Magnet Design and Conductor Requirements

G. Sabbi, LBNL

TFD Wire Specification Review
October 28, 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, design drivers, main features and optimization strategy
4. Magnet design: cable and coil parameters, magnetic, mechanical, quench protection
5. CDR feedback and follow-up
6. Wire and cable development and characterization
7. Summary

Test Facility Dipole 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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With guidance from
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Massachussetts Institute of Technology

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 design fabrication and test *(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 (HD/LD1, FRESCA2, HEPdipo)
    - Wire and cable parameters
  - 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

FRESCA2 Design and Development

Goal: upgrade of FRESCA facility at CERN

- Round bore 100 mm diameter; 13-15 T field
- *Block-coil design after detailed analysis and comparison with cosθ:*

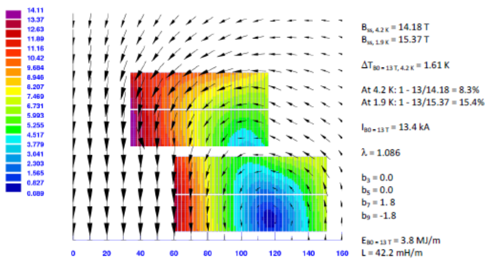


Fig. 10. Baseline block cross section (a quarter shown). The field in the coil is computed for a 13 T bore field.

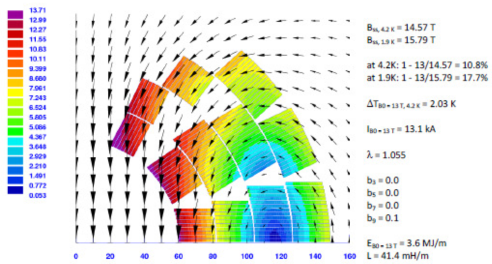
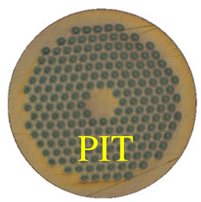


Fig. 6. Baseline cos-θ cross-section (a quarter shown). The field in the coil is computed for a 13 T bore field.

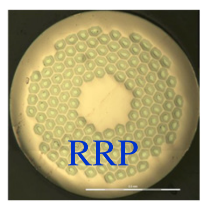
Wire:

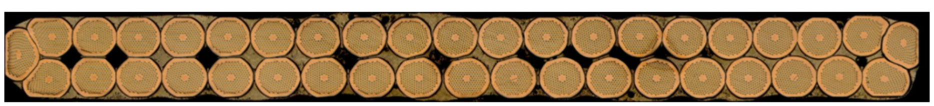
- *RRP (132/169) and PIT (192)*
- *Strand diameter: 1 mm*



Cable:

- *40 strands*
- *W 20.90 mm T 1.82 mm (bare)*
- *Braided insulation 0.16 mm*

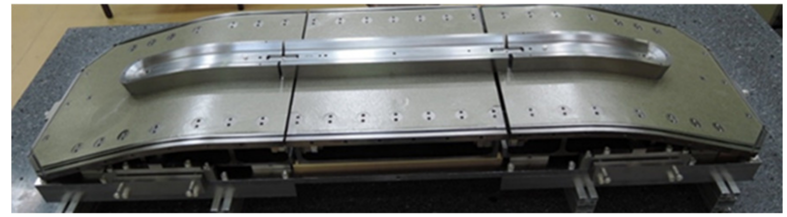


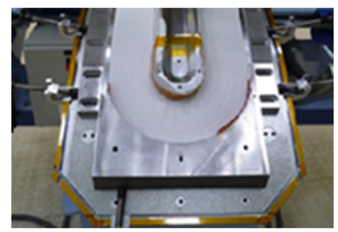


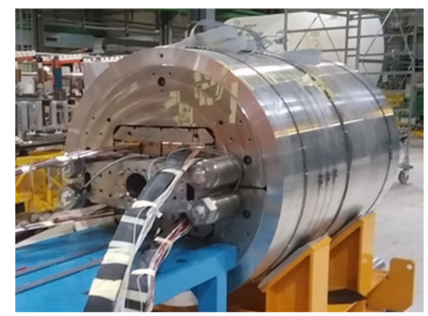
Magnet fabrication:

CEA: coil winding; CERN: coil reaction and impregnation, structure/assembly

- Included axial gaps for coil reaction







Test results:

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

HEPdipo Conceptual Design Study (2018)

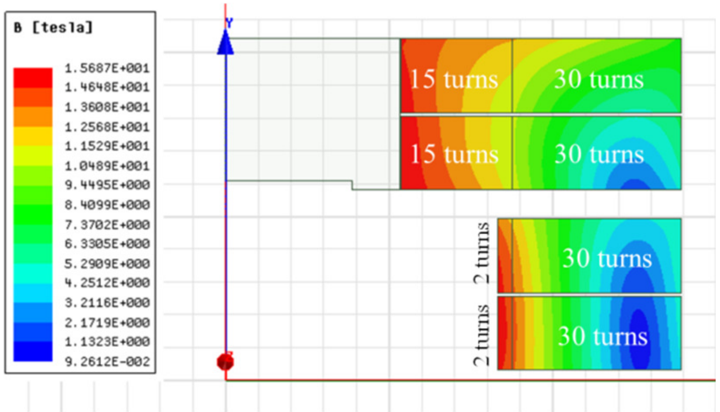
Design goals and features:

- EDIPO replacement/upgrade with 14-15 T field
- Block-coil based on FRESCA2 design choice and further supported by rectangular vs. round bore
- Considered both graded and non-graded coil

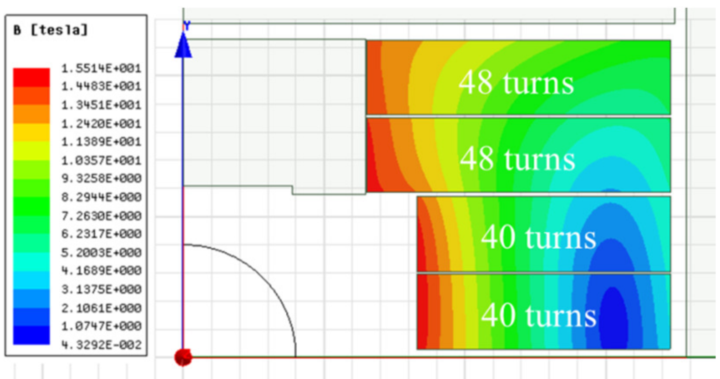
Wire and cable:

- Wide cable (>26 mm) required by vertical aperture with 4-layer (two double-layers) block-coil layout
- Large wire diameter (>1mm) required to keep aspect ratio within established limits (HD2)
- Use of existing wire/cable (LD1, QXF) considered for the graded design
- Converged on non-graded design and "DEM 1.1" wire (CERN/FCC procurement) w/ 44 strand cable
- Protection analysis showed low copper ratio is ok

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 <u>design</u> target with >15% margin on the load line at 1.9 K
  - Based on user's interest we fully optimize the design for the highest field
  - 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 based on EDIPO/LD1/FRESCA2, and rectangular bore
  - Non-graded coil compatible with target and reduces development time/risk
  - Field quality target at the ~20 unit level for consistent optimization
- Coil engineering, parts, tooling and fabrication procedures based on FRESCA2
  - *Some improvements required for reaction gaps design/implementation*
- Mechanical design: shell based structure with axial pre-load (HD, LD, FRESCA2)
  - Mechanical performance was the main driver in the design optimization including coil geometry, conductor, bore structure, inter-coil spacers etc.
  - Mechanical optimization is specific to TFD due to larger/rectangular aperture and higher field relative to FRESCA2 and HEPdipo

TFD Design Features and Optimization

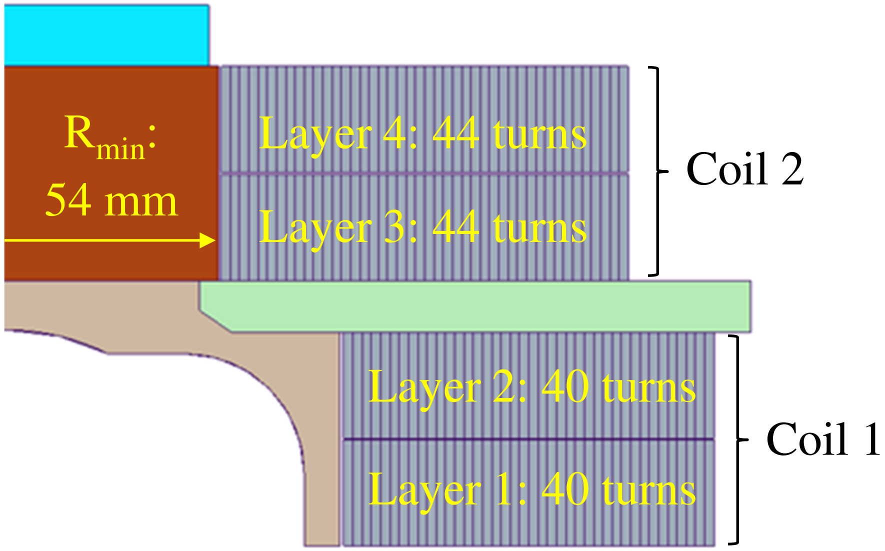
- Wire: RRP 162/169 based on field/margin requirements, design analysis and procurement experience (~50 km CERN/FCC and ~20 km TFD prototype coil)
- Cable: 44 strands, 1.1 mm based on HEPdipo/TFD studies and experience with TFD development cable fabrication and characterization
  - An alternative 48 strands, 1 mm diam. was presented to the CDR as a backup option but is not being pursued given the good results obtained
- Coil layout: block-coil, non graded, two double-layers with "LD" geometry
  - L3-L4 are shifted toward the pole relative to L1-L2. Selected over the "FRESCA2" (aligned) layout because of lower coil stress (magnetic efficiency is similar)
- Coil design: cross-section and length optimized for minimum conductor volume
  - Length of cable in each coil: 352 m (L1-L2); 365 m (L3-L4)
- Mechanical design: safe coil stresses at all steps and all structural components within established limits with 16 T preload
- Quench Protection: energy extraction is sufficient for safe magnet discharge
  - CLIQ included in the baseline plan for redundancy, but no quench heaters

TFD Cable and Coil Design Parameters

Cable and Insulation

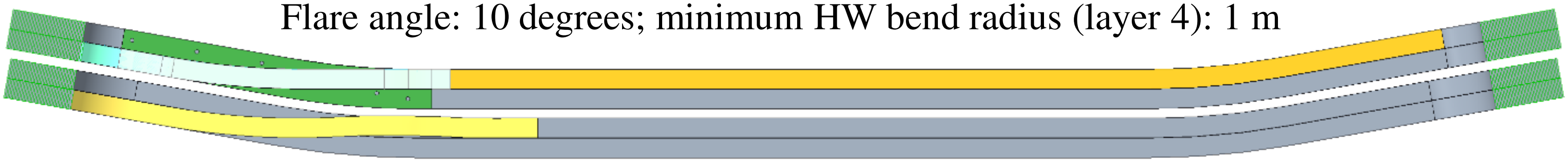
Parameter	Unit	Value
Strand diameter	mm	1.1
No. strands		44
Cable width (bare, before reaction)	mm	26.2
Cable thickness (bare, before reaction)	mm	1.91
Cable width (bare, post-reaction)	mm	26.46
Cable thickness (bare, post-reaction)	mm	1.99
Cable insulation thickness	mm	0.185
Inter-layer insulation thickness	mm	0.4

2D Coil geometry



3D Coil geometry

Flare angle: 10 degrees; minimum HW bend radius (layer 4): 1 m



Reference: TFD Coil and Structure Parameters, DF-1000-4369, A.4, 2021-10-22

<u>*Note*</u>*: parameters are still being adjusted as we get feedback from design, analysis and development*

Magnetic Design and Performance

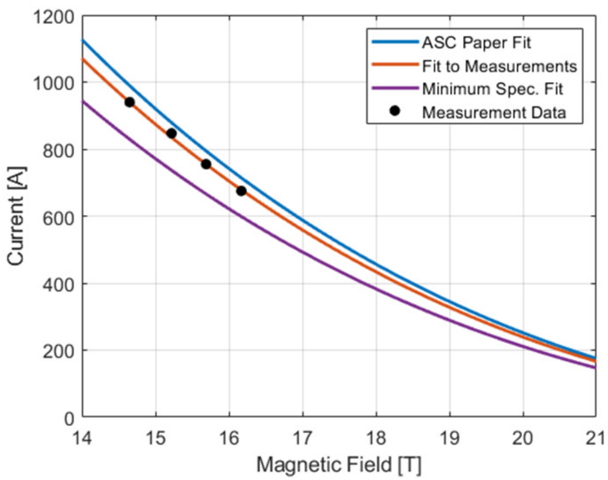
Critical current parametrization

Parameter	Unit	Value
Wire diameter	mm	1.1
Copper ratio		0.9
C_0	AT/mm^2	235520
α		1.0
T_{C0}^*	K	17.0
B_{C20}^*	T	30.0
Cabling degradation	%	5

$$j_c = \frac{C_o}{B}\left(1-t^{1.5}\right)^{\alpha}\left(1-t^2\right)^{\alpha} b^{0.5}\left(1-b\right)^2$$

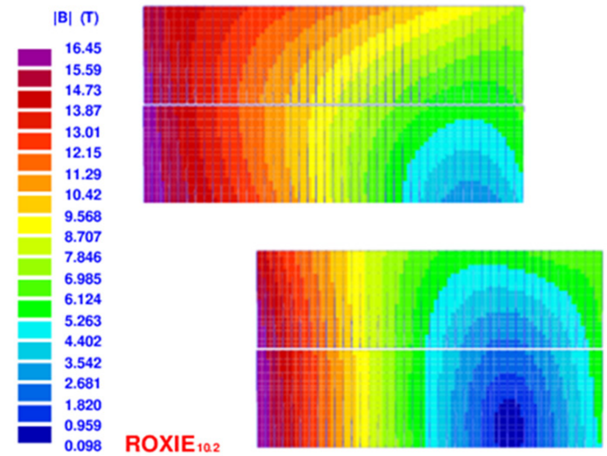
$$B_{C2} = B_{C20}(1-t^{1.52})$$

$$t = T/T_{C0} \quad b = B/B_{C2}$$



Field map and performance parameters at 16 T

Parameter	Unit	Value
Current (cable)	kA	16.23
Current (wire)	kA	0.37
Bore field	T	16.0
Max. field (coil 1)	T	16.5
Max. field (coil 2)	T	16.3
Fx (quadrant)	MN/m	16.2
Fy (quadrant)	MN/m	-9.03



Operating current (16T) vs. SSL current:

- Measured I_c: 81-82 %
- Min. spec I_c: < 85 %

Margin is not impacted by I_c degradation due to strain in the reversible regime →

At 15 T: 5% additional margin

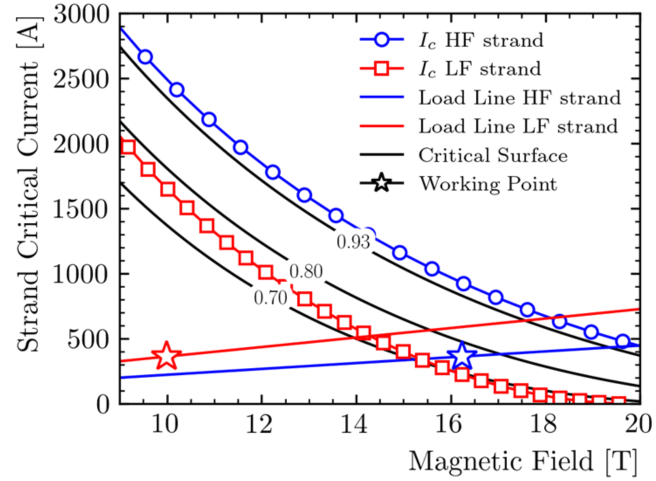
Cabling degradation:

Assumed: 5%, measured: 2%

Field quality:

< 0.3% at 50 mm radius

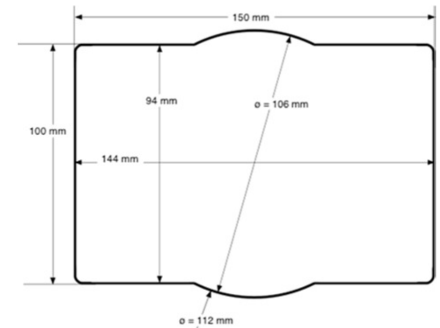
Short sample limit calculation w/strain (see talk by G. Vallone)



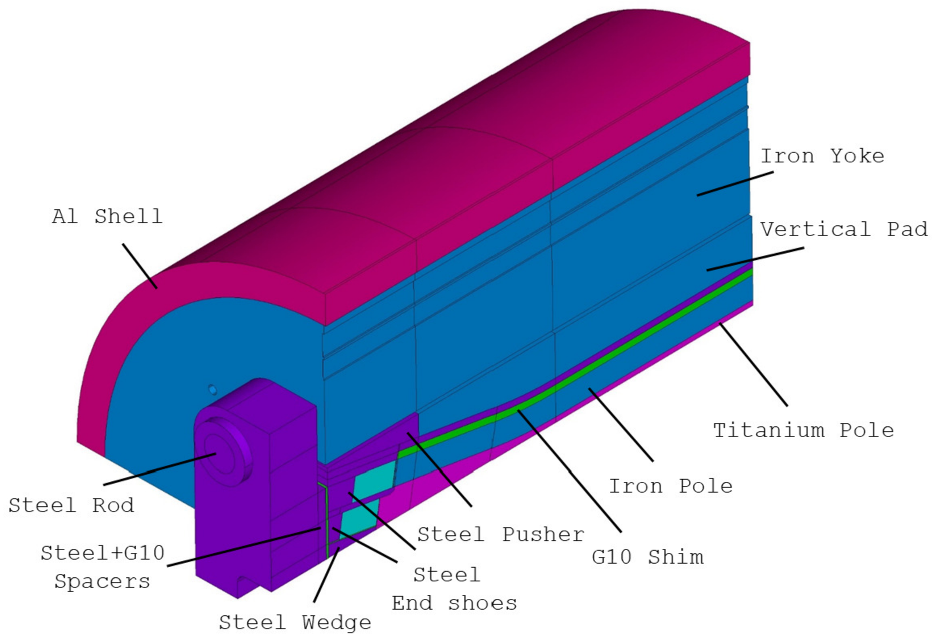
Mechanical Design

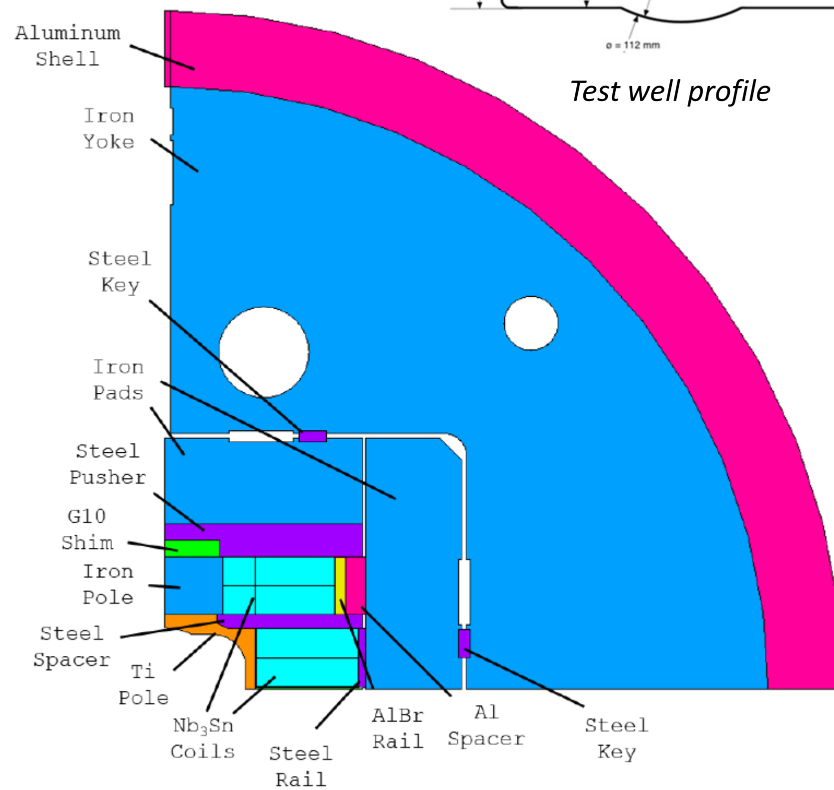
Shell-based structure with axial pre-load (HD, LD, FRESCA2, HEPdipo)
Design features introduced to control the coil stress:

- 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
- G10 shim above the pole



Test well profile

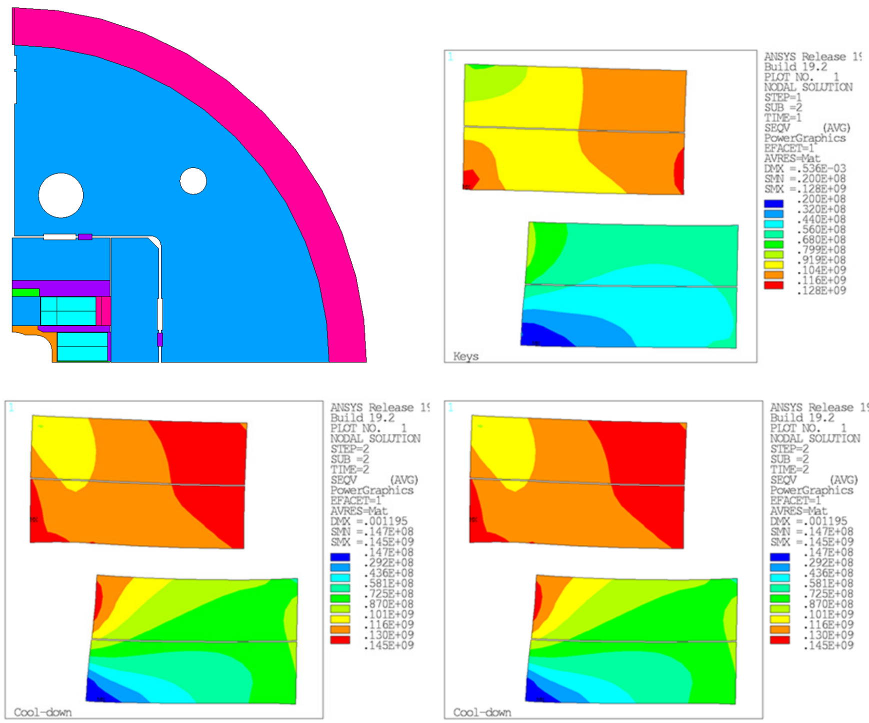




D. Arbelaez, P. Ferracin, R. Hafalia, D. Martins Araujo, G. Vallone et al.

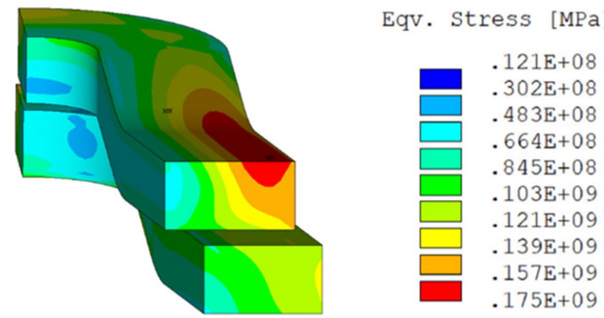
Mechanical Analysis

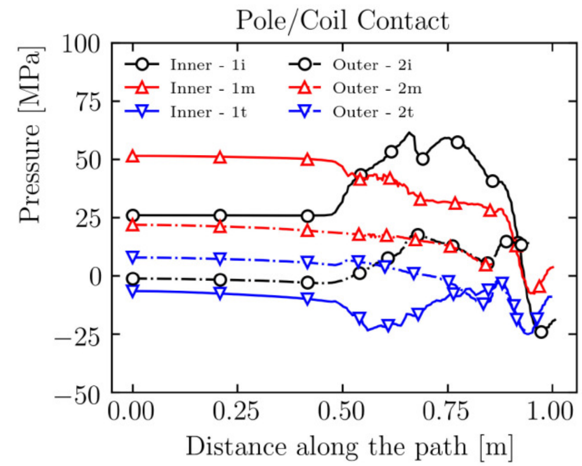
2D coil stress (assembly, cool-down, 16T)



- 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**

3D Coil stress and contact pressure at 16 T





<u>3D Field</u>:

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

Quench Protection - Reference Case

Protection analysis and parameters:

- Magnet design and quench conditions:
  - Magnetic length: 1.7 m
  - Field and current: 16 T, 15.5 kA
  - Stored energy: 12 MJ
  - Inductance : 97.2 mH (57.2 mH/m)
- Analysis performed with STEAM-LEDET
  - Accounts for coupling current effects
- Voltage limit: ±1 kV with symmetric ground
  - Dump resistor: 130 mΩ (2 kV)
- CLIQ parameters: 40 mF, 600 V (AUP unit)
- No Quench Heaters
- Detection + validation time: 15 ms
- Conductor parameters:
  - RRR=100
  - Copper fraction: 0.8
  - Twist pitch (strand/filament): 14 mm
  - Cable transposition length: 109 mm
  - Matrix cross resistance: 10 μΩ

V. Marinozzi, D. Arbelaez, E. Ravaioli, et al.

Main results:

- Energy extraction is sufficient to provide a safe discharge
- Hot-spot temperature 173K (vs. HiLumi 250K target/350K limit)
- However, in case of extraction failure magnet will not survive
- Need fully redundant extraction system, or a second system
- Baseline plan is to include CLIQ together with extraction
- We maintain the same voltage limit of ±1 kV
- With this constraint, T_{HS} is not improved when adding CLIQ but CLIQ will protect the magnet in case of extraction failure, although T_{HS} is higher (327 K, similar to HiLumi failure cases)

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

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

Quench Protection - Sensitivity Analysis

Parameter	Unit	Ref. Analysis	Range studied	Spec	Notes
Copper ratio		0.8	0.8-1.2	0.9	T_{HS} about 30-40 K lower for Cu/NCu=1.2 vs 0.8
Detection time	ms	15	15-45	15	T_{HS} about 25-30 K higher for 45 ms
R_{dump}	$\mu\Omega$	150	75-150	150	Half voltage but T_{HS} may increase up to 50-100K
CLIQ Voltage	V	600	300-1000	600	300 V insufficient. 1000 V performance is equivalent to dump but increases voltage and requires a special unit
Twist pitch	mm	14	14-21	19 ± 3	Slight improvement in T_{HS} for longer twist pitch
Transp. length	mm	109	109-160	155	Slight improvement in T_{HS} for increased transp. length
RRR		100	100-200	>100	T_{HS} ~20 K lower for RRR 300 vs.100 (HEPdipo study)
Transv. Res.	$\mu\Omega$	10	10-20	10	No significant effect for combined dump + CLIQ. 20-30K increase of T_{HS} for dump only or CLIQ only

	Hot spot temperature (only 600 V CLIQ)	Hot spot temperature (only 1 kV dump)	Hot spot temperature (1 kV dump + 600 V CLIQ)
Reference case	327 K	173 K	158 K
Filament twist pitch: 21 mm	319 K (- 2,4 %)	166 K (- 4%)	156 K (- 1.2 %)
Strand twist pitch: 160 mm	326 K (- 0.3 %)	169 K (- 2.3 %)	158 K (0 %)
Matrix transverse resistivity scaling factor: 2	356 K (+ 8.87 %)	193 K (+ 11.5 %)	161 K (+ 1.9 %)

V. Marinozzi, FNAL

Conceptual Design Review Feedback

Requirements and interfaces

- Clarify magnet and facility requirements and get stakeholder approval

  => In progress with input of IPT and EOC committees and HEP/FES community

Conductor and cable:

- Some preference for higher sub-element design for stability in large diameter wire

  => Selected 162/169 vs. 108/127 (although mainly driven by higher I_c)

- Consider a cable with more strands (48 vs 44) and a smaller wire (1 mm vs. 1.1 mm)

  => Insufficient resources/infrastructure to pursue two alternatives in parallel

  => No issues found cabling the 1.1 mm strand - 44 strand cable is preferred

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

  => Confirmed key design choices and started design optimization

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Conceptual Design Review Feedback

Magnet design (cont.):

- Consider increased margin to quench (conductor properties and magnetic design)
  - => Significant improvement with 1.1 mm 162/169 wire
  - => Magnetic design optimization to balance performance margin and coil size
- Consider increased shell thickness for margin (relative to using LD1 shell)
  - => Available margin on outer diameter allows to increase shell thickness
- Include CLIQ protection system for added robustness and redundancy
  - => Detailed protection analysis performed to optimize CLIQ configuration
  - => Baseline test facility design and operation plan includes CLIQ

Design tools, resources and collaboration:

- Team expertise and analysis capabilities are fully adequate
- Continue strong collaboration with FRESCA2/HEPdipo teams and US conductor Labs
  - => Conductor characterization at NHMFL, FNAL, CERN (details in next talks)
  - => FRESCA2engineering feedback, CAD models from CEA and CERN

https://conferences.lbl.gov/event/359/

Cable Development

- TFD "development cable" run (November 2020) using 3 km of RRP 108/127 wire procured by LBNL, and 3 km of 162/169 wire procured by CERN
- 108/127 used for initial feedback and broader exploration of parameter space
- Tests performed: *residual twist, winding properties, micrographs*
  - Final ~25 m long section was sent for insulation at NEEW
  - Cable and parts/tooling ready for a double-layer winding test (8+8 turns)
- Followed by 162/169: 4 main sections with different width and thickness
  - Used for detailed mechanical and electrical characterization (see next slide)

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

162/169 sections

Section	T [mm]	W [mm]
1302-A	1.93	25.86
1302-B	1.91	25.85
1302-C	1.91	26.08
1302-D	1.89	26.11
1302-E	1.89	26.10

- Next step: full-length "prototype cable" for fabrication of TFD "prototype coil"

D. Arbelaez, R. Hafalia, H. Higley, D. Martins Araujo, I. Pong, M. Naus et al.

Wire and Cable Characterization

The following tests were carried out on the development (162/169) wires and cables:

- LBNL: winding tests (next slide); metallography of extracted strands *(I. Pong presentation)*
- FNAL: I_c and RRR of virgin and extracted strands at 4.2K and 2.1K, for 665C and 680C reaction; field sweeps (0-10T-0) at >1kA, 4.2K and 2.1K to check stability *(D. Turrioni presentation)*
- NHMFL: I_c and RRR of virgin and extracted strands at 4.2K, 665C reaction *(J. Lu presentation)*
- NHMFL: strain characterization for both CERN and LBNL procured wire as a function of reaction temperature *(N. Cheggour presentation)*
- CERN: selected 1.9K tests to confirm scaling of 4.2K/2.1K results *(S. Hopkins presentation)*

The following tests are planned for the prototype and production wires, cables and coils:

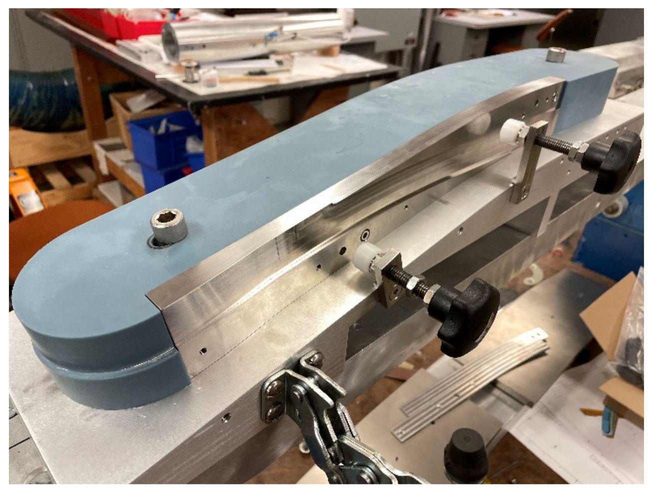
- Supplier QC as detailed in the wire specification – *results are available for the ~20 km TFD prototype wire order (I. Pong presentation)* and 50 km CERN order *(S. Hopkins presentation)*
- Verification tests (50% of S, 1/billet) and cable characterization (4 virgin+4 extracted): at FNAL for prototype wire/cable (contract in place); at NHMFL and FNAL for production wires/cables
- Mechanical QC: post-production cable samples
  - residual twist, 10-stack (bare and insulated) and metallography
- I_c and RRR of coil witness samples (virgin and extracted) to check reaction

Coil Winding Tests

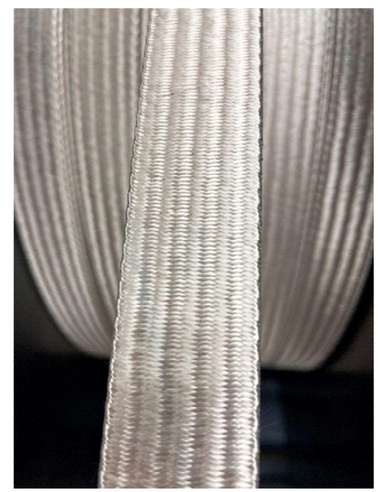
- Several winding tests were performed using (short) sections from the development cable run
  - All sections could be wound without any significant issues, independent of compaction
  - Even the 43 strand section could be wound (although it is clearly not a viable option)
  - Bending radii at the coil ends are very large compared with accelerator magnets
- HW bend at the end flares is the most critical – several tests and detailed CMM measurements and analysis were performed to conform the design to the optimal curvature for the cable
- Conclusion: cable design can be optimized for minimal I_c/RRR degradation
- Next step: double-layer winding test with optimized HW bend and incorporating layer transition

Single-layer, ~2 turns

Double-layer, 8+8 turns



Insulated cable



R. Lee, P. Mallon, J. Rudeiros Fernandez, J. Swanson et al.

Summary

- Magnet performance targets and design constraints have been defined based on user input and in agreement with the Fermilab test facility team
- Magnet design full advantage of the extensive technical background provided by previous design and development of large aperture, high field Nb_3Sn dipoles
  - Analysis of different options for magnet and conductor/cable design
  - Design of coil (parts, tooling, and fabrication processes) and shell-based structure
- Building on this past work, we have been able to make further improvements in critical areas, in particular to avoid degradation due to coil stress
  - Strain degradation is not expected to impact the magnet performance *(G. Vallone)*
- Magnet requirements are fully incorporated in the wire specification
  - Magnetic design and operating margins
  - Capability to fabricate cables with desired mechanical and electrical characteristics
  - Quench protection
- Experience from two significant procurements at LBNL *(I. Pong)* and CERN *(S. Hopkins)*
- Detailed characterization confirms that selected wire meets requirements for cabling, magnet fabrication and operation *(D. Turrioni, J. Lu, N. Cheggour)*