NSTX

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OEDGE modeling of tokamak-induced material migration in NSTX and NSTX-U

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55th APS-DPP

Denver, CO

November 11-15, 2013

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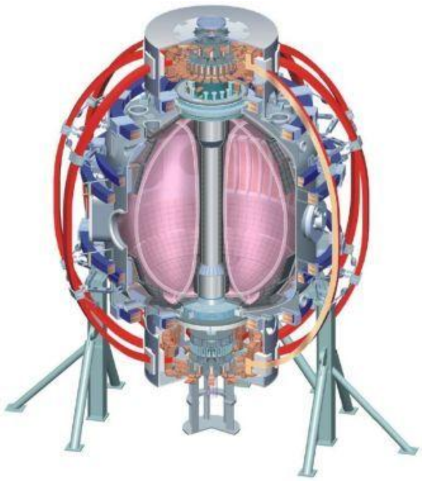

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Abstract

As fusion reactors scale up in size, power, and duty cycle, the quantity of material eroded from the plasma-facing components (PFCs) will rise to levels far above those seen in prior experiments. Changes to PFC composition and topography due to global-scale material migration could have drastic effects on tokamak operation, especially in mixed-material machines such as NSTX-U and ITER. As a first step in understanding tokamak-induced material migration in a compact geometry, net erosion of carbon PFCs in NSTX is modeled using the OEDGE code suite (DIVIMP, EIRENE, and OSM) [P. Stangeby et al., J. Nucl. Mater. 313-316, 883 (2003)]. The sensitivity of erosion patterns to various core and divertor plasma parameters is examined. A realistic NSTX plasma background is then applied to the NSTX-U geometry in order to provide an estimate of net erosion patterns that will be seen in NSTX-U's all-carbon initial phase. These simulations are used as a guide for the optimal placement of erosion diagnostics (quartz crystal microbalances, witness samples, and marker tiles) for use in the NSTX-U startup campaign.

Work supported by US DOE contract DE-AC02-09CH11466 and the DOE Fusion Energy Sciences Fellowship Program.

Erosion and migration of plasma facing materials is a potential issue for future fusion devices

- Excessive erosion of PFCs can lead to reduced lifetimes and have an unknown impact on plasma operation
  - Not a major problem in current devices, but will get much more noticeable as we move to high power and high duty cycle
- Crude estimates indicate large amounts of gross erosion in next-step devices
  - Scaling based on charge-exchange neutral flux to walls
  - Estimates assume poloidal uniformity

Machine	P_{max}/S $[\mathrm{MW/m^2}]$	τ_{annual} [s]	Yield [kg/yr]
DIII-D[1]	0.4	10^4	0.08 (C)
NSTX	0.2	3×10^3	0.012 (C)
NSTX-U	0.5	10^4	0.1 (C)
ITER[1]	0.15	10^6	92 (W)
ST-Pilot	0.98	10^7	1800 (W)
ARIES-AT	0.98	3×10^7	8000 (W)

[1]P.C. Stangeby, JNM 2011

GOAL OF THIS POSTER:
Assess gross erosion rates along the outer wall of NSTX, for a variety of outer divertor conditions, using advanced computing tools

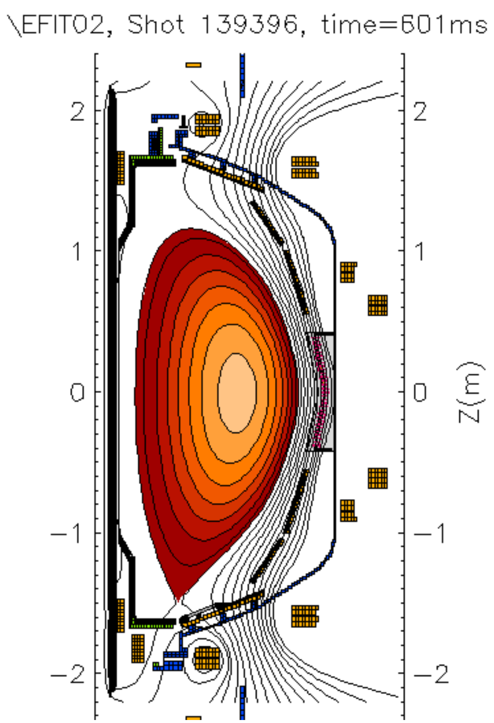
OEDGE (OSM-EIRENE-DIVIMP) is a code suite for SOL modeling, specializing in impurity transport

- OSM (Onion Skin Model) is a 1D plasma fluid code
  - Integrates plasma fluid equations along SOL flux tubes, starting at divertor targets and extending upstream
  - Can map out 2D SOL profiles without having to specify $D_\perp$

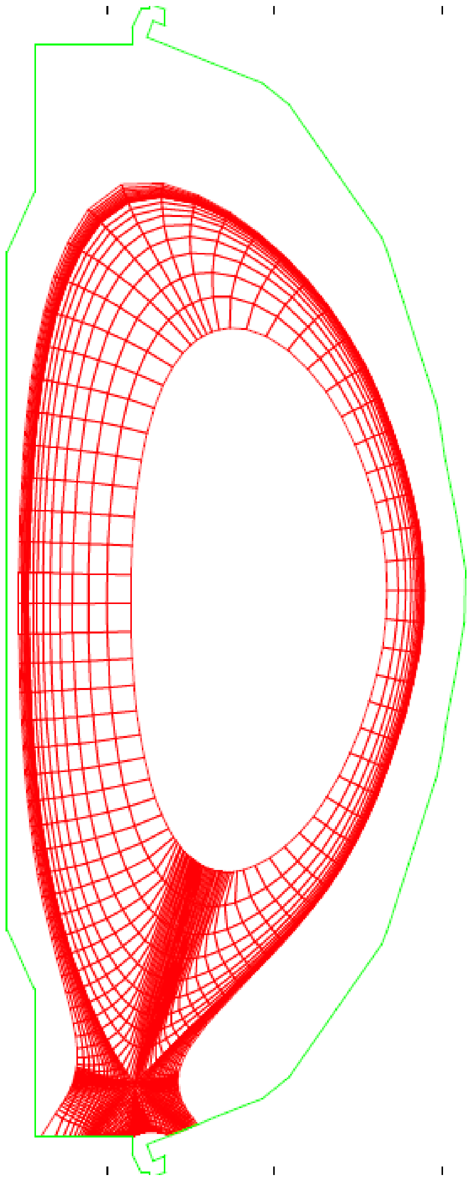
- EIRENE is a hydrogenic neutral Monte Carlo code
  - Handles neutral friction, recombination, charge exchange, and other atomic processes
  - Provides various source/sink terms to OSM when run iteratively

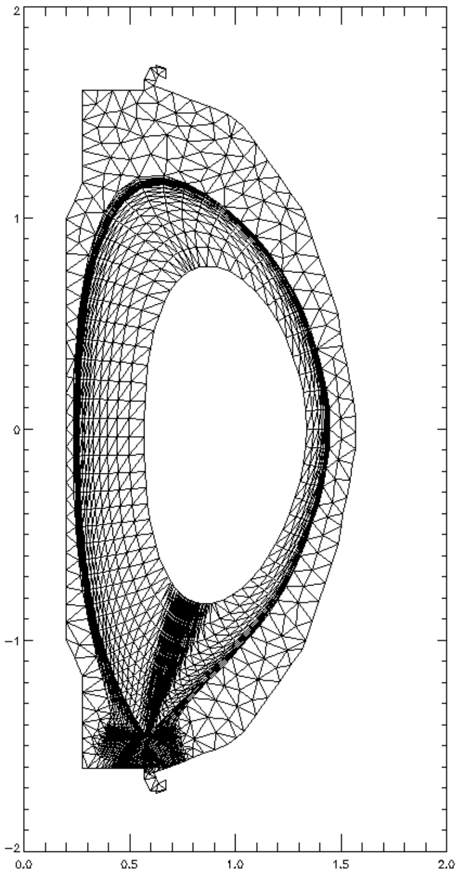
- DIVIMP is an impurity Monte Carlo code
  - Follows impurity ions/neutrals from birth to death
  - Allows detailed accounting of where impurities accumulate

Computational grid is based on real magnetic geometry



Magnetic equilibrium from EFIT turned into rectangular plasma grid by DG/Carre

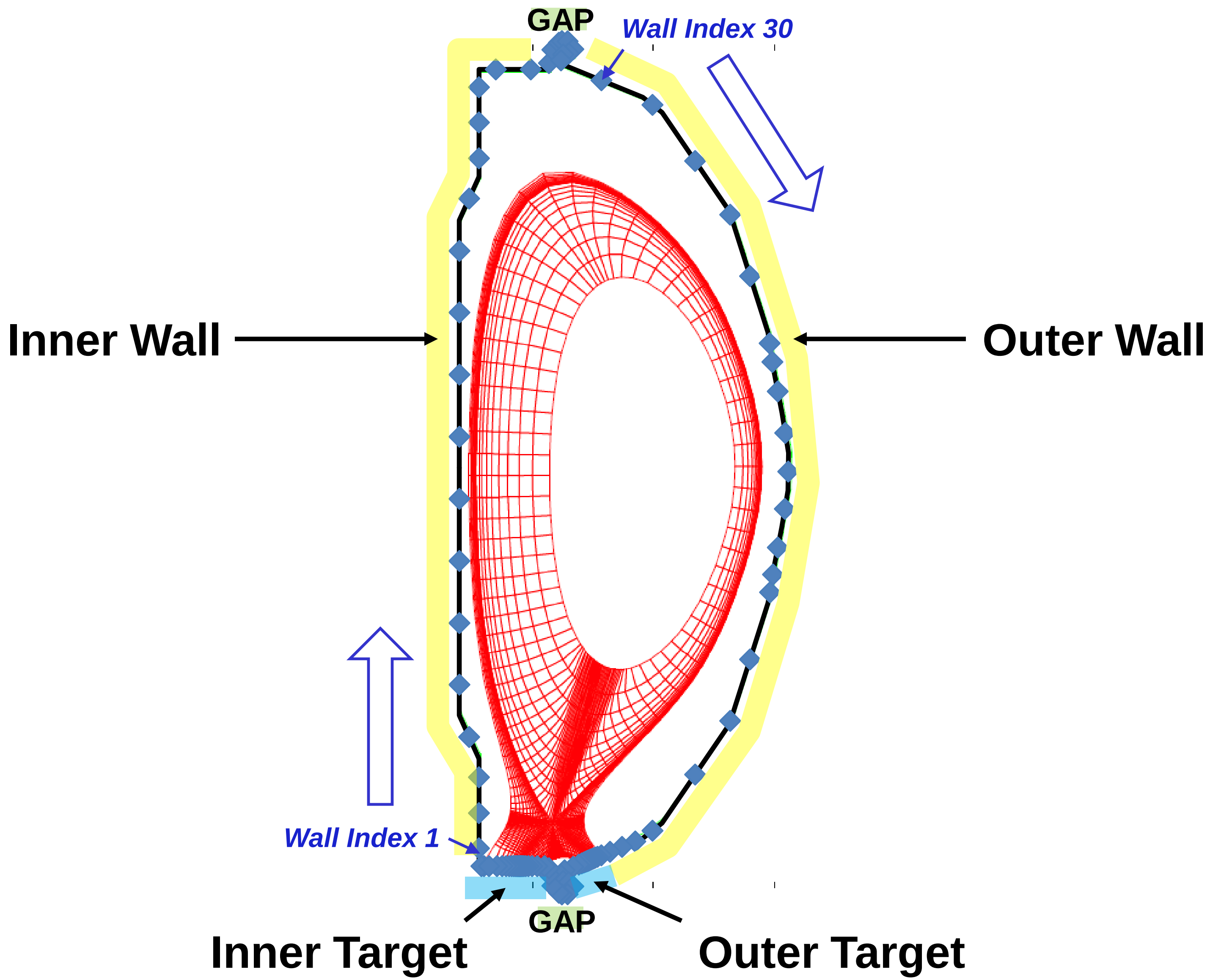




Triangular mesh (6848 cells) used by EIRENE for neutral dynamics

Plasma dynamics are calculated on rectangular grid (36 radial rings x 130 poloidal cuts)

Wall is discretized into 112 elements that mimic the actual NSTX PFC locations



We use a conduction-limited OSM method for calculating background plasma solutions

- Iterated with EIRENE to calculate particle/energy sources
  - Terms highlighted in RED
- Target n, Te, Ti taken as boundary condition for initial cell
  - Subsequent cells use n, Te, Ti from previous cell for B.C.
  - Terms highlighted in GREEN
- Solves 1D fluid equations for (n, T_e, T_i, v) in each cell using a Runge-Kutta solver
  - Particle conservation

$$\Gamma(s) = n(s) \cdot v(s) = \boxed{n_0 v_0} + \int_0^s \boxed{S(s')} ds'$$

We use a conduction-limited OSM method for calculating background plasma solutions

– Energy conservation (electrons)

$$\frac{d}{ds}\left(\frac{5}{2}\cdot n(s)\cdot v(s)\cdot kT_e(s)-\kappa_{0e}\cdot T_e(s)^{5/2}\frac{dT_e(s)}{ds}\right) = -P_{rad}(s)-P_{helpi}(s)-P_{ei}(s)$$

– Energy conservation (ions)

$$\frac{d}{ds}\left(\frac{5}{2}\cdot n(s)\cdot v(s)\cdot kT_i(s)+\frac{1}{2}m\cdot n(s)\cdot v(s)^3-\kappa_{0i}\cdot T_i(s)^{5/2}\frac{dT_i(s)}{ds}\right) = -P_{cx}(s)+P_{ei}(s)$$

– Momentum conservation

$$n(s)\left[\left(kT_e(s)+kT_i(s)\right)+m\cdot v(s)^2\right] = 2n_0(\mathrm{kT_{e0}}+\mathrm{kT_{i0}})$$

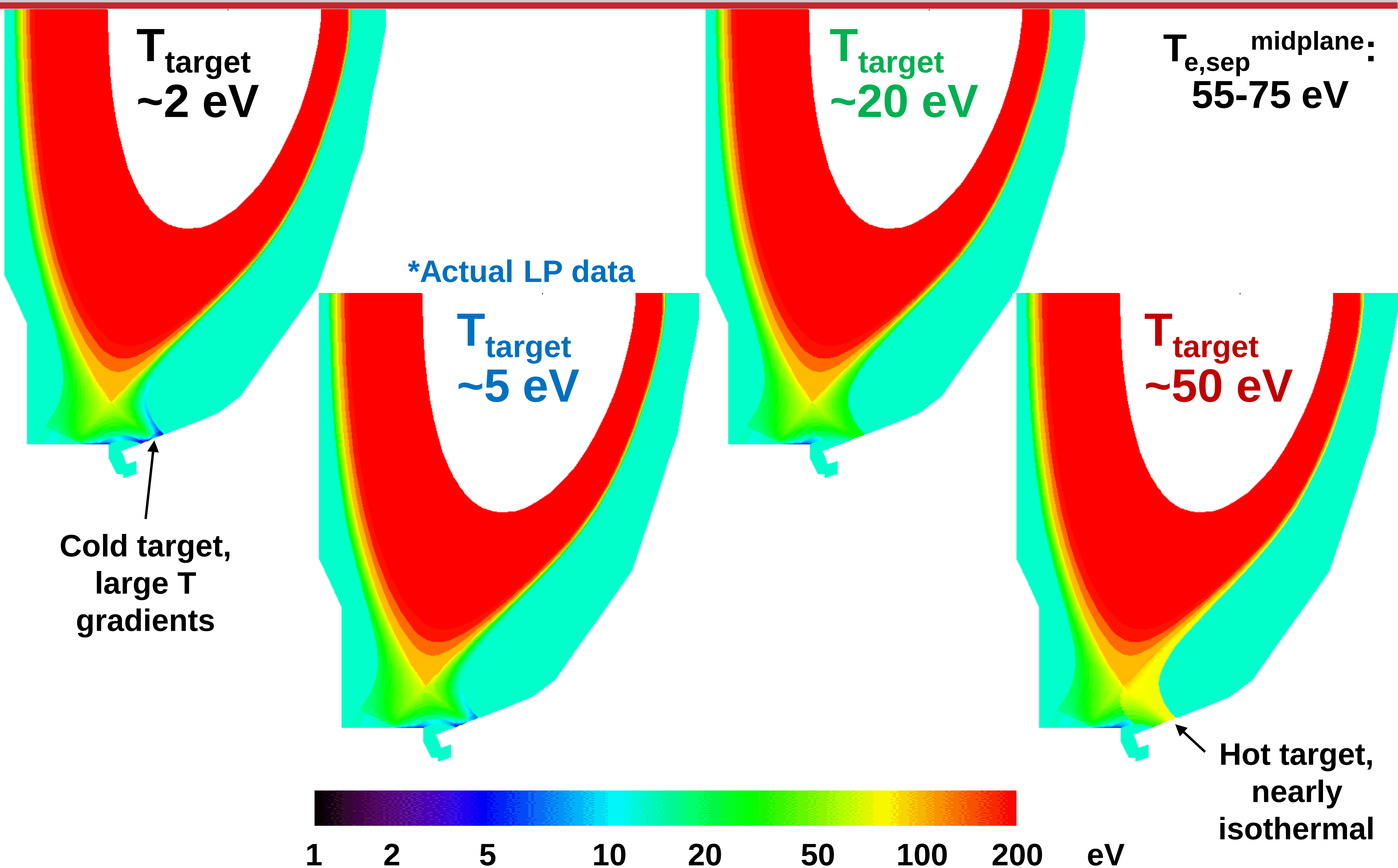
*Note: For those familiar with OEDGE, this is SOL Option 22

A sensitivity analysis was designed around a well-diagnosed NSTX discharge

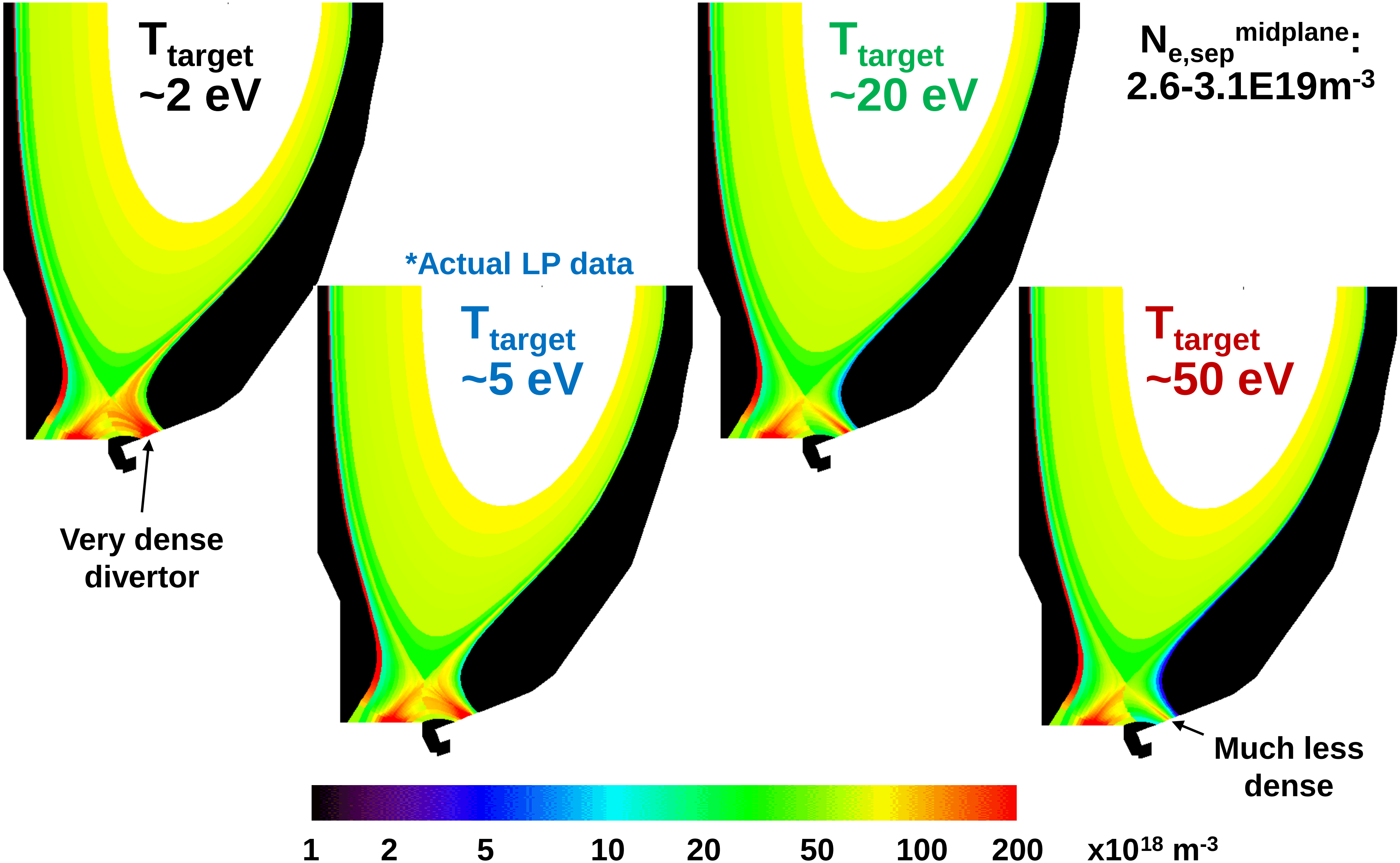
- Shot 139396 is a discharge from 2010 with the outer strike point on the Liquid Lithium Divertor (LLD)
  - ELMy H-mode -- 4 MW NBI-heated
  - 800 kA -- Low triangularity
  - Both divertor legs are attached

- Created a consistent scan of outer target plasma conditions by inputting different Langmuir probe values for n_{target}, T_{target} and letting OSM solve for plasma background
  - Kept target pressure (and hence upstream pressure) constant
  - Inner target held fixed at $T_e \sim T_i \sim 5$ eV, $N_e \sim 0.5\text{-}4E20$ m^{-3}

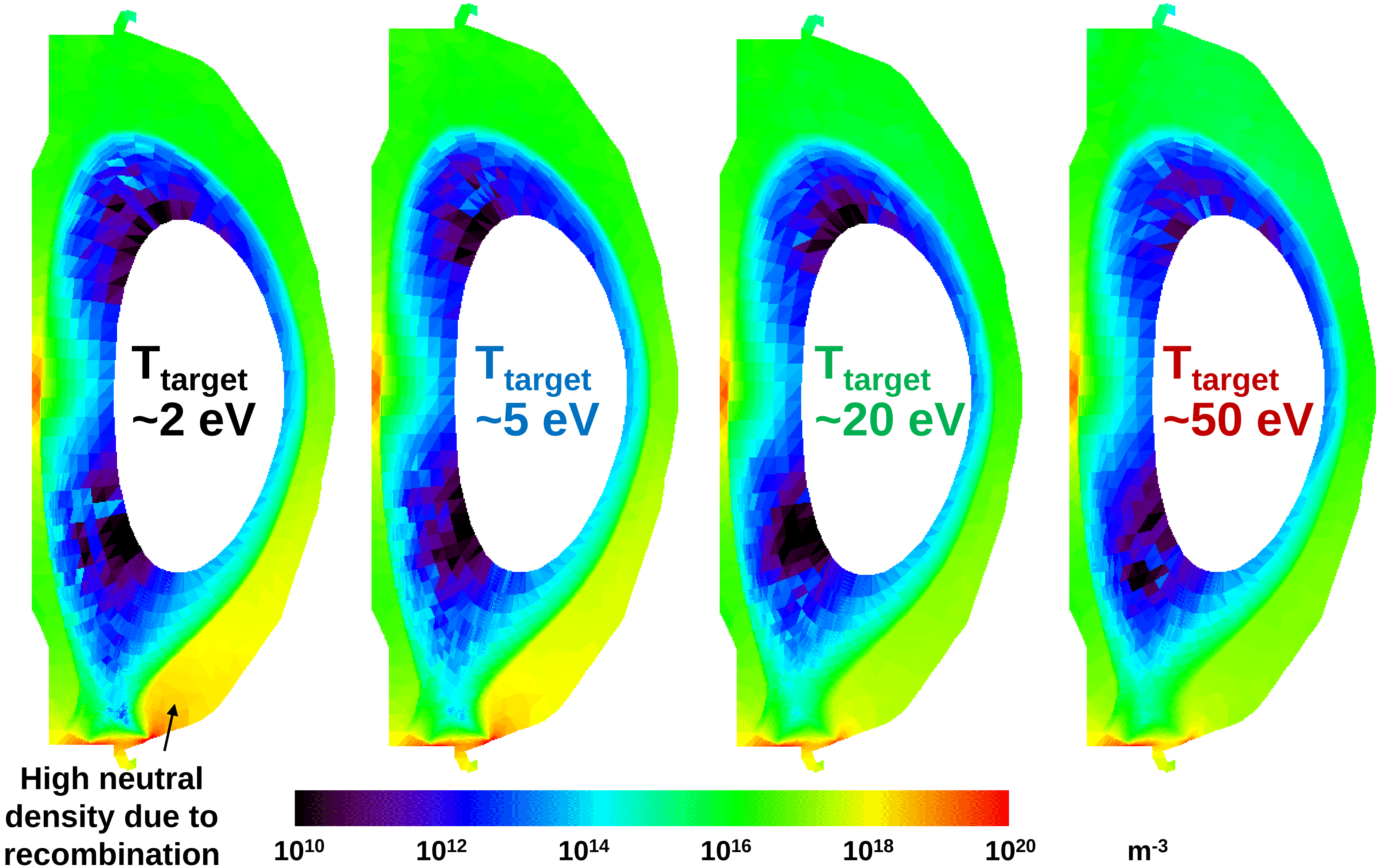
Electron temperature calculated by conduction-limited OSM



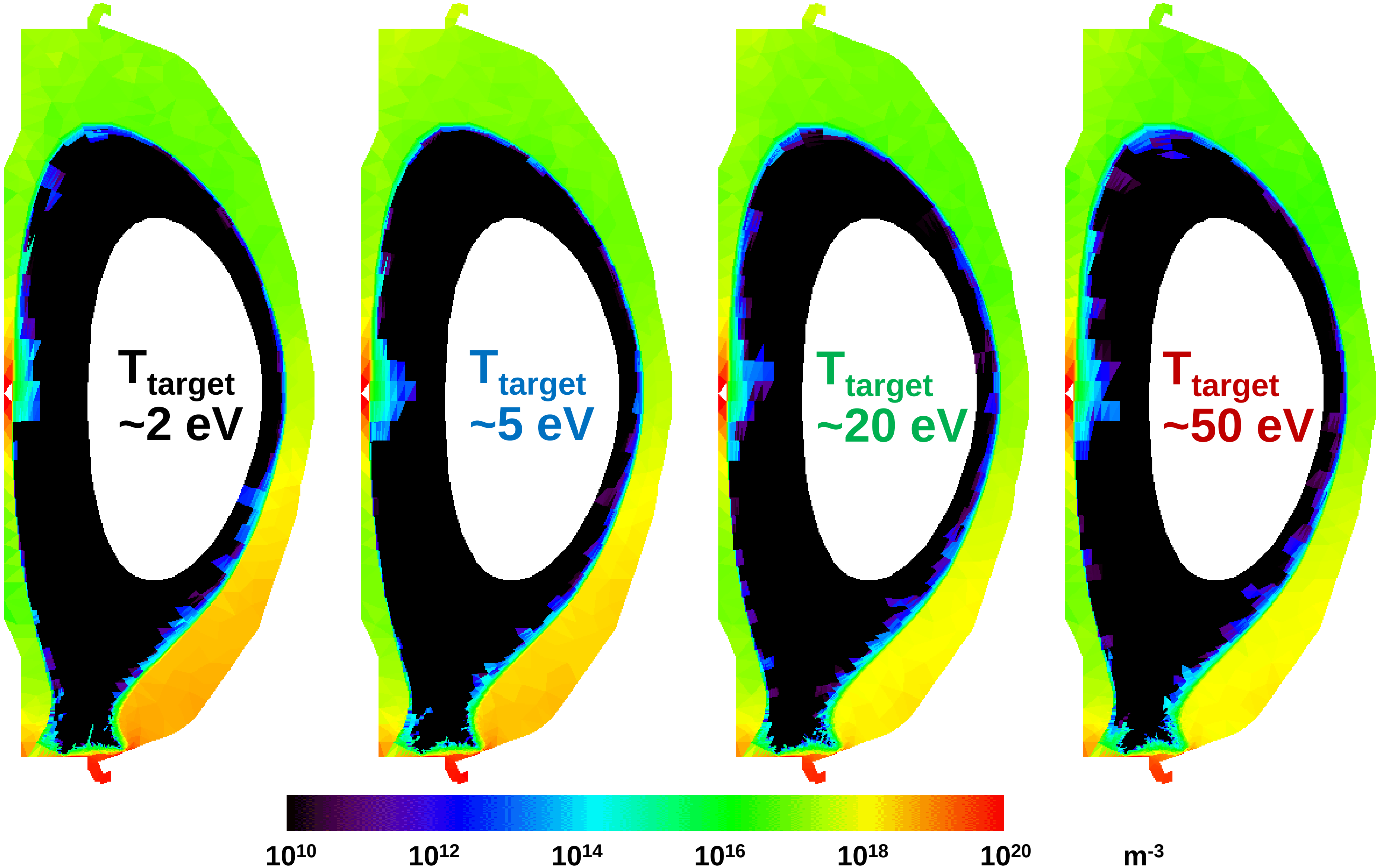
Plasma density calculated by conduction-limited OSM



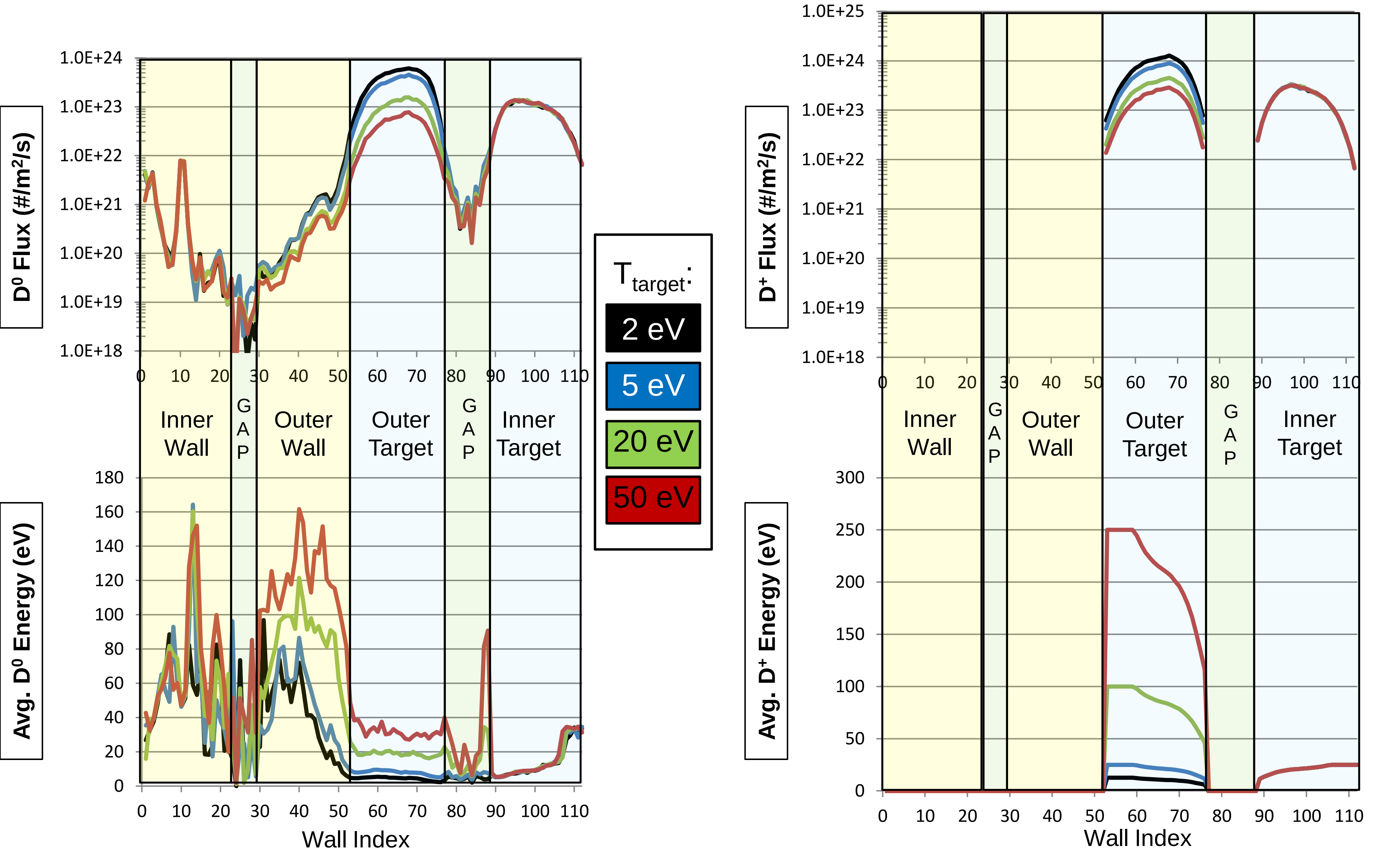
D^0 density (calculated by EIRENE) at wall decreases with increasing target temperature



D_2 density (calculated by EIRENE) at wall also decreases with increasing target temperature

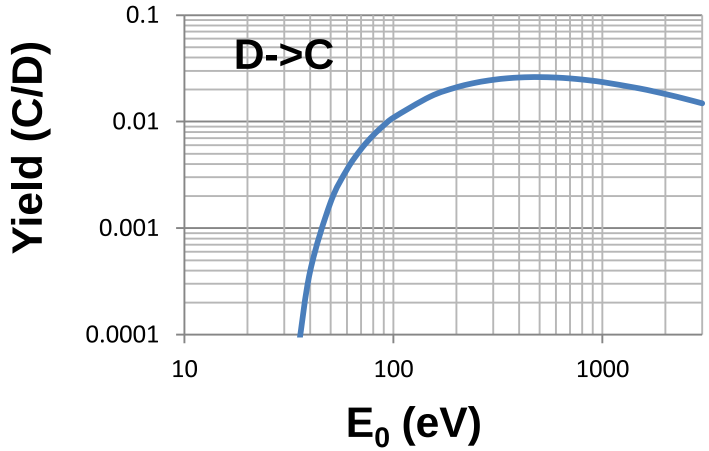


Poloidal profiles of D^0 and D^+ flux to wall and average incident energy show clear differences between the 4 cases



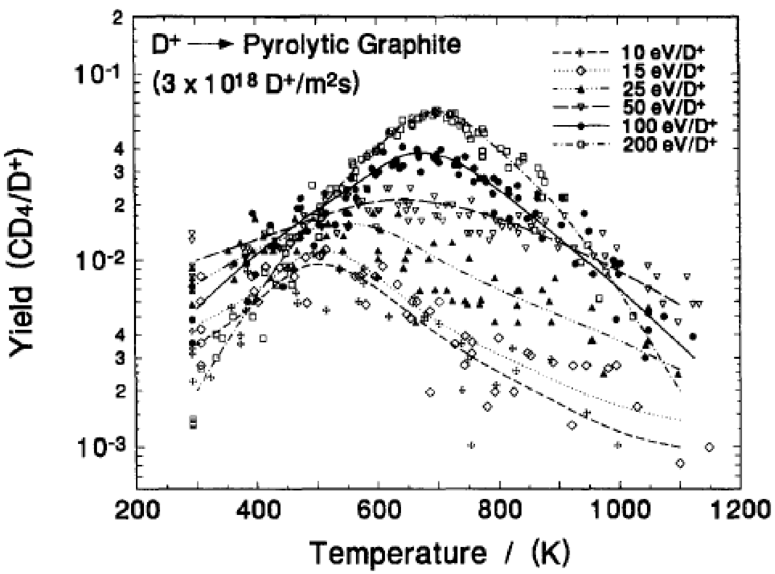
Erosion models based on empirical formula and sputtering databases

- Physical erosion model: Based off of Bohdansky formula, an empirical fit to numerous lab measurements

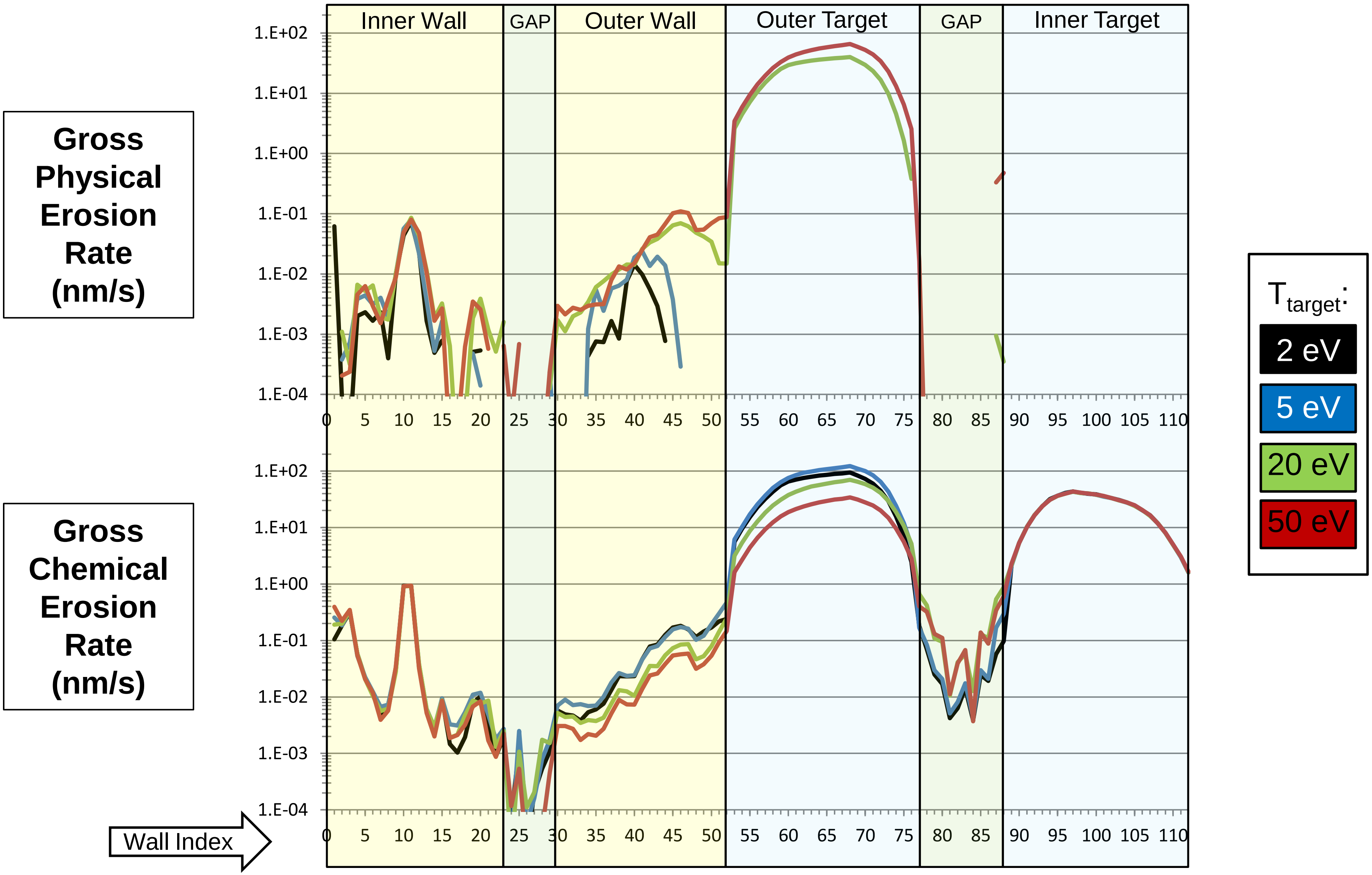


$$Y(E_0) = QS_n(\varepsilon)\left(1-\frac{E_{th}}{E_0}^{2/3}\right)\left(1-\frac{E_{th}}{E_0}\right)^2$$

  - No sputtering below threshold E
  - E_{th} for D->C: 30 eV
- Chemical erosion model:
  - Mech/Haasz 1997 database
  - No energy threshold



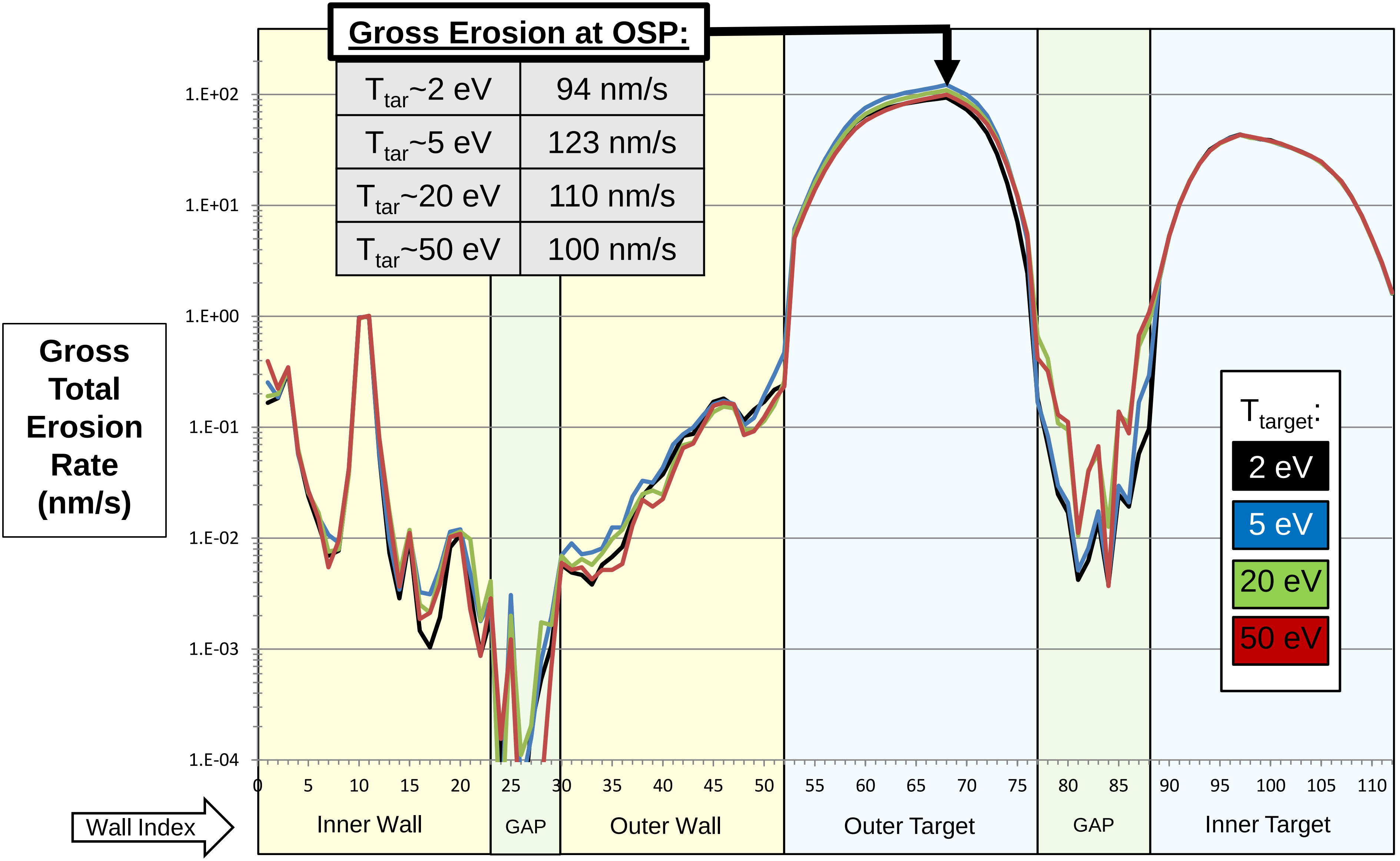
Each of 4 cases exhibit clear differences in gross physical and chemical erosion rates…



…But differences effectively disappear when looking at total gross erosion rates

Gross Erosion at OSP:

T_{tar}~2 eV	94 nm/s
T_{tar}~5 eV	123 nm/s
T_{tar}~20 eV	110 nm/s
T_{tar}~50 eV	100 nm/s



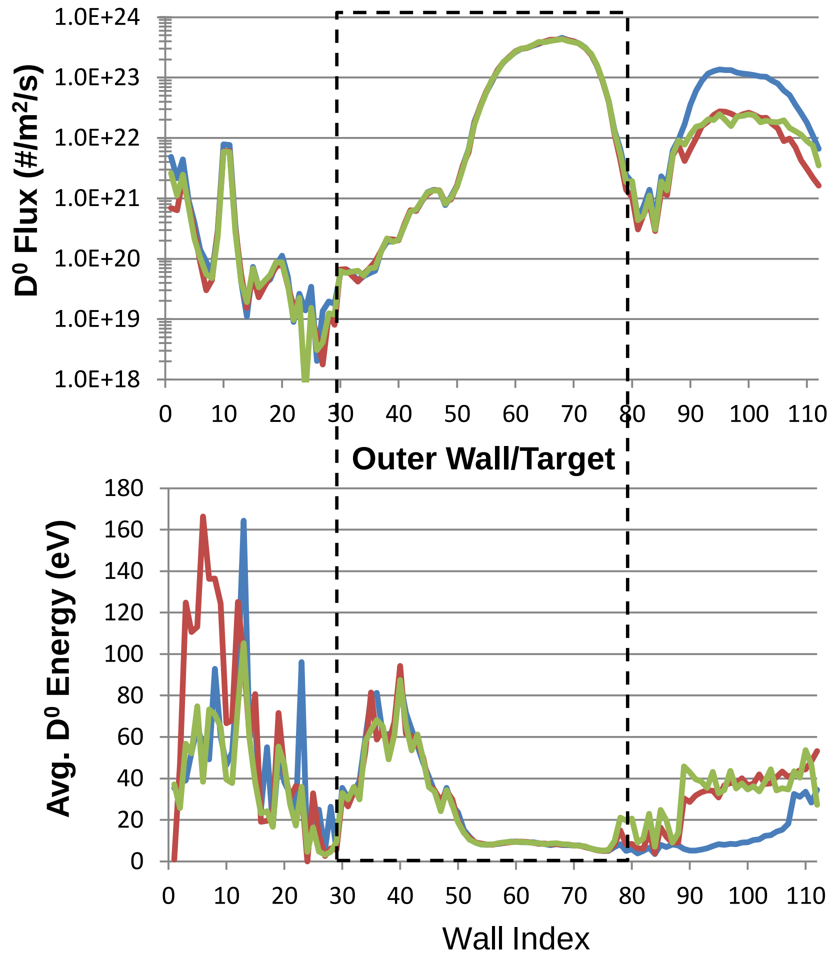
Discussion

- Exponential increase in gross erosion on wall closer to target
- Hotter, less dense plasmas exhibit more physical sputtering
  - Despite lower particle flux, ions and atoms are above the threshold energy for physical sputtering.
- Cold, dense plasmas lead to more chemical sputtering
  - No threshold energy for chemical sputtering
  - More particle flux to target due to higher density
  - More charge exchange neutrals to wall due to higher neutral density
- Total gross erosion appears to be roughly independent of outer divertor conditions
  - Does this hold for higher power, other plasma shapes?

Uncertainties in inner divertor modeling have negligible effect on outer wall gross erosion

- Outer leg is comparatively well-modeled due to good Langmuir probe data from LLD experiments
- Inner leg is more uncertain
- Outer wall/target gross erosion appears to have very little dependence on inner leg conditions
  - D^0 flux/energy on outer wall constant when outer leg model is held fixed, despite 3 very different inner leg models

Outer Leg: T_{tar}~5 eV
Inner Leg: T_{tar}~5 eV T_{tar}~50 eV Detached



Next Steps: Better plasma backgrounds, deposition profiles with DIVIMP

- The real quantity of interest in tokamaks is net erosion (i.e. gross erosion – gross deposition)
  - DIVIMP can follow a large number of “eroded” particles launched according to the magnitude and distribution of gross erosion
- Requires reliable plasma solutions throughout the machine
  - Impurity transport is a global process
  - Current NSTX OSM solutions are discontinuous at stagnation point, creating an erroneous particle trap
- Region between edge of plasma grid and outer wall is currently crudely modeled
  - Filling the empty space with plasma flux tubes might increase fidelity of simulation

Next Steps: A mixed material migration model for NSTX-U

- This analysis assumes a 100% carbon first wall and divertor, but NSTX-U will have periodic lithium evaporations (like NSTX) for density/ELM control
  - Sputter yields and reflection coefficients change with changing surface composition, chemistry (poorly understood)
  - Li coverage changes throughout campaign due to new evaporations, plasma transport

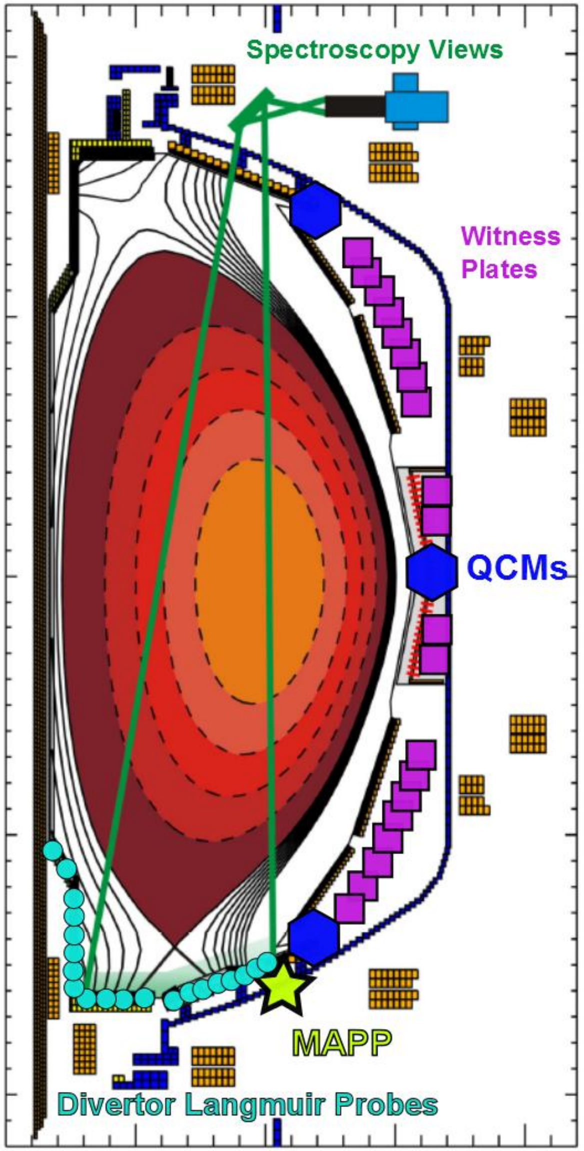
- Possible way forward: something akin to the WallDYN model [K. Schmid et al., J. Nucl. Mater., S284-S288, 415 (2011)]
  - Joins impurity transport in plasma (via DIVIMP) to surface evolution via a system of coupled differential algebraic equations
  - Currently in development for JET and ITER (Be, C, W)

Next Steps: Reinstall diagnostics for NSTX-U 2014/15 run

- Material migration studies will be a component of the inaugural NSTX-U experimental campaign (2014-15)

- Related diagnostics
  - Extensive in-tile Langmuir probe array, for OSM reconstructions
  - Divertor spectroscopy and filtered cameras, for gross erosion measurements
  - Materials Analysis and Particle Probe (MAPP), for shot-resolved surface analysis

- 3 Quartz crystal microbalances (QCMs)
  - 1 for characterizing Li evaporation
  - 2 for day-resolved net erosion measurements



Next Steps: Plan post-mortem tile analyses for after the NSTX-U 2014/15 run

- Poloidal array of silicon witness plates on outer wall
  - Campaign-integrated information on deposition and erosion due to charge exchange neutrals
  - Easy to install and remove
  - Li/C/O concentrations from ion beam analysis, useful for benchmarking mixed material simulations

- Plan to remove as many divertor tiles as possible for post-mortem ion beam analysis
  - Key data points for net erosion and mixed material migration in plasma-contacted regions
  - If Li layers exist, tile archaeology will provide “time-resolved” measurements of Li migration

Summary

- OEDGE (OSM-EIRENE-DIVIMP) is established as a tool for studying erosion in NSTX
- Clear poloidal variation is seen in gross erosion patterns
  - Exponential increase along outer wall when moving toward divertor
  - Peak gross erosion rate of ~100 nm/s (at strike point)
- Gross erosion pattern does not appear to depend on outer divertor target temperature/density
- Further experimental and modeling studies are planned for NSTX-U

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