NSTX

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Modeling core impurity reduction via divertor gas injection in NSTX

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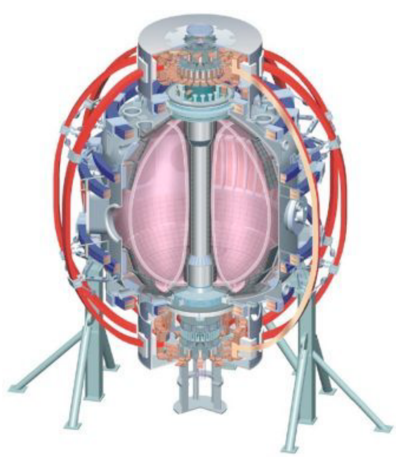
European Physical Society Conference on Plasma Physics
Stockholm, Sweden
July 2-6, 2012



Outline

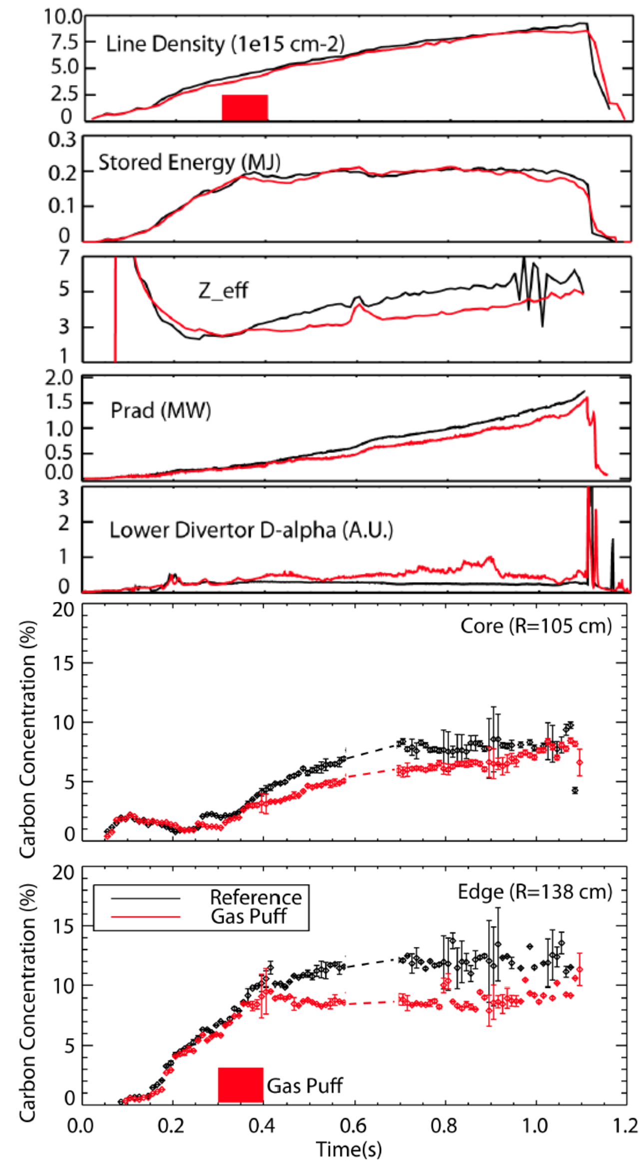
- Experimental details
- UEDGE modeling details
- Comparison of modeling to experiment
- Insights from modeling
- Conclusions

In NSTX, lithium conditioning led to impurity accumulation

- Lithium conditioning → impurity accumulation
  - Lithium-induced edge stabilization suppresses ELMs, allowing accumulation
- High impurity concentration can be problematic
  - P_{rad} up to 2 MW (largely due to high-Z impurities)
  - Lack of density control → disruption
  - Z_{eff} increase → resistivity increase → disruption
  - Fuel dilution
- Impurity control techniques have been developed on NSTX
  - ELM triggering with resonant magnetic perturbations (RMPs) [Canik PRL 2010]
  - Control plasma-wall interaction during startup phase
  - Partially detached divertor scenarios (gas puff, impurity seeding, snowflake)
  - **Deuterium gas puffing [Scotti APS 2010]**

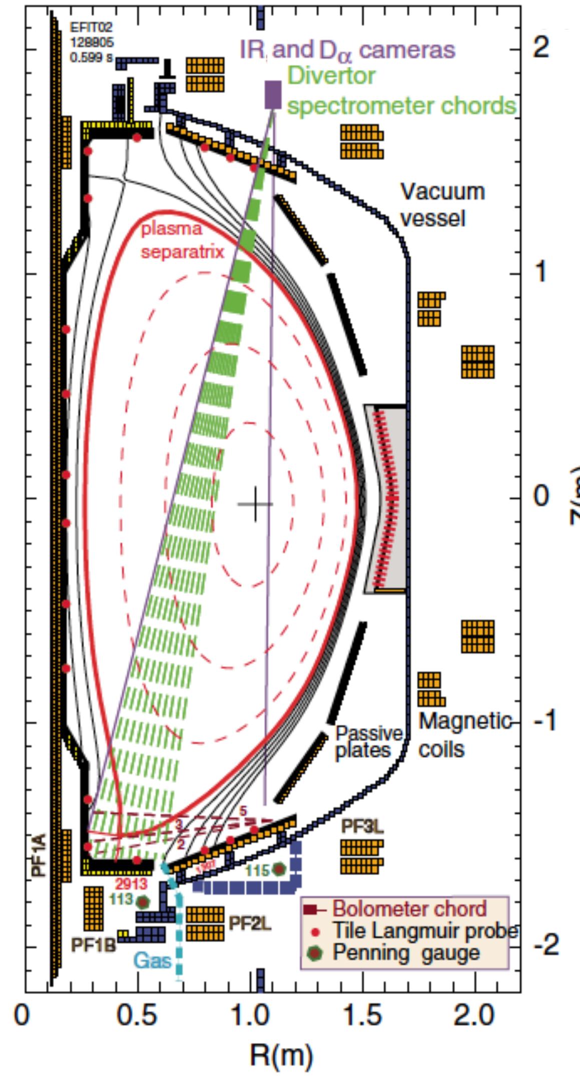
Divertor deuterium puffing on NSTX reduced impurity concentration by up to 30%

- ~1.25 x 10^{21} injected in 0.1 sec
  - 2000 atom-amp (A) injection rate ($1\ s^{-1} = 1.6 \times 10^{-19}$ A)
- Core plasma retains desirable properties
- Outer divertor remains attached
- Carbon concentration reduced 30%
- Deuterium puffing might…
  - Reduce sputtered influx
  - Modify parallel impurity transport
    - Divertor impurity retention
    - Other?



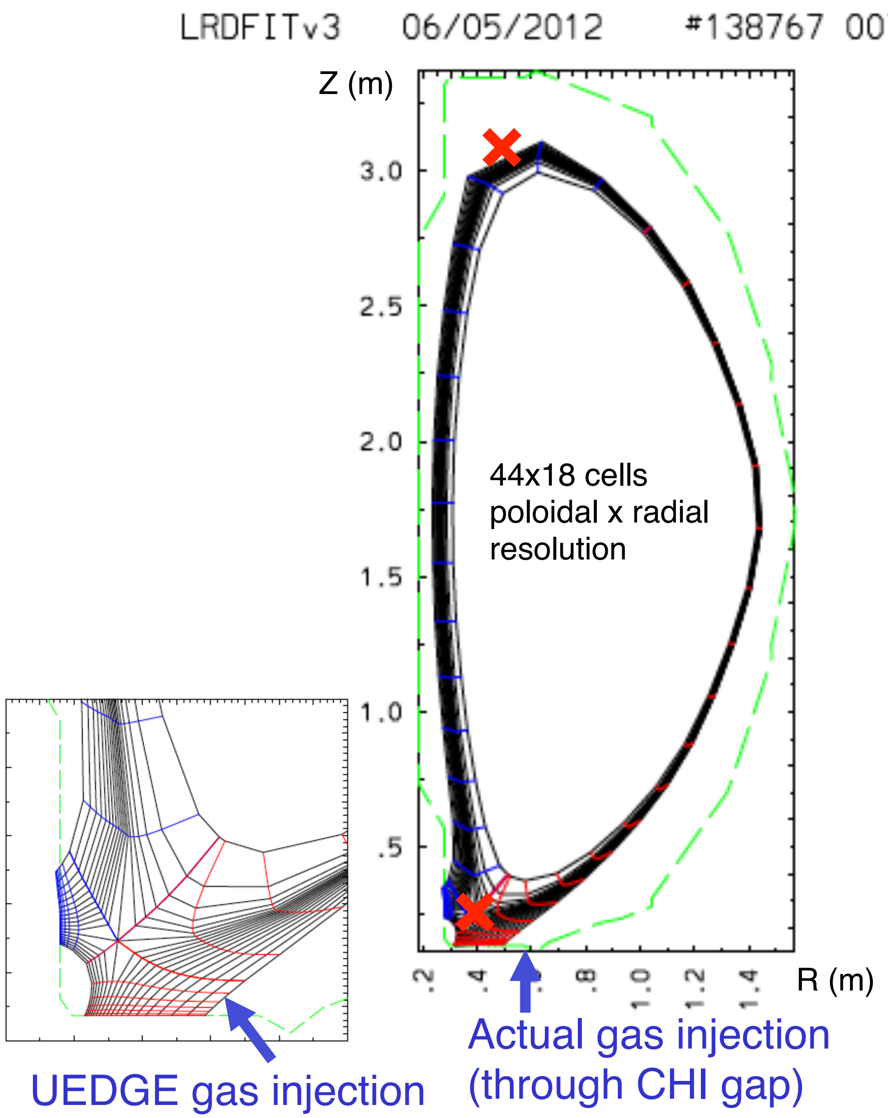
Divertor diagnostics include IR and visible cameras, divertor spectrometry, and tile Langmuir probes

- Divertor diagnostics
  - IR camera used to determine heat flux
  - Filtered visible cameras provide D_α and CII (658 nm) emission data
  - Tile Langmuir probes
    - Probes are in the far SOL of these high triangularity shots
- Outer midplane diagnostics
  - Thomson scattering gives n_e and T_e
  - ChERS gives $T_{C^{6+}}$ and $n_{C^{6+}}$



[Soukhanovskii NF '09]

The UEDGE 2D fluid transport code is used to study effects of gas puffing on carbon transport

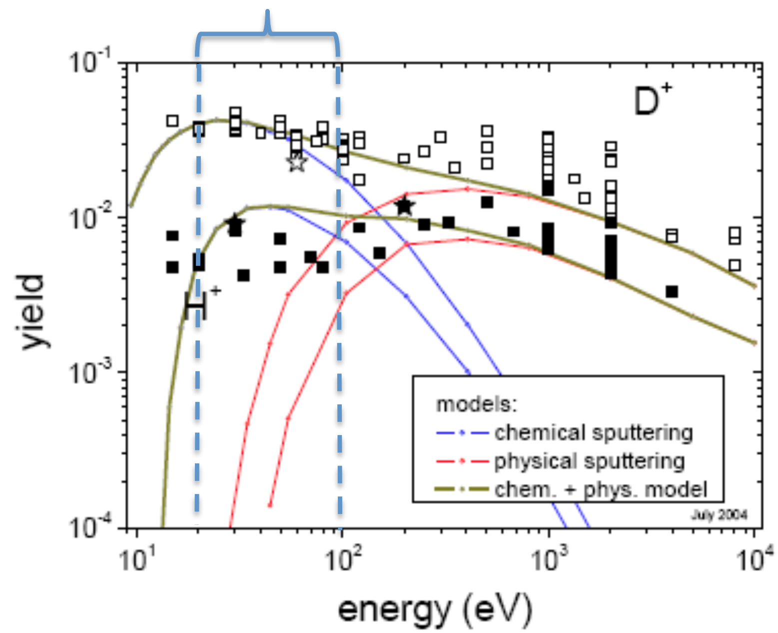


- Multi-species carbon model (C^{1+} - C^{6+})
- 0.96 < psi < 1.028 → ~6 mm SOL
- Deuterium gas injection is modeled as a cosine-shaped source with 0.2-m width at outer UEDGE grid boundary
- D_{perp} = 0.5 m^2/s, $\chi_{i,e}$ = 1.5 m^2/s
- Target recycling is 90% [Canik PoP 2011]; Wall recycling is 100%
- P_{SOL} = 3 MW (split between ion and e^- channels)
- Zero flux BC for neutral D and C at core
- Fixed core flux of D^+
- No drift effects
- Inward carbon pinch, v_{pinch}=-25 m/s
- **Scan from 0 to 1200 atom-amps continuous D injection**
  - Experimental rate is 2000 A for 0.1 s (1.25×10^{22} s^{-1})

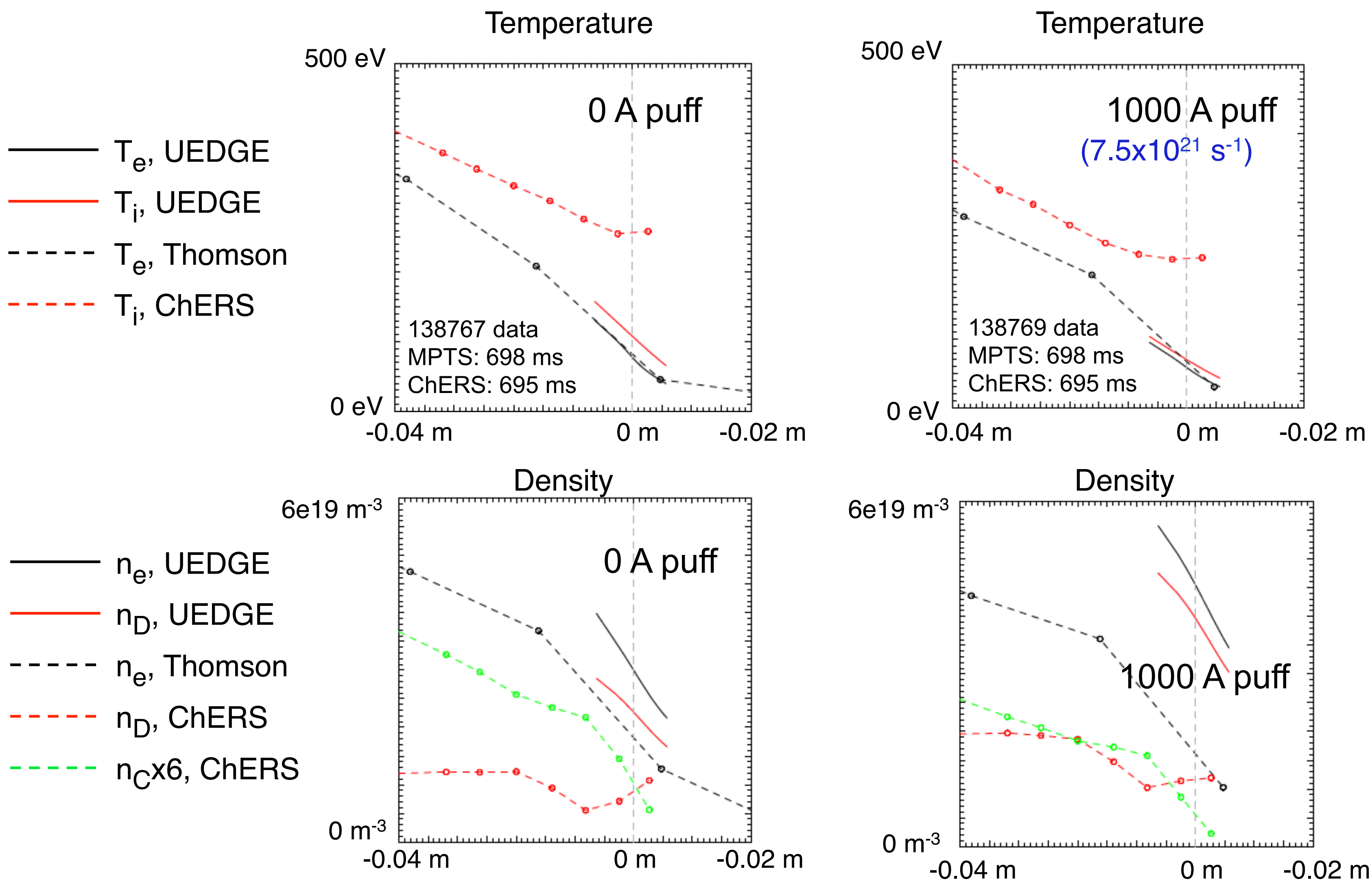
UEDGE includes physical and chemical carbon sputtering

- UEDGE includes physical and chemical sputtering of carbon
  - Physical and chemical sputtering models are from DIVIMP (U. Toronto)
  - Actual NSTX vessel wall is far from outer UEDGE boundary
    - Sputter yield reduced 10x at outer UEDGE boundary
  - T_{target}=500 K and T_{wall}=300 K assumed for all gas puff rates
    - Experimental T_{target} drops from ~600 K to ~400 K
- Lithium coating effects are not modeled
  - Complicated Li-C-D-O interaction still under investigation [e.g., Scotti PSI 2012]
- C-C and Li-C sputtering not included
  - C self-sputtering could be significant because of resonance between bombarding and target particles and the large (~10%) concentration of C near targets
    - But, this effect is probably not as important as Li coating!
  - Li-C probably not as important (no resonance)

Reducing energy from 100 to 20 eV, chemical sputtering goes up and physical sputtering goes down.



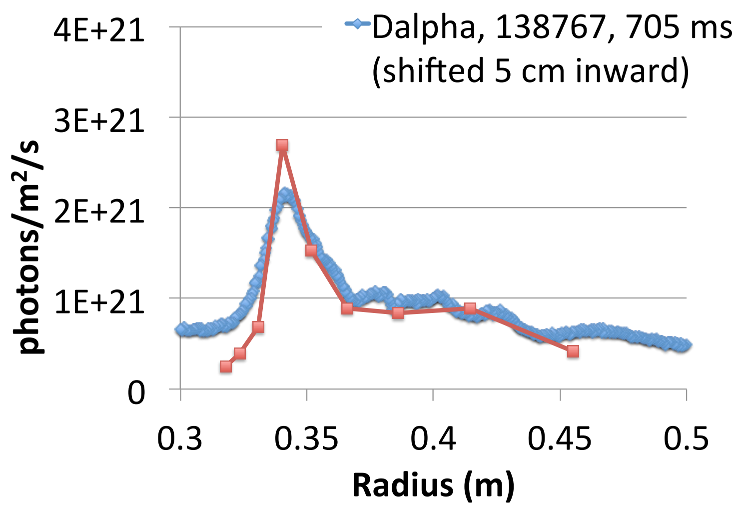
Midplane T_e matches well; T_i, n_e, n_i, not well-matched

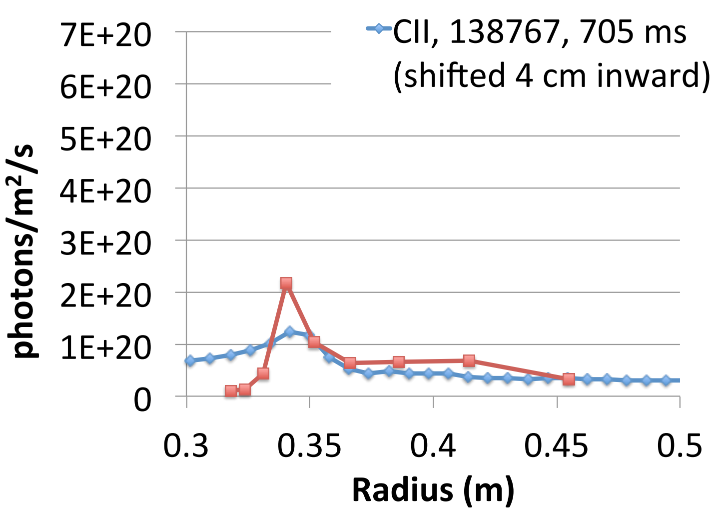


- *Note that the experimental data is shifted such that T_e=75 eV at the separatrix (to match the UEDGE solution)*

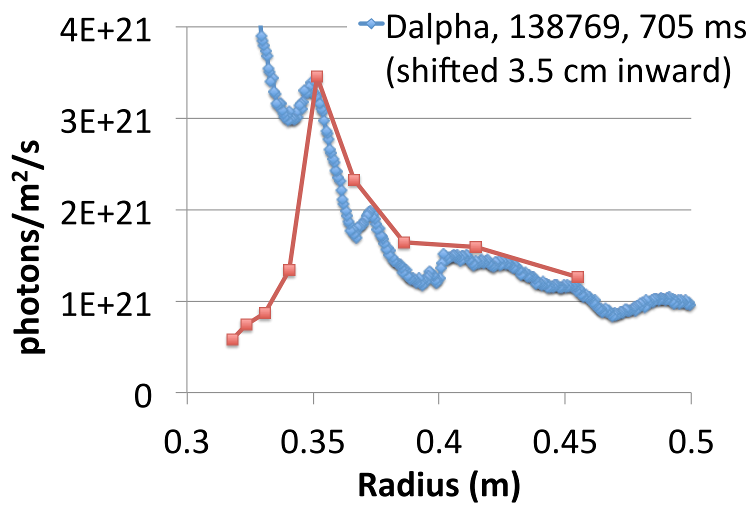
Outer divertor D_α profiles show good agreement; UEDGE CII intensities are too high

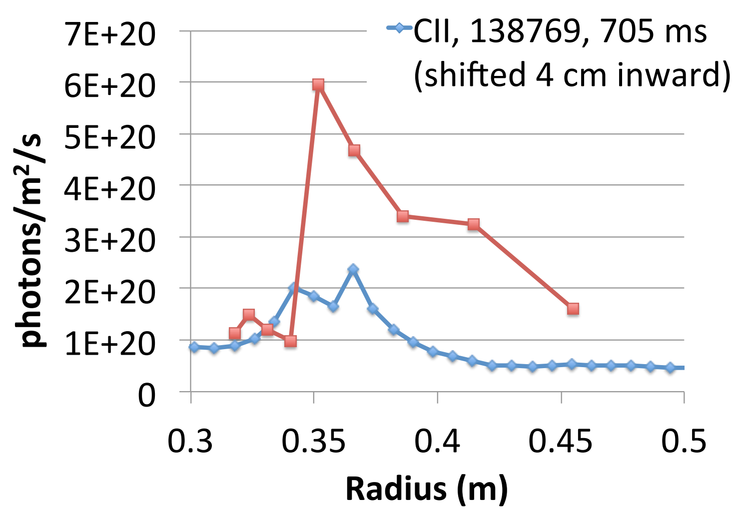
0 A puff



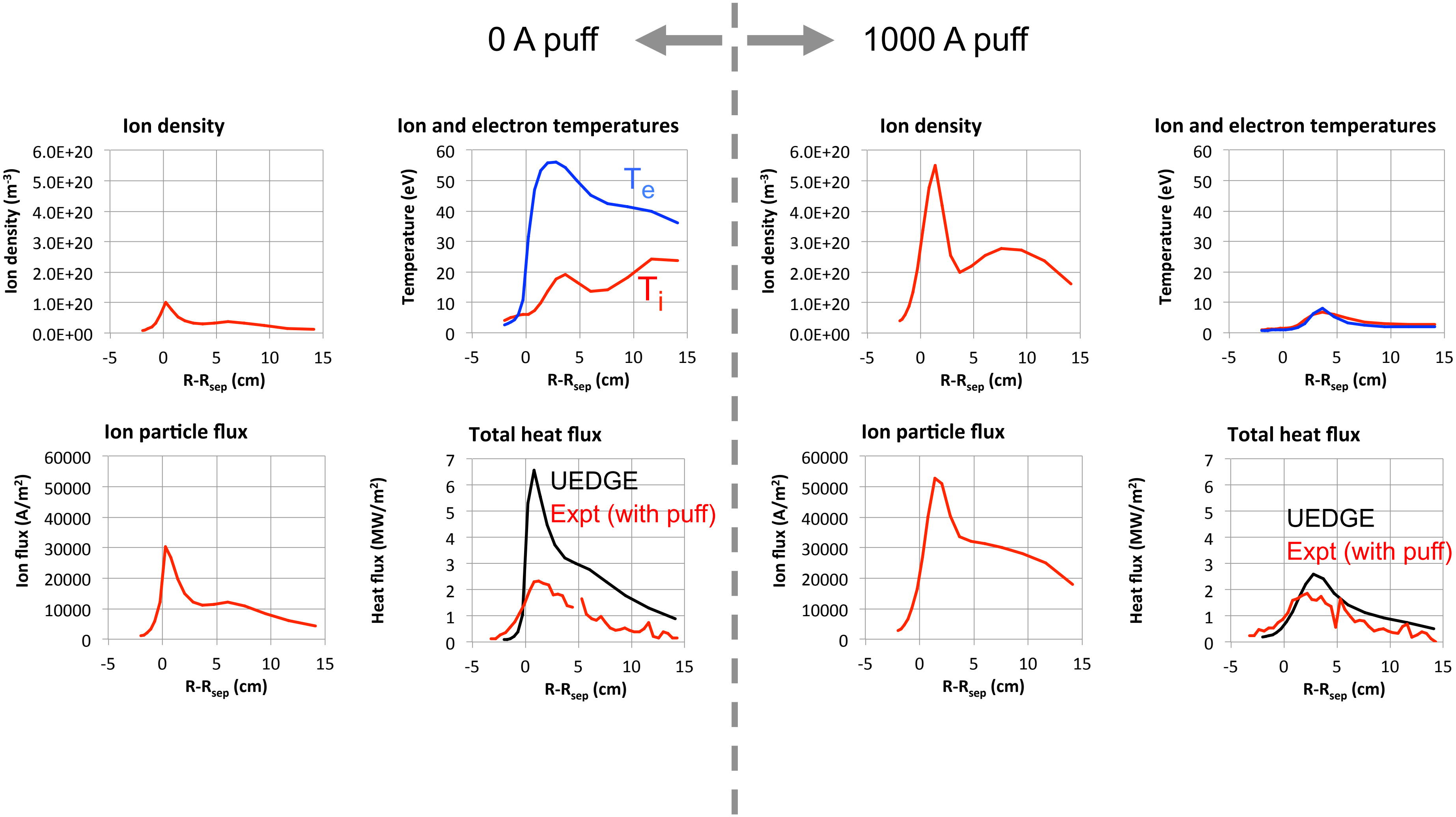


1000 A puff





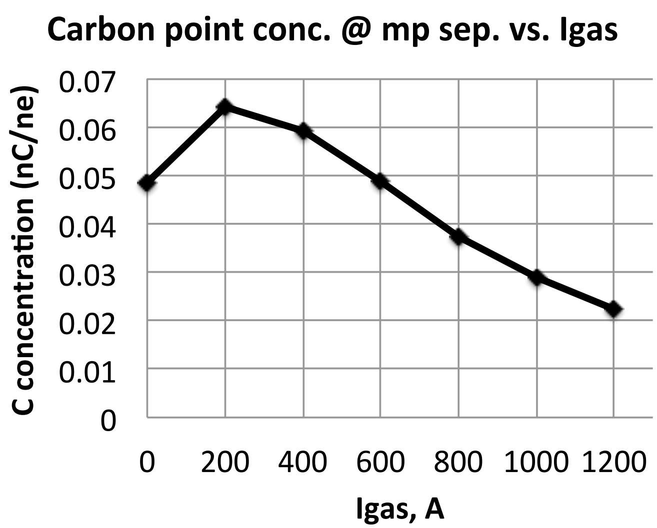
Outer divertor sees large temperature and heat flux reduction with 1000 A injection



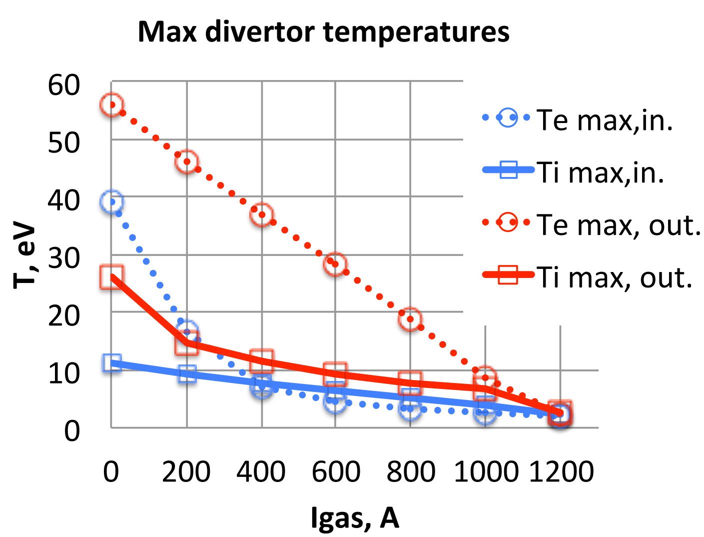
UEDGE plasma conditions are NSTX-relevant

- UEDGE edge plasma conditions suffice for qualitative assessment of divertor D_2 injection
  - Initial goal is to look for qualitative physical trends
- Close matching left for future work
  - T_e is reasonably well matched
    - Could collect data from many times to "fill out" radial profile since Thomson gives only a few points in the radial range of interest
  - n_e is not closely matched
    - Must reduce n_e (at given T_e) while matching heat flux profiles
    - Must modify model to avoid rise in ne with increasing divertor gas puff
  - T_i and n_i are not closely matched
    - Should tailor profiles of diffusivity and convective velocity
    - To get higher T_i, might need to modify 50/50 split of P_{SOL} between ions and e^- (e.g., 70/30 i/e^- split)
  - Comparison of CII emission suggests that UEDGE model could be improved by accounting for effects of lithium coating on sputtering

Carbon concentration is reduced with increasing deuterium gas injection

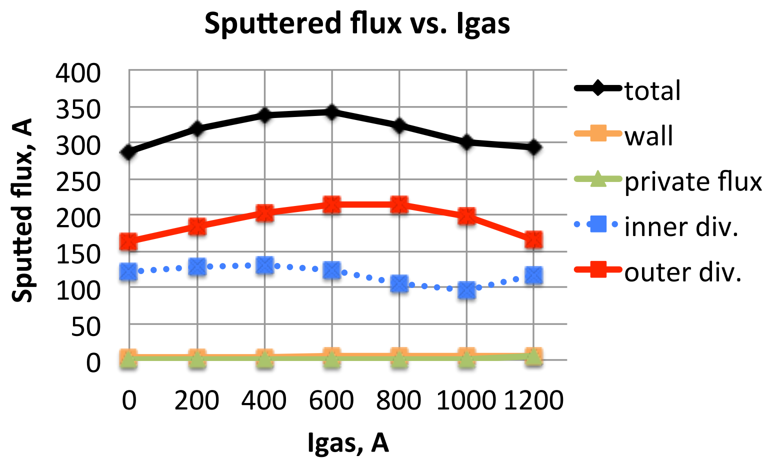


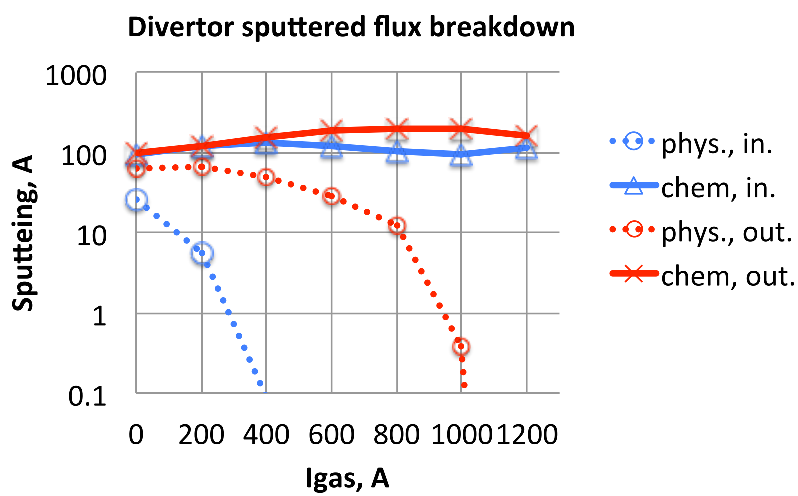
- Carbon concentration at the midplane separatrix is reduced by over 50% with 1200 A puff



- Divertor temperatures are reduced dramatically

Total sputtered flux remains nearly constant

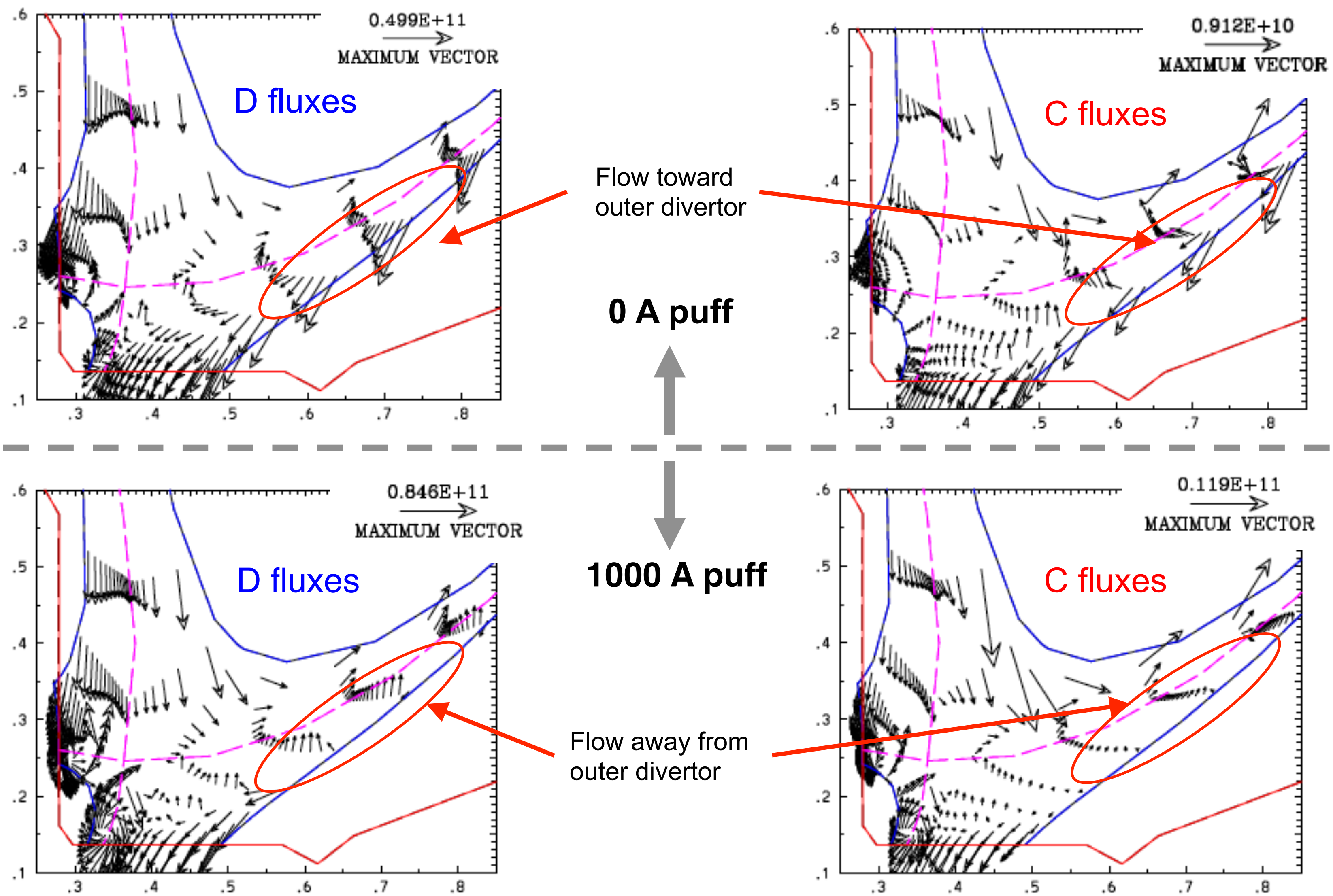




- Sputtered flux is dominated by inner and outer divertor sources

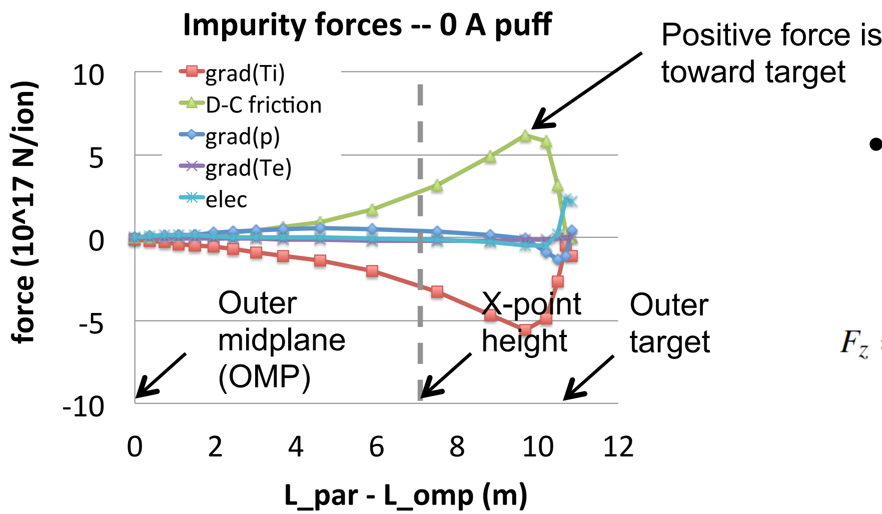
- Physical sputtered flux drops, but chemical sputtered flux rises

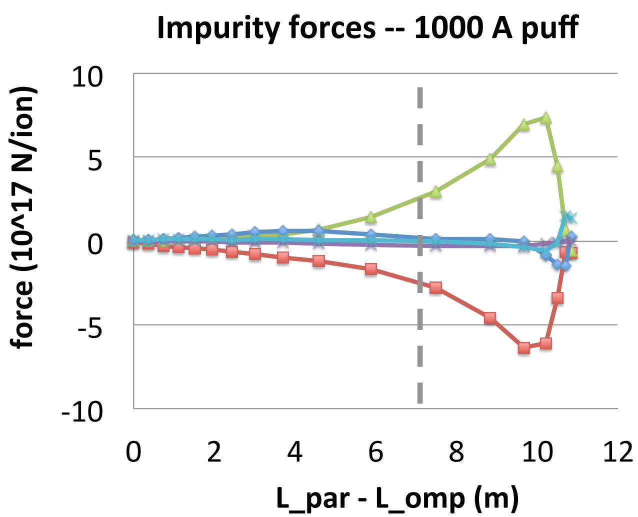
D gas injection causes D and C flow away from outer divertor



Parallel forces on carbon exhibit the expected balance

Data is plotted along a field line on the 2 mm flux surface.





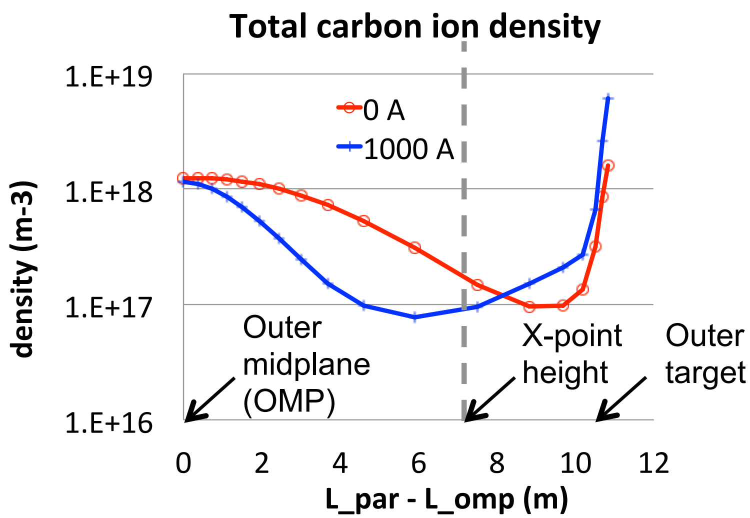
- Neglecting inertia, parallel impurity flow is governed by force balance:

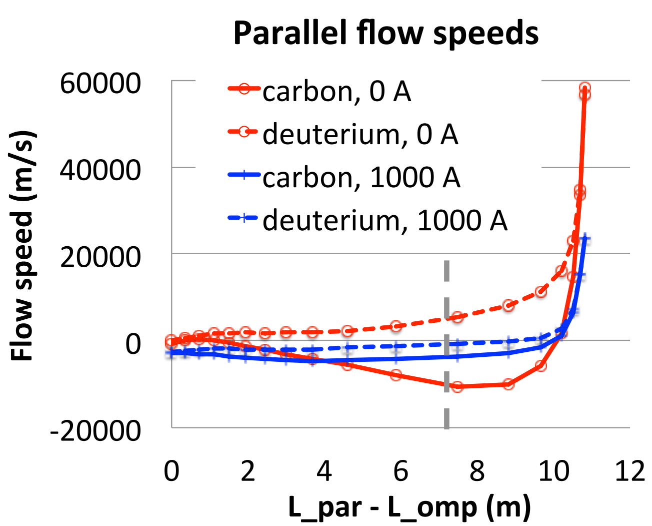
$$F_z = -\frac{1}{n_z}\frac{\mathrm{d}p_z}{\mathrm{d}s} + \underbrace{m_z\frac{(v_i - v_z)}{\tau_s}}_{F_{D\text{-}C\ fric}} + ZeE + \alpha_e\frac{\mathrm{d}(kT_e)}{\mathrm{d}s} + \underbrace{\beta_i\frac{\mathrm{d}(kT_i)}{\mathrm{d}s}}_{F_{grad(Ti)}} + \sim$$

- Ion temperature gradient force ($F_{grad(Ti)}$) and deuterium-carbon friction force ($F_{D\text{-}C\ fric}$) are dominant
- Only subtle changes are seen in these forces

Deuterium parallel flow changes dramatically in the SOL, affecting carbon distribution

Data is plotted along a field line on the 2 mm flux surface.





- n_C rises at outer target, but falls (slightly) at outer midplane
- n_C at X-point height is reduced
- Deuterium flow changes dramatically
  - **No injection:** strong flow from OMP to target
  - **1000 A injection:** stagnation below X-point and upward flow at OMP
- Carbon flow modified
  - **No injection:** flow stagnates near OMP
  - **1000 A injection:** upward flow at OMP
- "Flow-through" of carbon past OMP seems related to density reduction

Conclusions

- UEDGE gas puff study shows carbon impurity reduction with divertor deuterium gas injection
  - Observed reduction trend is consistent with experiment
  - Reduction seems related to “flow-through” of C past outer midplane
  - Reduction of carbon source is not seen
- Simulations could be improved in future work
  - Double null grid would give larger SOL and include upper divertor physics
  - More closely matching midplane profiles and divertor spectroscopy would increase confidence
  - Improved sputtering model could account for lithium divertor target coatings

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