Progress in Modeling of FNSF-AT


Presented at
US-Japan Workshop on
Fusion Power Plants and Related Advanced Technologies

8-9 March 2012
UC San Diego, Center for Magnetic Recording Research
US DOE: A Fusion Nuclear Science Facility to Provide, in Parallel with ITER, the Basis for DEMO

**TODAY’S RESEARCH FACILITIES**

- **ITER**
  - High energy gain burning plasma physics
  - Reactor scale superconducting technology

- **Fusion Nuclear Science Facility and Program**
  - Burning Plasma Dynamics and Control
  - Materials in a Fusion Environment and Harnessing Fusion Power

**DEMO**

- High gain, advanced physics, steady-state high duty factor fusion power
Options for the Fusion Nuclear Science Facility

- **FNSF-ST (larger step to DEMO)**
  - Operate steady-state
  - High neutron fluence for component testing
  - Provide a materials irradiation facility to test/validate fusion materials
  - Demonstrate tritium breeding
  - Show fusion can produce high-grade process heat and electricity

- **FNSF-AT adds:**
  - Produce significant fusion power (100-300 MW)
  - Demonstrate tritium self-sufficiency
  - Further develop AT physics towards Demo regimes

- **Pilot Plant (larger step from present program) adds:**
  - Generate net electricity
  - Reactor maintenance schemes
What is the Appropriate Size and Scope of Next Step Forward?

- Complements ITER
  - Not necessary to duplicate main efforts of ITER
- Addresses key identified gaps to DEMO
- Can be done now [start design]
  - Get us ready for DEMO construction triggered by Q=10 in ITER (~2030)
FNSF-AT — a Facility with Dual Mission: Fusion’s Nuclear Science and Advanced Tokamak with Burn

- Produce significant fusion power (100-300 MW)
- Operate steady-state with:
  - Modest energy gain ($1<Q<7$)
  - Duty factor of 0.3 a year with up to 2 weeks of continuous operation
  - High neutron fluence
    (3-6 MW-yr/m², 30-60 dpa lifetime)
- Provide a materials irradiation facility to develop/qualify advanced fusion materials
- Demonstrate tritium self-sufficiency
- Show fusion can produce high-grade process heat and electricity
- Further push AT physics towards Demo regimes
Why AT?
AT physics enables steady-state burning plasmas with

- >10x ITER neutron fluence
  - High fluence is required for FNSF‘s nuclear science development objective

- in compact device
  - Moderate size is required to demonstrate TBR>1 using only a moderate quantity of limited supply of tritium fuel
FNSF Must Have Tritium Breeding Ratio > 1 to Build a Supply to Start Up DEMO

- A 1000 MWe DEMO will burn 12 kg Tritium per month
- Tritium inventory available for DEMO at end of ITER and FNSF operation depends strongly on TBR in FNSF

[M.E. Sawan, TOFE (2010)]
Is AT realistic?
FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO

- 100% noninductive modes developed on DIII-D bracket FNSF-AT baseline
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles

Pulse length extension in next few years
FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO

- 100% noninductive modes developed on DIII-D bracket FNSF-AT baseline
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles
  **Pulse length extension in next few years**

- Baseline FNSF-AT to meet nuclear science mission
- More advanced scenarios to close physics gaps to DEMO
Why copper coils?
Demountable Copper Coils Enable Effective Nuclear Science Progress

- A Fusion Nuclear Science Facility **must be a research device**, maintainable, accessible, re-configurable
  - Change device components as understanding evolves
- Jointed copper coil enables changeouts of wall, blanket, divertor
  - Constructed as toroidally continuous ring structures
- Other devices will address superconducting coil issues
A Staged Approach to Learn and Improve Nuclear Components, Diagnostics, Operating Scenario

<table>
<thead>
<tr>
<th></th>
<th>START UP</th>
<th>FIRST MAIN BLANKET</th>
<th>SECOND MAIN BLANKET</th>
<th>THIRD MAIN BLANKET</th>
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<tbody>
<tr>
<td></td>
<td>H  D  DT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td></td>
<td>0 0 125 250</td>
<td>250 250</td>
<td>250 400</td>
</tr>
<tr>
<td>$P_{N/A_{WALL}}$ (MW/m²)</td>
<td></td>
<td>1 1 2</td>
<td>2 2</td>
<td>2 3.2</td>
</tr>
<tr>
<td>Pulse Length (Min)</td>
<td></td>
<td>SS SS</td>
<td>SS SS</td>
<td>SS SS</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>0.01 0.04</td>
<td>0.1 0.2</td>
<td>0.2 0.3</td>
<td>0.3 0.3</td>
</tr>
<tr>
<td>T Burned/Year (kG)</td>
<td>0.28 0.7</td>
<td>2.8</td>
<td>2.8 4.2</td>
<td>4.2 5</td>
</tr>
<tr>
<td>Net Produced/Year (kG)</td>
<td>-0.14 0.56</td>
<td>0.56</td>
<td>0.84</td>
<td>0.84 1</td>
</tr>
<tr>
<td>Main Blanket</td>
<td>He Cooled Solid Breeder Ferritic Steel</td>
<td>Dual Coolant Pb-Li Ferritic Steel</td>
<td>Best of TBMs RAFS?</td>
<td></td>
</tr>
<tr>
<td>TBR</td>
<td>0.8 1.2</td>
<td></td>
<td>1.2 1.2</td>
<td>1.2 1.2</td>
</tr>
<tr>
<td>Test Blankets</td>
<td></td>
<td>1.2</td>
<td>3.4 5.6</td>
<td>7.8 9.10</td>
</tr>
<tr>
<td>Accumulated Fluence (MW-yr/m²)</td>
<td>0.06 1.2</td>
<td></td>
<td>3.7</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Radiation damage survival strategy:

Nuclear facing structures do not see more than 2 MW-yr/m² (20 dpa) before removal.
Can Start FNSF-AT Design Now

**Shovel-ready**
- Standard coils
- Standard NBI
- Standard divertor
- Proven AT physics
- Proven materials

**Concept is open to new advances**
- Demountable superconducting coils
- Snowflake, SX divertor
- Negative NBI technology
- Advanced materials

Soukhanovskii, et al., IAEA 2010
Achieving the Baseline AT Performance of FDF Requires Resolving Some Outstanding Challenges

- Integration of high performance, steady-state, burning plasmas
- Compatibility of auxiliary systems with tritium self-sufficiency
- Maintenance and controlling of high-performance burning plasmas
- Heat and particle management
- Avoidance and mitigation of off-normal events
Nuclear Science Mission Can Be Accomplished by FNSF-AT Baseline Mode with Operating Margin

- Baseline FNSF-AT: 4x neutron flux of ITER and annual duty factor of 30%
  - 10x neutron fluence of ITER
  - Materials/components qualification for first few years of DEMO

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Lower BetaN, fbs, H98</th>
<th>Lower BT, fbs</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, aspect ratio</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>k, plasma elongation</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>Pf, fusion power</td>
<td>MW</td>
<td>290.07</td>
<td>159.07</td>
<td>144.65</td>
</tr>
<tr>
<td>Pinternal, power to run plant</td>
<td>MW</td>
<td>499.75</td>
<td>526.57</td>
<td>348.22</td>
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<tr>
<td>Qplasma, Pfusion/Paux</td>
<td>6.88</td>
<td>2.93</td>
<td>3.52</td>
<td>12.37</td>
</tr>
<tr>
<td>Pn/Awall, Neutron Power at Blanket</td>
<td>MW/m2</td>
<td>2.00</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>BetaN, normalized beta</td>
<td>mT/MA</td>
<td>3.69</td>
<td>2.65</td>
<td>3.69</td>
</tr>
<tr>
<td>fbs, bootstrap fraction</td>
<td>0.75</td>
<td>0.54</td>
<td>0.56</td>
<td>0.85</td>
</tr>
<tr>
<td>Ip, plasma current</td>
<td>MA</td>
<td>6.60</td>
<td>6.56</td>
<td>6.39</td>
</tr>
<tr>
<td>Bo, field on axis</td>
<td>T</td>
<td>5.44</td>
<td>5.44</td>
<td>3.90</td>
</tr>
<tr>
<td>Paux, Total Auxiliary Power</td>
<td>MW</td>
<td>42.16</td>
<td>54.22</td>
<td>41.11</td>
</tr>
<tr>
<td>Peak Heat Flux, Peak Heat Flux to Outer Divertor</td>
<td>MW/m2</td>
<td>6.70</td>
<td>6.83</td>
<td>5.19</td>
</tr>
</tbody>
</table>

Nominal parameters for some of the operating modes evaluated from a 0-D system optimizer model [Chan, Stambaugh, et al., FS&T (2010)]
Tritium Breeding Ratio in FNSF-AT is \( \geq 1 \) for Two Blanket Concepts Considered: DCLL and HCCB

- DCLL = Dual Coolant Lead Lithium
- HCCB = Helium Cooled Ceramic Breeder
- 3-D neutronics analysis using the DAG-MCNP code and FENDL-2.1 nuclear data library
- TBR = 1.09 (HCCB), 1.0 (DCLL)
  - Lost coverage in 16 midplane ports accounts to \( \sim 6\% \) in TBR

[M.E. Sawan, TOFE 2010 (to be published in FS&T)]
Compatibility of FNSF-AT Layout Supported by Detailed 3-D Neutronics Calculations

- Acceptable cumulative end-of-life organic insulator dose levels in TF, OH, and most PF coils
- Minor configuration change needed for PF coil in divertor region

\[ P_f = 240 \text{ MW} \]

[M.E. Sawan, TOFE 2010 (to be published in FS&T)]
Physics-Based Integrated Modeling Needs to Treat Realistic Edge Pedestal

- Pedestal height and width predicted by EPED model, successfully validated against several experiments [Snyder, et al. Nucl. Fusion (2011)]
  - Constraints based on intermediate wavelength peeling-ballooning modes and kinetic ballooning turbulence

- Peeling ballooning stability calculations predict that FNSF-AT pedestal will operate on peeling boundary, where QH-mode can exist
Steady-State Scenario Development - Iterative Process toward Self-consistent Physics Solution

0-D model, $\beta$-limit

Density Peaking (int. database)

Shaping, $R$, $B_T$, $I_p$

EPED model

Pedestal height & width

1.5-D OneTwo +GLF23+EFIT simulation

Steady-state equilibrium

Global stability ($n=0,1$)
Pedestal stability ($n>4$)

TGLF

Start-up scenario not yet developed
Steady-state Is Found via Iteration of Alternating Temperature Profiles and Current Profile Evolution

Free-boundary EFIT

Core density profile shape similar to pressure profile*

OneTwo +GLF23 ~1 sec. evolution j, T_e, T_i, Ω

Free-boundary EFIT

OneTwo +GLF23 ∂Eφ/∂r = 0 j

* Density pedestal fixed at EPED value, density peaking fixed at international database value [Angioni, et al., Nucl. Fusion (2007)]
FDF Modeling Yields Full Noninductive Current Drive and High Fusion Power with Combination of EC and LH

1.5-D OneTwo+GLF23+EFIT simulation

No NBI 
Most challenging scenario, but

ECH/ECCD only

ECH/ECCD + LHCD

• Simplifies tritium containment
• Increases area for tritium breeding
• Negative-ion NBI technology uncertain

Too much ECCD power required for steady-state baseline scenario ($\beta_N \sim 3.7$)

Steady-state baseline equilibrium:

\[ Q \sim 3, \quad P_{\text{fus}} \sim 230 \text{ MW}, \]
\[ P_{\text{EC}} = 55 \text{ MW}, \quad P_{\text{LH}} = 25 \text{ MW}, \]
\[ H_{98y2} \sim 1.2, \quad f_{\text{BS}} \sim 70\% \]
Evolution Has Reached Steady-state Equilibrium (or Very Close to It)
Steady-State Equilibrium for Baseline FDF Mode Has Desirable AT Features
ITB Formation Explained by Turbulent Transport Profiles

Transport Model – GLF23

Heat Conductivity (cm²/s)

- $\chi_e$
- $\chi_i$
- $\chi_{i,\text{neo}}$

$\rho$

$10^7$ $10^6$ $10^5$ $10^4$ $10^3$ $10^2$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$
## Summary Chart: Comparison of 0D and 1.5D Modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Baseline 0-D</th>
<th>Baseline 1.5-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>aspect ratio</td>
<td>3.5</td>
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<tr>
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<td>290</td>
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</tr>
<tr>
<td>BetaT</td>
<td>toroidal beta</td>
<td>5.79%</td>
<td>5.84%</td>
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<td>T</td>
<td>5.44</td>
</tr>
<tr>
<td>Zeff</td>
<td></td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Ti(0)</td>
<td>Ion Temperature</td>
<td>keV</td>
<td>16.41</td>
</tr>
<tr>
<td>&lt;Ti&gt;</td>
<td>Volume Averaged Ion Temp</td>
<td>keV</td>
<td>9.38</td>
</tr>
<tr>
<td>n(0)</td>
<td>Electron Density</td>
<td>E20/m3</td>
<td>3.14</td>
</tr>
<tr>
<td>&lt;n&gt;</td>
<td>Volume Averaged Elec Density</td>
<td>E20/m3</td>
<td>2.09</td>
</tr>
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</tr>
<tr>
<td>HITERN9812</td>
<td>H factor over ELMY H</td>
<td></td>
<td>1.60</td>
</tr>
</tbody>
</table>
Ideal MHD Stability Analysis Shows Configuration Stable to Global Modes

- All $n < 5$ modes stabilized by conformal wall at 1.15 times minor radius
  - All these modes are infernal modes with $n = 2$ least stable
  - $n = 5$ infernal mode remains unstable with wall on plasma
- High $n$ weak infernal modes stabilized by slightly reduced pressure gradient in low shear region and likely self stabilize and saturate
FNSF-AT Has Comparable Level of Controllability to DIII-D, with Conservative Coil Design Assumptions

- **Toroidally continuous vessel and blanket produce very low vertical growth rate**
  - $\gamma r_w \sim 0.67 \ (<< \gamma r_w \|_{DIII-D} \sim 2.5)$

- **Achievable control coil engineering assumptions**
  - Maximum voltage 6 kV (in 50 turns)
  - Maximum cross-section current density 1.5 kA/cm$^2$

- **Maximum controllable displacement comparable to DIII-D**
  - $\Delta Z_{MAX}/a \sim 12\%$
  - DIII-D typ. $\Delta Z_{MAX}/a \sim 10\%$ with no VDE
Axisymmetric Divertor Structures Allow Precision Tile Alignment, Enable Strong Divertor Plate Tilting

- 2-D analysis (SOLPS, J. Canik, ORNL) predict peak heat flux <10 MW/m²
  - Strong plate tilting
  - DND configuration
  - ~50% core radiation fraction
- Several approaches can be used in parallel to further reduce peak heat flux
  - SOL and divertor radiative dissipation
  - Flux expansion (X divertor, SX divertor, Snowflake divertor are being tested in experiments)
DIII-D Shows Radiative Dissipation and 3D Fields Are Viable Approaches to Reducing Peak Heat Flux

- Divertor radiation preferentially enhanced using puff and pump technique

- $P_{rad}/P_{NBI} \sim 60\%$ with $Z_{eff} \sim 2.0$
  - Argon and D$_2$ injection

- $\beta_N=2.6$, $H_{89}=2.0$, $G=0.4$ maintained
  - Experiments thus far focused on puff and pump studies, not fusion performance

- $n=3$ magnetic field used for ELM control also splits strike points

- Angular rotation of the 3D field will result in a time averaged broadening of the OSP footprint
Summary (1)

• Steady-state scenario development of FNSF-AT carried out using iterative process of alternating kinetic profiles (GLF23) and current profile evolution toward a self-consistent solution
  – No NBI to simplify tritium containment, increase area for tritium breeding, and avoid costly negative-ion NBI technology
  – Desired SS baseline equilibrium found using ECCD and LHCD

• Equilibrium ideal MHD stable for n<5, with pedestal height against predicted (EPED) ELM threshold

• Vertical controllability achievable with conservative coil design assumptions

• Peak divertor heat flux (SOLPS) comparable to ITER

• TBR>1 possible, neutron damage of coils acceptable using organic insulators (DAG-MCNP)
• Some key physics models are still missing - disruption, ELM dynamics

• Modeling of the plasma edge and PFC is preliminary – recycling, material erosion

• Whole Device Modeling is limited by speed of codes – hardware and software development required

• Extensive verification and validation effort remains
Key features of the FNSF-AT approach:

• FNSF-AT is on direct path towards attractive DEMO

• FNSF-AT plus ITER fill gaps to DEMO

• Ready to start design of FNSF-AT
  – Proven materials, proven physics for first stage of operation