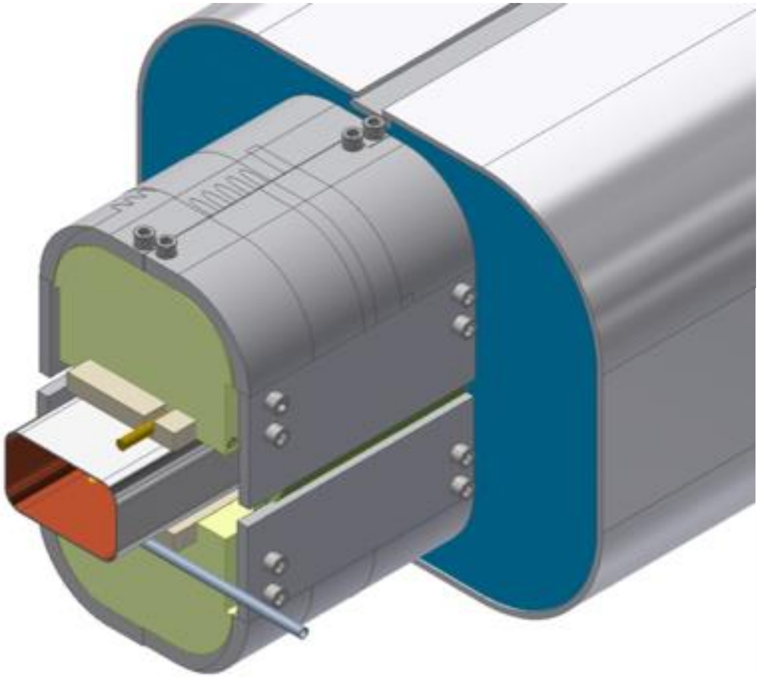
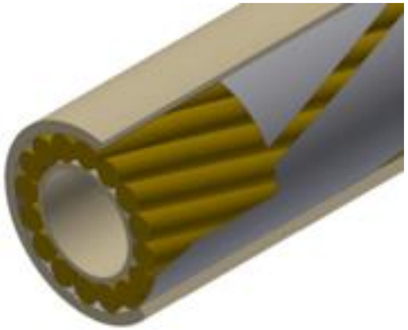
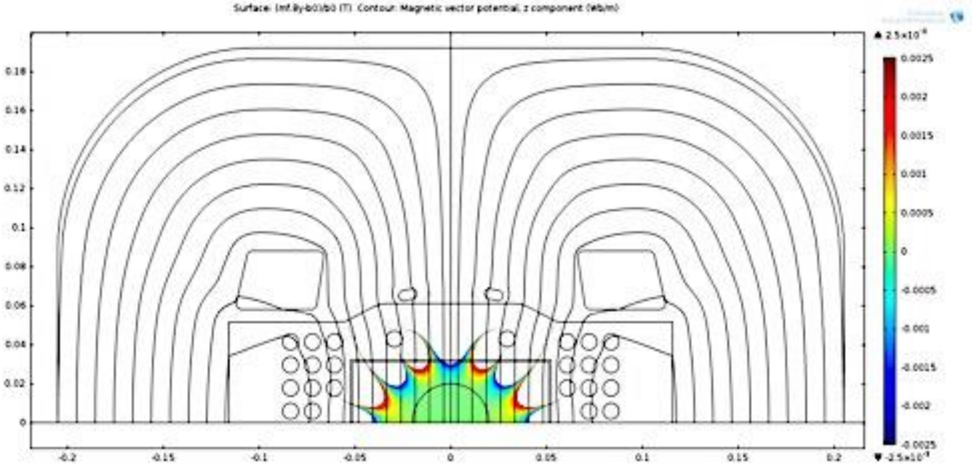
Design Studies and Prototyping of Superferric Magnets for EIC







Peter McIntyre

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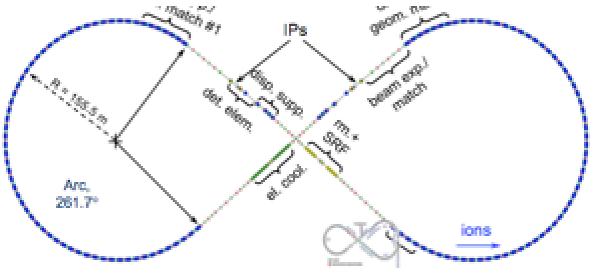
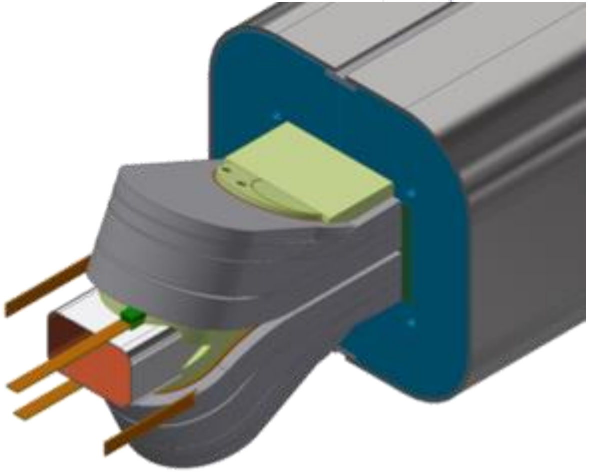
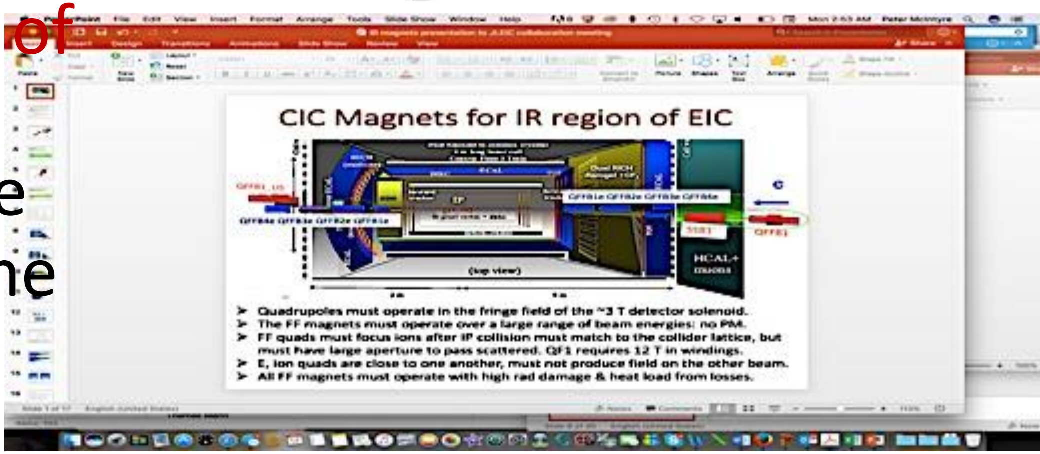
Description of the Project

- We are developing a 3 T superferric dipole with cable-in-conduit 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.







CIC Magnets for IR region of EIC

- ➢ Quadrupoles must operate in the fringe field of the ~3 T detector solenoid.
- ➢ The FF magnets must operate over a large range of beam energies: no PM.
- ➢ FF quads must focus ions after IP collision must match to the collider lattice, but must have large aperture to pass scattered. QF1 requires 12 T in windings.
- ➢ E, ion quads are close to one another, must not produce field on the other beam.
- ➢ All FF magnets must operate with high rad damage & heat load from losses.

Main goal of the project funded in FY16

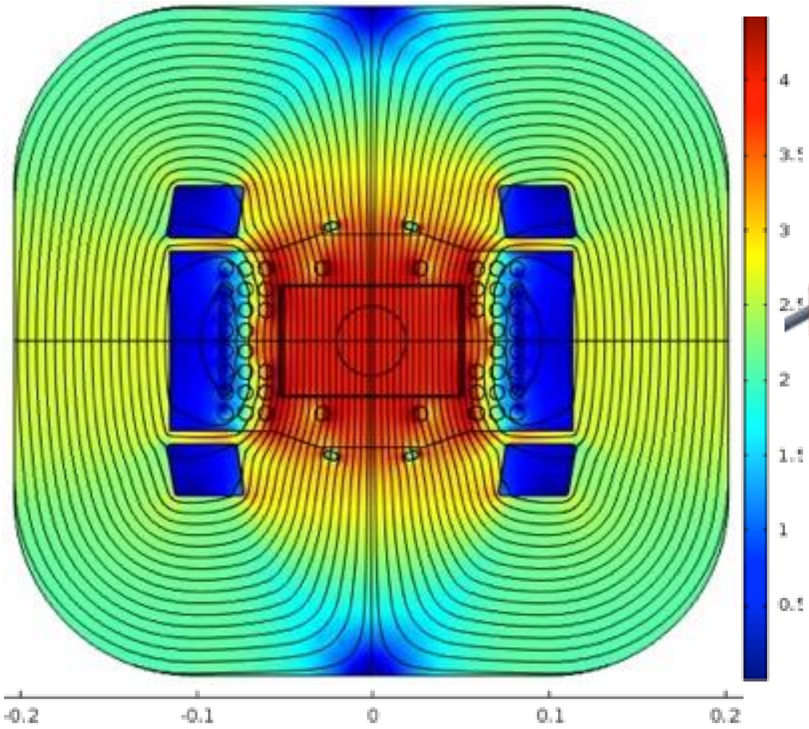
- $139K has been funded in FY16.
- Goals of the revised scope under that reduced funding:
  - fabricate a long length of CIC cable,
  - wind a few turns of the CIC cable onto the coil form that was fabricated in FY15 in order to evaluate the coil-winding methods using the final CIC cable.

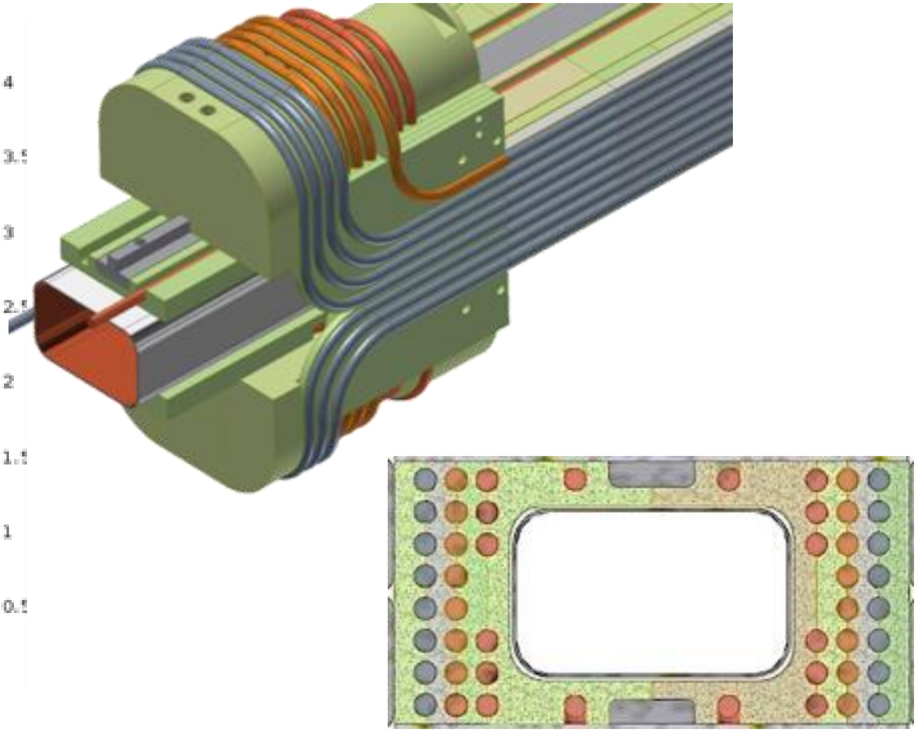
Expenditures by fiscal year

	FY14&15	FY16
Funds allocated	180K	139K
Actual costs to date	180K	95K

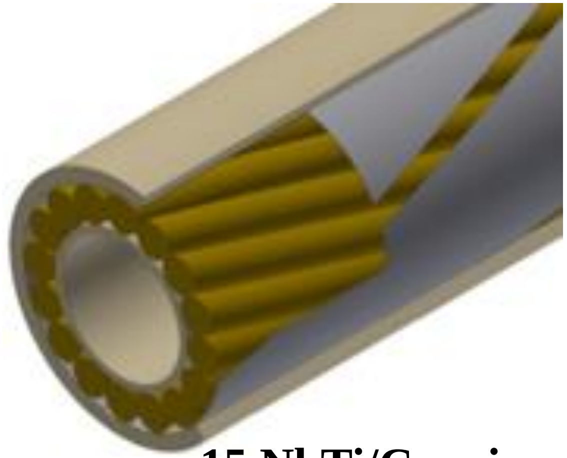
JLEIC Arc dipole: 3 Tesla, large aperture

The biggest challenge is to create a 10 cm x 6 cm aperture with the *field quality* ($b_n<10^{-4}$) needed for high-luminosity collisions and long luminosity lifetime – dynamic aperture

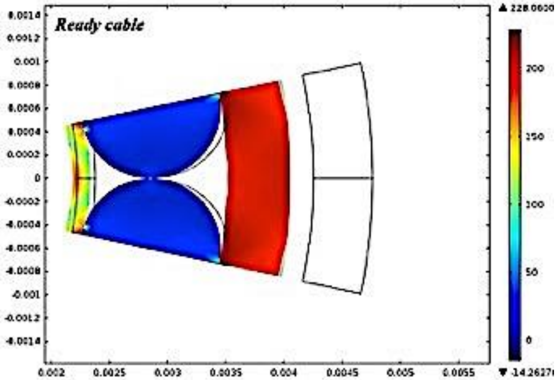




Key to cost-effective magnets: rectangular winding, cable-in-conduit conductor

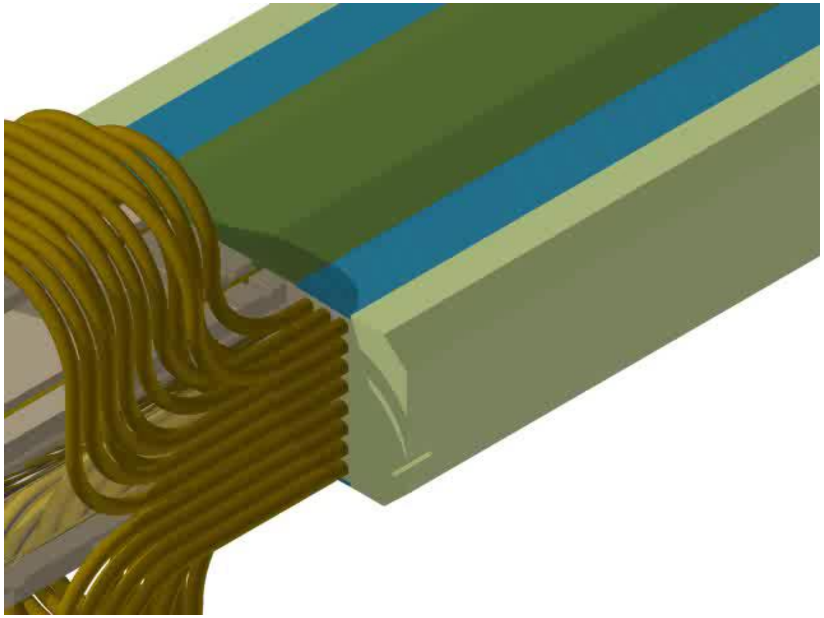


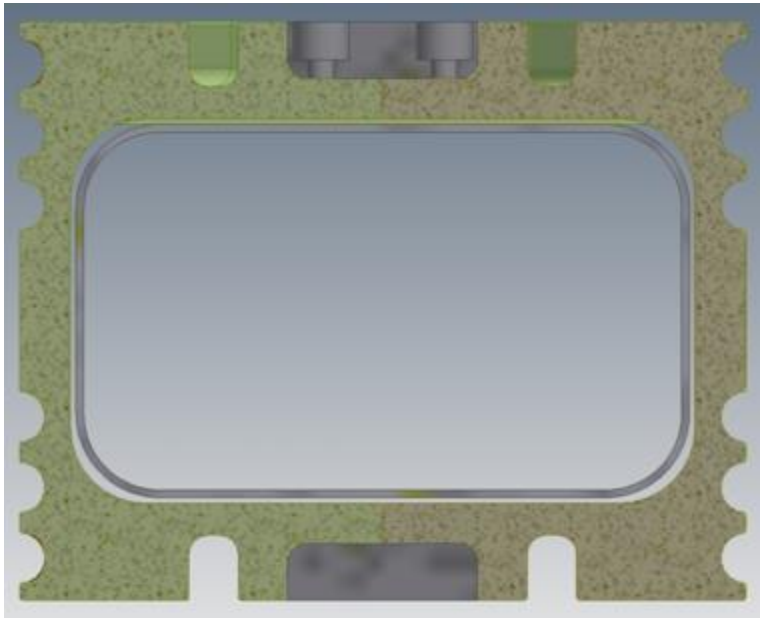
15 NbTi/Cu wires are cabled onto a perforated spring tube.



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:

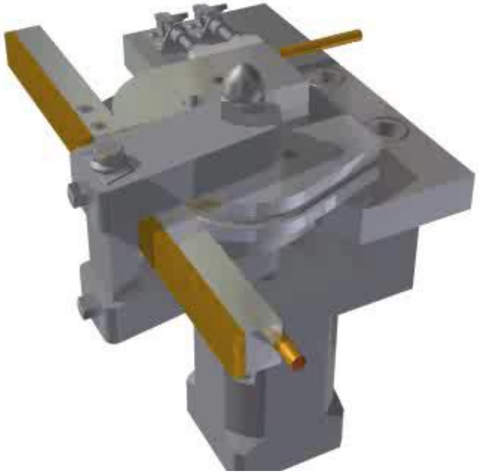
- All cables are positioned sandwiched between layers of precision-machined structure.
- Ends are formed to the side of the dipole, then popped into place in the structure layer.
- Overall coil assembly is preloaded within steel flux return, all windings immobilized.

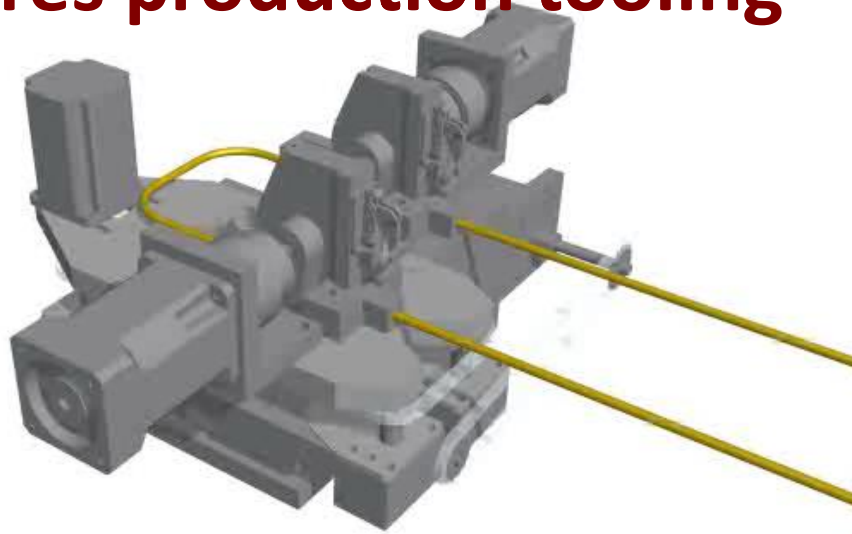
1. Fabricate inner form segments from 4”-thick G-11 fiber-reinforced epoxy slabs.
2. Assemble stack of segments for dipole body, using the CIC channels for alignment.
3. *Improvement:* Channels for cables are split equally on the facing segments.

3. Insert the SS beam tube, seal the ends, and epoxy impregnate the gap between segments and beam tube.

Assembly/alignment / epoxy impregnation of beam tube & winding structure

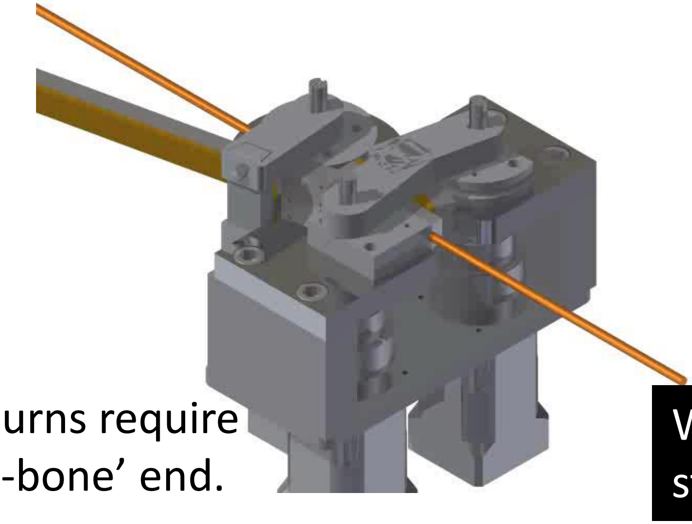
Forming the flared ends requires production tooling





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

1. Bend a U with the correct horizontal spacing.



3. 'Odd-man' turns require forming a 'dog-bone' end.

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

See videos of the real tools making these bends at https://goo.gl/VoSDOS

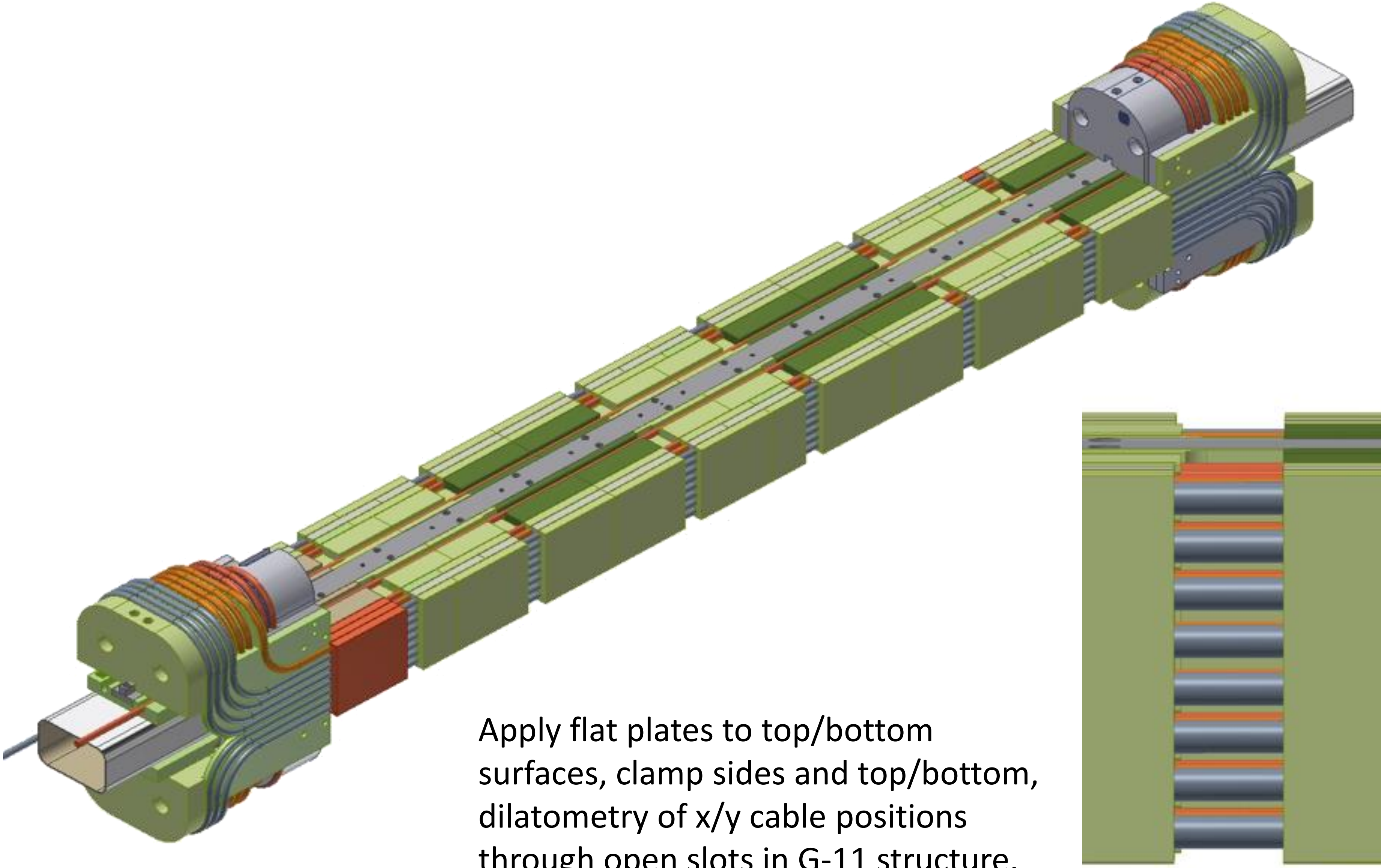
Motorized Benders in operation

Motorized bender to make planar U-bend.

Bender to make 90° flare on U-bend.

Motorized bender to form 'dog-bone' end.

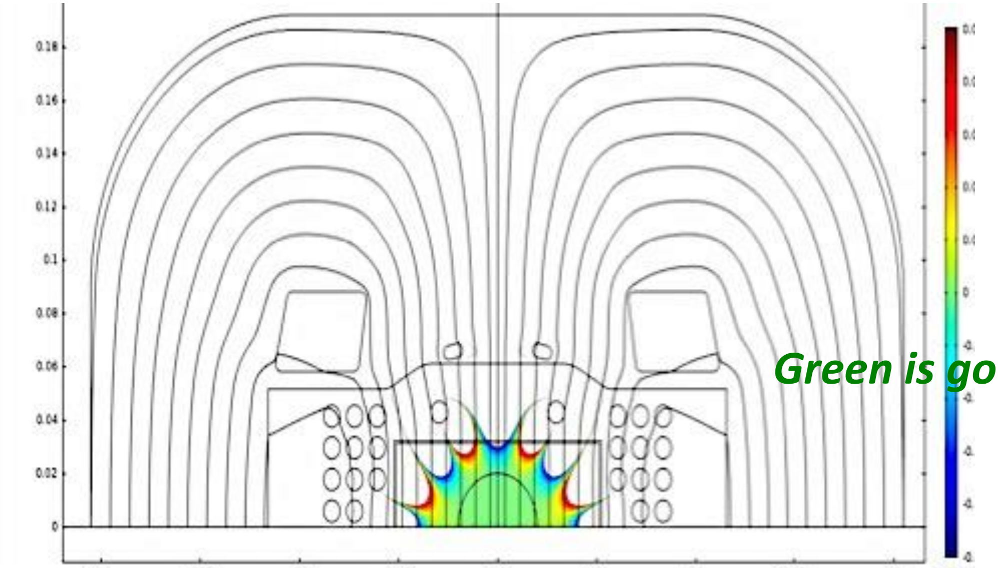
3-layer winding for a 1.2 m model dipole



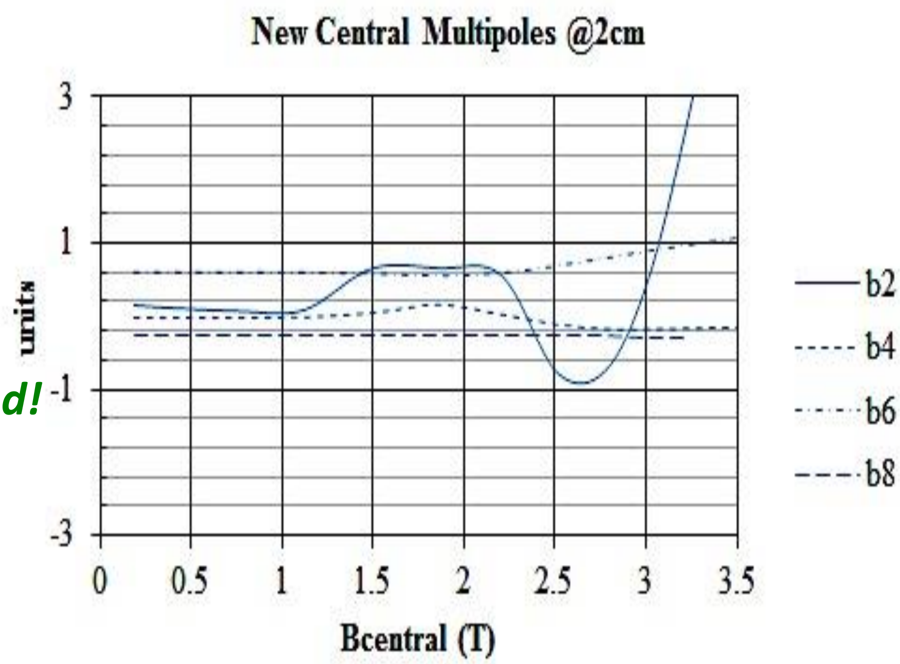
Apply flat plates to top/bottom surfaces, clamp sides and top/bottom, dilatometry of x/y cable positions through open slots in G-11 structure.

5/20/2016: Mockup winding complete

Now take the calculated systematic multipoles:



Green is good!



13.7 kA @ 3.0 T, b_n < 1 unit all fields

And simulate the effects of cable position errors.

Measure all cable positions – Calculate contributions to multipoles

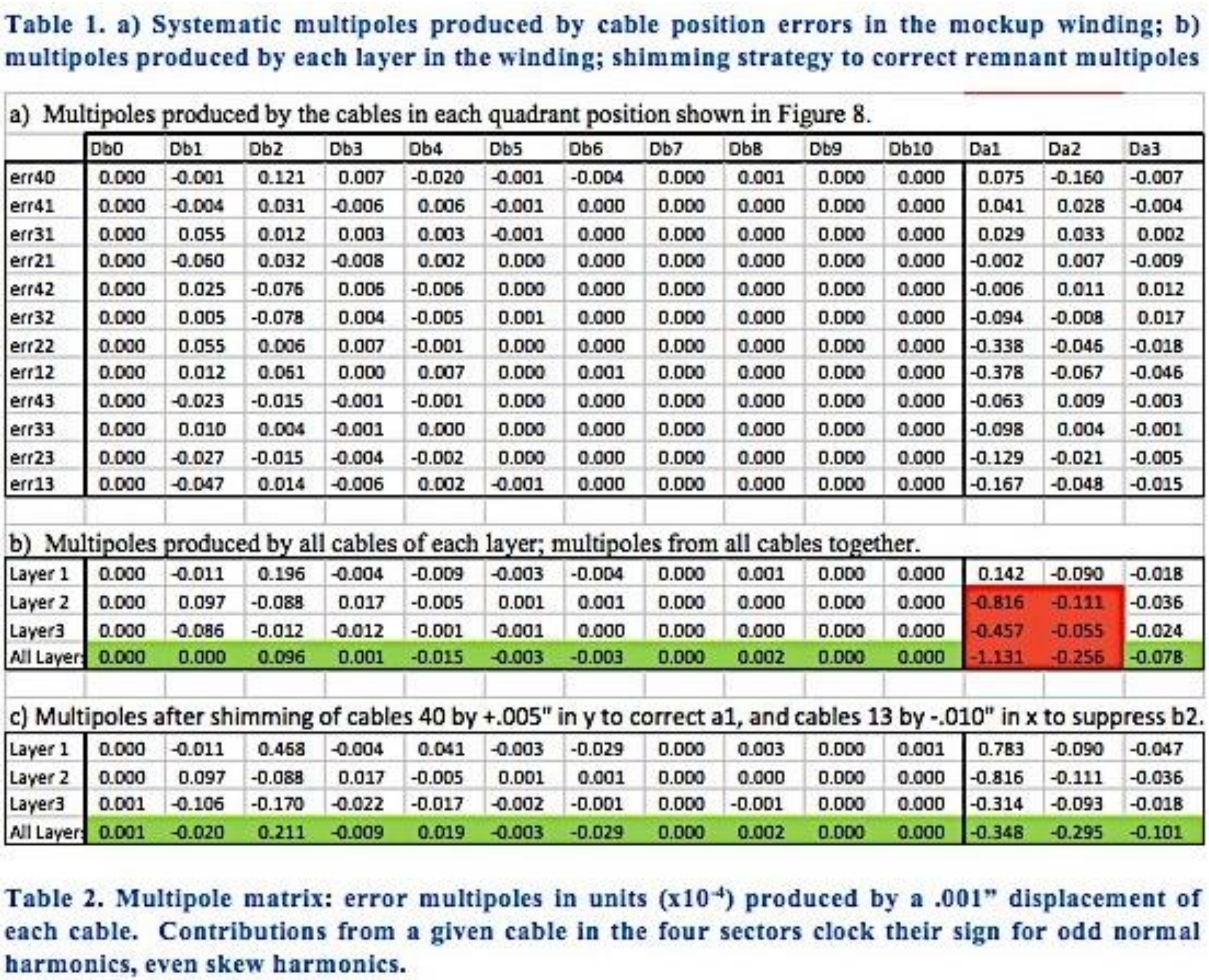


Table 1. a) Systematic multipoles produced by cable position errors in the mockup winding; b) multipoles produced by each layer in the winding; shimming strategy to correct remnant multipoles

a) Multipoles produced by the cables in each quadrant position shown in Figure 8.

	Db0	Db1	Db2	Db3	Db4	Db5	Db6	Db7	Db8	Db9	Db10	Da1	Da2	Da3
err40	0.000	-0.001	0.121	0.007	-0.020	-0.001	-0.004	0.000	0.001	0.000	0.000	0.075	-0.160	-0.007
err41	0.000	-0.004	0.031	-0.006	0.006	-0.001	0.000	0.000	0.000	0.000	0.000	0.041	0.028	-0.004
err31	0.000	0.055	0.012	0.003	0.003	-0.001	0.000	0.000	0.000	0.000	0.000	0.029	0.033	0.002
err21	0.000	-0.060	0.032	-0.008	0.002	0.000	0.000	0.000	0.000	0.000	0.000	-0.002	0.007	-0.009
err42	0.000	0.025	-0.076	0.006	-0.006	0.000	0.000	0.000	0.000	0.000	0.000	-0.006	0.011	0.012
err32	0.000	0.005	-0.078	0.004	-0.005	0.001	0.000	0.000	0.000	0.000	0.000	-0.094	-0.008	0.017
err22	0.000	0.055	0.006	0.007	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	-0.338	-0.046	-0.018
err12	0.000	0.012	0.061	0.000	0.007	0.000	0.001	0.000	0.000	0.000	0.000	-0.378	-0.067	-0.046
err43	0.000	-0.023	-0.015	-0.001	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	-0.063	0.009	-0.003
err33	0.000	0.010	0.004	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.098	0.004	-0.001
err23	0.000	-0.027	-0.015	-0.004	-0.002	0.000	0.000	0.000	0.000	0.000	0.000	-0.129	-0.021	-0.005
err13	0.000	-0.047	0.014	-0.006	0.002	-0.001	0.000	0.000	0.000	0.000	0.000	-0.167	-0.048	-0.015

b) Multipoles produced by all cables of each layer; multipoles from all cables together.

Layer 1	0.000	-0.011	0.196	-0.004	-0.009	-0.003	-0.004	0.000	0.001	0.000	0.000	0.142	-0.090	-0.018
Layer 2	0.000	0.097	-0.088	0.017	-0.005	0.001	0.001	0.000	0.000	0.000	0.000	-0.816	-0.111	-0.036
Layer3	0.000	-0.086	-0.012	-0.012	-0.001	-0.001	0.000	0.000	0.000	0.000	0.000	-0.457	-0.055	-0.024
All Layer	0.000	0.000	0.096	0.001	-0.015	-0.003	-0.003	0.000	0.002	0.000	0.000	-1.131	-0.256	-0.078

c) Multipoles after shimming of cables 40 by +.005" in y to correct a1, and cables 13 by -.010" in x to suppress b2.

Layer 1	0.000	-0.011	0.468	-0.004	0.041	-0.003	-0.029	0.000	0.003	0.000	0.001	0.783	-0.090	-0.047
Layer 2	0.000	0.097	-0.088	0.017	-0.005	0.001	0.001	0.000	0.000	0.000	0.000	-0.816	-0.111	-0.036
Layer3	0.001	-0.106	-0.170	-0.022	-0.017	-0.002	-0.001	0.000	-0.001	0.000	0.000	-0.314	-0.093	-0.018
All Layer	0.001	-0.020	0.211	-0.009	0.019	-0.003	-0.029	0.000	0.002	0.000	0.000	-0.348	-0.295	-0.101

Table 2. Multipole matrix: error multipoles in units ($x10^{-4}$) produced by a .001" displacement of each cable. Contributions from a given cable in the four sectors clock their sign for odd normal harmonics, even skew harmonics.

Shimming strategy to trim 2 dominant multipoles from warm measurements

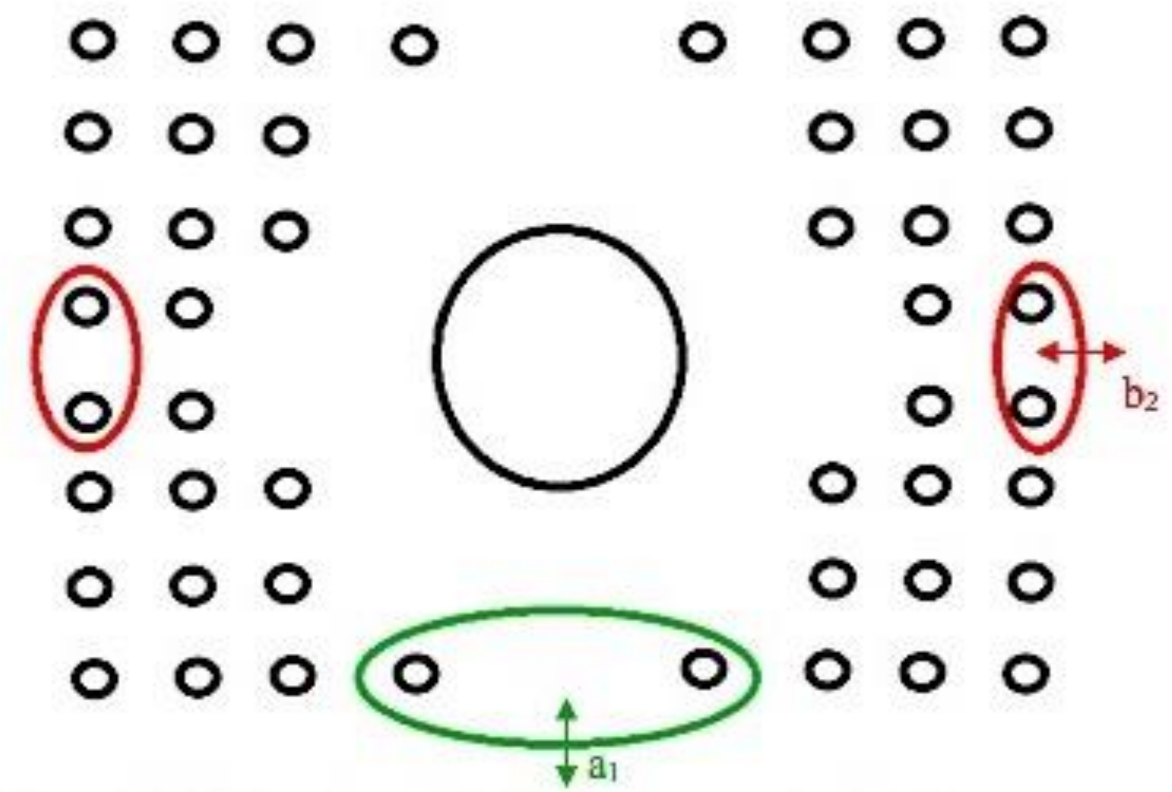


Figure 10. Shimming selected turns to correct multipoles.

Developing this workable strategy to trim a1, b2 multipoles after warm measurement is an important milestone in maturing the CIC superferric dipole for use in a collider. Doing it in practice will be a goal for model dipole construction and testing.

Current Status of magnet development:

- ✓We have built a 1.2m <u>mockup winding</u>.
- ✓We have measured cable positions to determine structure multipoles. We met the tolerances to provide the specified multipoles.
- ✓We developed a shim procedure to further reduce important multipoles if desired.

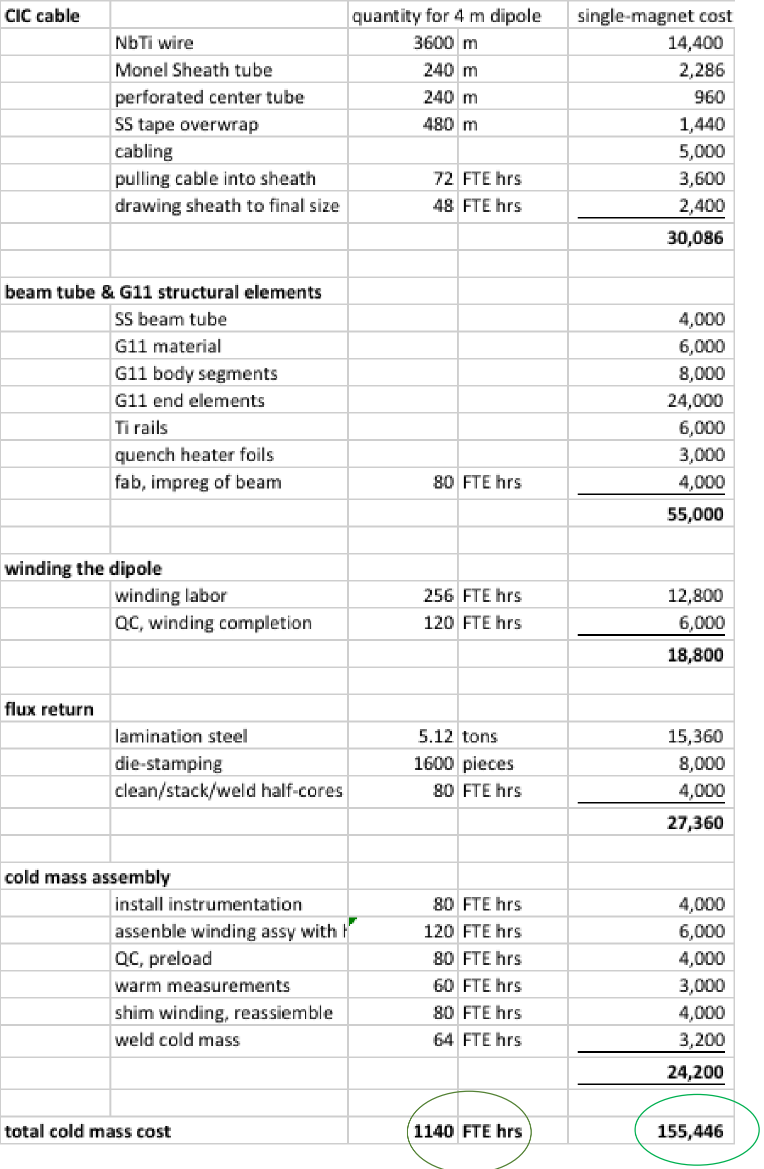
Current Status of CIC cable development

- ✓We have fabricated and tested short segments of CIC cable in its final form.
- ✓We have 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. We have placed orders for the NbTi wire, perforated center tube, and sheath tube that are required for fabrication of 125 m lengths of CIC cable.
- NE Electric Wire will cable the wires onto the center tube. We will pull cable into sheath tube and draw to final size at Texas A&M.

We will not be able to proceed with model dipole fabrication until DOE provides additional funds.

Funding needed to complete a 1.2 model dipole: $350K

It is worth a fresh look at the projected cost to build a first 4 m JLEIC dipole.

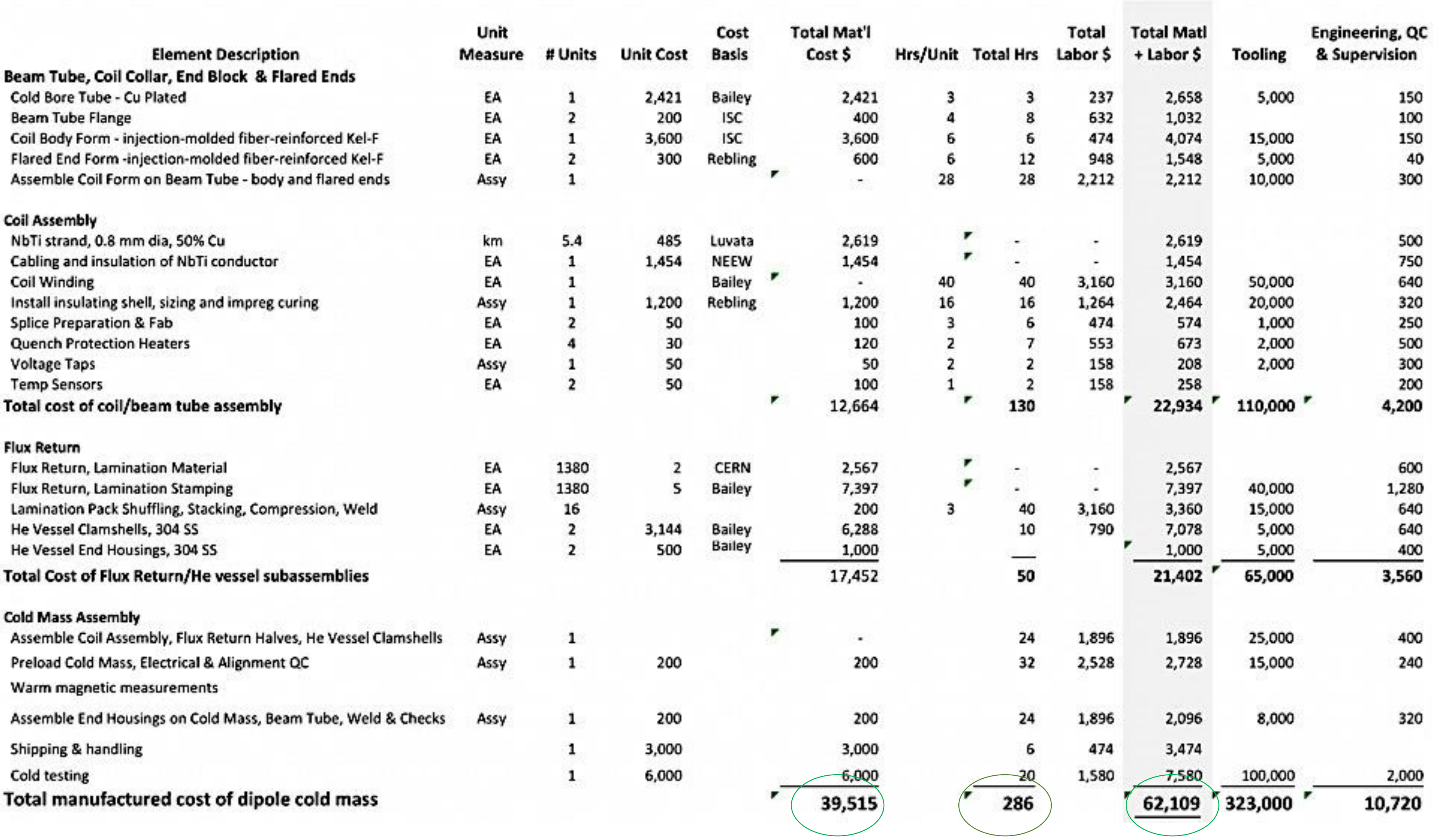


CIC cable		quantity for 4 m dipole		single-magnet cost
	NbTi wire	3600	m	14,400
	Monel Sheath tube	240	m	2,286
	perforated center tube	240	m	960
	SS tape overwrap	480	m	1,440
	cabling			5,000
	pulling cable into sheath	72	FTE hrs	3,600
	drawing sheath to final size	48	FTE hrs	2,400
				30,086
beam tube & 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 I	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**

The total costs for each category are ~1.4 x higher than the TAMU estimates in our first cost exercise in December 2014. But this is our current-best projection for the cost to build the *first* dipole.

I am optimistic that we will meet our original cost and performance objectives for the manufactured run of 256 dipoles for JLEIC.

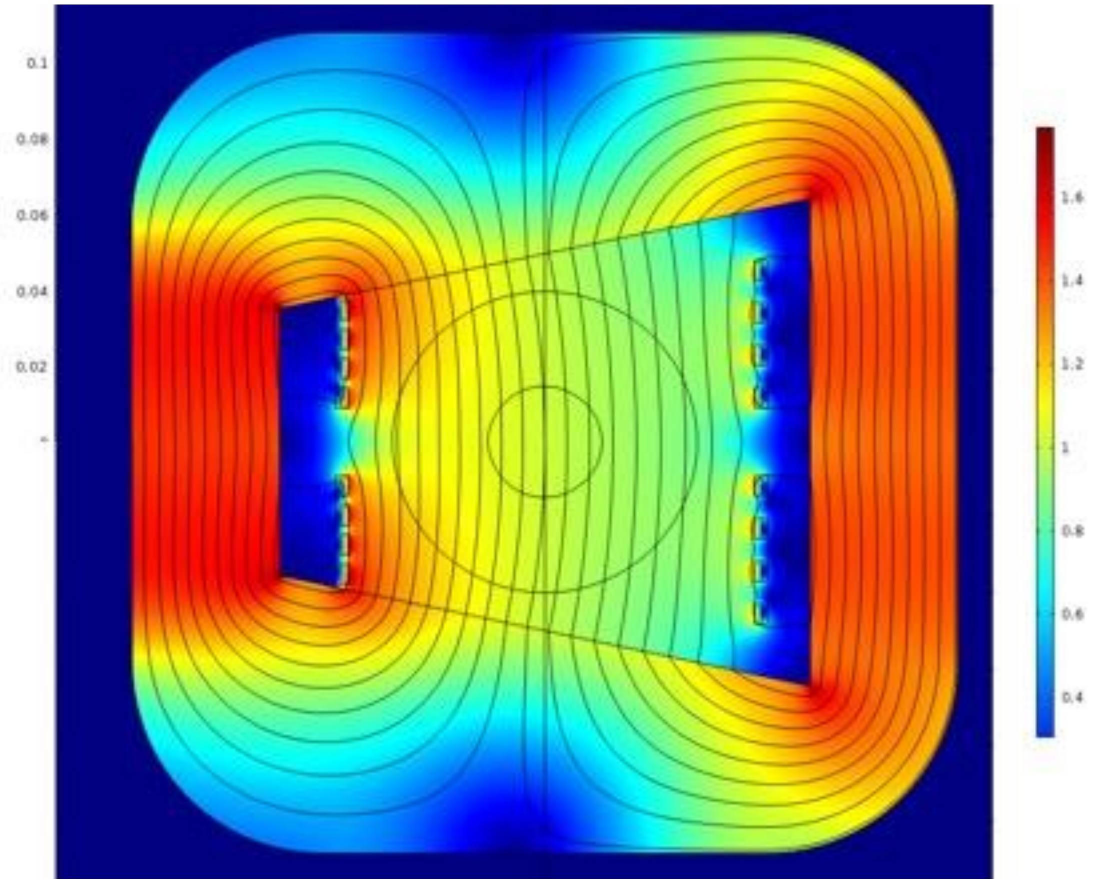
Bottom-up cost detail – dipole cold mass



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**

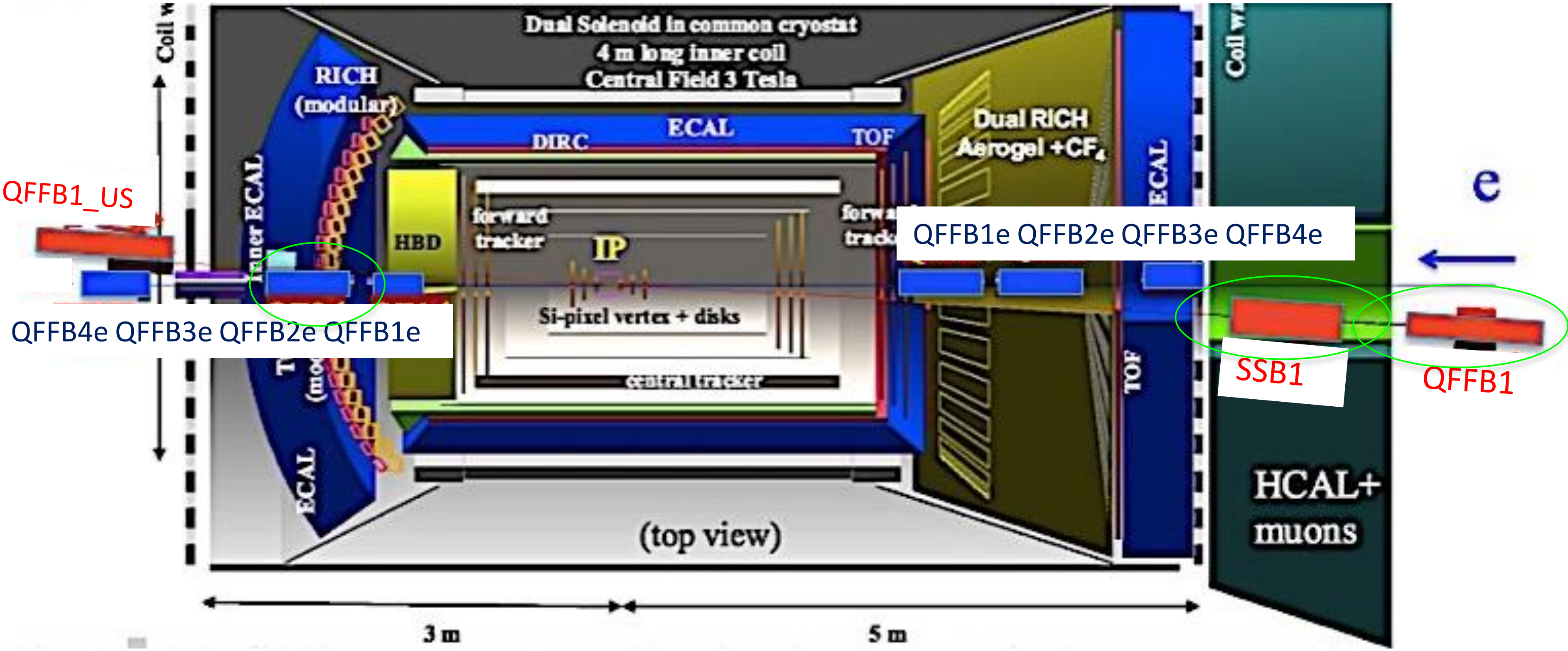
Dipole cold mass cost estimate presented at MEIC review 12/2014.

Combined-function dipole if needed for achromat matching to e-cooling



We designed this strong-focusing combined-function dipole for a low-energy d.c. e-cooling ring. We could develop a corresponding >2 T version if needed for achromat matching for the bunched-beam cooling section.

CIC Magnets for IR region of EIC



- Quadrupoles must operate in the fringe field of the ~3 T detector solenoid.
- The FF magnets must operate over a large range of beam energies: no PM.
- FF quads must focus ions after IP collision must match to the collider lattice, but must have large aperture to pass scattered. QF1 requires 12 T in windings.
- E, ion quads are close to one another, must not produce field on the other beam.
- All FF magnets must operate with high rad damage & heat load from losses.

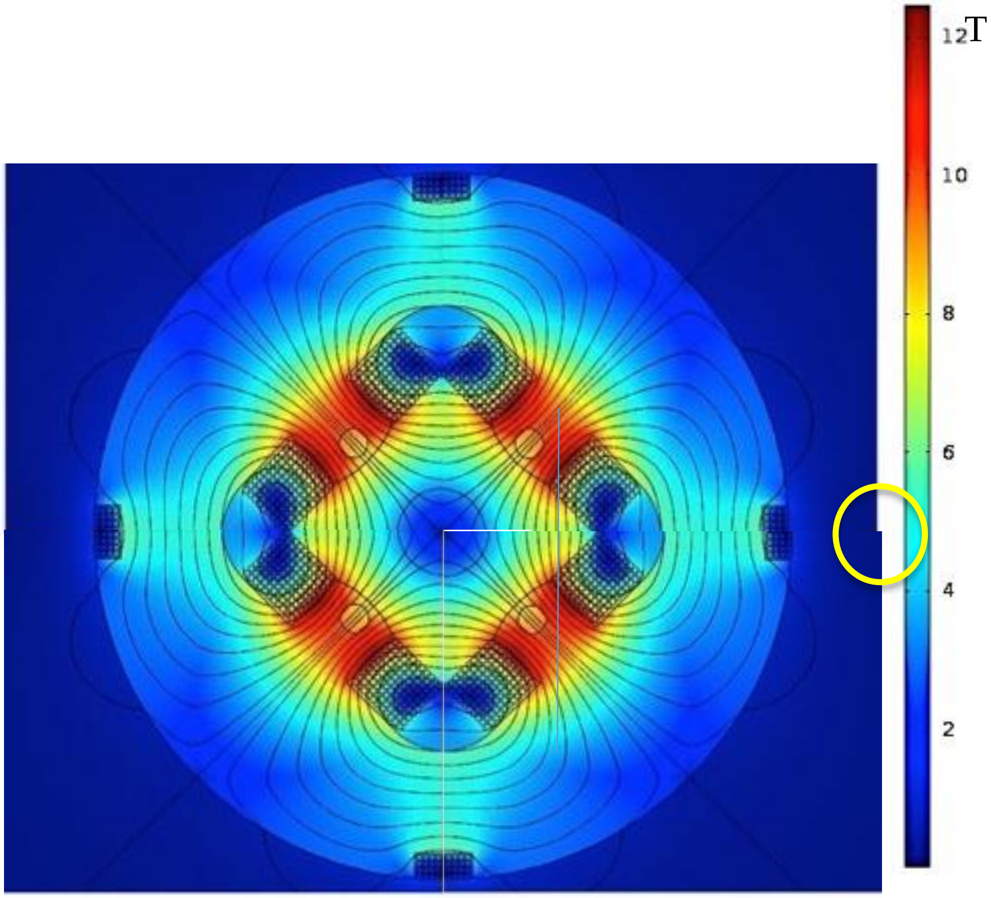
We have prepared conceptual designs for the four most difficult IR magnets

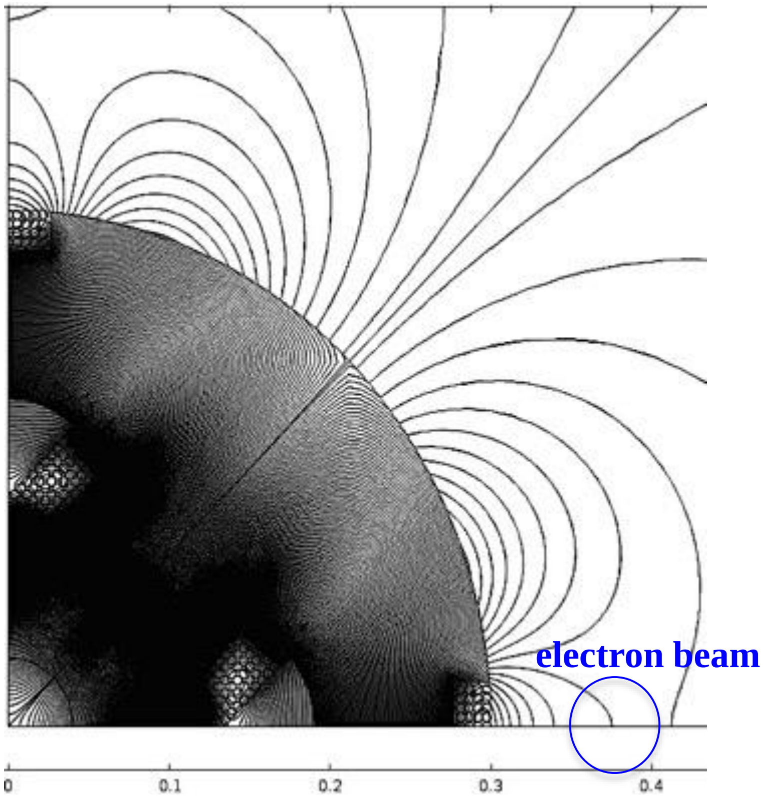
Ion Beam:
QFFB1: 90 T/m, 9 cm half-aperture, 36 cm from e-beam
SB1: 2 T, 340 mm aperture, 25 cm from the electron beam

Electron beam:
QFFB2e: 58 T/m gradient, 3 cm half-aperture, 10.5 cm from the ion beam
QFFB1e, QFFB2e are immersed in fringe field of spectrometer solenoid

- All designs utilize CIC conductor.
  - adaptable for challenging coil geometries
  - compact end windings
- Utilize MgB_2 superconductor for temperature margin in high radiation loss in QFFB1e, QFFB2e.
- Utilize Nb_3Sn superconductor for high gradient in QFFB1.
- Utilize sheath solenoid winding to cancel external flux from spectrometer solenoid.

Ion beam quad QFFB1: 90 T/m, 9 cm half-aperture, 36 cm from e-beam



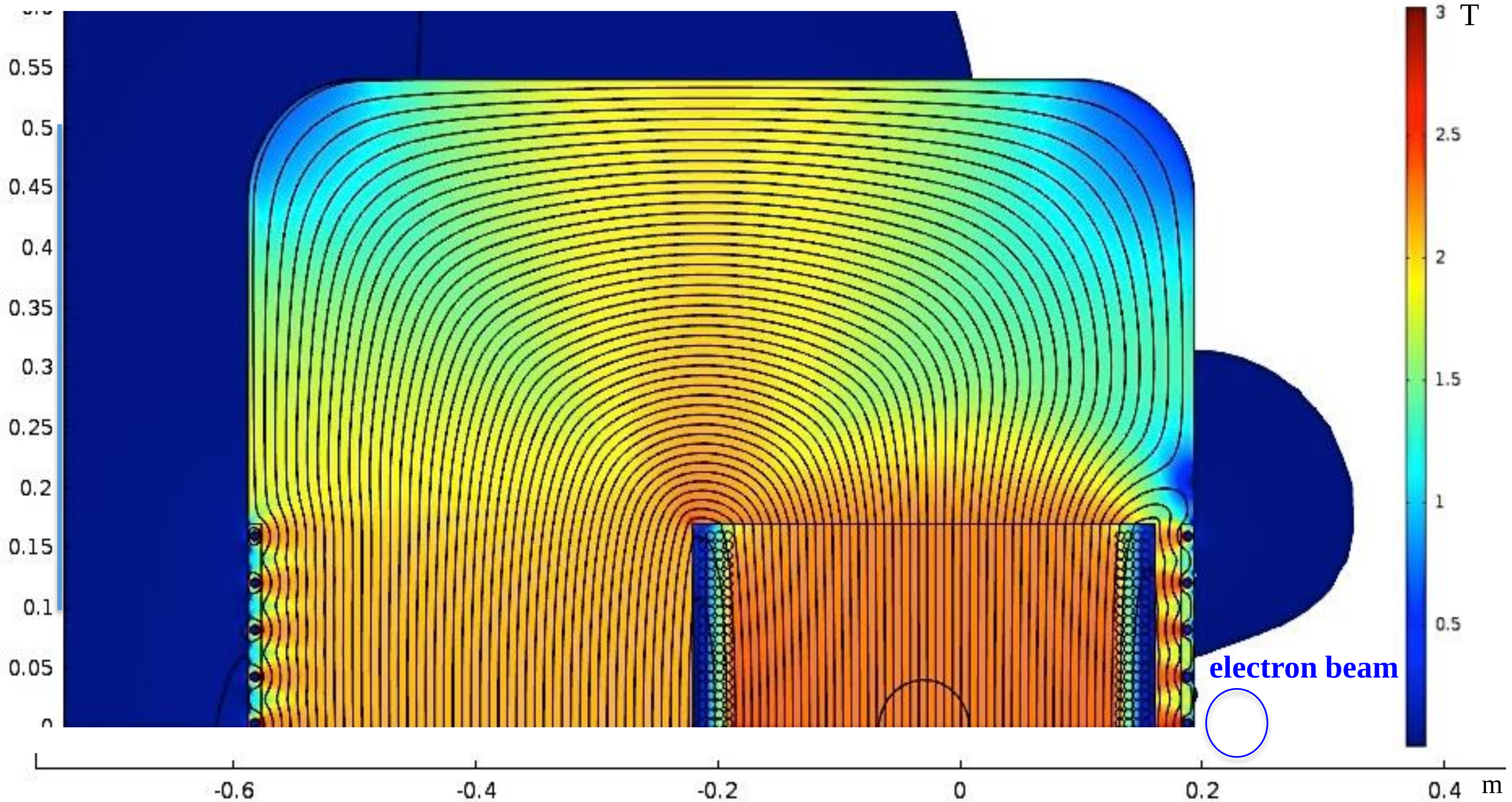


Reverse-current winding kills fringe field at the location of the electron beam.

9 kA cable current

Nb_3Sn windings, 4.2 K

Dipole SB1: 2 T, 340 mm aperture, 25 cm from the electron beam

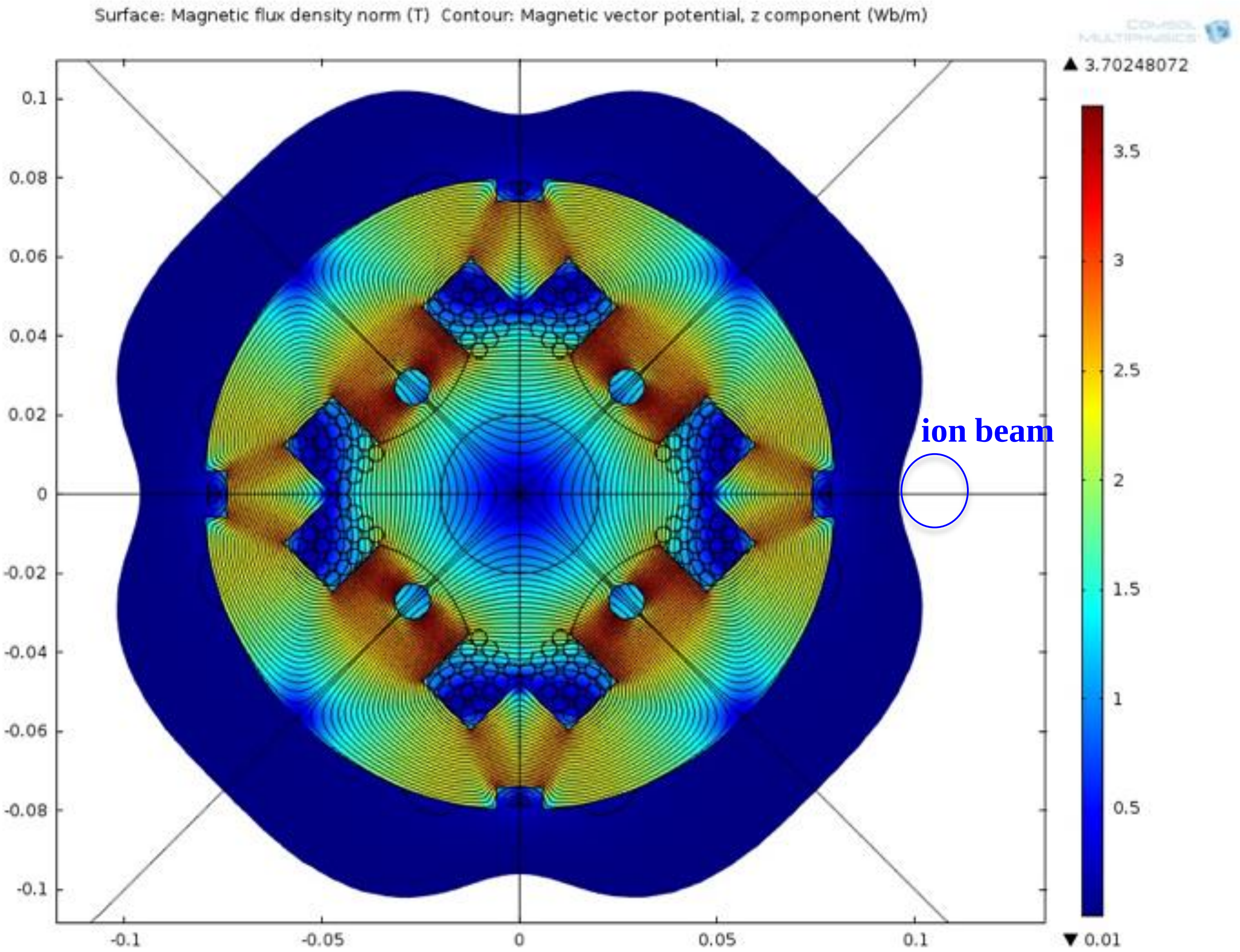


Window-frame C-geometry dipole configured as a Lambertson septum to suppress fringe field at electron beam.

4 kA cable current

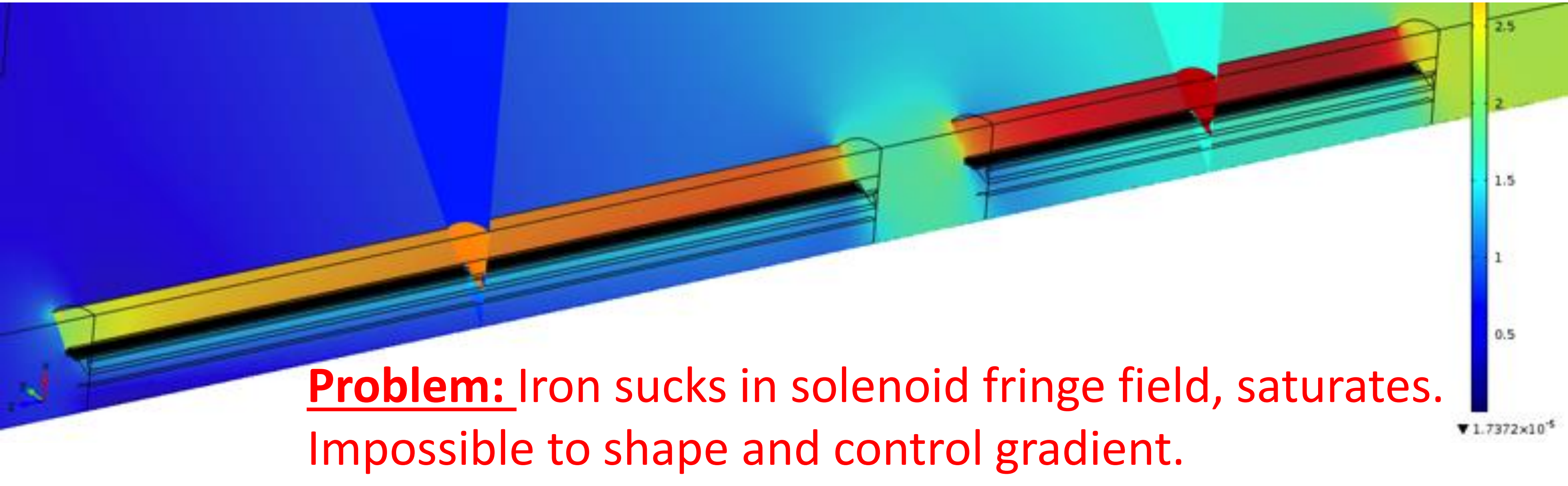
MgB_2 windings, 10 K

Quadrupole QFFB2e: 58 T/m gradient, 3 cm half-aperture, 10.5 cm from the ion beam

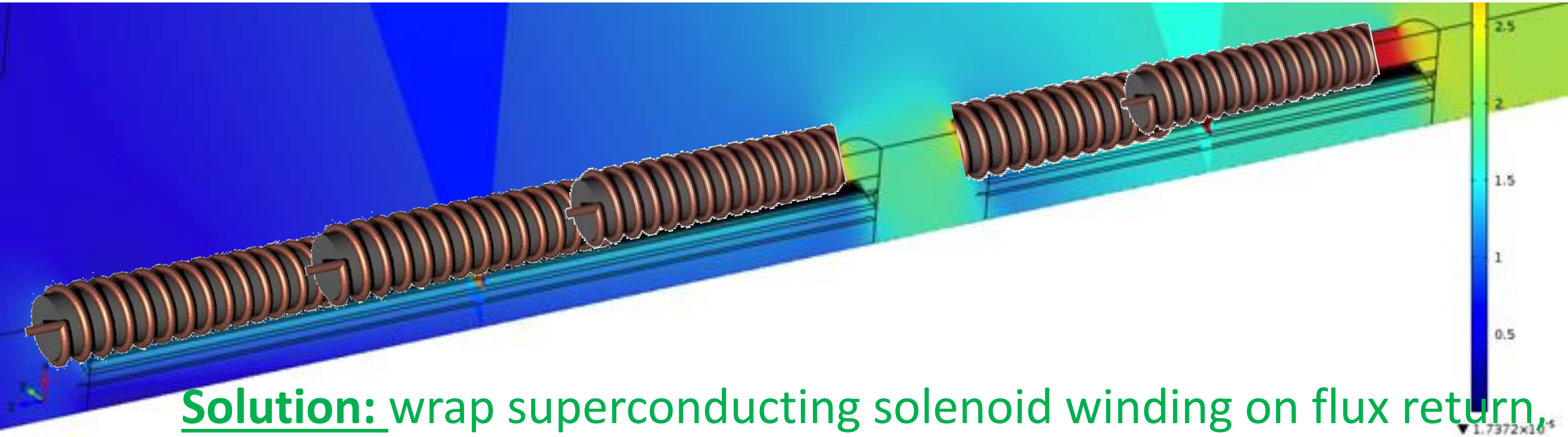


MgB$_2$ windings @ 10 K

Stealth magnetics: exclude fringe field



Problem: Iron sucks in solenoid fringe field, saturates. Impossible to shape and control gradient.



Solution: wrap superconducting solenoid winding on flux return, Adjust K(z) to exclude flux from spectrometer.

We have no funding to develop CIC IR magnets

- We have made preliminary magnetic designs that can achieve the requirements for all special magnets for the IR region of either eRHIC or JLEIC.
- CIC windings provide flexibility to meet the requirements with compact structure, suppress fields at the close-lying neighbor beam.
- CIC windings make it possible to use Nb_3Sn, MgB_2 superconductor to provide thermal headroom.
- Stealth magnetics can be used to operate superconducting quads in fringe field of spectrometer.

These are the most challenging magnets for EIC. It is important to begin serious development of model magnets that can meet the IR requirements.