Fusion Nuclear Science (FNS) Mission & High Priority Research Topics

Martin Peng, Aaron Sontag, Steffi Diem, John Canik, HM Park, M. Murakami, PJ Fogarty, Mike Cole

ORNL

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What does CTF do? [Abdou et al.]

I. “Scientific Exploration” to discover and investigate unexpected physical properties, and improve.

II. “Engineering Verification” to compare designs and select winners.

III. “Reliability Growth” to establish fusion nuclear component database for fusion DEMO (NRC required).

Physical properties important to FNST can have time constants up to $10^6$ s.

**Stage I**
- **Fusion “Break-in” & Scientific Exploration**
- **Physics**
  - $0.1 - 0.3$ MW-y/m$^2$
  - $\geq 0.5$ MW/m$^2$, burn $> 200$ s

**Stage II**
- **Engineering Feasibility & Performance Verification**
- **Modules**
  - $1 - 3$ MW-y/m$^2$
  - 1-2 MW/m$^2$
  - steady state or long burn
  - COT ~ 1-2 weeks

**Stage III**
- **Component Engineering Development & Reliability Growth**
- **Modules/Sectors**
  - $> 4 - 6$ MW-y/m$^2$
  - 1-2 MW/m$^2$
  - steady state or long burn
  - COT ~ 1-2 weeks

- **Initial exploration of coupled, prompt, phenomena in fusion environment**
- **Screen** and narrow blanket design concepts
- **Develop test methods and diagnostic capabilities**

- **Establish engineering feasibility** of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime)
- **Principles of tritium self-sufficiency**
- **Select 2 or 3 concepts for further development**

- **Failure modes, effects, and rates and mean time to replace/fix components** (for random failures and planned outage)
- **Iterative design / test / fail / analyze / improve programs aimed at reliability growth and safety**
- **Verify design and predict availability** of FNT components in DEMO
Where should **CTF** be located in fusion neutron fluence rate and plasma burn duration?

![Graph showing fusion neutron fluence rate vs. continuous plasma burn duration.](image)

- IFMIF (20-55 dpa/yr) →
- MTS (20 dpa/yr) →
- SNS (5 dpa/yr) →

**Fusion Neutron Fluence Rate (MW·yr/m²·yr)**

**Continuous Plasma Burn Duration (s)**
Properties of interest to Plasma-Facing Materials and Fusion Power Extraction depends on the synergy of multiple effects in a full fusion nuclear environment.

- IFMIF (20-55 dpa/yr)
- MTS (20 dpa/yr)
- SNS (5 dpa/yr)

Radiation effects:
- T build-up in hot FS and tungsten
- T build-up in solid breeders
- T permeation thru hot FS and tungsten
- T Recycling with wall bulk; T measurement
- Tungsten erosion, redeposition, lifetime

Continuous Plasma Burn Duration (s):
- D-D Tokamak Confinement
- CTF-II
- CTF-III
- E.U. Demo
- PP
- U.S. Demo

Fusion Neutron Fluence Rate (MW-yr/m²-yr):
- IFMIF (20-55 dpa/yr)
- MTS (20 dpa/yr)
- SNS (5 dpa/yr)
FNSF enables research on synergistic effects of the underlying physical mechanisms occurring in a fusion nuclear environment.
Conservative parameters are available for small $R_0$, low $A$ plasmas to address the FNS mission. Disruption-minimized: \( \beta_N \leq 0.75\beta_{N\text{-no-wall}} \); \( HH \leq 1.25 \); \( q_{\text{cyl}} \geq 2\times\text{limit} \); \( \tau_{Ei} = 0.7\tau_{i\text{-neo}} \); \( J_{\text{avgTF}} \leq 4 \text{ kA/cm}^2 \)

<table>
<thead>
<tr>
<th>Performance level</th>
<th>JET-DD</th>
<th>JET-DT</th>
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<tr>
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<td>NBI energy (kV)</td>
<td>120</td>
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<td>235</td>
<td>330</td>
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Plasma aggressiveness and aspect ratio have high leverages on tradeoffs in performance, cost, readiness, and risk.
FNSF – Fusion Nuclear Science Facility
A Compact Remote-Handled ST Fusion Device to Provide Flexible Neutron Fluxes (0.01–2.0 MW/m²) over >10 m² area for ≤ 10⁶ s

Mission: to enable investigations of synergistic effects of interest to plasma material interactions and fusion power extraction in a fusion nuclear environment – encountering four phases of matter across the nuclear, atomic, nano, meso, and macroscopic scales.
FNSF R&D can be staged: JET-level plasma pressure
DD-only for PMI science; JET-level DT, 2xJET DT, and
4xJET DT for fusion nuclear science that includes PMI

- IFMIF (20-55 dpa/yr) →
- MTS (20 dpa/yr) →
- SNS (5 dpa/yr) →

- Radiation effects
- T build-up in hot FS and tungsten
- T build-up in solid breeders
- T permeation thru hot FS and tungsten
- T Recycling with wall bulk; T measurement
- D-D Tokamak Confinement

Continuous Plasma Burn Duration (s)
Increasing $\beta_N$ to $\beta_{N\text{-no-wall}}$ enables $W_L = 3 \text{ MW/m}^2 \Rightarrow$ FNSF-AT ($H_H=1.5$, $f_{BS}=0.73$)

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<tr>
<th>Performance level</th>
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<th>6xJET</th>
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<td>Field, $B_T$ (T)</td>
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<td>140</td>
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<td>Avg density, $n_e$ ($10^{20}$/m$^3$)</td>
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<td>NBI energy (kV)</td>
<td>120</td>
<td>235</td>
<td>330</td>
<td>400</td>
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This provides opportunities to further advance the scientific and technical knowledge in plasma facing material and fusion power.
FNSF-AT, if allowed by advanced plasma, plasma material interactions, and fusion power extraction, would enable R&D at the Demo entry level conditions.
Modular compact ST fusion driver for hybrid requires minimal $I_{TF}/I_p$ and hence minimal $A$ and $B_T$

But need: $\beta_N \leq 1.5\beta_{N-no-wall}$; $H_H \leq 2$; $q_{cyl} \geq 1.1x\text{limit}$; $f_{BS} \sim 0.8$; $J_{avg} \sim 6 \text{ kA/cm}^2$

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**FNSF enables the investigation of synergistic effects of interest to plasma material interactions and fusion power extraction in a fusion nuclear environment – encountering four phases of matter, across the nuclear, atomic, nano, meso, and macroscopic scales.**

- FNS R&D can start with JET-level DT plasmas, progressively providing $W_L = 0.25$ MW/m$^2$ at $Q \sim 0.9$; 1 MW/m$^2$, $Q \sim 1.7$; and 2 MW/m$^2$, $Q \sim 2.5$
- Very conservative plasmas are assumed, minimizing disruptions and ensuring reliability ($\beta_N \leq 0.75 \beta_{N\text{-no-wall}}$; $q_{cyl} \geq 2 q_{cyl\text{-limit}}$; $H_H \leq 1.25$)
- JET-level DD plasma adequate for PFC materials R&D for very long pulse ($\leq 10^6$ s) under much reduced neutron radiation ($P_{\text{fusion}} \sim 0.2$ MW)
- A very long pulse linear high plasma heat flux test stand, complementing the long pulse S/C tokamaks, is being assessed
- By allowing $\beta_N \leq \beta_{N\text{-no-wall}}$ and $H_H \leq 1.5 \Rightarrow W_L = 3$ MW/m$^2$, $Q \sim 3.4$
- “Game-changing” progress in reliable very high confinement ($HH = 2$) and stability ($\beta_N = 7.5$) would enable ST applications to Fusion-Fission Hybrid.
Electron transport variation results in increase in device size

- Sensitivity study to determine impact of ST transport research
  - commonality with tokamak gives initial basis
  - need to extend to ST specific regime
    - ETG vs. TEM at FNSF relevant \( v^* \)

- Electron H-factor reduced from 0.7 to 0.25
  - \( R_0 \) increased by 20%
  - reduced sensitivity for HHe > 0.5

- parameters relatively insensitive to ions
  - consistent with electron dominated transport in ST

- Confinement also has strong implications on NBI current drive requirements
  - must understand transport to accurately predict NBI CD capability
Dynamic modeling to determine NBI current sustainment in progress

- Coupled codes for self-consistent current drive modeling
  - MHD equilibrium
  - transport
  - heating and CD

- Iterative to $d/dt=0$ current profile
  - GLF23 or measured NSTX profiles for transport
  - GLF23 works well at high-$A$, but not adequate for low-$A$
  - TGLF adds missing physics*
    - plasma shaping & finite-$A$
    - electron FLR
    - $B_{||}$ fluctuations
    - some benchmarking with MAST

- **Further benchmarking required**

* G.M. Staebler, IAEA FEC 08
**J.M. Park FASTRAN code
Variation in center-column shielding has large impact on device size

- Sensitivity study of center-column thickness at constant A

- Required thickness impacted by two Tier-1 issues:
  - plasma startup
    - is central induction required?
    - small MIC solenoid or iron core
  - magnet design
    - what is maximum allowable dpa for inner TF leg?
    - shielding to prevent radiation-induced embrittlement

- Increasing thickness > 0.1 m leads to linear rise in $R_0$, $I_p$ and $I_{TF}$
  - increased construction and operating costs
  - very high impact ➔ a top priority for ST research
Plasma startup without central solenoid is feasible

- Helicity injection shows promise for initiation from zero current
  - point-source and CHI geometries being investigated
  - both have achieved $I_p > 100 \text{ kA}$
  - techniques still have many remaining questions
    - plasma impurity content
    - current, particle, energy, and momentum transport across fields in a turbulent system
    - role of flows on equilibrium and stability

- RF techniques may also be viable for current initiation
  - EBW/ECH startup being studied on MAST
  - ECH startup successfully tested on DIII-D

- NBI to ramp-up and sustain at full current
  - must assess effects of fast-ion instabilities
Plasma Theory and Simulation guides and integrates our understanding.

- Develop fundamental plasma theory and the computational base needed to understand plasma behavior in fusion devices, to understand and exploit improved confinement regimes, and to develop new confinement configurations and technologies.
ITER Full Power Startup Simulation

- \( n_e(0) \) vs. time
- Auxiliary Heating Power
- On-axis temperature
- Total Plasma Current
- Power to Thermal Electrons
- Power to Thermal Ions
- \( T_e(0) \) and \( T_i(0) \)
- Electron and Ion temperature profiles
- J(rho) contributions
- Fusion alpha and beam densities
Maximum TF current density strongly affects design

• Sensitivity study of normal conducting magnet design
  – unique TF magnet will operate at limits of present technology
  – TF rod dissipation is \(~1/3\) of operating power
• TF magnet must satisfy several requirements
  – single-turn capable of 10+ MA
  – normal conducting
  – nuclear environment
• \(J_{TF}\) limited by thermal and electro-mechanical stresses
• Increased \(J_{TF}\) leads to decreased \(R_0, I_{TF}, I_p\)
  – reduced sensitivity above 40 A/mm\(^2\)
Center-column magnet design requires dedicated engineering study

- FEA indicates max. $J_{TF} < 20-40$ A/mm$^2$
  - assuming Glidcop Al-25
  - accounts for nuclear heating
  - does not include radiation embrittlement
- Dependent on TF radial and vertical build
  - length of rod
  - fraction of cooling channels
- Shielding to prevent embrittlement possible (< 0.1 DPA)
  - He cooled W first wall
  - annealing between pulses to restore material properties
  - coupled to shielding thickness study
- Joint design assessment also needed

Stress Analysis of Single-Turn TF*

Unmitigated heat flux in a low-A FNSF may be unacceptably high

- Geometry from Peng, PPCF 2005
- Core density, power from Peng IAEA FEC2008
- Target loads calculated with SOLPS
  - ITER radial transport

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<th></th>
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<th>$q_{cy}$</th>
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<th>$\beta_T$</th>
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<th>$T_{avge}$ [keV]</th>
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Managed by UT-Battelle for the U.S. Department of Energy
Sontag – ST for FNS Mission – 8/26/09
Novel solutions may be required for successful power handling

- Several options are available
  - Novel geometries, e.g. Snowflake, SuperX
  - New materials, liquid walls

- The SuperX Divertor (SXD) applies to ST geometry
  - Increased $R_{div} \rightarrow$ more wetted area
  - Longer connection lengths

*P. Valanju, APS08

*D. Ryutov, PoP 15 (2008) 092501
The Super-X Divertor has potential to resolve the heat flux problem for FNSF

- Calculated peak heat flux is reduced to ~7 MW/m² with SXD
  - Could be further reduced with impurity seeding
- Heat flux reduction is promising, but full PMI needs to be considered in simulations
  - Helium pumping
  - Erosion, material migration, lifetime
  - Impact off-normal events
- Encourages consideration of high plasma heat flux test stand
- Test planned in MAST
Assessment required to add detail to ST-based FNSF design point

• Sensitivity to physics assumptions
  – iterate optimizations of A, compare to normal A options
  – leverage near-term ST R&D

• TF center rod engineering requirements
  – Shielding and FEA of thermal and electro-mechanical stresses

• Use commonality with tokamak physics basis for ST transport
  – TGLF for predictive modeling of H-factors and current drive modeling

• Startup capability with minimal central induction
  – test in NSTX for coupling to NBI and ramp-up assessment
  – determine degree of central induction required

• Test of SXD to validate flux expansion capability (MAST)

• Equilibrium, stability & transport modeling for design
ST is potentially attractive option for integrated FNS study

• Conservative design points are available
  — wide margin to stability limits at required neutron flux
    • minimize plasma feedback control requirements
    • plasma-induced disruption avoidance
  — compact and maintainable

• Several Tier-1 issues must be resolved
  — TF magnet design
  — plasma startup, ramp-up and sustainment
  — electron confinement
  — PMI

• Ready for detailed modeling and assessment of design point and compare with normal A