High Temperature Superconductors for Fusion Nuclear Science Spherical Tokamak

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Background

PPPL is currently leading the design studies for next-step fusion devices based on the most promising magnetic configurations. Superconducting fusion magnets with high current density are particularly beneficial for low aspect ratio "spherical" tokamaks and the compact stellarators.

To integrate magnet design with burning plasma physics for fusion energy beyond ITER, a clear strategy with focused effort on targeted R&D activities is needed.

Methods

- PPPL is currently leading the design studies for the next-step fusion devices based on the most promising magnetic configurations. Superconducting fusion magnets with high current density are particularly beneficial for low aspect ratio "spherical" tokamaks and the compact stellarators.

Objectives

- Develop new HTS magnet technology for compact reactor magnets with integrated approach to close gaps between advances in HTS and fusion magnet design.
- Investigate coils of simplified fabrication (without VPI) to improve winding pack current density while subsequent lower cost and enhance radiation resistance.

Fusion magnet design integrated with physics

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Critical Issues and Fusion Magnet Challenges

- Can we extrapolate direct winding (achieved in High Field to larger dimension Toroidal Field coils for compact fusion reactor of >2 m R\text{f})
  - No organic insulation? – radiation tolerance
  - Superconducting (thermal stability) & radiation tolerance for central solenoid
  - HTS coils integrated and enhanced capability and thermal stability
  - No HTS cables? – high resistance (50 mm extension; for coils TT fusion discharge)

- No liquid helium? - Cryostat-cool (2014-2015 helium gas) no direct cooling channel

- Coils went through standard heat treatment from ITER specification in the PPPL vacuum brazing furnace. Tin leak was found in one of the small coils.

- Structural reinforcement (clamping rings) is applied on exterior of coil winding pack (remove the VPI process) to ensure compactness and structural integrity of winding pack while improving overall winding pack current density.

Conclusion and Development Strategy

- Integrated magnet design with burning plasma beyond ITER for economic fusion energy is needed to close the gap between advanced in applied HTS and next step fusion magnet design.
- Establish strong national & international collaborations to identify key elements of HTS strategy with targeted magnet R&D effort.
- Develop scalable models with multi-physics analysis tools to address challenging design issues such as radiation of Pancake coils.
- Explore novel high current density HTS cable configurations and advanced coil winding technologies.
- Optimize coil shape and structural design for better stress management in HTS coils of increased.

Coil Design – HTS is transformative for Fusion

- Fusion Magnet Design – integrated approach needed
  - Fusion Nuclear Science Spherical Tokamak (ST FNSK)
  - High power density, improved stability, and high at low aspect ratio A
  - Interaction with plasma performance (shielding, radiation)
  - Limitly with coil max stress, cooling, quench & coil protection

- ST FNSK – high neutron load radius & fluence (power plant)
  - Allow high field, compact size, high – beneficial for low aspect ratio ST
  - Significantly higher fusion power density P\text{fus} ~ 9 \times 10^8

- HTS for next step device – compact size (<3 m major radius)
  - Optimized coil shape – minimized stress/strain distribution
  - Radiation effects – essential for fusion reactor magnets (steady state)

Results

- HTS quench protection & enhance radiation tolerance with engineered insulation
  - With a higher density, more current extracted out of HTS coils and induced in Cu (loss), but at the cost of high temperature in Cu core due to the use.

Further tests of the no-insulation Nb3Sn coils with better control of current ramp rate (>1 A/s) showed excellent coil performance (40-50% wire current at critical achieved).

No-insulation coil reached ~900 A in current ramp and generated 3 T field at coil central bore.