U.S. Contributions to ITER R&D and Open Scientific Opportunities

by
C.M. Greenfield

Director, United States Burning Plasma Organization

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November 15, 2011

http://burningplasma.org
The US FES community is actively engaged in preparations for a “burning plasma world”

Most US research focused on making ITER a reality and ensuring its success

• The US Burning Plasma Organization
  – Mission: Advance the scientific understanding of burning plasmas and ensure the greatest benefit from a burning plasma experiment by coordinating relevant U.S. fusion research with broad community participation

• Research in support of ITER
  – The US is engaged in a wide variety of tasks for ITER
  – Not distinguishing here by funding source – some research is funded either directly by the IO or through the USIPO
    • Announcements of new tasks are made by the USBPO
  – What is still needed…
    ...In support of constructing ITER
    ...In support of the ITER research plan
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What is the US Burning Plasma Organization?

- The USBPO serves the community as the principal coordinating body for burning plasma (BP) research activities
  - Works with ITPA, labs, USIPO, ITER, DOE, etc.
- “Full” membership is open to researchers and graduate students who are active in burning plasma science and technology research, and whose home institution lies within the U.S.
  - Currently 372 registered members representing a cross section of the community
  - All are welcome; we particularly encourage students to join
  - [http://burningplasma.org](http://burningplasma.org)
How the USBPO fits into the US participation in ITER

- The USBPO acts as the science arm of the US domestic agency
- The USBPO is integrated with the US ITPA membership
- How ITER tasks come to the community
  1. “Official” requests come through the domestic agency (IO to IPO to BPO)
  2. Other tasks may come through the ITPA (under ITER auspices) as joint experiments, etc.
  3. Self-generated BPO tasks

The US was a leader in establishing domestic frameworks for ITER support
US BPO Organization

Chuck Greenfield (Director)
Amanda Hubbard (Deputy Director)
Nermin Uckan (Assistant Director for ITER Liaison)

Council:
Mike Mauel (Chair)
Michael Bell (Vice Chair)
+10 members at large

Research Committee made up of Topical Group Leadership

- MHD, Macroscopic Plasma Physics
  Ted Strait, François Waelbroeck
- Pedestal and Divertor/SOL
  Tony Leonard, Rajesh Maingi
- Fusion Engineering Science
  Larry Baylor, Russ Doerner
- Diagnostics
  Jim Terry, David Brower
- Plasma-Wave Interactions
  Gary Taylor, David Green

- Integrated Scenarios
  John Ferron, Stefan Gerhardt
- Operations and Control
  Mike Walker, Egemen Kolemen
- Modeling and Simulation
  Dylan Brennan, David Mikkelsen
- Confinement and Transport
  John Rice, George McKee
- Energetic Particles
  Eric Fredrickson, David Pace

Recent changes:
- Summer 2011
- Fall 2011

ITPA
The BPO distinguished itself in organizing the US FES community to contribute to ITER, starting with the design review, and following through many issues (ELM control, disruptions, control issues, etc.) that have come up since.

More recently, we have not had one “big thing” like the ITER design review, but the USBPO remains active:

- BPO organized response to proposed ITER deferrals in just a few days (summer, 2011)
- Prepare and host briefings for US delegation to ITER Science and Technology Advisory Committee (STAC) prior to each STAC meeting
- USBPO organized study of opportunities for international collaboration became input for FESAC subpanel
- Dissemination of information to community (next slide)
Dissemination of information to the community has become an important function of the USBPO

- **Monthly BPO eNews newsletter (542 subscribers!)**
  - Received by all members, and additional subscribers can sign up at [http://burningplasma.org/enews_signup](http://burningplasma.org/enews_signup)

- **Community video/web seminars using ESnet H.323 and ReadyTalk**
  - Typically, about 20 sites participate
  - To date, we have used these seminars to report on ITPA activities
  - This will expand to other topics – example: more introductory topics geared toward students and early-career scientists

- **Activities at annual APS-DPP conference**
  - This town meeting
  - Research in Support of ITER contributed oral session

- **We are considering a Burning Plasma Workshop**
  - Sometime in 2012, location and exact time TBD
  - Last community BP workshop was in 2005 – a lot has changed
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<td>J.A. Snipes</td>
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<td>NO4.00002 Plasma Response and Transport Associated with RMP ELM Suppression on DIII-D</td>
<td>M.R. Wade</td>
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<td>NO4.00003 Measuring Error Fields in ITER Before Its First Plasma</td>
<td>M.G. Bell</td>
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<td>NO4.00004 Effect of 3-D fields on the divertor detachment in NSTX</td>
<td>J-W. Ahn</td>
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<td>Guy Matthews</td>
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<td>NO4.00007 Shifting the CFC/W transition point on the first ITER divertor target plates: the effect on ITER plasmas</td>
<td>R.A. Kolesnikov</td>
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<td>NO4.00008 Study of deuterium removal from co-deposited beryllium layers by flash heating</td>
<td>Jonathan Yu</td>
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<td>NO4.00009 ITER-like Discharge Development in Alcator C-Mod</td>
<td>C.E. Kessel</td>
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<td>NO4.00010 Impact of different heating and current drive mixes on steady-state scenarios for ITER</td>
<td>M. Murakami</td>
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<td>NO4.00011 I-mode for ITER?</td>
<td>D.G. Whyte</td>
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<td>NO4.00012 Shape and Current Profile Effects on Runaway Electron Confinement</td>
<td>V.A. Izzo</td>
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<td>NO4.00013 Operating ITER Robustly Without Disruptions</td>
<td>D.A. Humphreys</td>
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<td>NO4.00014 Inter-ELM power decay length for ASDEX Upgrade, JET and ITER</td>
<td>Thomas Eich</td>
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<td>NO4.00015 Plans for ECE diagnostic components for ITER</td>
<td>M.E. Austin</td>
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The USBPO functions as the US community arm of the ITPA

- 1:1 connections between USBPO and ITPA topical groups
- USBPO directorate takes lead role in identifying and recommending US ITPA members to DOE
- USBPO Director participates in annual ITPA Coordinating Committee and Joint Experiments meeting
- ITPA topical groups meet twice a year, and identify joint experiments which their representatives bring back directly to C-Mod, NSTX, and DIII-D, who in turn include these efforts in their experimental planning
- As the ITPA expands from a focus on experimental tasks to modeling tasks, there might be more of an appropriate role for the BPO in organizing participation from groups that have not traditionally been involved; for example, university based theorists with no strong connection to one of the large labs

Specific actions for the BPO may include:
- Continuing to report on ITPA activities to the BPO community at web seminars
- BPO Task Groups may be formed, when needed, to assist with ITPA issues. We have been considering two such groups, supporting the first two joint modeling tasks; these groups are on hold as these tasks have been slow in starting.
The USBPO organization parallels that of the ITPA

USBPO Topical Groups and leaders (ITPA members)

- MHD, Macroscopic Plasma Physics
  - Ted Strait, François Waelbroeck

- Pedestal and Divertor/SOL
  - Tony Leonard, Rajesh Maingi

- Energetic Particles
  - Eric Fredrickson, David Pace

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ITPA Topical Groups

- MHD
- Pedestal
- Divertor and Scrape Off Layer
- Energetic Particles
- Transport and Confinement
- Diagnostics
- Integrated Operational Scenarios

- Fusion Simulation Project
- ITER Working Group on Integrated Modeling
- US & Int’l technology communities Virtual Laboratory for Technology

C.M. Greenfield/APS-DPP/November 2011
Looking forward…

- The community as a whole has been very proactive, and very engaged in efforts to make ITER successful
- Effort is underway internally to think about “what the BPO is for”
  - Looking for areas where the USBPO can “add value”
- The BPO will be more proactive in identifying tasks where coordination of the US community may be beneficial
  - Support of new ITPA modeling tasks
  - Other scientific areas, for example disruption mitigation and avoidance
  - ITER, when it begins operation, will be a collaborative experiment on an unprecedented scale. There are many possible ways to organize the experimental program, with many examples for us to point to. I propose to start a Task Group for the US community to develop our own vision of how this could work
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ITER experimental programme

Complete Tokamak Core

First Plasma

Hydrogen/ Helium Phase Complete

Deuterium Phase Complete

ITER Commissioning and Operations

<table>
<thead>
<tr>
<th>Year</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
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<th>2029</th>
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<th>2031</th>
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<tbody>
<tr>
<td>H/ He Operation C1</td>
<td>Start Torus PumpDown</td>
<td>Assembly Phase I</td>
<td>Plasma Development, H&amp;CD Commissioning, Diagnostics, Control, DMS Commissioning</td>
<td>Short Shutdown</td>
<td>15 MA and Disruption Forces, H&amp;CD Commissioning, He H-modes, ELM Mitigation</td>
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<tr>
<td>H/ He Operation C2</td>
<td>PumpDown &amp; Int Commission</td>
<td>First Plasma</td>
<td>Short Pulse Q=10</td>
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<td>D Operation</td>
<td>Hydrogen Commissioning</td>
<td>Q=10 Long Pulse</td>
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<tr>
<td>T-Plant Commissioning</td>
<td>Tritium Introduction</td>
<td>Full Heating capability</td>
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<td>DT Operation</td>
<td>~10% T-throughput</td>
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Courtesy of D. Campbell
R&D needs

• Key elements of ITER’s R&D needs

  − Emphasis on priority physics areas where input can provide a major contribution in the effort to reach the primary mission goal as rapidly as possible

  − And on areas (not many) where R&D can still influence the design of sub-systems
R&D needs

• The key elements are primarily in the areas of
  
  − Improved physics basis for and management of thermal loads – steady state and transient (e.g. detachment control, ELM control, disruption/RE mitigation)
  
  − Characterization of the plasma-wall interface → erosion, migration, dust production, fuel-retention in the ITER material mix, transient damage, lifetime
  
  − Fuel recovery
  
  − Integrated operational scenarios (H, He, D, DT), control and diagnostics, especially in an all-metal environment
Support of ITER is broad, across the community

• In preparing this talk, I received input from a large number of people
  – THANK YOU!
  – I only have a short time, so what you’ll see here are highlights of combined efforts across the community
  – I was not able to include all of the input – if I don’t mention your work specifically, please understand

• What I’ve left out
  – Diagnostics – you just heard from Réjean
  – Integrated modeling – mixed in with individual topical areas
    • A hallmark of the US program and part of the ongoing work in all areas
  – Building pieces of ITER: outside the scope of my talk, but it is happening

• Organization of this section
  – Topical areas with explicit needs defined by the ITER Organization listed first
    • Needs identified in red called out explicitly by IO (thanks to D. Campbell)
  – Other topical areas are important for predicting ITER performance – some reflect US community priorities
Minimizing the risk of damage from disruptions:
Avoidance and mitigation

• Recent and current research
  – Rapid shutdown demonstrated on many devices with gas and pellet injection
  – Demonstration of stabilization of a locked tearing mode
  – Runaway electron (RE) confinement
    • Demonstration of RE confinement and controlled dissipation
    • Modeling shows RE confinement improves with machine size
    • Experiment and modeling show low-κ limiter plasmas retain REs more than high-κ divertors
  – Disruption simulations

• What does ITER need?
  – Extension of RE control results to ITER-like conditions
  – Improvements in experimental database for thermal loads
  – Energy deposition characteristics of unmitigated RE
  – Development and testing of reliable mitigation systems
Limiting the damaging effect of ELMs: Avoidance, suppression, or mitigation

- Recent and current research
  - Naturally ELM-free operating scenarios such as QH-mode and I-mode
  - ELM pacing via vertical jogs and pellet injection
  - RMP ELM suppression demonstrated, progress on understanding the physics basis

- What does ITER need?
  - Extend naturally ELM-free scenarios and pellet pacing to ITER conditions
  - Physics understanding of RMP ELM suppression
    - Importance or not of resonant effects, role of ergodization, physics of particle transport,…
    - Effect of 3D fields structure on divertor
    - Interaction between core pellet fueling and RMP ELM suppression
  - Improved understanding of ELM physics (scaling, footprint, etc.)
Protecting the first wall:
Thermal loads, erosion,…

• **Recent and current research**
  – 2010 FES Joint Research Target on divertor heat flux width
    • Heat flux width $\sim 1/I_P$, no $B_T$ or $P_{\text{loss}}$ dependencies (1mm projected to ITER)
  – Material erosion, redeposition and migration
    • PISCES investigating beryllium erosion, migration and fuel retention for ITER's main wall
    • DIII-D has measured high Z erosion, redeposition and migration for ITER's proposed W divertor

• **What does ITER need?**
  – Improved physics basis and scaling for parallel heat flux width
  – Better characterization of secondary divertor
  – Understanding of SOL heat and particle transport
  – Benchmarking of ITER divertor detachment scenarios at high performance
  – More information about Be wall and W divertor – JET will provide the bulk of the information here
  – Consequences of damage to W monoblocks in the ITER divertor
  – Fuel recovery techniques
  – If there is a case to be made for C, new data will come from the US
Developing and qualifying operating scenarios to fulfill ITER’s mission

• Recent and current research
  – ITER demonstration discharges in baseline, hybrid, and steady-state scenarios
  – Ramp-up and ramp-down scenarios
  – Pending ITPA modeling task on current ramp

• What does ITER need?
  – Modeling to evaluate impact on scenario access of possible deferrals:
    • Heating and current drive systems
    • Reduced CS capability
  – Transport during ramp-up and ramp-down phases
  – Power requirements for H-mode access in all operation phases
  – Entry to and exit from H-mode (H98 ~1) ⇒ edge/core evolution around L-H/H-L transition and burn simulation experiments to develop control schemes for ITER
  – Fuelling of DT plasmas with high neutral SOL opacity ⇒ ITER fuel cycle assumptions
  – Transport in low rotation, majority electron heated plasmas.
  – Plasma confinement with $P_{\text{NET}} \sim P_{\text{L-H}}$
  – H-mode properties of He plasmas ⇒ consolidation of ITER non-active operation
  – Development of hybrid and advanced scenarios for ITER ⇒ plan for future H&CD upgrades and continued study of H&CD physics issues
Robust control will be needed for safe operation of high performance fusion plasmas

- Recent and current efforts (DIII-D, NSTX, C-Mod, PPPL, ORNL, GA, LLNL)
  - Scenario control development and controllability analysis
  - ITER PCS development
  - Requirements analysis and preliminary design of control related systems
  - ITER grounding experiment on C-Mod: testing common bonding network (CBN)
- What does ITER need?
  - Help define ITER experimental operations procedures
  - Profile control for avoidance of stability boundaries
  - Development of operations tools and infrastructure
  - PCS conceptual design review planned for 2012
  - Continuous need on current devices to advance PCS design or better define diagnostic/actuator/control requirements for ITER
    - Divertor detachment control at high power in all-metal environment using extrinsic seeding and ITER-relevant sensors
    - Real time first wall heat load monitoring and control
    - Control of ICRH coupling
    - Highest possible disruption prediction success rates
    - Experiments on core-isotope mix control with dominant core pellet fuelling
    - Experiments and modeling to study controllability of disturbance transients
    - Demonstration of shared actuator control & effective/robust event handling
Understanding and control of other MHD phenomena

• Recent and current research
  – NTM physics (DIII-D/NSTX): Joint experiment shows roles of aspect ratio, curvature stabilization, and $\Delta'$ in NTM stability, improving reliability of predictions for ITER
  – Assessment of ITER’s actuators for NTM control (R. La Haye)
  – RWM physics (NSTX/DIII-D): Validation and verification of several codes and models
  – RWM stabilization (NSTX)
    • Demonstration of advanced “state space” controller to expand stable high beta operating regime (NSTX)
    • Assessment of ITER’s actuators for RWM and error field control (S. Sabbagh)
  – Demonstration of active sawtooth control H-mode plasmas, in the presence of energetic ions (DIII-D, C-Mod)
  – Error field control (C-Mod, DIII-D, NSTX): New empirical scaling for error field thresholds in torque-free H-modes

• What does ITER need?
  – Improved predictability needed for disruption avoidance and access to high beta advanced scenarios
Energetic particle confinement and stability

• Recent and current research
  – Experiments and modeling of fast ion transport from Alfvénic modes and MHD

• What does ITER need?
  – Predictive capability for non-linear fast ion driven mode stability and transport
  – More work on role of fast ions in stability of ideal/resistive MHD
  – What happens to fast ions in disruptions?
  – Long way to go on saturation, chirping, transport, avalanching, multi-mode interactions and other non-linear phenomena.
  – Affect on beta limits, potential for triggering disruptions?
Developing a predictive understanding of the H-mode pedestal

• Recent and current research: 2011 FES Joint Research Target on pedestal structure
  – EPED works for C-Mod and DIII-D, need more work for NSTX
  – Data collected to test many models

• What does ITER need?
  – Predictive understanding needed in support of operational scenario design
  – Work will continue, building on the JRT results
Assessing the potential impact of Test Blanket Modules on fusion performance

- **Recent and current research**
  - Mockup in DIII-D used to study effects on confinement, rotation, stability, energetic particles,…
- **What does ITER need?**
  - Work will probably be complete within the next few weeks – only analysis remains
Summary

• Design of most ITER systems now complete and procurement underway

• Input from physics R&D still required to complete final design of a few components/systems/diagnostics (e.g. disruption mitigation systems, glow discharge cleaning, dust and tritium diagnostics)

• Continuous R&D required to prepare for ITER operations
  − Consolidation of aggressive plan for start of ITER Operations and efficient path to DT
  − Development of ITER scenarios compatible with operational restrictions and control capabilities
  − Optimization of ELM control schemes for maximum ITER performance
  − Development of disruption avoidance and mitigation strategies
  − Refinement of material migration, fuel retention, dust extrapolations (including development of measurement techniques and first mirror strategy)
  − Develop capability for accurate predictive modelling of ITER performance
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• Research in support of ITER
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  – There will be a continuous need for participation in these and new tasks
    • Information about new opportunities/challenges will continue to come through the USBPO and ITPA representatives

http://burningplasma.org