Advances in Measuring and Understanding Neutral Fueling and Pedestal Particle Transport at DIII-D

Laszlo Horvath
Princeton Plasma Physics Laboratory, US

with contributions from
R. Gerrú[2], F.M. Laggner[3], A. Bortolon[1], E.D. Emdee[1], G. Wilkie[1], J. Dunsmore[2], T. Wilks[2], J.W. Hughes[2], F. Scotti[4], M.G. Burke[4], S.R. Haskey[1], Q. Pratt[1], J. Balbin-Arias[5], T. Odstrcil[6]

[1]PPPL, [2]MIT PSFC, [3]NCSU, [4]LLNL, [5]W&M, [6]GA

EUROfusion PSD-DCT meeting
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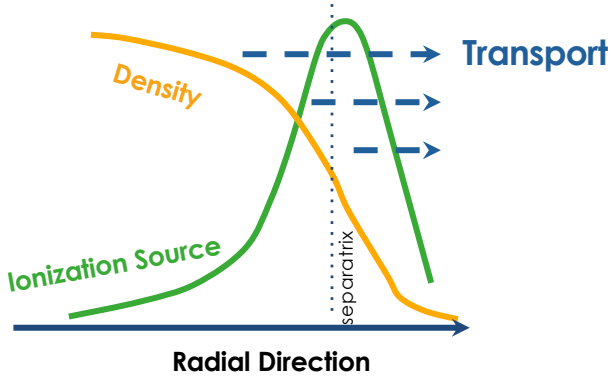
DIII-D NATIONAL FUSION FACILITY

MIT PSFC Plasma Science and Fusion Center

PPPL

Edge Particle Source is Dominated by Neutral Ionization in Current Experiments

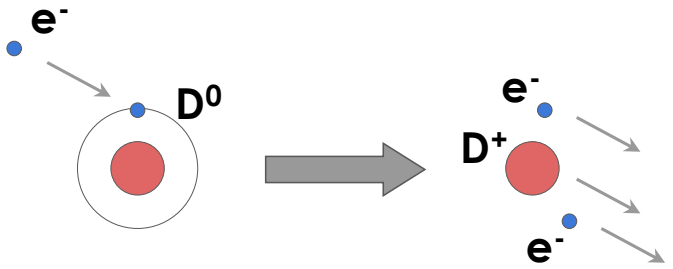
How the density pedestal is set by the balance of sources and transport?



$$\frac{\partial n}{\partial t} = -\nabla\Gamma + S$$

Density — Transport (Particle Flux) — Sources

- Particle source through ionization
- Proportional to neutral density (n_0)

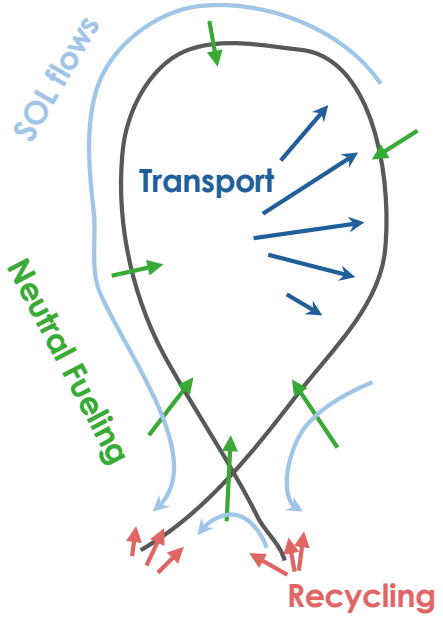


Outline

- How the plasma is fueled by neutrals
- Pedestal ionization source measurements
- Fueling and transport in large machines

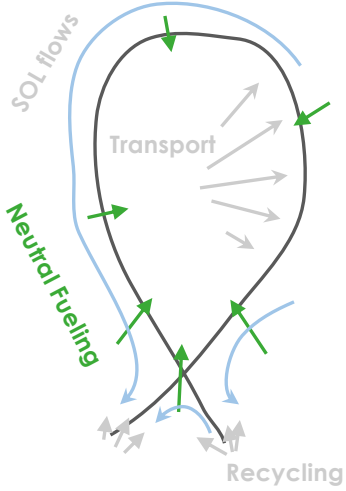
How the plasma is fueled by neutrals?

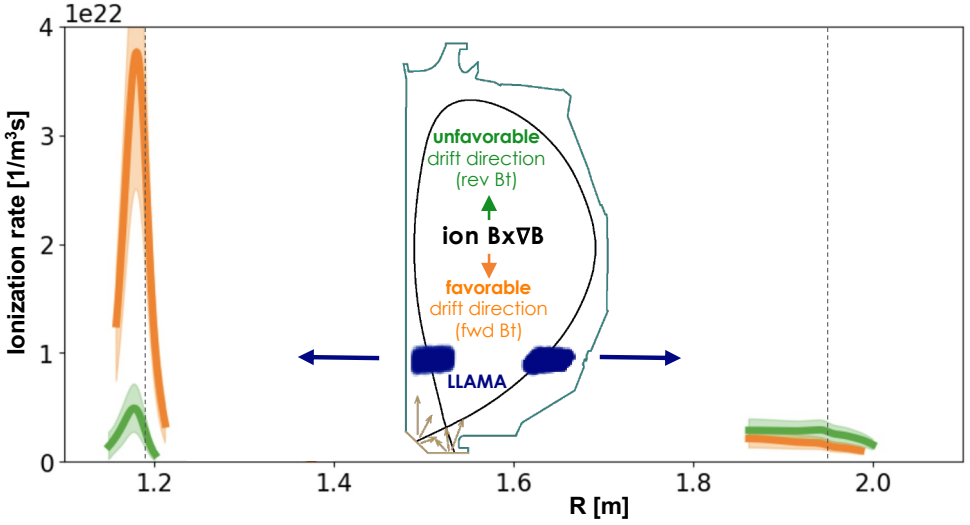
- Cross-field transport populates flux tubes
- SOL flows distribute flux to divertor
- Strong recycling source at the targets
- Neutral penetration

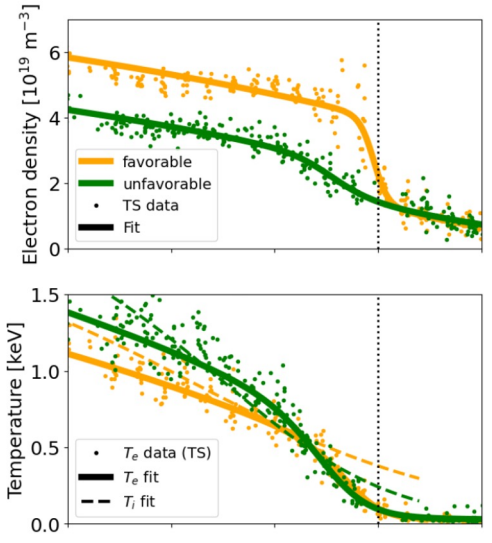


Strong Asymmetry in Pedestal Fueling Upon Reversal of Toroidal Magnetic Field is Observed

- Fueling dominated at HFS with favorable grad B drift direction
- More balanced in unfavorable grad B drift direction
- Similar to observations of divertor target measurements

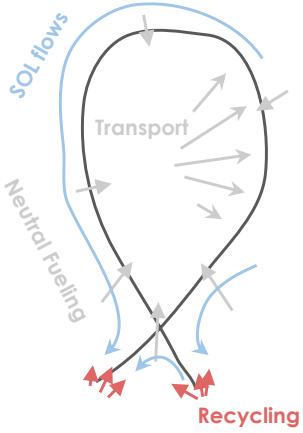


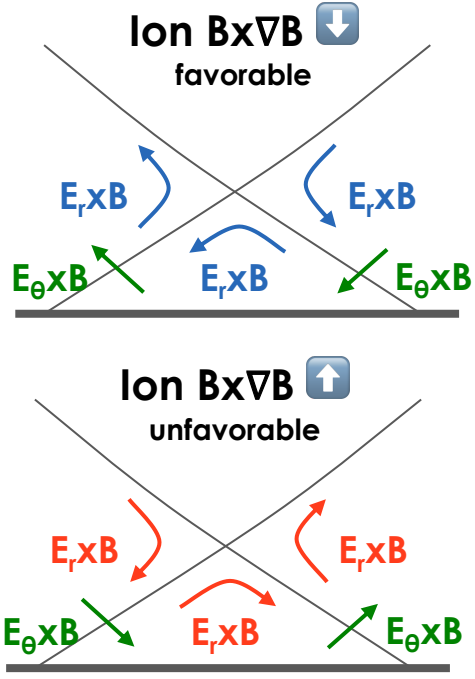




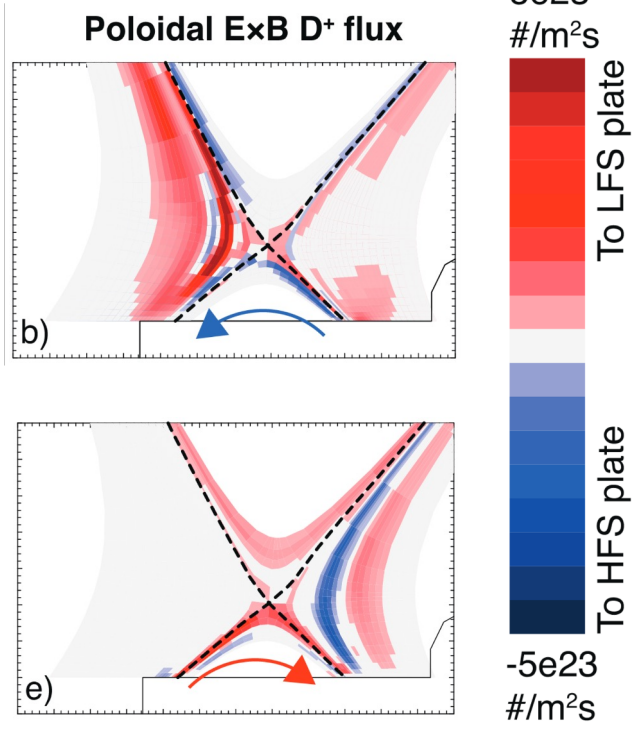
SOL Flows Play Important Role in Target Flux Asymmetries

- **Recycling Asymmetries Largely Attributed to Drifts in the PFR**
  - B_t direction reverse ExB drifts





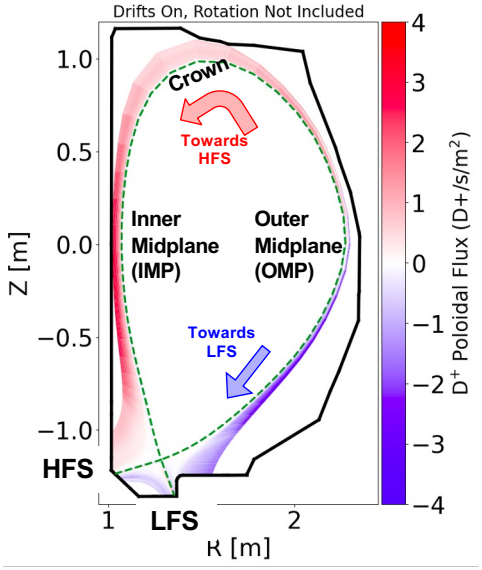
UEDGE simulations

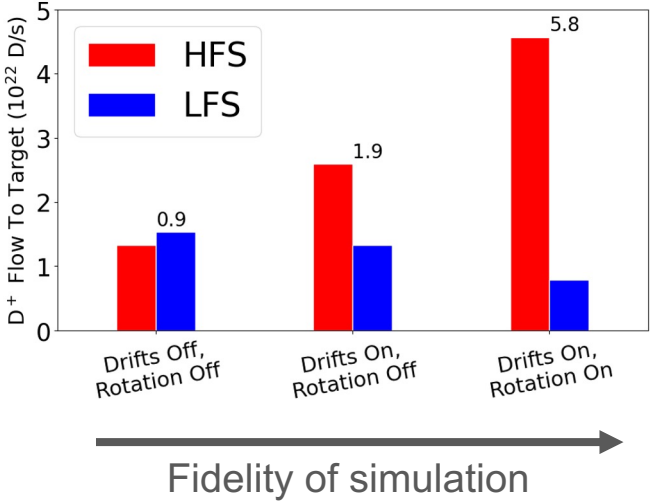


[Jaervinen NME 2017]

Poloidal Projection of Parallel Velocity can also Provide Large Contribution to the Poloidal Particle Flux

- **Parallel SOL flows distribute particle flux between the targets**
- **Drifts combined with an upstream rotation boundary condition lead to larger target recycling asymmetry (SOLPS-ITER)**

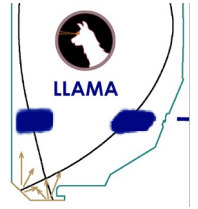


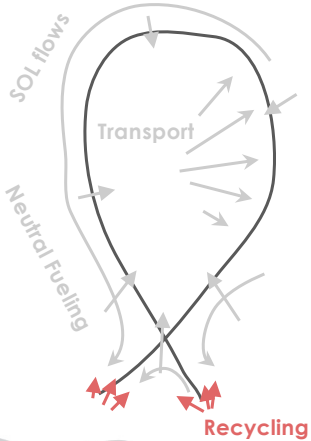


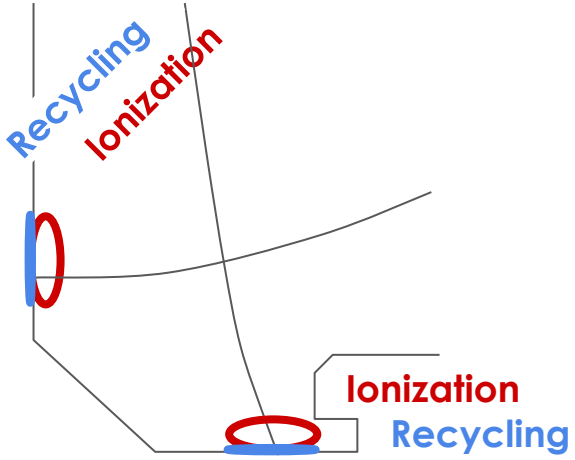
[Emdee PRL 2025]

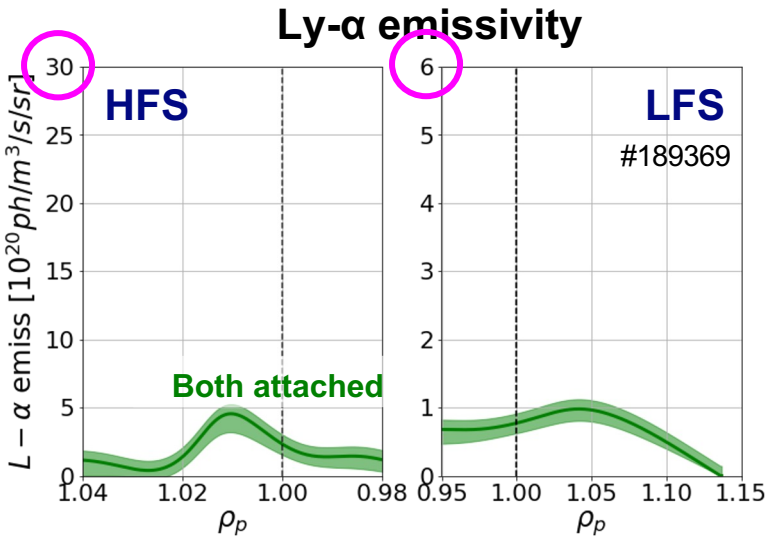
Strong HFS Fueling is Facilitated by Inner Divertor Detachment

- **<u>Attached targets:</u> Moderate asymmetry in Ly-α**
  - hot target, recycling





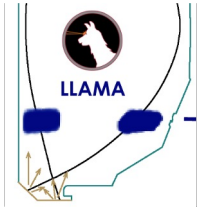


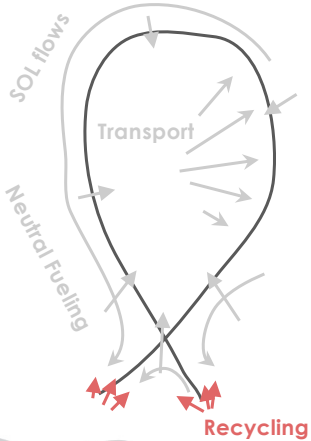


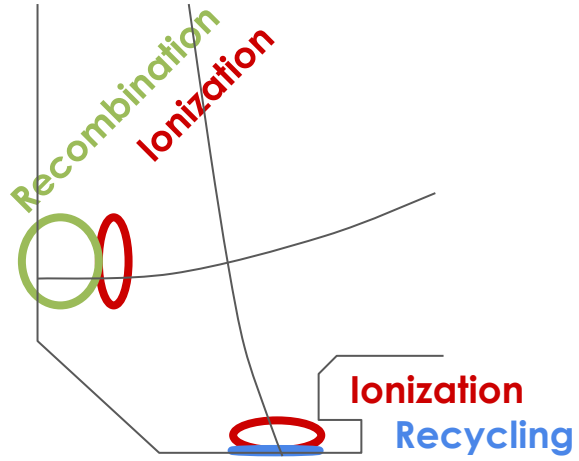
[Gerru submitted to NF]

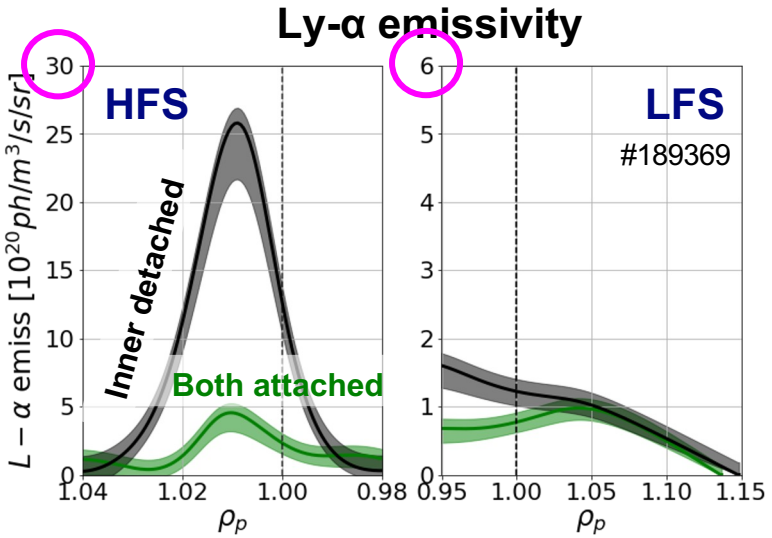
Strong HFS Fueling is Facilitated by Inner Divertor Detachment

- **Attached targets: Moderate asymmetry in Ly-α**
- **<u>Detached inner target</u>: Strong increase in HFS Ly-α**
  - Target recycling reduced
  - Recombination source, closer to upstream









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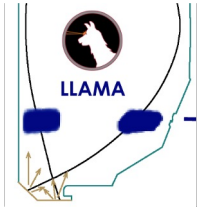
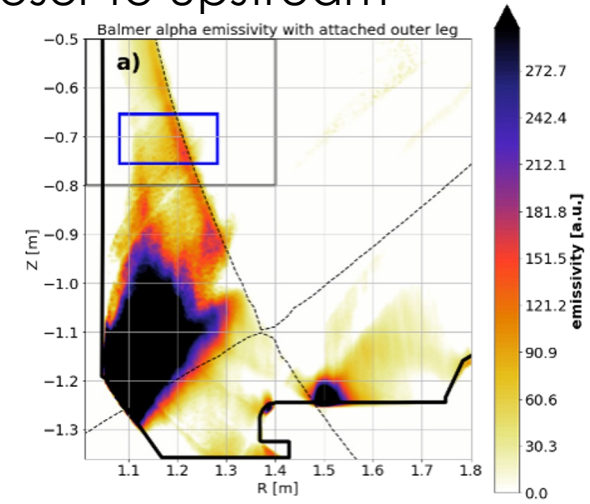
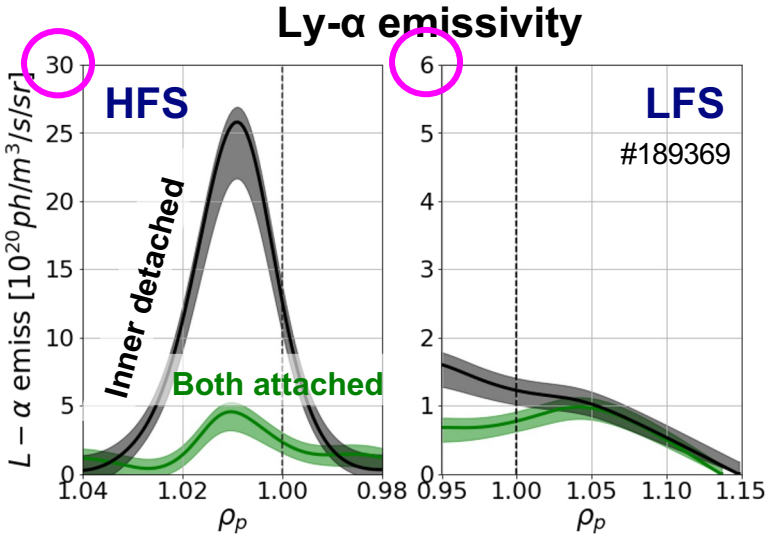


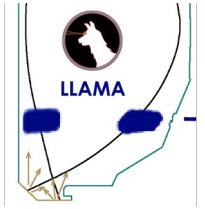




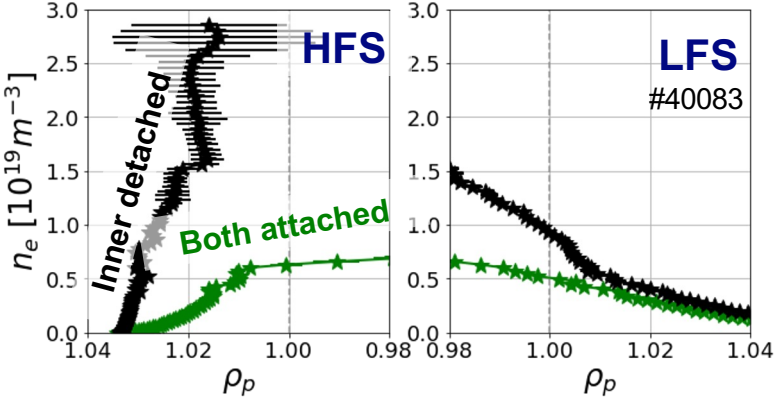
[Gerru submitted to NF]

Comparison between AUG n_e and DIII-D Ly-α Measurements Indicating Asymmetries Present in both Neutral and Electron Density

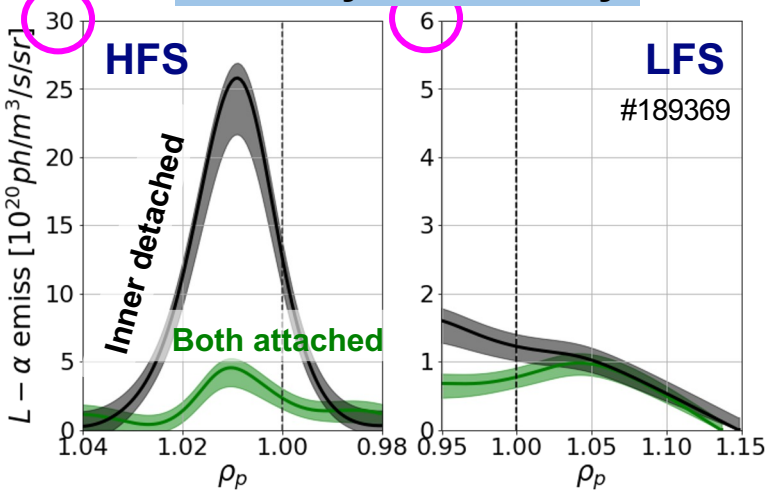
- Emissivity proportional to $n_e \times n_0$
- Qualitatively similar behaviour to n_e on AUG



AUG electron density



DIII-D Ly-α emissivity



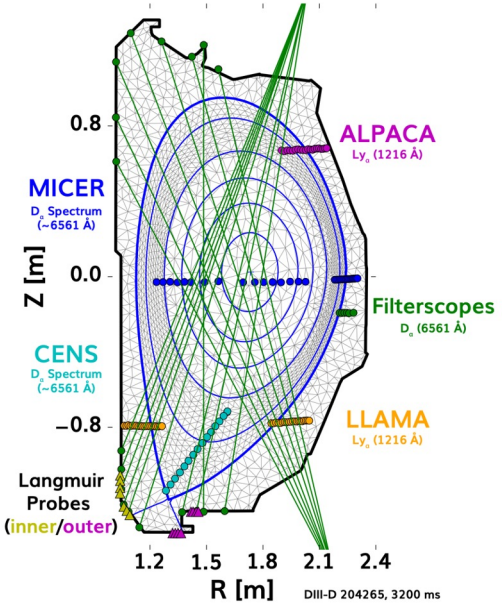
[Gerru submitted to NF]

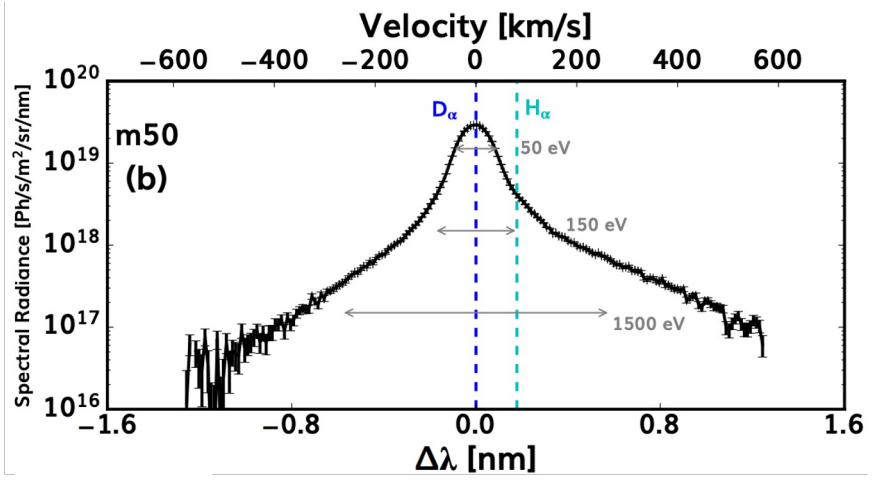
Outline

- How the plasma is fueled by neutrals
- Pedestal ionization source measurements
- Fueling and transport in large machines

Full 2D Pedestal Particle Source Reconstructed by the Combination of Neutral Diagnostics and Neutral Transport Modeling

- Fixed plasma background (n_e, T_e, T_i) from 1D profiles (confined region)
- Neutral source mimicking target Langmuir probe measurements
- DEGAS2 Monte Carlo kinetic neutral transport code for n_0





[Pratt in preparation]

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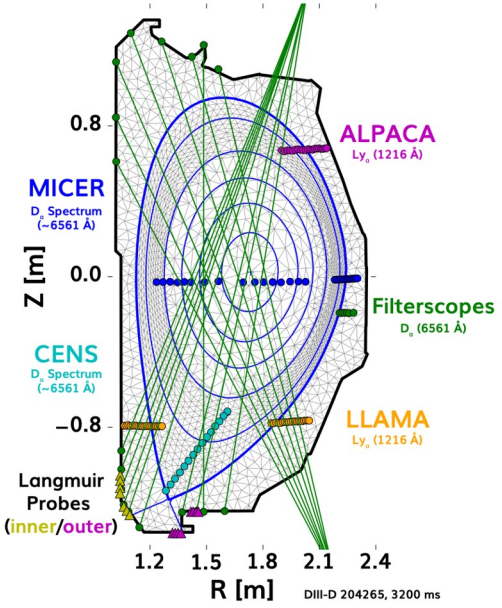
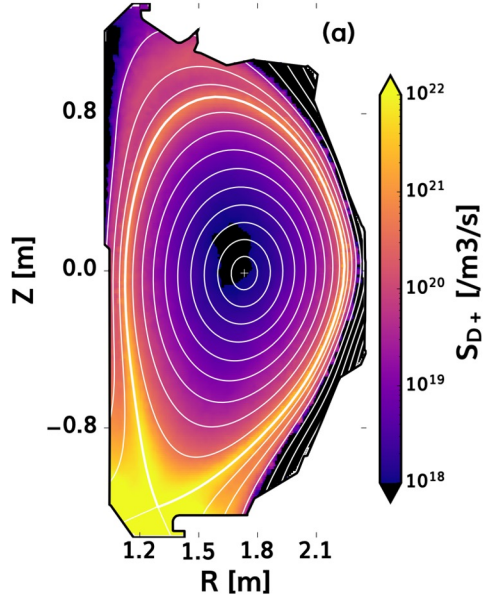


Iterations to match synthetic and measured diagnostic data

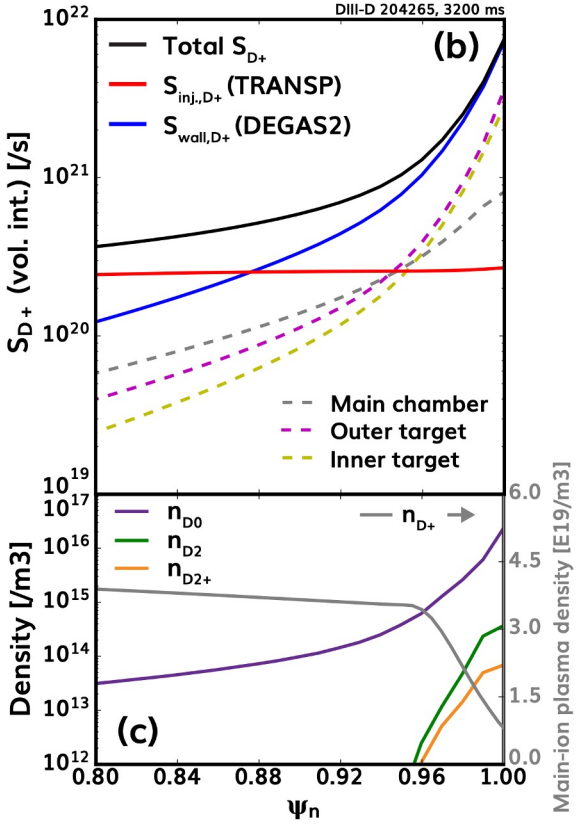
[Pratt in preparation]

Ionization source



Full 2D Pedestal Particle Source Reconstructed by the Combination of Neutral Diagnostics and Neutral Transport Modeling

- DIII-D ELMy H-mode plasma
- Main-chamber recycling 10x lower than diverter, but still very important: fueling at OMP more effective due to flux expansion
- Inferred flux surface averaged particle source key for particle transport model validation



[Pratt in preparation]

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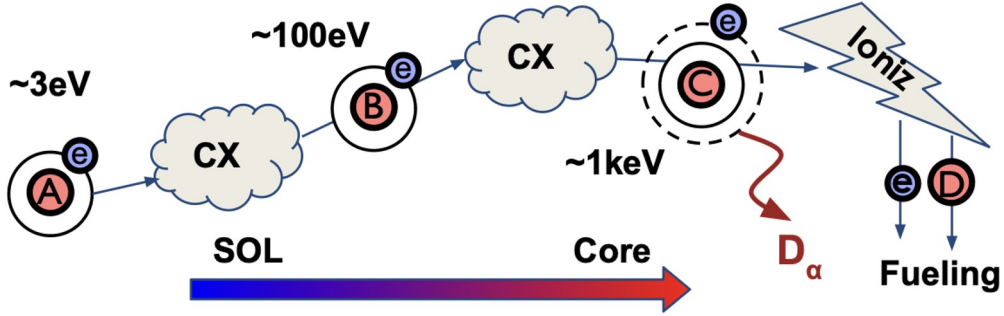
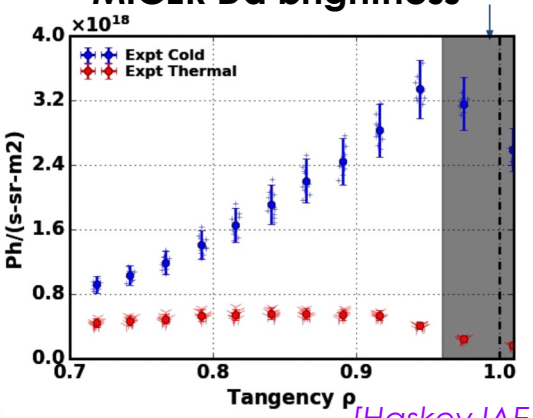
Charge-Exchange Neutrals with Higher Energy Penetrate Further into the Plasma

- Charge-exchange reaction creates higher energy neutrals → deeper penetration
- CENS and MICER sensitive to neutral energy (spectral resolution)
- Interpretative simulations (e.g. FIDASIM, DEGAS2) to infer cold and thermal densities

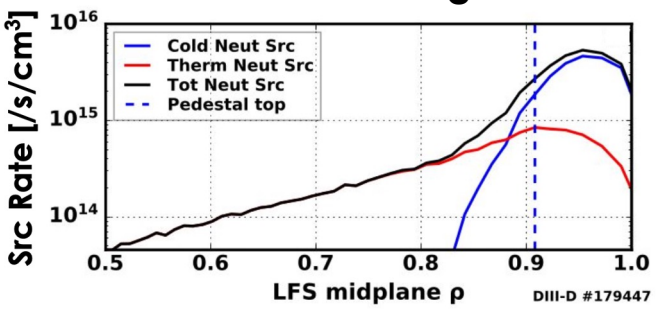


MICER Da brightness



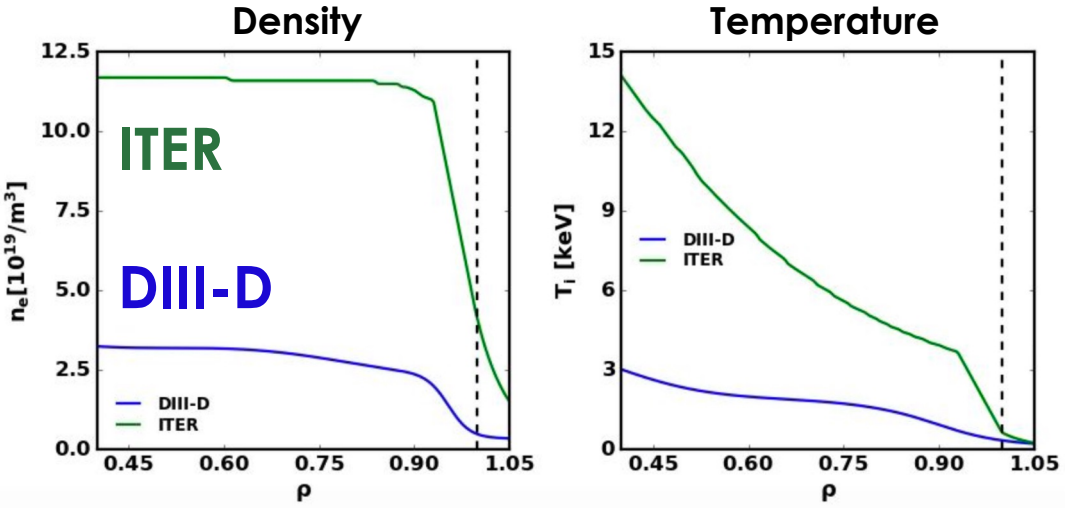
[Haskey IAEA 2023]

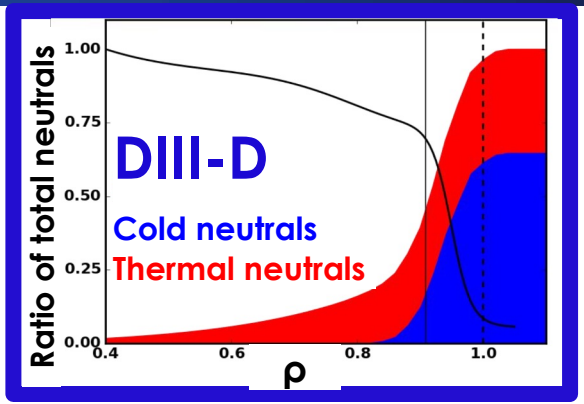
FIDASIM simulations fitting MICER data

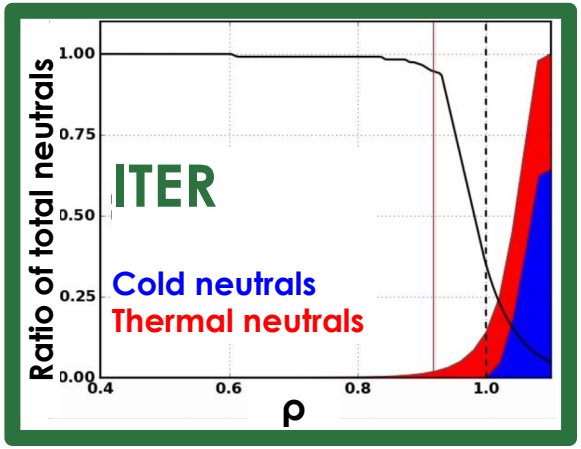


Only Thermal Neutrals Are Expected to Penetrate ITER Pedestals

- Thermal/CX neutrals dominate particle source inside pedestal, longer decay length
- CX neutrals particularly important for ITER, where 0% cold neutrals penetrate inside LCFS







[Haskey IAEA 2023]

Diffusive and Convective Particle Transport Studies Using Source Modulation and LLAMA

- **Source/Density modulations to infer edge *D*s and *v*s**
- **Direct measurements of the ionization source with LLAMA is key**
- **Inferred transport coefficients indicated the possible role of a particle pinch**

$$\frac{\partial n}{\partial t} = -\nabla \cdot \Gamma + S$$

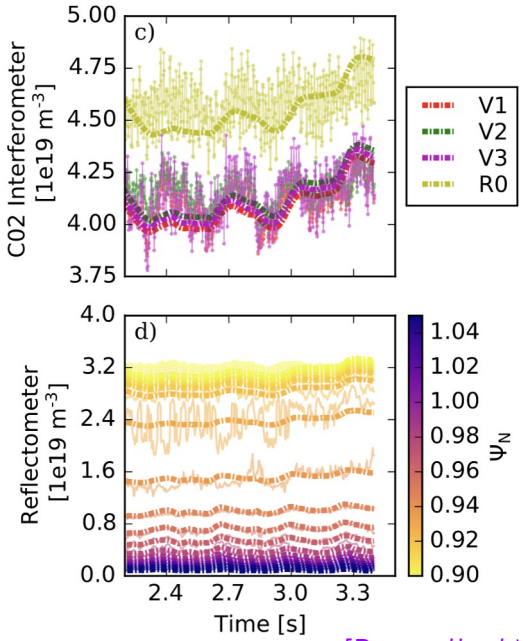
Particle Source

$$\Gamma = -D\nabla n + vn$$

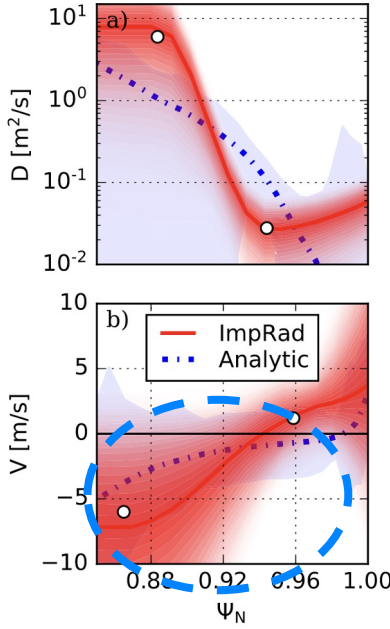
Diffusion **Convection**

See also
[Schuster NF 2022]
[Salmi PPCF 2023]

Forward modelling to match Density modulation



Inferred transport coefficients



[Rosenthal NF 2024]

Conclusions

- **Strong poloidal asymmetries in neutral fueling**
- **Role of PFR, main SOL flows and detachment are important in understanding fueling asymmetries**
- **Main chamber recycling important** (plasma can be fueled more effectively at OMP)
- **Future pedestals will be more opaque**
    - Profile stiffness, particle pinch, pellet fueling
- **Future work**
    - Understanding/predicting edge particle transport
    - Impurity transport and electron source