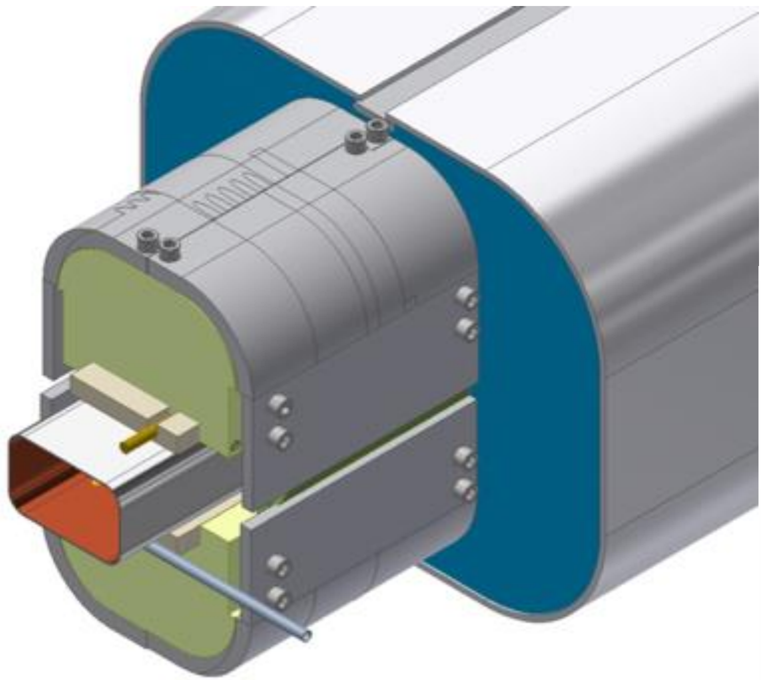
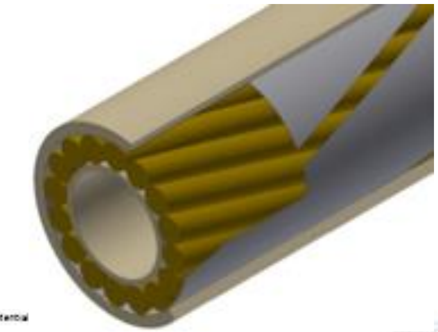
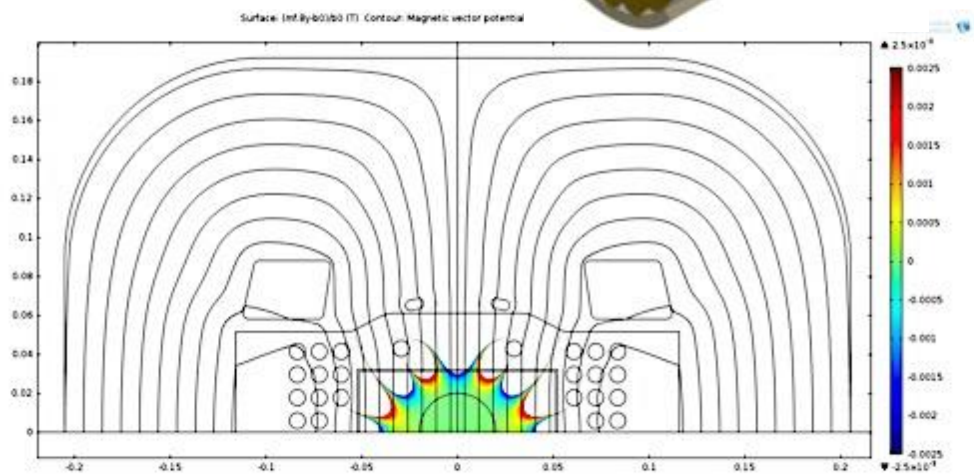
Superferric 3T CIC Dipole R&D 2016/17 Project Report







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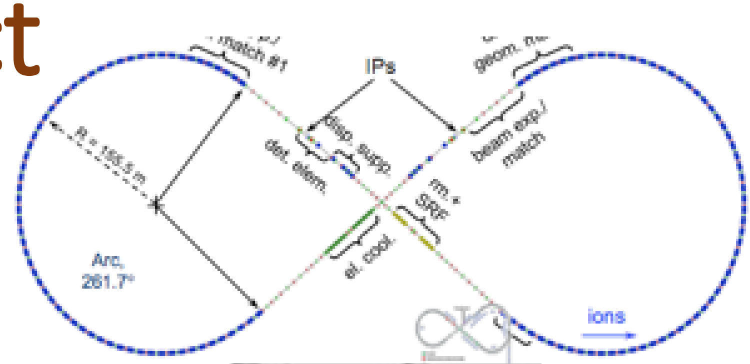
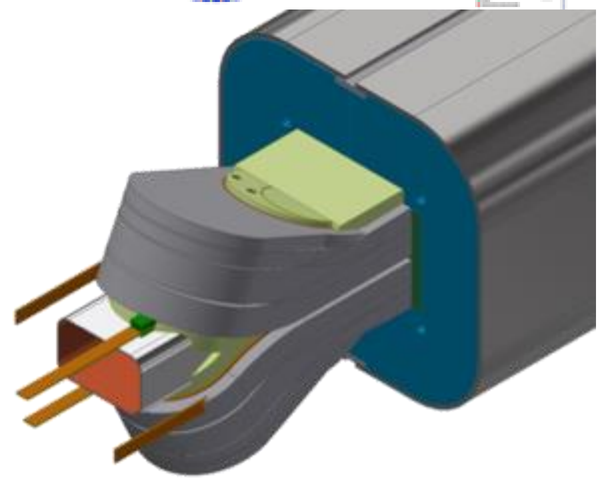
Texas A&M University

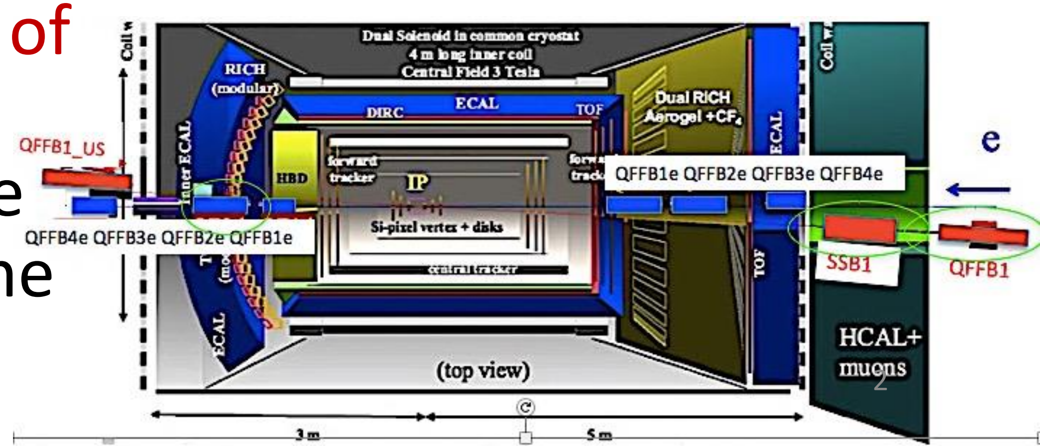
Description of the Project



- We are developing a 3 T superferric dipole with cable-in-conduit (CIC) superconductor for its windings. It is a cost-minimum basis for the Ion Ring for JLEIC.



- We have developed conceptual designs for the special magnets required for the IR designs of both eRHIC and JLEIC. The designs utilize the CIC cable to achieve all of the extreme IR requirements.



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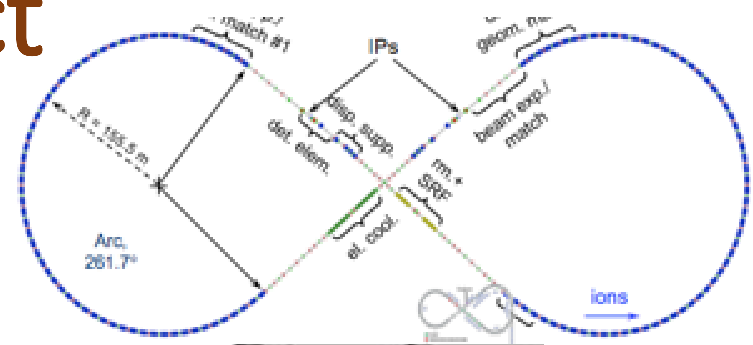

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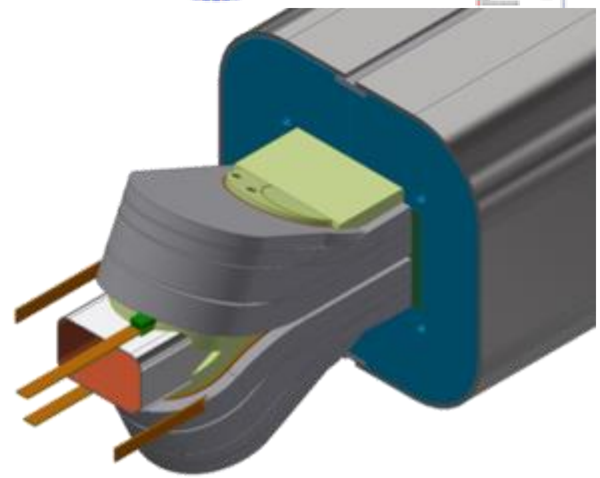

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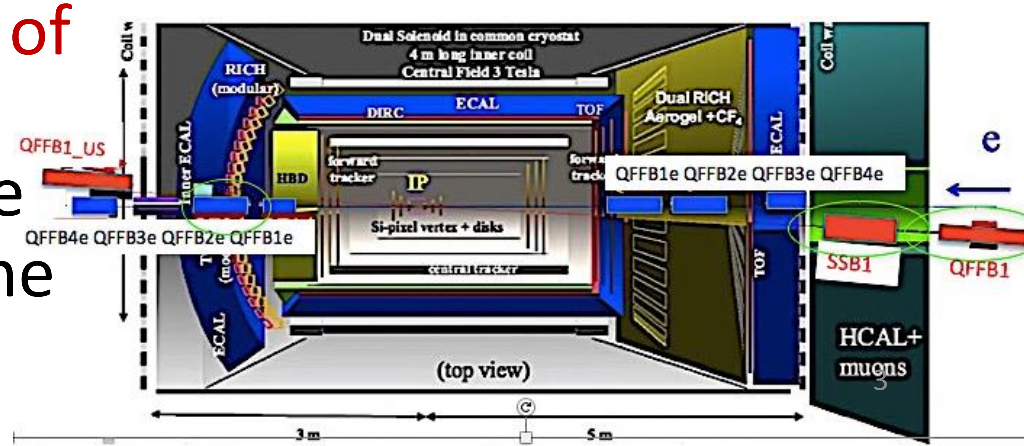
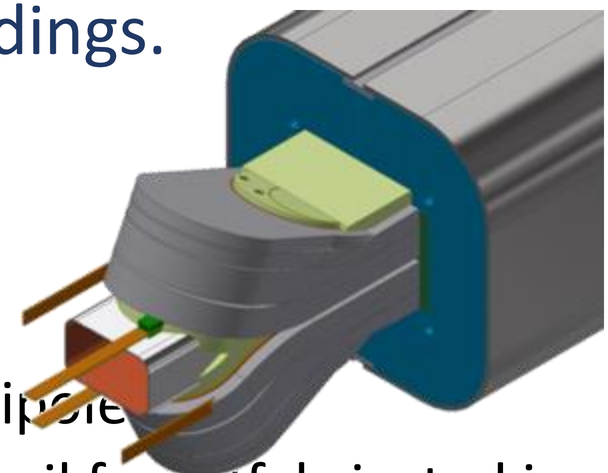


CIC Dipole R&D: 8/2017 – 3/2018

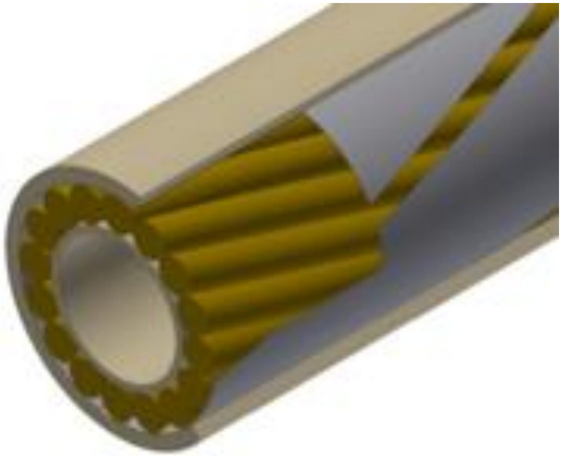


- We are developing a 3 T superferric dipole with cable-in-conduit (CIC) superconductor for its windings.
- $139K R&D was funded in August 2016.
- Goals of the 2016/17 R&D task:
  - Develop tooling for long-length CIC cable, incorporating all features required for the dipole
  - wind a few turns of the CIC cable onto the coil form (fabricated in FY15) and evaluate the coil-winding methods using CIC cable.
- $206K R&D was funded in August 2017.
- Goals of the 2017/18 R&D task:
  - Prepare long-length CIC cable
  - Fabricate optimized structural assembly for 1.2 m model dipole.
- I will report on progress toward these objectives.

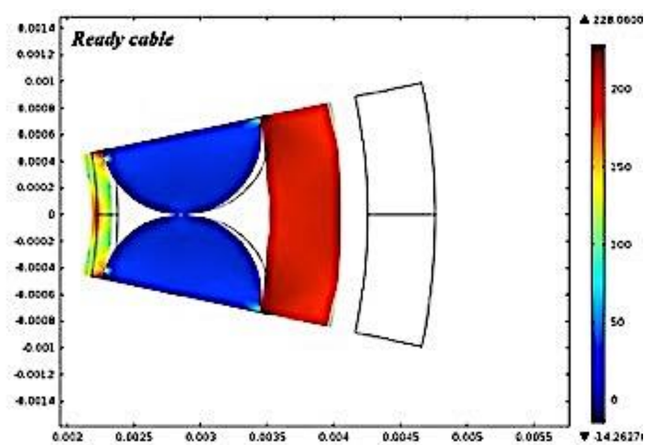
5/20/2016: Mockup winding complete

The culmination of our previous development was fabrication of a 1.2 mockup winding – validating ability to wind CIC and hold tolerances on conductor placement for collider field homogeneity.

First develop short lengths of CIC cable by hand



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

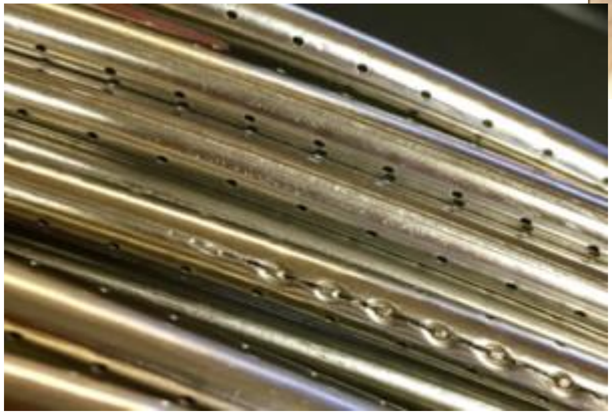


The cable is inserted in a sheath tube, and the sheath is drawn onto the cable to just compress the wires against the spring tube.

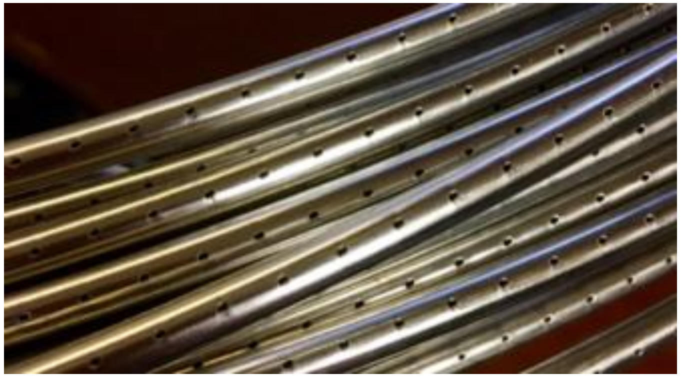
Path to long-length CIC cable

1. Perforated center tube (316L SS):
   - Punch pattern of holes in 316L SS foil strip:

   - Roll/weld strip to form tube:
   - Initial problems with weld puckers:



✓Problem solved:



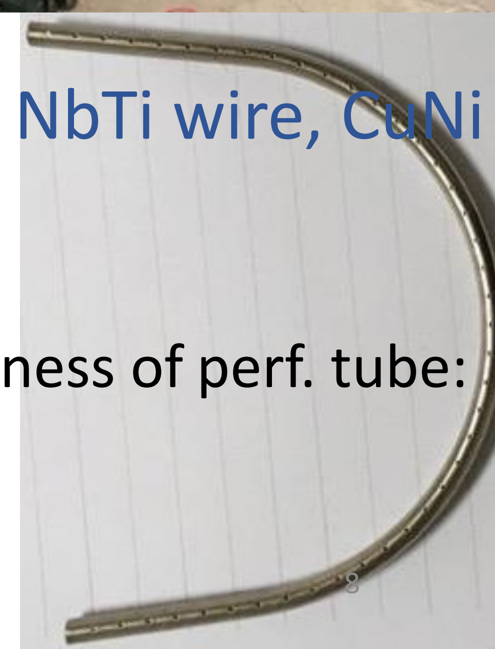
Three 125 m lenths have been fabricated, shipped to TX.

2. Draw perforated tube to final OD, removes weld bulge.

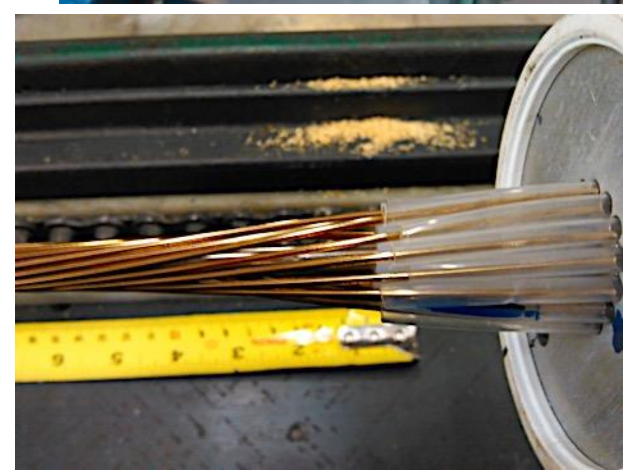
- ✓Installed/commissioned 12 m drawbench
- ✓Drew perf. tube to final size (4.762 mm)
- ✓Confirm roundness, dia. tolerance to $\pm .02mm$

3. Fabricate CIC cable using perf. center tube, NbTi wire, CuNi sheath

- ✓Form U-bend with 5 cm radius.
- ✓Remove sheath and wires, examine weld, roundness of perf. tube:



4. Fabricate long-length CIC cable on perf. center tube:



✓Developed a custom cabler that integrates on drawbench, maintains constant tension and twist pitch.

✓Completed 12 m cable.

- Extensible to 125 m inside USB.
- Option to cable at NEEW.

5. Long-length sheath tube

- Best choice for sheath material: seamless CuNi alloy 70600
  - ✓ Ordered from Small Tube Products, Delivered last year.
  - ✓ Excellent uniformity, high-strength
  - ✓ Weld/solder compatibility for splice joints
- Third option: continuous tube forming
  - HyperTech has developed CTFF to form sheath tube directly onto cable with SS foil overwrap.
  - Funded from SBIR Phase 1, successful
  - Phase 2 award notified, now on hold…
  - ✓ Demonstrated He leak-tight
  - ✓ Demonstrated no damage to wires in cable.

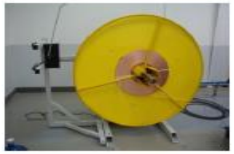
Payoff from Phase 2 SBIR @ HyperTech – 18-bobbin stranding machine @ ATC

ATC will assemble the long-length CIC manufacturing at their College Station: stranding machine, taping machine, caterpillar traction drives, long-length drawbench, and take-up of finished CIC on spool ready for coil-winding.

Expect to be making first long-length cables during Q1 of 2018.

Payoff from Phase 2 SBIR @ HyperTech - Continuous forming/welding of CIC sheath tube

Strip Payoff



Multi-wire or tape Payoff

Forming rolls

Closing Rolls

Laser Welding

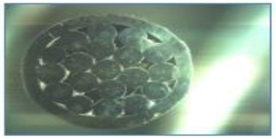
Roll Reducing

Straigtht Drawing

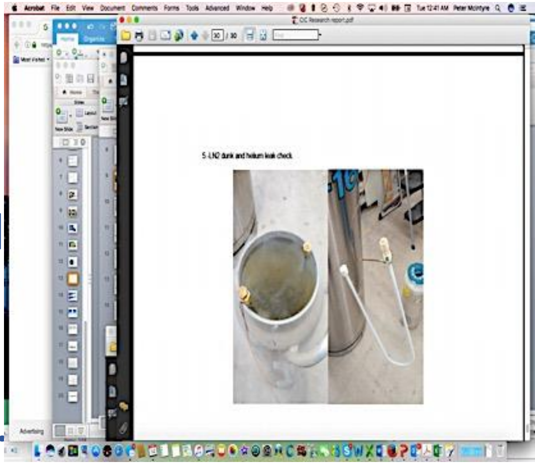
Tube Take-up

Operator Panel

Example of Welded Multifilament Wire could be stacked YBCO Tape



Hyper Tech has adapted its continuous-tube-forming process to form and laser-weld sheath tube on CIC cable (SBIR Phase 1). They can prepare km-length CIC cables with no length constraints.



- ✓ Validated that CTFF can weld Cu-Ni tube onto over-wrapped NbTi cable, no damage to superconductor
- ✓ Developed the weld process to produce He-tight seam – passed cold-shock leak tests of U-bends with He to 600 psig.

6. First medium-length CIC cable completed:

✓We have options for fabrication of long-length CIC cable:

- Cable NbTi wire and SS overwrap on perf tube @ USB, or @ NEEW.
- Pull cable into seamless sheath @ USB, or form CTFF @ HyperTech
- Draw cable to compact CIC @USB, or at Luvata.

We have succeeded in fabricating medium-length CIC cable entirely in-house

1.-Straighten the inner tube by using draw bench to pull perforated tube into straightener.

2.-Cabling 15 Al-Bronze 1.2mm OD wires around the 3/16" perforated tube with a 3" twist pitch.

2.1) Twist pitch maximum and minimum respectively –Pretty consistent

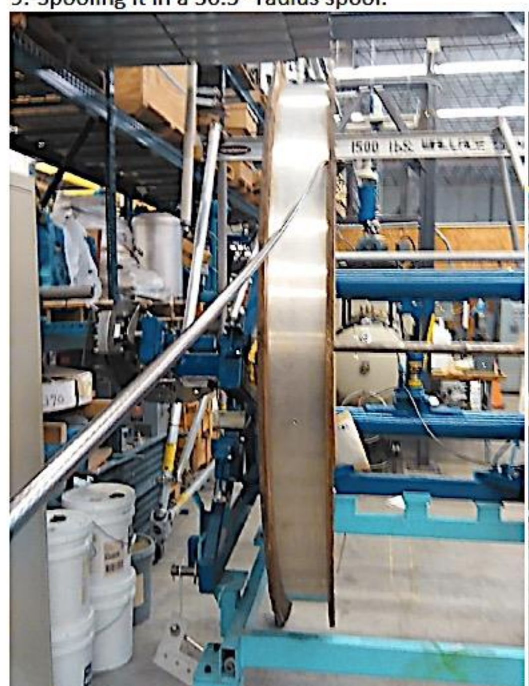
3.-0.001” Stainless Steel foil wrapped around without overlap. Secure at both ends with superglue.

5.-Inserction of “core” into outer tube by sliding into it

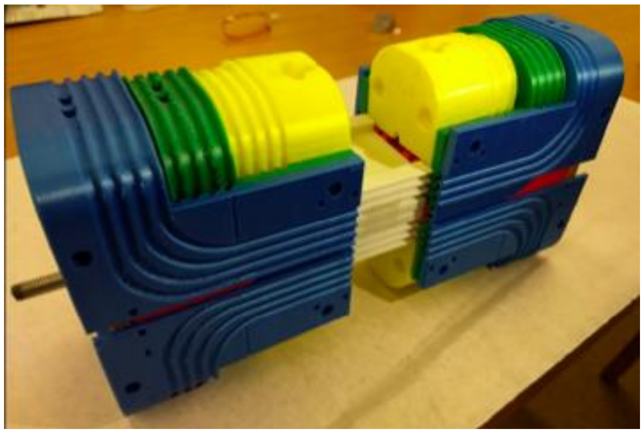
6.- Swaging tip of CIC with a .300” OD swage die

7.- Drawing process, using DSW-20 lube and .3475" Drawing die for the first run and a .320" for the final sizing.

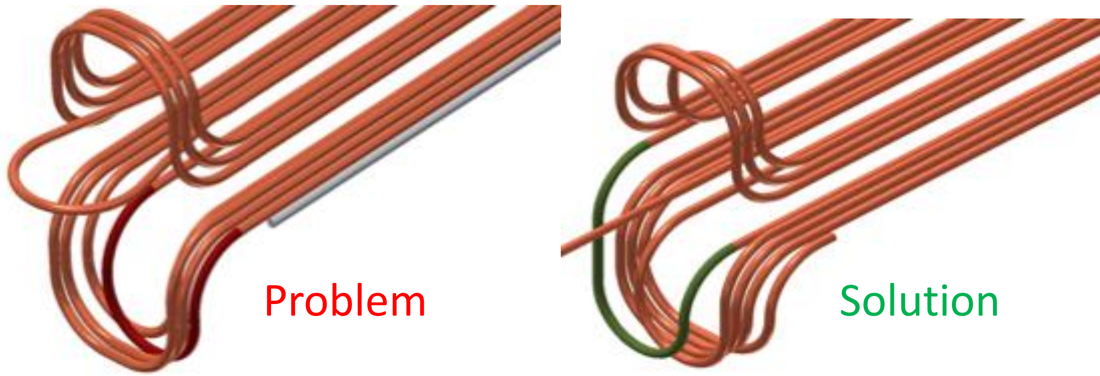
9.-Spooling it in a 30.5" radius spool.



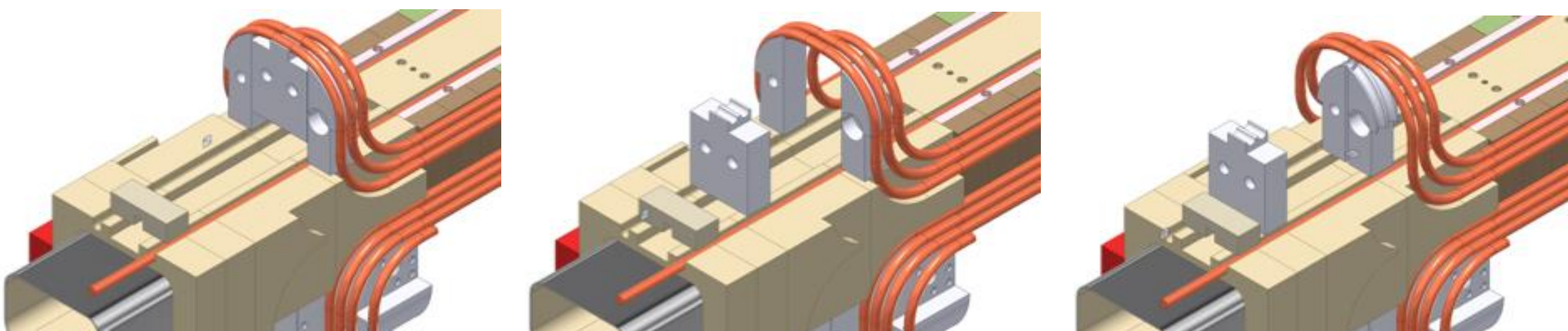
II. Develop optimized support structure for CIC windings



We fabricated a 4:1 scale model of support structure, assembled from 3-D-printed polymer parts.



Payoff: spotted two subtle problems in winding sequence. Cured each problem by slight changes in end geometry.



We divided each section of end structure into blocks that can be removed and replaced with windings in place. With this provision, no need to spread a formed turn in order to make a subsequent turn – no risk of inelastic strain.

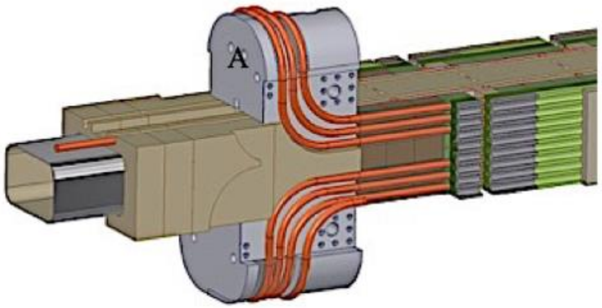


Figure 7. Layer 1 complete, supported on end support A.

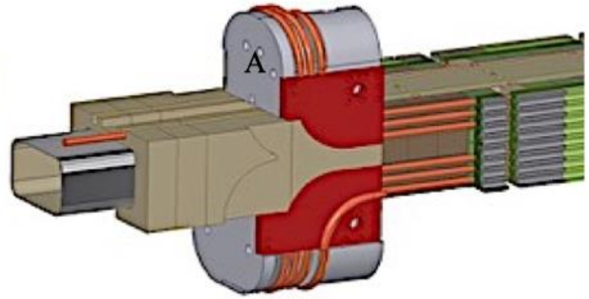


Figure 8. Side flags assembled on layer 1.

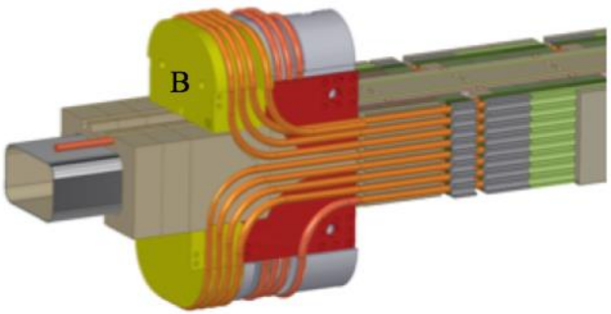


Figure 9. Layer 2 complete, supported on end support B.

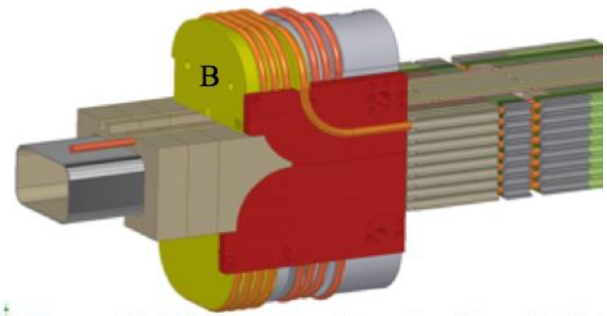


Figure 10. Side flags covering ends of layer 2, first turn of layer 3 in place.

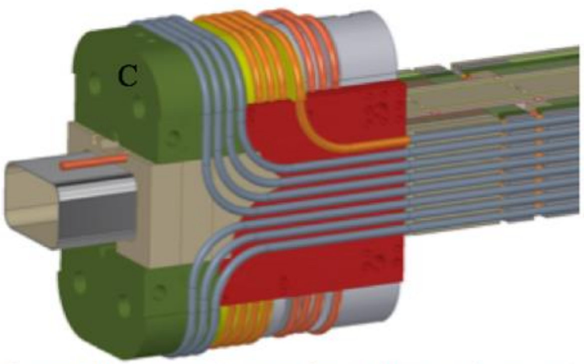


Figure 11. Layer 3 complete, supported on end support C.

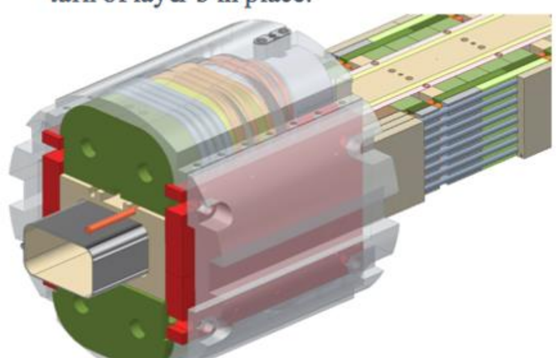
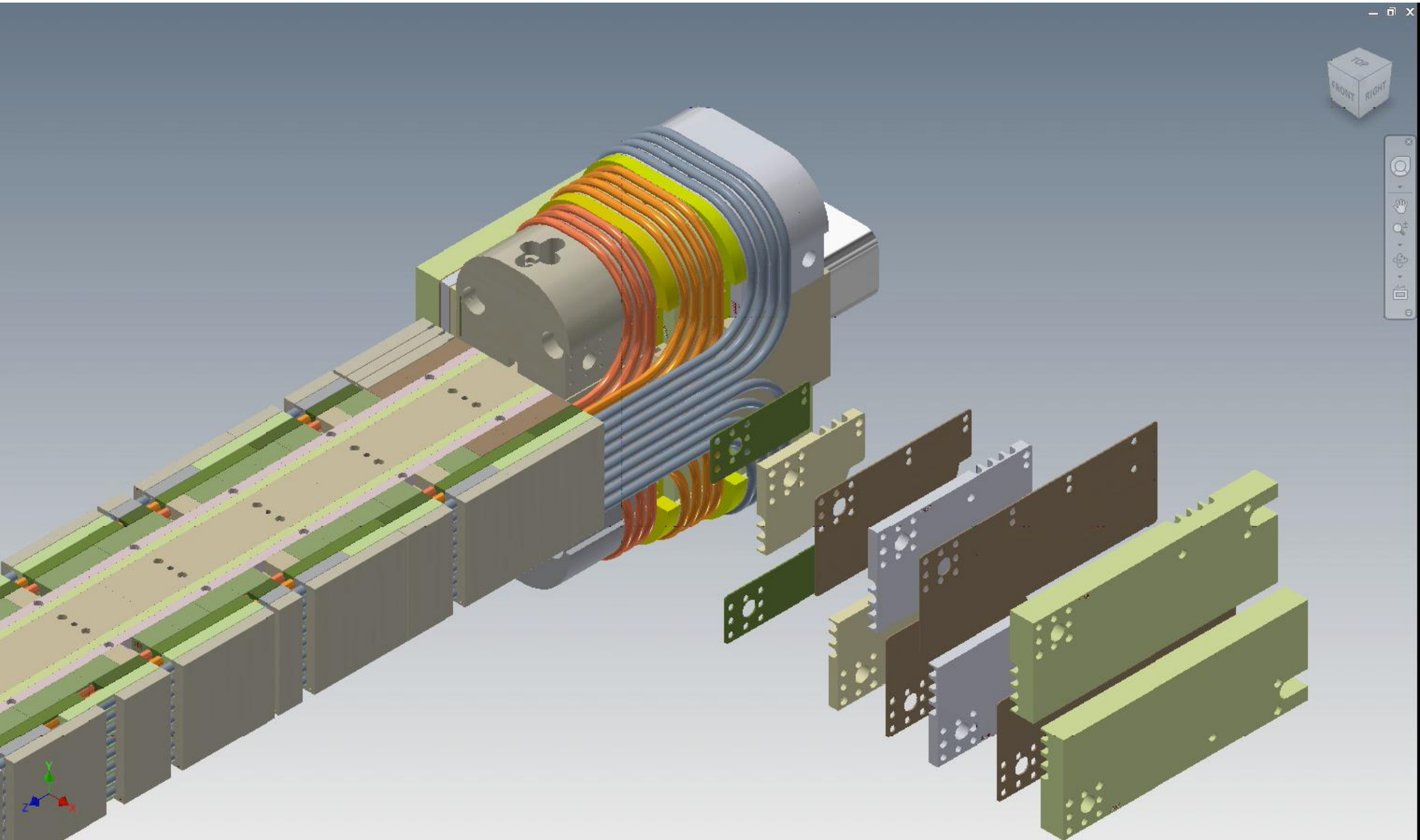


Figure 12. Spacer shoes assembled on all faces of the end assembly.

Sequence of end structure as windings completed



7. Form U-bends in CIC using the motorized tooling that was developed for the mockup winding.

- The tooling was developed to bend empty CuNi tube to the 5 cm radius required for the CIC end windings.
- The CIC cable is much stiffer than the empty tube.
- Form bends to determine whether the forming dies work correctly to bend CIC.
- Requires more overbend to overcome spring-back – must modify forming dies.

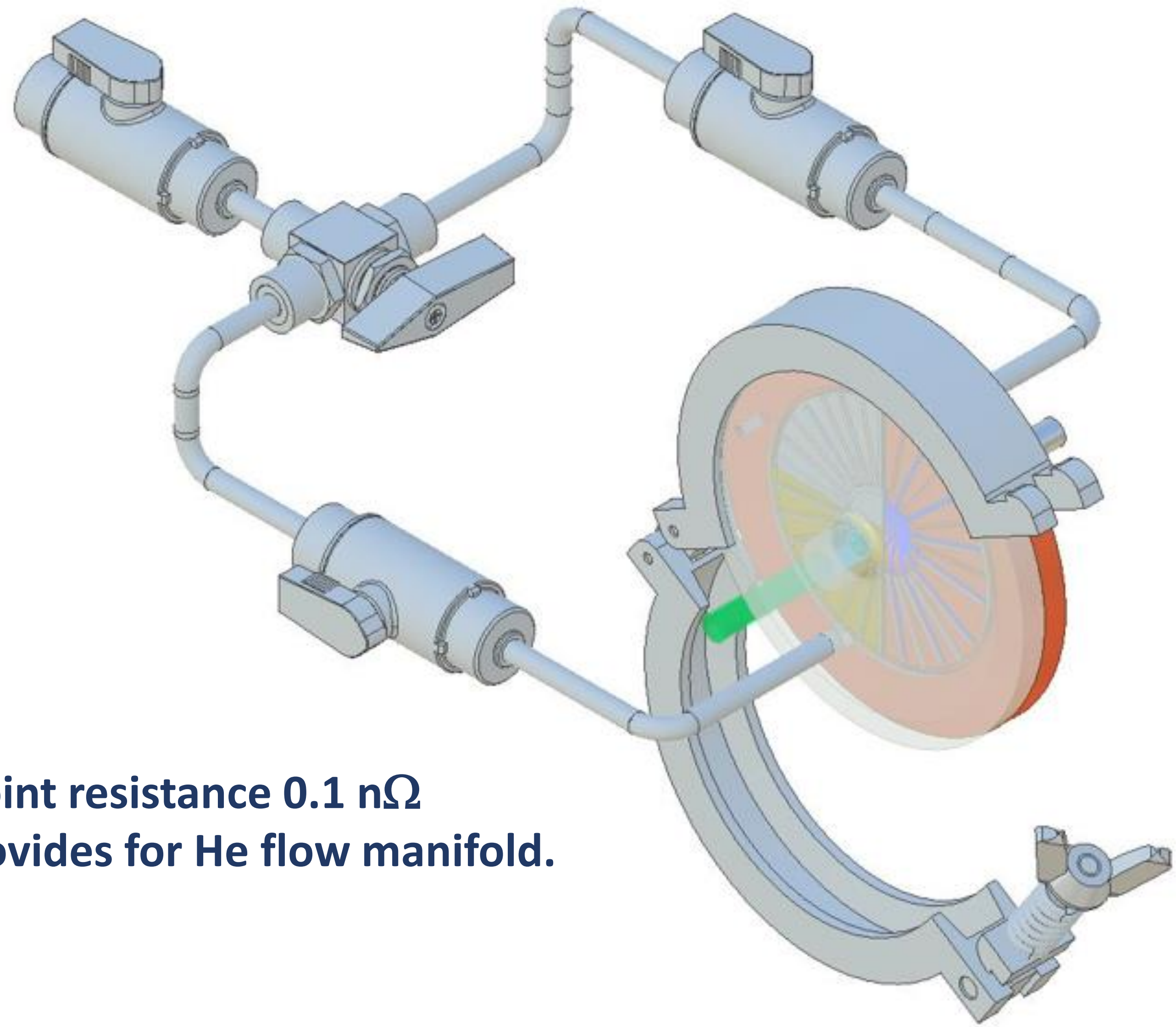
✓ Formed U-bends are intact inside, no problems.

Motorized bender to make planar U-bend.

Bender to make 90° flare on U-bend.

Motorized bender to form 'dog-bone' end.

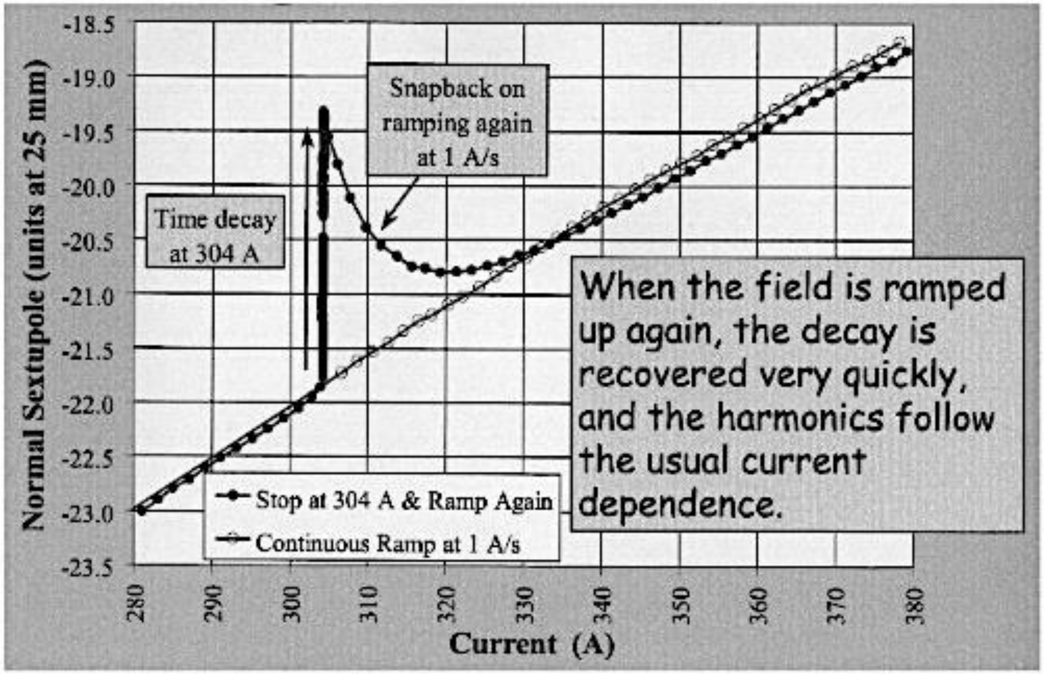
8. Splice joint should be robust, low-resistance, easily made/unmade



Calculated joint resistance 0.1 nΩ
Naturally provides for He flow manifold.

3. SNAPBACK

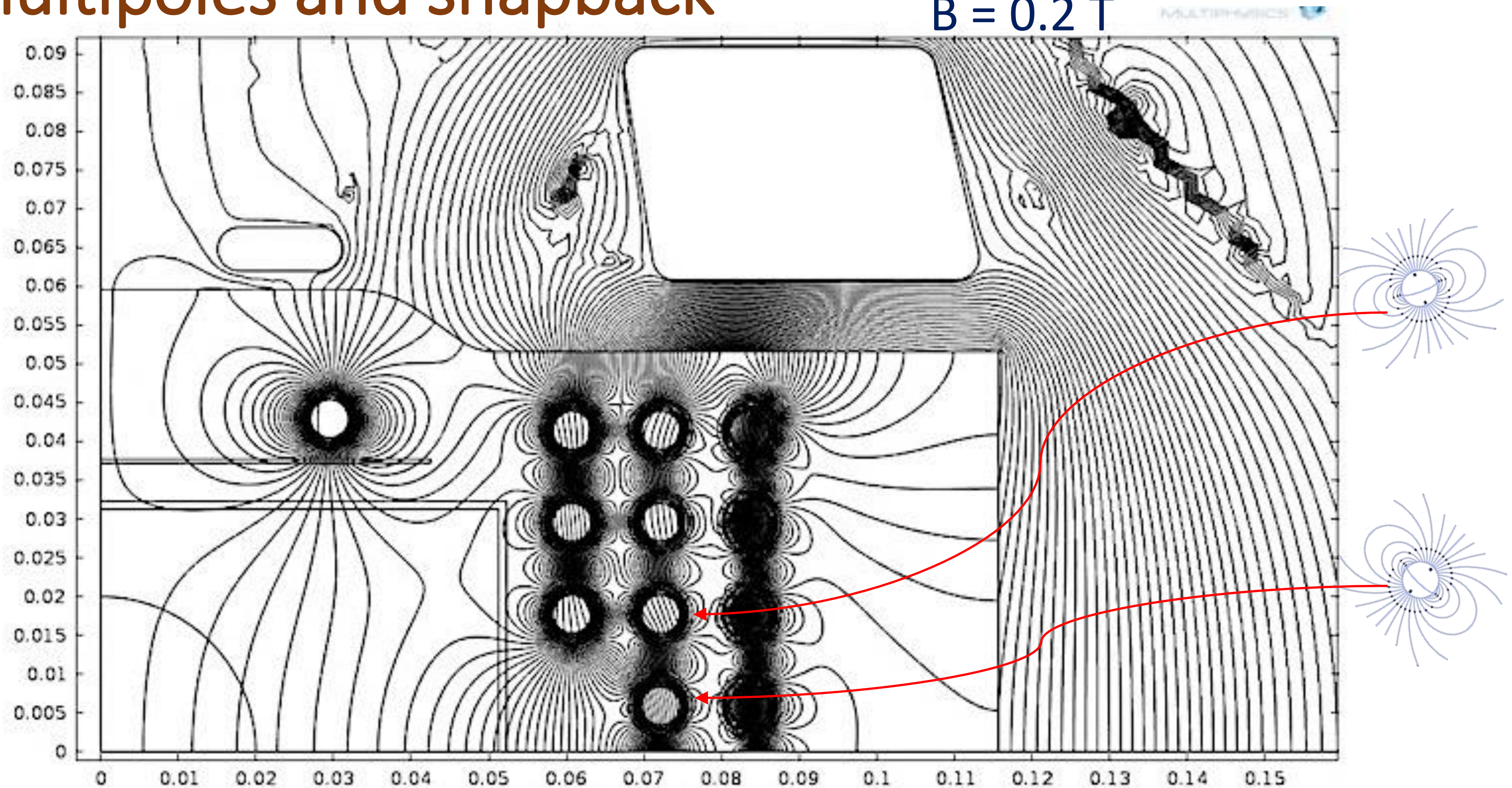
- Phenomenology
  - At the end of the injection, the beam is accelerated and the field is ramped up
  - In that moment, the decay of persistent currents disappears and the previous values are recovered



Snapback phenomenology in RHIC dipoles, from A. Jain, USPAS 2006, « Dynamic effects and … », slide 27

The block-coil geometry makes possible a flux-plate suppression of persistent-current multipoles and snapback

B = 0.2 T



The magnetizations within the wires of each turn of cable are oriented as a small transversely polarized 'permanent magnet' rod. The external fields combine to produce a residual multipolar field in the beam region.

Simulation of magnetization with and without the flux plate

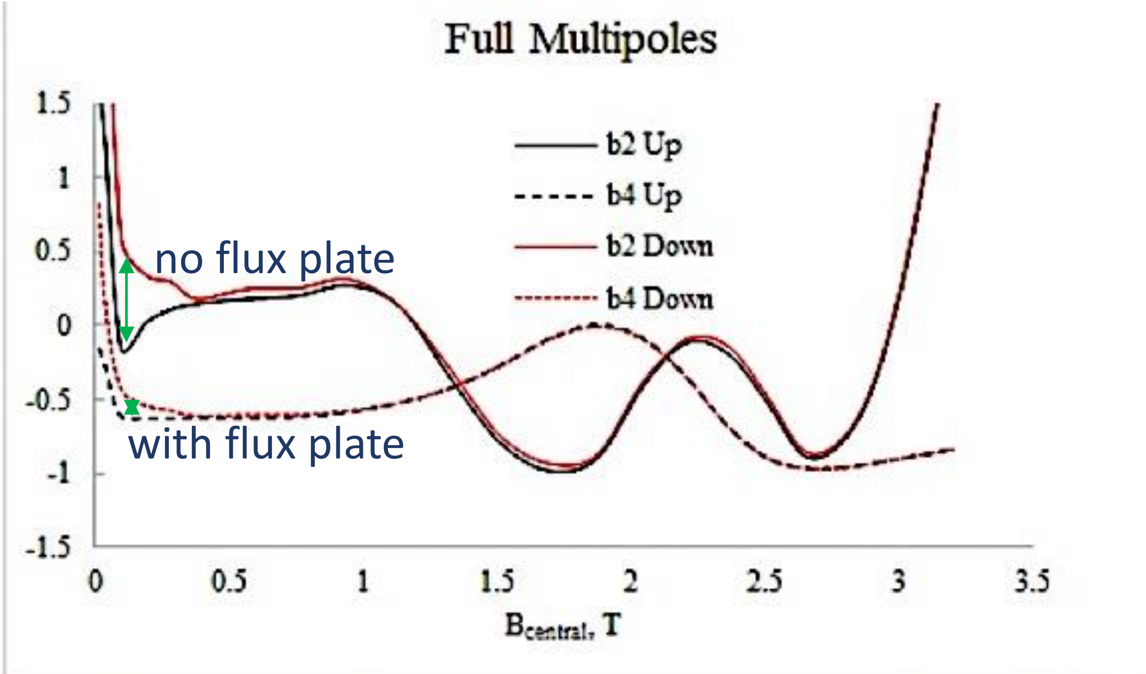
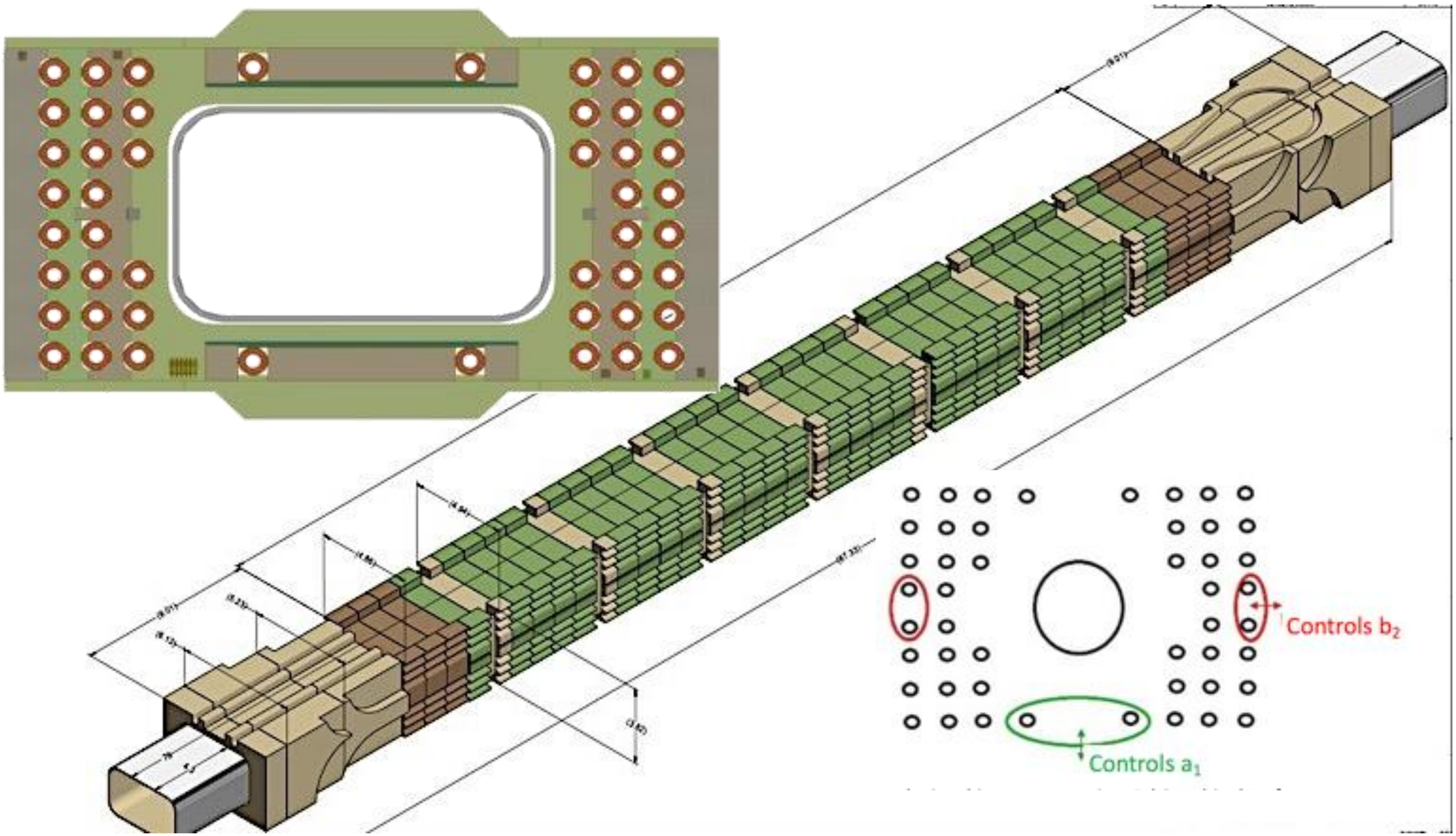


Figure 32. Multipoles during ramping up and down of the JLEIC dipole.

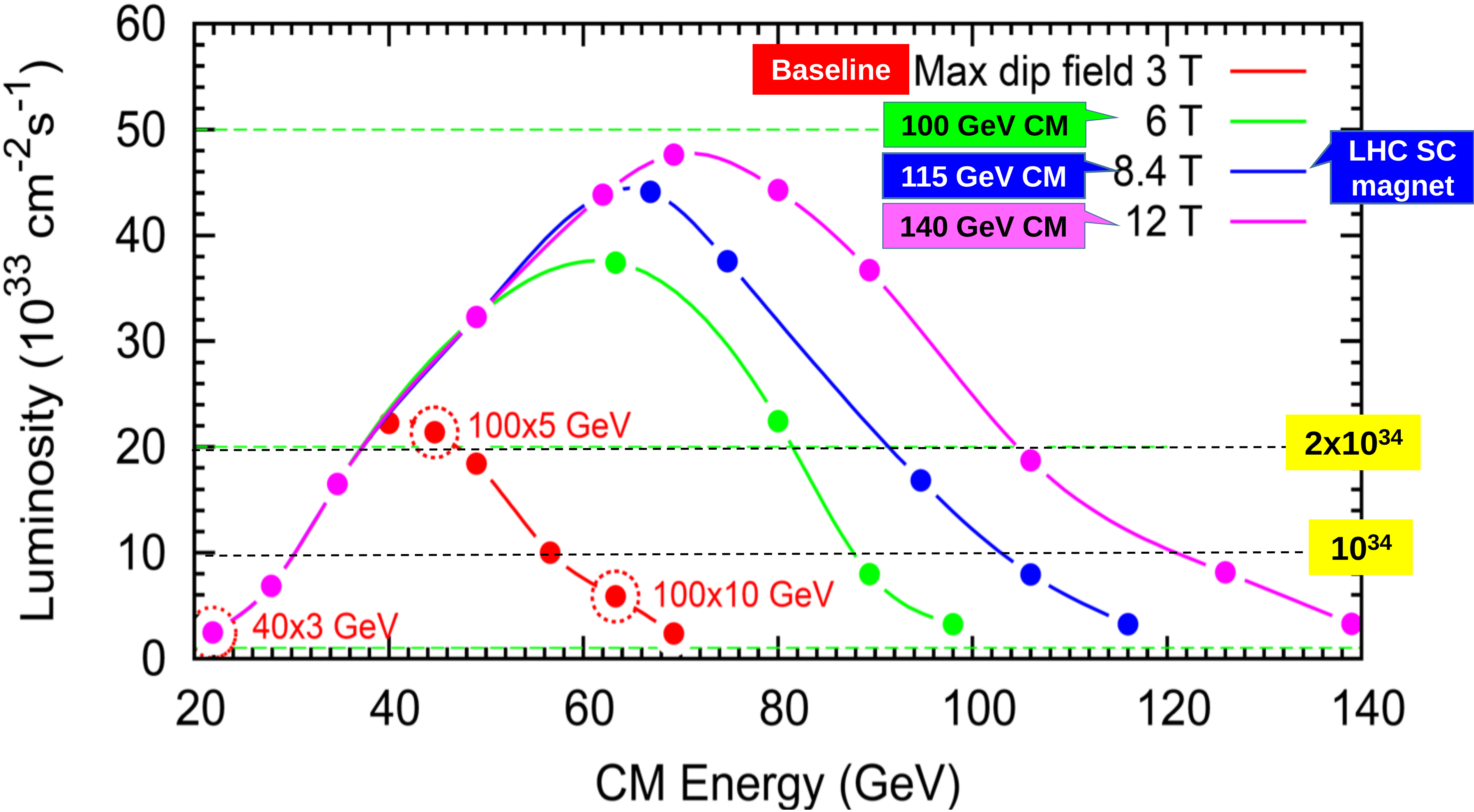
The steel flux plates suppress p.m. multipoles and snap-back by a ***factor 5.***

We have designed the CIC dipole structure to accommodate the flux plates.



The CIC winding locations are exactly the same.
The steel flux return is slightly modified to accommodate perturbations of saturation.
We propose to build half the body length using steel flux plate & mating flux return, the other half using SS dummy & its mating flux return: measure/compare both ways.

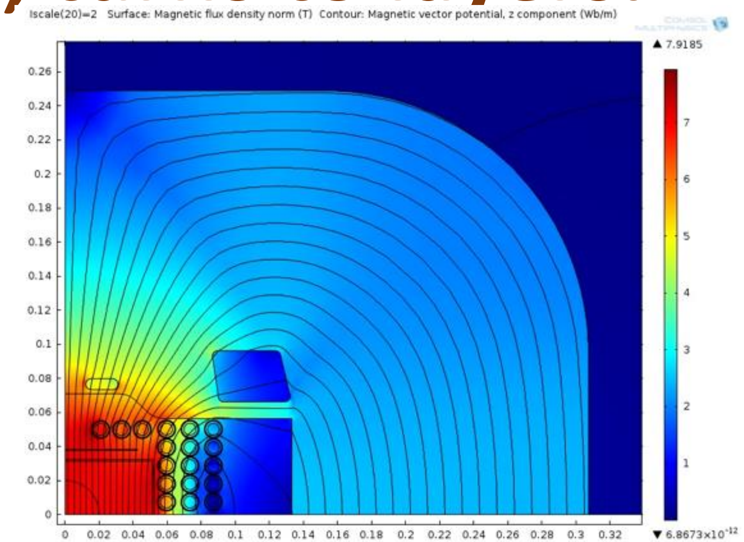
JLEIC *e-p* Luminosity & Upgrade Potential



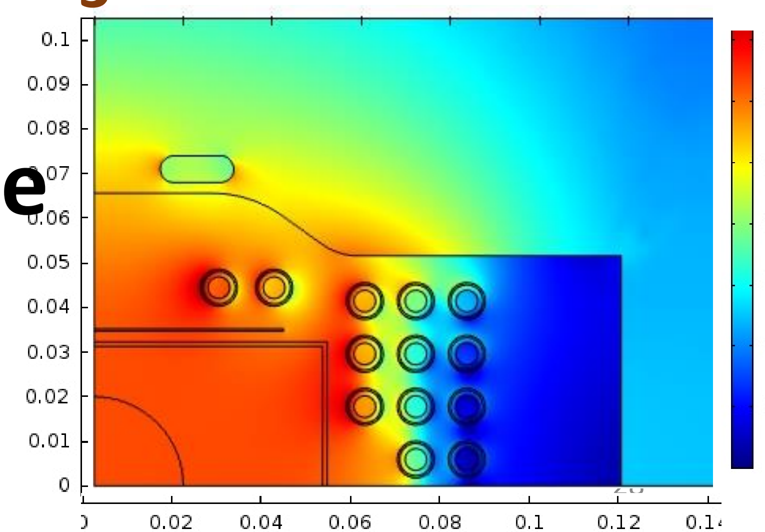
If it were feasible and affordable to make 6 T dipoles for the Ion Ring,
Maximum c.m. energy would double; maximum luminosity would double.
We have made several innovations that may make it feasible and affordable.

How to do it? Two options:

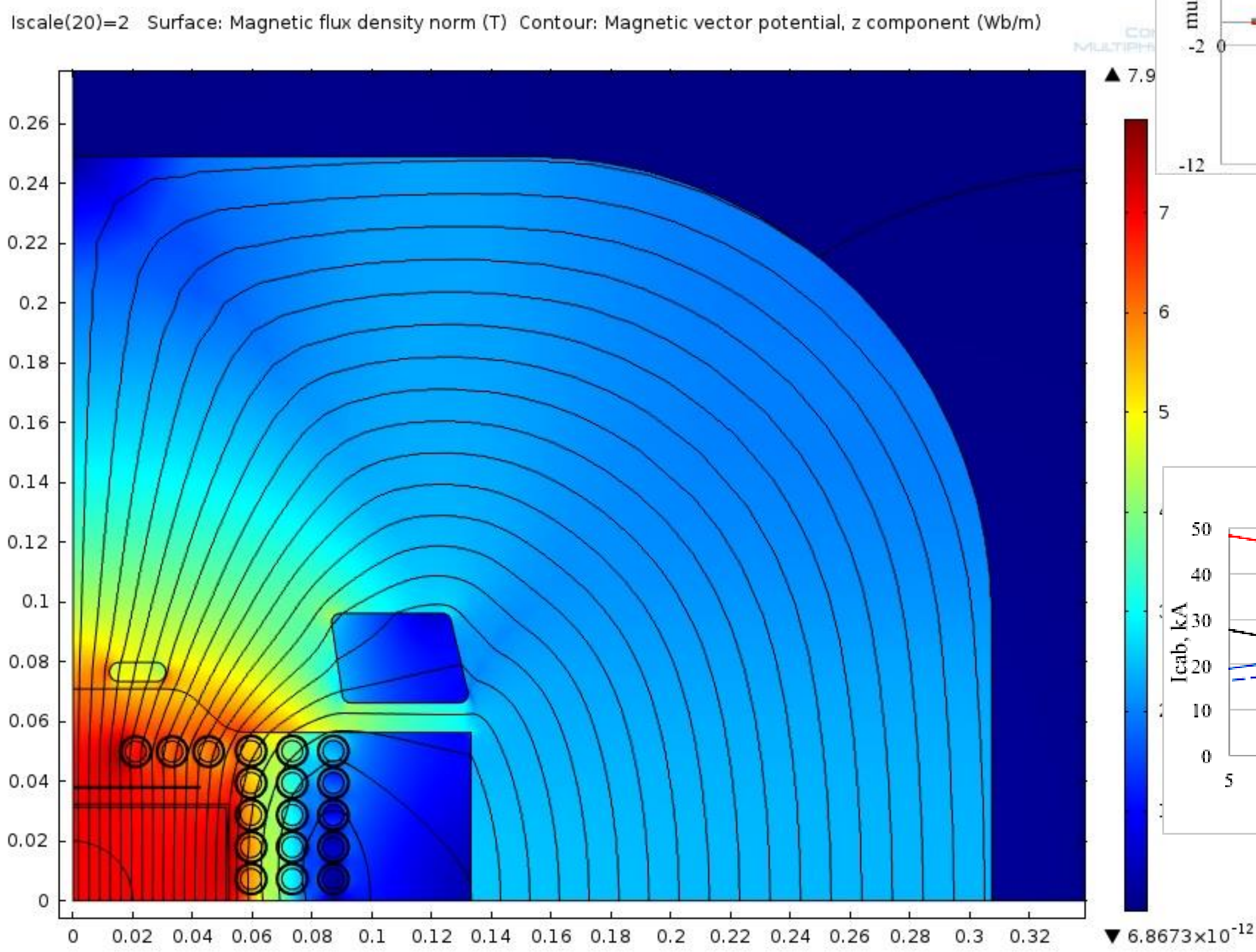
- **Add wires to NbTi CIC cable, turns to layers:**
  - **4 T using supercritical He**
  - **6 T using superfluid He**

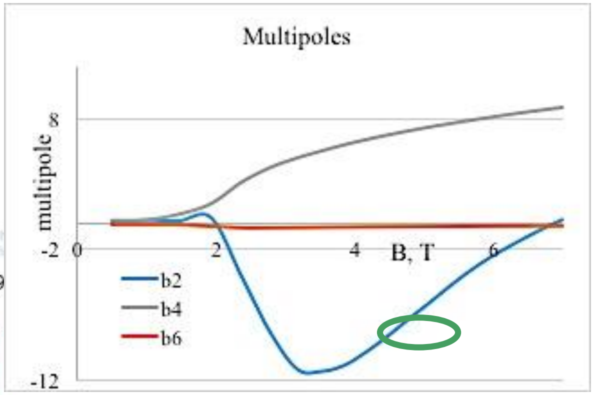


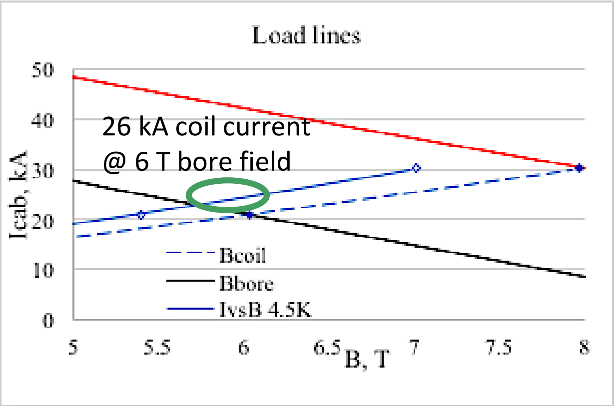
- **Replace NbTi CIC by new Nb_3Sn CIC developed for IR quads:**
  - **4 T using supercritical He**
  - **6 T using superfluid He**



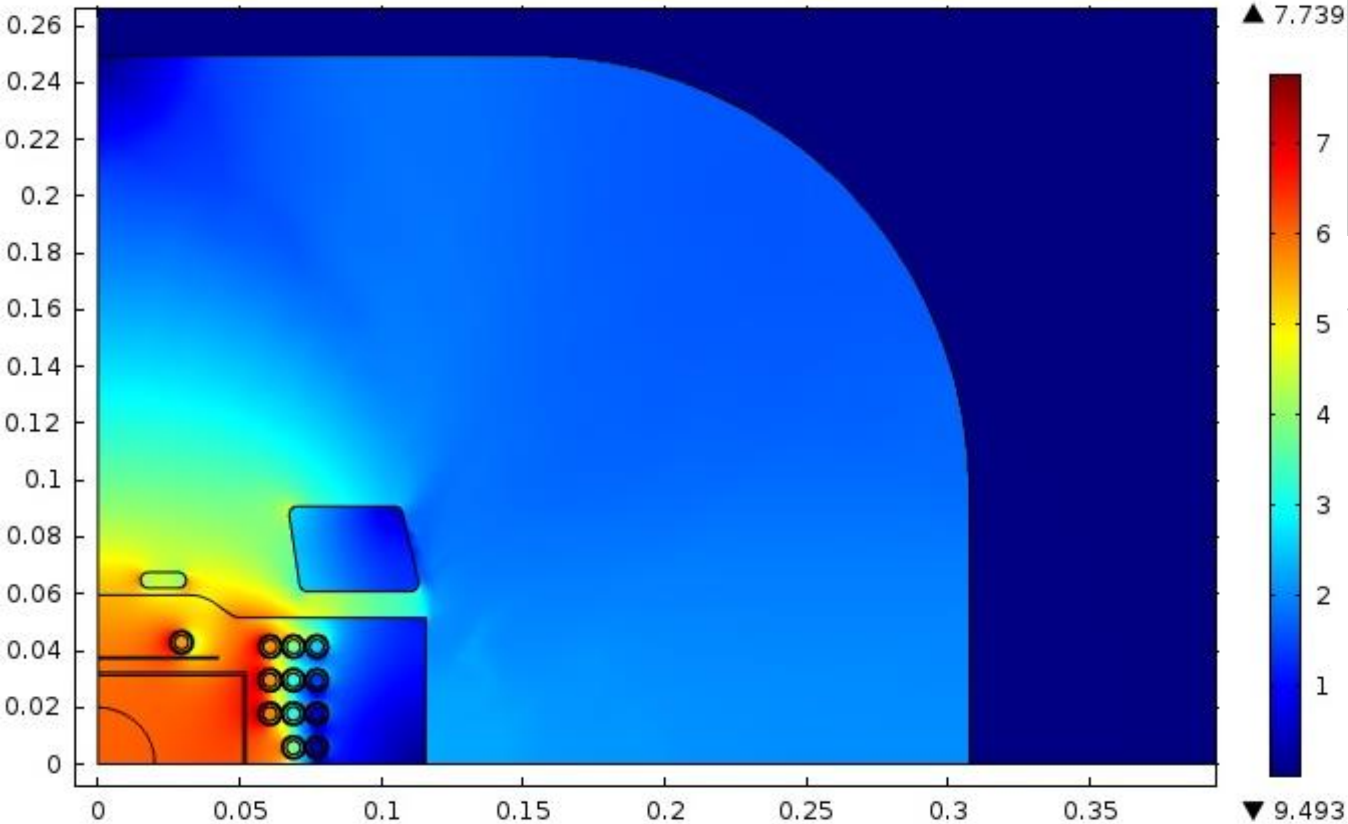
Beef up our NbTi cable, add a few turns, re-optimize fields

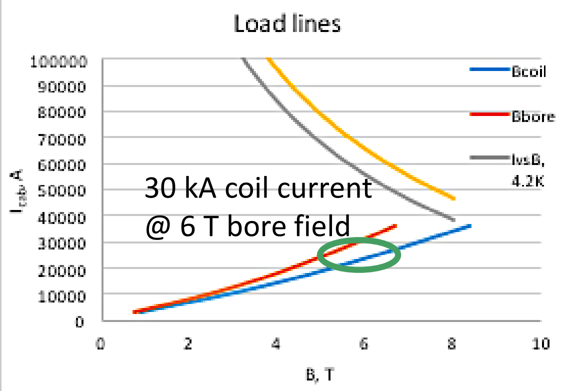


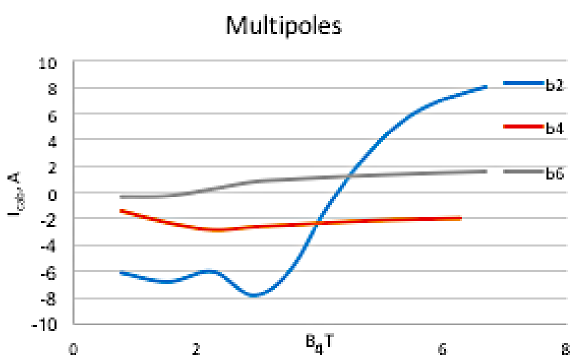




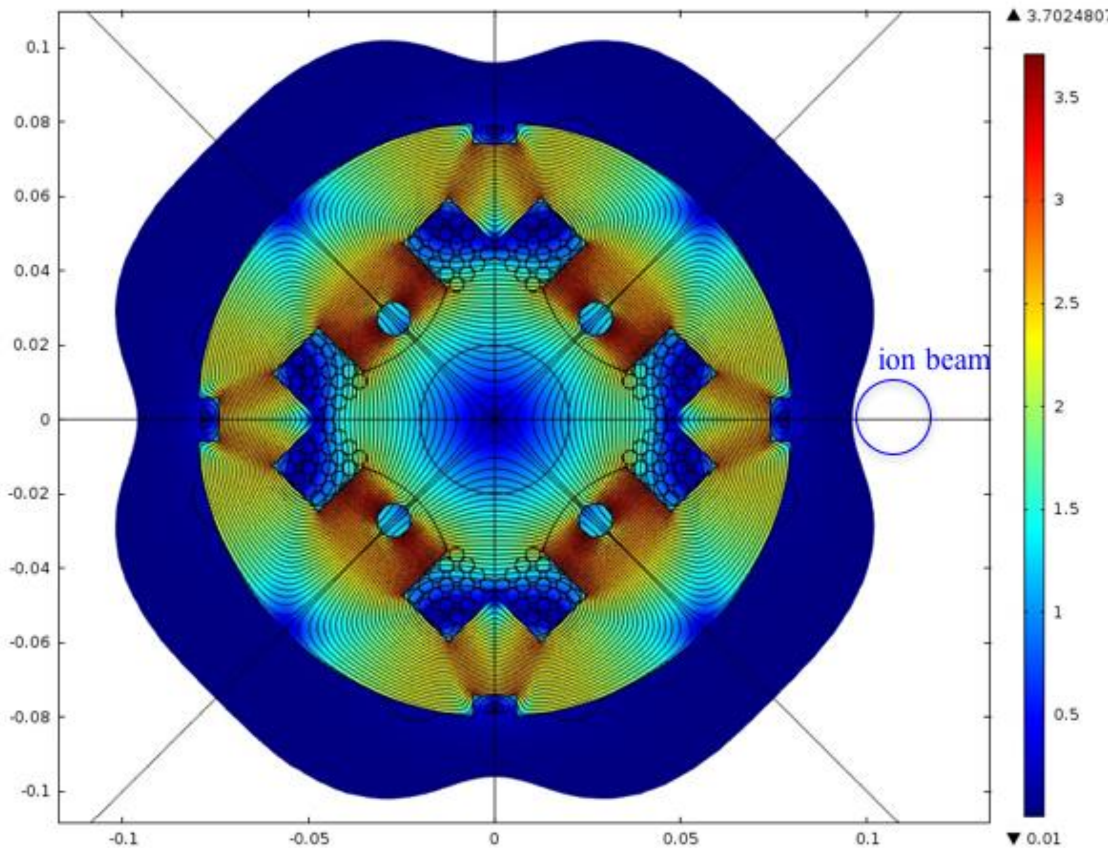
Payoff from Phase 1 SBIR to Hypertech: development of Nb_3Sn CIC for IR quads.







Success from Phase 1 SBIR @ HyperTech: fabricated Nb_3Sn-based CIC suitable for a high-field quad to meet IR quad specs.



	QI1
Field/gradient	89 T/m
superconductor	Nb_3Sn
Strand diameter	0.8
Cu:SC ratio	1.5
# strands	15
Cable diameter	5.8
Center tube OD	3.0
Sheath tube OD	6.0
# Turns/pole	120
Coil current	9.0
B_{max} in winding	11.56
J in superconductor	3000
stored energy	2.9
Operating temp	4.2

90 T/m, 17 cm half-aperture, 36 cm from e-beam.
Nb_3Sn superconductor @ 5 K.

We propose a 2-year scope of work and TAMU budget to build and test a 1.2 m 3 T model dipole.

- **FY2018: $500K**
  - Fabricate windings
  - Precision metrology of windings on structure
  - Instrumentation:
    - Quench heaters
    - Voltage taps
    - Splice joints and leads
  - Flux return structure
  - Assemble and preload

The scope and budget pick up where present $ leave off.

- **Fiscal 2019** **$400K**
- Warm measurements of harmonics, comparison with metrology and simulations
  - Evaluate shim strategy to cancel multipoles
  - Evaluate effects of preload strategy on harmonics
- Final assembly and checkout
- Cool-down
- Cold testing of the dipole
  - Multipole measurements
  - Ramp rate studies
  - Provisions for several rounds of warm-up/cool-down

Collateral SBIR efforts will be proposed for 2018

- **FY2018: HyperTech Phase 2 –**

  Nb_3Sn CIC for IR quads, 6 T Ion Ring arc dipoles
  - cold-test CIC coupons containing a single wire of Nb_3Sn
  - Form U-bends, measure short-sample for single-sc-wire in CIC
  - Fabricate quad winding using Nb_3Sn CIC, cold-test

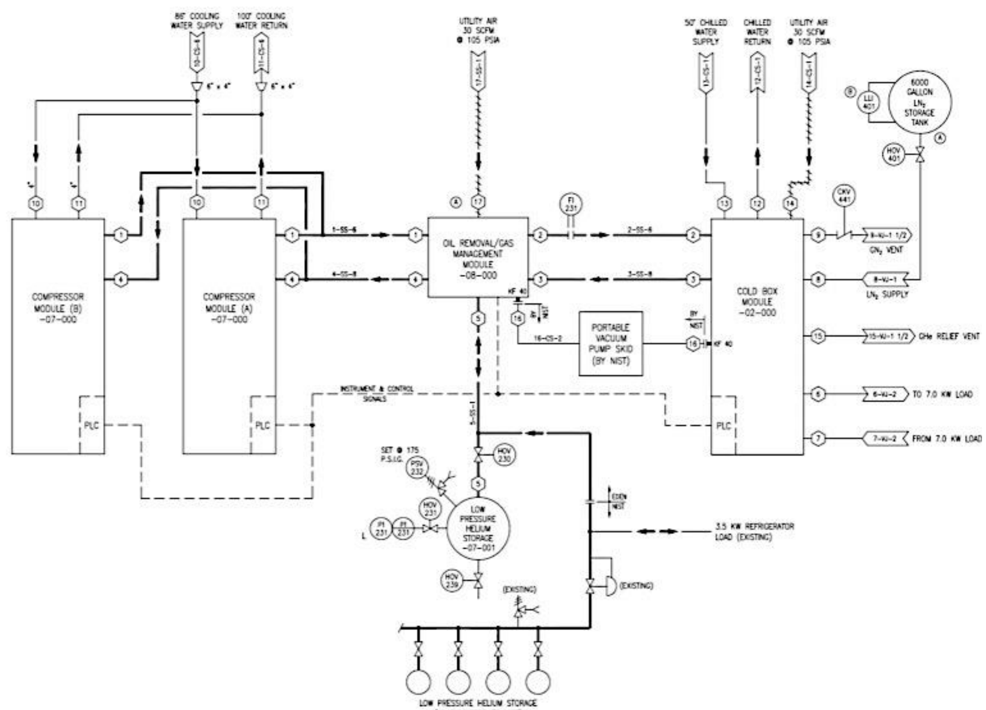
- **FY2018: ATC Phase 1 –**

  Develop magnetic, mechanical, cryo design for 6 T dipole that recovers all features of the 3 T NbTi CIC dipole but gives 6 T operation
  Build to operate @ 4 T with 5 K supercritical He
  Upgrade to operate @ 6 T with 1.8 K superfluid He

- **FY2018: HyperTech Phase 1 –**

  Develop test cryostat and cold box to operate a 1.2 m model dipole with supercritical He flow.
  - Piggybacks with TAMU procurement of compatible He liquifier.
  - Could be ready for use in 2019, just-in-time for completion of the T 3model dipole.
  - Design to operate with either supercritical He or superfluid He
  - Could be up-graded to test full-length prototype of CIC dipole..

Supercritical/Superfluid Cold Box and Test Cryostat



Current Status of CIC dipole development

- ✓Fabricated and tested short segments of CIC cable in final form.
- ✓Bent the CIC cable in the configuration required for the windings of the dipole. Verified short-sample current in extracted strands.
- ✓A 1.2 m model dipole requires a single 125 m CIC cable. A 4 m dipole requires two 125 m CIC cable segments.
- ✓Fabricated perforated center tubes and drawn to final size.
- ✓Cabled medium-length cable, pulled medium-length cable into sheath, drawn to final compaction @USB.
- ✓Validated that we can form medium-length CIC cable in U-bend for end windings, cable is fine inside.
- ✓ATC has ordered long-length stranding machine.
- ✓Developed and validated CTFF forming of sheath onto CIC.
- ✓CIC designs for 6 T dipoles, 90 T/m IR quads.