U.S. MAGNET DEVELOPMENT PROGRAM

SMCT program status and next steps

A.V. Zlobin

MDP General Meeting
10/23/2024

U.S. MAGNET DEVELOPMENT PROGRAM

Outline

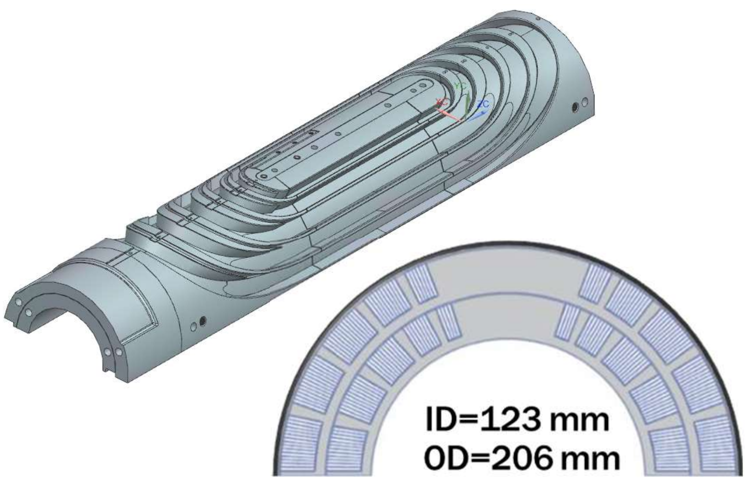
- Nb_3Sn SMCT program status and next steps
- Comments and recommendations for US MDP updated plan - Area I

U.S. MAGNET DEVELOPMENT PROGRAM

Part 1.
Nb_3Sn SMCT program status and next steps

Stress Management Cos-Theta (SMCT) coil concept

Nb_3Sn Rutherford cable



3D stress management using stainless steel mandrel

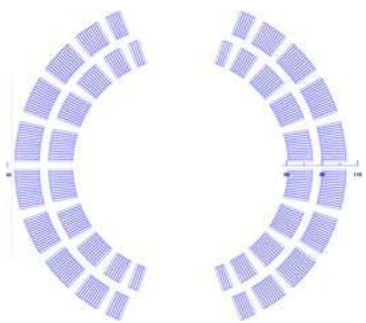
- The stress-managed cos-theta (SMCT) coil is a new concept being developed at Fermilab for High-Field (HF) and/or Large-Aperture (LA) accelerator magnets based on LTS and HTS.

- The SMCT structure is used to reduce large coil deformations under Lorentz forces and, thus, excessively large strains and stresses in the coil.

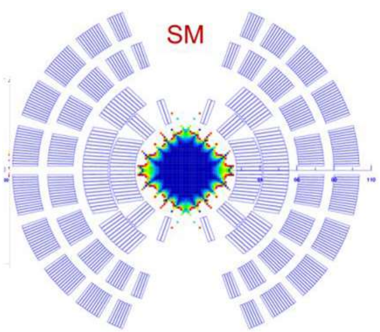
- A 123-mm aperture two-layer Nb_3Sn SMCT dipole coil has been developed at Fermilab to demonstrate the SM concept including coil design, fabrication technology and performance.

US-MDP Nb_3Sn SMCT task milestones

U.S. MAGNET DEVELOPMENT PROGRAM



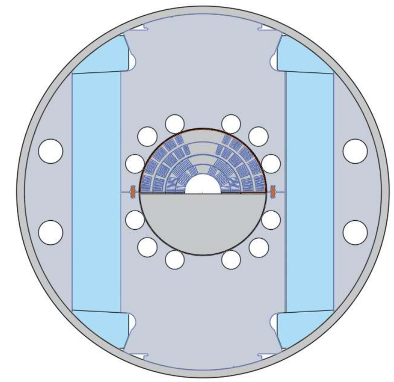
ID=123 mm, B_{des}~11 T

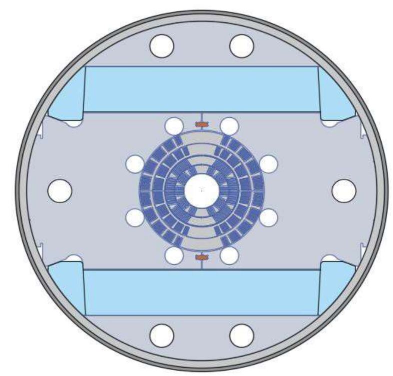


ID=60 mm, B_{des}~15 T

Milestone #	Description	Target
Al-M1a	Development and test of str… management concept using … erture and 4-layer small-ap… …coils and dipole mirror structu… **Completed**	Jun-23 => Feb 24
Al-M2a	Development, fabrication and test of stress management concept in a 2-layer 120-mm dipole with the fi…	Jun-24
Al-M3a	Assembly and te… **Modified** …nagement concept in a 4-la… …-mm 17 T dipole with stress management.	Sep-24

Al-M2a +Al-M3a	Development of the SMCT coil technology and test of stress management concept in a 2-layer 123-mm dipole with the field up to 11 T and in a 4-layer 60-mm dipole with the field up to 15 T.	Q4 FY26

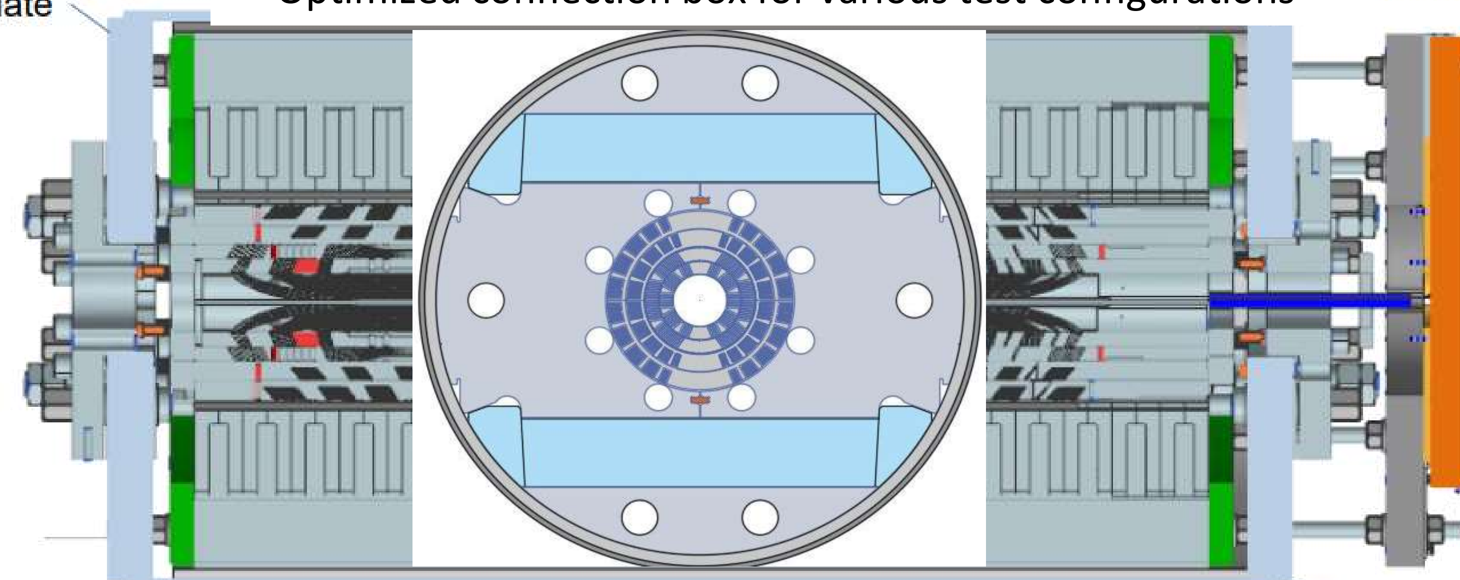




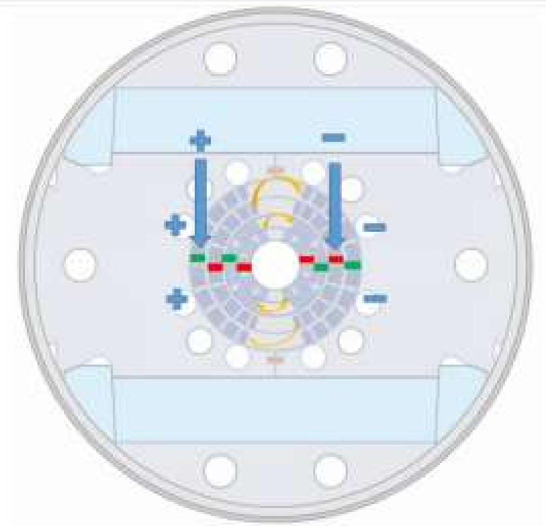
SMCTD1 design concept

Nb$_3$Sn Rutherford cable

- **Based on lessons learned from MDPCT1 and SMCTM1a/b**
- New optimized SMCT2 coil + 2 inner coils from MDPCT1
- Reinforced MDPCT1 mechanical structure
- Optimized coil end support
- Optimized connection box for various test configurations



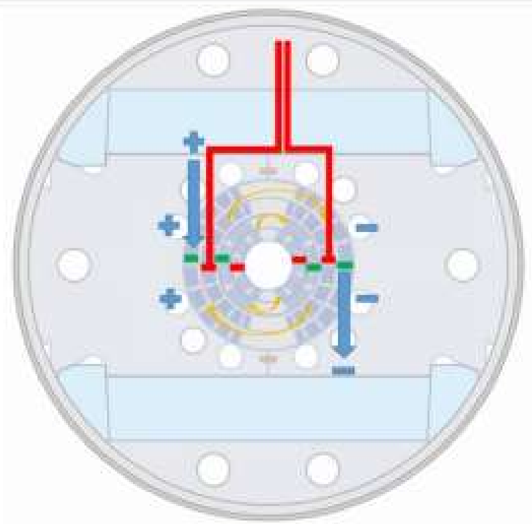
SMCTD1 test configurations and goals



SMCTD1a (123 mm SMCT2 coil)

SSL_{nom}	SSL_{deg}
14.0	**12.5**
14.2	12.7

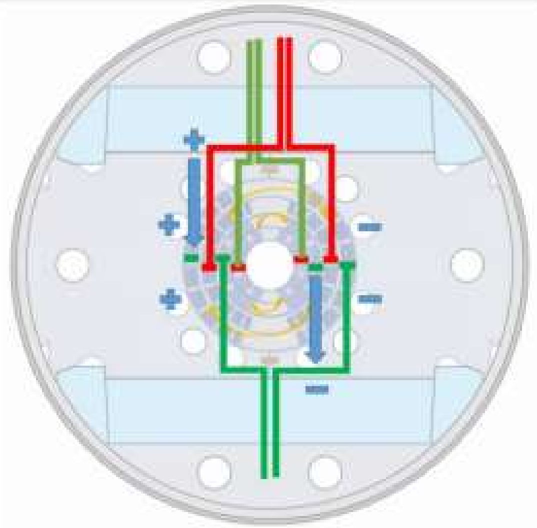
Test goal #1: Demonstration of 123 mm SMCT coil design and technology improvement



2L SMCTD1b (123 mm)

B_o, T	B_{max}, T
11.6	**13.3**
12.8	14.8

Test goal #2: Demonstration of SMCT coil technology in 123-mm aperture 2-layer 11+ T dipole



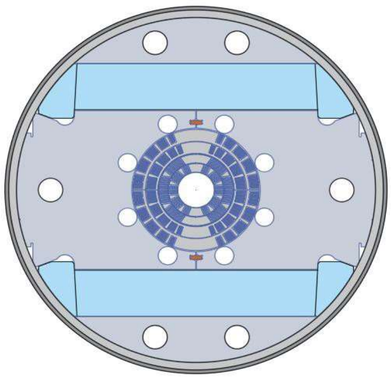
4L SMCTD1c (60 mm)

B_o, T	B_{max}, T
14.2	15.1
17.2	18.4

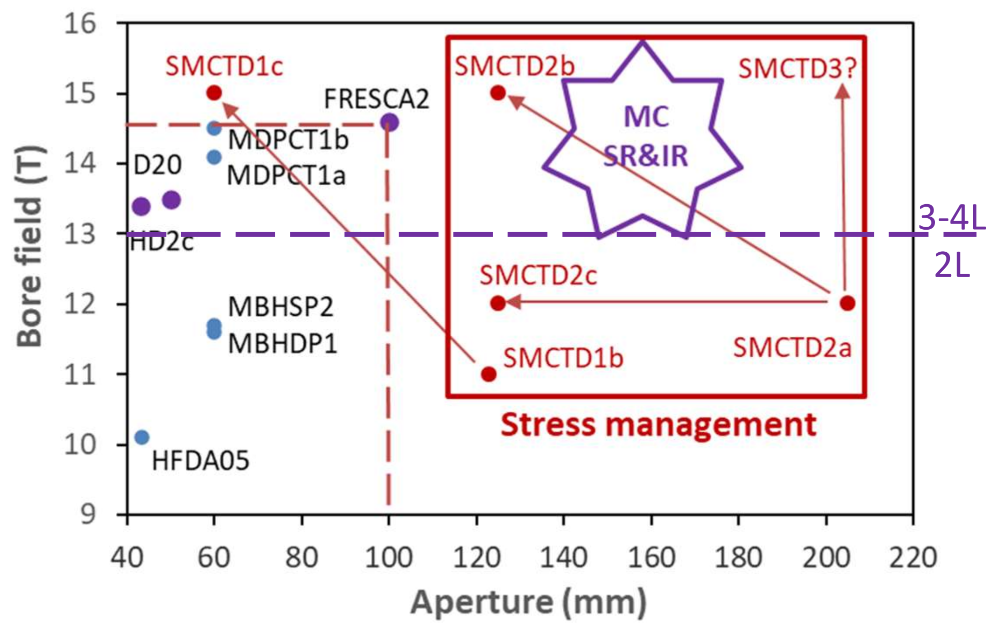
Test goal #3: Demonstration of SMCT coil technology in 60-mm aperture 4-layer 14+ T dipole

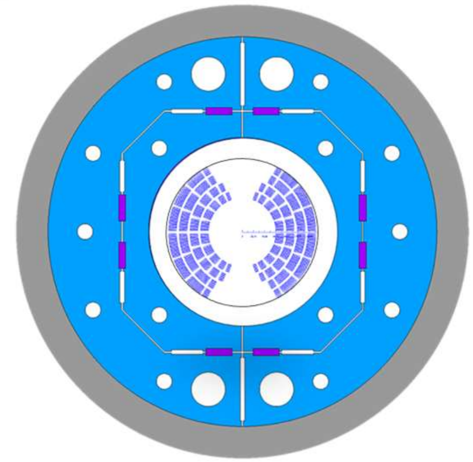
Nb_3Sn SMCT magnet program plan

U.S. MAGNET DEVELOPMENT PROGRAM



SMCTD1a/b/c
60/123 mm ID
600 mm OD
AL clamp structure





SMCTD2a/b/c
125/210 mm ID
780 mm OD
AL shell Utility Structure

FY25 | FY26 | FY27 | FY28

SMCTD1a/b/c - ***modified MDP milestone***

40-strand cable, SMCT2 coil, TELENE, AL clamp structure, VMTF

SMCTD2a/b/c - ***new MDP milestone?***

28-strand cable, 4 coils + tooling, TELENE, Utility structure, HFVMTF

U.S. MAGNET DEVELOPMENT PROGRAM

SMCTD1 updated schedule

	Main steps	FY25 Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	FY26 Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	SMCTD1																								
1	design	Ins			SK			EP			PB														
2	procurement	Ins	Ins			SK	SK		EP	EP		PB	PB												
3	SMCTM1 disassembly, inspection	x																							
4	cable preparation, coil winding		x																						
5	coil reaction			x	WSM																				
6	coil potting (Telene)				x	CSM																			
7	4 coils measurement-instrum					x	x																		
8	tooling and structure assembly							x																	
9	coil-yoke assembly								x																
10	coil pre-load, clamping									x															
11	skin installation and welding										x														
12	end plate welding, end load											x													
13	magnet instrumentation												x												
14	pizza box mounting													x											
15	production test													x											
16	SMCT2 coil test in SMCTD1a														x	x									
17	reconfiguration and test SMCTD1b																x	x							
18	reconfiguration and test SMCTD1c																		x	x					
19	Electromagnetic analysis			x	x	x	x						SSL		x	x	x	x	x	x					
20	Mechanical analysis			x	x	x	x	CSP		x	x	x			x	x	x	x	x	x					
	SMCTD2																								
1	SMCT3-6 3D magnetic D&A in UtS							x	x		x		x												
2	MCT3-6 3D mechanical D&A in UtS									x		x		x	x	x									

Ins - ground insulation
SK - 6 mm skin
EP - end plates, iron rods
PB - pizza box
WST - witness sample test
CSM - coil size measurement
CSP - coil shim plan
SSL - short sample limit

The schedule is based on the experience with MDPCM1 and SMCTM1 and availability of resources (staff and M&S)!

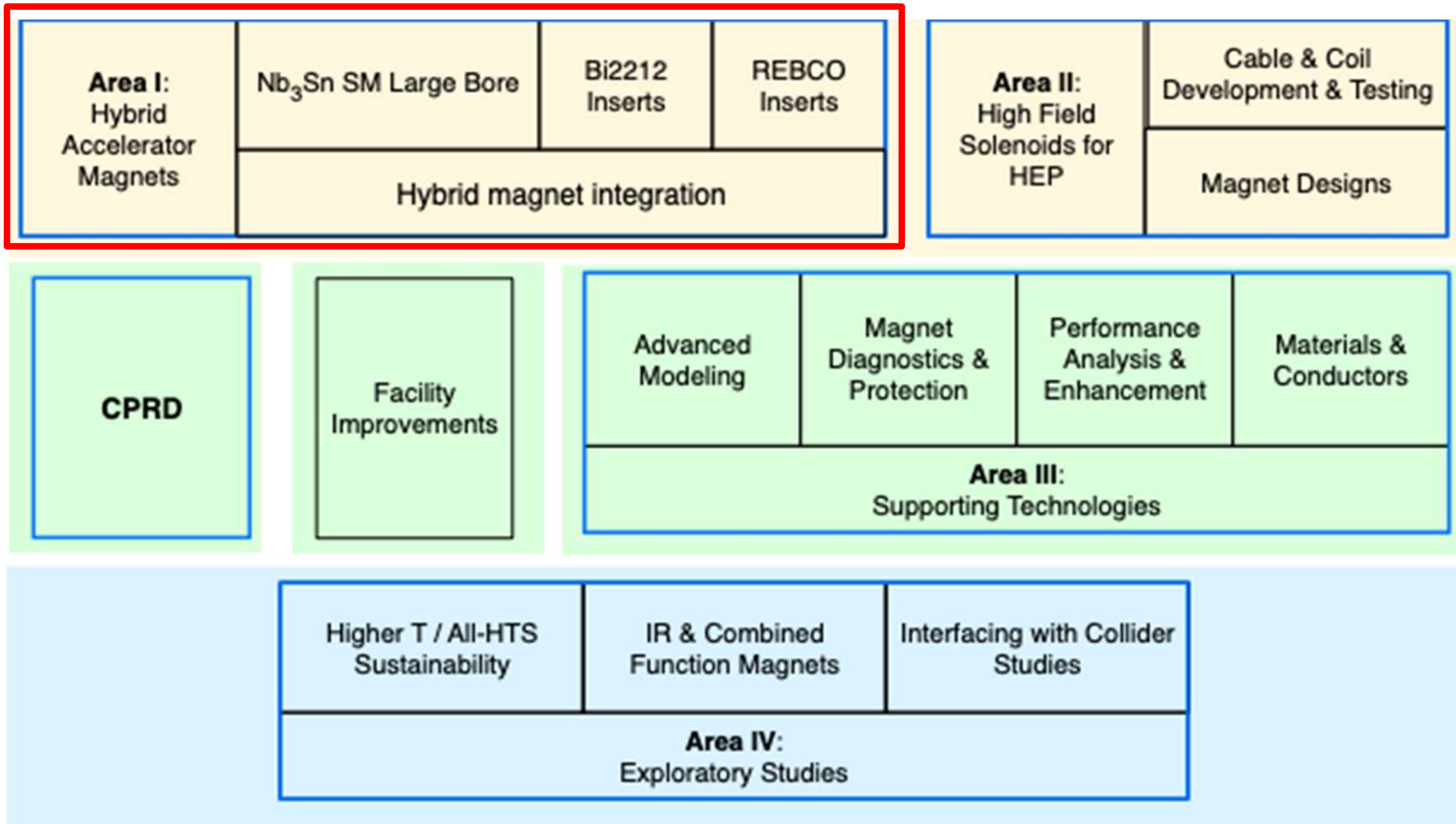
U.S. MAGNET DEVELOPMENT PROGRAM

Conclusion (Part 1)

- SMCTD1 plan has been updated and discussed
- FY25 resource request has been submitted to Steve
- Plan and schedule for SMCTD2 has been prepared, presented and discussed at Fermilab
- Collaboration with LBNL on the mechanical (“Utility”) structure for SMCTD2 is important
- Merging efforts and sharing expanses related to SMCTD2 development would significantly reinforce the program and reduce cost and schedule risks

Part 2.
Comments and recommendations for US MDP updated plan - Area I

Program Structure - Areas and sub-Areas

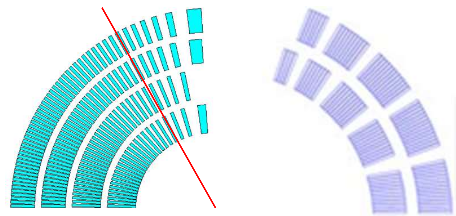


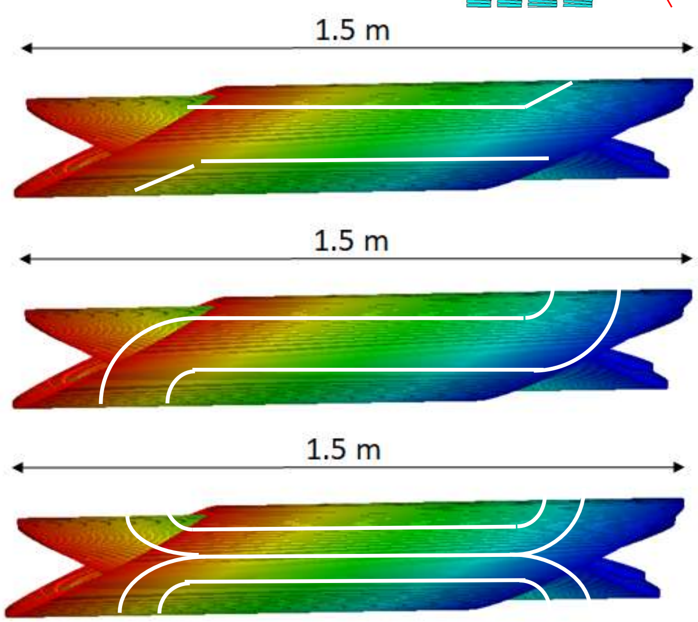
SMCT vs CCT design and technology

B_o reduction in CCT:

Cos15	0.97	3.40
Cos30	0.87	13.38
Cos45	0.71	29.26

CCT vs SMCT coil x-sections:





From CCT to CT (SMCT)

CCT (issues):

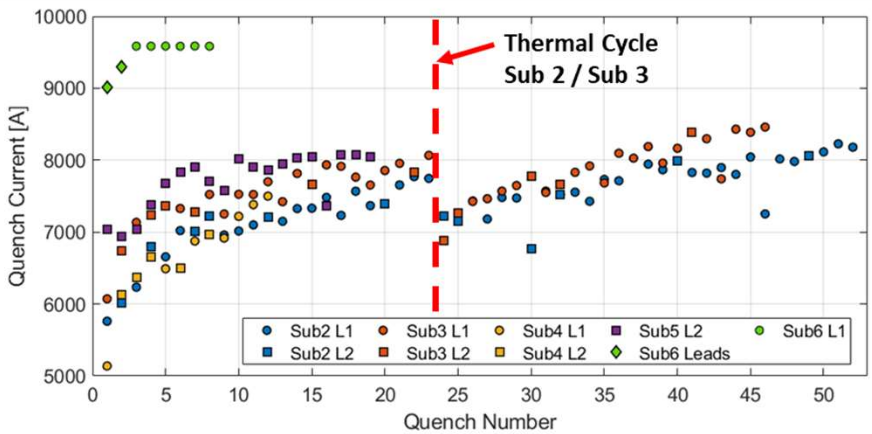
1. Even number of coils to compensate B axial
2. Reduction of Bo due to winding angle
3. Long ends
4. Large coil volume
5. Complicated axial coil assembly
6. Difficult radial coil pre-load
7. 3D structure – structure fabrication, coil scale up problems
8. Even turn groups – field quality optimization

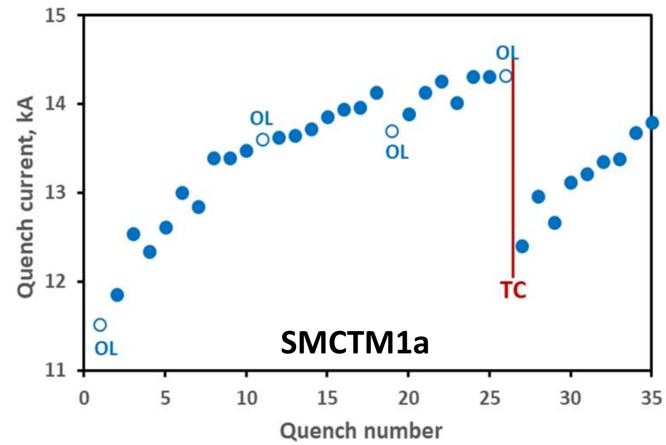
SMCT (advantages):

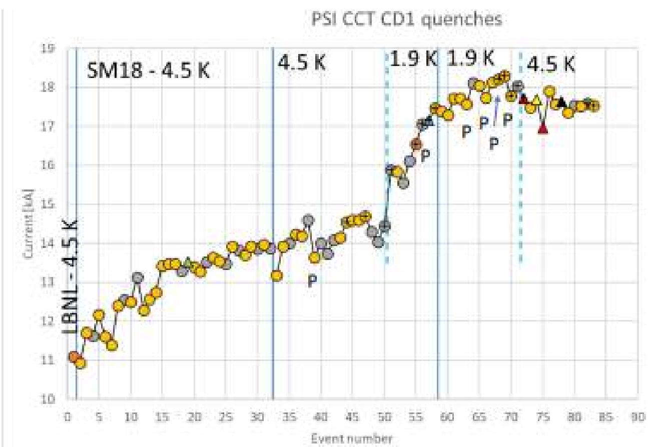
1. Odd or even number of coils
2. No Bo reduction
3. Short ends
4. Minimal coil volume
5. Transverse coil assembly
6. 3D ends - 3D printing technology
7. 2D structure (collar) in straight section - no scale up problem
8. Uneven turn groups – field quality

U.S. MAGNET DEVELOPMENT PROGRAM

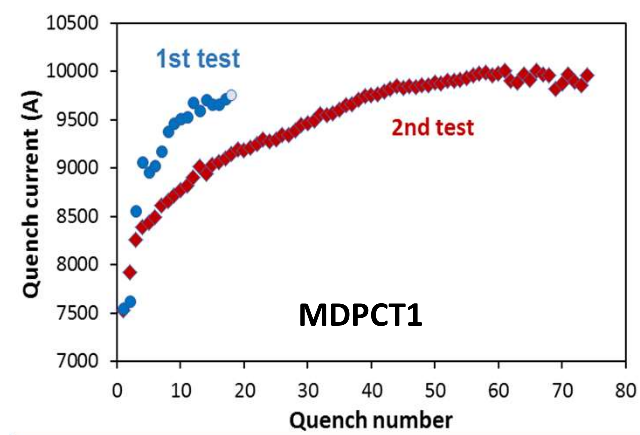
Quench performance comparison



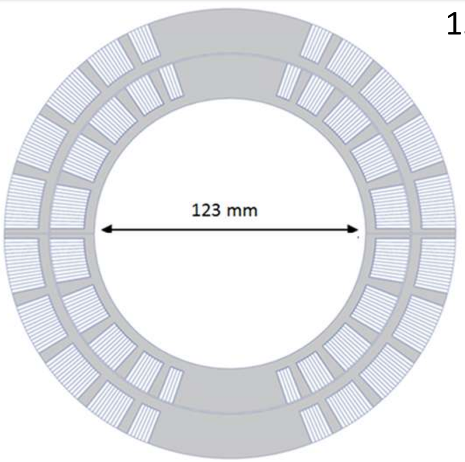




- **Magnet training is similar for CCT, SMCT and regular CT coils**
- **Training improvement is possible**
- **Large-aperture high-field coils are real**
- **Training memory, degradation are still a concern for both designs**

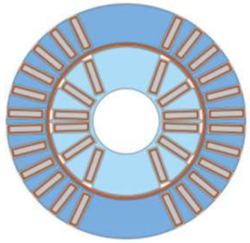


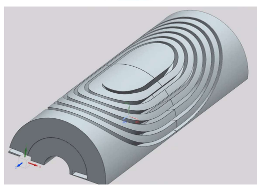
SMCT coil examples

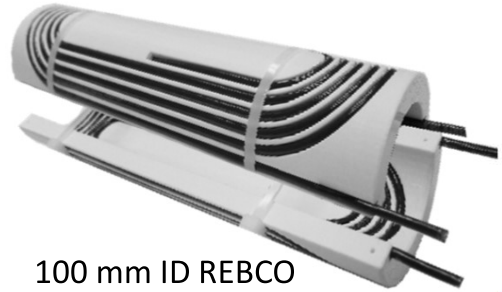


123-mm ID 2L Nb3Sn SMCT coil

15 mm ID Bi2212 2L SMCT coil



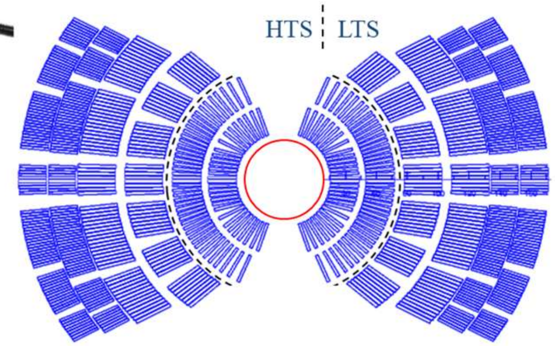




100 mm ID REBCO CORC 2L insert

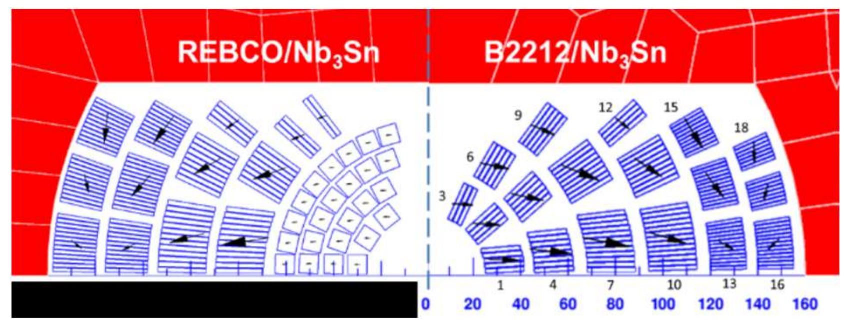
32-mm ID REBCO TST SMCT coil

Hybrid magnets

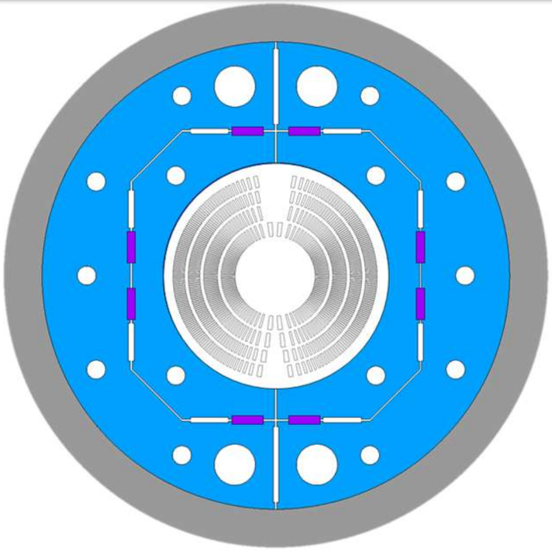


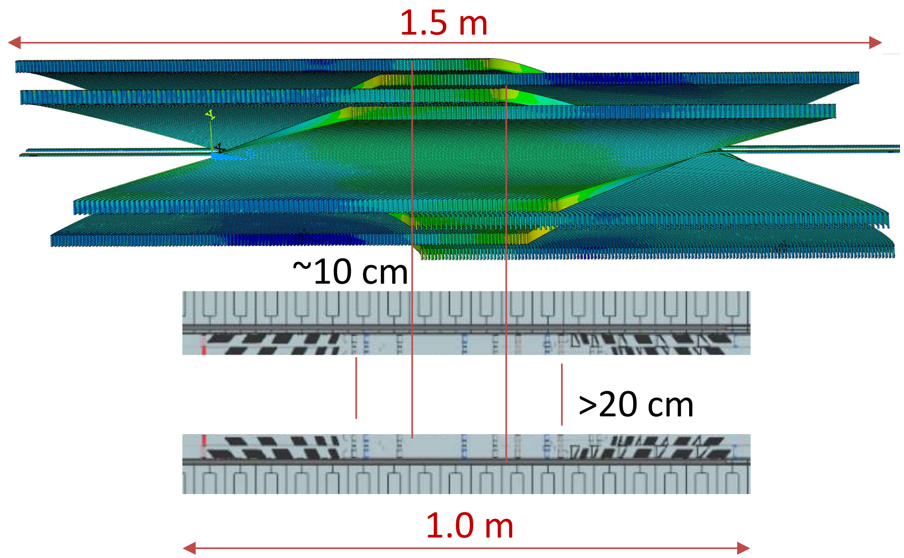
Conceptual designs of 20 T Hybrid dipole

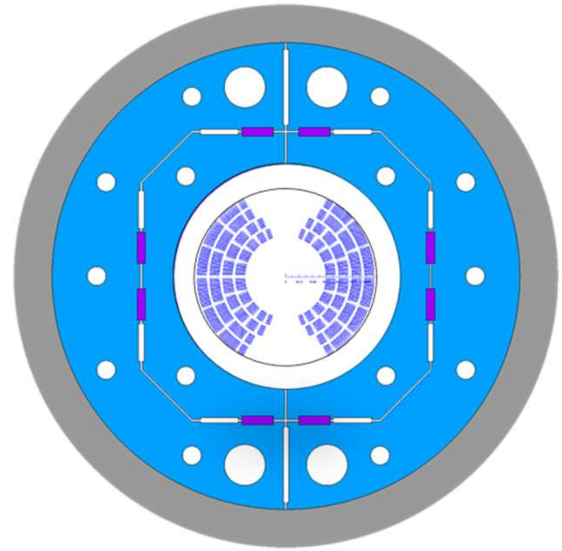
Area I: Hybrid Accelerator Magnets	Nb_3Sn SM Large Bore	Bi2212 Inserts	REBCO Inserts
	Hybrid magnet integration		



CCT6 vs SMCTD2





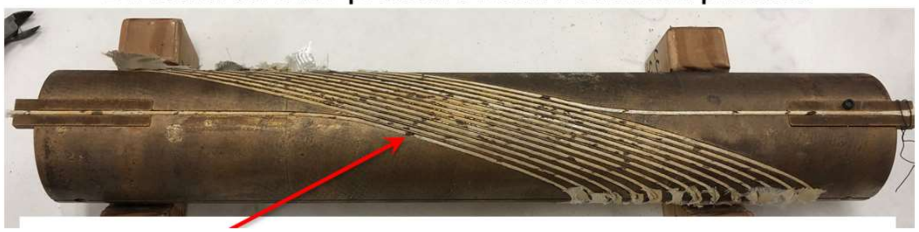


Target Parameters
- Bore diameter: 120 mm
- 4 layers
- Bore field of 12 T / 13 T for standalone operation (30+ % current margin at target fields of 12 T, 4.2 K and 13 T, 1.9 K)

Target Parameters
- Bore diameter: 123 mm
- 4 layers
- Max bore field of 15 T at 1.9 K => can be increased by using larger 20 mm wide cables and cable grading

HTS coils

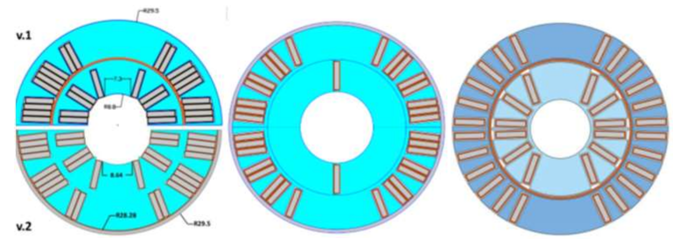
BIN5a after over-pressure heat treatment process



- Single coil, 39 cm long, 13 turns, inter-layer splices
- Bore diameter ~ 53 mm
- 9-strand Rutherford cable 4.03x1.47 mm^2

- Bi-2212 2L CCT magnet, 40 mm clear bore, 85 cm long
- 17-strand Rutherford cable 7.8x1.44 mm^2, 0.8 mm diameter strand
- No or short straight section

Bi2212 2L coil inserts with SM



- 2L single coil, 25-30 cm long, 36 turns
- No inter-layer splice
- Min bore diameter 15 mm
- 17-strand Rutherford cable 7.8x1.44 mm^2, ~12 m long
- 10-15 cm straight section

U.S. MAGNET DEVELOPMENT PROGRAM

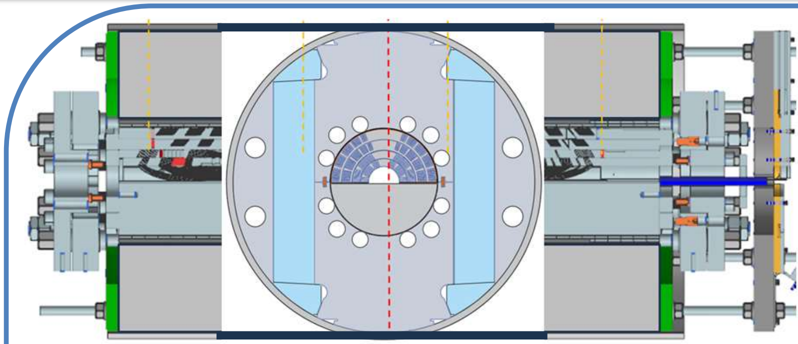
Conclusion (Part 2)

- SMCT coil has significant design and technological advantages wrt CCT coil
- Present quench performance is quite similar for CCT, SMCT and CT coils w/o SM
- SMCT coil is the only design approach acceptable for large-aperture high-field magnets for MS SR and IR
- SMCT approach perfectly fits into new MDP plan
- Concentrating MDP resources on the SMCT coil technology would allow increasing the productivity and outcome of the program
- *Let's organize special 1 day workshop to discuss SMCT vs CCT option for Nb_3Sn and HTS tasks*
- *This is the most appropriate time to take this decision!*

Backup slides

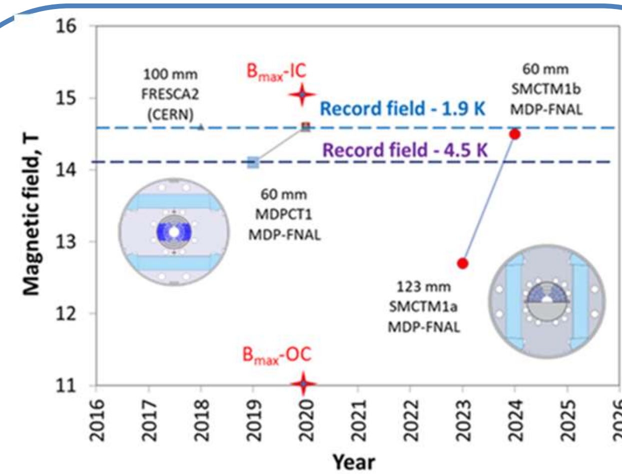
U.S. MAGNET DEVELOPMENT PROGRAM

SMCT1 coil test in mirror configuration



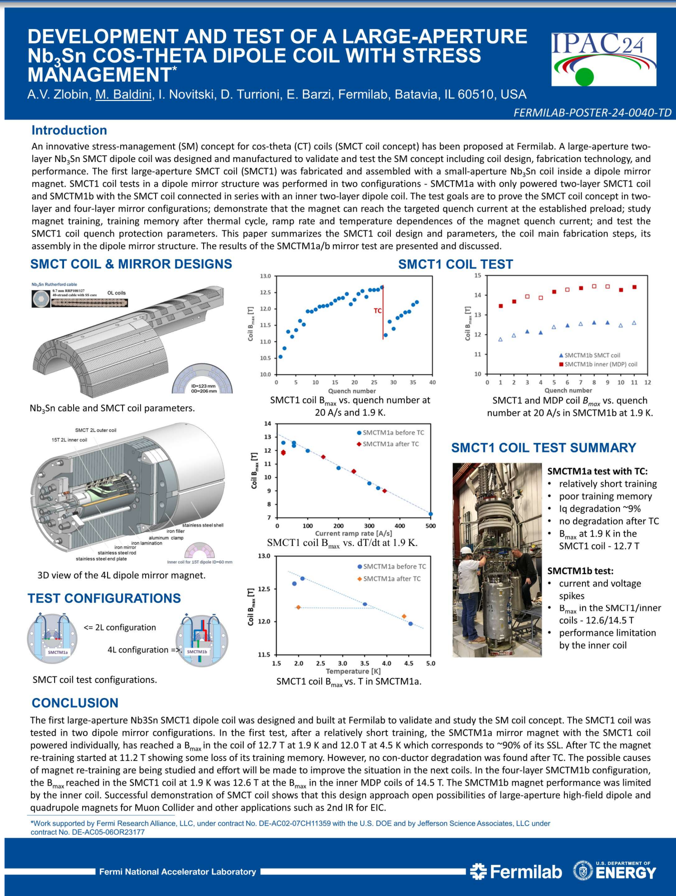
- The 1st 2L 123-mm ID SMCT coil has been developed and fabricated
- The SMCT coil was assembled with 60-mm ID 2L cos-theta coil (*previously tested in MDPCT1 dipole*) inside the dipole mirror structure SMCTM1
- Magnet fabrication – 2022-2023
- Delivered to VMTF - May 2023
- Test in two configurations - Sep 2023-Feb 2024

MDP milestone!



- SMCT1 coil has been tested in two configurations – 2-layer (SMCTM1a) and 4-layer (SMCTM1b)
- First data on SMCT coil training, training memory, degradation
- Record field of ~12.7 T has been achieved in 123 mm aperture Nb_3Sn ***dipole*** coil in 2L and 4L configurations

SMCTM1a/b result analysis and presentation - update


DEVELOPMENT AND TEST OF A LARGE-APERTURE Nb_3Sn COS-THETA DIPOLE COIL WITH STRESS MANAGEMENT*

A.V. Zlobin, M. Baldini, I. Novitski, D. Turrioni, E. Barzi, Fermilab, Batavia, IL 60510, USA

FERMILAB-POSTER-24-0040-TD

IPAC24

Introduction

An innovative stress-management (SM) concept for cos-theta (CT) coils (SMCT coil concept) has been proposed at Fermilab. A large-aperture two-layer Nb_3Sn SMCT dipole coil was designed and manufactured to validate and test the SM concept including coil design, fabrication technology, and performance. The first large-aperture SMCT coil (SMCT1) was fabricated and assembled with a small-aperture Nb_3Sn coil inside a dipole mirror magnet. SMCT1 coil tests in a dipole mirror structure was performed in two configurations - SMCTM1a with only powered two-layer SMCT1 coil and SMCTM1b with the SMCT coil connected in series with an inner two-layer dipole coil. The test goals are to prove the SMCT coil concept in two-layer and four-layer mirror configurations; demonstrate that the magnet can reach the targeted quench current at the established preload; study magnet training, training memory after thermal cycle, ramp rate and temperature dependences of the magnet quench current; and test the SMCT1 coil quench protection parameters. This paper summarizes the SMCT1 coil design and parameters, the coil main fabrication steps, its assembly in the dipole mirror structure. The results of the SMCTM1a/b mirror test are presented and discussed.

SMCT COIL & MIRROR DESIGNS

Nb_3Sn cable and SMCT coil parameters.

3D view of the 4L dipole mirror magnet.

TEST CONFIGURATIONS

SMCT coil test configurations.

SMCT1 COIL TEST

SMCT1 coil B_{max} vs. quench number at 20 A/s and 1.9 K.

SMCT1 and MDP coil B_{max} vs. quench number at 20 A/s in SMCTM1b at 1.9 K.

SMCT1 coil B_{max} vs. dT/dt at 1.9 K.

SMCT1 coil B_{max} vs. T in SMCTM1a.

SMCT1 COIL TEST SUMMARY

SMCTM1a test with TC:
- relatively short training
- poor training memory
- Iq degradation ~9%
- no degradation after TC
- B_{max} at 1.9 K in the SMCT1 coil - 12.7 T

SMCTM1b test:
- current and voltage spikes
- B_{max} in the SMCT1/inner coils - 12.6/14.5 T
- performance limitation by the inner coil

CONCLUSION

The first large-aperture Nb3Sn SMCT1 dipole coil was designed and built at Fermilab to validate and study the SM coil concept. The SMCT1 coil was tested in two dipole mirror configurations. In the first test, after a relatively short training, the SMCTM1a mirror magnet with the SMCT1 coil powered individually, has reached a B_{max} in the coil of 12.7 T at 1.9 K and 12.0 T at 4.5 K which corresponds to ~90% of its SSL. After TC the magnet re-training started at 11.2 T showing some loss of its training memory. However, no con-ductor degradation was found after TC. The possible causes of magnet re-training are being studied and effort will be made to improve the situation in the next coils. In the four-layer SMCTM1b configuration, the B_{max} reached in the SMCT1 coil at 1.9 K was 12.6 T at the B_{max} in the inner MDP coils of 14.5 T. The SMCTM1b magnet performance was limited by the inner coil. Successful demonstration of SMCT coil shows that this design approach open possibilities of large-aperture high-field dipole and quadrupole magnets for Muon Collider and other applications such as 2nd IR for EIC.

*Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. DOE and by Jefferson Science Associates, LLC under contract No. DE-AC05-06OR23177

Fermi National Accelerator Laboratory — Fermilab — U.S. DEPARTMENT OF ENERGY

11th Mechanical and Electromagnetic Properties of Composite Superconductors Workshop - MEM'2024:

ASC'2024:

- A.V. Zlobin et al., "Test of a 4-layer Nb_3Sn cos-theta dipole coil with stress management," invited talk