U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn Cos-Theta Magnets: Program overview and 15 T dipole status

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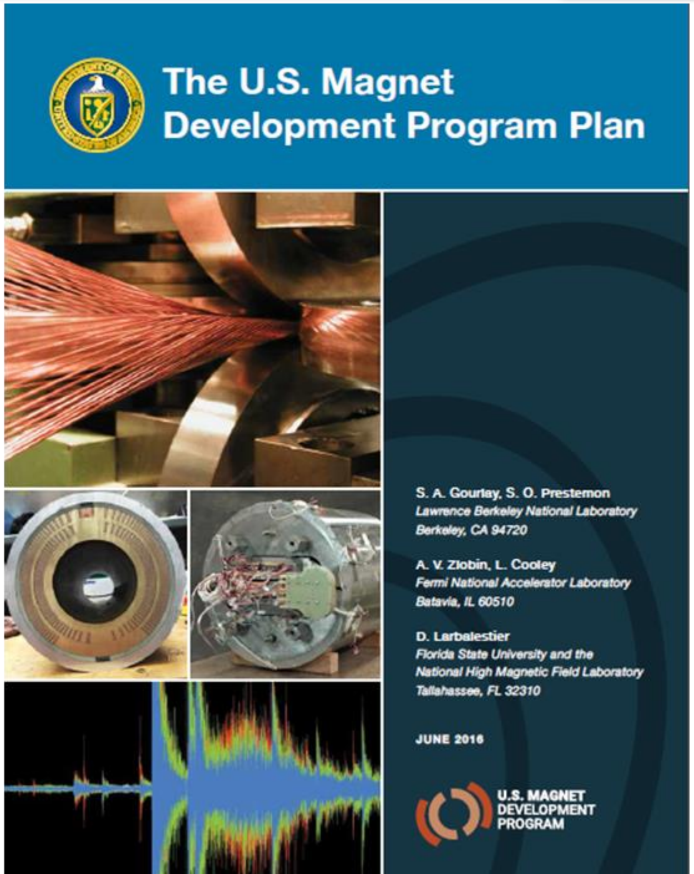
Outline



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- Nb_3Sn Cos-theta dipole program plan and steps
- Step 1
  - 15 T dipole demonstrator design and parameters
  - Design and procurement status
  - MM
  - Coil fabrication
  - HT optimization and witness sample data
- Step 2
  - Coil parts L1-L2 and L3-L4
  - Strand and Cable
- Step 3
  - Design study of 60-mm aperture 16-17 T dipole with stress management
- Large-aperture Nb_3Sn dipoles
  - Design study of 120-mm aperture 13-15 T dipole with stress management
- Schedule, milestones, budget, staff

Nb_3Sn cos-theta magnet R&D plan

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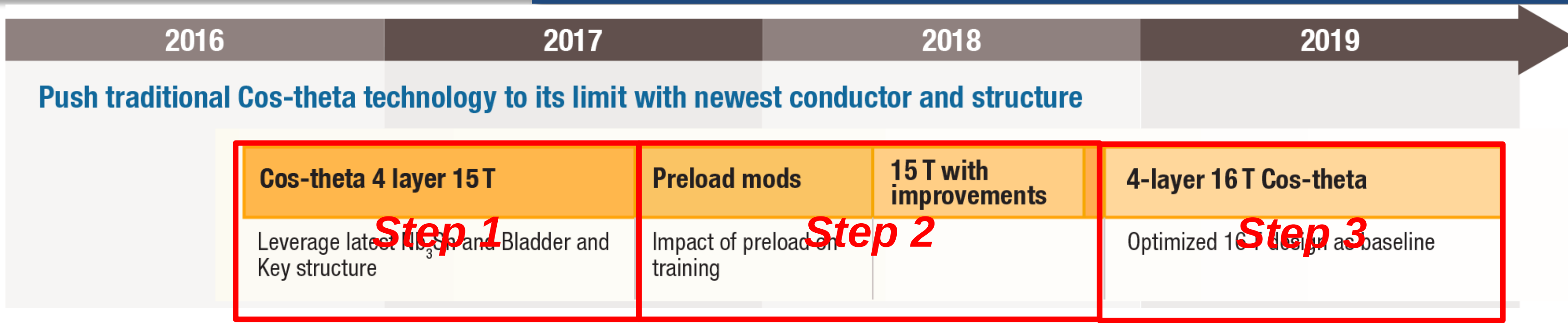
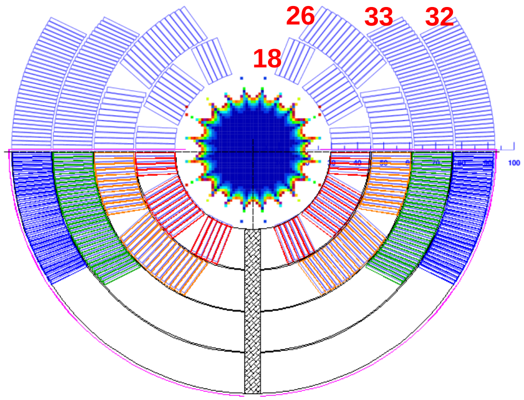


- Step 1: 15 T dipole demonstrator design.
  - explore the target field and force range
  - serve as a technical and cost basis for comparison with new concepts
  - opportunity for program integration, particularly in the area of support structure design, and for exploration of various support structures.
  - most cost effective way to get into a field range that would exceed the LBNL D20 dipole built almost 20 years ago.
- Step 2: A successful series of magnets will provide a platform for performance improvement by integrating the outcomes of the Technology Development program.
- Step 3: 16 cos-theta design to explore the limit of Nb_3Sn in this geometry.

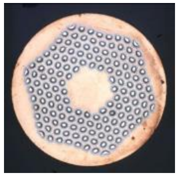
MDP 15 T Dipole Demonstrator design

- Coil:
  - 60-mm aperture, 4-layer graded coil
  - W_{sc} = 68 kg/m/aperture

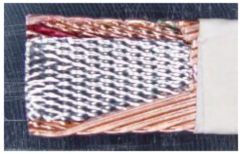


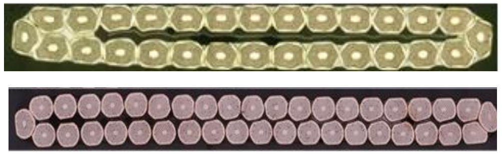
- Cable:
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - 0.025 mm x 11 mm SS core
  - Insulation: E-glass tape

RRP-108/127
0.7 mm

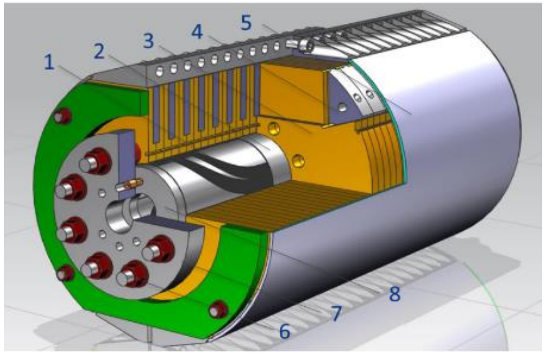


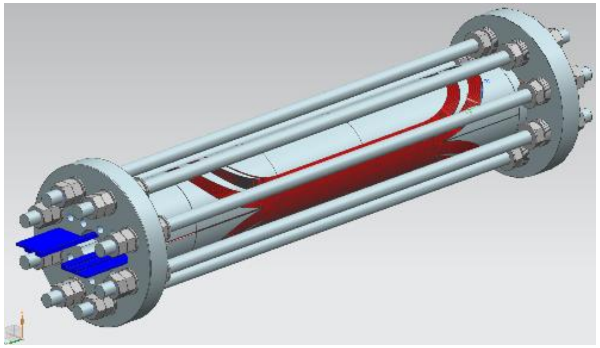
RRP-150/169
1 mm





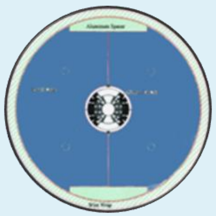
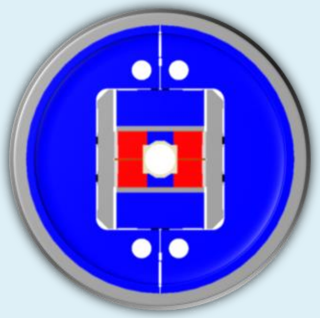
- Mechanical structure:
  - Thin StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - Thick end plates and StSt rods
  - Cold mass OD<610 mm

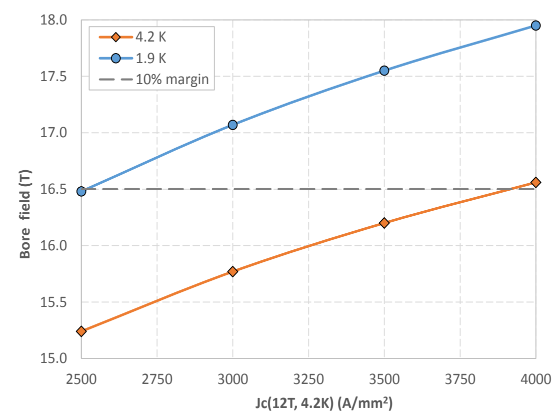




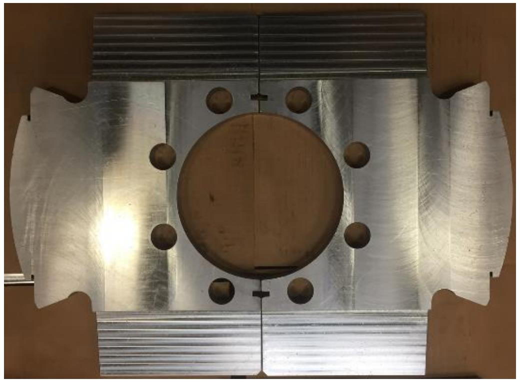
- Magnet SSL estimated based on the cable test data: B_{ap}=15.3 T at 4.5 K and B_{ap}=16.7 T at 1.9 K.

Magnet Parameters

Parameter	D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)	HFDD (MDP)
				
Test year	1997	2008	2017	2018 (plan)
Max bore field [T]	13.35 (14.7*)	15.4	16.5 (18*)	15.2 (16.5*)
Design field B_{des} [T]	13.35	15.4	13	15
Design margin B_{max}/B_{des}	1.0 (1.1*)	1.0	1.26 (1.4*)	1.04 (1.13*)
Tested margin B_{max} [T]	12.8 (13.5*)	13.8	~13	TBD
St. energy at B_{des} [MJ/m]	0.82	0.84	4.6	1.7
F_x/quad at B_{des} [MN/m]	4.8	5.6	7.7	7.4
F_y/quad at B_{des} [MN/m]	-2.4	-2.6	-4.1	-4.5
Coil aperture [mm]	50	45	100	60



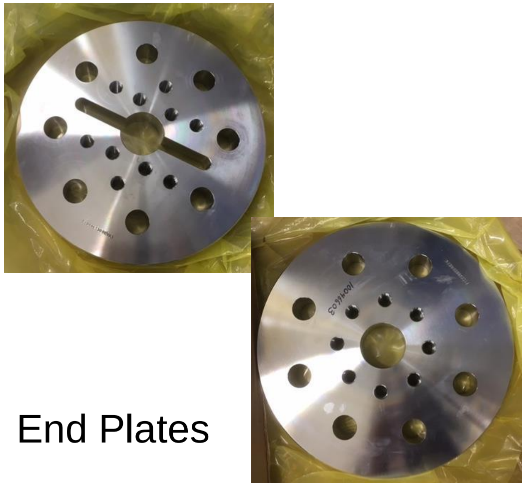
Mechanical Stricture



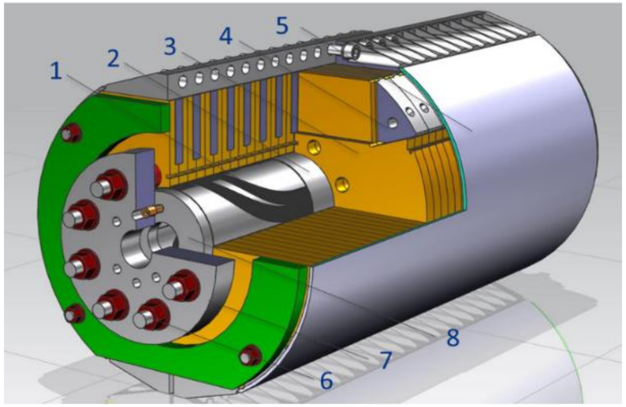
Iron Laminations

StSt Skin

AL I-Clamps



End Plates



Fillers

Axial Rods

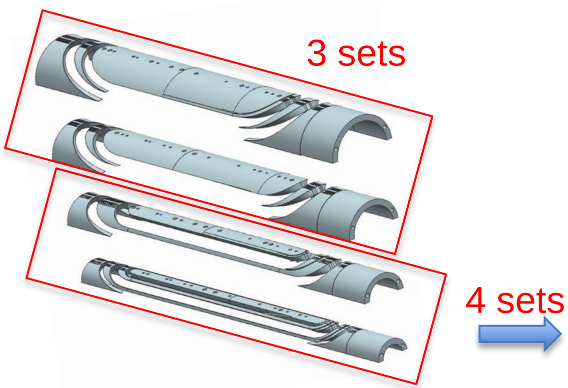
All structural components are available

Coil Components

Cable (FNAL)

- 420 m of 28-strand cable (4UL)
- 350 m of 40-strand cable (3UL)

L3/4 parts (FNAL)

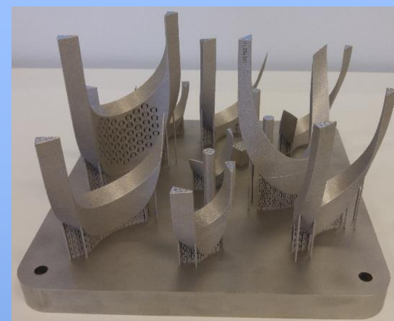


Traces (LBNL/FNAL)

L2

L4

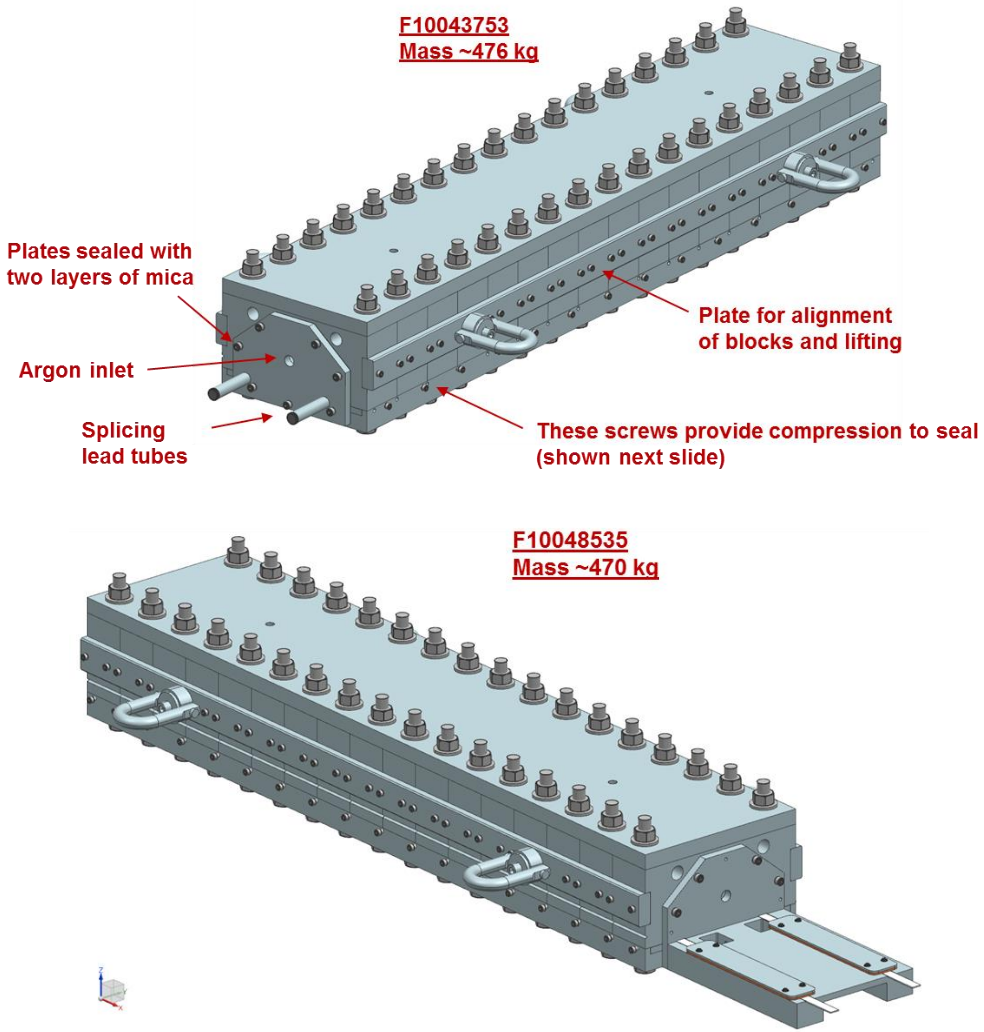
L1/2 parts (CERN)



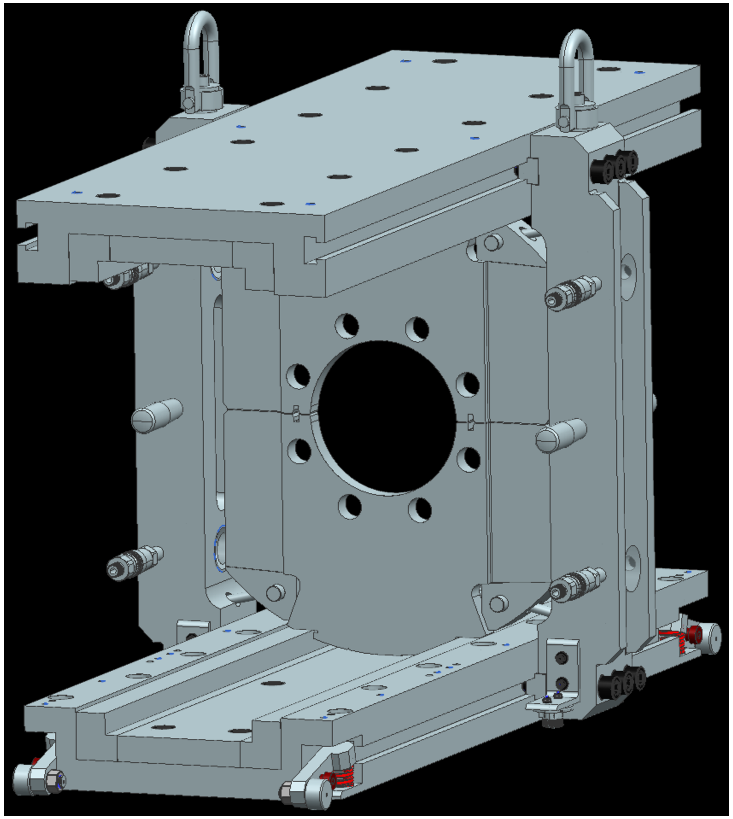
Ti and Cop Wedges

Ti poles and spacers, SS saddles

Tooling

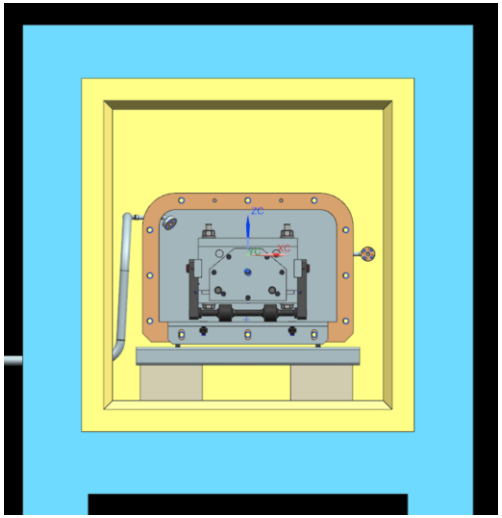


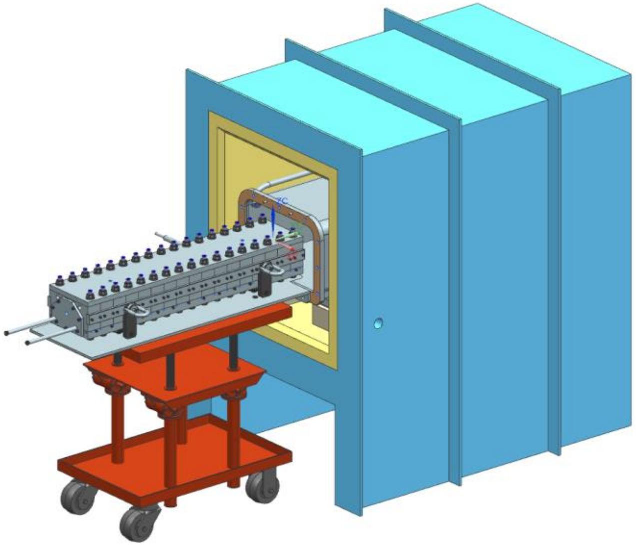
- Reaction/impregnation
- Yoking



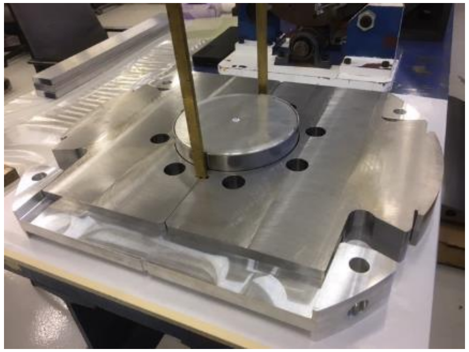
Infrastructure

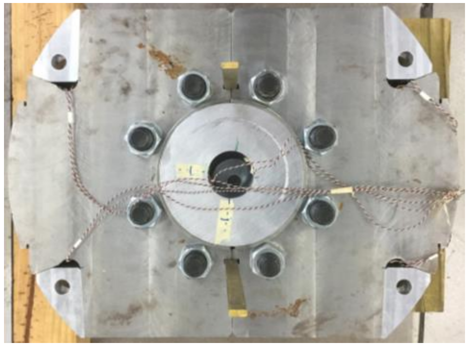
- Winding table and tensioner
- Curing press
- Reaction oven and retort

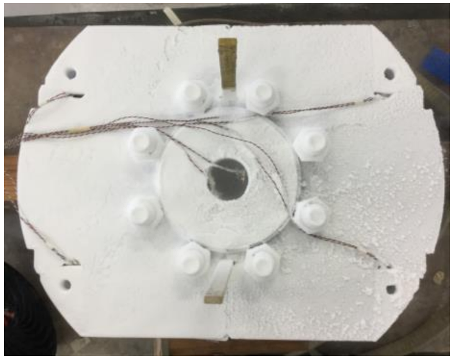




Mechanical Models







Models:

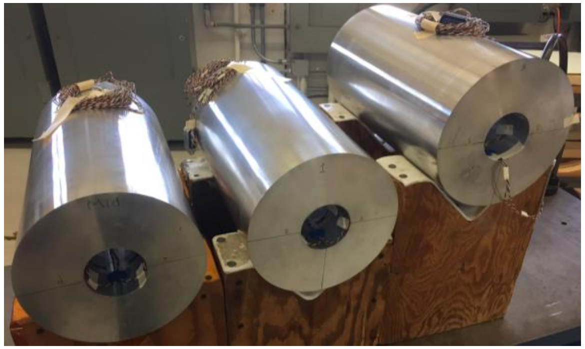
- 5 cm long
- 1 m long

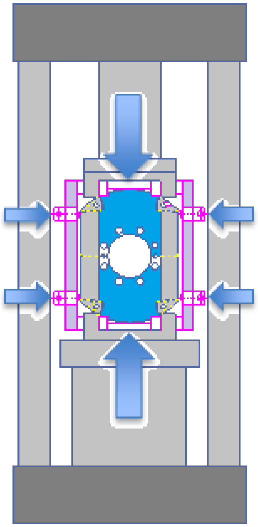
MM components:

- iron laminations
- Al I-clamps
- coil-yoke shim
- instrumented “dummy” Al coils (short and full-size)

Goals:

- To test all main components of the mechanical structure and tooling
- Develop a coil assembly plan and pre-stress targets
- Check instrumentation
- FEA validation





L3/L4 coil fabrication

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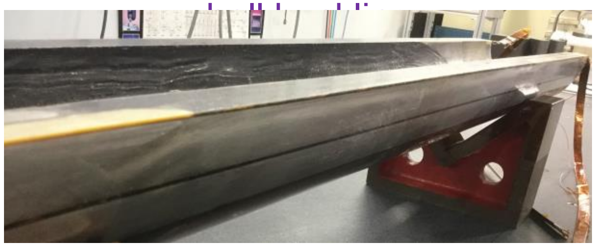
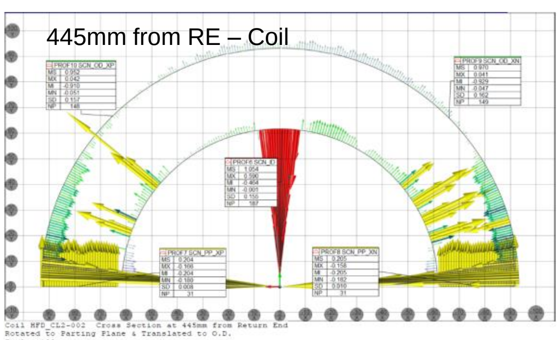
Coil #1

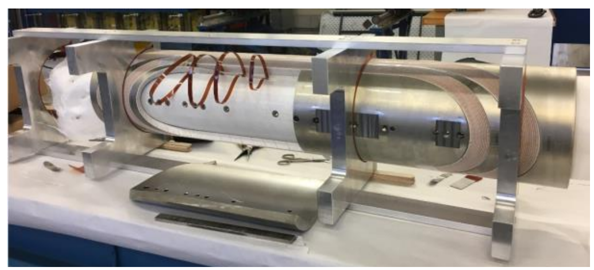
- Coil winding-curing-reaction-impregnation is complete
  - 8 witness samples tested
- Coil size was measured
  - damaged due to

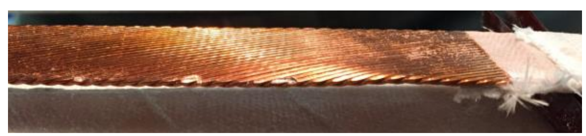


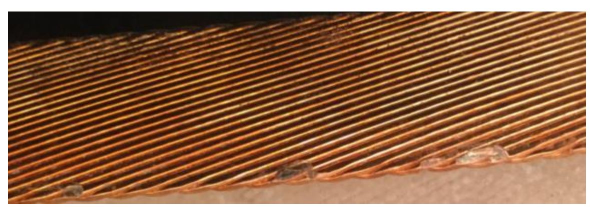


Coil #2

- Coil winding-curing is complete
- Short in the transition cable has been found and repaired
- Strand damage was found in transition area

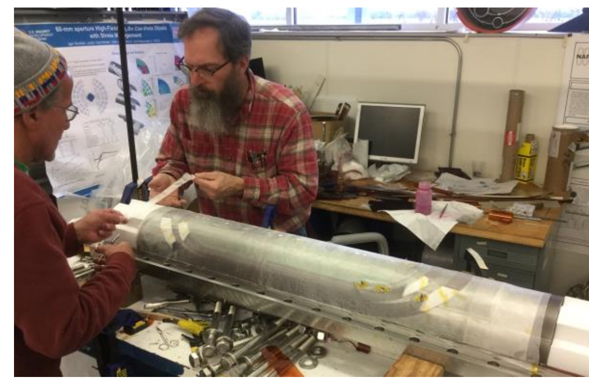






Coil #3

- Coil wounding-curing-reaction is complete
  - 7 witness samples tested
- Preparation to impregnation is in progress



Coil #4

- To be fabricated to replace coil #1
  - Coil parts from coil #2
  - Cable is available

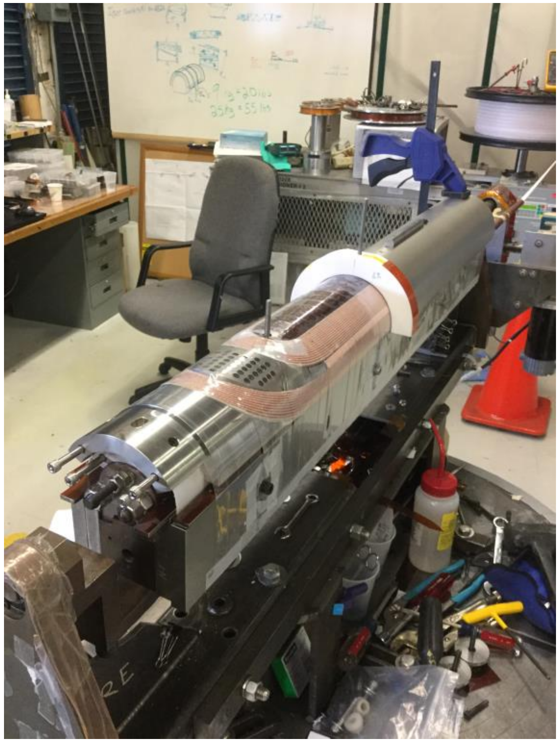
Coil #5 (spare coil)

- Need coil parts and cable

L1/L2 coil fabrication

Coil #1
- Coil winding-curing is complete
- Preparation to reaction has started

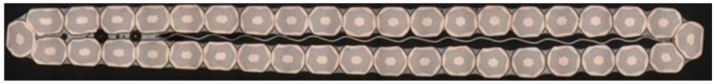
Coil #2
- Coil winding-curing is complete



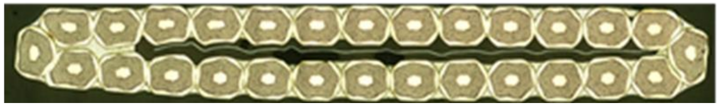
Coil #3 (spare coil)
- Coil winding will start soon after relocation of winding table
  - cable and parts are available

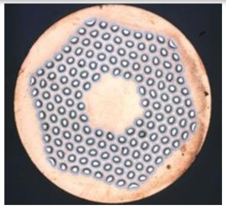
Coil Heat Treatment Optimization

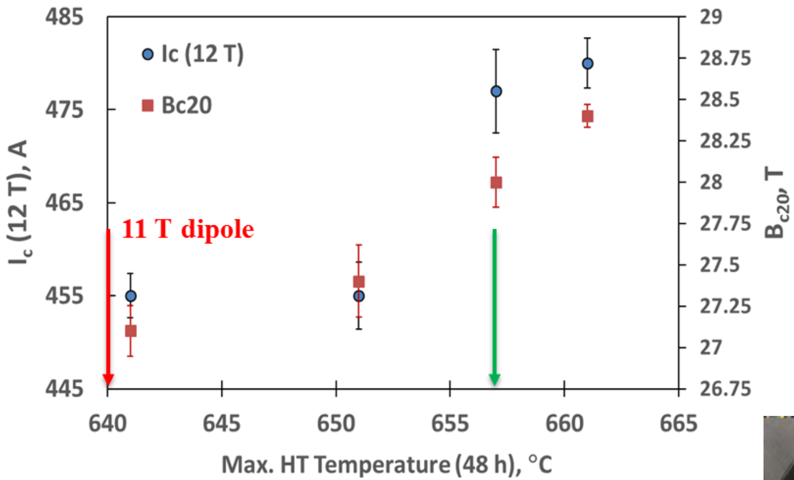
0.7 mm RRP108/127
40-strand cable with SS core

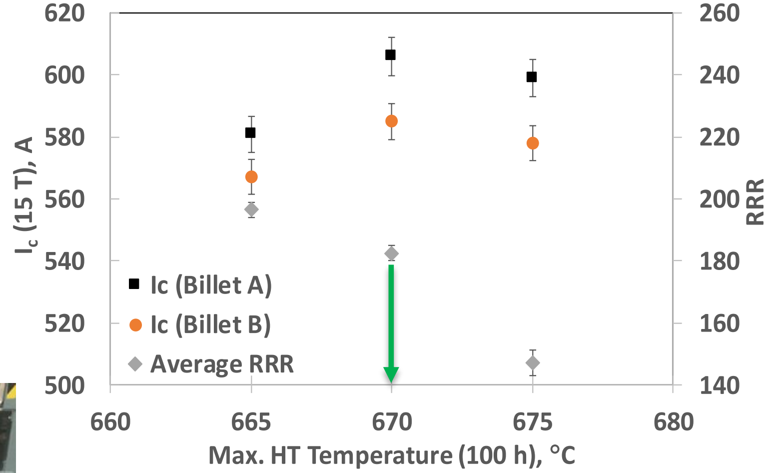


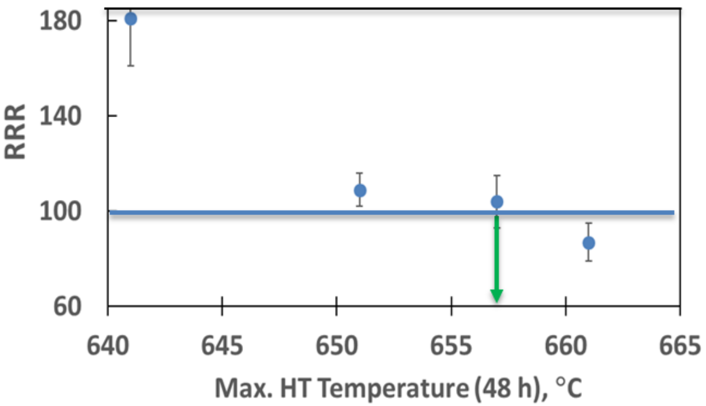
1 mm RRP150/169
28-strand cable with SS core











L3-L4 witness samples:

Location: tooling - 1R+3E, retort - 2R+6E

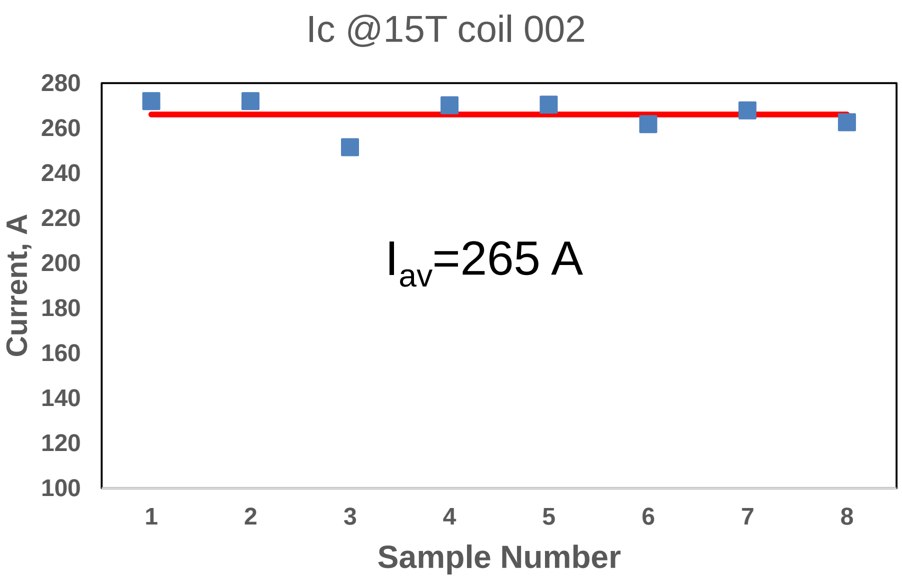
Ic (12 T)_Extracted (Tooling) = 504 A

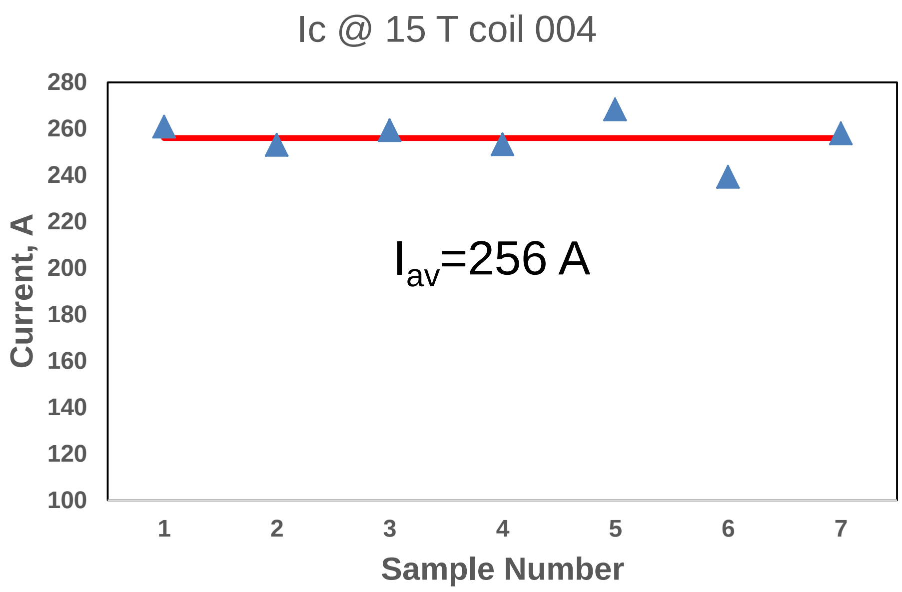
Ic (12 T)_Extracted (Retort) = (498 ± 3) A

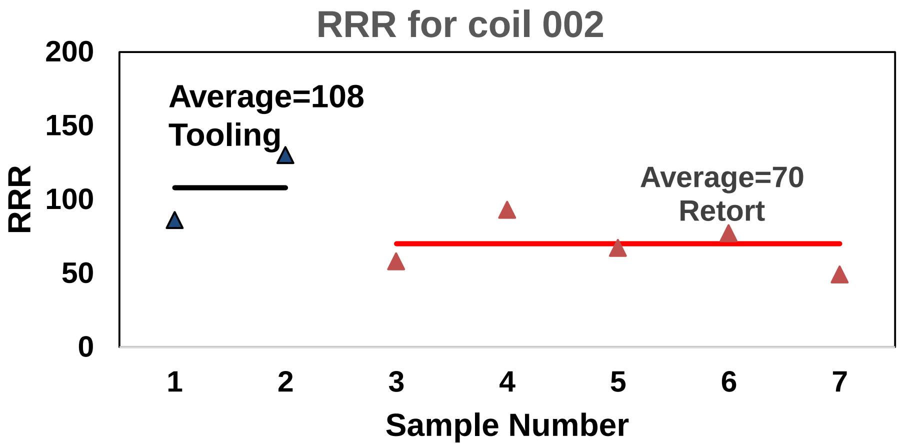
RRR_Extracted (Tooling) = 108 ± 22

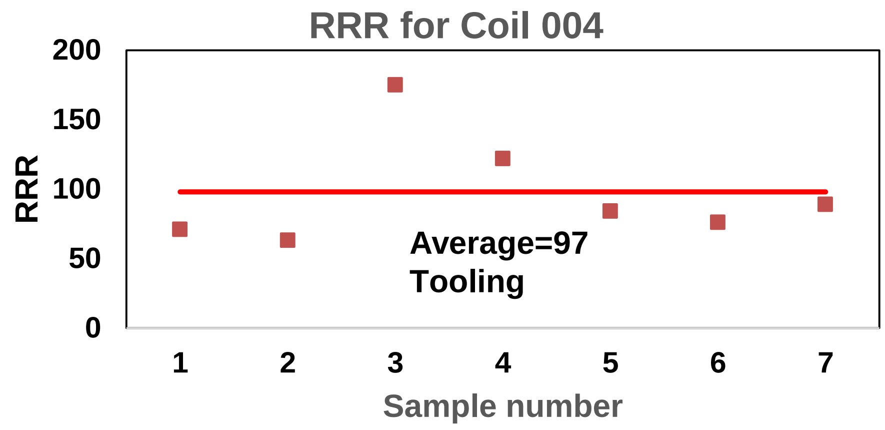
RRR_Extracted (Retort) = 74 ± 6

Comparison of L3/L4 coils #1 and #3

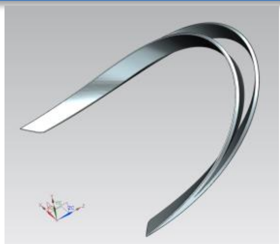


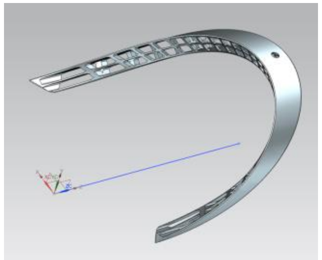






Preparation to 2nd model (Step 2)





- Coil parts L1-L2 and L3-L4
  - L1-L2 – 2 sets available
  - L3-L4 – need 2 sets (~60k$)
    - coil part design and technology to reduce the cost and time
- Cable
  - 40 strand cable – need 2-3 UL
  - 28 strand cable – 2 UL available +1-2 UL
- Strand
  - 0.7 mm – available at FNAL (need to pay off)
  - 1 mm – ~70 kg in procurement
  - Cu strands – to be procured (~5 k$)
- Cable insulation
  - S2 glass tape (6.5$/m, ~1k$/coil)
    - braiding ~13 $/m

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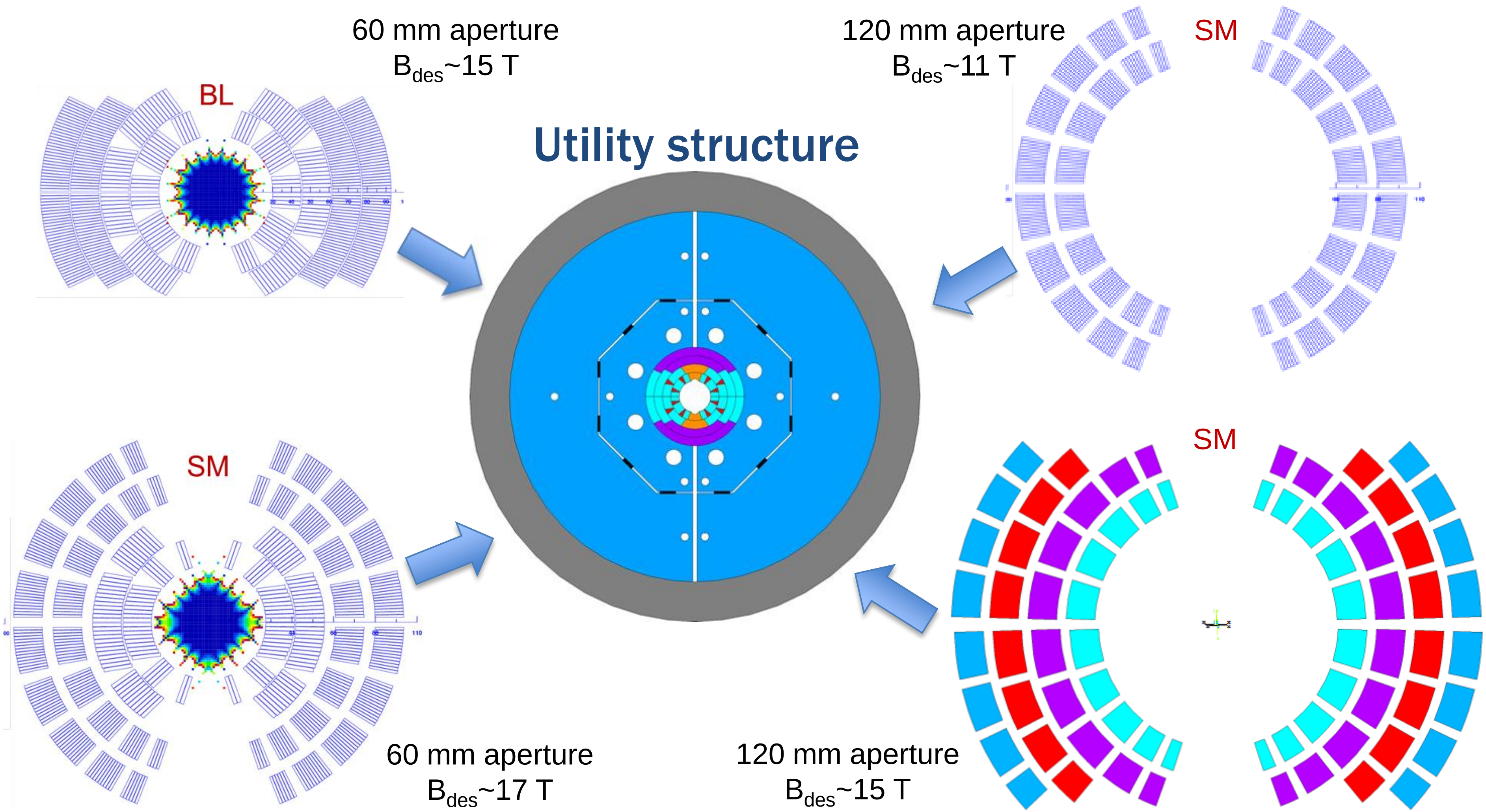
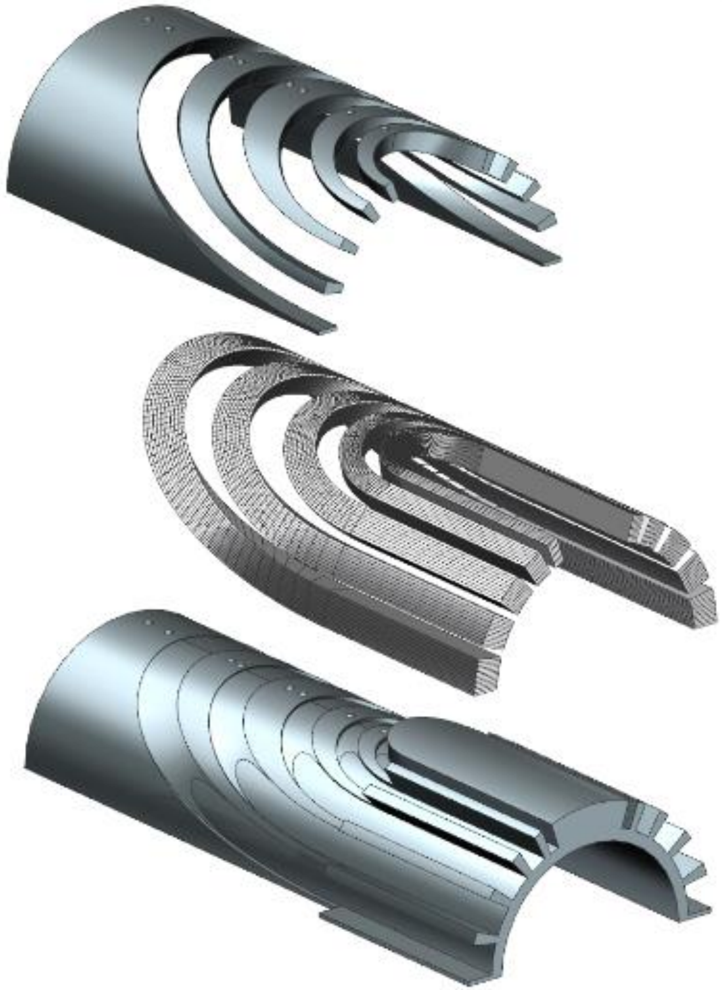
Cos-theta dipoles with stress management

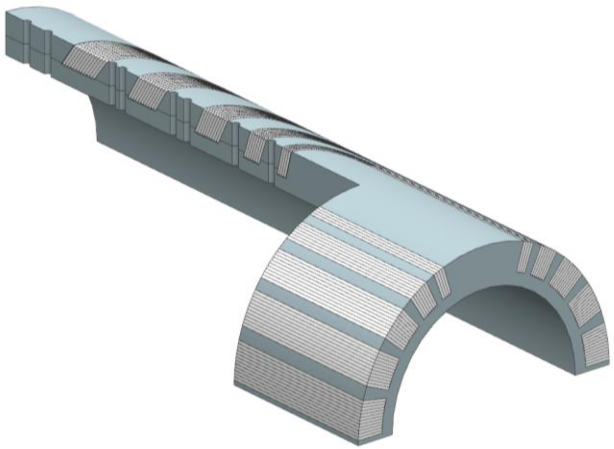


Coil stress management technology

- Two possible end designs and technologies
  - Design 1: winding with spacers
  - Design 2: winding into slots



Design 1



Design 2

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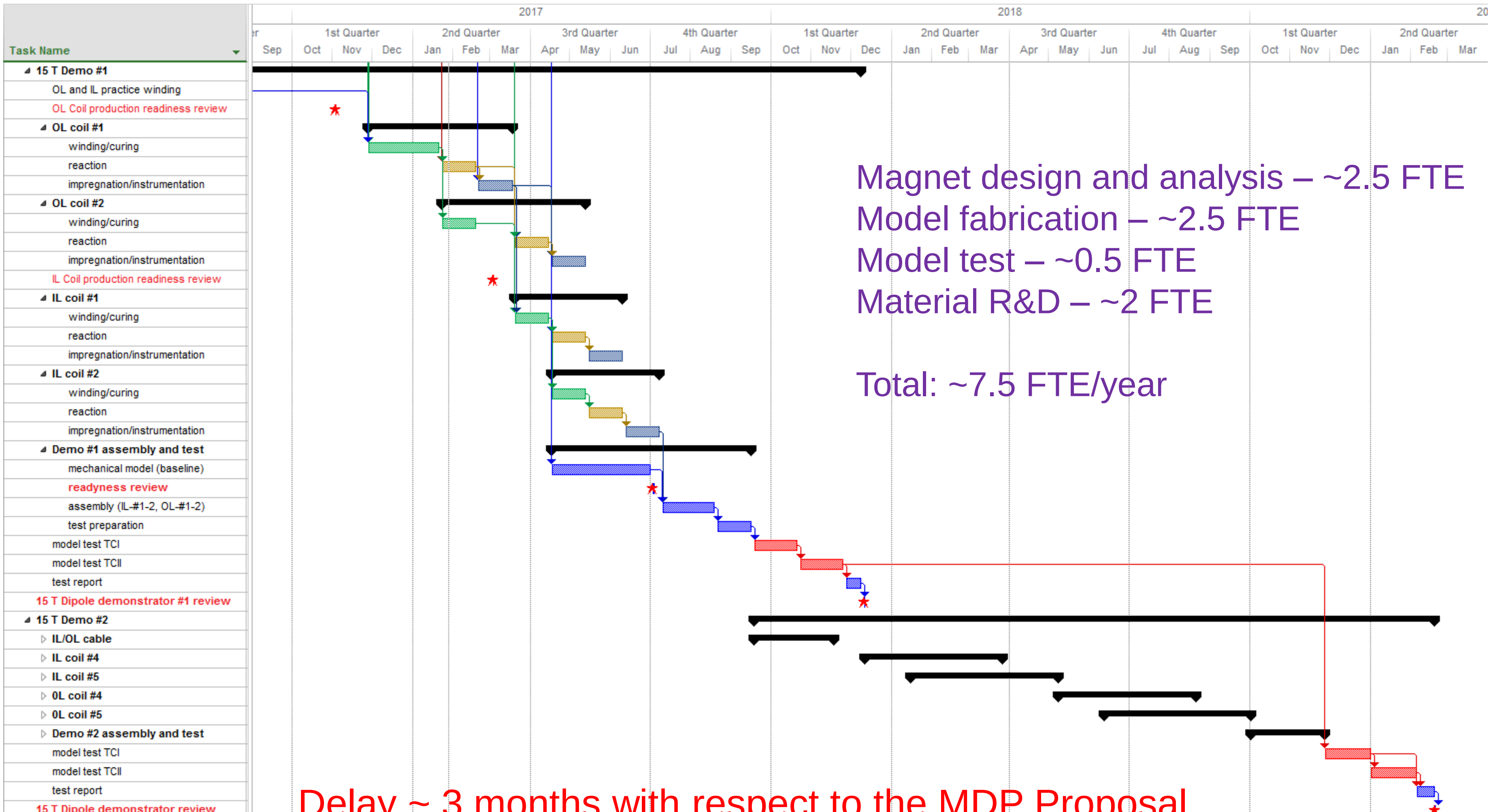
15 T Dipole demonstrator schedule



Magnet design and analysis – ~2.5 FTE
Model fabrication – ~2.5 FTE
Model test – ~0.5 FTE
Material R&D – ~2 FTE

Total: ~7.5 FTE/year

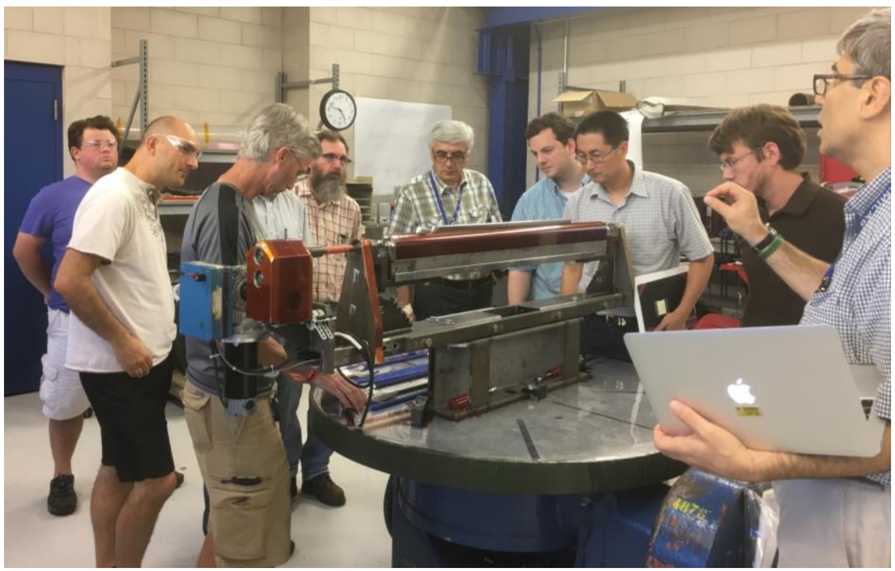
Delay ~ 3 months with respect to the MDP Proposal

Program reviews

Coil production readiness review September 20, 2017. Recommendations:

- 3 on the coil and tooling design
- 3 on magnet design, fabrication plan and status
- 5 on cable and coil parts Inventory, QC and travelers, resources, safety
- 4 on instrumentation

Most of those recommendations have been implemented.



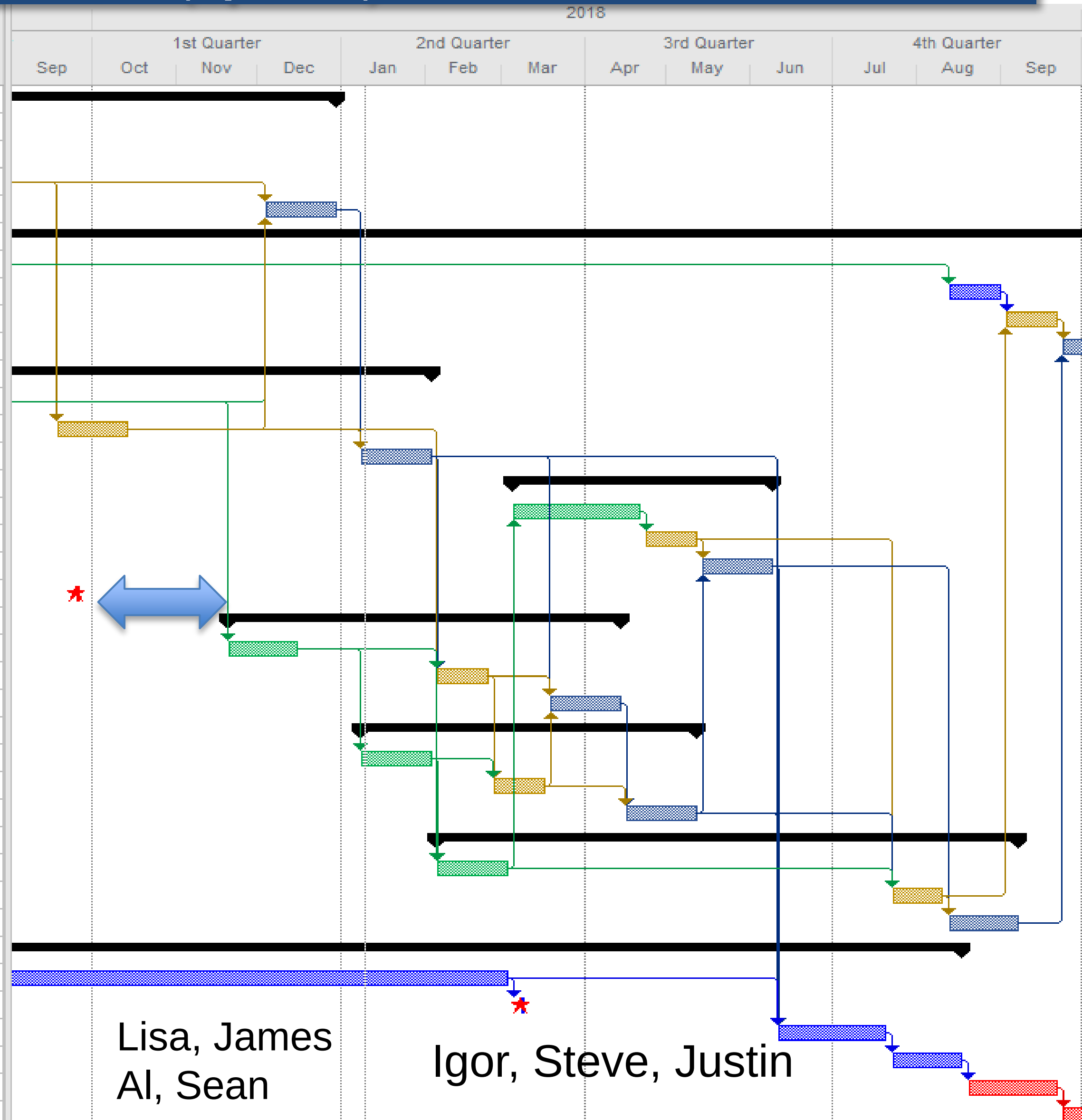
Internal coil production review January 11, 2018

- 5 recommendations

All comments and recommendations were carefully studied and implemented.

New coil (opt. #2)

Task Name	Duration	Start	Finish
OL coil #1 HFD-CL2-002	**285 days**	**Mon 11/28/16**	**Fri 12/29/17**
winding/curing	17 wks	Mon 11/28/16	Fri 3/24/17
winding/curing	4 wks	Mon 3/27/17	Fri 4/21/17
reaction	4 wks	Mon 5/22/17	Fri 6/16/17
impregnation/instrumentation	4 wks	Mon 12/4/17	Fri 12/29/17
OL coil #2 HFD-CL2-003	**330 days**	**Mon 7/17/17**	**Fri 10/19/18**
winding/curing	4 wks	Mon 7/17/17	Fri 8/11/17
repair	3 wks	Mon 8/13/18	Fri 8/31/18
reaction	3 wks	Mon 9/3/18	Fri 9/21/18
impregnation/instrumentation	4 wks	Mon 9/24/18	Fri 10/19/18
OL coil #3 HFD-CL2-004	**160 days**	**Mon 6/26/17**	**Fri 2/2/18**
winding/curing	4 wks	Mon 6/26/17	Fri 7/21/17
reaction	4 wks	Mon 9/18/17	Fri 10/13/17
impregnation/instrumentation	4 wks	Mon 1/8/18	Fri 2/2/18
OL coil #4 HFD-CL2-005	**70 days**	**Mon 3/5/18**	**Fri 6/8/18**
winding/curing	7 wks	Mon 3/5/18	Fri 4/20/18
reaction	3 wks	Mon 4/23/18	Fri 5/11/18
impregnation/instrumentation	4 wks	Mon 5/14/18	Fri 6/8/18
IL Coil production readiness review	1 day	Mon 9/25/17	Mon 9/25/17
IL coil #1 HFD-CL1-001	**105 days**	**Mon 11/20/17**	**Fri 4/13/18**
winding/curing	4 wks	Mon 11/20/17	Fri 12/15/17
reaction	3 wks	Mon 2/5/18	Fri 2/23/18
impregnation/instrumentation	4 wks	Mon 3/19/18	Fri 4/13/18
IL coil #2 HFD-CL1-002	**90 days**	**Mon 1/8/18**	**Fri 5/11/18**
winding/curing	4 wks	Mon 1/8/18	Fri 2/2/18
reaction	3 wks	Mon 2/26/18	Fri 3/16/18
impregnation/instrumentation	4 wks	Mon 4/16/18	Fri 5/11/18
IL coil #3 HFD-CL1-003	**155 days**	**Mon 2/5/18**	**Fri 9/7/18**
winding/curing	4 wks	Mon 2/5/18	Fri 3/2/18
reaction	3 wks	Mon 7/23/18	Fri 8/10/18
impregnation/instrumentation	4 wks	Mon 8/13/18	Fri 9/7/18
Demo #1 assembly and test	**285 days?**	**Mon 7/17/17**	**Fri 8/17/18**
mechanical model (baseline)	33 wks	Mon 7/17/17	Fri 3/2/18
readyness review	1 day?	Thu 3/8/18	Thu 3/8/18
assembly (IL-#1-2, OL-#1-2)	6 wks	Mon 6/11/18	Fri 7/20/18
test preparation	4 wks	Mon 7/23/18	Fri 8/17/18
model test TCI	5 wks	Mon 8/20/18	Fri 9/21/18
model test TCII	5 wks	Mon 9/24/18	Fri 10/26/18



U.S. MAGNET DEVELOPMENT PROGRAM

Schedule and Milestones

	FY17				FY18				FY19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Nb_3Sn												
Cosine-Theta Baseline												
Test & Decision Milestones	Comparison study of alternative mechanical structures. Informs Driving Questions 3, 6, 9.	Mechanical model assembly, instrumentation and test is complete. Informs Driving Questions 3, 9.	Review and select the mechanical structure for the first 15 T 4-layer Cos-theta dipole.	4-layer Cosine-theta 15 T	Retest of previous 4-layer Cosine-theta 15 T with preload modifications			4-layer Cosine-theta 15 T	Engineering design of 16 T dipole model suitable for HE-LHC or FCC		4-layer Cosine-theta 16 T	
Primary Focus/ Significance	Done	Q3	Structure selected	Establish baseline with best understood coil geometry. Investigate stress limits in a coil design without resorting to stress management. Informs Driving Questions 1, 2, 4, 5, 7. Overall contribution to experience base, feedback for modeling and simulation tool development, diagnostics development.	Important for establishing warm prestress limits and impact on training. Informs Driving Questions 1, 2, 4, 5, 7.			Incorporate improvements and lessons learned from previous 4-layer dipole. Informs Driving Questions 1, 2, 4, 5, 7.	Structure analysis and selection for 50 mm aperture dipole model is complete.		Push to the field limit in optimized 16 T design. Start to incorporate cost reduction strategies. Informs Driving Questions 1, 2, 3, 4, 5, 6, 7, 9.	Evaluate feasibility and next steps. Consider possible alternate routes based on previous design studies and accumulated experience.
								4-layer Cosine-theta 15T	Retest of previous 4-layer Cosine-theta 15T with preload modifications		4-layer Cosine-theta 15 T	
								Establish baseline with [illegible] stress limits in a coil design without resorting to stress ma[illegible] Informs Driv[illegible] 1, 2, 4, 5, 7. Overall contribution to experience base, feedback for modeling and simulation tool development, diagnostics development.	Important for establishing [illegible]estress limits [illegible]ct on training. Inform[illegible] Driving Questions 1, 2, 4, 5, 7.		Incorporate improvements and lessons learned from previous 4-layer dipole. Informs Driving Questions 1, 2, 4, 5, 7.	

- Step 1 delay ~1 year wrt original MDP plan
- Step 2 delay ~9 months
- Step 3 delay could be ~3months

Conclusions

- Good progress during past year
- Fabrication of 15 T dipole demonstrator is in progress
  - Design and procurement are complete
  - Infrastructure prepared
  - Coil fabrication is in progress
  - Mechanical structure is being tested
  - Magnet test is scheduled for Q4 of FY18
- Design studies of 16 T dipole with small aperture is complete
  - ready to start SM coil technology development
- Design studies of large-aperture 15 T dipole is in progress
- Progress is limited by available resources both M&S funding and Labor (mainly techs)