International Workshop on Cutting-Edge Plasma Physics

5 - 16 July 2010

Yearning for Burning:
Plasma Physics and Fusion Energy Science

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Yearning for Burning: Plasma Physics and Fusion Energy Science

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U.S. Burning Plasma Organization, USDOE

- Scientific challenge
- International planning
- Site selection
- Clear mission
- Organization
- Cost
- Research coordination

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“Pope” of fusion physics: M. Rosenbluth

- **Early participant at ICTP Trieste**
  - Many original contributions to fusion and plasma physics
  - Before Texas: Professor at Institute for Advanced Study (Princeton)
  - Founder of IFS (U. Texas)
  - After Texas: Chief Scientist, ITER Organization (EDA phase)

- **From Yearning to Burning (2000)**
  - “The ‘yearn to burn’ is well motivated. Most of us came into the fusion program with the dream of fusion energy. The dream persists.”
Plasmas are everywhere

Plasmas - the 4th state of matter

- Magnetic fusion reactor
- Inertial confinement fusion

- Solar core
- Solar corona
- Lightning
- Solar wind
- Neon sign
- Interstellar space
- Fluorescent light
- Aurora
- Flames
- Solids, liquids, and gases too cool and dense for classical plasmas to exist

Number Density (Charged Particles / m^3)

Temperature (°C)

10^8
10^6
10^4
10^2
10^15
10^9
10^10
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ITER
National Ignition Facility

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Wide applicability of plasma physics

Makes use of: mechanics, E&M, stat mech, relativity, math physics, numerical analysis, quantum mech, solid state, AMO, ...

- Low-temperature plasmas
- Magnetosphere, solar, & astrophysical plasmas
- Geophysical fluid dynamics
- Laser interactions
- Meta-materials, photonics
- High-performance simulation techniques
- Nonlinear dynamics
- Applied mathematics
- Nuclear engineering
- Fusion energy sciences
ITER will demonstrate scientific and technical feasibility of fusion

• ITER ("the way") is essential next step in development of fusion
  – Today: 10 MW, 1 sec, gain = 1
  – ITER: 500 MW, >400 sec, gain ≥ 10

• The world’s biggest fusion energy research project ("burning plasma")
  – 15 MA plasma current, 5.3 T magnetic field, 6.2 m major radius, 2.0 m plasma minor radius, 840 m³ plasma volume, superconducting
  – €10B to construct, then operate for 20 years ("first plasma" in 2019)

• An international collaboration
  – 7 partners, 50% of world’s population
  – EU the host Member; sited in France
  – Unprecedented example of big-science international physics collaboration
ITER is a “tokamak” = confines doughnut-shape plasma with helical magnetic fields.
ITER:
A big international project motivated by a big international scientific challenge
Producing a self-sustaining fusion-heated plasma is a grand challenge

1928  Fusion reactions explain energy radiated by stars [Atkinson & Houtermans]

1932  Fusion reactions discovered in laboratory [Oliphant]

1935  Fusion reactors understood as Coulomb barrier tunneling [Gamow]

1939  Theory of fusion power cycle for stars [Bethe–Nobel Prize 1967]

1950  US approval to develop hydrogen bomb “Super” [Teller]

1951-52  Invention of the tokamak [Tamm and Sakharov]

1950’s  US Project Sherwood (classified) on controlled thermonuclear fusion

1958  2nd UN Atoms for Peace Conference (Geneva): declassification of magnetic fusion research

1968  Russian tokamak results with high temperature presented at IAEA Fusion Energy Conference

Since then: Worldwide explosion in tokamak research, culminating in experiments on TFTR (US), JET (EU), JT-60U (Japan), etc.
What is a “burning plasma”?

- “Burning” plasma = ions undergo thermonuclear fusion reactions, which supply self-heating to the plasma

- The energy output $E_{\text{out}}$ is huge (global implications):
  \[ E_{\text{out}} = 450 \times E_{\text{in}} \]

- The required energy input $E_{\text{in}}$ is also large:
  \[ 20 \text{ keV} = 200 \text{ million °K} \]

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D-T fusion

- The “easiest” fusion reaction uses hydrogen isotopes: deuterium (D) and tritium (T)
  - D is plentiful in sea water
  - T can be generated from lithium
  - He is harmless (even useful)

\[ _1^1D + _1^3T \rightarrow _2^4He + _0^1n \]

Energy/Fusion: \( \varepsilon_f = 17.6 \text{ MeV} \)
Fusion gain $Q$

\[ \frac{dW}{dt} \rightarrow 0 \Rightarrow P_\alpha + P_{\text{heat}} = \frac{W}{\tau_E} \]

Define fusion energy gain, 
\[ Q \equiv \frac{P_{\text{fusion}}}{P_{\text{heat}}} = \frac{5P_\alpha}{P_{\text{heat}}} \]

Define $\alpha$-heating fraction, 
\[ f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{\text{heat}}} = \frac{Q}{Q+5} \]

**Breakeven**  
$Q = 1$  \quad  $f_\alpha = 17\%$

**Burning plasma regime**  
$Q = 5$  \quad  $f_\alpha = 50\%$

$Q = 10$ (ITER)  \quad  $f_\alpha = 60\%$

$Q = 20$  \quad  $f_\alpha = 80\%$

$Q = \infty$  \quad  $f_\alpha = 100\%$
Initial D-T experiments

- **Joint European Torus (JET)**
  - “Preliminary Tritium Experiment” (1991): \( P_{DT} > 1 \) MW
  - Subsequently: \( Q=0.9 \) (transient breakeven), \( Q=0.2 \) (long pulse)
  - 16 MW fusion power

- **Tokamak Fusion Test Reactor (TFTR)**
  - Dec 1993 to Apr 1997: 1000 discharges with 50/50 D-T fuel
  - \( P_{DT} = 10.7 \) MW, \( Q=0.2 \) (long pulse)
  - Results:
    - Favorable isotope scaling
    - Self-heating by alpha particles
    - Alpha-driven instability
    - Tritium and helium “ash” transport
    - Tritium retention in walls and dust
    - Safe tritium handling (1M curies)
Status of magnetic fusion

- **Lawson Diagram:**
  - Achieved $T_i$ required for fusion, but need $\sim 10 \times n \tau_E$
  - Achieved $n \tau_E \approx \frac{1}{2}$ required for fusion, but need $\sim 10 \times T_i$

- **No experiment has yet entered the burning plasma regime**
  - Such an experiment is the next logical step forward on the path to fusion energy
  - The world fusion program is technically and scientifically ready to proceed now with a burning plasma experiment

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International planning for ITER
History of the ITER project

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<th>Year</th>
<th>P.-H. Rebut</th>
<th>R. Aymar</th>
<th>K. Ikeda</th>
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**Conceptual Design Activities**

- **ITER 98**
  - Original ITER
    - \( R = 8.1 \) m
    - \( Pf = 1500 \) MW
    - \( Q = \infty \)
  - SWG(Task#1, #2)

- **ITER 01**
  - Compact ITER
    - \( R = 6.2 \) m
    - \( Pf = 500 \) MW
    - \( Q \geq 10 \)

**Negotiations**

- **US-USSR Summit**
  - Gorbachev & Reagan

**Agreement Signed**

- ITER Agreement signed

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International developments

  - Four partners: Euratom, Japan, US, and USSR
  - Sponsored by IAEA
  - Produced conceptual design for 600 MW(th) device and 860-page accompanying report
- **ITER Conceptual Design Activity (CDA): 1987-1990**
- **ITER Engineering Design Activity (EDA): 1992-98**
  - Four partners: EU, JA, RF, and US
  - Work sites in San Diego, Naka (JA), and Garching (EU)
  - US withdrew from ITER Project in 1998
  - San Diego site shut in 1999; personnel transferred to Naka Site
- **ITER Fusion Ignition Advanced Tokamak (FIAT)**
  - CTA and ITA phases 1999-2003
  - US re-entered ITER in 2003
- **ITER Implementing Agreement signed 21 Nov 2006**
  - Seven partners: CN, EU (host), IN, JA, KO, RF, US
- **ITER Organization became legal entity in Oct 2007**
ITER: an international project

ITER Implementing Agreement signed 21 Nov 2006 by EU, Japan, Russia, USA, Korea, China, and India
- Signing ceremony hosted by French President Chirac (Elysée Palace)
- Dr. Raymond Orbach (Undersecretary for Energy) signed for the US
Deciding on the site for ITER
Site bids: 4 ➔ 2 ➔ 1

- Japan - Rokkasho
- Spain - Vandellòs
- Canada - Clarington
- France - Cadarache
Time line on decision of ITER host

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
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<tr>
<td>2001 May</td>
<td>Bid submitted by Canada (Toronto).</td>
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<td>2001</td>
<td>Bids submitted by France, Spain, and Japan.</td>
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<td>2003 Nov</td>
<td>EU support concentrated on France; Canada withdrew.</td>
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<td>Deadlocked vote by ITER partners between Japan and EU.</td>
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<td>2004 June</td>
<td>Japan increased its bid by $1B; EU matched it.</td>
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<td>2004 Dec</td>
<td>EU hinted it would build ITER by itself if no 6-party agreement.</td>
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<td>2004-2005</td>
<td>EU and Japan negotiated privately.</td>
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<td>Japan agreed to withdraw its bid, in return for a concessions package: 20% of the research positions while providing only 10% of the expenses; EU to subsidize half the cost for certain new fusion facilities in Japan (“Broader Approach”); EU support for for Japanese candidate as ITER director-general</td>
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<td>2005 June</td>
<td>Unanimous vote by ITER partners to accept EU bid</td>
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<tr>
<td>2006 May</td>
<td>Initialing of ITER Agreement. Transmittal to Congress for 120-day review required by Energy Policy Act of 2005</td>
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<tr>
<td>2006 Nov</td>
<td>Signing of ITER Agreement in Paris</td>
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Proposed site in Japan

- Rokkasho-mura
  - Aomori Prefecture (northern Japan)
  - Mutsu-Ogawara Development Area, close to existing nuclear fuel cycle facilities
  - Under JA-EU Broader Approach, will house IFERC
EU-Japan Broader Approach

IFERC in Rokkasho

IFERC Project
- DEMO Design, R&D
- Remote Experiment
- Computer Simulation

DEMO Plant

ITER

IFMIF/EVEDA

Satellite Tokamak

In Naka

JT-60SA

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Broader Approach site

BA Site in Rokkasho - Present Status -

- Administration & Research Building
- Computer Simulation & Remote Experimentation Building
- DEMO R&D Building
- IFMIF/EVEDA Accelerator Building
- Power Station 30 MVA

September 4, 2009
ITER’s final location

- To be built in Cadarache, France (EU)
  - Near Marseille (in Provence-Alpes-Cote d’Azur region)
  - First plasma operation in 2019, D-T operation by 2027
ITER, currently under construction in the South of France, aims to demonstrate that fusion is an energy source of the future.

Future layout

Present (Mar 2010)
A clear mission for the ITER project
Attachment 6  Achievements of ITER
Physics R&D

Integrate experimental results of tokamaks from all over the world to establish physics basis for plasma performance of ITER.
ITER design goals

• **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
New features in a burning plasma

- **Dominant self-heating (exothermic)**
  - “Autonomous” system: reduced capability to control current, pressure, and rotation profiles by means of external RF power and neutral beams

- **High performance requirements**
  - Sustained, simultaneous achievement of high temperature and density, good macroscopic stability, good confinement of plasma energy
  - Robust plasma-wall facing components and diagnostics that can withstand high heat and neutron wall loadings

- **Long pulse length**
  - BP experiment should have pulse length long compared to the current redistribution time ($\tau_{\text{pulse}} \gg \tau_{\text{CR}}$) to investigate resistively equilibrated current and pressure profiles in the presence of strong alpha heating

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More new features in burning plasma

- **Strong coupling**
  - Transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly due to the fusion self-heating

- **Size scaling**
  - Much larger volume than present expts

- **Large population of super-thermal alpha particles**
  - Different behavior from thermal ions
  - Affect stability, confinement, heating, etc.

- **Nuclear environment**
  - Gamma/neutron radiation, tritium retention, dust, tritium breeding

*Cross sections of present EU D-shape tokamaks compared to the cross section of ITER*
ITER physics R&D needs

• Issues listed by ITER as urgent
  – Mitigation of disruptions and runaway electrons
  – Access to high confinement (H-mode)
  – ELM control
  – Plasma-facing component material
  – Plasma scenarios
  – Integrated modeling
  – Tritium breeding

• ITER science challenges to be discussed in lecture #2
Organization can be as much of a challenge as science and technology
ITER top leadership

• **Director-General Kaname Ikeda**
  - Deputy Minister for Science and Technology, Japan
  - Executive Director, National Space Development Agency, Japan
  - Ambassador to Croatia

• **Principal Deputy Director-General & Project Construction Leader Dr. Norbert Holtkamp**
  - Research Group Head, S-Band Linear Collider, DESY, Germany
  - Division Director, Spallation Neutron Source, ORNL, USA
ITER staffing projection

Staff Ramp Up IO Team

At present:
450 staff
+ 350 extra
= 800 on site
Other organizational challenges

- **Communication**
  - International video-conferencing techniques
  - Integrated document management

- **Intellectual property rights to data**
  - Who owns ITER’s photons?

- **Management styles, cultural differences, flag waving,**...

- **Multi-national safety regulations**

- **Import/export regulations**

- **Outreach for public visibility**
  - Web site, newsletter, movies, brochures, PR and educational materials,...
  - YouTube movies on ITER

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US ITER Project Office booth at 2008 AAAS Meeting
Determining the cost and how to pay for ITER
ITER construction cost-sharing

A
Systems suited only to Host Party industry
- Buildings
- Machine assembly
- System installation
- Piping, wiring, etc.
- Assembly/installation labour

B
Residue of systems, jointly funded, purchased by ITER Project Team

C
“Contributions in Kind”
Major systems provided directly by Members

Overall cost sharing:
EU 5/11, Others 6 Members 1/11 each, Overall contingency up to 10% of total.

Overall costs shared according to agreed evaluation of A+B+C
US in-kind hardware contributions

**ORNL**
- 7 Central Solenoid Coils
- 8% of Toroidal Field Conductor
- Pellet Injector
- 20% First Wall/Shield
- 75% Cooling for Divertor, Vacuum Vessel, ...

**PPPL**
- Steady State Power Components

**ORNL**
- 15% of Port-based Diagnostics
- 100% Ion Cyclotron Transmission Lines
- 100% Electron Cyclotron Transmission Lines

**ORNL**
- Roughing Pumps, Standard Vacuum Components

**SRNL**
- Tokamak Exhaust Processing System

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U.S. Burning Plasma Organization:
To coordinate, facilitate, and promote burning plasma science in the US research program
Preparing for “burning plasma era”

• U.S. Burning Plasma Organization (USBPO) was created in 2005 as a community-based entity
  – Mission: Advance the 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)
  – Council (12 members)
  – Research Committee (20) = leaders/deputy leaders of 10 Topical Groups
  – Directorate (5)
  – International Tokamak Physics Activity (ITPA): 49 Topical Group members + 3 Coordinating Committee members from the US
Broad Expertise of USBPO Topical Groups

Research Committee made up of Leaders and Deputies of 10 Topical Groups

- MHD, Macroscopic Plasma Physics
- Plasma-Boundary Interfaces
- Fusion Engineering Science
- Diagnostics
- Plasma-Wave Interactions
- Integrated Scenarios
- Operations and Control
- Modeling and Simulation
- Confinement and Transport
- Energetic Particles

Council:
- Amanda Hubbard (Chair)
- Mike Zarnstorff (Vice Chair)
- +10 members at large + ITER Chief Techologist

Executive Committee members in red

MEMBERS (currently 331)

Membership in USBPO is open to any fusion researcher who joins one or more topical groups.

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USBPO integrated with ITPA in US

March 2010: Plasma-Boundary Interfaces topical group was renamed “Pedestal and Divertor/SOL.”
USBPO communication role

• **USBPO web site** ([www.burningplasma.org](http://www.burningplasma.org))
  - All presentations, white papers, progress reports are publicly available
  - Limited-access pages for US STAC, Council, Topical Groups, ...

• **USBPO eNews**
  - 480 subscribers (from 95 institutions); Jan 2010 eNews was 40th issue
  - “Director’s Corner” column, feature articles, ITPA meeting reports, calendar of fusion events, research highlights

• **IT capabilities**
  - Bi-weekly videoconference Research Comm and Executive Comm meetings; quarterly video conference Council meetings
  - Technical briefings for US STAC members
  - Remote seminars: e.g., “LH Capabilities for ITER” (Feb 2009)
4th ITER International Summer School

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

• Theme: MHD and Plasma Control in Magnetic Fusion Devices
  – Lectures (20), poster sessions (2), hands-on computer lab sessions (4)

• Participation
  – 133 participants from 17 countries and 48 institutions
References


• **Burning Plasma: Bringing a Star to Earth** (National Academy of Science, 2004)

• **Progress in the ITER Physics Basis**, Nuclear Fusion (2007)