Massachusetts Institute of Technology

Bates Research and Engineering Center

Proposal to EIC: IR Magnets

H. Witte, on behalf of MIT Team
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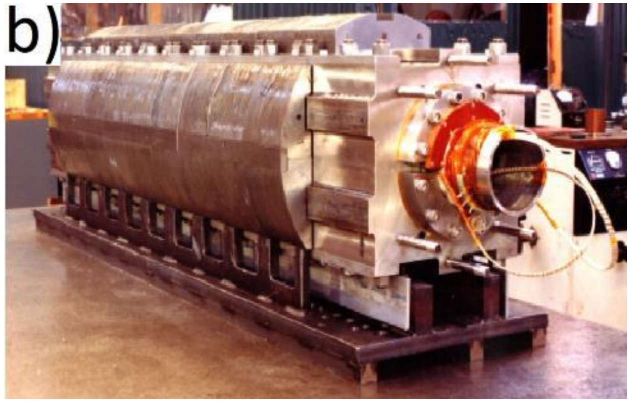
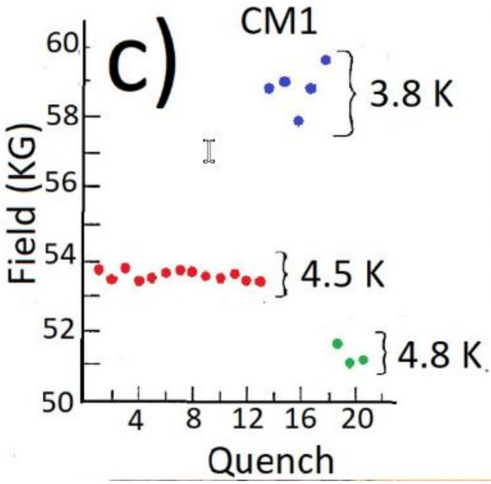
3/11/2025

One should always start with a joke…

- … but I don’t have one (at least a good one)
- An interesting story will have to do
- 1980: problems with the Isabelle magnet
  - Isabelle: 400 GeV Center of Mass energy
  - Required field: 5T
  - Only first magnet worked, others after 45 training quenches
- The Bob Palmer Magnet (‘the Rebellion’)
  - Alvin Tollestrup, Carl Goodzeit, Rick Fernow, Bill Sampson…
  - $40k budget (Nick Samios)
  - ‘Borrowed’ cable from FNAL
  - Peter Marston, MIT: machining of tooling parts, cured stack of cable (a bill that was never paid?)





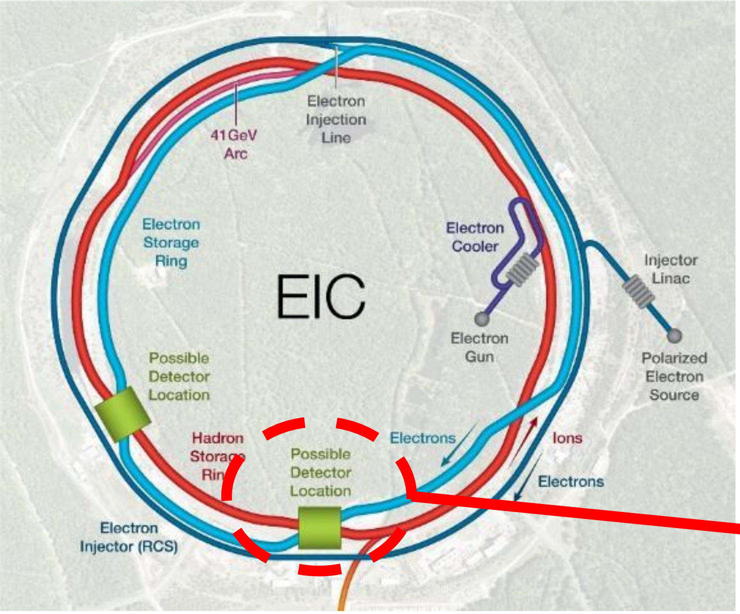
Overview

- Proposal
- Challenges B0pF
- New concept for B0pF
  - Quenches
  - Structural improvements
- Workplan/Schedule

Proposal

- MIT takes responsibility for B0pF
    - Design
    - Detectors
    - Cryostat
    - Integration
    - Testing
- Manufacturing
    - In-house or with industrial partner
- ‘Turn-key’ delivery

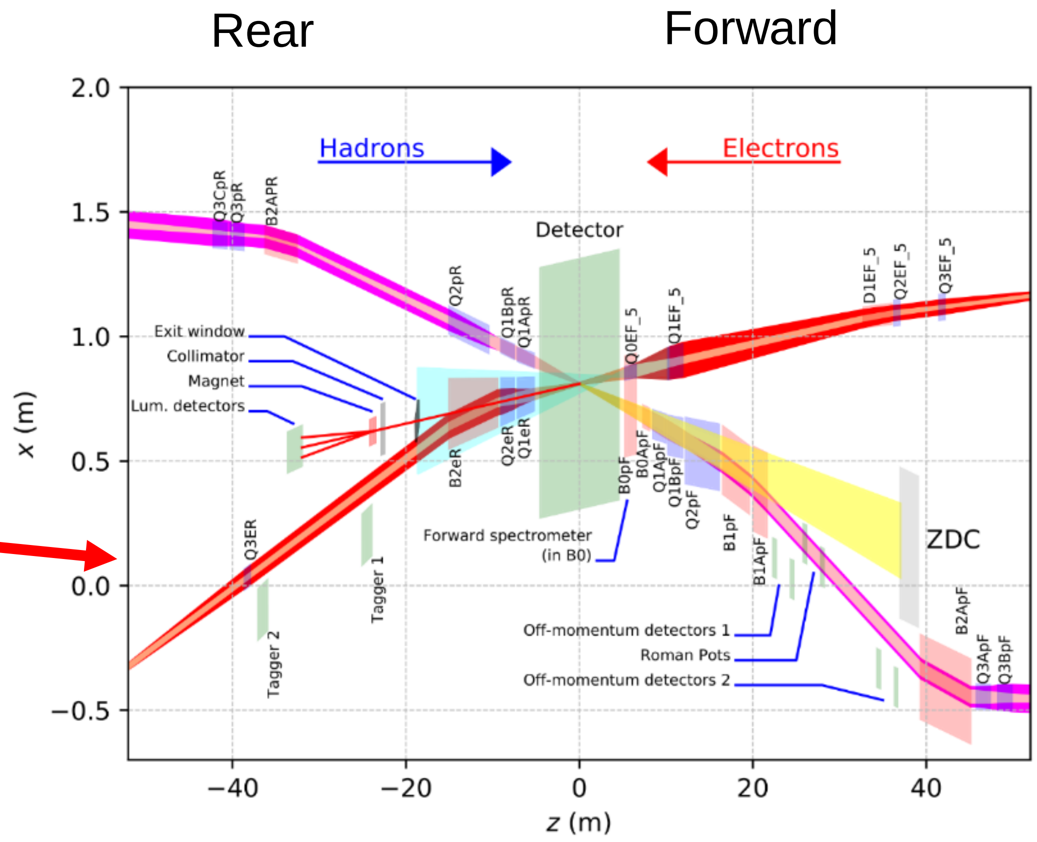
EIC IR: Overview



IR location: IR6

Magnet Technology Challenges:

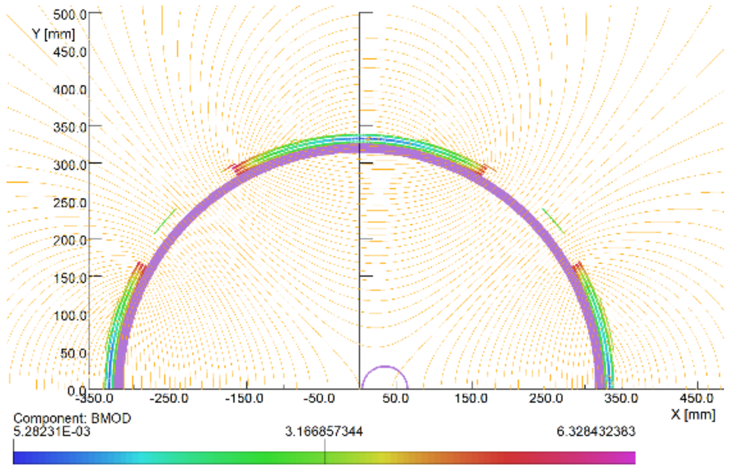
- Crosstalk
- Field/gradient requirements
- Apertures



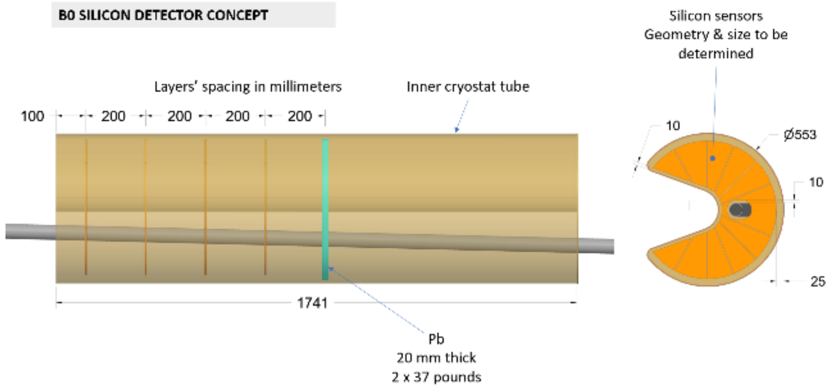
CCT Magnets: Q1ApR, Q1eR, B0ApF
Skew quads, vertical corrector

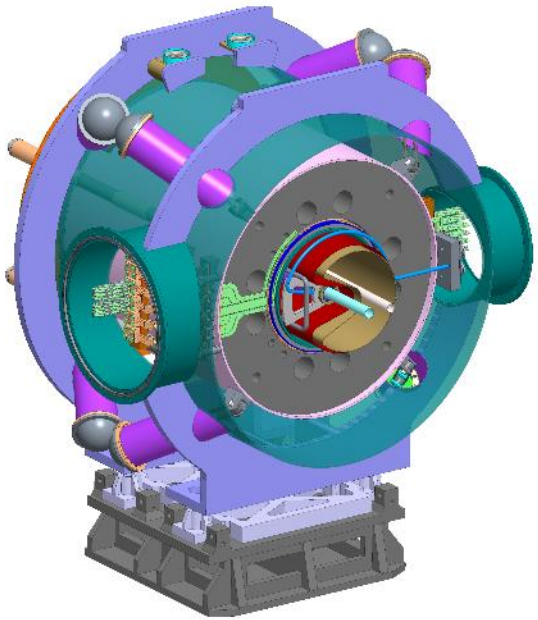
Each rectangle: required minimum aperture, not magnet size
Things are tight – Tapered CCT magnets to solve (some) of the issues

B0pF Forward Spectrometer



- **Measures particles emerging from the breakup of the colliding hadrons**
- **Only ~6m from IP**
  - Beams not very separated (crossing angle 25mrad)
- **Beams share magnet aperture**
  - Hadrons: 1.3T field
  - Electrons: 14T/m gradient
- **Present implementation: combined function magnet**
  - Large aperture quadrupole; zero field axis shifted with dipole
- **Space constraints/large aperture**
  - Requires 2K
- **B0pF is essential for the forward side of the IR (beyond its importance for physics)**





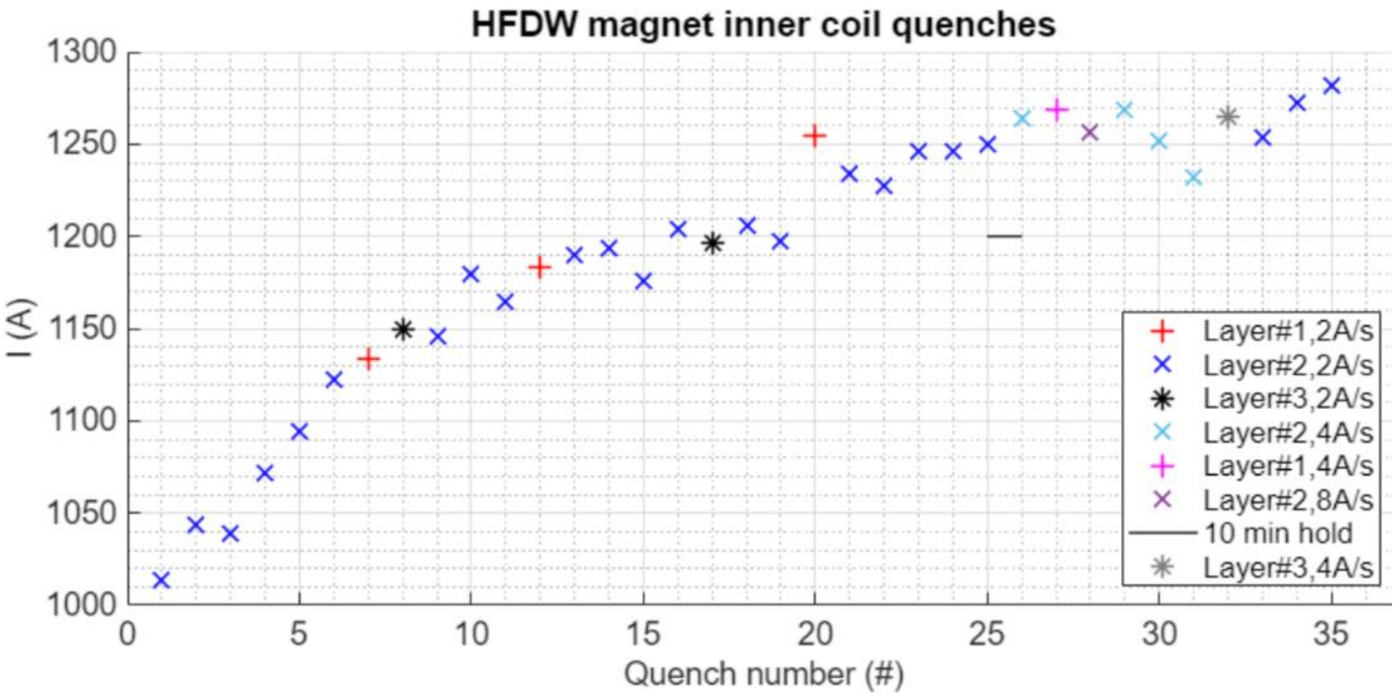
Courtesy of
K. Hamdi (BNL)

B0pF – Initial Workplan

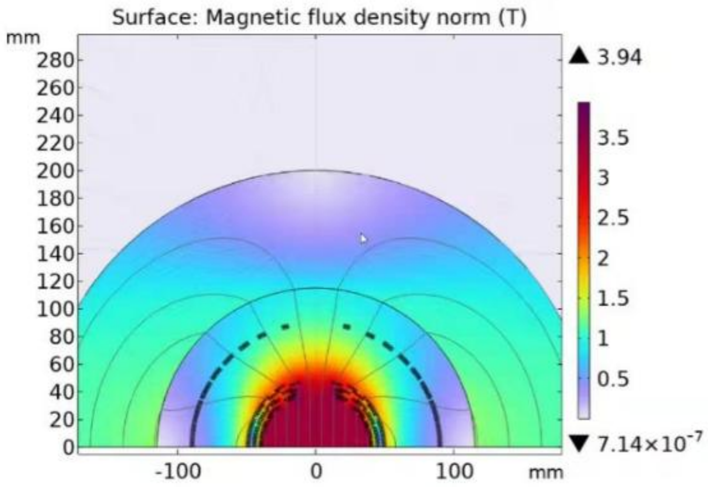
- Re-evaluate design of B0pF
- Present implementation is based large aperture quadrupole, which may not be ideal
  - Preliminary studies show that a pure dipole could lead to a lower peak field
  - Requires bucking coil for electron beam
- Address structural and quench issues
  - Larger cable
  - Approach: wire in groove
  - Individual turns supported by steel former
  - VPI soldering technique, developed at MIT (PSFC)
    - Used successfully for HTS, transfer concept to LTS
    - (NbTi has a history of performance in soldered configurations)

Statement of Problem

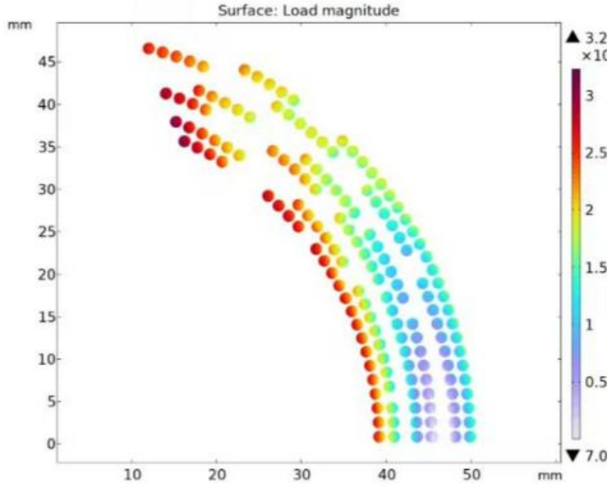
- B0pF: large aperture, high field magnet
  - Aperture: ~0.6m
  - B_{peak}, wire: 4.8T
  - Stored energy: 800kJ
- Direct wind technology limitations
  - HFDW magnet trained to only ~1260A
    - ~3.15T aperture field, ~80mm aperture
    - (designed for 5.6T)
  - Small cable (1.42mm dia)
  - Stored energy: ~28kJ
- Challenges direct wind
  - **mechanically 'soft' structure**
  - Large cable not possible (intrinsic limitation)
  - Low current: **quench protection** issues



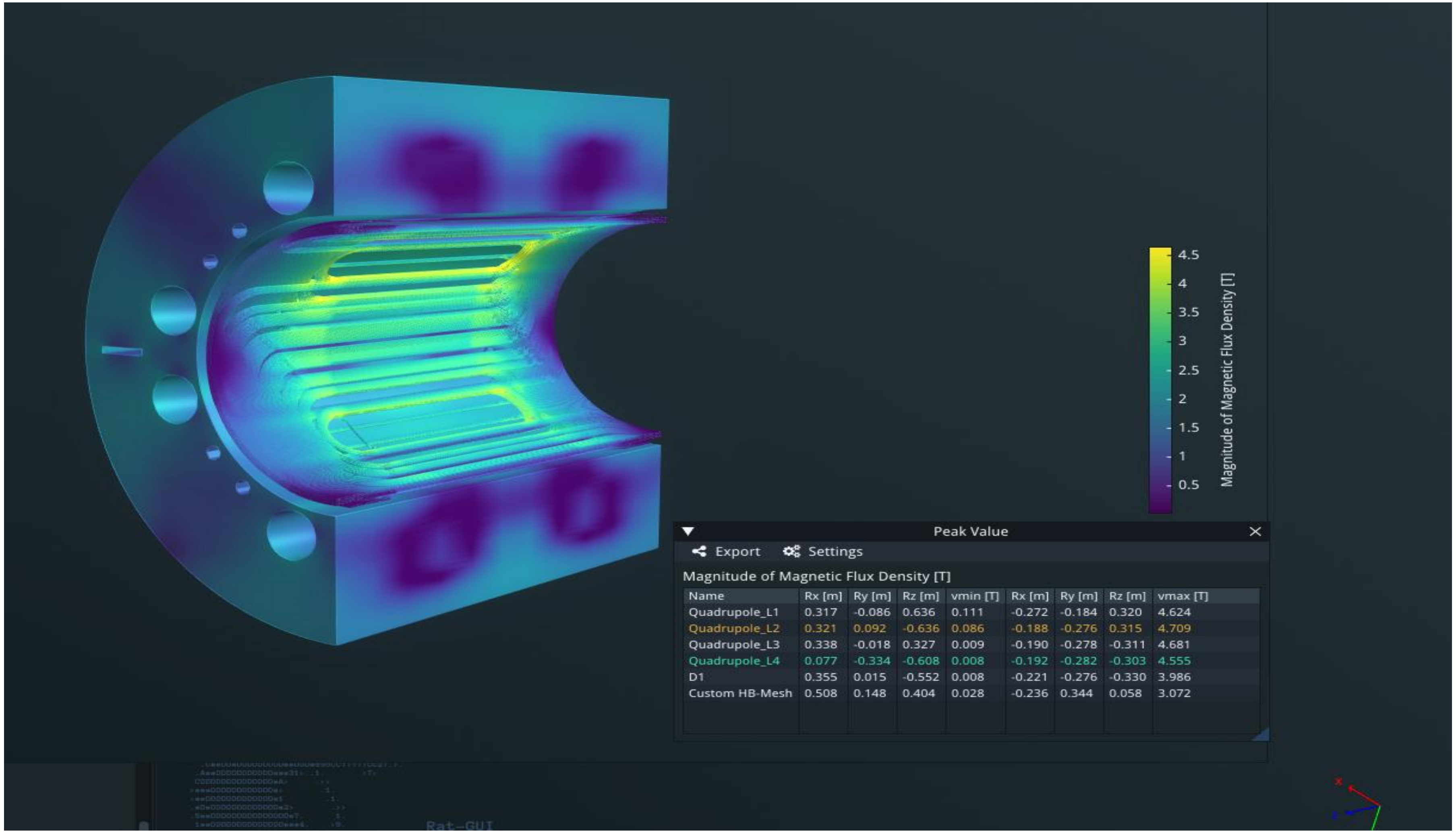
Ramp inner coil only to 1300 A with iron



Applied load magnitude in SME



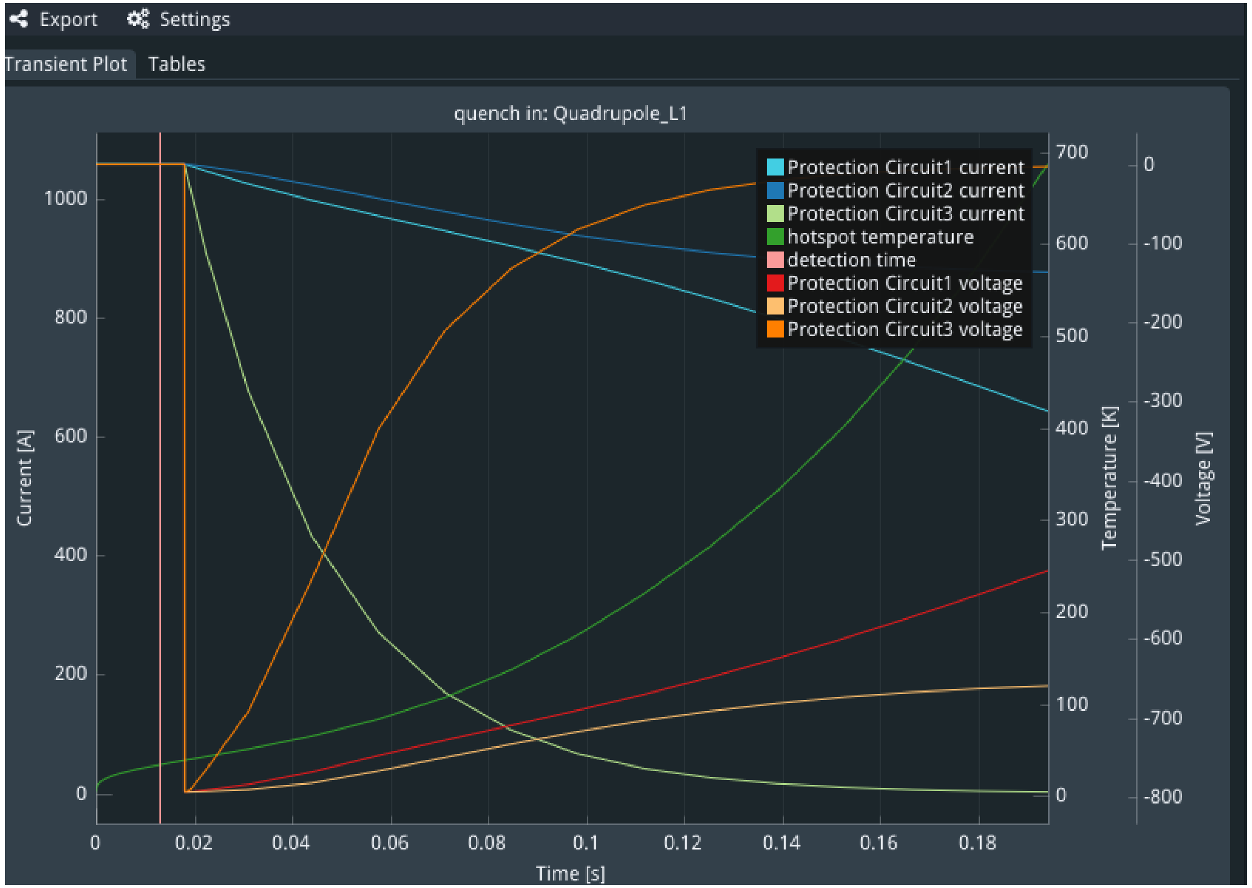
B0PF Peak Field Calculation
(energize hadron dipole and quadrupole in series with 1058A)

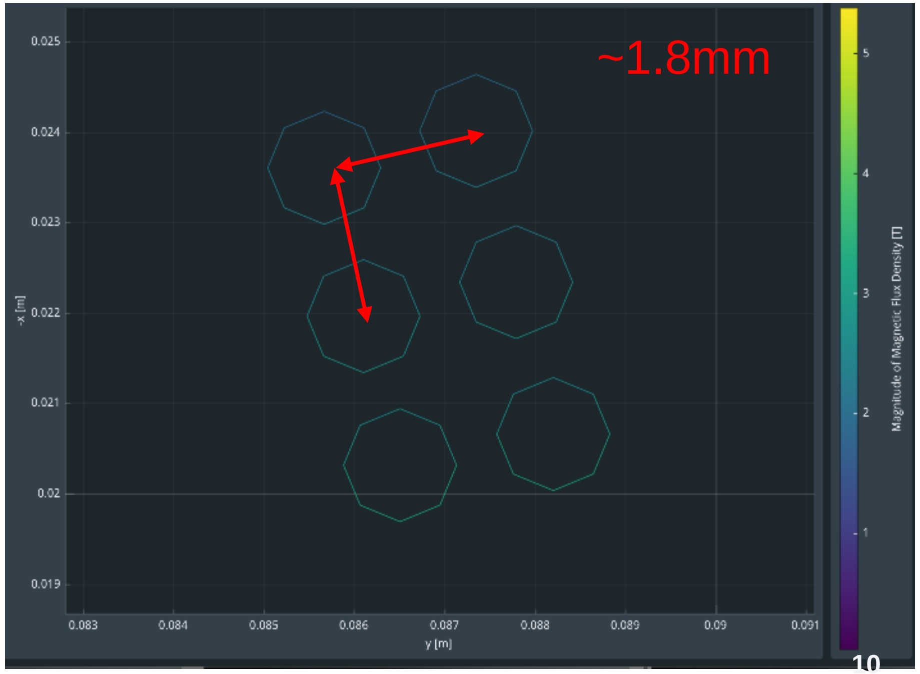


Name	Rx [m]	Ry [m]	Rz [m]	vmin [T]	Rx [m]	Ry [m]	Rz [m]	vmax [T]
Quadrupole_L1	0.317	-0.086	0.636	0.111	-0.272	-0.184	0.320	4.624
Quadrupole_L2	0.321	0.092	-0.636	0.086	-0.188	-0.276	0.315	4.709
Quadrupole_L3	0.338	-0.018	0.327	0.009	-0.190	-0.278	-0.311	4.681
Quadrupole_L4	0.077	-0.334	-0.608	0.008	-0.192	-0.282	-0.303	4.555
D1	0.355	0.015	-0.552	0.008	-0.221	-0.276	-0.330	3.986
Custom HB-Mesh	0.508	0.148	0.404	0.028	-0.236	0.344	0.058	3.072

B0PF quench simulation results

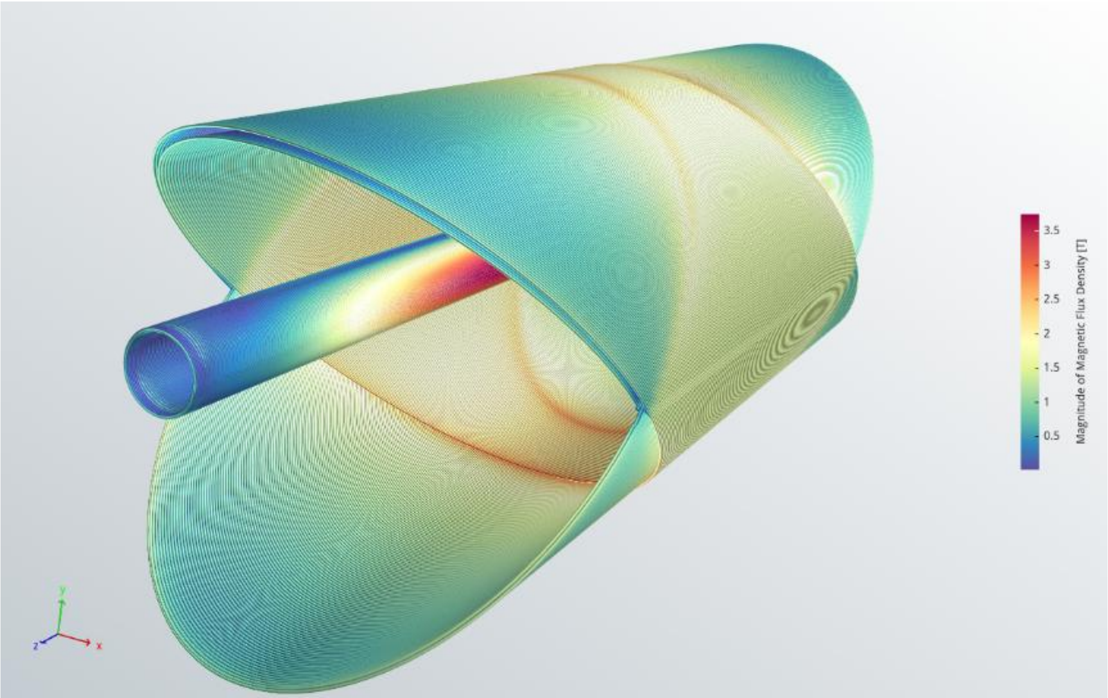
0.75ohm dump resistor /10ms quench delay/0.1V voltage threshold /3-loop protection circuits/no QP heater



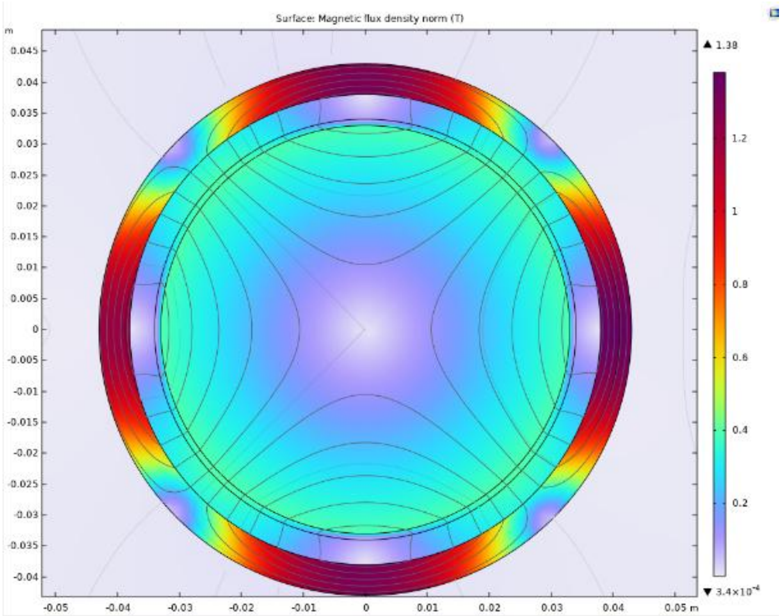


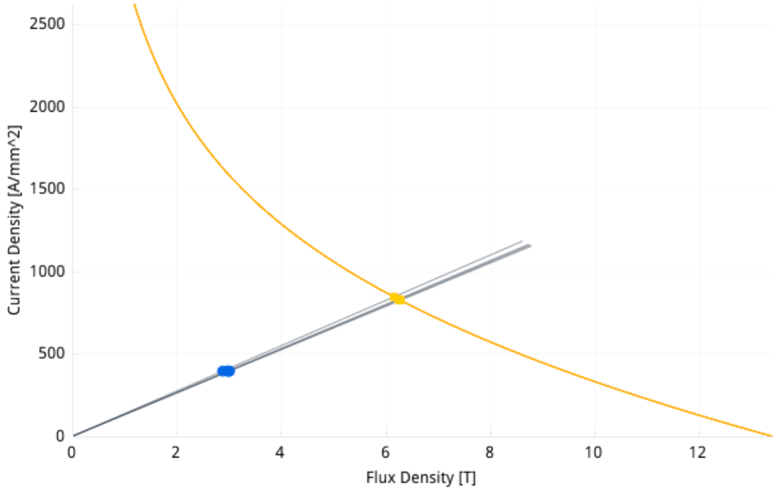
Wire spacing – transverse quench propagation velocity?

B0pF – New Design



- Based on pure dipole (CCT)
  - Lower peak field on wire: 2T vs 4.7T
- Larger Cable: 6.25mm^2 vs 1.2mm^2
  - 1.065mm strand, Cu:Sc 1.6
  - 7 strands
- Quenches safely (70K, single dump resistor)
  - 20 ms delay
- Margin: 50%
- Energy: 400kJ vs 800kJ
- Compensation concept
  - Bucking coil – reduces field to mT
  - Iron collar
    (also return yoke for quad)





Addressing the Mechanical Issues

- Direct wind technique:
  - Voids are filled with fibre glass cloth
  - Tension roving overwrap
  - Fill with epoxy
- Can this be supported better?
  - Use same technique which was successful for 20T HTS large aperture magnet for fusion
  - Wire in groove
  - Key: vacuum pressure solder impregnation
  - Peak IxB: 800 kN/m (B0pF: two orders of magnitude lower)
- **Restrict movement, avoid quenches**

What was the SPARC Toroidal Field Model (TFMC) Coil Project?

1. Developed REBCO conductor technologies (2017-2019)

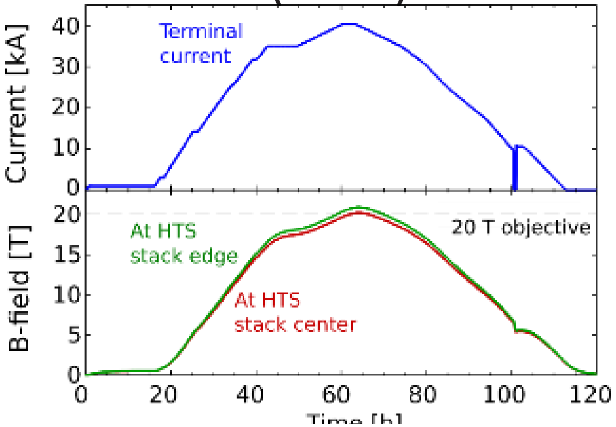
VIPER cables

NINT coils

2. Designed and built the TF model coil (2019-2021)

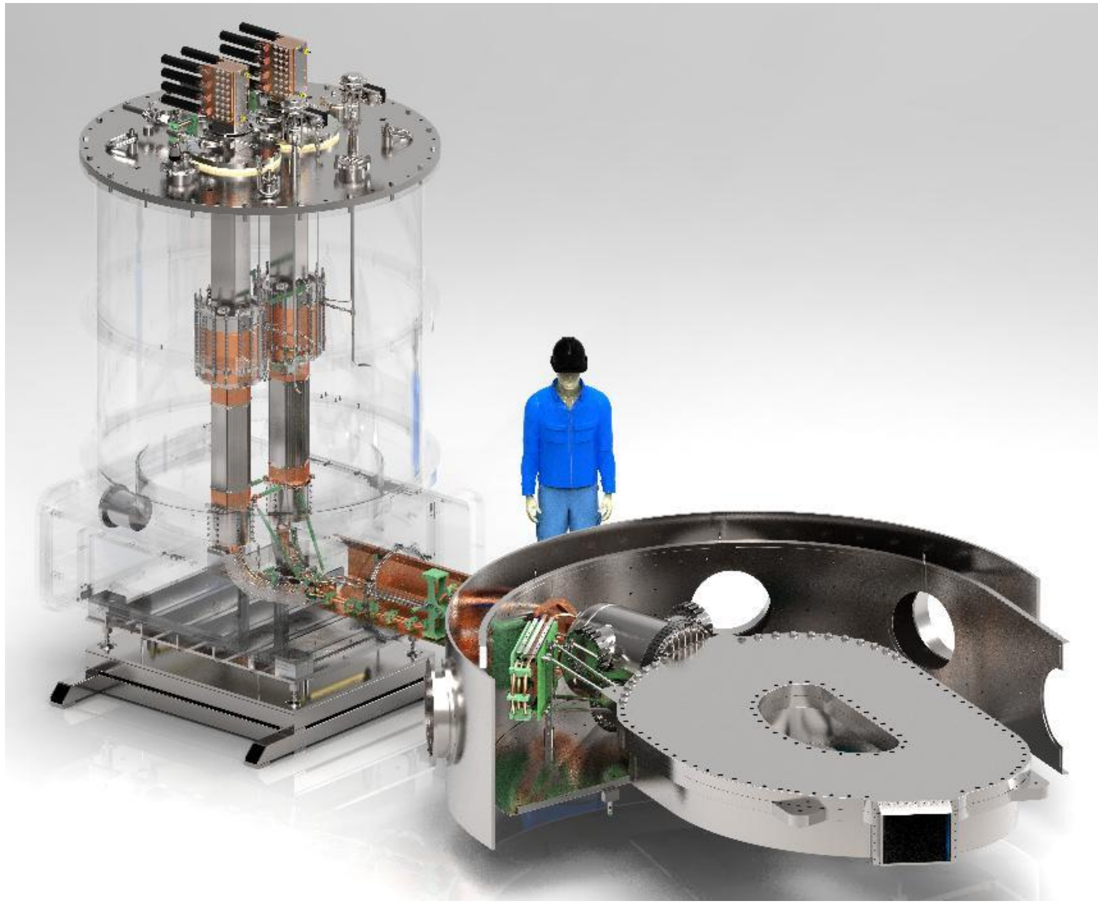
3. Built and commissioned the test facility (2020-2021)

4. Achieved 20 tesla full performance test (2021)



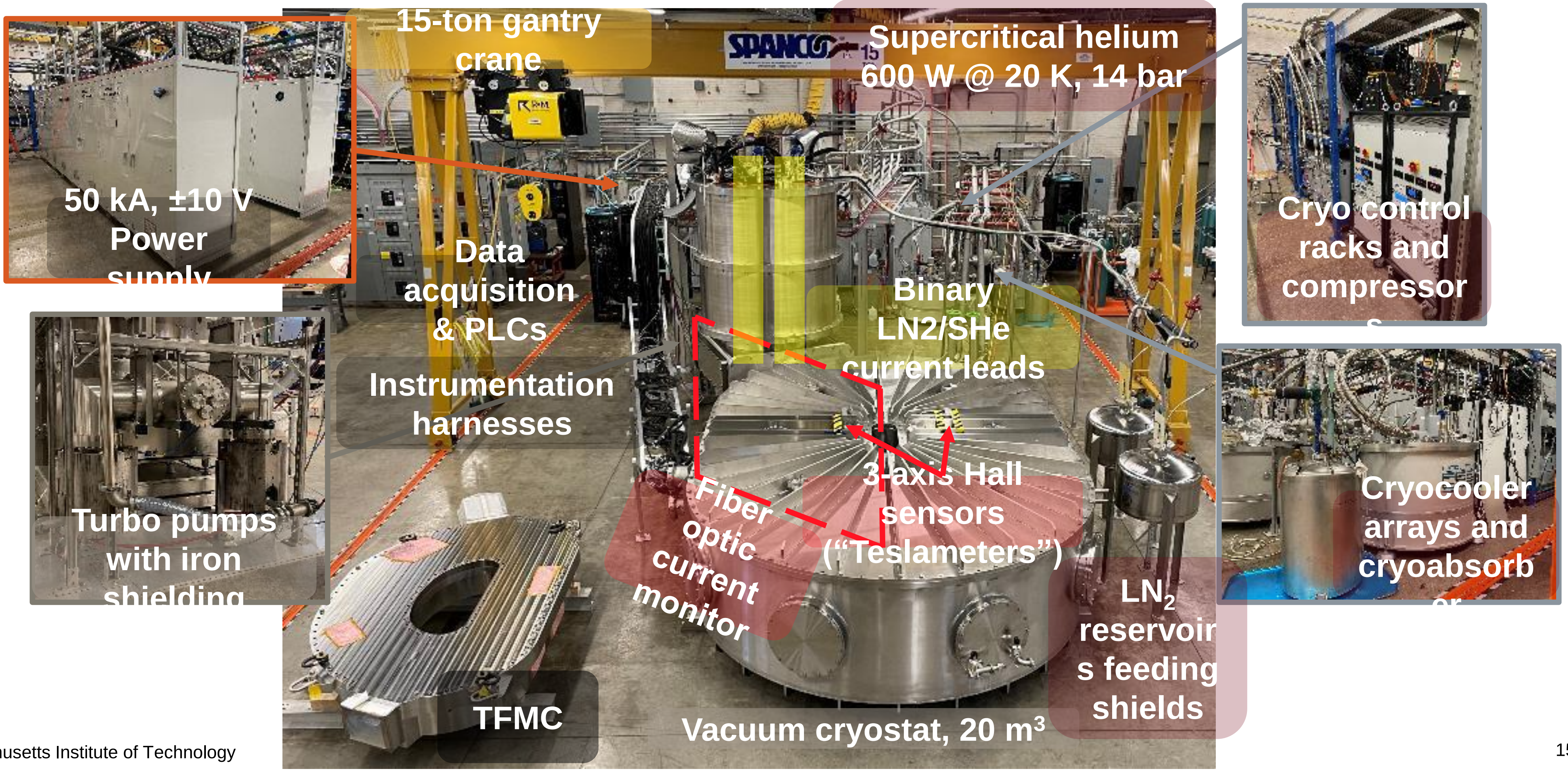
Completed in ~4 years by MIT and CFS in partnership with our vendors

The TFMC Project in one picture: magnet and test facility

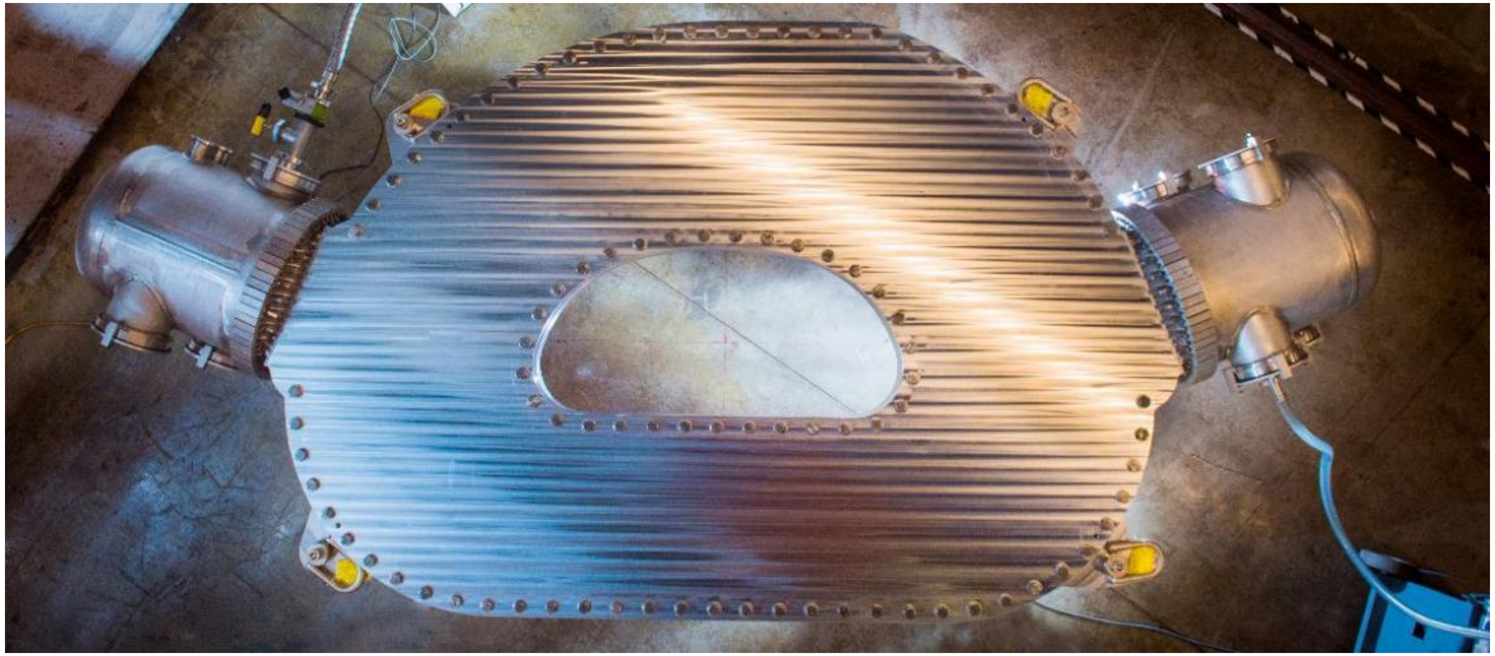


The TFMC was designed and primarily fabricated (w/ external vendors) and assembled at MIT with REBCO procurement+ QA/QC and pancake winding at CFS

The TFMC Project in one picture: magnet and test facility



The TFMC is a large scale 20 T no-insulation REBCO magnet

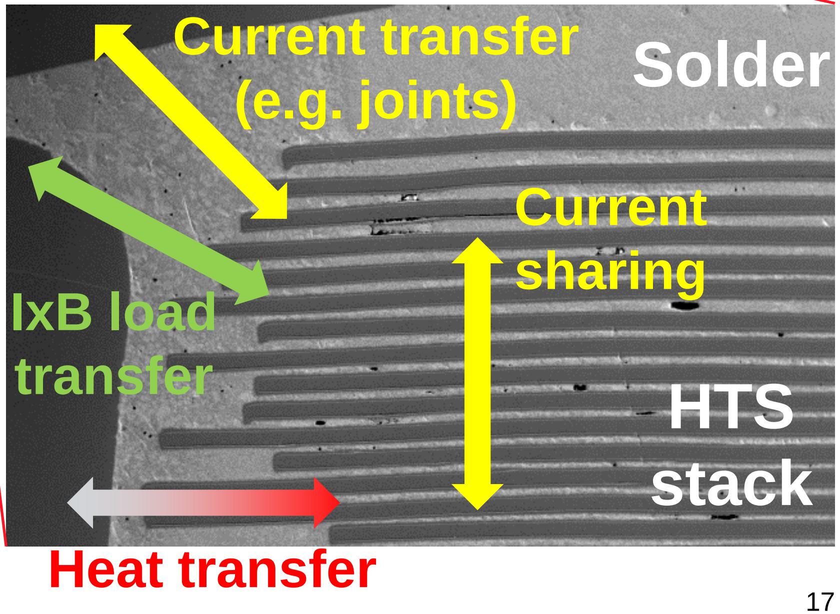


Nominal Design Parameter	Value
Number of pancakes	16
Total turns	256
Total REBCO tape	270 km
Operating temperature	20 K
Coolant type	Supercrit. He
Operating coolant pressure	20 bar (max)
Operating terminal current	40 kA
Peak magnetic field	20 T
Peak IxB force on REBCO	800 kN/m
Inductance	0.14 H
Magnetic stored energy	110 MJ
WP mass	5,113 kg
WP current density	153 A/mm^2
WP + case mass	10,058 kg
WP + case linear size	2.9 x 1.9 m

LL #3: REBCO has proven impressively resilient to vacuum pressure solder impregnation in VIPER cables and TFMC

- VPI soldering was successfully developed for VIPER cables and for TFMC
- Process results in acceptable solder-induced Ic degradation (~2-3%) for full-scale **HTS** conductors
- Over 100+ VPI solder processes to date
  - Adaptation to cables, coils, plates, …
- VPI soldering REBCO is a critical enabler:
  1. Demonstrated stability against high IxB cyclic loads
  2. Enabled simple, robust, ~nΩ electrical joints
  3. Provides high levels of thermal stability
- For B0pF: highest performance VPI solder to immobilize NbTi cable, allowing traditional insulation technique

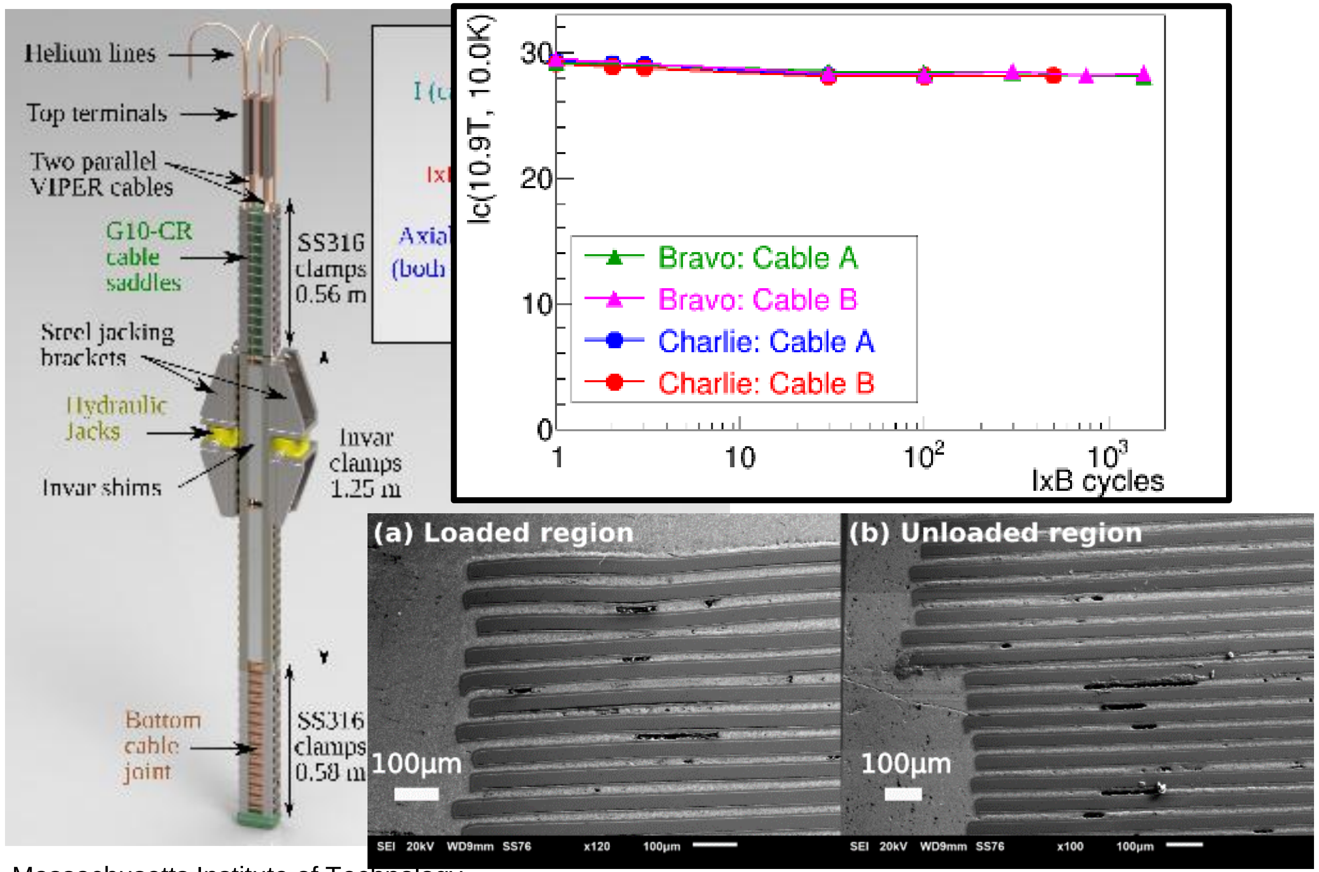
REBCO survive and enable high-quality solder with low-frequency, small voids over long lengths with excellent bonding to solve challenges in high-field magnets

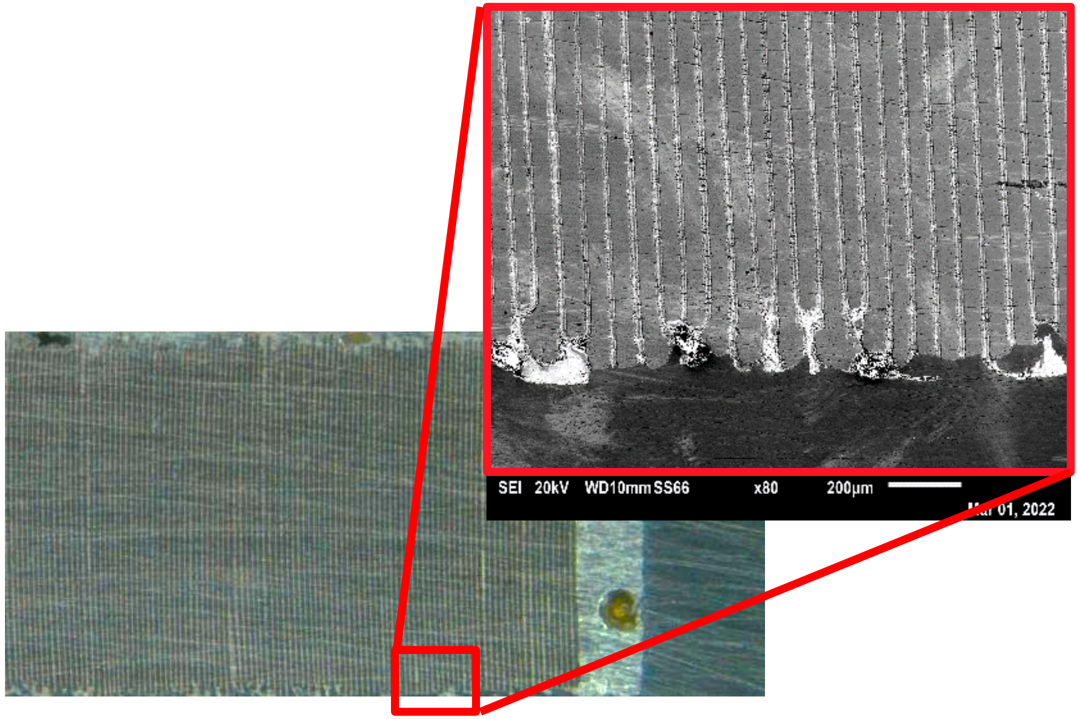


LL #4: VPI solder stabilized REBCO has survived high IxB loading, relevant axial strain, and thermal cycling

VIPER Cables: Consistent, stable Ic (<5% Ic degradation) after 1500 IxB cycles at 382 kN/m loading (all angles on REBCO stack) with ~0.3% axial strain and thermal cycles

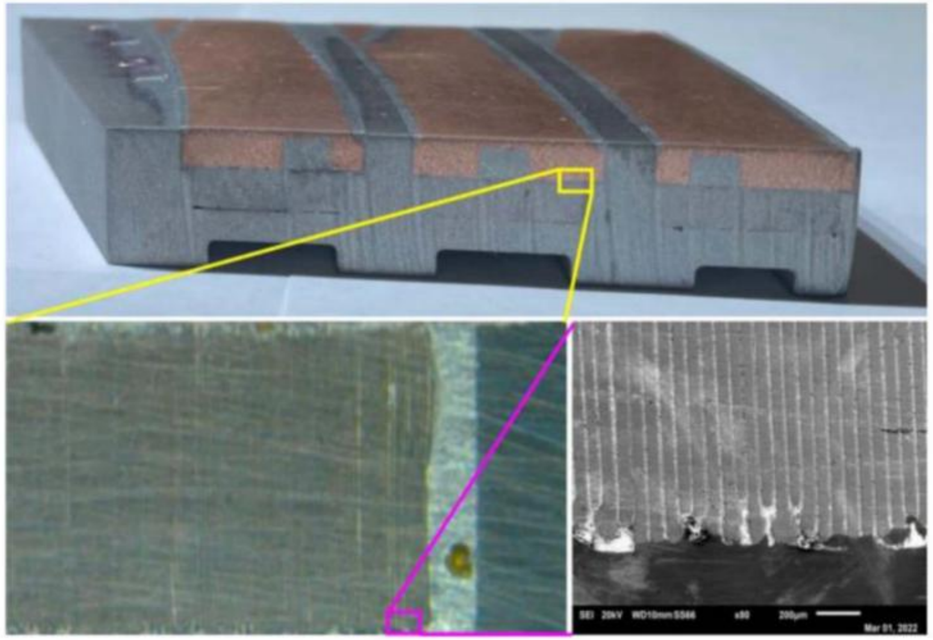
TFMC: Negligible Ic degradation after fabrication and several IxB cycles at >800 kN/m (perp. to REBCO plane) (small, isolated damage in low-frequency solder voids)





REBCO operational performance at the tape- or stack-level to date exceeds what is required for high-field SC fusion cables/magnets.

VPI Soldering

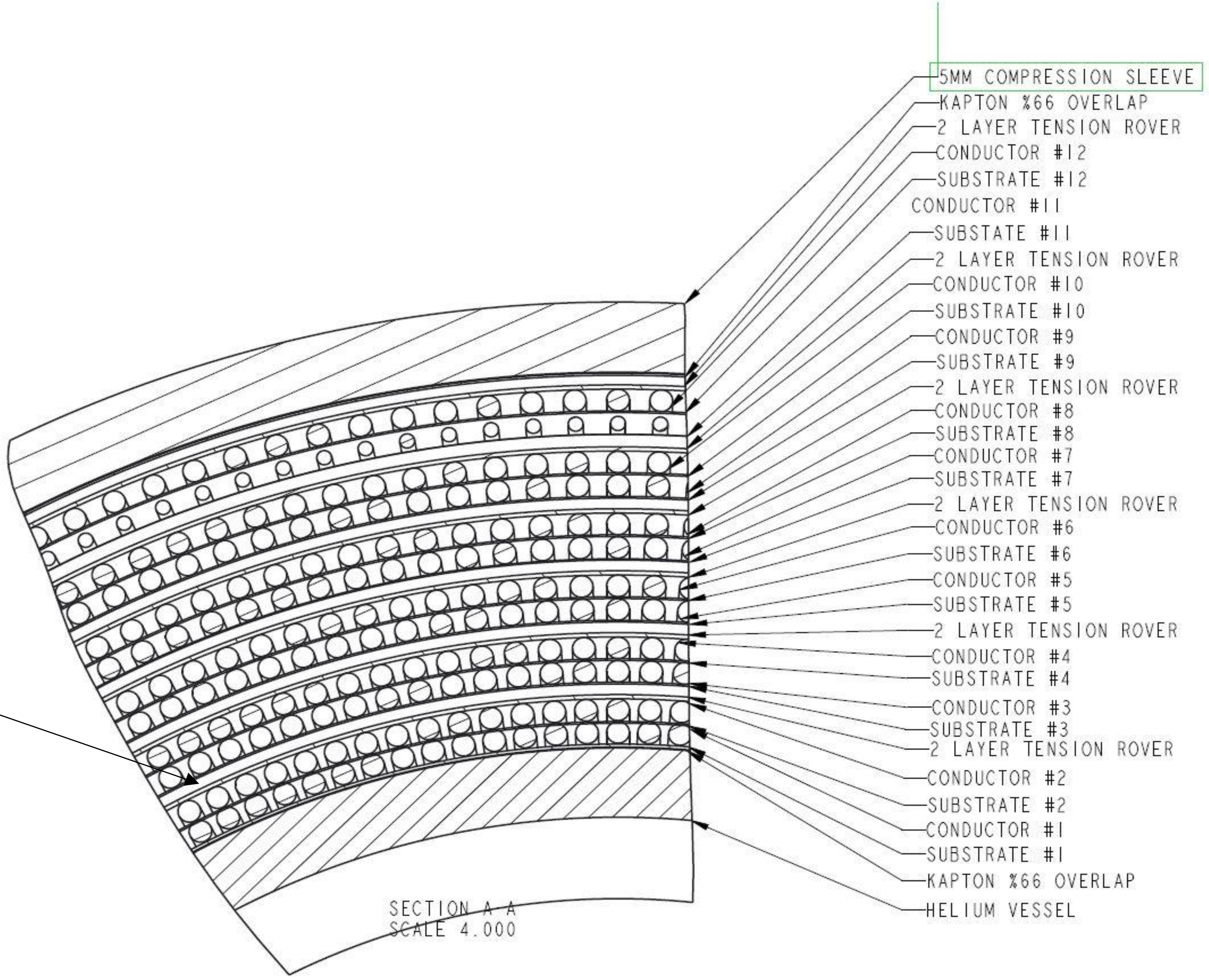


Mechanical stabilization of HTS stack

VPI solder assembly (MIT)

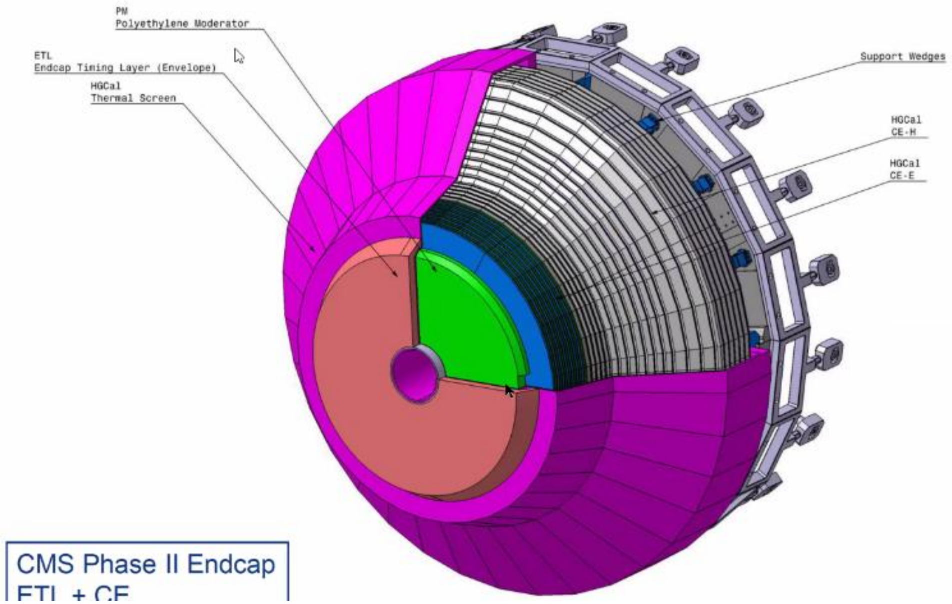
Direct Wind - Coil Construction

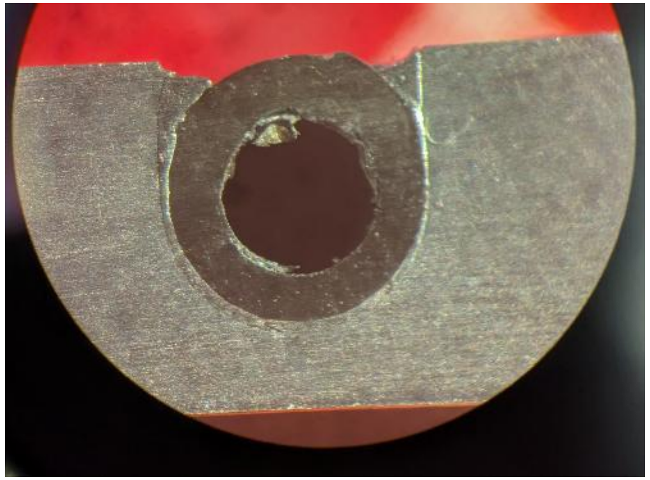
- Cross section drawing;
  - Inner Helium Vessel (Coil Support Tube).
  - 12 layers of 6 around 1 superconducting cable (1.575mm dia.).
    - Wound in pairs
    - Each layer wound on B-stage substrate.
  - Large gaps filled with 5 layers b-stage fiberglass cloth.
  - Interstitial areas between conductors, filled with Stycast 2850 FT.
  - Tension Roving added after each double layer (20lbs@ 18 turns/inch)
  - .75mm thick layer of machined fiberglass (after each double layer).
  - Outer compression sleeve (.1mm diametric interference fit with coil).

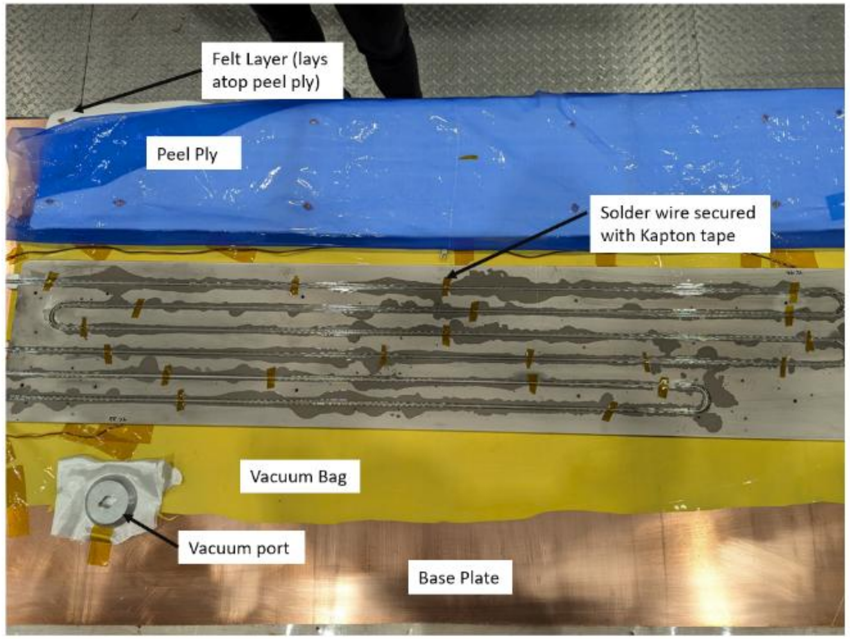


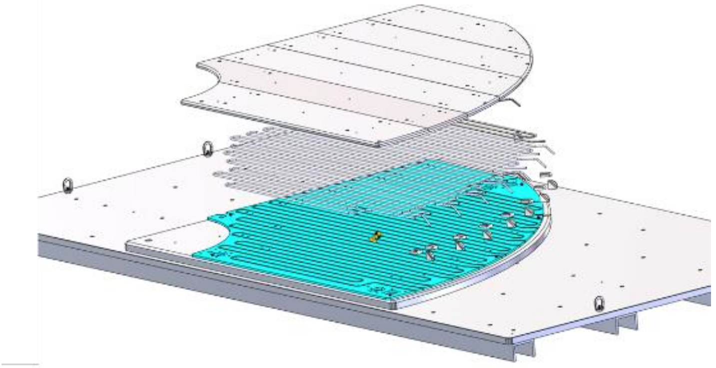
CMS@LHC ETL Evaporators/Cooling Plates

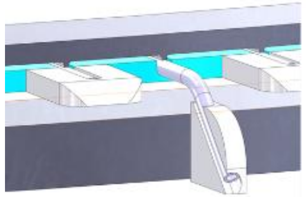
- Need very thin Al plates (6.35 mm thick /~ 3 m linear size)
- Silicon detectors need to operate at -25C with good uniformity (1K)
- Only 98mm space available
- CO_2 evaporative cooling
    - Stainless cooling tubes
    - Need excellent thermal contact: **vacuum-bagged reflow soldering** (adaptation of VPI process)





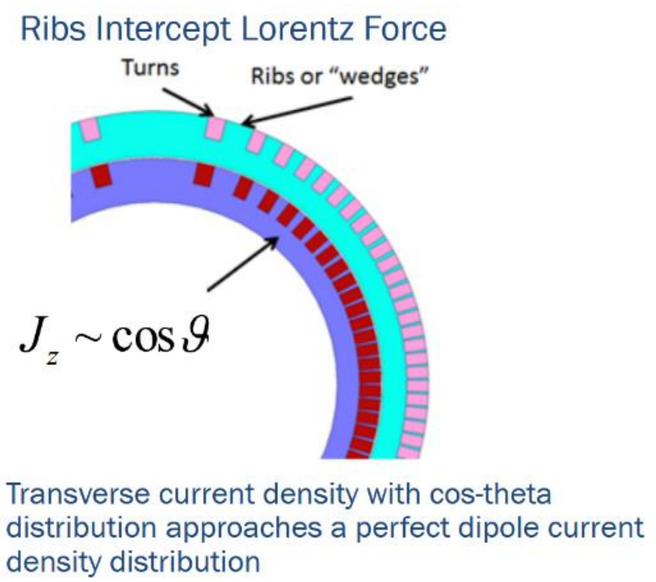


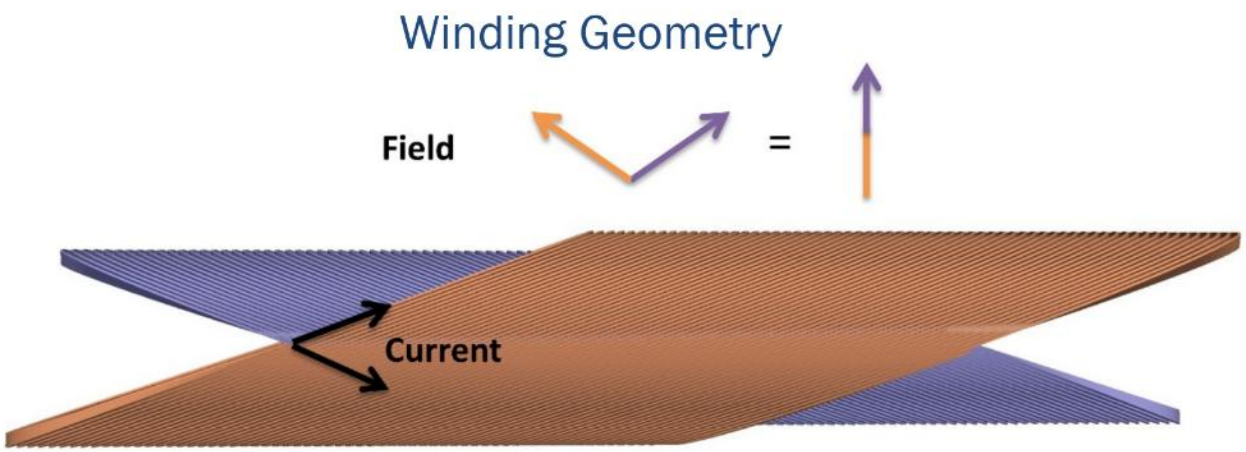




LBNL: CCT Magnet

- What are the chances of this working?
- LBNL experience – Nb_3Sn



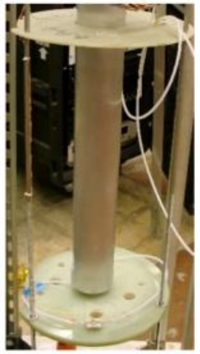


LBNL - CCT

CCT1

- 2.5 T short-sample dipole
- 50 mm clear bore
- 8 strd. NbTi cable
- not impregnated
- 11/2013: ***tested up to 2.5 T***

CCT1

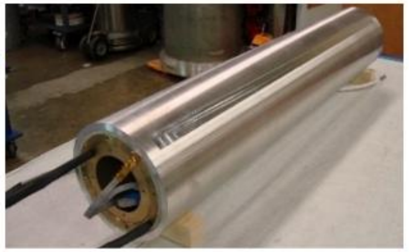


NbTi

CCT2

- 5.3 T short-sample dipole
- 90 mm clear bore
- 23 strd. NbTi cable (0.8 mm SSC Inner)
- epoxy impregnated
- 5/2015: **tested up to 4.7 T**

CCT2



CCT3/4

CCT3/4

- 10.5 T bore field at round wire short-sample (RRP 54/61)
- 90 mm clear bore
- CCT3 03/2016: **reached bore field=7.4 T (conductor damage)**
- CCT4 08/2017: **reached bore field=9.1 T (substantial training)**

Nb_3Sn

CCT5

9.7 T bore field at round wire short-sample (RRP 108/127)

- 90 mm clear bore
- 10/2018: Achieved 8.51T (87.7% short-sample)
- Still substantial training, but improved from CCT4

Why B0pF?

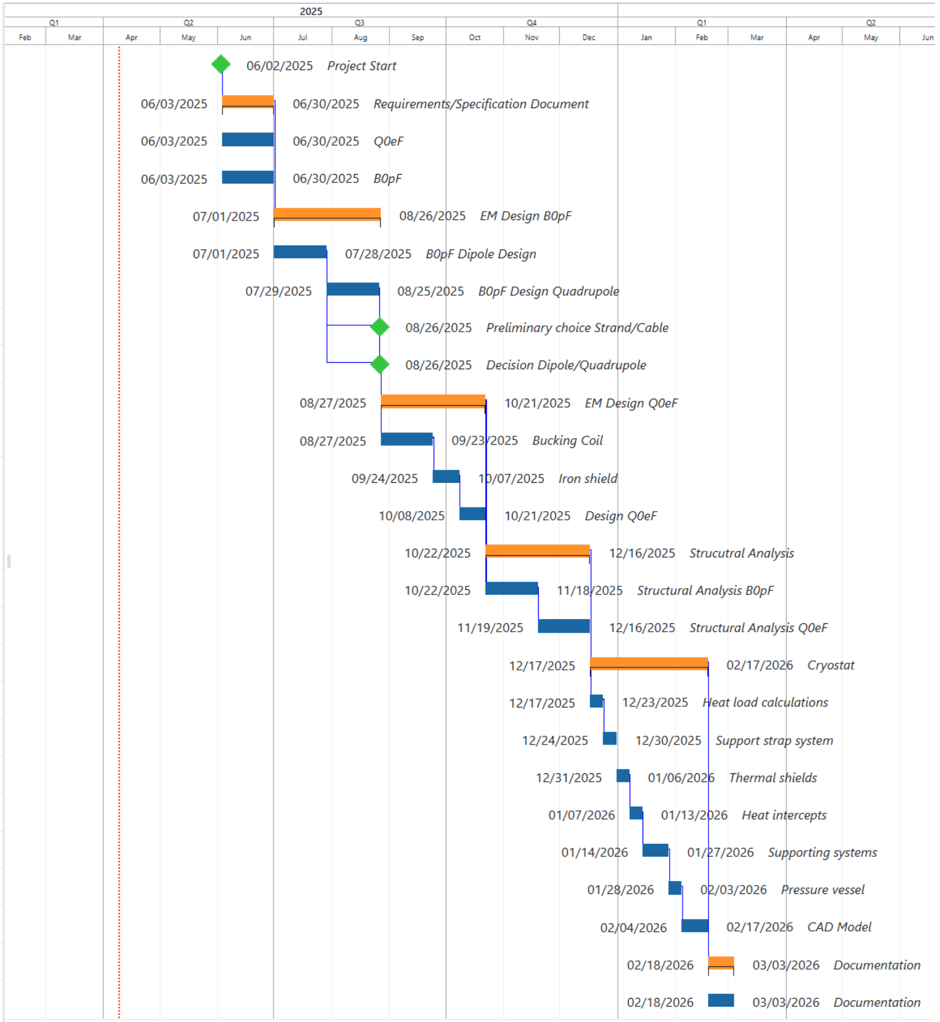
- B0pF important not only for physics but also for machine
  - Separation between beams
- Standalone magnet
  - Relatively easy to separate out
- Combination with detectors – MIT can provide complete package
- Not that sensitive to conductor placement
  - Bucking coil wrecks havoc on field quality – sextupole (known)
  - Large aperture

Initial Work Plan

- Conceptual EM Design
    - B0pF: study dipole vs. quadrupole
        - Fringe field
        - Bucking coil for electron quad
    - Basic quench analysis
    - Margin/loadline
    - **Choice of conductor/cable**
    - Field quality
    - Field map for physics
    - Milestone: preliminary choice of design concept
- Structural analysis
    - Stress/strain analysis of typical direct wind magnet
    - Stress/strain analysis of improved design

Preliminary Schedule

ID	TYPE	SUBJECT	STATUS	START DATE	FINISH DATE	DURATION
63	MILESTONE	Project Start	New	06/02/2025	06/02/2025	
53	PHASE	Requirements/Specification Document	New	06/03/2025	06/30/2025	20 days
55	TASK	Q0eF	New	06/03/2025	06/30/2025	20 days
54	TASK	B0pF	New	06/03/2025	06/30/2025	20 days
51	PHASE	EM Design B0pF	New	07/01/2025	08/26/2025	41 days
56	TASK	B0pF Dipole Design	New	07/01/2025	07/28/2025	20 days
57	TASK	B0pF Design Quadrupole	New	07/29/2025	08/25/2025	20 days
62	MILESTONE	Preliminary choice Strand/Cable	New	08/26/2025	08/26/2025	
58	MILESTONE	Decision Dipole/Quadrupole	New	08/26/2025	08/26/2025	
52	PHASE	EM Design Q0eF	New	08/27/2025	10/21/2025	40 days
59	TASK	Bucking Coil	New	08/27/2025	09/23/2025	20 days
60	TASK	Iron shield	New	09/24/2025	10/07/2025	10 days
61	TASK	Design Q0eF	New	10/08/2025	10/21/2025	10 days
64	PHASE	Strucutral Analysis	New	10/22/2025	12/16/2025	40 days
65	TASK	Structural Analysis B0pF	New	10/22/2025	11/18/2025	20 days
66	TASK	Structural Analysis Q0eF	New	11/19/2025	12/16/2025	20 days
69	PHASE	Cryostat	New	12/17/2025	02/17/2026	45 days
70	TASK	Heat load calculations	New	12/17/2025	12/23/2025	5 days
71	TASK	Support strap system	New	12/24/2025	12/30/2025	5 days
72	TASK	Thermal shields	New	12/31/2025	01/06/2026	5 days
73	TASK	Heat intercepts	New	01/07/2026	01/13/2026	5 days
74	TASK	Supporting systems	New	01/14/2026	01/27/2026	10 days
75	TASK	Pressure vessel	New	01/28/2026	02/03/2026	5 days
76	TASK	CAD Model	New	02/04/2026	02/17/2026	10 days
67	PHASE	Documentation	New	02/18/2026	03/03/2026	10 days
68	TASK	Documentation	New	02/18/2026	03/03/2026	10 days



Open Issues/Questions

- Collaboration
  - EIC?
  - Engage students
- Construction
  - In-house/industrial
  - VPI process: MIT
- VPI impregnation
  - **Insulated** ~~vs non~~
- Measurement equipment
  - No rotating coil setup
- What does it take to make a small demonstrator?
  - Fail fast, fail early
  - MIT has capability to turn around prototypes fast, all in-house (including testing)
- NbTi strand
  - Preliminary design based on 1.065mm dia strand

Magnet Technology at MIT - Expertise

- Magnet design expertise
- EIC IR expertise
- Cryo expertise
- Vacuum expertise
- Structural mechanics expertise
- Software
  - COMSOL
  - ANSYS
  - Opera
- PSFC
  - VPI soldering technique
  - Quench protection

Magnet Technology at MIT – Facilities/Equipment

- MIT Bates
  - ~80 acres of land
  - 100,000 square feet of office and lab space
  - 12 MW of power available
  - Power supplies
    - 2400A, 215kW PS
  - Bates HPRC
- PSFC
  - Fabrication and VPI solder capabilities
  - He Liquifier
    - New Linde 70L/h cryoplant
    - C.f. AUP magnet: needs 1000L (15000lbs)
  - Superconducting magnet test facility (50 kA, 10V)
- Various cryostats

Things to discuss

- Collaboration
- Scope
  - B0pF
  - Direct wind machine for larger cable?
  - Testing?
  - Q1ABpF? (tapered quads)
  - B0ApF?
- Strand/cable
- Next steps

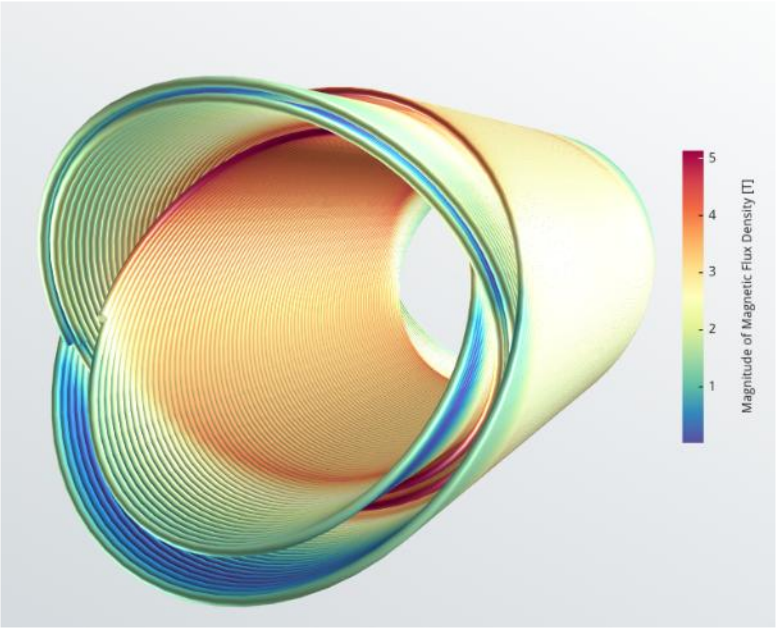
Summary

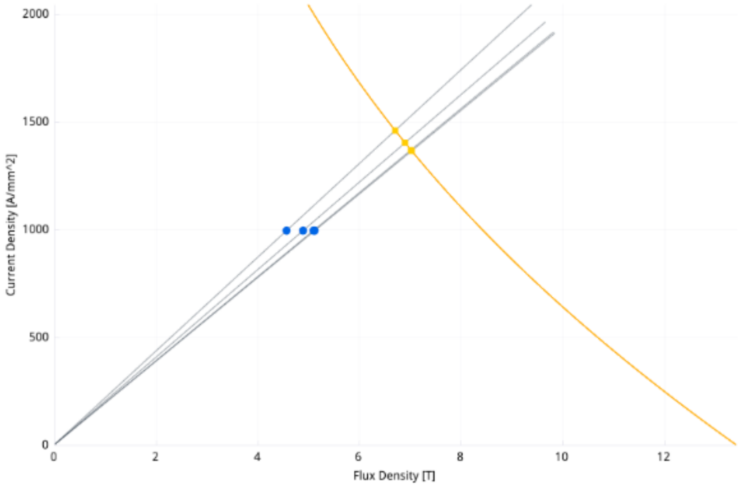
- MIT: long experience in Magnet Technology
  - Francis Bitter Lab, PSFC
  - Peter Marston
  - Bruce Montgomery
  - 20T all HTS fusion magnet
- B0pF: challenging magnet, but MIT has the technology to make this work
  - VPI soldering technique
  - Larger cable to address quench issues
  - Integration with detectors
- Other opportunities?
- Bates and PSFC: experienced team, eager to get to work
  - Teams have a long history working together

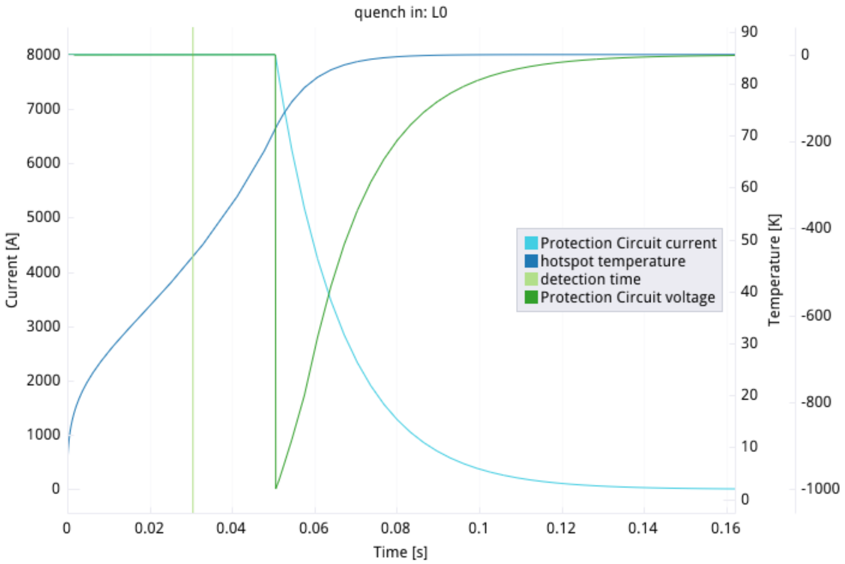
Additional Slides

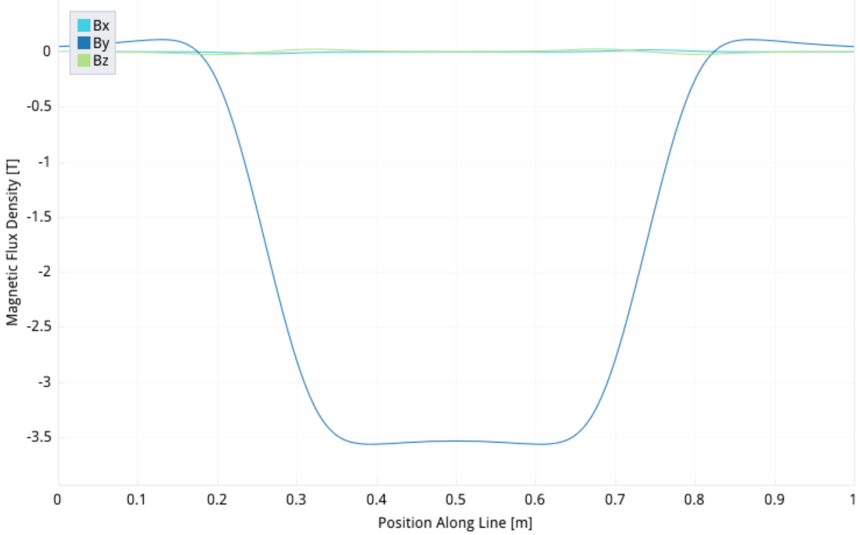
B0ApF

- Requirements:
  - Aperture: 120mm (coil)
  - Length: 0.6m (magnetic length)
  - Field: 3.3T
  - (c.f. HFDW: 80mm aperture, max. 3.1T)
- Same cable as B0pF
  - Hot spot <90K









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