Neutral Transport from Wall to Scrape-Off Layer

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"Edge Plasma Physics and Plasma Material Interactions in the Fusion Power Plant Regime"

Why Do Neutrals Matter?

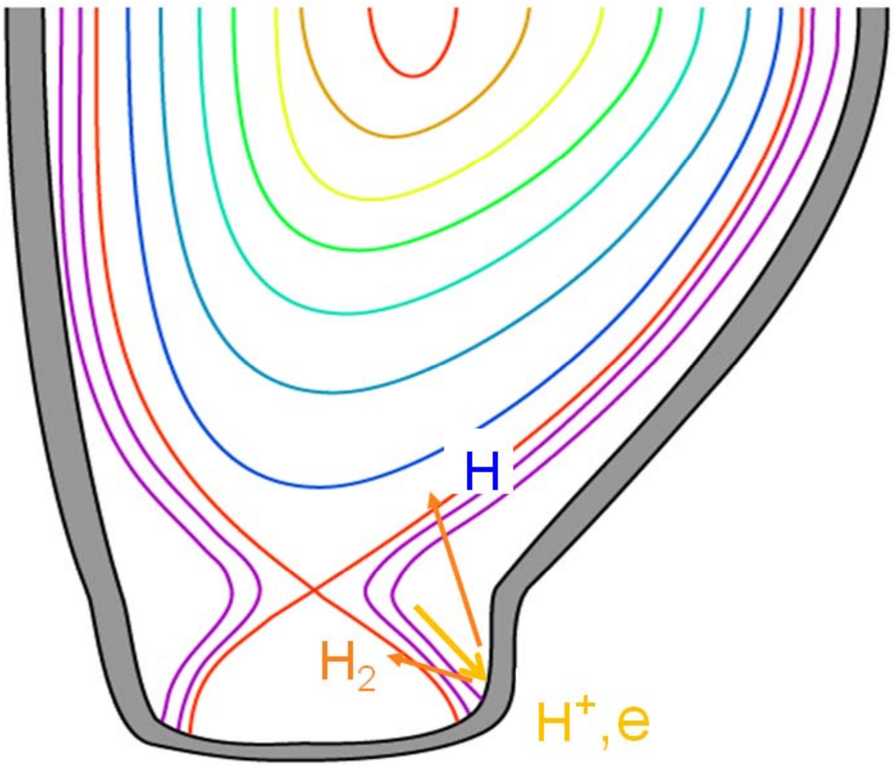
- Wall is sink for plasma, but not mass: recycling
- Sputtered impurities leave wall as neutral atoms & molecules
- Fueling, beam heating, pumping involve neutrals
- Detachment hinges on neutral–plasma interactions
- Play a role in edge transport & turbulence / H–mode (?)
- Increase impurity radiation rate
- Basis for edge & core diagnostics

Outline

- Neutral sources
  - Recycling
  - Sputtering
  - External sources
  - Volume recombination
- Interactions
  - Plasma–material interactions
  - Plasma–neutral reactions
  - Detachment
  - Radiation trapping
- Other stuff

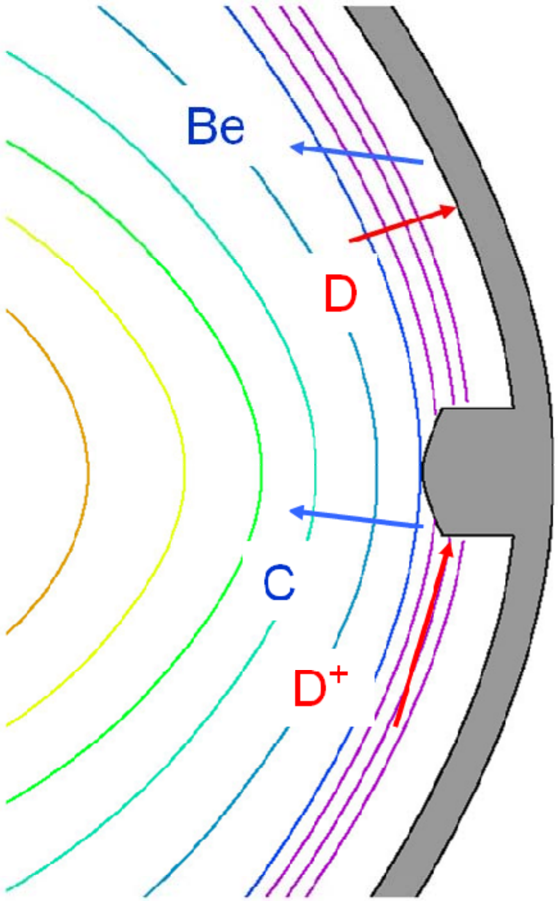
Wall is Sink for Plasma, But Not for Mass: Recycling [Stangeby 2000]

- Flows along open field lines to surfaces,
- Ions accelerated through sheath → PMI:
  - Backscattering → H,
  - Or Absorption,
  - Desorbed as H_2 in steady state.
- H_2: absorbed & desorbed.
- Kinetic details:
  - Backscattered velocity distribution,
  - Ro-vibrational state of molecules?
- Other issues:
  - Real PMI,
  - Permanent absorption / wall pumping.



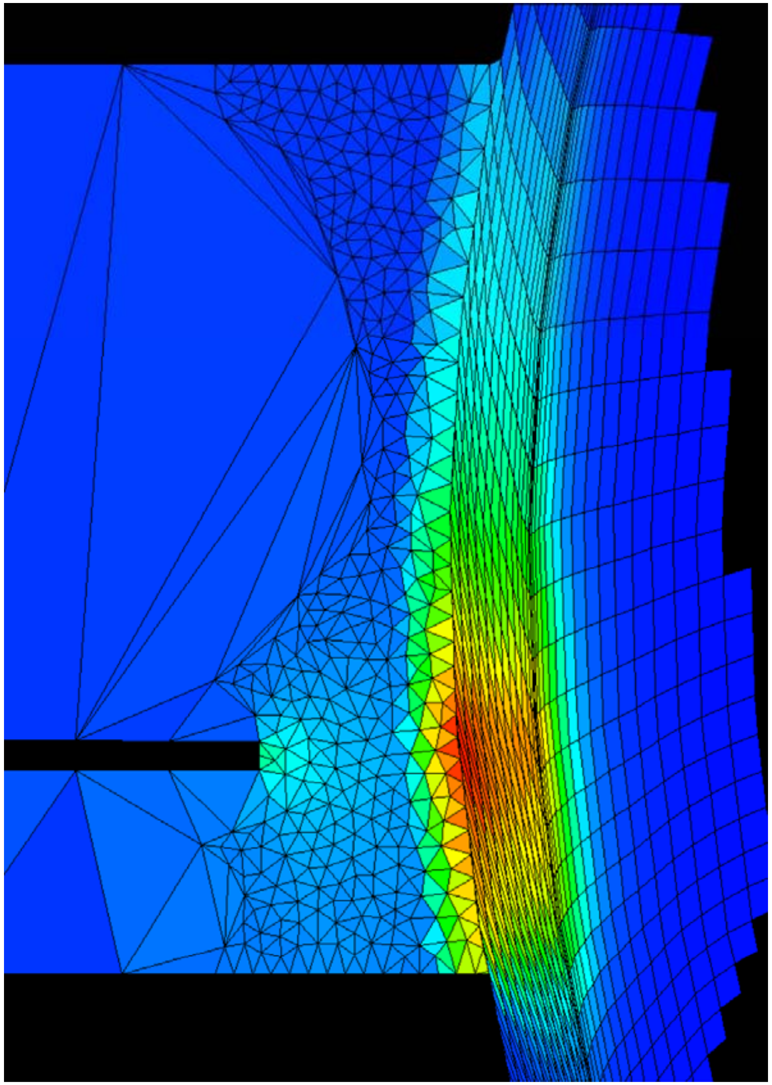
Sputtered Impurities Leave Wall as Neutral Atoms & Molecules

- ⇒cross magnetic field lines.
- Particles knock off substrate atoms ⇒ physical sputtering.
- E.g., ions going through sheath when $T_e > 100$ eV.
- Or atoms CX'ing with hot ions,
  - Main chamber erosion & deposition issue for ITER [Kotov 2009].
- Chemical sputtering
  - Usually refers to hydrocarbons formed on graphite.



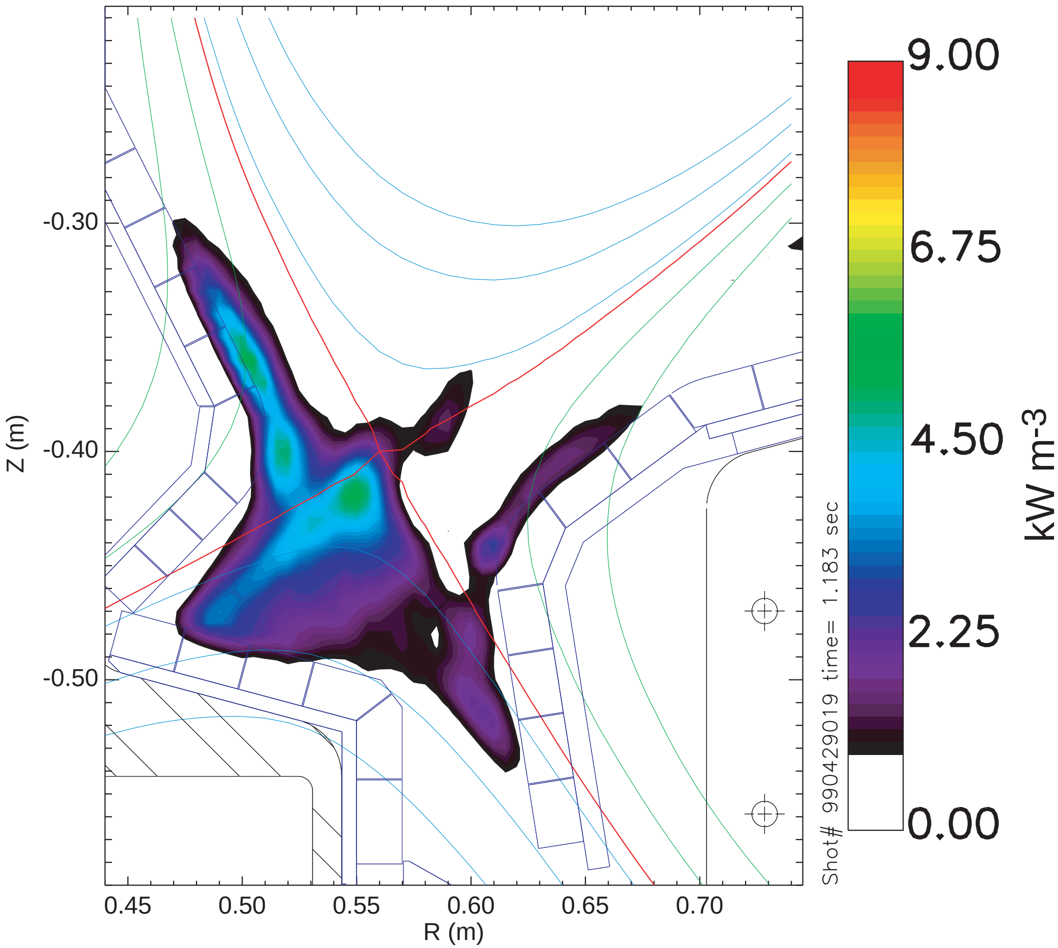
Fueling, Beam Heating, Pumping Based on Neutrals

- Gas Puff:
  - Easy to install & control,
  - Flexible timing, composition, rate,
  - Easy to simulate!
  - Big drawback: poor penetration,
- Higher density methods more efficient:
  - Pellet,
  - Supersonic gas injection,
  - Molecular clusters.
  - Better not just due to speed,
  - On HFS, aided by ∇B drift [Lang 1997].
  - Difficult to model because of impact on plasma parameters & equilibrium.
- Neutral beam injection:
  - Reliable heating with extensive database.
  - Deep core fueling in present day devices.
  - Can be modeled.
  - Basis for several diagnostics.



Volume Recombination of Hydrogen Can Be Dominant Neutral Source

- If T_e low enough, say, < 1 eV.
- Detect by D_γ / D_α,
- Ratios & rates come from atomic physics model.
- Recombination included in edge simulation codes,
  - Sensitivity to T_e complicates interpretation of experimental data [Lisgo 2005].
- Observed in detached plasmas.



[Boswell 2001]

Outline

- Neutral sources
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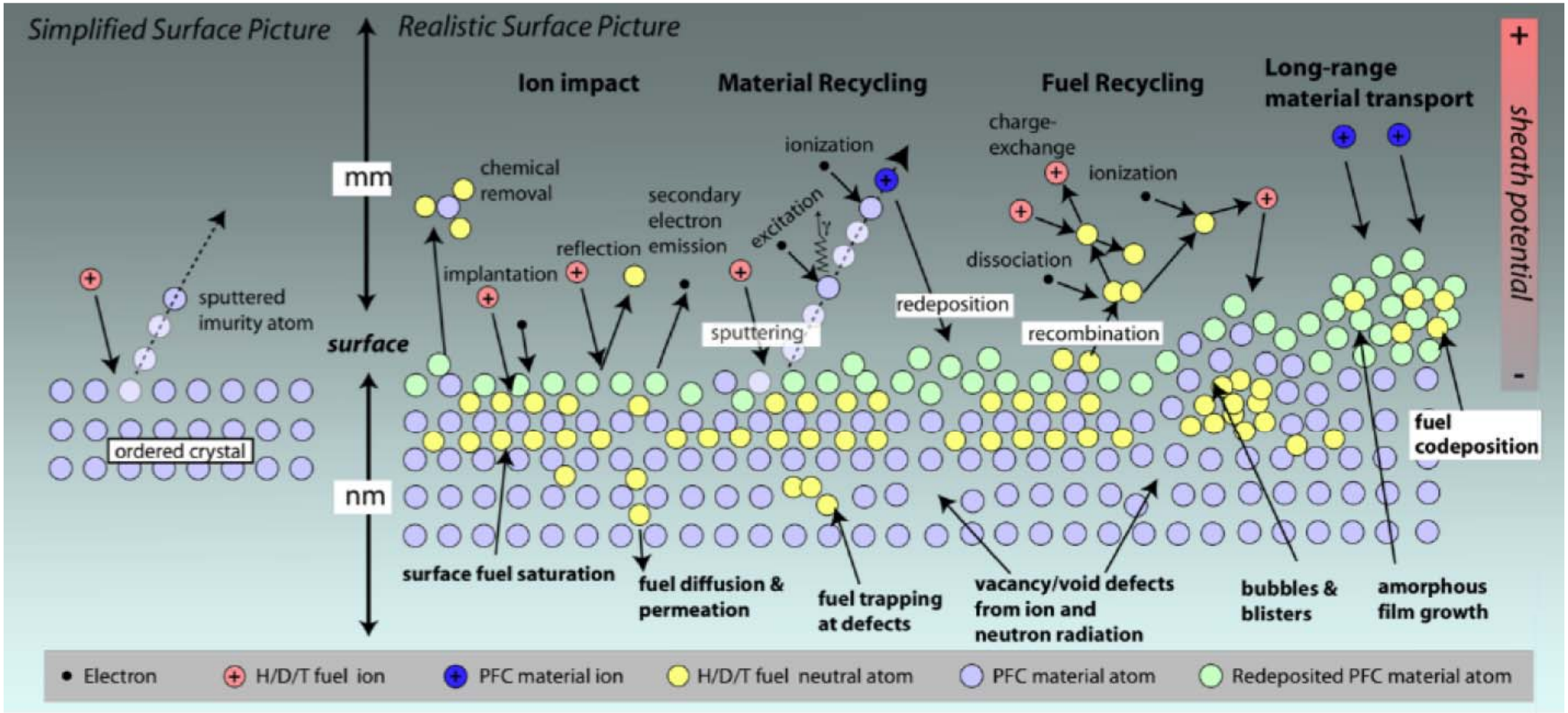
  - Plasma-material interactions
  - Plasma-neutral reactions
  - Detachment
  - Radiation trapping
- Other stuff

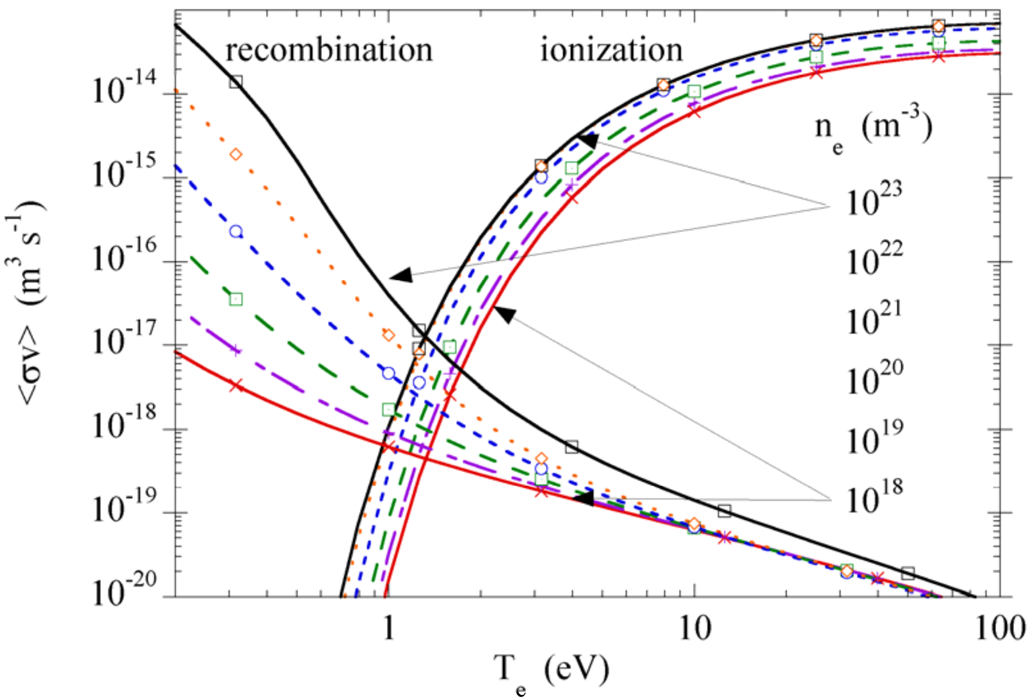
Descriptions of Materials & PMI in Neutral Transport Codes Relatively Simple



* Whyte and Wirth, unpublished

Electron Impact Ionization of Hydrogen is a Multi-Step Process

- Collisions excite, de-excite, & ionize,
- Atoms can decay radiatively.
- Timescales comparable ⇒ treat all.
- Ionization of H(n=0) is one of thousands [Loch 2009].
- Excited states equilibrate faster than ground state changes,
  - ⇒ collisional radiative model.
  - Yields effective rates of ionization and recombination for ground state.
  - Functions of n_e & T_e.
- & line emission (D_α), total radiation, electron cooling rates.
- Assumes plasma optically thin.
- Similar data for He [Loch 2009], Li [Loch 2006]…

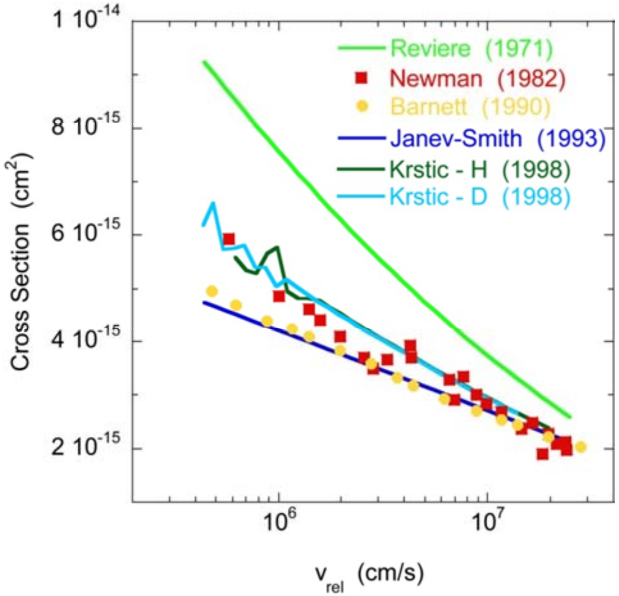


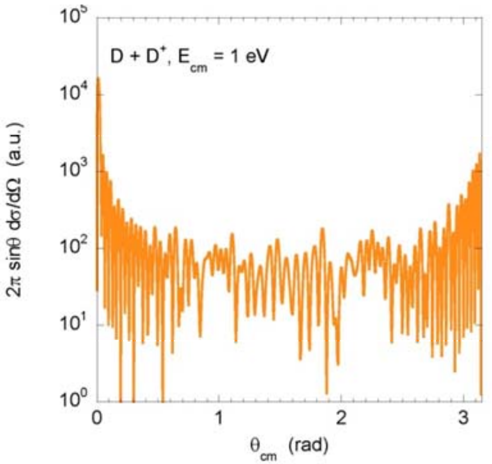
[Post 1995]

$$\frac{Dn_0}{Dt} = -n_0 n_e S_{\text{eff}} + n_i n_e R_{\text{eff}}$$

Charge Exchange & Elastic Scattering Exchange Momentum & Energy Between Ions & Neutrals

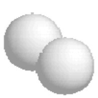
- $H + H^+ \rightarrow H^+ + H$,
  - Pure CX: 180° scattering in center of mass,
  - Below ~1 eV, momentum transfer from elastic scattering also important.
  - Fully quantal calculations of $d\sigma/d\Omega$ describe as single reaction [Krstic 1998].
- $H_2 + H^+ \rightarrow H_2 + H^+$,
  - Elastic scattering transfers energy to $H_2 \Rightarrow$ longer mfp [Krstic 1998].
- Neutral-neutral: $H + H$, $H + H_2$, …
  - Nonlinear $\Rightarrow$ iterative BGK [Kotov 2006],
  - Significant impact on ITER neutral pressure & pumping [Kukushkin 2005].



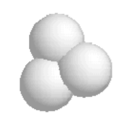


H_2, H_2^+: How Big Does the Zoo Need to Be?

- Lower $T_e \Rightarrow H_2$ longer lifetime $\Rightarrow$ additional processes,
  - Vibrational excitation & de-excitation,
  - $\Rightarrow$ ion conversion: $H_2(v) + H^+ \rightarrow H_2^+ + H$,
  - More species: H_3^+, H^-.
- Predicted "Molecule Assisted Recombination" [Krasheninnikov 1997],
  - AUG modeling [Fantz 2001], showed instead "Molecule Assisted Dissociation"!
- "Collisional radiative" rates for H_2, H_2^+: [Sawada 1995], [Greenland 2001], [Pigarov 2002], [Kotov 2006],
  - Treating $H_2(v)$ as "excited state".
- In ITER simulations, H_2 CR model increases PFR pressure & neutral power flux to targets. [Kukushkin 2005].
- In general, should include $H_2(v)$ [Reiter 2007],
  - But, has not had significant impact on macroscopic divertor parameters.



$$\frac{dn_{H_2}}{dt} = -\left(D_{H_2} + S_{H_2} + I_{H_2}\right) n_e n_{H_2}$$



$$\frac{dn_{H_2^+}}{dt} = S_{H_2} n_e n_{H_2} - \left(R_{H_2^+} + D_{H_2^+} + S_{H_2^+}\right) n_e n_{H_2^+}$$

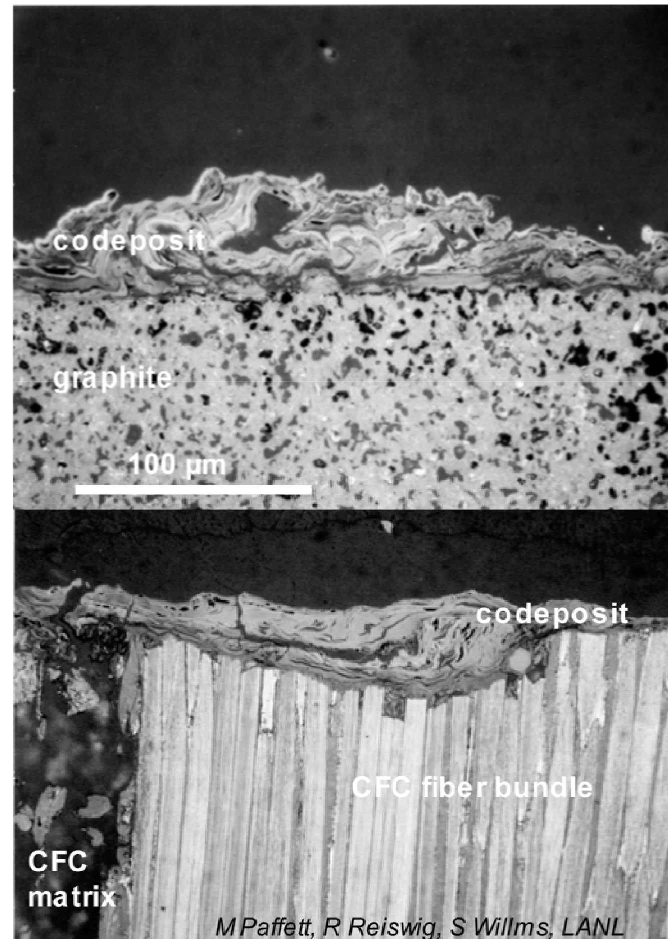
$$\frac{dn_H}{dt} = \left(2D_{H_2} + I_{H_2+}\right) n_e n_{H_2} + \left(2R_{H_2^+} + D_{H_2^+}\right) n_e n_{H_2^+} - I_H n_e n_H + R_H n_e n_{H+}$$

$$\frac{dn_{H^+}}{dt} = I_{H_2} n_e n_{H_2} + \left(D_{H_2^+} + 2S_{H_2^+}\right) n_e n_{H_2^+} + I_H n_e n_H - R_H n_e n_{H+}$$

[Kotov 2006]

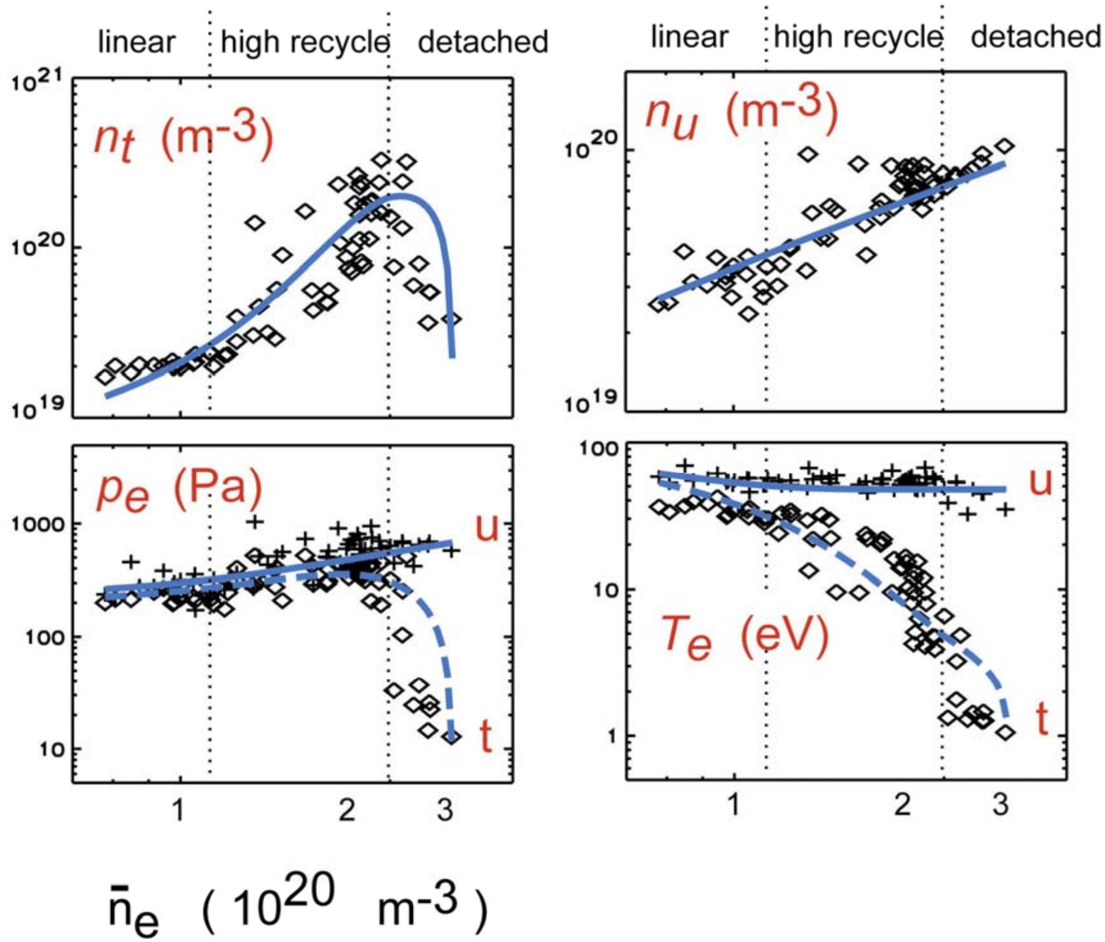
Another Reason to Get Rid of Carbon

- Would like to avoid carbon because of T inventory [Federici 2001].
- If we really understood hydrocarbon creation, transport, & deposition...
- Starting point: data for dissociation & ionization of hydrocarbons,
  - CH_y, C_2H_y, C_3H_y [Janev 2002], [Janev 2004],
  - HYDKIN reaction analysis tool: http://www.hydkin.de
- Resulting systems very complicated!
  - 700 processes for C_3H_y!
  - Many more fragmentation channels.
- Different pathways dominate at low (1 – 2 eV) & high T_e (> 10 eV) [Reiter 2009] ⇒ simpler models may be possible.



Partial Detachment Allows ITER to Radiate 60 – 70% of Divertor Power

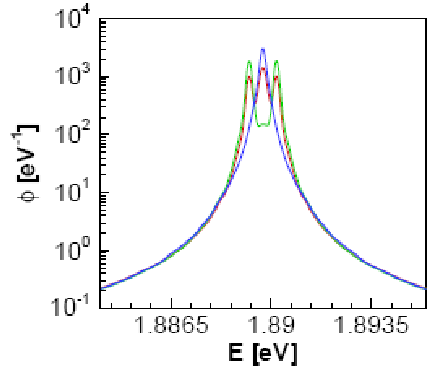
- Via photons & neutrals [Pitts 2009].
- $j_{sat} \downarrow$, but $D_\alpha \uparrow$ with increasing $\langle n_e \rangle$ [Stangeby 2000],
  - & $T_e < 1 - 2$ eV or pressure drop along field line.
- Complicated interplay of many processes $\Rightarrow$ different types of detachment.
  - Ion-neutral friction to removes momentum & power,
  - Recombination may be present, but not controlling,
  - Radiation trapping.
- Simulation of observed detachment behavior difficult [Wischmeier 2009].

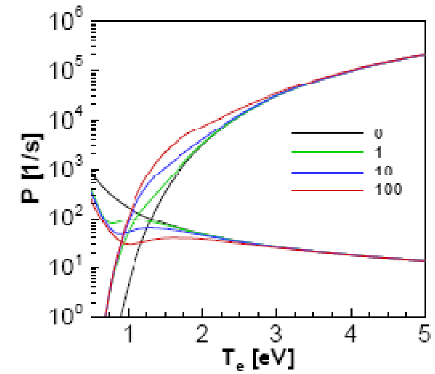


[Pitcher 1997]

Lyman-α MFP << Local Dimensions for ITER Divertor

- For Ly-α ~ 0.2 cm / $n_D(10^{20}\ m^{-3})$ [Post 1995],
  - ⇒ Photons reabsorbed by atoms ⇒ "trapped".
- Couples plasma ↔ neutrals ↔ radiation,
  - & line shape effects important.
- EIRENE models photons in same way as atoms & molecules,
  - Add photo-excitation to H CR model [Reiter 2002],
  - Include Zeeman splitting, and, for Ly-α, fine structure Zeeman-Stark profiles [Reiter 2007].
  - 2x increase in ITER n_e, lower T_e [Reiter 2007].
  - ~100% of Ly-α trapped & 60-90% inner divertor ionization due to "radiative stimulated ionization".
- Alternative: add plasma transport model to NLTE code CRETIN [Adams 2004],
  - Used to benchmark modified CR rates [Scott 2004] ⇒ $S_{eff}(n_e, T_e, L)$, $R_{eff}(n_e, T_e, L)$ & use in existing plasma & neutral transport codes.
  - Approximate treatment may suffice for high opacity [Scott 2004], [Kotov 2006].



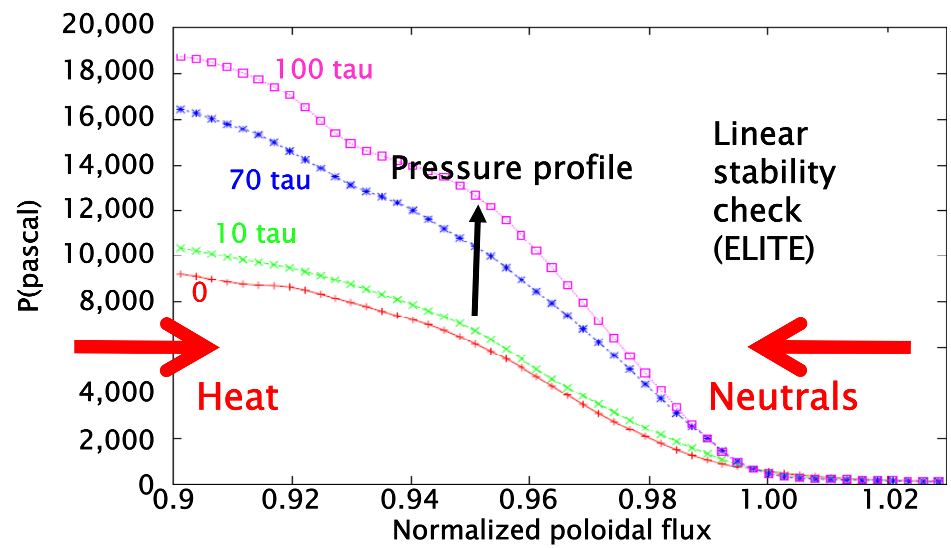


[Adams 2003]

How Important are Neutrals for Edge Turbulence & Transport?

- Investigated by Center for Plasma Edge Simulation
  - SciDAC Proto-FSP, C. S. Chang – PI.
- Developing simulations of edge pedestal buildup & ELM crash via:
  - XGC0 – kinetic neoclassical guiding center particle code [Chang 2004],
  - DEGAS 2 – kinetic Monte Carlo neutral transport code,
  - ELITE– Linear MHD code,
  - M3D – Extended MHD code.
- Roles in problem:
  - XGC0 – Plasma transport, self-consistent E_r,
  - DEGAS 2 – Ionization source feeding pedestal buildup,
  - ELITE– detect ELM instability,
  - M3D – simulate nonlinear ELM crash.
- Other impacts of neutrals being investigated,
  - E.g., modifications to ion distribution function.

Pedestal buildup in XGC0

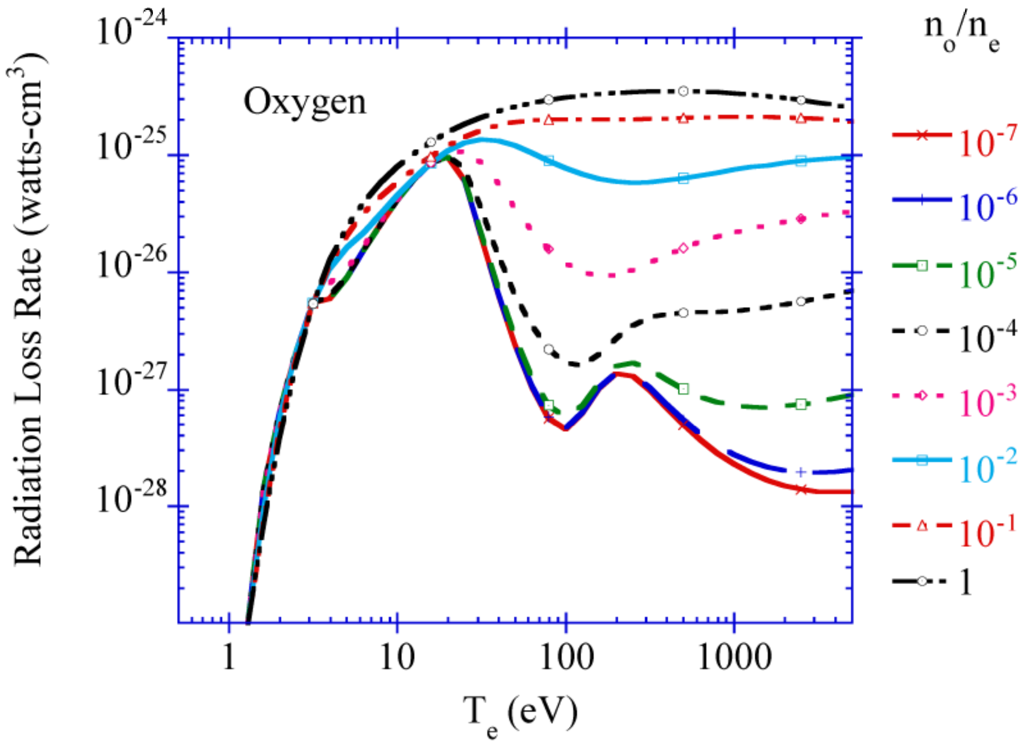


ψ_N

[Park 2007]

Pumping, Impurity Radiation & Diagnostics

- Helium pumping [Kukushkin 2009]
  - Code results given high credibility,
  - Used to evaluate divertor design.
- Impurity CX with H,
  - Reduces average charge state ⇒ increased radiation.
- Neutral based diagnostics
  - CX recombination spectroscopy,
  - Gas puff imaging, etc.
  - Beam emission spectroscopy,
  - Motional Stark Effect.



[Post 1995]

Conclusions

- Do we understand neutral transport?
  - Why else would we develop detailed 3-D, kinetic, neutral transport models?
- But, we don't have a complete picture:
  - Simulations depend on uncertain plasma parameters,
  - Incomplete atomic physics data,
  - And rudimentary PMI.
- We've got a lot of work to get to a predictive model:
  - Fusion Simulation Program,
  - Expanding PMI research effort.

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Interpretation of Light Emission

- Neutral transport calculations readily yield volumetric light emission (e.g., Dalpha) amenable to calculation of synthetic diagnostics and comparison with experimental data.
- However, emission rates may be sensitive to Te,
  - And ne, Te may vary locally over short times due to intermittent turbulent transport,
  - Because emission nonlinear function of Te, time average emission ≠ emission at average Te.
- Interpretation further complicated by light reflections,
  - Occasionally problematic in past,
  - Much more so with full metal machines and shiny Li coatings,
  - For Li, using Ly-alpha lines instead.