Impurity sputtering and SOL transport for mixed-material walls in ITER*

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ITER walls are made up of beryllium, tungsten, and carbon

- For various reasons, ITER has decided on mixed-material PFCs
- These materials sputter and mix throughout the SOL, and redeposit
- Such redeposition can change material properties

This work begins to quantify such material migration
Probe data shows structure of far-SOL in DIII-D (Rudakov et al., Nucl. Fusion ‘05)
Previous ITER divertor-plasma modeling assumed diffusive radial transport only; we add convection

- ITER assumes 100 MW power input to SOL
- Here carbon modeled as a 3% concentration
- Anomalous radial diffusion set at $D = 0.3 \, \text{m}^2/\text{s}$, $\chi_{e,i} = 1 \, \text{m}^2/\text{s}$
- We add a radial convection term on outboard side, as experiments and simulations imply

$$\Gamma_n = -D \frac{dn}{dr} + V_{\text{conv}} n$$
Plasma fluxes to the wall increase more than local density owing to ionization of recycled gas

- Since $n_i$ and $V_{\text{conv}}$ increase, the $nV$ flux is much larger
- Ionized neutrals contribute the flux
- Ion temperature decreases some owing to cold ionization source; ion energy flux slower
- Hot cx-neutrals, sheath drop to be added to energy flux
ITER utilizes a single-null divertor with steeply-inclined divertor plates

- Nearly vertical plates reduce heat flux & facilitate plasma detachment
- Carbon radiation helps reduce $T_e$ near strike point to allow He pumping

Poloidal cross-section showing edge-plasma region
Physical sputtering of Be, C, and W is strongly energy dependent; W sensitive to energetic tails
Be physical sputtering yields acceptable core concentration for $V_{y_{\text{conv-max}}} = 70 \text{ m/s at wall}$

- Roughly consistent with WBC, but shows separatrix structure (should understand this better)

- About 1% Be concentration at core edge; tolerable, but non-trivial with long timescale for steady-state

- Convection level is uncertain, so Be estimates are also
Charge-exchange hydrogen can present a substantial sputtering source at the wall

Plasma for $r < 3.7$ cm from UEDGE case ffC.6 with convective transport; plasma for $r > 3.7$ cm for 3 models

- Case 1: $n_i = 10^{19}$
- Case 2: $n_i = 10^{18}$
- Case 3: $n_i = 10^{17}$

Graphs showing radial distance from separatrix (cm) vs. ion density ($10^{19}$ m$^{-3}$) and ion temperature (eV).
DEGAS 2 is used to calculate the energy spectrum of hydrogen neutrals incident on the wall.
We have doubled the size of the SOL, which brings in the upper X-point & 2 separatrices.
We can now consistently treat the SOL plasma striking the W baffle

\[ \psi_{\text{max}} = 1.035 \]

\[ \psi_{\text{max}} = 1.07 \]
Midplane $n_i$ and $n_g$ are most strongly affected by the expanded SOL; less main wall recycling

- Substantial effort to improve UEDGE to work for these cases; convergence “routine”
- Busty character of blobs, ELMs can change far-SOL
The far SOL has been extended even further in recent simulations; includes all of lower W baffle

\[ \psi_{\text{max}} = 1.09 \]
Hydrogen particle flux is much larger to the divertor than the walls, but …

- Inclusion of extended SOL allows us to evaluate wall flux details
- Quantifies “window frame” idea (Lipschultz, Whyte et al.) for ITER

![Graph showing ion flux to lower divertor/baffle and radial hydrogen ion flux to wall.]

- Peak flux \( \sim 10^2 \) larger than that to wall
Extended SOL simulations show large fluxes to upper X-point and W baffle regions

- Comparing $psi_{\text{max}} = 1.035$ (SN) to $psi_{\text{max}} = 1.07$ (UBDN) shows $\sim1/2$ of wall flux concentrates at the upper X-point and W baffle regions

- Such localized fluxes $\sim10+$ times the “average” wall flux
Temperature profiles show that upper localized X-point region is hotter than W-baffle region.
Sputtered W from the baffle-only provides an estimate for high-Z impurity intrusion

- Incident energy spectrum uncertain
- W sputtering yield is uncertain at lower energies

\[ \psi = 1.07 \]

\[ \psi_{\text{max}} = 1.07 \]
Simulation of W sputtering and penetration from lower baffle region shows small concentrations

- Yield curve is physical sputtering of W in the baffle region only (estimated)
- Ionization and recombination are taken for W
- W concentration is low - \( \sim 10^{-6} \); very sensitive to ELMs, imp. transport model
- Location of sputtering is important - midplane worse for impurity intrusion
Time-dependent transport is being incorporated in UEDGE to model blobs and ELMs

H-α light from MAST tokamak shows ELM structure (Kirk)
Summary and plans

• Be levels at core boundary ~1%; timescale for S.S. is ~1 sec
  – Be can coat C plates; good, lowers chemical sputtering
  – Be can also coat W baffle; bad, lowers melting temperature of W

• W sputtering from lower baffle may not be a problem, but uncertainties are large:
  – fully-extended far-SOL not yet included in analysis
  – W sputtering sensitive to incident energy, especially ELMs
  – CX-sputtering energy spectrum from DEGAS 2 indicates that a high energy tail may be worrisome for W

• Extending simulations to far SOL beyond 2nd separatrix quantifies localized fluxes to upper X-point and W-baffle regions

• Time-dependent model of blobs, ELMs can change far-SOL plasma and wall flux; to be investigated