IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue 53, July 2023.
Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Coated Conductors and HTS Magnets for Compact Fusion

Yuhu Zhai

Princeton Plasma Physics Laboratory

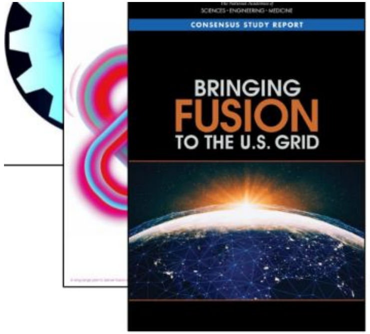
PPPL Team
T. Brown, J. Menard, M. Zarnstorff, P. Titus, C. Kessel (now with ORNL)

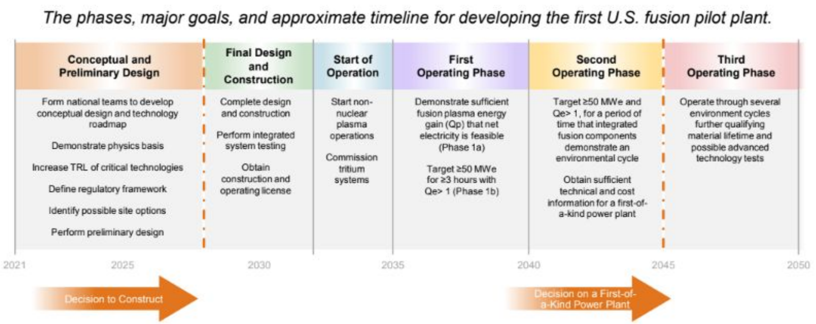
Collaboration Team
D. van der Laan, Advanced Conductor Technologies, D. Larbalestier & D. Davis, FSU-ASC-NHMFL

Coated Conductor Application Workshop at University of Houston April 4-6, 2023

U.S. Strategic Reports Emphasize Fusion Pilot Plant

- **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:** Bring Fusion to U.S. Grid -> ***30 GW of additional generation resources needed annually from '40 t0 '50 based on reference case analysis***



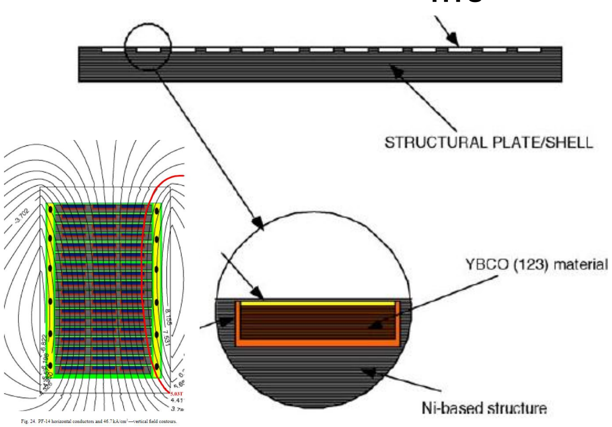


- Establish scientific and technical basis for a fusion pilot plant by 2040s
- Next step test facilities (tokamaks and compact stellarators)
  - Establish mission need to close integration & magnet R&D gap(s)

PPPL design studies for low-A tokamaks/stellarators

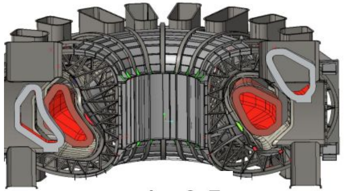
- Establish scientific and technical basis for a fusion pilot plant by 2040s
  - Integrate self-driven current with high core confinement, pressure, heat flux
- Steady-state to reduce disruptions, cyclic fatigue and need for pulsed power systems to enhance reliability and more compact to reduce size & cost

Dahlgren et al, 2006

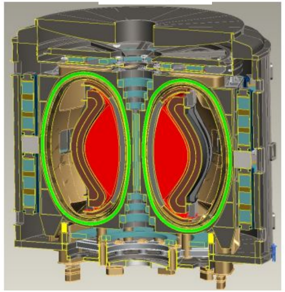


First HTS magnet system was proposed in **ARIES AT** studies (Fusion Eng. Des., 2006)

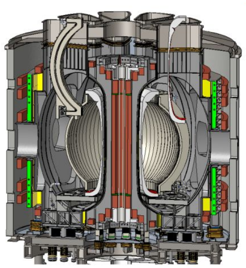
2014-2016



A = 6–7



2016-2022

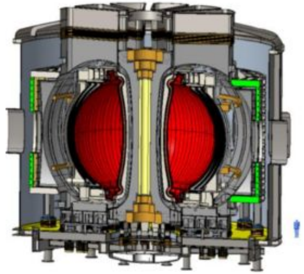


Sustained high power-density (SHPD) tokamak A = 2–2.5

R=1-1.6m, HTS TF SHPD and EXhaust and Confinement Integration Tokamak Experiment (EXCITE)

FNSF & FPP A=2, R=3m HTS TF / P_{net} = 50-100 MWe

2021-2022



ST Advanced Reactor (STAR) Fusion Power Plant

A=2–2.2, R=4–4.5m, HTS TF

P_{net} = 200-500MWe

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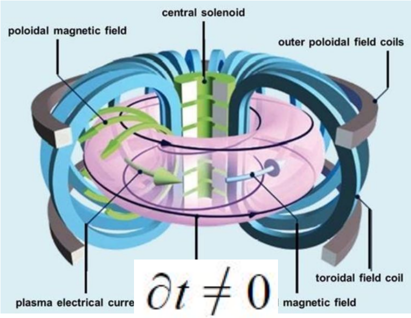
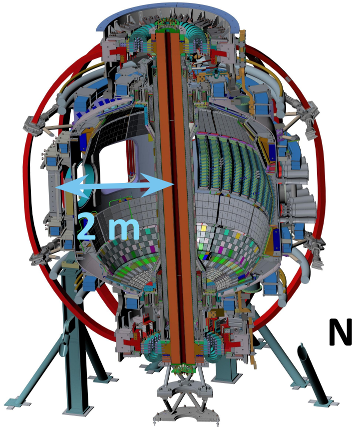
Two Different Magnetic Configurations

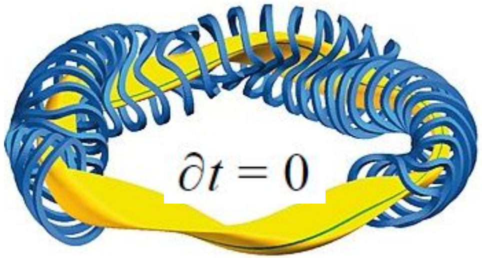


Plasma disruption drives engineering design!



NSTX-U, PPPL

HTS Conductors	HTS Magnets
Ideal - isotropic, low cost, low loss, high Jc & high strength, rad. resistant, flexible design & easy integrate into coil design	Conduction or 10-20 K gas cooled, 16-20 T on coils, high winding pack J_e
YBCO - anisotropic, high cost, large losses, high strength, screening current; high risk CICCs, no heat treatment	High field, compact steady state TF coils, >10 kA cables, quench and stress management
Coated Conductor application - High current cables **Different specs for diff. coils**	High current density, high field OH coils for plasma startups (>kA/s or 1-3 T/s ramp rate)



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

MUSE, PPPL

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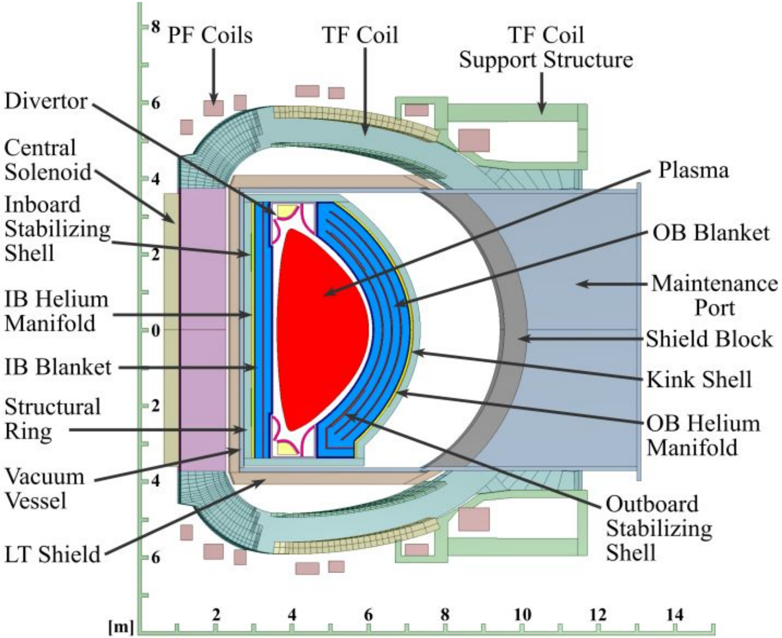
Fusion Energy Systems Studies - Fusion Nuclear Science Facility

- Missions established in FNSF study for any intermediate device (ITER -> Power Plant)
  - Advance fusion neutron exposure of all core components toward the FPP level
  - Routinely operate plasma for very long durations (hours, days to weeks)
- Advance enabling technologies
  - Develop power plant relevant subsystems including high field magnet system



Total Stored energy 2x of ITER per TF coil
Total centering & vertical forces are 2~2.5x of ITER per TF IB leg

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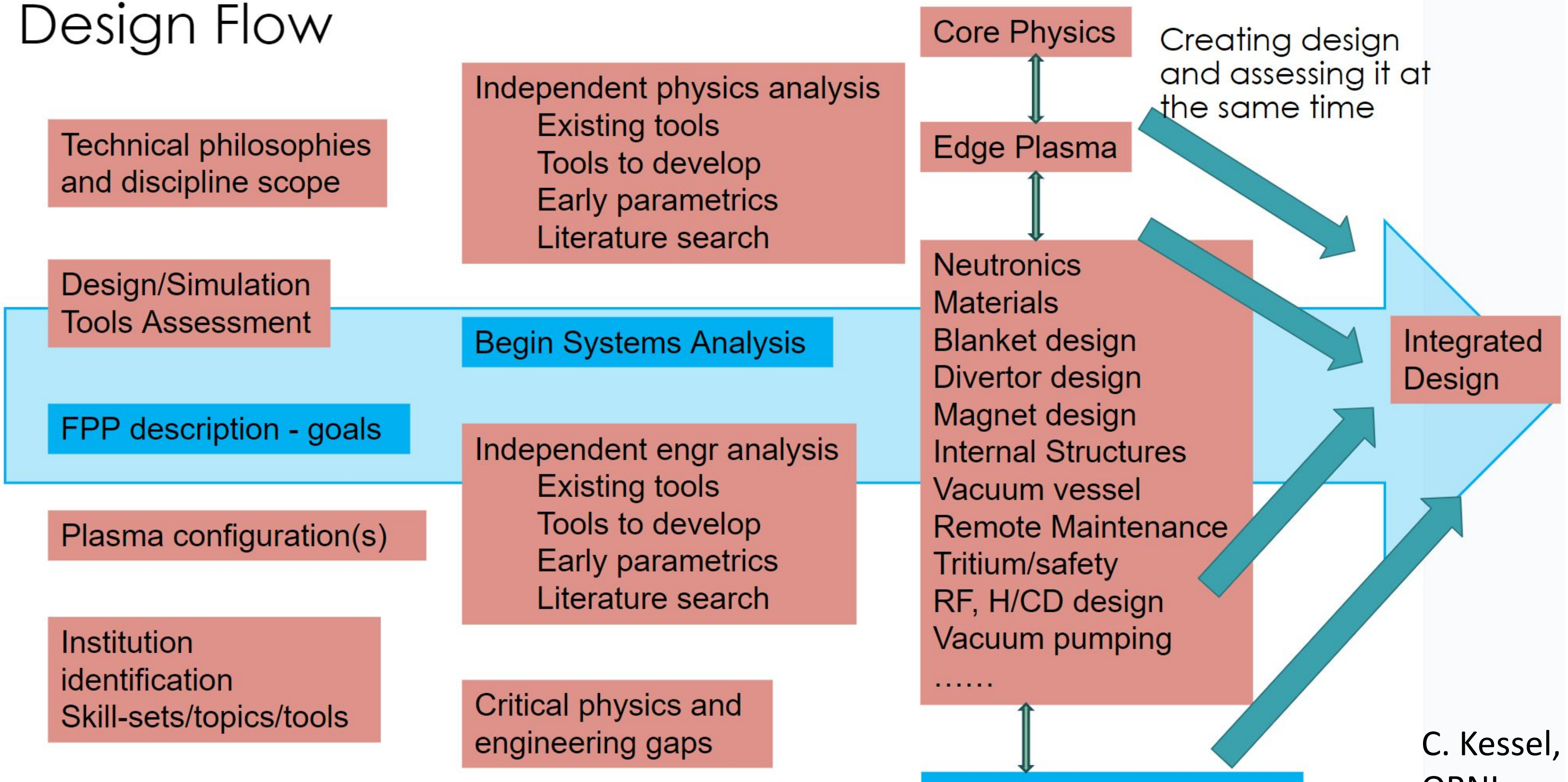
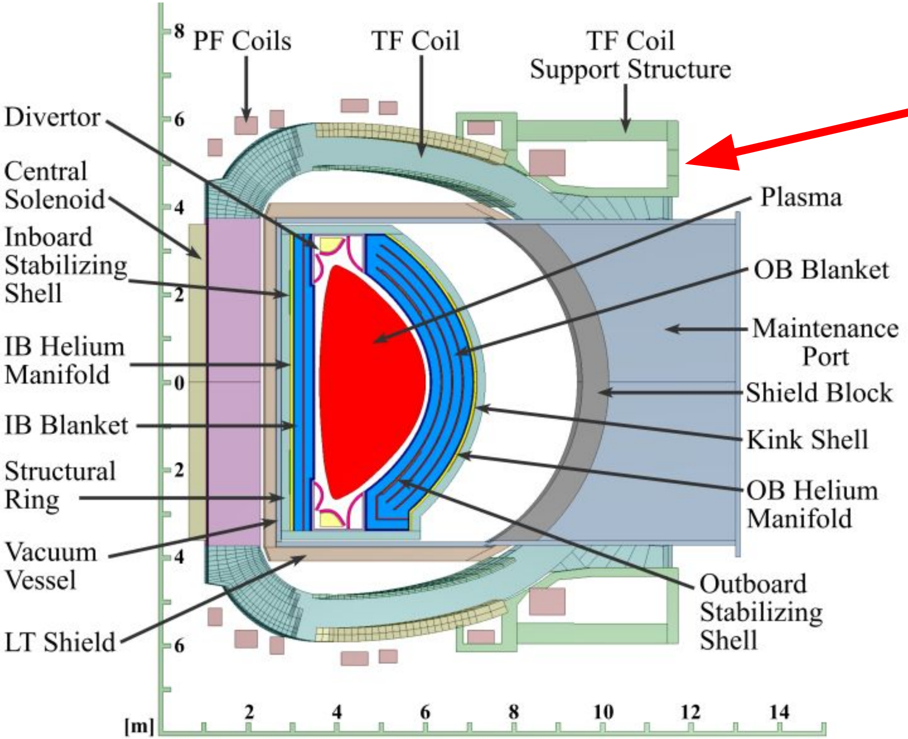
Design Flow



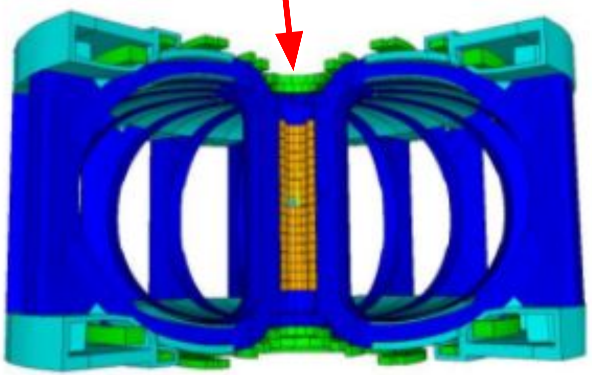
Integrated Design for Fusion Nuclear Science Facility

C. Kessel, ORNL

Fusion Nuclear Science Facility Coil System Design



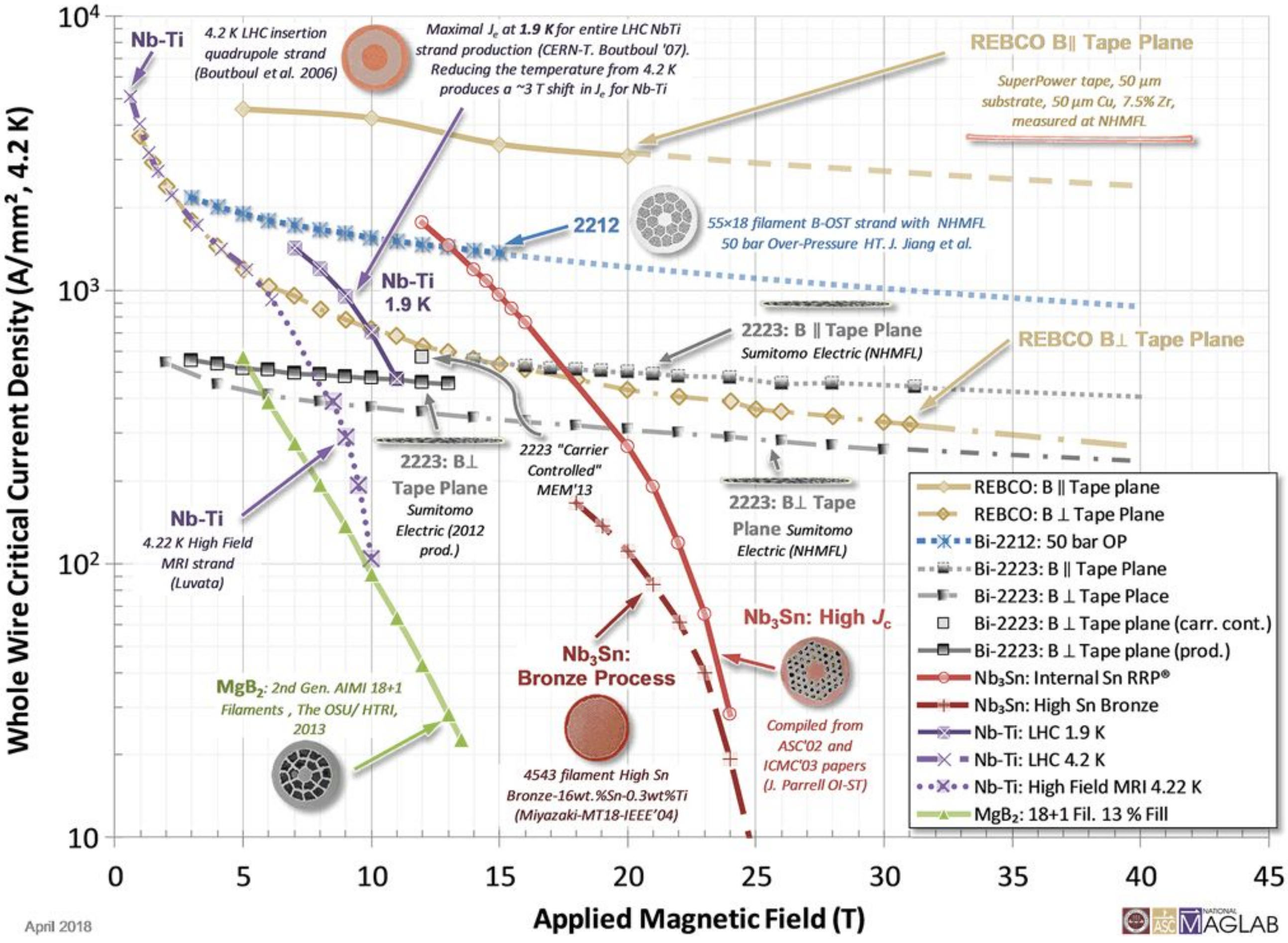
inter coil support structure to react OOP bending



Magnet integration for WP optimization

Zhai et al., Conceptual design of HTS magnets for FNSF, *Fusion Eng. Des.*, 168 (2021) 112611 (here)

Engineering Critical Current Density vs. Applied Field

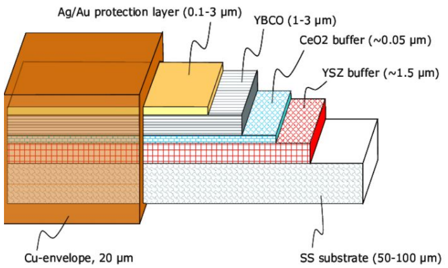


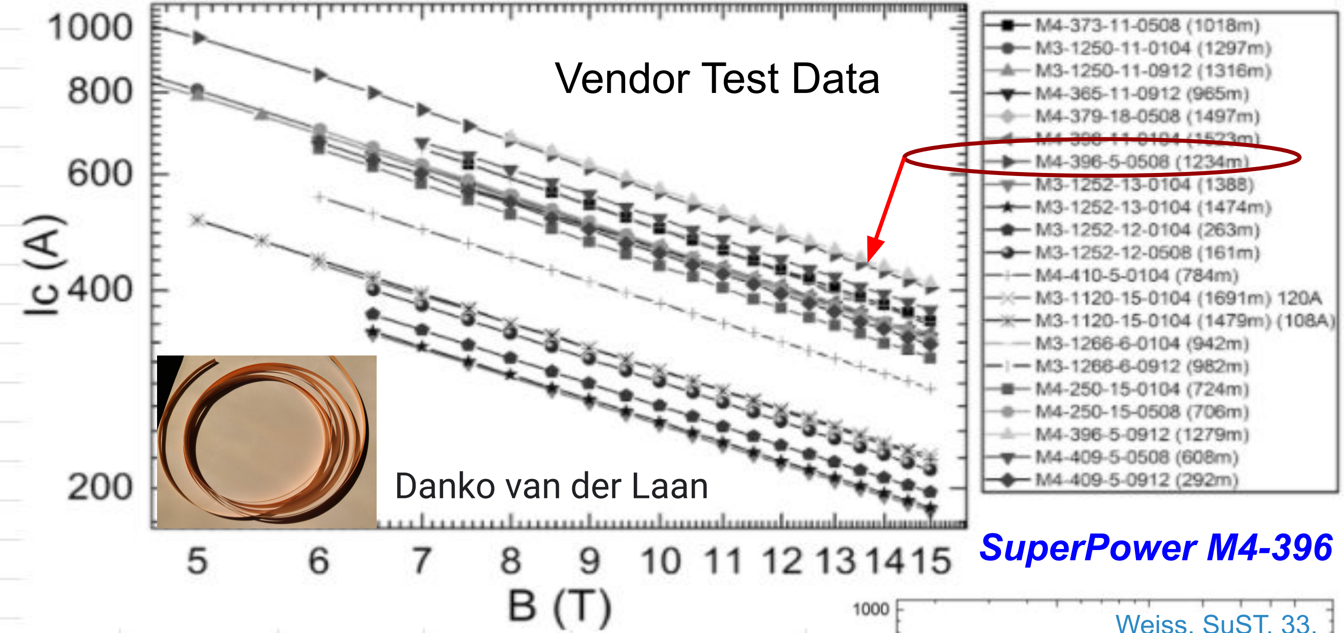
Coated conductor with attractive properties for Fusion Nuclear Science Facility magnet design and optimization!

Relevant Conductor Critical Current Performance

ReBCO tape (Superpower M4-396) performance - min
I_c (6T) = 800 A

I_c (77K, s.f.) = 137.14 A
I_c (4.2K, 20T) = 305 A

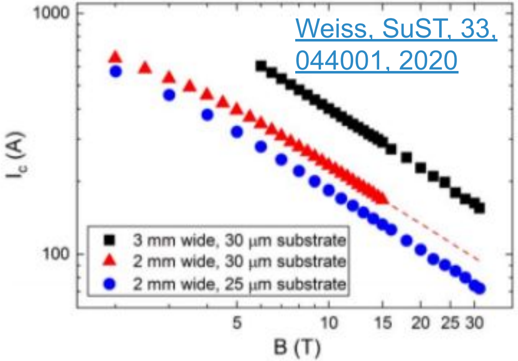




SuperPower M4-396

High current density cables consisting of multiple coated conductors are essential for engineering design of the next step configuration studies to allow space for interior plasma components.

Tape used to construct **CORC®**

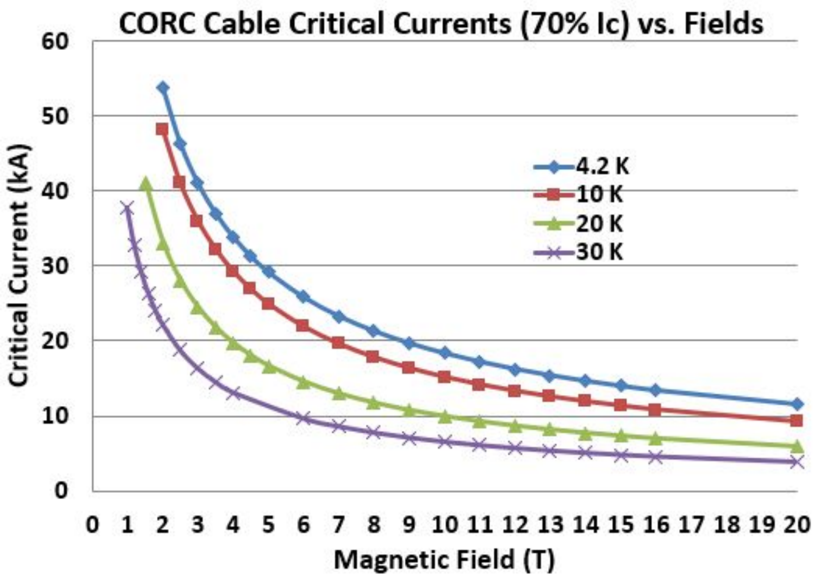


Weiss, SuST, 33, 044001, 2020

Fusion Nuclear Science Facility (FNSF) TF Magnet Conductors

6-around-1 **CORC®** CICC with performance up to >60 kA at (4.2K, 20T)

CORC® cable	**I_c (4.2 K) 70 %**	**Diameter (mm)**
HF - 50 tape 50 micron	305 A/tape - 20 T	8
MF - 38 tapes	406 A/tape - 14 T	7.2
LF - 24 tapes	635 A/ tape - 8 T	6.375



ReBCO tape (superpower M4-396) performance - min I_c (6T) = 800 A

Ic (77K, s.f.) = 137.14 A
Ic (4.2K, 20T) = 305 A

CORC® cable performance
I_{op} (70% I_c) = 10.67 kA @ (4.2K, 20T)

CORC® current density > 150 A/mm²

FNSF TF WP, 4.2 K performance with force flow LHe cooling

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Fusion Nuclear Science Facility TF Design Parameters

	ITER	FNSF
Conductor	Nb_3Sn CICC	6-around-1 CICC
Major Radius (m)	6.2	4.8
Minor Radius (m)	2	1.2
Plasma Current (MA)	15	8.0
Plasma Center B (T)	5.3	9.3
TF Operating Current (kA)	68	64
TF Max B Field (T)	11.8	20.3
WP Je (A/mm^2)	17	39
TF A-Turns (MA)	9.1	14.0
# of Turns	134	218
# of TF Coils	18	16
Fusion Power (MW)	500	450

	ITER	FNSF
TF WP IB Radius (m)	2.78	2.2
TF WP outer radius (m)	10.75	10.5
Centering force per IB leg (MN/m)	54	142-153
VSF per half coil (MN)	205	488-530
VSF per inboard leg (MN)	103	244-265
Length of Coil Centerline (m)	34.1	33.1
Winding Pack volume (m^3)	12.4	11
Inductance per Coil (H)	1.0	2.5
Total Stored Energy (GJ)	41	80

Parameter per TF Coil	ITER	FNSF	
		Single CORC	6-around-1
Stored Energy (GJ)	2.3	3.5	5.0
Inductance (H)	1.0	61.2	2.5

Total Stored energy 2x of ITER / TF coil

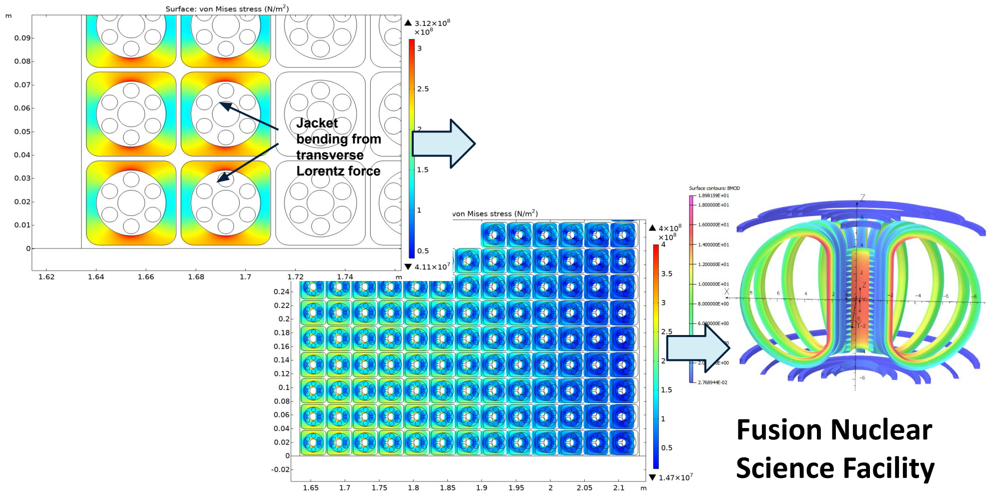
Total centering & vertical forces are 2~2.5x of ITER per TF IB leg

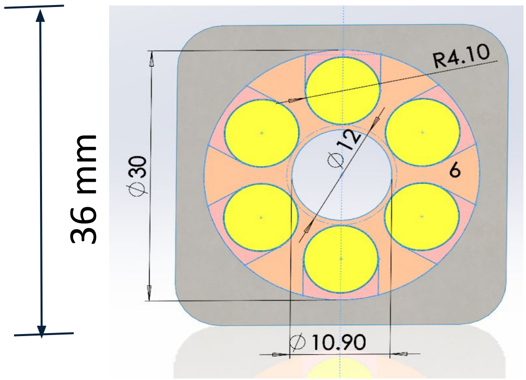
Inductance per TF coil drops to 2.5 H if 6-around-1 CICC is used

TF Coil Design - 6-around-1 CORC® CICC with conductor grading

- 36 mm square conductor (5 mm corner radius)
- Adjusted CORC cable dimension from high to low field regions

Jacketed conductor in TF winding pack





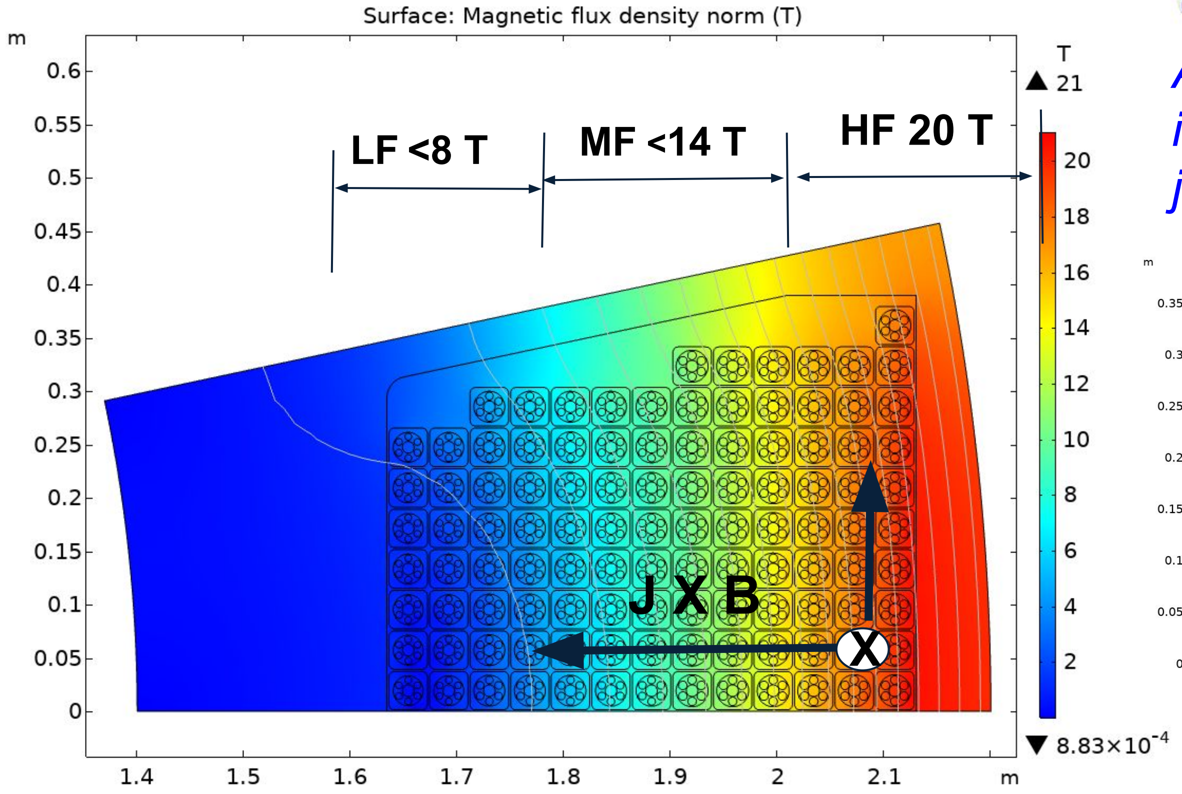
HF CICC	30 mm diam	50 tapes
MF CICC	28 mm diam	38 tapes
LF CICC	26 mm diam	24 tapes

more consistent and systematic studies are needed to de-risk FPPs!

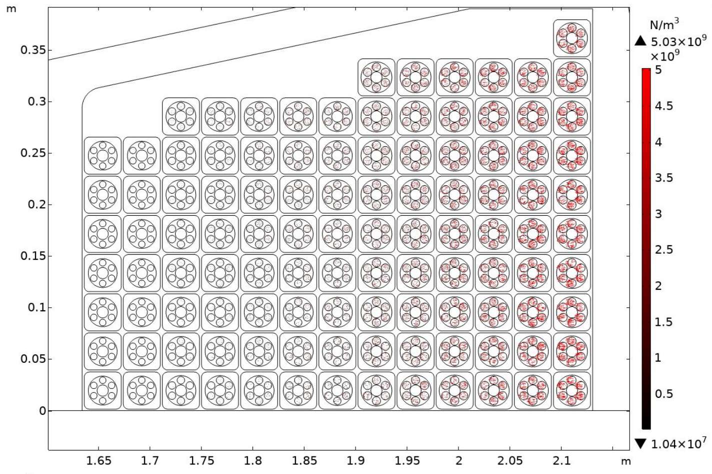
6-around-1 CORC® fits into TF winding pack with **218** turns with 2 mm turn insulation

TF Winding Pack Layout for Fusion Nuclear Science Facility

Conductor grading based on field distribution in inboard leg winding pack



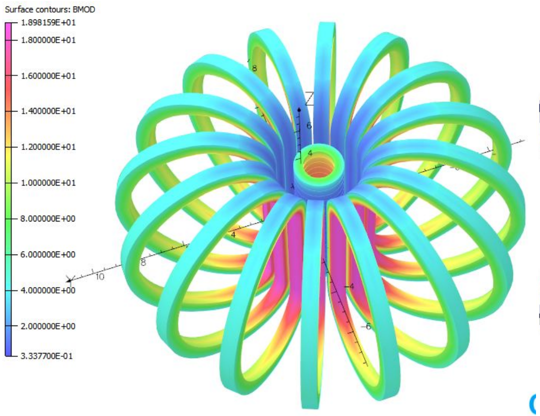
A thicker cable (w more tapes) in HF region; less tape thicker jacket in Low Field (LF) region

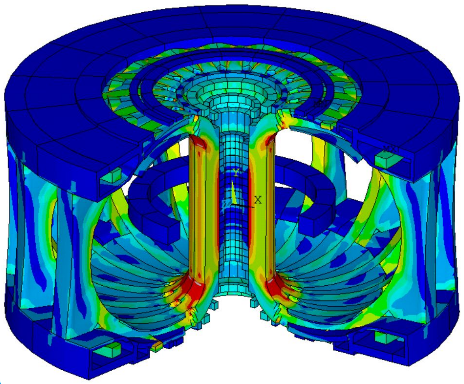


body force density in TF WP

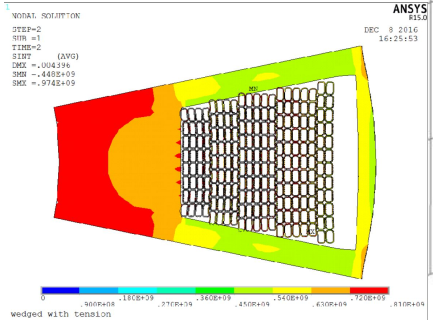
Zhai et al., Conceptual design of HTS magnets for FNSF, *Fusion Eng. Des.*, 168 (2021) 112611 (here)

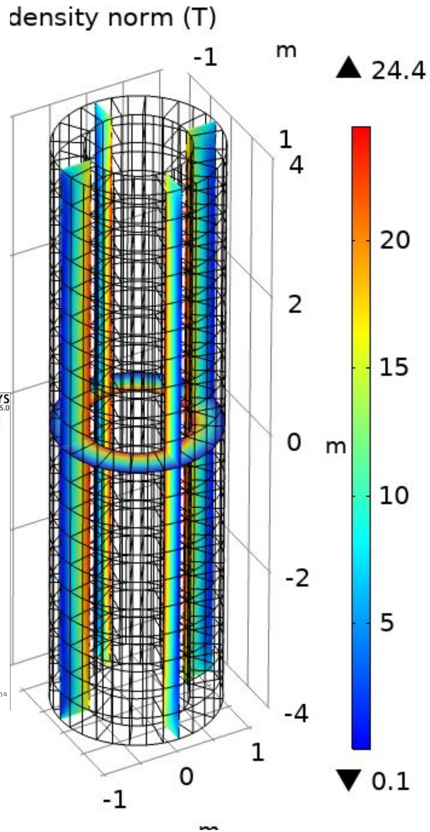
- Magnet system is an integral part of reactor design
  - Equilibrium scenarios / plasma operations
- In-board radial build & engineering design analysis
  - TF-CS structural interaction (bucked or wedged)





TF winding pack stress



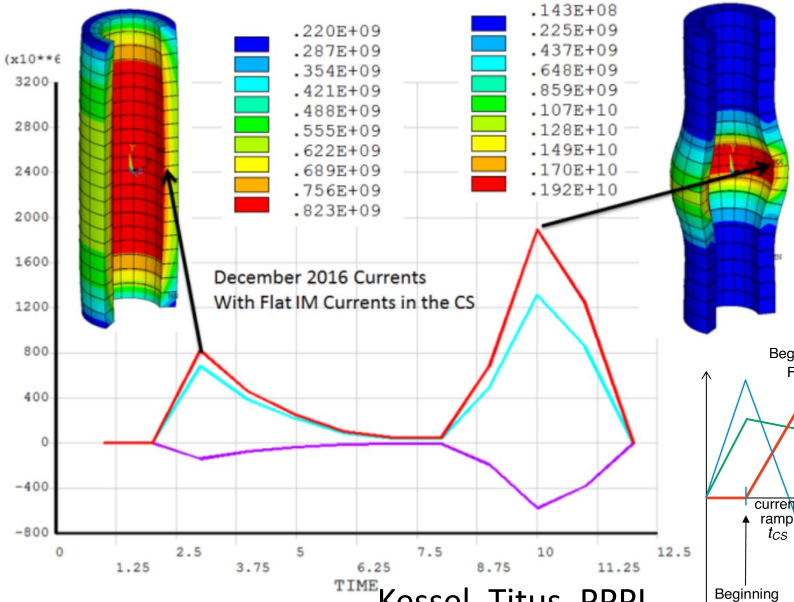


CS current backbias for plasma startup B_{max} is >24 T

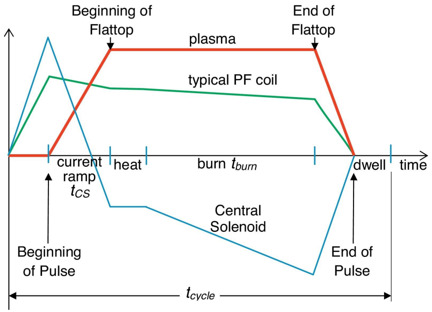
Peak stress on CS coil mid-plane is ~630 MPa (< 660 MPa design stress)

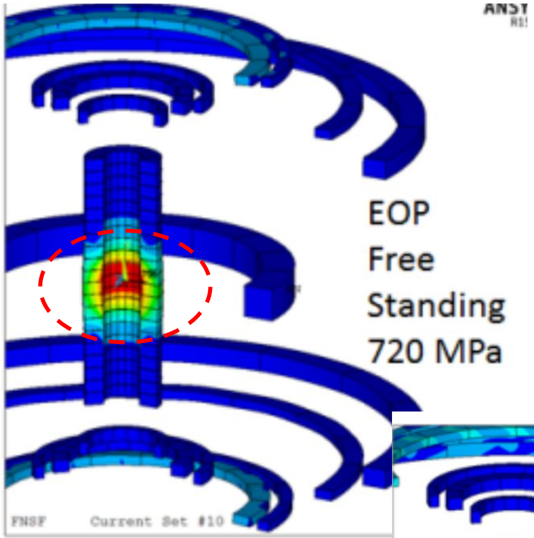
FNSF Central Solenoid Operations

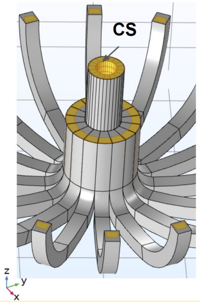
Stand alone solenoid



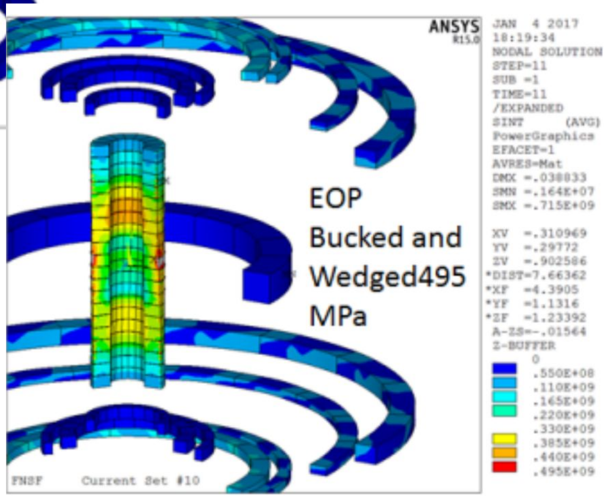
Kessel, Titus, PPPL



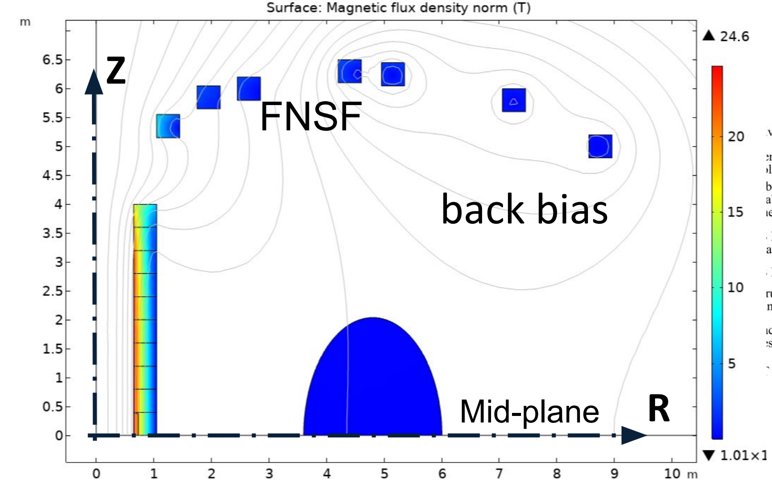


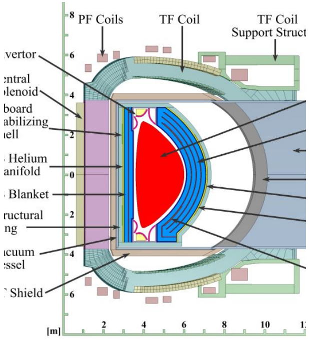


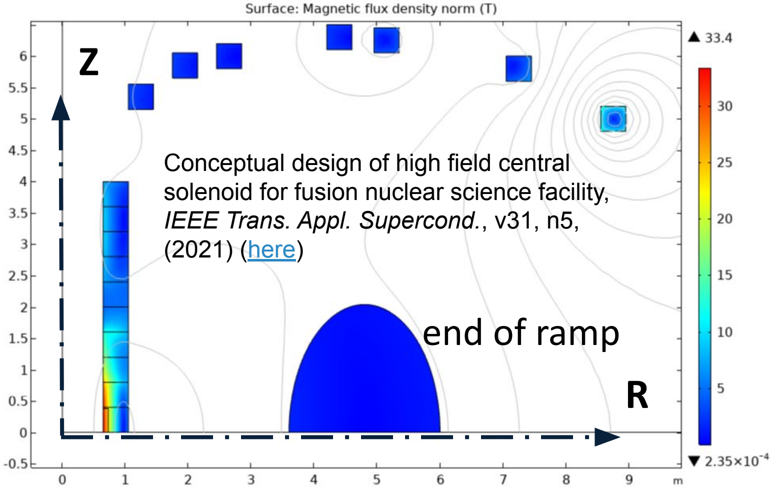
Bucked and Wedged

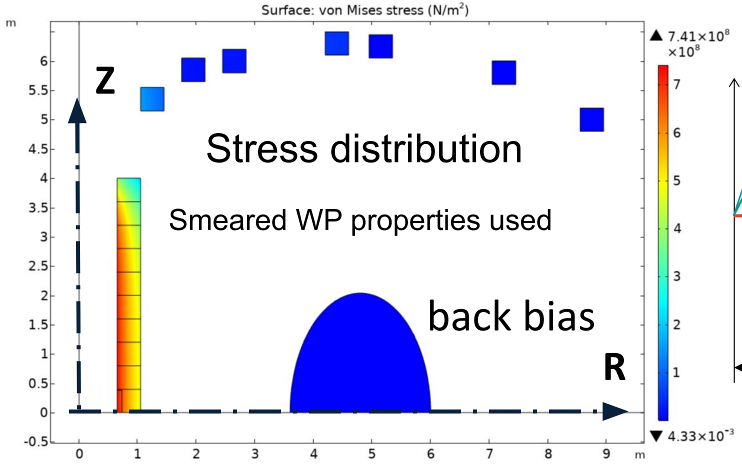


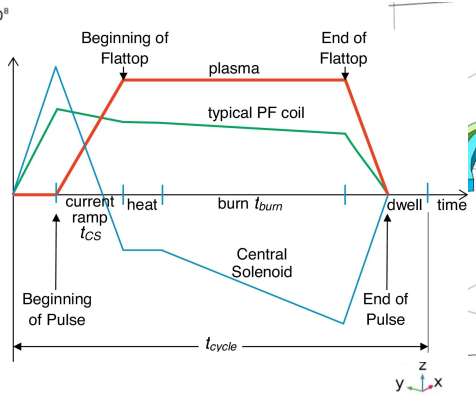
CS-PF coil system for Fusion Nuclear Science Facility (FNSF)

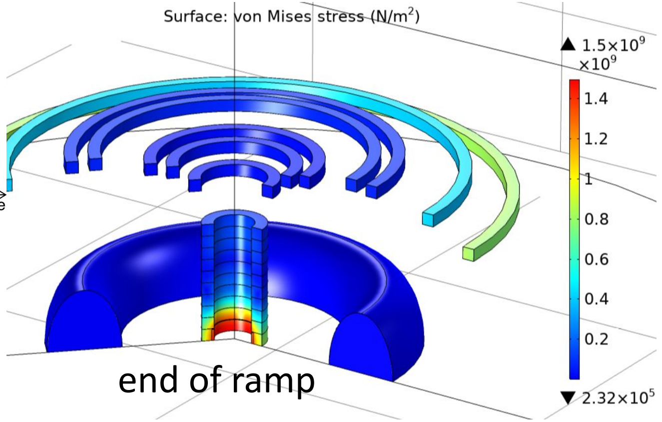






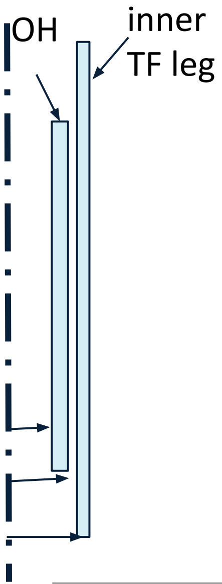


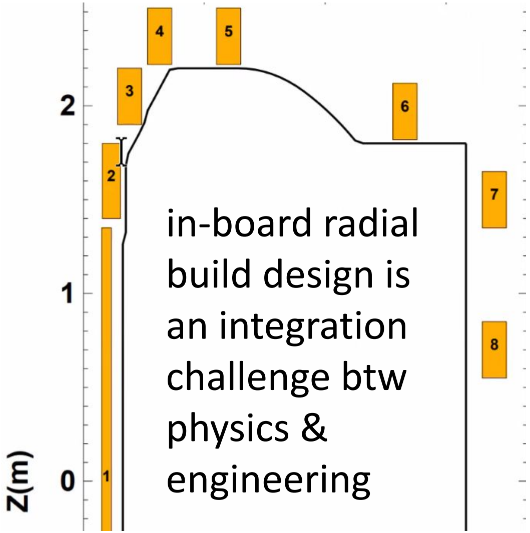




Coil parameters for spherical tokamak design studies

- Challenge in-board radial build





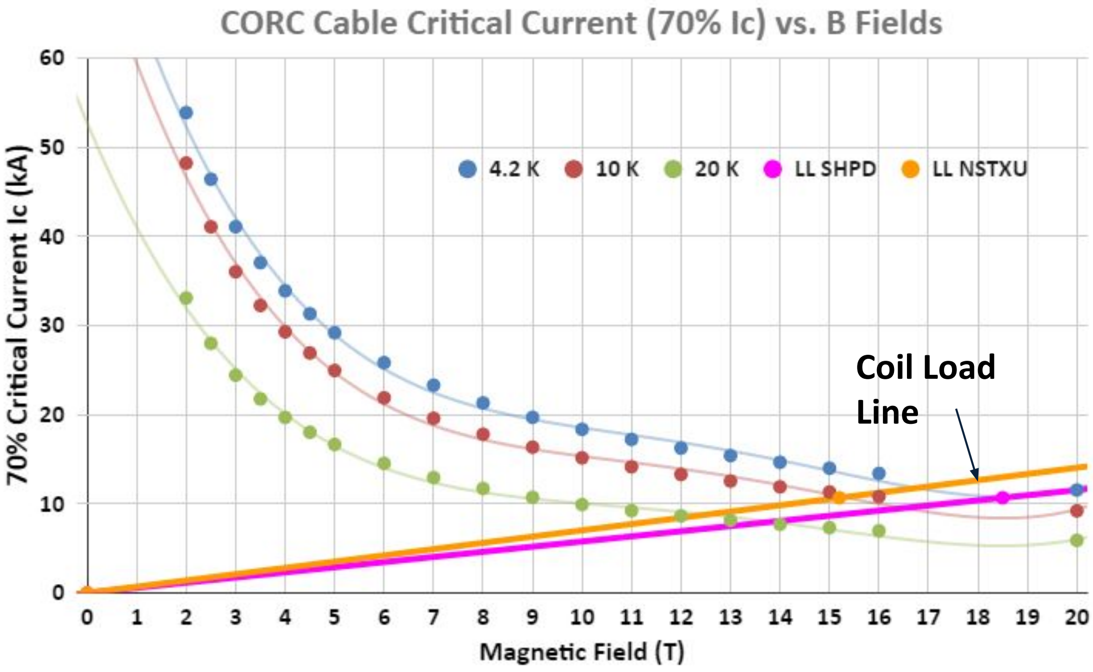
in-board radial build design is an integration challenge btw physics & engineering

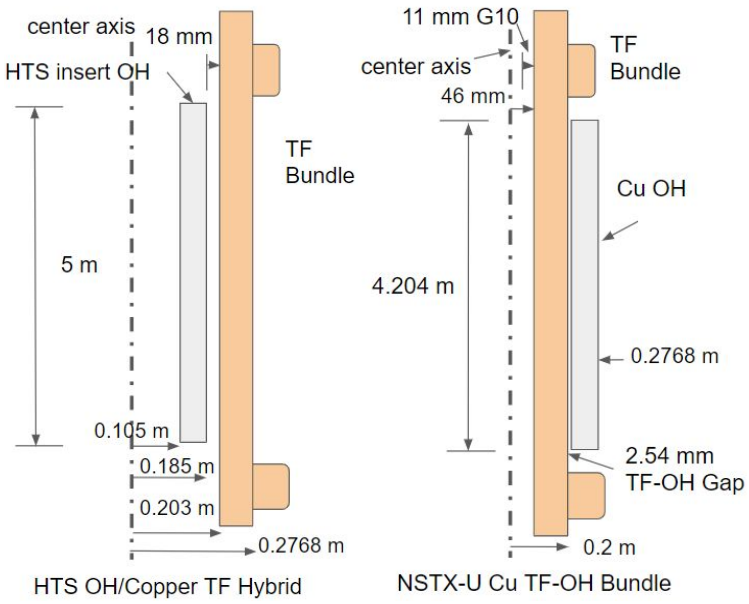
Gap (mm)	NSTX-U	SHPD
TF-CS	2.5	5-8

Parameters	SHPD
Major radius (m)	1.2
Minor radius (m)	0.6
Plasma current (MA)	4.5
Plasma center B (T)	5.5
TF current / coil (MA)	3.6
J_{wp} (A/mm^2)	80
TF coil B_{max} (T)	13
No. of TF coils	10

CORC® Solenoid Model Coil for Compact Tokamak

- HTS solenoids for plasma startups - fast ramping (kA/s), high field & high winding pack current density



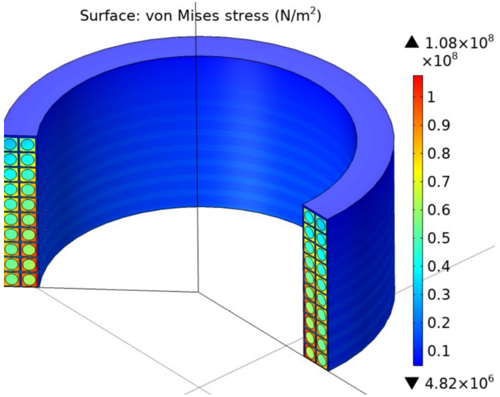


Cabled coated conductor OH solenoid to decouple TF inner legs from OH solenoid NSTXU, SHPD/FPP

HTS cable test program to validate ST-FPP CS design

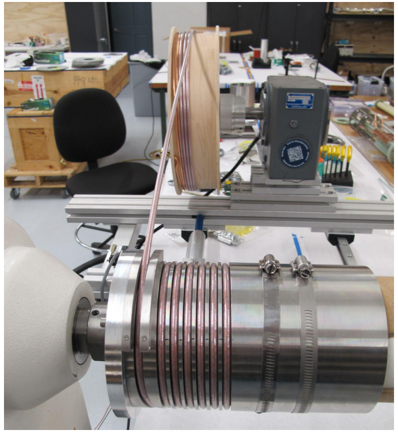
- Mature design concept and address critical issues by subscale coil testing
- Test coils in a unique large bore magnet at ASC-NHMFL to validate design

2 layer CORC® model coil



Design & tested in ST relevant operating parameters

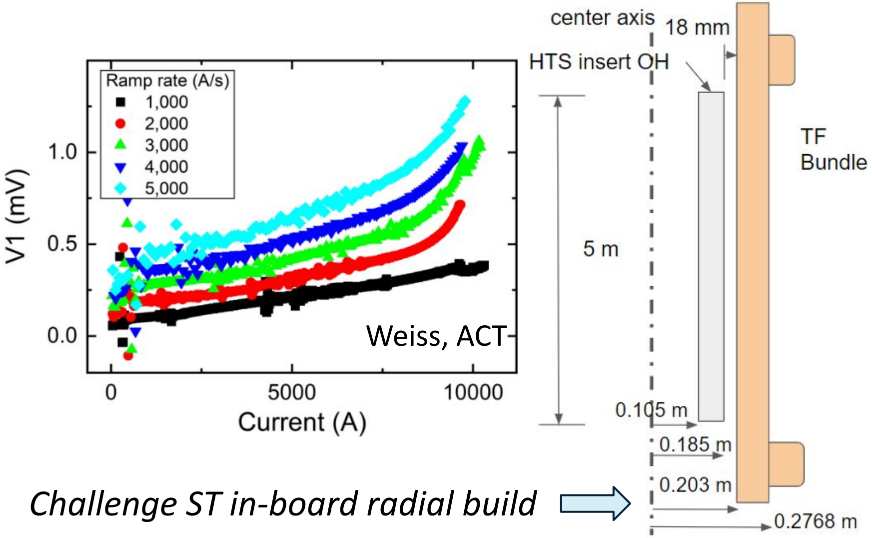
Winding at ACT (DOE SBIR)



Conductor on Round Core (CORC®)

no impregnation

Stable behavior at 4 K self-field, kA/s ramp rate



Challenge ST in-board radial build

No degradation after fast ramping on cabled model coil static test (PPPL-ACT-NHMFL)

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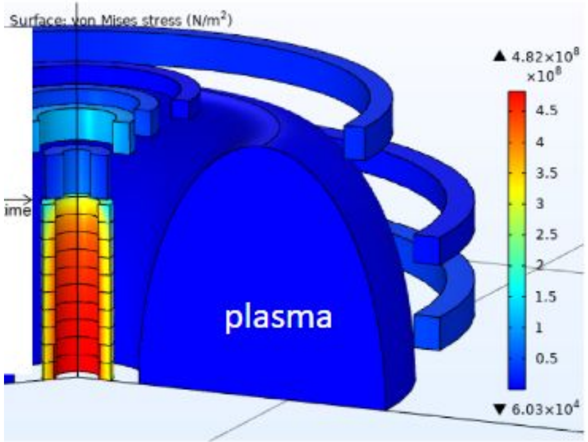
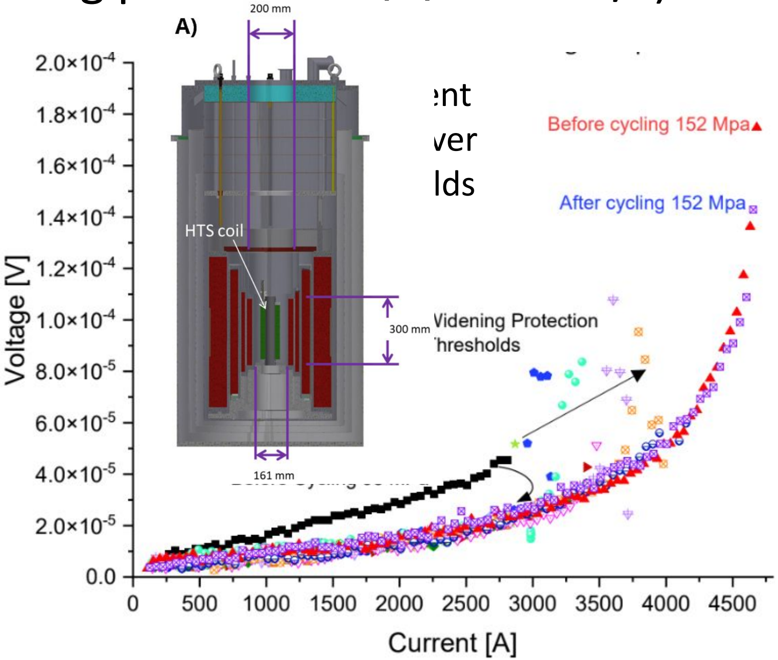
HTS cable test program to validate ST-FPP CS design

- No signs of degradation from the high field low-cycle fatigue of CORC insert solenoid tested with SHPD-FPP relevant operating parameters (up to 5 kA/s)

Parameters	SHPD
Major radius (m)	1.2
Minor radius (m)	0.6
Plasma current (MA)	4.5
Plasma center B (T)	5.5
TF current / coil (MA)	3.6
J_{wp} (A/mm^2)	80
TF coil B_{max} (T)	13
No. of TF coils	10



Tens of thousands of cyclic load fatigue test may be needed for pulsed machine



Model coil has ~40% diameter of a central solenoid needed for SHPD - tested 1-3 T/s ramp rates, 12 T (higher than the ITER CS)

High field low-cycle fatigue testing of HTS insert solenoid with ST-FPP parameters, Davis ASC'22

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Summary

- Exploring reliable coated conductor & cable options is vital
- Leverage R&D capabilities in high field magnet and fusion to de-risk fusion pilot plants; differences in requirements
- Integration challenges vs. CS cyclic fatigue for pulsed machine operations to close R&D gaps
- Coated conductor for a broad range Fusion Pilot Plant configs.
  - R&D on design, testing, prototyping subscale solenoids
  - Test program to validate cables & CICCs for FPP relevant coils