PHYSICS OF BURNING PLASMAS:

PHYSICS INACCESSIBLE TO PRESENT FACILITIES

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OUTLINE

- **Introduction**
- **Three Classes of Burning Plasma Physics inaccessable to contemporary tokamak facilities**
    1. **Effects of energetic α-particles**
    2. **Self-heating**
    3. **Physics of reactor-scale plasmas**
- **Examples of inaccessable 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 α-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 α-particle heating with transport loss determines device scale**
- **Scale affects balance of many processes with diverse scalings**

PHYSICS INACCESSABLE TO PRESENT FACILITIES: α–PARTICLES AND SELF-HEATING / THERMAL STABILITY

1. Energetic Particle physics is affected by scale: $\tau_E >> \tau_s$.

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

- **TAE mode numbers are higher** $n \geq 10$ **; turbulent modes??**

2. Self-heating and thermal stability

- **Energy confinement scaling results in relation for fusion power produced by an ignited, thermally-stable plasma**

$$P_{fus} \quad n^3(H_H)^7 d^{3.5} \qquad d=n_T n_D/n_e^2$$

- **Fusion power controlled by density but very sensitive to confinement multiplier**
- **How fast can core density and, transport barriers change?**

PHYSICS INACCESSABLE TO PRESENT FACILITIES: DISRUPTIONS AND β-LIMIT

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** $\Gamma \approx I_p \left(I_{Alfven} \ell n\Lambda\right)^{-1}$ **> 25.**

4. Operational β-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 INACCESSABLE TO PRESENT FACILITIES:
CONFINEMENT ISSUES

5. Core confinement scaling

- Value of ρ^* 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 β, ν^* have attached divertors**
- **Integrated demonstration of detached divertors with core confinement at reactor-like β, ν^* 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 INACCESSABLE TO PRESENT FACILITIES: CORE-EDGE INTEGRATION: H–MODE AND DENSITY-LIMITS

9. While ITER Demonstration Discharges (with ITER-like β, ν^*) 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 wheras a reactor will operate close the Greenwald density.

- **Density scaling at constant β, ν^* 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 β > 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 inaccessable 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