US Burning Plasma Physics Program

- Opportunities for burning plasma R&D discovery and innovation
- US involvement in ITER R&D

James W. Van Dam
U.S. Burning Plasma Organization
Entering “burning plasma era”

• **U.S. Burning Plasma Organization is community-based**
  – Mission: *Advance scientific understanding of burning plasmas and ensure the greatest benefit from burning plasma experiments by coordinating relevant U.S. fusion research with broad community participation*

• **Broad community participation:**
  – Regular members (316 from 55 institutions)
  – Associate members (15 from 9 non-US institutions)

• **USBPO web site ([www.burningplasma.org](http://www.burningplasma.org))**
  – All presentations, white papers, progress reports are publicly available
  – *eNews* monthly newsletter: 480 subscribers (from 95 institutions)
    • “Director’s Corner” column, feature articles, ITPA meeting reports, calendar of fusion events, research highlights, community reports
USBPO role in ITER support

• **US ITER Project Office (ORNL)**
  - Main link to ITER
  - Provides hardware & technical contributions

• **USBPO**
  - Coordinates US burning plasma physics research
  - USBPO director is also the US ITER Project Office chief scientist
  - Companion to the Virtual Laboratory for Technology
Expertise of USBPO topical groups

Research Committee made up of Topical Group Leadership

- **MHD, Macroscopic Plasma Physics**
  - Ted Strait, François Waelbrock
- **Boundary**
  - Tom Rognlien, Tony Leonard
- **Fusion Engineering Science**
  - Richard Nygren, Larry Baylor
- **Diagnostics**
  - Jim Terry, David Brower
- **Plasma-Wave Interactions**
  - Steve Wukitch, Gary Taylor

- **Integrated Scenarios**
  - John Ferron, Amanda Hubbard
- **Operations and Control**
  - David Gates, Mike Walker
- **Modeling and Simulation**
  - Dylan Brennan, Dave Mikkelsen
- **Confinement and Transport**
  - John Rice, George McKee
- **Energetic Particles**
  - Donald Spong, Eric Fredrickson

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

Executive Committee members in red

ITPA

Jim Van Dam (Director)
Chuck Greenfield (Deputy Director)
Nermin Uckan (Assistant Director for ITER Liaison)

Council:
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+10 members at large
USBPO integrated with ITPA in US

Mar 2010: Plasma-Boundary Interfaces topical group was renamed “Pedestal and Divertor/SOL”
US scientists involved in ITER groups

• ITER Council and its committees:
  – Council (3), MAC (5), STAC (5), TBM Program Committee (4)

• International Tokamak Physics Activity (ITPA)
  – US scientists serve as 3 of 7 Topical Group leaders and 1 deputy leader
  – US scientist serves as chair of the ITPA Coordinating Committee

• ITER working groups
  – Integrated Modeling Expert Group (2)
  – ITER Research Plan International Working Group (5)
  – New: Plasma Control Working Group
  – Proposed: Particle and Impurity Transport Working Group
Burning plasma goals of ITER

• **Physics:**
  – Produce a plasma dominated by alpha particle heating
  – Produce significant fusion power amplification \((Q \geq 10)\) in long-pulse operation
  – Achieve steady-state operation of a tokamak \((Q = 5)\)
  – Retain the possibility of exploring “controlled ignition” \((Q \geq 30)\)

• **Technology:**
  – Demonstrate integrated operation of technologies for a fusion power plant
  – Test components required for a fusion power plant
  – Test concepts for a tritium breeding module

• **These are exciting opportunities for scientific discovery and innovation in the new burning plasma regime**
Enabling research to meet ITER goals

• **Table given in Appendix to *ITER Research Plan* document**
  – Disruption mitigation (& runaways)
  – H-mode threshold
  – ELM mitigation
  – Vertical stability control
  – Reliable high-power heating
  – Divertor performance with tungsten plasma-facing components
  – Toroidal field ripple effect on performance
  – Lack of plasma rotation
  – Tritium retention
  – Radiative divertor operation
  – Achieve densities near Greenwald limit
  – Particle control

Some examples of the many US contributions to ITER R&D to be noted on following pages

• **Present-day, non-burning experiments can help address these issues**
Mitigation of disruptions

- ITER plans to use massive impurity-gas injection (MGI)
  - DIII-D and C-Mod have shown good mitigation of heat loads, vessel currents, & resulting forces with MGI

- Other possible methods
  - Injection of “killer” pellets (shell pellets, shattered pellets)
  - Injection of liquid jets

- Some open science issues
  - Early prediction and detection
  - Better theoretical understanding
Experiments on runaway electrons (RE)

• Runaways in DIII-D
  – Rapid shutdown by Ar pellet injection; high-Z material (Ar) in core is RE seed
  – Observe 400 kA RE plateaus

• Runaways in C-Mod
  – Rapid shutdown by MGI; use LHCD prior to MGI to produce large RE seed
  – No RE plateaus observed

• Runaway position control
  – Loop voltage control → remove energy from RE beam
  – Position control → RE beam held in place & energy dissipates

• Interesting RE results in TFTR
  – RE tail formation and extended confinement [Fredrickson ITPA 2010]
Modeling of runaway electrons

- **Avalanche during disruptions can produce large runaway current**
  - Seed runaway population grows exponentially with plasma current
  - Growth can be prevented with losses: e.g., radial transport by disruption-induced MHD (from contraction of plasma current due to rapid cooling thermal quench)

- **NIMROD simulations (MHD + impurity radiation + runaway orbits)**
  - Studied shape (diverted vs limited), impurity injection method (pellet vs gas), and machine size (C-Mod, DIII-D, ITER)

- **Findings:**
  - Stochasticity extends to separatrix in smaller machines, but not ITER
  - MHD perturbation amplitude $\sim R^{-1}$
  - Runaway confinement time $\sim R^3$
  - Duration of MHD fluctuations $\sim R$
  - Not likely to de-confine runaways in ITER

- **IAEA FEC theory summary**
  - Need for more work on disruptions, L-H transition, MHD-turbulence interaction, edge-core integration

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Izzo (IAEA 2010)
Access to high confinement (H-mode)

• **Issue**
  – ITER plans to operate in “high confinement” H-mode with edge transport barrier. Desirable to achieve this in pre-nuclear operation phase (H or He) to test ELM physics and divertor hardware. What is the L-mode to H-mode power threshold?

• **Experimental results**
  – ITPA joint expts in C-Mod, DIII-D, and NSTX (+ EU tokamaks)
  – L-H power threshold higher in He than D (C-Mod 20-80%, DIII-D 30-50%). Still higher in H.
  – Smaller difference (up to 20%) between He, D found in NSTX

• **Direction**
  – Given variation in L-H thresholds, prudent for ITER to plan for higher power thresholds for H-modes in pre-nuclear phase
  – ITPA will further study physics mechanisms and H-mode, ELM regimes in helium
Understand and control ELMs

- **Issue**
  - Edge Localized Modes (ELMs) are periodic rapid relaxations of edge temperature & density.
  - Such heat pulses in ITER could damage wall and divertor.

- **Methods to mitigate/avoid ELMs planned for ITER**
  - Edge ergodization by resonant magnetic perturbation coils
    - Why RMPs increase transport?
  - Pellet pace-making
    - 14 → 25 Hz pellets; ELM energy fraction reduced ~4X

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Greenfield (IAEA 2010)

Baylor (IAEA 2010)
In-vessel coils for ITER

• IVC design team has been led by PPPL
  – IVC system comprised of two subsystems:
    • Vertical stability coils (2 PF coils above and below the midplane): orange
    • ELM control coils (27 RMP coils on wall of vacuum vessel): green & blue
  – Successful Preliminary Design Review held week of Oct 18

• Each IVC wound from 50 m conductor
  – Conductor consists of 59-mm OD SS jacket, magnesium oxide insulating layer, and inner Cu conductor (water cooled)
Regimes without large ELMs

- **Issue**
  - Regimes with continuous, benign relaxation mechanism found in US (and other) tokamaks: extrapolate to ITER?

- **C-Mod:**
  - Enhanced $D_\alpha$ H-mode, without ELMs
  - “I-mode” with energy barrier but no particle barrier [Whyte (IAEA 2010)]

- **NSTX:**
  - Small ELM regimes
  - ELMs suppressed with Li-coated divertor & walls
  - Controlled ELMs triggered with pulsed 3D fields and vertical jogs [Maingi (PRL 09)]

- **DIII-D:**
  - Quiescent H-mode (no ELMs): recently extended to near-zero NBI torque, with nonzero counter-directed NTV torque [Garofalo (IAEA 2010)]
Alternate ELM control methods

- **USBPO brain-storming session on “alternate” (non-RMP) ELM control methods**
  - Held April 9 by videoconference; 35 participants; 13 presentations, followed by extensive discussion and critique
  - Written summary presented at ITPA Pedestal TG Meeting (April 14-16)

- **Ideas presented can be categorized as:**
  1. Driving scrape-off layer/edge plasma currents and flows
  2. Variations of the MHD equilibrium (triangularity, magnetic shear)
  3. ELM pacing (vertical jogs, pellet injection, plasma guns)
  4. Alternate confinement modes (QH-mode, I-mode)

- **Decision at recent ITER Council mtg to include ELM control coils**
Recent US visit by ITER Director-General

- New ITER DG Osamu Motojima & Acting Head of Dept for ITER Project Gary Johnson visited US ITER Project Office and USDOE the week of Sept. 14

Pellet injection laboratory at ORNL

With USIPO staff members
TBM simulation experiments for ITER

• Issue
  – ITER plans to test 6 tritium-breeding Test Blanket Modules (@ ~ 1 ton ferromagnetic steel)
  – Will create localized, non-axisymmetric error fields larger than toroidal field ripple (0.4%)
  – Potential effects on H-mode confinement, rotation, ELMs, alpha particle loss, etc.

• TBM simulation experiments on DIII-D
  – Fabricated and installed coil to mock up error field of 2 TBMs in one port
  – Expts conducted Nov 2009 by international team, with 12 scientists from ITER & 5 Members
  – Results help set limits on allowable magnetic field ripple [Schaffer (IAEA & APS 2010)]

• Theory simulations of ITER alpha loss due to TBMs

DIII-D coil

ITER with 3 TBMs and TF ripple alpha loss patterns

Ripple contours – outer surface
Recent US Physics Tasks for ITER

• **ITER Physics Task Agreements (2009-2010)**
  – Generally, 12-month Tasks (some for 4, 16, 18 and recently 24 months)
  – Notices circulated by USBPO; proposals sent to USIPO; decisions by ITER Org
  – Task Agreements awarded so far:
    • 7 to US, plus 2 to US+EU and 1 to US+IN+JA
    • 6 to EU, 2 to JA, and 1 jointly to RF+JA

**Two examples**

ITER error fields with IPEC code: EFC and RMP coil requirements to avoid locking against worst error field [Park, Boozer, Menard]

ITER scenario simulations with different heating and current drive sources during ramp-up [Kessel, Jardin, Kritz]
ITER International Summer School

- 4th ITER International Summer School held in US this year
  - May 31-June 4, University of Texas
  - Sponsors: National Instruments, USBPO, French Embassy in US, ....

- Theme: MHD and Plasma Control in Magnetic Fusion Devices

- Participation
  - 133 participants from 17 countries and 48 institutions

  "Fusion is the future, and the future is in your hands."

- 20 lecturers from 7 countries & ITER

- 4 computer lab sessions
ITER Postdoctorals

• Monaco funding 5 ITER Postdocs @ 2 yrs
  – 2008: Max Jewell (Wisconsin): PhD thesis on superconductivity; currently researching the qualification of ITER Nb3Sn superconductors

• Monaco Fusion Energy Days conference (23-25 Nov 2010)
  – Day 1: Global energy context and Member energy policies
  – Day 2: ITER Baseline and industrial aspects
  – Day 3: ITER-IAEA Technical Mtg on of ITER Materials and Technologies
  – One student was invited from each ITER Member (travel expenses paid)
    • Ryan Hunt (UCLA–Nucl Eng) attended from the US
ITER papers at IAEA FEC

- 9 ITER-category oral papers
  - 2 presented by US lead authors

- 55 ITER-category poster papers
  - 8 presented by US lead authors
Recognition of ITER-relevant US work

2009 Prize to Steve Sabbagh (Columbia): Record beta values in NSTX and analysis of RWM stability

2010 Prize to John Rice (MIT): Universal scaling from experimental results for intrinsic rotation

- Awarded annually (since 2006) to recognize outstanding work published in *Nuclear Fusion*
  - Selected by Board of Editors, based on citation record and scientific impact
  - Past awardees: Tim Luce (06), Clemente Angioni (07), Todd Evans (08)
  - Four of the five winners so far have been US scientists (representing the three major experimental facilities)
Burning plasma at APS-DPP Meeting

• Town Meeting on ITER Status (Tues, Nov 9, 7:30-9:30 p.m.)
  – Gyung-Su Lee (MAC): *New ITER Baseline and Risk Assessment*
  – Alberto Loarte (ITER): *Scientific Status of ITER*
  – Brad Nelson (USIPO): *US Engineering and Technology R&D for ITER*
  – Jim Van Dam (USBPO): *US Scientific Contributions to ITER R&D*
  – Discussion session: moderator Mike Mauel (USBPO Council)

• Two contributed ITER oral sessions (@ 11 ten-minute talks)
  – *ITER-1 Session* (Thursday, Nov 11, 2:00–4:12 p.m.)
  – *ITER-II Session* (Friday, Nov 12, 9:30 a.m.–12:30 p.m.)

• Town Meeting talks are posted on USBPO web site
Summary

• Burning plasma studies on ITER open up new regime of plasma physics of an exothermic medium

• **US program contributing strongly to ITER R&D needs**
  – Involves experiments, diagnostics, theory, and simulations
  – Coordinated efforts of program facilities, university/lab/industry scientists, and organizations (USIPO, ITPA, USBPO, VLT, etc.)

• **Many exciting research issues in burning plasma science for ITER operation and next-generation experiments (DEMO)**
  – Near-term urgent R&D needs
  – Medium-term R&D issues leading up to First Plasma and DT Operation
  – Longer-term R&D for ITER long-pulse campaign and FNSF/DEMO