Progress Toward Burning Plasmas

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The next frontier

- **Understanding the behavior of burning plasmas** is the challenge faced by fusion research today, as a necessary step towards the ultimate demonstration of fusion as a source of energy
  - ITER, to be operated as an international project, will push research efforts into this new regime of burning plasma science

- **Outline of this talk:**
  1. Distinguishing features of “burning plasmas”
  2. Scientific issues for burning plasmas
  3. Grand challenge of burning plasmas
FEATURES OF BURNING PLASMAS
My focus: magnetic confinement
What is a “burning” plasma?

- In a 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:
  \[ 20 \text{ keV} = 200 \text{ million } ^{\circ}\text{K} \]
Thermonuclear fusion reactions

- “Burning” plasma = dominantly **self-heated** by fusion products (e.g., alpha particles) from thermonuclear reactions in the plasma.

- Reactions of interest for laboratory fusion power:

\[
D^+ + D^+ \rightarrow 3\text{He}^{++} (0.82 \text{ MeV}) + n^0 (2.5 \text{ MeV})
\]

\[
\rightarrow T^+ (1 \text{ MeV}) + p^+ (3 \text{ MeV})
\]

\[
D^+ + 3\text{He}^{++} \rightarrow 4\text{He}^{++} (3.6 \text{ MeV}) + p^+ (14.7 \text{ MeV})
\]

- **Plasma**

\[
D^+ + T^+ \rightarrow 4\text{He}^{++} (3.5 \text{ MeV}) + n^0 (14.1 \text{ MeV})
\]

- **Solid**

\[
\text{Li}^6 + n \rightarrow 4\text{He} (2.1 \text{ MeV}) + T (2.7 \text{ MeV})
\]
D-T fusion

- The “easiest” fusion reaction uses hydrogen isotopes: deuterium (D) & tritium (T):

\[ ^1D^2 + ^1T^3 \rightarrow ^2He^4 + ^0n^1 \]

(3.5 MeV) (14.1 MeV)

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

Nuclear cross sections
Better definition of “burning”

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

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

Define \( \alpha \)-heating fraction, \( f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{\text{heat}}} = \frac{Q}{Q+5} \)

<table>
<thead>
<tr>
<th>Breakeven</th>
<th>( Q = 1 )</th>
<th>( f_\alpha = 17% )</th>
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<tbody>
<tr>
<td>Burning plasma regime</td>
<td>( Q = 5 )</td>
<td>( f_\alpha = 50% )</td>
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<tr>
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<td>( Q = 10 ) (ITER)</td>
<td>( f_\alpha = 60% )</td>
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<td>( Q = 20 )</td>
<td>( f_\alpha = 80% )</td>
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<tr>
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<td>( Q = \infty ) (ignition)</td>
<td>( f_\alpha = 100% )</td>
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SCIENCE ISSUES FOR BURNING PLASMAS
Many of the same challenges as today

- **Confinement**
  - H mode, internal transport barriers, electron thermal transport, momentum transport, …

- **MHD macrostability**
  - Resistive wall modes, neoclassical tearing modes, pressure-driven instabilities, ELMs, disruptions, sawteeth, fast-ion instabilities, …

- **Power and particle control**
  - Impurities, plasma-facing component materials, divertor design, …

- **Long-pulse operation**
  - Heating and current drive, profile control, hybrid scenarios, …

- **Diagnostics**
  - High time/space resolution, velocity distribution measurements, …

- **Plasma control**
  - Start-up, real-time feedback and control, …
New burning plasma challenges

Uniquely BP issues
- **Alpha particles**
  - Large population of supra-thermal ions
- **Self-heating**
  - “Autonomous” system (self-organized profiles)
  - Thermal stability

Reactor-scale BP issues
- **Scaling with size & B field**
- **High performance**
  - Operational limits, heat flux on PFCs
- **Nuclear environment**
  - Radiation, tritium retention, dust, tritium breeding

Integration of nonlinearly coupled elements
Alpha particle characteristics

- **Plasma ions and electrons:**
  - $T_{i,e} \sim 10\text{-}20$ keV
  - “Frozen-in” behavior to lowest order (MHD description)
  - Thermodynamic equilibrium (Maxwellian distribution)

- **Other energetic particles:**
  - Supra-thermal ions from neutral beam injection and ICRH wave heating
    - Can simulate $\alpha$ particle effects without reactivity
    - Also present in burning plasmas with auxiliary heating
  - Run-away electrons associated with disruptions
  - Also of interest to space and astrophysical plasmas (e.g., proton ring in Earth’s magnetosphere)

- **Alpha particles:**
  - High energy: $T_{\alpha,\text{birth}}^{\text{DT}} = 3.5$ MeV
  - Not “frozen” to B-field lines (require kinetic description)
  - Low density ($n_\alpha < n_{i,e}$), but comparable pressure ($p_\alpha \sim p_{i,e}$)
  - Non-Maxwellian “slowing down” distribution
  - Centrally peaked profile
    \[
    \left| \nabla p_\alpha / p_\alpha \right|^{-1} \leq a / 2
    \]
\(\alpha\)-particle driven instabilities

- **D-T fusion** \(\alpha\)-particles (3.5 MeV) can resonate with shear Alfvén waves: \(v_\alpha \geq v_A\).
- One of these instabilities is the Toroidal Alfvén Eigenmode (TAE)
  - Analogy to band-gaps in solid-state crystals ("fiberglass wave guide")
- Zoology of various *AE instabilities
- Could cause loss of \(\alpha\)'s
  - Reduce self-heating; increase wall thermal loading
  - Much progress on characterizing and ameliorating such instabilities (and even utilizing for internal plasma diagnostic)

*Heidbrink, Phys. Pl. 9 (2002) 2113
Determining the size of a burning plasma

- Large size determined by:
  - Need for sufficient confinement
  - High power density (materials)
  - Radiation shielding of SC magnets

Scaling prediction for energy confinement time $\tau_{th}$

Confinement scaling for fusion triple product $nT\tau_E$
Size scaling in ITER

• Significant difference
  – Current tokamaks have normalized Larmor radius $\rho_i^* = \rho_i/a = 0.5–1.5 \times 10^{-2}$, whereas burning plasmas (ITER) have $\rho_i^* = 1–2 \times 10^{-3}$

• New issues for very small $\rho^*$
  – Internal transport barrier formation
  – Hybrid regimes
  – Confinement scaling
  – Neoclassical tearing mode threshold
  – Alfvén eigenmode stable spectrum

Cross sections of existing D-shaped tokamaks compared to the cross section of ITER
Tritium supply

- Large consumption of tritium during fusion
  - 55.8 kg per 1000 MW of fusion power per year

- Production and cost
  - CANDU reactors: 27 kg over 40 years, $30M/kg currently
  - Other fission reactors: 2-3 kg/yr @$84-130M/kg

- Tritium breeding for self-sufficiency
  - World supply of tritium is sufficient for 20 years of ITER operation (will need ~17.5 kg, leaving ~5 kg)
  - Tritium breeding technology, to be tested on ITER, will be required for DEMO and reactors
Test Blanket Modules

- **TBMs**
  - Sometime during ITER research program, Test Blanket Modules will be installed to investigate breeding of tritium (fusion nuclear technology)
  - ITER has 3 ports for blanket testing, and 2 TBMs can be installed in each port
  - Issues: Will the neutron fluence be high enough? Will TBM ferritic content lead to large magnetic field ripple?

- **Other methods**
  - Fission reactors, accelerator-based point neutron sources, non-neutron test stands
GRAND CHALLENGE OF BURNING PLASMAS
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 reactions understood as Coulomb barrier tunneling [Gamow]
1939  Theory of fusion power cycle for stars [Bethe – Nobel Prize 1967]
1950  Use of fusion for military objectives
1950’s Invention of tokamak, helical system, mirror, etc.
1958  2nd UN Atoms for Peace Conference (Geneva): magnetic fusion research was de-classified
1968  Russian results on high-temperature tokamak plasmas presented at IAEA Fusion Energy Conference

Since then: Huge progress worldwide in toroidal plasma research, leading to the attainment of fusion-grade plasma parameters
Initial D-T experiments

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

- **Tokamak Fusion Test Reactor (TFTR)**
  - Dec 1993–Apr 1997: 1,000 discharges with 50/50 D-T fuel
  - $P_{DT} = 10.7$ MW, $Q = 0.2$ (long pulse)
Initial tritium results

- D-T experiments on TFTR measured:
  - Favorable isotope scaling
  - $\alpha$-particle heating
  - $\alpha$-driven instability
  - Tritium and helium “ash” transport
  - Tritium retention in walls and dust
  - Safe tritium handling (1M curies)
Progress in magnetic fusion

• Approaching ignition:
  – High density path: Achieved $T_i$ required for fusion, but need $\sim 10 \times n\tau_E$
  – High temperature path: Achieved $n\tau_E \approx 1/2$ required for fusion, but need $\sim 10 \times T_i$

• The world fusion program is technically and scientifically ready to proceed now with a burning plasma experiment
  – Such an experiment is the next logical step forward on the path to fusion energy
  – ITER is the next step forward
ITER will demonstrate scientific and technological feasibility of fusion

• ITER (“the way” in Latin) is essential next step in development of fusion
  – **Existing facilities**: 10 MW(th) for a few sec with gain ≤1
  – **ITER**: 500 MW(th) for >400 sec & gain ≥10

• The world’s biggest fusion energy research project (“burning plasma”)
  – Tokamak, 6.2 m major radius, 2.0 m plasma minor radius, 840 m$^3$ plasma volume
  – Superconducting coils: 15 MA plasma current, 5.3 T toroidal magnetic field
  – 10B € to build, then operate for 20 years (first plasma in 2018)

• An international collaboration
  – 7 international partners, representing 50% of world’s population
  – EU the host partner, with the site in France
ITER design goals

Physics:

• Produce a plasma dominated by $\alpha$-particle heating
• Produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
• Aim to 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
# History of the ITER project

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1988</td>
<td>Conceptual Design Activities开始</td>
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<tr>
<td>1989</td>
<td>Engineering Design Activities开始</td>
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<td>1990</td>
<td>Extended EDA</td>
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<td>1991</td>
<td>CTA ITA</td>
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<td>1992</td>
<td>COEDA</td>
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<td>1993</td>
<td>US-USSR Summit</td>
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<td>1994</td>
<td>(ITER 98) Original ITER: R = 8.1 m, Pf = 1500 MW, Q = \infty</td>
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<td>1995</td>
<td>(ITER 01) Compact ITER: R = 6.2 m, Pf = 500 MW, Q ≥ 10</td>
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<td>1996</td>
<td>ITER Agreement signed</td>
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<td>2008</td>
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*Note: The table above summarizes the key events and milestones in the history of the ITER project.*
International progress toward ITER

  - Four partners: Euratom, Japan, US, and USSR; sponsored by IAEA
  - Produced conceptual design for 600 MW(th) device and 860-page accompanying report

- ITER phases
    - Four partners: EU, JA, RF, and US
    - Work sites in San Diego (US), Naka (JA), and Garching (EU)
  - ITER Fusion Ignition Advanced Tokamak (FIAT)
    - CTA and ITA phases 1999-2003
    - US withdrew from ITER Project in 1998 and re-entered in 2003

- ITER Organization establishment
  - 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 site bids: 4 —> 2 —> 1

Japan - Rokkasho

Spain - Vandellós

Canada - Clarington

France - Cadarache
Final location for ITER

- To be built in Cadarache, France
  - Near Marseille (in Provence-Alpes-Cote d’Azur region)
  - First plasma operation in 2018, D-T operation in 2024
Funding arrangements for ITER

• Construction cost
  – 5/11ths from European Union as ITER host
  – 1/11th in-kind contribution from each of 6 other partners (CN, IN, JA, KO, RF, US)
  – India joined as 7th ITER partner in 2005; hence there is now a 10% contingency

• Kazakhstan interest in full Membership
  – May 2007 expression of intention
  – April 2008 Kazakhstan delegation visited ITER

• Partnership Arrangement with Monaco
  – Signed 16 Jan 2008 by ITER DG Ikeda and Monaco Minister of State (in back: Prince Albert II)
  – 5.5 M€ over 10 years to fund 5 ITER postdoctoral fellowships and host international conferences
Organizational structure

- Possible organizational template for future global science projects (e.g., ILC)
ITER top leadership

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

Principal Deputy Director-General & Project Construction Leader
Norbert Holtkamp
– Research Group Head, S-Band Linear Collider, DESY
– Division Director, Spallation Neutron Source, ORNL
Coordinating US burning plasma effort

- DOE Office of Fusion Energy Sciences
  - SC Assoc Director (acting)
  - Research Division
  - ITER and International Division

- US ITER Project Office
  - N. Sauthoff, Director
    - US ITER Chief Scientist
      - (USBPO Director)
    - US ITER Chief Technologist
      - (VLT Director)

- USBPO Council
  - (13 members)
    - Director
    - Deputy Director
    - Ass’t Director for ITER Liaison
    - Research Committee

- USBPO Directorate
  - Director
  - Topical Group Management
    - MHD Stability
    - Confinement/Transport
    - Boundary
    - Wave Interactions
    - Energetic Particles
    - Integrated Scenarios
    - Fusion Engineering
    - Modeling/Simulation
    - Operation/Control
    - Diagnostics

ITPA: Virtual Laboratory for Technology
Extra-scientific challenges

- Communication
  - Modern 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
  - Public relations and educational materials, movies, photos, brochures, web site, posters, …
  - YouTube clip of ITER wave heating

US ITER Project Office booth at 2008 American Association for Advancement of Science Meeting
ITER construction is underway

CEA Cadarache

ITER Tokamak Building
Final layout (artist’s conception)
Progress toward burning plasmas

• Since the 2nd UN Conference on Peaceful Uses of Atomic Energy (1958), the worldwide fusion energy effort has made great scientific and technical progress
  – Facilitated by emphasis on international collaborations
  – Motivated by awareness of the potential benefit of fusion energy for all humanity

• The next frontier for fusion science is the study of burning plasmas
  – The ITER facility—an unprecedented model for big-science international collaboration—will advance the development of fusion into this exciting new regime
ITER movie

References


- *Progress in the ITER Physics Basis*, Nuclear Fusion, vol. 47, no. 6, pp. S1-S413 (June 2007)

- ITER Organization: [www.iter.org](http://www.iter.org)

- US ITER Project Office: [www.usiter.org](http://www.usiter.org)

- US Burning Plasma Organization: [www.burningplasma.org](http://www.burningplasma.org)