Long-term Fusion Vision, Strategy, and Role

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Presented to the NAS Committee for a Strategic Plan for US Burning Plasma Research
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Outline

Perspectives on:
1. Status of US research supporting burning plasma science

2. PPPL plans that might strengthen or accelerate US research in burning plasma science

3. Strategic elements supporting a long-term vision for US fusion energy research and promote leadership in the field

Building on the talk by R.J. Hawryluk in Austin, TX
Summary

• **Strong participation in ITER** is the best approach to develop burning plasma research, technology, and understanding
  – advance to fusion energy research

• **Innovation is required to improve fusion energy prospects in US**
  – reduce size, cost, and increase efficiency, reliability of burning plasma
  – examples: liquid metals, compact tokamaks (ST) and stellarators, HTS, advanced materials...
  – advance towards commercial fusion power

• **Both provide opportunities for US leadership**
US Burning Plasma Research is Centered on ITER

• ITER is the US facility for burning plasma research
  – Construction is well along
  – Benefits from world-wide effort and investment

• US participation in science and technology development
  – Training of US personnel in all aspects
  – Significant US leadership

• Thru ITER: joint ownership of results, IP rights, expertise

-- The science and technology from ITER will inform all magnetic-confinement approaches
Status of US Burning Plasma Research Activities

- ITER design is largely fixed, candidate Q=10 scenarios identified
  - Steady state Q=5 scenario is still being investigated

- PPPL leading US diagnostic design and development
  Critical for ITER’s research capability
  Area of US leadership & responsibility, including port design

- Develop validated approaches for high-priority topics
  - Disruptions and runaway electron beams
  - Edge instability (ELM) suppression
  - Power-exhaust width
Disruption & Runaway Electron Mitigation

• SciDAC - Center for Tokamak Transient Simulations (PPPL led collab.)
  – 3D simulation of tokamak disruptions with conducting wall
  – Disruption dynamics, shattered pellet mitigation, connect to engr.

• SciDAC - SCREAM on runaway electron modeling (PPPL led collab.)
  – New results: generation & scattering by Whistler waves
  – Appears to explain puzzling experimental observations
  – ITER implications not yet evaluated

• Deep-learning pre-disruption trigger for mitigation (Internal funding)
• Rail-gun launched pellet mitigation, for hot plasma edge (Internal funding, with U. Washington)
Edge Instability Control Window Understood

- Building on experiments at DIII-D and NSTX
- Control of KSTAR edge stability using 3-rows of perturbation coils at edge
- Vary amplitude and toroidal phase of middle rows of coils
- Quantitative validation of theoretical model for edge instabilities control

Experimental Validation of Model

IPEC Prediction of stability Space

- Locking threshold exceeded
- Suppression threshold met

access to "hidden window"

Non-resonant 3D perturbations
• Initially understood thru heuristic drift-model (PPPL)

• Prediction for ITER: < 1mm heat flux width => very high heat flux

• XGC1 (PPPL) reproduces data variation, but predicts turbulence broadens ITER. Is this correct?

• NSTX-U will test broadening & mitigation by flux expansion
2. Accelerate Preparations for Burning Plasma Science: Integrated Modeling

- High fidelity integrated model of burning plasma thru DOE Exascale Proj.
- Initial focus: core-edge tight integration, building on SciDAC models

Integration Framework

Tight / loose coupling methods

Plasma-Material Interaction
Heating & Fueling
Large-scale Instabilities
Energetic Particles

Multi-scale time advance

See talk by A. Bhattacharjee
• Reduced fidelity, faster, integrated models under development
  – For predictive modeling of proposed experiments
  – For routine analysis of data
  – Verified with high-fidelity models
  – Validated on current experiments, including DIII-D and NSTX-U

• Especially important for high pressure ($\beta$) and bootstrap-current for long-pulse experiments, due to non-linear evolution of equilibrium

• Similar efforts starting for stellarators
Example: NSTX-U is studying $\alpha$-particle instabilities applicable to ITER

NSTX-U will:
- assess confinement of fast-ions in high-performance ST regimes
- extend predictive capabilities for energetic particle dynamics in burning plasma regime

NSTX-U: Fast-ion dynamic range spanning ST and conventional A burning plasma regime

Vary beam pitch angle, pressure profile $\rightarrow$ Assess mode stability as a function of ion phase space
3. Long-term Vision toward Fusion Energy

- ITER is a physics and technology experiment.
  Will provide knowledge & experience for fusion energy research.

- As in the 2004 NRC Burning Plasma Report, ITER is not a prototype for a commercial power reactor in the US.
  - Need higher performance for size and cost.

- Next steps based on ITER are larger and likely more expensive, e.g. EU DEMO.

<table>
<thead>
<tr>
<th>EU DEMO pulsed-ind.</th>
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<tbody>
<tr>
<td>$R_0$ (m)</td>
<td>9.0</td>
</tr>
<tr>
<td>$a$ (m)</td>
<td>2.5</td>
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<tr>
<td>$B_T$ (T)</td>
<td>6.5</td>
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<tr>
<td>$I_p$ (MA)</td>
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<tr>
<td>$f_{\text{Boot}}$</td>
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<td>$\beta$</td>
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<td>$H_{98,y2}$</td>
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<tr>
<td>$P_{\text{thermal}}$</td>
<td>2.2 GW</td>
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<tr>
<td>$P_{\text{electric}}$</td>
<td>500 MW</td>
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In some countries, fusion will be developed by their government.

US: development of commercial fusion will be led by industry
   – Role of government is to enable by developing underlying science
   – Enable via public-private partnerships

Interest by start-up companies very important

Sign of success in developing scientific and technical basis for fusion
   – Assessment that gaps probably can be closed
   – Builds on world-wide experiments (all kinds) and ITER

Focus on prioritizing and resolving risks
   – At minimum scale (cost) and on a rapid timescale
Industry Requests

- Safety
- Long-term economically competitive
- Rapid construction and moderate capital cost per unit
- Licensing simplicity
- Reliability, availability, maintainability, inspectability (RAMI)
- Steady state, with load-following (quick shutdown/restart)
- Public acceptance
  - No need for wide-area evacuation

After EPRI, LIFE Adv. Committee

*Not the same approach as some of our international partners*
Implications: Innovation is Needed

• Robust, reliable operation – eliminate disruptions and “off normal events”
  – Thin first wall for T-breeding

• More efficient production of energy and use of plant
  – Higher fusion power density => higher $\beta$ and/or $B$
  – Less recirculating power

• Smaller unit size than 1 GWe, especially during development

• Robust power handling with reduced maintenance

• Simplify, probably by elimination of some sub-systems

• Need long-lived materials, to reduce maintenance (esp. divertor)
Innovation Opportunities

• Liquid-metal boundaries (see M. Jaworski)
  – High power-flux, eliminate erosion, allows low-Z wall and higher confinement
    (NSTX-U, EAST?)

• Spherical tokamak (see S. Gerhardt)
  – More compact, high $\beta$, higher magnetic field utilization, lower capital cost
    (NSTX-U & MAST-U)

• Higher efficiency current drive
  – Helicon-wave and inside launch lower-hybrid current-drive (DIII-D & KSTAR)

• Compact stellarators / 3D-Tokamaks (committee’s teleconference)
  – Eliminate disruptions, eliminate current-drive; high $\beta$, high density, high gain
    (US led, but ?)
• **HTS magnets** (see M. Greenwald, S. Prestemon)
  – Higher B, higher current density, enables compact configurations
  – May allow simpler coil design

• **Advanced materials**
  – Longer life, higher strength at high temperature
  – Reduce maintenance, increase availability, increase thermal conv. efficiency

• **Use validated simulation to guide extrapolation** (See A. Bhattacharjee)
  – Reduce risks

• **Aim at a “pilot plant”** (see J. Menard)
  – Address integration risks at modest scale
  – Then mature technology and operating experience together
  – If innovations achieve high Q, net-power production is easier than life-time testing

*PPPL is exploring many of these potential innovations with the community.*
• During ITER construction and burning plasma operation:
  – Explore and mature innovations
  – Attempt multi-innovation integration, increasing TRL
  – Validate models for simulation

• Assess combined results from ITER and innovations in modeled projections

• Go forward when projected systems are compelling, and address commercial needs
  – Pilot Plant as small as credible, to reduce risks, build confidence
Strategy without ITER: Innovate

• US out of ITER: loss of technical expertise, experience, momentum
  – Missed iteration will delay US advance to burning plasma research
  – Recover by exploring and maturing innovations; integrating

• Assess results from innovations combined with world’s experiments in modeled projections, but will not have full ITER knowledge

• Go forward when projected systems are compelling, motivate funds
  – Recover burning plasma expertise and experience
  – May use innovations to partner with other programs post-ITER
  – Pilot Plant as small as credible, to reduce risks, build confidence
• **Strong participation in ITER** is the best approach to develop burning plasma research, technology, and understanding
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