Boundary Plasma Issues in Burning Plasma Science

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Issues present in any magnetic fusion configuration:

1. wide dispersal of power
2. high divertor gas pressures
3. eliminate impurity production
4. screening of impurities
5. burning plasma experiment?
(1) Wide Dispersal of Power

- parallel power density \( (q_u) \) flowing in the SOL in next-step devices is a serious issue

- material surfaces can handle \((5 \text{ MW m}^{-2})\) steady-state with active cooling, perhaps \(20 \text{ MW m}^{-2}\) pulsed

- divertor plate and magnetic geometry buys factor \(~100\), i.e. \(q_u \sim 0.5 \text{ GW m}^{-2}\) steady-state, \(q_u \sim 2.0 \text{ GW m}^{-2}\) pulsed

- c.f. \underline{ITER}, \(q_u \sim 1\) to \(2 \text{ GW m}^{-2}\), \underline{C-Mod} \(\sim 0.5 \text{ GW m}^{-2}\), \underline{DIII-D} \(\sim 0.2 \text{ GW m}^{-2}\)

- \textbf{in steady-state (> secs)}, reduce \(q_u\) by \(~4\) by divertor radiation processes (detached or partially detached), i.e. impurities needed (at least in the divertor → screening)

- \textbf{pulsed ( ~ secs)}, can handle power, particularly if strike points are swept (BPX), but \(T_i\) will be high → impurity production, high \(Z_{\text{eff}}\) (not desirable mode of operation )

- we know a lot more now than during the BPX design!
(1) Wide Dispersal of Power/(cont)

• high recycling or detached regimes essential:
  – elevated divertor radiation
  – results in high divertor plasma/neutral densities

• criterion for high recycling and cold divertor, $T_t \sim 5$ eV
  (a prerequisite for detachment):

\[
\frac{L^{4/7} n_u^2}{q_u^{10/7}} > 3 \times 10^{29} \quad \text{(SI units)}
\]

• this is essentially a collisionality parameter:

  collisional $\rightarrow$ develop parallel gradients
(1) Wide Dispersal of Power/(cont)

- most important parameter: power width $\lambda_P$

$$q_u \sim \frac{P_{SOL}}{\lambda_P}$$

- $\lambda_P$ determined by relative rates of cross-field ($\chi_\perp$) and parallel heat transport (Spitzer conductivity):

$$\lambda_P \sim \frac{(n_u \chi_\perp)^{7/9}}{P_{SOL}^{5/9}}$$

- $q_u$ at high power and especially in H-mode rises strongly: i.e. as $P_{SOL} \uparrow$ and $\chi_\perp \downarrow$, then $\lambda_P \uparrow\uparrow$

- we have very little solid scaling for $\chi_\perp$ amongst different machines $\Rightarrow$ a real need from present experiments!
(1) Wide Dispersal of Power/(cont)

ELMs

- ELMs exhaust power in short periods of time (< 1 ms)

- Type I: $\Delta E/E = 0.02$ to $0.06$, gives 2 to 6 MJ m$^{-2}$ (ITER) on divertor plate, significant erosion expected above 1.5 MJ m$^{-2}$

- mitigating factors: - radiation (non-coronal)
  - $\lambda_P$ broadening

- probably depends on details, particularly density, impurity content, etc  $\Rightarrow$ research on present experiments needed
(2) High Divertor Gas Pressures

- while maintaining low main chamber pressure for H-modes (tight baffling??)

allows efficient pumping to:
- remove helium ash
- induce SOL flow towards divertor
- control density

helium exhaust time, i.e. $\tau_{\text{He}}$, limited by extraction rate at the edge (maybe not with ITB)

present results are encouraging: $\tau_{\text{He}} < 10 \tau_{\text{E}}$

scaling to reactor is favorable, i.e. $\tau_{\text{He}} \sim a$, $\tau_{\text{E}} \sim a^2$
(3) Eliminate Impurity Production

- high recycling or detached regime ($T_t < 5$ eV) will ensure target plate physical sputtering is small

- chemical sputtering of carbon a serious issue (no energy threshold), existing graphite machines rarely have $Z_{\text{eff}} < 1.5 \Rightarrow$ avoid graphite (also essential to avoid tritium inventory problems through co-deposition)

- throat region is interface between energetic plasma and neutrals $\Rightarrow$ potential for CX sputtering (perhaps use high Z material here, has high energy threshold)

- interaction at walls of tenuous plasma:
  1. how does plasma reach wall? (rapid $\perp$ transport?)
  2. can dominate core impurity contamination
  3. volatile impurity gases reduced with boronization
(4) Screening of Impurities

- we need impurities to radiate power:
  1. mantle (~ 10% to 50% in present machines) – not desirable since this means (a) core contamination (b) reduction of $P_{SOL}$ (c) confinement degradation
  2. divertor – highly desirable

- how to have divertor enrichment ($\eta \equiv c_{\text{gas}}/c_{\text{plasma}}$) for impurities (including helium)?

- flow entrainment to fight thermal force:
  1. natural: rely on the relative mfp’s of the impurity atoms compared with the hydrogenic atoms,
     (a) helium dilution, $0.1 < \eta_{\text{He}} < 0.8$
     (b) N, Ne, Ar strong enrichment, $\eta_z = 5$ to 20
  2. generate flow: into the divertor,
     (a) strong divertor pumping with main chamber fuel puffing
     (b) neutral gas manipulation, e.g. plate/baffle geometry, by-passes

- validate present codes for application to the Next-Step
Why do we need a Burning Plasma Experiment?

because...

$\lambda_P$, ELMs, main chamber recycling $\Rightarrow$ we really cannot predict these with any certainty