A Path to a Fusion DEMO as a Next Step After ITER

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In Addition to What We Learn in ITER, What Else Do We Need to Learn to Build an Electricity Producing DEMO?

ITER
High energy gain burning plasma physics
Reactor scale superconducting technology

?

DEMO
High gain, advanced physics, steady-state high duty factor fusion power

TODAY’S RESEARCH FACILITIES
Tokamaks Have Made Excellent Progress in Fusion Power

- JET: 16 MW, 0.68 GJ fusion energy
- TFTR: 10.7 MW, 1.55 GJ fusion energy
- Worldwide research efforts since 2000 have focused on building ITER, to carry actual fusion power output up to reactor scale
  - Q=10 in 2030
In Addition to What We Learn in ITER, What Else Do We Need to Learn to Build an Electricity Producing DEMO?

ITER
High energy gain burning plasma physics
Reactor scale superconducting technology

TODAY’S RESEARCH FACILITIES

• Addresses remaining gaps to DEMO
• Can be done now
  □ Get us ready for DEMO construction triggered by Q=10 in ITER (~2030)

DEMO
High gain, advanced physics, steady-state high duty factor fusion power
US MFE Community – Remaining Gaps to DEMO Have Been Identified

2007 FESAC Planning Panel

<table>
<thead>
<tr>
<th>Initiative</th>
<th>How Initiatives Could Address Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ITER - AT extension</td>
<td>1</td>
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<tr>
<td>2. ITER - AT extension</td>
<td>1</td>
</tr>
<tr>
<td>3. Integrated advanced physics demonstration (IDT)</td>
<td>2</td>
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<tr>
<td>4. Integrated PWI/FUS experiment (IDP)</td>
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<tr>
<td>5. Disruption-free experiments</td>
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<td>6. Engineering and materials science modeling and experimental validation initiative</td>
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<tr>
<td>7. Materials qualification facility</td>
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</tbody>
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2009 Research Needs Workshop

US MFE Leadership –

- Towards a Fusion Nuclear Science Facility
  - Burning Plasma Dynamics and Control
  - Materials in a Fusion Environment and Harnessing Fusion Power
Appropriate Size of Next Step Forward?

- FNSF choices lie on continuum between present program and DEMO
  [Ray Fonck, EPRI 2011]
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
Appropriate Size of Next Step Forward?

- FNSF choices lie on continuum between present program and DEMO
  [Ray Fonck, EPRI 2011]

- FNSF-AT can be designed now and operate in parallel with ITER
- Readiness for DEMO construction triggered by Q=10 in ITER (~2030)
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>
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<tbody>
<tr>
<td>A</td>
<td>aspect ratio</td>
<td>3.5</td>
<td>3.5</td>
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</tr>
<tr>
<td>k</td>
<td>plasma elongation</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
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<tr>
<td>Pf</td>
<td>fusion power</td>
<td>MW</td>
<td>290.07</td>
<td>159.07</td>
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<tr>
<td>Pinternal</td>
<td>power to run plant</td>
<td>MW</td>
<td>499.75</td>
<td>526.57</td>
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<tr>
<td>Qplasma</td>
<td>Pfusion/Paux</td>
<td>6.88</td>
<td>2.93</td>
<td>3.52</td>
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<td>Pn/Awall</td>
<td>Neutron Power at Blanket</td>
<td>MW/m2</td>
<td>2.00</td>
<td>1.10</td>
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<tr>
<td>BetaN</td>
<td>normalized beta</td>
<td>mT/MA</td>
<td>3.69</td>
<td>2.65</td>
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<tr>
<td>fbs</td>
<td>bootstrap fraction</td>
<td>0.75</td>
<td>0.54</td>
<td>0.56</td>
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<tr>
<td>Ip</td>
<td>plasma current</td>
<td>MA</td>
<td>6.60</td>
<td>6.56</td>
</tr>
<tr>
<td>Bo</td>
<td>field on axis</td>
<td>T</td>
<td>5.44</td>
<td>5.44</td>
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<tr>
<td>Paux</td>
<td>Total Auxiliary Power</td>
<td>MW</td>
<td>42.16</td>
<td>54.22</td>
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<tr>
<td>Peak Heat Flux</td>
<td>Peak Heat Flux to Outer Divertor</td>
<td>MW/m2</td>
<td>6.70</td>
<td>6.83</td>
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</table>

Nominal parameters for some of the operating modes evaluated from a 0-D system optimizer model [Chan, Stambaugh, et al, FS&T (2010)]
AT Physics Enables Nuclear Mission at Modest Size

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)]
• 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
  – Other devices will address superconducting coil issues

Titus et al. SOFE (2009)
A Staged Approach to Learn and Improve Nuclear Components, Diagnostics, Operating Scenario

Radiation damage survival strategy:

Nuclear facing structures do not see more than 2 MW-yr/m² (20 dpa) before removal
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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<tr>
<td></td>
<td>H</td>
<td>D</td>
<td>DT</td>
<td></td>
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<tr>
<td>Fusion Power (MW)</td>
<td>0</td>
<td>0</td>
<td>125</td>
<td>250</td>
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<tr>
<td>$P_N/A_{WALL}$ (MW/m$^2$)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Pulse Length (Min)</td>
<td>1</td>
<td>10</td>
<td>SS</td>
<td>SS</td>
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<tr>
<td>Duty Factor</td>
<td>0.01</td>
<td>0.04</td>
<td>0.1</td>
<td>0.2</td>
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<tr>
<td>T Burned/Year (kG)</td>
<td>0.28</td>
<td>0.7</td>
<td>2.8</td>
<td>2.8</td>
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<tr>
<td>Net Produced/Year (kG)</td>
<td>0.14</td>
<td>0.56</td>
<td></td>
<td>0.56</td>
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<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>
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<tr>
<td>TBR</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
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<tr>
<td>Test Blankets</td>
<td>1,2</td>
<td></td>
<td>3,4</td>
<td>5,6</td>
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<tr>
<td>Accumulated</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fluence (MW-yr/m$^2$)</td>
<td>0.06</td>
<td>1.2</td>
<td>3.7</td>
<td></td>
</tr>
</tbody>
</table>

Diagnostics development and testing:

- **ITER-like set (start)**
- **Reduced set**
- **DEMO-like set**
FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO

- 100% non-inductive 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% non-inductive modes developed on DIII-D bracket FNSF-AT baseline
  - Negative central magnetic shear
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Pulse length extension in next few years

- Baseline FNSF-AT to meet nuclear science mission

- More advanced scenarios to close physics gaps to DEMO
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
Complementary Research on FNSF-AT, ITER, SC Tokamaks, and Materials Irradiation Facilities Enables DEMO

TODAY’S RESEARCH FACILITIES

FNSF-AT
Learn to extract fusion power and make fusion fuel — high neutron flux, fluence, duty factor

ITER
High energy gain burning plasma physics Reactor scale superconducting technology

Superconducting Tokamaks
EAST KSTAR SST-1 JT-60SA
Long pulse advanced physics

Materials Irradiation Facilities

DEMO
High gain, advanced physics, steady-state high duty factor fusion power

AM Garofalo, 32nd FPA Meeting, 2011
The Physics Basis for FNSF-AT Can Be Available from Experiments and Simulation in the Next Few Years

- Required stability values achieved in 100% non-inductive plasmas (extend pulse length)
- RWM stabilization by rotation/kinetic effects
- NTM stabilization by ECCD
- ELM elimination by QH mode operation, RMPs
- Disruption avoidance and mitigation
- Confinement quality required already obtained in long pulse DIII-D plasmas
- Bootstrap fraction already achieved
- Far off-axis LHCD in high density H-mode
- Pumped, high triangularity plasma
- Plasma control system
- Power exhaust: more challenging than DIII-D and comparable to ITER
- PFC tritium retention – oxygen bake and hot wall

Green=done
Blue=near term
FNSF-AT Will Get Us Ready For DEMO Construction Triggered By Q=10 in ITER

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 design FNSF-AT now
A Fast Track Plan to Get to a Net Electric DEMO

| ITER Key Schedule Elements | 16 | 17 | 18 | 19 | 2020 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 2030 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 2040 |
|----------------------------|----|----|----|----|------|----|----|----|----|----|----|----|----|----|------|----|----|----|----|----|----|----|----|----|----|----|
| Fusion Nuclear Science Facility (FNSF) and Program | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Commissioning Operation (H, D, DT pulsed) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Show Significant Steady-State Fusion Power | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Helium Cooled Ceramic Breeder Blanket | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Show Fusion Can Produce Its Own Fuel | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Produce High Grade Process Heat From Fusion | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Show Fusion Can Produce Electricity | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Dual Coolant Lead Lithium Blanket | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Oxide Dispersion Strengthened Ferritic Steel Blanket | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Operate a Blanket With DEMO Relevant Irradiation Lifetimes | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Field Plasma Diagnostics Suitable for a Power Plant | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Fusion Materials Irradiation and Development Program | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Materials and Full Components Irradiation in FNSF | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Accelerator Based Lifetime Irradiation Data | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Initial Data | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Triple Ion Beam Facility | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Data on ODS Ferritic Steel | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Fission Reactor Irradiations | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Net Electric DEMO Power Plant (1000 MWe) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Initiate Design: | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Build: | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Blanket Decision: | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Operation: | | | | | | | | | | | | | | | | | | | | | | | | | | | |

DEMO design initiated by first plasma in ITER. DEMO construction triggered by Q=10 in ITER, first phase accomplishments in FNSF, and materials data on ODS Ferritic Steel. FNSF enables choice between two most promising blanket types for DEMO.