Develop the Basis for Plasma Material Interface (PMI) Solutions for FNSF

FESAC Strategic Planning Panel

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Divertor/PFC Challenge: Reliably Dissipate Heat and Particle Flux in a GW-scale Fusion Reactor

Prior studies show gaps

- Predictable boundary plasma control to bridge the transition from the hot fusion core to material surfaces.
- Qualified plasma-facing components designed for the expected reactor environment
- Fully integrated solutions for core, boundary, and components producing high fusion gain.

Starting FNSF design by 2025 increases urgency to resolve the PMI challenge
FNSF and DEMO-Scale Tokamak Design Studies Inform Research Needs for Plasma Material Interface Solutions

Divertor target heat flux

\[ q_{\text{target}} = \frac{(1-f_{\text{rad}})P_{\text{loss}}}{2\pi R_{\text{target}} \lambda_{q,\text{mp}} f_{\exp}} \]

\[ P_{\text{loss}} = P_{\text{CD}} + 0.2xP_{\alpha} \]

- Physics
- Design/Engineering
Solution-based Science Initiatives Can Provide A Reasonable Basis for Designing the FNSF Divertor

1. **Develop robust boundary-plasma solutions to mitigate PMI challenges**
   a. Comprehensive measurements and coordinated multi-machine experiments
   b. Upgrades to existing tokamaks (Diagnostics, divertors, power)
   c. Boundary simulation centers with analysts tightly coupled to experiments

2. **Design and Test Candidate PFC Materials (partner with BES)**
   a. Develop new materials and materials technology [simulation + testing labs]
   b. Materials exposure in linear plasma facilities (existing US and international)
      Radiation-damage evaluation (access needed to neutron sources)
   c. Plasma material interaction experiments in tokamaks (existing US and international)

3. **Pursue Core-Edge Physics and Operational Integration**
   a. Test large-area samples of candidate PFC materials at realistic operating temperatures in high-performance tokamaks
   b. Use SC long-pulse experiments to evaluate steady-state PFC operation [international]

Consistent with ReNeW Theme 3: Taming the Plasma Material Interface
Boundary-plasma Control Requires Edge Radiation and Divertor Detachment to Reduce Surface Heat Flux, Erosion

- Basic physical processes identified
- **Validated 2D predictive model needed**
- Role of geometry, boundary conditions uncertain
- Extend to higher power density, radiation fraction

Recombining detached divertor ($T_e < 2eV$)

Divertor radiative cooling enables recombination

Increasing core plasma density

Strongly reduced divertor heat flux

Boundary impurity radiation reduces $P_{SOL}$

Radius usually small in present exps
Developing Boundary-plasma Solutions Iteratively Links Facilities – Measurements – Simulation

Experiments
- Operational flexibility
- Configurational flexibility
- Diagnostic Access
- Run Time

Simulation
- Code Development
- Visualization Tools
- Comparison with data (Analysts)

Measurements
- 2D coverage
- Visualization tools
- Operation
- New Instruments
It Is Imperative to Develop Boundary-plasma Solutions Using Non-Nuclear Confinement Facilities
Fusion Program Must Engage the Materials Science Community to Develop Materials, Processes, Components

- Existing fusion PFC materials have known problems (W, C, Be, Li)
  - Sputtering and long-term material migration
  - Core plasma sensitive to high-Z contamination
  - Transients, Tritium retention, neutron damage

- High-Z divertor materials may work (cold detached divertor plasma)

- Divertor and first wall material surfaces will be at high temperature (~900°C)

- ITER first-wall not designed to meet steady-state reactor requirements

- New Materials, Components, Mitigation Techniques are required
Relevant Time, Temperature, and Spatial Scales Motivates Targeted Materials Research In a Wide Range of Facilities

- $\tau_{\text{SOL}}$: 0.1ms – 10s
- $\tau_E$, $\tau_{\text{surf}}$: ~ 1s – 10s
- $\tau_{\text{particle}}$: ~ 100s
- $\tau_{\text{Resistive}}$: ~ 300s
- $\tau_{\text{Blanket}}$: ~ $10^6$s
- $\tau_{\text{migration}}$: ~ $10^7$s

1. **Material science laboratories:** Design and evaluate new candidate materials

2. **Linear facilities:** Expose candidate materials to relevant test environments

3. **Tokamaks:** Evaluate samples under plasma exposure (short & long pulse)

   *Pulse length requirements are driven by sensitivity of the measurement.*

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Zenobia, Garrison, Kulcinski
*JNM, 425, 83–92 (2012)*

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Tungsten sample
U. Wisconsin thesis

DIII-D DiMES
Moly sample
Separatrix intercept
High-Z Erosion Rates Measured in DIII-D

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JET
ITER
Enhanced Simulation Efforts Are Needed to Develop Validated Predictive Capability to Guide PFC Design

- Validated Simulations are key to quantitative divertor optimization and to Materials design/development
  - Processes are coupled, nonlinear, multi-dimensional
  - Quantitative prediction beyond the reach of analytical models

- Present effort on Boundary/SOL/Divertor/PMI simulation is subcritical given the demand and challenge

- Close interaction with experiment is needed (analysts)

- Startup: 2 centers: 1 plasma + 1 materials (BES partners)
Self-Consistent Core – Edge Solutions Must Be Evident to Begin FNSF Design

- **Upgrades to US tokamaks offer a cost effective start on core-edge integration**
  - Develop non-inductive scenarios (startup, ramp-up, high Te/Ti, low rotation)
  - Explore integrated divertor operation: new components, materials, high temp walls
  - Develop disruption avoidance and mitigation systems

- **Enhanced collaborations with SC tokamaks provide sufficient pulse length for materials to reach steady-state conditions**
  - High performance stability and control for many resistive times: $2\tau_R \rightarrow 50\tau_R$
  - High-heat flux components in thermal equilibrium (recycling, etc.)
  - Explore/confirm long term trends in material migration

<table>
<thead>
<tr>
<th>JT-60SA (2019): 100sec</th>
<th>EAST: 1000sec</th>
<th>KSTAR: 300sec</th>
</tr>
</thead>
</table>

[Images of tokamak components and integration systems]
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**Consistent with ReNeW Theme 3: Taming the Plasma Material Interface**
additional backup material
Time Is Short to Address the PMI Challenge For Being Ready to Start FNSF Design In 2025

FNSF Readiness to Proceed
- Mission
- Acceptable Cost
- Acceptable Risk (TRL step)
Realistic Assessment of Scientific Goals, Cost, & Schedule Must Drive Investments in DivSOL – PMI Research

- What is required to advance Technical Readiness Levels?
- Where best to do the work? (required research capabilities)
- When will required new capabilities be available and at what cost?

<table>
<thead>
<tr>
<th>Eight specific investment options</th>
<th>New Facility Operating Cost (ea.)</th>
</tr>
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<tbody>
<tr>
<td>✔️ 1. Theory/Computational Research Groups</td>
<td>($6 – 20M/yr)</td>
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<tr>
<td>✔️ 2. Linear PMI and SOL physics facilities</td>
<td>($25M facility/ $5M/yr)</td>
</tr>
<tr>
<td>✔️ 3. Existing non-activated tokamaks</td>
<td>($50M upgrades/$30M/yr)</td>
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<tr>
<td>4. Other new long-pulse, non-activated tokamaks</td>
<td>($300M /$50M/yr)</td>
</tr>
<tr>
<td>✔️ 5. Very long-pulse, high performance tokamaks</td>
<td>($1B /$100M/yr)</td>
</tr>
<tr>
<td>6. ITER</td>
<td>($30B /$1500M/yr)</td>
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</tbody>
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Specific Challenges of DEMO-scale Fusion Related to the Plasma Boundary (Plain English Version)

- Fueling and density control, ash removal
- PFC melting due to steady and transient heat loads
- Impurity control
- PMI: sputtering, erosion, and changes to surface structure/composition
- Structural damage due to neutrons and helium implantation

Three Initiatives to Address These Challenges:
Plasma-Based Solutions, PFC/Materials Development, Core/Edge Integration