U.S. MAGNET DEVELOPMENT PROGRAM

MDP Nb_3Sn Cos-theta magnets: FY20-FY23 plan

MDP general meeting
October 23, 2019

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Fermi National Accelerator Laboratory

Outline

- FY16-FY19 MDP Nb_3Sn cos-theta magnet R&D plan and main results

- FY20-FY23 planning
  - guideline
  - justification and demonstration
  - goals, deliverables, approach
  - general plan, outcome, R&D questions and collaboration

- FY20 focus:
  - FY20 Nb_3Sn cos-theta magnets R&D detailed plan and schedule

- Summary

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MDP Nb_3Sn cos-theta magnets: FY16-FY19 R&D plan

2016	2017	2018	2019

Push traditional Cos-theta technology to its limit with newest conductor and structure

Cos-theta 4 layer 15 T	Preload mods	15 T with improvements	4-layer 16 T Cos-theta
Leverage latest Nb_3Sn and Bladder and Key structure	Impact of preload on training		Optimized 16 T design as baseline

- ***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.
  - *Done. The magnet was tested in June 2019.*
- ***Step 2***: A successful series of magnets will provide a platform for performance improvement by integrating the outcomes of the Technology Development program.
  - *In progress. The 2^{nd} test with optimized azimuthal and axial coil preload is in January 2020.*
- ***Step 3***: 16 T cos-theta design to explore the limit of Nb_3Sn in this geometry.
  - *Done. 17 T 60-mm aperture and 15 T 120-mm aperture coil designs with SM and two mechanical structures have been proposed and analyzed.*

MDP Nb_3Sn cos-theta magnets: R&D deliverables

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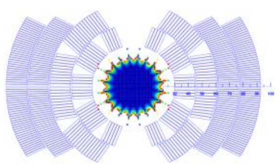
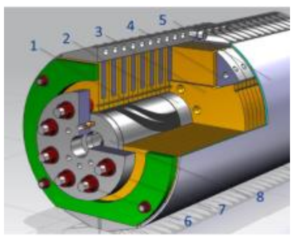
2016	2017	2018	2019

Push traditional Cos-theta technology to its limit with newest conductor and structure

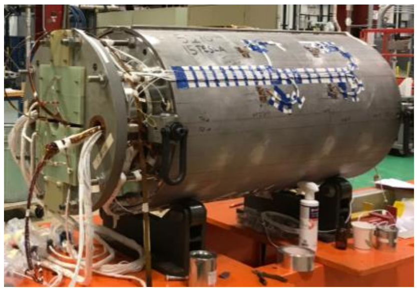
Cos-theta 4 layer 15 T	Preload mods	15 T with improvements	4-layer 16 T Cos-theta
Leverage latest Nb_3Sn and Bladder and Key structure	Impact of preload on training		Optimized 16 T design as baseline



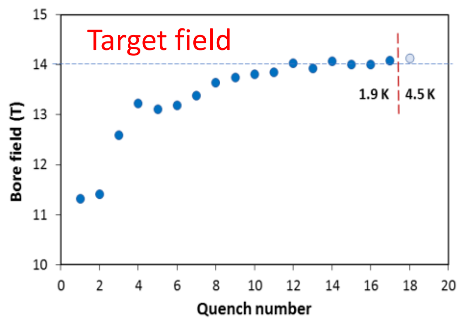
4-layer graded coil + technology



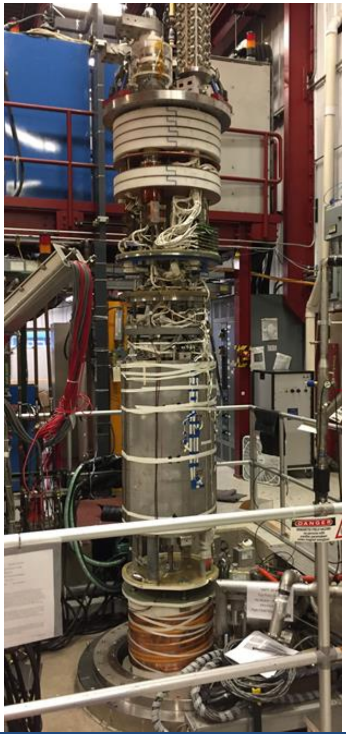
Innovative 600-mm OD mechanical structures for accelerator magnets + technology



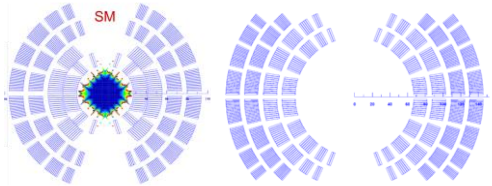
MDPCT1 cos-theta dipole design and technology demonstrator



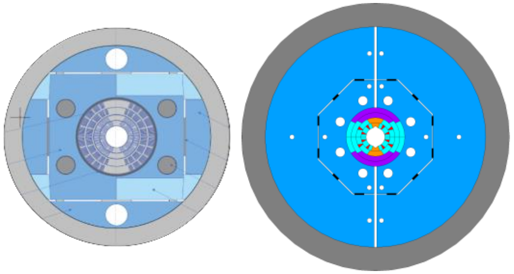
MDPCT1 training in 1st test



B_{des}~17 T, 60 mm ID B_{des}~15 T, 120 mm ID



4-layer 60-mm aperture 17 T and 120 mm aperture 15 T cos-theta dipole coil with stress management



600-mm OD and 750-mm OD (utility) structures to test high-field cos-theta coils

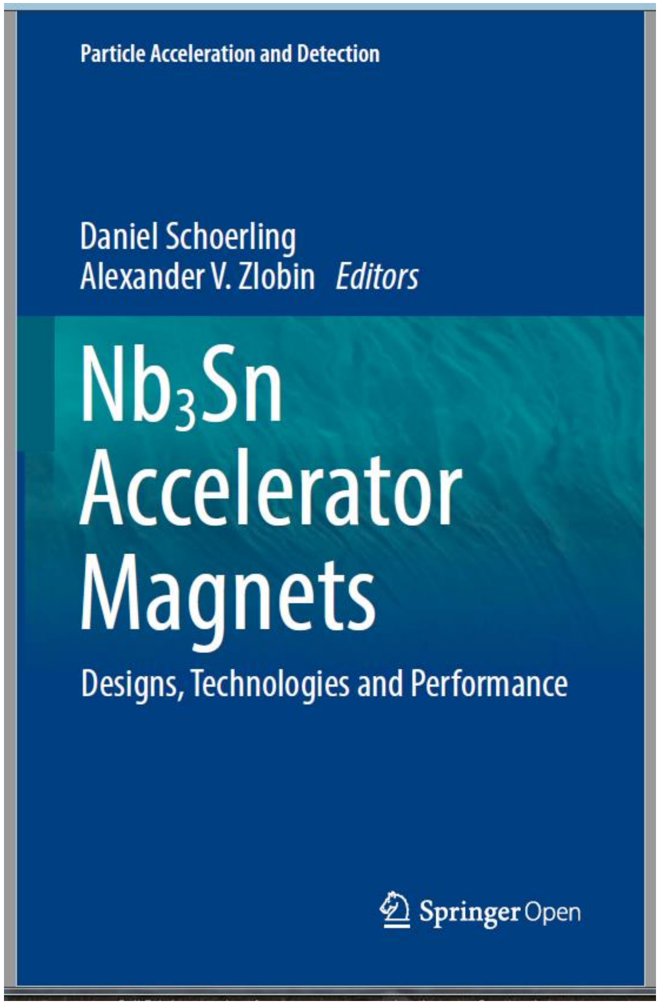
MDP Nb_3Sn cos-theta magnets: publications

1. A.V. Zlobin et al., “Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider”, Proceedings of IPAC2015, Richmond, VA, USA, p.3365.
2. V.V. Kashikhin et al., “Magnetic and structural design of a 15 T Nb_3Sn accelerator dipole model”, CEC/ICMC2015, Tucsan (AR), June 2015. IOP Conference Series: Materials Science and Engineering, v.101, issue 1, p.012055, 2015.
3. I. Novitski et al., “Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab”, IEEE Trans. on Appl. Supercond., Vol. 26, Issue 3, June 2016, 4001007.
4. E. Barzi et al., “Nb_3Sn RRP® Strand and Rutherford Cable Development for a 15 T Dipole Demonstrator,” IEEE Trans. on Appl. Supercond., Vol. 26, Issue 3, June 2016, 4001007.
5. I. Novitski, A.V. Zlobin, “Development and Comparison of Mechanical Structures for FNAL 15 T Nb_3Sn Dipole Demonstrator”, ISBN 978-3-95450-180-9 Proceedings of NAPAC2016, Chicago, IL, USA MOPOB30, p.137
6. V.V. Kashikhin, A.V. Zlobin, “Persistent Current Effect in 15-16 T Nb_3Sn Accelerator Dipoles and its Correction”, ISBN 978-3-95450-180-9 Proceedings of NAPAC2016, Chicago, IL, USA, THA1CO04, p. 1061
7. S. Stoynev, K. Riemer. A. V. Zlobin, “Quench Training Analysis of Nb3Sn Accelerator Magnets”, ISBN 978-3-95450-180-9 Proceedings of NAPAC2016, Chicago, IL, USA MOPOB40, p. 155
8. I. Novitski, J. Carmichael, V.V. Kashikhin, A.V. Zlobin, “High-Field Nb_3Sn Cos-theta Dipole with Stress Management,” FERMILAB-CONF-17-340-TD,
9. E. Barzi et al., “Heat Treatment Optimization of Rutherford Cables for a 15 T Nb_3Sn Dipole Demonstrator”, IEEE Trans. on Appl. Supercond., Vol. 27, Issue 4, June 2017, 4802905
10. I. Novitski et al., “High-Field Nb_3Sn Cos-theta Dipole with Stress Management,” FERMILAB-CONF-17-340-TD.
11. V.V. Kashikhin, I. Novitski, A.V. Zlobin, “Design studies and optimization of a high-field dipole for a future Very High Energy pp Collider”, Proceedings of IPAC2017, Copenhagen, Denmark WEPVA140, p.3597
12. Pei Li, S. Krave, A. Zlobin, “Study of Thermomechanical Properties of The Epoxy-Impregnated Cable Composite for a 15 T Nb_3Sn Dipole Demonstrator,” IOP Conf. Series: Materials Science and Engineering 279 (2017) 012020 doi:10.1088/1757-899X/279/1/012020
13. C. Kokkinos et al., “FEA Model and Mechanical Analysis of the Nb_3Sn 15 T Dipole Demonstrator,” IEEE Trans. on Appl. Supercond., Vol. 28, Issue 3, April 2018, 4007406
14. A.V. Zlobin, V.V. Kashikhin, I. Novitski, “Large-aperture high-field Nb_3Sn dipole magnets,” Proc. of IPAC2018, WEPML026, p.2738.
15. A.V. Zlobin, J. Carmichael, V.V. Kashikhin, I. Novitski, “Conceptual design of a 17 T Nb_3Sn accelerator dipole magnet,” Proc. of IPAC2018, WEPML027, p.2742.
16. D. Tommasini et al.,“Status of the 16 T dipole development program for a future hadron collider,” IEEE Trans. on Appl. Supercond., Vol. 28, Issue 3, April 2018, 4001305
17. C. Orozco et al., “Assembly and Tests of Mechanical Models of the 15 T Nb_3Sn Dipole Demonstrator,” IEEE Trans. on Appl. Supercond., Vol. 29, Issue 5, August 2019, 4003404
18. M. Juchno et al., “Mechanical Utility Structure for Testing High Field Superconducting Dipole Magnets,”, IEEE Trans. on Appl. Supercond., Vol. 29, Issue 5, August 2019, 4001604
19. S. Stoynev et al., “Analysis of Nb_3Sn Accelerator Magnet Training,” IEEE Trans. on Appl. Supercond., Vol. 29, Issue 5, August 2019, 4001206
20. D. Schoerling et al., “The 16 T Dipole Development Program for FCC and HE-LHC,” IEEE Trans. on Appl. Supercond., Vol. 29, Issue 5, August 2019, 4003109
21. G. Velev et al., “Fermilab superconducting Nb_3Sn high field magnet R&D program,” Proceedings of IPAC2019, Melbourne, Australia, May 2019, p.3597
22. A.V. Zlobin et al., “Quench performance and field quality of the 15 T Nb_3Sn dipole demonstrator MDPCT1 in the first test run”, NAPAC2019, September 2019. MOPLO20
23. A.V. Zlobin et al., “Development and First Test of a 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, MT-26, IEEE2020
24. T. Strauss et al., “First field quality measurements of a 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, MT-26, IEEE2020
25. …

The Book

- Nb_3Sn Accelerator Magnets – Designs, Technologies and Performance, Springer 2019
- ~450 pages on Nb_3Sn accelerator magnet (dipoles) designs, technologies and performance covering the period of time from 1967 until 2019
- written by world experts in Nb_3Sn accelerator magnet technologies
- open access
- available online

https://link.springer.com/book/10.1007/978-3-030-16118-7



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International news on 15 T dipole

1. https://news.fnal.gov/2019/09/fermilab-achieves-world-record-field-strength-for-accelerator-magnet/
2. https://cerncourier.com/a/dipole-marks-path-to-future-collider/
3. https://gizmodo.com/scientists-debut-powerful-magnet-for-future-particle-co-1838079628
4. https://m.news.yandex.ru/story/V_SSHA_pokazali_prototip_magnita_dlya_kollajdera_budushhego–4c2d3f531e60a04f8f8f8ffac50a70ef?lr=213&stid=I5udKqW6&persistent_id=74551612&from=instory&turbo=1
5. https://nplus1.ru/news/2019/09/16/future-magnet
6. https://www.ferra.ru/news/techlife/uchyonye-nashli-sposob-sdelat-uskoriteli-chastic-eshyo-moshnee-16-09-2019.htm
7. https://faktom.ru/34461_amerikancy_izgotovili_prototip_magnita_dlya_kollajdera_budushhego_newmelo
8. https://hightech.fm/2019/09/16/magnet-collaider
9. http://k.sina.com.cn/article_5044281310_12ca99fde02000xtl0.html?cre=tianyi&mod=pcpager_fintoutiao&loc=30&r=9&rfunc=100&tj=none&tr=9
10. http://www.xinhuanet.com/science/2019-09/11/c_138383027.htm
11. https://m.xianjichina.com/special/detail_418081.html
12. http://tiasang.com.vn/-doi-moi-sang-tao/Phong-thi-nghiem-Fermi-Dat-ky-luc-the-gioi-ve-cuong-do-tu-truong-cho-nam-cham-may-gia-toc-20614
13. https://kopalniawiedzy.pl/Fermilab-magnes-niobowo-cynowy-Wielki-Zderzacz-Hadronow-LHC-akcelerator-czastek,30716?utm_source=newsletter&utm_medium=email&utm_campaign=ft-190918
14. https://cryogenicsociety.org/37208/news/fermilab_achieves_world-record_field_strength_for_accelerator_magnet/?utm_source=newsletter&utm_medium=email&utm_campaign=ft-191003
15. https://cerncourier.com/a/accelerating-magnet-technology/

FY20-FY23 Planning Guideline (Soren)

- Some general guideline
  - Roadmaps should go out a few years and follow the "cartoon approach"
  - All major elements should have involvement of staff from at least 2 labs

- Questions to consider:
  - Cos-theta is "morphing" into the new stress-managing approach – need strong rationale
    - Does it garner best of cos-theta and CCT, or worst of both?
    - Does the development plan fully leverage MDP's experience and modeling capabilities?
    - Does the plan include steps that build confidence on "short" timescales?

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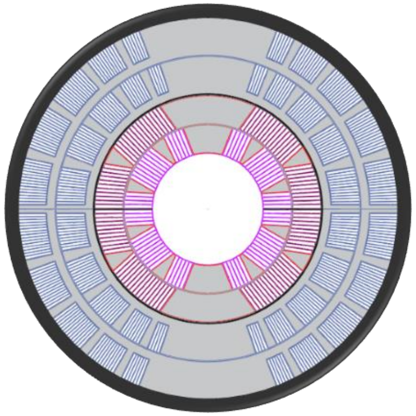
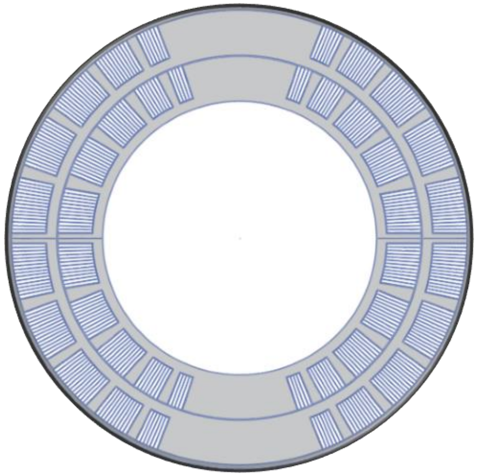
SM justification



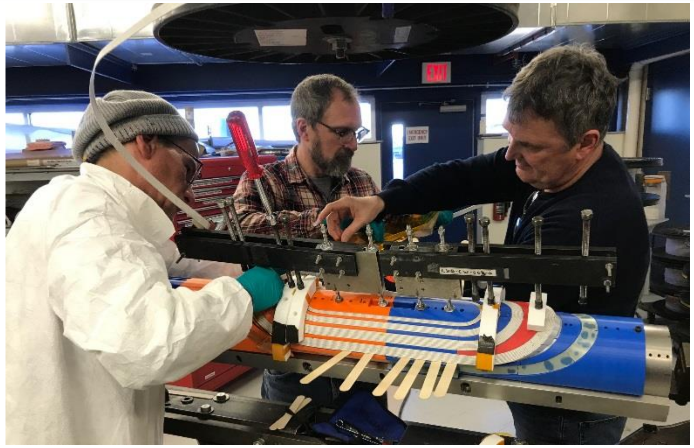
Stress management in outer layers (small aperture)



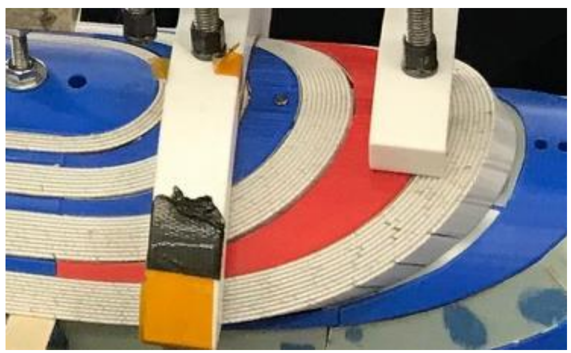
Stress management in whole coil (large aperture)

Category	SMCT vs CCT
Design	• Use of wide cables • Smaller coil volume • Shorter coil ends • Possibility of skew harmonics compensation in 2-in-1 configuration • Add SM to selected layers • Simpler and less costly coil support structure • Simpler and more reliable coil ground insulation • Use collar in the coil straight section • Simple coil length scale up
Fabrication	• Faster coil winding • No coil curing • Better axial and transverse control of cable expansion • Minimized epoxy volume (coil ends and straight section)
Instrumentation	• Use of VT, acoustic and strain gauges • Traditional strip heaters for protection
Assembly and preload	• Simpler assembly of multilayer coils • Better control of azimuthal and radial preload, and end support
Tests	• Test of half-coils in magnetic mirror configuration
Scale up	• Simpler and less expensive coil scale up

SM coil design and technology 1st demonstration



- Parts: 3D printing technology
- Winding in slots
- Room for cable expansion during reaction



FY20-FY23 Goals, deliverables, approach

Goals	Deliverables
Continue addressing MDP driving questions 1-9, special attention to magnet degradation and training	Reports, publications, presentations
Develop and demonstrate a new approach of managing the radial and azimuthal stresses in brittle cos-theta coils	Fabrication and test of 4-6 dipole coils with stress management
Demonstrate bore field up to 17 T at 1.9 K with 60-mm aperture and up to 15 T at 1.9 K with 120-mm aperture in Nb_3Sn dipole magnets with stress management	Development and test of short dipole mirror models and short dipole magnets
Develop capabilities to test cables, HTS coils and inserts, etc. for MDP and other programs	Development and test of Nb_3Sn dipole outsert magnet

- **Approach**
  - **Integrate technical expertise and capabilities of MDP participating labs**
    - **design and analysis**
    - **fabrication infrastructure and instrumentation**
    - **test facilities**
  - **Achieve fast R&D turnaround time**
    - **test up to 2 magnets /year**
  - **Minimize R&D cost**
    - **use available tooling, magnet materials and components, test facilities**

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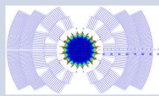
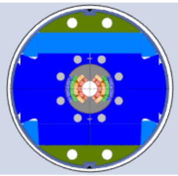
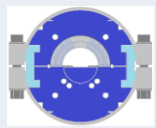
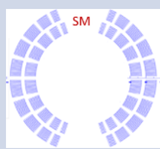
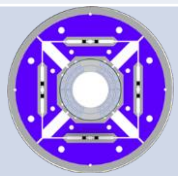
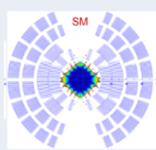
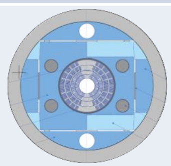
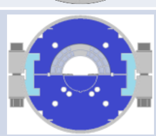
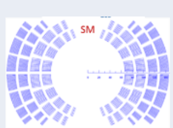
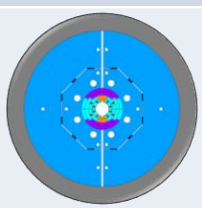
FY20-FY23 plan and outcomes

Task	Coil	Structure	FY20	FY21	FY22	FY23
Task 1. MDPCT1 re-assembly and test			Task 1.	Testing HTS coils up to 50-mm OD and cable samples in fields up to ~13 T		
Task 2. 2-layer 120-mm SM coil in dipole mirror structure	 		Task 2.	Testing HTS half-coils 120 mm OD in background fields up to 11 T		
Task 3. 2-layer 120-mm 11 T SM dipole in modified MDPCT1 or HQ2 structure	 			Task 3. Testing HTS inserts up to 120 mm OD in background fields up to 11 T		
Task 4. 4-layer 60-mm 17 T dipole in modified MDPCT1 structure	 			Task 4.	Testing HTS half-coils up to 60-mm OD up to ~15 T background field	
Task 5. 2-layer 190-mm SM coil in dipole mirror structure					Task 5.	
Task 6. 4-layer 120-mm aperture 15 T SM dipole	 				Task 6.	Testing HTS inserts up to 120-mm OD in 15 T field

R&D questions and collaboration

- **R&D questions**

FY20:
1. What is the field limit of the cos-theta design w/o SM (MDPCT1)?
2. What is the effect of the azimuthal stress manage-ment on the coil training and its quench limit?
3. What is the effect of the azimuthal + radial stress management on the coil training and its performance limit?
4. Is the mirror structure adequate to test HTS half-coils in background fields up to 11 T?

FY21:
1. What are the field limits of the 120-mm and 60-mm aperture cos-theta dipole designs with azimuthal and radial stress management?
2. What is the effect of the azimuthal and radial stress management on the dipole magnet training?
3. What are limitations of magnet support structures?
4. …

FY22:
1. Is the new mechanical structure adequate to test small HTS inserts in background fields up to 15-16 T?
2. …

FY23:
1. Is the utility structure adequate to test Nb_3Sn dipole coils with large HTS inserts in background fields up to 15 T?
2. …

- **Collaboration**
  - LBNL – mechanical analysis, mechanical structure analysis and modification, coil and magnet instrumentation, quench data analysis, HTS insert design and fabrication, HTS coil powering and QP
  - BNL – magnet test and data analysis, HTS insert design and fabrication (TBD)

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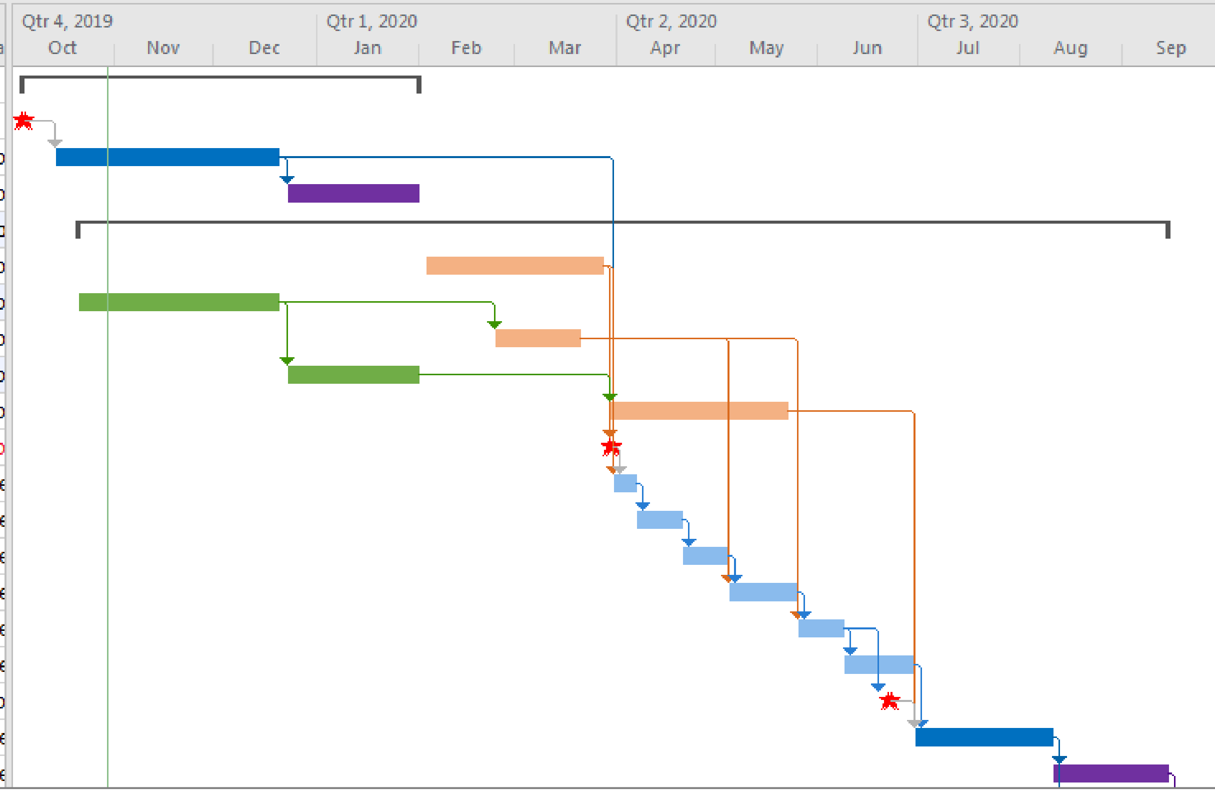
FY20 Nb_3Sn cos-theta R&D plan and schedule

Task Name	Duration	Sta
MDPCT1 re-assembly and test	86 days	Fri
reassembly review	1 day	Fri
magnet assembly	10 wks	Mo
magnet test	6 wks	Mo
SM coil fabrication and mirror test	236 days	Mo
coil part procurement	8 wks	Mo
R/I tooling modification	9 wks	Mo
R/I tooling procurement	4 wks	Mo
mirror yoke and core modification	6 wks	Mo
mirror yoke and core procurement	8 wks	Mo
coil fabrication review	1 day	Mo
cable insulation	1 wk	Tue
IL coil winding and wiring	2 wks	Tue
OL coil winding and wiring	2 wks	Tue
coil reaction	3 wks	Tue
coil impregnation	2 wks	Tue
coil instrumentation	3 wks	Tue
assembly and test review	1 day	Mo
mirror assembly and wiring	6 wks	Tue
mirror test	5 wks	Tue



The coil fabrication and mirror assembly and test schedule is based on

- the availability of coil fabrication tooling and mirror structure (only small modifications are needed)
- the previous experience with the SM practice coil fabrication and mirror magnet assemblies and tests.

Summary

Program goals:

- Explore and extend the operation parameter space for Nb_3Sn accelerator magnets
  - B_{max} from 14-15 T to 17 T,
  - coil ID from 50-60 mm to 120+ mm
  - stored energy
- Develop and demonstrate SM approach (designs, materials, technologies) for shell-type Nb_3Sn and any other brittle, stress/stain sensitive superconducting coils including HTS
- Study and optimize quench performance (training, degradation), field quality and quench protection of high-field accelerator magnets with SM
- Develop and demonstrate strong and efficient mechanical structures for accelerator magnets