The SPARC Toroidal Field Model Coil (TFMC)

Zach Hartwig | Project Head | MIT

Given on behalf of the TFMC Team

MT27 | Fukuoka, Japan | 2021

All credit to the exceptional team that delivered the TFMC Project

Commonwealth
Fusion Systems

Plasma Science and
Fusion Center

All credit to the exceptional team that delivered the TFMC Project

- *Chief Engineer*: Rui Vieira
- *Group leaders*: Brian LaBombard (E&M), Chris Lammi (Analysis), Joy Dunn (Manufacturing),
  Ted Golfinopoulos and Phil Michael (Test)
- *Team*:
  - Sue Agabian
  - Dave Arsenault
  - Raheem Barnett
  - Mike Barry
  - Bill Beck
  - Dave Bellofatto
  - Willie Burke
  - Jason Burrows
  - Bill Byford
  - Charlie Cauley
  - Sarah Chamberlain
  - David Chavarria
  - Jessica Cheng
  - Jim Chicarello
  - Karen Cote
  - Corinne Cotta
  - Mary Davenport
  - Van Diep
  - Eric Dombrowski
  - Jeff Doody
  - Raouf Doos
  - Brian Eberlin
  - Jose Estrada
  - Vinny Fry
  - Matt Fulton
  - Sarah Garberg
  - Bob Granetz
  - Aliya Greenberg
  - Sam Heller
  - Amanda Hubbard
  - Ernie Ihloff
  - Jim Irby
  - Mark Iverson
  - Peter Jardin
  - Sergey Kuznetsov
  - Rich Landry
  - Ed Lamere
  - Rick Lations
  - Rick Leccacorvi
  - Matt Levine
  - George MacKay
  - Kristen Metcalfe
  - Phil Michael
  - Kevin Moazeni
  - Bob Mumgaard
  - John Mota
  - Theodore Mouratidis
  - JP Muncks
  - Rick Murray
  - Tesha Myers
  - Dan Nash
  - Ben Nottingham
  - Andy Pfeiffer
  - Sam Pierson
  - Clayton Purdy
  - Alexi Radovinsky
  - DJ Ravikumar
  - Veronica Reyes
  - Ron Rosati
  - Mike Rowell
  - Dior Sattarov
  - Wayne Saunders
  - Pat Schweiger
  - Shane Schweiger
  - Maise Shepard
  - Syunichi Shiraiwa
  - Maria Silveira
  - Brandon Sorbom
  - Pete Stahle
  - Ken Stevens
  - Joe Stiebler
  - Deepthi Tammana
  - Tom Toland
  - Dave Tracey
  - Ronnie Turcotte
  - Kiran Uppalapati
  - Matt Vernacchia
  - Chris Vidal
  - Alex Warner
  - Amy Watterson
  - Dennis Whyte
  - Sidney Wilcox
  - Michael Wolf **
  - Bruce Wood
  - Lihua Zhou
  - Alex Zhukovsky

All work funded by Commonwealth Fusion Systems

[**] Karlsruhe Institute of Technology

Context: High-field fusion energy and early HTS R&D (2 min)

The SPARC Toroidal Field Model Coil (12 min)

- *Program*: Requirements and objectives
- *Magnet*: Specifications, design, and assembly
- *Facility*: Capabilities and key enabling technologies
- *Test*: Results of the first full performance 20 T ramp

Summary (1 min)

This talk is intended as a high-level overview and status of an extensive on-going project.
More in-depth presentation of the project will be in upcoming publications and conferences.

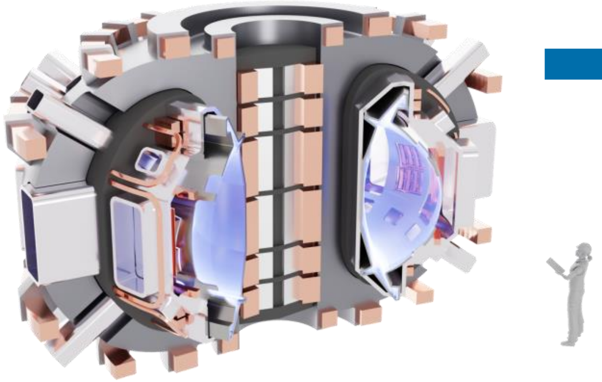
HTS magnets enable the high-field path to fusion energy

High-field fusion science → **Phase 1: Technology R&D** → **Phase 2: Demonstration** → **Phase 3: Commercialization**

Alcator C-Mod

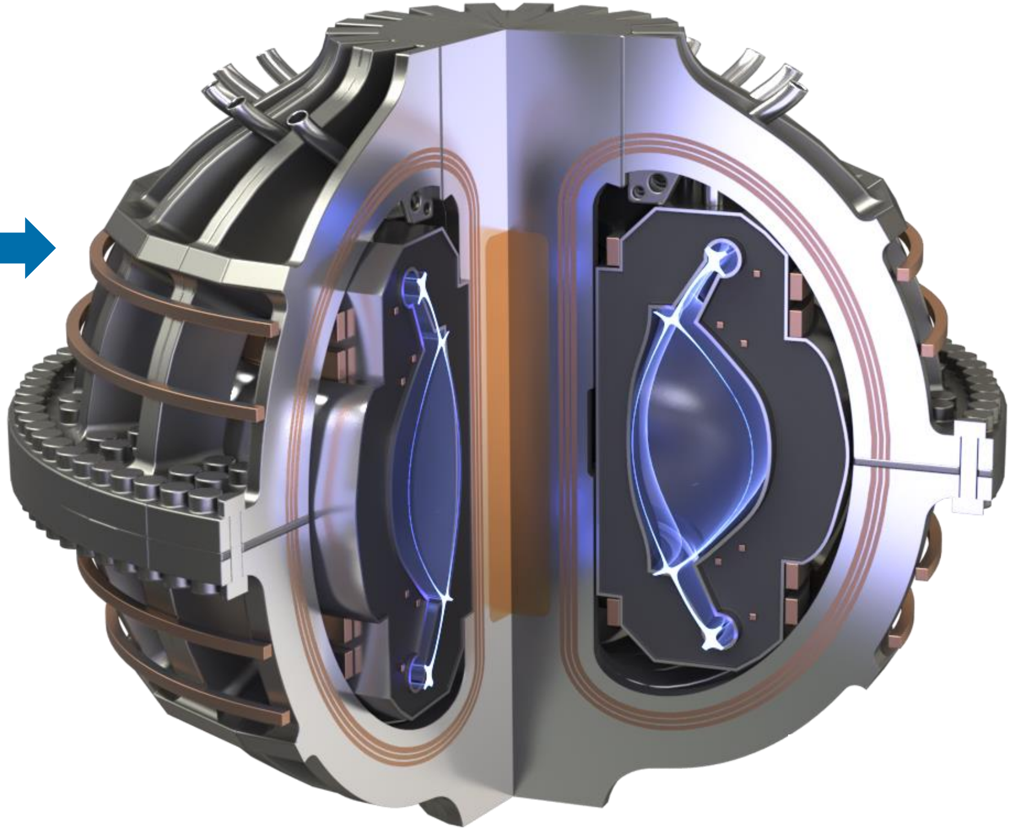
HTS CICC-like concepts

No-insulation HTS concepts



SPARC

Q>2



ARC

2016 **2021** **2025** **2030s**

HTS magnets enable the high-field path to fusion energy

High-field fusion science → **Phase 1: Technology R&D** → **Phase 2: Demonstration** → **Phase 3: Commercialization**

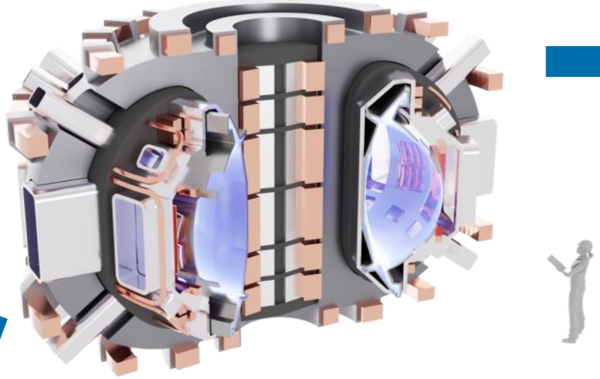
Alcator C-Mod

HTS CICC-like concepts

No-insulation HTS concepts

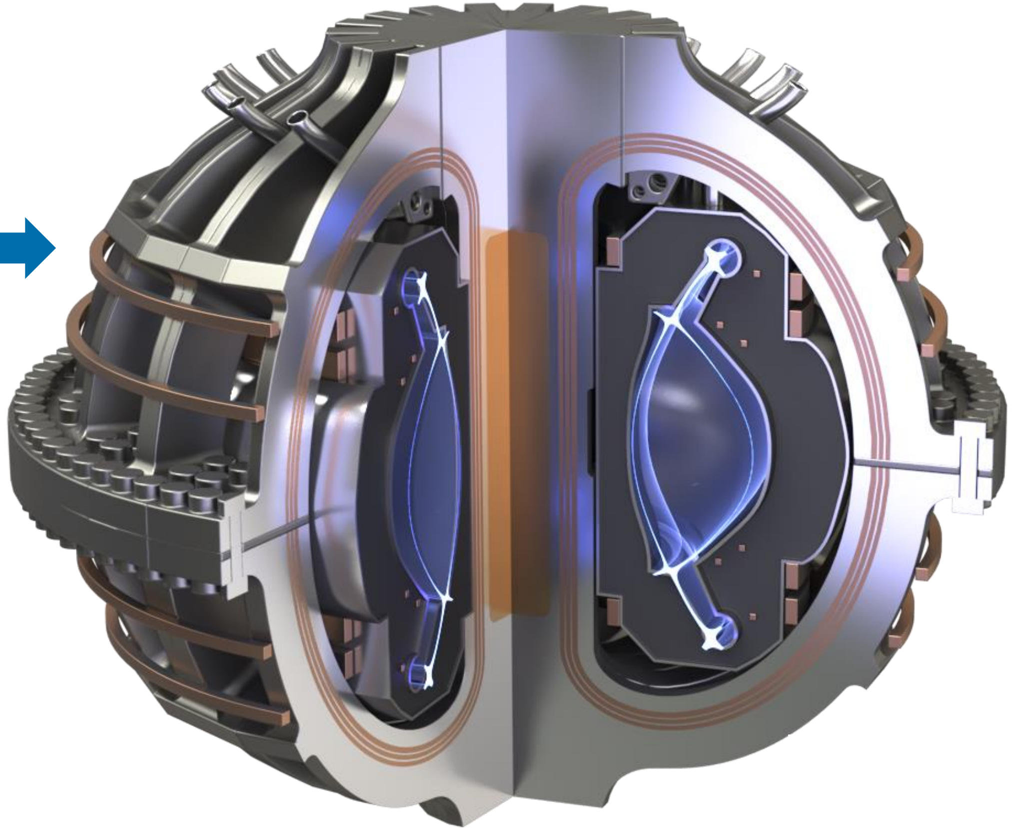
SPARC magnet R&D (2017-2019)

HTS model coil (2019-2021)



SPARC

Q>2



ARC

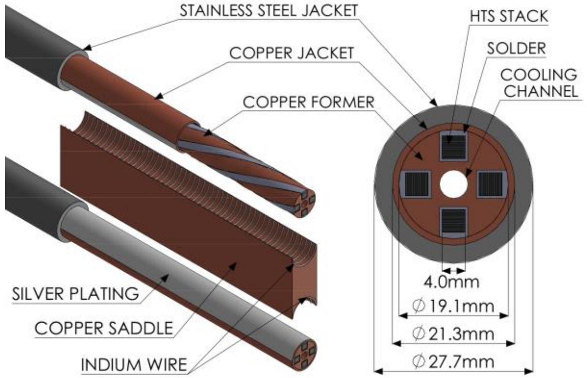
2016 **2021** **2025** **2030s**

Early R&D resulted in two viable high-field HTS technologies

Starting in 2017, both technologies were built on HTS magnet work pioneered at MIT

VIPER HTS cables

- Based on traditional SC CICC cables using the TSTC architecture for REBCO tapes [1]
- Demonstrated high IxB robustness, fiber optic quench detection, ~nΩ joints [2,3]
- Developed for *multiple* SPARC applications:
  - High current feeder cables
  - AC magnets: SPARC CS, PF (w/ modifications)
  - DC magnets: back-up for SPARC TF



VIPER SULTAN assembly (2018)

[1] M. Takayasu *et al.,* IEEE Trans. Appl. Sup., **21** (2011) 2340
[2] Z. S. Hartwig *et al.,* SuST, **33** (2020) 11LT01
[3] E. E. Salazar *et al.,* SuST, **34** (2021) 035027

Early R&D resulted in two viable high-field HTS technologies

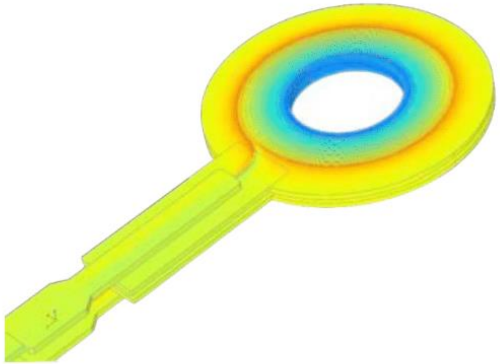
Starting in 2017, both technologies were built on HTS magnet work pioneered at MIT

VIPER HTS cables

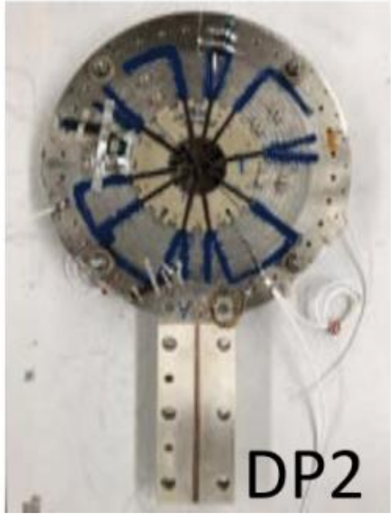
- Based on traditional SC CICC cables using the TSTC architecture for REBCO tapes [1]
- Demonstrated high IxB robustness, fiber optic quench detection, ~nΩ joints [2,3]
- Developed for *multiple* SPARC applications:
  - High current feeder cables
  - AC magnets: SPARC CS, PF (w/ modifications)
  - DC magnets: back-up for SPARC TF

No Insulation No Twist (NINT) Coils

- HTS cable-based adaptation of single tape NI coils [4] with innovations to enable large-scale fusion magnets
- Demonstrated passive quench handling, advanced EM modeling capabilities, low voltage operation
- Developed for a *specific* SPARC application:
  - DC magnet: SPARC TF magnet -> The TFMC



EM simulation of a NINT coil



[1] M. Takayasu *et al.*, IEEE Trans. Appl. Sup., **21** (2011) 2340
[2] Z. S. Hartwig *et al.*, SuST, **33** (2020) 11LT01
[3] E. E. Salazar *et al.*, SuST, **34** (2021) 035027

[4] S. Hahn *et al.*, IEEE Trans. Appl. Sup., **21** (2011) 1592

The TFMC Project seeks to eliminate risk in the production and operation of large-scale HTS DC magnets

RISK	
Design	Achieve SPARC requirements (B_{peak}, J_{wp}, $P_{cooling}$, etc); EM modeling tools; …
Supply Chain	HTS supply and characterization; Structural materials; large-scale vendors; …
Fabrication	Tooling; Manufacturing process and equipment; Process control, Scalability, …
High field	Structural loading; IxB and strain on HTS; I_c limits on HTS; …
Operation	Current leads; Feeder cables; Instrumentation; Cooling system; …
Quench	Stored magnetic energy; high pressure coolant; induced eddy forces; …

Objective: Design, build, and test (1) a representative SPARC TF model coil and (2) a fully capable test facility in 2 years to maximize risk retirement for SPARC

Time Frame: July 2019 – Sep 2021

Team Size: 80+ people at 3 sites

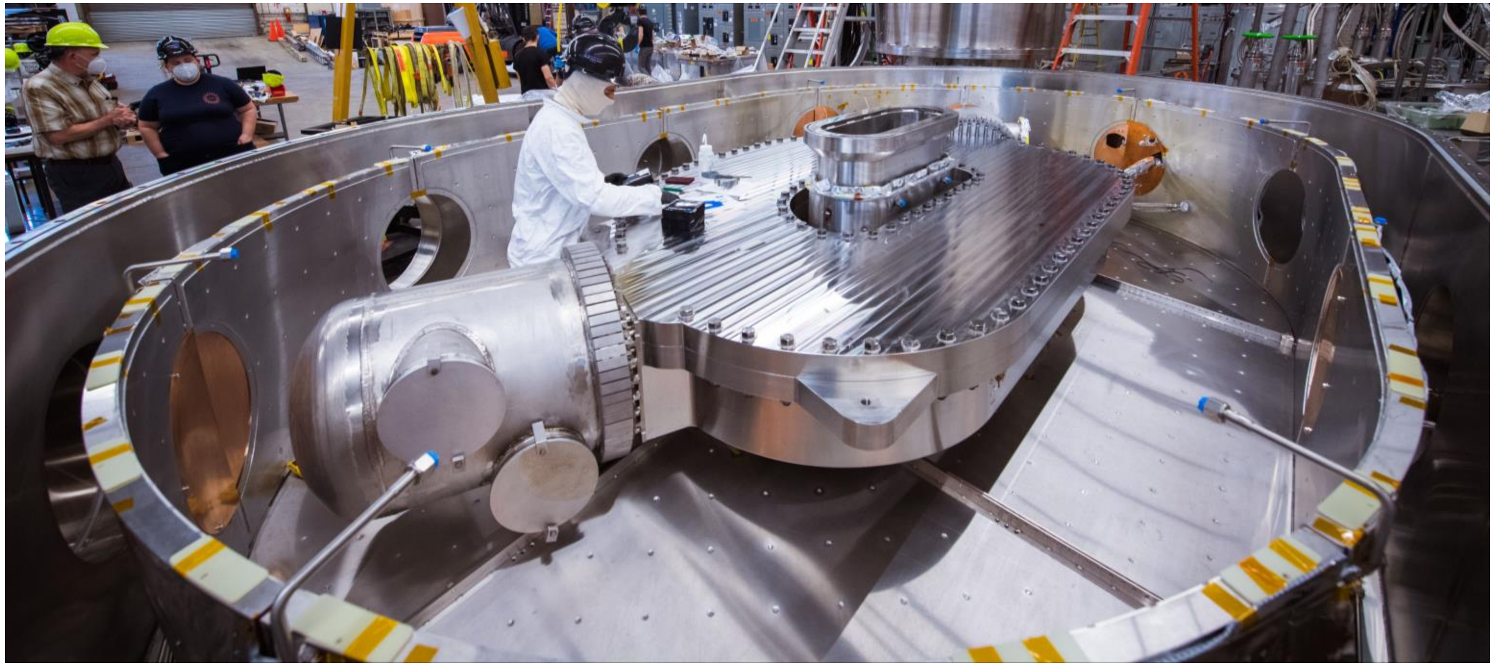
The TFMC is the first NI large-scale high-field fusion magnet

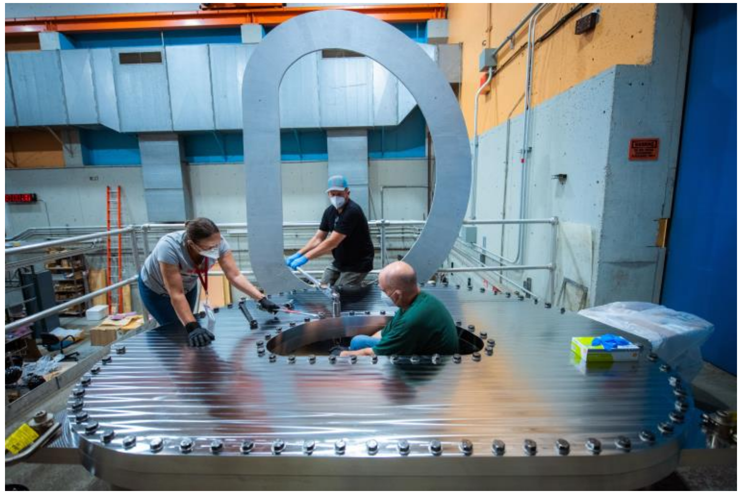
Targeting peak fields >20 T with simple manufacturing, novel cooling, passive quench handling

1.9 meters

2.9 meters

Parameters of the SPARC Toroidal Field Model Coil

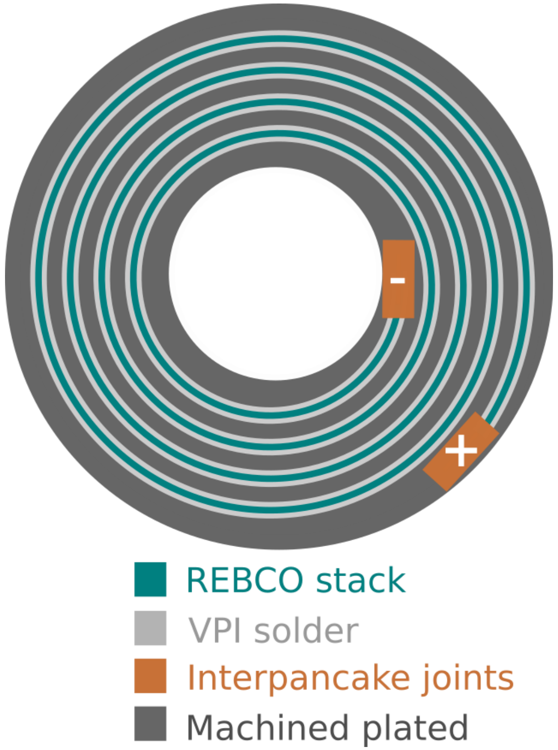




Nominal Operating Parameter	Value
Number of pancakes	16
Total turns	256
Total REBCO tape	270 km
Operating temperature	20 K
Coolant type	Supercrit. He
Operating coolant pressure	20 bar
Operating terminal current	40 kA
Peak magnetic field	20 T
Peak IxB force on REBCO	800 kN/m
Inductance	0.14 H
Magnetic 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

TFMC uses an HTS stack-in-plate channel design

- Pancakes
  - A machined steel radial plate with channels for HTS and cooling
  - The HTS is stack wound into the grooves
  - The HTS stack is terminated at internal pancake-to-pancake joints
  - VPI solder process bonds mechanically, electrically, and thermally



TFMC is based on NI HTS stack-in-plate channel design

- Pancakes
  - A machined steel radial plate with channels for HTS and cooling
  - The HTS is stack wound into the grooves, capped with copper
  - The HTS stack is terminated at internal pancake-to-pancake joints
  - VPI solder process bonds mechanically, electrically, and thermally
- Winding pack
  - The core of the winding pack comprises 16 stacked, internally jointed pancakes
  - Winding pack has 2 top and bottom termination plates for current leads
- Magnet
  - The winding pack is contained within a steel structural and pressure vessel case
  - High pressure plena on the case enable current, cooling, and instrumentation

TFMC is based on NI HTS stack-in-plate channel design

- Pancakes
  - A machined steel radial plate with channels for HTS and cooling
  - The HTS is stack wound into the grooves, capped with copper
  - The HTS stack is terminated at internal pancake-to-pancake joints
  - VPI solder process bonds mechanically, electrically, and thermally
- Winding pack
  - The core of the winding pack is 16 stacked, internally jointed pancakes
  - Winding pack has 2 top and bottom termination plates for current leads
- Magnet
  - The winding pack is contained within a steel structural and pressure vessel case
  - High pressure plena on the case enable current, cooling, and instrumentation

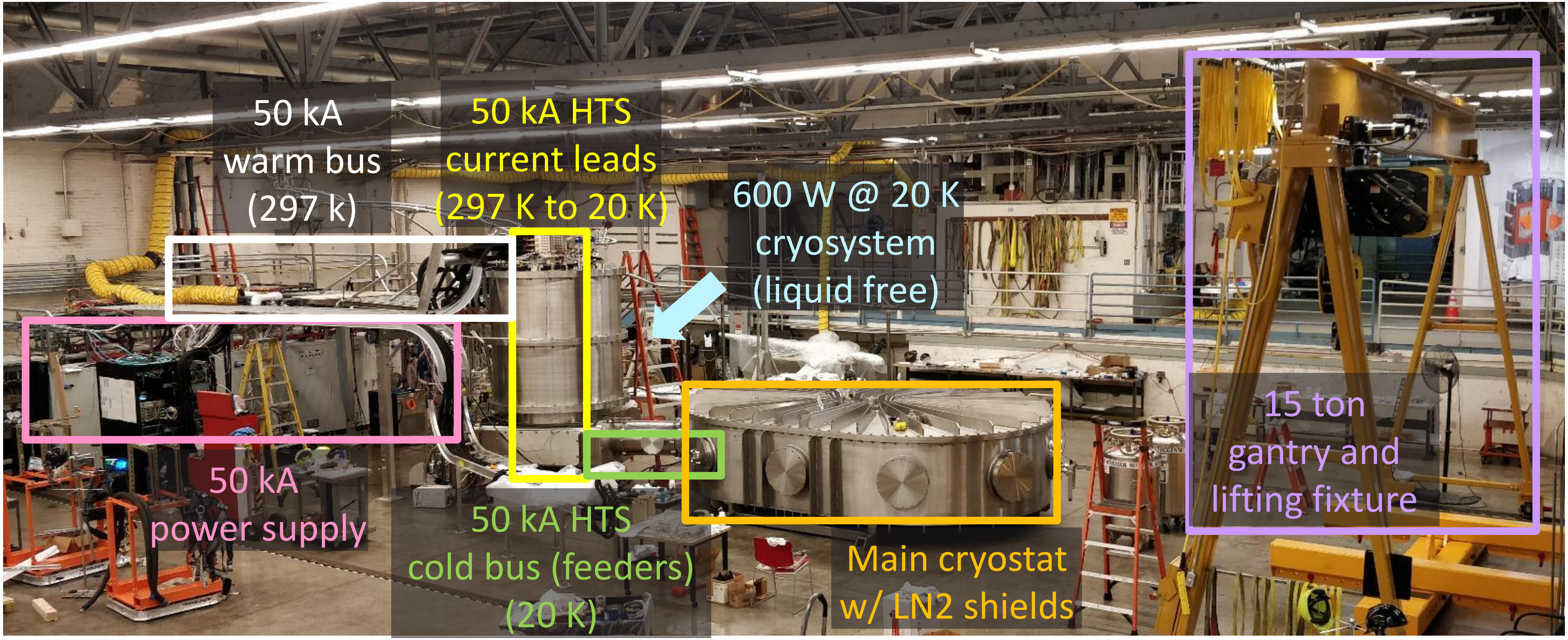
Propose Design Features	Advantage(s) to be proven in the TFMC Project
Modular, simple construction	Rapid assembly; Maintenance options; scalable for commercial production
Intrinsically low voltage (<1 V)	Minimal insulation; simple fabrication, low voltage leads and feeds, safety
High thermal stability	Robust to damage, defects, and off-normal events
Pressure vessel cooling approach	Enhanced heat removal; Local cooling optimization; simplified manifolding
High winding pack current density	Compact magnet; expanded design space
Passively safe to quench	No quench detection systems

A new magnet test facility has been established at MIT

Facility provides substantial test capabilities for the TFMC and future magnet R&D

A new magnet test facility has been established at MIT

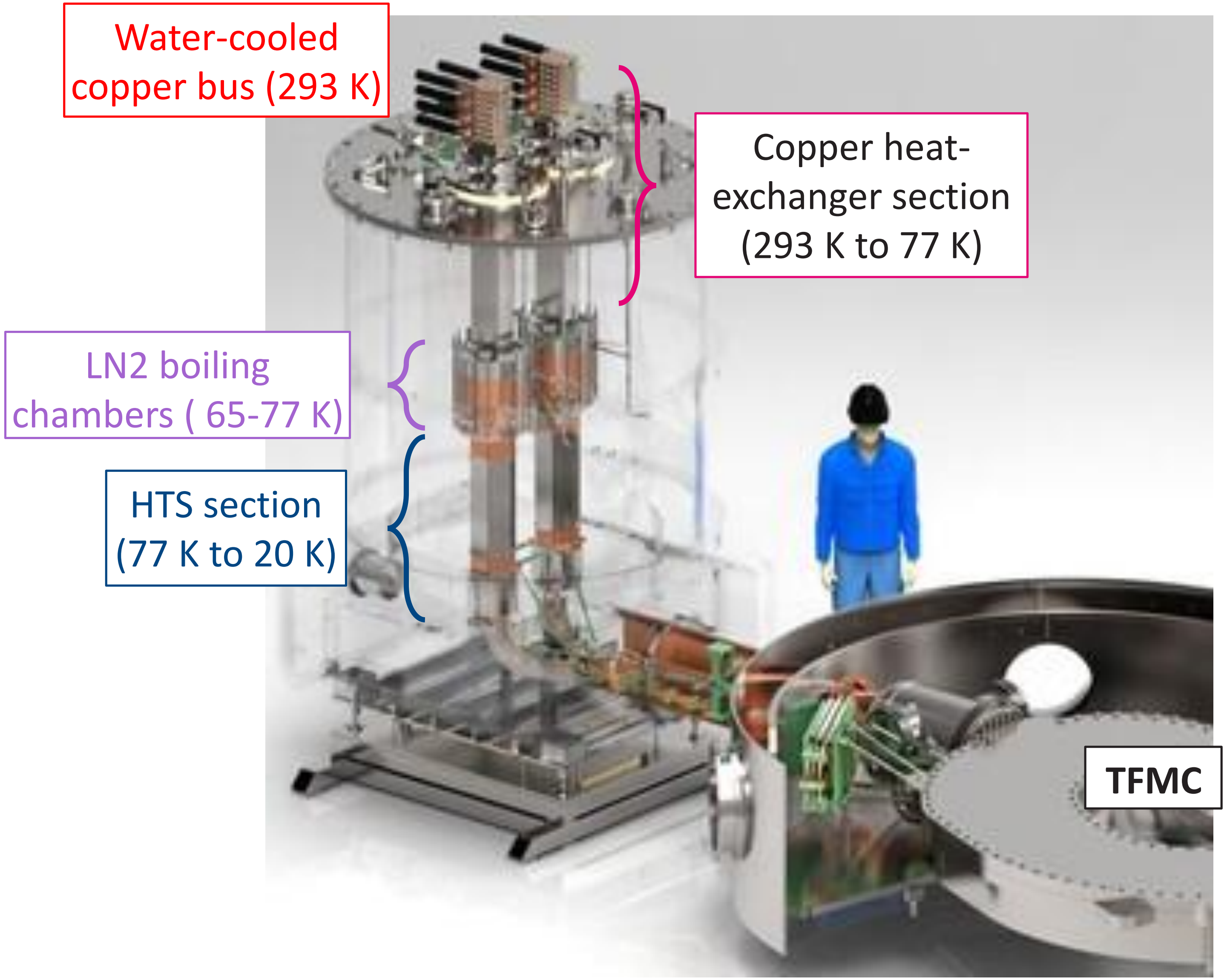
Facility provides substantial test capabilities for the TFMC and future magnet R&D



Not shown: SHe and LN2 distribution systems; Vacuum systems; I&C system; Safety systems; Control Room

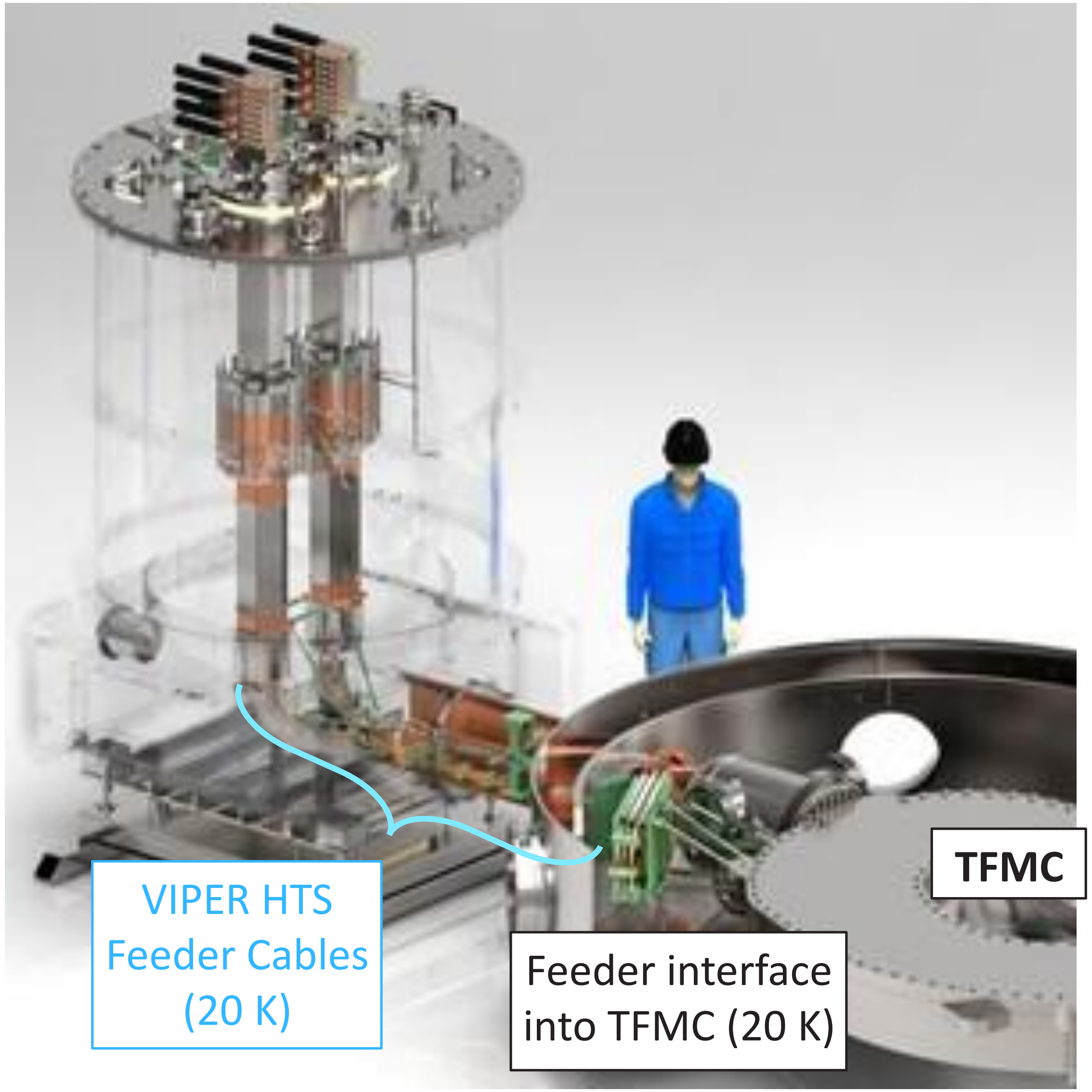
Binary 50 kA HTS current leads and feeder system proven

- Binary HTS current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN2 section can be sub-cooled to enable high current performance
  - In-house development required to meet performance and schedule requirements



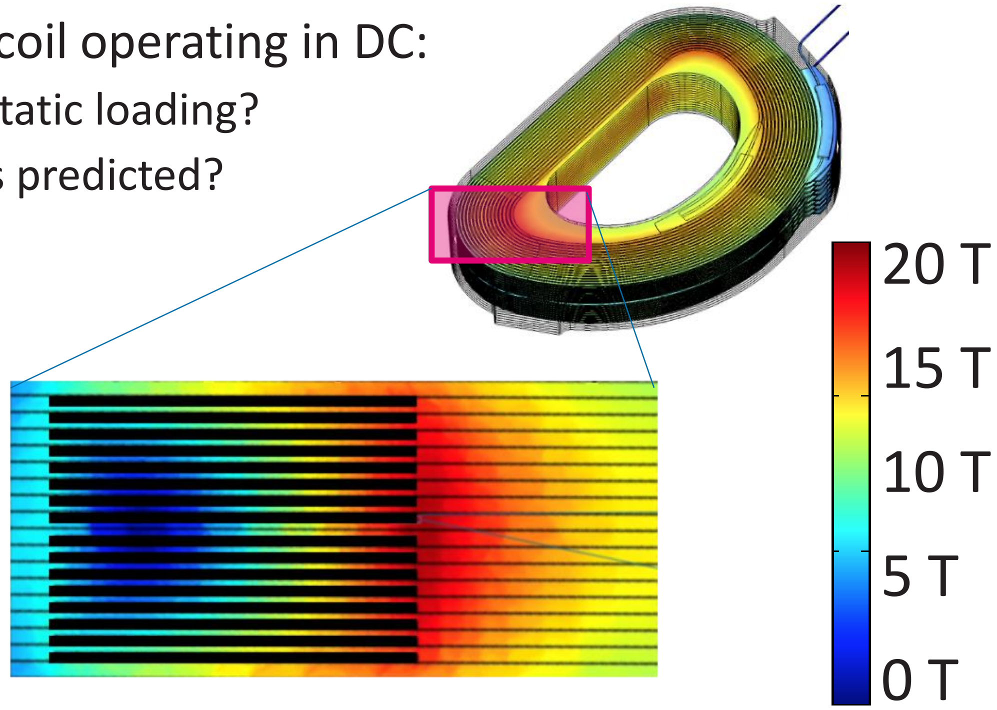
Binary 50 kA HTS current leads and feeder system proven

- Binary HTS current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN2 section can be sub-cooled to enable high current performance
  - In-house development required to meet performance and schedule requirements
- Feeder system to magnet composed of 3 sets of VIPER HTS cables
  - Complex shape to mitigate thermally induced differential strain due to cooldown
  - 3 sets of joints to simplify assembly
  - Unique high-pressure feedthrough to enable connection to TFMC magnet
- Leads and feeder system commissioned in advance of TFMC installation
  - Tested to 41 kA (max required current)
  - All joints with 1.5 – 2.0 nOhm performance



1st Test: Assess DC operation of the TFMC at full performance

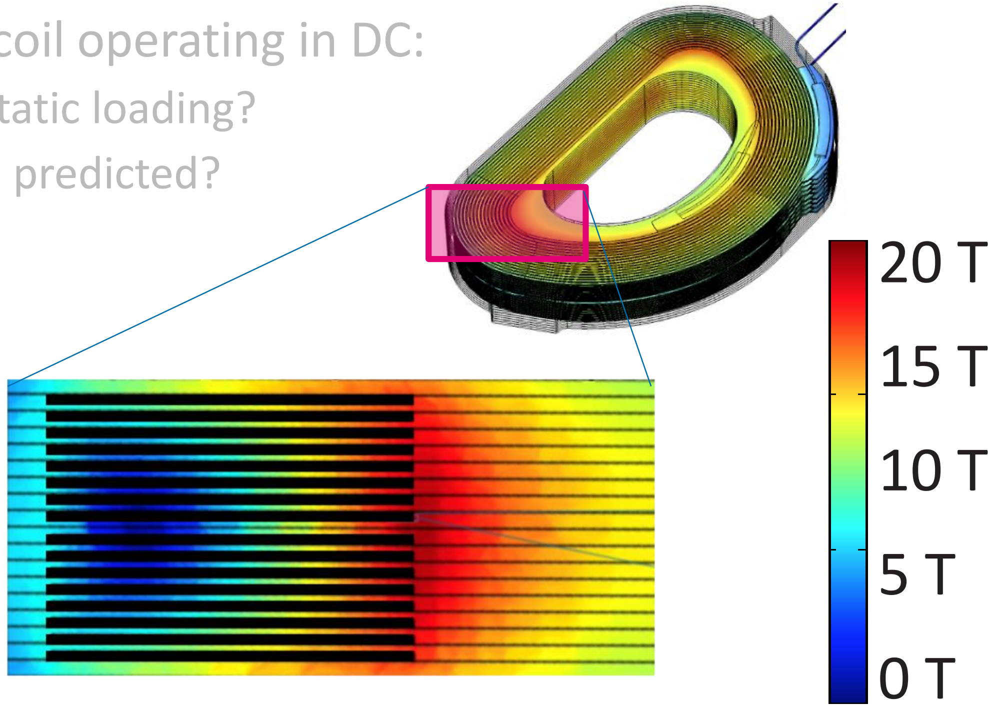
- First full-performance test asked 3 primary questions of the coil operating in DC:
  - Does the TFMC precisely match design B-field and withstand static loading?
  - Does the coil distribute current during charging and flat-top as predicted?
  - Does the TFMC distribute voltage (heating) as predicted?



EM simulations of B-field at $I_{terminal}$=40 kA (top) and the test plan for the approach to 20 T (bottom)

1st Test: Assess DC operation of the TFMC at full performance

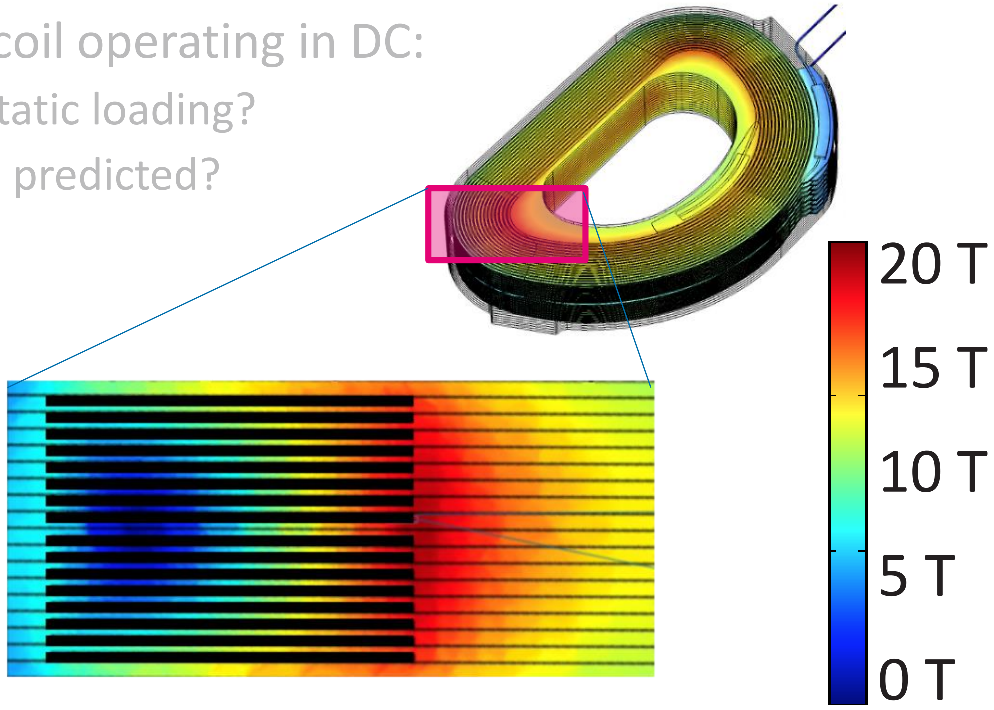
- First full-performance test asked 3 primary questions of the coil operating in DC:
    - Does the TFMC precisely match design B-field and withstand static loading?
    - Does the coil distribute current during charging and flat-top as predicted?
    - Does the TFMC distribute voltage (heating) as predicted?
- The winding pack contained an extensive array of *internal* embedded instrumentation to provide complete characterization of the coil electrically and thermally
    - >180 voltage taps (internal)
    - >30 Cernoxes RTDs (internal)
    - 4 embedded hall probes (internal)
    - Helium flow and pressure sensors (internal)
    - Strain gauges (external)
- Two external 3D hall probes were used to produce robust confirmation of magnetic field metrology
    - Calibrated against fiber optic current sensors (FOCS) measuring azimuthal current in the coil



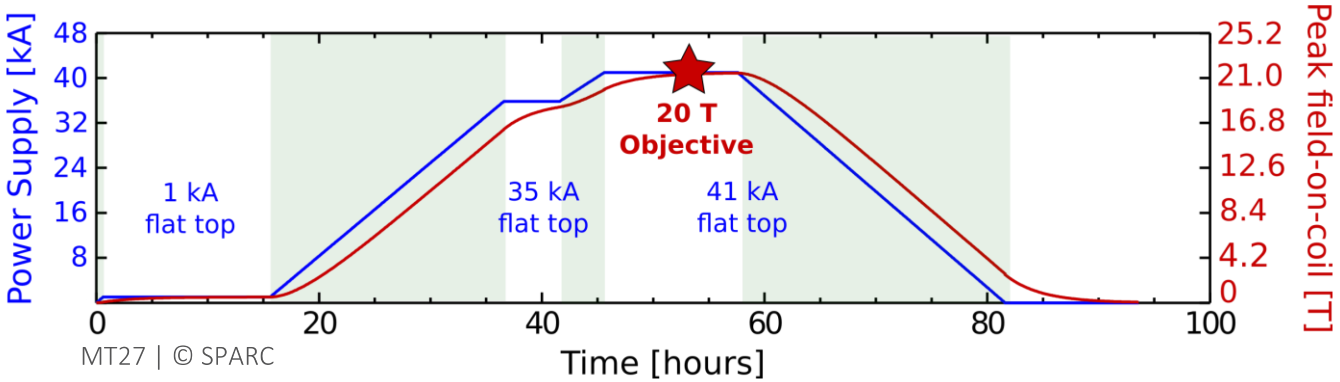
EM simulations of B-field at $I_{terminal}$=40 kA (top) and the test plan for the approach to 20 T (bottom)

1st Test: Assess DC operation of the TFMC at full performance

- First full-performance test asked 3 primary questions of the coil operating in DC:
    - Does the TFMC precisely match design B-field and withstand static loading?
    - Does the coil distribute current during charging and flat-top as predicted?
    - Does the TFMC distribute voltage (heating) as predicted?
- The winding pack contained an extensive array of *internal* embedded instrumentation to provide complete characterization of the coil electrically and thermally
    - >180 voltage taps (internal)
    - >30 Cernoxes RTDs (internal)
    - 4 embedded hall probes (internal)
    - Helium flow and pressure sensors (internal)
    - Strain gauges (external)
- Two external 3D hall probes were used to produce robust confirmation of magnetic field metrology
    - Calibrated against fiber optic current sensors (FOCS) measuring azimuthal current in the coil



EM simulations of B-field at $I_{terminal}$=40 kA (top) and the test plan for the approach to 20 T (bottom)

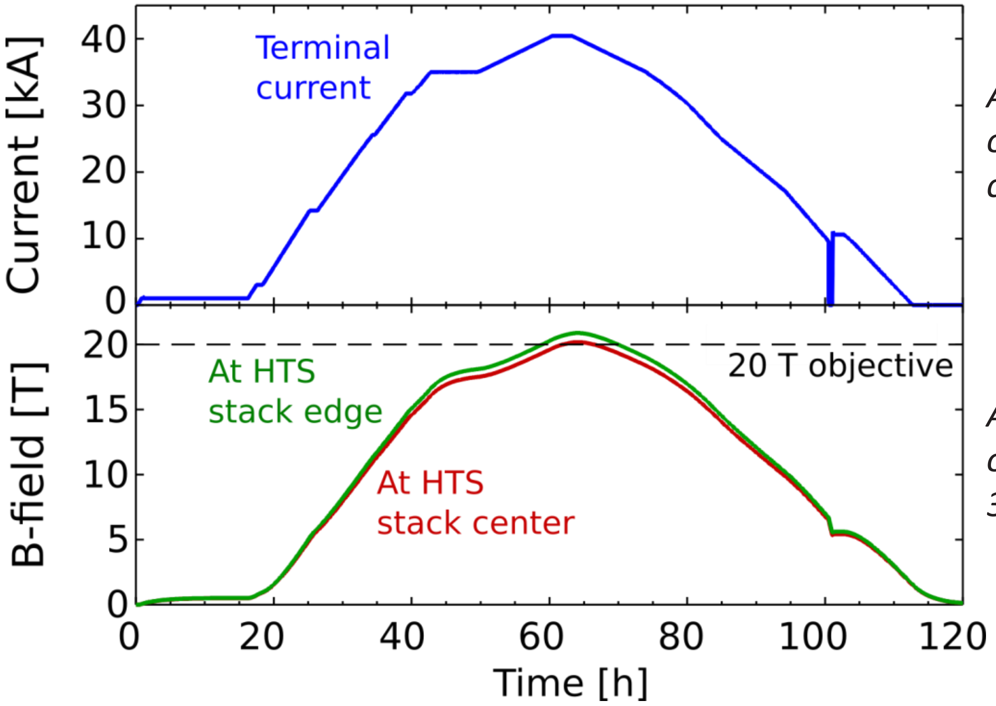


1st Test: Key performance objectives met for the TFMC at 20 T

First full performance test largely followed the plan predicted by experience and modeling:

Vacuum: 2 day pump down to 10^{-6} torr vacuum
Cooldown: 7 day cooldown from 293 to 18 K
Charging: 5 day test campaign to ramp to 20 T back to 0 T

Experimental measurements of 20 T ramp



As measured on fiber optic current sensor

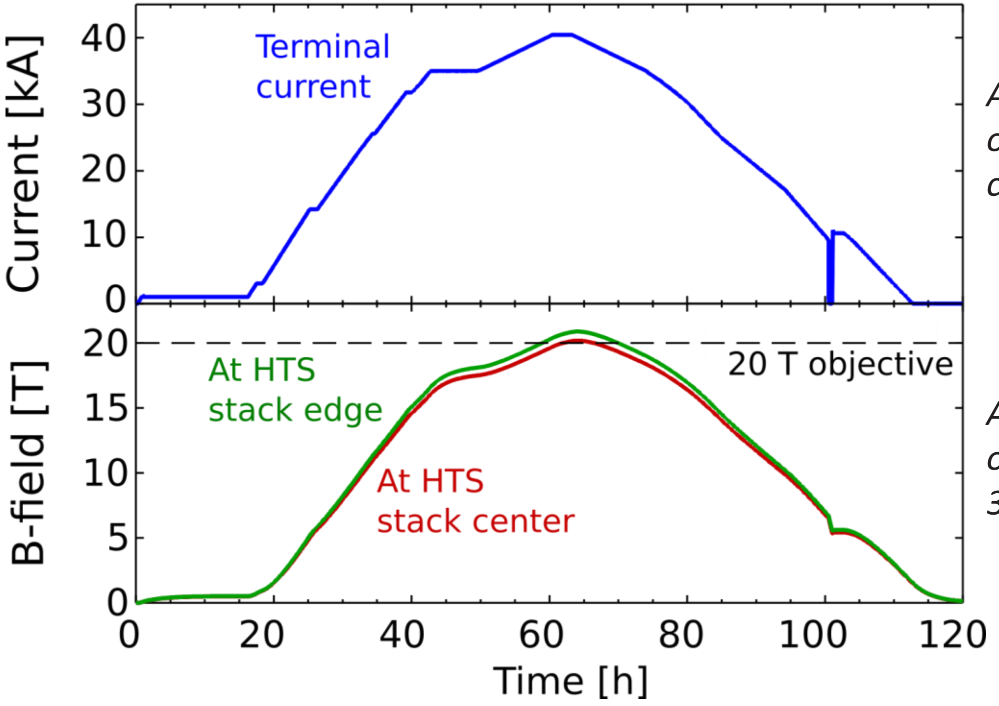
As measured on 2 external 3D hall probes

1st Test: Key performance objectives met for the TFMC at 20 T

First full performance test largely followed the plan predicted by experience and modeling:

Vacuum: 2 day pump down to 10^{-6} torr vacuum
Cooldown: 7 day cooldown from 293 to 18 K
Charging: 5 day test campaign to ramp to 20 T back to 0 T

Experimental measurements of 20 T ramp



As measured on fiber optic current sensor

As measured on 2 external 3D hall probes

High-field performance confirmed

- B~20.3 T average on inner radius HTS stacks
- IxB>800 kN/M radial loading on HTS stacks

Low-resistance internal pancake-to-pancake joints

- R of 1.0-1.5 nΩ at maximum current of ~40 kA
- Structural robust within 5 T (outer) and 12 T (inner)

Excellent cryogenic performance, stability, control

- WP temperature control between 18 – 32 K
- WP temperature uniformity of 1 – 2 K

Significant structural loading handled as designed

- Winding pack stress >800 MPa, case >900 MPa
- Smooth stress-strain; strain gauges matched prediction

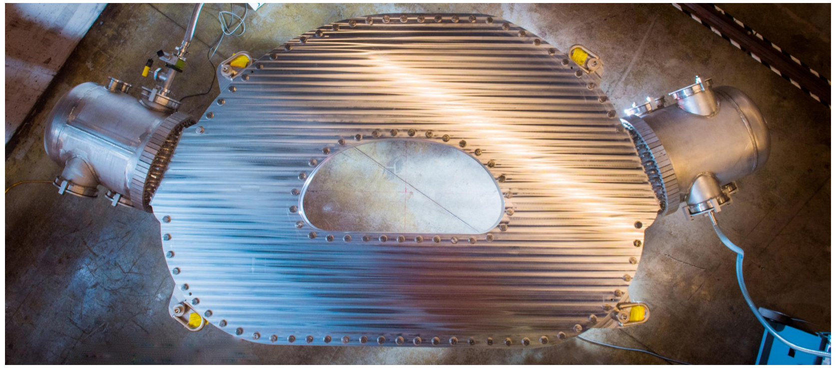
Excellent matches to simulated predictions

- Global B-field magnitude and 3D metrology
- Magnet charging/settling times
- Voltage distribution within pancakes
- Cryogenic cooling and temperature distributions

The TFMC has established a solid foundation to design and operate large-scale, large-bore HTS magnets exceeding 20 tesla

The TFMC has begun a new generation of superconducting magnets at unprecedented performance and compact size

- Established manufacturing knowledge base to begin commercial-scale production
- Created enabling innovations (e.g. 50 kA HTS current leads, advanced EM modeling, etc.)
- Resulted in establishment of a new, highly capable magnet test facility at MIT



The TFMC and other MIT-CFS R&D will continue to retire critical risk for SPARC and large-scale NI HTS magnets

- Exploring passive quench handling and assessment of operation limits
- Robustness to mechanical and thermal cycling
- EM model validation and extrapolation to the SPARC TF design

TFMC-like performance (> 20 T peak field-on-coil) would enable SPARC to achieve a $Q_{physics}$=11 (burning plasma regime)

- 40x smaller net-energy fusion tokamaks than traditional LTS magnets
- Increased future economic prospects (= P_{fusion} with much less mass/volume and cost)