Science and Technology Issues and Opportunities for a Burning Plasma Science Experiment

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Science and Technology Considerations for a BPSX*

- Foreseeable near-term BPSX’s will be tokamaks
- Plasma performance (nT\(\tau\)) significantly above that achievable in present tokamaks is required
- Enhanced or new technologies are required
- This presentation examines several key generic BPSX requirements and the resulting ‘BP’ technology needs
- A BPSX can also provide a unique stimulus/opportunities to develop and test generic future MFE technologies

*generic Burning Plasma Science Experiment
Selected Topics and Organization

- High-field/long-pulse TF and PF magnets
- PFCs: power loading and pulse duration, T-retention and disruption resistance/tolerance (also Session 1)
- BP-compatible/enabling H/CD (also Session 2)
- AT-enabling H/CD, etc. (Session 2)
- BP- and AT-compatible diagnostics (Session 5)

Framework for Consideration:

Science → BP Technologies → BP Science Ops

Fusion Tech Ops
Acknowledgements and Cautions

• The analyses presented here are supported by General Atomics internal funding: opinions expressed are those of the author alone

• Methodologies adopted derive from a long succession of [would-be] first-of-kind burning plasma experiments: INTOR, FED, ITER-CDA, ITER-EDA, CIT, BPX, ....

• Qualitative parameters are based on public-accessible machine concept data and do not necessarily constitute a fully accurate or equivalent comparison basis. Small distinctions among concepts in computed parameters are not necessarily meaningful

• Don’t attempt BPSX comparisons like this at home, at least without taking adequate protective measures!
BP Regime Access Requirements

- Maximum \( \langle n \rangle \langle T \rangle \tau_E \) in tokamaks increases approximately as \((I^*A)^2\)

- Stellarator and [sparse] ST data fall on the same scaling (and hence tend to confirm the A dependence of the tokamak scaling, which spans a range \( A = 2.5 - 5 \))

- There are factor-of-2 variations (±) among the tokamak data (profiles, other significant parameters, optimization, ....). IA is not the only performance predicting parameter

- BP regime (\( Q \sim 10 \)) typically requires \( \langle n \rangle \langle T \rangle \tau_E \geq 2-4 \times 10^{21} \text{ m}^{-3} \text{ keV.s} \) (varies owing to assumptions about profiles, impurities, self-consistent He, .....)

- BP requires \( IA \geq 30 \text{ MA} \) (eg. \( \geq 10 \text{ MA} \) at \( A = 3 \); cf. JET-EFDA IA = \~12 MA)

- \( IA \geq 40 \text{ MA} \) provides modest margin; \( IA \geq 60 \text{ MA} \) yields ‘ignition’ \( (Q \geq 25) \) and/or a ‘reactor-prototype’ device

\[ \langle n \rangle \langle T \rangle \tau_E (10^{20} \text{ m}^{-3} \text{ keV.s}) \]

- 1st and 2nd-generation tokamaks: OH or L-mode, DD
- 2nd and 3rd-generation tokamaks (ITER DB3): ELMy H-mode, DD, various open symbols as identified
- ITER or BP tokamak projections: ELMy H-mode, DT, \( Q \geq 10 \)
- Spherical tokamak (\( A \leq 2 \))
- Stellarator and [sparse] ST data fall on the same scaling (and hence tend to confirm the A dependence of the tokamak scaling, which spans a range \( A = 2.5 - 5 \))
- There are factor-of-2 variations (±) among the tokamak data (profiles, other significant parameters, optimization, ....). IA is not the only performance predicting parameter
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Magnet and shielding requirements set BPSX size

\[ a = \frac{d_{P-TF} + \frac{q_{95} I_A * A}{5 B_{max} C(\kappa, \delta) C(A)}}{A-1} \]

\[ R_O = A a \]

- Minimum size and A are also constrained by OH solenoid requirement

<table>
<thead>
<tr>
<th>Device</th>
<th>ITER-FDR</th>
<th>ITER-FEAT</th>
<th>FIRE-10T</th>
<th>FIRE*-10T</th>
<th>IGNITOR</th>
<th>M-Cu-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.91</td>
<td>3.10</td>
<td>3.81</td>
<td>3.60</td>
<td>2.81</td>
<td>3.16</td>
</tr>
<tr>
<td>I(MA)</td>
<td>21.0</td>
<td>15.2</td>
<td>6.6</td>
<td>7.7</td>
<td>11.5</td>
<td>14.2</td>
</tr>
<tr>
<td>(\kappa_{95})</td>
<td>1.60</td>
<td>1.70</td>
<td>1.80</td>
<td>1.80</td>
<td>1.83</td>
<td>1.77</td>
</tr>
<tr>
<td>(\delta_{95})</td>
<td>0.25</td>
<td>0.33</td>
<td>0.40</td>
<td>0.40</td>
<td>0.43</td>
<td>0.33</td>
</tr>
<tr>
<td>(q_{95})</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>(B_{max} (T))</td>
<td>11.7</td>
<td>11.3</td>
<td>15.3</td>
<td>14.8</td>
<td>21.8</td>
<td>10.5</td>
</tr>
<tr>
<td>(d_{P-TF} (m))</td>
<td>1.45</td>
<td>1.25</td>
<td>0.167</td>
<td>0.167</td>
<td>0.08</td>
<td>0.54</td>
</tr>
<tr>
<td>a (m)</td>
<td>2.80</td>
<td>2.00</td>
<td>0.521</td>
<td>0.597</td>
<td>0.47</td>
<td>1.61</td>
</tr>
<tr>
<td>(R_O (m))</td>
<td>8.14</td>
<td>6.20</td>
<td>1.98</td>
<td>2.15</td>
<td>1.32</td>
<td>5.05</td>
</tr>
<tr>
<td>(B_0 (T))</td>
<td>5.61</td>
<td>5.38</td>
<td>10.0</td>
<td>9.6</td>
<td>12.7</td>
<td>6.1</td>
</tr>
<tr>
<td>I(A (MA))</td>
<td>61</td>
<td>47</td>
<td>25</td>
<td>28</td>
<td>32</td>
<td>45</td>
</tr>
</tbody>
</table>
High $B_{\text{max}}$, Low A and No Shielding Yield Smallest $R_o$

- $B_{\text{max}} \geq \sim 16 \text{ T}$ pushes to (or above) ‘pure-Cu’ stress limit
Pulse Duration (with inductive/OH current drive)

- Compact inertially-cooled designs are thermal and OH-limited
- Larger designs with steady-state TF are OH-limited (OH V-s swing)
- Absolute pulse duration increases strongly with $R_o$, but confinement-normalized duration increase is $\sim 10$-x weaker:
BPSX Magnet Technology Summary

• A variety of resistive (copper) and superconducting (SC) magnet technologies to support $Q \geq 10$ BPSX’s have been identified

• Concepts separate into two categories based on TF magnet cooling (inertial or steady-state) and at-magnet peak field:
  1) cryo-precooled copper (typically with some alloying), inertially cooled, with 15-22 T peak fields, or
  2) steady-state resistive pure copper or SC, with peak fields 10-12 T

• Machine size ($R_o$) decreases strongly with higher $B_{TF}$ and/or weakly with lower $A$. But OH requirement sets a limit on minimum $A$

• TF structural limitations apply to all concepts and are important configuration drivers, especially for compact designs

• For both inertial and steady-state concepts, OH solenoid flux swing sets an $V$-$s$ limited plasma current/burn duration

• For compact inertial-Cu designs, TF thermal and OH duration limits are similar; for steady-state TF designs, OH duration limit sets burn duration

• Reliable magnet operation will be critical: all BPSX designs will require essentially full-field, full-current operation (for ??? pulses)
BPSX Plasma Facing Component Requirements

• A BPSX will require a larger scale (size and/or field strength) and higher power (aux + alpha) device than the largest present tokamaks. PFCs, VVs, etc. will also be exposed to significant volumetric neutron heating.

• Increase in ‘scale’ and plasma power (plus neutron heating) results in an increase in the effective plasma wall loading — $P_{th}/A_{FW}$ and also in the plasma specific energy — $W_{th}/A_{FW}$

• These increases plus the effects of neutron irradiation on material and structure properties and PFC maintenance impact BPSX PFC selection, design and operation planning.

• In addition, BPSX PFC’s must be selected to minimize T retention (in co-deposited layers). Use of carbon may be constrained or prohibited.

• Finally, in almost all cases, BPSX primary PFCs will operate in thermal steady state and require active cooling. Provision will also be needed to replace eroded or damaged PFCs on a regular basis.
BPSX PFC Parameters (Estimated)

- A BPSX requires a larger scale (size and/or field strength) and higher (aux + alpha) power device than the largest present tokamaks.

- PFC ‘steady-state’ power/area (MW/m²) and disruption energy (MJ/m²) are appreciably higher than in present ‘long-pulse’ (~10 s) tokamaks:

<table>
<thead>
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<th>Device</th>
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<td>7.7</td>
<td>11.5</td>
<td>15.0</td>
</tr>
<tr>
<td>R₀ (m)</td>
<td>8.14</td>
<td>6.20</td>
<td>1.98</td>
<td>2.15</td>
<td>1.32</td>
<td>5.00</td>
</tr>
<tr>
<td>P_{fus} (MW)</td>
<td>1500</td>
<td>410</td>
<td>150</td>
<td>150</td>
<td>180</td>
<td>325</td>
</tr>
<tr>
<td>P_{α} (MW)</td>
<td>300</td>
<td>82</td>
<td>30</td>
<td>30</td>
<td>37</td>
<td>65</td>
</tr>
<tr>
<td>P_{aux} (MW)</td>
<td>0</td>
<td>40</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>P_{tot}/A_{wall} (MW/m²)</td>
<td>1.19^a</td>
<td>0.61</td>
<td>2.4</td>
<td>1.9</td>
<td>5.0</td>
<td>0.94</td>
</tr>
<tr>
<td>P/A_{div}</td>
<td>39^b</td>
<td>21</td>
<td>24</td>
<td>22</td>
<td>44^c</td>
<td>27</td>
</tr>
<tr>
<td>W_{th} (MJ)</td>
<td>1100</td>
<td>325</td>
<td>27</td>
<td>35</td>
<td>~10</td>
<td>235</td>
</tr>
<tr>
<td>W_{th}/A_{div} (MJ/m²)</td>
<td>70</td>
<td>28</td>
<td>7.2</td>
<td>8.5</td>
<td>4.0</td>
<td>25</td>
</tr>
</tbody>
</table>

(a) Basis: total power = neutron + alpha + auxiliary, uniformly spread over first wall
(b) Basis: 0.67*(alpha + aux) power to divertor; 10-x SOL expansion; SOL = 0.01 m (R ind.)
(c) Basis: same divertor geometry and SOL as others: design is with a limited plasma.
**BPSX Divertor Thermal and Disruption Loadings**

- **Thermal loading:** present BPSX’s except IGNITOR(div)] have ‘raw’ (without radiative mitigation) power loadings ~25 MW/m² (ITER-EDA R&D goal/achievement)
- All BPSX’s will need radiative PFC power mitigation for ‘routine’ operation ($P_{div} \leq 10$ MW/m²)
- **Disruption loading:** all BPSX’s have ‘raw’ (without plasma shielding) divertor loadings ≥10-x PFC surface vaporization threshold. Disruption-affected PFC’s will be consumable components. Disruption avoidance (frequency reduction) is needed; will pay off!
BPSX Auxiliary Heating and Current Drive

- All BPSX’s will require, provide substantial auxiliary heating/CD
- Port power density \( (A_{\text{port}} \leq 0.05 A_{\text{wall}}) \) increases with decreasing \( R_o \)

![Graph showing the relationship between \( R_o \) and \( P_{\text{aux, installed}}(0.05A_{\text{wall}}) \)]
BPSX Auxiliary Heating and/or Current Drive

• H/CD selection and installed power mix (or possibly installable mixes) varies among BPSX candidates; constrained by H/CD technologies, plasma access and parameters and H/CD cost(s)

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<tr>
<td>$R_0$ (m)</td>
<td>8.14</td>
<td>6.20</td>
<td>1.98</td>
<td>2.15</td>
<td>1.32</td>
<td>5.00</td>
</tr>
<tr>
<td>$P_{aux} (Q = 10)$ (MW)</td>
<td>NA</td>
<td>40</td>
<td>15</td>
<td>15</td>
<td>10-20</td>
<td>40 (~FEAT)</td>
</tr>
<tr>
<td>Install’d $P_{H/CD}$ (MW)</td>
<td>100</td>
<td>70 (100)</td>
<td>45?</td>
<td>55</td>
<td>10-20?</td>
<td>70 (? , ~FEAT)</td>
</tr>
<tr>
<td>NI-NBI (tang) (MW)</td>
<td>50</td>
<td>33</td>
<td>???</td>
<td>???</td>
<td>NA</td>
<td>40 (~FEAT)</td>
</tr>
<tr>
<td>PI-NBI ($\perp$)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>???</td>
</tr>
<tr>
<td>ICRF</td>
<td>50(a)</td>
<td>20(b)</td>
<td>30</td>
<td>30</td>
<td>10-20</td>
<td>~FEAT</td>
</tr>
<tr>
<td>LHRF (MW/m²)</td>
<td>50(a)</td>
<td>0(b) (20)</td>
<td>15?</td>
<td>25</td>
<td>?</td>
<td>~FEAT</td>
</tr>
<tr>
<td>ECRF</td>
<td>50(a)</td>
<td>20(b)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>~FEAT</td>
</tr>
</tbody>
</table>

(a) maximum option; final mix in addition to NBI TBD
(b) initial selection; other options added later

• High-field/compact candidates: ICRF with LHRF option/addition; NBI or EC likely ‘not applicable’; port power densities higher for all

• Low-field: NBI with ICRF/LHRF/ECRF options/additions; lower port power densities and/or more available ports/mix options
Summary (Objective)

• BPSX feasibility and cost-effectiveness depends on three key technologies: HP-magnets, HP-PFCs, and magnet/concept-compatible H/CD

• Magnet technology is the concept driver. Options has been identified and design concepts have been correspondingly optimized to address various embodiments of the basic Q = 10 ‘BPS mission’. All proposed magnet technologies have been or likely can be shown to be ‘feasible’

• There is a correlation among TF cooling (inertial or steady-state) and peak field (10 - 22 T), device major radius and energy-confinement-normalized fusion burn duration. Smaller (larger) designs trade compactness (cost) for increasingly longer normalized burn duration. In the large device category, both SC and steady-state resistive Cu options with similar OH-limited burn duration are feasible.

• Divertor PFC power loadings and vaporization-energy normalized disruption loadings are similar and equally challenging across the whole spectrum of BPSX’s. T-retention will constrain material choices

• Choice of peak/plasma TF field determines H/CD options/mix. Compact high-B options focus on IC and LH; larger low-B options can also accommodate NI-NBI and ECRF and typically also allow a ‘cafeteria’ mix of the four possible H/CD candidates. Long-pulse/ss ‘sources’ are needed
Conclusions and Opinions

• Fusion science needs fusion technology (and vice-versa)

• Fusion technology is [close to being] ready for a BPSX

• But the challenges are great, and we must not lose sight of the fact that the scientific success of a BPSX will hinge critically on the achievement of adequate performance of all of its enabling technologies

• Conversely, given success with these enabling technologies, and then success with the ensuing plasma science, fusion will, for the first time, have a means to achieve routine production of copious amounts of fusion power, and to begin exploring the real challenges of fusion energy

“It is far better to light just one small BPSX than to curse the darkness.”