Development and First Test of the US-MDP 15 T Nb$_3$Sn Dipole Demonstrator MDPCT1

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In June 2019 the HFM group at Fermilab has tested a new accelerator dipole magnet based on Nb$_3$Sn superconductor, which produced a world record field of 14.1 Tesla at 4.5 K.

Outline

- Magnet design and analysis
- Magnet technology
- Quench performance (training)
- Conclusions and next steps
• The 15 T dipole demonstrator project was initiated in 2015 at Fermilab in response to recommendations of the Particle Physics Project Prioritization Panel (P5) and HEPAP Accelerator R&D subpanel.

• In June 2016, the Office of High Energy Physics at US-DOE created the national MDP to integrate accelerator magnet R&D in the United States and coordinate it with the international effort. The project became a key task of the MDP.

• In 2017 this effort received support also by the EuroCirCol program, making it a truly International endeavor.
15 T Dipole Program Goals

- Demonstration of 15+ T field level in accelerator magnet with \( \text{Nb}_3\text{Sn} \) superconductor
- **Study and optimization of:**
  - magnet quench performance and mechanics
  - field quality
  - quench protection
  - cost optimization
15 T Dipole Design Selection

Innovative mechanical design:
- Min number of parts
- Widely available materials
- 3D clamp-iron lock
- Aluminum I-clamps
- SS 12.5mm thick welded skin
- Cold mass OD=612mm
- Criteria:
  - structural integrity, coil stress and deformation

Coil geometry:
- 60-mm aperture
- Min conductor volume
- 4-layer graded “block-cos-theta” coil
- Selection criteria: $B_{\text{max}}$, FQ, forces, protection

![Diagram of coil geometry and innovative mechanical design](image-url)
Magnet Conductor Limit

**Magnet conductor limit** for the wire $J_c(12T,4.2K)\sim 2.6 \text{ kA/mm}^2$

- $B_{ap}=15.3T \ @4.5K$
- $B_{ap}=16.7T \ @1.9K$
Magnet **mechanical design limit** is determined by the coil maximum stress and the coil turn separation from poles at 15T bore field.
MM Goals:

- Test brittle yoke and clamps
- Validate mechanical analysis, 2-3D
- Develop coil pre-stress targets

Iron Lamination Stress, MPa

Clamp Stress, MPa

SG location

margin

Iron lam stress in magnet

AL clamp stress in magnet

estimated limit

margin

Test 300Kmax, Test 77Kmax, FEA 300K, FEA 77K
Coil Components

Cable (FNAL)

L3/4 parts (FNAL)

Traces (LBNL/FNAL)

L1/2 parts (CERN contribution)

4 sets

3 sets

Ti and Cop Wedges

Ti poles and spacers, SS saddles

L2

L4
Coil winding and curing using ceramic binder

Coil reaction

Coil lead splicing, epoxy impregnation

Coil size measurement, instrumentation

Coil fabrication, measurement and instrumentation time ~3 months
Sensitivity study of $I_c$ and RRR to heat treatment parameters
• Witness sample data are close to the target $I_c$
• Good reproducibility of witness sample data for IL and OL coils
• Magnet **short sample limit**: 15.16 T @4.5K and 16.84 T @1.9K
Coil Interfaces Analysis and Optimization

L2 OD by 80 mic smaller

L3 ID by 88 mic smaller

L4 OD by 187 mic smaller

L2 OD by 96 mic smaller

L4 OD by 80 mic smaller
Coil Assembly and Preload Scheme

Yoke-Skin Radial interference

Coil-Coil Radial interface

Coil Mid-Plane shims

Shell-Yoke Radial interference

Pole-Coil boundary

Yoke-Yoke gap taper

Skin tension

Clamp-Yoke interference

2.5 mm Steel Shell

1.8 mm SS Shell

2A=3.5mil Kapton

2mil Kapton

1mil SS strip

4mil Kapton

2mil Kapton

1mil SS strip

2mil Kapton

2A=3.5mil Kapton

2mil Kapton

1mil SS strip

4mil Kapton

2mil Kapton

Coil

Mid-Plane

shims

Yoke

Yoke

radial

interference
TAC Recommendations

Report of the Technical Advisory Committee for the U.S. Magnet Development Program

February 22, 2019

Recommendations:

• Maintain as the priority for the cos-theta approach using the clamped mechanical structural design to realize a field of about 14 T, with special attention to mechanical stress management and control.

• Continue with demonstration of 15 T cos-theta performance only after the review of the 14 T magnet test results and feedback from the international workshop.
Coil stress diagrams reconstruction based on the assembly data

- Conservative coil pre-stress: $S_{\text{max}}$ at all steps < 150 Mpa
- 13T - tension starts to develop between poles and coil turns
- 14T - max tension < 30MPa
Magnet End Mechanics

- 8 30mm stainless steel rods and 2 50mm thick end plates constrain combined load from the inner and outer coils
- Axial load at 300K ~40kN per end
- Major end load at 4K applied to the inner coils
- Calculated LF\textsubscript{axial} per end at 14T 1250kN
Coil Assembly, Yoking and Skinning

Magnet assembly ~3 months
Magnet Test Preparation

Test preparation
~1.5 months
Instrumentation

- Voltage taps
- Strain Gauges skin, clamps bullets, poles, coils
- Quench antennas
- Acoustic sensors
- Thermometers

SG on inner coil ID

Traces on outer coil OD

Skin gauges location
Magnet Training Goal - 14T

- Magnet was trained at 1.9K
- Training plateau after 11 quenches
- IL quenches: 2 in coil 2
- OL quenches: 8 in coil 4
  7 in coil 5
- First quenches above 11 T
- Last quench at 4.5K:
  \( B_{\text{measured}} = -14.10 \pm 0.04 \) T
  \( B_{\text{calculated}} = -14.112 \) T
• 1-m long dipole model MDPCT1 has been developed, fabricated and first tested at Fermilab (June 2019)
• The goals of the first test have been achieved
  \[ B_{\text{max}} = 14.10 \pm 0.04 \, \text{T} \] 
  record field at 4.5 K for accelerator magnets!

Next steps:
• Magnet re-assembly
  - increase coil pre-load to achieve the goal of 15 T
  - improve instrumentation
• Magnet second test in January of 2020
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