Boundary Science Requirements for Fusion Power

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Workshop on Burning Plasma Science:
Exploring the Fusion Science Frontier

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INTRODUCTION

- Take "compelling" $\leftrightarrow$ issues that stand in way of making fusion power,

Core-Boundary Interaction $\Leftarrow$

Tritium Retention (for C)

Helium Pumping

PFC Heating by Fast α's

Disruption Damage Effects $\Leftarrow$

Erosion / PFC Lifetime $\Leftarrow$

Dust Generation

PFC Fatigue & Neutron Damage

- Which *could* be addressed by a burning plasma experiment (bpx):
  - If it has DT ($Q \geq 5$),
  - If it has High Stored Energy (> 1 MJ/m^2 disruptions),
  - If it has Long Pulses / High Duty Factor (mm of erosion, 10's kg dust),
- Which *need* a bpx?
- Which does a bpx need? At least one . . .

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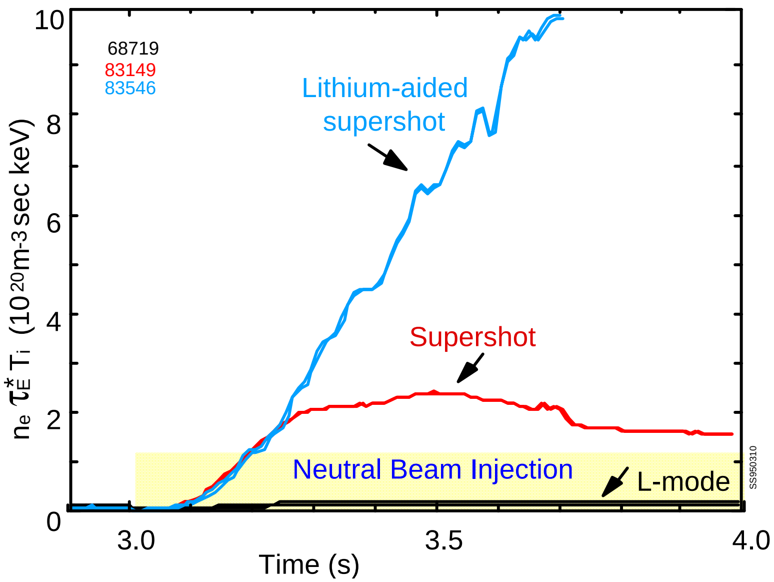
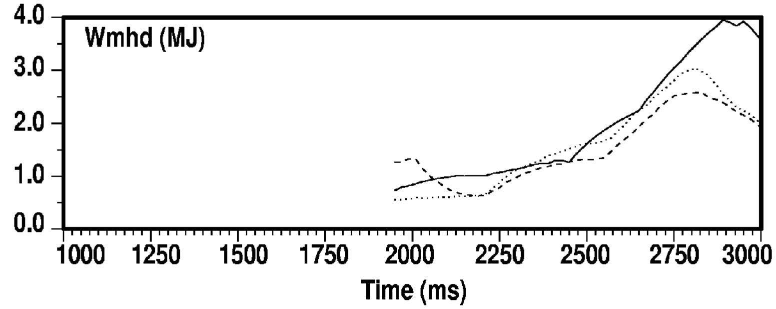
Control of Plasma Boundary Necessary to Access Burning Plasmas

- *Necessary*, not just sufficient.
- Wall conditions have huge impact on core performance,
- Examples from TFTR (Mansfield), DIII-D (Jackson, '96 PSI):





Must Control Surface Heat Fluxes To Avoid Impurities & Material Loss

- Led to development of power spreading techniques; new materials,
  - E.g., divertor detachment, RI mode; W rods, Cu alloys.
- Must do this while maintaining core boundary conditions,
  - While handling fuelling required for core density & pumping He.
- What about stability (robustness)?
  - Wall perturbations that lead to $\tau_E \uparrow \Rightarrow P_{\mathrm{SOL}} \uparrow$,
  - $\Rightarrow$ designs need margin.
- Can only test simultaneously on “bpx” because scalings differ (Perkins),
  - To have confidence, need to understand underlying science,
  - As an example, consider detachment.

Detached Plasma Operation Well Characterized & Modeled, But Not Completely Understood

- Nice discussion in Stangeby's book,
- To define, consider $\overline{n}_e$ ramp:
  1. At detachment, current to target probes rolls over & decreases,
  2. While D_α in divertor continues increasing.
  3. Also see target pressure $\ll$ midplane pressure.
- Edge plasma requirements for detachment:
  - Need ion-neutral friction & volume recombination to be significant, $\Rightarrow$ target temperature $<$ few eV.
  - Stangeby's 2-point model gives scaling of transition between high-recycling & detached regimes,
    - $\ast$ Power & momentum balance determine particle balance.

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$$n_{u,\mathrm{crit}} = 4.2 \times 10^{15} \frac{P_{\mathrm{SOL}}^{5/7} L^{1/14} (1 - f_{\mathrm{power}})^{9/14}}{\chi_{\perp}^{5/14} (aR)^{5/7}},$$

- Apart from f_{power}, $\Rightarrow n_u$ and P_{SOL} cannot be varied independently,
  - Must also be consistent with core confinement.
- This provides a basic understanding, but simulations represent solution of coupled nonlinear problems. Still need to know more about:
  1. $\perp$ transport, inside & outside separatrix,
  2. Impurity generation, transport, radiation,
  3. Supersonic flow & role of convection,
  4. Cross-field drifts,
  5. Trapping of Lyman-α radiation,
  6. "Molecular Activated Recombination."
- $\Rightarrow$ models still evolving,

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Disruption Damage Effects in Burning Plasma Experiment Will Be Qualitatively Different

- Disruption energy density will cross material vaporization threshold,
  - Existing devices, < 1 MJ/m^2,
  - At 1 MJ/m^2, have significant surface vaporization,
  - Burning plasma experiment will have 10–100 MJ/m^2.
  - $\Rightarrow$ can test vapor shielding effect seen in models.
    - $*$ Would reduce erosion,
    - $*$ But, divertor targets would still be considered “consumable”.

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- Runaway current I_{ra} may reach $\sim I_p$ in a burning plasma,
  - Importance of “electron avalanche” increases exponentially with I_p,
  - Gain ~ 100 for current tokamaks ($I_p = 2$ MA),
  - $\sim 10^7$ for FIRE,
    * $\Rightarrow$ need relatively large (~ 1 A) seed to get dangerous I_{ra},
  - $\sim 10^{16}$ for ITER-FEAT,
    * $\Rightarrow$ need only minute seed current.
  - Runaway losses due to MHD fluctuations may lead to lower gains,
  - But, should design surfaces to tolerate $I_{\mathrm{ra}} \sim 1$ MA.
- Deconditioning effects of disruptions likely greater,
  - $\Rightarrow$ need efficient recovery techniques (for C surfaces).

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PMI Issues in Long Pulse bpx Will Be Very Different

- $\geq 10^2$ extrapolation factor in PMI parameters (Counsell, Federici)

Parameter	Existing	ITER 1998
DT Particles / Pulse	6×10^{22}	7×10^{25}
Peak Divertor Energy (W yr / m^2)	4×10^{10}	8×10^{12}
Type I ELM Energy (MJ)	0.4	50
Disruption Magnetic Energy (MJ)	15	1100
Disruption Energy Density (MJ/m^2)	~ 0.1	> 10
T Retention Fraction	$> 10\%$	0.1% (reactor)
Pulse Length (s)	10	1000
Duty Factor	$< 10^{-3}$	0.1
Energy Content (MJ)	15	> 1000

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Would Need Much Better Plasma-Materials Interaction Science To Confidently Extrapolate To Long Pulse bpx

- Fusion has considered only effect of materials on plasma (impurities),
  - But for long pulse bpx, must consider effect of plasma on materials.
- Range of complexity of materials models:

  Simple single recycling coefficient (e.g., as in UEDGE)

  Intermediate reflection coefficient, absorbed fraction, sputtering yield, $f(\vec{v})$ for neutrals coming off surface (e.g., DEGAS 2, REDEP)

  Complex detailed description of material structure & composition vs. $\vec{x}, t$; response to fluxes, including collective effects (????)
- Last step analogous to leap from τ_E scalings to GK simulations.
  - Requires similar advances in diagnostics & more experimental effort.
- Only in process of making that leap will 'science" answers to these PMI problems be found.

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CONCLUSIONS

- Burning plasma will need control of plasma boundary.
  - And control of surface heat fluxes to avoid impurities.
  - Only a bpx can test consistency & stability of both requirements.
  - To be confident, will need to know more about transport, . . .
- Disruptions will be qualitatively worse in burning plasma,
  - Can test vapor shielding models,
  - And check predictions of runaway electron conversion.
- PMI issues in a long-pulse bpx will be very different,
  - Need much improved materials science to have confidence,
    - Especially diagnostics & run time,
      - Good materials diagnostics would allow *control* over wall sources.

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