Burning Plasma Experiment Requirements and FIRE

Dale Meade

Presented to
UFA Burning Plasma Physics Workshop
University of Texas, Austin, TX

December 11, 2000
Fusion Science Objectives for a Major Next Step Experiment

• Explore and understand the physics of alpha-dominated fusion plasmas:
  • Energy and particle transport (extend confinement predictability)
  • Macroscopic stability ($\beta$-limit, wall stabilization, NTMs)
  • Wave-particle interactions (fast alpha driven effects)
  • Plasma boundary (density limit, power and particle flow)
  • Strong coupling of previous issues due to self-heating (self-organization?)

• Test techniques to control and optimize alpha-dominated plasmas.

• Sustain alpha-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.

• Explore and understand some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.

We must Burn to Learn!!

F. Perkins and N. Sauthoff, FIRE Wkshp
A Next Step Option (NSO) Should Provide the Capability to Explore Burning Plasma Physics, Advanced Toroidal Physics and their Coupling.

Attractive MFE Reactor (e.g. ARIES Vision)

Burning Plasma Physics

Fusion Plasma Physics

Advanced Toroidal Physics

Existing Devices

Emerging Advanced Data Base, Toroidal Data Base

Alpha Dominated

\( f_\alpha = \frac{P_\alpha}{(P_\alpha + P_{\text{ext}})} > 0.5 \),

\( \tau_{\text{Burn}} > 15 \tau_E, 2 - 3 \tau_{\text{He}} \)

Burning Plasma Physics Requirements

Advanced Toroidal Requirements

Large Bootstrap Fraction, Profile Control & Long Pulse

\( Np^* > 0.5 Np^*(\text{ARIES}), \)

\( \tau_{\text{pulse}} > 2 - 3 \tau_{\text{skin}} \)

Existing Devices (Existing, Emerging Advanced Data Base, Toroidal Data Base)

Advanced Toroidal Physics

 existing devices

emerging advanced data base, toroidal data base
### Dimensionless Parameters Required for Fusion Plasma Physics Experiment

<table>
<thead>
<tr>
<th>Explore and Understand Fusion Plasmas</th>
<th>Core*</th>
<th>Edge</th>
<th>Alpha</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy and Particle Transport</td>
<td>BR$^{5/4}$</td>
<td>?</td>
<td>$P_\alpha/P_{\text{heat}}$</td>
<td>$\tau/\tau_{\alpha s}$</td>
</tr>
<tr>
<td>Macroscopic Stability</td>
<td>&gt;0.5</td>
<td>&gt;0.5</td>
<td>$\beta_\alpha \sim$ ARIES</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Wave Particle (alpha heating, fast alpha)</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Plasma Boundary</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
<td>3 to 5</td>
</tr>
<tr>
<td>Test Control and Optimization Techniques</td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
<td>5</td>
</tr>
<tr>
<td>Sustain Alpha Dominated Plasmas</td>
<td>ARIES-AT 1</td>
<td>0.9</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Exhaust of power, particles and ash</td>
<td>FIRE Goals 0.6</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Profile evolution impact on $\tau_E$, MHD</td>
<td>JET/TFTR D-T Experiments 0.3</td>
<td>0.04</td>
<td>~3</td>
<td>10</td>
</tr>
</tbody>
</table>

* Core parameters are normalized to ARIES-AT BR$^{5/4}$
**Fusion Ignition Research Experiment (FIRE)**

**Design Goals**

- \( R = 2.0 \text{ m}, \quad a = 0.525 \text{ m} \)
- \( B = 10 \text{ T}, \quad (12 \text{T})^* \)
- \( W_{\text{mag}} = 3.8 \text{ GJ}, \quad (5.5 \text{T})^* \)
- \( I_p = 6.5 \text{ MA}, \quad (7.7 \text{ MA})^* \)
- \( P_{\alpha > P_{\text{aux}}}, P_{\text{fusion}} < 200 \text{ MW} \)
- Burn Time \( \approx 18.5 \text{s} \ (\approx 12 \text{s})^* \)
- Tokamak Cost \( \leq \$0.3B \)
- Base Project Cost \( \leq \$1B \)

* Higher Field Mode

**Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.**

http://fire.pppl.gov
# Basic Parameters and Features of FIRE Reference Baseline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, major radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>a, minor radius</td>
<td>0.525 m</td>
</tr>
<tr>
<td>( \kappa_{95} ), elongation at 95% flux surface</td>
<td>( \sim 1.8 )</td>
</tr>
<tr>
<td>( \delta_{95} ), triangularity at 95% flux surface</td>
<td>( \sim 0.4 )</td>
</tr>
<tr>
<td>q(_{95} ), safety factor at 95% flux surface</td>
<td>( &gt;3 )</td>
</tr>
<tr>
<td>( B_t ), toroidal magnetic field</td>
<td>10 T with 16 coils, 0.34% ripple @ Outer MP</td>
</tr>
<tr>
<td>Toroidal magnet energy</td>
<td>3.7 GJ</td>
</tr>
<tr>
<td>( I_p ), plasma current</td>
<td>( \sim 6.5 ) MA (7.7 MA at 12 T)</td>
</tr>
<tr>
<td>Magnetic field flat top, burn time</td>
<td>26 s at 10 T in ( \text{dd} ), 18.5 s @ ( \text{Pdt} ) ( \sim 200 ) MW)</td>
</tr>
<tr>
<td>Pulse repetition time</td>
<td>( \sim 3 ) hr @ full field and full pulse length</td>
</tr>
<tr>
<td>ICRF heating power, maximum</td>
<td>30 MW, 100MHz for 2( \omega )(_T ), 4 mid-plane ports</td>
</tr>
<tr>
<td>Neutral beam heating</td>
<td>None, may have diagnostic neutral beam</td>
</tr>
<tr>
<td>Lower Hybrid Current Drive</td>
<td>None in baseline, upgrade for AT phase</td>
</tr>
<tr>
<td>Plasma fueling</td>
<td>Pellet injection (( \geq 2.5 ) km/s vertical launch inside mag axis, possible guided slower speed pellets)</td>
</tr>
<tr>
<td>First wall materials</td>
<td>Be tiles, no carbon</td>
</tr>
<tr>
<td>First wall cooling</td>
<td>Conduction cooled to water cooled Cu plates</td>
</tr>
<tr>
<td>Divertor configuration</td>
<td>Double null, fixed X point, detached mode</td>
</tr>
<tr>
<td>Divertor plate</td>
<td>W rods on Cu backing plate (ITER R&amp;D)</td>
</tr>
<tr>
<td>Divertor plate cooling</td>
<td>Inner plate-conduction, outer plate/baffle- water</td>
</tr>
<tr>
<td>Fusion Power/ Fusion Power Density</td>
<td>200 MW, ( \sim 10 ) MW m-3 in plasma</td>
</tr>
<tr>
<td>Neutron wall loading</td>
<td>( \sim 3 ) MW m-2</td>
</tr>
<tr>
<td>Lifetime Fusion Production</td>
<td>5 TJ (BPX had 6.5 TJ)</td>
</tr>
<tr>
<td>Total pulses at full field/power</td>
<td>3,000 (same as BPX), 30,000 at 2/3 ( B_t ) and ( I_p )</td>
</tr>
<tr>
<td>Tritium site inventory</td>
<td>Goal &lt; 30 g, Category 3, Low Hazard Nuclear Facility</td>
</tr>
</tbody>
</table>

Higher Field Mode \( B = 12 \)T and \( I_p = 7.7 \)MA with a 12 second flat top has been identified.
FIRE would have Access for Diagnostics and Heating

- 16 mid-plane ports  1.3m x 0.65m
- 32 divertor ports  0.5m x 0.2m (16 for cryopumps/cooling water
- 24 vertical ports  0.13m diam
FIRE is Compatible with Advanced Tokamak Features

Features

- DN pumped divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports

Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510, remainder OFHC C10200

Compression Ring

Double Wall Vacuum Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding (60% steel & 40% water)

Vertical Feedback Coil

Passive Stabilizer Plates
space for wall mode stabilizers

W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.
Projections of FIRE Compared to EnvisionedReactors

- FIRST "ITER" Reactor
  - Toschi et al

- Base 12T 7.7MA
- Base 12T 7.7MA
- FIRE* 10T 7.7MA
- FIRE* 10T 6.44MA

- JET H-Mode Data Base

- ARIES-AT, Najmabadi, Q = 50

- P_{fusion} = 150 MW
- \frac{n}{n_{GW}} = 0.7
- \frac{n(0)}{\langle n \rangle_V} = 1.5
- \frac{n(0)}{\langle n \rangle_V} = 1.2

- FIRE*
  - R = 2.14 m, a = 0.595 m
  - A = 3.6

- \beta_N > 1.7, 2.7 < q_{95} < 3.5
- \kappa > 1.7, \frac{n}{n_{GW}} = 0.5 - 0.8, and Z_{eff} < 2 have

- \langle H98(y,2) \rangle = 1.1
- \langle \frac{n(0)}{\langle n \rangle_V} \rangle = 1.2
FIRE* 10T, R = 2.14m, 7.7 MA, H(y,2) = 1.1, $\alpha_n = 0.2$
1 1/2-D Simulation of Burn Control in FIRE

- ITER98(y, 2) scaling with \( H(y,2) = 1.1 \), \( n(0)/<n> = 1.25 \) and \( n/n_{GW} = 0.59 \)
- Pulse Duration \( \approx 30 \tau_E \), \( 6 \tau_{He} \) and \( \sim 1.5 \tau_{skin} \)

http://fire.pppl.gov
Helium Ash Accumulation could be Explored on FIRE

Adjust divertor pumping to control helium ash

TSC/Kessel/21-q.ps
FIRE could Access “Long Pulse” Advanced Tokamak Mode Studies at Reduced Toroidal Field.

Note: FIRE is ≈ 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.

The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range from steady-state non-burning advanced-tokamak modes to “quasi-equilibrium” burning plasmas in advanced tokamak modes.
Physics - NSO PAC review with Action Plan to follow up on Recommendations

- Mission endorsed (recommend even more excitement)
- Evaluate FIRE performance on the basis of recent scalings e.g., ITER98(y,2) and recent results with enhanced regimes e.g., pellet fueling
- Enhanced performance design point being developed with $I_p \sim 7.7$ MA to increase confidence of high gain while maintaining pulse length ($\sim 1.5 \tau_{cr}$)
- Potential for advanced tokamak modes is being developed

Engineering

- Pre-Conceptual Design Activity has addressed all subsystems. Engineering Report 2000 completed, see http://fire.pppl.gov. CD is available on request
- Baseline design of 10 T /20 s flat top and 12 T/12 s flat top exceeds original design goals of 10 T/10 s flat top.
- Actively cooled W outer divertor and baffle with conduction cooled inner W divertor, and Be first wall on Cu substrate satisfy cooling requirements.
- Cost Estimate of Baseline design gives $1.2B(FY-99$) for Green Field site with good possibility of < $1B(FY-99$) at an existing site.
Potential Next Step Burning Plasma Experiments and Demonstrations in MFE

ARIES-ST (1 GWe)

<table>
<thead>
<tr>
<th>Cost Drivers</th>
<th>ARIES-ST</th>
<th>ITER-FEAT</th>
<th>ARIES-RS</th>
<th>JET</th>
<th>FIRE</th>
<th>IGNITOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Volume (m³)</td>
<td>810</td>
<td>837</td>
<td>350</td>
<td>95</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Plasma Surface (m²)</td>
<td>580</td>
<td>678</td>
<td>440</td>
<td>150</td>
<td>60</td>
<td>36</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>28</td>
<td>15</td>
<td>11</td>
<td>4</td>
<td>6.5</td>
<td>12</td>
</tr>
<tr>
<td>Magnet Energy (GJ)</td>
<td>29</td>
<td>50</td>
<td>85</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>3000</td>
<td>500</td>
<td>2200</td>
<td>16</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Burn Time (s), inductive</td>
<td>steady</td>
<td>steady*</td>
<td>steady</td>
<td>1</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

* assumes non-inductive current drive
Timetable for “Burn to Learn” Phase of Fusion

- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for \( \geq 15 \) years.

- Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing “advanced” tokamak program and could begin alpha-dominated experiments by \( \sim 10 \) years.

- More than one high gain burning plasma facility is needed in the world program.

- The information “exists now” to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.