Test Facility Dipole: Design, Status and Plan

G. Sabbi, LBNL

External Oversight Committee
January 7, 2021

Presentation Outline

1. Magnet requirements
2. Technical background: large bore, high field Nb_3Sn dipole development for HEP and FES
   - *Recent design studies and TFD approach*
3. Performance targets and optimization strategy
4. Design status: magnetic, mechanical, quench protection
5. Conductor and cable development
6. Engineering design and coil fabrication infrastructure
7. Test facility interfaces
8. Project Execution Plan: specifications, WBS, development and fabrication approach, schedule and milestones
9. Summary

Magnet Requirements

Two main sources:

- HEPdipo study (EDIPO upgrade at PSI)
- US user survey

Key US input on applied magnetic field (§2)

- "Highest possible field": ≥15 T with Nb_3Sn at 1.9 K

Test well geometry:

- Aperture: minimum 140x90 (HxV) mm (150x100 mm preferred) with superimposed round 106 mm diam.
- Uniform (1%) length: 0.6-1 m

Superimposed AC field and fast-ramped background field are not a priority

High Temperature Superconductor Cable Test Facility Specifications

Compiled by
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July 15, 2018

Based on input from key stakeholders:

- **Universities**
  - MIT: Makoto Takayasu
  - Tufts: Luisa Chiesa
- **Industry**
  - ACT: Danko Van der Laan
  - CFS: Bob Mumgaard, Brandon Sorbom
  - TAE Technologies: Dennis W. Lieurance
- **Laboratories**
  - ASC/NHMFL: Lance Cooley, Mark Bird
  - LBNL: Xiaorong Wang
  - PPPL: Yuhu Zhai
  - ORNL: Robert Duckworth

Contents

Technical Background

- The Test Facility Dipole design is based on studies and development of large aperture, high field dipoles over the past 15+ years:

  1. LARP studies of HL-LHC "Dipole First" IR *(LBNL/FNAL/BNL, 2003-04)*
  2. EFTA Dipole (EDIPO) Design Study *(EFDA/CEA/CRPP/FZK/LBNL, 2004-06)*
  3. LD1 magnet design *(2009-12)* at LBNL
  4. FRESCA2 magnet development *(CERN/CEA/EuCARD, 2010-2018)*
  5. HEPdipo design study (CERN/PSI/F4E/LBNL, 2017+)

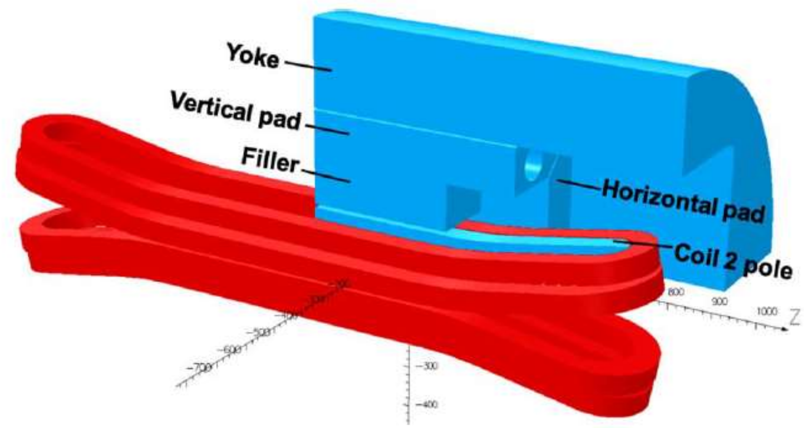
- We are taking full advantage of these efforts and experience to accelerate the TFD development and decrease risk in a broad range of areas, in particular:

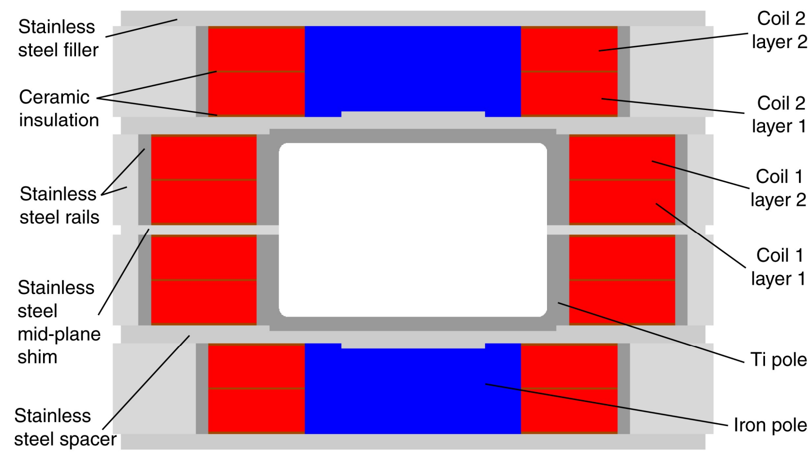
  - Winding layout and parameters (LARP, EFDA, LD1/HD, FRESCA2, HEPdipo)
  - Coil tooling, parts, and fabrication process (FRESCA2, LD/HD)
  - Magnetic, mechanical, protection analysis and validation (FRESCA2, HEPdipo)

- However, while building on this experience we are also optimizing the design to reflect the specific TFD requirements, in particular the higher field target

LD1 Design at LBNL

- Several proposals for high field cable/insert testing presented to GARD over the years
  - LD1 proposal was presented in 2009 and received strong support various HEP and AFRD Reviews
- Rectangular bore (144 x 94 mm) for insert coil testing and fusion cable compatibility
- Block-coil design was selected because of the rectangular bore and synergies with the ongoing HD2 model development (cable, coil design, fabrication processes)
- Received start-up funding from ARRA in 2010 but no follow-up funding
- Focus on large coil infrastructure (reaction oven, potting chamber) which now enables fabrication of TFD at LBNL
- Also performed magnet design, procured some components (cable, structure)





Ref. P. Ferracin et al., IEEE TASC 22(2), 2012

FRESCA2 Design Study

Goal: upgrade of FRESCA facility at CERN

- Round bore 100+ mm diameter and 13+ T field

Detailed analysis of cos θ and block design options:

- Historical review (in particular D20 and HD2)
- Optimization, analysis and comparison of magnetic and mechanical performance based on *realistic and consistent (two double-layers) designs of each type*

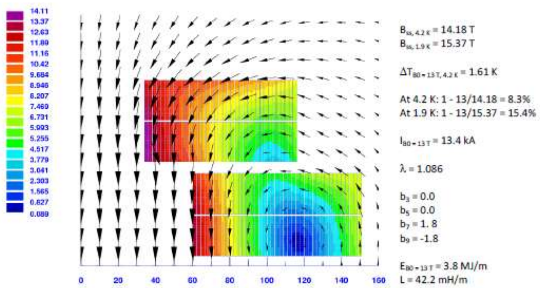


Fig. 10. Baseline block cross section (a quarter shown). The field in the coil is computed for a 13 T bore field.

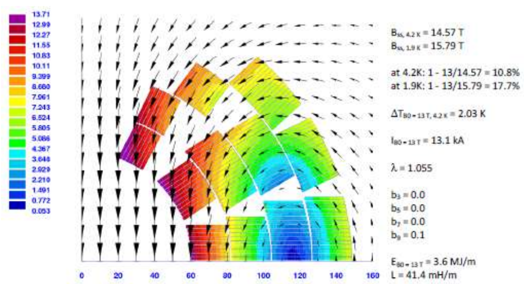


Fig. 6. Baseline cos-θ cross-section (a quarter shown). The field in the coil is computed for a 13 T bore field.

- Qualitative comparison: magnetic/mechanical aspects, end geometry, tooling parts and fabrication
- Block type layout was selected citing advantages in design and fabrication

EuCARD-REP-2010-002

EuCARD

European Coordination for Accelerator Research and Development

PUBLICATION

EuCARD-HFM dipole model design options

EuCARD-HFM, MPWG (CERN/CEA) *et al*

28 October 2010

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579.

This work is part of EuCARD Work Package **7: Super-conducting High Field Magnets for higher luminosities and energies.**

The electronic version of this EuCARD Publication is available via the EuCARD web site <http://cern.ch/eucard> or on the CERN Document Server at the following URL: <http://cdsweb.cern.ch/record/1267962

EuCARD-REP-2010-002

Magnet Pre-design Working Group:
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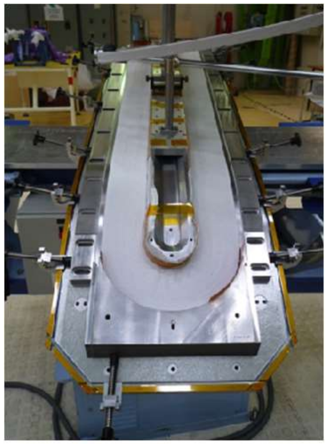
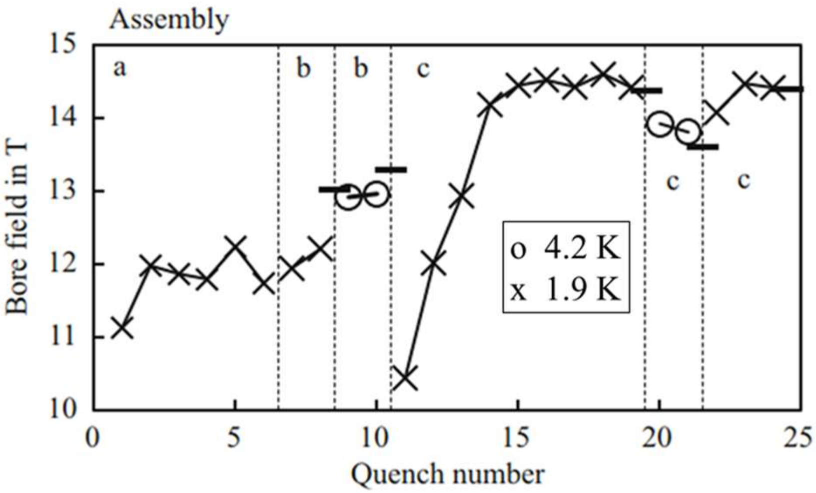
FRESCA2 Fabrication and Test Results

- Coil winding: CEA
- Coil reaction and impregnation, magnet assembly and test: CERN



Assembly	Preload	Field	Comments
FRESCA2a (2/2017)	13 T	12.2 T	Coil 3401: splice damage and QH failure
FRESCA2b (8/17)	13 T	13.3 T	Coil 3401 replaced by 3403
FRESCA2c (4/18)	15 T	14.6 T	Full re-assembly and Pre-load increase

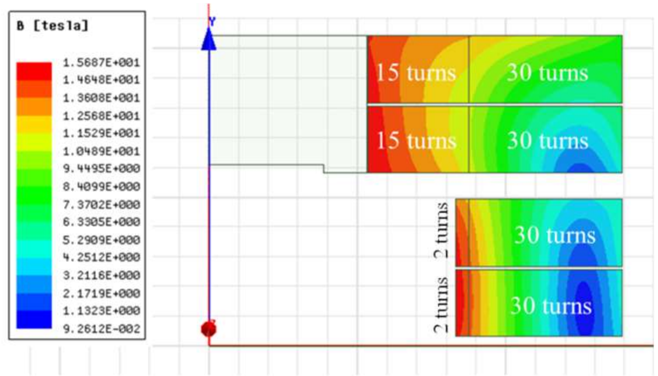


- FRESCA2 provides a solid basis for TFD design approach, performance expectations, coil tooling and fabrication processes

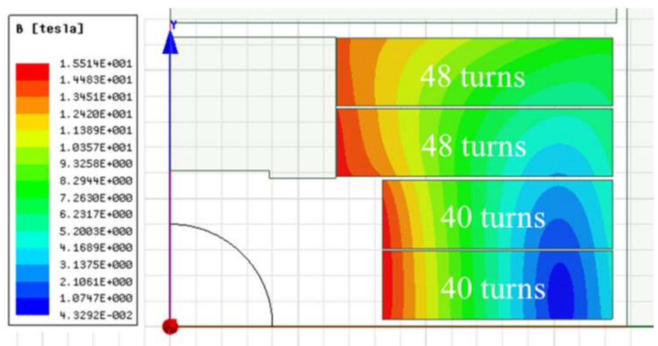
HEPdipo Conceptual Design Study (2018)

- The EDIPO magnet was irreversibly damaged in 2017 due to an unprotected quench. The facility infrastructure was not damaged
- A collaboration of PSI, CERN, F4E and LBNL was established to study a replacement of EDIPO with a higher field target (14-15 T vs. 12.4 T)
- Two main options were considered, both cases used a racetrack (block/saddle) coil layout with either an upgraded CICC or Rutherford cable
  - *Based on FRESCA2 design choice and further supported by rectangular vs. round bore*
- Field increase for CICC was found to be limited
- Both a graded and non-graded Rutherford cable option were considered: non-graded option was preferred to lower risk

Graded (A_{sc}=64 cm^2)



Non-Graded (A_{sc}=105 cm^2)



Reference: P. Bruzzone et al., "Conceptual Design of a Large Aperture Dipole for Testing of Cables and Insert Coils at High Field", IEEE TASC Vol. 28, No. 3, April 2018, Art. # 4005505

TFD Design Targets and Approach

- Field: 16 T design target with ~15% margin on the load line at 1.9 K
  - Users are interested in the highest possible field, reflected in guidance
  - Setting a 16 T goal helps fully optimize the design
  - A conservative pre-load target (e.g. 14 T) will be implemented in the first assembly cycle and optimized as needed based on test results
  - 15 T is used as reference for operation
- Coil layout: block-type, non-graded coil
  - Block-coil follows from EDIPO/LD1/FRESCA2 studies, FRESCA2 performance demonstration, and rectangular bore
  - Non-graded coil can reach 16 T at <85% SSL (1.9K) with less development time/risk
  - Field quality at the ~20 unit level for consistent comparison of options
- Coil engineering, parts, tooling and fabrication procedures will be based on FRESCA2 experience
- Larger/rectangular aperture and higher field leads to a different design optimization relative to FRESCA2
  - Mechanical performance is the main driver and determines the detailed design of the coil geometry, bore structure, inter-coil spacers etc.

TFD Design Overview

- Wire: highest J_c/I_c desired: focus on RRP 162/169 under development for FCC
- Cable: target 44 strands, 1.1 mm; alternative 48 strands, 1 mm as a backup option following FRESCA2 and HD/LD experience
- Coil layout: a non-graded coil layout was selected over graded coil after comparing performance potential and fabrication challenges
- Quench Protection: energy extraction can provide safe magnet discharge after a quench in terms of voltages and hot spot temperatures
- Mechanical optimization resulted in safe coil stresses at all steps with 16 T preload and strict criteria on allowed tension at the pole
- Two non-graded block coil layouts - "LD" and "FRESCA2" - were compared and the LD layout was selected
- Bore structural design meets aperture requirements but further optimization will be performed taking into account user feedback
- CAD models are consistent with dimensional/weight limits agreed upon with the test facility.
- A length reduction may be allowed by design optimization and user requirements

Magnetic Design

Strand parameters

Parameter	Value - A †	Value - B ‡
Wire Diameter [mm]	1.1	1.1
Cu to non-Cu ratio	0.9	1.17
Wire Architecture	RRP 162/169	RRP 108/127
C_0 [AT/mm^2]	235520	222800
α	1.0	1.0
$T_{C0}*$ [K]	17.0	17.0
$B_{C20}*$ [T]	30.0	29.3
Cabling Degradation [%]	5	5

† FCC development wire.
‡ Values scaled from the 0.85 mm HL-LHC MQXF wire to a 1.1 mm diameter.

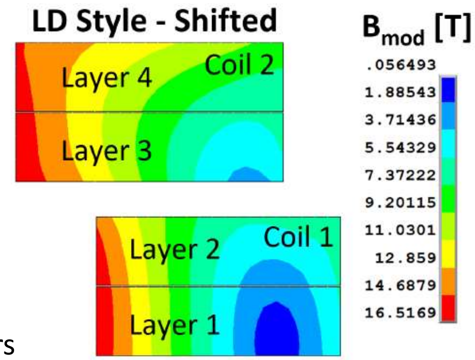
Cable parameters (*)

Parameter	Value
Number of Strands	44
Cable Width †	26.2 mm
Cable Thickness †	1.95 mm
Insulation Thickness	0.15 mm

† After heat treatment.

(*) selected for the conceptual design optimization. A cross-section iteration will be performed with final parameters

Coil layout and field map

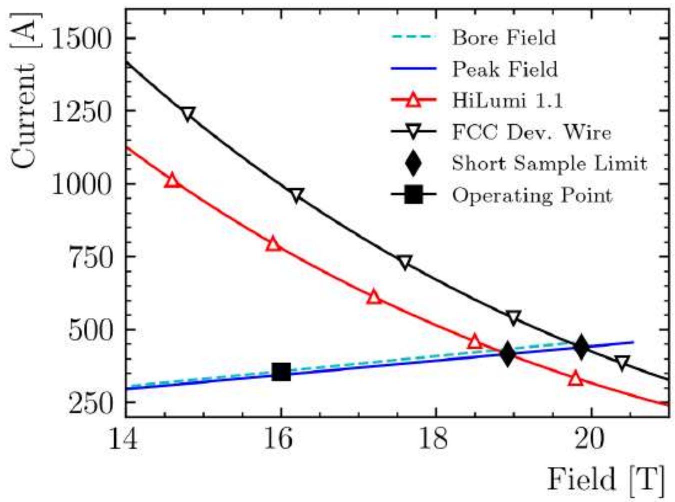


Performance parameters at 16 T

Parameter	Shifted	Aligned
Operating Current	15.6 kA	15.5 kA
Short Sample Current	19.2 kA	19.1 kA
Load Line Margin	81.2%	81.0%
Max Field (coil 1)	16.5 T	16.5 T
Max Field (coil 2)	16.1 T	16.0 T
Stored Energy (per quadrant)	1.8 MJ/m	1.8 MJ/m
Total Fx (inner)	6.3 MN/m	6.3 MN/m
Total Fy (inner)	-2.7 MN/m	-1.8 MN/m
Total Fx (outer)	10.0 MN/m	9.6 MN/m
Total Fy (outer)	-6.9 MN/m	-7.6 MN/m

Field quality: < 0.2% at 50 mm radius

Short sample limit



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Quench Protection Analysis

Quench protection study parameters:

- Analysis performed with STEAM-LEDET
- Current: 15.5 kA
- Detection + validation time: 15 ms
- Voltage limit: ±1 kV with symmetric ground
- Dump resistor: 130 mΩ (2 kV) – 75 mΩ (1 kV)
- Options with and without CLIQ
- CLIQ parameters: 40 mF, 600 V (AUP unit)
- No Quench Heaters

Conductor parameters:

Material	Nb_3Sn
Strand diameter	1.1 mm
Number of strands	44
Bare width	26.2 mm
Bare heigth	1.95 mm
Insulation thickness	0.145 mm
RRR	100
Cu/NCu	0.8 (min) – 1.17 (max)
C_0 for J_c (Summers fit)	255230 AT/mm^2

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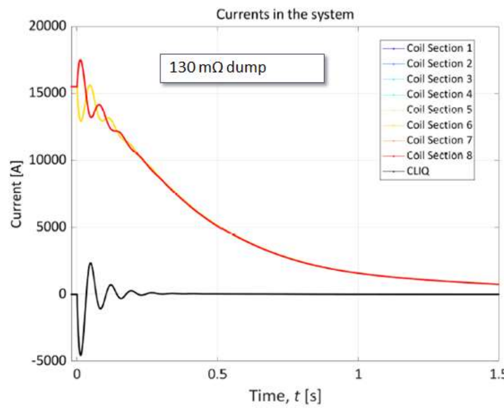
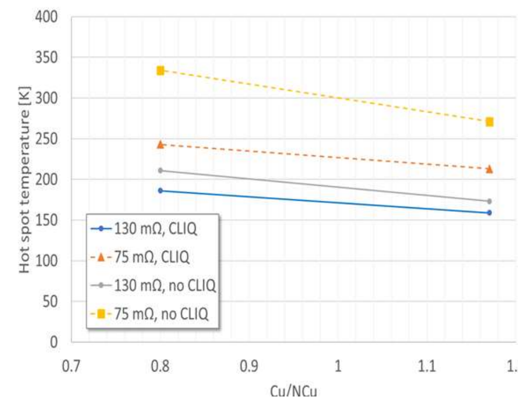
Current decay, energy extraction and hot spot temperature





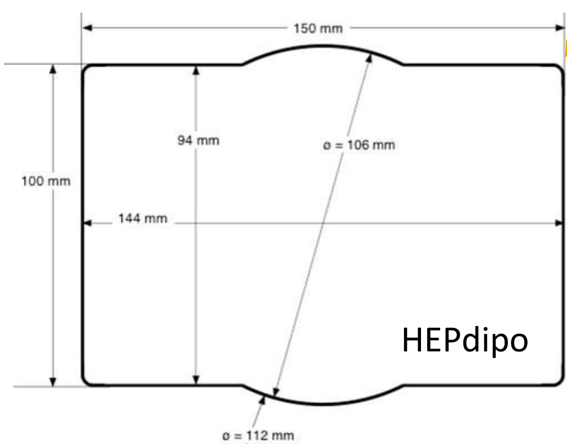
Case	Energy extracted [%]	Energy extracted [MJ]	Energy in magnet [MJ]
130 mΩ, CLIQ	65	7.6	4.4
130 mΩ, no CLIQ	72	8.4	3.6
75 mΩ, CLIQ	40	4.7	7.3
75 mΩ, no CLIQ	48	5.6	6.4

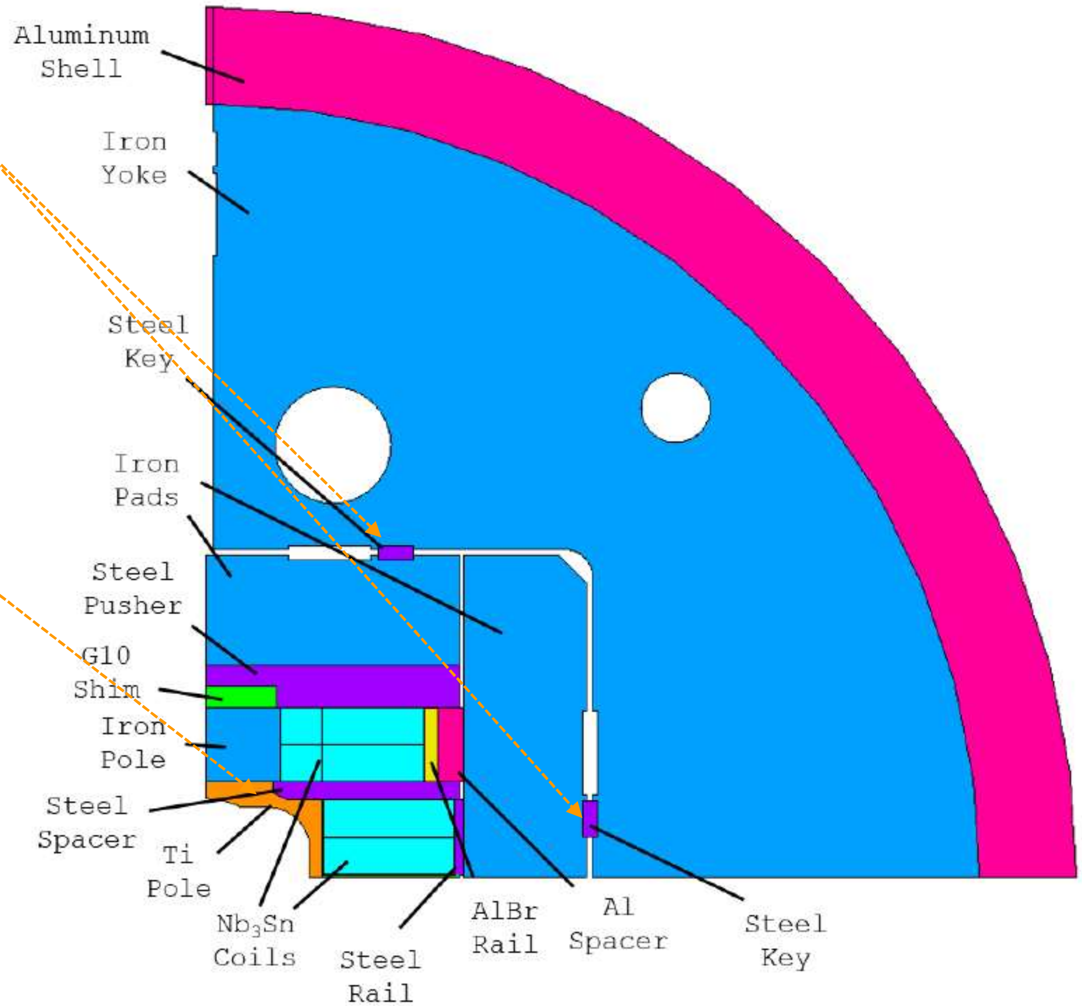
Case	Hot Spot Temperature [K]	Peak voltage to ground [kV]
Only 130 mΩ dump (reference)	173	1
600 V, 40 mF CLIQ	159	2
Reverse CLIQ polarities	171	1

Mechanical Design

Design features to control the coil stress:

- Key position defined to limit the max. tension at the pole/coil interface
- Al. bronze rail with Al shim
- Inner and outer coil individually shimmed
- 30 mm radius of the inner pole and G10 shim above the pole
    - Reduces stress in the pole
    - Limits the pole bending, reducing the tension 'spikes' at the pole/coil
    - May be reduced with further design optimization





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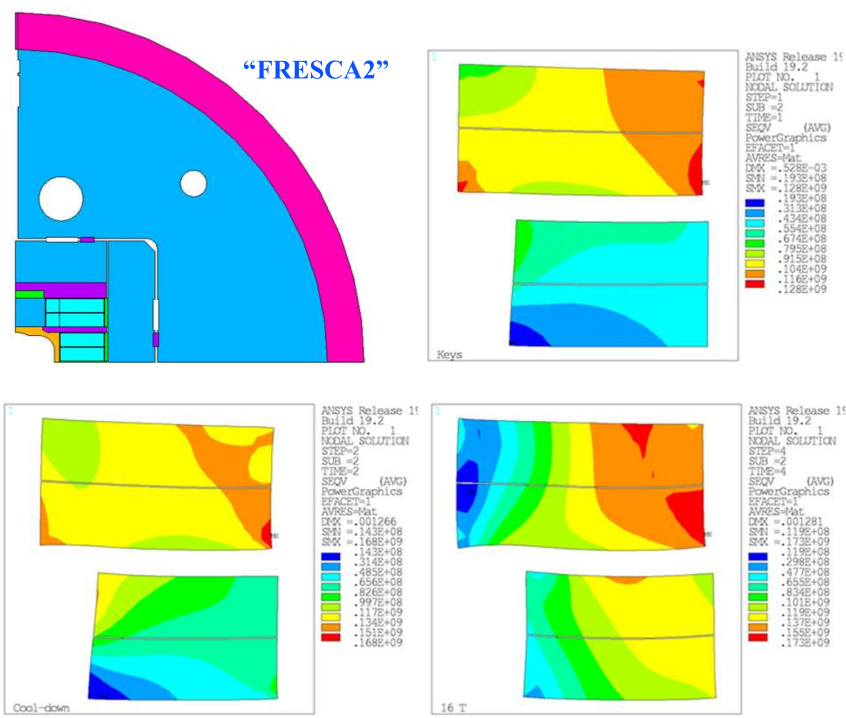
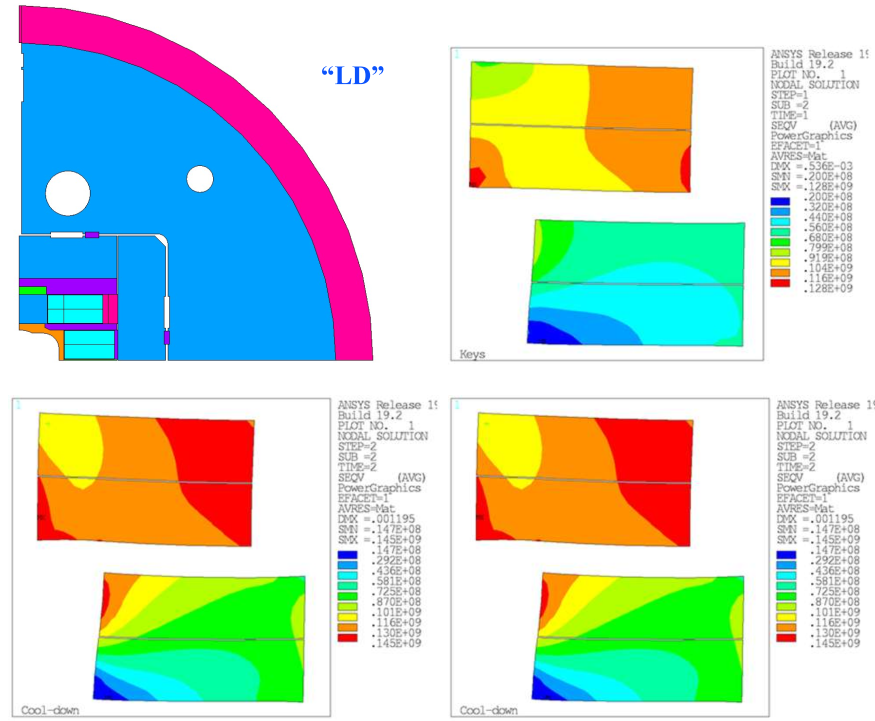
Mechanical Analysis (2D)

Using stringent design criteria on maximum pole-coil tension and material limits





- Max stress at R.T.: 128 MPa
- Max stress at cold: **168 MPa**
- Max stress at 16 T, in high field region: 122 MPa
- Max stress at 16 T, in low field region: **173 MPa**

- Max stress at R.T.: 128 MPa
- Max stress at cold: **145 MPa**
- Max stress at 16 T, in high field region: 131 MPa
- Max stress at 16 T, in low field region: **166 MPa**

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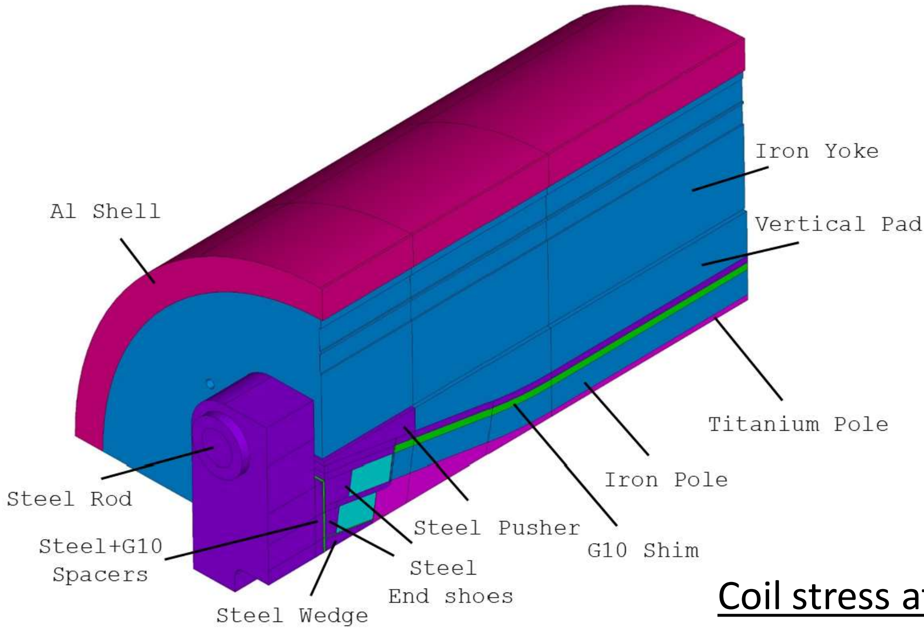
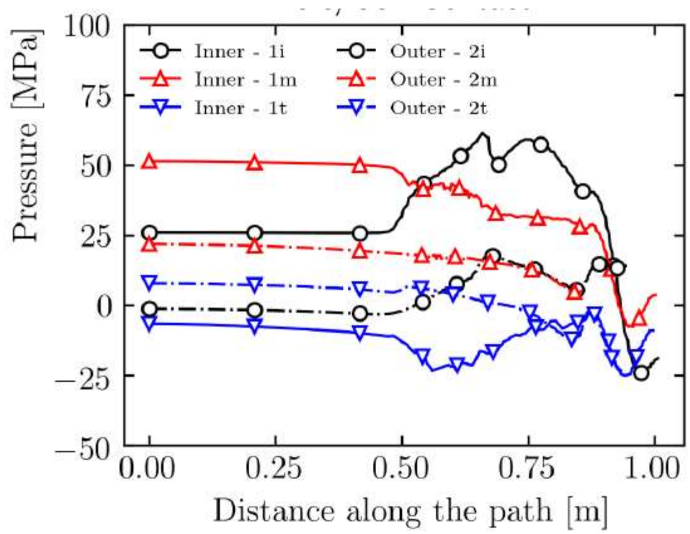
3D Design and Analysis

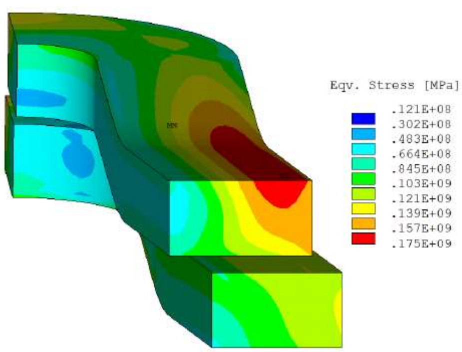
3D Design and Components



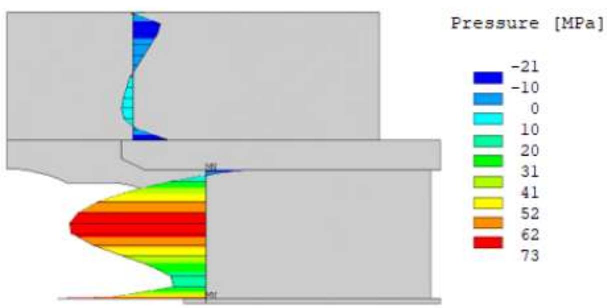
Contact pressure at coil/pole (16 T)



Coil stress at 16 T



Contact pressure at center (2D, 16 T)



3D Field

- Magnetic length: 1.7 m
- Field homogeneity: <1% over 1 m

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Conceptual Design Review Feedback (6/20)

Requirements and interfaces

- Clarify magnet and facility requirements and get stakeholder approval

Conductor and cable:

- Some preference for higher sub-element design for stability in large diameter wire
- Consider a cable with more strands (48 vs 44) and a smaller wire (1 mm vs. 1.1 mm)

Magnet design:

- Alternatives have been properly considered and selected design minimizes risk
- Main elements of the design fully endorsed by the committee: block coil, non-graded layout, shell-based structure
- Consider increased margin to quench (conductor properties and magnetic design)
- Consider increased shell thickness for margin (relative to using LD1 shell)
- Include CLIQ protection system for added robustness and redundancy

Design tools, resources and collaboration:

- Team expertise and analysis capabilities are fully adequate
- Continue strong collaboration with FRESCA2/HEPdipo teams and US conductor Labs

CDR follow-up and recent progress

Interfaces between magnet and facility:

- Focus on quench protection analysis, mechanical interfaces between magnet and cryostat, design optimization to control magnetic forces due to fringe fields

Conductor and cable:

- Protection analysis results allow to confirm selection of the 169 sub-element design
- Received 3 km of 169 strand from CERN for preliminary cabling studies
- Development cable run completed and characterization effort starting
- Started procurement of ~200 kg of strand for first practice coil

Magnet design

- Use of 169 conductor with 0.9 copper ratio allows to increase margin to quench by about 3%, addressing review recommendation without increasing coil volume

Project planning:

- Revised development plan and schedule to reflect post-CDR baseline
- In progress: budget revision to match the updated plan

Cable Development

- First TFD cable run ("development cable") was completed in November 2020
- Using 3 km of RRP 108/127 wire procured by LBNL, and 3 km of 162/169 wire procured by CERN (sufficient for about 60 m of cable for each type)

Nominal cabling parameters

Parameter	Unit	Value
Number fo strands		44
Width	mm	26.0
Thickness	mm	1.9
Keystone angle		0
Transposition pitch	mm	155
Planetary ratio		-.57:1

Parameter ranges considered

Parameter	Unit	Min	Max
Number of strands		43	44
Cable width	mm	25.7	26.3
Cable thickness	mm	1.85	2.05
Transposition pitch	mm	125	185
Planetary ratio		-1:1	0

- 108/127 used for initial feedback and broader exploration of parameter space
- Tests performed: residual twist, winding properties, micrographs

- Four longer sections with different width and thickness made with 162/169

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Conductor and Cable: Next Steps

Sample distribution for cable 1302 (162/169 wire)

Sample ID	Total length	Dimensions	LBNL	FNAL	CERN
Unit	[m]	[mm]	[m]	[m]	[m]
1302-A	20	1.93 x 25.9	7.5	2.5	10
1302-B	15	1.91 x 25.9	5	2.5	7.5
1302-C	10	1.91 x 26.1	3.5	2.5	4
1302-D	10	1.89 x 26.1	3.5	2.5	4

Virgin strand samples for reference (162/169 wire)

Sample length	Number of samples				
[m]	Total	LBNL	FNAL	NHMFL	CERN
2.5	44	18	8	10	8

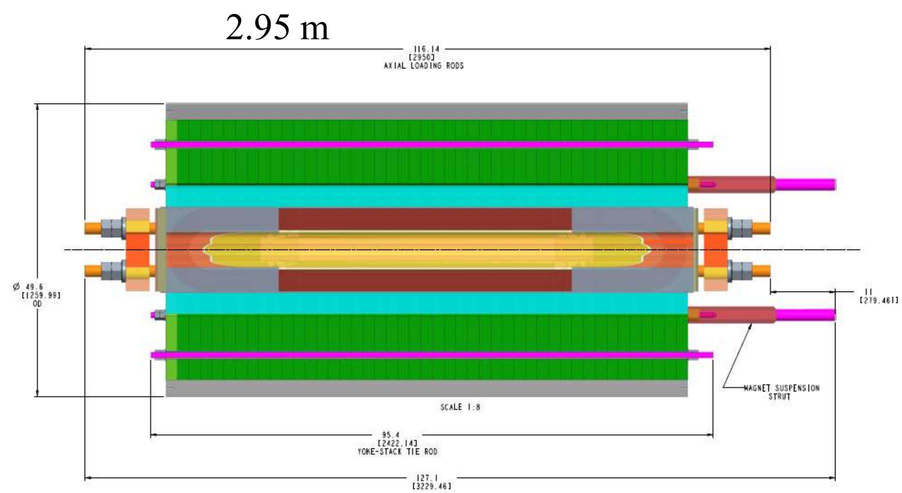
Cable characterization plan

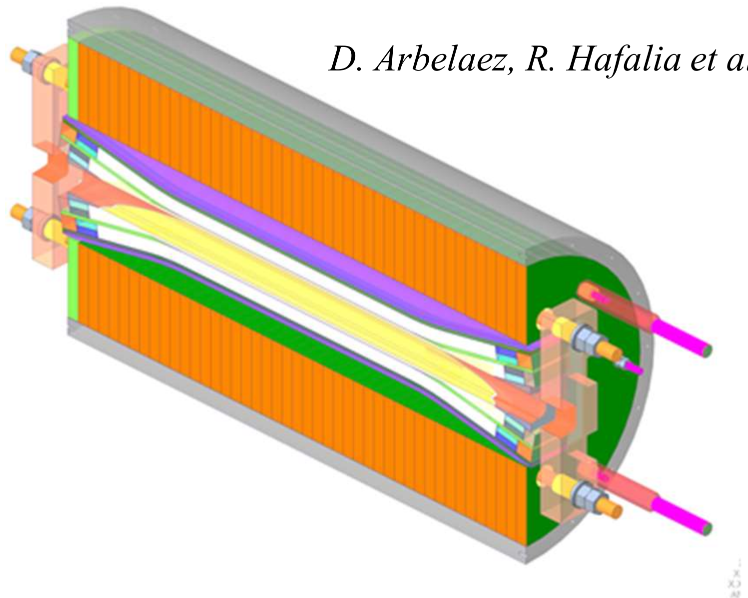
Test	LBNL	FNAL	NHMFL	CERN
Coil winding, bending profile	X			X
Micrographs	X			X
Expansion after reaction	X			X
Insulation (braiding)	X			X
10-stacks	X			X
Ic @ 4.2 K (RS+XS, HT1+HT2)		X		X
RRR (RS+XS, HT1+HT2)		X		X
Ic @ 1.9 K (RS+XS, HT1+HT2)		X		X
Is @ 1.9 K (XS, HT1+HT2)		X		X
Strain sensitivity (HT1+HT2)			X	

- We expect to complete the cable characterization by the end of March
- Followed by external review of conductor specification for production orders
- In the meantime, a specification has been developed (based on CERN FCC) and internally approved for the “prototype” cable (full length, final parameters)
- Procurement of 200 kg of wire for prototype cable has started (issued solicitation, order not yet placed)
- Prototype cable will be used for first practice coil

Engineering Design and Coil Tooling

- Preliminary CAD models are being implemented in support of magnet design and test facility interfaces
- Upgrade coil winding infrastructure to allow transverse mounting of the baseplate
- Re-commissioning of reaction oven and potting tooling in a new location may be required





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Test Facility Interfaces and Specifications

FERMILAB APS-TD/MS	High Field Vertical Magnet Test Facility (VMTF) FNAL-LBNL Interface Document (Mechanical)	Doc. No. ED0012168 Rev. No. 1.4 Date: 6/4/2020 Page 1 of 6

FERMILAB
APS-TD
Magnet Sector

HFVMTF
FNAL-LBNL Mechanical Interface Document

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- Discussions between LBNL and FNAL teams are ongoing as the design of magnet and facility is in progress
  - Mechanical interfaces (magnet dimensions, weight, supports)
  - Electrical interfaces (powering, instrumentation, protection)
- **Interface document is capturing current status and will evolve in a formal agreement as the design matures and is finalized**

Table 1 HFVMTF Dimensions

	HFVMTF	**VMTF (for Reference)**
LHe vessel – ID of upper part (above lambda plate)	57.118 in	28 in
LHe vessel – ID of lower part (below lambda plate)	55.118 in	28 in
Sidearm HX – OD of bellows	8 in	6.8 in
80 K shield - OD	70 in	39 in
Vacuum vessel - OD	73 in	42 in
Vacuum vessel top plate feet – bolt circle (BC) diameter	85 in	54 in
Vacuum vessel top plate - OD	87 in	56 in
Distance between LHe vessel centerline and sidearm HX centerline	TBD	18.88 in
Distance between LHe vessel centerline and centerline of 80 K shield and vacuum vessel	TBD	4.06 in

Table 2 Magnet Parameters – Interface by the Cryostat

Specification	**Value**	**Approved by FNAL**	**Approved by LBNL**
Magnet Shell Outer Diameter not larger than	1.3m	yes	yes
Total Magnet Length	3.1 m	See Note 2 and 3	Preliminary
Total Magnet Weight	20000 kg	yes	Preliminary
Magnet Stored Energy	20 MJ	Under discussion	Preliminary

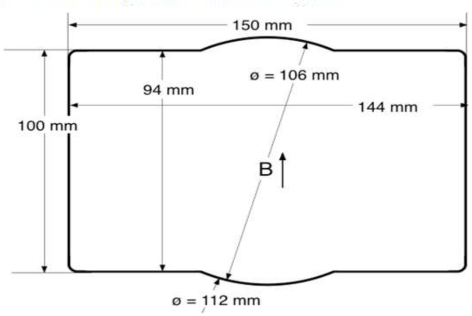
Preliminary Project Execution Plan

- A preliminary project execution plan was submitted to DOE
- Following the guidelines and structure for 413.3b projects
- DOE feedback: ok but simplify in some areas to allow more flexibility in project execution and reduce cost (e.g. key performance parameters, financial reporting, management structure)

Table 1. Preliminary Key Performance Parameters and Design Parameters

System	Parameter	KPP	
		Threshold	Objective
Cold mass	Central field	15 T @ 1.9K	16 T @ 1.9 K
Cold mass	Field quality (transverse) at high field	<1% at 40 mm radius	<0.1% at 40 mm radius
Cold mass	Length of 1% uniform field	70 cm	100 cm
Cold mass	Length of 0.1% uniform field	35 cm	50 cm
System	**Parameter**	**Design Value or Range**	
Cold mass	Operating Current	<20 kA	
Cold mass	Weight	<25t	
Cold mass	Stored energy at 15 T	<20 MJ	
Test well (*)	Horizontal aperture at vertical mid-plane	144 mm	
Test well (*)	Vertical aperture at horizontal mid-plane	106 mm	

(*) Note: the test well transverse profile is optimized for both structural support and compatibility with test sample geometry. A preliminary profile is shown in Fig. 1. Further optimization at the round corners is expected in conjunction with the magnet mechanical analysis.



Preliminary Project Execution Plan
for the
High Field Test Facility Dipole (HF-TDF) Project
at Lawrence Berkeley National Laboratory

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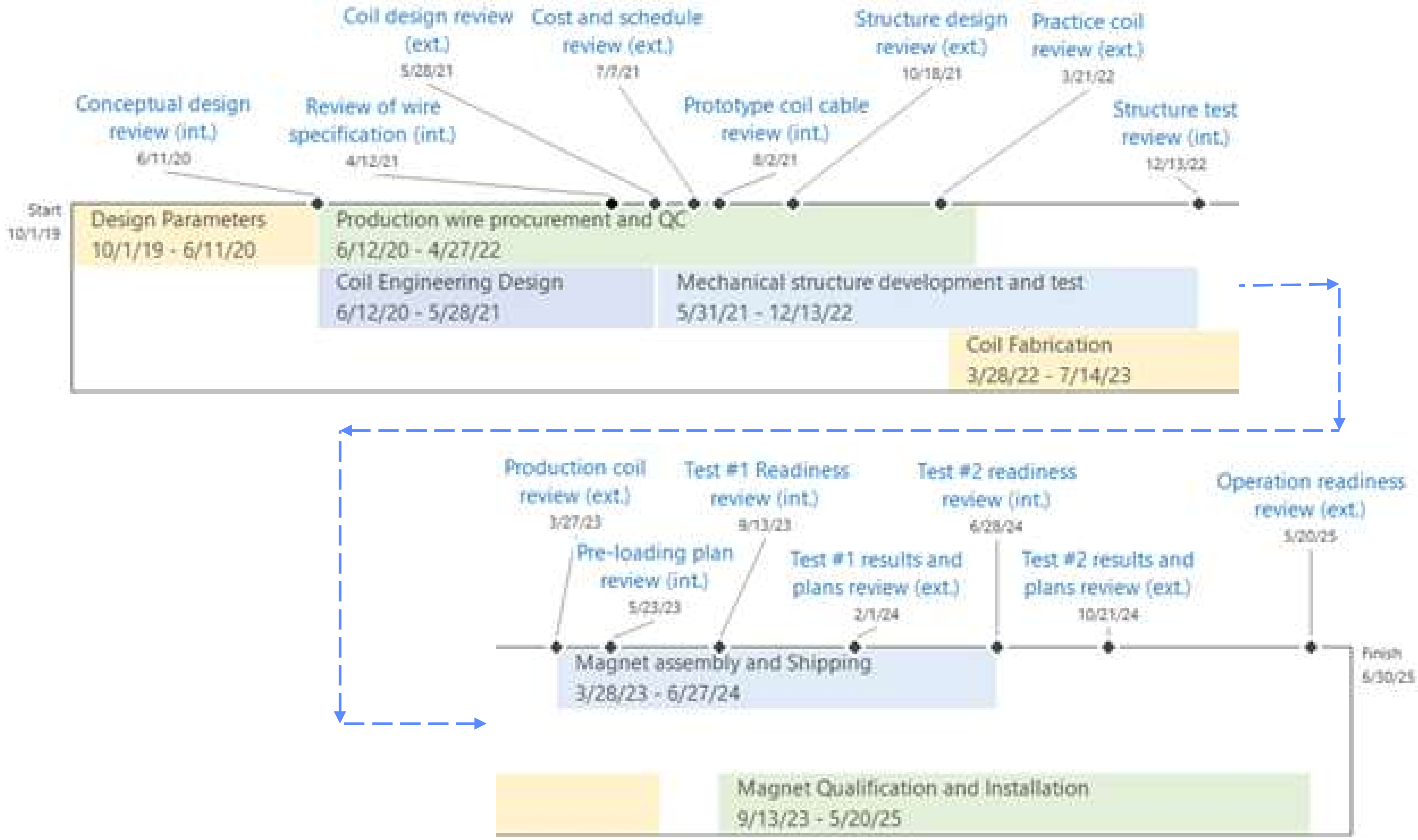
Preliminary Work Breakdown Structure

WBS	WBS Title	WBS Description
1.1	**Project Management**	Provide labor resources for Project Management, Engineering, Project Controls, Finance, ES&H, Quality, Risk, and Procurement.
1.2	**Test facility integration and coordination**	Define mechanical and electrical interfaces between magnet and test facility to ensure a successful qualification test, followed by final installation and operation in the high field test facility.
1.3	**Preliminary Design**	Evaluation of design alternatives for wire, cable, coil geometry, and mechanical structure. Fabrication of prototype cables using representative strand, and selection of the cable and magnet parameters to achieve an optimal balance of performance, cost and schedule. Preliminary magnetic, mechanical and protection analysis to ensure that the key parameters are within established limits so that that target performance can be achieved.
1.4	**Engineering design**	Based on the conceptual design, refine all details of the coil and structure, and the magnet assembly plan. Transition from physics models (e.g. TOSCA, ANSYS etc.) to engineering CAD models to be used as a basis for the design and procurement of individual parts and tooling, and to define the magnet assembly process ensuring its viability at each step. Engineering design (e.g. drawing packages) of components not included
1.5	**Wire specification and procurement**	Develop and approve specification of wire design and performance requirements. Place contracts for wire procurement, including tests to be performed by the vendor prior to shipping. Monitor wire production and address any issues that might arise. Evaluate results of vendor's test, approve shipping, and receive wire. Performing additional verification and optimization of electromagnetic properties at LBNL, in particular Ic and RRR. Specify coil heat treatment schedule.
1.6	**Cable Fabrication, characterization and insulation**	Fabricate cable for two copper coils, two practice coils, four production coils and two spare coils. Depending on wire piece length, multiple cable ULs may be combined in a single run. Task activities include strand mapping based on available inventory, re-spooling and mounting, cabling run and QC. Cable insulation is expected to be performed by an external vendor. A fiberglass braid will be installed on the cable following established processed for Nb3Sn cables.
1.7	**Coil Parts, Materials, and Tooling**	Design and procurement of parts for the fabrication of 10 coils (five inner double-layers and five outer double-layers). Coil parts include poles, base and top plates, end wedges, side rails, layer transition and splice supports, consumable materials (ground insulation, binder, and epoxy), instrumentation (traces, voltage taps, strain gauges, wiring). This task includes engineering drawings and specifications, placing contracts, monitoring production, analysis of qualification tests prior to shipping, performing additional qualification tests on receiving, and storing prior to coil production. Design and procurement of winding tooling. This task includes engineering design/drawings and component specifications; placing contracts; monitoring production; analysis of qualification tests prior to shipping; additional qualification tests on delivery, and tooling assembly at LBNL. Design and procurement of reaction/impregnation tooling. This task includes engineering drawings and specification, placing contracts, monitoring production, analysis of qualification tests prior to shipping, additional qualification tests on delivery, and tooling assembly at LBNL.
1.8	**Coil Fabrication**	Fabricate two copper coils, two practice coils, four production coils and two spare coils. Major steps are winding, curing, reaction impregnation and instrumentation. The copper/practice coils will further develop the winding and impregnation procedure but focus on the reaction process in particular provisions for coil dimensional changes and avoiding any damage to the conductor. The production and spare coils will focus on product uniformity and detailed QA at all steps.
1.9	**Structure Fabrication and Pre-assembly**	Procurement of structure components (shell, yoke, masters, pads, axial support components, keys, strain gauges and wires). This task includes engineering drawings and specifications, placing contracts, monitoring production, analysis of qualification tests prior to shipping, additional qualification tests on delivery. Pre-assembly of laminations to be performed at either the vendor or LBNL. Install strain gauges on shell; perform shell-yoke sub-assembly. Procure dummy coil pack, insert in structure, pre-load and perform a cool-down test. Analysis of results.
1.10	**Magnet assembly and shipping**	Planning and supervision of the magnet vertical tests to be performed at Fermilab, and analysis of the test results in collaboration with the Fermilab team. Support of the final installation in the high field facility
1.11	**Magnet qualification**	Planning and supervision of the magnet vertical tests to be performed at Fermilab, and analysis of the test results in collaboration with the Fermilab team. Support of the final installation in the high field facility

Magnet Development and Fabrication Plan

- The TFD plan follows the approach used in similar high field magnet programs and projects (e.g. LARP/QXF, FRESCA2)
- In particular, significant resources are allocated to magnet development and production phase has built-in "scope" contingency to mitigate risk
- Development (~46% of total project cost):
  - Conceptual design and analysis
  - Cable development and characterization
  - Nb_3Sn practice coils
  - A magnet assembly and cool-down using instrumented aluminum coils to verify design calculations and strain gauge instrumentation
- Production (~36% of total project cost)
  - Coil fabrication (two inner and two outer), magnet assembly and test
- Scope contingency (~18% of total project cost, ~51% of production cost):
  - One set of spare coils (one inner and one outer double-layer)
  - Two complete cycles of assembly and vertical test to allow for an adjustment of pre-load and/or replacing one or two coils with spares.

Magnet Schedule



Summary

- Magnet specifications, performance targets and test facility interfaces have been defined and documented
  - Some key design parameters (e.g. magnet length) still need to be finalized with user/EOB feedback and detailed engineering design and optimization
- We are taking full advantage of the extensive technical background provided by previous design and development of large aperture, high field Nb_3Sn dipoles
  - Analysis and comparison of different design options
  - Design of coil parts, tooling, and fabrication processes
  - Support structure
- Building on this past work, we have been able to make further improvements in critical areas, particularly regarding coil stress
  - 16 T pre-load under strict design criteria on allowed tension
  - < 150 MPa at cool-down (near pole); < 170 MPa at 16 T (in the low field area)
- First cabling run completed and characterization effort starting
- Design is sufficiently advanced to support detailed project plan, schedule and cost