Characterization of deuterium neutral density profiles in the NSTX-Upgrade

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Abstract

Neutral density profiles are measured on the outboard midplane of the National Spherical Torus Experiment Upgrade (NSTX-U) using a 2D camera looking at the D-alpha emission. In magnetically-confined fusion devices, assessing the distribution of neutrals is critical to estimate particle sources and energy loss mechanisms in the edge plasmas, which play an important role in defining the structure of the H-mode density and temperature pedestals. Neutral densities are calculated by inverting the line-integrated D-alpha brightness and using local measurements of electron density and temperature to infer atomic rate coefficients. Neutral distribution on the low-field-side midplane is compared for L- and H-mode discharges in NSTX-U, including the evolution during sawtooth and ELM cycles. Neutral density profiles with boronized wall conditions in NSTX-U are compared with those measured in lithium-conditioned discharges in NSTX. The particle source profiles will be inferred from simulations with the Monte Carlo neutral transport code DEGAS2 and the multi-fluid edge transport code UEDGE, constrained by the experimental D-alpha emissivity.
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Summary

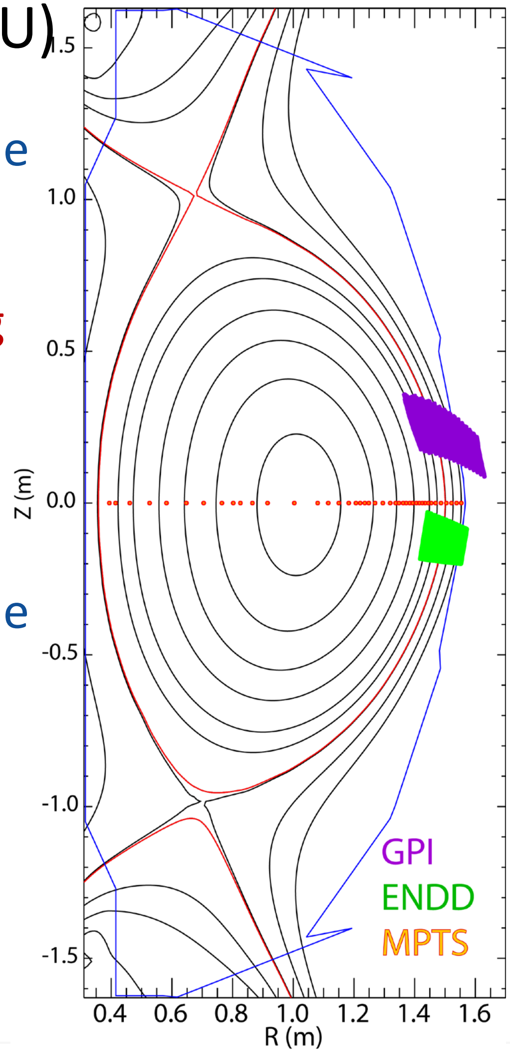
- Neutral density profiles are inferred from D-α emissivity on the low field side midplane of the National Spherical Torus Experiment Upgrade
- Neutral densities are compared at two toroidal locations. The proximity of a recycling surface results in higher neutral densities with comparable radial profiles. Reasons for difference are being investigated.
- In L-mode discharges neutral densities are correlated with divertor recycling, main chamber recycling and low field side fueling
- Initial modeling with the UEDGE code constrained by midplane and divertor D-α indicates that core penetration efficiencies of 43% for midplane sources and 3% for divertor target sources
  - Artificial baffling of divertor possibly affecting penetration of divertor source
- Initial interpretation of emission profiles via DEGAS2 simulations shows good agreement in emissivity profile shape

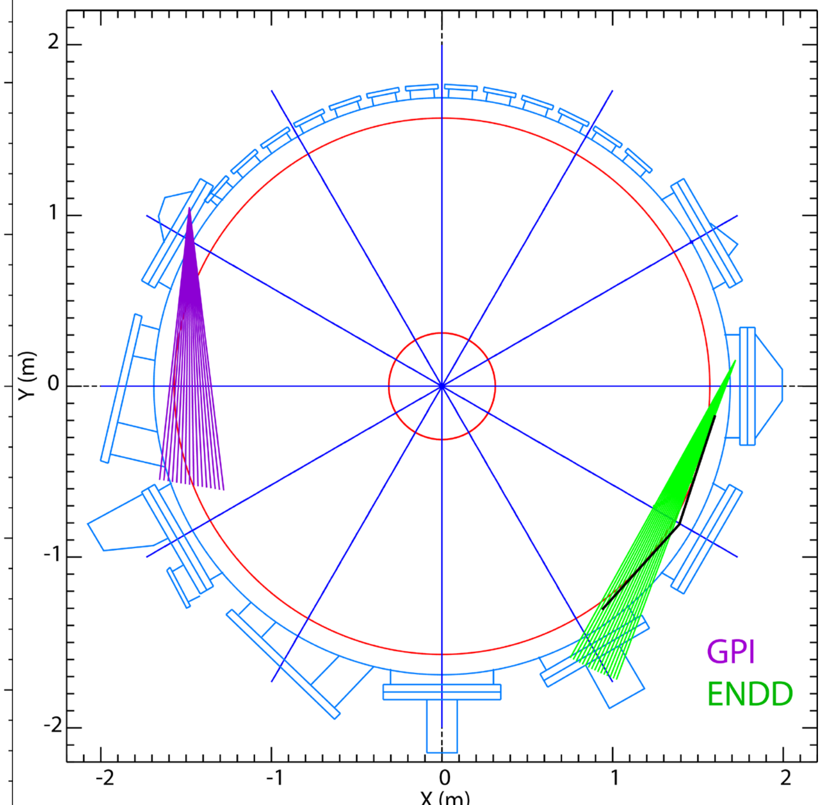
Motivation/Outline

- Neutrals distribution is critical to estimate particle sources and energy loss mechanisms in the edge plasmas
  - Important role in defining the structure of the H-mode density and temperature pedestals
- This work covers:
  - Determination of midplane neutral density profiles and core ionization rate profiles from different camera views in NSTX-U
  - Scaling of midplane neutral densities
  - Initial interpretation of neutral density profiles via 2D fluid modeling
- Work is performed towards the 2019 Joint Research Target milestone

Hydrogenic emission monitored via two toroidally separated 2D cameras with tangential views

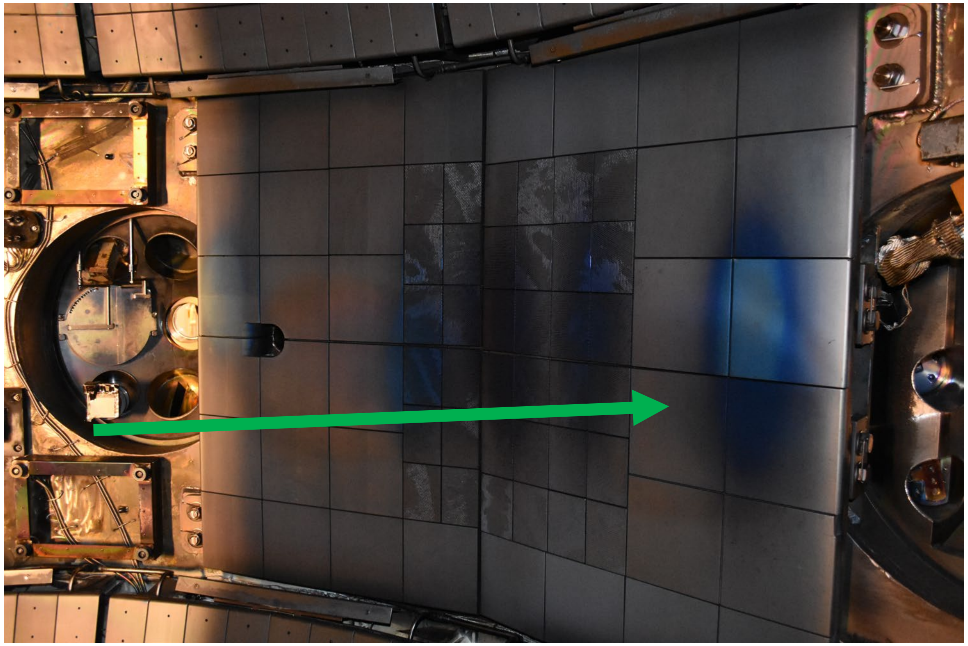
- ENDD (new in NSTX-U)
  - 127x128 CCD camera
  - 1000x800 fiber bundle
  - D_a filter
  - 3.7 ms integration
  - Proximity to recycling surface (NBI armor)
- Passive GPI view:
  - 64X80 fast CMOS
  - 1000x800 fiber bundle
  - 10 µs integration
  - No limiter surfaces nearby view
  - More challenging inversion



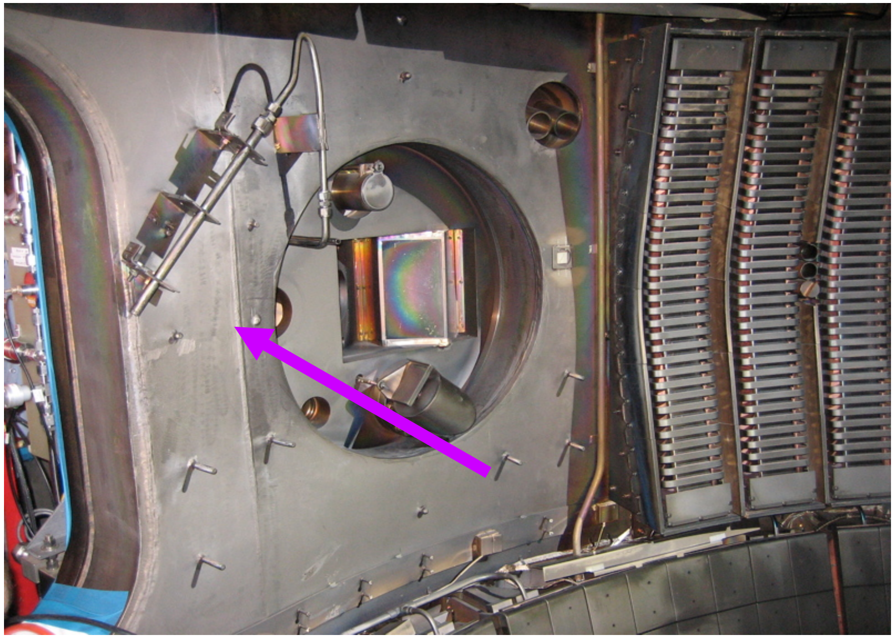


Hydrogenic emission monitored via two toroidally separated 2D cameras with tangential views

ENDD view



GPI view

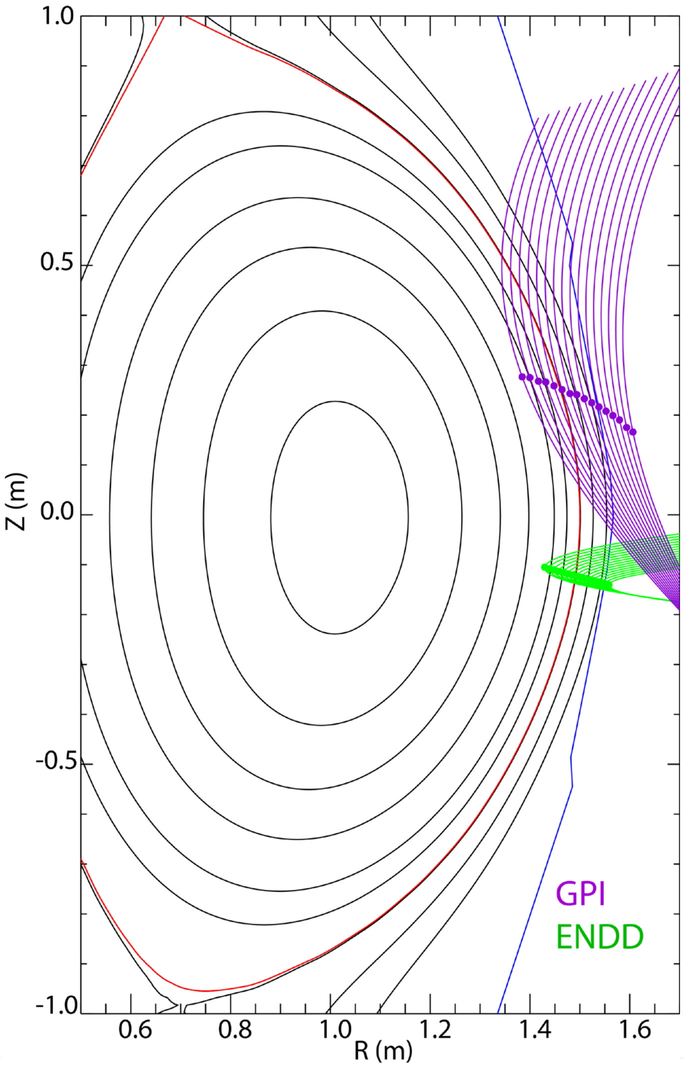


3D inversion used to derive emissivity profiles from line integrated brightness in different views

- ENDD and passive GPI provide line-integrated measurements through a D_α filter
- Emissivity calculated from brightness using matrix inversion:
  - Length matrix calculated for 3D geometry using EFIT equilibrium
  - Assumes toroidal symmetry and constant emissivity along flux surface

$$4\pi B_i = \sum_j L_{ij} E_j \qquad E_j = 4\pi \sum_i L_{ij}^{-1} B_i$$

- Pixels are binned poloidally
- Tangency is mapped to Z=0 for direct use of TS measurements



Upper estimate of neutral density obtained from D_α emissivity using local T_e, n_e measurements

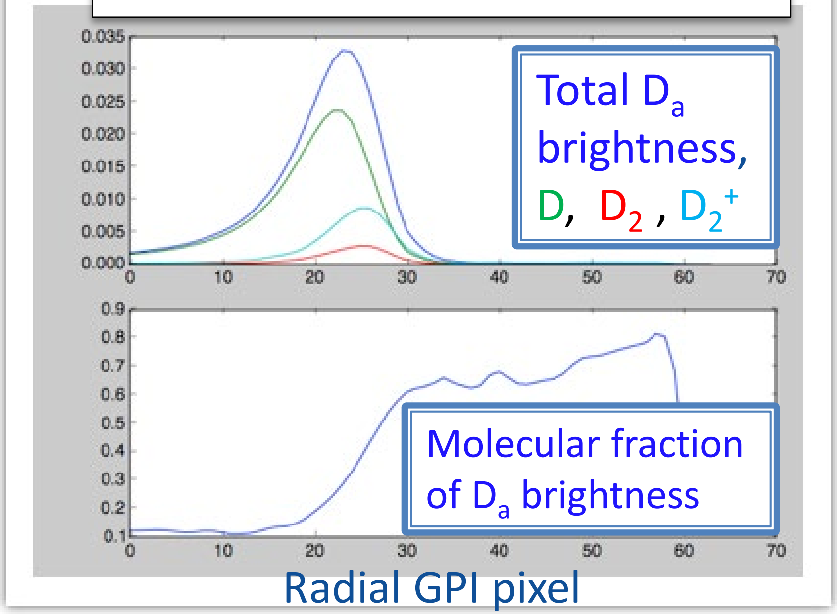
- Assuming all emission from neutrals excited by electron impact
  - Using local T_e, n_e values from MPTS to estimate photon emission coefficients

$$E_{D\alpha} = n_e n_D(1s)\left[\frac{n_D(n=3)}{n_D(1s)}\right] A_{3\to 2} = n_e n_D(1s) \times PEC_{ex}$$

$$n_D = \frac{E_{D\alpha}}{n_e PEC_{ex}}$$

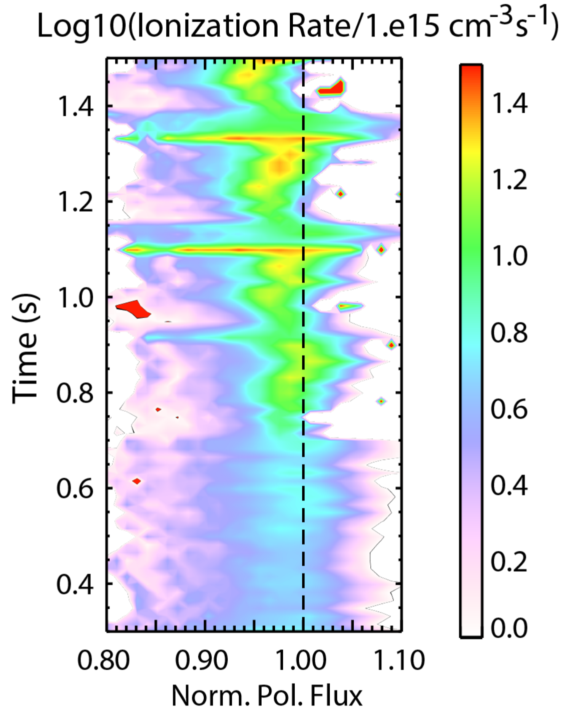
- Recombination contribution negligible
- Molecular contribution to D_α emission important in SOL
  - Method yields an upper estimate of n_D in SOL, ~correct in core
  - DEGAS2 simulations ongoing to account for molecular contribution

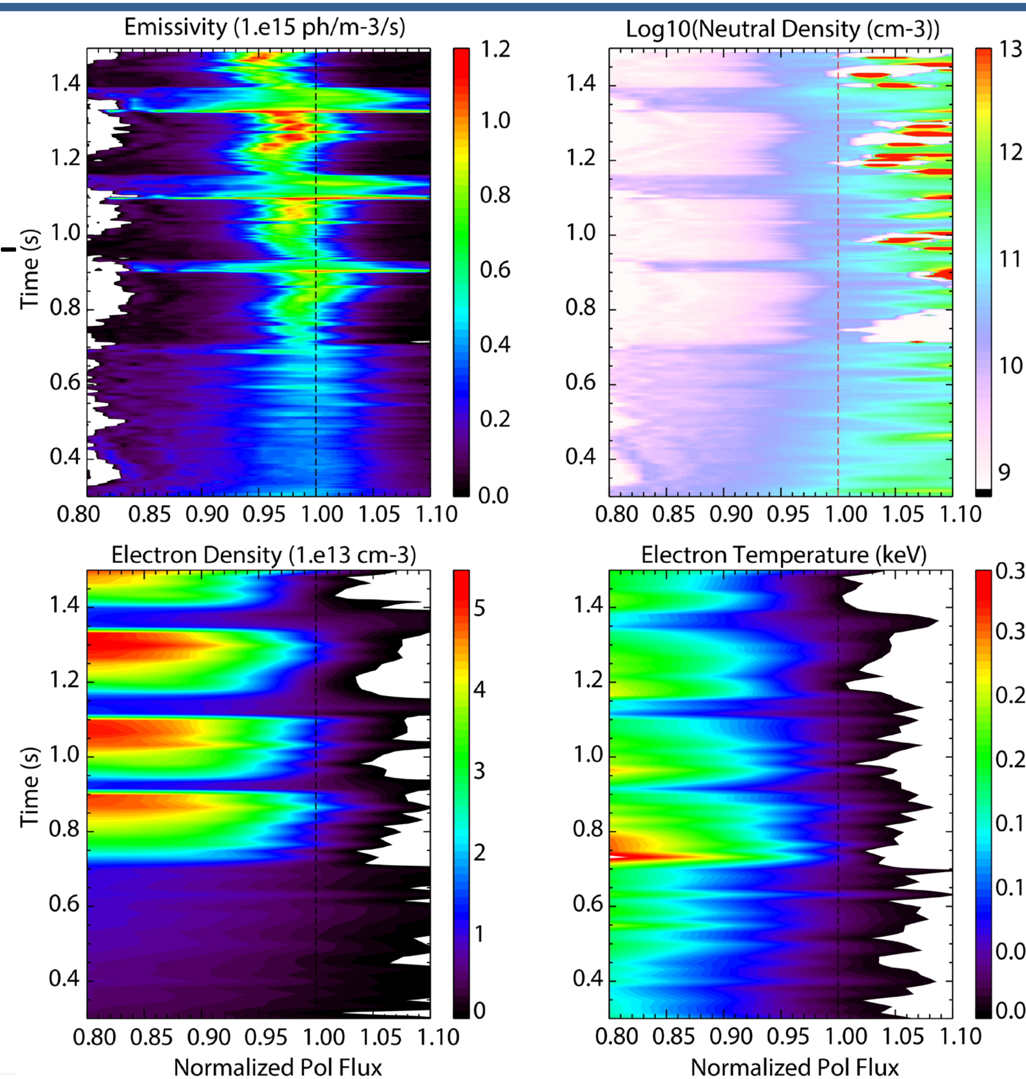
DEGAS2 simulations for GPI view in NSTX H-mode



Constant SOL neutral density throughout discharge, core neutral density determined by n_e evolution

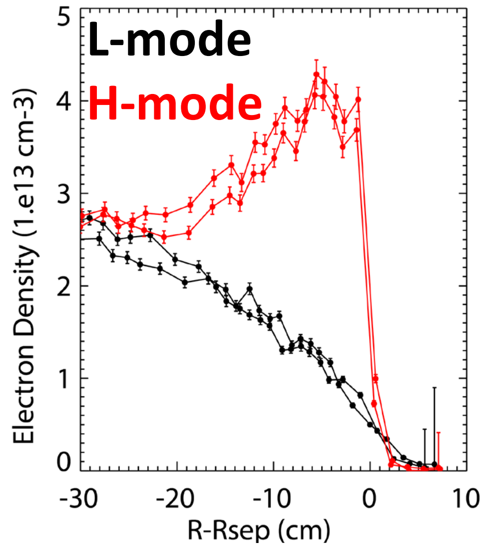
- NSTX-U discharge 204500
  - L-mode with 4 L-H transitions
- Large decrease in core n_D in H-mode phase due to higher n_e

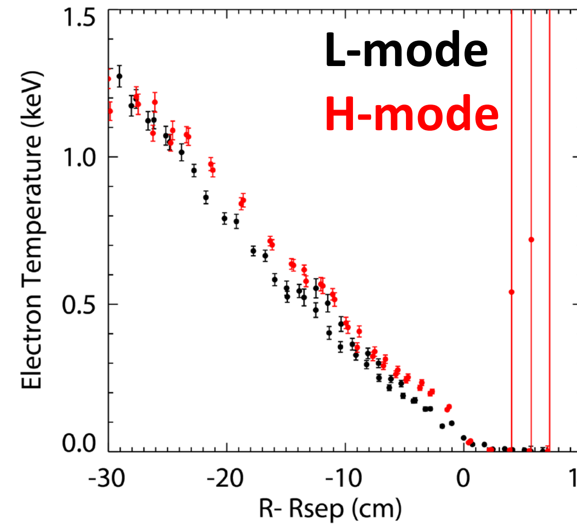


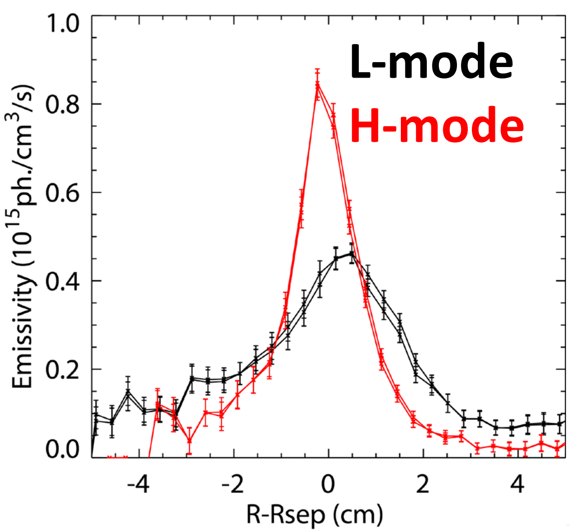


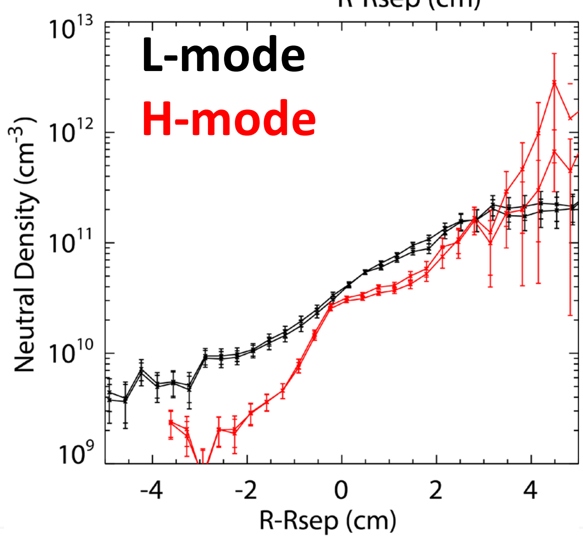
Narrower emissivity profiles and steeper neutral density decay observed in H-mode conditions

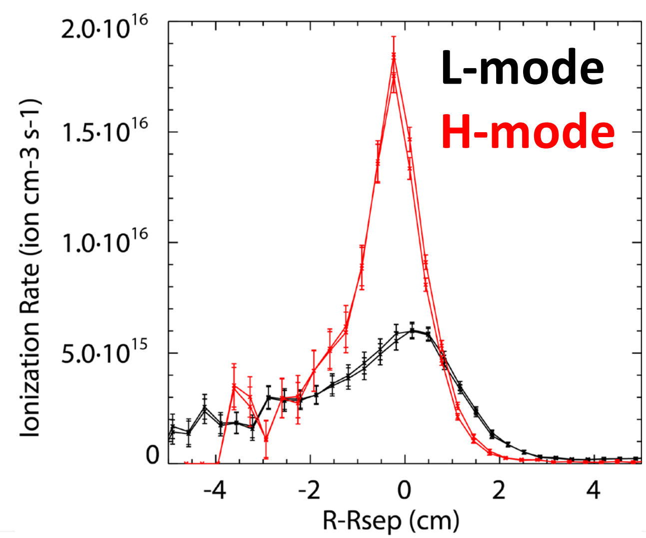
- Peak emissivity at LCFS
- Shorter n_D gradient scale length due to higher n_e in H-mode
- Comparable n_D in SOL





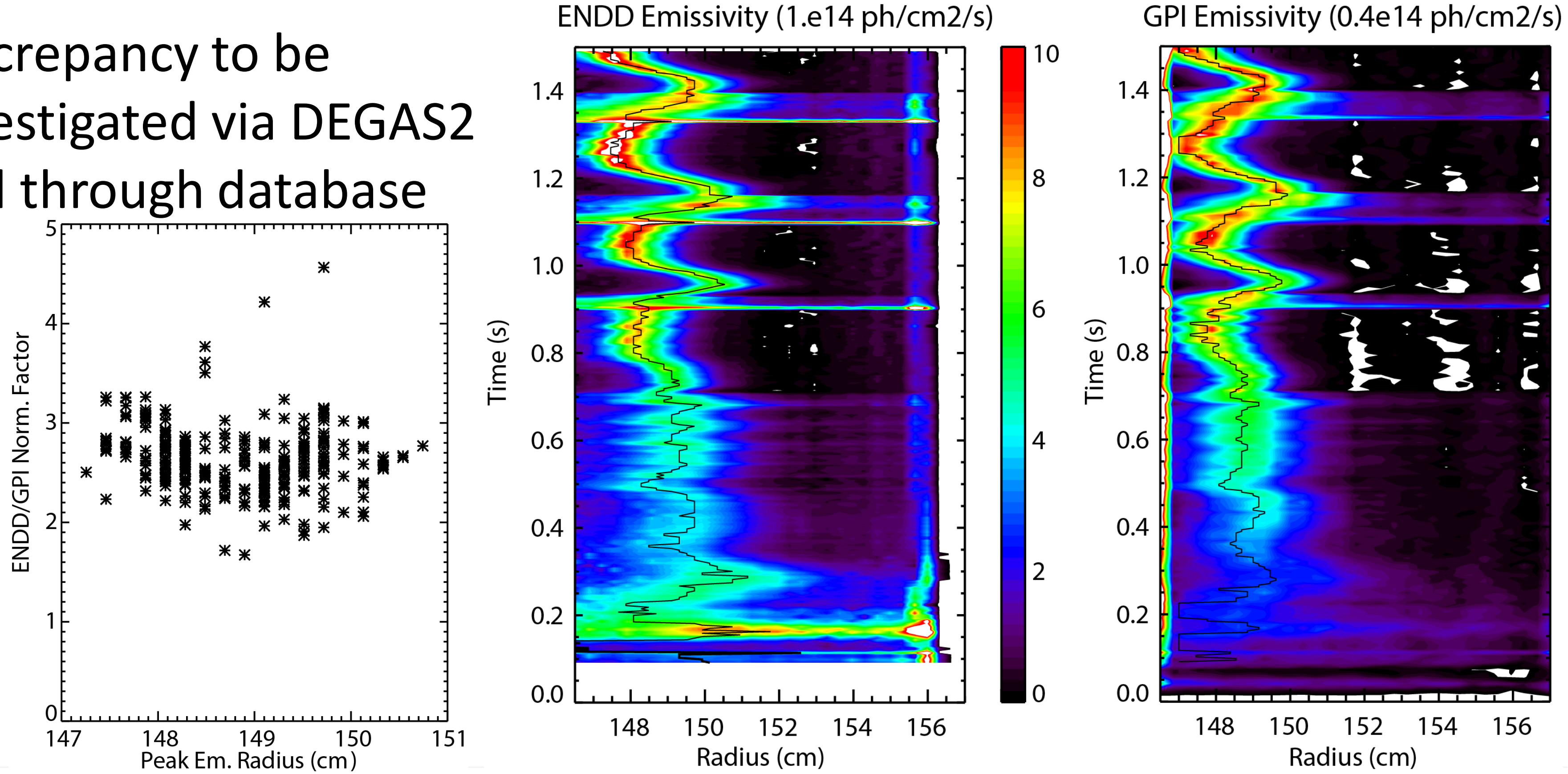






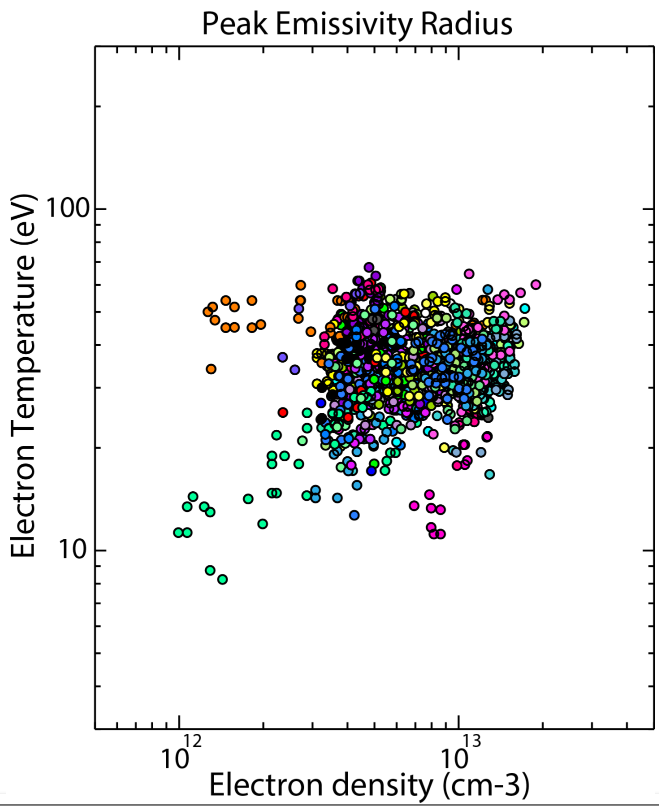
Higher ENDD emissivity might suggest role of NBI armor on neutral densities at ENDD location

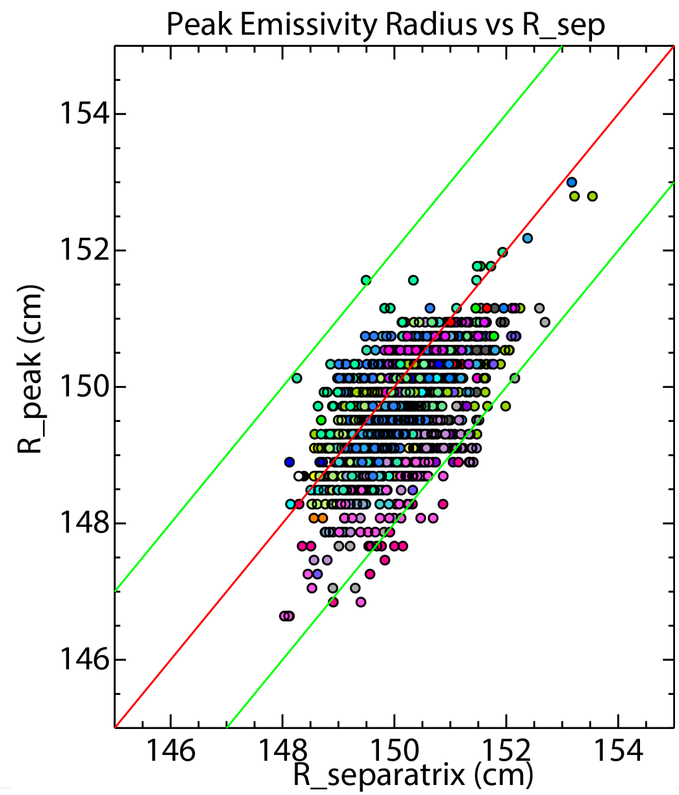
- Emissivity higher at ENDD location by X2.5, similar profile shape
  - unaffected by distance from wall in single discharge
  - effect of recycling on beam armor or baffling?
- Discrepancy to be investigated via DEGAS2 and through database



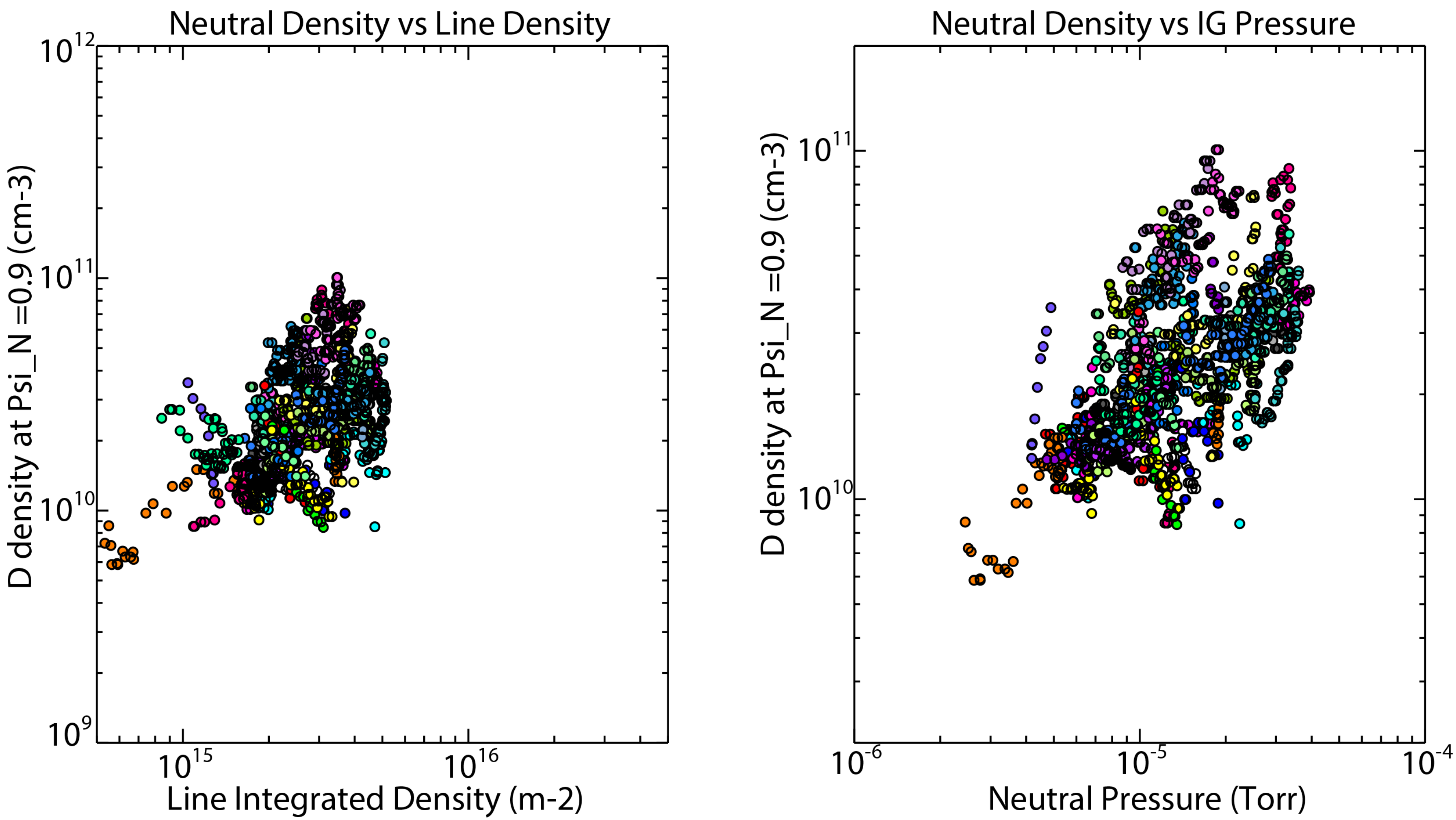
Statistical analysis over ~60 L-mode discharges to infer main trends for midplane n_D

- 60 NSTX-U discharges, limited to L-mode intervals, ENDD profiles at MPTS time points
- Peak emissivity localized at LCFS +/-1cm, follows T_e=25-50 eV



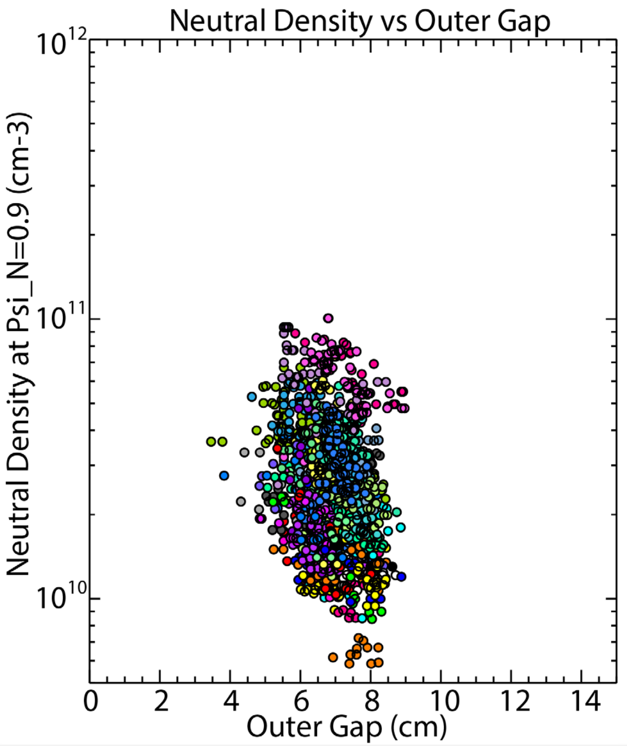


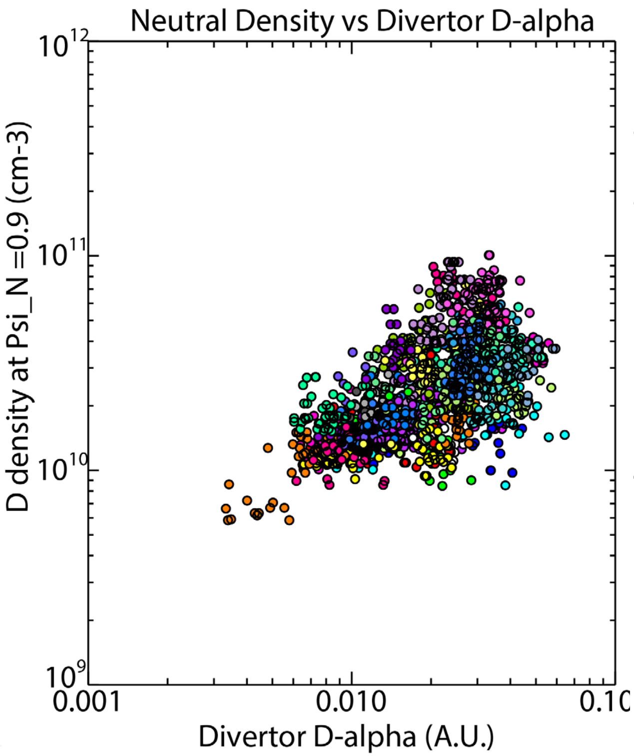
Midplane neutral density correlated with vessel pressure from ionization gauge, line averaged n_e

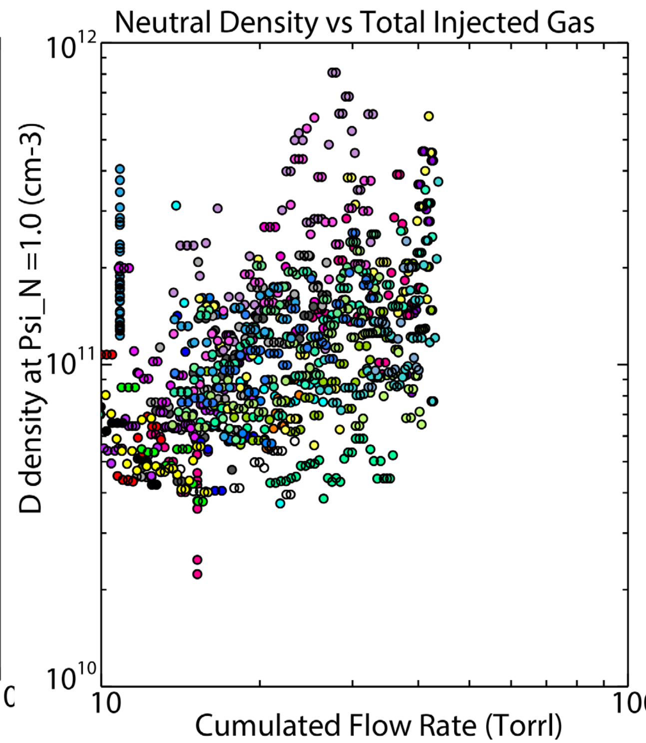


In L-mode plasmas: divertor recycling, main wall recycling and fueling correlate with midplane n_D

- Separatrix n_D correlated with outer gap, injected gas, divertor D-alpha
- Edge n_D correlates with divertor recycling, main chamber recycling and LFS fueling

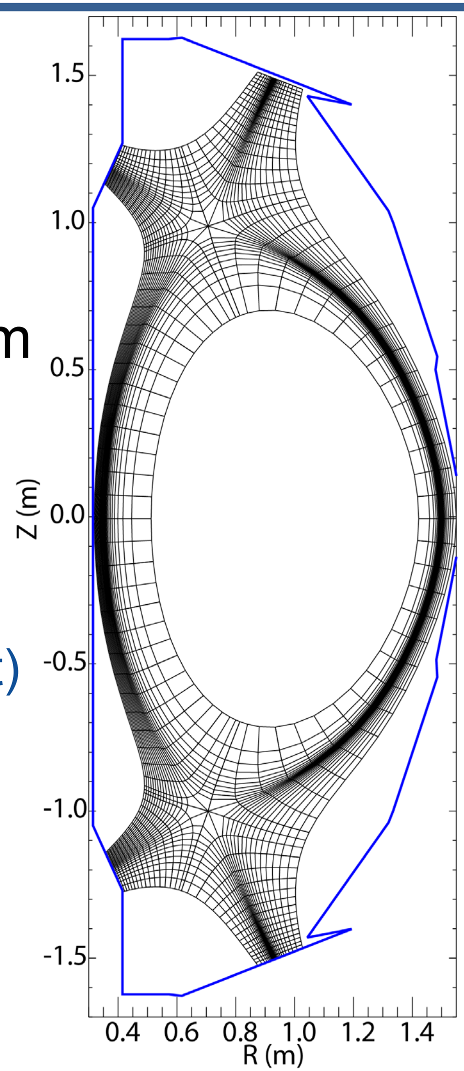






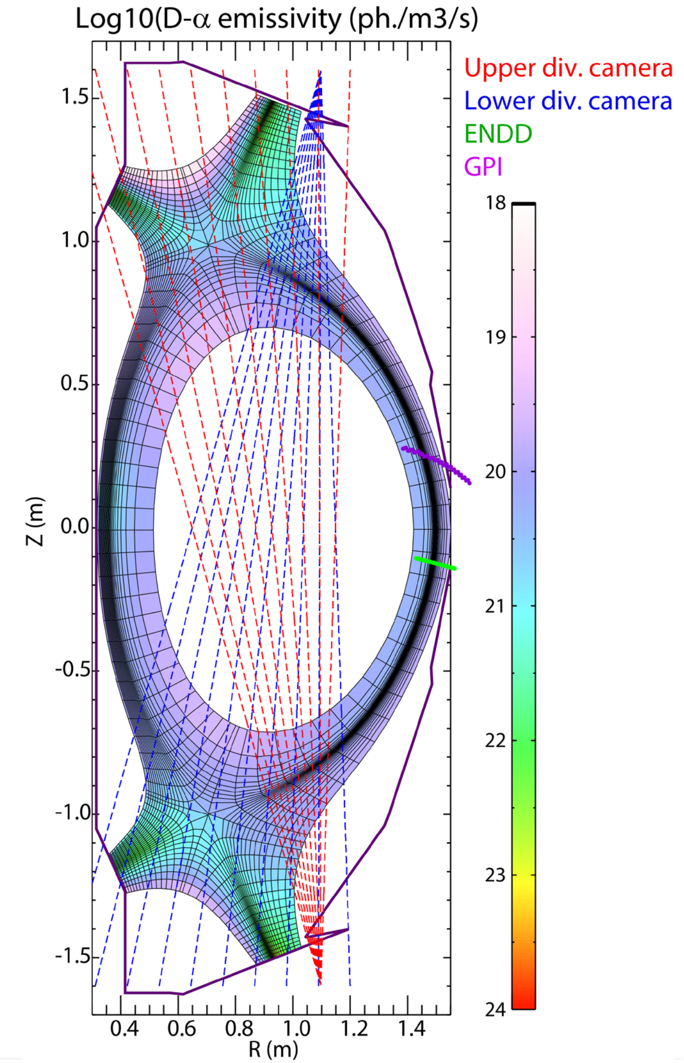
Multi-fluid edge transport code UEDGE used to study neutral distribution and core fueling

- UEDGE, 2D multi-fluid edge code:
  - Fluid (Braginskii) model for D^0, D^+, e^-
  - Classical parallel transport, *ad-hoc* radial transport
  - Full cross-field drifts model
  - χ_e, χ_i, D_{perp} to match exp. midplane profiles
- Balanced double null grid based on EFIT02 equilibrium
  - 126 poloidal x 25 radial cells
  - Norm. Poloidal Flux 0.7-1.2
    - Grid extends until LFS limiter
    - Core boundary to ~satisfy zero neutral flux BC
    - Full ENDD radial coverage
  - Power B.C. on core boundary: P_{sep} ~1 MW (equally split)
  - Ion flux B.C. on core boundary: -24 A (16 A NBI - 40A dN/dt)
  - Zero neutral flux at core boundary
- Neutrals BC:
  - 97% divertor target recycling, 100% albedo
  - Momentum recycling (recycm):
    - -0.5, slipping BC (-10), thermal momentum flux BC (-11)
  - 150A LFS gas injection, 100A HFS gas injection



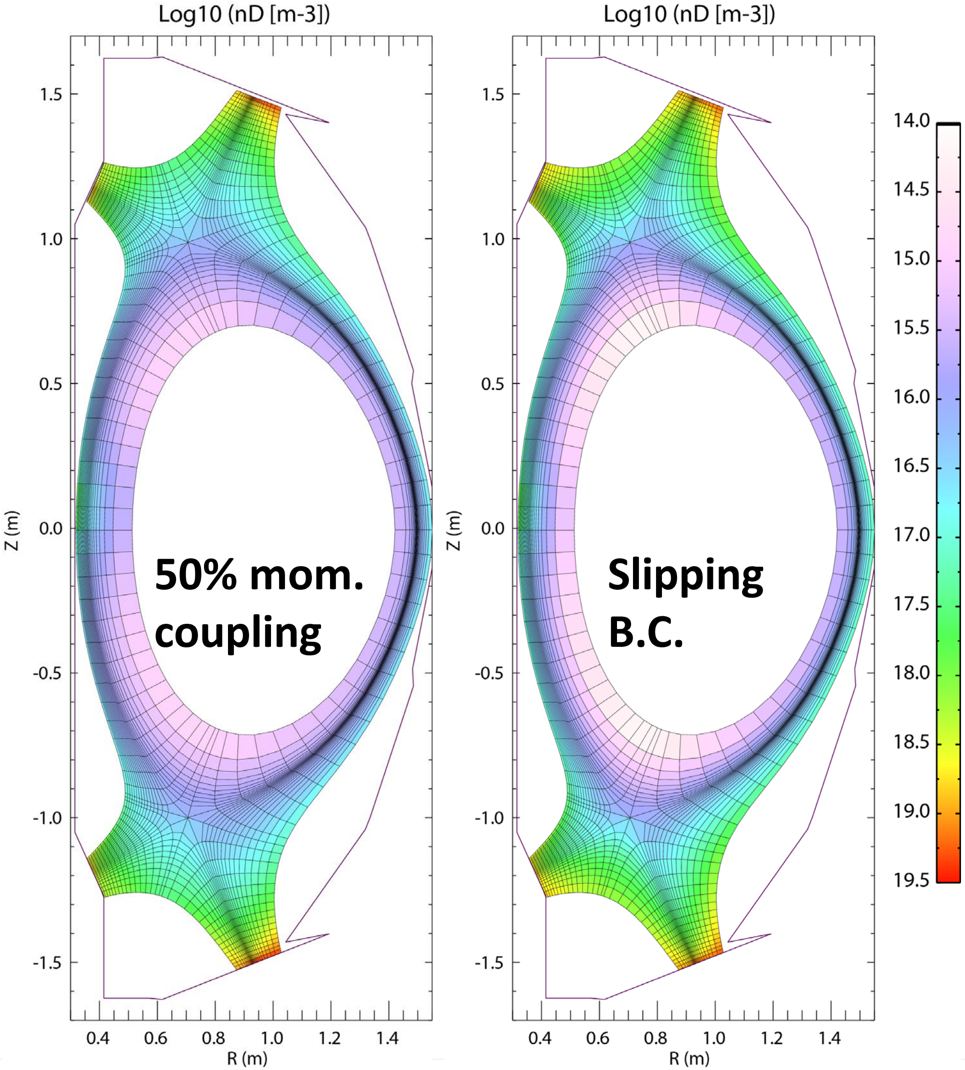
Synthetic diagnostics to reconstruct measured midplane D-α emissivity and divertor brightness

- D-α emissivity calculated in IDL from UEDGE outputs
  - Photon emission coefficients from DEGAS2 collisional radiative model
- ENDD and GPI emissivity calculated at experimental tangency radii
- Divertor brightness from line integration
- Synthetic diagnostic is compared to absolutely calibrated diagnostic measurements



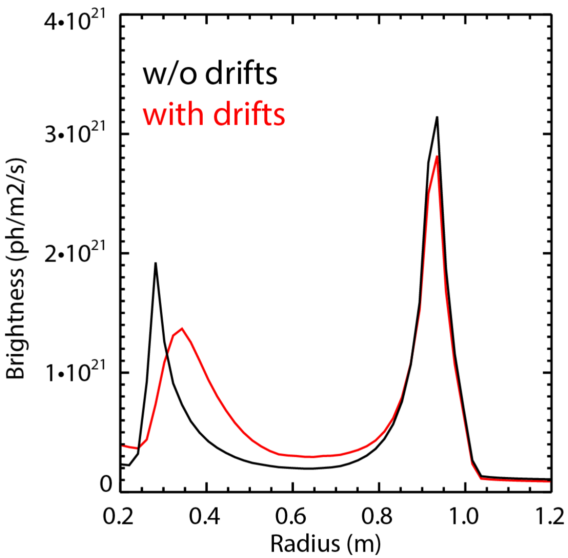
Midplane neutral densities affected by choice of neutral B.C. on UEDGE divertor target, wall

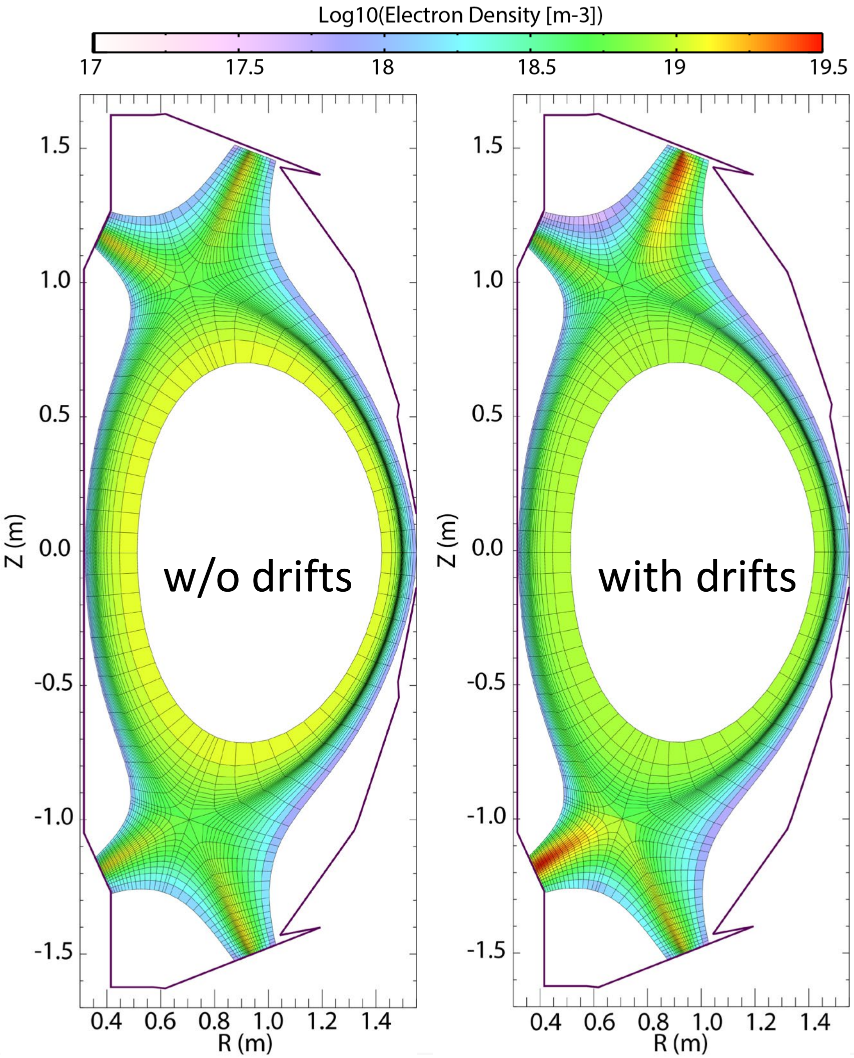
- Fixed momentum recycling coeff. (-0.5), over-predicts divertor neutral compression
- Better agreement in midplane/divertor D-α observed with slipping and momentum loss boundary conditions
- UEDGE wall at grid extremes creates artificial closed divertor
  - Prevents neutrals streaming from divertor to main chamber
- MC simulations (DEGAS2, EIRENE) will be performed on UEDGE plasma background



Inclusion of cross field drifts increases inner strike point density, modifies in-out D-α asymmetry

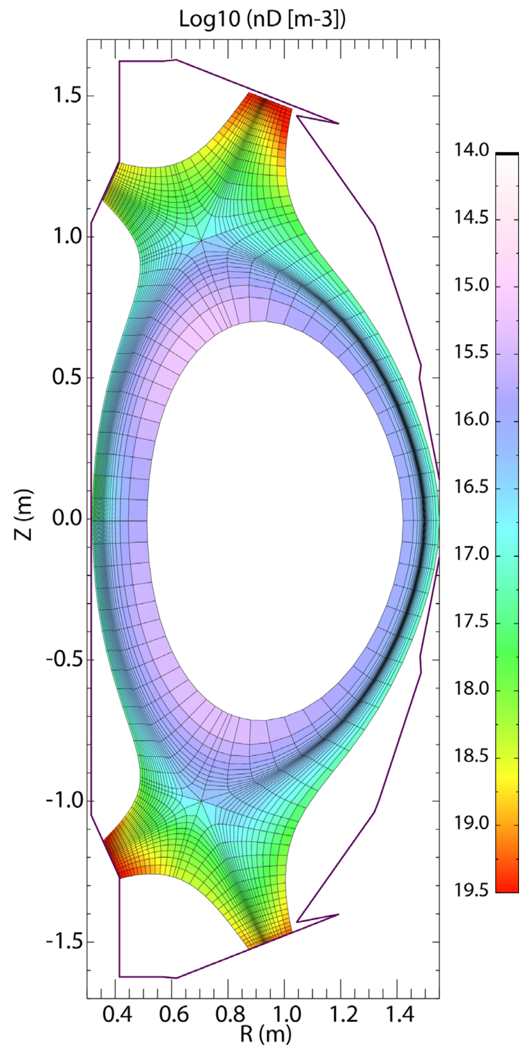
- Cross-field drifts move particles from outer leg to inner leg in lower div., from inner leg to outer leg in upper div.
- Only observable during experiment is in-out asymmetry in D-α emission, which is only marginally modified

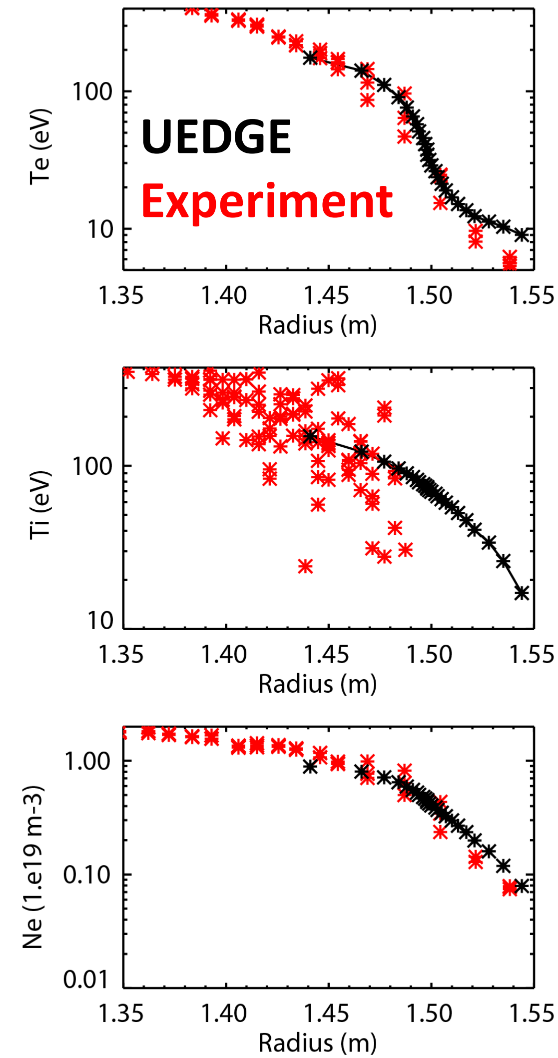




Experimental profiles matched with flat electron ion heat conductivities, ramping SOL diffusivity

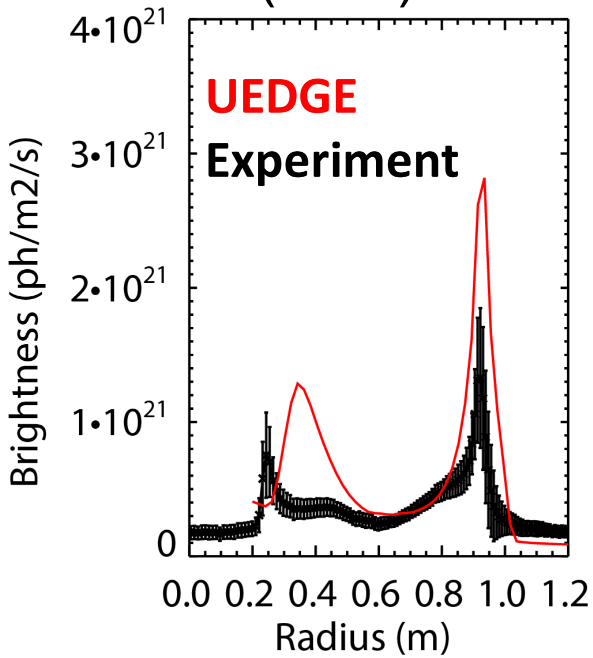
- χi, χe ~flat from LCFS to wall 6-8 m^2/s
- D=1.5-1.75 m^2/s from core to LCFS, increasing to 8 m^2/s at the wall
- Solution non-unique but matching D-α profiles limits range of particle diffusivities
  - Also due to limited midplane penetration of divertor recycled neutrals

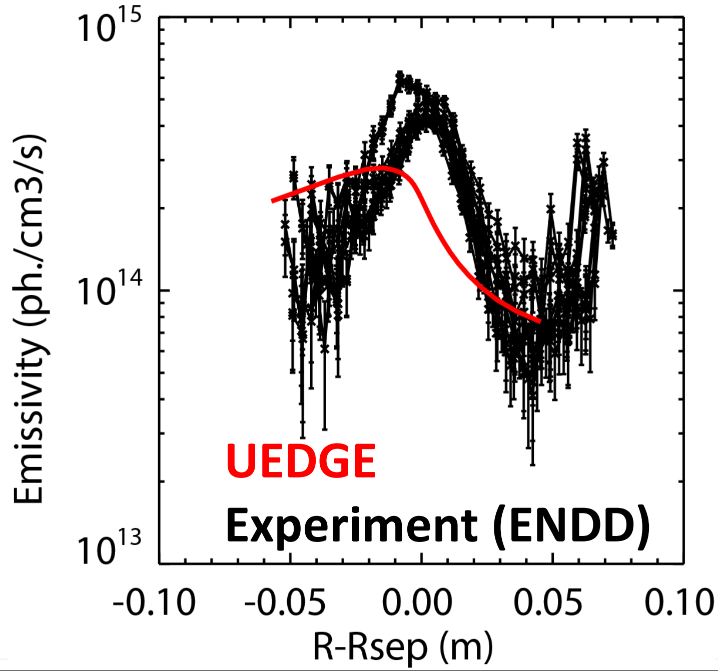




Large far SOL diffusivity needed to match ENDD D_α magnitude, higher fueling efficiency for main chamber recycled neutrals

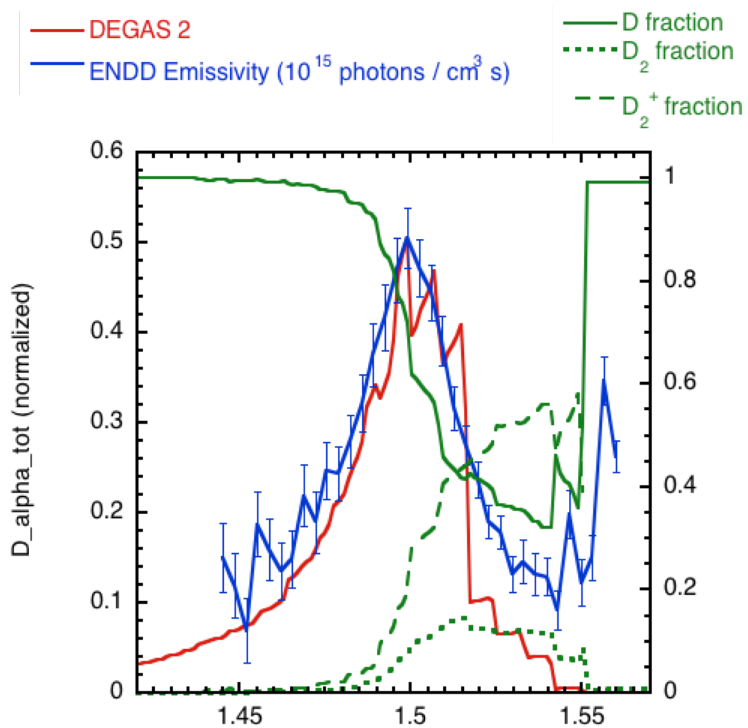
- Neutral density too high in divertor, too low at midplane
  - Could match reducing rec. or albedo, possibly due to artificial divertor closure
- Midplane D_α matched with large SOL particle diffusivity, deviations in profile shape
- Fueling efficiency for wall recycled neutrals ~43%, target recycled neutrals few % (~3%)

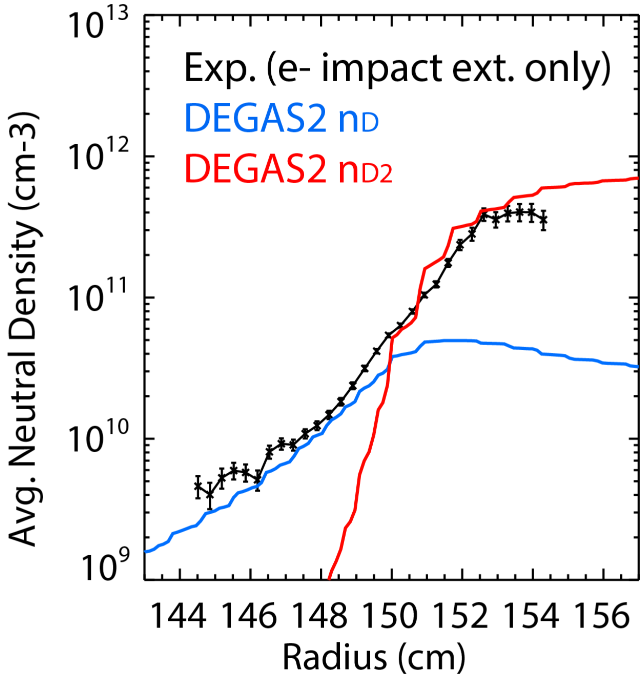




Initial DEGAS2 simulations match ENDD emissivity profile, n_D profiles only accurate inside LCFS

- DEGAS2 simulations performed using midplane n_e, T_e profiles to model D_α emissivity and contribution from molecular processes [Stotler, PoP 2015]
- Good agreement in midplane D_α emissivity profile shape
- Most of emission outside LCFS (~150cm) due to atoms excited by molecular processes





Future work

- Interpretation of emissivity profiles via DEGAS2 following method developed in NSTX [D. Stotler, PoP 2015]
- Investigate difference between GPI and ENDD emissivities
- Compare UEDGE neutral solution to DEGAS2/EIRENE MC simulations via one-way coupling
  - Improve neutrals boundary conditions at UEDGE wall
- Extend study to different configurations (e.g., short leg divertor), H-mode discharges and pedestal fueling studies