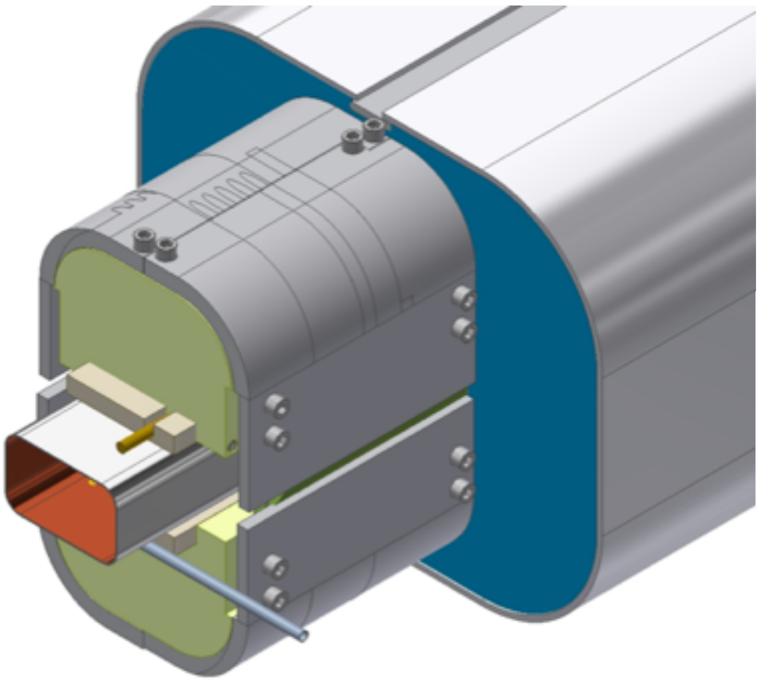
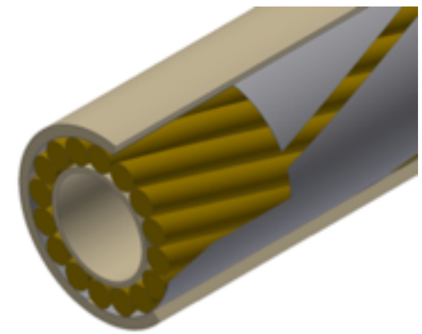
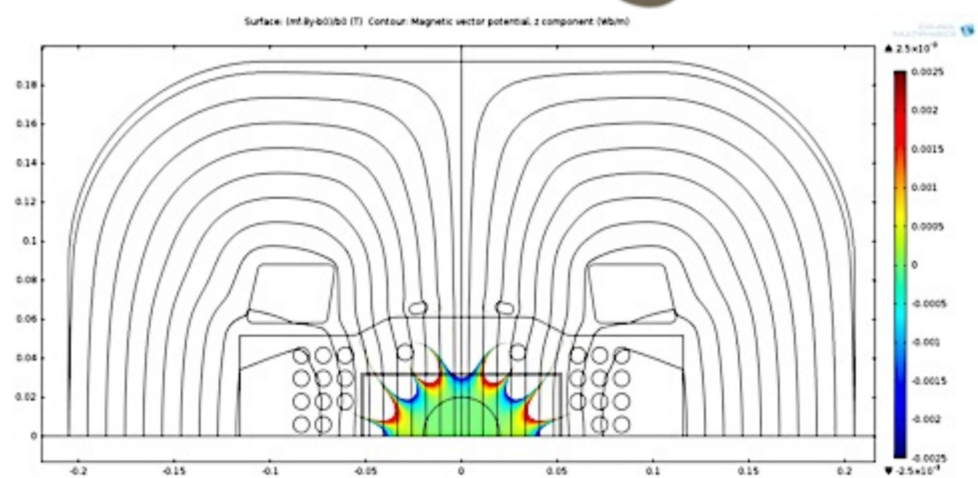
Superferric 3T CIC Dipole R&D 2016/17 Project Report







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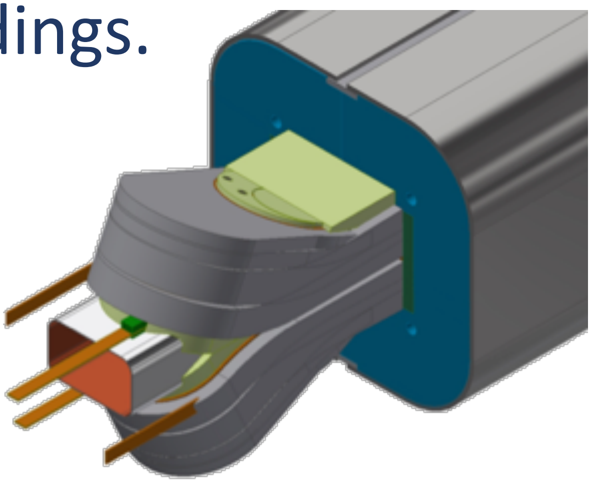
CIC Dipole R&D: 8/2017 – 3/2018

- 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.

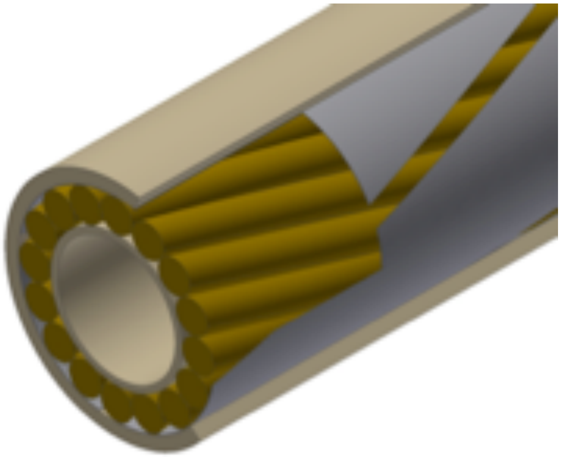


- Goals of the 2016/17 R&D task:
  - fabricate a long length of CIC cable, incorporating all features required for the CIC dipole.
  - wind a few turns of the CIC cable onto the coil form (fabricated in FY15) and evaluate the coil-winding methods using CIC cable.
  - Develop methods for splice joints and quench protection suitable for use in a 1.2 m model dipole and in 4 m JLEIC dipoles.
- I will report on our success in these goals and our proposal to build a 1.2 m model dipole ready to test by 4/2018.

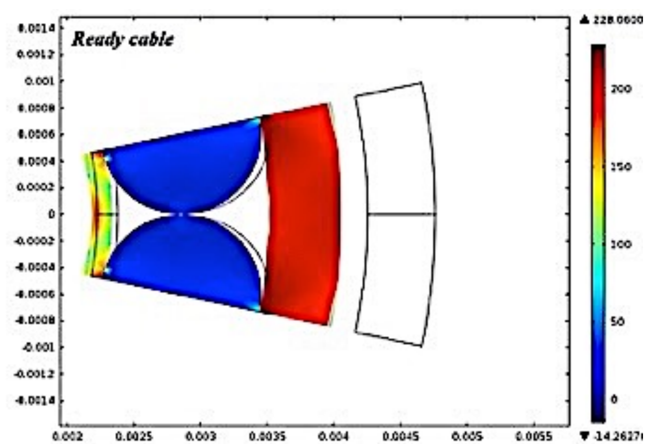
5/20/2016: Mockup winding complete

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.

Develop long-length CIC cable



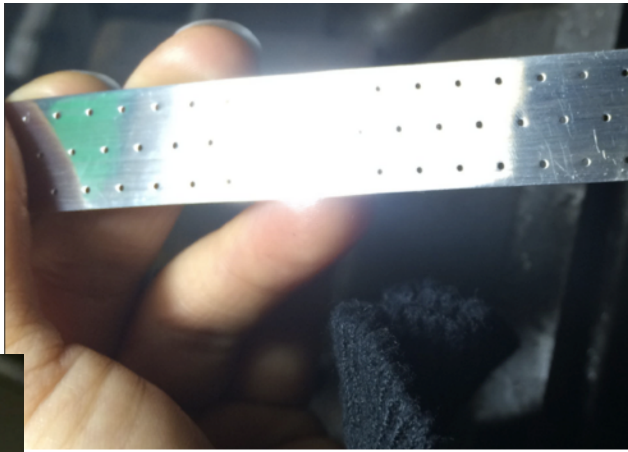
15 NbTi/Cu wires are cabled onto a perforated spring tube.



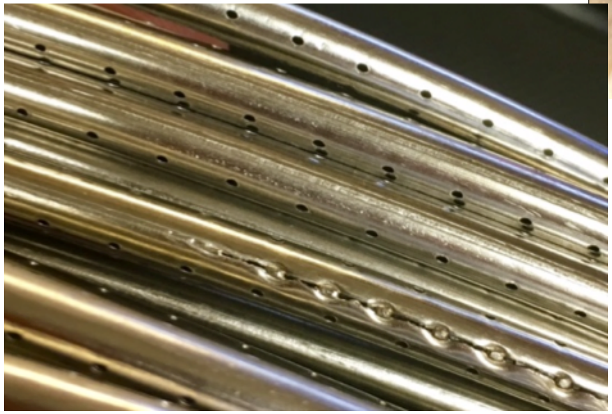
The cable is inserted in a sheath tube, and the sheath is drawn onto the cable to just compress the wires against the spring tube.

Path to long-length CIC cable

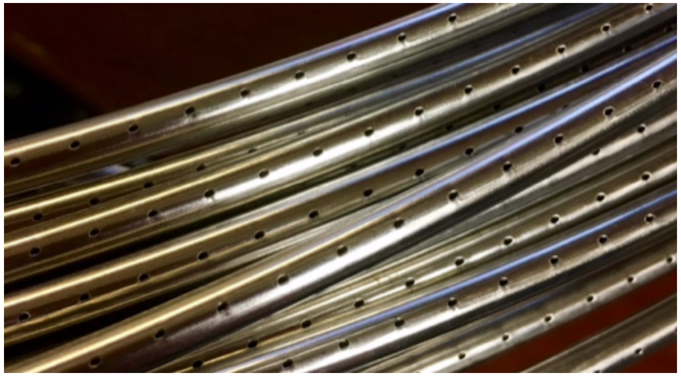
1. Perforated center tube (316L SS):
   - Punch pattern of holes in 316L SS foil strip:



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



✓Problem solved:



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

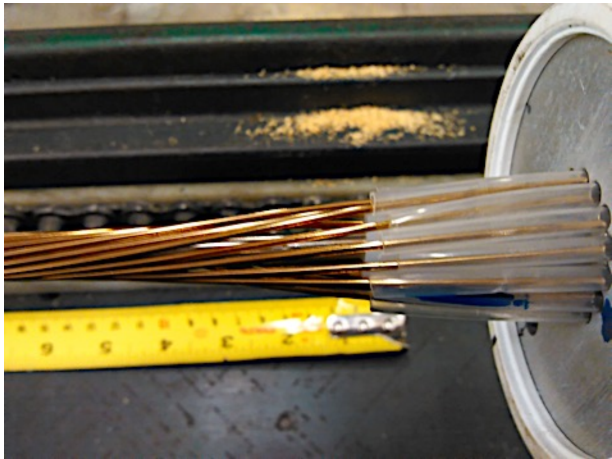
- ✓Form U-bend with 5 cm radius.
- ✓Remove sheath and wires, examine weld, roundness of perf. tube:

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.

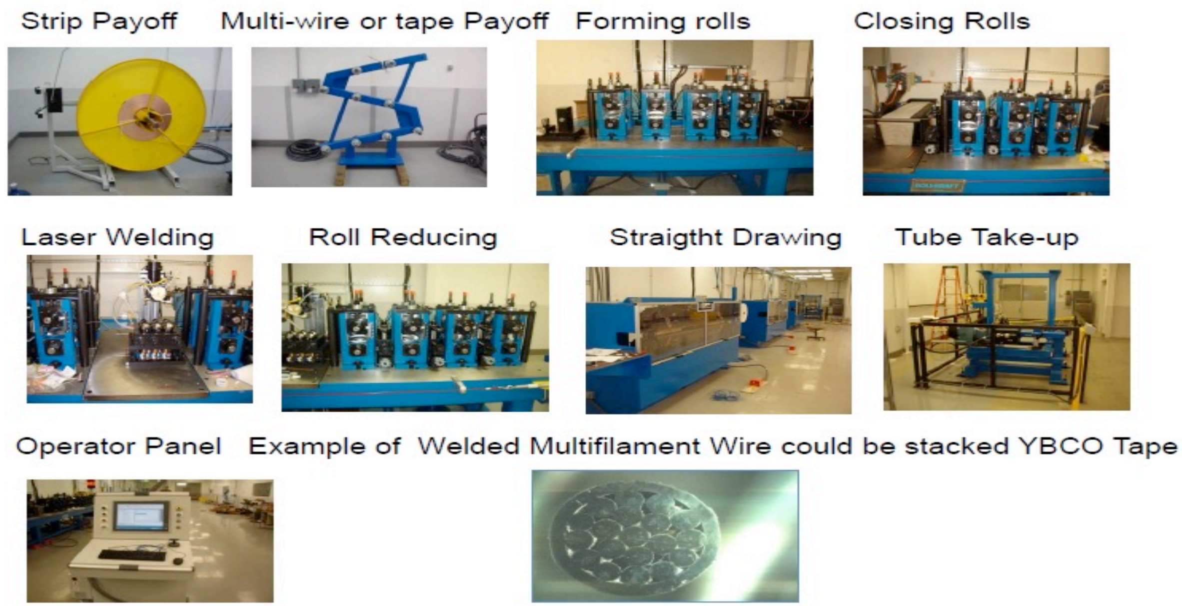
- Extensible to 125 m inside USB.
- Option to cable at NEEW.



5. Long-length sheath tube

- Original choice for sheath: seamless Monel 400
  - Ordered from Shanghai Phoenix Alloy
  - They made bad billet (composition or heat treat)
  - Tube broke repeatedly in drawing
- Equally good alternative: seamless CuNi alloy 70600
  - ✓ Ordered from Small Tube Products, Delivered last week.
  - ✓ 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.

Continuous forming/welding of sheath tube on CIC cable - CTFF



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 Monel tube onto NbTi cable, no damage.
- ✓ Developed the weld process to produce He-tight seam – passed cold-shock pressure tests with He to 600 psig.

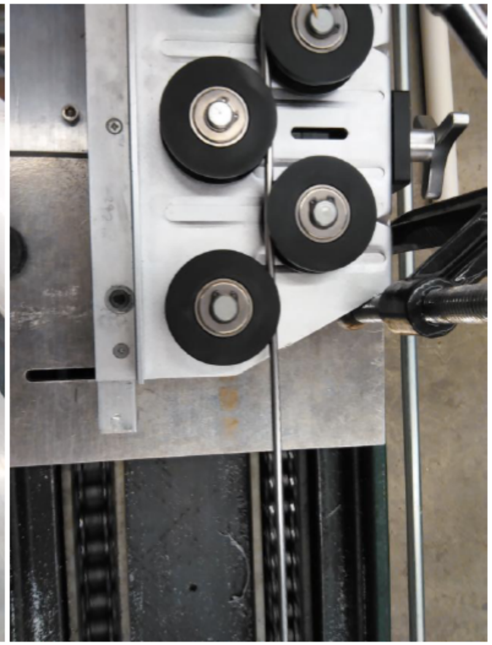
6. First medium-length CIC cable completed:

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

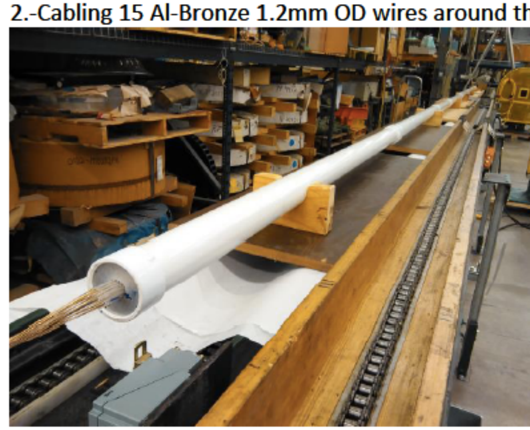
- Cable NbTi wire and SS overwrap on perf tube @ USB, or @ NEEW.
- Pull cable into seamless sheath @ USB, or form CTFF @ HyperTech
- Draw cable to compact CIC @USB, or at Luvata.

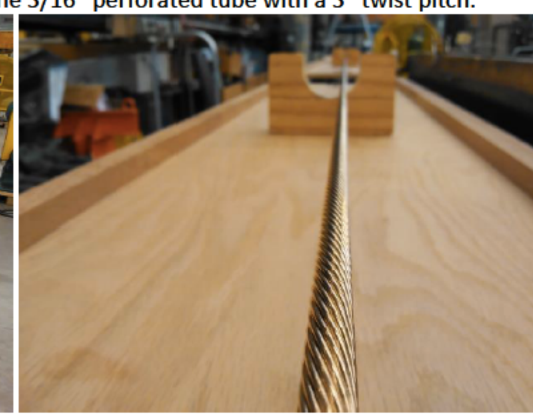
We have succeeded in fabricating long-length CIC cable entirely in-house

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

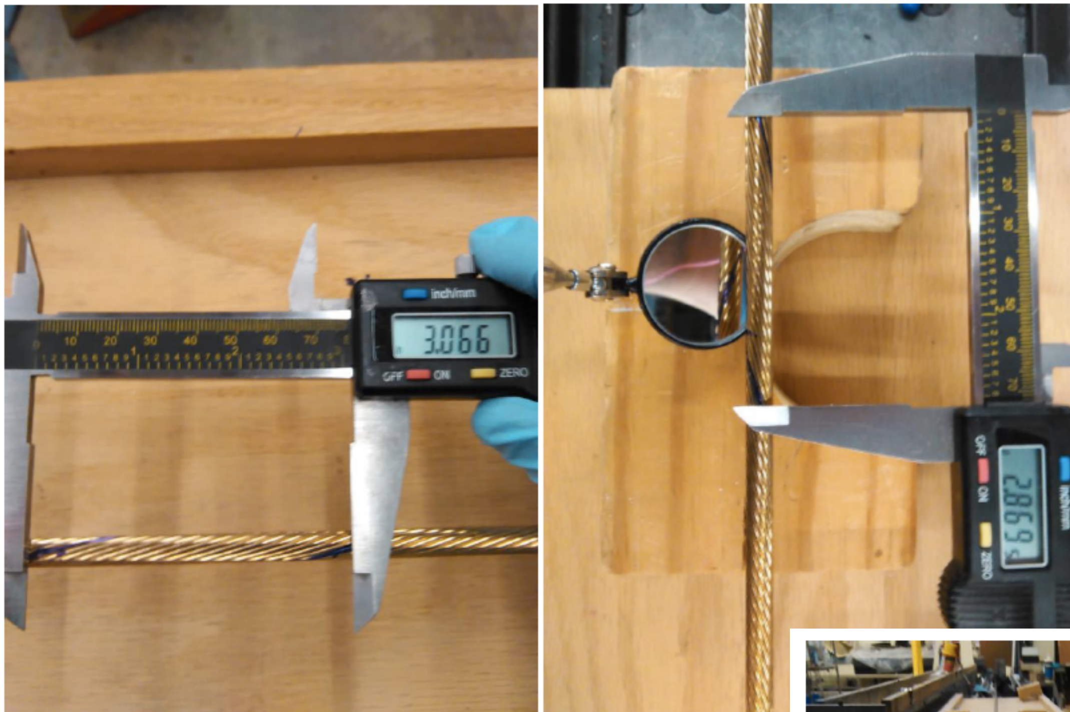


2.-Cabling 15 Al-Bronze 1.2mm OD wires around the 3/16" perforated tube with a 3" twist pitch.

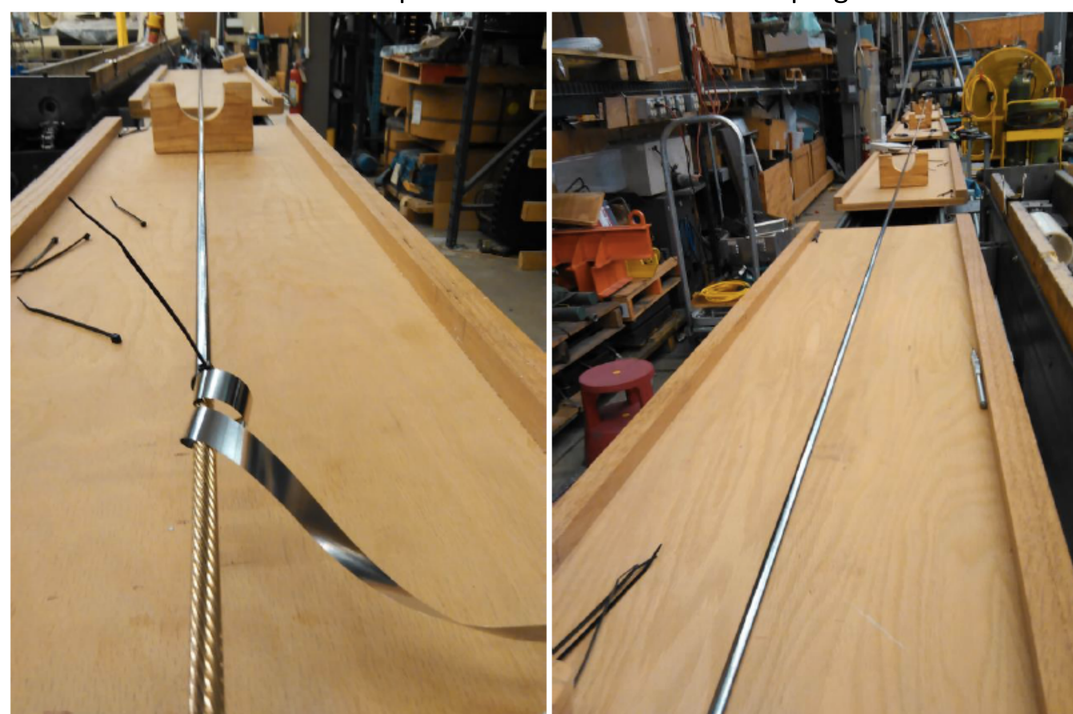




2.1) Twist pitch maximum and minimum respectively –Pretty consistent

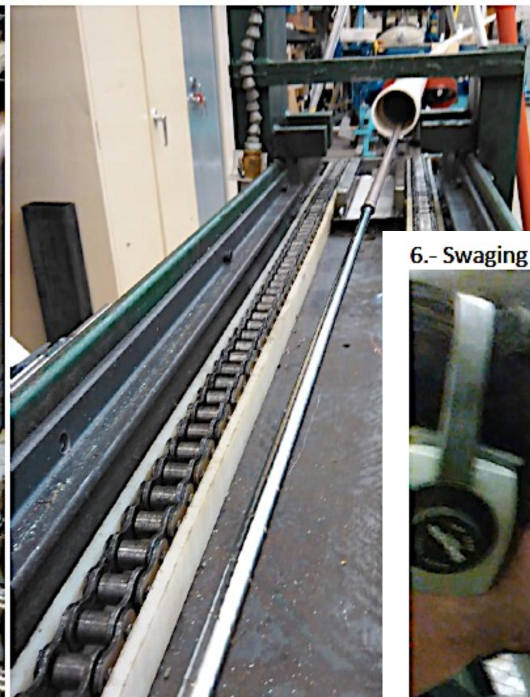


3.-0.001” Stainless Steel foil wrapped around without overlap. Secure at both ends with superglue.



4.-Straighten outer tube same procedure as #1 -Spool custom built-

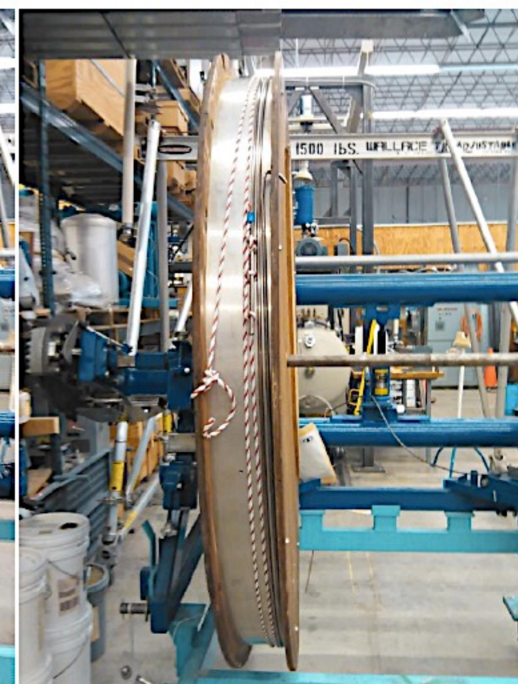
5.-Inserction of “core” into outer tube by sliding into it



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.

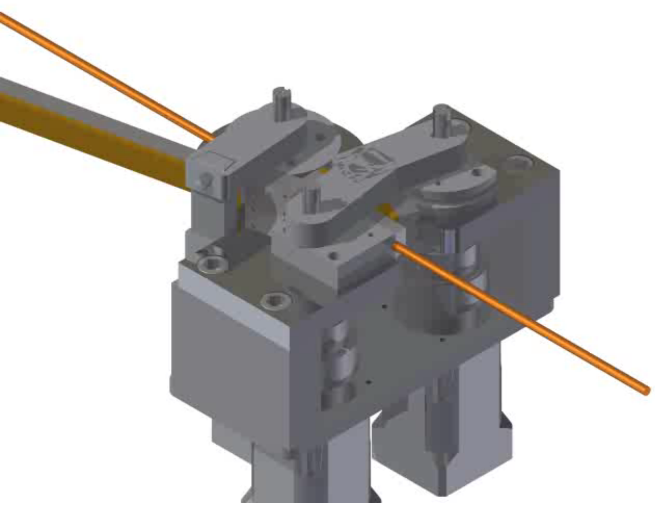
9.-Spooling it in a 30.5" radius spool.

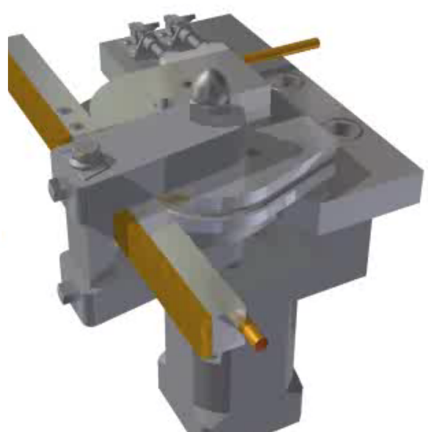


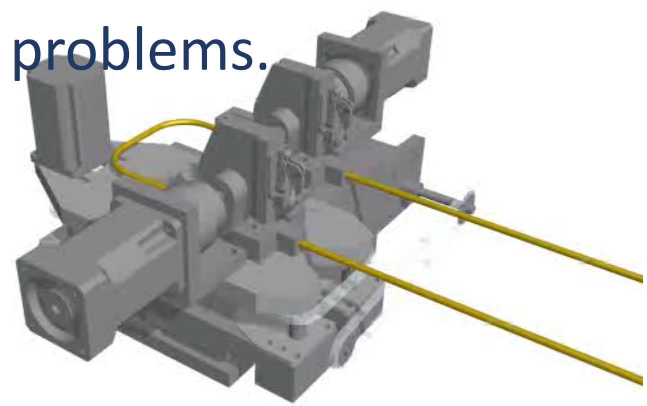
7. Form U-bends in CIC using the motorized tooling that was developed for the mockup winding.

- 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.

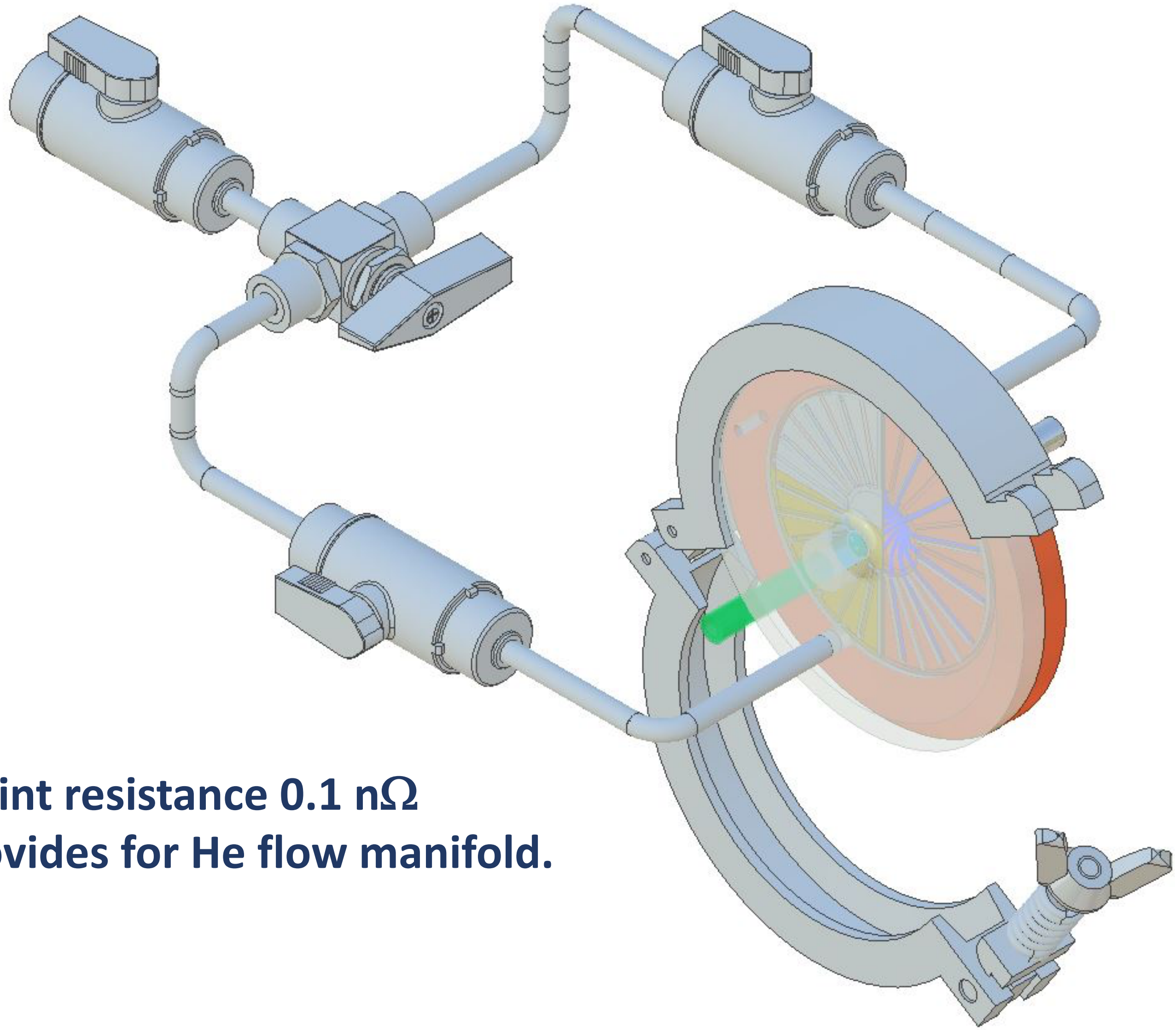
✓Formed U-bends are intact inside, no problems.







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



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

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

- FY2018: $500K
  - 125 m cable lengths
  - FRP structure
  - Fabricate windings

Flux return	FRP structure	125 m CIC cable	Fabricate windings	Instrumentation	Warm measurements

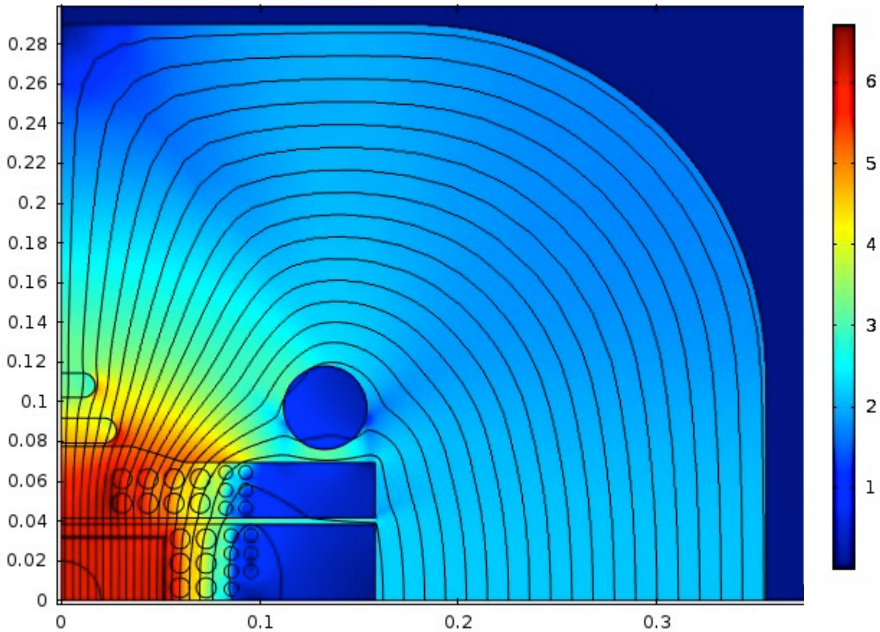
  - Precision metrology of windings on structure
  - Instrumentation:
    - Quench heaters
    - Voltage taps
    - Splice joints and leads
  - Flux return structure
  - Assemble and preload

- Fiscal 2019 $400K + BNL expense
  - 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

Current Status of CIC dipole development

- ✓Fabricated and tested short segments of CIC cable in its final form.
- ✓Bent the CIC cable in the configuration required for the windings of the dipole. We have verified the 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.
- ✓Successfully cabled medium-length cable @ USB.
- ✓Successfully pulled medium-length cable into sheath, drawn to final compaction.
- ✓Validated that we can form medium-length CIC cable in U-bend for end windings, cable is fine inside.
- ✓Developed and validated CTFF forming of sheath onto CIC

EIC Review Panel challenged us to consider option of Energy Doubler

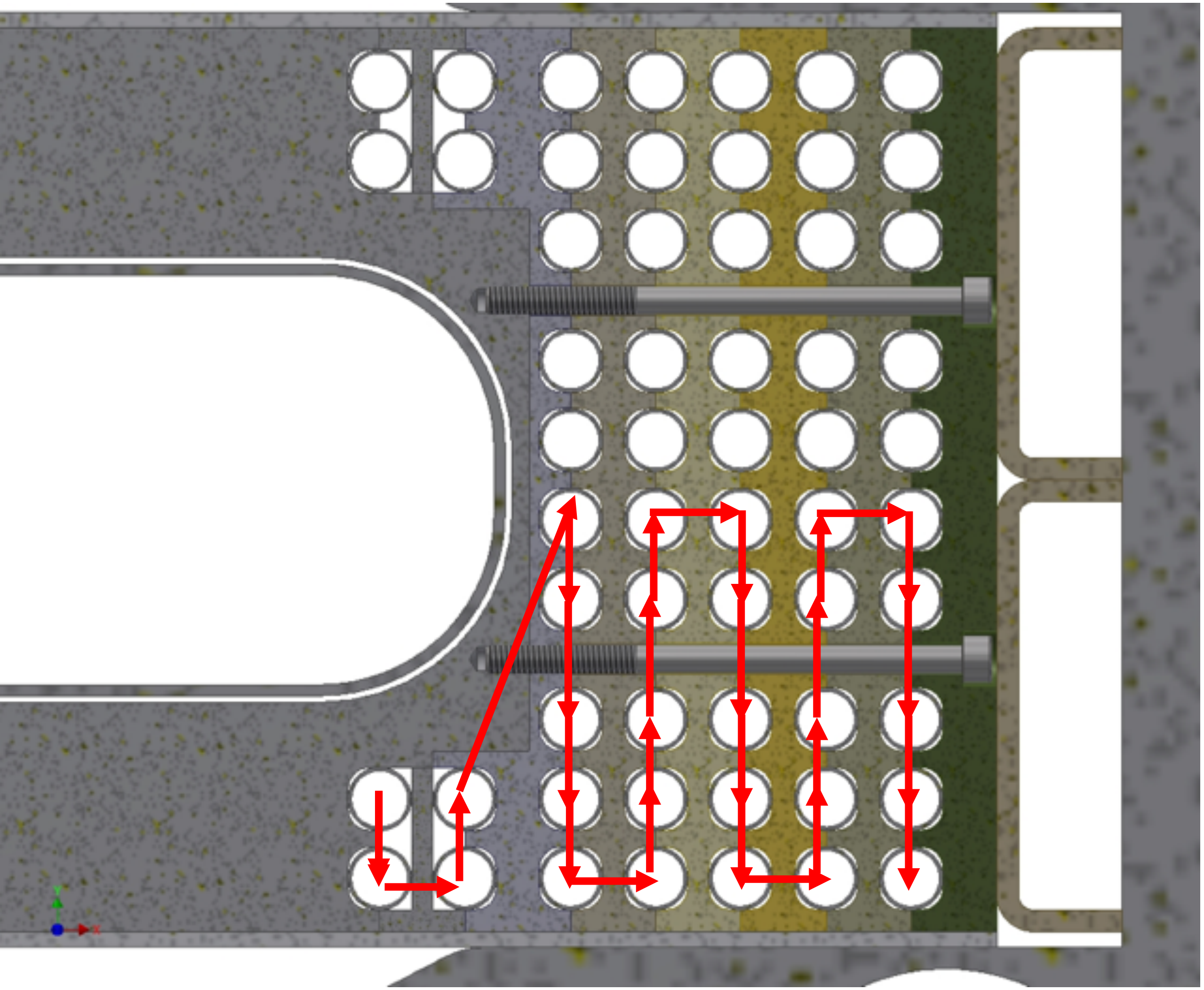


Design field B_0	3 T	6 T	6T graded
Coil current	13.7 kA	17.2 kA	18.6
Coil field @ B_0	3.5 T	6.9 T	7.1
Bore field @ SS	3.8 T	6.2 T	6.4
# turns in coil	24	54	54
Cable:			
# strands	15	14	18/10
strand dia.	1.2 mm	1.5 mm	1.39 mm
total s.c. area	8 cm^2	27 cm^2	23 cm^2
Flux return size	20 cm	33 cm	35 cm

We significantly improved our earlier 6 T CIC design by grading the conductor.

Magnet cost for a CIC dipole is proportional to # turns, flux return size.
On that basis, 6 T dipoles would cost ~2.25 x cost of 3 T.
Compare to cos θ, for which cost ~ B^2.

6 T coil structure is same as for 3 T CIC dipole, but 5 layers instead of 3 layers

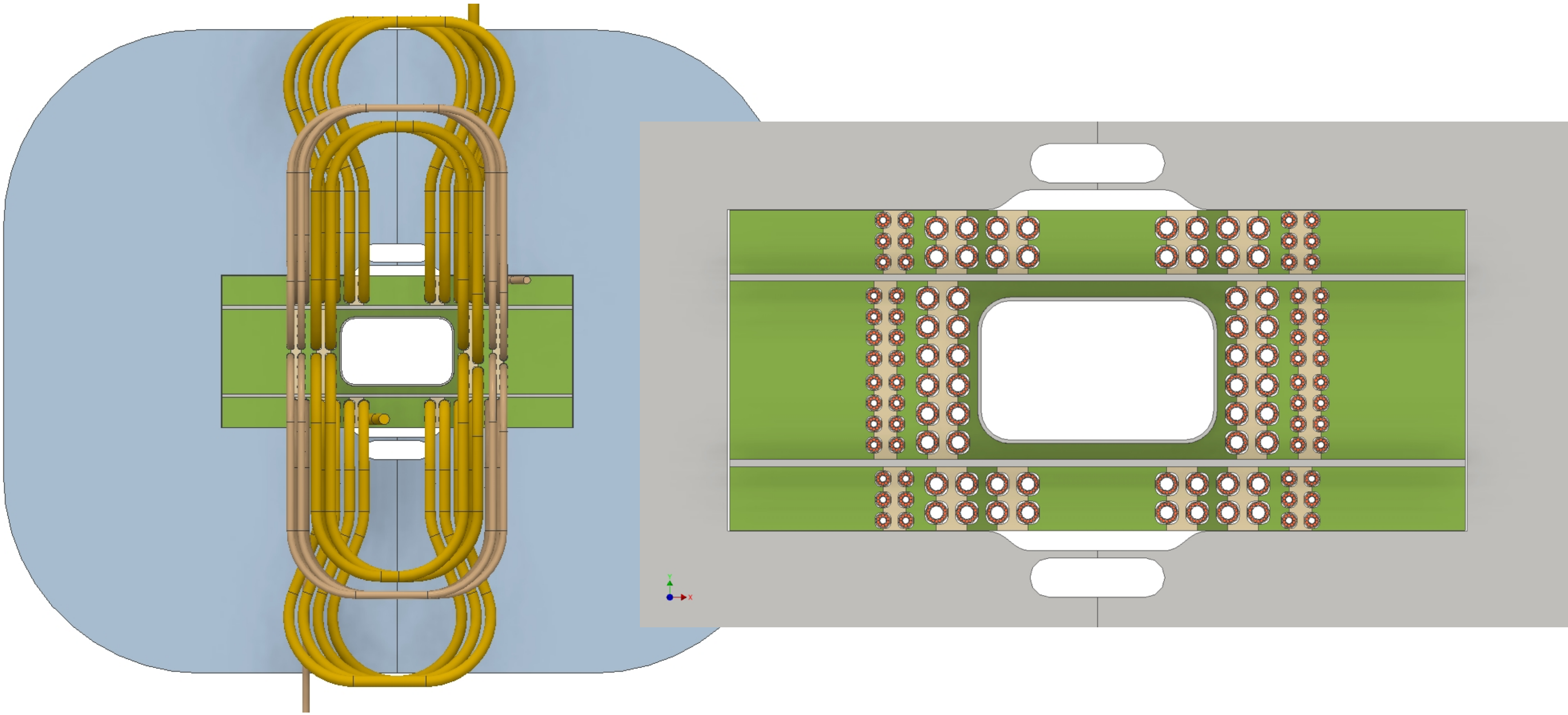


Half-winding of a 4 m dipole = 27 turns
~ 540 m CIC cable length

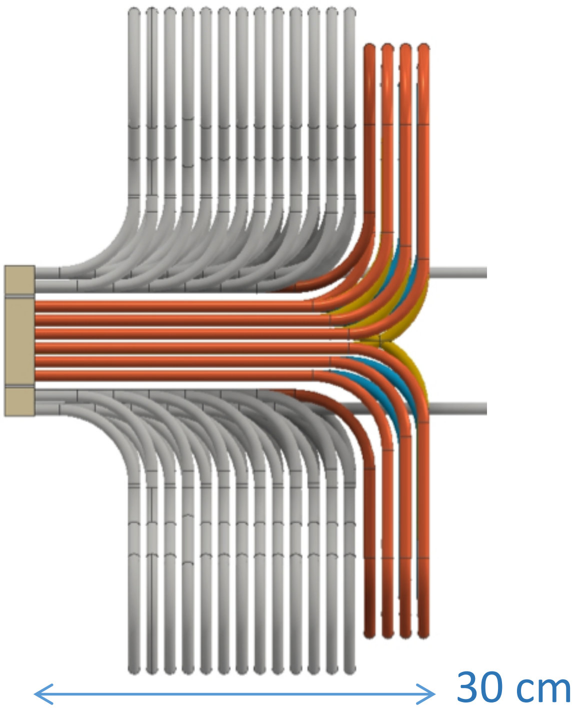
Priority on completing the development of continuous tube—forming fabrication of sheath tube directly onto cable

Building/testing a 3 T model dipole would go far toward validating the 6 T cousin.

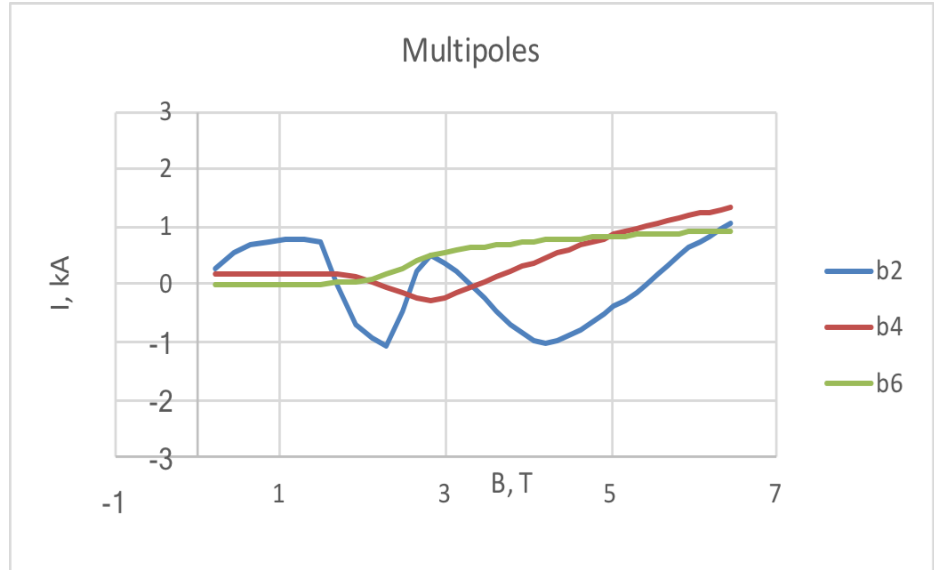
End region is bigger but workable

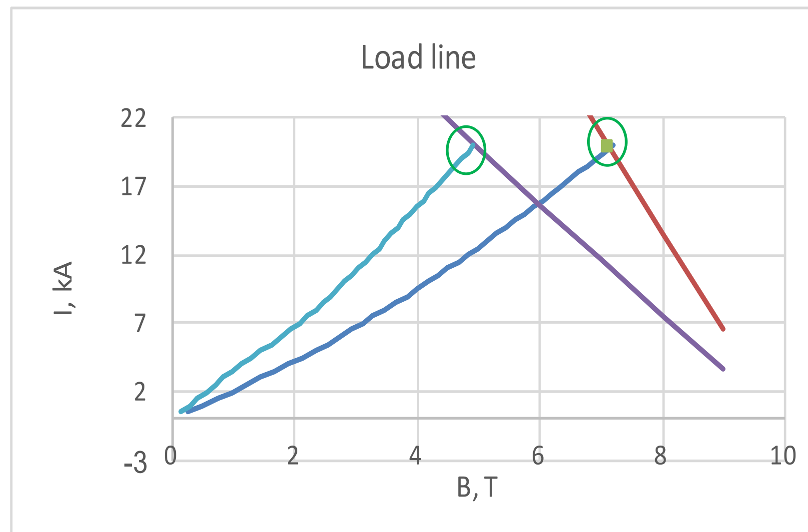


6 T CIC dipole design parameters

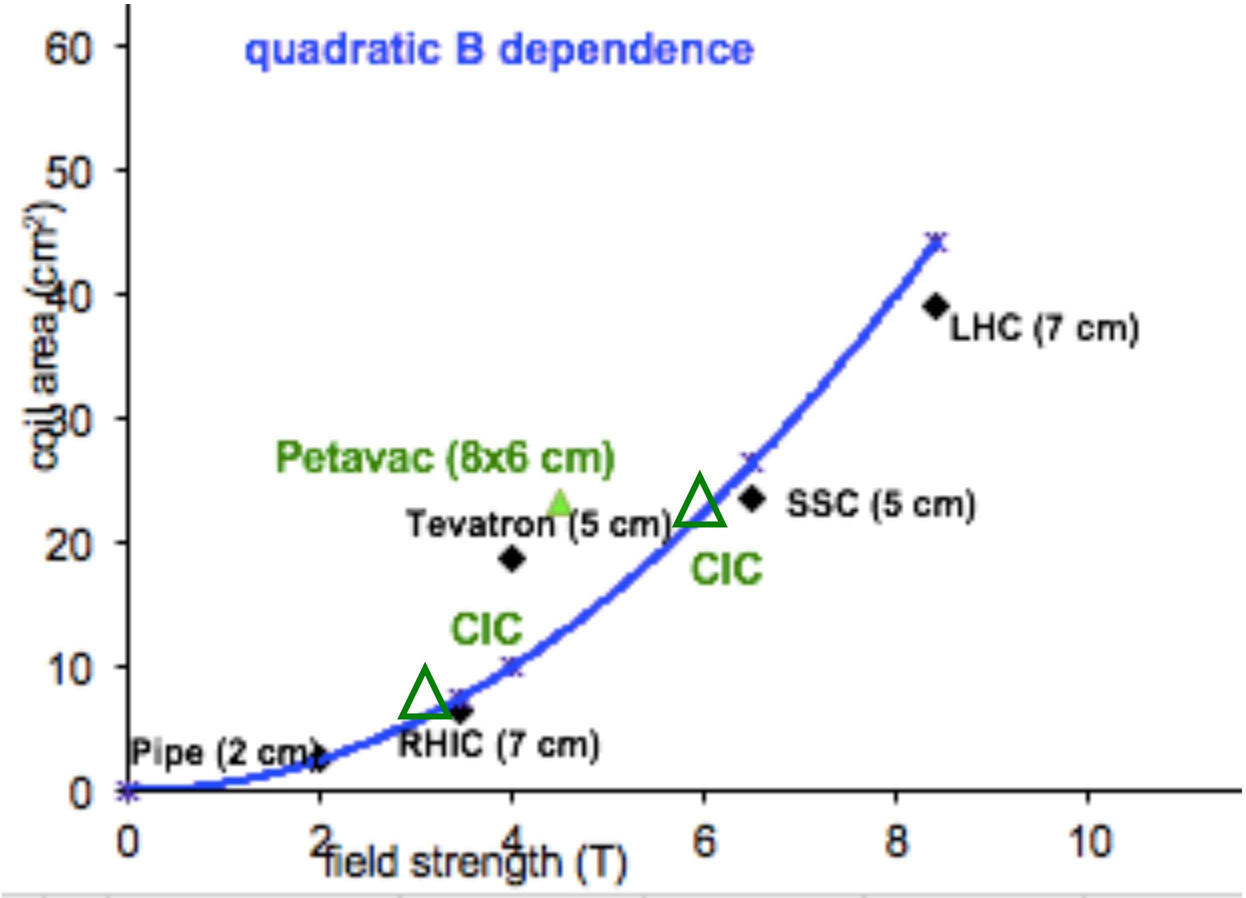


dstrand	**1.39**	**mm**
Nstrands	**18/10**	
Cu/Sc	**1.2**	
	9.94/6.8	
Dcable	**8**	**mm**
Bssl	**6.39**	**T**
Bcab	**7.14**	**T**
Issl	**19800**	**A**
Estored	**216**	**kJ/m**
L	**1.10**	**mH/m**





The CIC block-coil dipole is amp-efficient.



Value engineering

2014: Design a superconducting dipole to optimize cost/performance for JLEIC requirements.

Element Description	Unit Measure	# Units	Unit Cost	Cost Basis	Total Mat'l Cost $	Hrs/Unit	Total Hrs	Total Labor $	Total Matl + Labor $	Tooling	Engineering, QC & Supervision
Beam Tube, Coil Collar, End Block & Flared Ends											
Cold Bore Tube - Cu Plated	EA	1	2,421	Bailey	2,421	3	3	237	2,658	5,000	150
Beam Tube Flange	EA	2	200	ISC	400	4	8	632	1,032		100
Coil Body Form - injection-molded fiber-reinforced Kel-F	EA	1	3,600	ISC	3,600	6	6	474	4,074	15,000	150
Flared End Form -injection-molded fiber-reinforced Kel-F	EA	2	300	Rebling	600	6	12	948	1,548	5,000	40
Assemble Coil Form on Beam Tube - body and flared ends	Assy	1			-	28	28	2,212	2,212	10,000	300
Coil Assembly											
NbTi strand, 0.8 mm dia, 50% Cu	km	5.4	485	Luvata	2,619		-	-	2,619		500
Cabling and insulation of NbTi conductor	EA	1	1,454	NEEW	1,454		-	-	1,454		750
Coil Winding	EA	1		Bailey	-	40	40	3,160	3,160	50,000	640
Install insulating shell, sizing and impreg curing	Assy	1	1,200	Rebling	1,200	16	16	1,264	2,464	20,000	320
Splice Preparation & Fab	EA	2	50		100	3	6	474	574	1,000	250
Quench Protection Heaters	EA	4	30		120	2	7	553	673	2,000	500
Voltage Taps	Assy	1	50		50	2	2	158	208	2,000	300
Temp Sensors	EA	2	50		100	1	2	158	258		200
Total cost of coil/beam tube assembly					**12,664**		**130**		**22,934**	**110,000**	**4,200**
Flux Return											
Flux Return, Lamination Material	EA	1380	2	CERN	2,567		-	-	2,567		600
Flux Return, Lamination Stamping	EA	1380	5	Bailey	7,397		-	-	7,397	40,000	1,280
Lamination Pack Shuffling, Stacking, Compression, Weld	Assy	16			200	3	40	3,160	3,360	15,000	640
He Vessel Clamshells, 304 SS	EA	2	3,144	Bailey	6,288		10	790	7,078	5,000	640
He Vessel End Housings, 304 SS	EA	2	500	Bailey	1,000				1,000	5,000	400
Total Cost of Flux Return/He vessel subassemblies					**17,452**		**50**		**21,402**	**65,000**	**3,560**
Cold Mass Assembly											
Assemble Coil Assembly, Flux Return Halves, He Vessel Clamshells	Assy	1			-		24	1,896	1,896	25,000	400
Preload Cold Mass, Electrical & Alignment QC	Assy	1	200		200		32	2,528	2,728	15,000	240
Warm magnetic measurements											
Assemble End Housings on Cold Mass, Beam Tube, Weld & Checks	Assy	1	200		200		24	1,896	2,096	8,000	320
Shipping & handling		1	3,000		3,000		6	474	3,474		
Cold testing		1	6,000		6,000		20	1,580	7,580	100,000	2,000
Total manufactured cost of dipole cold mass					**39,515**		**286**		**62,109**	**323,000**	**10,720**

Develop a cost model, based on previous history of s.c. dipoles (SSC, RHIC, HERA, LCH, SIS100) to guide the optimization.

Predict ~$100K per 4 m dipole cold mass.

2016: Develop production tooling, build mock-up winding, measure cable positions

CIC cable		quantity for 4 m dipole		single-magnet cost
	NbTi wire	3600	m	14,400
	Monel Sheath tube	240	m	2,286
	perforated center tube	240	m	960
	SS tape overwrap	480	m	1,440
	cabling			5,000
	pulling cable into sheath	72	FTE hrs	3,600
	drawing sheath to final size	48	FTE hrs	2,400
				30,086
beam tube & G11 structural elements				
	SS beam tube			4,000
	G11 material			6,000
	G11 body segments			8,000
	G11 end elements			24,000
	Ti rails			6,000
	quench heater foils			3,000
	fab, impreg of beam	80	FTE hrs	4,000
				55,000
winding the dipole				
	winding labor	256	FTE hrs	12,800
	QC, winding completion	120	FTE hrs	6,000
				18,800
flux return				
	lamination steel	5.12	tons	15,360
	die-stamping	1600	pieces	8,000
	clean/stack/weld half-cores	80	FTE hrs	4,000
				27,360
cold mass assembly				
	install instrumentation	80	FTE hrs	4,000
	assenble winding assy with	120	FTE hrs	6,000
	QC, preload	80	FTE hrs	4,000
	warm measurements	60	FTE hrs	3,000
	shim winding, reassiemble	80	FTE hrs	4,000
	weld cold mass	64	FTE hrs	3,200
				24,200
total cold mass cost		**1140**	**FTE hrs**	**155,446**

Using what we now know, we made a revised cost projection using actual labor, actual tooling, actual materials and fabrication contracts.

Estimate $155K/dipole for first cold masses.

Consistent with first estimates!

Based upon our experience to date, I am confident that we should be able to build the arc dipoles and quadrupoles for approximately the budget that we estimated two years ago when we began.

SBIRs that benefit our development of the ring dipoles and the IR magnets

- MAG1: Phase 2 for development of continuous tube forming of sheath tube onto the cable for long-length CIC cable.
- MAG4: Phase 1 for development of CIC cable containing Nb_3Sn and MgB_2 wires.