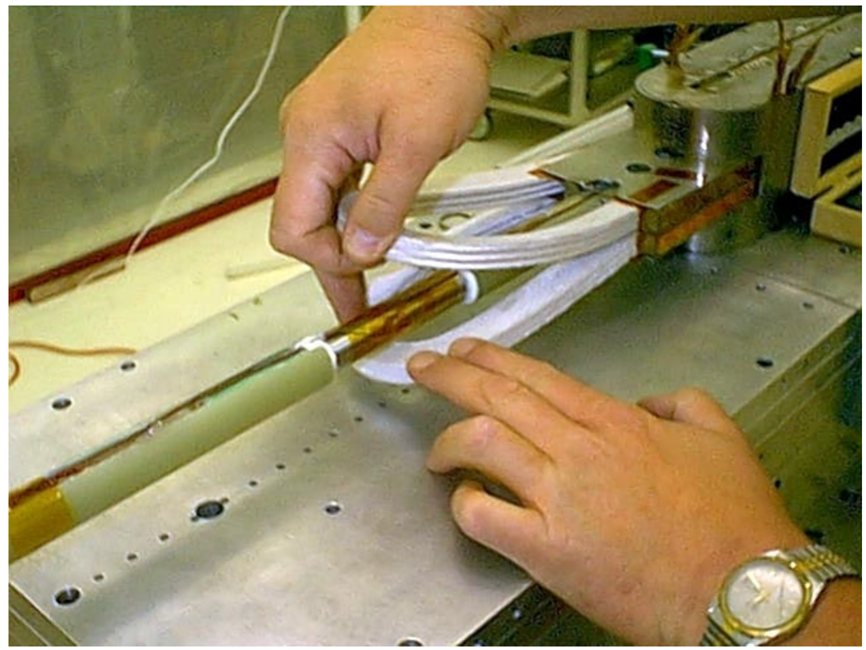


- Ribs are EDM cut, give dimensional control and bypass of stress.
- Plates are fabricated as two half shells, welded together at the ends to control axial stress.



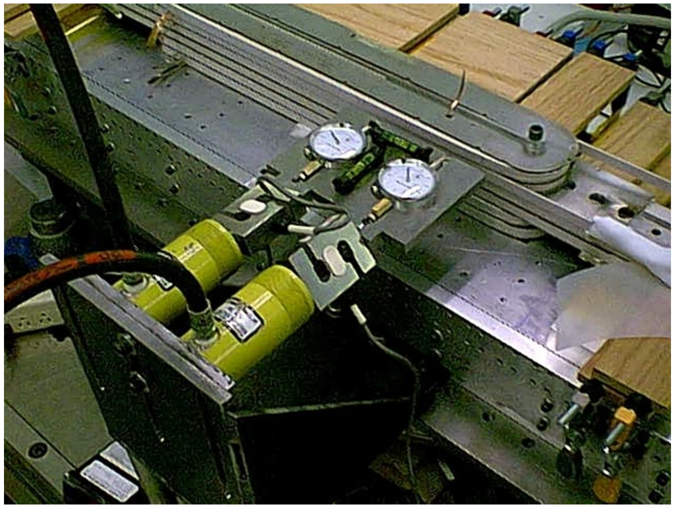
Bending ends on a pancake is easy!

- Coil package is flexible, ends are easily bent by hand.
- Practice dipole was built with planar coils, Nb_3Sn model will have ends of center 2 layers bent 90^o.

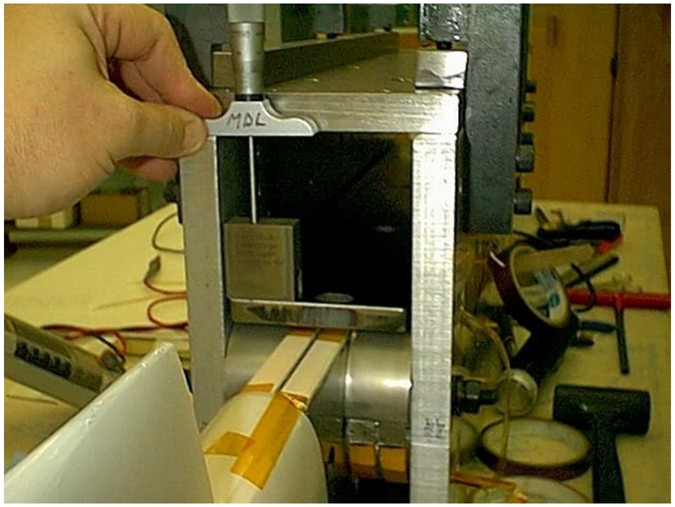


Measure & control coil placement

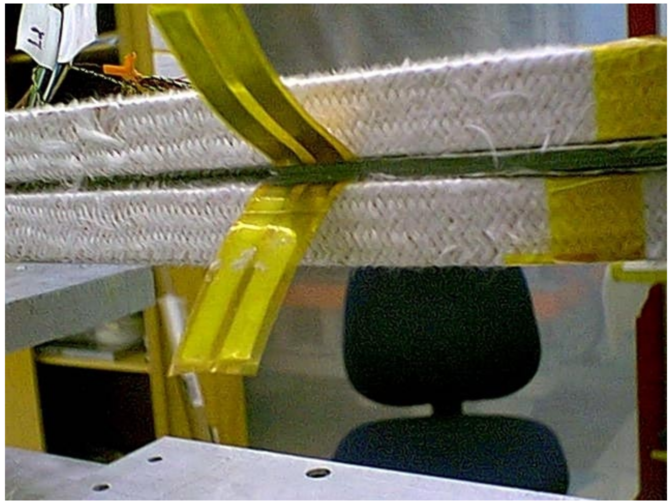
- Measure coil thickness as function of compressive load

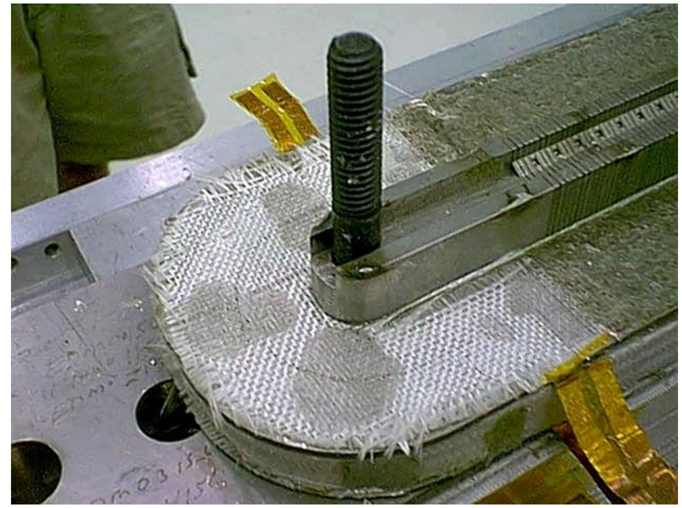


- Measure plate, rib locations as preload is applied, to assure closure of the rib/plate interface



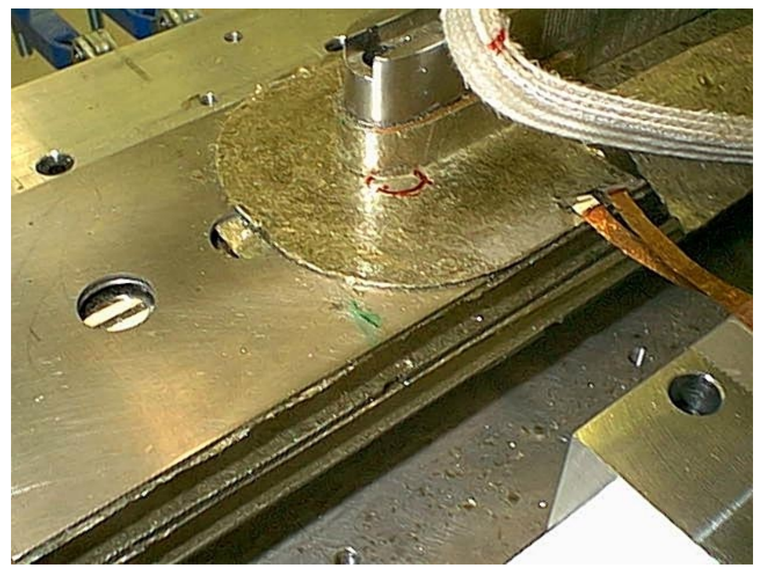
Quench heaters – how best to insulate?





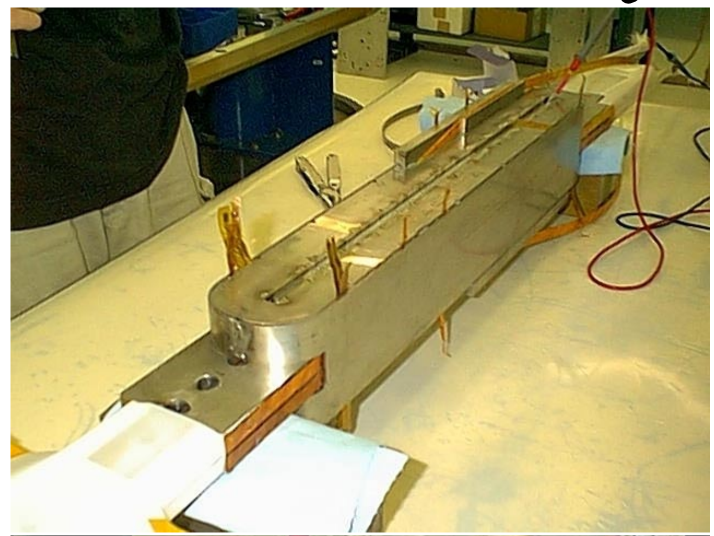
- A triple failure: cable frayed on tight bend, mica paper frayed in winding, S-glass fabric shifted in assembly.

- Dilemma between good electrical insulation, good heat transport.



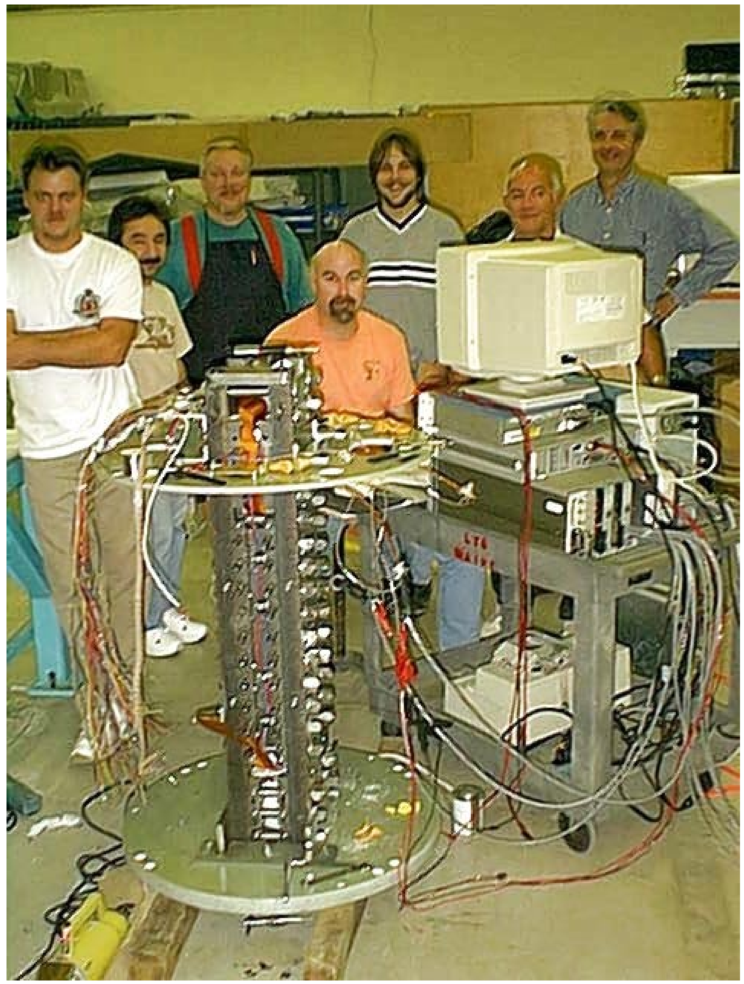
Interconnections, final assembly

- Leads brought out along top and bottom in support rails

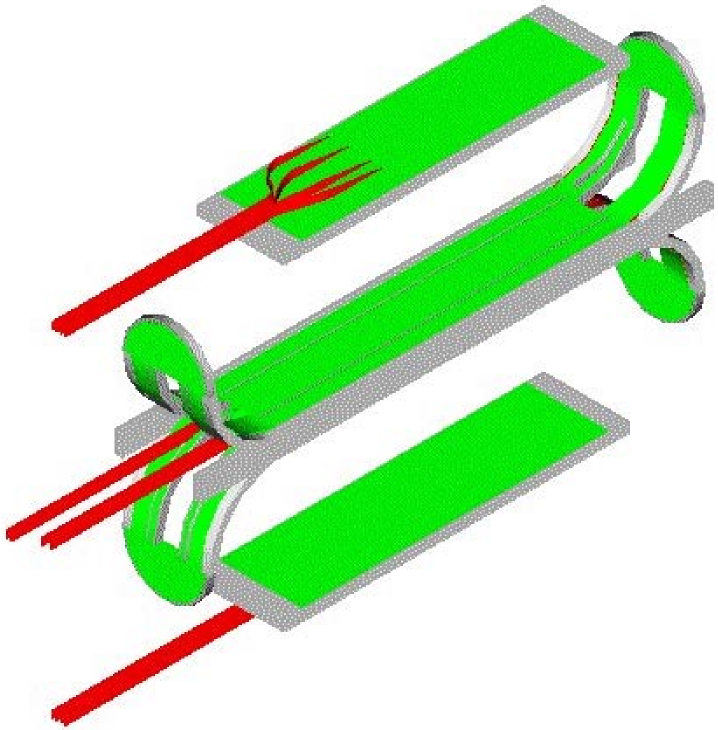


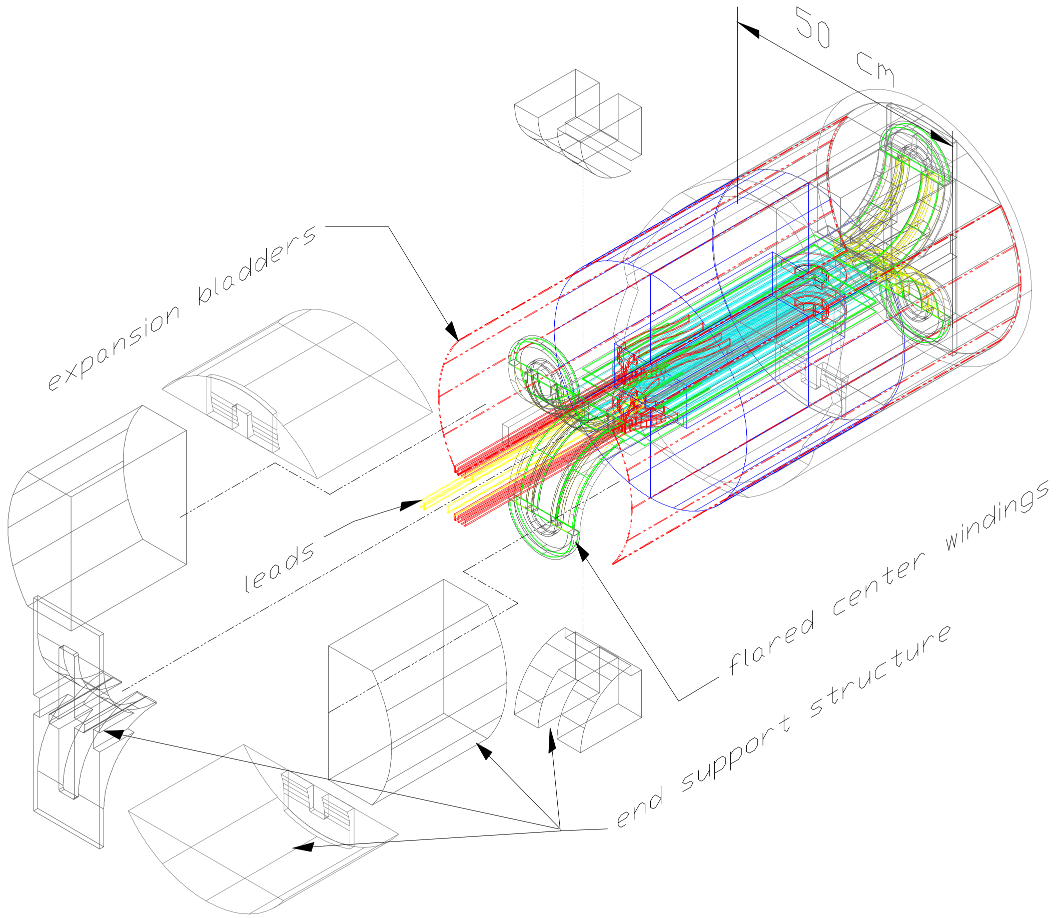
- All electrical connections routed on flex PC top/bottom

The 7 Tesla NbTi learning model is complete and shipped to LBL for testing



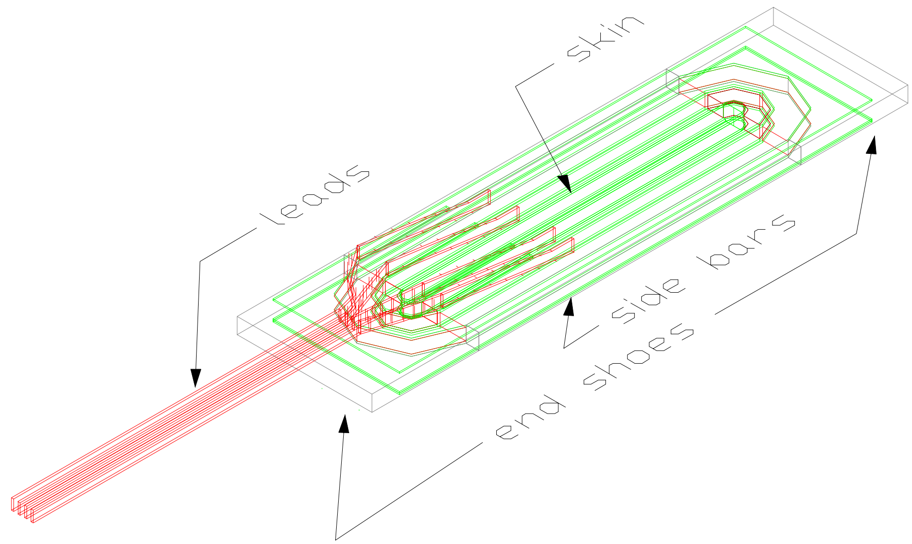
12 Tesla Nb_3Sn design



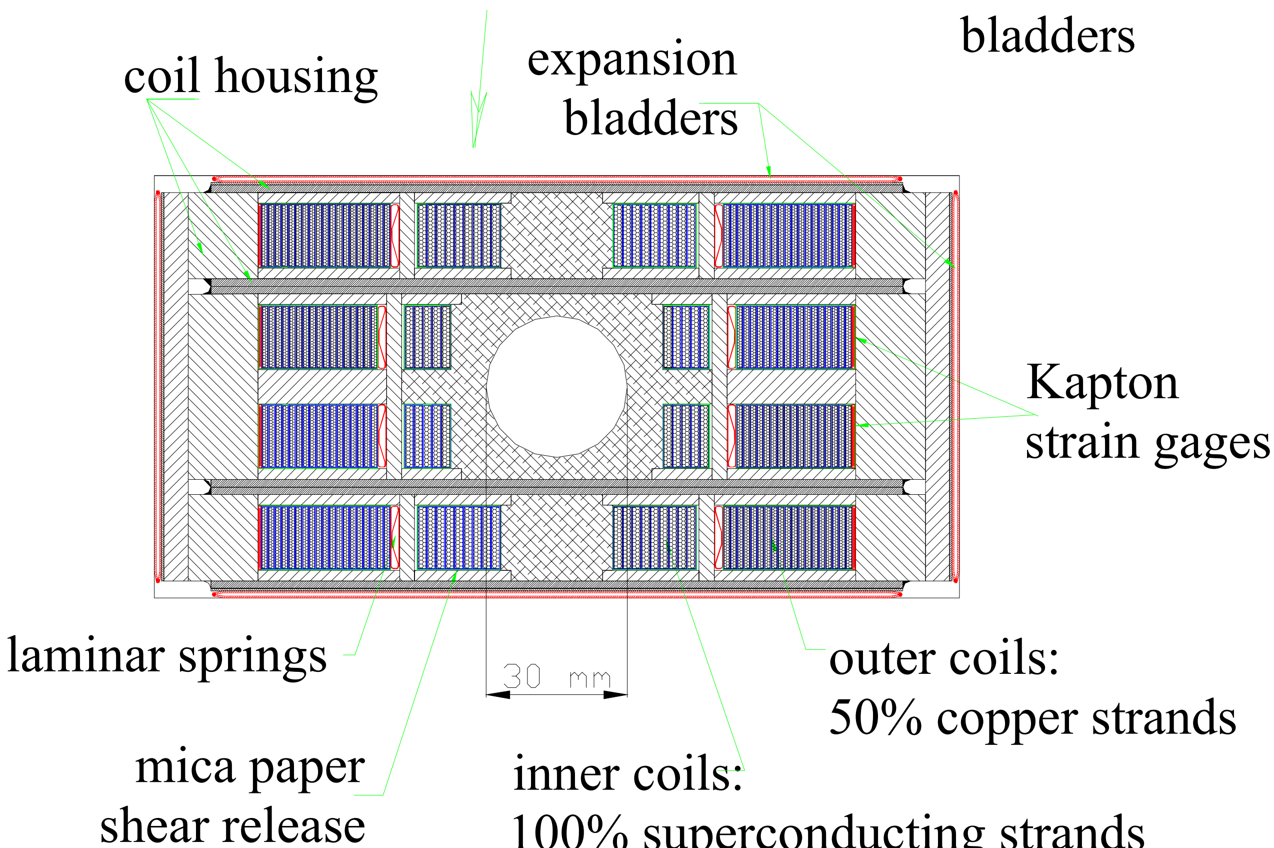


Pancake coils contain internal complete internal structure

- Side bars give stiff support, tie ends
- Skins welded to side bars – preload
- Pusher shoes on ends – axial preload
- Straight leads

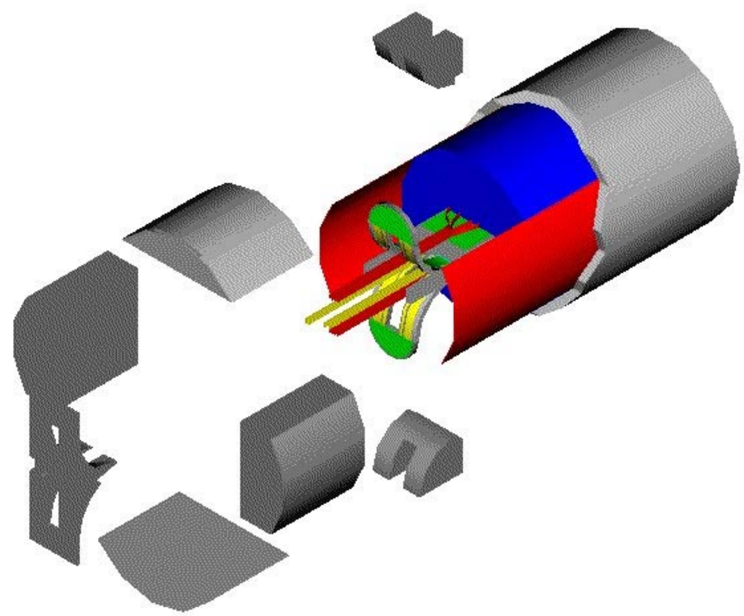


Preload coil within flux return using additional bladders



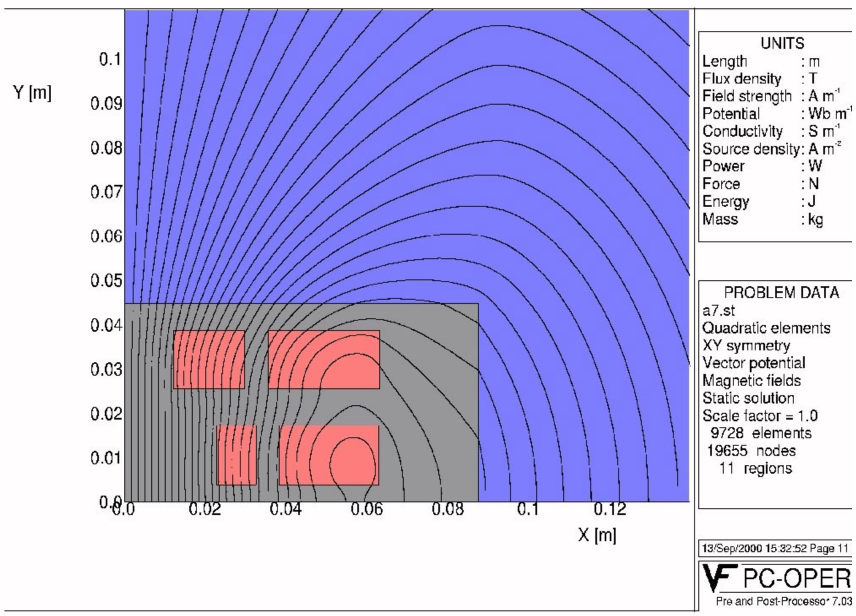
Provide overall preload using expansion bladders

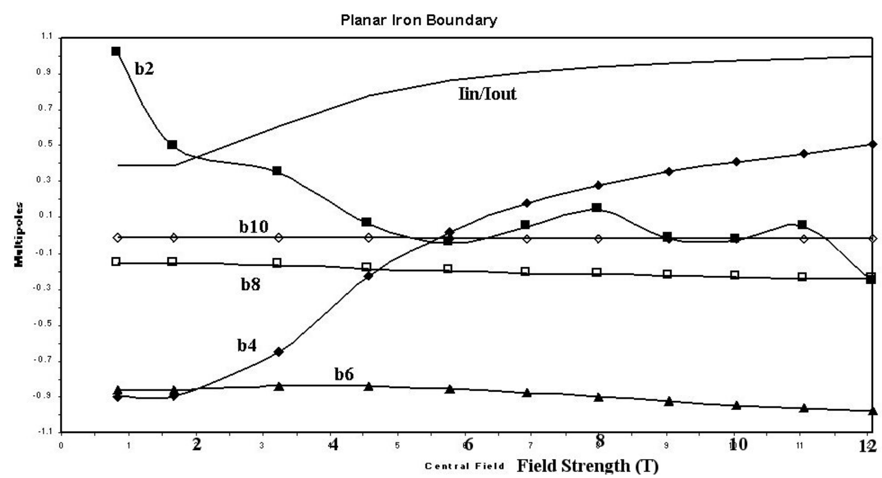
- Flux return split vertically, serves as piston
- Bladders filled with low-melt Wood's metal
- Bladders located between flux return and Al shell
- 2,000 psi pressure delivers full field Lorentz load
- In cooldown, Al shell delivers additional preload



Magnetics: planar steel, current program

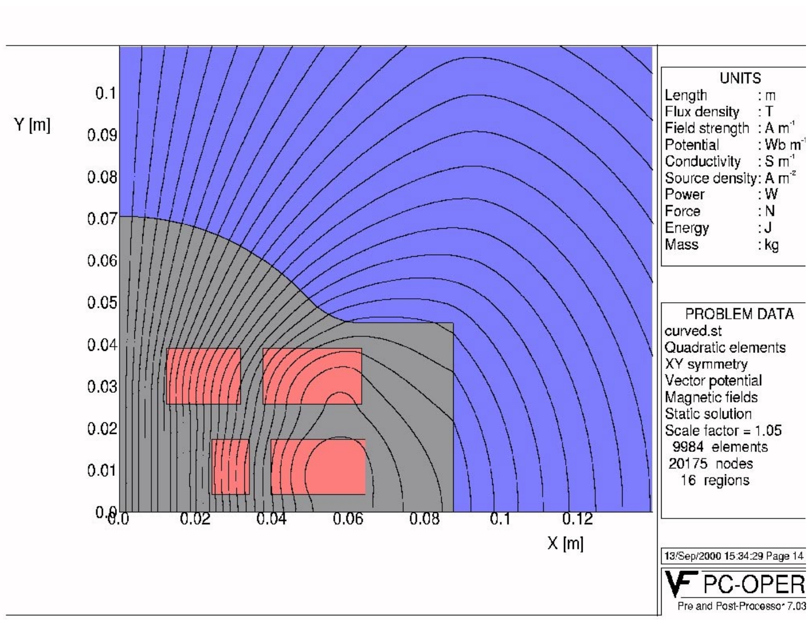
- Planar steel boundaries
- Suppress persistent current multipoles 10x
- Current program I_{in}, I_{out} to yield $b_n < 10^{-4}\ cm^{-n}$

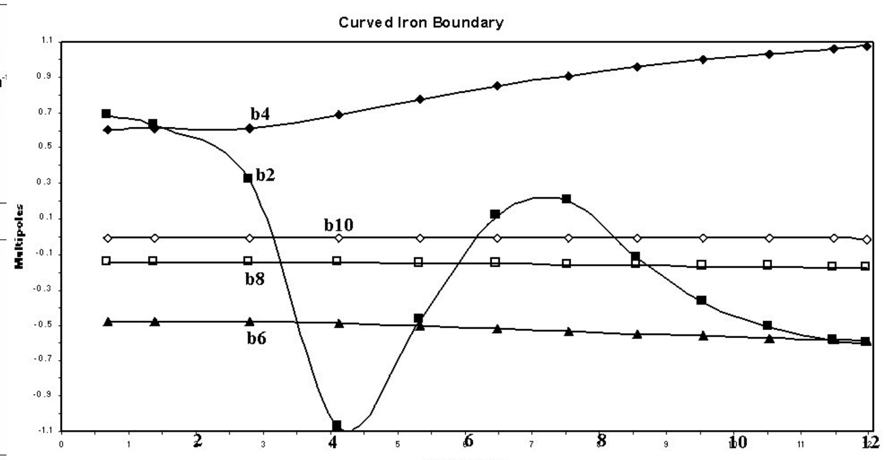




Magnetics: contoured steel, single current

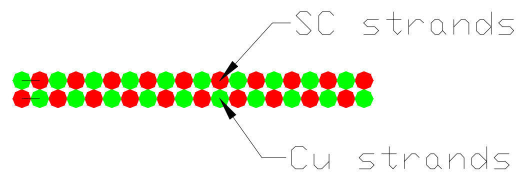
- All windings operate at a single current
- Contour flux return to cancel b_2 at injection
- $b_n < 10^{-4}$ cm^{-n} over 20:1 field range (no holes!)





Optimize the conductor

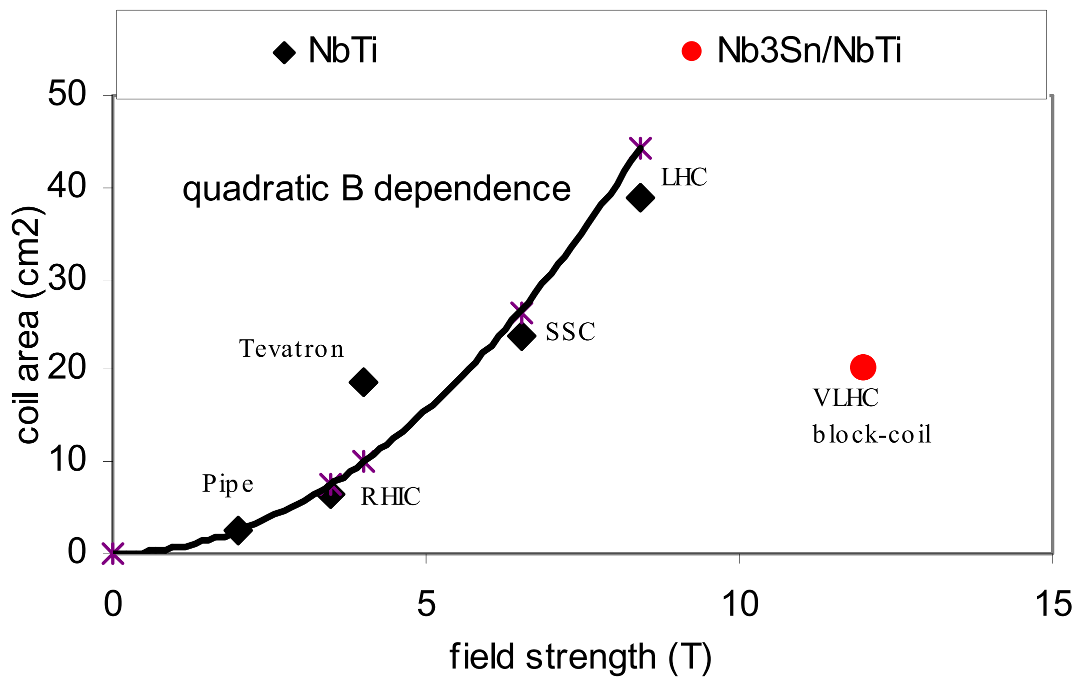
- Quench stability – enough Cu to heal microquenches – much less Cu than…
- Quench protection – distribute the energy during a quench -- $j_{Cu} < 2{,}000$ A/mm^2
- The expensive way: draw Cu into SC strand for both stability and protection.
- The optimized way:



draw Cu into SC strand only for stability (~40%)

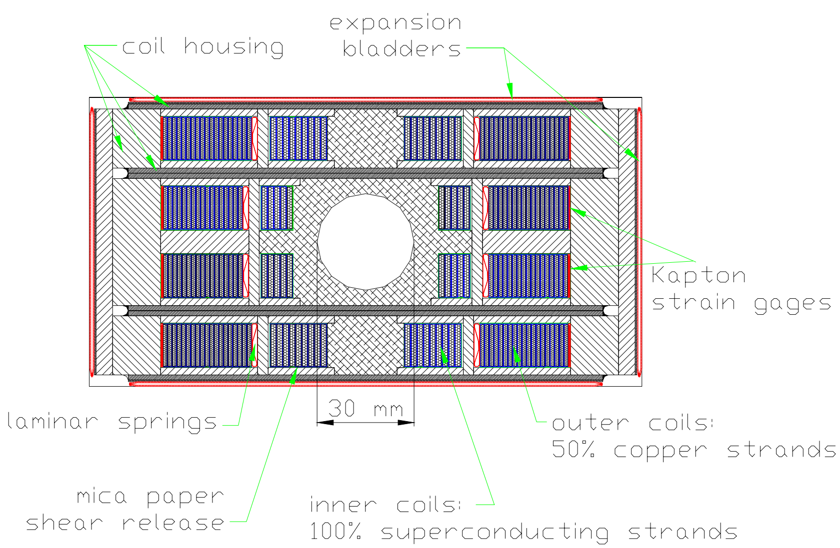
cable pure Cu strands with SC strands for protection.

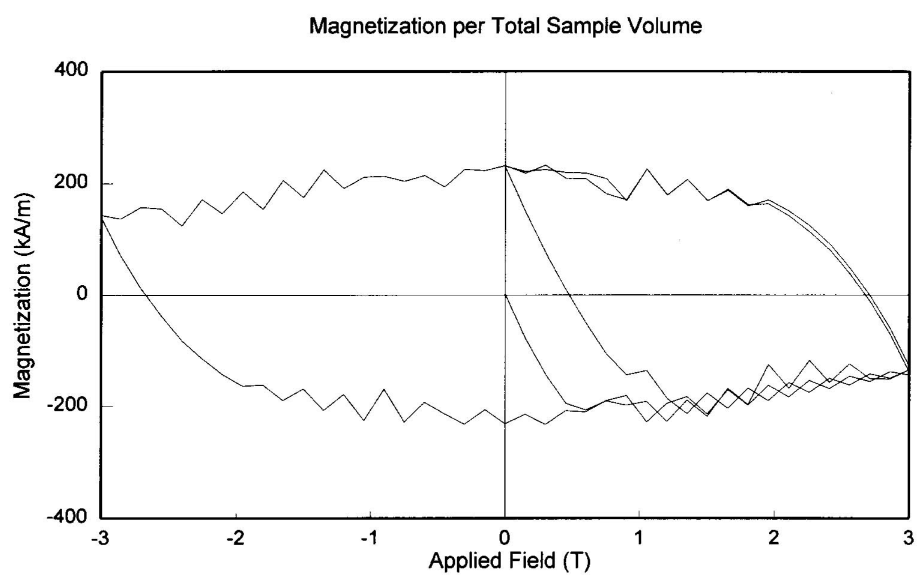
Half the outer coils are “free” Cu strands = half the cost!



Suppression of Persistent-Current Magnetization Multipoles

- Persistent-current fields are generated from current loops within the “filaments”.



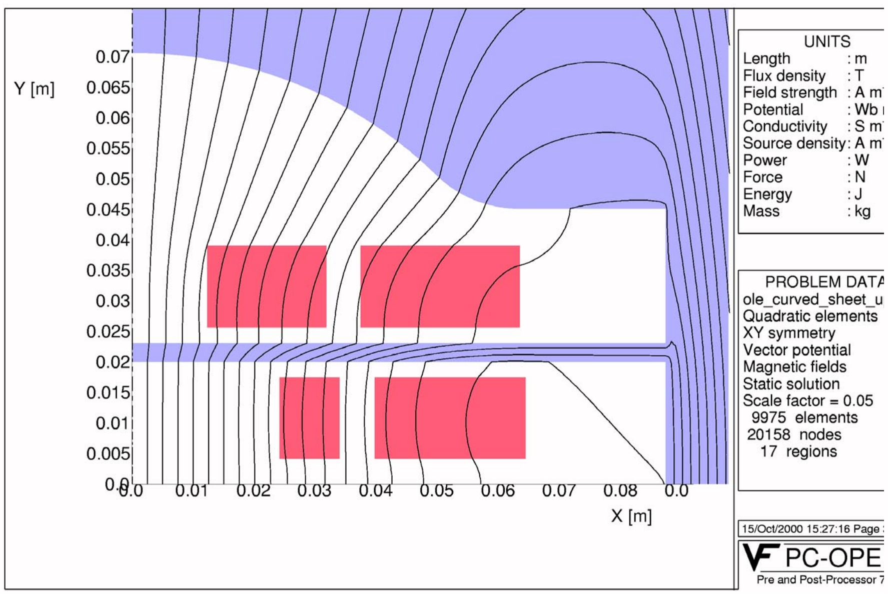


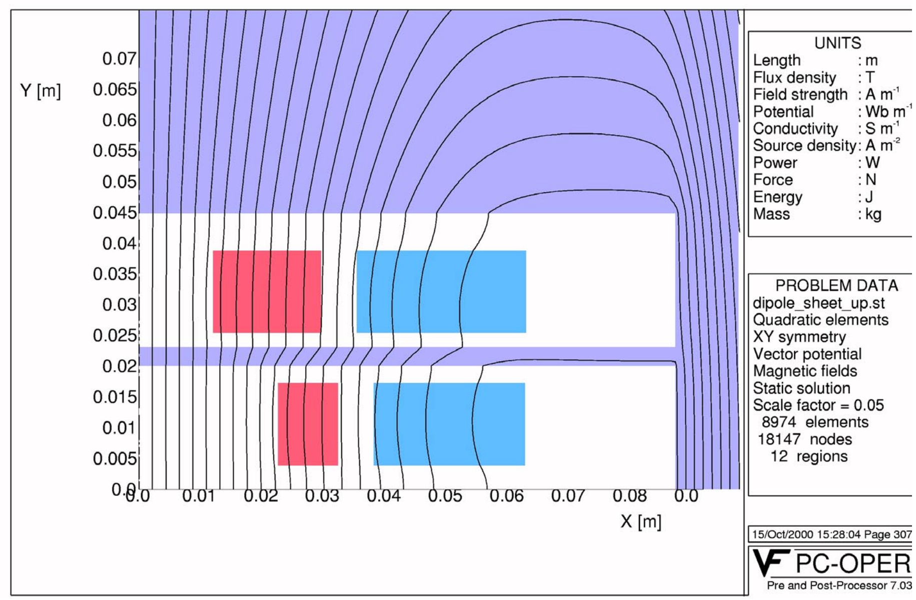
The steel boundary in a block-coil dipole suppresses p.c. multipoles at low field

We have evaluated five scenarios for p.c. multipoles. Same coil assembly in all cases.

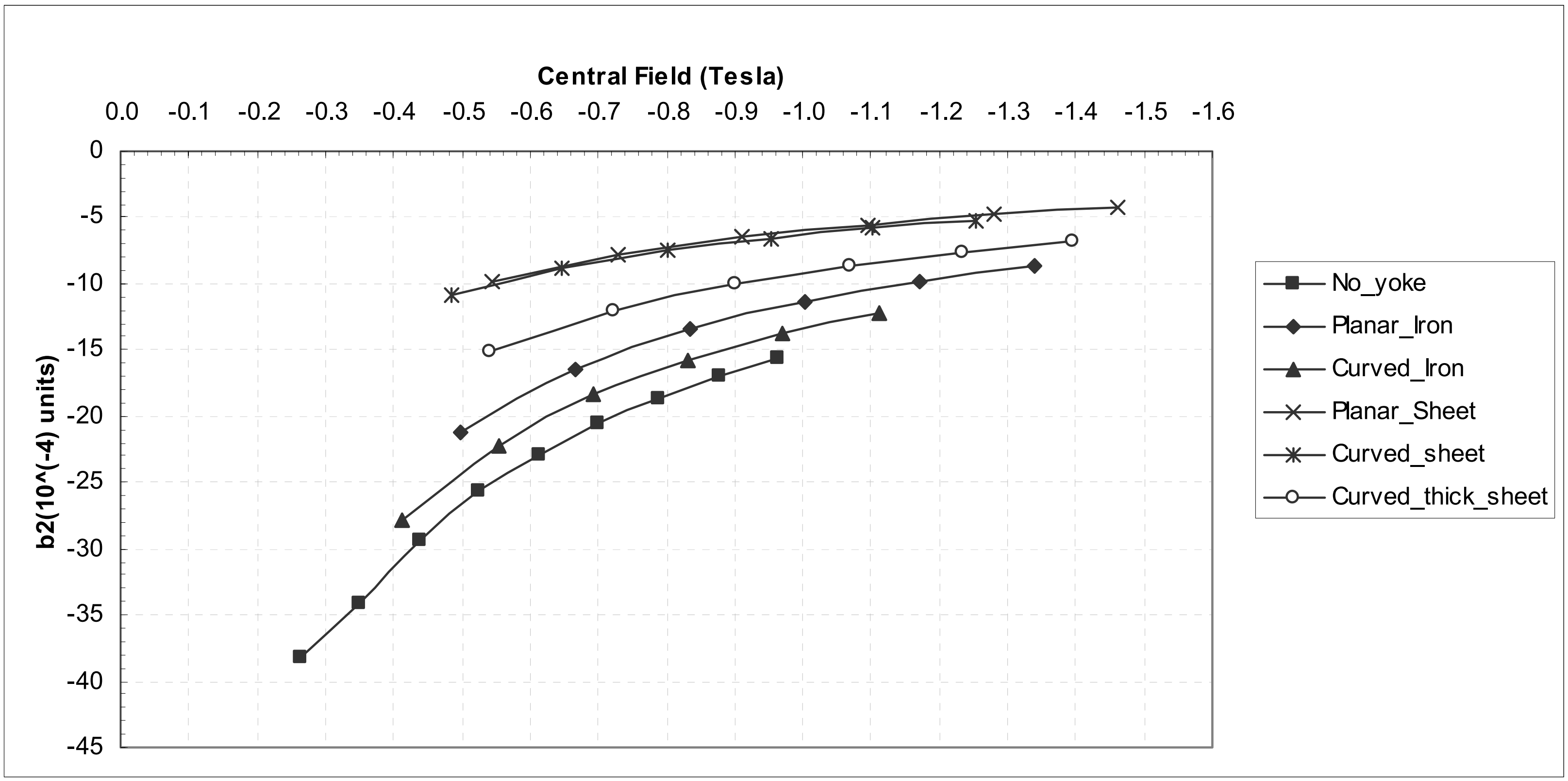
- Flat-pole flux return
- Curved-pole flux return
- Flat-pole flux return and 3 mm steel sheet
- Curved-pole flux return and 3 mm steel sheet
- No flux return (~equivalent to cos θ)

The steel flux plate redistributes flux to suppress multipoles





The flux sheet suppresses persistent-current multipoles 3x



Magnets are expensive in a hadron collider, but so is the tunnel