INTRODUCTION TO BURNING PLASMA PHYSICS

Gerald A. Navratil
*Columbia University*

American Physical Society - Division of Plasma Physics
2001 Annual Meeting, Long Beach, CA
1 November 2001
THANKS TO MANY PEOPLE WHO HELPED...

BILL DORLAND
BOB GROSS
RICH HAWRYLUK
ALI MAHDAVI
DALE MEADE
RIP PERKINS
TOM PETRIE
PETE POLITZER
STEW PRAGER
JIM STRACHAN
JIM VAN DAM
...AND OTHERS

+ UFA BURNING PLASMA WORKSHOP - AUSTIN 2000
+ UFA BURNING PLASMA WORKSHOP - SAN DIEGO 2001
+ FESAC BURNING PLASMA PANEL & REPORT
Producing and understanding a sustained fusion heated plasma is a grand challenge problem for our field.
### DT Fusion

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

\[ (3.5 \text{ MeV}) \quad (14.1 \text{ MeV}) \]

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

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

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

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

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

FUSION POWER DENSITY: \[ p_f = R \varepsilon_f = \frac{1}{4} n^2 <\sigma v> \varepsilon_f \] 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

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

\( \alpha \)-heating power

Additional heating input

loss rate
STEADY-STATE FUSION POWER BALANCE

\[ \frac{dW}{dt} \rightarrow 0 \implies P_\alpha + P_{\text{heat}} = \frac{W}{\tau_E}, \quad P_{\text{heat}} = \text{ext. supplied heating} \]

Define fusion energy gain,

\[ Q \equiv \frac{P_{\text{fusion}}}{P_{\text{heat}}} = \frac{5 P_\alpha}{P_{\text{heat}}} \]

Define \( \alpha \)-heating fraction,

\[ f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{\text{heat}}} = \frac{Q}{Q+5} \]

Scientific Breakeven

\[ \begin{array}{ccc}
Q &=& 1 \\
\quad f_\alpha &=& 17\% \\
\end{array} \]

Burning Plasma Regime

\[ \begin{array}{ccc}
Q &=& 5 \\
\quad f_\alpha &=& 50\% \\
Q &=& 10 \\
\quad f_\alpha &=& 60\% \\
Q &=& 20 \\
\quad f_\alpha &=& 80\% \\
Q &=& \infty \\
\quad f_\alpha &=& 100\% \\
\end{array} \]
PARAMETERIZATION OF Q VERSUS nT\tau_E OR P\tau_E

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

\[ nT\tau_E = p\tau_E = \frac{12T^2}{<\sigma v> \varepsilon_\alpha (1 + \frac{5}{Q})} \]

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

\( <\sigma v> \propto T^2 \)

and \( p \) is limited by MHD stability in magnetically confined plasmas

Ignition \( Q = \infty \Rightarrow p\tau_E > \frac{12T^2}{<\sigma v> \varepsilon_\alpha} \)
• Basic Requirements for a Burning Plasma
• Frontier Science Issues: What do we want to know?
• $Q\sim 1$ Results: At the Threshold
• $Q\sim 5$: $\alpha$-effects on TAE Stability
• $Q\sim 10$: Strong Non-Linear Coupling
• $Q\geq 20$: Burn Control & Ignition
• Taking the “Next Step”
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
There are two types of burning plasma issues...

**Getting There & Staying There:**

- **Density, Temperature, and** $\tau_E$ **required for** $Q \geq 5$
- **MHD Stability at required pressure for** $Q \geq 5$
- **Plasma equilibrium sustainment** ($\tau > \tau_{\text{skin}}$)
- **Power, fueling, & reaction product control**

**New Science Phenomena to be Explored**

- **$Q \geq 5$:** Alpha effects on stability & turbulence
- **$Q \geq 10$:** Strong, non-linear coupling between alphas, pressure driven current, turbulent transport, MHD stability, & boundary-plasma
- **$Q \geq 20$:** Stability, control, and propagation of the fusion burn and fusion ignition transient phenomena
**IMPORTANT PHYSICAL PROPERTIES OF α-HEATING**

- **FOR Q ~ 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 ~ 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 α**
  $v_{Ti} \sim 6 \times 10^5 \text{ m/s}$ $v_\alpha \sim 1.3 \times 10^7 \text{ m/s}$ $v_{Te} \sim 6 \times 10^7 \text{ m/s}$
  - Note at $B \sim 5 \text{ T}$: $v_{\text{Alfvén}} \sim 5 \times 10^6 \text{ m/s} < v_\alpha$

- **CAN IMMEDIATELY DEDUCE:**
  1) $\alpha$-PARTICLES MAY HAVE STRONG RESONANT INTERACTION WITH ALFVÉN WAVES.
  2) $T_i \sim T_e$ since $v_\alpha \gg v_{Ti}$ AND $m_\alpha \gg m_e$ THE $\alpha$-PARTICLES SLOW PREDOMINANTLY ON ELECTRONS.
How Close Are We to Burning Plasma Regime?

- Tokamak experiments have approached $Q \sim 1$ regime.
Q \leq 1 \text{ Results from TFTR and JET}

At the Burning Plasma Threshold
### 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 Alfven 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>$1 \times 10^{20} \text{ m}^{-3}$</td>
<td>$0.4 \times 10^{20} \text{ m}^{-3}$</td>
</tr>
<tr>
<td>$nT\tau$</td>
<td>$4.3 \times 10^{20} \text{ m}^{-3} \text{ keVs}$</td>
<td>$8.3 \times 10^{20} \text{ m}^{-3} \text{ keVs}$</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>
FUSION ALPHAS ARE CONFINED AND SLOW DOWN CLASSICALLY IN TFTR

- JET reports same conclusion using detailed modeling of $\alpha$-heating power balance.
JET DT EXPERIMENTS SHOW α-HEATING OF CENTRAL ELECTRONS

- D/T ratio varied & maximum $\Delta T_e \sim 3$ keV at 60% $T$
NO $\alpha$-driven Alfvénic Instabilities seen in TFTR and JET in highest fusion power DT plasmas

- AE stable due to strong damping by beam and plasma ions in NBI heated hot ion mode plasmas.
- AE modes were observed in equilibria with low shear and higher central $q$ just after NBI turned off.
Q \sim 5: \alpha\text{-effects on TAE stability}
### ALPHA PARTICLE EFFECTS: KEY DIMENSIONLESS PARAMETERS

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>Range of Interest (e.g. ARIES-RS/AT)</th>
<th>ITER-FEAT (reference)</th>
<th>FIRE (reference)</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{V_\alpha}{V_A(0)} )</td>
<td>( \approx 2.0 )</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>( \frac{\rho_\alpha}{a} )</td>
<td>( \approx 0.02 )</td>
<td>0.016</td>
<td>0.028</td>
</tr>
<tr>
<td>Max ( R \nabla \beta_\alpha )</td>
<td>( 0.03–0.15^* )</td>
<td>0.05</td>
<td>0.035</td>
</tr>
</tbody>
</table>
GEOMETRIC EFFECTS ON ALFVEN WAVES

- Uniform Slab \( \omega = k_{\parallel}v_A \)

- 1D cylinder \( \omega = k_{\parallel}v_A(r) \)

- Continuous spectrum, shear Alfvén resonance
GEOMETRIC EFFECTS ON ALFVEN WAVES

Add 2D toroidal effects:

- Periodic boundary conditions for toroidal mode number, n, and poloidal mode number, m
- m and m+1 are coupled and a “gap” is opened in the otherwise continuous spectrum
**GEOMETRIC EFFECTS ON ALFVEN WAVES**

Add elliptical cross-section effects:

- \( m \) and \( m+2 \) are now coupled and an elliptical “gap” is opened in the continuous spectrum.

Add triangularity cross-section effects:

- \( m \) and \( m+3 \) are now coupled and a triangularity “gap” is opened in the continuous spectrum.
GEOMETRIC EFFECTS ON ALFVEN WAVES

Discrete Modes Appear in Gaps in the Continuum:

- Alfvén wave continuum is strongly damped.
- TAE gap-modes are less damped: free energy from $\nabla p_\alpha$ tapped by wave/particle resonance drive from $\alpha$-particles may destabilize these modes.
BASIC ALFVÉN EIGENMODE PHYSICS EXTENDS TO RANGE OF TOROIDAL CONFIGURATIONS

Tokamak:  

Spherical Torus:

Stellarator:

- Details of spectra differ but underlying physics and modeling tools are common.
New Alpha Effects Expected on Scale of Burning Plasma

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

- Smaller value of $\rho_{\alpha}/\langle a \rangle$ in a Burning Plasma may lead to a “sea” of resonantly overlapping unstable modes & possible large alpha transport.

- Reliable simulations not possible...needs experimental information in new regime.

This and other alpha physics will be discussed in more detail in next talk by Bill Heidbrink...
Q \sim 10: Strong Non-Linear Coupling
BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

BASIC COUPLING OF FUSION ALPHA HEATING:
Burning Plasma System is Highly Non-Linear...

Add Alpha Driven TAE Modes:
Burning Plasma System is Highly Non-Linear...

Add Complex Physics of Alpha Driven TAE Modes:

- Ion Temperature $T_i$
- $\tau_{ei}$
- $T_e$
- $\alpha$-losses $\tau_{\alpha e}$
- Fusion Reaction Rate: $P_\alpha$

No Longer Predictive inScale
Size of Burning Plasma Regime

- Geometry Effects
- Resonant Exitation
- Damping Nonlinear Saturation
MAJOR DISCOVERY OF THE 1990’s:
ION TURBULENCE CAN BE ELIMINATED

- Color contour map of fluctuation intensity as function of time from FIR scattering data
  - Higher frequencies correspond to core, low to edge

- Total ion thermal diffusivity at time of peak performance
  - $H = 4.5$ $W = 4.2$ MJ
  - $\beta = 6.7\%$ $\beta_N = 4.0$

NCS H–mode edge

\[ \chi_i^{\text{tot}} = Q_i/n_i \nabla T_i \]
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
Combination of Turbulence Suppression & Bootstrap Current Leads to Steady-State Advanced Tokamak

- Data from JT-60U shows sustained transport barrier and 100% non-inductive current drive
PLASMA BOUNDARY PHYSICS: HEAT REMOVAL & CONFINEMENT

EDGE PEDESTAL STRONGLY COUPLED TO CONFINEMENT:
INTERNAL $\nabla T$ LIMITED BY MICROTURBULENCE SO EDGE $T$
CONTROLS CENTRAL FUSION REACTIVITY:

\[ P_{\text{FUSION}} \sim [T_{\text{EDGE}}]^7 \]

ENERGETIC IONS MODIFY $\Delta$:
COUPLING TO $\alpha$-PARTICLES.

HEAT REMOVAL SOLUTIONS TREND TO HIGH EDGE DENSITY —
BUT BOOTSTRAP CURRENT SUSTAINED STEADY-STATE
PLASMAS TREND TOWARDS LOWER EDGE DENSITY:
COMPATABILITY AN OPEN ISSUE IN BURNING PLASMA REGIME
## Pedestal Temperature Requirements for Q=10

<table>
<thead>
<tr>
<th>Device</th>
<th>Flat ne*</th>
<th>Peaked ne*</th>
<th>Peaked ne w/ reversed q</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGNITOR‡</td>
<td>5.1</td>
<td>5.0</td>
<td>5.1 keV</td>
</tr>
<tr>
<td>FIRE</td>
<td>4.1</td>
<td>4.0</td>
<td>3.4 keV</td>
</tr>
<tr>
<td>ITER-FEAT‡‡</td>
<td>5.8</td>
<td>5.6</td>
<td>5.4 keV</td>
</tr>
</tbody>
</table>

* flat density cases have monotonic safety factor profile

* $n_{eo} / n_{ped} = 1.5$ with $n_{ped}$ held fixed from flat density case

* 10 MW auxiliary heating

* 11.4 MW auxiliary heating

* 50 MW auxiliary heating
ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Transformer source of poloidal flux

Auxiliary Current Drive

Auxiliary Heating

Auxiliary Angular Momentum

$V_{\text{loop}}$

$j_{\text{cd}}$

Bootstrap Current

Neoclassical poloidal flux diffusion

$B'_{\theta}$

Conductivity profile

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

Temperature profiles couple magnetic and heat diffusion loops

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

Profiles:

$p, T, n, v_{\phi}$

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

$\frac{dp}{dr}$

Conductivity profile

$\sigma$

T

$\chi$'s

$P_{\text{tot}}$

$p, T, n, v_{\phi}$
Q > 20:

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

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

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

Solve for \( P_{\text{heat}} \) in steady-state: \[
P_{\text{heat}} = \frac{3 \, nT}{\tau_E (n, T)} - \frac{1}{4} n^2 \varepsilon_\alpha V \langle \sigma v \rangle
\]
TRANSIENT BURN PHENOMENA WHEN Q ≥ 20

Time dependent energy balance: \[
\frac{d}{dt} [3 \, nT] = \frac{1}{4} \, n^2 \, \varepsilon_\alpha \, V \, \langle \sigma v \rangle + P_{\text{heat}} \, \frac{3 \, nT}{\tau_E (n,T)}
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\frac{d}{dt} [3 \, nT] = \frac{1}{4} \, n^2 \varepsilon_\alpha \langle \sigma v \rangle + P_{\text{heat}} \frac{3 \, nT}{\tau_E (n,T)}
\]
- At fixed \( n \) and high \( Q \) system can be thermally unstable

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

\[
P_{\text{heat}} = \frac{3 \, nT}{\tau_E (n,T)} - \frac{1}{4} \, n^2 \varepsilon_\alpha \langle \sigma v \rangle
\]
MORE “REALISTIC” POWER BALANCE

• ITER POPCON Power Balance Analysis

• Additional limits on density, pressure, & power thresholds constrain operating space.
FUSION “BURN” PROPAGATION AT HIGH Q

Deflagration – sub-sonic
  - Mediated by diffusive thermal conductivity, $\chi$

In steady-state
  $\tau_d \sim \frac{\delta^2}{\chi}$

Diffusive Time Scale

Fusion Burn Time Scale
  $\tau_{\text{burn}} \sim \frac{W}{P_f}$

$\delta \sim \sqrt{\frac{\chi W}{P_f}}$

$V_b \sim \frac{\delta}{\tau_{\text{burn}}} \sim \sqrt{\frac{\chi P_f}{W}}$
FUSION BURN PROPAGATION AT HIGH Q

- **Example Parameters**
  
  \[
  \begin{align*}
  n & \sim 4 \times 10^{20} \text{ m}^{-3} \\
  T & \sim 20 \text{ keV} \\
  P_\alpha & \sim 10 \text{ MW/m}^3 \\
  W = 3nT & \sim 3.8 \text{ MJ/m}^3 \\
  \chi & \sim 0.1 \text{ m}^2/\text{s} \\
  \delta & \sim 0.2 \text{ m} \\
  V_b & \sim 0.5 \text{ m/s}
  \end{align*}
  \]
Comments on “Next Steps” for Study of Burning Plasmas
Major Advances & Discoveries of 90’s Lay Foundation for Next Step Burning Plasma Experiments

- **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
Modest Confinement Extrapolation Needed for BP

Dimensionless Parameters

\[ \omega_c \tau \]
\[ \rho^* = \rho/a \]
\[ \nu^* = \nu_c/\nu_b \]
\[ \beta \]

Similarity Parameter

\[ B R^{5/4} \]

Kadomtsev, 1975

\[ B \tau_{\text{Eth}} \sim \rho^{*-2.88} \beta^{-0.69} \nu^*^{-0.08} \]
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.*

• **Physics basis for burning plasma step was nearly in hand in 1986 with proposals for CIT & later BPX:** If built we now know it would have reached $Q > 5$.

• **Dramatic progress in 1990’s has established a sound basis for exploration of the burning plasma regime.**

• **We must work together NOW to take this important burning plasma step.**