PHYSICS OF BURNING PLASMAS:

PHYSICS INACCESSIBLE TO PRESENT FACILITIES

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OUTLINE

• Introduction

• Three Classes of Burning Plasma Physics inaccessible to contemporary tokamak facilities
  
  1. Effects of energetic $\alpha$-particles
  2. Self-heating
  3. Physics of reactor-scale plasmas

• Examples of inaccessible burning plasma physics

• Conclusions
INTRODUCTION

• A fusion reactor confining a burning plasma is the ultimate goal of the fusion energy sciences program.

- Design of a reactor must rest on robust experimental demonstrations of its physics basis and operational scenarios.

• Three questions arise:

1. How do we extrapolate the physics processes dominant in contemporary tokamaks to a reactor-scale facility?

2. What new physics will be encountered in a reactor?

3. What capabilities do candidate burning plasma experiments have to address both extrapolations and these new physics processes?

• This talk addresses Question 2: What must we learn from burning plasma experiments?
THREE ELEMENTS OF BURNING PLASMA PHYSICS

1. Energetic Particle Physics arising from 3.5 Mev $\alpha$-particles
   - Heats electrons; eliminates hot ion modes relying on $T_i >> T_e$.
   - Drives Alfven Eigenmodes towards instability.
   - Interacts with $(m,n) = (1,1)$ modes - sawteeth & fishbones

2. Self-Heating and Thermal stability
   - Interacts with core and edge transport barriers - thermal stability
   - Self-consistency of steady-state plasmas
   - Simulation in Upgrades via auxiliary heating power controlled by DD neutrons?

3. Reactor-scale physics — sets many design requirements
   - Near balance of $\alpha$-particle heating with transport loss determines device scale
   - Scale affects balance of many processes with diverse scalings
PHYSICS INACCESSIBLE TO PRESENT FACILITIES:
α–PARTICLES AND SELF-HEATING / THERMAL STABILITY

1. Energetic Particle physics is affected by scale: \( \tau_E \gg \tau_s \).

   - Smaller driving source at reactor scale
     \[
     \frac{n_{\text{fast}}}{n} = \left( \frac{3T}{E_{\text{fast}}} \right) \left( \frac{\tau_s}{\tau_E} \right)
     \]

   - \( n_{\text{fast}} \) \geq 10; turbulent modes??

2. Self-heating and thermal stability

   - Energy confinement scaling results in relation for fusion power produced by an ignited, thermally-stable plasma
     \[
     P_{\text{fus}} \propto n^3 (H_H)^7 d^{3.5} \quad d = n_T n_D / n_e^2
     \]

   - Fusion power controlled by density but very sensitive to confinement multiplier
   - How fast can core density and, transport barriers change?
3. Disruptions lead to vaporization of divertor chamber and runaways

- Thermal quench energy impulse $W/aR$ factor-of-15 larger than JET
- Large source of impurities for subsequent current quench stage
- Runaway avalanche growth e-foldings $\Gamma \approx I_p \left( I_{\text{Alfven}} \ln \Lambda \right)^{-1} > 25.$

4. Operational $\beta$-limit:

- Controlled by Neoclassical Tearing Modes (inductive tokamak)?
- In a reactor time scales are long
  - Effectiveness of ECCD control of NTMs on ~ 50s growth time
  - Sawteeth (and hence seed islands) are infrequent ~100s
PHYSICS INACCESSIBLE TO PRESENT FACILITIES: 
CONFINEMENT ISSUES

5. Core confinement scaling

• Value of $\rho^*$ is a factor-of-5 less than JET
• Will "almost gyroBohm" scaling continue to hold?
• Relative importance of “core” versus “pedestal” energy content

6. H-mode power threshold

• Factor-of-2 uncertainty for reactor-scale devices
• Data scatter prevents present devices from determining size-scaling
• Theory presently unable to predict size scaling
• Investigation in a reactor-scale plasma is needed.
PHYSICS INACCESSABLE TO PRESENT FACILITIES: 
CORE-EDGE INTEGRATION: POWER AND PARTICLE CONTROL

7. Power dispersal:

- Present tokamak discharges with ITER $\beta$, $\nu^*$ have attached divertors
- Integrated demonstration of detached divertors with core confinement at reactor-like $\beta$, $\nu^*$ not possible
- For a reactor, higher $T_e$ just inside SOL inhibits MARFES
- Predictive 2D divertor simulations need perpendicular diffusivity

8. Core fuelling by inside pellet launch combined with high baffling of a reactor-scale facility controls main chamber neutral pressure
PHYSICS INACCESSIBLE TO PRESENT FACILITIES: CORE-EDGE INTEGRATION: H-MODE AND DENSITY-LIMITS

9. While ITER Demonstration Discharges (with ITER-like $\beta, \nu^*$) in present devices have transport losses appreciably above the H-mode power threshold, a reactor-scale device will operate close to the power threshold

- Transport losses scale differently from power threshold
- Will the full H-mode confinement be realized?

10. ITER Demonstration Discharges have a density well below the Greenwald limit whereas a reactor will operate close the Greenwald density.

- Density scaling at constant $\beta, \nu^*$ differs from Greenwald

11. In general, an integrated demonstration of a reactor-scale core and edge physics is not possible in contemporary facilities.
STEADY-STATE OPERATION

1. High - bootstrap fraction requires relatively high- \( q \) and a reverse-shear \( q \)-profile.

   • To achieve desired \( \beta > 3\% \), plasmas must operate in the "wall-stabilized" regime where resistive wall modes arise.

   • Resistive wall modes stabilized by rotation or feedback

   • Presently, wall-stabilized plasmas exhibit a spontaneous spin-down that prevents rotation from providing the needed stabilization

2. It follows that steady-state burning plasma experiments must have active \( n=1 \) feedback coils and a source of rotation drive to determine design requirements for a steady-state reactor.

   • NBI beam energy increases and driven rotation frequency decreases in a reactor-scale device.
CONCLUSIONS

1. Reactor-scale burning plasma physics has features which are inaccessible to investigation in present facilities*.  
   - The experimental physics of a reactor scale device will be original.

2. Design of a demonstration power reactor must rest on experimental demonstration in a burning plasma facility of its physics basis and operational modes.

3. To progress towards the fusion power goal, we must

"Burn to Learn"

* A more detailed account appears in Chapter 9, ITER Physics Basis