The SPARC Toroidal Field Model Coil Project

Zach Hartwig

Associate Professor | MIT
PI and Head | TFMC Project

CERN Seminar
July 27 2022

PSFC

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

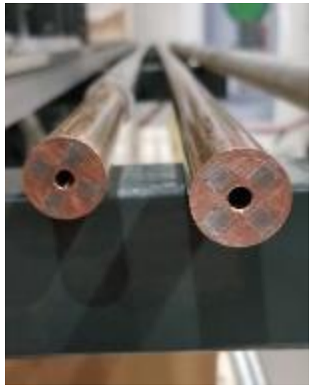
- *Chief Engineer*: Rui Vieira
- *Group leaders*: Brian LaBombard (E&M), Chris Lammi (Analysis), Joy Dunn (Manufacturing), Ted Golfinopoulos and Phil Michael (Test)
- *Team*:
  - Sue Agabian
  - Dave Arsenault
  - Raheem Barnett
  - Mike Barry
  - Bill Beck
  - Dave Bellofatto
  - Willie Burke
  - Jason 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

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

1. Developed REBCO conductor technologies (2017-2019)



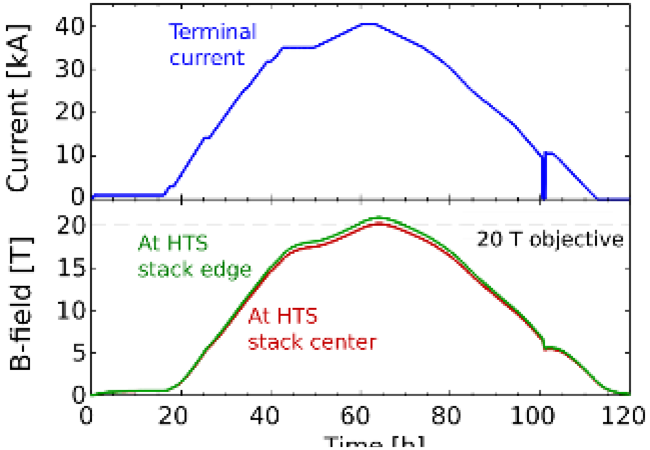
Cables

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 accelerated high-field SC magnets for fusion

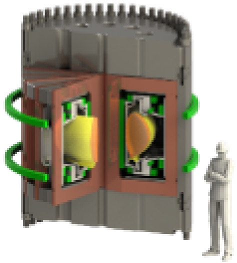
MIT
PSFC

High-field fusion science

Phase 1: Technology R&D

Phase 2: Demonstration

Phase 3: Commercialization



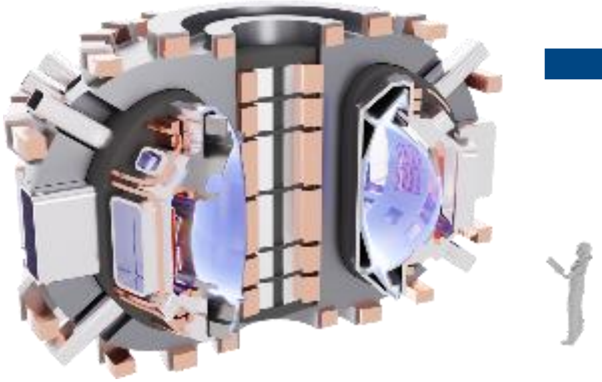
Alcator C-Mod

REBCO CIC concepts

No-insulation REBCO concepts

2016

2021

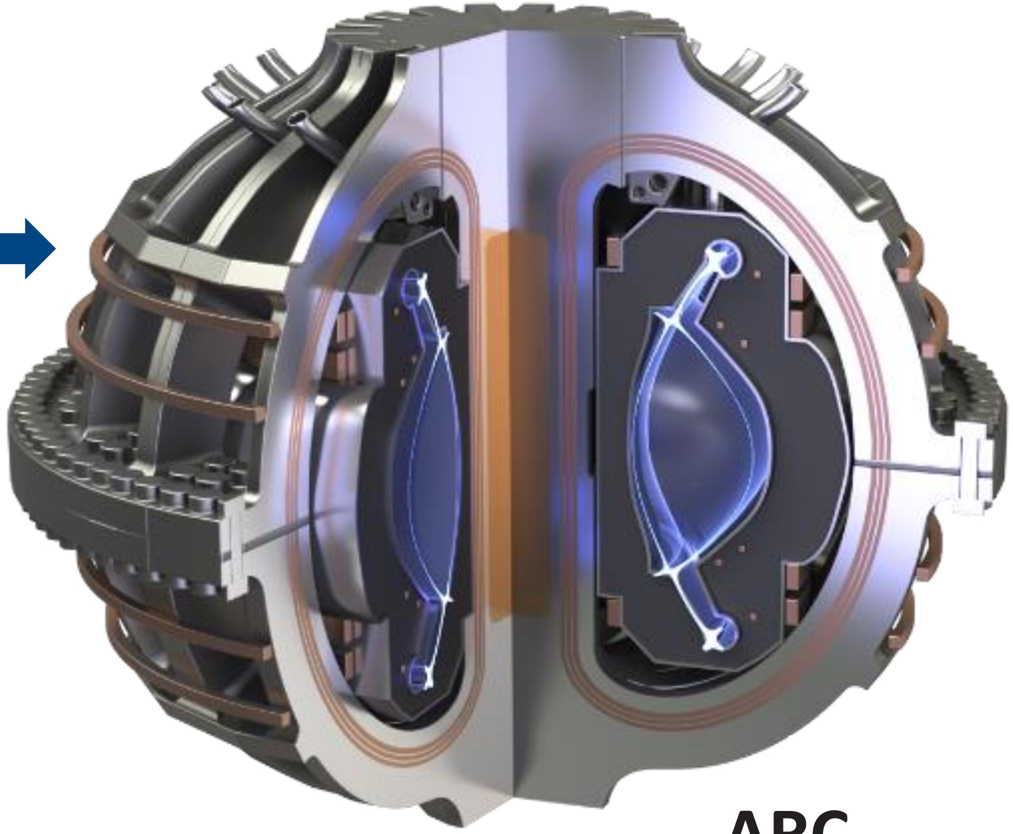


SPARC

Q>2

P > 100 MW

2025



ARC

Q > 10

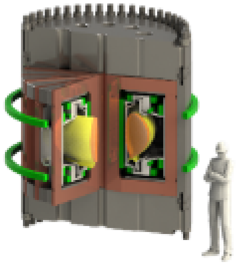
P > 200 MWe

2030s

The TFMC Project accelerated high-field SC magnets for fusion

MIT
PSFC

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

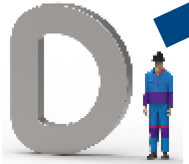


Alcator C-Mod

REBCO CIC concepts

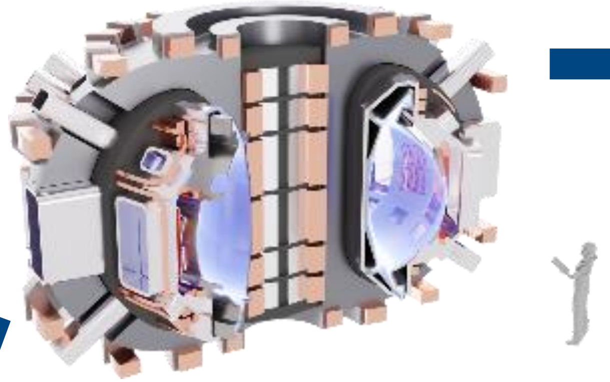
No-insulation REBCO concepts

SPARC magnet R&D (2017-2019)



HTS model coil (2019-2021)

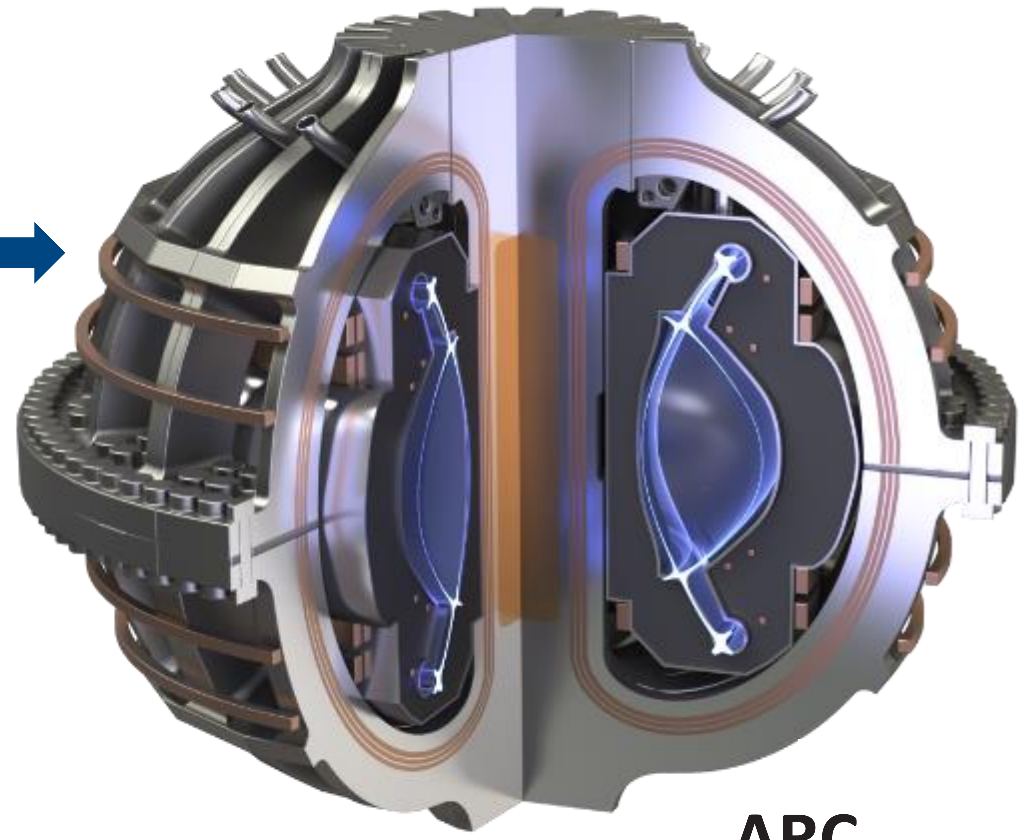
The TFMC Project



SPARC

Q>2

P > 100 MW



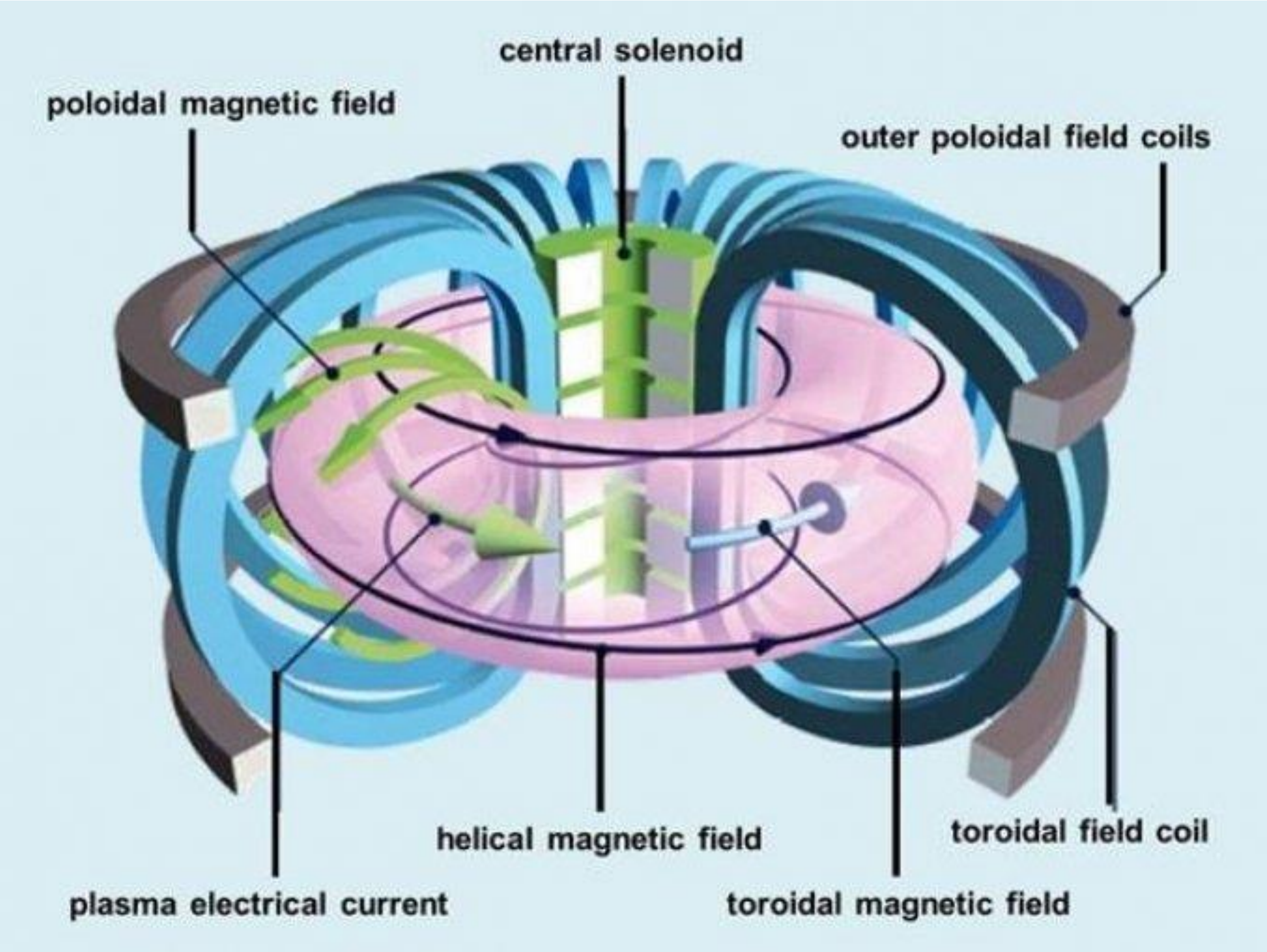
ARC

Q > 10

P > 200 MWe

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

Tokamaks are fusion devices with 3 main magnet systems



Toroidal Field (TF) magnet: Creates the primary magnetic field that provides plasma confinement

Central Solenoid (CS) magnet: Creates a poloidal magnetic field that gives the toroidal field a “twist” by driving current inductively in the toroidal direction

Poloidal Field (PF) magnets: Creates Magnetic fields that position, shape, stabilize, and divert the plasma

The TF magnet is a steady-state, high-field magnet

What is it:

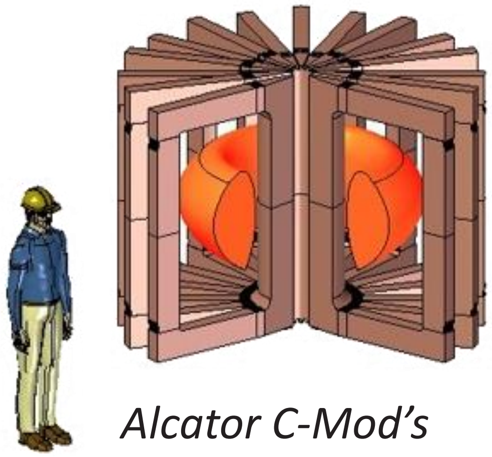
- A toroidally-shaped solenoid electromagnet that is composed of many individual coils
- Coils are typically copper magnets (resistive) but increasingly superconducting (non-resistive)

Purpose:

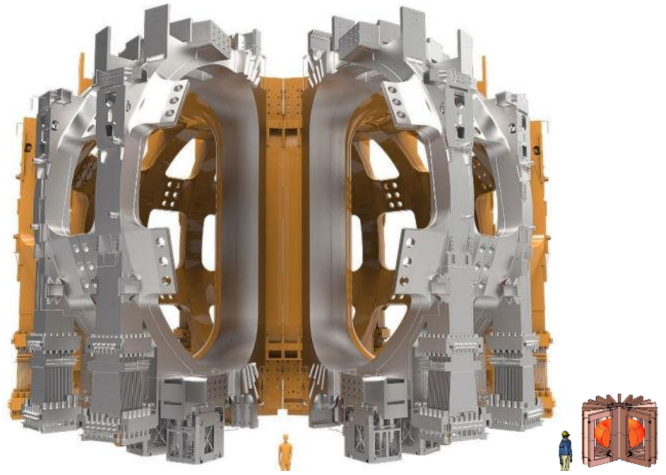
- Create the primary toroidal magnetic field that provides the main plasma confinement

Challenges:

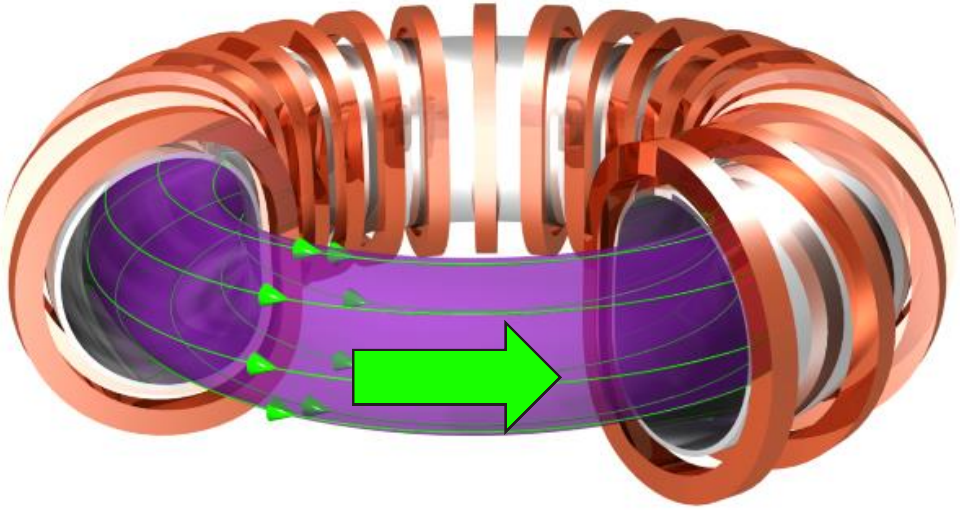
- Carry sufficient current to achieve required field
- Robust to massive electromechanical forces
- Ensure sufficient cooling access to coils
- Low toroidal field ripple to prevent particle loss
- Robust to quench (detection and protection)
- Support/translate superstructure loads



Alcator C-Mod's copper TF magnet



ITER's Nb3Sn superconducting TF magnet



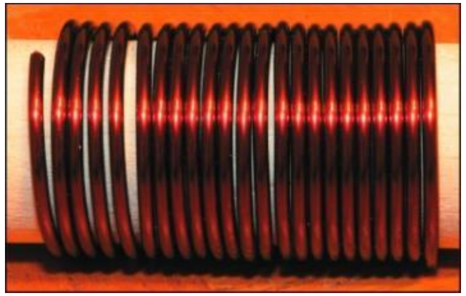
History lesson: Fusion has always maximized the toroidal field! Fusion performance metrics go like ~B^4

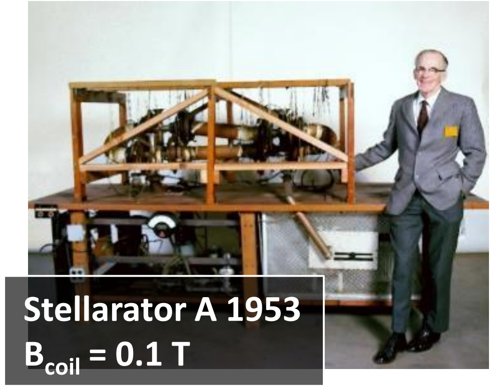
MIT PSFC

1950-1960s:

Copper wire

The pioneers



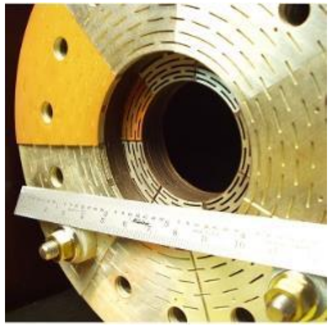


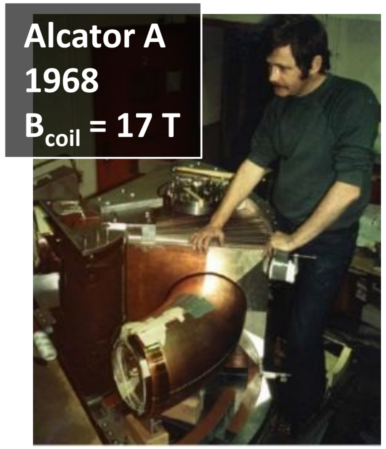
Stellarator A 1953
B_{coil} = 0.1 T

1960-1980s:

Cryogenic Bitter plates

The Alcators at MIT



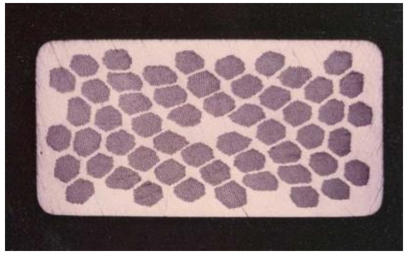


Alcator A
1968
B_{coil} = 17 T

1980-2000s:

NbTi superconductors

First SC fusion devices



Tore Supra 1988
B_{coil} = 9 T

1990s-2010s:

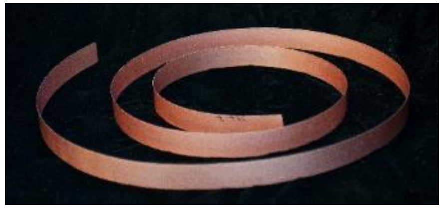
Nb_3Sn for higher field

Reactor-class devices

ITER 2015
B_{coil} = 13 T

2010-2020s:

REBCO: very high magnetic fields



REBCO: Rare Earth Barium Copper Oxide

?

Outline

- Early REBCO conductor/coil R&D
- TFMC magnet and test facility
- 20 T TFMC test program
- (If time/interest: Other REBCO R&D at MIT)

** All the work presented here will be presented in more detail in upcoming publications and conference (e.g. ASC2022)

Early REBCO conductor/coil R&D: 2017-2019

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

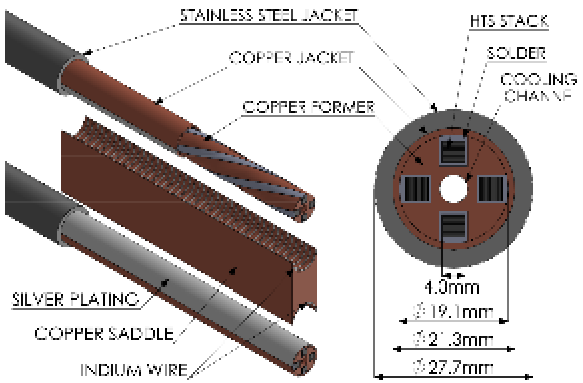
MIT PSFC

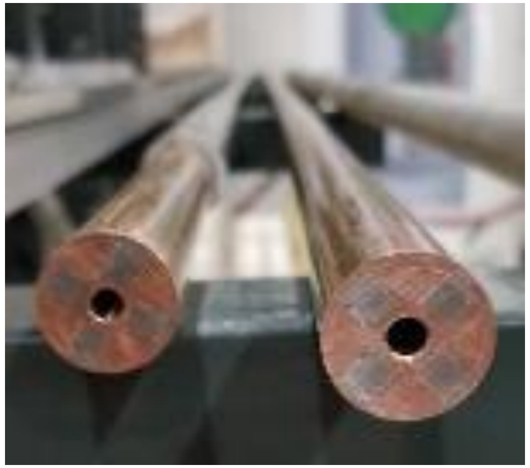
Starting in 2017, both technologies were built on REBCO magnet work pioneered at MIT

VIPER HTS cables [1]

- Based on traditional SC CIC cables using the TSTC architecture for REBCO tapes [2]

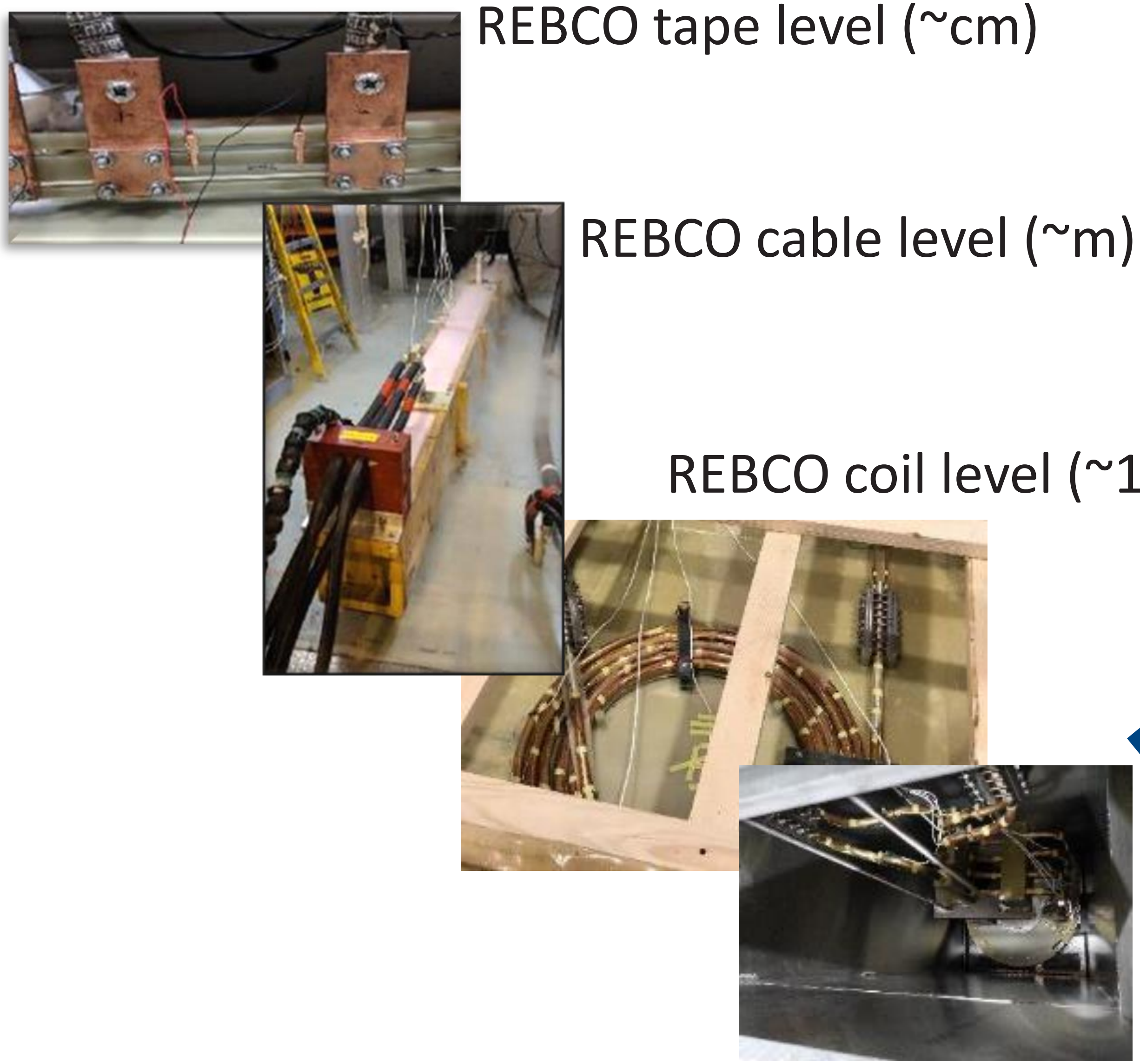
- Developed for *multiple* SPARC applications:
  - High current feeder cables
  - AC magnets: SPARC CS, PF (w/ modifications)
  - DC magnets: SPARC TF magnet





[1] Z. Hartwig *et al.*, SuST, **33** (2021) 11LT01
[2] M. Takayasu *et al.*, IEEE TAS, **21** (2011) 2340

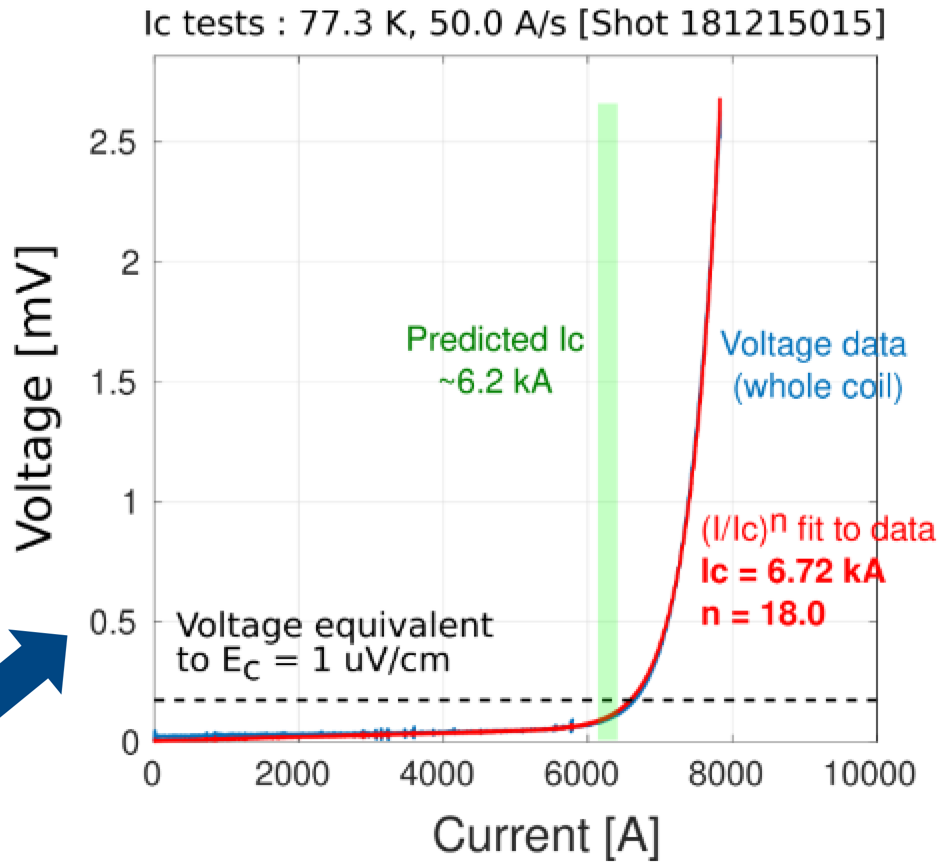
VIPER cable: Small-to-medium scale 77 K testing at MIT



REBCO tape level (~cm)

REBCO cable level (~m)

REBCO coil level (~10m)

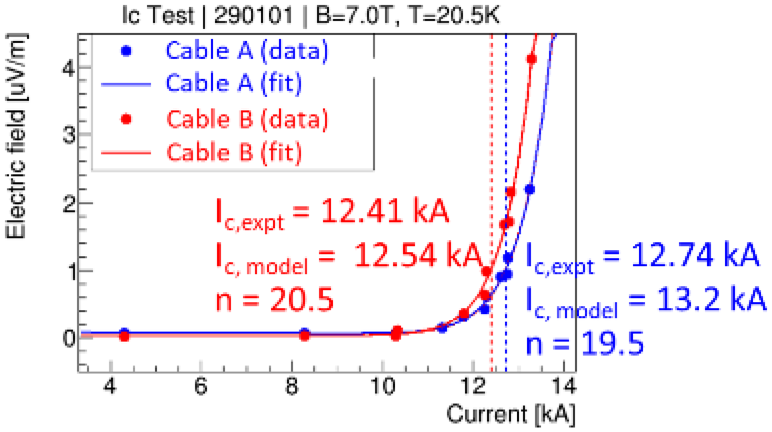


- Voltage taps at 2m spanning the main cable measured Ic in good agreement with prediction
- Leads showed no Ic degradation and all joints demonstrated acceptable resistance at 77.3 K

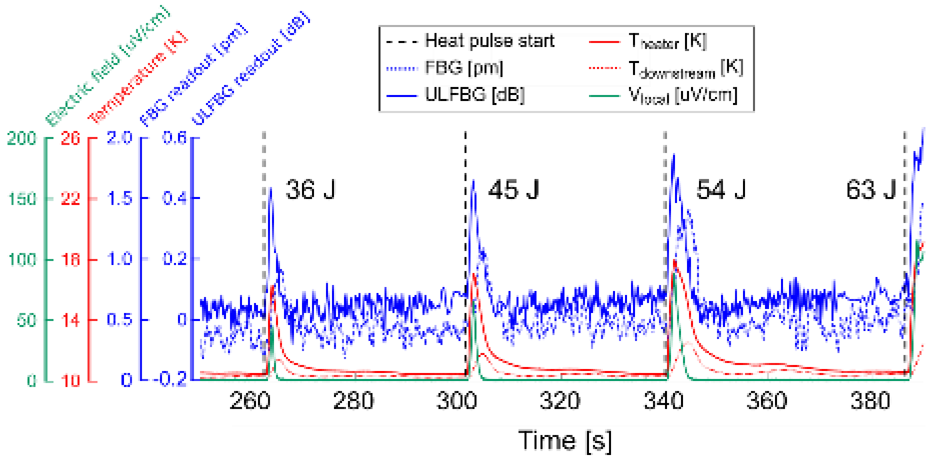
VIPER cable: 4 SULTAN tests in 4 months w/ 4 objectives

MIT PSFC

Alpha: Qualification, model validation and moderate IxB cyclic loading



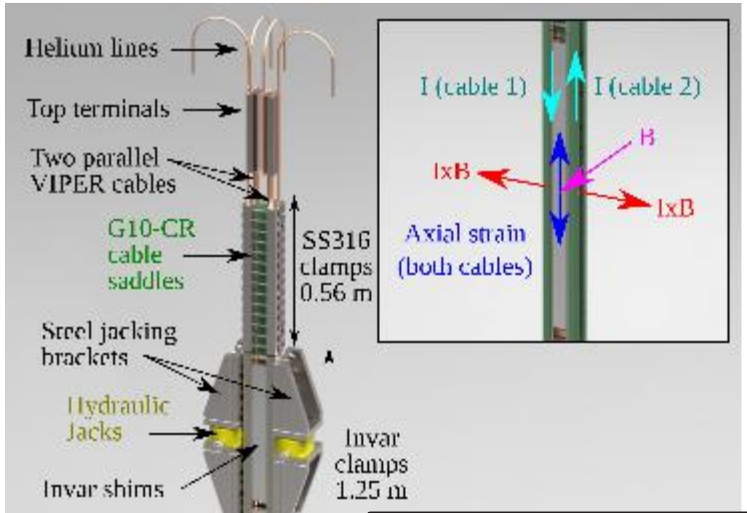
Delta: Quench detection (voltage, fiber optic (x4), acoustic (passive, active) and dynamics



[1] E. Salazar *et al.* SuST **34** (2021) 035027

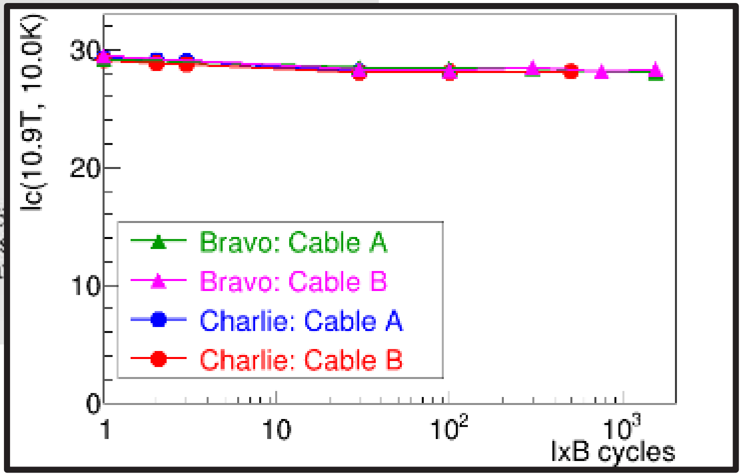
Bravo: High IxB cyclic loading at 382 kN/m for 1500 cycles)

Charlie: High IxB cyclic loading with ~0.3% axial strain in REBCO



Special SULTAN Assembly to enable axial strain during testing

[3] V Fry *et al.* Accepted by SuST, 2022.



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

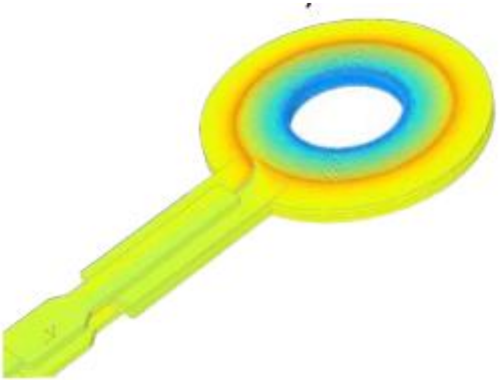
Starting in 2017, both technologies were built on HTS magnet work pioneered at MIT

VIPER HTS cables

- Based on traditional SC CICC cables using the TSTC architecture for REBCO tapes [1]
- Developed for *multiple* SPARC applications:
  - High current feeder cables
  - AC magnets: SPARC CS, PF (w/ modifications)
  - DC magnet: SPARC TF magnet

No Insulation No Twist (NINT) Coils

- HTS cable-based adaptation of single tape NI coils [2] with innovations to enable large-scale fusion magnets
- Developed for a *specific* SPARC application:
  - DC magnet: SPARC TF magnet



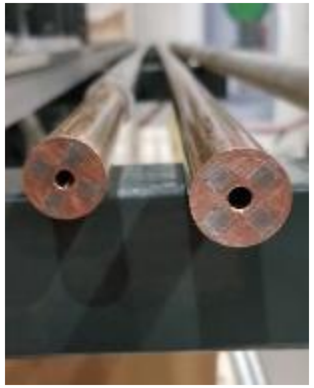
EM simulation of a NINT coil

[2] S. Hahn *et al.*, IEEE TAS, **21** (2011) 1592

Decision was made to pursue a full-scale no-insulation coil test

MIT
PSFC

VIPER would be the platform for AC coils (central solenoid, poloidal field coils) and backup for DC coils (toroidal field) in the SPARC tokamak



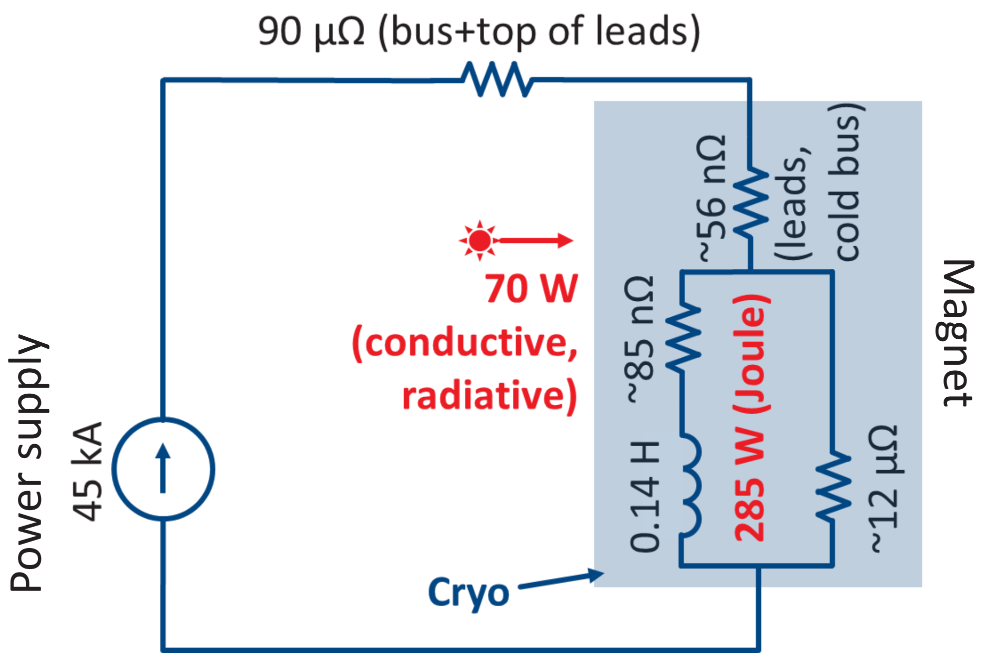
NI coils would be the platform for the DC coil (toroidal field magnet) in the SPARC tokamak

A comprehensive magnet test program was needed to prove out the potential advantages of NI coil technology at the scale and performance required for fusion-relevance

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
Pressure vessel cooling approach	Enhanced heat removal; Local cooling optimization; simplified manifolding
High winding pack current density	Compact magnet; expanded design space
High thermal stability	Robust to damage, defects, and off-normal events
Resiliency to quench	No quench detection systems, no active mitigation systems

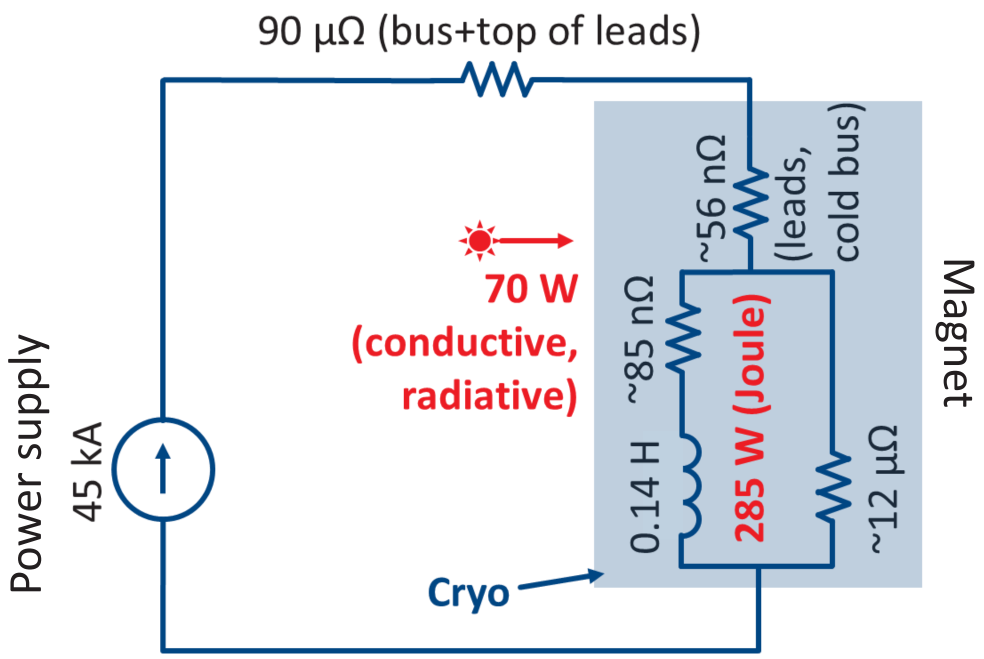
I’ll attempt large-scale NI coil physics in 1 slide due to time

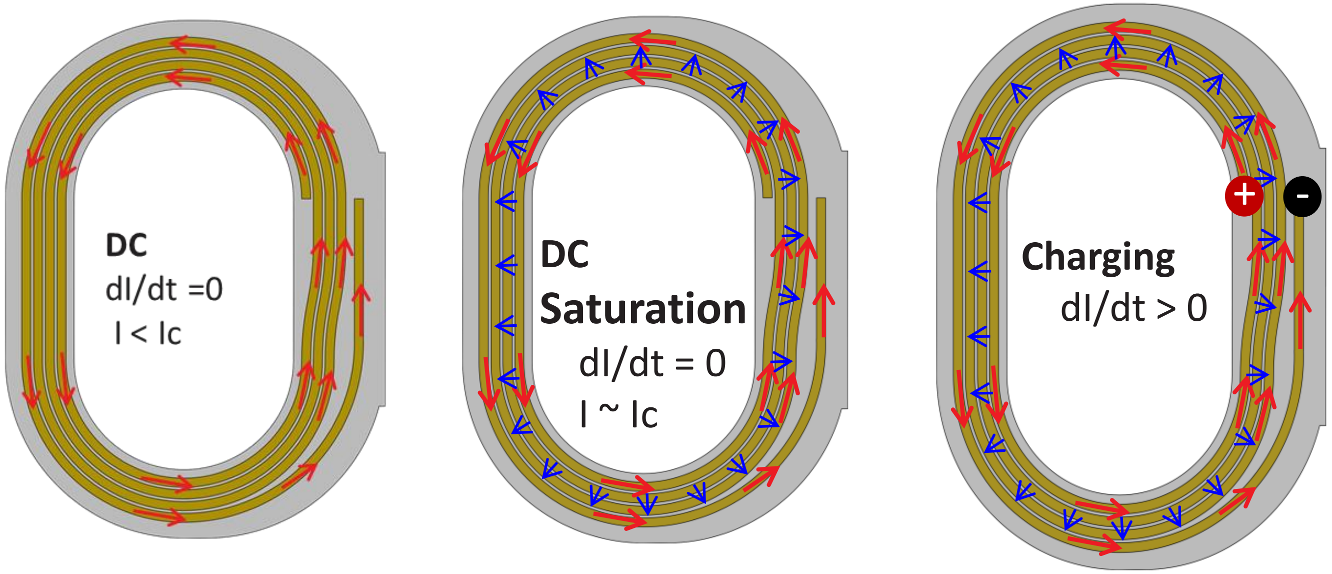
MIT PSFC



- Magnet and circuit can be thought of as a simple “lumped element” model
- No turn-to-turn insulation! Non-REBCO materials are effectively insulators under DC conditions
- Current can take one of two paths depending on the state (DC or charging) and performance
    - Azimuthal: REBCO with small R, large L
    - Radial: Turn-to-turn steel/copper large R

I’ll attempt large-scale NI coil physics in 1 slide due to time

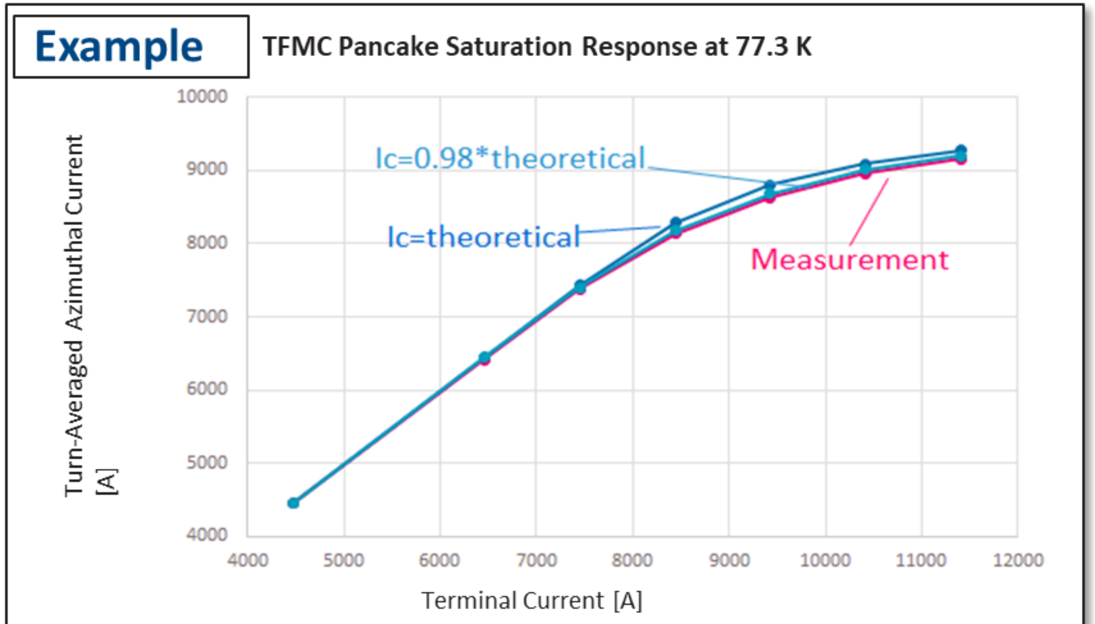




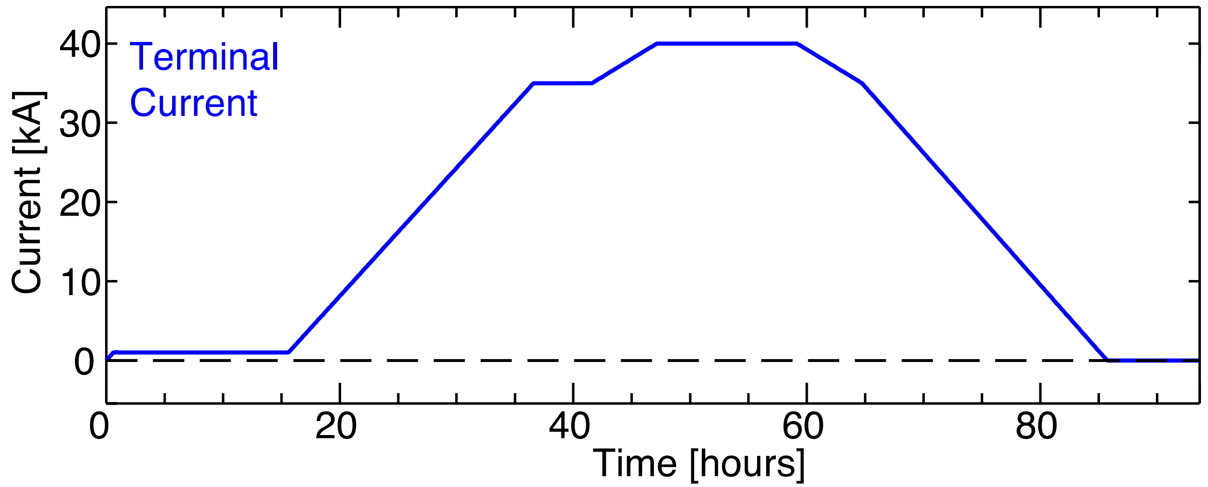
- Magnet and circuit can be thought of as a simple “lumped element” model
- No turn-to-turn insulation! Non-REBCO materials are effectively insulators under DC conditions
- Current can take one of two paths depending on the state (DC or charging) and performance
    - Azimuthal: REBCO with small R, large L
    - Radial: Turn-to-turn steel/copper large R

- **DC (I<Ic):** Current flows entirely azimuthally with
- **DC Saturation (I~Ic):** Current starts to shunt in the radial direction due REBCO transition voltage. Heating in the magnet occurs, lowering the cryostability
- **Charging/Discharging:** Current flows strongly in the radial direction and converts to azimuthal direction with L/R time. Heating proportional to ramp rate!

Some consequences of NI coil physics



All 16 TFMC pancakes were tested by comparing measured saturation response against theoretical.



- Terminal current vs. magnet field is not linear! The coil saturates as I~Ic approached
- Result is voltage (e.g. power) and heating in the winding pack that can threaten cryostability

- Charging/discharging rates are limited by cooling system and heat removal efficiency, resulting in long charging times
- The TFMC had L/R ~ 3.5 h, resulting in long experimental campaigns and limits on testing (e.g. cycling)

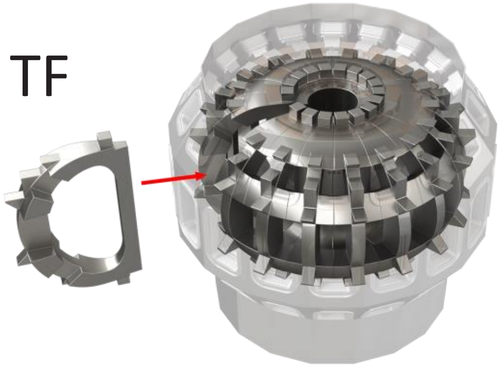
MIT
PSFC

TFMC magnet and test facility: 2019-2021

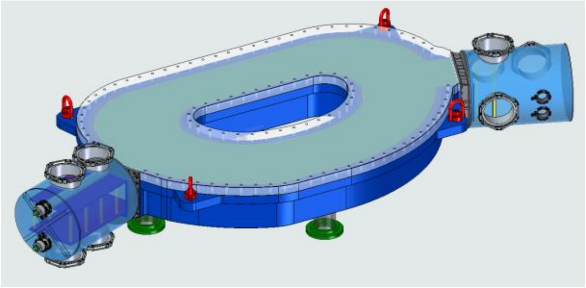
TFMC requirements were set by the SPARC TF coil design

MIT
PSFC

SPARC TF



TF Model Coil



- ❑12.2 T magnetic field on-axis (22T on HTS tape)
- ❑Acceptable toroidal field ripple; azimuthal current deficit less than 0.5% in every coil; design value of Iop/Ic attained
- ❑HTS conductor capable of handing Lorentz loads
- ❑Acceptable joint resistances
- ❑Acceptable coil dissipation
- ❑Electrical performance as projected by EM models
- ❑Cryogenic coolant design capable of handling SPARC neutron loads (pressure vessel design)
- ❑Employ modular, grooved stacked-plate pancake construction to facilitate rapid manufacturing

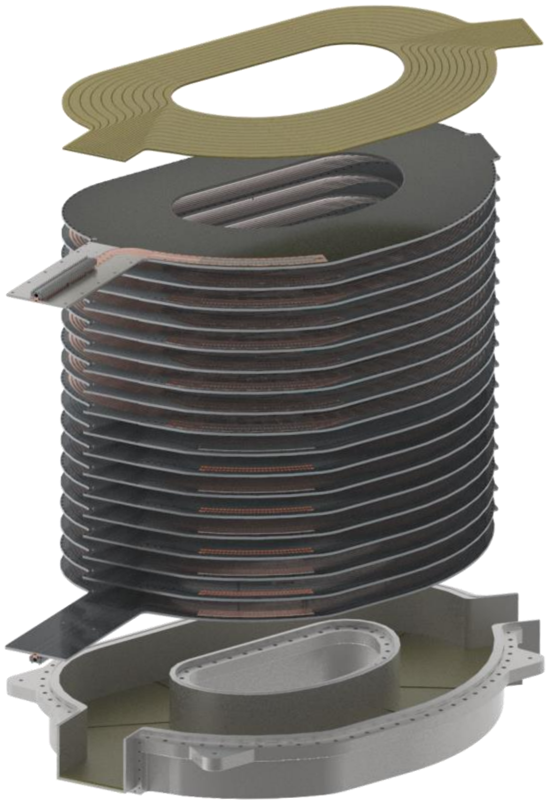
- ✓Demonstrate 20T on HTS tape in large-bore D-shaped coil at > 50% linear size of TF
- ✓Demonstrate accurate projections of HTS tape performance
- ✓Demonstrate HTS conductor Lorenz loading at TF levels (> 700 kN-m)
- ✓Demonstrate viable joint design and performance
- ✓Demonstrate / validate accurate EM models
- ✓Employ internal coil winding architecture that is essentially identical to that employed by TF
- ✓Construct coil within 2 year time frame, using manufacturing methods that transfer to SPARC TF

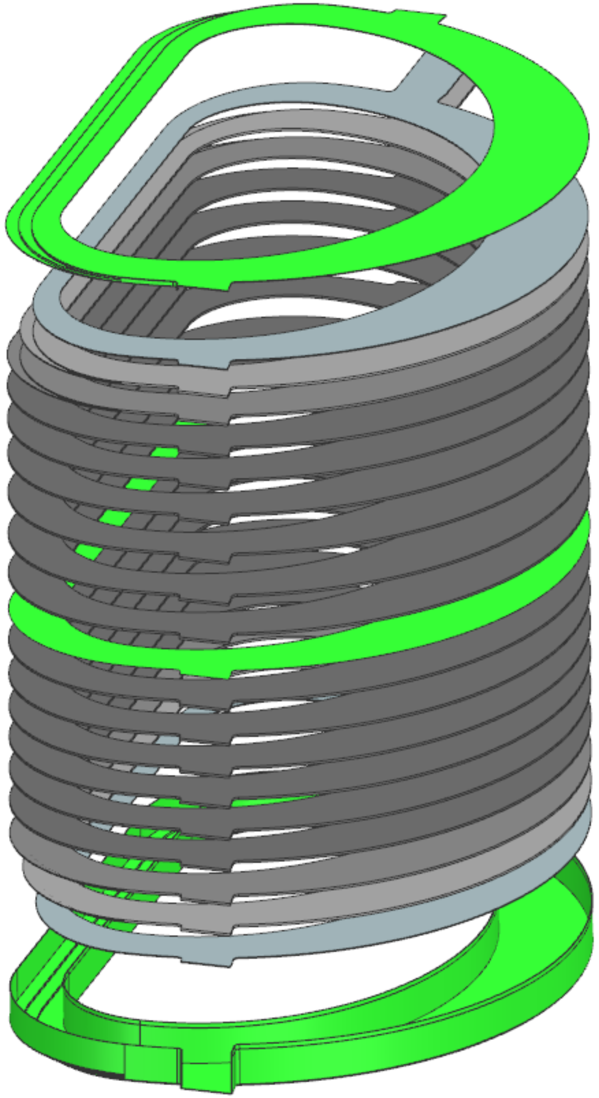
The TFMC’s requirements were set by the SPARC TF magnet

MIT
PSFC

TFMC

- Modular, stacked-plate construction
- 256 turns total
- 16 full pancakes (16 turns each)
- HTS tape stacks, soldered into grooves
- Mirrored winding pack
- Integral pc-to-pc joints
- Pancake-to-pancake insulation
- Integrated coolant channels
- Case is supercritical helium pressure vessel





SPARC TF – V2B

- Modular, stacked-plate construction
- 200 turns total
- 12 full pancakes (16 turns)
- 2 partial pancakes (10 turns)
- 2 partial pancakes (6 turns)
- HTS tape stacks, soldered into grooves
- Mirrored winding pack
- Integral pc-to-pc joints
- Pancake-to-pancake insulation
- Integrated coolant channels
- Case is supercritical helium pressure vessel

Winding Pack	R-width	Z-height
TFMC	1.6 m	2.6 m
SPARC	3.0 m	4.3 m

Same winding pack architecture

The TFMC Project eliminated risk in the physics, fabrication, and operation of large-scale REBCO (NI) 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 current; high pressure coolant; …

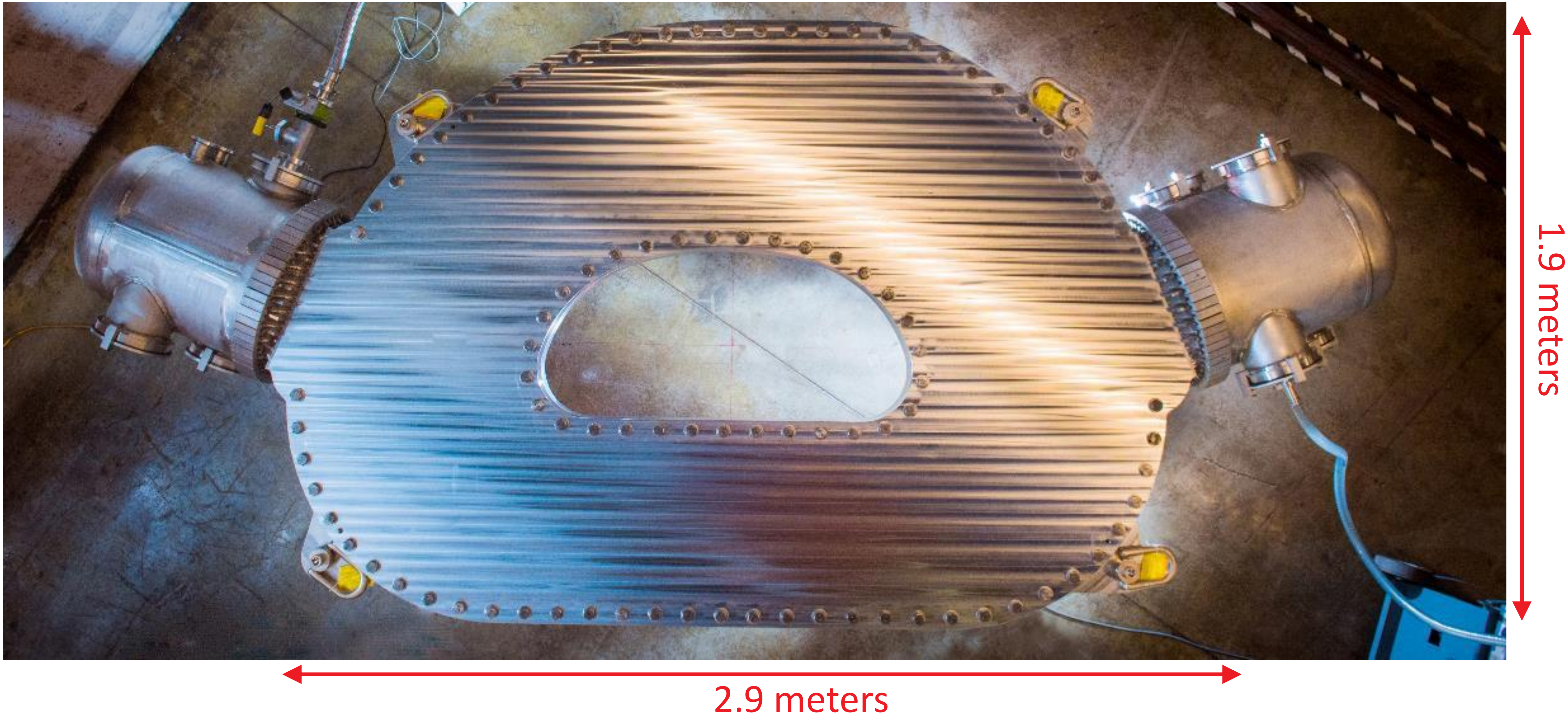
Objective: Design, build, and test (1) a representative SPARC TF model coil and (2) a fully capable test facility in 2 years to maximize risk retirement for SPARC

Team Size: 80+ people at 3 sites

The TFMC is the first large-scale high-field REBCO magnet

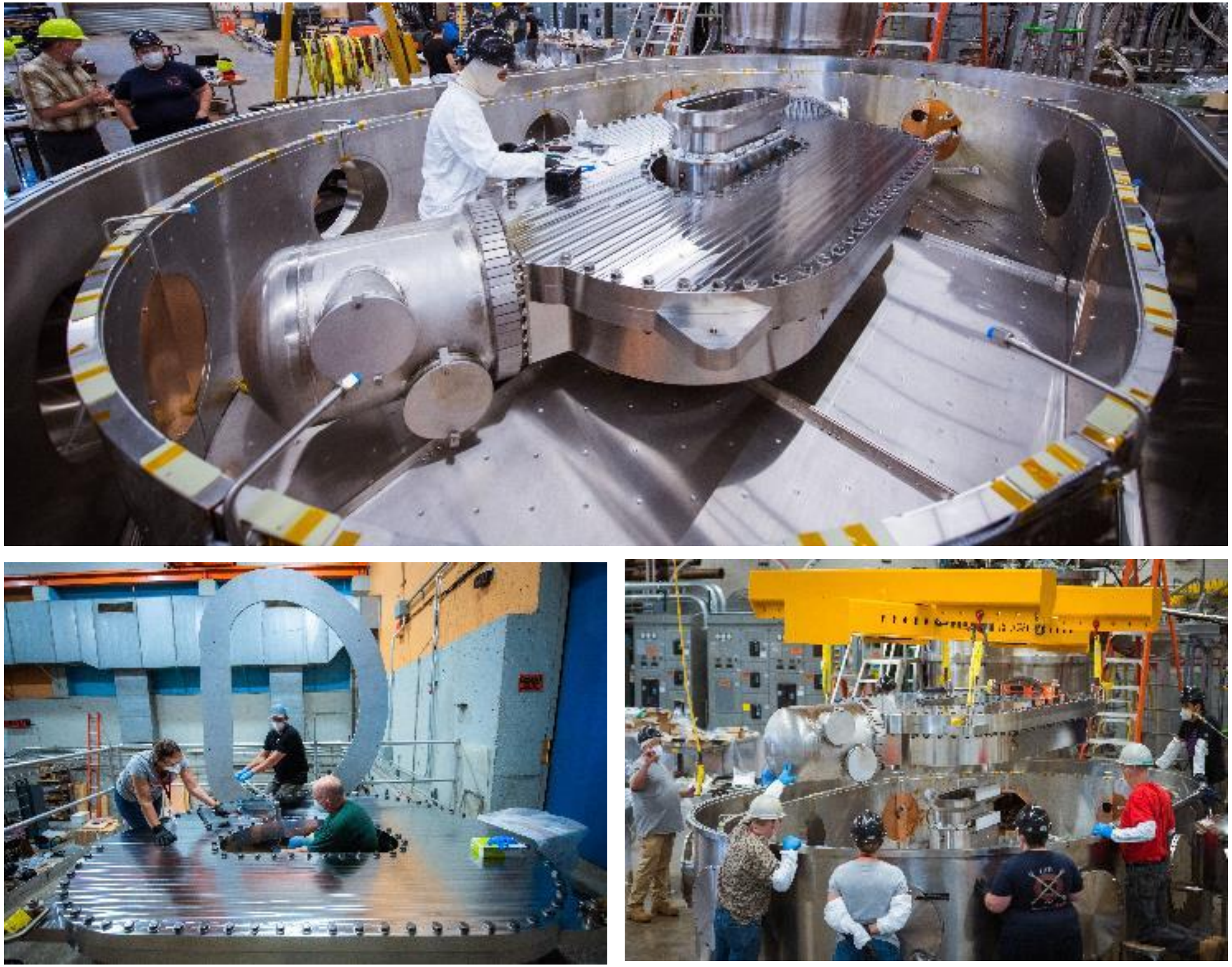
MIT
PSFC

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



The TFMC at a glance

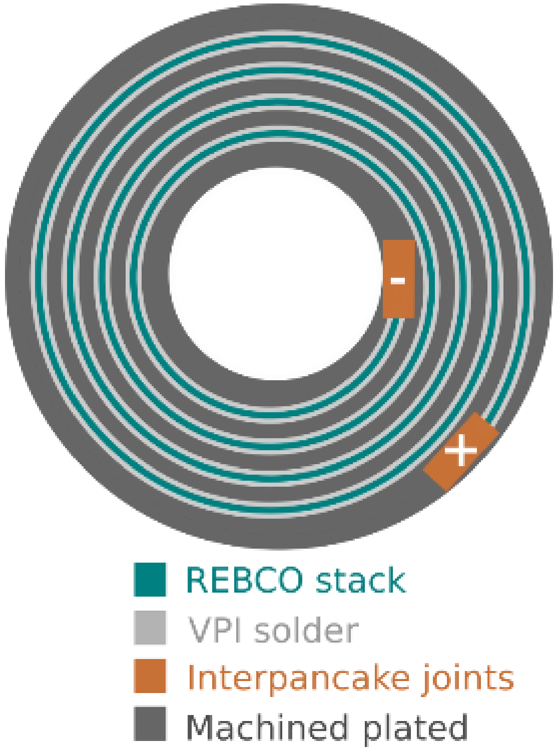
MIT
PSFC

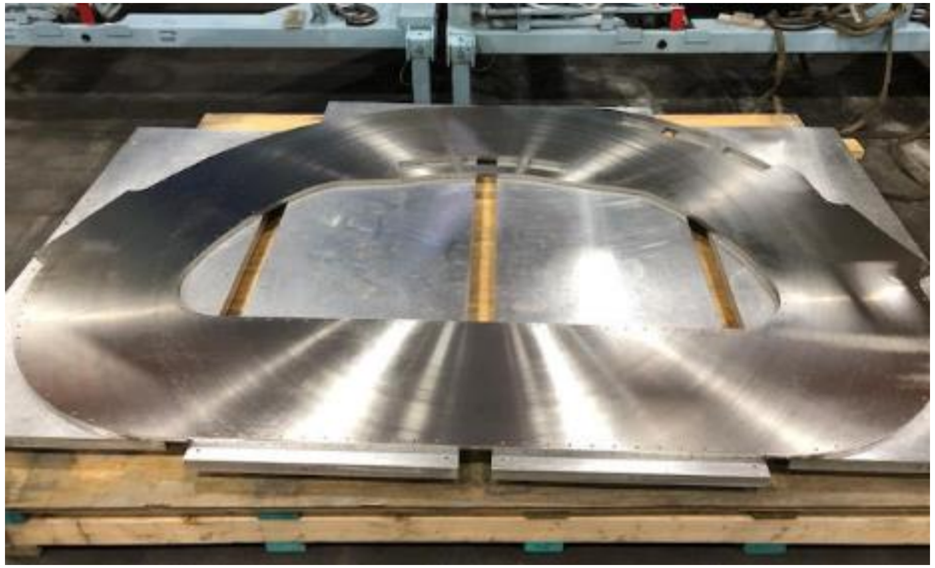


Nominal Design Parameter	Value
Number of pancakes	16
Total turns	256
Total REBCO tape	270 km
Operating temperature	20 K
Coolant type	Supercrit. He
Operating coolant pressure	20 bar (max)
Operating terminal current	40 kA
Peak magnetic field	20 T
Peak IxB force on REBCO	800 kN/m
Inductance	0.14 H
Magnetic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

TFMC employs an HTS stack-in-plate design for pancakes

- Pancakes
  - A large steel plate is machined on both sides:
    - One side contains channels for HTS stacks
    - The other side contains pancake-specific cooling channels
  - 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

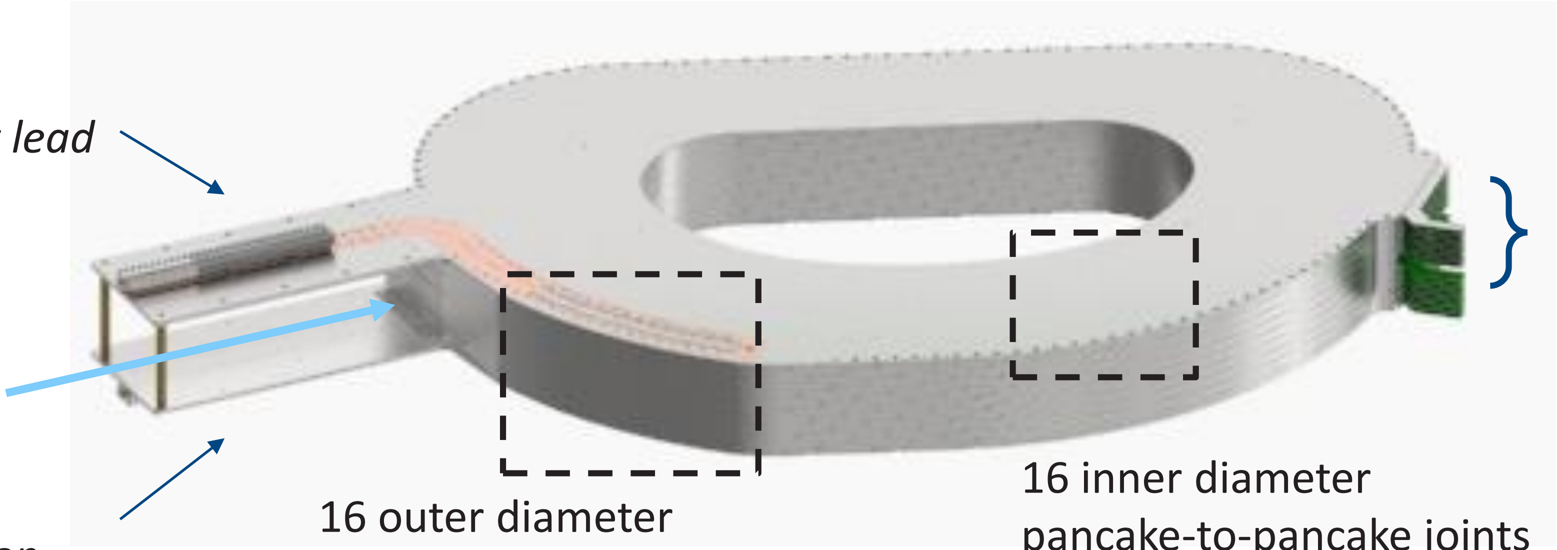




16 pancakes are combined into the winding pack

MIT PSFC

- Winding pack
  - The winding pack comprises 16 stacked, internally jointed pancakes
  - Winding pack has 2 top and bottom termination plates for current leads



Top termination plate w/ - current lead

Helium coolant enters the cooling channels in plates

Bottom termination plate w/ + current lead

16 outer diameter pancake-to-pancake joints

16 inner diameter pancake-to-pancake joints

16 pancake stack

The winding pack is enclosed in a “bucket-and-lid” style case

- Magnet
  - The winding pack is encased in a steel structural and pressure vessel case
  - High pressure plena enable current, cooling, and instrumentation

Top case piece

Pressure seal plate

Top ground insulation

Winding pack

Bottom case piece with internal ground insulation

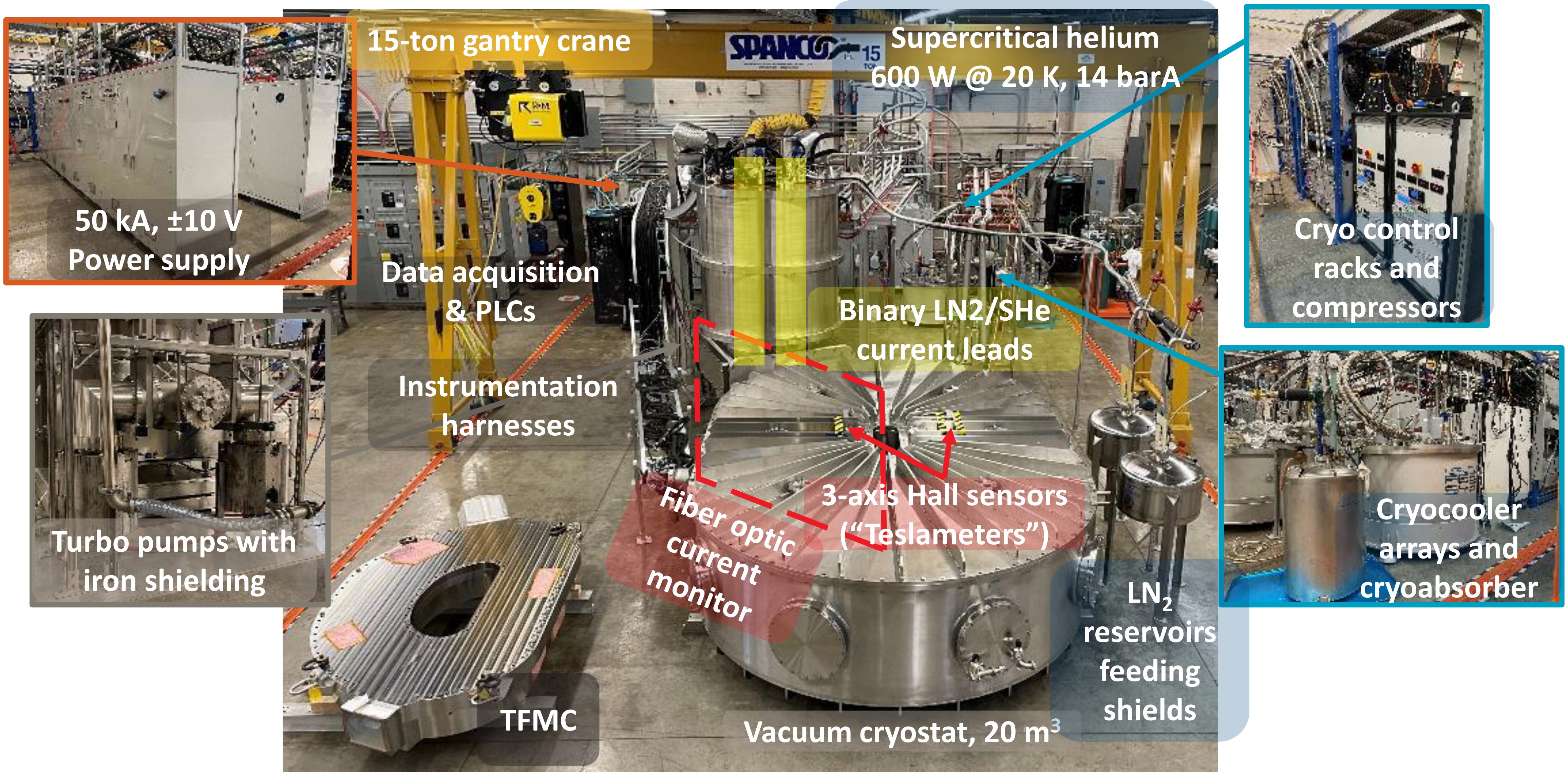
A new magnet test facility was established at MIT

The TFMC was designed, fabricated (w/ vendors), and assembled at MIT

REBCO procurement + QA/QC and some pancake winding at CFS

The test facility was designed, built, and commissioned at MIT

A new magnet test facility was established at MIT



15-ton gantry crane

Supercritical helium
600 W @ 20 K, 14 barA

50 kA, ±10 V
Power supply

Data acquisition
& PLCs

Cryo control
racks and
compressors

Binary LN2/SHe
current leads

Instrumentation
harnesses

Turbo pumps with
iron shielding

3-axis Hall sensors
(“Teslameters”)

Fiber optic
current
monitor

Cryocooler
arrays and
cryoabsorber

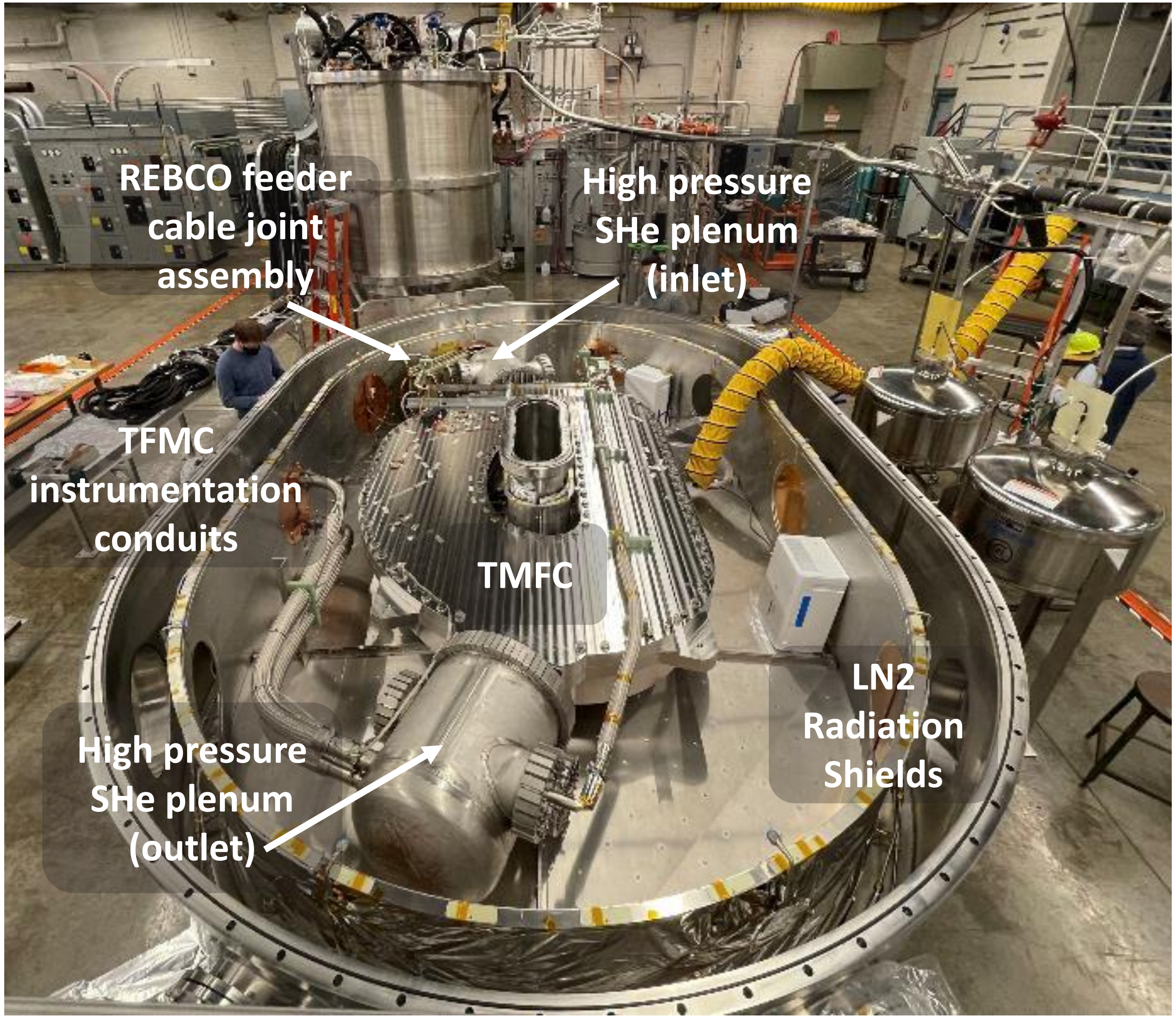
LN_2
reservoirs
feeding
shields

TFMC

Vacuum cryostat, 20 m^3

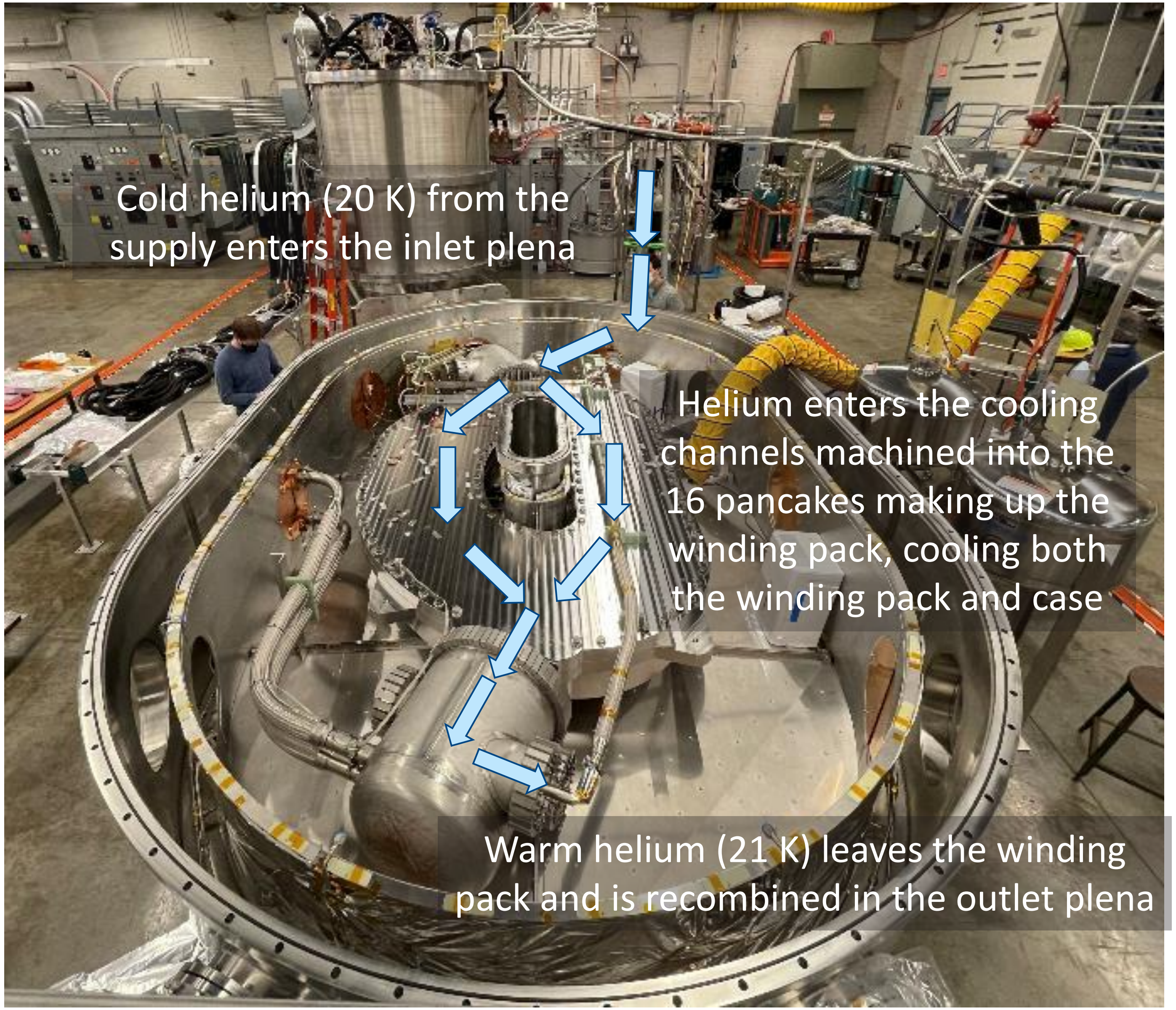
A view of the TFMC installed within the main cryostat

MIT PSFC



The case functions as a cryogenic pressure vessel for cooling

MIT PSFC



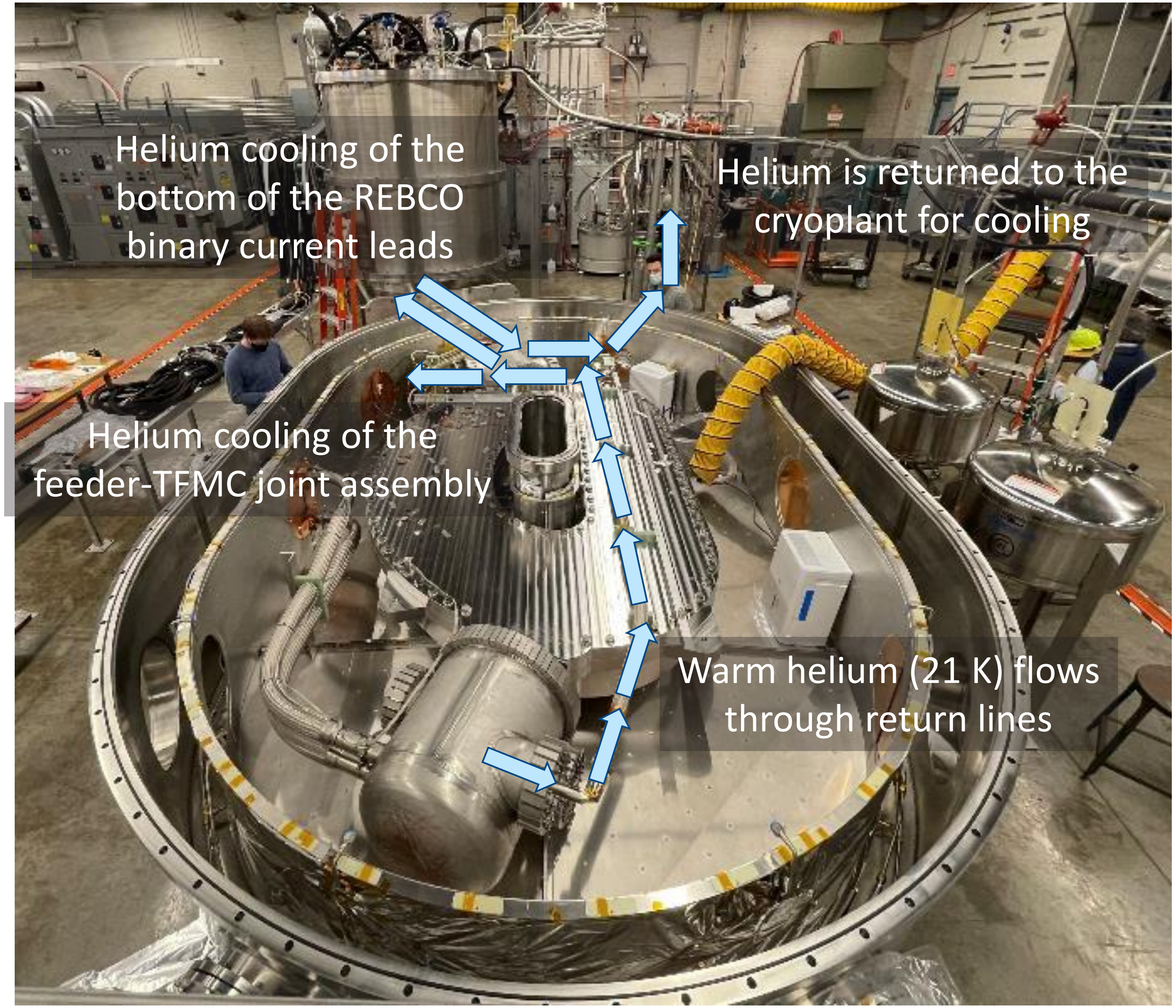
Cold helium (20 K) from the supply enters the inlet plena

Helium enters the cooling channels machined into the 16 pancakes making up the winding pack, cooling both the winding pack and case

Warm helium (21 K) leaves the winding pack and is recombined in the outlet plena

Helium exhaust from the magnet cools the leads and feeders

MIT PSFC



Helium cooling of the bottom of the REBCO binary current leads

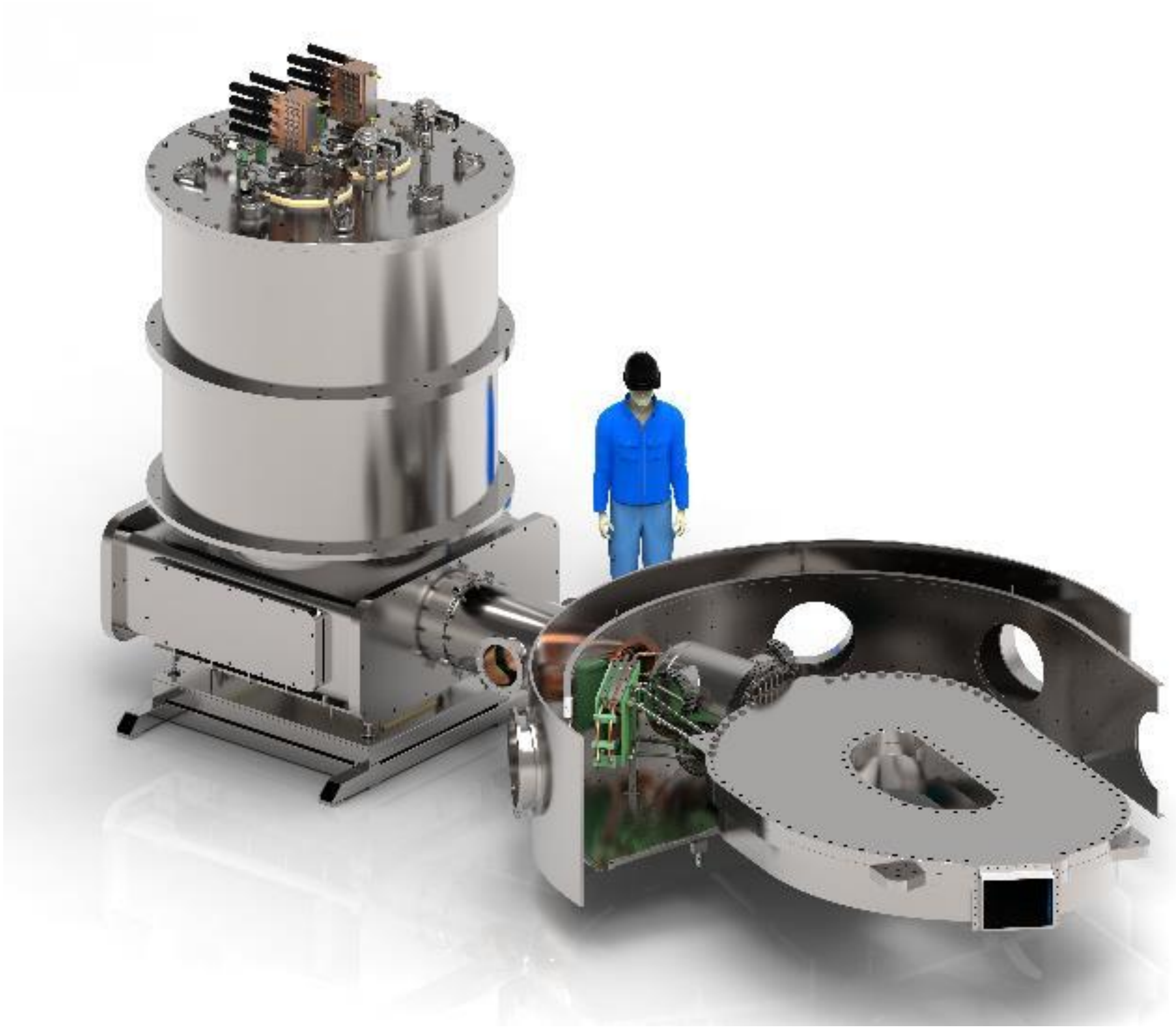
Helium is returned to the cryoplant for cooling

Helium cooling of the feeder-TFMC joint assembly

Warm helium (21 K) flows through return lines

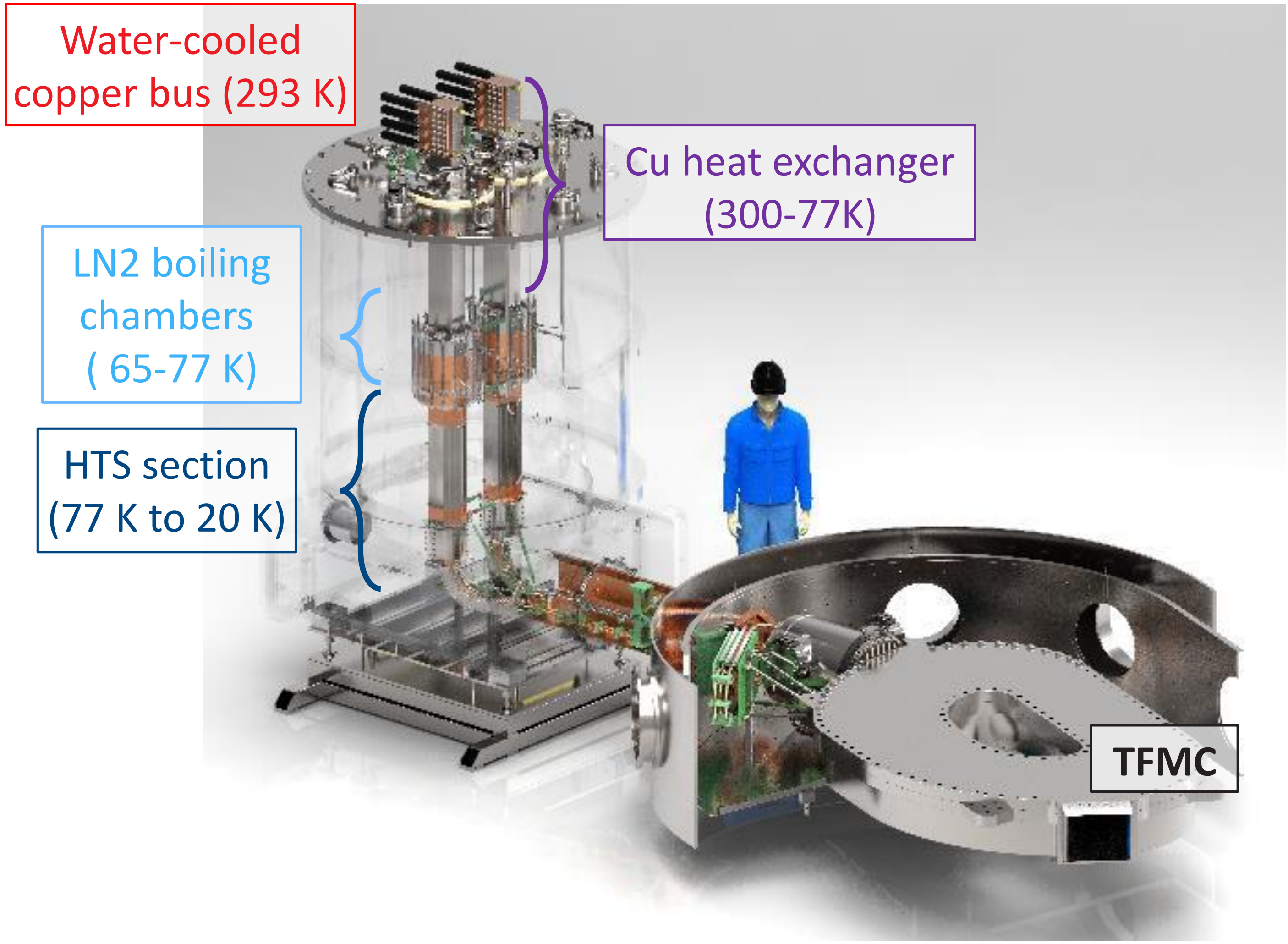
50 kA binary REBCO current leads and feeder system developed

MIT
PSFC



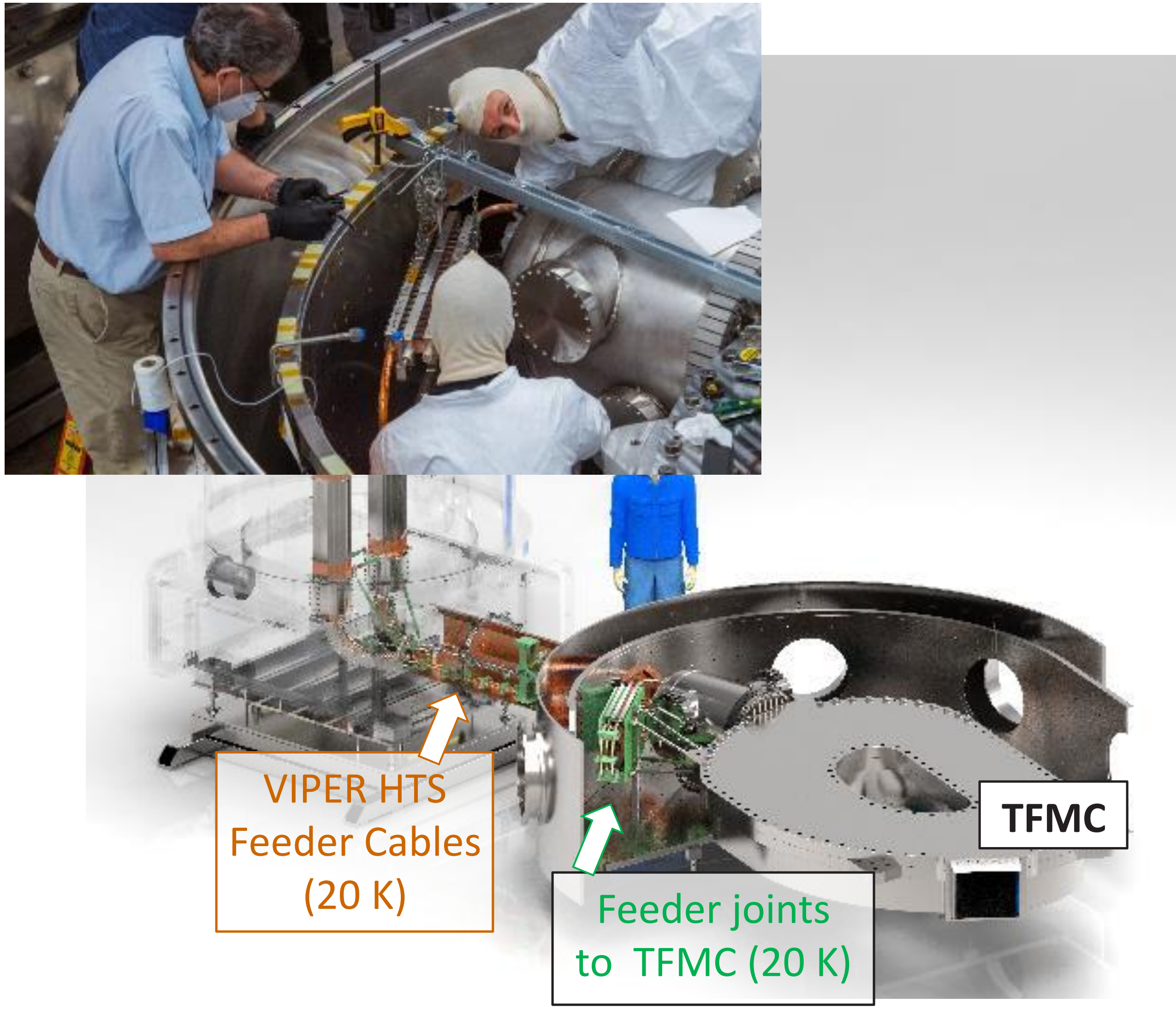
Binary 50 kA HTS current leads and feeder system proven

- REBCO current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN_2 (sub-cooled if desired) and SHe cooled
  - In-house development required to meet performance and schedule requirements



Binary 50 kA HTS current leads and feeder system proven

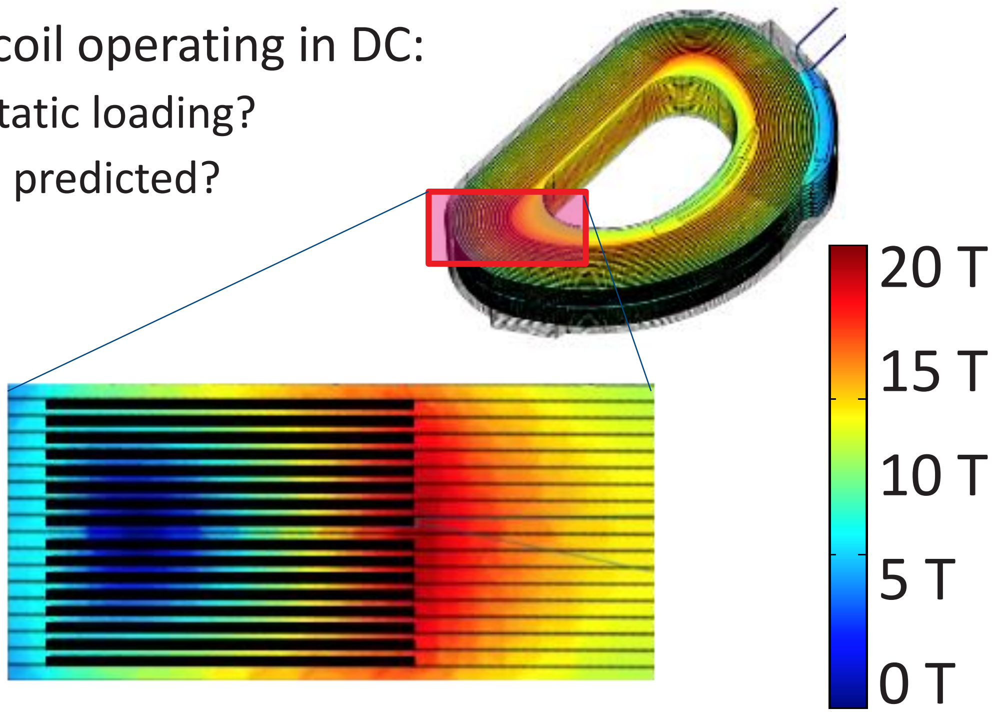
- Binary HTS current leads were designed, fabricated, and commissioned in-house
  - Designed to supply up to 50 kA for low voltage DC magnets
  - LN2 section can be sub-cooled to enable high current performance
  - In-house development required to meet performance and schedule requirements
- Feeder system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



20 tesla test program : Sept 2021

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

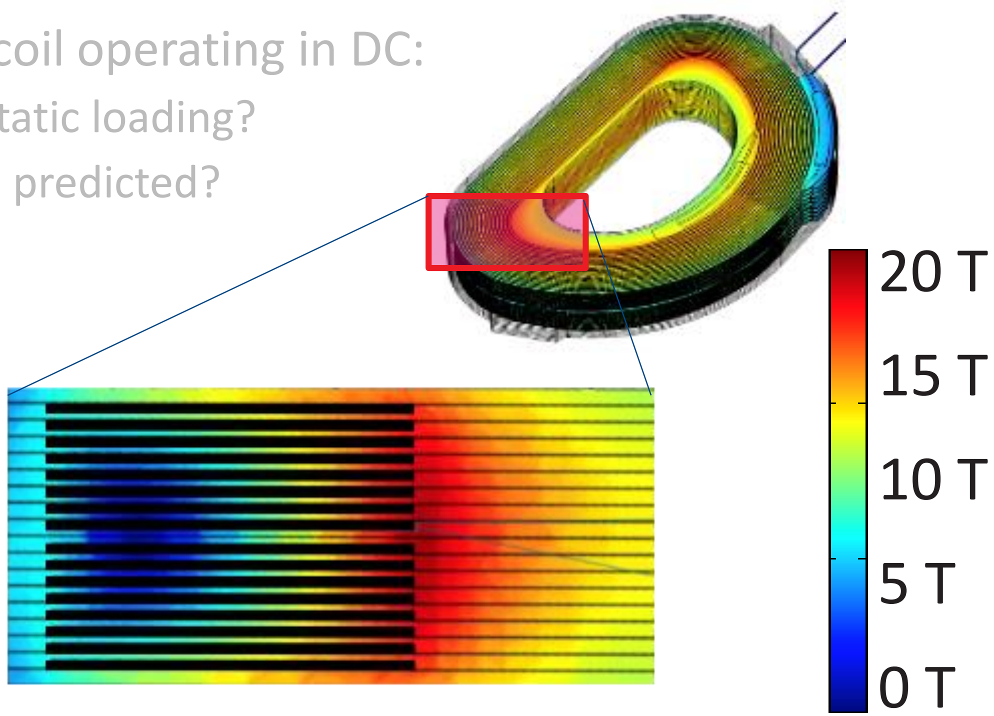
- First full-performance test asked 3 primary questions of the coil operating in DC:
    - Does the TFMC precisely match design B-field and withstand static loading?
    - Does the coil distribute current during charging and flat-top as predicted?
    - Does the TFMC distribute voltage (heating) as predicted?



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

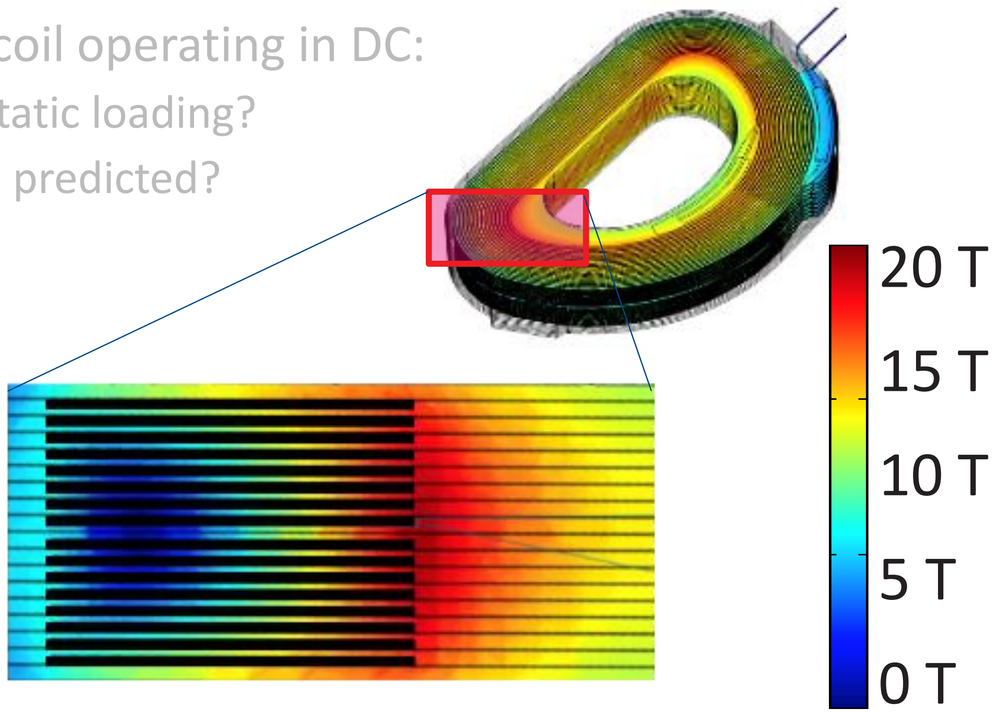
- First full-performance test asked 3 primary questions of the coil operating in DC:
  - Does the TFMC precisely match design B-field and withstand static loading?
  - Does the coil distribute current during charging and flat-top as predicted?
  - Does the TFMC distribute voltage (heating) as predicted?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



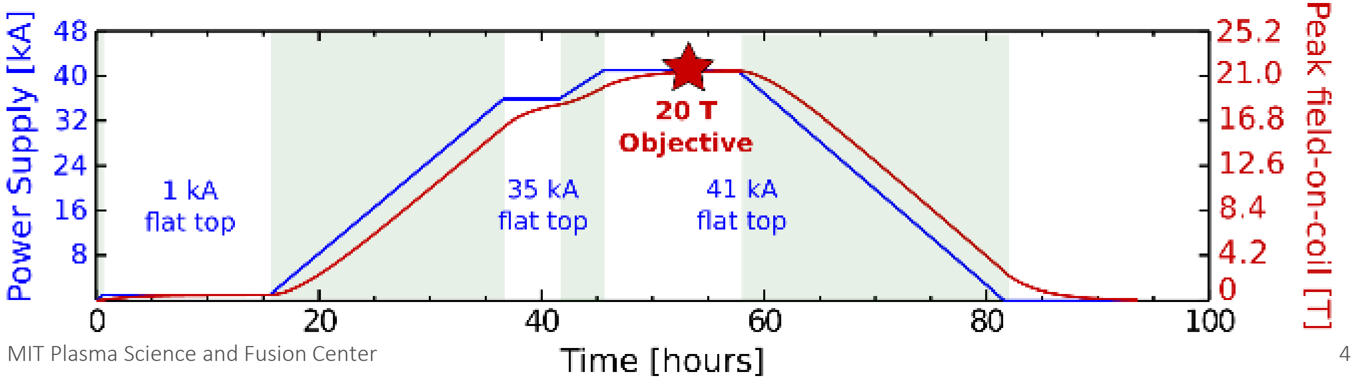
EM simulations of B-field at $I_{terminal}$=40 kA (top) and the test plan for the approach to 20 T (bottom)

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)

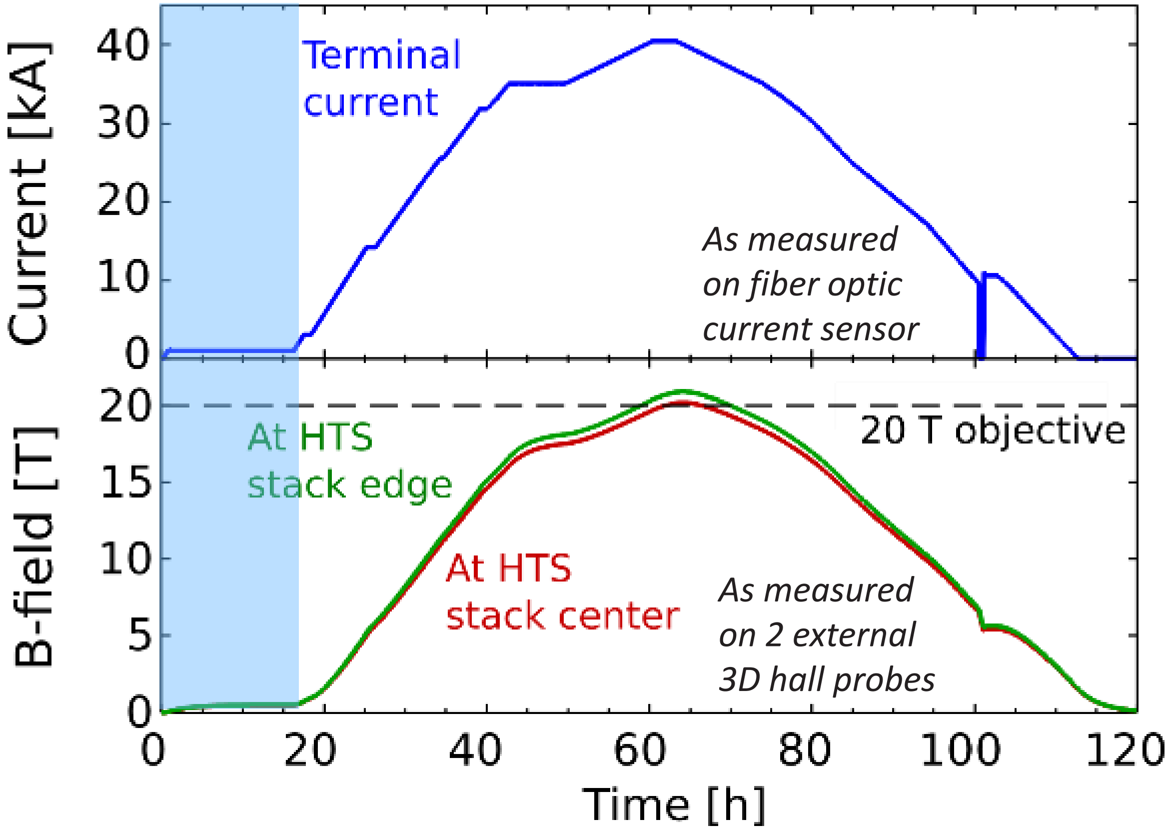


1^{st} Test: Key performance objectives met for the TFMC at 20 T

MIT
PSFC

Step 1: Ramp to and hold at 1 kA for 15 hours

- Electrical and thermal stability check
- L/R radial current decay measurement to <1 %
- Calibration of FOCS against 3D teslameters



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

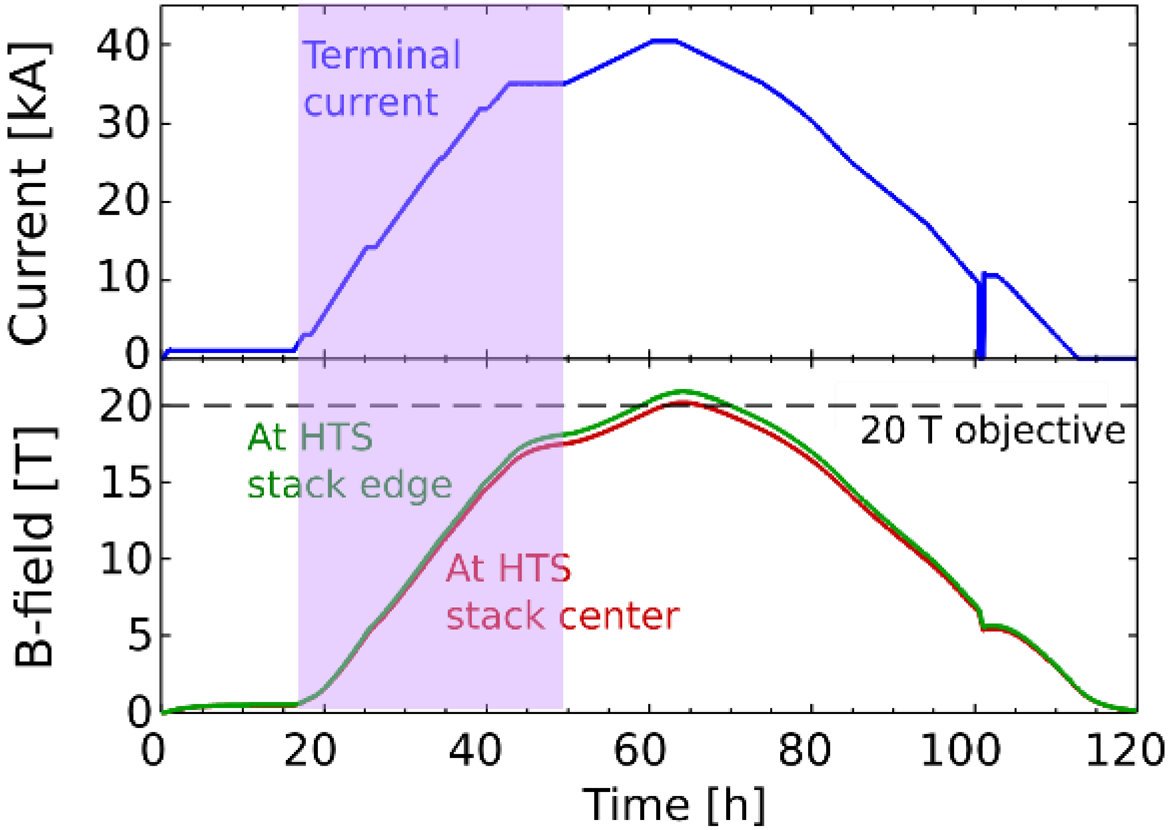
MIT
PSFC

Step 1: Ramp to and hold at 1 kA for 15 hours

- Electrical and thermal stability check
- L/R radial current decay measurement to <1 %
- Calibration of FOCS against 3D teslameters

Step 2: Ramp to and hold at 35 kA for 8 hours

- Pancake joint, HTS stack resistance meas’ts
- Evaluation of thermal stability, cooling capabilities
- Charging dissipation meas’ts: 245 W



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

MIT
PSFC

Step 1: Ramp to and hold at 1 kA for 15 hours

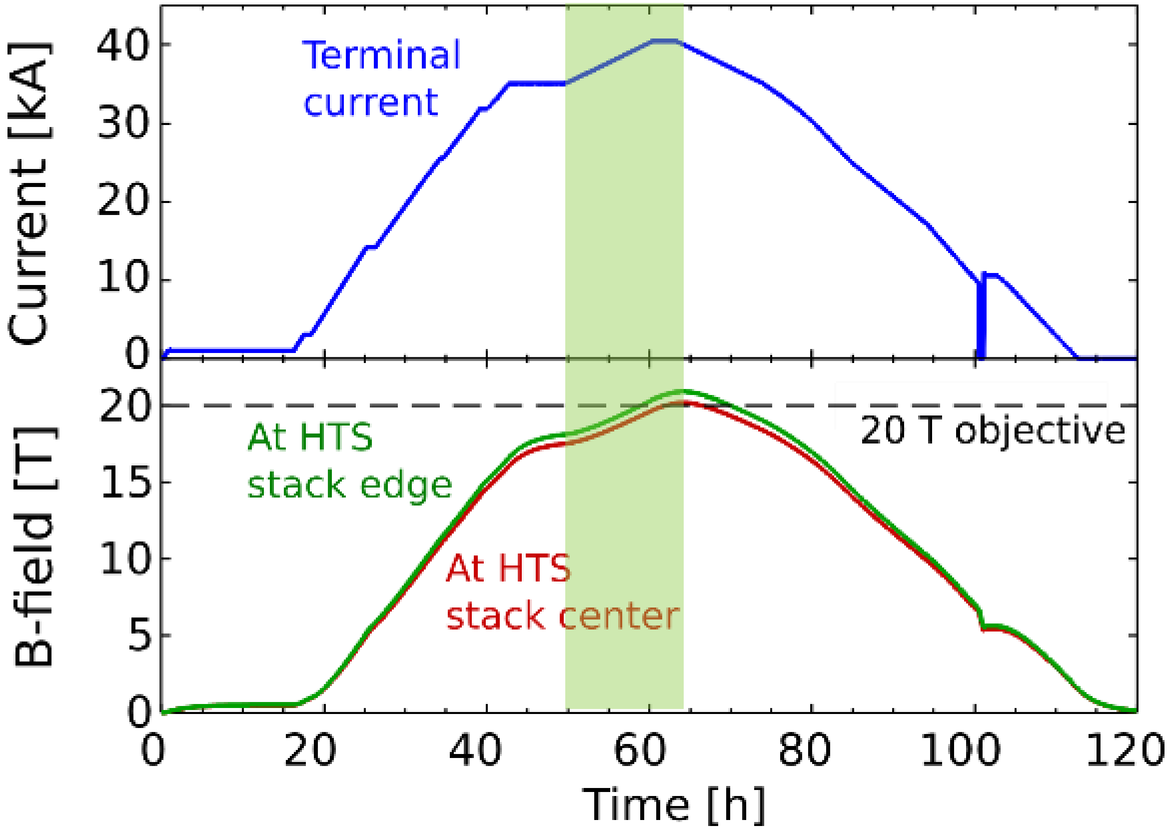
- Electrical and thermal stability check
- L/R radial current decay measurement to <1 %
- Calibration of FOCS against 3D teslameters

Step 2: Ramp to and hold at 35 kA for 8 hours

- Pancake joint, HTS stack resistance meas'ts
- Evaluation of thermal stability, cooling capabilities
- Charging dissipation meas'ts: 245W

Step 3: Ramp and hold at 40.5 kA for 5 hours

- Achievement of ~20.5 T peak field-on-coil
- Achievement of 109 MJ stored energy
- Steady state dissipation meas'ts: 112 W



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

Step 1: Ramp to and hold at 1 kA for 15 hours

- Electrical and thermal stability check
- L/R radial current decay measurement to <1 %
- Calibration of FOCS against 3D teslameters

Step 2: Ramp to and hold at 35 kA for 8 hours

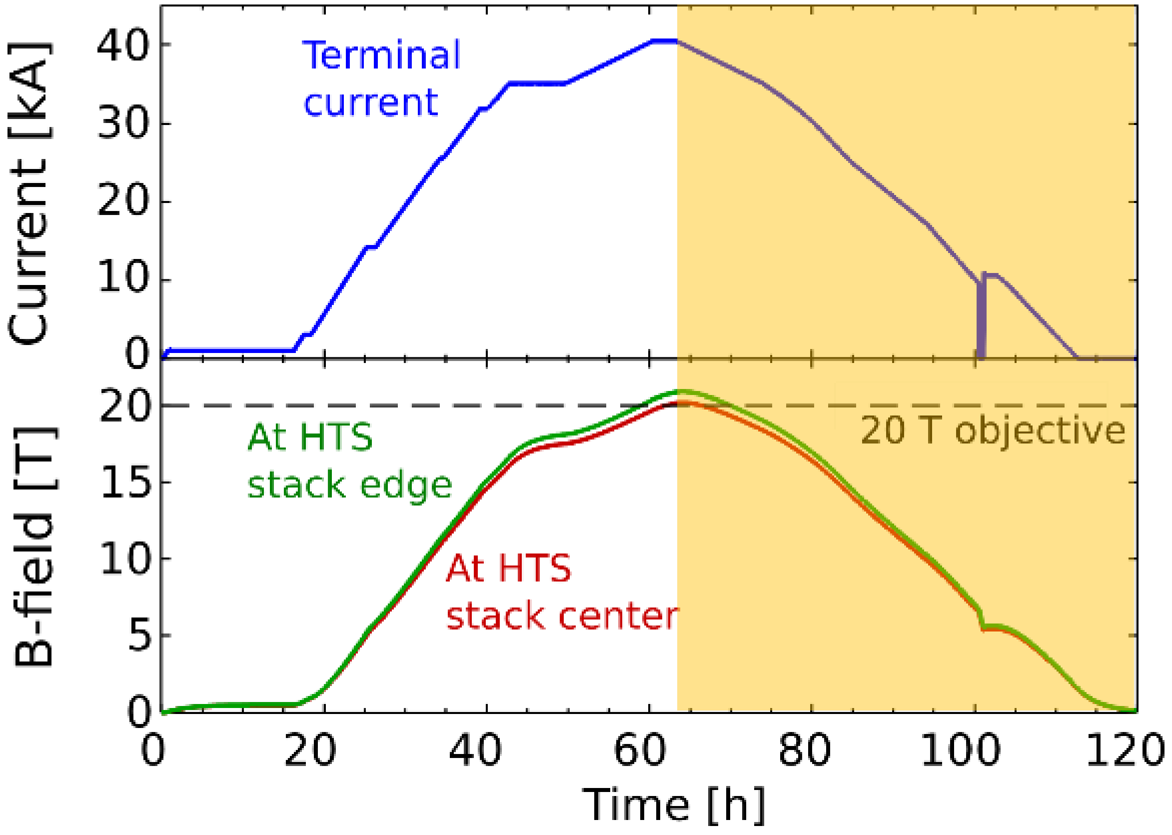
- Pancake joint, HTS stack resistance meas'ts
- Evaluation of thermal stability, cooling capabilities
- Charging dissipation meas'ts: 245W

Step 3: Ramp and hold at 40.5 kA for 5 hours

- Achievement of ~20.5 T peak field-on-coil
- Achievement of 109 MJ stored energy
- Steady state dissipation meas'ts: 112 W

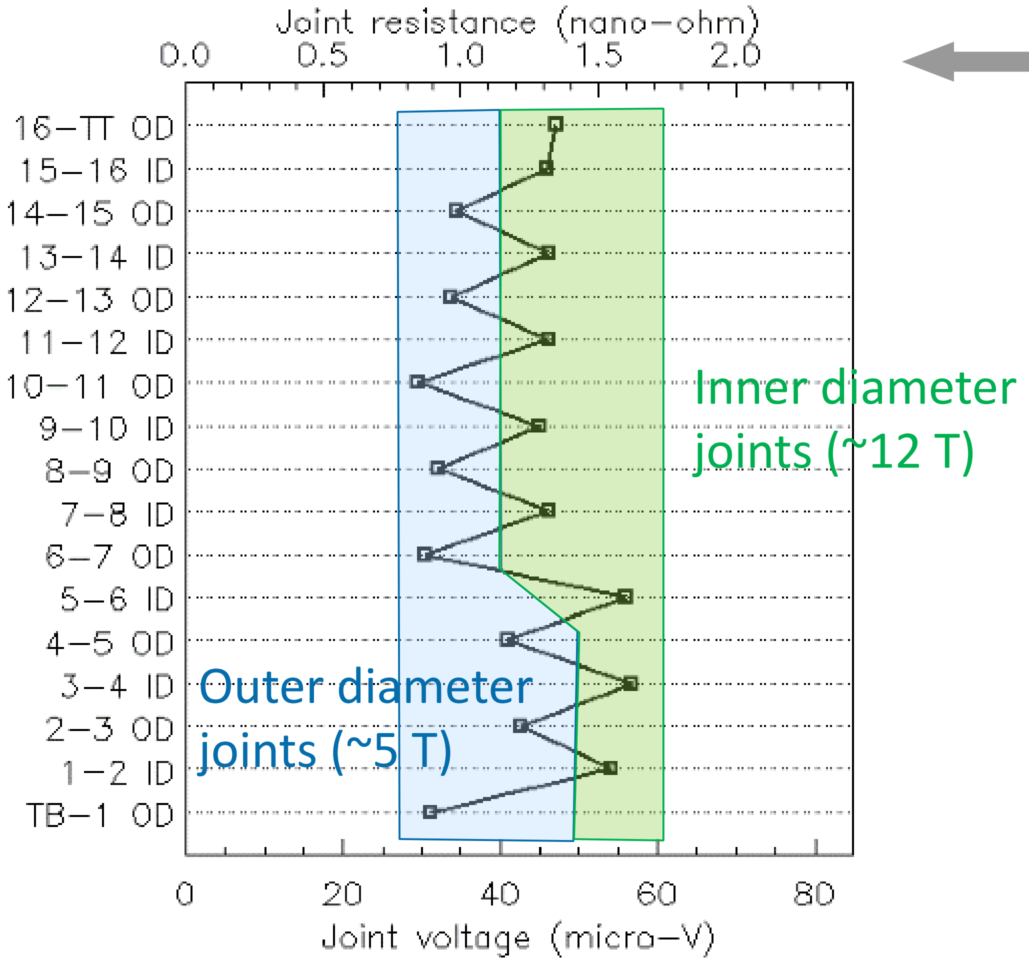
Step 4: Ramp down to 0 kA

- Cambridge power blew up substation around 100 h
- Coil remained charged and thermally stable despite ~2 kW of dissipation for 29 minutes.
- No quench and no damage sustained providing surprise initial data and confirmation of NI coil quench handling albeit at low currents (9.5 kA) and lower stored energy



1^{st} Test: Other key performance objectives that were met

MIT PSFC



Low-resistance internal pancake-to-pancake joints

- R of 1.0-1.5 nΩ at maximum current of ~40.5 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 REBCO magnets exceeding 20 tesla

MIT PSFC

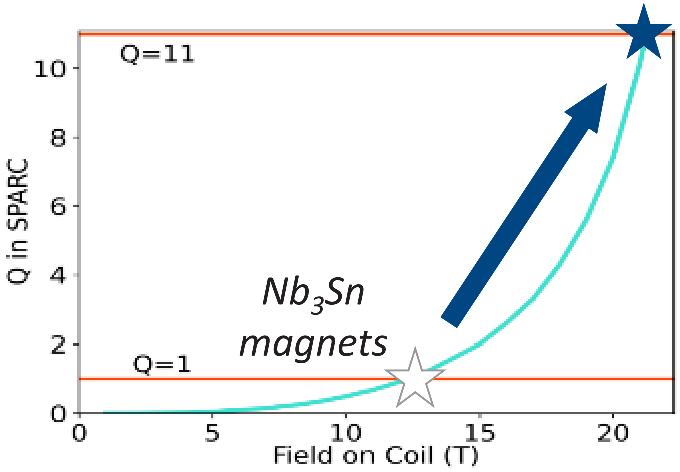
The TFMC has begun a new generation of superconducting magnets at unprecedented performance and compact size

- 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

There remains important experiment work to be done

- Assessing the operational limits of quench resiliency
- Robustness to degradation from mechanical, thermal cycling

TFMC NI Design Feature	TFMC Scorecard
Modular, simple construction	**Success**
Intrinsically low voltage (<1 V)	**Success**
Pressure vessel cooling approach	**Success**
High winding pack current density	**Success**
High thermal stability	**Partial success** (but more work required)
Resiliency to quench	**Incomplete** (active program underway now)



20 T magnets enable compact high-field fusion tokamaks to achieve 10x the power out over power in.