Pedestal fuelling studies with LLAMA on DIII-D

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with contributions from
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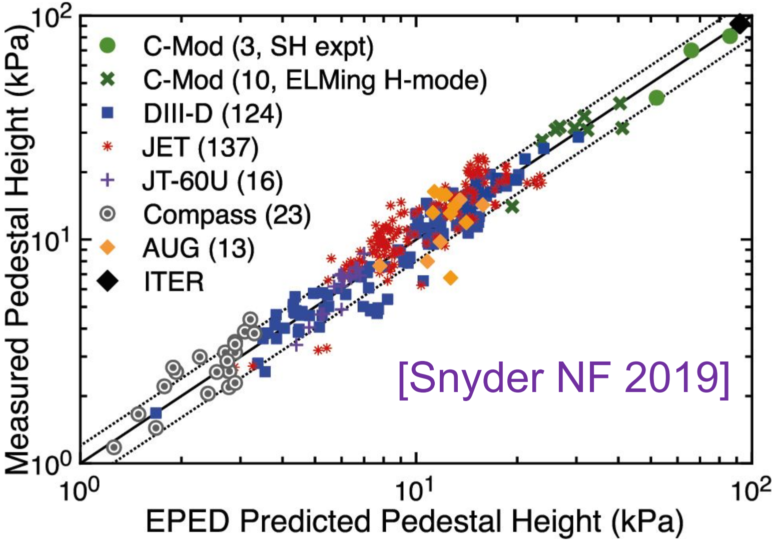
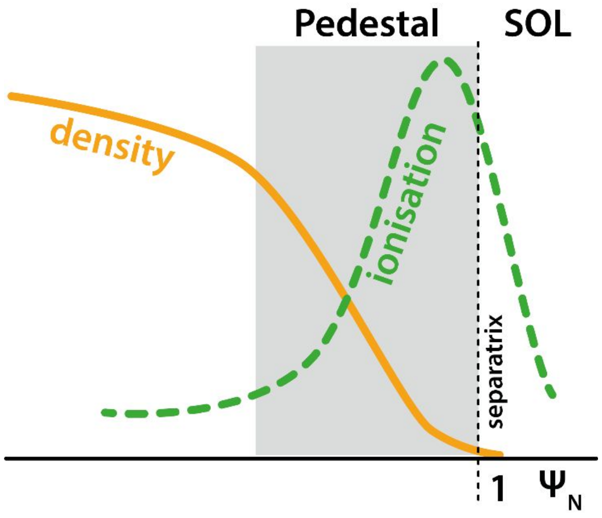
DIII-D NATIONAL FUSION FACILITY NC STATE MIT PSFC Plasma Science and Fusion Center PPPL

Understanding what sets the pedestal density structure is essential for pedestal predictions

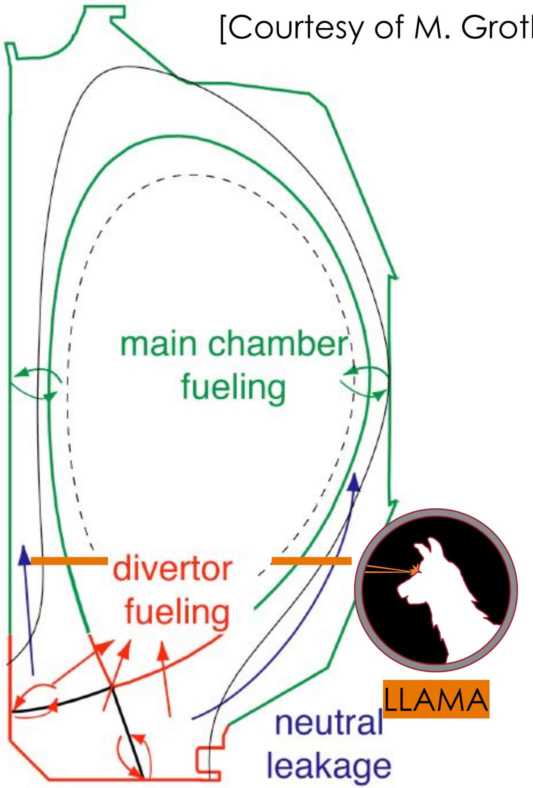




- EPED-like reduced model can predict p_e, but no model for n_e
- Role of fuelling vs transport in the density pedestal is an open question [Mordijck NF 2020]

Quantification of the pedestal particle source is essential for model validation

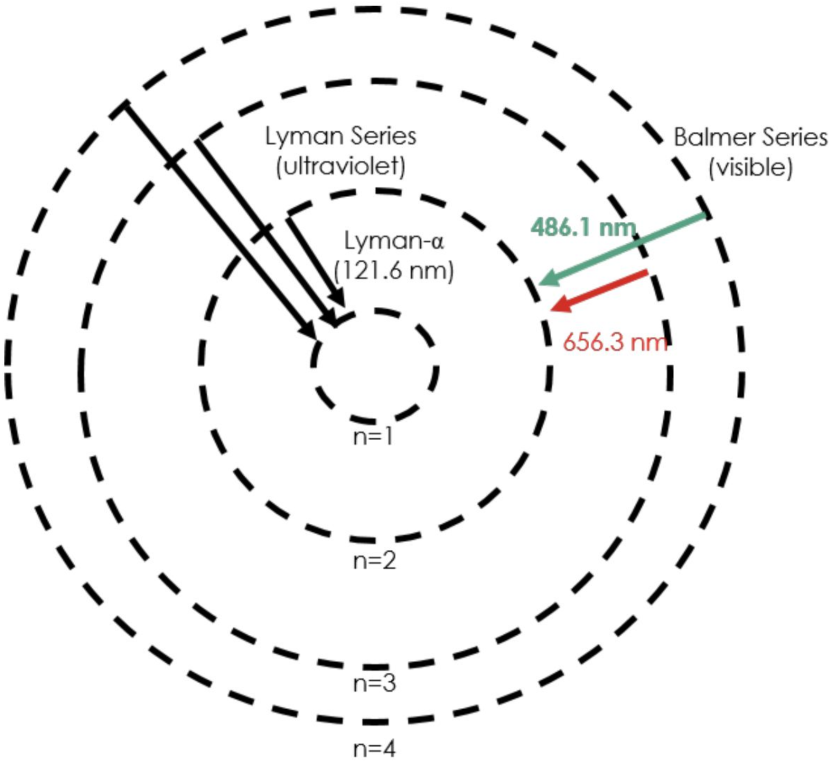
- **Sources of neutrals - “at least” a 2D problem**
  - Ion recycling at wall and div. targets
  - Inner leg detachment
- **Pedestal fueling take place:**
  - Directly via main chamber SOL
  - Directly via divertor region
  - Indirectly via leakage
- **Measurement Of Neutral Density And Pedestal Particle Source To Understand Fueling**



Outline

- LLAMA is the Lyman Alpha Measurement Apparatus
- Poloidal asymmetries in fuelling
- Edge-transport simulations
- Transport studies with LLAMA
- The future: ALPACA
- Conclusions

Measuring atomic line radiation to infer neutral density



Neutral Density $n_D = E_a / F(n_e, T_e)$

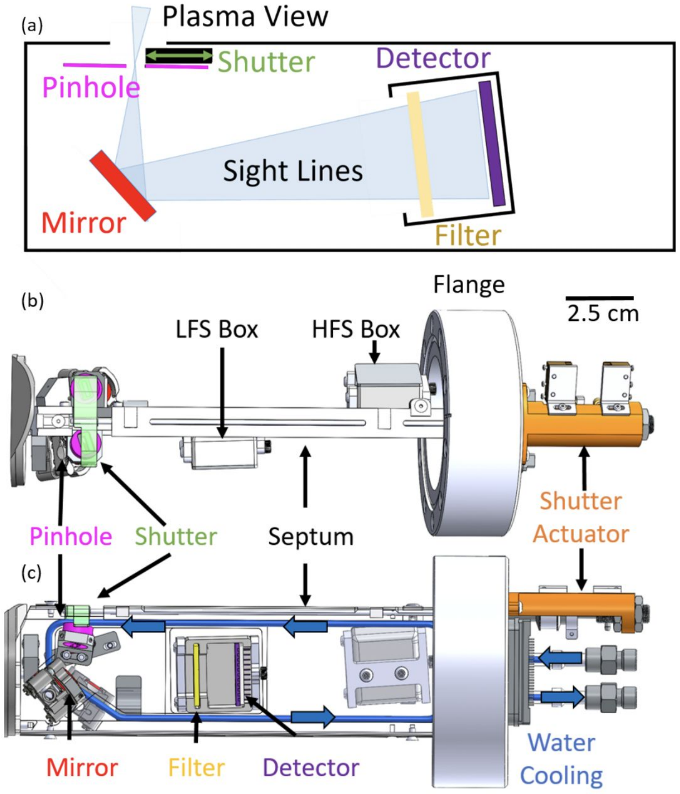
Emissivity

Rate Coefficients

Ionization Rate $S_{ion} = E_a\, G(n_e, T_e)$

- Why use Lyman instead of Balmer?
  - Large intensity
  - Lower reflections
  - Lower molecular components
- Drawback of Lyman
  - VUV: in-vacuum optics, low transmission
  - Difficult calibration

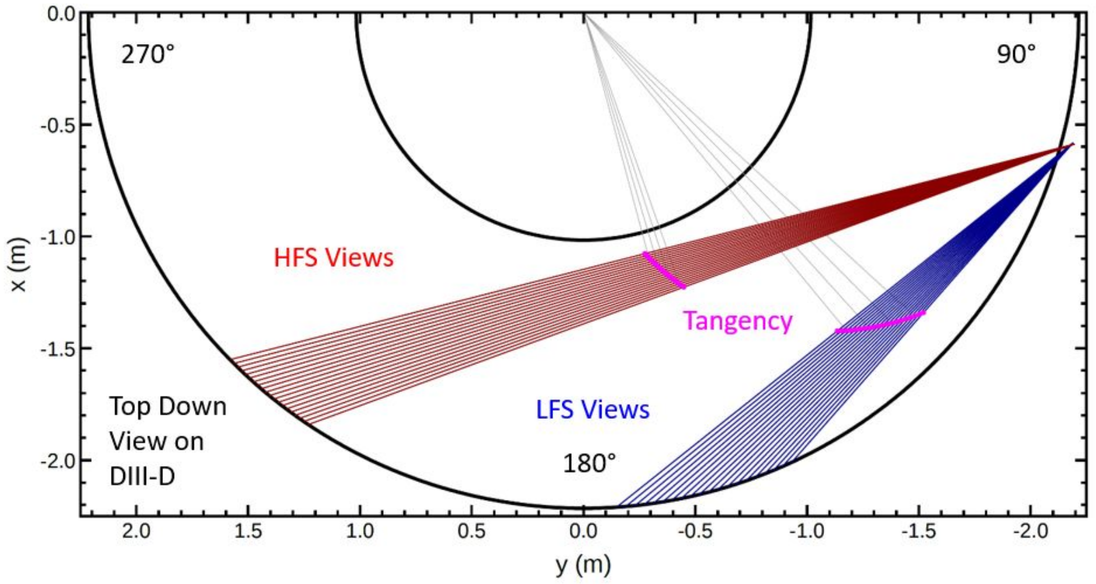
LLAMA is the Lyman Alpha Measurement Apparatus

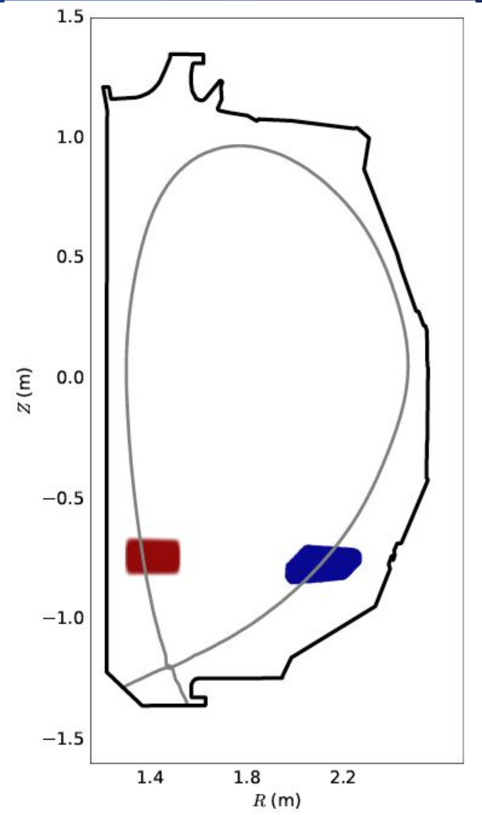


- **Developed through a PPPL-MIT partnership**
- **Installed on DIII-D in 2019**
- **Compact design**
- **Spectral sensitive components**
  - Bragg mirror (FWHM ~ 5 nm)
  - Interference filter (FWHM ~ 7 nm)
  - AXUV photodiode
- **Temporal responsivity**
  - AXUV photodiode - Transimpedance amplifier
    - 10^8 V/A gain, 1 kHz low pass filter

LLAMA views above the X-point with radial coverage at the edge

- 20 channels on each side
- Radial resolution of ~2 cm FWHM with ~20 cm total coverage

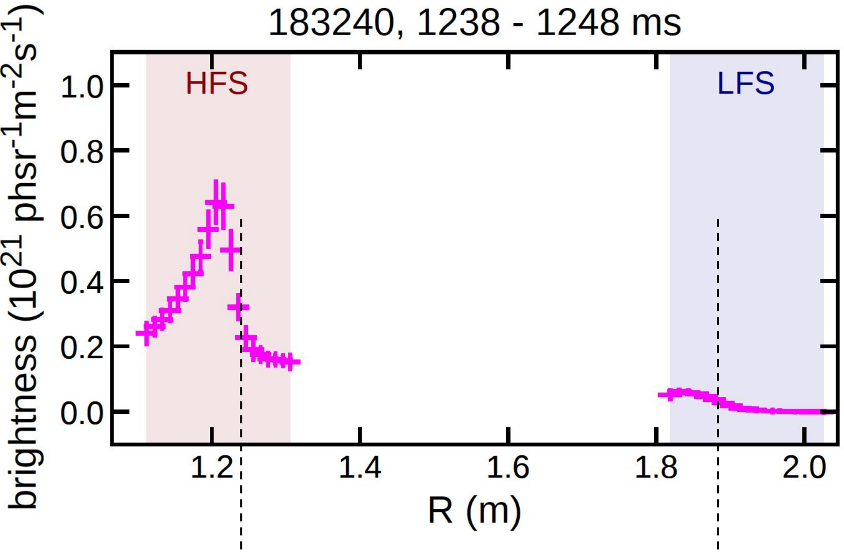


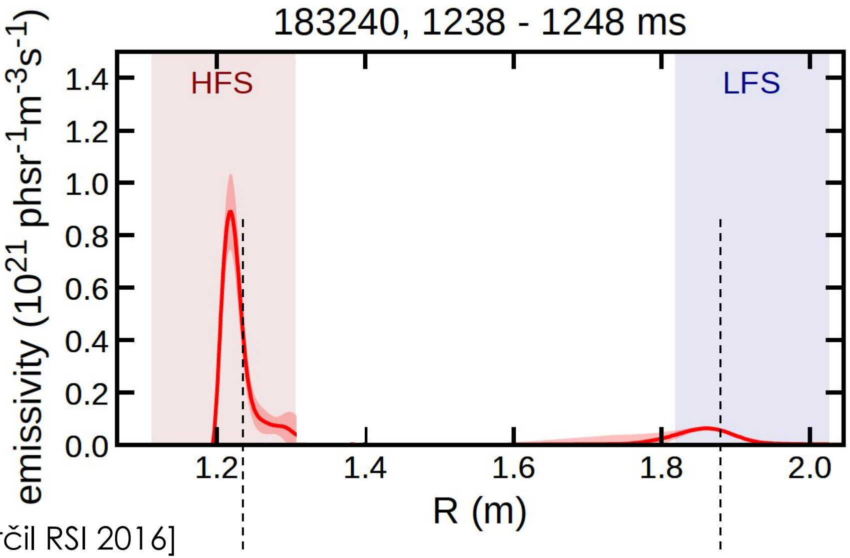


Toroidal views allow for emissivity inversion

LLAMA measurement (Ly-α brightness)

Radial profile (Ly-α emissivity)





[T. Odstrčil RSI 2016]

Neutral Density $n_D = \mathbf{E_a} / F(n_e, T_e)$

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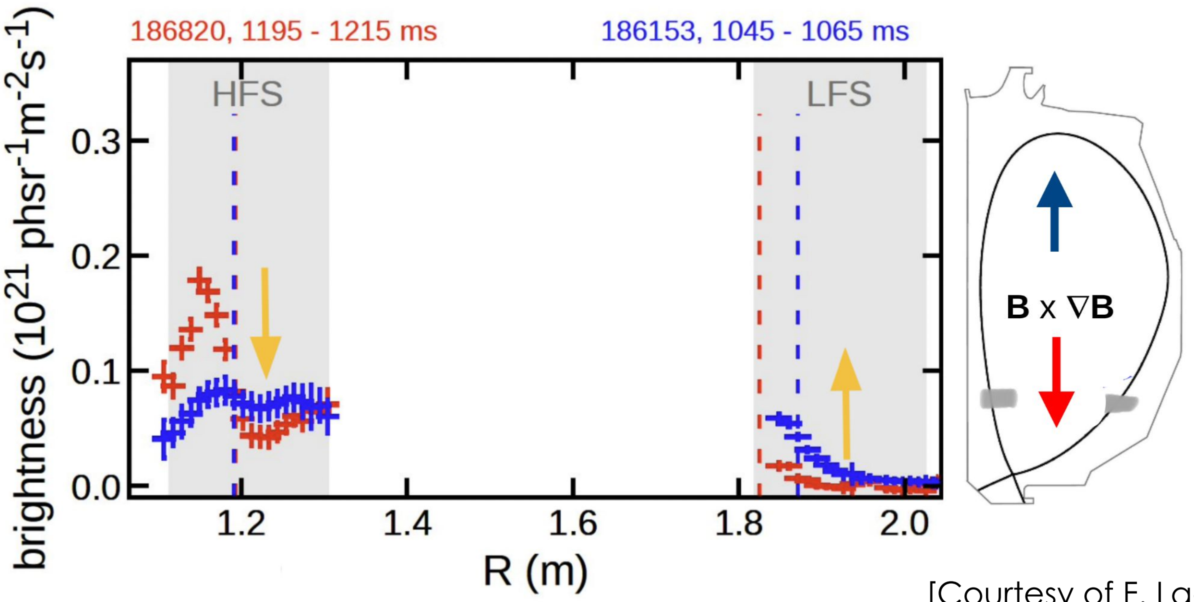
Strong asymmetry in pedestal fueling upon reversal of toroidal magnetic field is observed

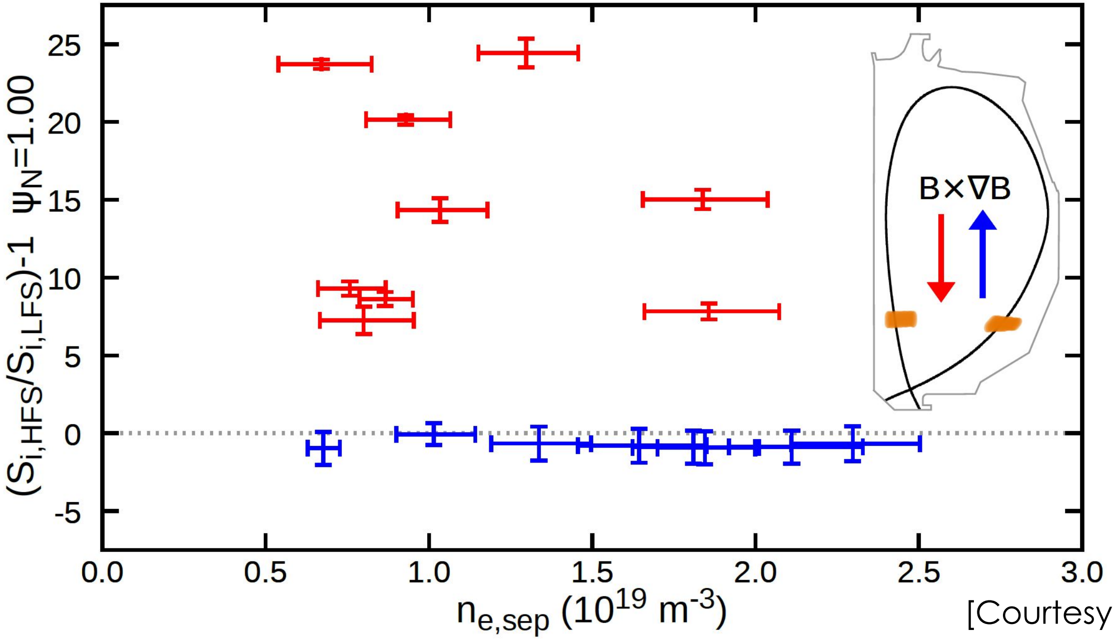
- **H-modes with same shape and electron density**
- **Fuelling dominated at the HFS with favourable drift direction**



[Courtesy of F. Laggner]

Ionization source asymmetries present across wider dataset with favourable drift direction

- Up to 25 times larger $S_{i,HFS}$ than $S_{i,LFS}$ with ion $B\times\nabla B$ directed downwards
- Cases with ion $B\times\nabla B$ directed upwards have HFS-LFS symmetric S_i



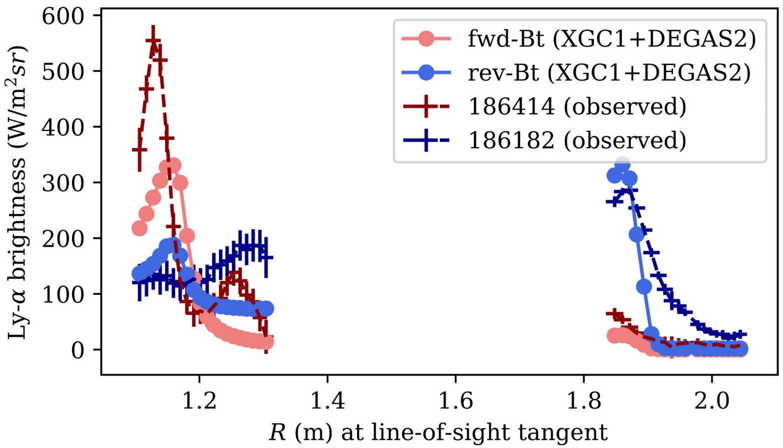
[Courtesy of F. Laggner]

Turbulent XGC1 simulations reproduce observed fuelling asymmetries

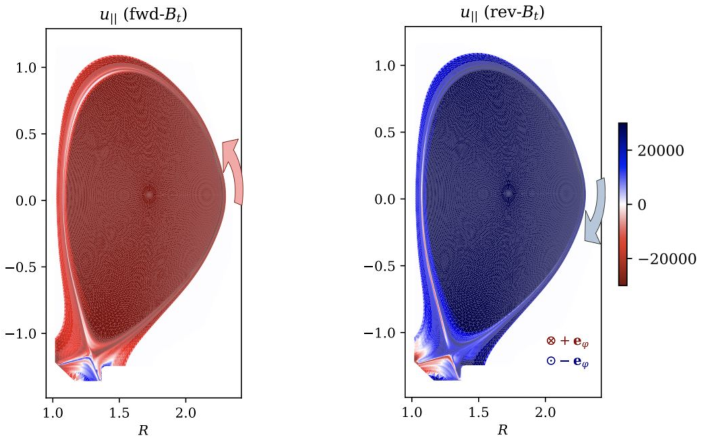
Collaboration with G. Wilkie & XGC group

[Courtesy of G. Wilkie]

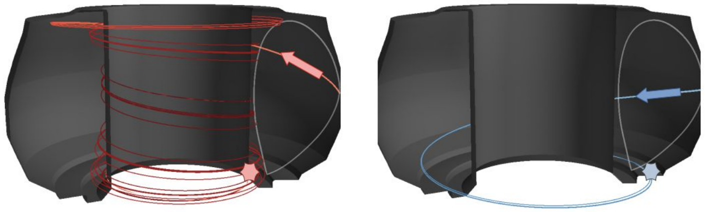
- **XGC1+DEGAS2 with synthetic diagnostic**
- **Asymmetry caused by a combination of ExB and parallel flow reversal**
- **Reversal of ion flows modify the primary recycling location**



Parallel flow:

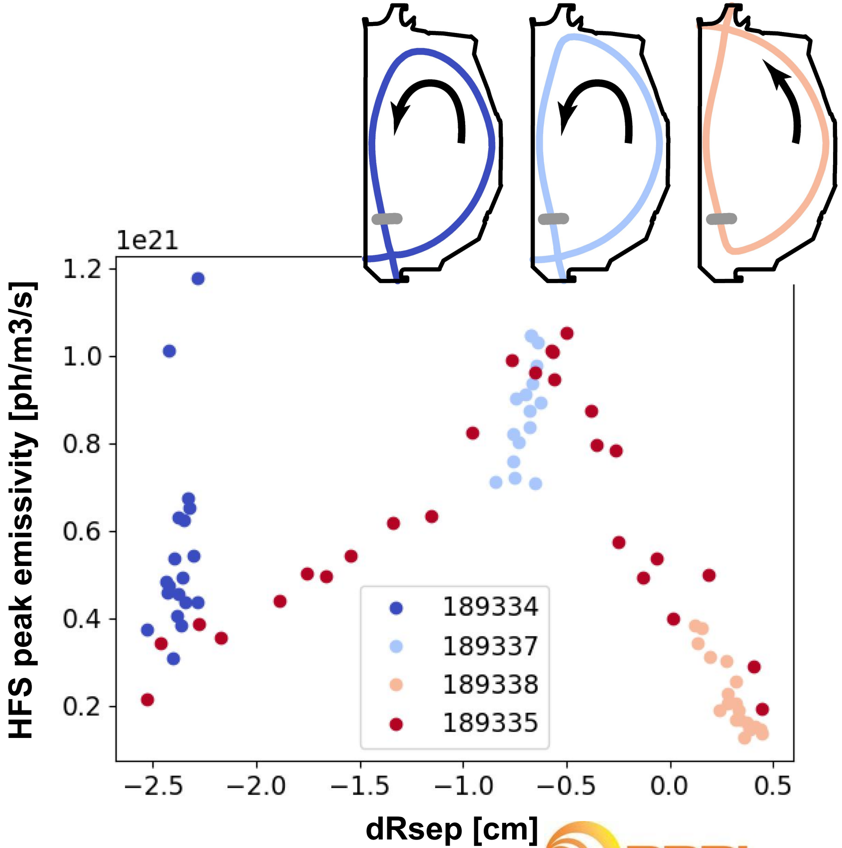


Following field lines in the dominant direction of flow:



In-out ionization asymmetry is shown to drop by an order of magnitude when changing the magnetic balance from LSN to DN

- **Further experiments: magnetic configurations varied from lower-single-null (LSN) through double-null (DN) to upper-single-null (USN) scanning**
- **Preliminary analysis indicating the reduction in ion flux arriving at the inner target as configuration shifts from lower biased to upper biased**



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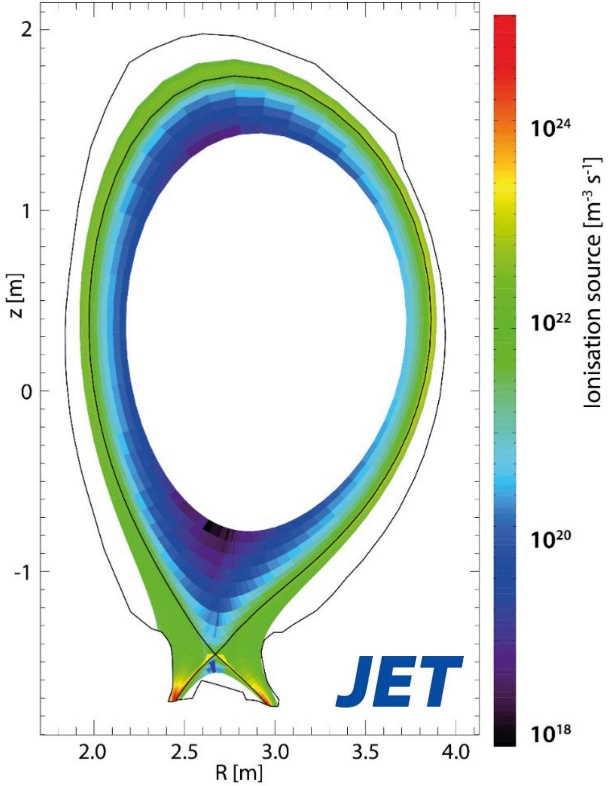
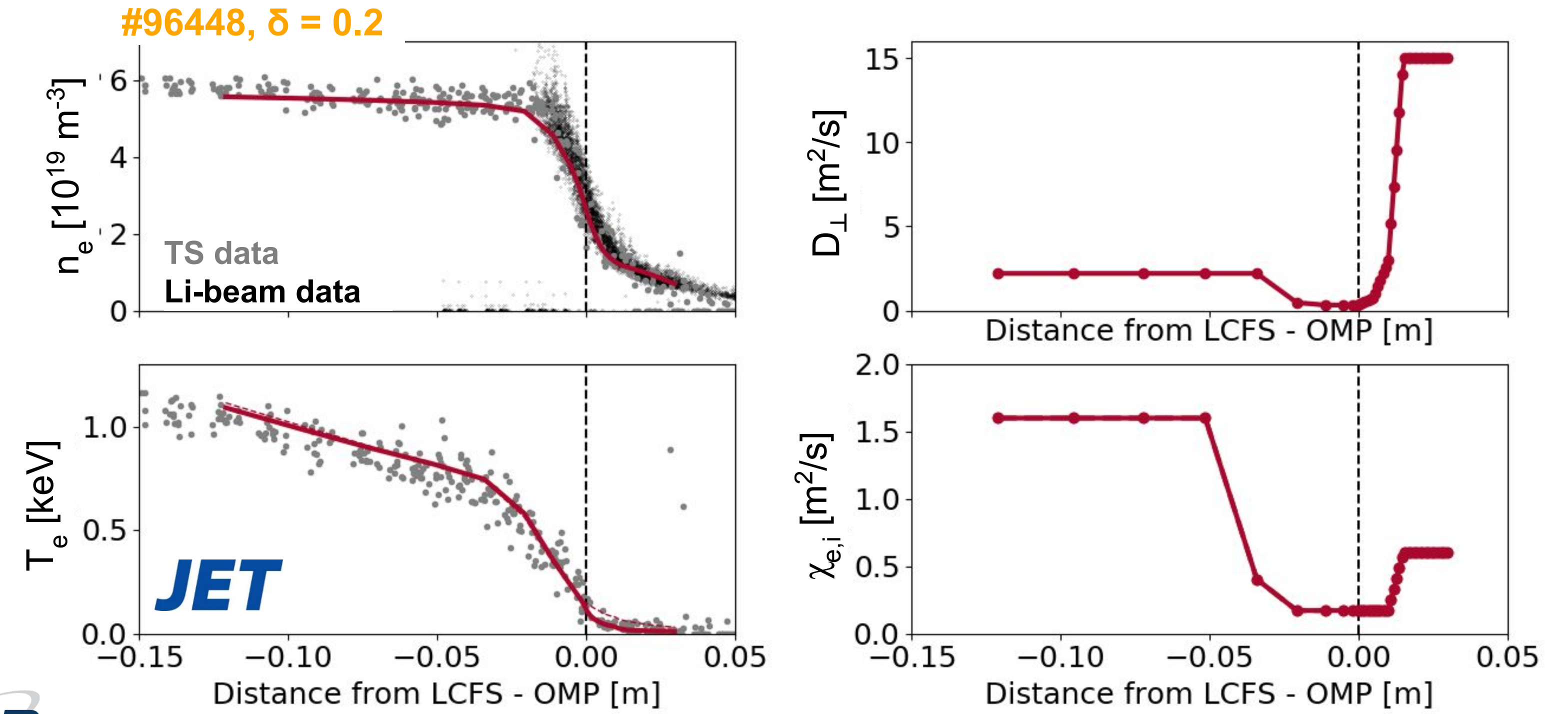
2D edge-transport simulations



- **Short detour to JET**
- **Multi-fluid, Braginskii equations for the parallel transport (SOLPS, EDGE2D, SOLEDGE2D, UEDGE, …)**
- **Monte-Carlo kinetic neutral code (EIRENE, DEGAS2, …)**
- **Ad-hoc diffusive perpendicular transport coefficients are iterated to match experiments**

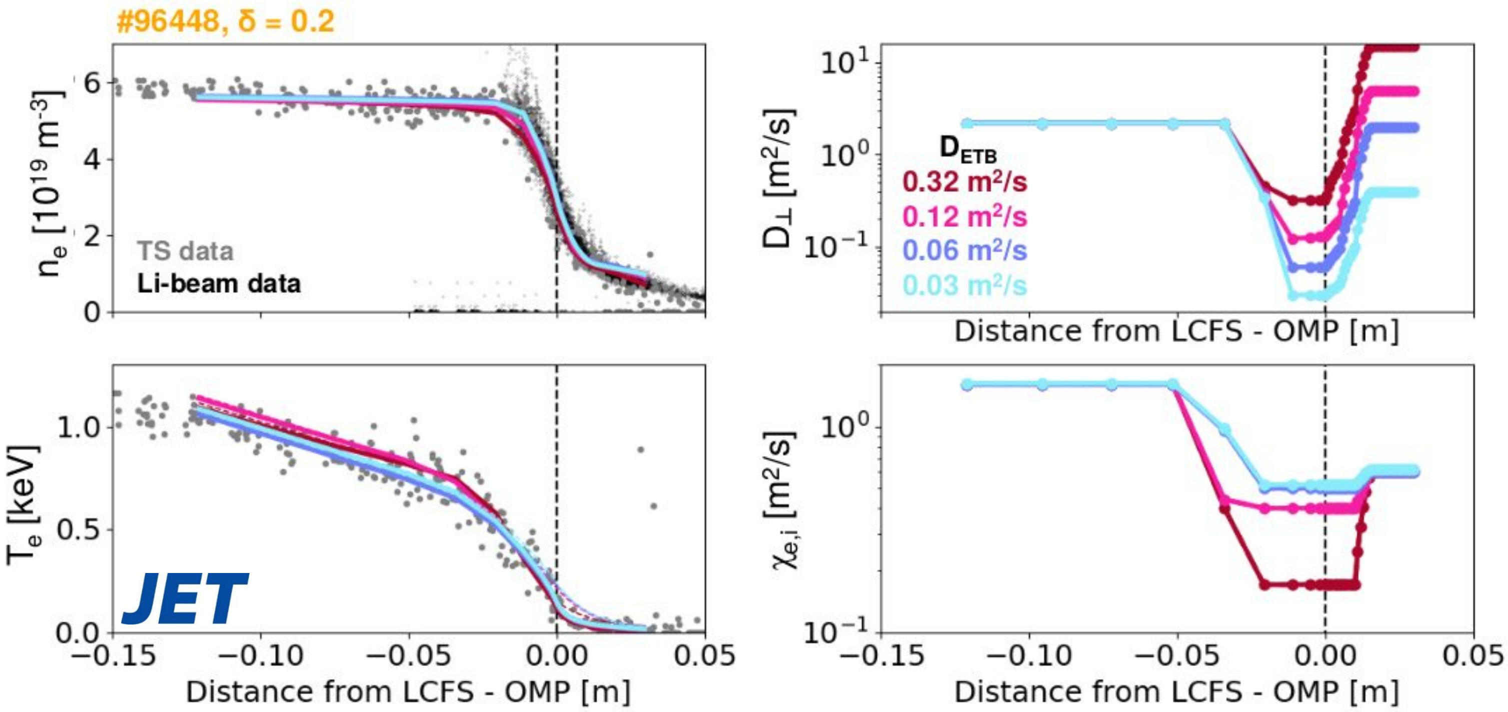
Estimating the pedestal particle source and transport coefficients with interpretative EDGE2D-EIRENE simulations

- EDGE2D-EIRENE: coupled **2D plasma fluid + neutral particle Monte-Carlo** codes
- Iterating $D_\perp$ and $\chi_{\perp e}$ (= $\chi_{\perp i}$) to match: **upstream n_e, T_e** from experiment



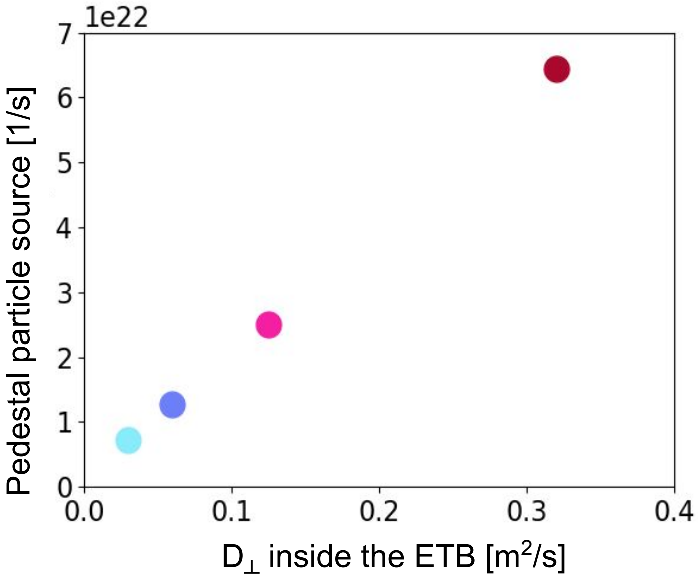
Multiple EDGE2D-EIRENE solutions reproducing the same experimental upstream ne, Te profiles

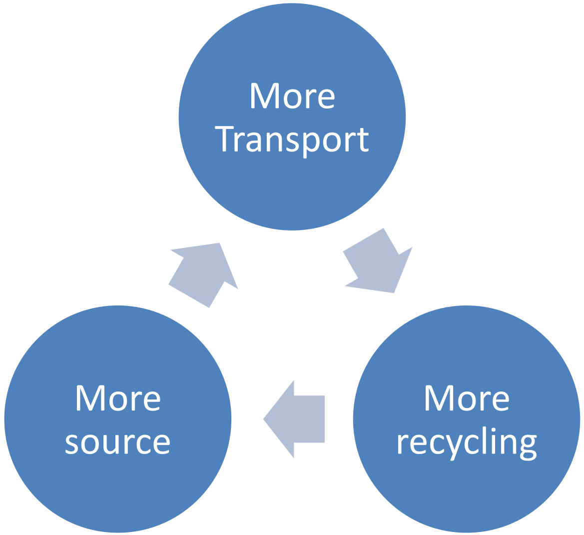
- EDGE2D-EIRENE: coupled **2D plasma fluid + neutral particle Monte-Carlo** codes
- Iterating $D_\perp$ and $\chi_{\perp e}$ (= $\chi_{\perp i}$) to match: **upstream n_e, T_e** from exp. (slow recovery phase)
- $D_\perp$ scanned in ETB and SOL: no unique solution with only upstream n_e, T_e (and divertor) constraints



Recycling compensates the changes in transport

- Multiple solutions to match same upstream profiles can be obtained (see also [Groth EPS 2011])
- Increase in transport ($D_\perp$) is compensated by higher source: higher particle flux → increased recycling

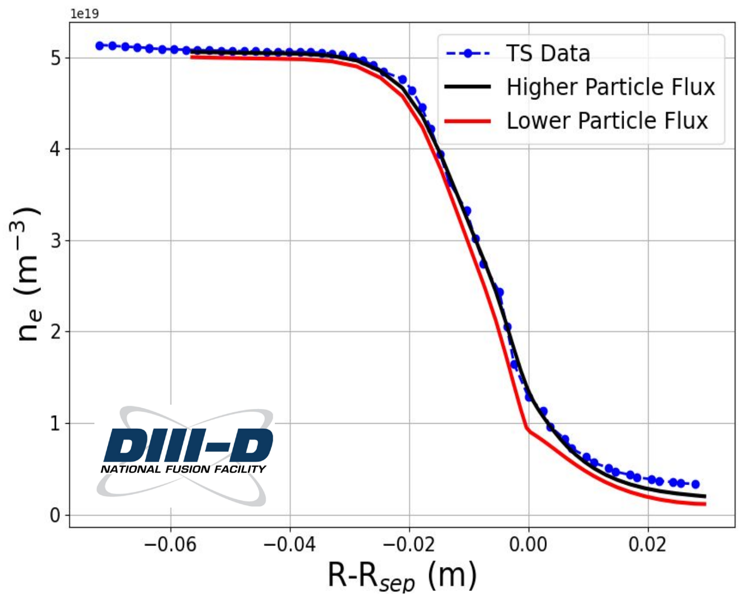


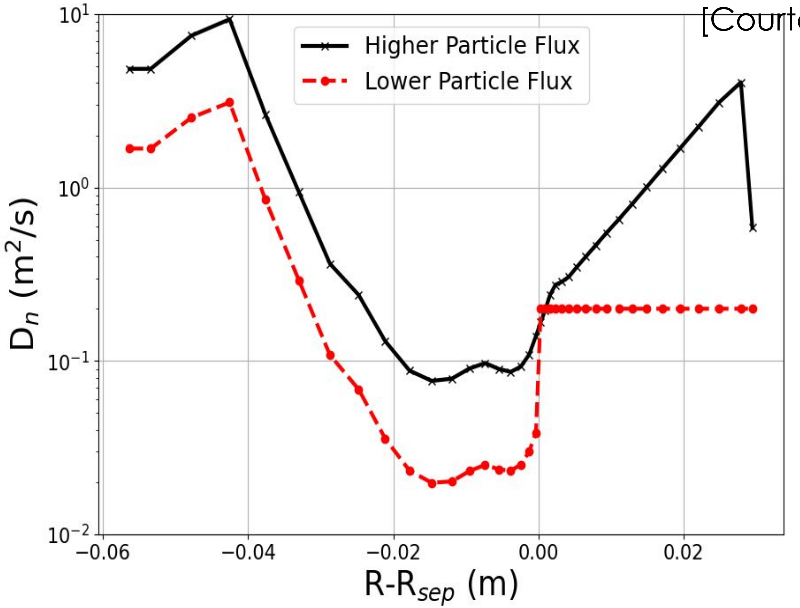


→ Main chamber particle source needs to be constrained: LLAMA

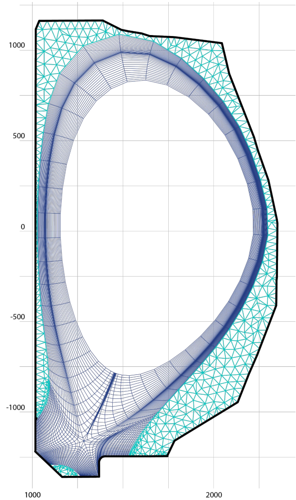
Some progress on JET with Dα [Horvath PPCF 2023], but problem with reflections

SOLPS-ITER simulations of DIII-D H-mode





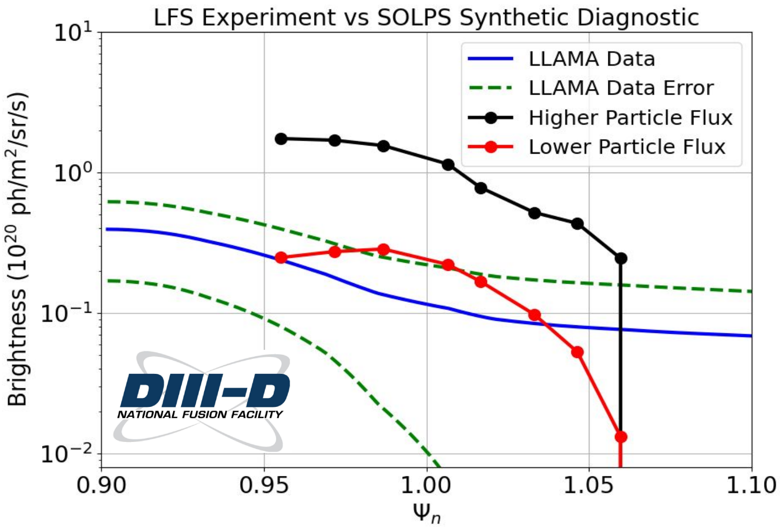
[Courtesy of E. Emdee]

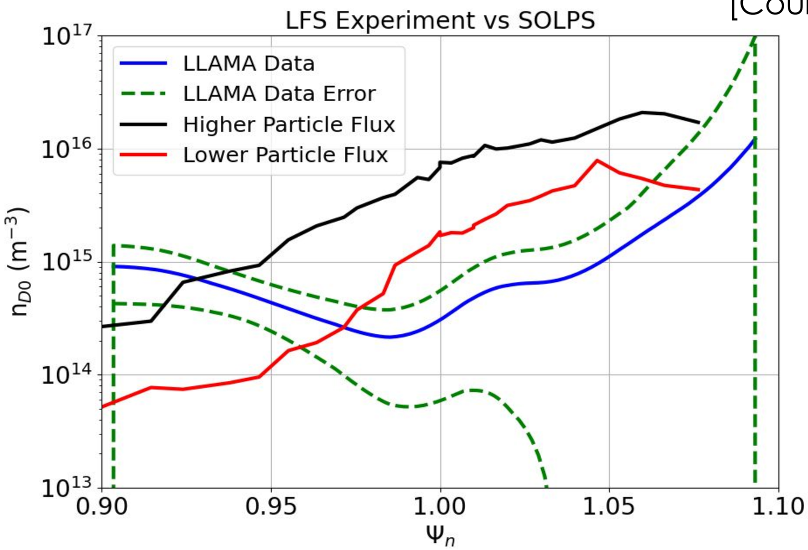


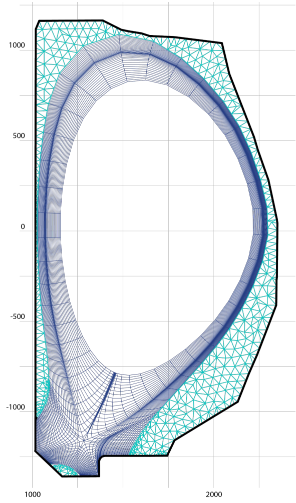
- **Upstream profiles can be matched with different transport coefficients**
- **Boundary conditions somewhat different between cases (work in progress)**

LLAMA measurements constrain particle source in simulations

[Courtesy of E. Emdee]







- **Increased transport leads to higher particle source**
- **Simulations with cross-field drifts in progress to study in-out asymmetries**

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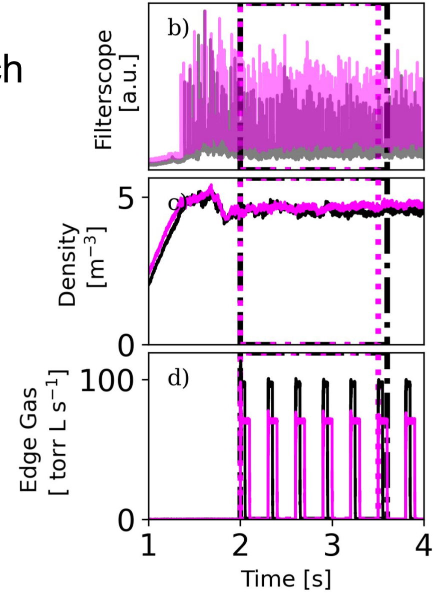
Diffusive and convective particle transport studies using pedestal modulation and LLAMA

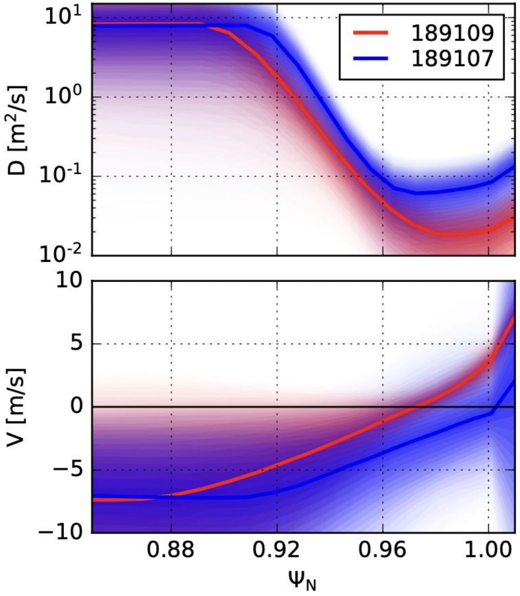
- External (gas puff modulation) or internal (ELMs) pedestal modulation to infer edge Ds and vs
- High temporal and spatial resolution measurements of the ionization source with LLAMA is key
- Inferred transport coefficients in indicated the possible role of a particle pinch

Particle Source

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

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





[Rosenthal PhD 2023]

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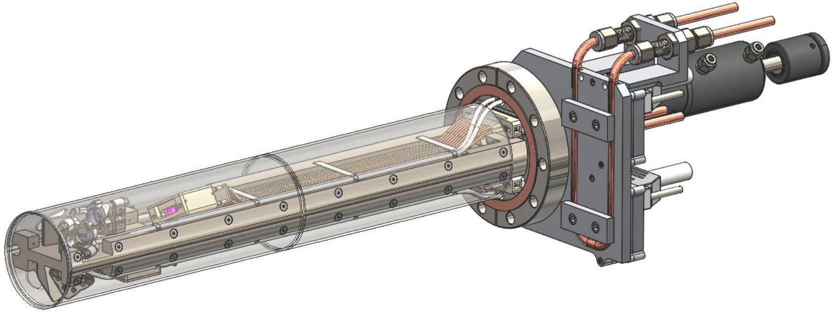
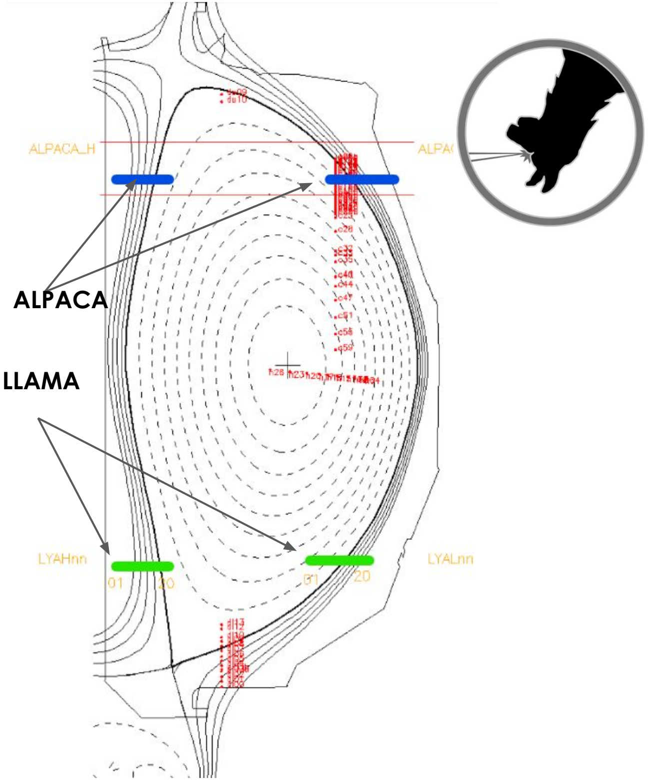
ALPACA - LLAMA expansion to measure neutrals in the upper main chamber

- Simultaneous measurement of neutrals at 4 poloidal locations
- Study different divertor configurations, better coverage for USN and DN plasmas
- In/out and up/down fuelling asymmetries
- Kudos to PPPL engineering and I&C groups
- Installation on DIII-D scheduled for Jan 2024

David Mauzey





Conclusions

- LLAMA measures Ly-a radiation providing information about the edge particle source
- Large in-out asymmetries in fuelling observed depending on drift direction
- XGC1 simulations reproducing the fuelling asymmetry: change of recycling location due to reversal in ExB and parallel flow direction
- LLAMA is crucial to constrain edge-transport simulations
- Pedestal modulation studies with LLAMA allow for the inference of Ds and vs at the edge: indication of particle pinch in the pedestal
- Next DIII-D campaign in 2024 with an expansion of LLAMA views: ALPACA