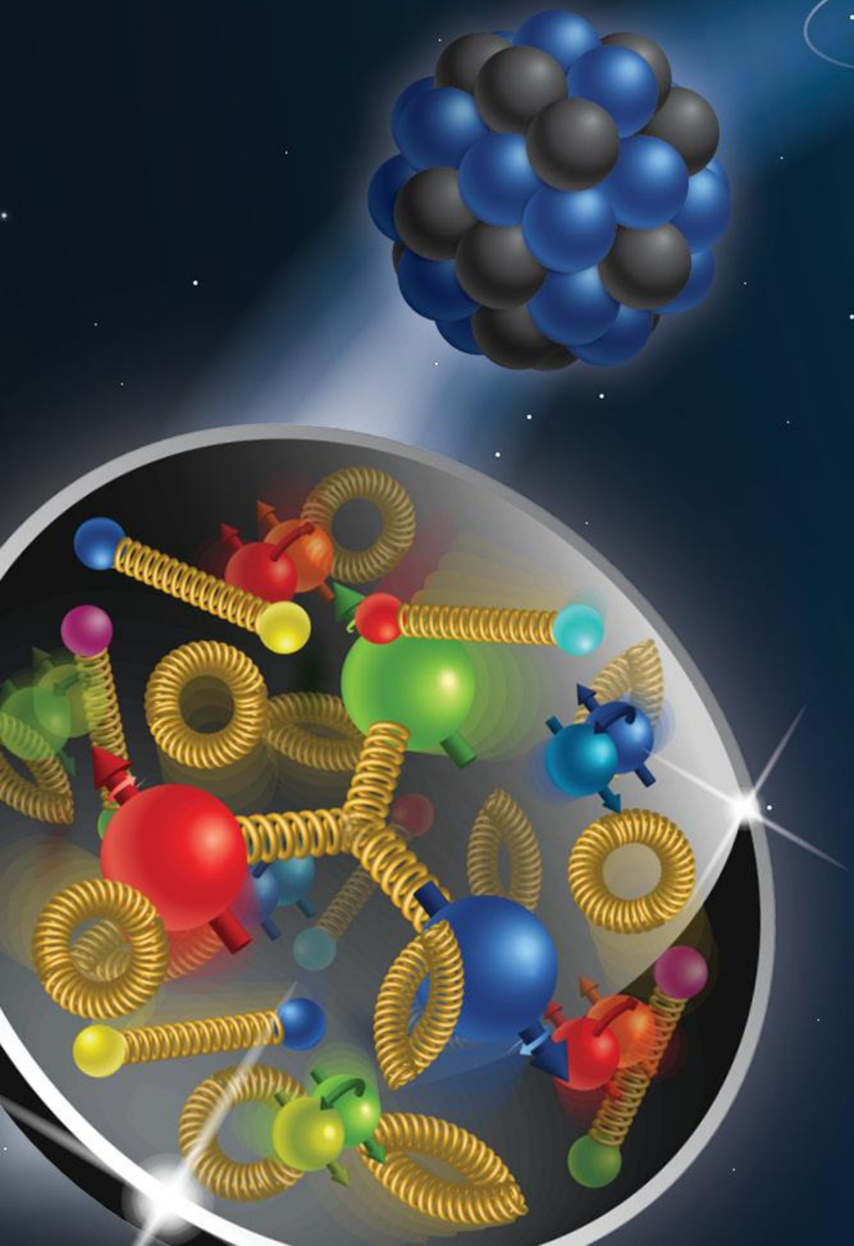

High Gradient Actively Shielded Nb_3Sn Quadrupole

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GianLuca Sabbi

Lawrence Berkeley National Laboratory

Tim Michalski

Thomas Jefferson National Accelerator Facility

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

Collaboration

- BNL (M. Anerella)
  - Magnet design & analysis
  - Shield coil fabrication
  - Assembly tooling & Test tooling design & fabrication
  - Magnet test

- LBNL (G. Sabbi)
  - LARP coil selection, QA & delivery
  - Cross-check magnet 2D analysis, develop 3D analysis
  - Support assembly & test

- TJNAF (T. Michalski)
  - parts fabrication & procurement
  - testing participation

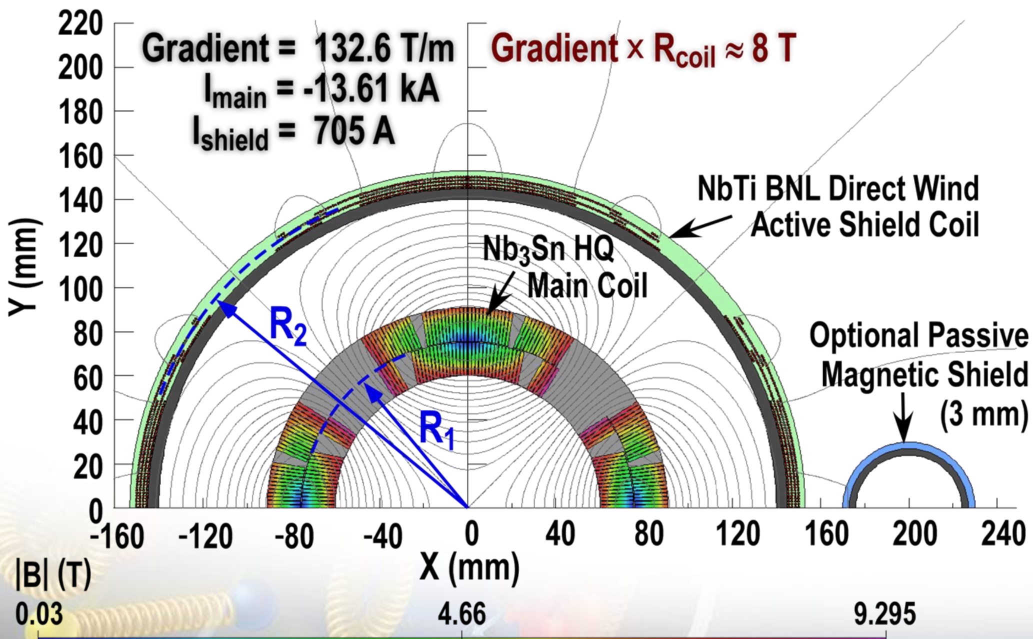
Design and Prototyping of Superconducting EIC – Interaction Region Magnets

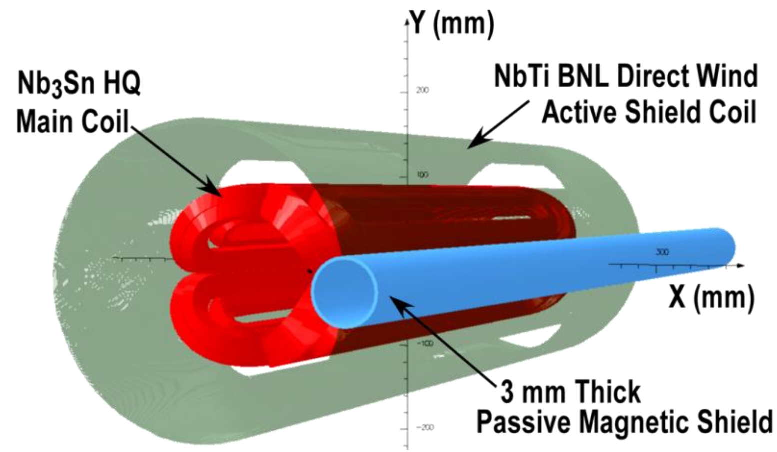
Funding Source	PI	R&D Report Priority #	R&D Panel Priority Rating
FY17	M. Anerella	28	Hi-C

- The panel identified the validation of magnet designs associated with high-acceptance interaction points by prototyping as a key area that is common for all EIC concepts (p. 41)

Overview

- Hadron IR quads need large apertures & high gradients.
- Must protect e-beam from large external B-fields.
- Solution is to use actively shielded coil geometry [1].
- "proof of principle" using existing 120mm aperture Nb3Sn coils



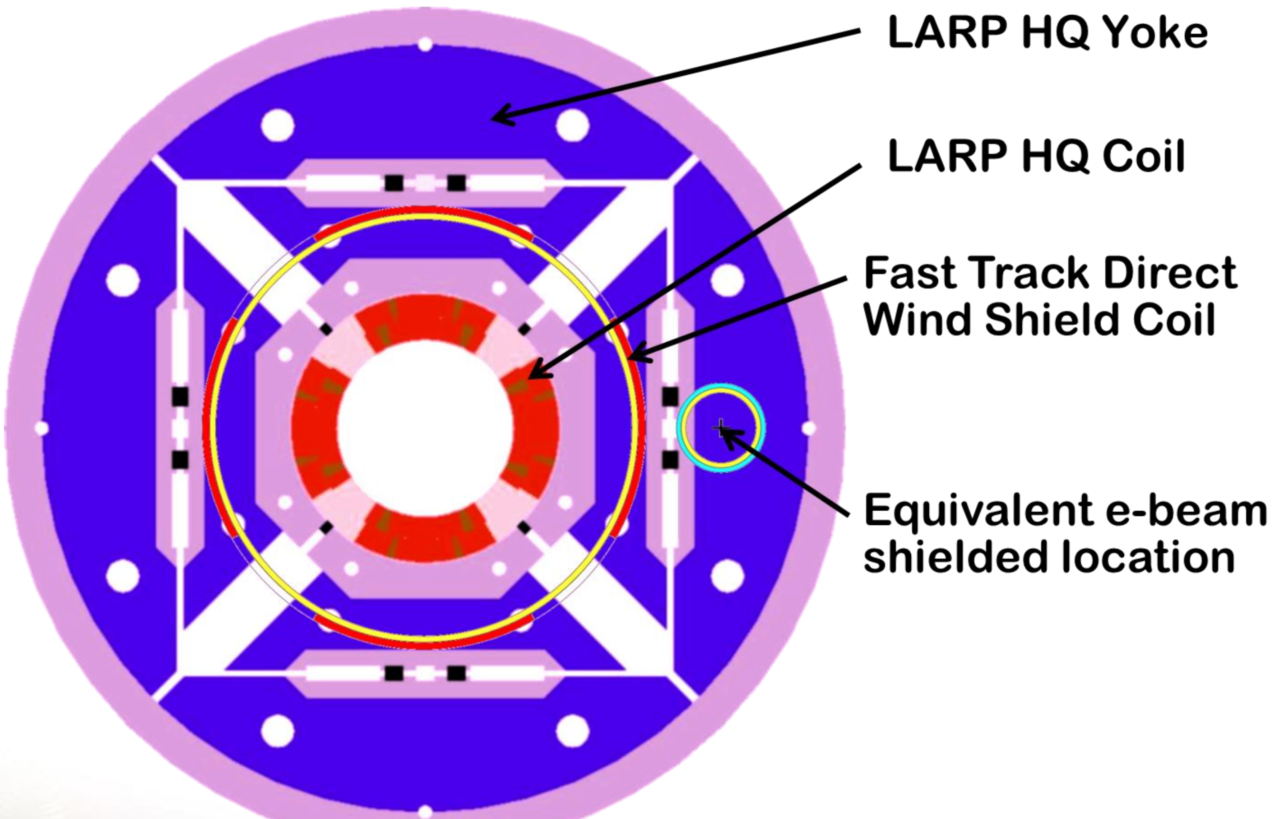


Courtesy of Brett Parker

[1] B. Parker *et.al.* https://doi.org/10.18429/JACoW-IPAC2018-WEPMF014

Perspective

Why not use existing, e.g., LHC High Luminosity Upgrade technology/designs in the EIC IR?

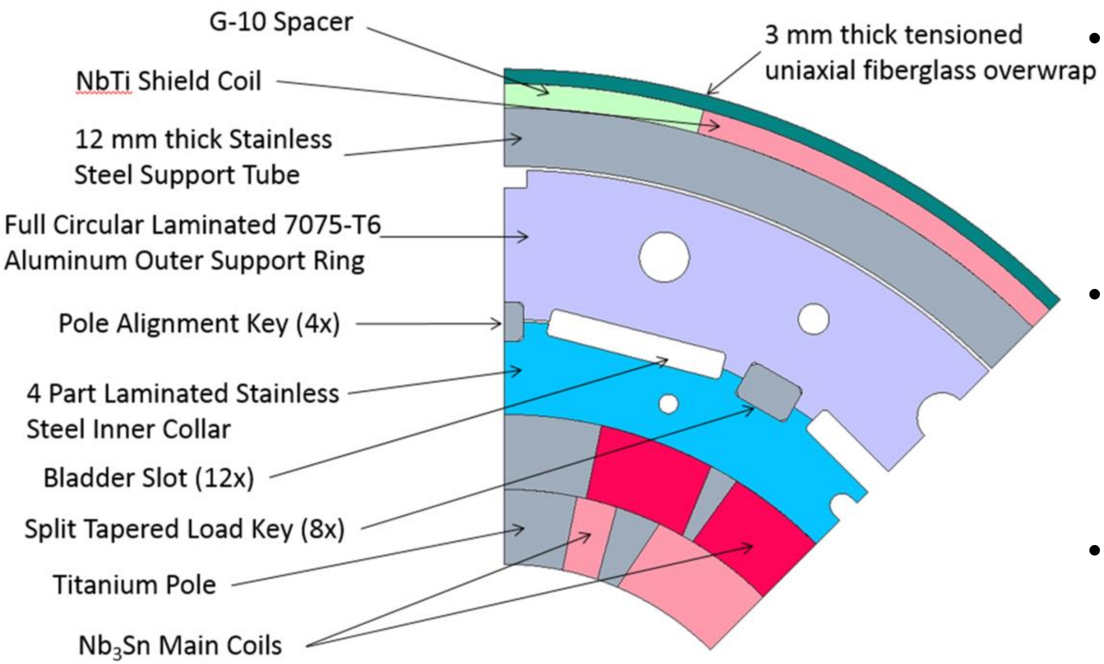


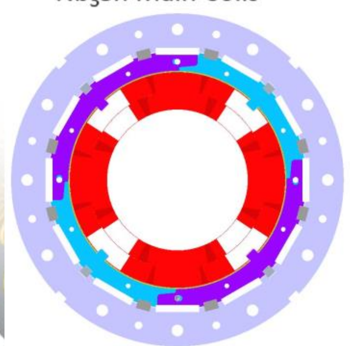
Electron beam cuts through magnetic / mechanical structure

120mm LHC Accelerator Research Program (LARP) Nb_3Sn High Gradient Quad

Design

Compact mechanical structure "Proof of Principle", i.e., NOT a specific IR solution





Design Parameters	Unit	Value
Clear aperture	mm	120
Gradient	T/m	133
Peak Field	T	9.3
Current (main coil)	kA	13.6
Current (shield coil)	kA	0.7

- Magnet uses tested Nb_3Sn (LARP) 120mm Rutherford main coils inside a (Ø1mm, 7 strand NbTi cable) Direct Wind shield coil.
- In this way we leverage LARP high field Nb_3Sn R&D experience to make a prototype test with minimal risk, investment and time.
- The shield coil provides zero field at the electron beam and reduces the net gradient of the main coil by 7% and also reduces the main coil's net outward Lorentz force (which is unlike a magnetic yoke which would increase the force experienced by the main coil).

Status Summary – details in following slides

BNL

- Magnet design is complete
- Assembly tooling fabrication is complete & assembled
- Testing tooling fabrication is complete & being assembled
- 15cm long mockup assembly & test is complete
- Main quadrupole structure assembly has started
- Shield quadrupole coil assembly has started

LBNL

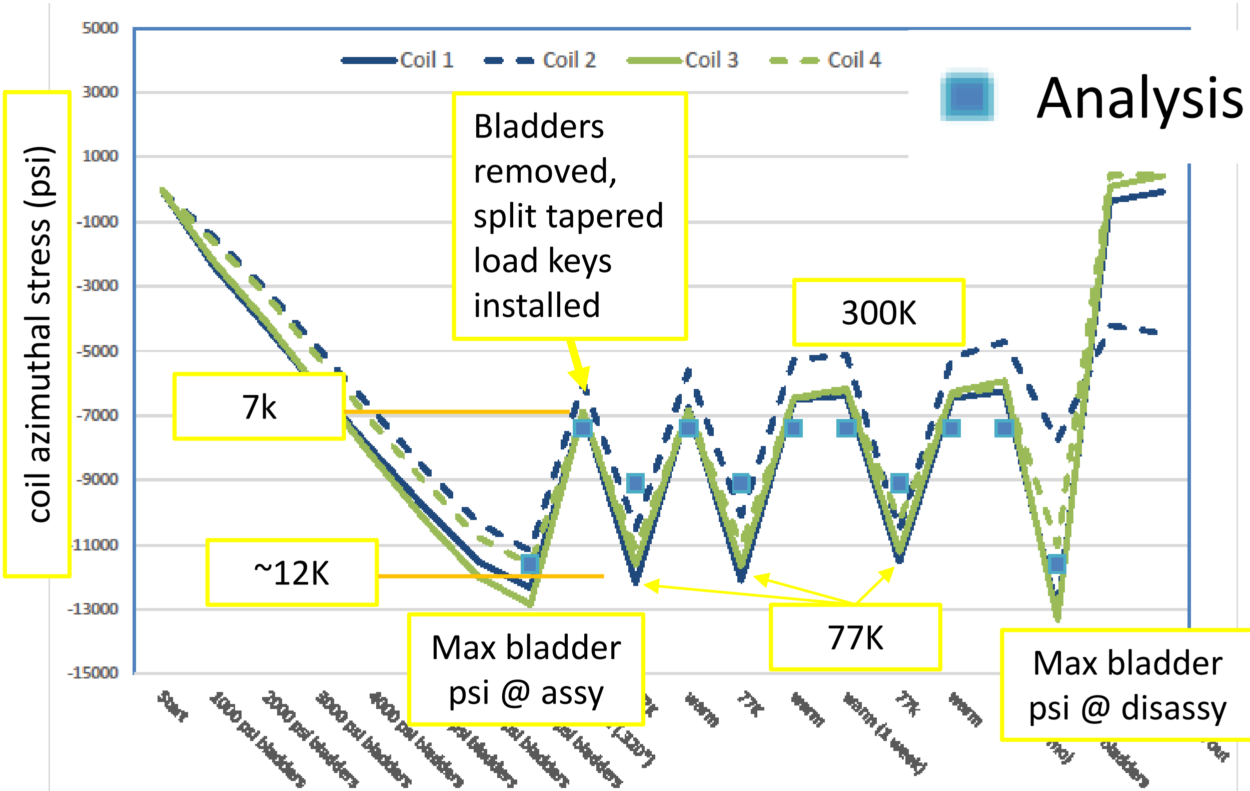
- LARP coils have been selected, inspected & delivered
- 2D azimuthal load analysis including impact of coil size variations is complete
- 3D model and end region analysis: coupled axial and azimuthal load is complete

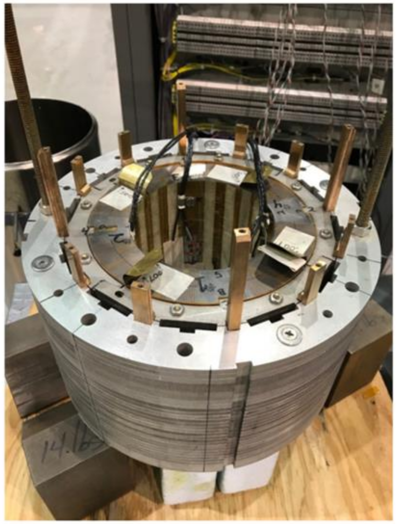
(Results submitted for publication in IEEE/TASC: G. Vallone et al., “3D Mechanical Analysis of a Compact Nb3Sn IR Quadrupole for EIC”)

TJNAF

- All parts have been fabricated, most are delivered, a few corrections are underway

BNL progress: 15cm mockup - 2-D experimental confirmation of mechanical structure





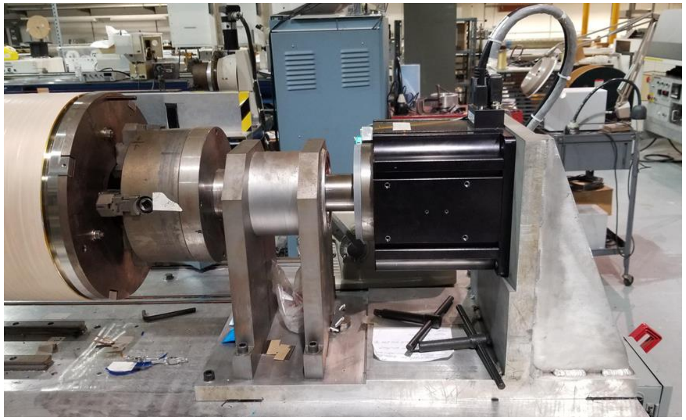
- Excellent results:
  - Validation of revised gauge installation methods
  - Max. applied load versus net coil preload measured values closely match analysis
  - Increase in coil preload due to cooldown measured values are *better* than analysis

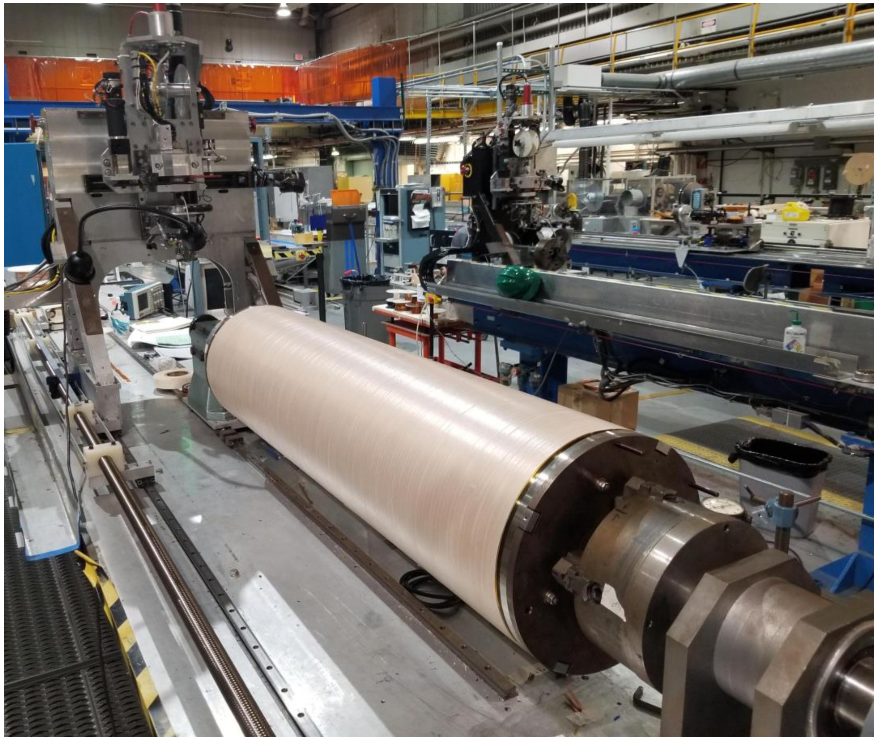
Main quadrupole assembly

Main quad coils installed on assembly mandrel:

- ~ 6 month delay due to COVID
- Electrical issues previously reported by LBNL confirmed in electrical testing – *data consistent with values seen during prior HQ magnet tests at LBNL and CERN*
- Operational plan developed (leave suspect heaters open, use dump resistor + CLIQ, etc.) to mitigate risks
- Assembly continuing

Shield quadrupole coil assembly



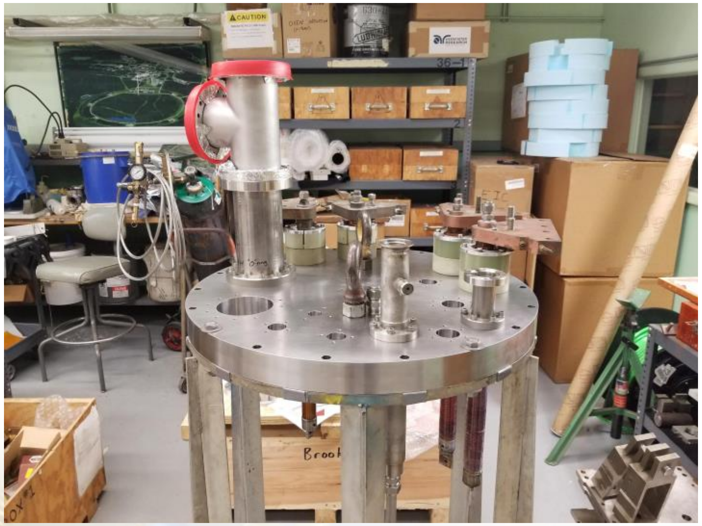


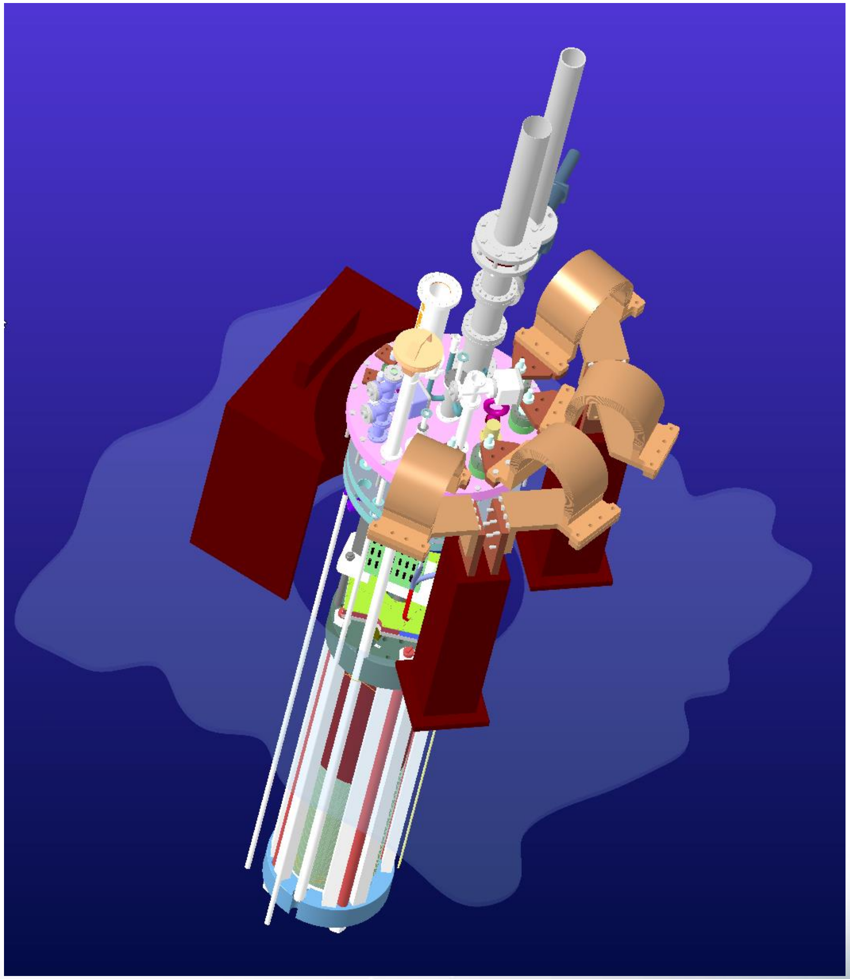
Coil wiring underway:

- Several months required to program, commission new large capacity drive motor (needed for large size, weight, of stainless steel support tube)
- ~ 6 month delay due to COVID
- Delamination of epoxy impregnated fiberglass after cure of 2nd layer
- 1st of 4 layers restarting now

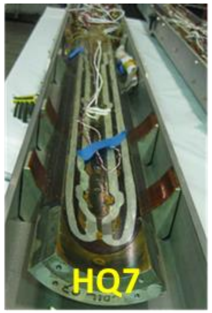
Testing top hat

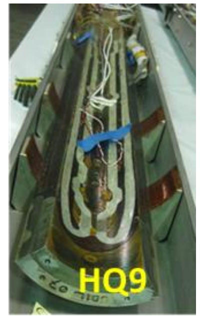
- All parts are received
- Assembly has started
- Work is supporting schedule



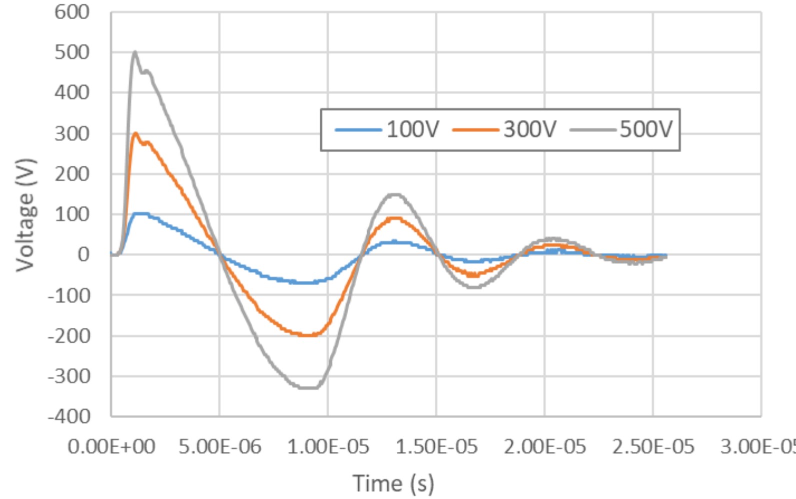


LBNL Progress - HQ Coil Selection, QA & Shipping





Impulse test (Coil 8)



Hi-pot matrix (Coil 7)

Voltage Applied (Target/*Actual*)	Coil				
PHA01	700/*700*	PHA01			
PHA02	1000/*1000*		PHA02		
PHB01	1000/*100*			PHB01	
PHB02	300/*300*				PHB02
LE IL ES	700/*700*	500/*500*	500/*500*		
LE OL ES	750/*750*			500/*500*	300/*300*
RE IL ES	1000/*1000*	500/*500*	500/*500*		
RE OL ES	1000/*1000*			500/*500*	300/*300*
Island	R Only/*28k Ω*				

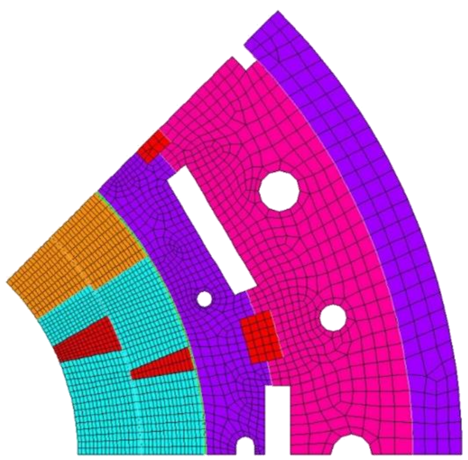
Voltage taps and quench heaters

Coil #	PH Label	Resistance (Ω)
5	PH05A01	6.5
	PH05A02	6.5
	PH05B01	6.2
	PH05B02	6.1
7	PH07A01	6.4
	PH07A02	6.4
	PH07B01	6
	PH07B02	6
8	PH08A01	6.7
	PH08A02	6.7
	PH08B01	6.2
	PH08B02	6.3
9	PH09A01	6.5
	PH09A02	6.4
	PH09B01	6.1
	PH09B02	6

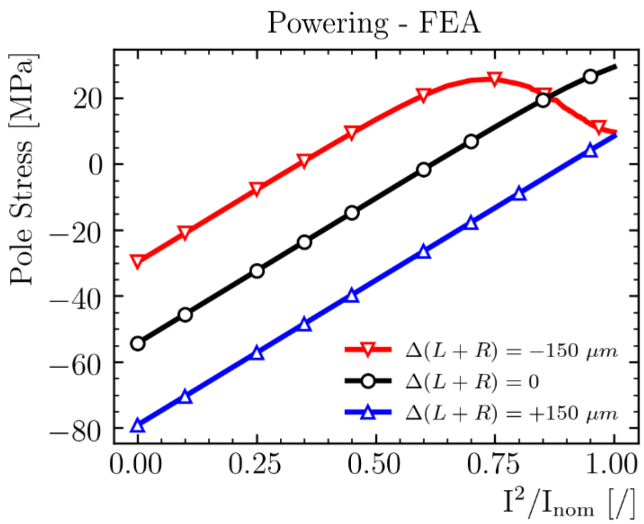
Coil #	V_Tap	Voltage Measured (2 Amp)	Resistance Calculated (Ω)
5	VT05A01	0.3035	0.15175
	VT05A02	0.3033	0.15165
	VT05A03	0.2958	0.1479
	VT05A04	0.2044	0.1022
	VT05A05	0.1734	0.0867
	VT05A06	0.173	0.0865
	VT05A07	OPEN	
	VT05A08	0.1704	0.0852
	VT05A09	OPEN	
	VT05A10	0.1687	0.08435
	VT05B10	0.1672	0.0836
	VT05B09	0.166	0.083
	VT05B08	0.165	0.0825
	VT05B07	0.1643	0.08215
	VT05B06	0.1632	0.0816
	VT05B05	0.1621	0.08105
	VT05B04	0.0803	0.04015
	VT05B03	0.0084	0.0042
	VT05B02	OPEN	
	VT05B01	0.0007	0.00035

Azimuthal Loading and Coil Size

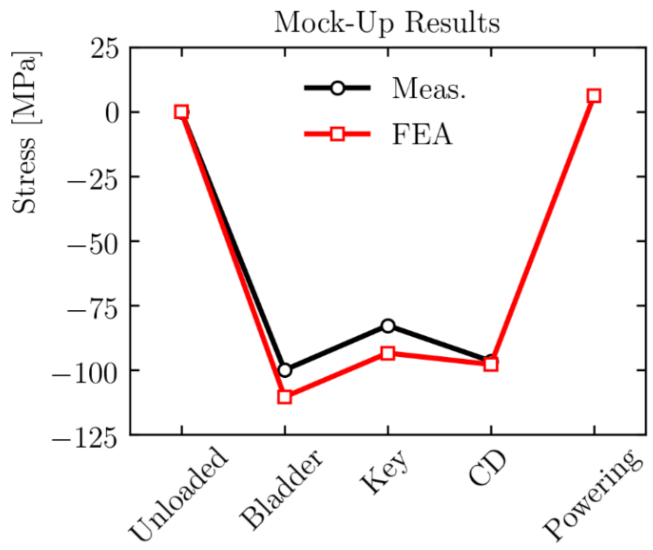
2D FEA Model



Effect of coil size variations

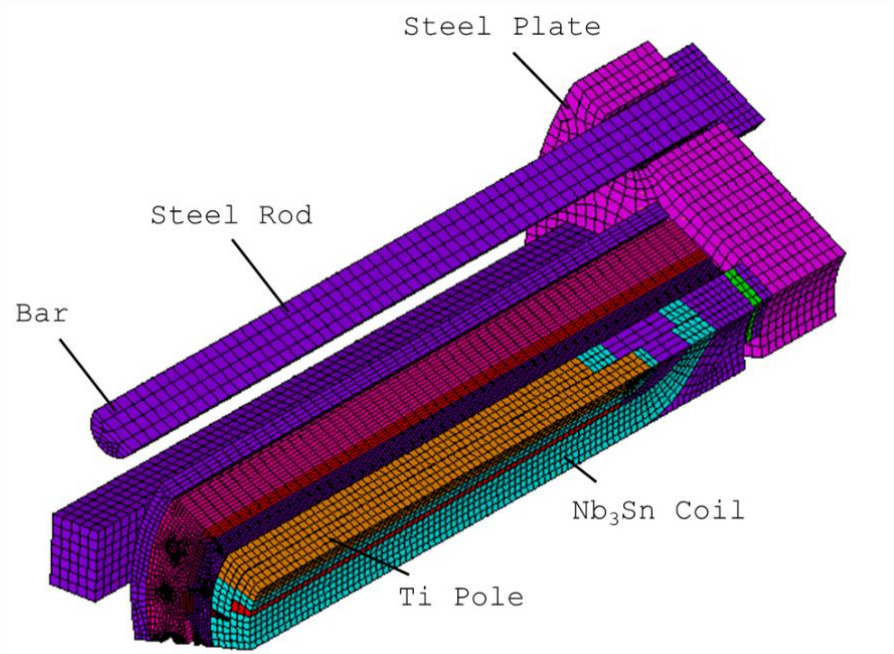


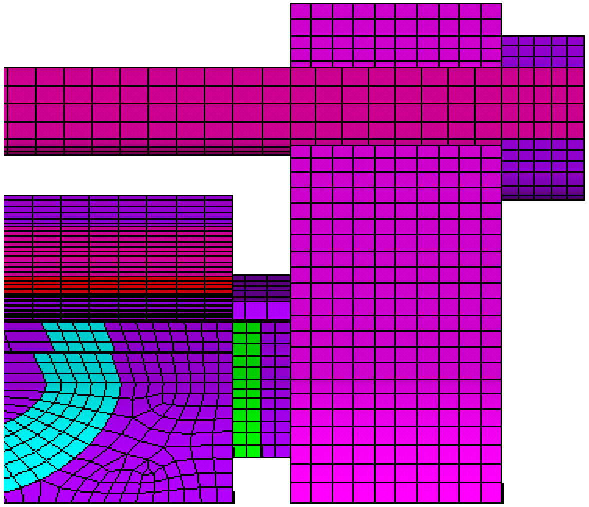
Comparison with measurements



- **Coil size variations due to fabrication tooling and coil components tolerances**
- **Local stress will be a function of coil size and stiffness, and structure stiffness**
- **For a 150 μm size variation, stress variation of ~20 MPa (30% lower than in MQXF)**
  - **EIC structure is less sensitive to coil size variations**
- **2D** model used as building block and reference/cross-check for the 3D model

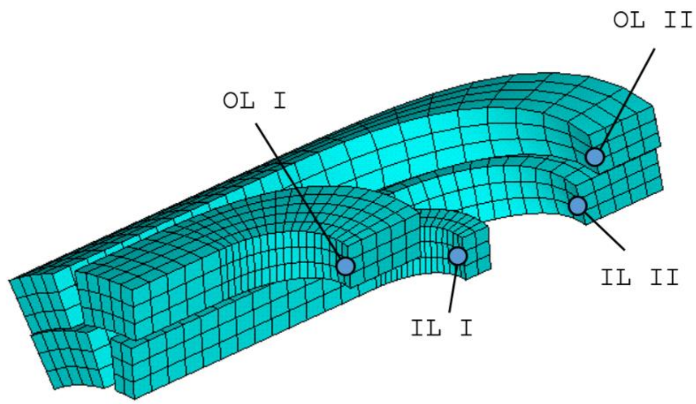
3D FEA Model

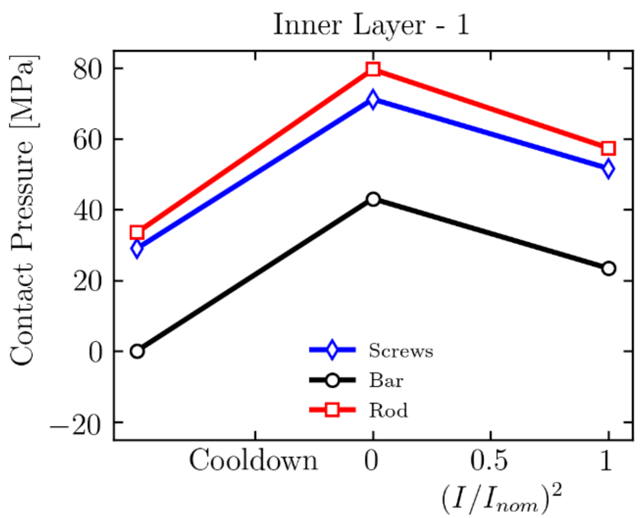




- A **3D** FEW **model** is required to explore the performance of the novel longitudinal loading system:
  - Apply prestress to the rods ~ against the bars
  - Torque the set screws to apply prestress to the coil
  - Load measured with bullet gauges and strain gauges on the steel rods

3D FEA Results: Axial Loading



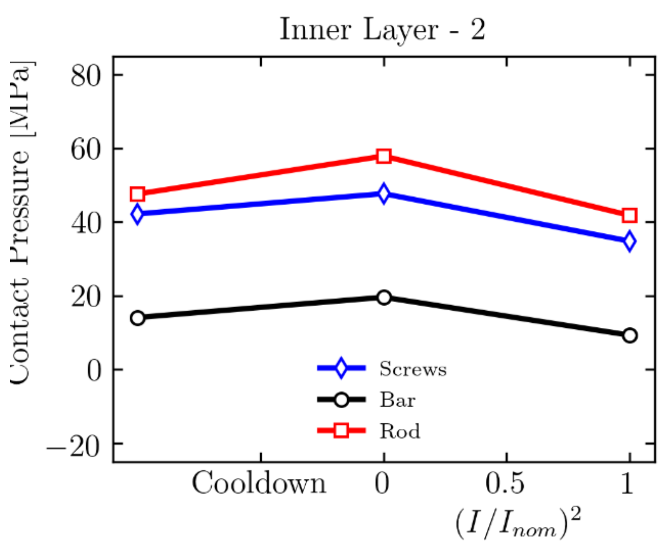


Three cases are considered: bars installed and torque applied on the set screws (Screws), bars installed with no torque applied on the set screws (Bar), no bars installed (Rod).

Advantages of the novel longitudinal loading system:

- Small reduction (mostly on the second block) of the contact pressure variation during powering
- Reduced longitudinal motion of the coils: from 88 μm to 34 μm → minimize quench training

Coil pre-load reduction due to axial bars is acceptable since sufficient margin is available in the EIC design



JLab progress

Providing the bulk of parts fabrication & procurement:

- All parts complete *including inspections*
- Most received at BNL, some remaining to be shipped, supporting schedule
- A few reworks of final lead splice assembly parts underway, supporting schedule

Courtesy T. Michalski

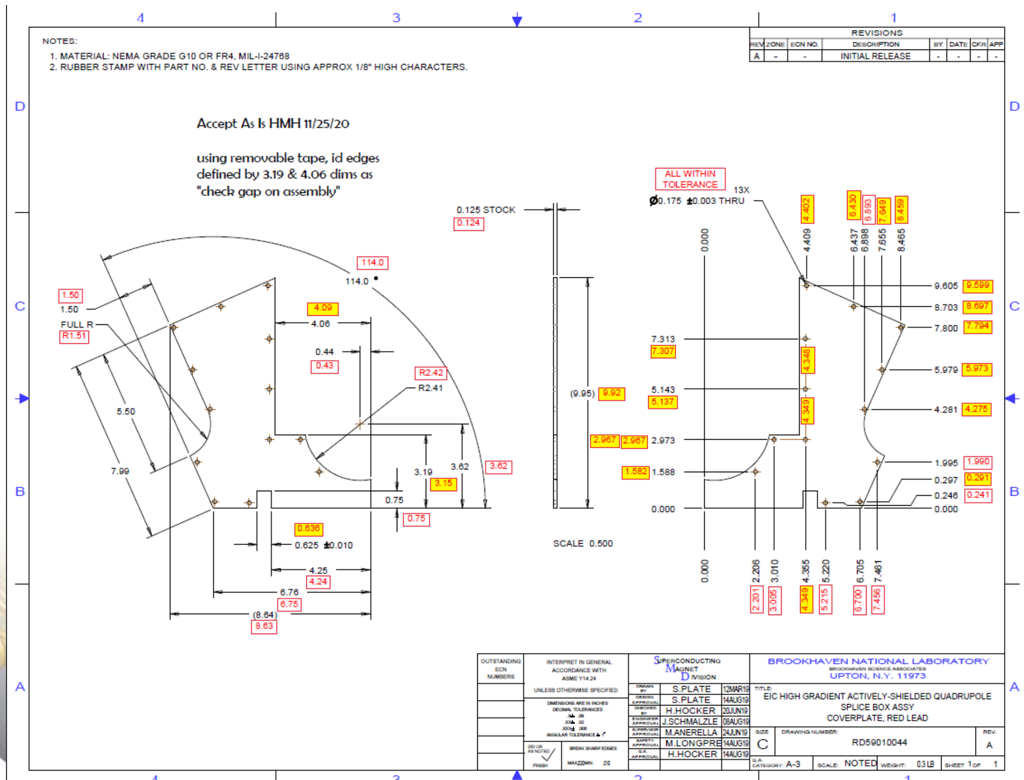



Figure 1: End Plate, Non-Lead End


Figure 2: Misc. components, keys, rods, shims, end load bolts

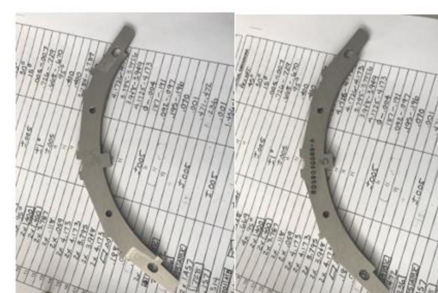


Figure 3: Coil Collar Lamination

Budgets

BNL

	FY2018	FY2019	FY2020	FY2021	Total
a) Funds allocated	$1,140,000	$1,140,000			$2,280,000
b) Actual costs to date	$128,638	$496,892	$753,410	$121,072	$1,500,012
c) Uncosted Commitments					$1,724
d) Uncommitted funds					$778,264

TJNAF

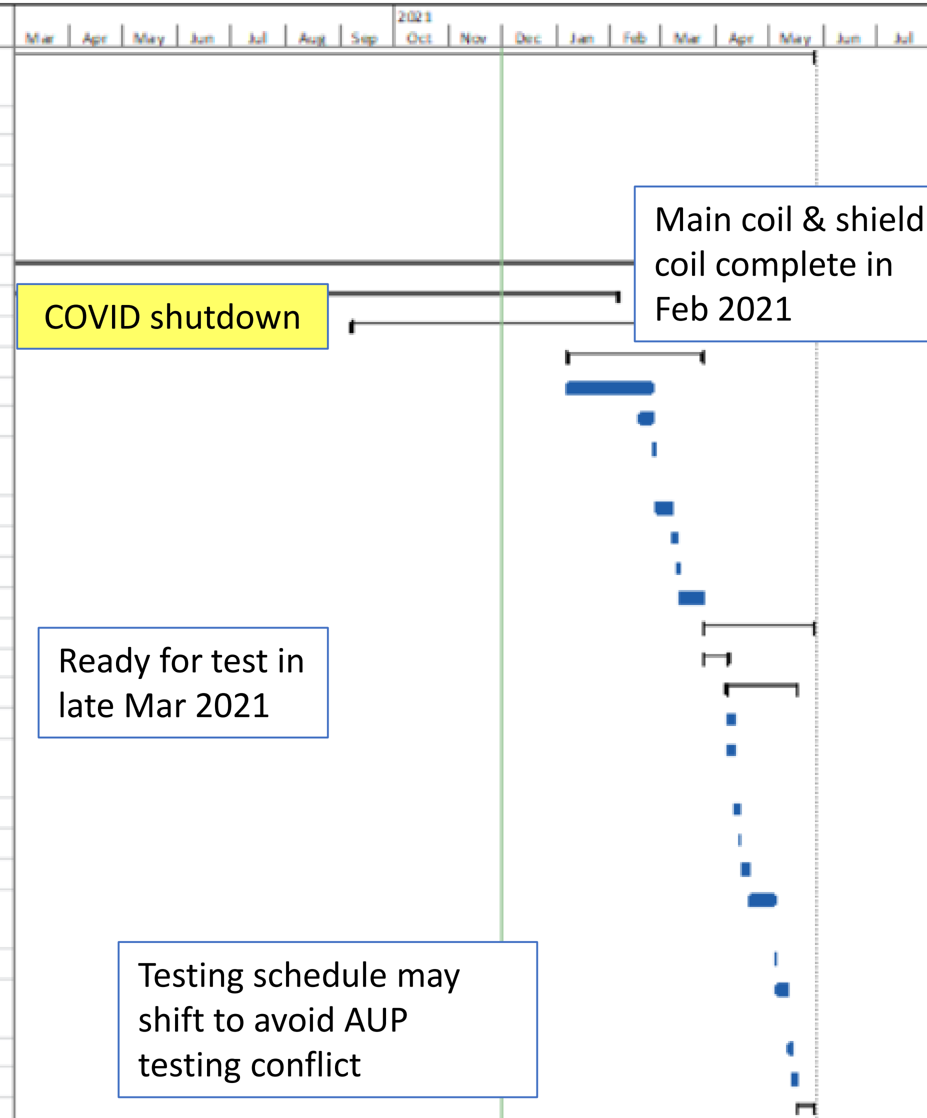
	FY 2019	FY 2020	FY 2021	TOTAL
a) Funds Allocated	$218,000	$218,000	$0	$436,000
b) Actual Costs to Date	$163,851	$246,646	$5,518	$416,015
c) Uncosted Commitments	$0	$0	$0	$0
d) Uncommitted Funds	$0	$0	$19,985	$19,985

LBNL

	FY2018	FY2019	FY2020	FY2021	Total
a) Funds allocated	$100,000	$100,000			$200,000
b) Actual costs to date	$25,030.96	$69,206.70	$35,195.16	$21,504	$150,936.82
c) Uncosted Commitments	$0	$0	$0	$0	$0
d) Uncommitted funds					$49,063.18

Working Schedule to Completion

ID	WBS	% Complete	Task Name	Duration	Start	Finish
1	1	60%	**High Gradient Actively Shielded Quadrupole**	**708.5 days**	**Wed 8/1/18**	**Thu 5/27/21**
2	1.1	94%	**Design**	**248 days**	**Wed 8/1/18**	**Mon 7/29/19**
10	1.2	70%	**Parts Fabrication**	**332 days**	**Wed 8/29/18**	**Tue 12/31/19**
17	1.3	79%	**Installation**	**312 days**	**Thu 9/27/18**	**Tue 12/31/19**
22	1.4	100%	receive/inspect HQ coils at LBNL	259 days	Mon 10/1/18	Mon 10/14/19
25	1.5	26%	**Assembly**	**285.5 da**	**Mon 2/10/20**	**Thu 3/25/21**
26	1.5.1	30%	**main quad**	**252 days**	**Mon 2/10/20**	**Thu 2/4/21**
36	1.5.2	30%	**shield quad**	**109.5 da**	**Tue 9/8/20**	**Wed 2/17/21**
81	1.5.3	0%	**magnet assembly**	**53 days**	**Thu 1/7/21**	**Thu 3/25/21**
82	1.5.3.1	0%	install, wire axial strain gaug	32 days	Thu 1/7/21	Wed 2/24/21
83	1.5.3.2	0%	align / connect coils	5 days	Wed 2/17/21	Wed 2/24/21
84	1.5.3.3	0%	install electron beam tube, Hall probes	2 days	Wed 2/24/21	Fri 2/26/21
85	1.5.3.4	0%	install end plates	6 days	Fri 2/26/21	Mon 3/8/21
86	1.5.3.5	0%	apply main quad axial loa	2 days	Mon 3/8/21	Wed 3/10/21
87	1.5.3.6	0%	electrical tests	1 day	Wed 3/10/21	Thu 3/11/21
88	1.5.3.7	0%	solder leads / install splice	10 days	Thu 3/11/21	Thu 3/25/21
89	1.6	0%	**Magnet Test**	**45 days**	**Thu 3/25/21**	**Thu 5/27/21**
90	1.6.1	0%	**prepare for test**	**10 days**	**Thu 3/25/21**	**Thu 4/8/21**
97	1.6.2	0%	**Cold Test**	**28 days**	**Wed 4/7/21**	**Mon 5/17/21**
98	1.6.2.1	0%	turn on refrigerator / mak	3 days	Wed 4/7/21	Mon 4/12/21
99	1.6.2.2	0%	300K electrical checkout / warm measurements	2 days	Thu 4/8/21	Mon 4/12/21
100	1.6.2.3	0%	cool magnet to 4.5K	2 days	Mon 4/12/21	Wed 4/14/21
101	1.6.2.4	0%	4.5K electrical checkout	1 day	Wed 4/14/21	Thu 4/15/21
102	1.6.2.5	0%	QPR tests	3 days	Thu 4/15/21	Tue 4/20/21
103	1.6.2.6	0%	4.5K main quad training quenches (20)	10 days	Tue 4/20/21	Tue 5/4/21
104	1.6.2.7	0%	4.5K shield quad ramp te	1 day	Tue 5/4/21	Wed 5/5/21
105	1.6.2.8	0%	magnetic "zero field" measurements	5 days	Wed 5/5/21	Wed 5/12/21
106	1.6.2.9	0%	warmup	2 days	Wed 5/12/21	Fri 5/14/21
107	1.6.2.10	0%	300K electrical checkout	1 day	Fri 5/14/21	Mon 5/17/21
108	1.6.3	0%	**breakdown test**	**8 days**	**Mon 5/17/21**	**Thu 5/27/21**



Summary

- Good progress made by all collaborators
- Good technical status
- Good financial status
- Some schedule slip, but ample float remains