Boundary Plasma Issues in Burning Plasma Science

C S Pitcher, MIT PSFC

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 MW m^{-2}) steady-state with active cooling, perhaps 20 MW m^{-2} pulsed**

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

- **c.f. ITER, q_u ~ 1 to 2 GW m^{-2}, C-Mod ~ 0.5 GW m^{-2}, DIII-D ~ 0.2 GW m^{-2}**

- **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)**

- **pulsed (~ secs), can handle power, particularly if strike points are swept (BPX), but T_t will be high → impurity production, high Z_{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):**

$$\frac{L^{4/7}\, n_u^2}{q_u^{10/7}} > 3 \times 10^{29} \qquad \text{(SI units)}$$

- **this is essentially a collisionality parameter:**

collisional $\rightarrow$ develop parallel gradients

(1) Wide Dispersal of Power/(cont)

- **most important parameter: power width λ_P**

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

- **λ_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)
  - λ_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. τ_{He} , limited by extraction rate at the edge (maybe not with ITB)**

- **present results are encouraging:** $\tau_{He} < 10\ \tau_E$

- **scaling to reactor is favorable, i.e.** $\tau_{He} \sim a$, $\tau_E \sim a^2$

(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_{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 ($\eta \equiv c_{gas}/c_{plasma}$) 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, $0.1 < \eta_{He} < 0.8$**
        - **(b) N, Ne, Ar strong enrichment, η_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**

(5) Why do we need a Burning Plasma Experiment?

because….

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