Alternative Approaches to Ignition in Tokamaks

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Topics

• What have we learned about ion confinement from tokamak experiments?
  - 25 years of non-DT experiments across a wide range of machines
  - 4 machine-years of DT experiments in TFTR and JET

• Are there ways to exploit this experience in a next step?
Conventional Tokamaks Confine Energetic Ions Well

• Neutral beam and minority ICRF heating depends on this
  - PLT first demonstrated hot-ion \( (T_i \sim 7\text{keV}) \) operation with NBI (1978)
  - very successful in many tokamaks

• J.F. Clarke investigated ignition with \( T_i > T_e \) [Nucl. Fusion 20 (1980) 563]
  - neoclassical ions: \( \tau_{Ei}[s] = 0.73 \, I_p[\text{MA}]^2 \, T_i[\text{keV}]^{1/2} \, n_i[10^{20}\text{m}^{-3}]^{-1} \)
  - Alcator scaling for electrons: \( \tau_{Ee}[s] = 0.76 \, a[\text{m}]^2 \, n_e[10^{20}\text{m}^{-3}] \)
  \( \Rightarrow n\tau \) for ignition reduced by factor \( \sim 2 \) with \( T_i \approx 30\text{keV}; T_e \approx 25\text{keV} \)

• Discovery of L-mode scaling in 1980’s quelled enthusiasm
  - both electrons and ions worse than originally hoped \textit{but}

• Hot-ion modes continued to produce the best fusion performance
  - L-mode, H-mode, ERS/ERS/OS; limiter/divertor

• DT experiments showed good confinement of fusion alpha-particles
## Comparison of Achieved Plasma Parameters with ITER

<table>
<thead>
<tr>
<th>Central values</th>
<th>ITER(^1)</th>
<th>TFTR</th>
<th>JET(^2)</th>
<th>JT-60U(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma composition</td>
<td>DT</td>
<td>DT</td>
<td>DT</td>
<td>D</td>
</tr>
<tr>
<td>Mode</td>
<td>ELMy H-mode</td>
<td>Supershot</td>
<td>Hot-ion ELM-free H-mode</td>
<td>Reversed-shear High-(\beta_p)</td>
</tr>
<tr>
<td>(n_e [10^{20} \text{m}^{-3}])</td>
<td>1.3</td>
<td>1.02</td>
<td>0.42</td>
<td>0.85</td>
</tr>
<tr>
<td>(n_{\text{DT}} [10^{20} \text{m}^{-3}])</td>
<td>0.8</td>
<td>0.60</td>
<td>0.35</td>
<td>0.48 (n(_i))</td>
</tr>
<tr>
<td>(n_{\text{He}} [10^{20} \text{m}^{-3}])</td>
<td>0.2</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_i [\text{keV}])</td>
<td>19</td>
<td>40</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>(T_e [\text{keV}])</td>
<td>21</td>
<td>13</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>(Z_{\text{eff}})</td>
<td>1.8</td>
<td>1.8</td>
<td>2.1</td>
<td>3.2</td>
</tr>
<tr>
<td>(P_{\text{tot}} [\text{MPa}])</td>
<td>0.8</td>
<td>0.75</td>
<td>0.37</td>
<td>0.22</td>
</tr>
<tr>
<td>(P_{\alpha} [\text{MWm}^{-3}]) (source)</td>
<td>0.5</td>
<td>0.45</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>(P_{\text{aux}} [\text{MWm}^{-3}])</td>
<td>0</td>
<td>3.4</td>
<td>0.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\(^1\) ITER Final Design Review Document  
\(^3\) S. Ishida et al., paper IAEA-CN-69/OV1/1, IAEA Fusion Energy Conference, Yokohama, Oct. 1998

- Confinement and pulse length are the remaining issues!
DT Plasmas are NOT the Same as Their D Progenitors

- There was a pronounced isotope scaling of confinement in TFTR

<table>
<thead>
<tr>
<th>Average ion mass: ~1.9 (D), ~2.5 (D-T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_E ) (D-T) / ( \tau_E ) (D)</td>
</tr>
<tr>
<td>Reverse Shear</td>
</tr>
<tr>
<td>( \langle A \rangle^0 )</td>
</tr>
</tbody>
</table>

- JET H-modes showed positive mass scaling of pedestal, *negative in core*
Hot Ion Plasmas in TFTR Showed a Favorable $T_i$ Scaling

- Trends are not consistent with naïve Bohm or gyro-Bohm scaling but
- Can be modeled by invoking turbulence suppression by $E \times B$ shear
Isotope Scaling Changed Constraints on DT Operation

- TRANSP had predicted a DT:DD power ratio of ~180 at constant $T_i$ (1990)
- Needed to operate at higher $I_p$, $B_T$ to accommodate higher $P_{NB}$, $T_i$
Substantial Direct Alpha Heating of Ions for $T_e > 15$ keV

\[ n_e = 1.0 \times 10^{20} \text{m}^{-3}, \quad n_{DT} = 0.9 \times 10^{20} \text{m}^{-3}, \quad Z_{\text{eff}} = 1.50, \quad Z_{\text{imp}} = 6.0 \]
Good Ion Confinement Produces Hot-Ions at Ignition

- $n_{DT} : n_H : n_{He} : n_C = 0.80 : 0.05 : 0.05 : 0.01$ (based on TFTR experience)
  - $P_\alpha$ and $P_{ie} \propto n^2 \Rightarrow T_i/T_e$ independent of density at ignition
Penalty is Higher $\beta_{\text{tot}}$ and $\beta_{\alpha}/\beta_{\text{tot}}$

- Cannot simultaneously minimize $n\tau$ and $\beta_{\text{tot}}$ at ignition
Regime Expands for High-Q with Preferential Ion Heating

- \( Q = 10; \ P_{i,\text{ext}} / P_{e,\text{ext}} = 2 \)

\[ \frac{\tau_{Ei}}{\tau_{Ee}} = 5, 2, 1 \]

\[ n_e \cdot \tau_E \quad (10^{20} \text{m}^{-3} \cdot \text{s}) \]

\[ \frac{t}{E_i} / \frac{t}{E_e} \]

\[ T_e (\text{keV}) \quad T_i (\text{keV}) \]
Convective Losses Dominate in Core of Supershots

- Ion thermal flux: \( q_i = -n_i \gamma_i k \nabla T_i + CkT_i \Gamma_i \); \( \Gamma_i \) = particle flux
  - \( C = \frac{5}{2} \) for uniform losses (= average particle energy + p.dV work)
  - \( C = \frac{3}{2} \) for supershots consistent with energy dependence of \( D_i \)

- Convective losses probably too high in standard supershots to ignite, but
  - Balance of conduction and convection in core not well determined

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ERS Plasmas Combine Low $\chi_{i}$ with Greatly Reduced $D_e$

- Flux balance effective $\chi$: $q = - n \cdot \chi_{\text{eff}} \cdot \nabla T$ (includes convected heat flow)
- $\chi_{e}$ reduced near $q_{\text{min}}$ but increased inside

*TFTR*
Construct Simple 1-D Solution for a Hot-Ion $Q = 10$ Plasma

- $<P_{\text{fus}}> \approx 0.45$ MWm$^{-3}$ (ITER: 0.75); $\tau_E = 2.7$ s (ITER: 5.8 s for ignition)
Embodiment of a Hot-Ion $Q = 10$ Plasma

- From 1-D calculation: $<p> = \frac{2}{3} (\langle P_\alpha \rangle + \langle P_{aux} \rangle) \tau_E = 0.25 \text{ MPa}$

- Choose moderately conservative assumptions
  - Inverse aspect ratio: $\varepsilon = 1/3$
  - Elongation: $b/a = \kappa = 1.6$
  - Engineering safety factor: $q_e = (\pi/\mu_0) (1 + \kappa^2) \varepsilon a B / I = 3$
  - Troyon-normalized-$\beta$: $\beta_N = 10^8 <\beta> a B / I = 80 \pi <p> a / B I = 2$

- Calculate
  - Toroidal field: $B = 5.6 \text{ T}$
  - Ratio of plasma current to minor radius: $I / a = 5.5 \text{ MAm}^{-1}$
  - For $a = 1.5\text{m}$, $R = 4.5\text{m}$, $I = 8.2\text{MA} \Rightarrow P_{\text{fus}} = 150\text{MW}, P_{\text{aux}} = 15\text{MW}$
  - $H_{\text{ITER-89P}} = 3.4$
  - Would need $\chi_i \sim 0.2 \text{ m}^2\text{s}^{-1}$ and $\chi_e \sim 0.8 \text{ m}^2\text{s}^{-1}$ for $r/a < 0.6$

- This is within the bounds of what might be achievable
Conclusions and Future Directions

• We have to use DT plasmas ("the real thing") if we are interested in fusion.

• We should re-examine approaches to ignition in regimes than the "traditional" ELMy H-mode route.

• Hot-ion regimes have produced the best performance in all large tokamaks and are not incompatible with high-Q and, possibly, ignition in DT.

• *It is quite conceivable that a hot-ion mode is a stable self-organized state of a predominantly self-heated tokamak plasma.*

• In the meantime, study hot-ion regimes in large tokamaks:
  - mechanism: sheared flow, $T_i/T_e > 1$, $L_n$ $\Leftarrow$ theory progress
  - is strong central fueling necessary? $\Leftarrow$ reduced D regimes
  - MHD and TAE stability margins $\Leftarrow$ optimize r.m.s. pressure
  - size scaling in comparable regimes $\Leftarrow$ controlled experiments
  - put effort into controlling what matters $\Leftarrow$ edge control
  - investigate alpha channeling $\Leftarrow$ improves prospects