Burning Plasma Science: The Challenge and Opportunity

Gerald A. Navratil

Columbia University

2004 AAAS Annual Meeting
Symposium on Burning Plasma Physics
Seattle, WA
12-16 February 2004
OUTLINE

• BASIC REQUIREMENTS FOR A BURNING PLASMA
• FRONTIER SCIENCE ISSUES: WHAT DO WE WANT TO KNOW?
• $Q \approx 1$ RESULTS: AT THE THRESHOLD
• $Q \approx 5$: $\alpha$-EFFECTS ON TAE STABILITY
• $Q \approx 10$: STRONG NON-LINEAR COUPLING
• $Q \geq 20$: BURN CONTROL & IGNITION
• TAKING THE “NEXT STEP”: ITER
DT FUSION

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

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

Fusion Reaction Rate, \( R \) for a Maxwellian

\[
R = \int \int \sigma (\mathbf{v}') \mathbf{v}' f_D (\mathbf{v}_D) f_T (\mathbf{v}_T) d^3 \mathbf{v}_D d^3 \mathbf{v}_T
\]

where \( \mathbf{v}' = \mathbf{v}_D - \mathbf{v}_T \)

\[
R = n_D n_T \langle \sigma v \rangle
\]
FUSION “SELF-HEATING” POWER BALANCE

FUSION POWER DENSITY: \[ p_f = R\varepsilon_f = \frac{1}{4} n^2\langle \sigma v \rangle \varepsilon_f \] for \( n_D = n_T = \frac{1}{2} n \)

TOTAL THERMAL ENERGY IN FUSION FUEL, \[ W = \int \left\{ \frac{3}{2} nT_i + \frac{3}{2} nT_e \right\} d^3x = 3nTV \]

DEFINE “ENERGY CONFINEMENT TIME”, \( \tau_E \equiv \frac{W}{P_{\text{loss}}} \)

ENERGY BALANCE

\[ \frac{dW}{dT} = \left\{ \frac{1}{4} n^2\langle \sigma v \rangle \varepsilon_\alpha V + P_{\text{heat}} \right\} - \frac{W}{\tau_E} \]

- \( \alpha \)-heating power
- Additional heating input
- Loss rate
STEADY-STATE FUSION POWER BALANCE

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

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>Scientific Breakeven</th>
<th>( Q )</th>
<th>( f_\alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burning Plasma Regime</td>
<td>( Q = 1 )</td>
<td>17%</td>
</tr>
<tr>
<td>( Q = 5 )</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>( Q = 10 )</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>( Q = 20 )</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>( Q = \infty )</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>
PARAMETERIZATION OF Q VERSUS nTτ_E OR Pτ_E

Recast power balance: $P_\alpha + P_{\text{heat}} = \frac{W}{\tau_E}$

$nT\tau_E = p\tau_E = \frac{12T^2}{\langle \sigma v \rangle \varepsilon_\alpha (1 + \frac{5}{Q})}$

Useful since in 10–20 keV range where $p\tau_E$ is minimum for given $Q$

$\langle \sigma v \rangle \propto T^2$

and $p$ is limited by MHD stability in magnetically confined plasmas

Ignition $Q = \infty \Rightarrow p\tau_E > \frac{12T^2}{\langle \sigma v \rangle \varepsilon_\alpha}$
Toroidal Magnetic Confinement of Plasma
• Tokamak experiments have approached $Q \sim 1$ regime.
BURNING PLASMA IS A NEW REGIME: FUNDAMENTALLY DIFFERENT PHYSICS

NEW ELEMENTS IN A BURNING PLASMAS:

- SELF-HEATED BY FUSION ALPHAS
- SIGNIFICANT ISOTROPIC ENERGETIC POPULATION OF 3.5 MeV ALPHAS
- LARGER DEVICE SCALE SIZE

PLASMA IS NOW AN EXOTHERMIC MEDIUM & HIGHLY NON-LINEAR

COMBUSTION SCIENCE ≠ LOCALLY HEATED GAS DYNAMICS

FISSION REACTOR FUEL PHYSICS ≠ RESISTIVELY HEATED FUEL BUNDLES

⇒ OPPORTUNITY FOR UNEXPECTED DISCOVERY IS VERY HIGH⇐
IMPORTANT PHYSICAL PROPERTIES OF $\alpha$-HEATING

- FOR $Q \sim 10$: $nT\tau_E \sim 2 \times 10^{21} \text{ m}^{-3} \text{ keV s}$ for $T \sim 10 \text{ keV}$
  + WHEN NON-IDEAL EFFECTS (PROFILES, HE ACCUMULATION, IMPURITIES) SOMEWHAT LARGER VALUE $\sim 3 \times 10^{21} \text{ m}^{-3} \text{ keV s}$
- FOR TOKAMAK "TYPICAL" PARAMETERS AT $Q \sim 10$
  $n \sim 2 \times 10^{20} \text{ m}^{-3}$ $T \sim 10 \text{ keV}$ $\tau_E \sim 1.5 \text{ s}$
- BASIC PARAMETERS OF DT PLASMA AND $\alpha$
  $V_{Ti} \sim 6 \times 10^5 \text{ m/s}$ $V_\alpha \sim 1.3 \times 10^7 \text{ m/s}$ $V_{Te} \sim 6 \times 10^7 \text{ m/s}$
  Note at $B \sim 5 \text{ T}$: $V_{Alfvén} \sim 5 \times 10^6 \text{ m/s} < V_\alpha$
- CAN IMMEDIATELY DEDUCE:
  1) $\alpha$-PARTICLES MAY HAVE STRONG RESONANT INTERACTION WITH ALFVEN WAVES.
  2) $T_i \sim T_e$ since $V_\alpha >> V_{Ti}$ AND $m_\alpha >> m_e$ THE $\alpha$-PARTICLES SLOW PREDOMINANTLY ON ELECTRONS.
$Q \leq 1$ Results from TFTR and JET

At the Burning Plasma Threshold
# DT EXPERIMENTS ON TFTR AND JET

<table>
<thead>
<tr>
<th></th>
<th>TFTR</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Transient Q</td>
<td>0.27</td>
<td>0.61</td>
</tr>
<tr>
<td>( \alpha ) Confinement</td>
<td>Classical</td>
<td>Classical</td>
</tr>
<tr>
<td>( \alpha ) Slowing Down</td>
<td>Classical</td>
<td>Classical</td>
</tr>
<tr>
<td>( \alpha ) Heating Observed</td>
<td>Yes, but weak</td>
<td>Yes</td>
</tr>
</tbody>
</table>
JET DT EXPERIMENTS SHOW α-HEATING OF CENTRAL ELECTRONS

- D/T ratio varied & maximum $\Delta T_e \sim 3$ keV at 60% T
## DT Experiments on TFTR and JET

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TFTR</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Transient Q</td>
<td>0.27</td>
<td>0.61</td>
</tr>
<tr>
<td>$\alpha$ Confinement</td>
<td>Classical</td>
<td>Classical</td>
</tr>
<tr>
<td>$\alpha$ Slowing Down</td>
<td>Classical</td>
<td>Classical</td>
</tr>
<tr>
<td>$\alpha$ Heating Observed</td>
<td>Yes, but weak</td>
<td>Yes</td>
</tr>
<tr>
<td>$\alpha$ Driven Alfvén Waves in Highest $P_\alpha$ Plasmas</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$T_i$</td>
<td>36 keV</td>
<td>28 keV</td>
</tr>
<tr>
<td>$T_e$</td>
<td>13 keV</td>
<td>14 keV</td>
</tr>
<tr>
<td>$n$</td>
<td>$1 \times 10^{20}$ m$^{-3}$</td>
<td>$0.4 \times 10^{20}$ m$^{-3}$</td>
</tr>
<tr>
<td>$nT\tau$</td>
<td>$4.3 \times 10^{20}$ m$^{-3}$ keVs</td>
<td>$8.3 \times 10^{20}$ m$^{-3}$ keVs</td>
</tr>
<tr>
<td>$f_\alpha$</td>
<td>5%</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>[$\sim$2MW]</td>
<td>[$\sim$3 MW]</td>
</tr>
</tbody>
</table>
Q ~ 5: α-EFFECTS ON TAE STABILITY
Three dimensionless parameters will characterize the physics of alpha-particle-driven instabilities:

- Alfven Mach Number: \( \frac{V_\alpha}{V_A(0)} \)
- Number of Alpha Lamor Radii (inverse): \( \frac{\rho_\alpha}{a} \)
- Maximum Alpha Pressure Gradient (scaled): \( \text{Max } R \nabla \beta_\alpha \)

<table>
<thead>
<tr>
<th>Fusion Power Plant (e.g. ARIES-RS/AT)</th>
<th>ITER</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{V_\alpha}{V_A(0)} )</td>
<td>≈ 2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>( \frac{\rho_\alpha}{a} )</td>
<td>≈ 0.02</td>
<td>0.016</td>
</tr>
<tr>
<td>Max R ( \nabla \beta_\alpha )</td>
<td>0.03–0.15</td>
<td>0.05</td>
</tr>
</tbody>
</table>
New Alpha Effects Expected on Scale of Burning Plasma

• Present experiments show alpha transport due to only a few global modes.

• Smaller value of $\frac{\rho_\alpha}{<a>}$ in a Burning Plasma should lead to a “sea” of resonantly overlapping unstable modes & possible large alpha transport.

• Reliable simulations not possible with our ‘standard model’...needs experimental information in new regime.
Q ~ 10: Strong Non-Linear Coupling & Steady-State High $\square$ Operation
**Burning Plasma System is Highly Non-Linear...**

**Basic Coupling of Fusion Alpha Heating:**

![Diagram of fusion reactor coupling](image)
Burning Plasma System is Highly Non-Linear...

Add Alpha Driven TAE Modes:

- Ion Temperature $T_i$
- Fusion Reaction Rate: $P_\alpha$
- Te
- $\tau_{ei}$
- $\tau_{\alpha e}$
- TAE Modes
- $R \nabla \beta_\alpha$
Burning Plasma System is highly non-linear...

Add complex physics of Alpha Driven TAE modes:

No longer predictive in scale size of burning plasma regime
**MAJOR DISCOVERY OF THE 1990’s:**
**SHEARED FLOW CAUSES TRANSPORT SUPPRESSION**

**Gyrokinetic Theory**
- Simulations show turbulent eddies disrupted by strongly sheared plasma flow

**Experiment**
- Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Thermonuclear Heating
ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Auxiliary Heating

External

Internal

Thermonuclear Heating

Profiles:
\( p, T, n, v_\phi \)

Anomalous & Neoclassical heat, particle and \( v_\phi \) diffusion

\( p, T, n, v_\phi \)

\( P_{\text{tot}} \)

Fast, Blue heat and \( v_\phi \) transport cycle
**ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS**

- **Auxiliary Heating**
- **Auxiliary Angular Momentum**

**Profiles:**
- $p, T, n, v_{\phi}$

**Thermonuclear Heating**
- $p, T, n$
- $p, T, n, v_{\phi}$

**Anomalous & Neoclassical**
- Neoclassical heat, particle and $v_{\phi}$ diffusion

**Turbulent and Neoclassical transport coefficients** $\chi$
- Poloidal field dependence
- Velocity shear stabilization

**Fast, Blue heat and $v_{\phi}$ transport cycle**

**Temperature profiles couple magnetic and heat diffusion loops**
Q > 20:

Burn Control & Ignition Transient Phenomena
TRANSIENT BURN PHENOMENA WHEN $Q \geq 20$

Time dependent energy balance:  \[
\frac{d}{dt} [3 \, nT] = \frac{1}{4} \, n^2 \varepsilon_\alpha \, V \, <\sigma v> + P_{\text{heat}} - \frac{3 \, nT}{\tau_E (n,T)}
\]

- At fixed $n$ and high $Q$ system can be thermally unstable

Solve for $P_{\text{heat}}$ in steady-state:  \[
P_{\text{heat}} = \frac{3 \, nT}{\tau_E (n,T)} - \frac{1}{4} \, n^2 \varepsilon_\alpha \, V \, <\sigma v>
\]

![Plot showing n vs T with an ignition region annotated]
TRANSIENT BURN PHENOMENA WHEN $Q \geq 20$

Time dependent energy balance:

$$\frac{d}{dt} [3 \, nT] = \frac{1}{4} \, n^2 \varepsilon \alpha \cdot V \cdot \langle \sigma v \rangle + P_{\text{heat}} - \frac{3 \, nT}{\tau_E (n,T)}$$

- At fixed $n$ and high $Q$ system can be thermally unstable

Solve for $P_{\text{heat}}$ in steady-state:

$$P_{\text{heat}} = \frac{3 \, nT}{\tau_E (n,T)} - \frac{1}{4} \, n^2 \varepsilon \alpha \cdot V \cdot \langle \sigma v \rangle$$
TRANSIENT BURN PHENOMENA WHEN Q ≥ 20

Time dependent energy balance: \[ \frac{d}{dt} [3 nT] = \frac{1}{4} n^2 \varepsilon_\alpha V <\sigma v> + P_{\text{heat}} - \frac{3 nT}{\tau_E (n,T)} \]

- At fixed \( n \) and high \( Q \) system can be thermally unstable

Solve for \( P_{\text{heat}} \) in steady-state: \[ P_{\text{heat}} = \frac{3 nT}{\tau_E (n,T)} - \frac{1}{4} n^2 \varepsilon_\alpha V <\sigma v> \]
Taking the Next Step in Burning Plasmas: ITER
Major Advances & Discoveries of 90’s Lay Foundation for Next Step Burning Plasma Experiments

- **Burning Plasma Experiment**

  - **MHD**
    - q-profile control and measurement
    - steady-state, bootstrap equilibria
    - active mode control of kink & tearing
  
  - **Transport & Turbulence**
    - shear-flow turbulence suppression
    - gyro-kinetic theory based models
    - extensive data-base models on transport using dimensionless scaling
  
  - **Wave/Particle Interactions**
    - alpha heating in DT found to be classical for $Q \leq 1$
    - “standard model” of Alfvén Eigenmodes
    - LHCD & ECCD used for near SS & mode control
  
  - **Plasma Wall Interactions**
    - detached divertor demonstrated
    - large scale models developed
    - high heat-flux metallic technology developed
Burning Plasma Physics - The Next Frontier

Three Options Examined by US at Snowmass 2002

FESAC & Nat'l Academy endorsed US try to proceed with ITER

FIRE
US Based International Modular Strategy

ITER
JA, EU or CA Based International Partnership

IGNITOR
Italian Based International Collaboration
“I am pleased to announce today, that President Bush has decided that the United States will join the international negotiations on ITER.”

Secretary of Energy Spencer Abraham  
30 January 2003

...we know that this experiment is a crucial element in the path forward to satisfying global energy demand.

President Bush has faith in American science. And he knows the huge energy challenges for the United States and for the world that fusion science seeks to tackle.

And let me tell you, he is not one for taking baby steps when leaps are called for.

By the time our young children reach middle age, fusion may begin to deliver energy independence and energy abundance to all nations rich and poor. Fusion is a promise for the future we must not ignore.

But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program ... at the universities and at our other labs.
The ITER Design: Poloidal Elevation

ITER parameters in Q = 10 reference inductive scenario

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Plasma current</td>
<td>15 MA</td>
</tr>
<tr>
<td>Toroidal magnetic field</td>
<td>5.3T</td>
</tr>
<tr>
<td>Elongation / triangularity</td>
<td>1.85 / 0.49</td>
</tr>
<tr>
<td>Fusion power amplification</td>
<td>≥ 10</td>
</tr>
<tr>
<td>Fusion power</td>
<td>~400 MW</td>
</tr>
<tr>
<td>Plasma burn duration</td>
<td>~400 s</td>
</tr>
</tbody>
</table>
ITER Design Goals

Physics:

• ITER is designed to 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
ITER Plans & Status

AIMS AT CONSTRUCTION START IN 2006 – FIRST PLASMA 2015:

SIX PARTNERS NEGOTIATING TO CONSTRUCT

CHINA       JAPAN
EU          RUSSIA
KOREA       USA

INTERNATIONAL NEGOTIATIONS MUST CHOOSE SITE

JAPAN       OFFERED SITE IN ROKKASHO
EU           OFFERED SITE IN CADARACHE

⇒ CONSENSUS DECISION REQUIRED: SPRING 2004? ⇐
CONCLUDING COMMENTS & DISCUSSION

• Burning Plasma Studies open a new regime of plasma physics of an exothermic medium:
  IS THE GRAND CHALLENGE PROBLEM IN OUR FIELD.

• Dramatic progress in 1990’s has established a sound basis for exploration of the Burning Plasma regime.

• US working with International Community to build first magnetically confined burning plasma: ITER

• High level of excitement in the plasma physics community as we (hopefully) soon start construction of long anticipated Burning Plasma Experiment.