Magnet Activities at PPPL & Summary of First Fusion Magnet Workshop Findings

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Yuhu Zhai Princeton Plasma Physics Laboratory

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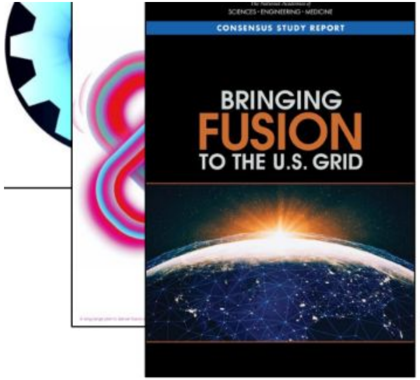
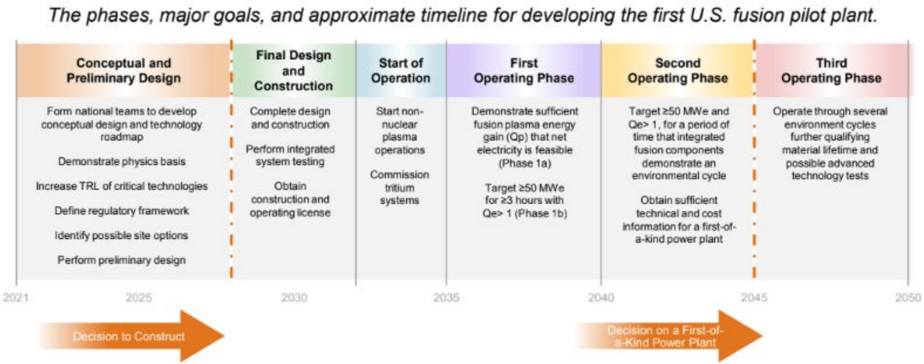
U.S. Strategic Reports on Bringing Fusion to U.S. Grid

- **Goal:** Make 50-100 MW net electricity, extended to long pulses
- **Road Map:** Design in 2020s, Construct in 2030s and Operate in 2030s-2040s
  - **NAS Report:** *30GW of additional generation resources is needed annually reference case analysis*
- **Private Sector: Significant achievement, push on aggressive high field approach**
  - Tests identified critical engineering issues being resolved
  - Quench in large-scale REBCO magnets remains the most significant technical challenge





- Fusion Pilot Plant - DOE milestone-based program
- INFUSE - Public private partnership
- **Possible public programs designed to complement FPP initiatives & beyond!**

Opportunities in Magnets to Bridge Critical Gaps

- **Large bore high field solenoid magnets for sciences**
  - Condensed matter physics - STM probe (>40 T) - P5 panel report
  - Cosmic frontier - Axion Search & Dark Matter Radio Program
  - Synergies for accelerators, Muon collider magnet program (US MDP)

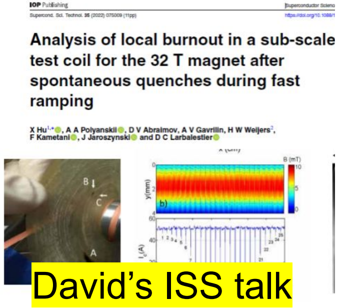
- **R&D infrastructure access to high field test facility**
  - Reel-to-reel REBCO inspection is critical gap @ high field, low temp. cond.
  - Large bore cryogen free testbed (30cm, 7.5T) to meet common test needs
  - Fast ramp field test stand (50cm, 3T, 10T/s) Nat'l labs &private companies

- **High current density fusion magnets developed by public & private**
  - Viable alt. conductors & high current density SC cables - critical gaps
  - Partnerships (Gauss, Bruker, Type One, Stellarex, Princeton Univ, NHMFL)
  - FESAC US test facilities (midscale stellarator, eXcite, FIRST etc.)

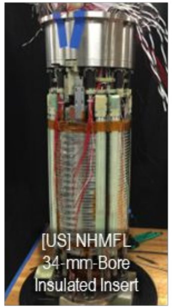
HF Magnet Technology Critical for Science & Applications

Obstacles to HTS magnet technology

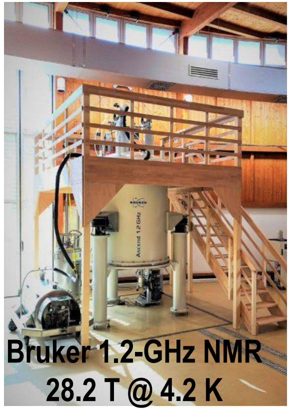
- One important problem of insulated, **single-strand REBCO magnets is burn out at defects.** A 32 T prototype coil burned after more than 100 forced quenches at I<<Ic when tested under fast ramp conditions which produced heating that locally made I > Ic
- **A genuinely multifilament HTS conductor is Bi-2212** (Ulf Trociewitz talk on Thursday Morning)



32-T-Class User Magnets
15-T LTS + 17-T REBCO HTS



> 20 T All HTS Magnets
Towards LHe-Free



Ultra-High-Field Magnet

Compact Fusion Magnet

"REBCO magnets 've been made for 16+ yrs but only few NMR users have 28T magnets: cost of ~$15M each"
D. *Larbalestier, ASC-NHMFL, ISS-2023 talk*

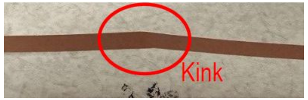
7/10 HTS HF magnet damaged

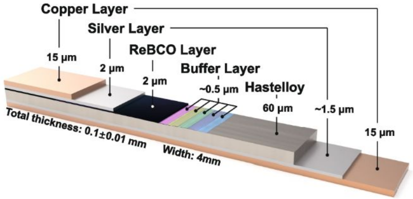
screening current over-stress; quench in fast discharges; fatigue/delamination/buckling etc.

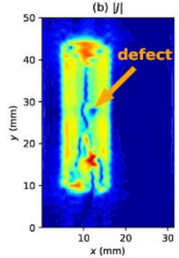
HTS Conductor Technology - Material Characterization

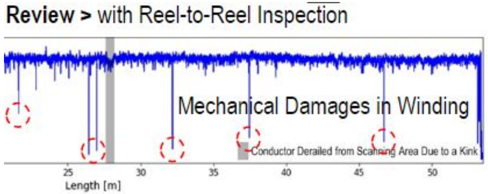
Magnet challenges at high field could be coupled with conductor issues

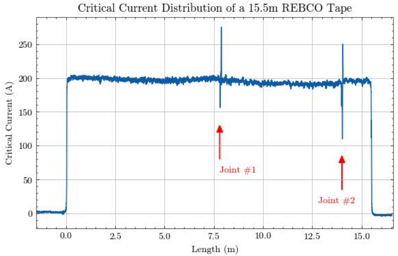
- Intrinsic defects from manufacturing
  - Localized hot spot, non-detectable quench
- An-isotropic material properties
  - Delamination, Ic(B, T, Ø) & thermal fatigue
- Screening current induced over-stress
  - Mechanical failure



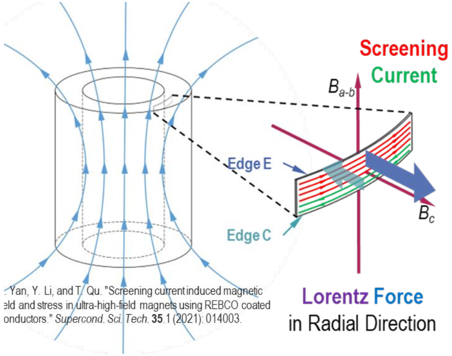








Delamination of YBCO layer



High-Field HTS Solenoids for the Future of Particle Physics

R. Bernstein[1], T. Bose[2], A. Chou[1], B. Echenard[3], S. Gourlay[1], S. Jindariani[1], ...

December 21, 2023

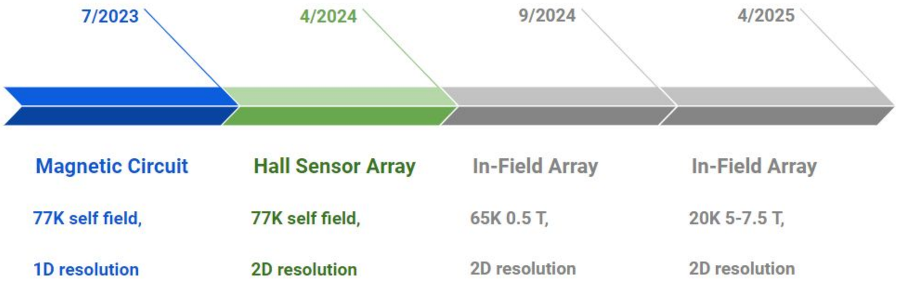
Synergies with HEP [P5 report](#) [& High magnetic field science](#)

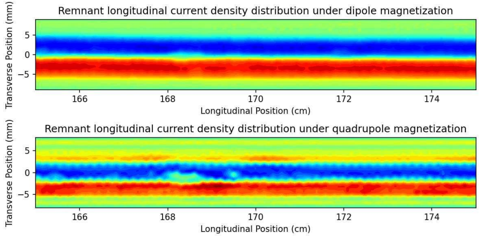
Phase 1: Characterization for Commercial HTS materials

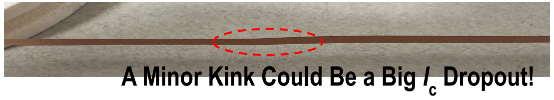
- **Development of Continuous HTS Inspection System at PPPL**
  (1) Industrial standard required for inspecting HTS performance consistency
  (2) China national standard GB/T 41640-2022 for 2G-HTS

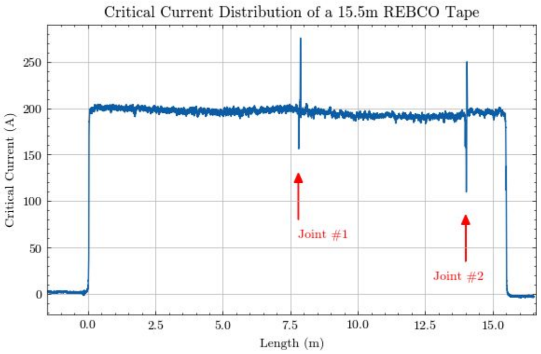
- **Winding Improvement with Reel-to-Reel Measurements**

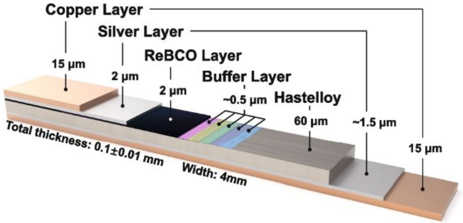
- ***Upgrading System to Enable Low-T High-B Measurements***

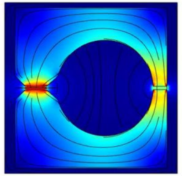


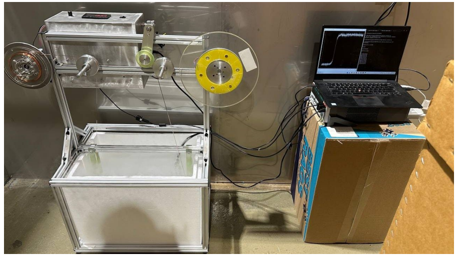


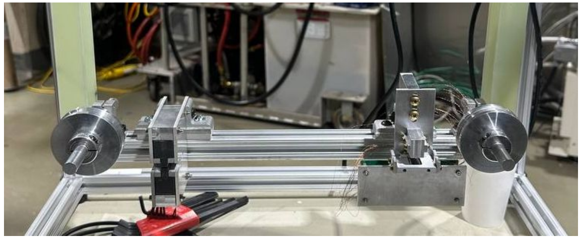








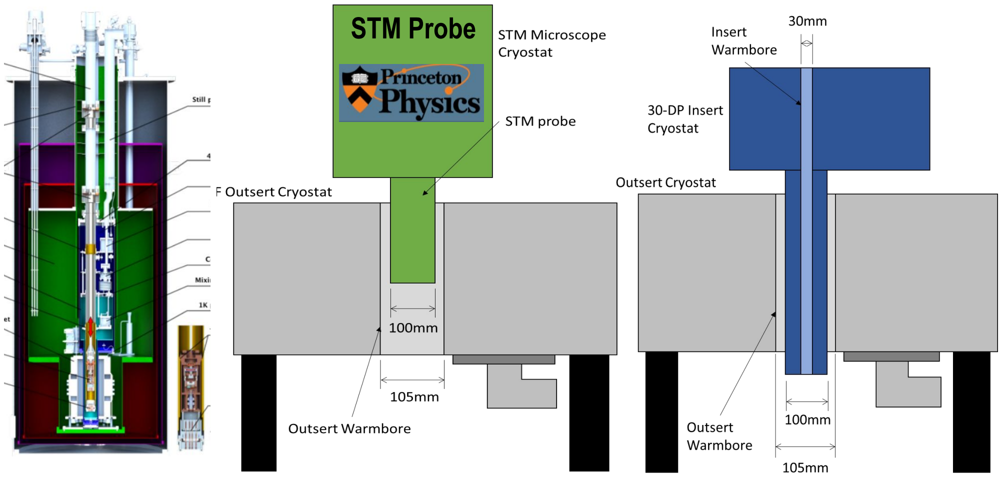




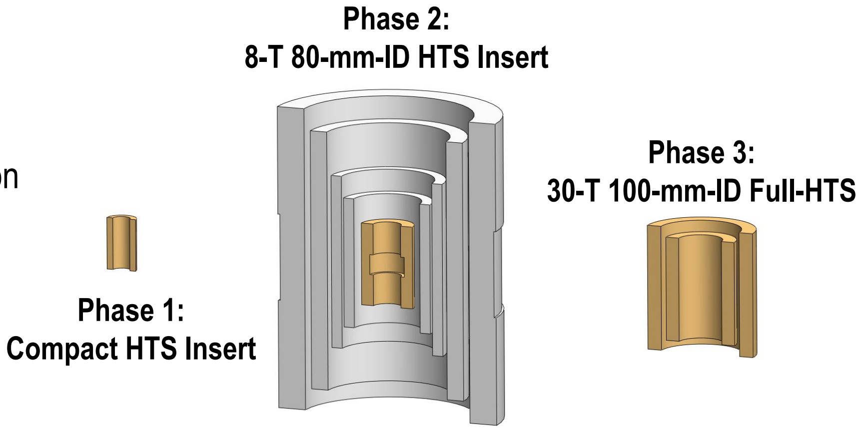
HTS Magnets for Quantum Physics and Compact Fusion

(1) Evaluate the large-bore, ultra-high-field (UHF, > 30 T) magnet technology for quantum physics research, including scanning tunneling microscopy (STM)

(2) Develop a large-bore user magnet compatible with next-generation STM, while higher field accessible with HTS inserts



Yazdani Group **Ong Group**



Phase 1 – Compact Insert Coil: 2 T at 65 K; > 5 T at 4.2 K
(1) Focusing on quality control: winding process, low-resistance joints
(2) Tested 0.8 T @ 77 K, 2 T @ 65 K; **tested > 5 T @ 4.2 K.**

Phase 2 – HTS Insert Prototype: > 20 T with an LTS outsert
(1) Stress management; demonstrate LHe-free operation
(2) Strategy for **quench mitigation and protection**

Phase 3 – Full HTS Magnet: > 30-T, ~ 100-mm bore size
Targeting high-field, large-bore easy access user magnet

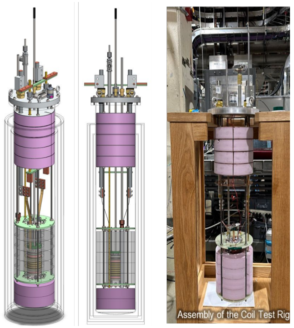
HTS Insert Test up to 5.2 T

- **Compact Coil Design for Tight-Space Cryostat**
  (1) No-insulation coil for structural stiffness and quench mitigation
  (2) Meet radial constraint for inserting into the NSTX-U TF bundle

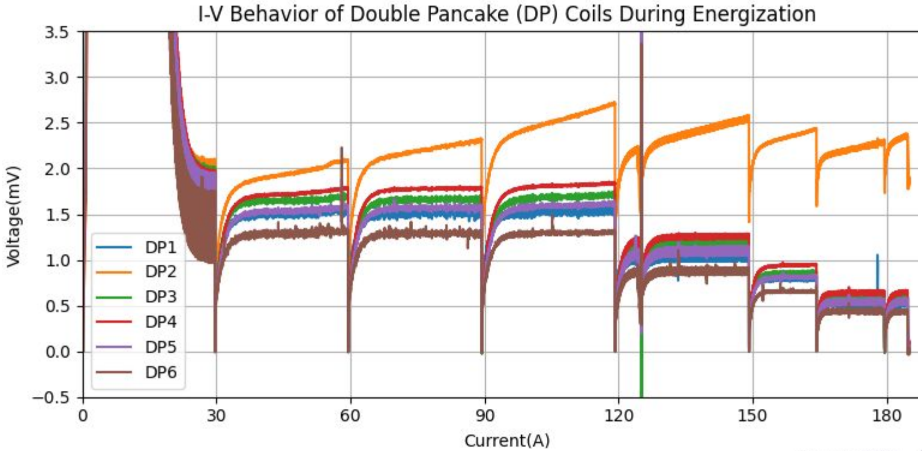
- **6 Double Pancake Stack** 41.3-mm ID, and 70-mm OD wound of 4-mm wide tapes. Extendable to full central solenoid scale.

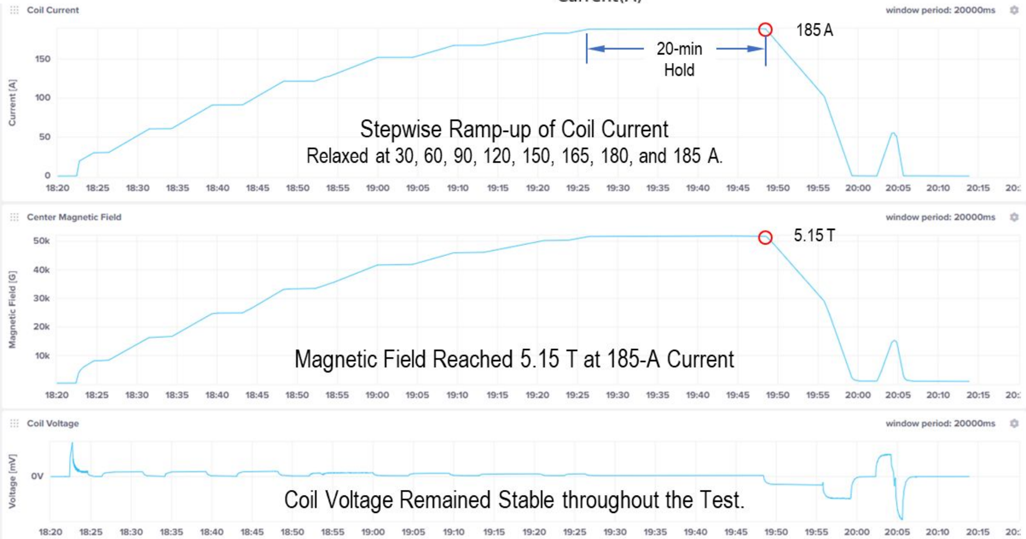
- **Upgrading Infrastructure, Focus on Quality Control**
  (1) Reel-to-reel inspection/characterization system for HTS
  (2) Winding machine allowing co-winding and precise tension control

- **Achievement in Magnetic Field**
  (1) **2.07 T** with 75-A at **65 K**;
  (2) **5.15 T** with 185-A at **4.2 K.**



- **Issues Found in LHe Test**
  (1) Delamination of REBCO at solder joints; common
  (2) A DP coil showed resistance after assembly.



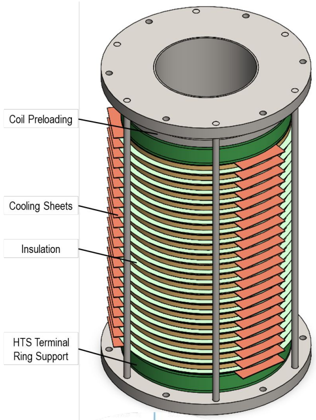


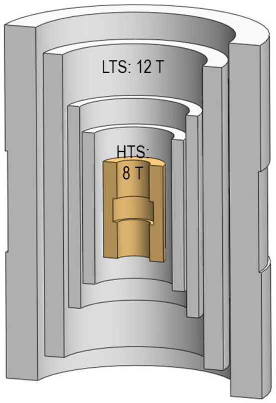
Phase 2: Large-Bore High Field HTS Model Coil

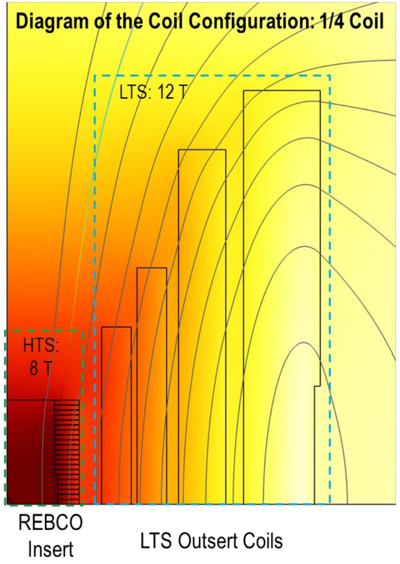
Manage the screening-current stress and quench mitigation in Phase 2, then move on to detail the 30-T magnet.

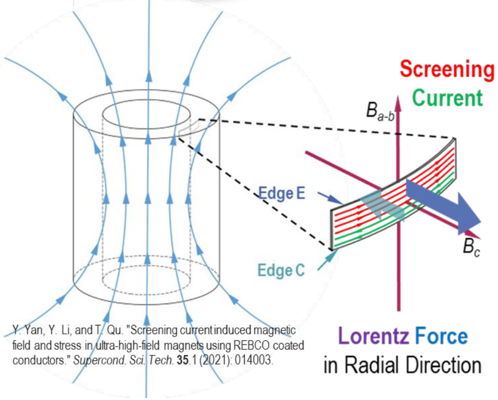
		Design 2C	
Coil		Regular Coil	Notched Coil
# of Coil		16	5
Inner Radius	a_1 [mm]	40	42.25
Outer Radius	a_2 [mm]	61.875	61.875
# of Turns	Single Pancake	175	157
1/2 Height	b [mm]	94.601	
Central Field	B_0 [T]	8.0	
Current	I_{op} [A]	197.3	
Homogeneity	10-mm DSV	26 ppm	
Inductance	[H]	1.916	
Conductor	REBCO		
Width	w [mm]	4	4
Occupied Height	[mm]	4.2	4.2
Thickness	t [µm]	75	75
Co-Winding	t_{CW} [µm]	50	50
Cooling Plate	per DP [mm]	0.6096	
Length	[m]	112.02	102.72
Subtotal	[m]	2640	880
Total Length	[km]	2.31	

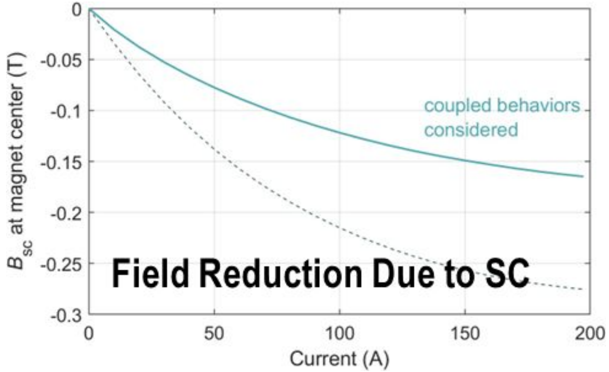
Stress level critical even without considering screening current.





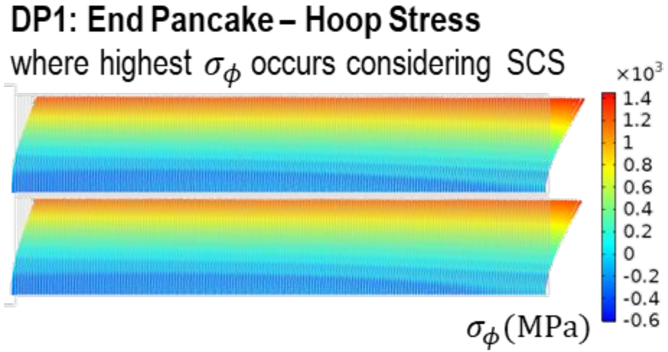


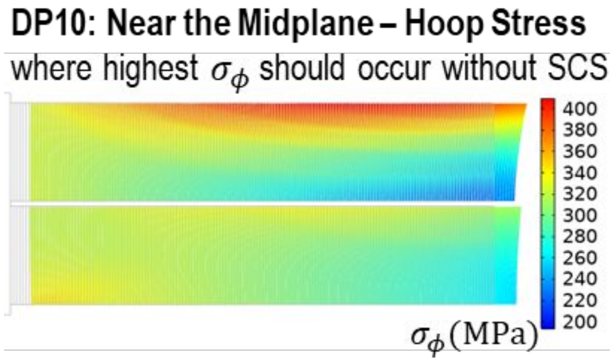


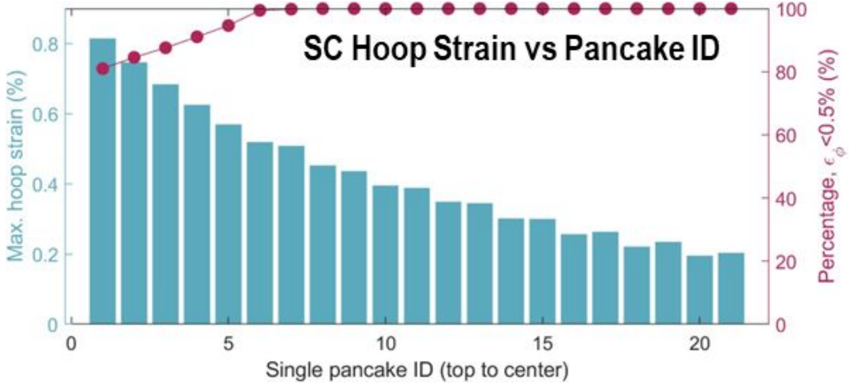


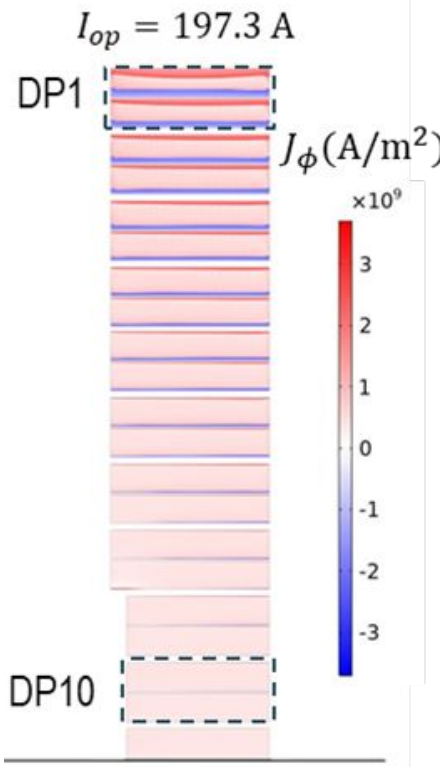
Screening Current Stress Management

- **Screening Current Distribution + Associated Hoop Stress/Strain**
- **Mitigation of Screening-Current Stress on End Pancake Coils** (1) Overband reinforcement



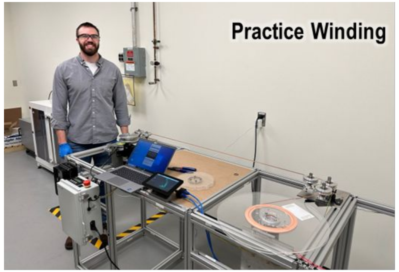


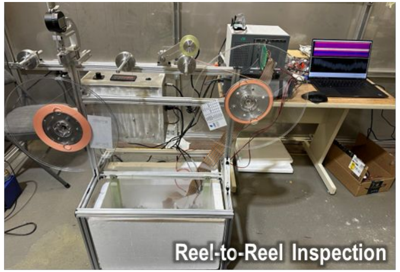


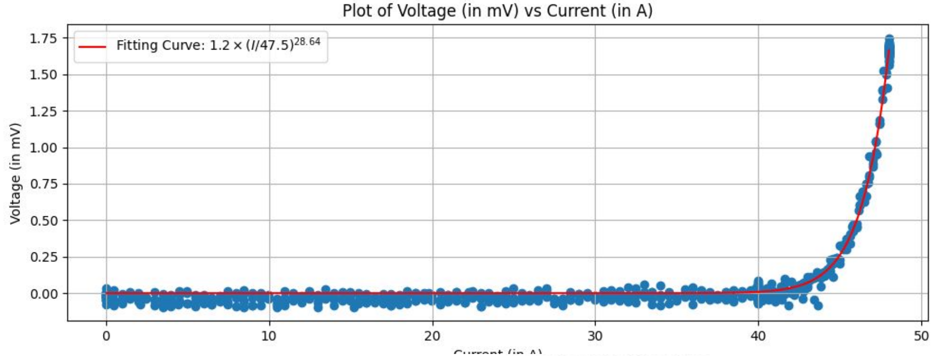


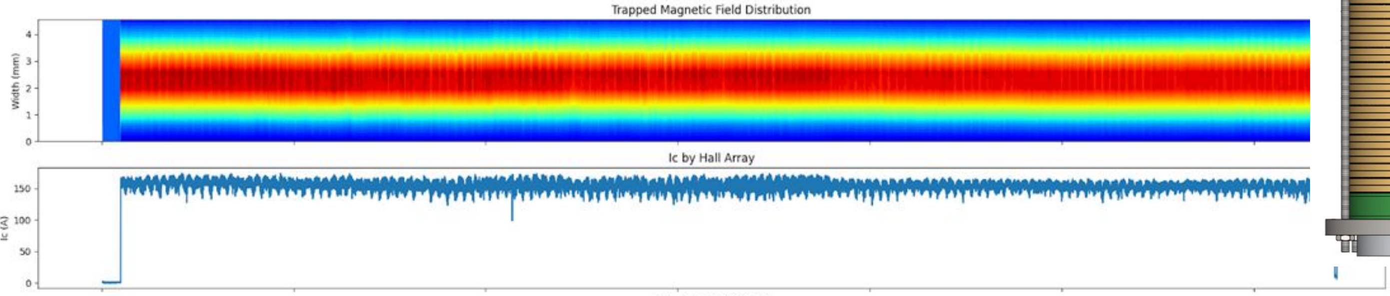
Phase 2: Large-Bore High Field HTS Model Coil

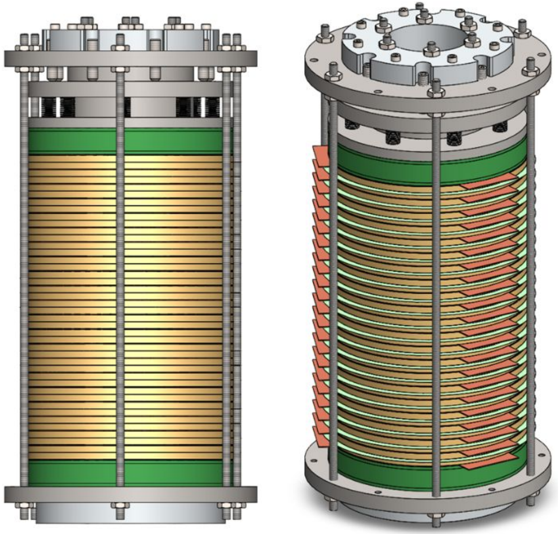
- YBCO conductor reel-to-reel inspections
- Winding and cryogenic testing of the 21 DP coils
- Assemble all DPs for lower temperature testing









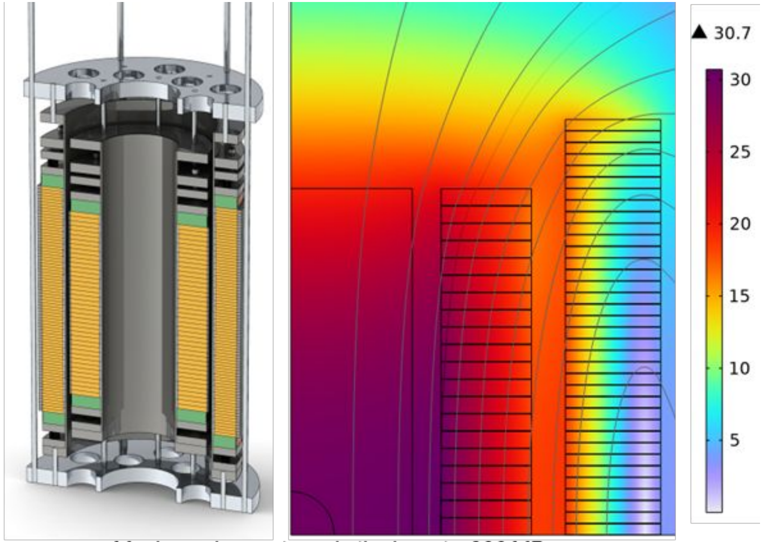


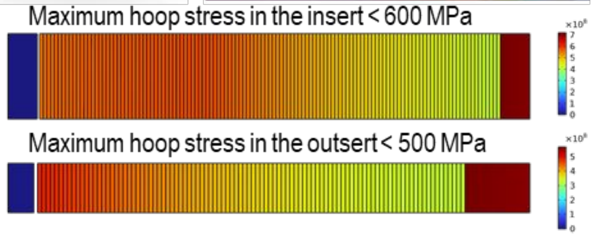
Phase 3: 30-T-Class Large-Bore Full-HTS Magnet

First-Cut Design and Stress Computation

Once we finalize approach to manage the screening-current stress and quench mitigation in Phase 2, we will move on to detail the 30-T magnet.

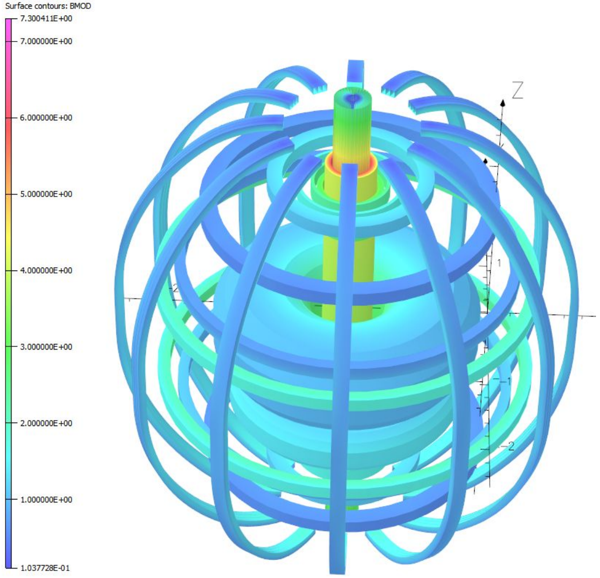
Parameters	Coil 1 (Insert)	Coil 2 (Outsert)
Material	REBCO + SUS304 Co-Winding	
Conductor (Width; Thickness)	6 mm; 75 um	4 mm; 60 um
Co-Winding SUS304 Thickness	50 um	50 um
Winding ID $2a_1$; OD $2a_2$	104 mm; 179 mm	200 mm; 256.3 mm
Coil Height $2b$	120 mm	148 mm
# of Turns/Double-Pancake	600	512
# of Double-Pancakes	20	37
SUS304 Overband	2 mm	5 mm
Transport Current	254.7 A	
Conductor Current Density	566.0 A/mm^2	1061.3 A/mm^2
Winding Pack Current Density	339.6 A/mm^2	578.9 A/mm^2
Winding Pack Hoop Stress	581 MPa	389 MPa
Central Field Contribution	13.78 T	16.22 T
Conductor Length Required	5.4 km	13.6 km

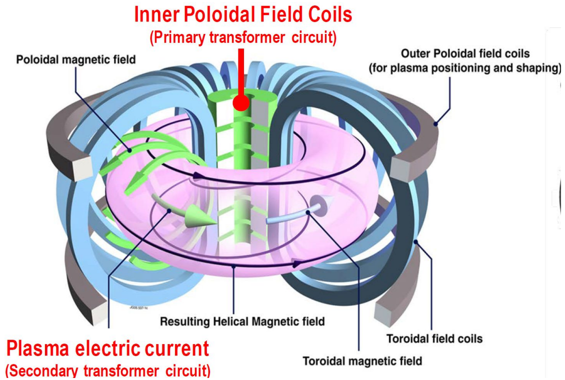




Stress level critical even without considering screening current.

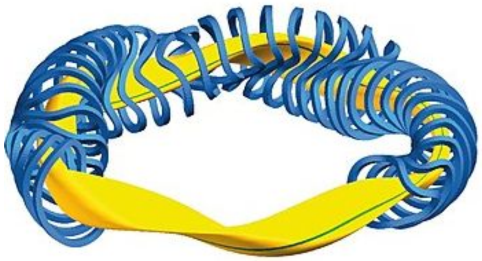
High Current Density Fusion Magnet System





$\partial t \neq 0$

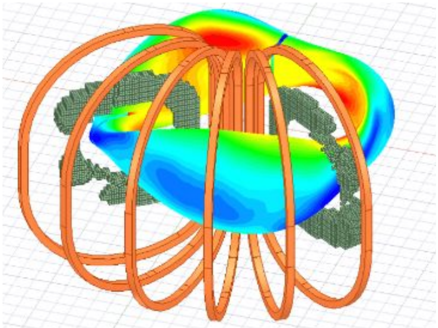
Disruption drives engineering design!



$\partial t = 0$

No disruptions & driven plasma currents & Typ. static B field

dB/dt (T/s)	ITER	EAST	K-STAR
TF Coils	1.7-6.6	?	?
CS & PF	2.0-5.5	7-10.6	8



High Field HTS Model Coil Fatigue Test for ST-FPP CS Design Validation

Scientific Achievement

- PPPL-ACT-FSU collaborated on a fast-ramp, HTS cable model coil with high-field fatigue testing to de-risk ST-FPP Central Solenoid - design and pulsed tokamak ops.
- Novel design of the coil support without impregnation in winding pack tested in field and 5 kA/s ramp rates is relevant for high field FPP operations

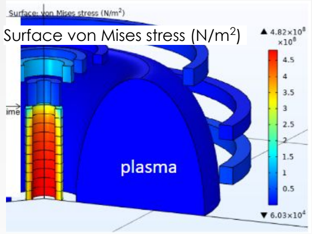
Significance and Impact

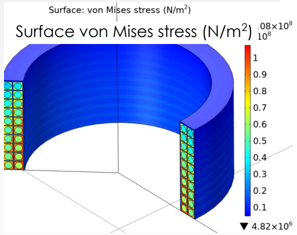
- Self-field testing at 4 K and 77 K demonstrated fast ramp rates with stable operation for FPP-relevant OH design and pulse operation
- Screening current manageable in non-impregnated REBCO cable coils
- Key results for FPP OH coil design from high field cyclic load testing

Research Details

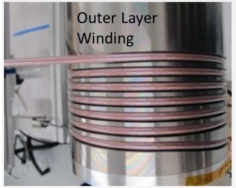
- No sign of degradation seen in high field & low-cycle fatigue testing - I_C>80% sum of tapes
- Matched inductance voltage taps significantly improved quench monitoring, allowing observation of consistent, stable V-I transitions through ~75 cycles at ~175 MPa in 12 T background field
- Demonstrate feasibility of direct dry wound (non-VPI) coil design

High field CS and STAR Coil System



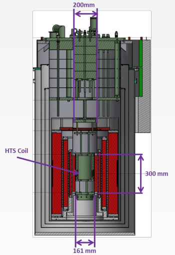


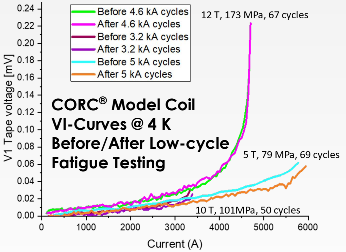
A two layer Cable Model Coil



Prototype Ohmic Heating CORC Cable Solenoid		
Cable	Product No.	ACT- CORC, 20191113-3
	Tape	M4-534-105 0508
	Insulation	Heat Shrink + Kapton between Cu tape and cable
	Diameter [mm]	5.86
ID ; OD ; Height [mm]		119; 152; 60
Turn ; Layer (Total)		6; 2 (12)
Coil constant [mT/A]		0.102
Inductance [mH]		~ 0.019
Conductor length [m]		5.1

Fatigue Test	Cycles	B_{app} [T]	Peak JBr stress [MPa]	Min cycle I_{op} [A]	Max cycle I_{op} [A]
1	69	5	79	2200	5000
2	50	10	101	2000	3200
3	127	12	107	1600	2800
4	67	12	173	3400	4600





High Field Test Facility
161 mm, 12 T, 10 kA

Y. Zhai, T. Brown, and J. Menard

Z. Johnson, J. Weiss, van der Laan

D. Davis, U. Trociewitz, and D. Larbalestier

PPPL PRINCETON PLASMA PHYSICS LABORATORY

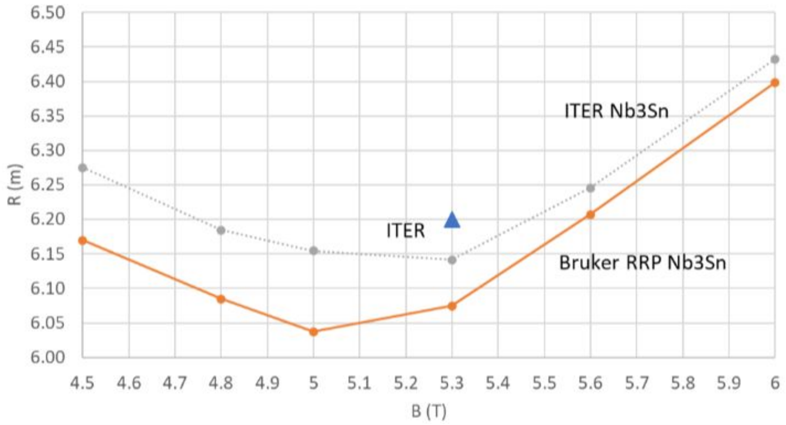
Advanced Conductor Technologies LLC
www.advancedconductor.com

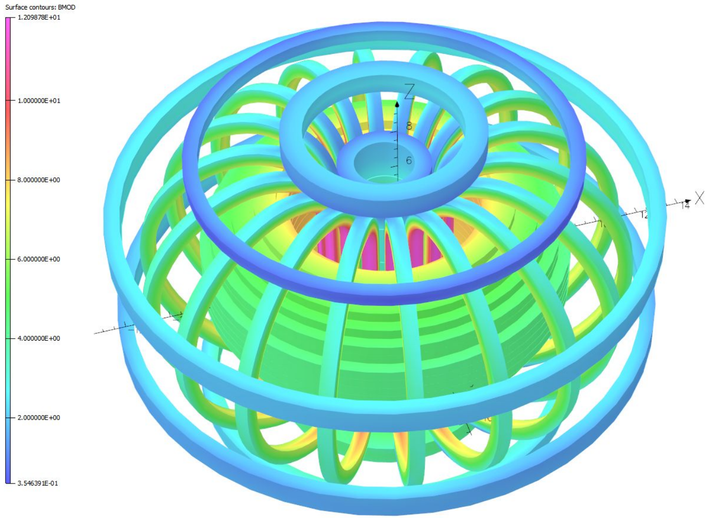
NATIONAL HIGH MAGNETIC FIELD LABORATORY

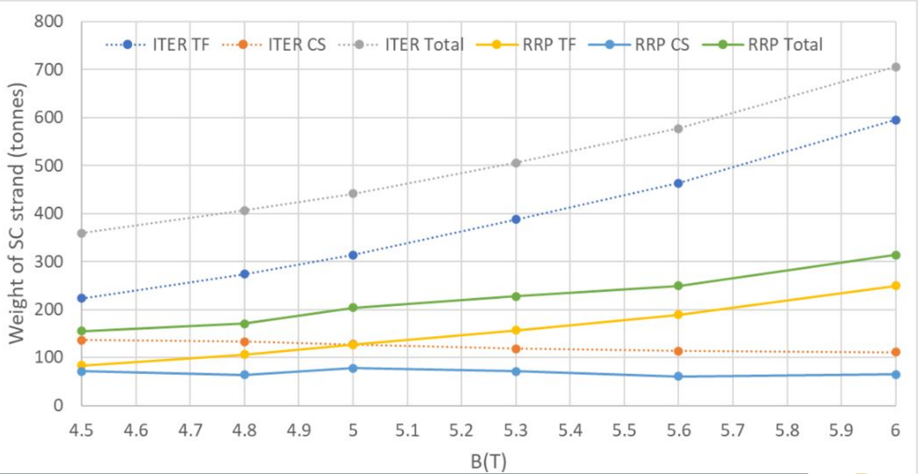
Reference, XXXX, ##, 2023

Impact on FPP with High Jc RRP Systems studies

Impact machine size (field, radius, radial build) relative small but affect net weight of sc strands more significantly - varying roughly as ratio of TF critical current in low to high performance strands







March ‘23 Fusion Magnet Community Workshop

- *There is a pressing need for a strong U.S. public program* in underlying superconducting magnet science & technology to help deploy commercial fusion energy on the timelines proposed by private companies
- *A community-led process shall be developed* by establishing all stakeholder roles, prioritizing scientific issues and proposing research thrusts as part of new FES roadmap development (10-15 years)
- *Significant opportunities exist to improve maturity of magnet technology* in support of private sector efforts to demonstrate reliability and economically viable high field compact fusion

Report of *Fusion Magnet Workshop* *March 14-15, 2023 in Princeton, NJ*

R&D Gaps in March '23 Workshop Report

- Radiation effects in superconducting magnet materials
- Test facilities for fusion-relevant radiation damage
- Test facilities for large-scale cable and magnet tests
- Quench detection and mitigation strategies
- Magnet materials science and technology
- Characterization of commercial HTS materials
- Development of multiscale modeling capabilities
- Science foundations for future magnet technologies
- Hands-on, at-scale opportunities for workforce development

RFI and call for white papers due today for next workshop planning!

Objectives of 2024 Workshop (FES Roadmap)

- ***To define a new base program for fusion magnets*** and determine how it can best advance critical science & technology, test stands, workforce; be positioned to support private efforts towards commercial fusion (Bold Decadal Vision link).
- ***To prioritize research addressing R&D gaps and outstanding technical challenges***, proposed near- & long-term test facilities required in the public program.
- ***To develop a R&D roadmap*** that extends U.S. leadership in superconducting M&ST for fusion to support a first-of-kind FPP in the 2030s and a fusion industry beyond.
- ***To identify critical opportunities and synergies with other research fields*** using large-scale superconducting magnets (HEP, high field magnet research, NMR/MRI).
- ***To develop a fusion magnet education program*** to generate an essential workforce by leveraging capabilities of universities, national labs, and the fusion industry.

R&D Roadmap Develop. & Community Activities

Our Fusion community has been very active! Thank You for your engagement!

***FES Vision Talk* by JP Allain**

- **IFE BRN June 2022**
- **Fusion Prototypical Neutron Source Workshop Sept 2022 Hosted by EPRI**
- **Fusion Non-proliferation Hosted by PPPL in Jan**
- **Fusion Neutronics Hosted by ORNL in Jan**
  - Follow-on: Report summary and workshop
- **Fusion Magnet R&D Hosted by PPPL in Mar**
  - Follow-on: Fusion Magnet Workshop
- **Fusion Blanket and Fuel Cycle Hosted by EPRI in May**
  - Follow-on: Blanket and Fuel Cycle Page and a workshop roadmap report
- **Fusion Materials Hosted by EPRI Nov 14-15**

The Road to Fusion Energy is through *combined* private sector "pull" and public sector "push" - with extraordinary gaps to address

Build LRP FM&T Gap Facilities

A Fusion S&T Roadmap with metrics to track progress

- Our role in FES is to **focus** on the science and technology gaps as our "bridge" to realize a viable path towards fusion energy (an "interim stage")

Site visits to meet magnet stakeholders in fusion industry

Name List	Date and time	In-person or Virtual	Attendances
Realta Fusion	1/29/2024	Virtual Meeting Notes	Realta - Craig Jacobson, Dominick Bindl, Cary Forest OC - Larbalestier, Prestemon, Zhai
TAE	1/26/2024	Virtual Meeting Notes	TAE - Greg Snitchler OC - Prestemon, Hartwig, Zhai
STELLAREX	1/12/2024	Virtual Meeting Notes	Stellarex - Mike Zarnstorff OC - Larbalestier, Prestemon, Duckworth, Zhai
Type One	1/11/2024	Virtual Meeting Notes	Type One - Zachary Johnson OC - Larbalestier, Prestemon, Zhai
GA and TE	12/11/2023	Onsite at ITER CS fabrication and test facilities Agenda & Notes	GA - John Smith, Nikolai Norausky, Amani Zalzali TE - Greg Brittles, Liam Brennan OC - Larbalestier, Prestemon, Duckworth, Zhai
CFS	11/21/2023	Onsite at Devens, MA Agenda & notes	CFS - Mumgaard, Sorbom, Segal, Woulfe OC - Duckworth, Forest, Larbalestier, Prestemon, Zhai
MIT-PSFC	11/20/2023	Onsite at PSFC, MIT Agenda & notes	PSFC - Hartwig, Whyte, OC - Forest, Duckworth, Larbalestier, Prestemon, Zhai

Test Facilities

- There are substantial cable and self-field magnet test facilities but limitation on conductor and coil testing to advance technology may not be on existing facilities - funded R&D at scales needed to de-risk FPP

- New test capabilities for assessing HTS conductors under conditions need to be developed - *fusion-relevant radiation conditions under operating conditions*

	Operating Currents	Testing space / volume	Cryogenic Cooling	Background field if applicable
MIT PSFC	10 kA to 50 kA	20 m^3	SCHe at 20 K with 600 W	
FSU ASC	10 kA	⌀ 160 mm clear bore	4.2 K	12 T solenoid field
General Atomics	up to 50 kA	160 m^3	SCHe at 4.5 K with 1 kW	
BNL	7.5 kA to 40 kA	⌀ 500 mm to 610 mm 31 mm x 335 mm aperture	4.2 K 4.2 K	 10.2 T dipole field
FNL	2 kA to 28 kA 100 kA*	⌀ 54 mm to 147 mm 94 mm x 144 mm aperture*	1.8 to 100 K 4.5 K to 50 K*	15 T 16 T*

*Joint FES/HEP facility under development at FNL that is expected to come online in 2025

- *Large bore (0.5 m), high field (15 T) sc magnet test capability to push stress in prototype coils* and minimize the amount of conductor needed in a given coil geometry
- *Pulsed current test facility to address issues of ac loss heating, cyclic stress* during high ramp rates
- High DC current (25 kA) to provide SS evaluation of quench and long-term operating stability
- Integrated advanced cooling for *increased operating temperatures to address LHe supply issues*

Summary

- Magnet R&Ds bridge critical gaps - A need for a fusion magnet program
- Unique expertises & opportunities to support fusion magnet development
- Explore synergies with others for accelerator, Muon collider magnet (US MDP) - Partnership with NHMFL, LBNL, FANL and BNL etc.
- Training of next gen. diverse workforce at all levels (scientist/engineer/tech)

- Next workshop will focus on a R&D plan (FES roadmap development)
- Challenges for high field compact tokamaks for fusion

Please contribute to the next phase of the R&D program planning!