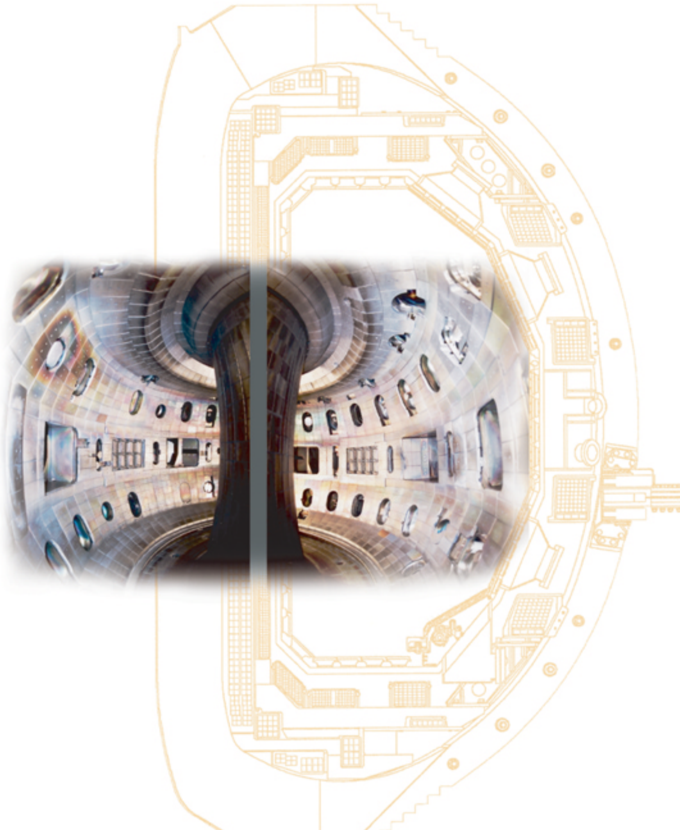
# Implications of Wall Recycling and Carbon Source Locations on Core Plasma Fueling and Impurity Content in DIII-D



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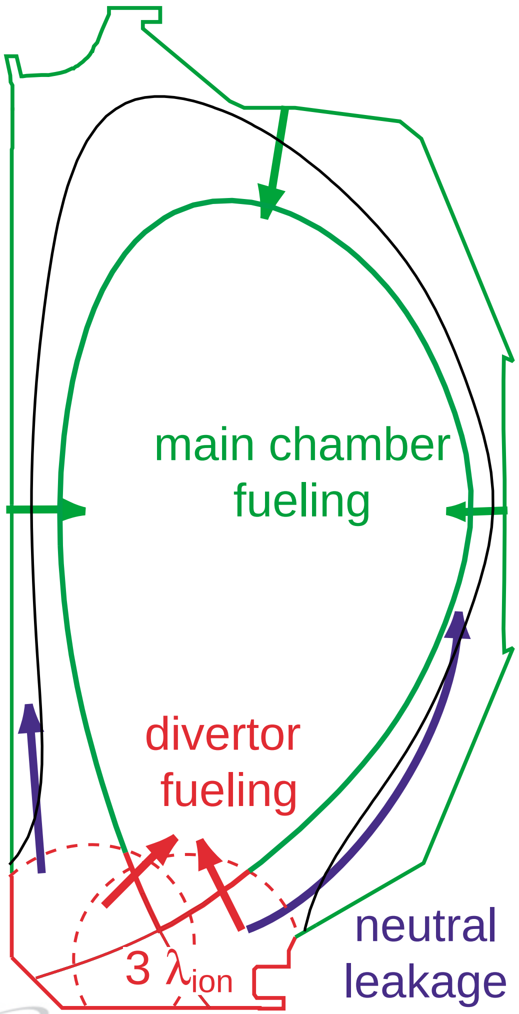
# Motivation: Poloidal distribution of core plasma fueling and impurity sources affect core plasma performance




- **Fuel source distribution modifies height and width of H-mode density pedestal** ***[Mahdavi et al. PoP 2003]***
- **Core power balance is sensitive to impurity content**

→ **Understanding needed to predict performance in future devices**

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- **Three principal fueling channels:**
  - **Div. → x-point region → core**
  - **Div. → neutral leakage → core**
  - **Main walls → core**
- **More efficient screening of divertor sources due to divertor geometry than main wall sources**

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# Summary and methodology

- **Poloidal distribution of fueling in L-mode and ELMy H-mode suggests that ...**
  - **Dominant core plasma fueling occurs near divertor X-point region due to recycling at the divertor targets**
  - **Significant neutral leakage from divertor into inner main SOL**
  - **Divertor target plates and divertor walls are dominant carbon sources**
  - **Carbon ion leakage from divertor into main SOL is the main transport mechanism that sets core carbon content**

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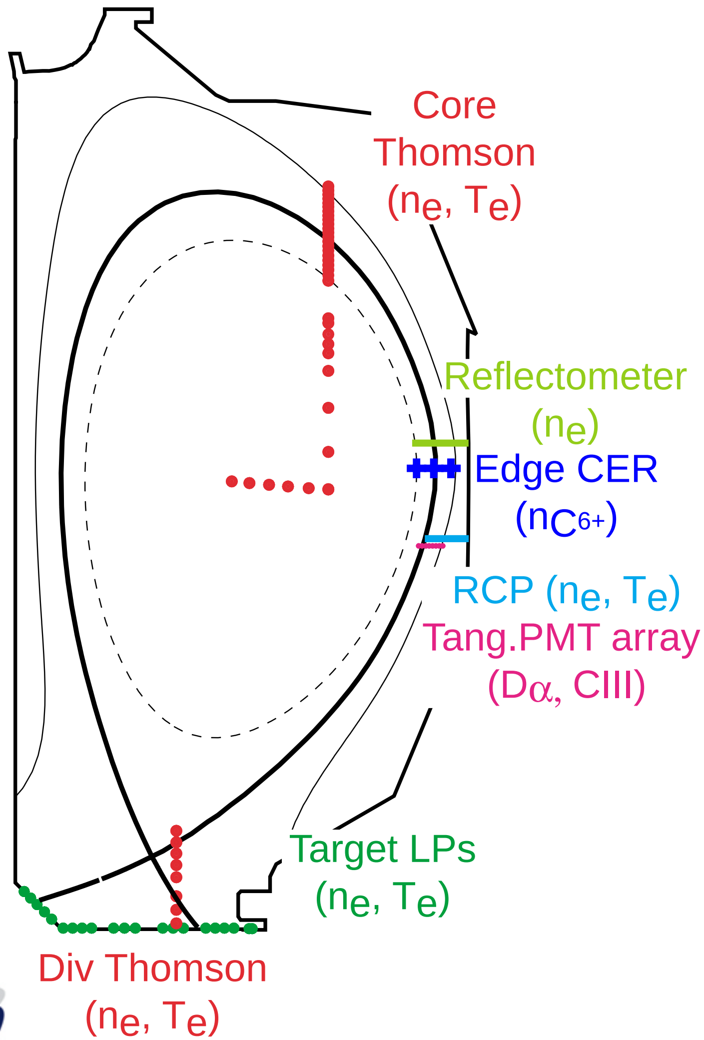
- **Methodology**
  - **Detailed measurement of plasma parameters in main and divertor SOL, including 2-D emission distribution of $D_\alpha$, CII, CIII**
  - \+ **Data-constrained UEDGE/DEGAS2 2-D boundary modeling of deuterium neutrals and ions, and carbon transport**

# Extensive edge diagnostic system was employed to characterize divertor and main SOL




- Spatially resolved ($\Delta R_{mid}$<1 cm) measurement of main SOL plasma parameter in outer main SOL
  - Thomson scattering
  - Reflectometer
  - Reciprocating probe
  - Edge charge-exchange
  - Tangential PMT array
- Divertor heat and particle flux profiles
  - Target Langmuir probes
  - Infra-red camera
- 2-D $n_e$ and $T_e$ distribution in outer divertor leg using Thomson scattering

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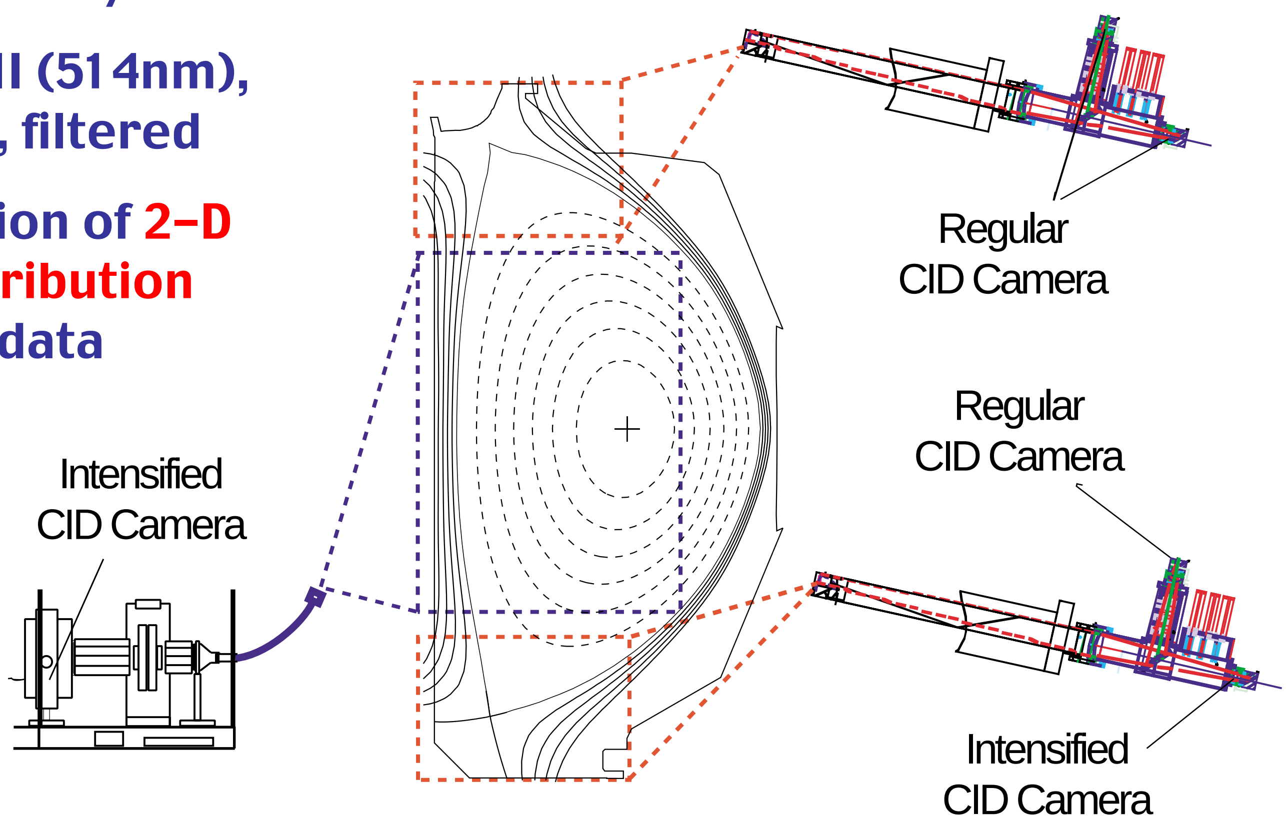
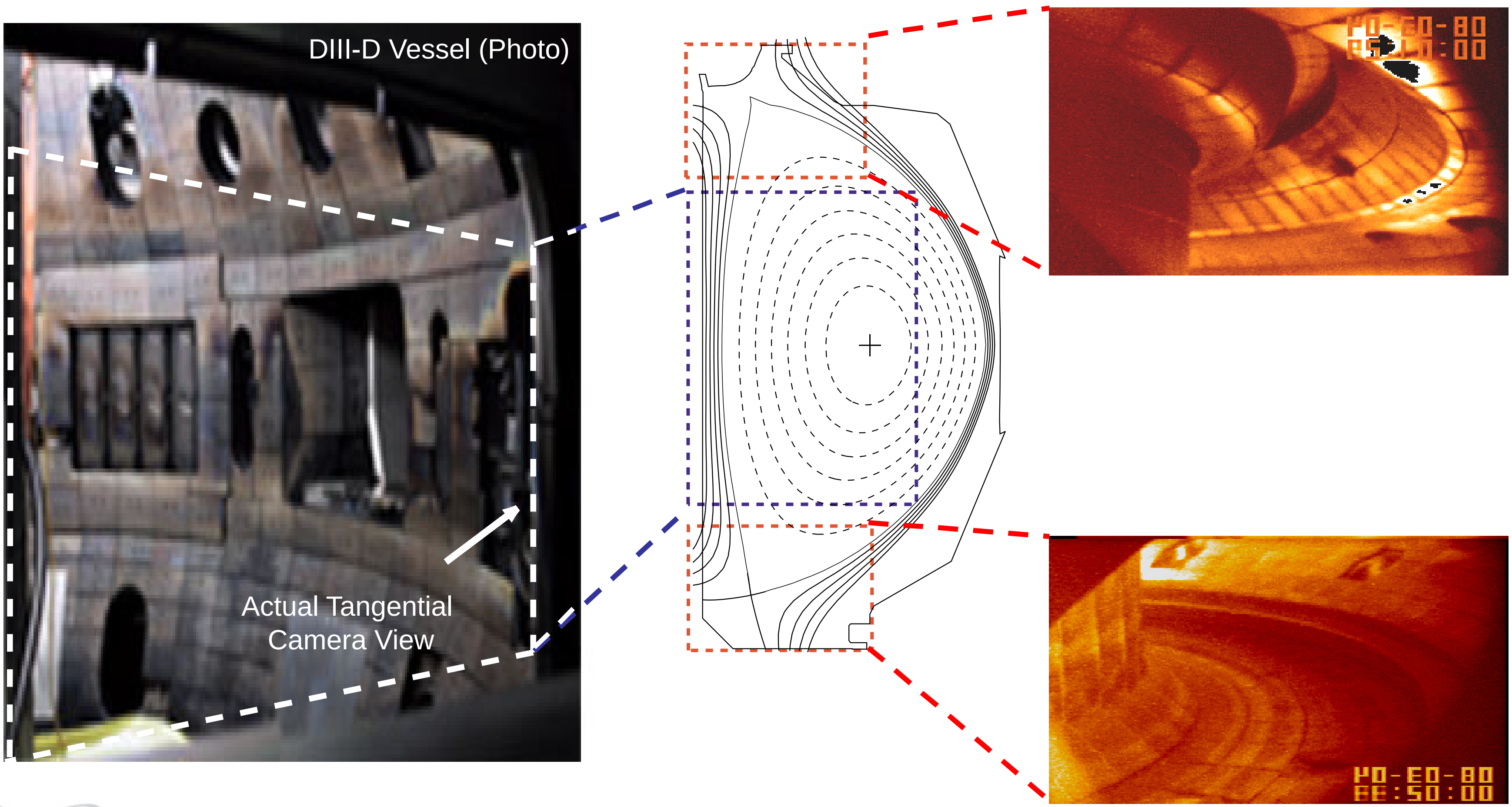
# Tangentially viewing cameras measured emission over a region of 85% of the poloidal cross-section

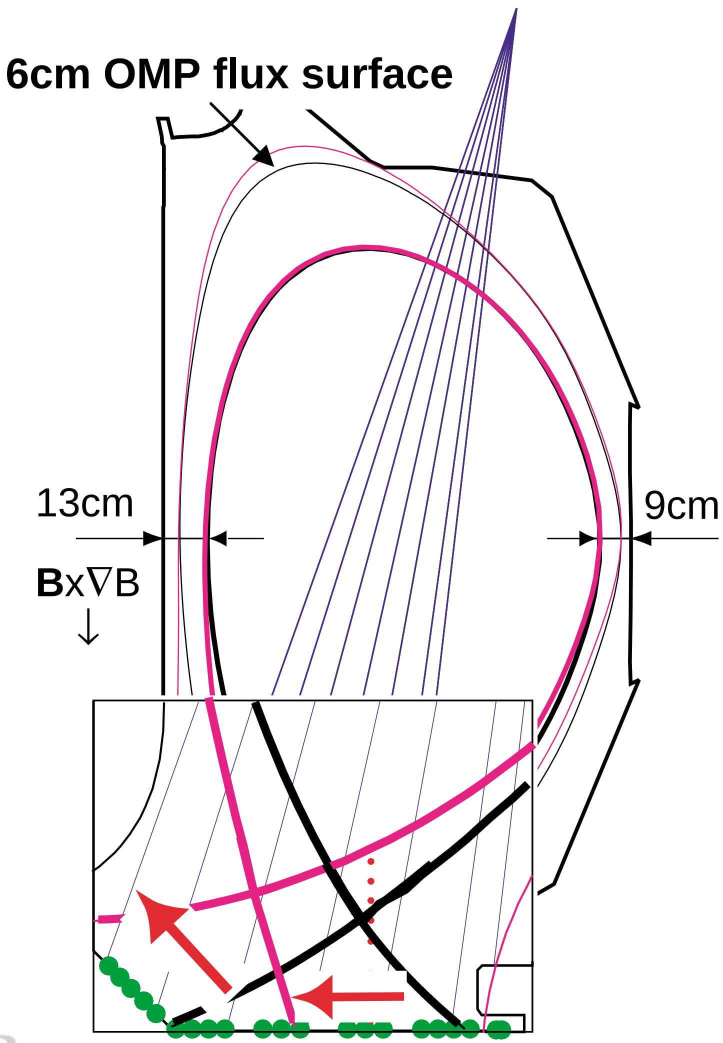
- **Rad-hardened, 8bit CIDs**
- **Two intensified systems**
- **Visible: $D_\alpha$, CII (514nm), CIII (465nm), filtered**
- **Reconstruction of 2-D poloidal distribution from image data**



# Divertor cameras span region from target plates to 60–80cm into main chamber, midplane camera spans inner and outer SOL (–70cm < Z < 60cm)



# Lower-single null L-mode with $n/n_{GW} = 0.2 \rightarrow 0.4$ optimized for diagnosis of divertor and main SOL




- Magnetic configuration
  - LSN, Bx∇B into lower divertor
  - Inner gap 13cm, outer gap 9cm
  - 7cm flux surface intersects upper baffle limiter
  - 30cm strike point sweep for high spatial resolution
- Three density levels, varied shot-to-shot:
  - $\langle n_e \rangle = 2.6 \times 10^{19}\ m^{-3}$ ($n/n_{GW}=0.24$)
  - $\langle n_e \rangle = 3.1 \times 10^{19}\ m^{-3}$ ($n/n_{GW}=0.29$)
  - $\langle n_e \rangle = 4.1 \times 10^{19}\ m^{-3}$ ($n/n_{GW}=0.37$)

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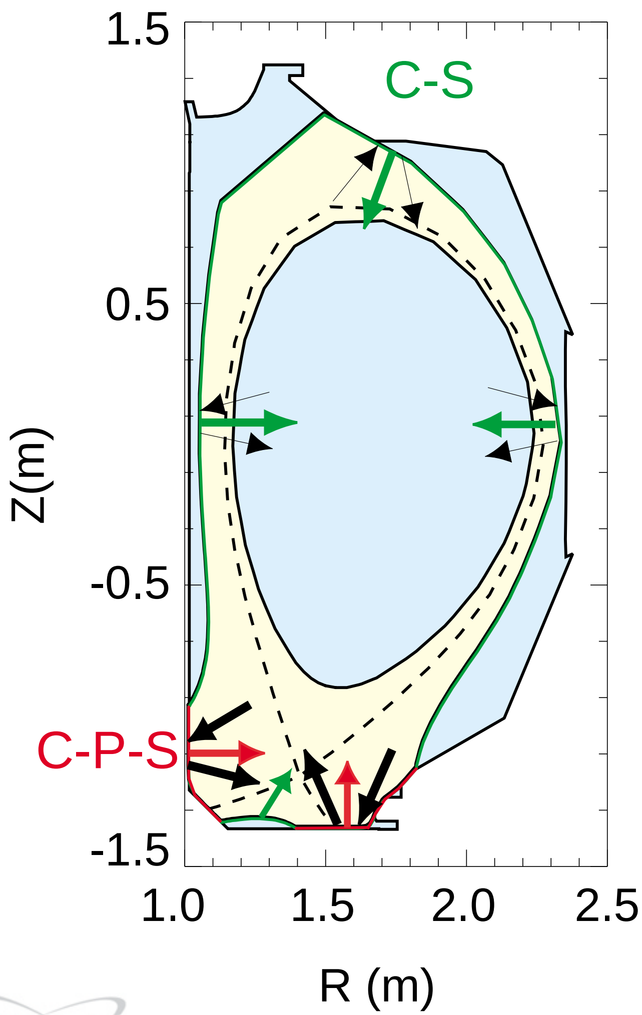
# Model neutral transport with DEGAS2 on background plasma calculated by fluid edge code UEDGE




- **UEDGE w/ classical drifts and carbon transport model, 0.94 $\leq \Psi_N \leq$ 1.15**
- **Purely diffusive radial transport, $D_\perp$, $\chi_e$, $\chi_i$ spatially constant**
- **BC: finite ion flux across outer grid, returned as neutrals**
- **BC: 5% wall pumping of neutrals outer UEDGE grid boundary 20cm above targets**
- **Carbon: C–P–S at target, C–S at outer UEDGE grid boundary** ***[Eckstein JNM 1997, Davis JNM 1997]***
- **Launch DEGAS2 neutrals from target plate, CX-walk and reflections, plasma prescription for halo region**

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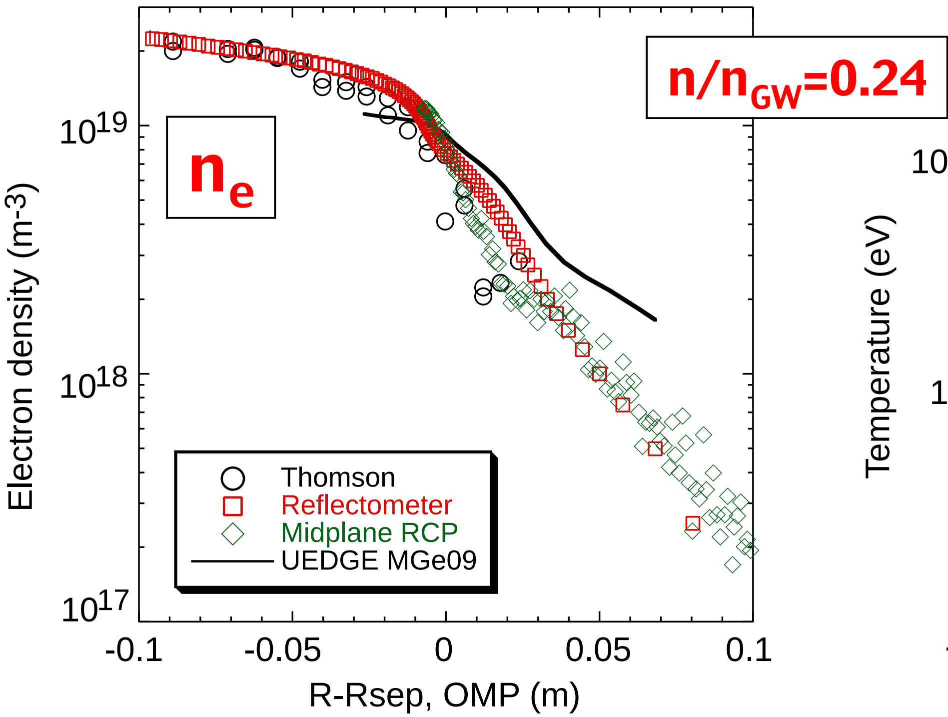
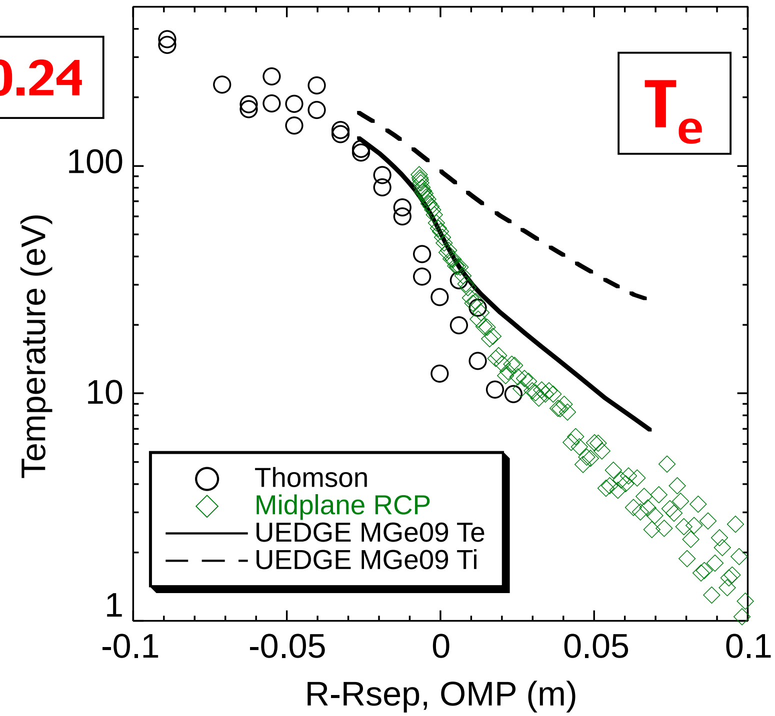
# Modeling lowest density case: Experimental core and outer main SOL $n_e$ and $T_e$ were simulated in UEGDE using spatially const. $D_\perp = 0.65\ m^2/s$ and $\chi_e = \chi_i = 2.6\ m^2/s$

- **Excellent agreement in experimental upstream $n_e$ and $T_e$ parameters measured by three independent techniques**

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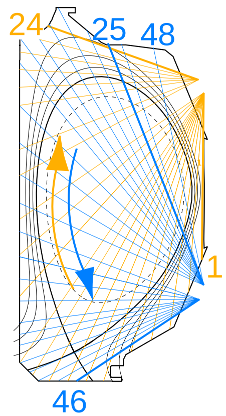
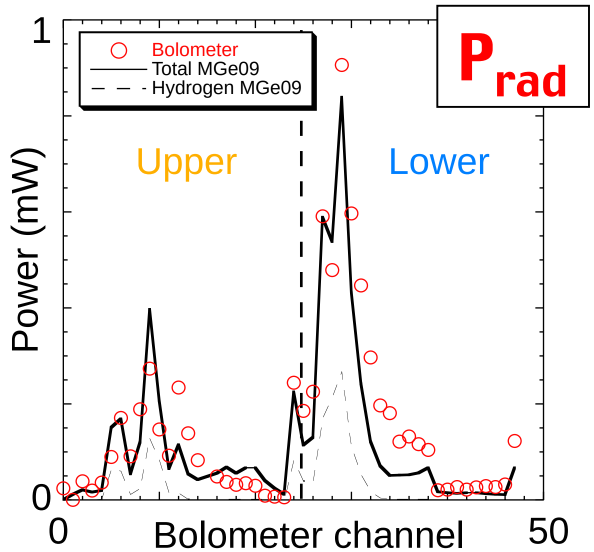
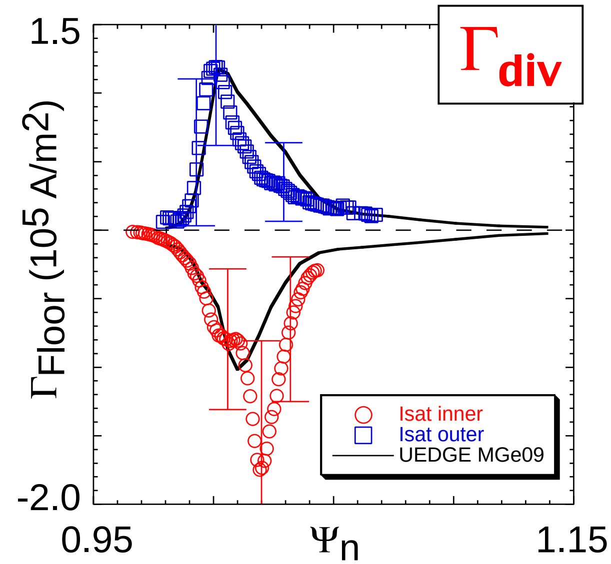
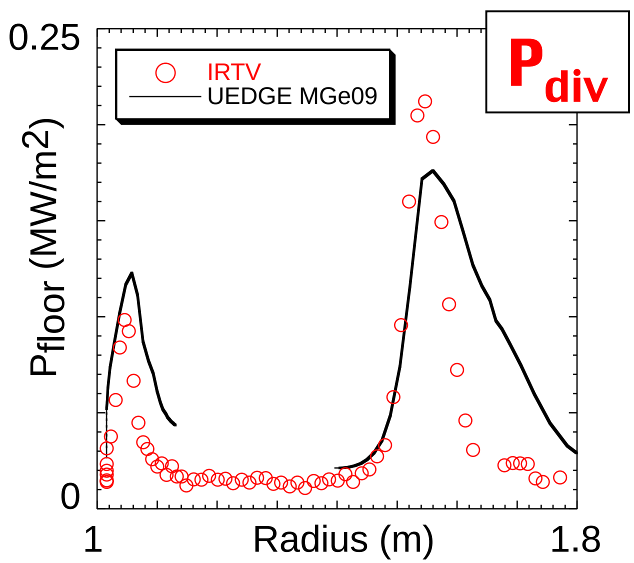
# UEDGE simulation match experimental total radiated power, divertor heat flux, and particle flux to divertor plates to within factor of 2








- **LP analysis:**
  - **$T_{e,OSP} \approx 25$eV $\rightarrow$ well-attached outer leg**
  - **$T_{e,ISP} \leq 8$eV $\rightarrow$ partially detached inner leg**

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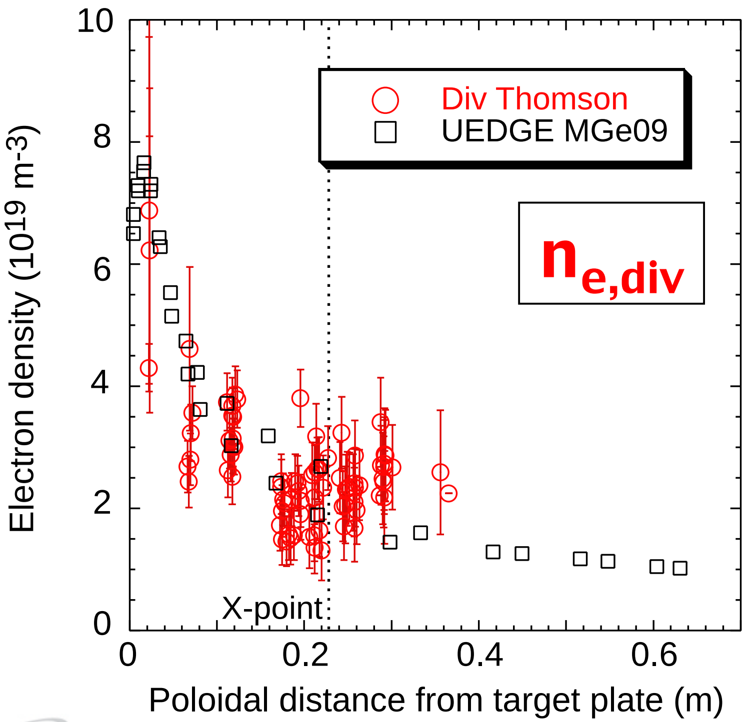
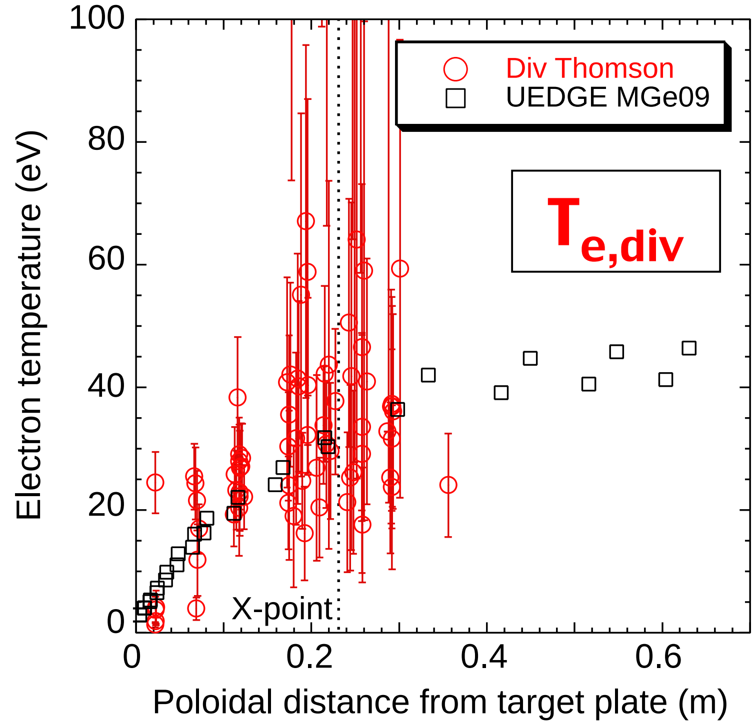
# UEDGE simulation also agree with divertor Thomson $n_e$ and $T_e$ profiles in outer divertor leg

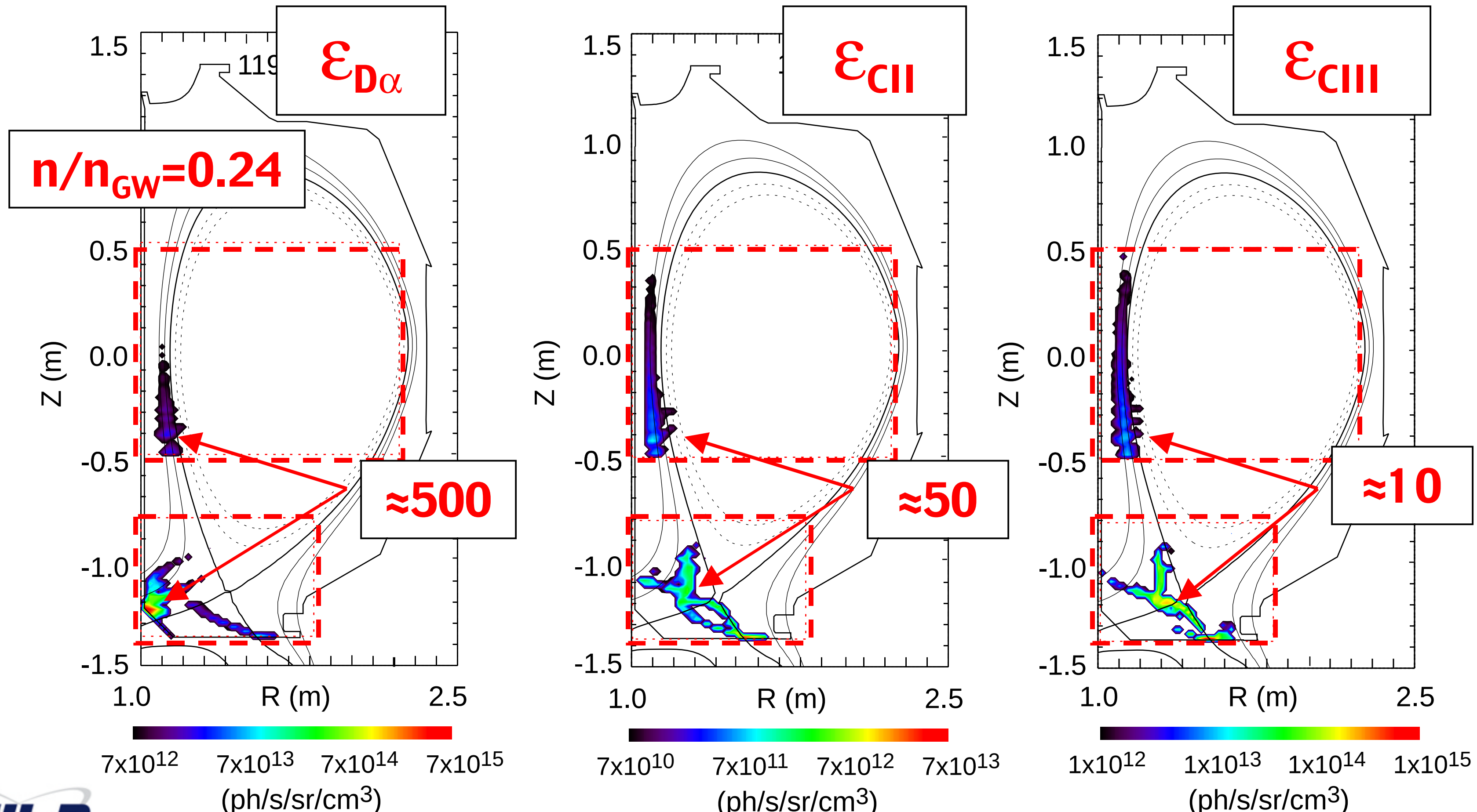
- **Near-separatrix divertor Thomson data in common SOL obtained during strike point sweep: $1.002 \leq \Psi_N \leq 1.008$**
- **$T_e$ just above target plate unusually low – known problem with Thomson analysis, UEDGE calculated $T_e$ at plate $\rightarrow$ 2eV**



# Experimental 2-D intensity distribution of $D_\alpha$, CII, and CIII is dominated by emission from the divertor

- **CII and CIII emission well off inner divertor target plates**
  **$\rightarrow$ Te of inner divertor plasma < 5eV, consistent w/ LP measurements**

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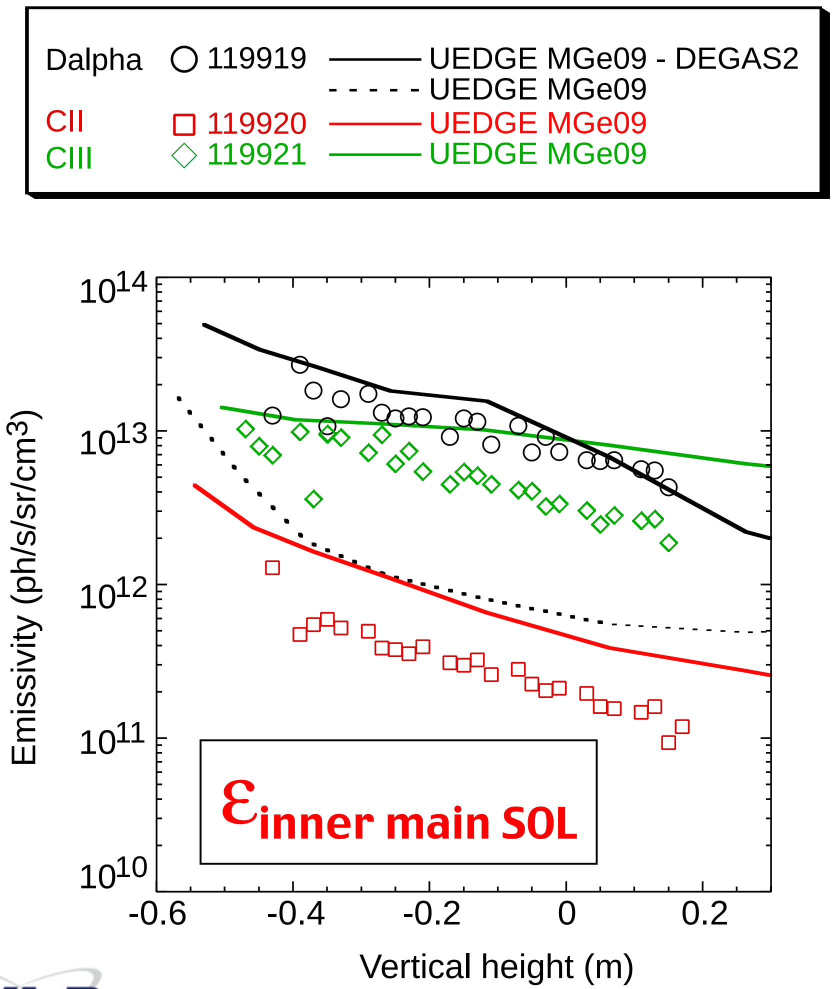
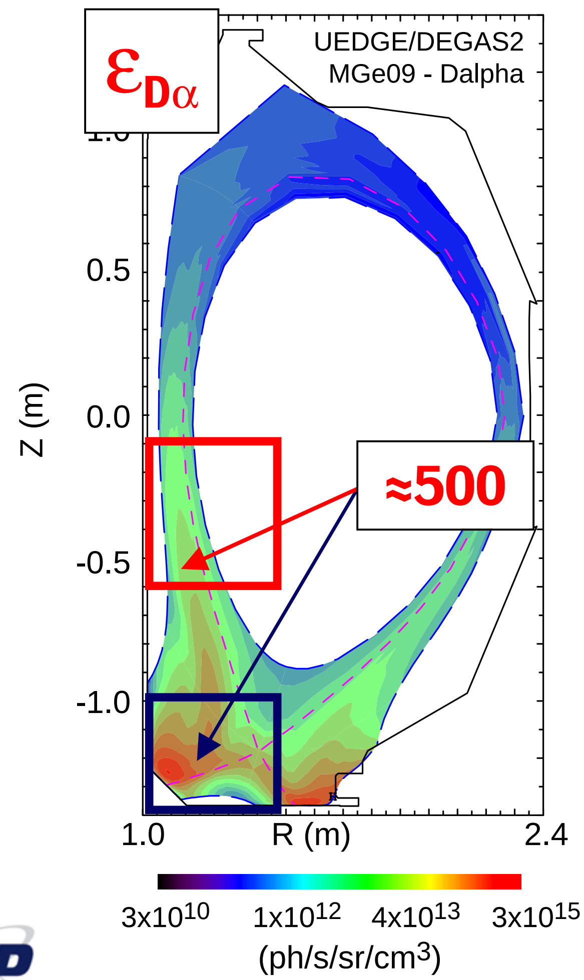
# Inner midplane emission $D_\alpha$, CII, and CIII peaks in region nearest to divertor X-point



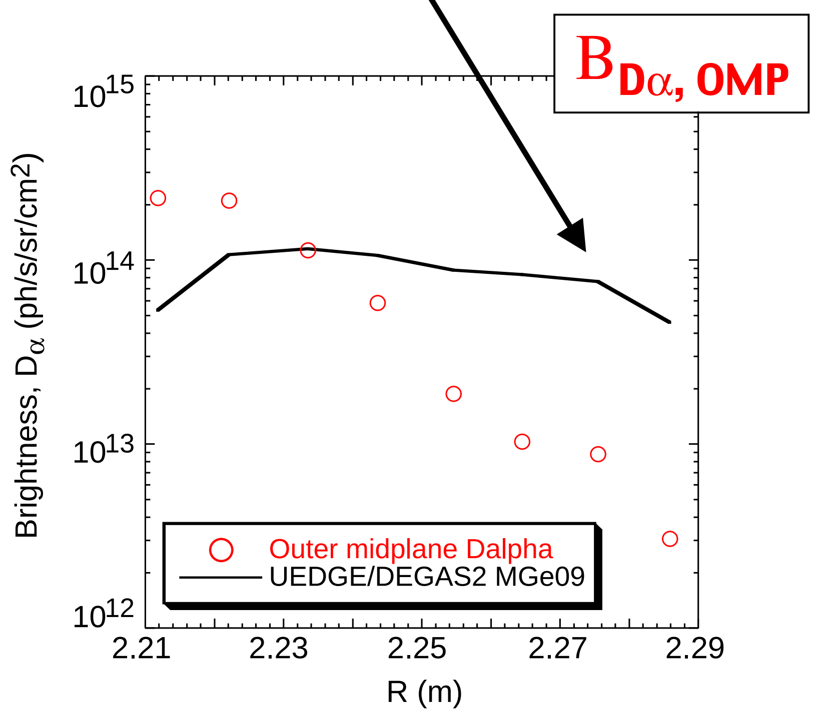

| | | | |
|---|---|---|---|
| $\langle n_e \rangle$ ($10^{19}$ $m^{-3}$) | 2.6 | 3.1 | 4.1 |
| $n/n_{GW}$ | 0.24 | 0.29 | 0.37 |
| $L_{pol,D\alpha}$ (m) | 0.5 | 0.4 | 0.4 |
| $L_{pol,CII}$ (m) | 0.3 | 0.4 | 0.3 |
| $L_{pol,\ CIII}$ (m) | 0.3 | 0.3 | 0.5 |

- **Poloidal fall-off length in inner midplane SOL ~ 0.3m – 0.5m**
- **Poloidal variation of inner midplane emission only weakly sensitive to core (and divertor) densities**

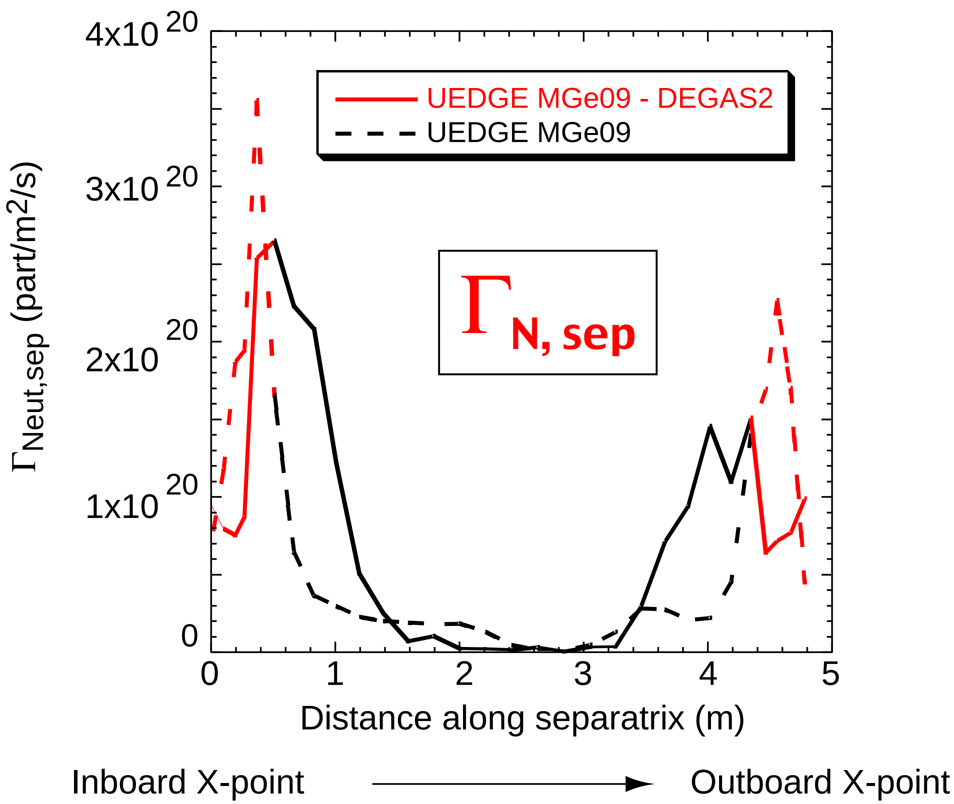
# Calculated $D_\alpha$ emission using UEDGE/DEGAS2 agrees quantitatively with measurements in lower divertor and inner midplane region




- Order-of-magnitude $D_\alpha$ emissivity matched, but far-SOL $D_\alpha$ overestimated by UEDGE/DEGAS2



# UEDGE/DEGAS2 simulations indicate that core plasma is fueled by divertor X-point region and neutral leakage




- **DEGAS2: Comparable fueling through X-point region and due to neutral leakage (42% divertor vs. 58% leakage)**
- **UEDGE alone (w/o neutral leakage in halo region): stronger X-point fueling (71% div. vs. 29% leakage)**

→ **Poloidal core fueling profile sensitive to whether and how halo plasma region is modeled**

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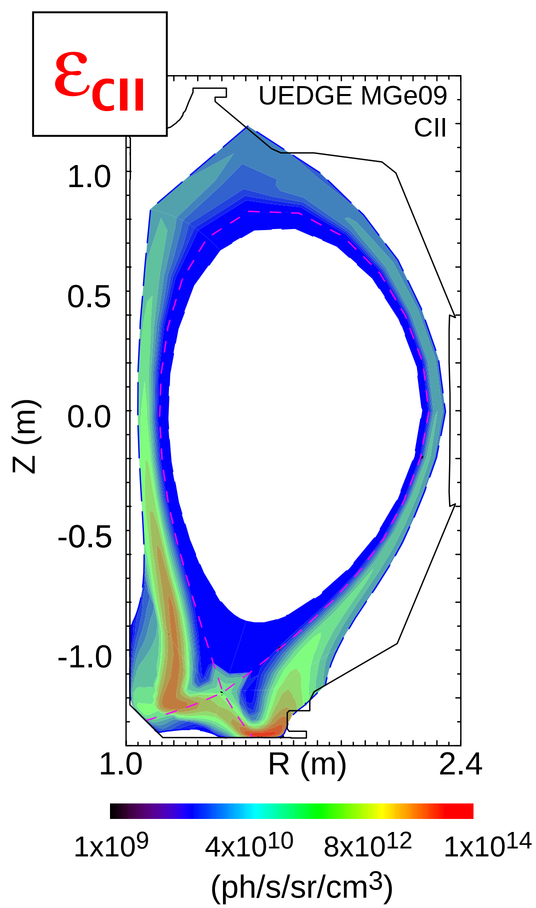
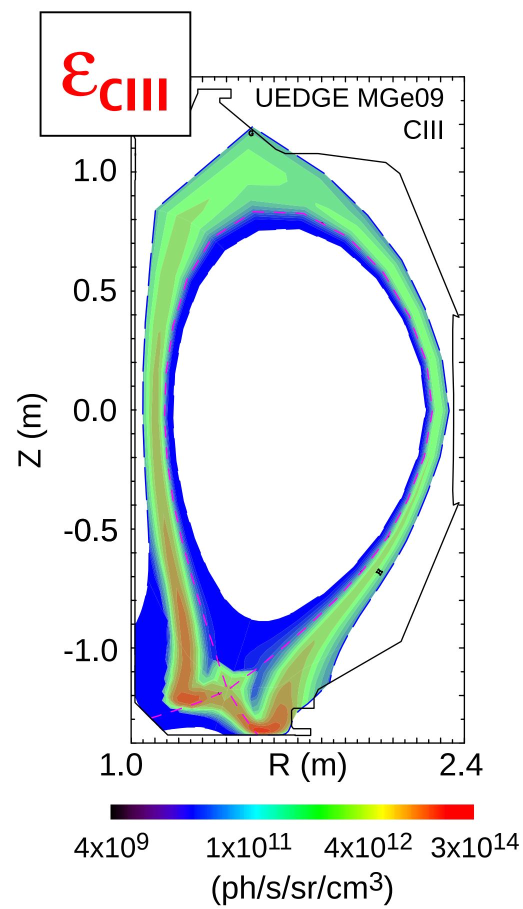
# UEDGE-simulated CII and CIII distribution peaks well above inner divertor target plate →due to significantly colder inner divertor plasma than outer

- **Higher fraction of low-charge-state carbon in inner main SOL than in outer, poloidally extended toward plasma "top"**

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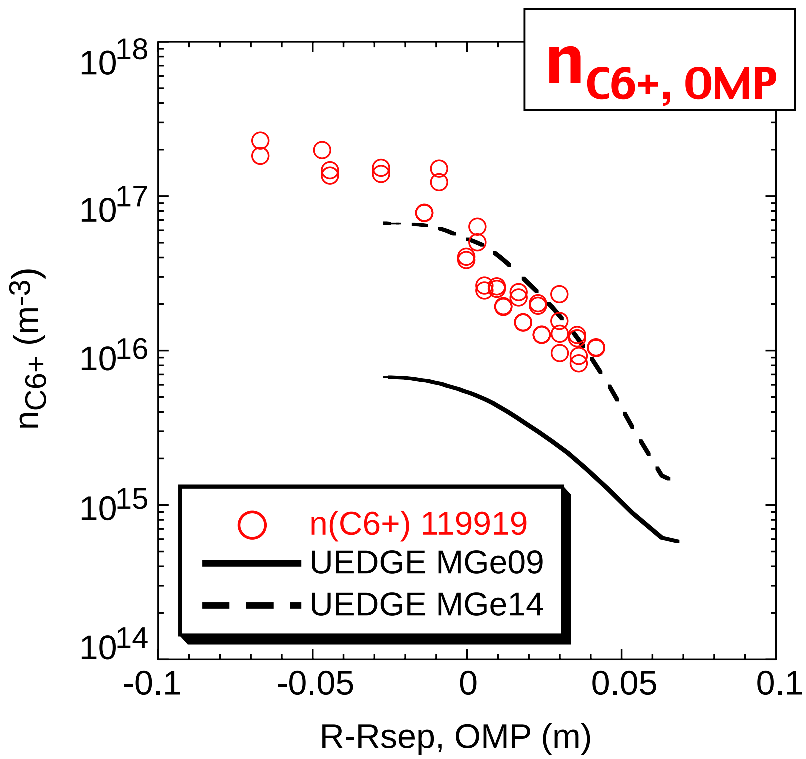
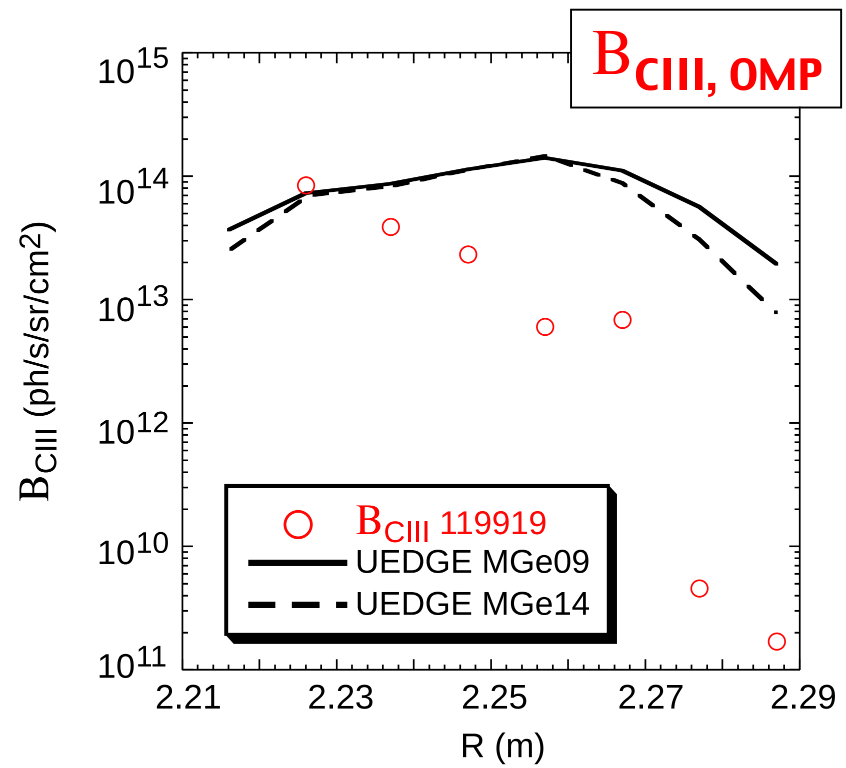
# Small changes of diffusivities for carbon has strong effect on high-charge state density profiles

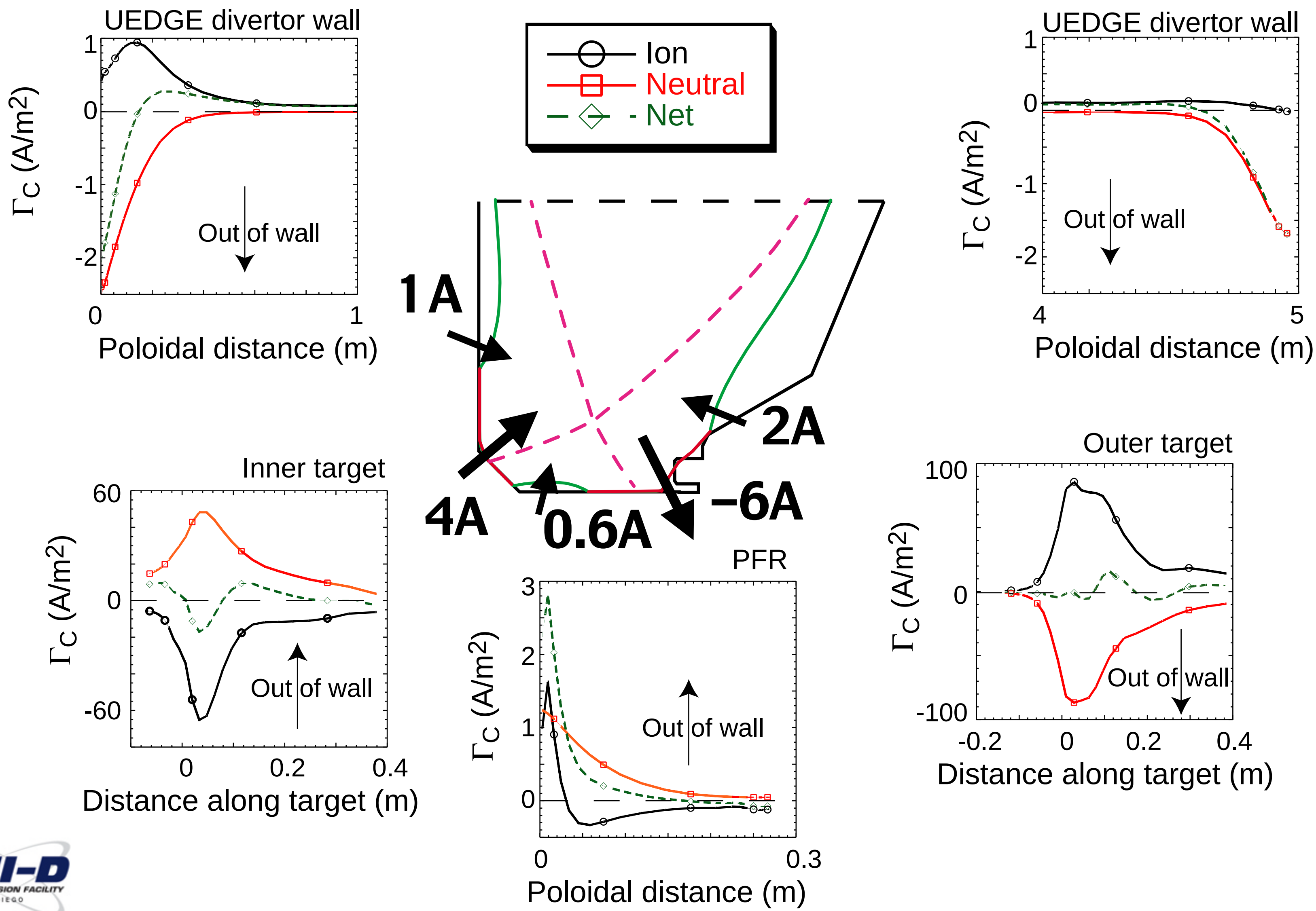
- **Decreasing all (particle and heat) diffusivities by 35% changes $n_{C6+}$ by an order of magnitude (!)**
- **Low-charge-state carbon emission more robust to these changes**



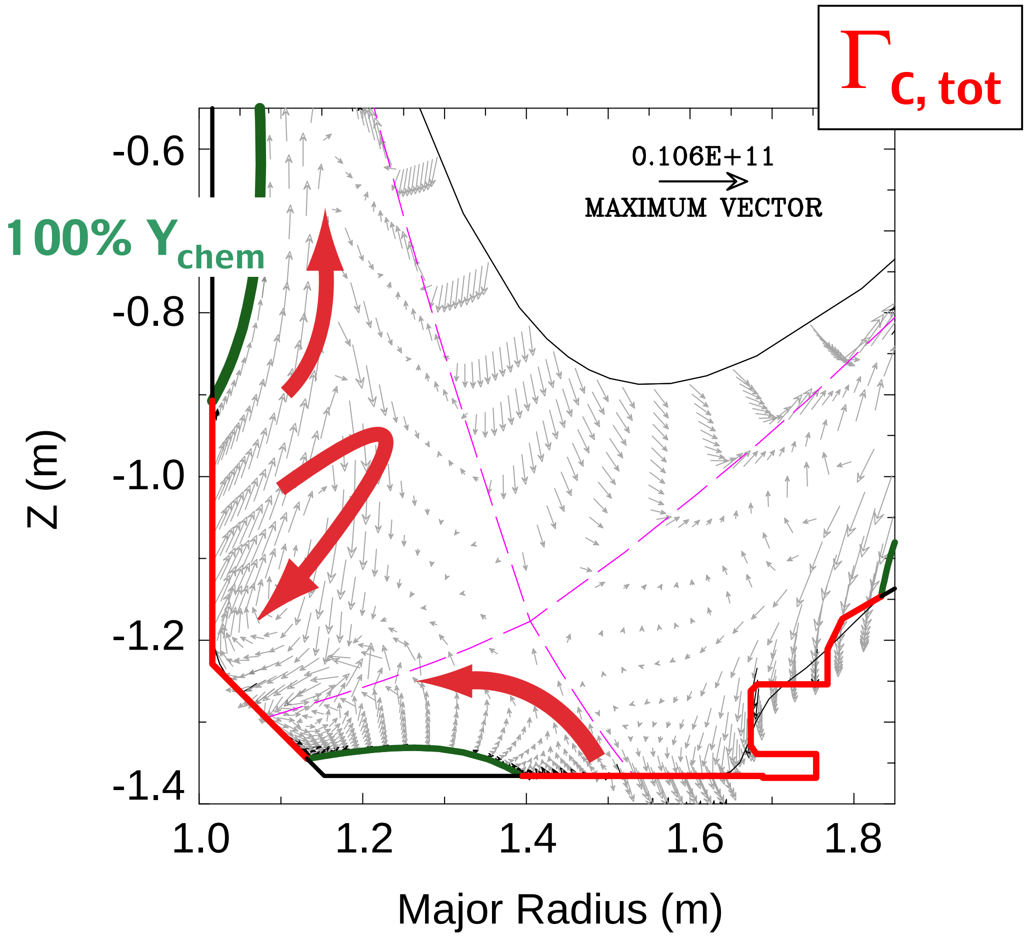




- **MGe09: $D_\perp = 0.65 m^2/s$, $\chi_e = \chi_i = 2.6 m^2/s$, MGe14: $D_\perp = 0.38 m^2/s$, $\chi_e = \chi_i = 1.5 m^2/s$**

# Significant chemical sputtering of carbon on inner plate and divertor walls; outer plate region of net deposition



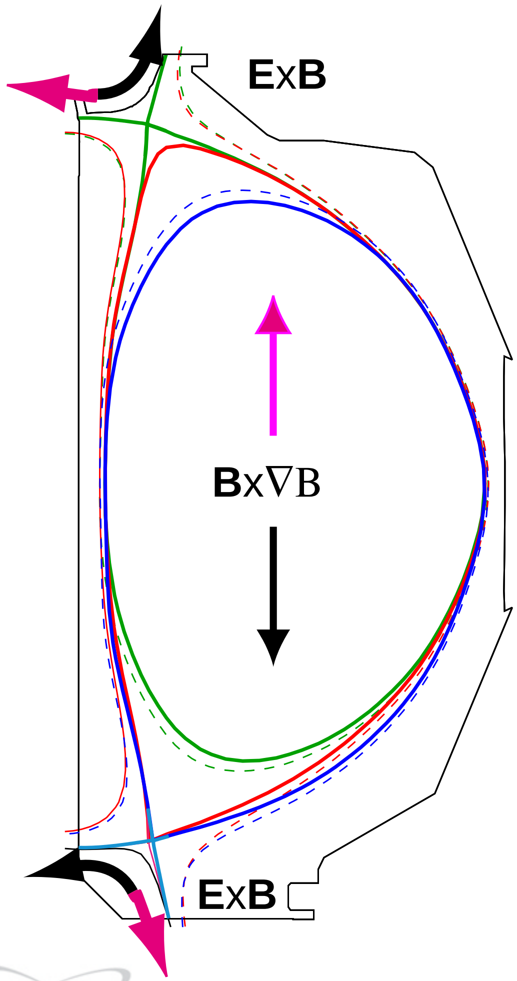
# UEDGE predicts ion carbon leakage into inner main SOL above the X-point due to dominant $\nabla T_i$ force

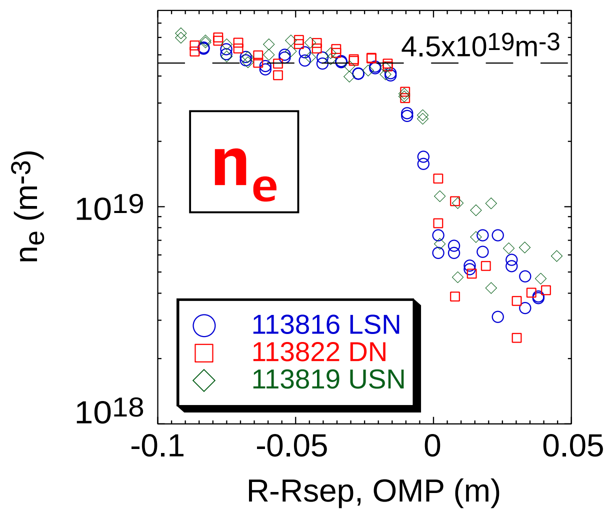


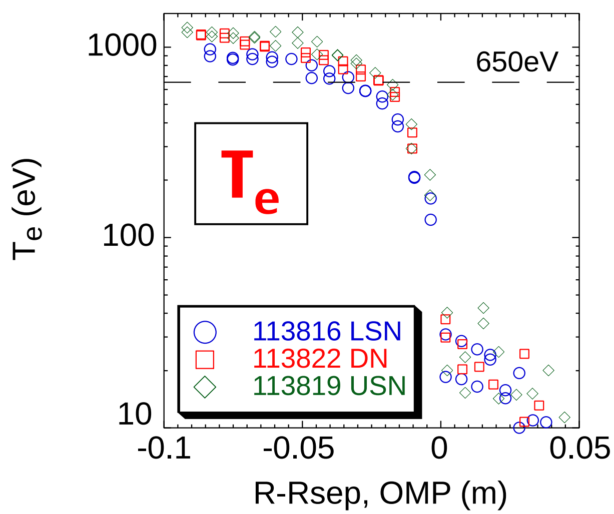

100% $Y_{chem}$ + 100% $Y_{phys}$

- Net transfer of carbon from outer to inner wall region
- Flow reversal away from inner target in far-SOL
- Leakage for Z>−0.8m: $\nabla T_i$ force exceeds frictional drag from background plasma

# Fueling and particle transport in medium-density ELMy H-mode in single and double-null configurations




- Beam-heated ELMy H-modes: $H_{89}$~2
- $n/n_{GW}$~0.4
- dRsep=0, ±4 cm < outer gap=6 cm
- Vary direction of $B_T$, but keep $I_P$, to study effect of Bx∇B and ExB

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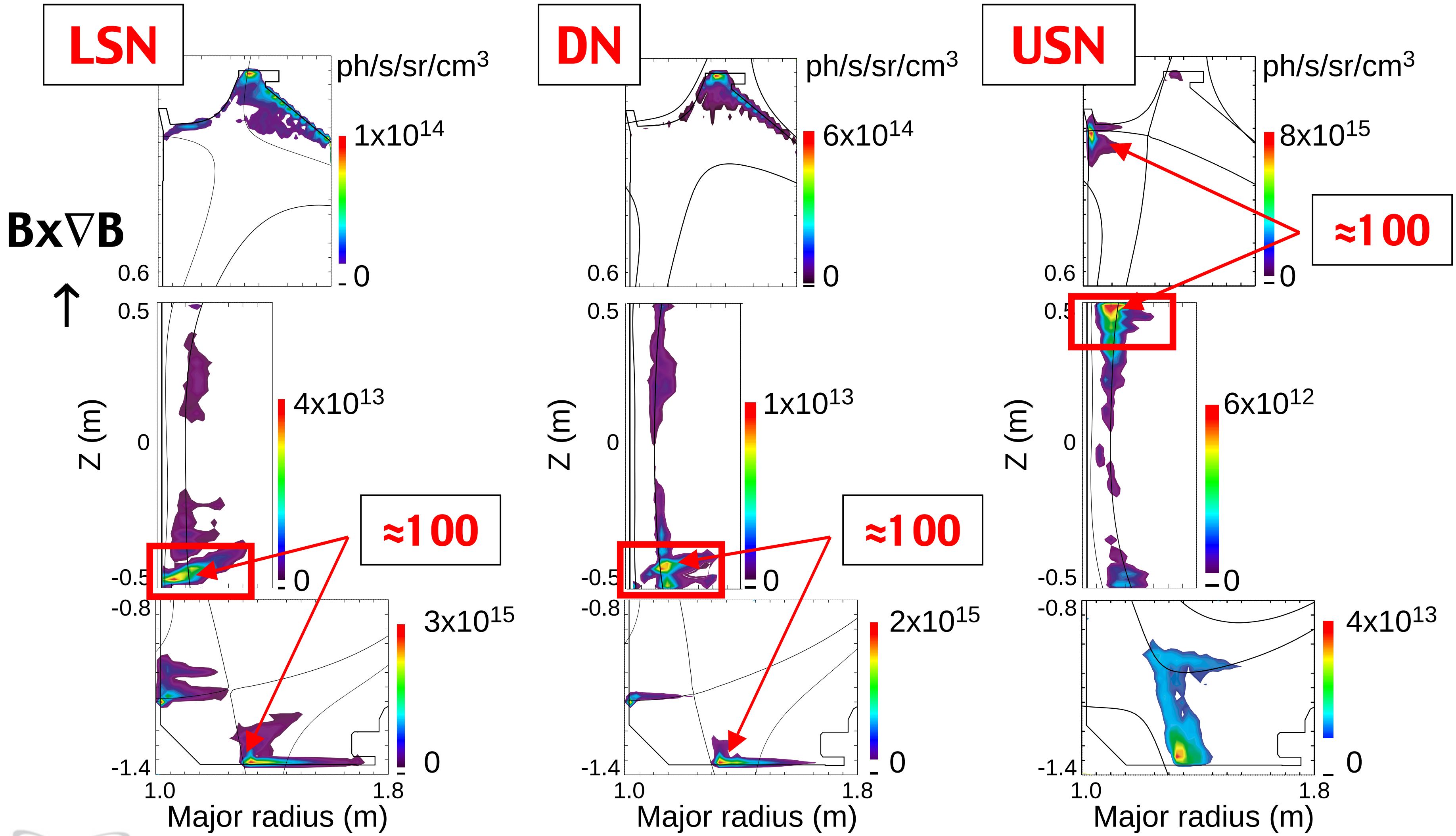
# $D_\alpha$ emission is strongest in primary divertor, in inner SOL it peaks nearest to primary X–point region

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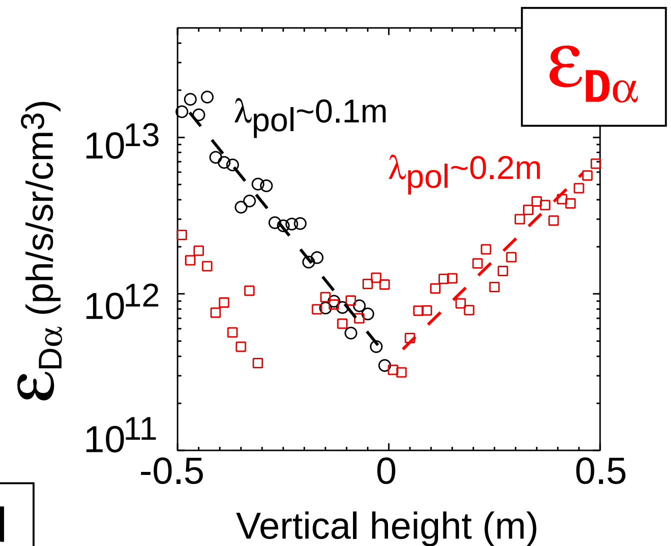
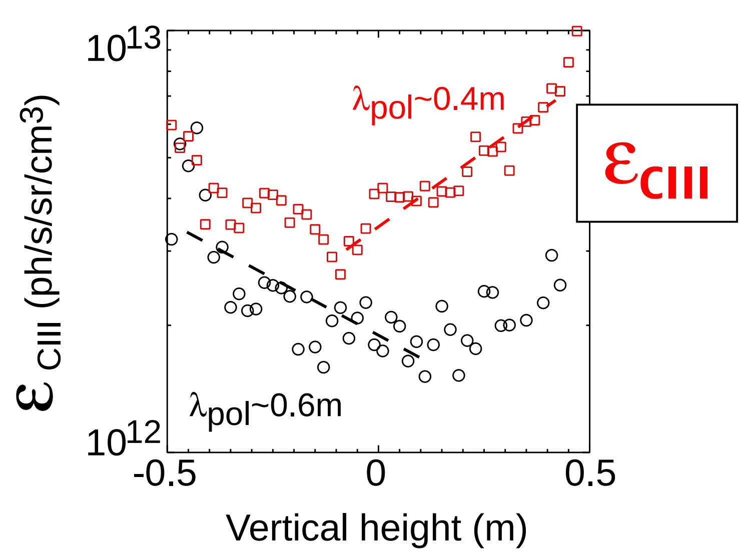
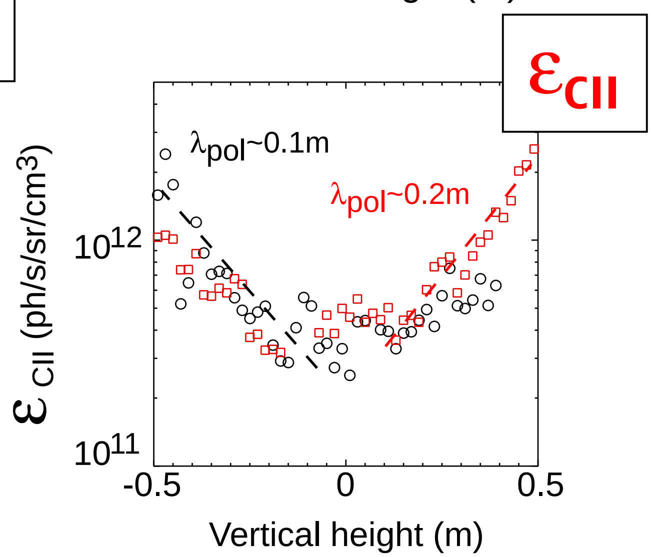
# Poloidal fall-off lengths of $D_\alpha$, CII, CIII emission in inner midplane SOL only weakly dependent on divertor geometry and direction of ion Bx∇B



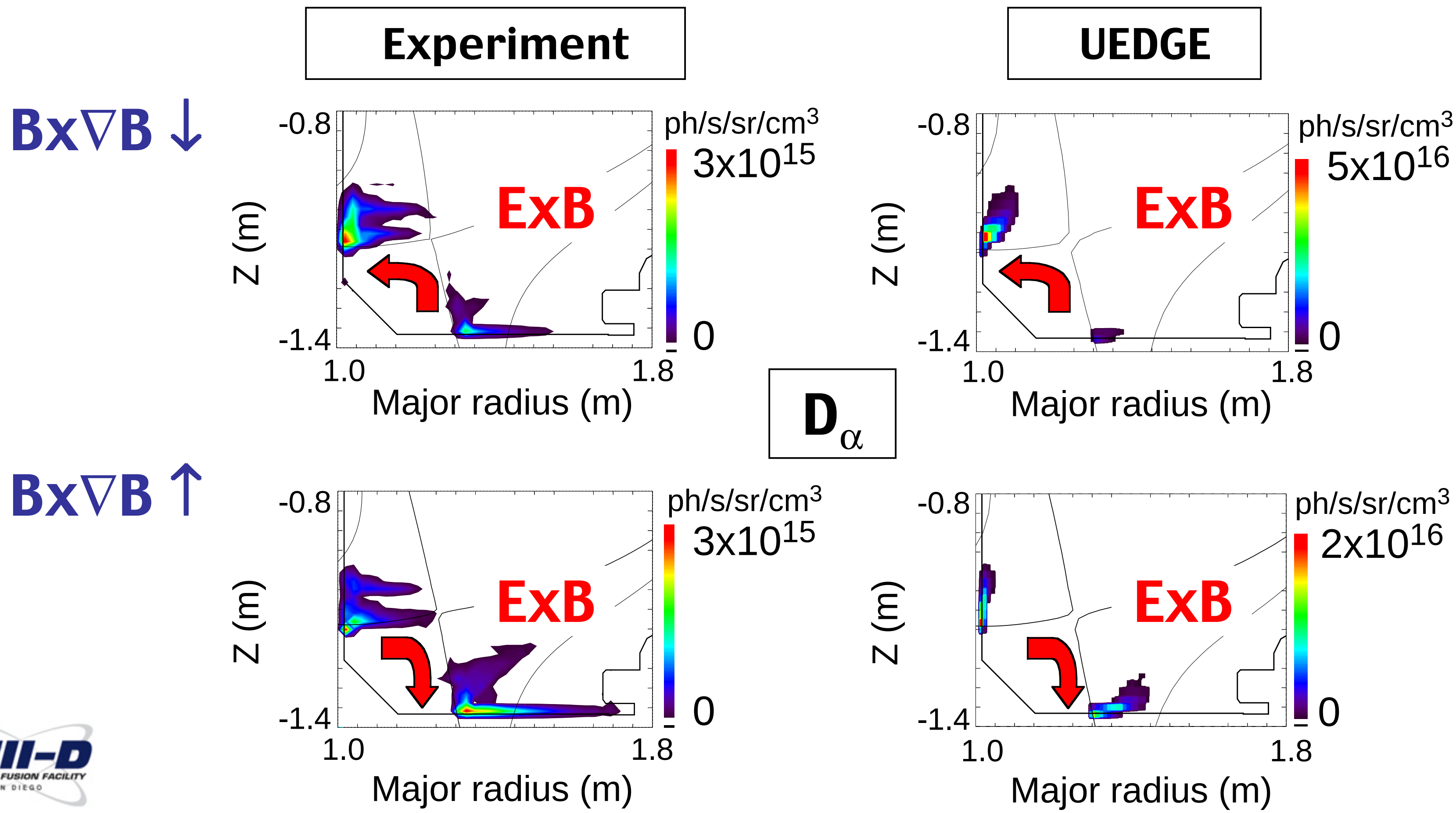

○ LSN
□ USN



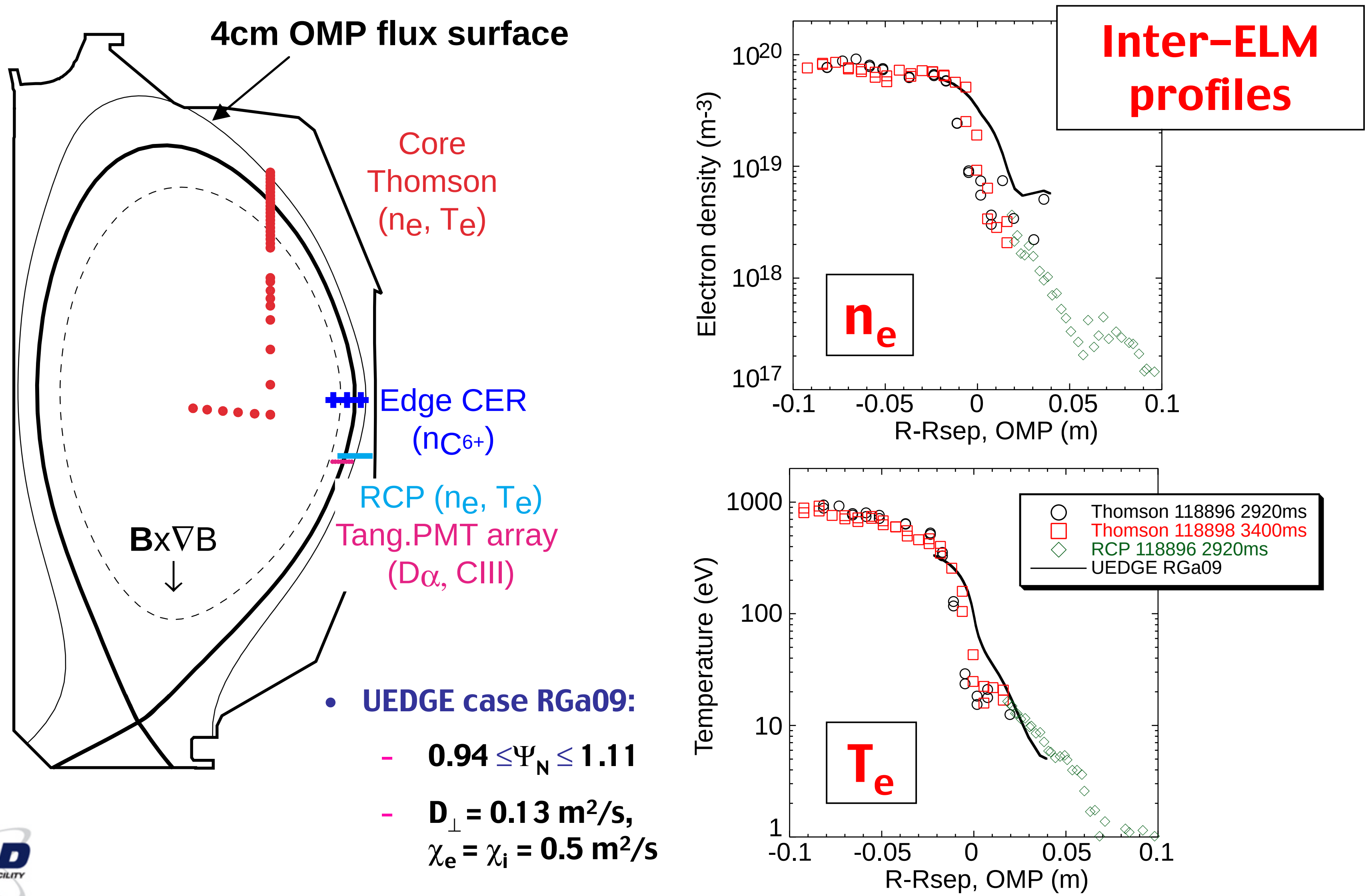

- CIII emission more poloidally extended than $D_\alpha$ and CII
- Emission from secondary X-point region

# Effect of ExB drifts on $D_\alpha$ emission profiles stronger in the divertors than in inner midplane, qualitatively reproduced in UEDGE only when using drifts

- Effects due to ExB drifts observed in both upper and lower divertor
- Modeling of inner midplane profiles shows variation with drift direction, not observed in the experiments

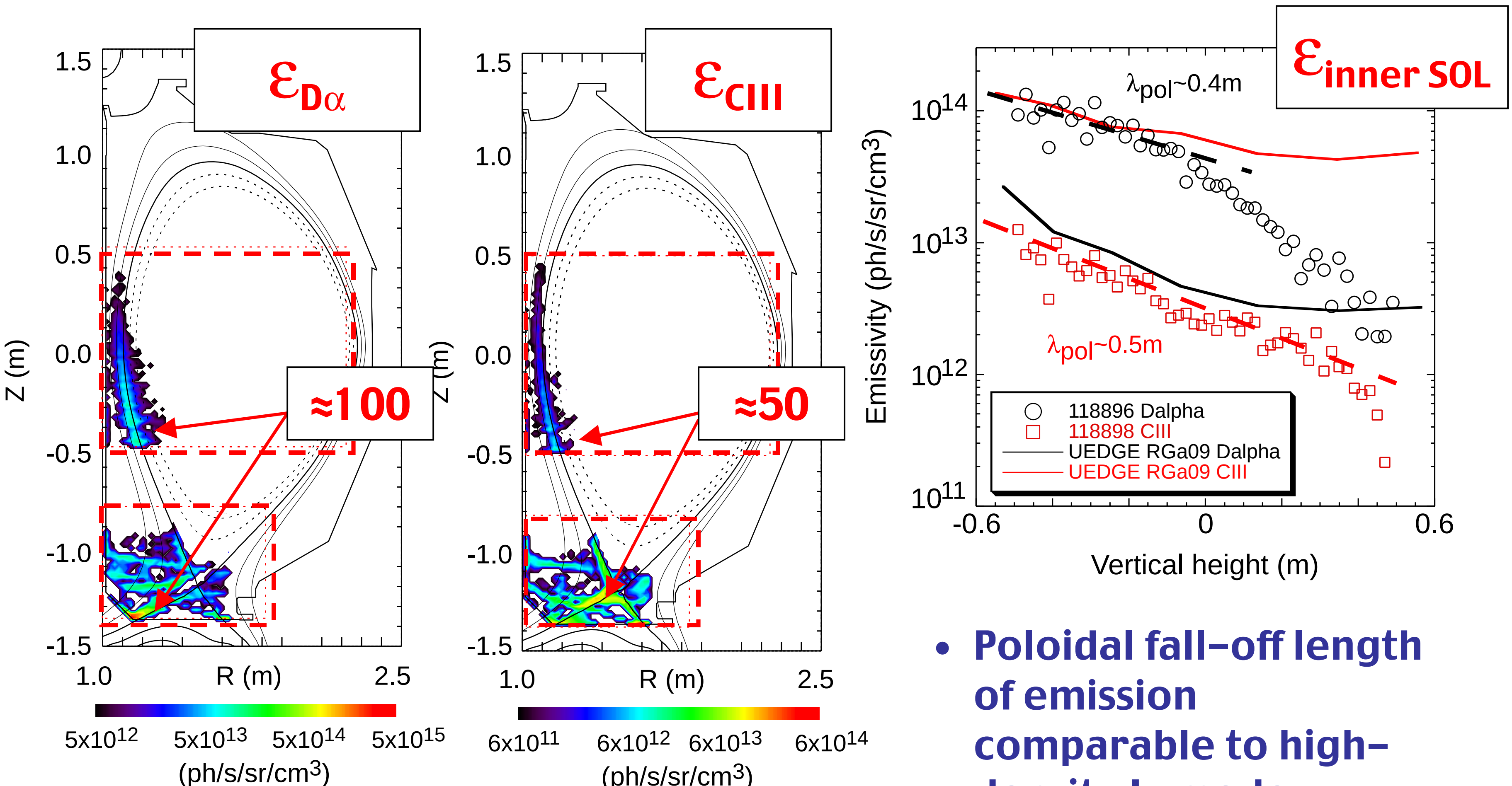


# Lower-single null ELMy H-mode with $n/n_{GW} = 0.7$ optimized for diagnosis of divertor and main SOL




- **UEDGE case RGa09:**
  - $0.94 \leq \Psi_N \leq 1.11$
  - $D_\perp = 0.13\ m^2/s$, $\chi_e = \chi_i = 0.5\ m^2/s$

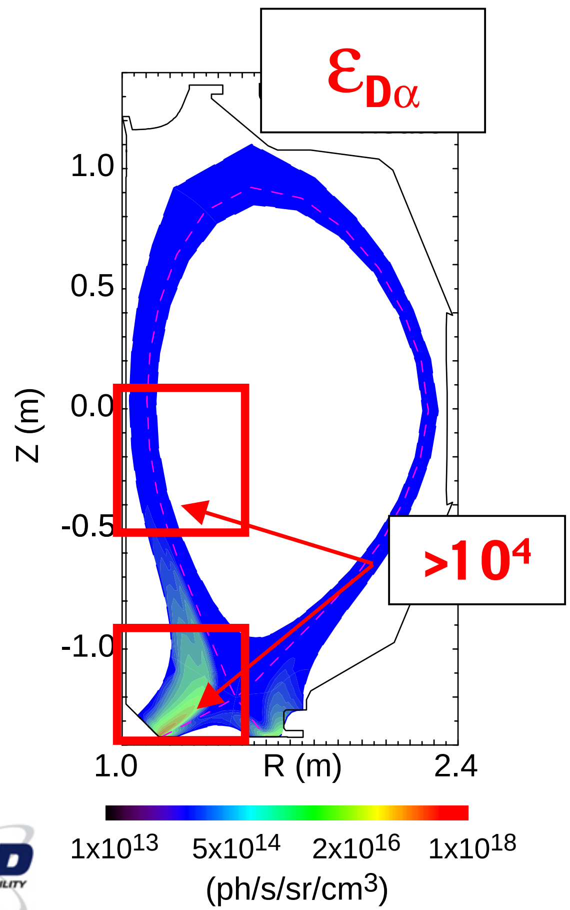
# Inner midplane $D_\alpha$ and CIII emission profiles strongly peaked toward lower divertor X-point

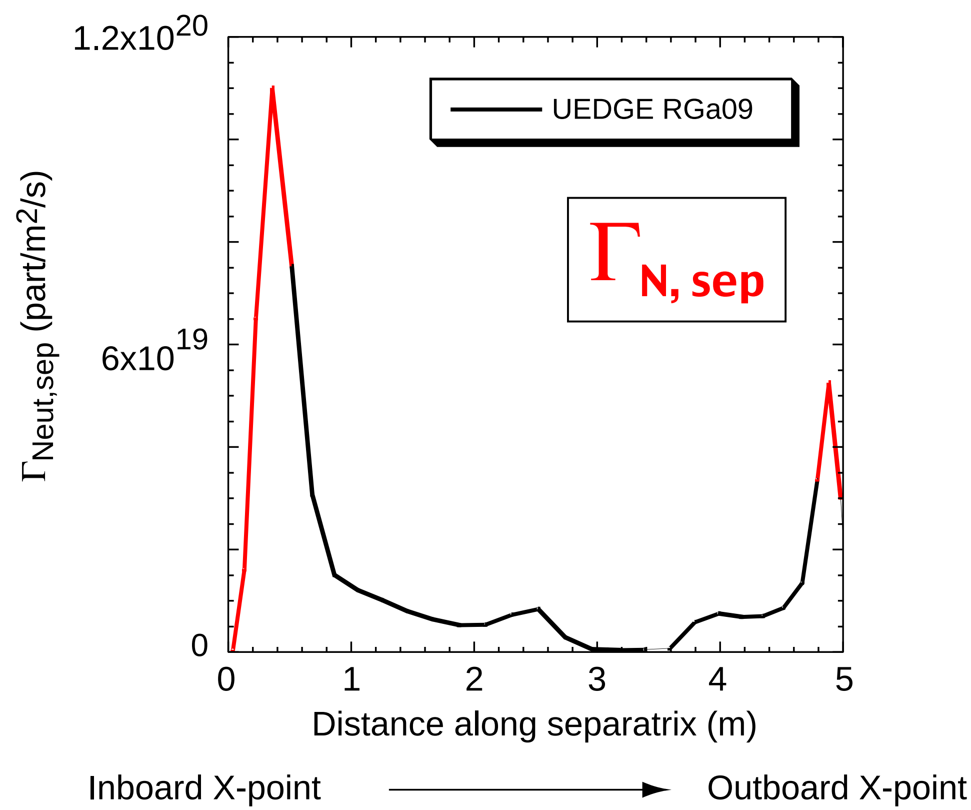



- **Poloidal fall-off length of emission comparable to high-density L-mode**

# Strong core plasma fueling from inner divertor and main SOL region calculated by UEDGE

- **Significant neutral leakage from inner divertor region: divertor X-point fueling 63% of total core fueling, 37% neutral leakage → allowing leakage in halo region (DEGAS2) will increase this ratio**

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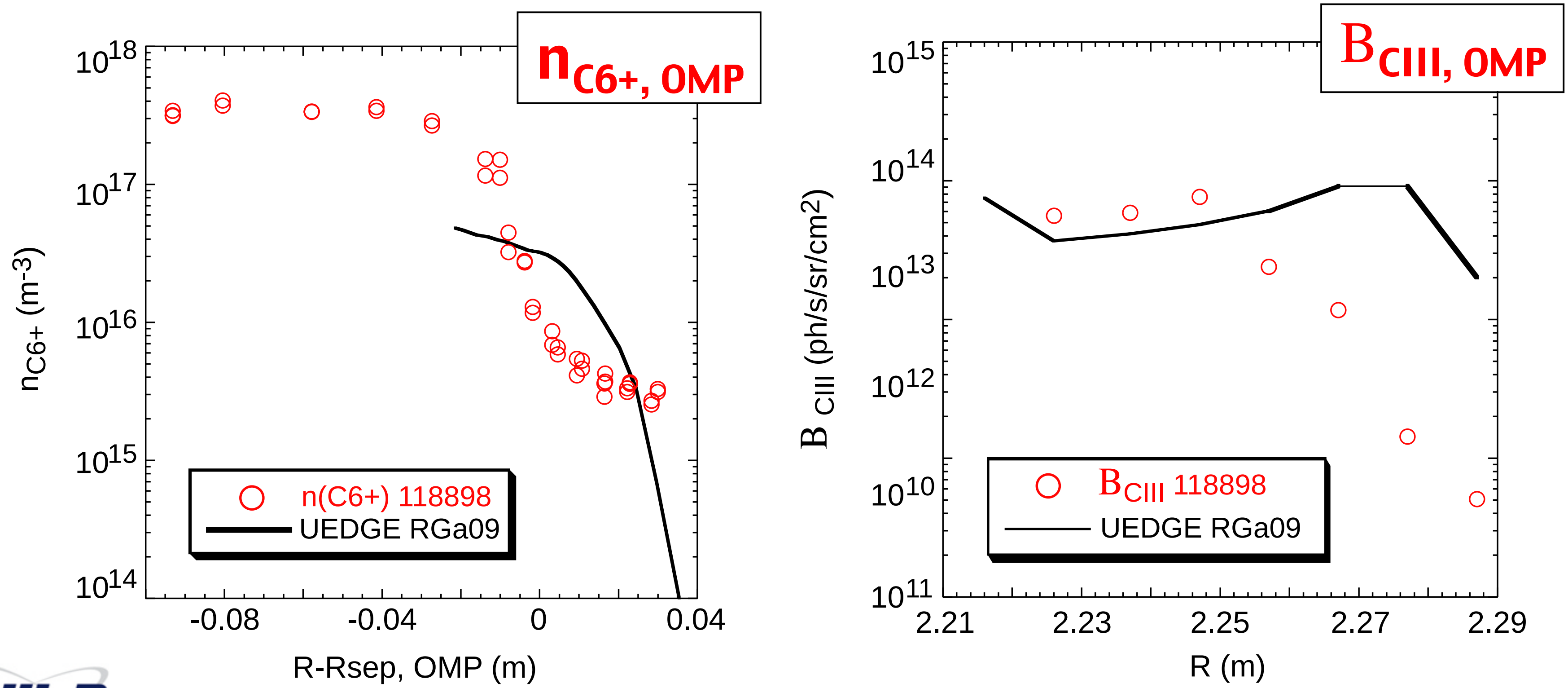
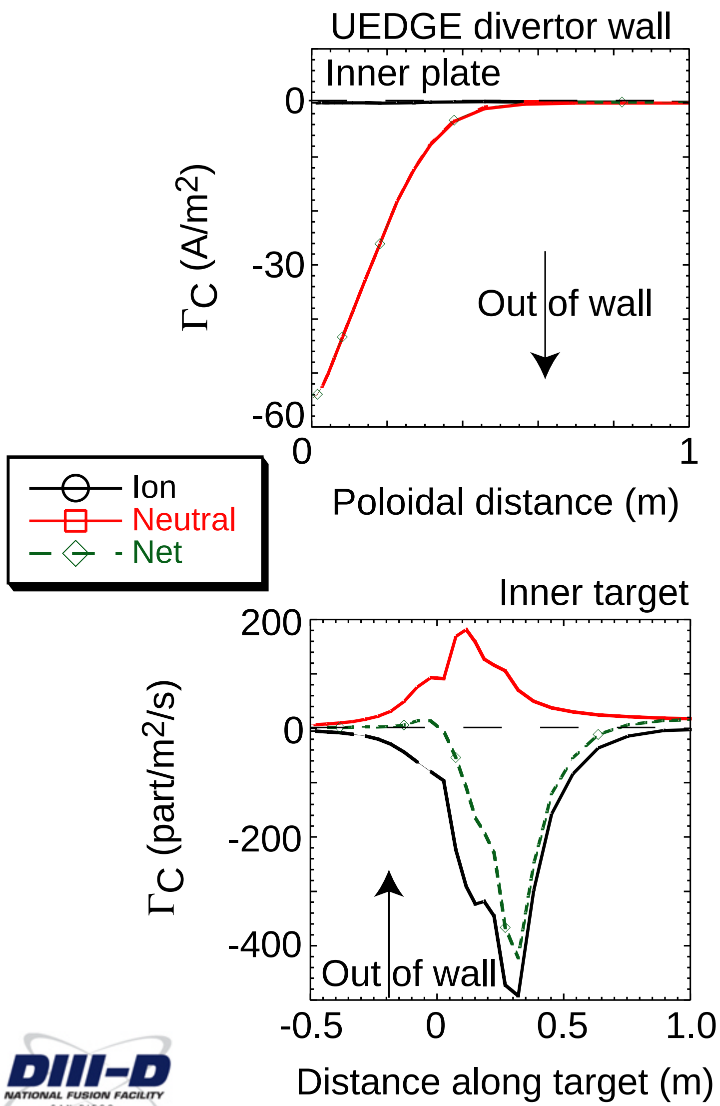
# Order-of-magnitude agreement between measured and calculated upstream carbon density and CIII emission

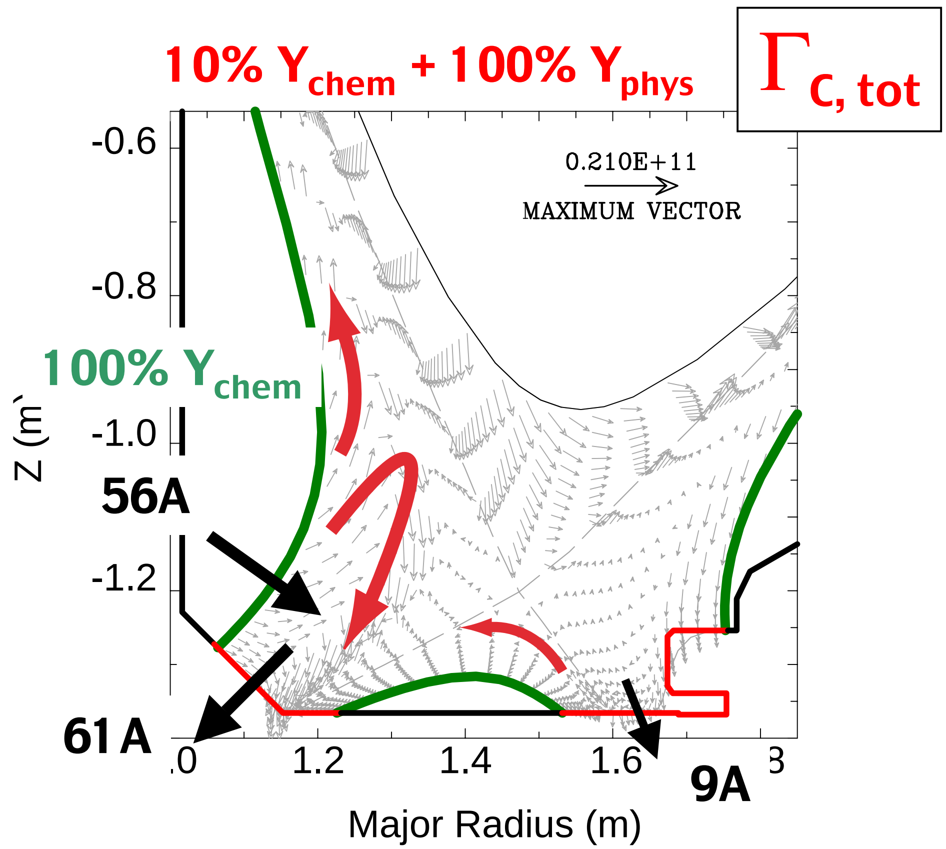
- **Steep gradient region in UEDGE in SOL, measured inside separatrix**
- **Outer midplane CIII emission matched inside separatrix, but not in main SOL**



# Main carbon source is inner divertor wall; inner and outer target plates are areas of net deposition




- **Carbon leakage from inner divertor region due to flow reversal in far-SOL of inner divertor plasma**



# Summary

- Assessment of poloidal distribution of core fueling in DIII-D L-mode and ELMy H-mode plasmas using ...
  - Detailed measurements of plasma parameters in the divertor and main SOL, including 2-D emission distribution of $D_\alpha$, CII, CIII
  - Data-constrained UEDGE/DEGAS2 2-D boundary modeling of deuterium neutrals and ions, and carbon transport
- Poloidal fueling distribution suggests that ...
  - Dominant core plasma fueling occurs near divertor X-point region due to recycling at the divertor targets
  - Significant neutral leakage from (colder) inner divertor into inner main SOL
- Divertor target plates and divertor walls are dominant carbon sources
- Carbon ion leakage from divertor into main SOL is the main transport mechanism that sets core carbon content