A Thrust for Integration of High-Performance Steady-State Burning-Plasma Behavior Relevant to Demo

Dale Meade
Fusion Innovation Research and Energy®
Princeton, NJ
United States of America

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Fusion Research Themes (FESAC)

Theme A – Creating a High-Performance Steady-State Burning Plasma
(a heat source from magnetic fusion)

Theme B – Taming the Plasma Materials Interface
(interface between heat source and furnace wall, and extracting plasma exhaust power)

Theme C – Harnessing the Power of Fusion
(extracting neutron power, breeding tritium, remote handling, safety/environment)

• These themes follow a systems or process based approach, sometimes called Holistic approach to the R&D of complex systems - eg space craft.

• They form a natural overlapping sequence
Key Questions related to the Physics of a Demo Plasma

- A Demo plasma with high fusion gain, high neutron wall loading, high bootstrap fraction for efficient steady state and high power density plasma exhaust is a highly integrated plasma system. Some questions:
  - Is good confinement compatible with $P_{\alpha}$ defined profiles?
  - Does transport depend on non-linearly on the pressure profile?
  - Is high beta compatible with $P_{\alpha}$ defined profiles?
  - Does the plasma evolve to a stable self-organized state?
  - Will alpha heating drive a self-heating sawtooth?
  - Can the plasma be sustained and controlled with low power?
  - What are the optimum temperature and density regimes for simultaneous high Q, efficient CD and long life divertor operation?
  - Many more........

- Can we quantify the gaps between today, ITER and a Demo?
High-Performance Steady-State Burning-Plasma Issues

**High Fusion Gain** - attain good confinement with profiles defined by alpha heating \( P_{\alpha}/P_{\text{ext}} = Q/5 \), possible non-linear dependence of transport on gradients, coupled to edge plasma by pedestal, optimum temperature for fusion \( \sim 15 \) keV and high density but efficient current drive favors higher \( T \sim 30 \) keV and lower density.

**Sustainment (100% NI)** - produce large bootstrap current with pressure profiles defined by alpha heating and residual current driven efficiently by low power \( P_{\text{cd}} \leq 5P_{\alpha}/Q \).

**High Fusion Power Density** \( (\beta^2 B^4 <\sigma v>/T^2) \) - to provide high neutron wall loading. Can near optimum \( \beta \) be attained for alpha-defined profiles?

**Plasma Control** \( (P_{\text{cd}} + P_{\text{cont}} = 5P_{\alpha}/Q) \) - maintain plasma control (esp. disruptions) with low power typically < 0.15\( P_{\alpha} \). Will a burning plasma evolve to a self-organized state with good confinement, high bootstrap and high \( \beta \)?

**Exhaust Power Density** - can high exhaust power densities be handled while maintaining edge plasma for high \( Q \) and efficient CD with long PFC lifetime?

**Self-Conditioned PFCs** - will the PFCs self-condition that is consistent with high \( Q \) and \( \beta \), and long PFC lifetime?
**High-Performance Steady-State Burning-Plasma**

**Metrics and Gaps**

<table>
<thead>
<tr>
<th>Table I. Individual Issue (Metric)</th>
<th>Today* (&gt;10τ_E)</th>
<th>ITER</th>
<th>ARIES-I</th>
<th>ARIES-AT</th>
<th>&lt;Gap&gt; IT to AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Gain (Q)</td>
<td>&lt; 0.2</td>
<td>5</td>
<td>20</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>Self-heating (%)</td>
<td>4</td>
<td>50</td>
<td>80</td>
<td>91</td>
<td>1.7</td>
</tr>
<tr>
<td>Sustainment (100% NI)** (P_{cd}/P_α)</td>
<td>&gt;25</td>
<td>1</td>
<td>0.25</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Current Drive fraction (1-f_{bs}) (%)</td>
<td>~30</td>
<td>~50</td>
<td>32</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Neutron Wall Loading (MWm^{-2})</td>
<td>0.1</td>
<td>0.5</td>
<td>2.5</td>
<td>3.3</td>
<td>6</td>
</tr>
<tr>
<td>Plasma Pressure (atm)</td>
<td>1.6</td>
<td>2.5</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Fusion Power density (MWm^{-3})</td>
<td>0.3</td>
<td>0.5</td>
<td>4</td>
<td>4.7</td>
<td>8</td>
</tr>
<tr>
<td>Plasma Control* (P_{cont}/P_α)</td>
<td>&gt;25</td>
<td>1</td>
<td>0.25</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Exhaust Power Density (P_{heat}/A_\text{ps} (MWm^{-2})</td>
<td>0.85</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Self-Condition PFCs &amp; FW f(t_{pulse}, T, φ,</td>
<td>No</td>
<td>?</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
</tbody>
</table>

* Not all simultaneous

** Current Drive Power + Plasma Control Power = 5 P_α/Q

Assumes ITER will be upgraded with addition of Lower Hybrid current drive for Scenario 4.

- ARIES-I And ARIES-AT span the range of a possible DEMO.
- Individual gaps between ITER (scenario 4) and ARIES range between 1.7 and 10.
Description of integration issues
Integrate Fusion Gain, Sustainment and Exhaust Power Density

Table I. Individual Issue (Metric) | Today* (>10τE) | ITER | ARIES-I | ARIES-AT | <Gap> IT to AR
--- | --- | --- | --- | --- | ---
**Fusion Gain (Q)** | < 0.2 | 5 | 20 | 50 | 7
Self-heating (%) | 4 | 50 | 80 | 91 | 1.7
**Sustainment (100% NI)** \( \frac{P_{cd}}{P_\alpha} \) | >25 | 1 | 0.25 | 0.1 | 6
Current Drive fraction \( (1-f_{ps}) \) (%) | ~30 | ~50 | 32 | 9 | 2.5
Neutron Wall Loading \( \text{(MWm}^{-2}\text{)} \) | 0.1 | 0.5 | 2.5 | 3.3 | 6
Plasma Pressure \( \text{(atm)} \) | 1.6 | 2.5 | 10 | 10 | 4
Fusion Power density \( \text{(MWm}^{-3}\text{)} \) | 0.3 | 0.5 | 4 | 4.7 | 8
Plasma Control* \( \frac{P_{cont}}{P_\alpha} \) | >25 | 1 | 0.25 | 0.1 | 6
**Exhaust Power Density** \( \frac{P_{heat}}{A_{ps}} \) \( \text{(MWm}^{-2}\text{)} \) | 0.85 | 0.2 | 1 | 1 | 5
Self-Condition PFCs & FW \( f(t_{pulse}, T, \phi) \), | No | ? | Yes | Yes | ?

* Not all simultaneous

**Current Drive Power + Plasma Control Power = 5 \( P_\alpha/Q \)
Assumes ITER will be upgraded with addition of Lower Hybrid current drive for Scenario 4.

- The individual gaps are taken to be independent, therefore the Integration Gap is the product of individual gaps.

- The Integration Gap for Fusion Gain, Sustainment and Exhaust Power density is \( \approx 200 \)
A Thrust for Integration of High-Performance Steady-State Burning-Plasma Behavior Relevant to Demo

Key Objectives of Thrust

• Determine and understand conditions for attaining a Demo-relevant burning plasma.

• Determine and understand conditions for sustaining and controlling a Demo-relevant plasma that is dominately self-heated, with dominately self-driven currents and dominately self-conditioned PFCs.

• Test and Refine Predictive Modeling on a Demo relevant plasma.

• Together with ITER, and other Thrusts provide the knowledge basis for the design of a tokamak based Demo.
Strategy for Integrating Demo Relevant Plasma Issues

- Aggressively exploit simulation on existing DD facilities and computer models
  - target specific objectives/tasks with SC action teams
  - exploit Asian superconducting facilities
  - simulate burning plasma phenomena to the extent possible

- Begin a study of the Fusion Plasma Integration Facility that would address the integration issues of a Demo-relevant High-Performance Steady-State Burning plasma and serve as a D-T satellite tokamak for ITER.
  - refine key objectives and research requirements
  - define general characteristics of possible facilities (iterate with above)
  - since the cost will be significant, start with a plan that has a sequence of upgrades that spreads the cost and allows success to bootstrap funding for the next stage or objective.
  - begin the pre-conceptual design of a facility(s) within a year to assess technical feasibility and cost range.

Note: Not building a major Burning Plasma facility is very expensive

Since 1997 US MFE has spent $3.4B ($4B in FY08 $)
Since 1989 US MFE has spent $6B ($7.5B in FY08 $)