Studies of Next-Step Spherical Tokamaks Using High-Temperature Superconductors

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Multi-institutional effort exploring low aspect ratio tokamak concepts

Fusion nuclear science facilities and pilot plants based on the spherical tokamak

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Paper summarizing 5 year study of Cu and HTS STs recently published in Nuclear Fusion
Possible missions for next-steps

1. Integrate high-performance, steady-state, exhaust
   - Divertor test-tokamak - DTT

2. Fusion-relevant neutron wall loading
   - $\Gamma_n \sim 1-2\text{MW/m}^2$, fluence: $\geq 6\text{MW-yr/m}^2$

3. Tritium self-sufficiency
   - Tritium breeding ratio TBR $\geq 1$

4. Electrical self-sufficiency
   - $Q_{eng} = P_{electric} / P_{consumed} \sim 1$

5. Large net electricity generation
   - $Q_{eng} >> 1$, $P_{electric} = 0.5-1$ GWe

This talk will discuss PPPL-led studies of how low-A “spherical” tokamaks could fulfill these missions.
What is optimal A for HTS FNSF / Pilot Plant?

- $P_{fus} / V \sim \varepsilon (\beta_N \kappa B_T)^4$ at fixed bootstrap fraction
- $\beta_N$ and $\kappa$ increase at lower aspect ratio
- But $B_T$ decreases at lower A – depends strongly on:
  - Thickness of inboard shielding and breeding blanket
  - HTS allowable field and current density
Approach:

- Fix plasma major radius and heating power (50MW)
  - $R_0 = 3\text{m}$ – smallest size for $Q_{\text{eng}} > 1$ and high fluence
- Apply magnet & plasma constraints (see backup)
  - HTS strain: 0.3%, $\beta_N$: n=1 no-wall, $\kappa$: $0.95 \times$ limit, $f_{GW} = 0.8$
- Vary aspect ratio from $A = 1.6$ to 4
- Vary HTS current density, peak field
  - Also scan inboard shielding thickness
- Compute $Q_{\text{DT}}$, $Q_{\text{eng}}$, and required $H_{98}$ (unconstrained)
HTS cables using REBCO tapes achieving high winding pack current density at high $B_T$.

Conductor on Round Core Cables (CORC)
$J_{WP} \sim 70 \text{MA/m}^2$ 19T

Base cable: 50 tapes YBCO Tapes with 38 $\mu$m substrate (Van Der Laan, HTS4Fusion, 2015)

Higher $J_{cable}$ HTS cable concepts under development:

Base Conductor He Gas Cooled
8kA,
$J_{WP} \sim 160 \text{MA/m}^2$
High TF winding-pack current density required to access highest $B_T$ at lower $A$

$J_{WP}$ [MA/m²]

19T: Present
CORC HTS limit

12T: ITER-like
TF coil limit
(Nb₃Sn, 11.8T)

- Coil structure sized to maintain ≤ 0.3% strain on winding pack for all cases shown here
- Effective inboard WC neutron shield thickness = 60cm
High current density HTS cable motivates consideration of low-A tokamak pilot plants

- **ITER-like TF constraints:**
  - $J_{WP}=20\text{MA/m}^2$, $B_{\text{max}} \leq 12\text{T}$
  - $P_{\text{fusion}} \leq 130\text{MW}$
  - $P_{\text{net}} < -90\text{MW}$

- $J_{WP} \sim 30\text{MA/m}^2$, $B_{\text{max}} \leq 19\text{T}$
  - $P_{\text{fusion}} \sim 400\text{MW}$
  - Small $P_{\text{net}}$ at $A=2.2-3.5$

- $J_{WP} \geq 70\text{MA/m}^2$, $B_{\text{max}} \leq 19\text{T}$
  - $P_{\text{fusion}} \sim 500-600\text{MW}$
  - $P_{\text{net}} = 80-100\text{MW}$ at $A=1.9-2.3$

$A \sim 2$ attractive at high $J_{WP}$
A ≥ 2 pilot plant scenarios have elevated H > 1, I_P = 6-12MA, f_{BS} ~ 80% (not shown)

Effective inboard WC n-shield thickness = 60cm
A ≤ 2 maximizes TF magnet utilization

Fusion power / TF coil volume

Eff. shield thickness:
- 0.3m
- 0.4m
- 0.5m
- 0.6m
- 0.7m

$\text{J}_{\text{WP}} = 70\text{MA/m}^2$
Need inboard breeding for TBR > 1 at A=2

Outboard TBR \sim 0.92

TBR = 1.04 (4\% margin)

10cm IB blanket sufficient for TBR > 1.04
Model blanket and shield thickness vs. A
A \geq 3 maximizes blanket utilization

Fusion power / blanket volume

Eff. shield thickness:
- 0.3m
- 0.4m
- 0.5m
- 0.6m
- 0.7m

J_{WP} = 70MA/m^2
A=2, R₀ = 3m HTS-TF FNSF / Pilot Plant

\[ B_T = 4T, I_P = 12.5\text{MA} \]
\[ \kappa = 2.5, \delta = 0.55 \]
\[ \beta_N = 4.2, \beta_T = 9\% \]
\[ H_{98} = 1.8, H_{\text{Petty-08}} = 1.3 \]
\[ f_{gw} = 0.80, f_{\text{BS}} = 0.76 \]

Startup \( I_P \) (OH) ~ 2MA

\[ J_{\text{WP}} = 70\text{MA/m}^2 \]
\[ B_{T\text{-max}} = 17.5T \]

No joints in TF
Vertical maintenance

\[ P_{\text{fusion}} = 520 \text{ MW} \]
\[ P_{\text{NBI}} = 50 \text{ MW}, E_{\text{NBI}} = 0.5\text{MeV} \]
\[ Q_{\text{DT}} = 10.4 \]
\[ Q_{\text{eng}} = 1.35 \]
\[ P_{\text{net}} = 73 \text{ MW} \]

\[ \langle W_n \rangle = 1.3 \text{ MW/m}^2 \]
Peak n-flux = 2.4 MW/m²
Peak n-fluence = 7 MWy/m²

Cryostat volume ~ 1/3 of ITER
Inboard and outboard blanket vertical maintenance

Outboard blanket removed

Inboard blanket removed once outboard blanket sectors removed – depending on the toroidal extent of the inboard blanket
Long-leg divertor
\( q_{\text{div}} = 9 \text{MW/m}^2, \ R_{\text{strike}} = 4.2 \text{m} \)

Detachment can further reduce \( q_{\text{div}} \sim 2\text{-}3x \)

Liquid metal (short-leg)
\( q_{\text{div}} = 21 \text{MW/m}^2, \ R_{\text{strike}} = 2.5 \text{m} \)

Long-leg / Super-X
Geometry also compatible with “vapor box” concepts (Ono / Goldston)

Shorter leg LM divertor

Divertor heat flux
Exploring liquid metal divertor design similar to flowing water curtain systems

LM injector system can be assembled in a single or double unit

LM containment structure

Shield block

Ferritic steel backing plate
HTS ST-FNSF design with Li flow on divertor and inboard surfaces

Double null liquid metal divertor system

Li flows from upper divertor down the inboard wall, exiting just after the lower inboard divertor. Separate Li cooling of lower divertor
Benefits of shorter-leg LM high-heat-flux divertor:

• Significantly reduce outboard PF coil current
  – Reduced PF size, force, structure

• Eliminate separate upper cryo-stat (for PF5U)

• Li wall pumping could help increase H
Summary

• Developed new self-consistent configurations for low-A FNSFs / Pilot Plants
  – Long-leg and/or LM divertor, T self-sufficient, only ex-vessel TF and PF coils, vertical maintenance

• Compact Pilot Plants achievable by combining improved stability of low-A + advanced magnets
  – Optimal A will be informed by results from NSTX-U and MAST-U and REBCO TF magnet development

• Liquid metal divertors for high heat flux could simplify cryostat, reduce coil currents/forces
  – Higher confinement from liquid Li also beneficial