Progress on Advanced Tokamak Scenario Modeling for FIRE

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(with help from D. Ignat and T.K. Mau)

2nd UFA Workshop on Burning Plasmas
San Diego, May 1-3, 2001
Advanced Tokamak Development is Viewed as a Sequence of Improvements*

Increase $\beta_N$
- Stabilize NTM’s
- Stabilize $n=1$ RWM
- Stabilize $n>1$ RWM

Increase $f_{bs}$ and $f_{noninductive}$
- Increase $\beta_N$
- Current drive
- Control of $n$ and $T$ profiles

*includes simultaneous plasma edge/SOL/divertor improvements
Access to Higher $\beta$ AT Plasmas

JET is systematically higher than ITER($y$, 2) scaling.
Quasi-Stationary AT Burning Plasmas are the Primary Focus

- The safety factor is held by non-inductive current
  - Bootstrap current
  - LHCD off-axis (other possibilities are NBI and HHFW)
  - ICRF/FW on axis
- Pulse lengths 3-5 x $\tau_{\text{diff}}$ (30-50 s)
- $Q=5$
- $1.0 < H(y,2) < 1.8$

Transient burning AT plasmas can be produced with inductive current

Long pulse DD (non-burning) plasmas can be created with pulse lengths up to >200 s at $B_t=4$ T, $I_p=2$ MA
FIRE Can Access Various Pulse Lengths by Varying $B_T$

Note: FIRE is $\approx$ the same physical size as TPX and KSTAR. At $Q = 10$ parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT.
Ideal MHD Stability Identifies Attractive AT Plasmas

• No n=1 stabilization
  – \( q_{\text{min}} = 2.1-2.2 \)
  – \( 2.5 < \beta_N < 3.0 \)
  – \( 0.5 < r/a(q_{\text{min}}) < 0.8 \)
  – \( 3.3 < I_p(\text{MA}) < 5.5 \)
  – \( 0.3 < f_{bs} < 0.5 \)

• With n=1 stabilization
  --> strong benefit
  – \( q_{\text{min}} = 2.1-2.2 \)
  – \( 3.4 < \beta_N < 3.6 \)
  – \( 0.5 < r/a(q_{\text{min}}) < 0.8 \)
  – \( 3.3 < I_p(\text{MA}) < 5.5 \)
  – \( 0.5 < f_{bs} < 0.75 \)

*plasmas with \( q_{\text{min}} = 1.3-1.4 \) also identified, but these have (3,2) and (2,1) NTMs, and no improvement in \( \beta_N \) when n=1 is stabilized

**pockets of n=1 stability at \( q_{\text{min}} \) just above integer values are found, although the depth of the pocket is unclear
FIRE AT Modes; \( B_t=8.5 \ T, \ A=3.8, \ \kappa=1.9, \ \delta=0.65 \)

\( n(0)/<n>=1.5; \) * balloon limited; \( n=1,2,3 \) checked for \( n=1 \) stabilized

\[
\begin{array}{llll}
q_{\text{min}}=2.1-2.2 & n=1 \text{ stabilized} & \text{lower of } 4^*li & \text{or } 1.15^*\beta N \\
\left(\frac{r}{a}\right)(q_{\text{min}})=0.5 & \beta N=3.4 & \beta N=3.45 \\
q^*=4.15 & q_{\text{min}}=2.16 & \beta N=3.0 & \beta N=3.4 \\
\beta p=2.37 & \text{li}(3)=0.68 & \text{li}(1)=0.88 & \text{fbs}=0.62 \text{ fbs}=0.65 \text{ fbs}=0.65 \\
\beta N=3.0 & \beta N=3.4 & \beta N=3.45 & \beta N=3.45 \\
\beta N=2.8 & \beta N=3.45 & \beta N=2.8 & \beta N=2.8 \\
\beta N=2.5 & \beta N=3.60 & \beta N=2.32 & \beta N=2.32 \\
\beta p=1.18 & q_{\text{min}}=2.20 & \text{li}(3)=0.45 & \text{li}(1)=0.58 \text{ fbs}=0.54 \text{ fbs}=0.75 \text{ fbs}=0.50 \\
\end{array}
\]
FIRE AT Modes; $B_t=8.5 \, T$, $A=3.8$, $\kappa=1.9$, $\delta=0.65$

$n(0)/<n>=1.5$; * balloon limited; $n=1,2,3$ checked for $n=1$ stabilized

<table>
<thead>
<tr>
<th>$q_{\text{min}}=1.3-1.4$</th>
<th>n=1 stabilized</th>
<th>lower of $4*\text{li}$ or $1.15*\beta_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r/a(q_{\text{min}})=.50$</td>
<td>$I_p=5.02$</td>
<td>$\beta_N=3.55$</td>
</tr>
<tr>
<td>$q^*=2.69$</td>
<td>$q_{\text{min}}=1.37$</td>
<td>$\beta_N=3.55$</td>
</tr>
<tr>
<td>$\beta_p=1.89$</td>
<td>$\text{li}(3)=0.71$</td>
<td>$\text{li}(3)=0.71$</td>
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<tr>
<td></td>
<td>$\text{li}(1)=0.92$</td>
<td>$\text{li}(1)=0.92$</td>
</tr>
<tr>
<td></td>
<td>$\text{fbs}=0.50$</td>
<td>$\text{fbs}=0.50$</td>
</tr>
<tr>
<td>$r/a(q_{\text{min}})=.65$</td>
<td>$I_p=5.85$</td>
<td>$\beta_N=3.15$</td>
</tr>
<tr>
<td>$q^*=2.32$</td>
<td>$q_{\text{min}}=1.37$</td>
<td>$\beta_N=3.15$</td>
</tr>
<tr>
<td>$\beta_p=1.38$</td>
<td>$\text{li}(3)=0.67$</td>
<td>$\text{li}(3)=0.67$</td>
</tr>
<tr>
<td></td>
<td>$\text{li}(1)=0.86$</td>
<td>$\text{li}(1)=0.86$</td>
</tr>
<tr>
<td></td>
<td>$\text{fbs}=0.38$</td>
<td>$\text{fbs}=0.38$</td>
</tr>
</tbody>
</table>
Benefit of n=1 RWM Stabilization

$q_{\text{min}} = 2.1$, $r/a(q_{\text{min}}) = 0.8$, $I_p = 5.3$ MA, $B_T = 8.5$ T, $R/a = 3.8$, (5,2) and (3,1) NTM’s, allows wider range for value of $q_{\text{min}}$, $n(0)/<n> = 1.4$-$1.5$

LHCD shape and location modeled from ray-tracing calculations

$n=1$ not stabilized

$\beta_N = 2.55$

$f_{bs} = 0.55$

$I_{LH} = 2.2$ MA

$I_{BS} = 3.0$ MA

$n=1$ stabilized

$\beta_N = 3.6$

$f_{bs} = 0.75$

$I_{LH} = 1.4$ MA

$I_{BS} = 3.8$ MA
Bootstrap Current and the q Profile

Both cases have $q_{\text{min}}=2.1-2.2$, stable up to $\beta_N=2.85$, $r/a(q_{\text{min}}) = 0.65$, same n profiles $n(0)/\langle n \rangle=1.45$, $f_{bs}=0.6$

- Bootstrap current profile determined by n, T profiles $\rightarrow$ q
- There are points with fixed $f_{bs}$ as a function of $\beta_N$ and $n(0)/\langle n \rangle$
- At what $f_{bs}$ do we need to control n and T profiles?
External Current Drive and Heating for FIRE

- 30 MW ICRF (ion heating) for ELMy H-mode;
  - 4 ports, 100-150 MHz
- <10 MW ICRF/FW (electron heating/CD) for AT mode;
  - 1 (or 2) ports, 90-110 MHz, phasable
  - Want to use same ICRF equipment
- 20-30 MW LHCD (electron heating/CD) for AT mode;
  - 2-3 ports, 5.6 GHz, $n_|| = 2.0-2.5$
  - For NTM control
- ?? MW ECH/ECCD (electron heating/CD) for startup and NTM control (issue is high $B_T$ and high density)
Lower Hybrid for Off-Axis Current Drive on FIRE

LSC lower hybrid ray tracing calculation

\[ P_{\text{LH}} = 30 \text{ MW} \]

\[ I_{\text{LH}} = 2.4 \text{ MA} \]

\[ N_\parallel = 2.0, \Delta N_\parallel = 0.3 \]

\[ I_{\text{BS}} = 2.6 \text{ MA} \]

*alpha particle absorption of LH power? -- ripple loss of alphas may mitigate this

Note radial coordinate is poloidal flux
External Current Drive and Heating for FIRE (other possibilities)

- 120 keV NBI (positive ion); deposition to $\rho > 0.7$; good off-axis current profile and rotation
- HHFW (300-800 MHz); deeper penetration than LH

CD analysis by T.K.Mau for ARIES-AT
Dynamic Burning AT Simulations with TSC-LSC for FIRE

Ip=5.5 MA, Bt=8.5 T, Q=7.5,
\( \beta_N=3.0 \), \( \beta=4.4\% \), \( P_{LH}=20 \) MW,
\( I_{LH}=1.7 \) MA, \( I_{BS}=3.5 \) MA, \( I_{FW}=0.35 \) MA

\[ H(y,2)=1.6 \]
Dynamic Burning AT Simulations with TSC-LSC for FIRE

Plasma becomes quasi-stationary after 10 s
Conclusions

- $q_{\text{min}}$ around 2.1-2.2 is found to provide a good combination of
  - Beta limit with and without $n=1$ stabilization—*increase these*
  - High plasma current—*not too high*
  - Elimination of $(3,2)$ and $(2,1)$ NTM’s—*but $(5,2)$ and $(3,1)$ exist*
  - Lower CD power—*need to reduce this*
- Less than 2 MA of LHCD is required, leading to powers of 20-30 MW from LSC lower hybrid calculations
- Stabilization of $n=1$ RWM would yield attractive configurations
- Need to find techniques for density profile peaking to enhance bootstrap current
- TSC-LSC simulations indicate that we can create quasi-stationary plasmas for flattop burn
Future Work for FIRE Burning AT Plasma Development

- Continue ideal MHD stability search
  - Pressure profile and $q^*$ variations
  - Edge profile effects
  - $n=1$ stabilized plasmas
- NTM requirements
- Examine DIII-D AT experiments
- Examine C-Mod AT experiments
- CD analysis
  - Reduce $P_{CD}$, raise $f_{bs}$
  - LHCD, HHFW, NBI
  - ICRF/FW
  - ECCD
- TSC-LSC dynamic discharge simulations
  - Plasma formation in shortest time
  - Energy and particle transport models
  - Control of $j$, $n$, $T$
Experimental AT Observations to Guide FIRE AT Development

• DIII-D
  – NBI strong rotation source
  – ITB/turbulence suppression --> profiles
  – Edge plasma conditions/pumped divertor
  – n=1 RWM feedback
  – NTM stabilization

• C-Mod
  – Anomalous ICRF rotation
  – ITB/turbulence suppression --> profiles
  – LHCD/current profile control
  – High density core/edge
  – Detached divertor

The differences between the devices are likely to be the most important
Burning AT Plasma Issues

- Ripple losses are larger due to high $q$, low $I_p$ and low $B_T$
- Alfvén eigenmodes are expected to be more severe
- NTM suppression
  - LHCD and/or ECCD
- RWM stabilization
  - $n=1$ feedback
  - Then what for $n>1$ RWM’s
- Impurities for control

- $T_n$ profile control
  - Density peaking vs $\beta_n$ for bootstrap current
  - ITB relaxation, or turbulence suppression without ITB

- Plasma rotation
  - Bulk rotation for RWM stability
  - Sheared rotation for turbulence suppression

- Plasma edge conditions
  - L-mode or H-mode
  - Radiation characteristics
FIRE can Test Advanced Regimes of Relevance to ARIES-AT

Confinement Required to access this regime

\[ Q = 10, \quad HH = 1.2 \]
or
\[ Q = 5, \quad HH = 1.06 \]
Needs self-consistent current drive power

Duration
\[ \sim 2 \text{ tau\_skin} \]

\begin{verbatim}
Case 1
Modest
AT
30
Flat top(s) 60
5.65 \( I_p(MA) \)
9.00 \( B_T(T) \)
2.90 \( q_0 \)
2.60 \( q_{\min} \)
1.31 \( \beta_p \)
2.60 \( \beta_N \)
3.10 \( \beta(\%) \)
0.42 \( \ell_i \)
0.50 \( f_{bs} \)
165 \( P_{\text{fus}}(MW) \)
29.4 \( W_{\text{th}}(MJ) \)
0.65 \( n_e/n_{\text{Gr}} \)
2.40 \( \alpha\text{-loss}(\%) \)
\end{verbatim}

Confinement Required to access this regime

\[ Q = 10, \quad HH = 1.56 \]
or
\[ Q = 5, \quad HH = 1.36 \]

Duration
\[ \sim 4 \text{ tau\_skin} \]