Motivation for Building a High-Field Tokamak Burning Plasma Experiment

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A Few of the Reasons to Build a High-Field Tokamak Reactor

\[ B \sim 12 \text{ tesla}, \quad R \sim 1.75 \text{ m}, \quad \text{cost} \sim \$1 \text{ B} \]

1. Test physics of alpha heating
2. Test gyro-radius scaling of confinement
3. Test the scaling of H-mode (onset and pedestal height)
4. Can Internal Transport Barriers be produced in reactors?
5. Does strong electron heating produce particle pinches?
6. Test effect of large sawtooth oscillations on reactor performance
7. Test divertors at high heat loads
8. What will $\langle Z_{\text{eff}} \rangle$ be in fusion reactors?
9. Public proof of ignition
Test Physics of Alpha Heating

• Fast alphas may degrade or enhance performance
  – Fast alphas might drive new instabilities (such as TAE modes)
  – The electron heating from fast alphas might cause particle pinches $\rightarrow$ more peaked density profiles

• Fast alphas may be ejected by sawtooth oscillations or they may stabilize sawtooth oscillations
  – Very broad sawtooth mixing radius in fusion reactors

• High field tokamak reactor designs have:
  – high plasma density
    $\rightarrow$ short slowing down time for fast alphas but high source rate
  – moderate size and high energy density
    $\rightarrow$ short confinement times
Gyro-Radius Scaling

The normalized gyro-radius is defined as

$$\rho_* \equiv \rho_s / a = (2T_e M_i) / (eB_T a) = 4.57 \times 10^{-3} q \frac{T_e[\text{keV}] M_i[\text{AMU}]}{B_T[\text{tesla}] a[\text{m}]}$$

In present-day tokamaks, $3.7 < \rho_*(0) \times 10^3 < 12.8$

In fusion reactor designs with $T_e(0) = 20 \text{ keV}$

<table>
<thead>
<tr>
<th>Design</th>
<th>$a[\text{m}]$</th>
<th>$B_T[\text{tesla}]$</th>
<th>$\rho_*(0) \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER-EDA</td>
<td>2.8</td>
<td>5.7</td>
<td>2.0</td>
</tr>
<tr>
<td>ITER-FEAT</td>
<td>2.0</td>
<td>5.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Mazzucato</td>
<td>1.1</td>
<td>8.0</td>
<td>3.2</td>
</tr>
<tr>
<td>BPX (1991)</td>
<td>0.8</td>
<td>9.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Ignitor</td>
<td>0.455</td>
<td>13.0</td>
<td>5.5</td>
</tr>
<tr>
<td>FIRE</td>
<td>0.525</td>
<td>10.0</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Transport Barriers

• Need to test scaling relations for H-mode
  – Conditions needed to produce and maintain H-mode
  – Height of temperature and density pedestal which has a strong effect on core confinement
  – Control ELMs
  – Models are being developed for H-mode pedestal

• Internal Transport Barriers (ITBs) for enhanced confinement
  – It may be possible to produce Internal Transport Barriers in fusion reactors
  – It has been shown in C-mod that ICRF can drive significant plasma velocity and flow shear
  – Can use current ramp to produce reversed magnetic shear (which helps produce ITBs)
Particle Pinches

• Peaked hydrogenic density profiles enhance fusion reactor performance
  – The reason is simple: more fuel in hottest part of plasma

• Peaked helium and impurity profiles degrade performance
  – Low Z impurities dilute fuel

• There is theoretical evidence that strong electron heating can produce particle pinches

• There is experimental evidence that RF heating can produce peaked density profile under some conditions
Large Sawtooth Oscillations

• In most fusion reactor designs, sawteeth are very broad ($r_{\text{mix}}/a \approx 60\%$ or more) and large amplitude
  
  – Reason: reactor designs push parameter limits: high elongation and high current (low magnetic $q$)

• Sawteeth may have large effect on fast alphas, fusion heating, and confinement
  
  – We do not know if fast alphas will be ejected by giant sawteeth
  – Simulations show pulse of fusion heating with each sawtooth crash

• Sawteeth can be delayed or avoided ($q_{\text{axis}} > 1$)
  
  – Use current ramp to transiently keep $q_{\text{axis}} > 1$
  – Use current drive and bootstrap current for long pulse
  – Fast alphas may help stabilize sawteeth
Ignitor Impurity Scan

![Graph showing power vs. time with different effective charges](image-url)
Test Divertors at High Heat Loads

- At sufficiently high density, divertors can radiate away most of the heat flux from the plasma
  - This reduces heat flux to divertor plate
  - But the high edge density may adversely affect confinement
- Test divertors in pulsed mode before going to steady state

What will $\langle Z_{\text{eff}} \rangle$ be in fusion reactors?

- High impurity content ($\langle Z_{\text{eff}} \rangle$) degrades fusion reactor performance
  - No way to extrapolate $\langle Z_{\text{eff}} \rangle$ to fusion reactors