Coated Conductors and HTS Magnets for Compact Fusion

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PPPL Team
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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
• **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 to ‘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

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

Dahlgren et al., 2006

HTS

ST Advanced Reactor (STAR)
Fusion Power Plant
A=2–2.2, R=4–4.5m, HTS TF
P_{net} = 200-500 MWe

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

Two Different Magnetic Configurations

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

Plasma disruption drives engineering design!

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

NSTX-U, PPPL

• 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
Integrated Design for Fusion Nuclear Science Facility

Design Flow

- Technical philosophies and discipline scope
- Design/Simulation Tools Assessment
- FPP description - goals
- Plasma configuration(s)
- Institution identification Skill-sets/topics/tools

Independent physics analysis
Existing tools
Tools to develop
Early parametrics
Literature search

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Tools to develop
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Core Physics
Edge Plasma
Neutronics
Materials
Blanket design
Divertor design
Magnet design
Internal Structures
Vacuum vessel
Remote Maintenance
Tritium/safety
RF, H/CD design
Vacuum pumping

Creating design and assessing it at the same time

Systems Configuration (BoP, costing, etc.)

Integrated Design

C. Kessel, ORNL
Zhai et al., Conceptual design of HTS magnets for FNSF, Fusion Eng. Des., 168 (2021) 112611 (here)
Coated conductor with attractive properties for Fusion Nuclear Science Facility magnet design and optimization!
ReBCO tape (Superpower M4-396) performance - min

\[ I_c \ (6T) = 800 \ A \]

\[ I_c \ (77K, \ s.f.) = 137.14 \ A \]

\[ I_c \ (4.2K, \ 20T) = 305 \ A \]

Vendor Test Data

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

<table>
<thead>
<tr>
<th>CORC® cable</th>
<th>$I_c$ (4.2 K) 70%</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF - 50 tape 50 micron</td>
<td>305 A/tape - 20 T</td>
<td>8</td>
</tr>
<tr>
<td>MF - 38 tapes</td>
<td>406 A/tape - 14 T</td>
<td>7.2</td>
</tr>
<tr>
<td>LF - 24 tapes</td>
<td>635 A/ tape - 8 T</td>
<td>6.375</td>
</tr>
</tbody>
</table>

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

**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


*Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.*
### Fusion Nuclear Science Facility TF Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>FNSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Nb$_3$Sn CICC</td>
<td>6-around-1 CICC</td>
</tr>
<tr>
<td>Major Radius (m)</td>
<td>6.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Minor Radius (m)</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>15</td>
<td>8.0</td>
</tr>
<tr>
<td>Plasma Center B (T)</td>
<td>5.3</td>
<td>9.3</td>
</tr>
<tr>
<td>TF Operating Current (kA)</td>
<td>68</td>
<td>64</td>
</tr>
<tr>
<td>TF Max B Field (T)</td>
<td>11.8</td>
<td>20.3</td>
</tr>
<tr>
<td>WP Je (A/mm$^2$)</td>
<td>17</td>
<td>39</td>
</tr>
<tr>
<td>TF A-Turns (MA)</td>
<td>9.1</td>
<td>14.0</td>
</tr>
<tr>
<td># of Turns</td>
<td>134</td>
<td>218</td>
</tr>
<tr>
<td># of TF Coils</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>500</td>
<td>450</td>
</tr>
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</table>

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

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
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

Zhai et al., Conceptual design of HTS magnets for FNSF, *Fusion Eng. Des.*, 168 (2021) 112611 (here)
TF-CS Magnet System for Fusion Nuclear Science Facility

- 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)

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

Peak stress on CS coil mid-plane is $\sim 630$ MPa ($< 660$ MPa design stress)
Integration Challenges for Inboard TF and CS coil System

FNSF Central Solenoid Operations

Stand alone solenoid

Bucked and Wedged

Kessel, Titus, PPPL
CS-PF coil system for Fusion Nuclear Science Facility (FNSF)

Coil parameters for spherical tokamak design studies

- Challenge in-board radial build

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<td>Major radius (m)</td>
<td>1.2</td>
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<tr>
<td>Minor radius (m)</td>
<td>0.6</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
<td>4.5</td>
</tr>
<tr>
<td>Plasma center B (T)</td>
<td>5.5</td>
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<tr>
<td>TF current / coil (MA)</td>
<td>3.6</td>
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<tr>
<td>J_{wp} (A/mm^2)</td>
<td>80</td>
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<td>TF coil B_{max} (T)</td>
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Gap (mm) | NSTX-U | SHPD
--- | --- | ---
TF-CS    | 2.5    | 5-8
• 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

Winding at ACT (DOE SBIR)

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

Design & tested in ST relevant operating parameters

Conductor on Round Core (CORC®)

no impregnation

Challenge ST in-board radial build

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

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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)

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

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