Flexibility Requirements for a Burning Plasma Experiment

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The Dichotomy in Burning Plasma Experimental Goals

- A burning plasma experiment must explore:

  - the physics of the coupling of transport and stability to a dominantly self-generated internal heat source;

  - the plasma physical effects arising from an intense population of energetic alpha particles.

- A tokamak burning plasma experiment should be able to explore these issues both in the conventional H-mode regime and in the "optimized shear" advanced tokamak regime.

- To delineate fully the physics of burning plasmas, a burning plasma experiment must be able to attain:

  - "good" regimes in which coupled transport/stability/heating can be studied <u>without</u> deleterious alpha-particle effects;

  - "bad" regimes in which deleterious alpha effects (AE modes, etc.) are so strong that alpha heating is seriously degraded.

- For a burning plasma experiment such as FIRE to be able to attain <u>both</u> "good" and "bad" regimes, the key appears to be:

  - adequate density and density-profile control,

  which should top the list of "flexibility requirements".

A Burning Plasma Experiment: Two Examples

	ITER-FEAT	FIRE*
Reference Goal	Q = 10	Q = 10
Fusion Power (MW)	400	150
Heating Power (MW)	40	15 (30)
Plasma Major Radius (m)	6.2	2.14
Plasma Minor Radius (m)	2.0	0.595
Plasma Current (MA)	15.0	7.7
Field at Plasma Center (T)	5.3	10.0
Elongation (κ_{95})	1.7	1.77
Average Triangularity (δ_{95})	0.35	0.4
Safety Factor (q_{95})	3.00	3.05
Volume Average Density (10^{20} m^{-3})	1.0	4.6
Density (Line Av.)÷Greenwald Density	0.85	0.70
Density Profile, exponent α_n	0.1	0.2
Average Temperature, $\langle T \rangle_n$ (keV)	8.5	6.4
Temperature Profile, exponent α_T	1.0	1.0
Helium and Impurities	same assumptions	
Separatrix Power ÷ L-H Threshold	1.6	1.3
Beta, total including alphas (%)	2.5	2.3
Beta-Normal, total incl. alphas, β_N	1.8	1.8
Transport Confinement Time, $\tau_{E,tr}$(s)	3.5	1.0
H-Mode Multiplier ($H_{98Hy(2)}$)	1.00	1.09
Inductive Current Flat-top, τ_{pulse} (s)	400	20
Skin Time (2nd mode), τ_{skin} (s)	160	10
Number of τ_{skin}'s, τ_{pulse}/τ_{skin}	2.5	2.0

* Most recent parameters for FIRE

Conclusion: Plasma physics is essentially identical

Alpha-Particle Effects: Key Dimensionless Parameters

- Three dimensionless parameters will characterize the physics of alpha-particle-driven instabilities:
  - Alfven Mach Number: $v_\alpha/v_A(0)$
  - Number of Alpha Larmor Radii (inverse): ρ_α/a
  - Maximum Alpha Pressure Gradient (scaled): Max R β_α

	Range of Interest (e.g. ARIES-RS/AT)	ITER-FEAT (reference)	FIRE (reference)
$v_\alpha/v_A(0)$	≈ 2.0	1.9	2.2
ρ_α/ a	≈ 0.02	0.016	0.028
Max R β_α	0.03-0.15 *	0.05	0.035

(* reflects interest in an extended range of beta and fusion power density)

- An essential requirement for a burning plasma experiment is that it be able to explore a <u>broad range</u> of values of Max R β_α — the single most important parameter for alpha-particle effects.
- This requirement can be fulfilled in an experiment such as FIRE, provided there is <u>adequate density and profile control</u>.

Alpha-Particle Regimes Accessible in FIRE

- Consider densities <u>below</u> the reference density.
- Consider profiles <u>more peaked</u> than the reference profile.
- All cases have $P_{\mathbf{fusion}}$ = 150 MW and $H_{\mathbf{98Hy(2)}}$ = 1.0 -1.1.

<u>Values obtainable for the key parameter Max R β_α</u>
(Q-values shown in parenthesis)

	$\alpha_n = 0.2$ $\alpha_T = 1.0$	$\alpha_n = 0.5$ $\alpha_T = 1.4$	$\alpha_n = 1.0$ $\alpha_T = 2.0$
$n_{\mathbf{e20}} = 4.6$	0.035 (10)	0.04 (15*)	0.05 (15*)
$n_{\mathbf{e20}} = 3.8$	0.05 (9)	0.06 (15)	0.07 (20*)
$n_{\mathbf{e20}} = 3.2$	0.08 (7.5)	0.09 (12)	0.11 (≥30)
$n_{\mathbf{e20}} = 2.7$	0.11 (6)	0.13 (10)	0.16 (≥30)

(* limited by power to exceed the L-H transition threshold)

- We see that FIRE can access the entire range of values of the parameter Max R β_α, provided there is good density control, some profile control, and somewhat more (up to a factor 2) auxiliary power than is needed for the reference case.

Flexibility Requirements for Burning Plasma Experiment
(in descending order of importance)

Flexibility Requirement	Purpose
Pumped divertor (with adjustable pumping)	Density control. Helium exhaust studies.
Inside-launch pellet fueling	Density profile control
Somewhat more heating power	Enhanced alpha population (factor ≈ 2) than for reference case at low density, lower-Q
Large access ports	Multiple heating options
Feedback-controlled fueling and auxiliary power	Control of fusion power. Maintenance of H-mode.
Localised steerable current drive (e.g., ECCD, LHCD?)	Control of neoclassical tearing modes
Heating during current ramp	Alpha effects in “optimized shear” AT modes
Pulse length ≥ skin time (for current redistribution)	Current profile relaxation in AT modes
Outer-plasma current drive (e.g., LHCD)	Alpha effects in sustained optimized-shear AT modes
Resonant rf for helium transport	Accelerated helium transport to plasma edge
(Possibly) Feedback-controlled medium-Z impurity injection	Edge plasma control. Limit power to target plate.