The Impact of Divertor Magnetic Balance and Particle Drifts on Radiating Divertor Behavior in DIII-D

by
T.W. Petrie

for

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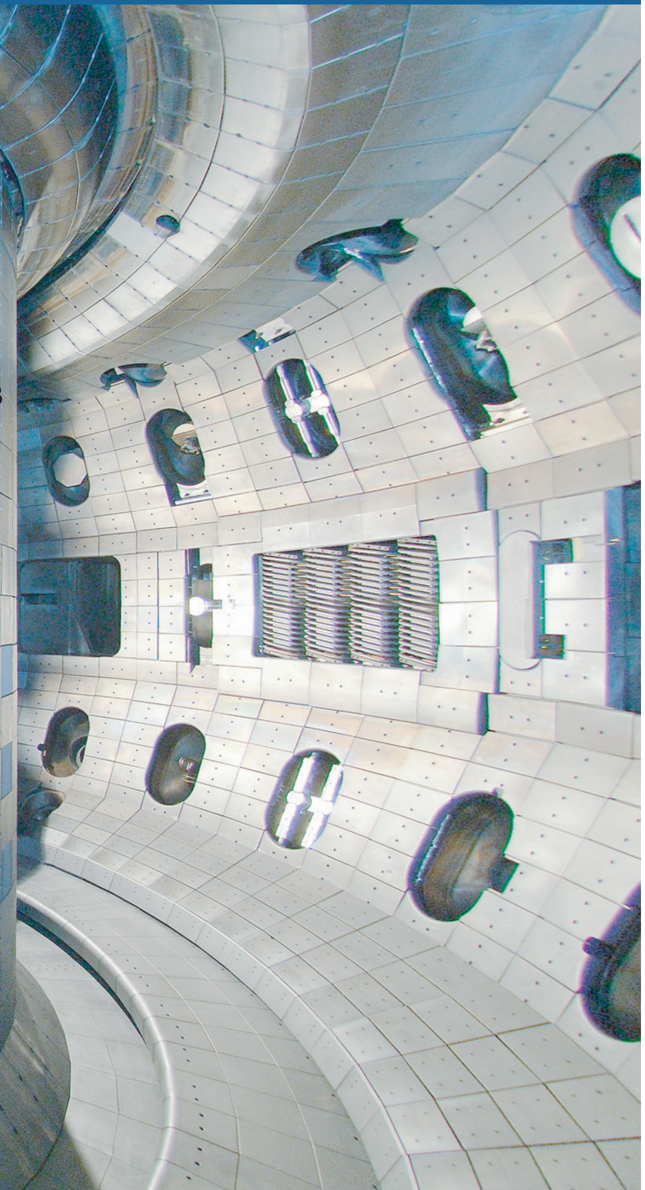


Introduction

- **Radiating Divertor Approach for Reducing Divertor Heat Flux**
  - Seed impurities are injected into the private flux region
  - Upstream gas puffing and particle pumping at the divertor targets
    $\rightarrow$ Enhanced deuterium flow into the divertor
    $\rightarrow$ More difficult for impurities to escape the divertor
  - Result: *More uniform dispersal of incident power in divertor + mantle*

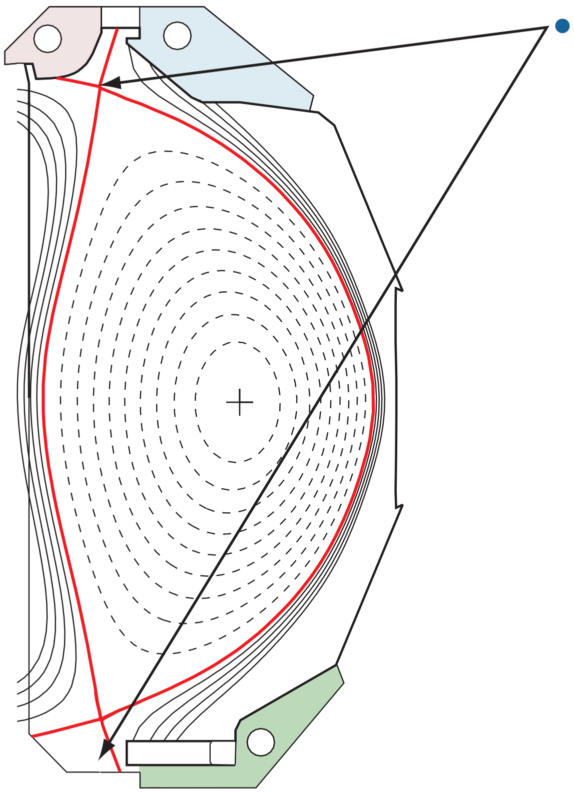
- **Best Result (so far) for Single-null Plasmas**
  - Ion $B \times \nabla B$ drift is directed away from the X-point
  - 60-65% reduction in the peak heat flux at the OSP
  - $n_e/n_{eG} \approx 0.65$, $P_{RAD}/P_{IN} \approx 0.65$, $H_{89P} \approx 2$, Zeff ≈ 2.1

- **Earlier experiments[1,2] on DIII-D have suggested that successful radiating divertor operation might be sensitive to**
  - Ion $B \times \nabla B$ drift direction
  - Divertor closure
  - Magnetic balance, e.g., Single-null vs Double-null

1 M. Wade, et al., Nucl. Fusion 38 (1998)1839

2 T. Petrie, et al., Nucl. Mater. 363-365 (2007)416

DIII–D Geometry is Well-Suited for Puff-and-Pump Experiments with High-δ Plasma Shapes Near Double-Null



- **Experimental arrangement**
  - The upper divertor is more “closed” than the lower divertor

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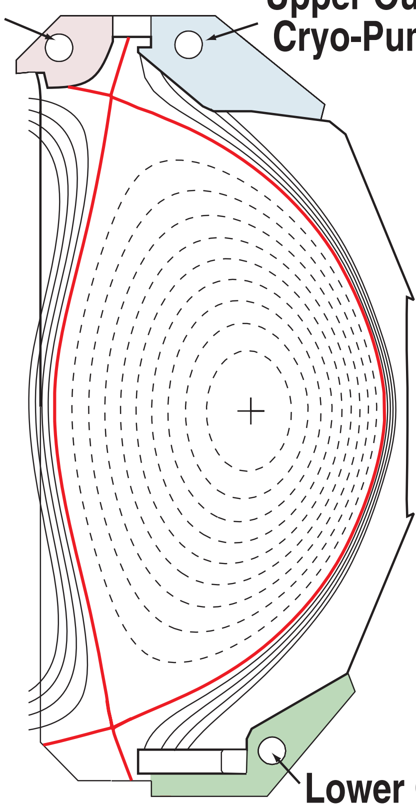

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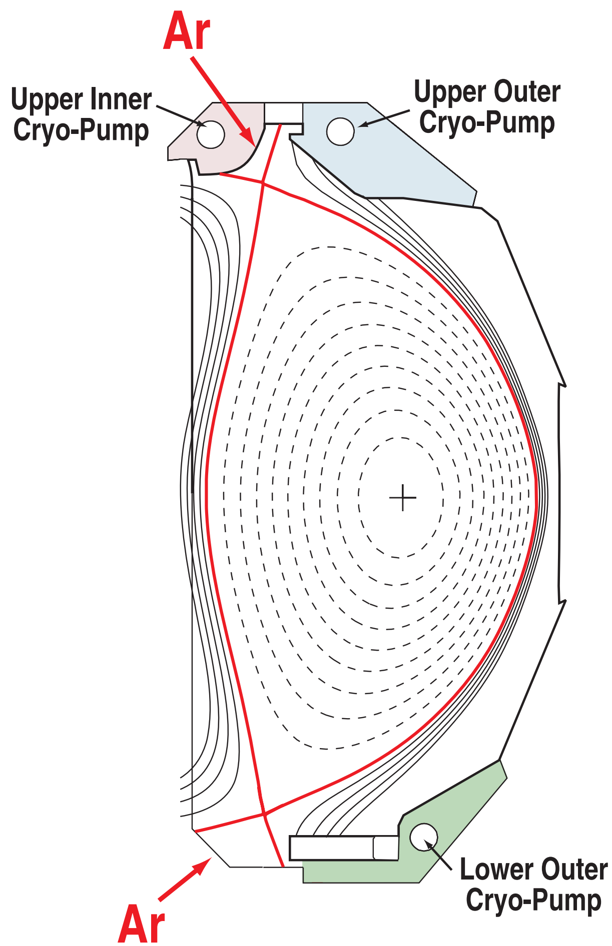

- Experimental arrangement
  - The upper divertor is more "closed" than the lower divertor
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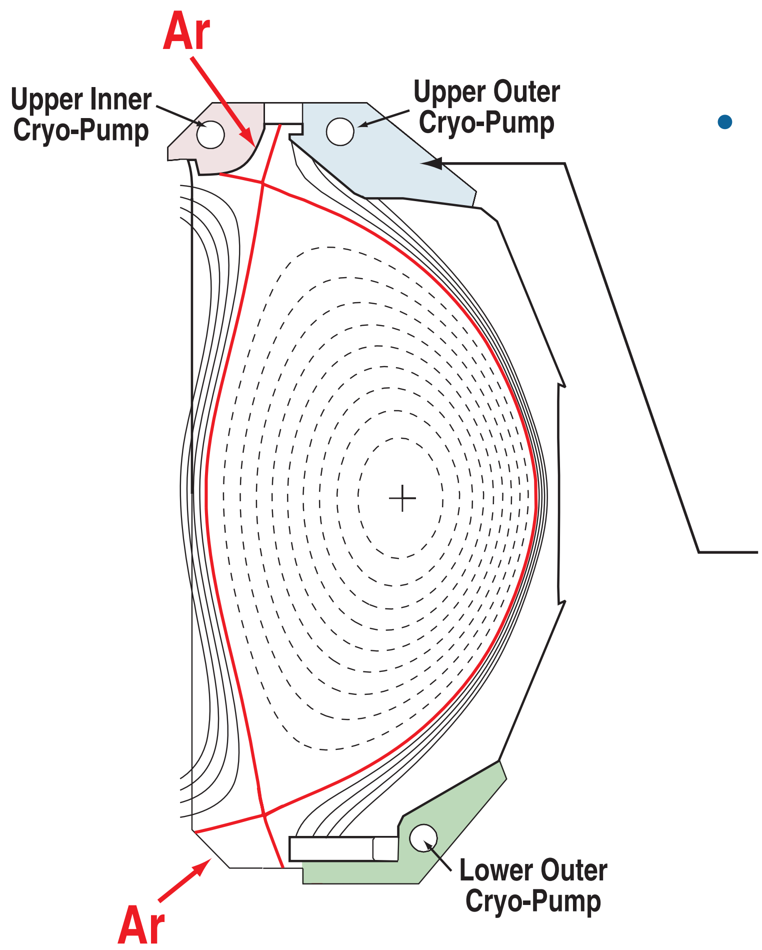

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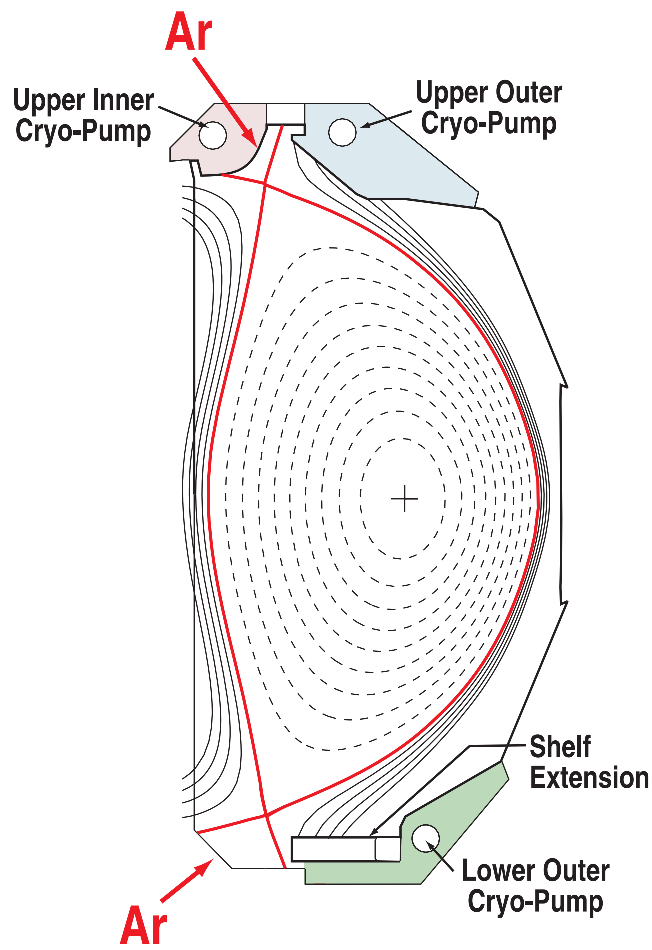

Experimental arrangement

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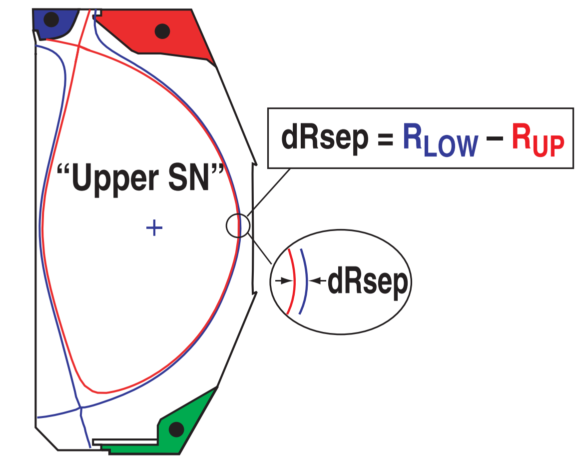
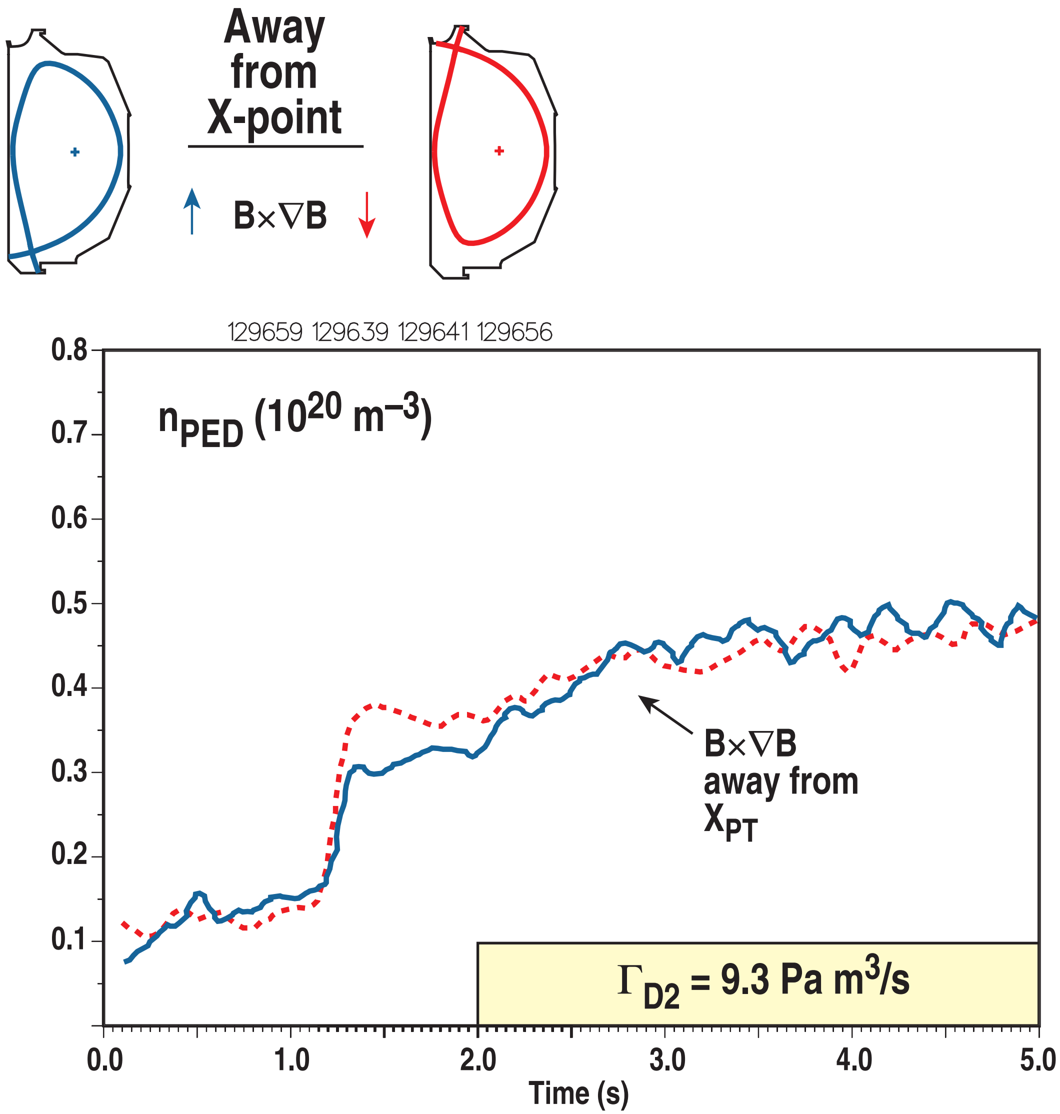
- Three cryopumps are independently controlled
- The seed impurity (argon) can be injected into the private flux regions of either divertor
- Argon pressure measurements are made in the upper outer plenum
- $|dRsep| \lesssim 1.5$ cm for all shots in this study
  - * "SN" → $|dRsep| \gtrsim 1$ cm
  - * "DN" → $dRsep = 0$



Pedestal Density is Correlated More to Ion B×∇B Drift Direction Than to Differences in DIII-D Divertor Geometry



- **To match exhaust characteristics, only the outer pump in the dominant divertor is activated**

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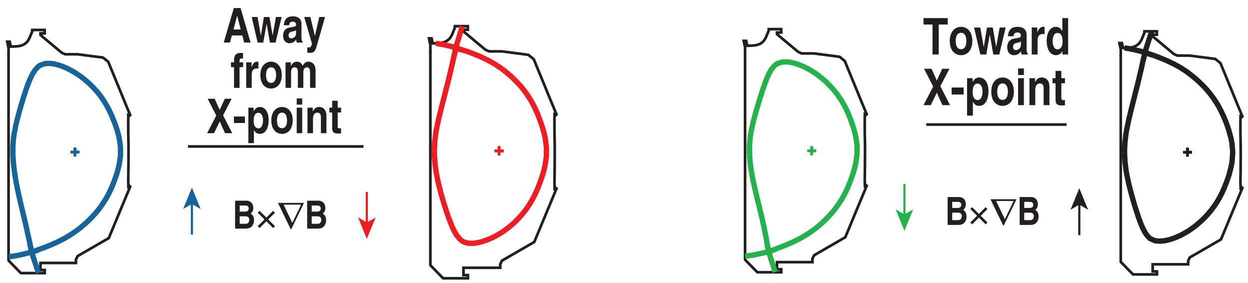

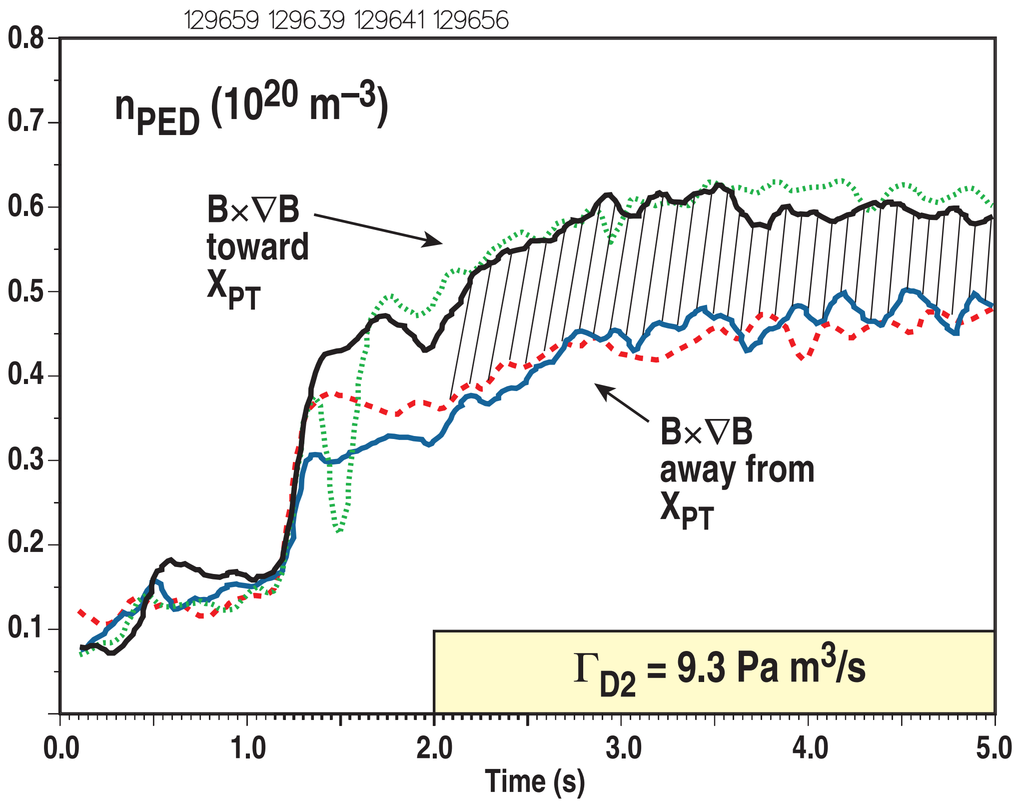

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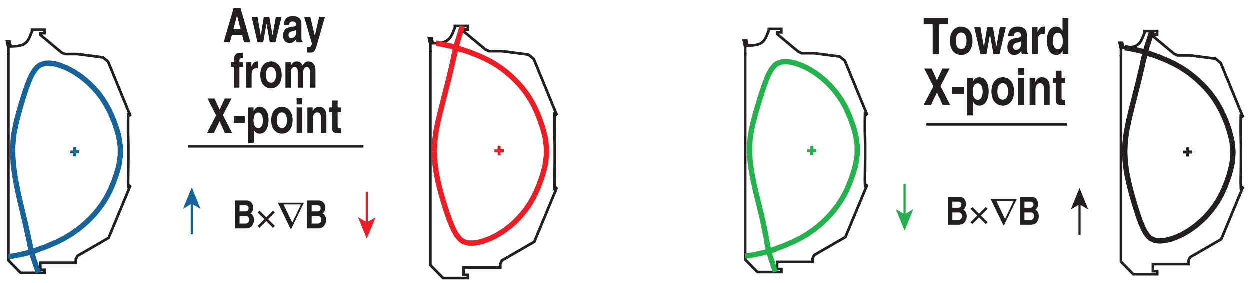
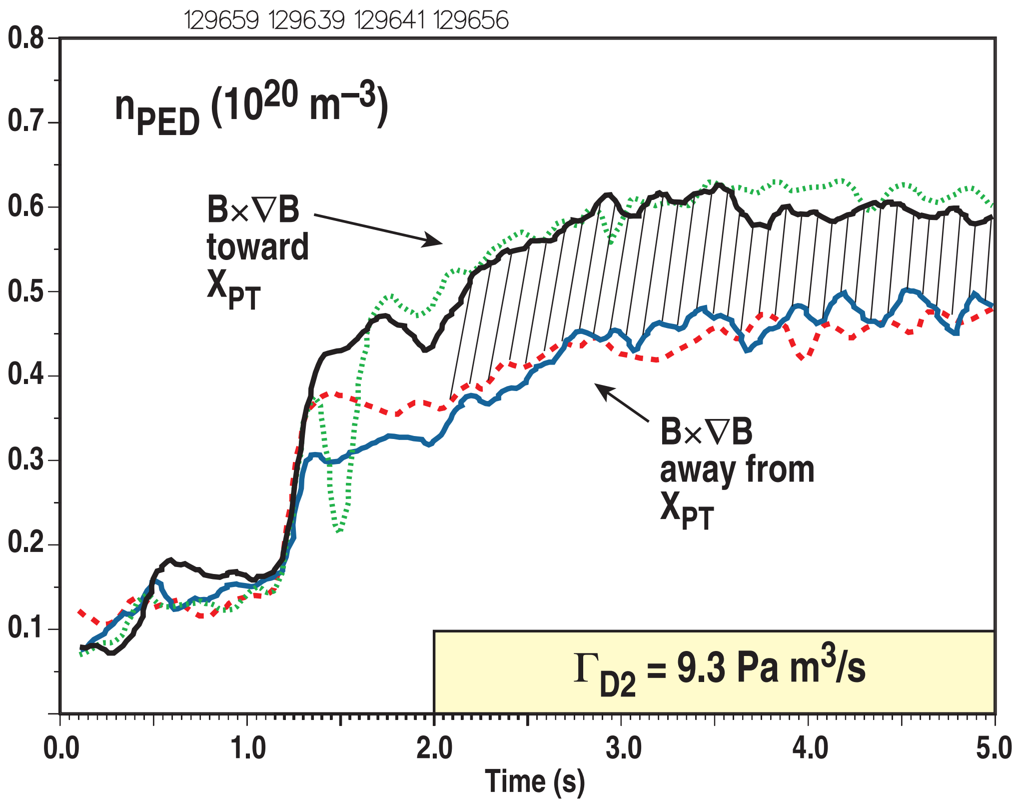
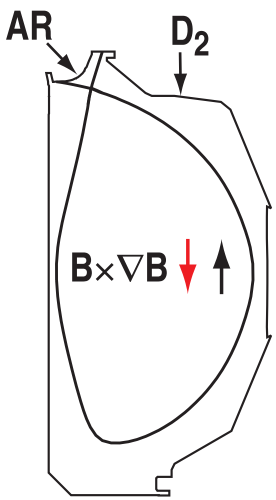




- To match exhaust characteristics, only the outer pump in the dominant divertor is activated
- Significant difference in pedestal density between B×∇B cases
- This result is consistent with previous work highlighting the possible role of particle drifts in plasma fueling*, although other factors are also likely in play

*M. Groth, *et al.*, J. Nucl. Mater **290-293** (2005) 452

Argon Accumulation Inside "SN" Plasmas and Argon Pumping in the Divertor was Sensitive to the Ion B×∇B Drift Direction



dRsep = +1.2 cm

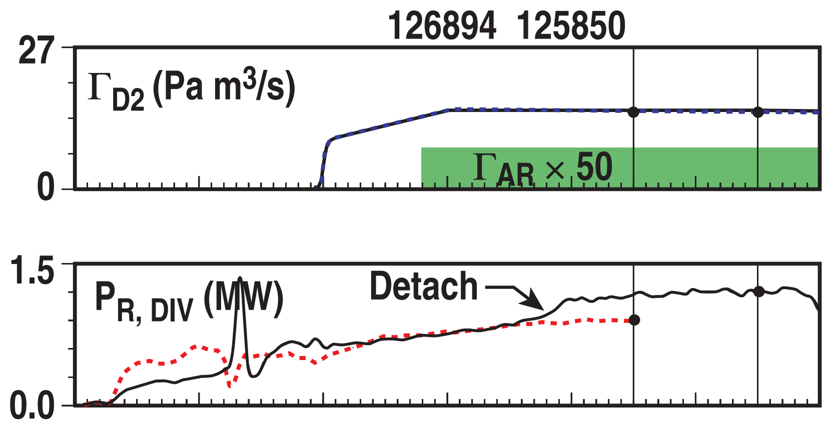
I_P = 1.2 MA

B_T = 1.8 T

P_{IN} = 6 MW

$\beta_N \simeq 2$

$\frac{\tau_E}{\tau_{89}} \simeq 1.7$



- Same Γ_{D2} and Γ_{AR} injection rates for each case
- Divertor radiated power
  - Partial detachment of inner divertor leg for B×∇B↑
  - B×∇B↓ attached at all times

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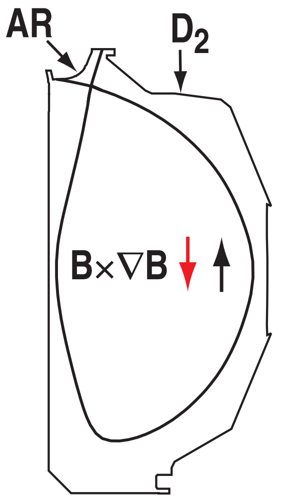

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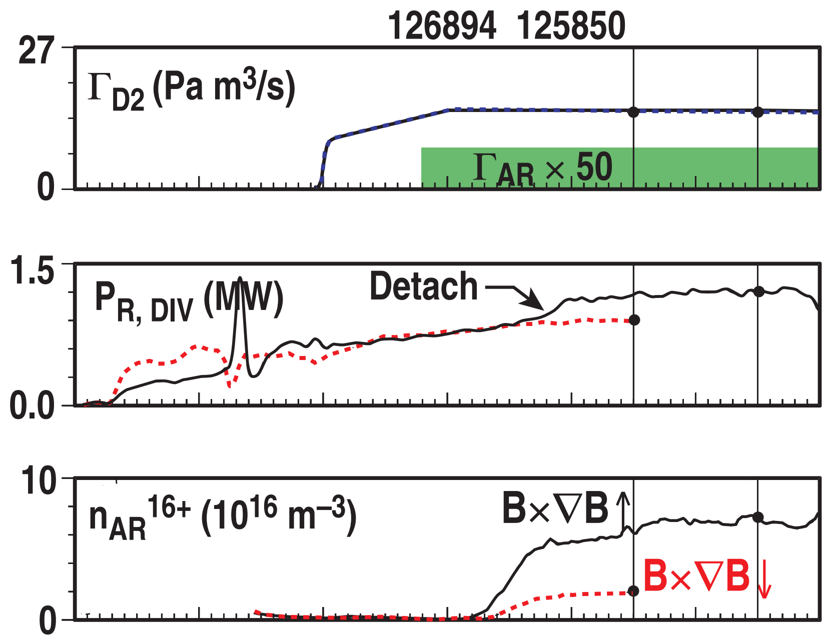

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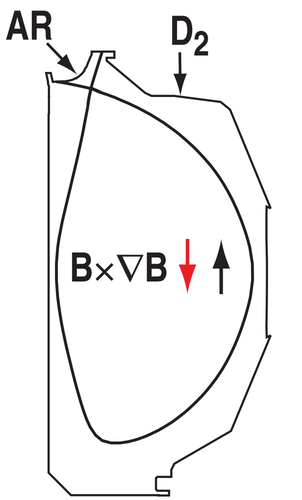

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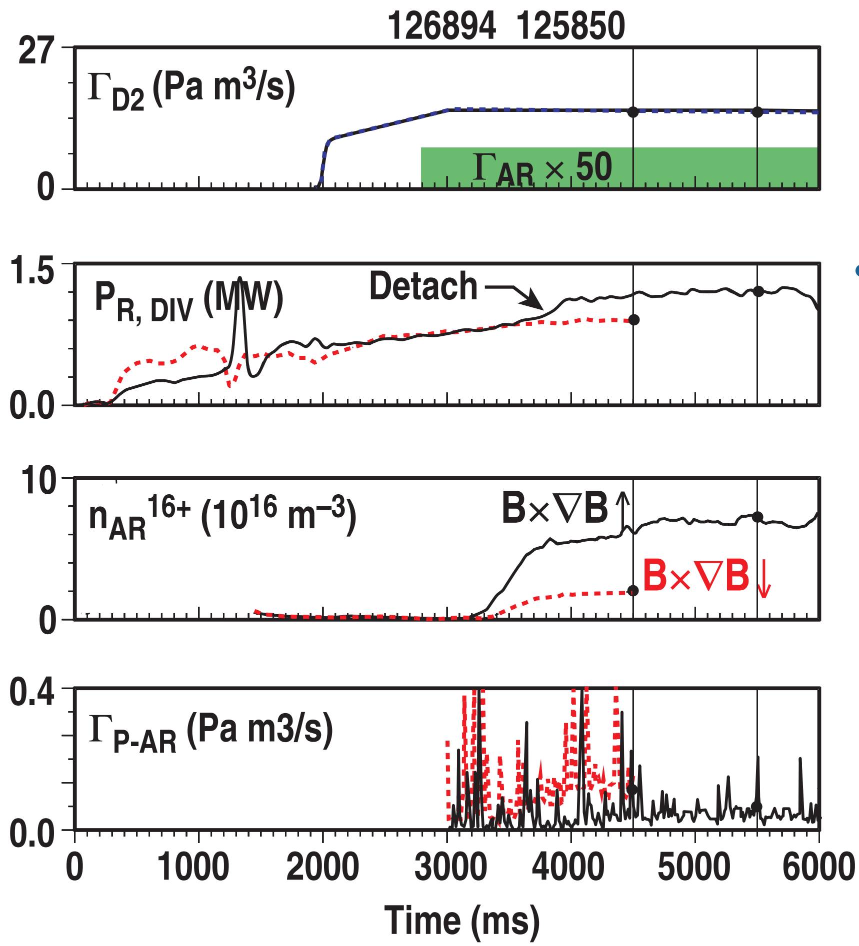

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- **~3× argon in core for B×∇B↑**
- **Ar removal fraction**
  - $\frac{\Gamma_{P\text{-}AR}}{\Gamma_{AR}} \approx$ **0.85 for B×∇B↓**
  - $\frac{\Gamma_{P\text{-}AR}}{\Gamma_{AR}} \approx$ **0.35 for B×∇B↑**

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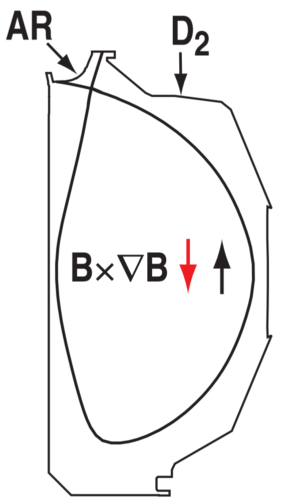

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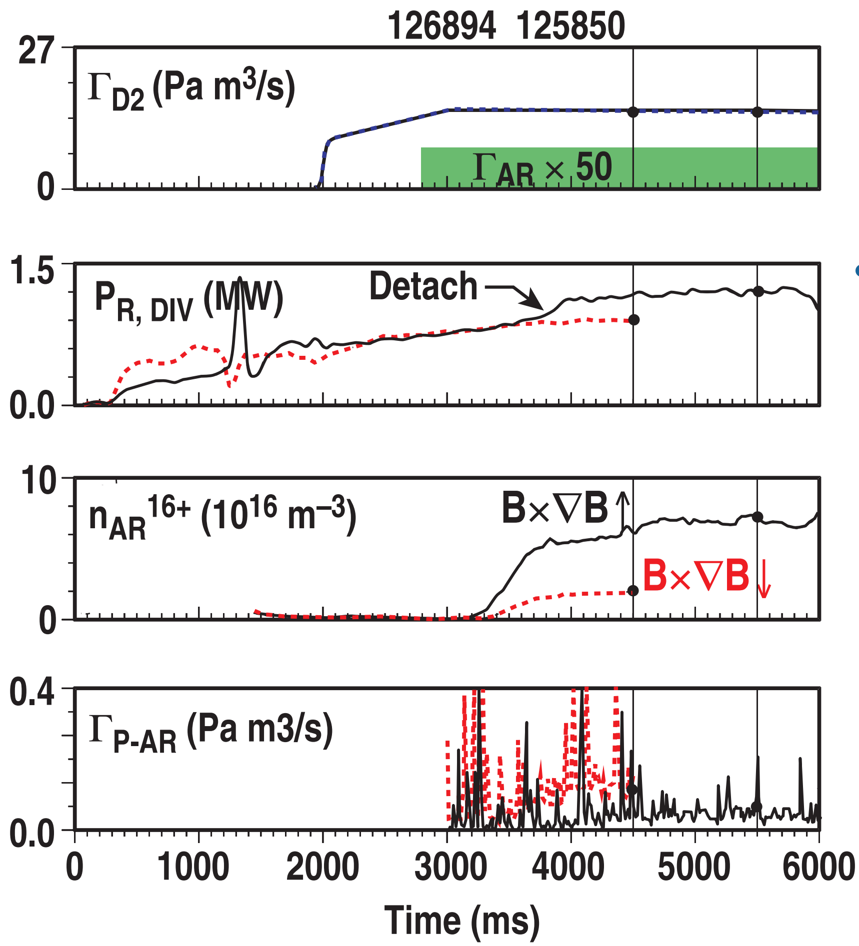

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⇒ Reconciles 1998 and 2005 experiments

M. Wade, *et al.*, Nucl. Fusion 38 (1998) 1839

T. Petrie, *et al.*, J. Nucl. Mater. 363-365 (2007) 416

Particle Drifts Play a Critical Role in Predictions of Radiative Divertor Performance

- **Recycling is pronounced along the outer divertor structure**

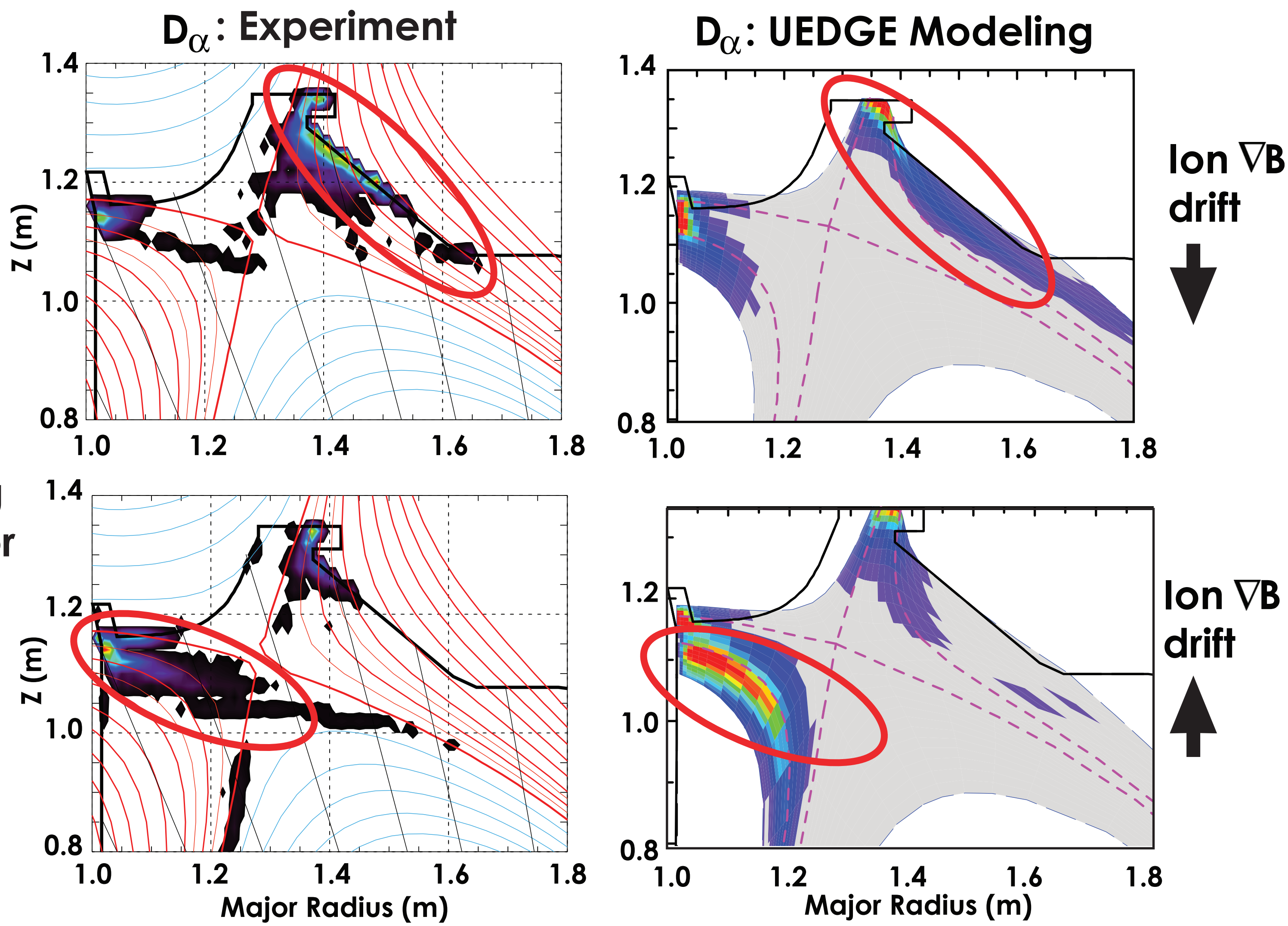
- **Recycling is strong in the inner divertor**

UEDGE Modeling

– H-mode

– Particle drifts

– Finite dRsep



Particle Drifts Play a Critical Role in Predictions of Radiative Divertor Performance

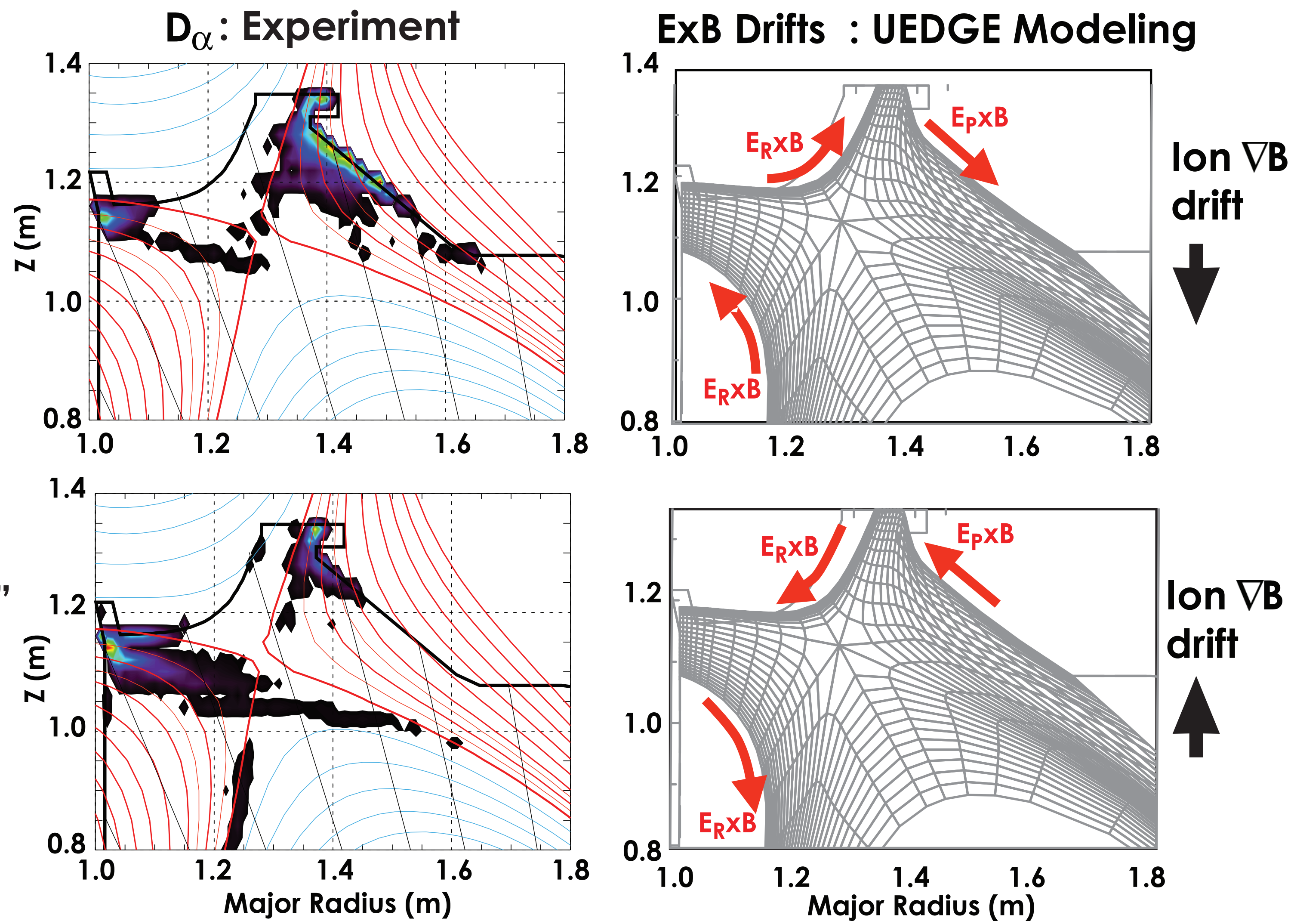
- **Drifts push ions to outer divertor and then inner target is little affected**

- **Drifts push ions to inner divertor which can detach with only “modest” argon injection**

Electric fields

$E_R \propto -\partial T_e/\partial r$

$E_p \propto -\partial T_e/\partial s_{||}$



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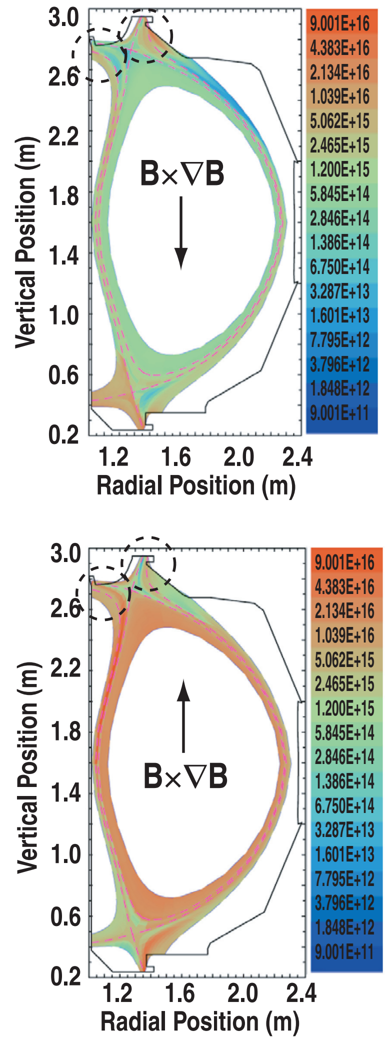
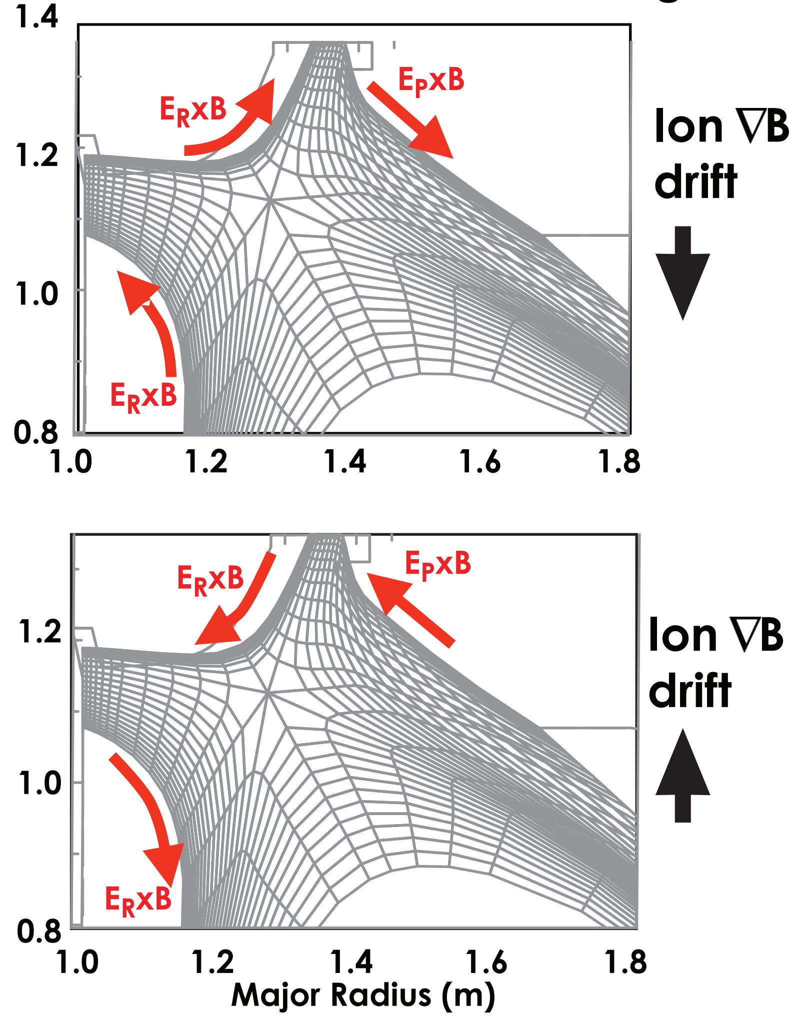
Argon injected into divertor follows D_α pattern

- Drifts push ions to inner divertor which can detach with only "modest" argon injection

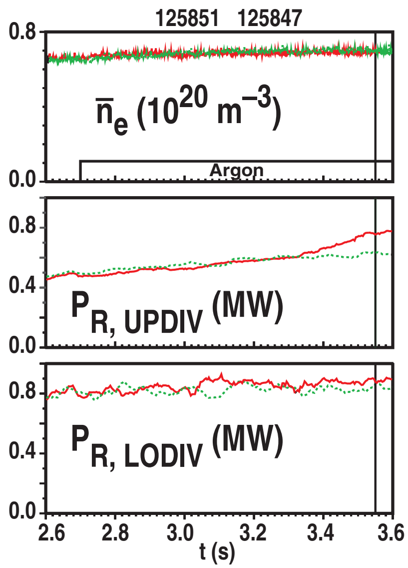
Argon Distribution



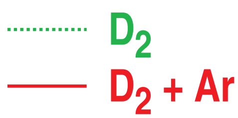
ExB Drifts : UEDGE Modeling



Measureable Increases in Radiated Power Were Observed First in the Divertor OPPOSITE the $B \times \nabla B$ Direction in DN

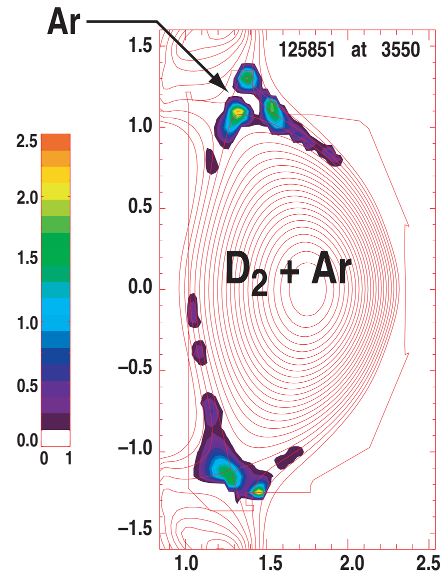


$B \times \nabla B$↓



$\Delta P_{R, UPDIV} \simeq + 0.22$ MW

$\Delta P_{R, LODIV} \simeq + 0.02$ MW



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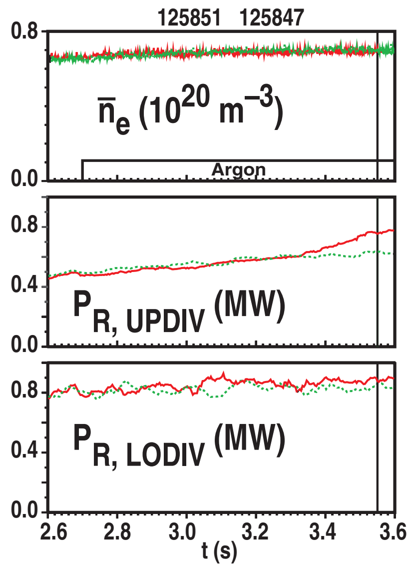

$B \times \nabla B \downarrow$

D2 (dotted green)

D2 + Ar (solid red)

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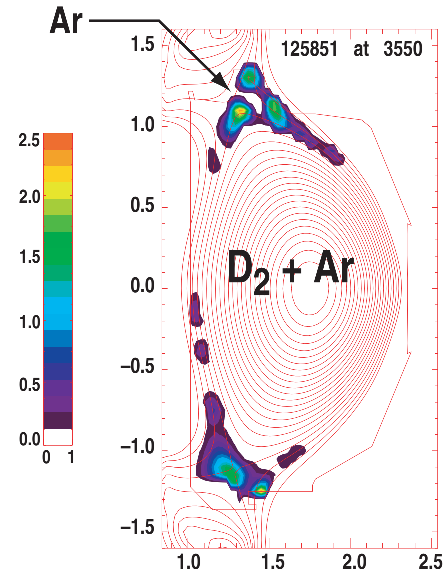

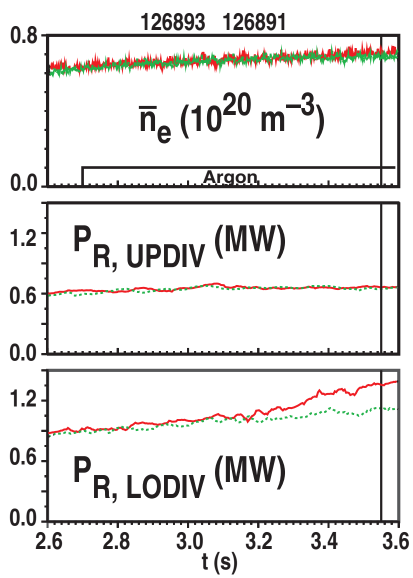

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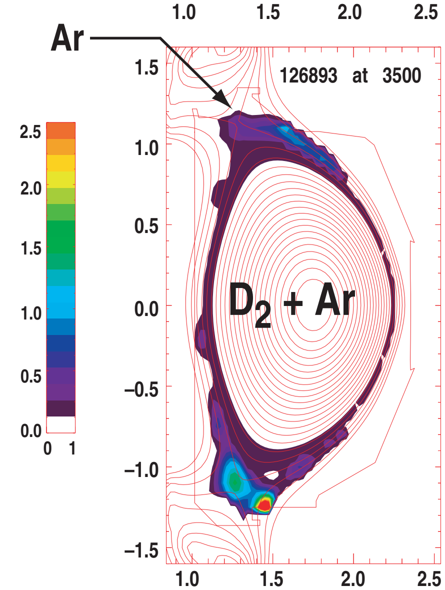

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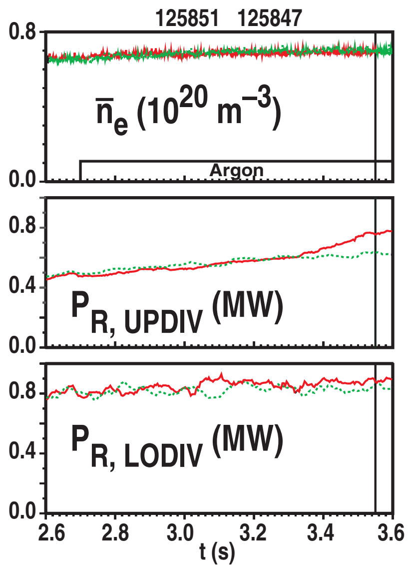

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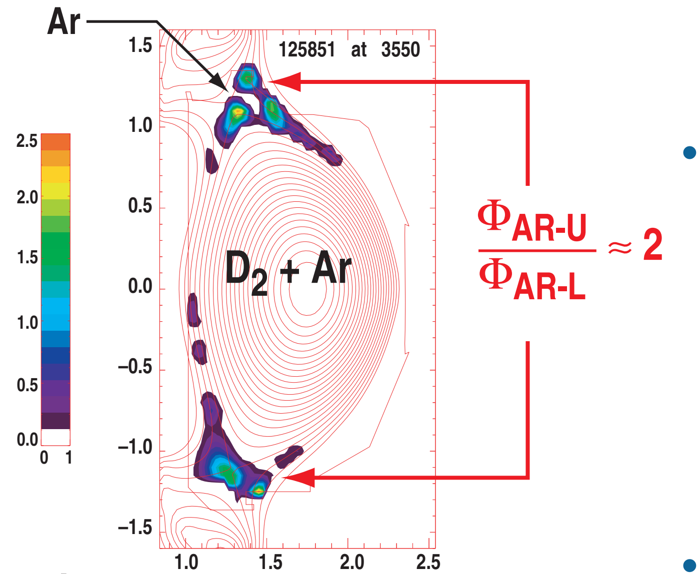
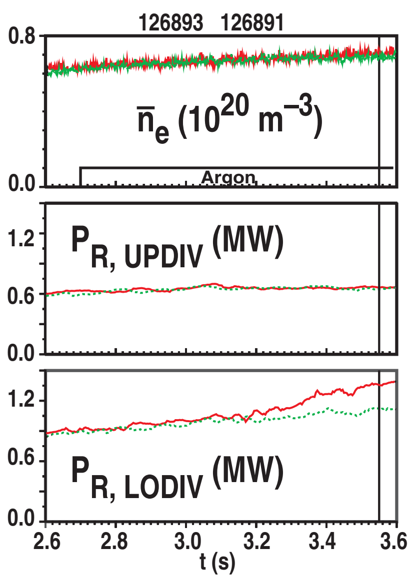


- Same overall result when argon was injected from the lower divertor



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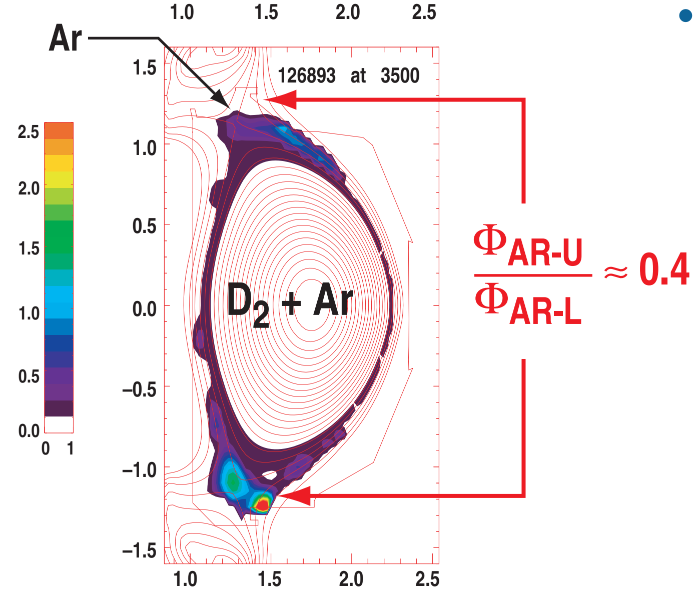
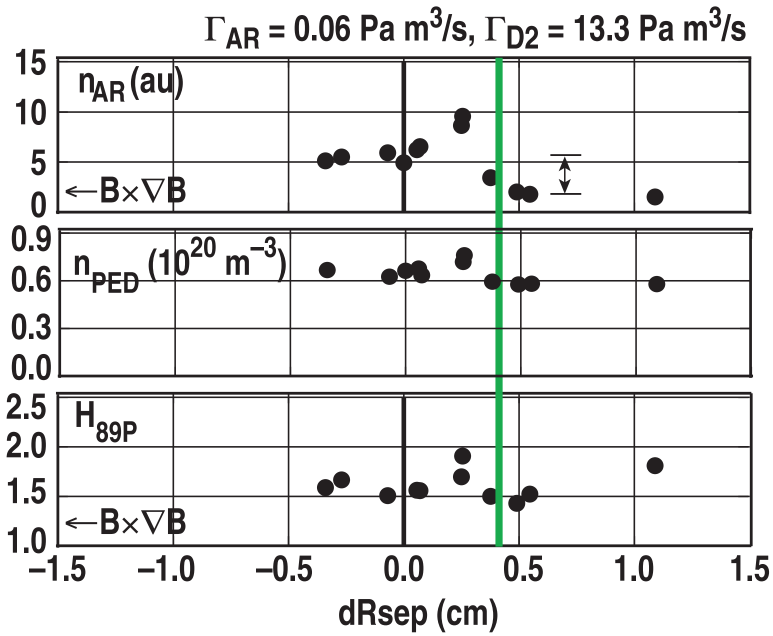


- Balance in radiated power between upper and lower divertor challenging

Significant Reductions in Argon Density in the Main Plasma was Observed Near dRsep = 0.4 cm



- n_{AR} dropped by a factor of ~3× between dRsep = 0 and dRsep = 0.5 cm
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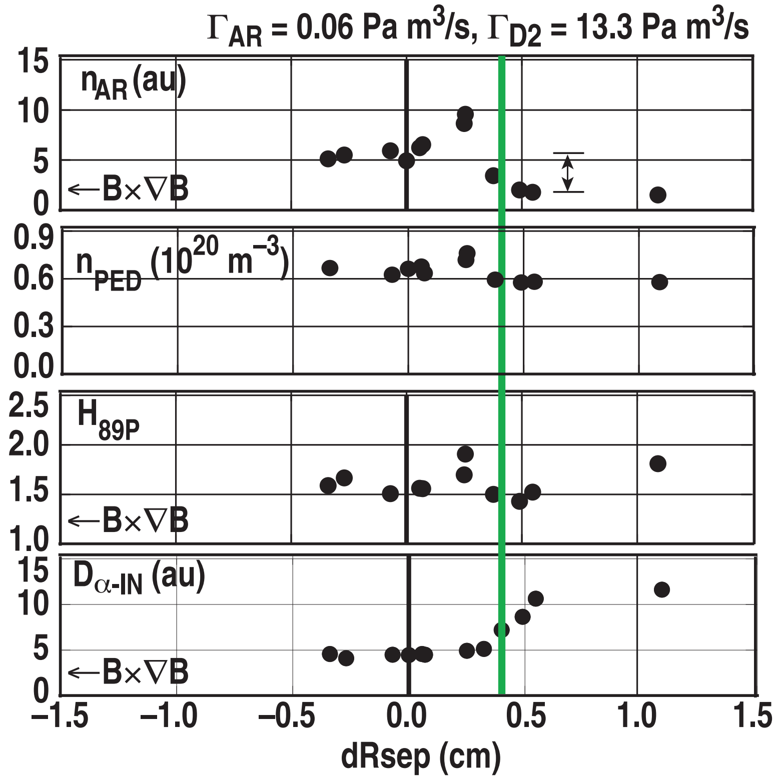

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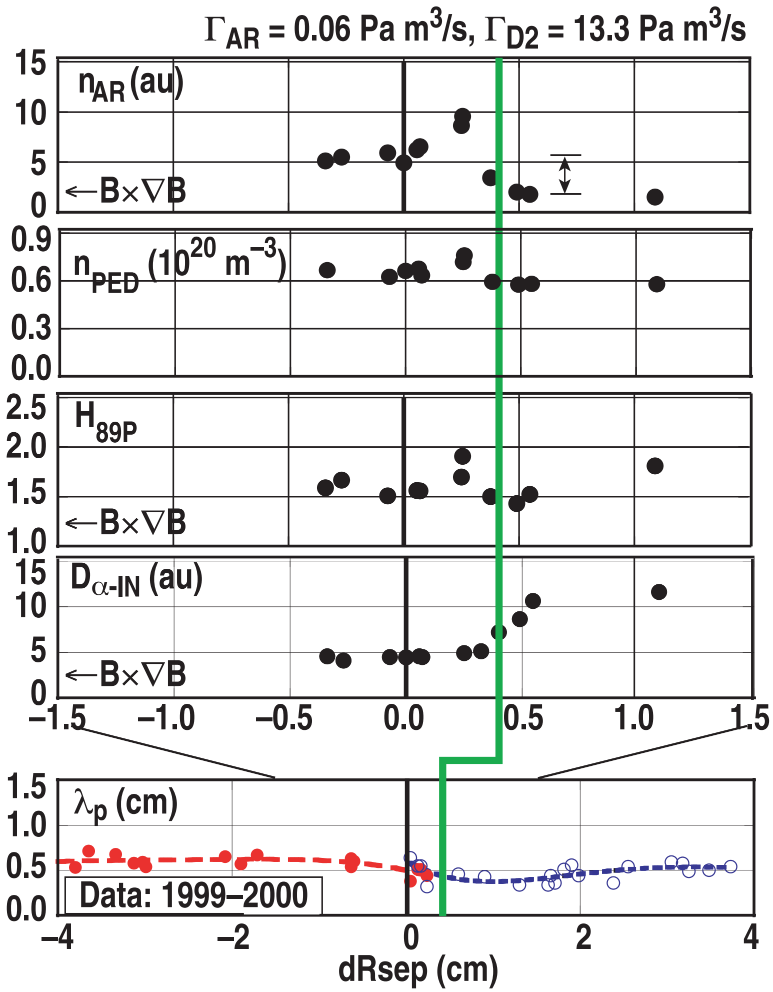

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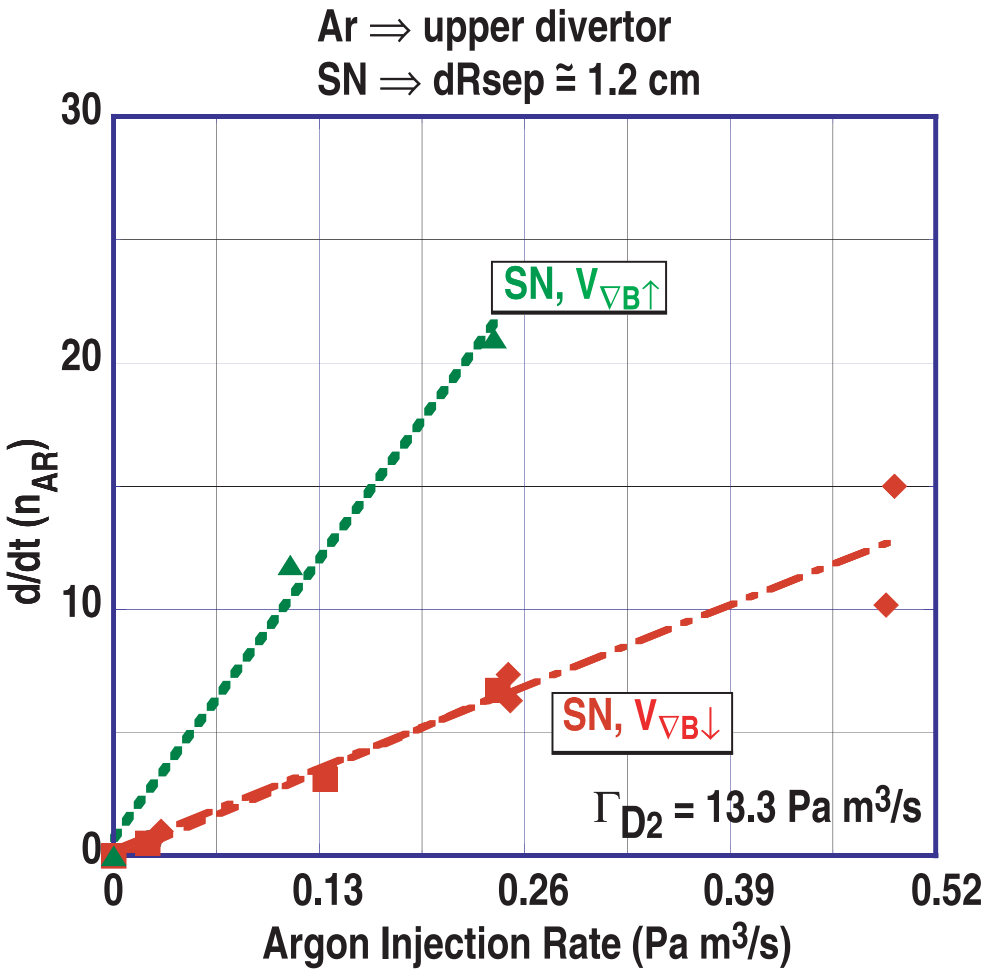
- Transition region near dRsep ≃ 0.4 cm ≃ λ_p

Conclusions

- **Experiments show that effective control of impurity inventory requires unbalanced double-null with ion ∇B drift out of dominant divertor**
  → result independent of physical divertor geometry in DIII–D

- **Breakthrough in fluid modeling with drifts qualitatively explains this result by the ExB drift pattern in the divertor**

The Rate at Which Argon Accumulates in the Core Depends of B×∇B Direction and Magnetic Balance



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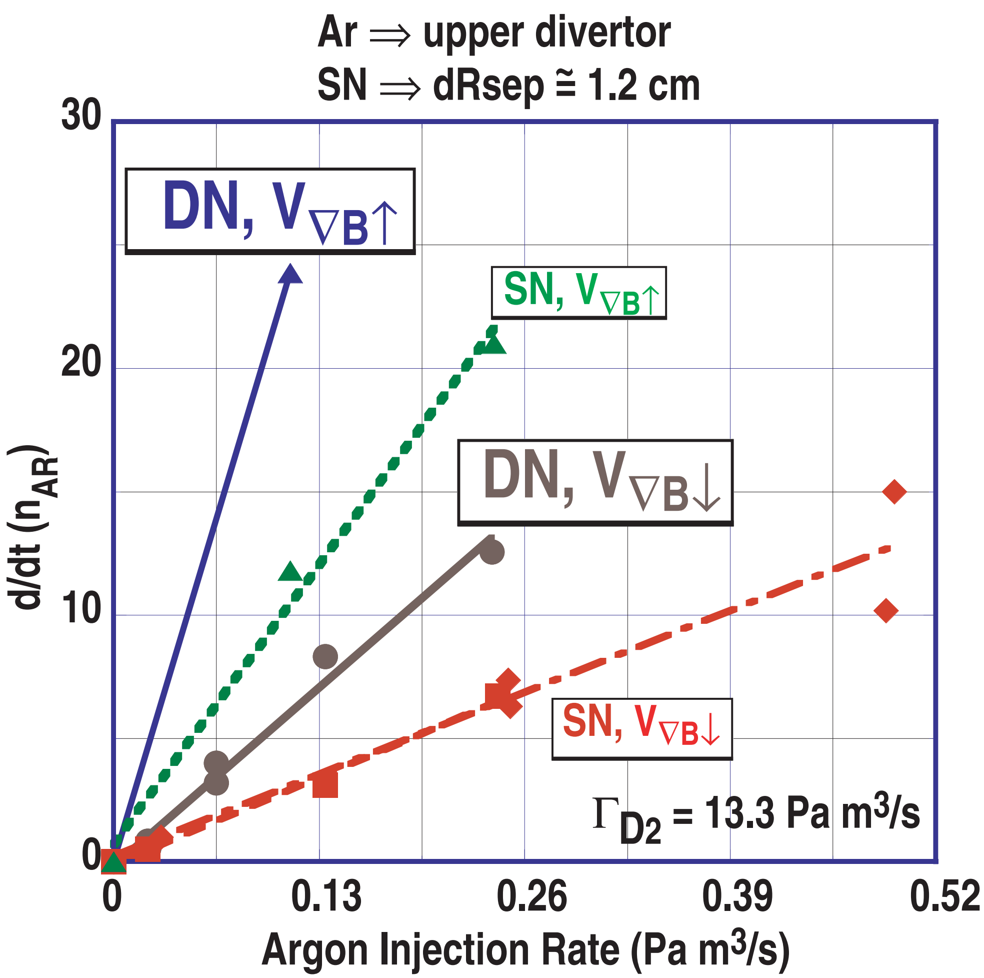

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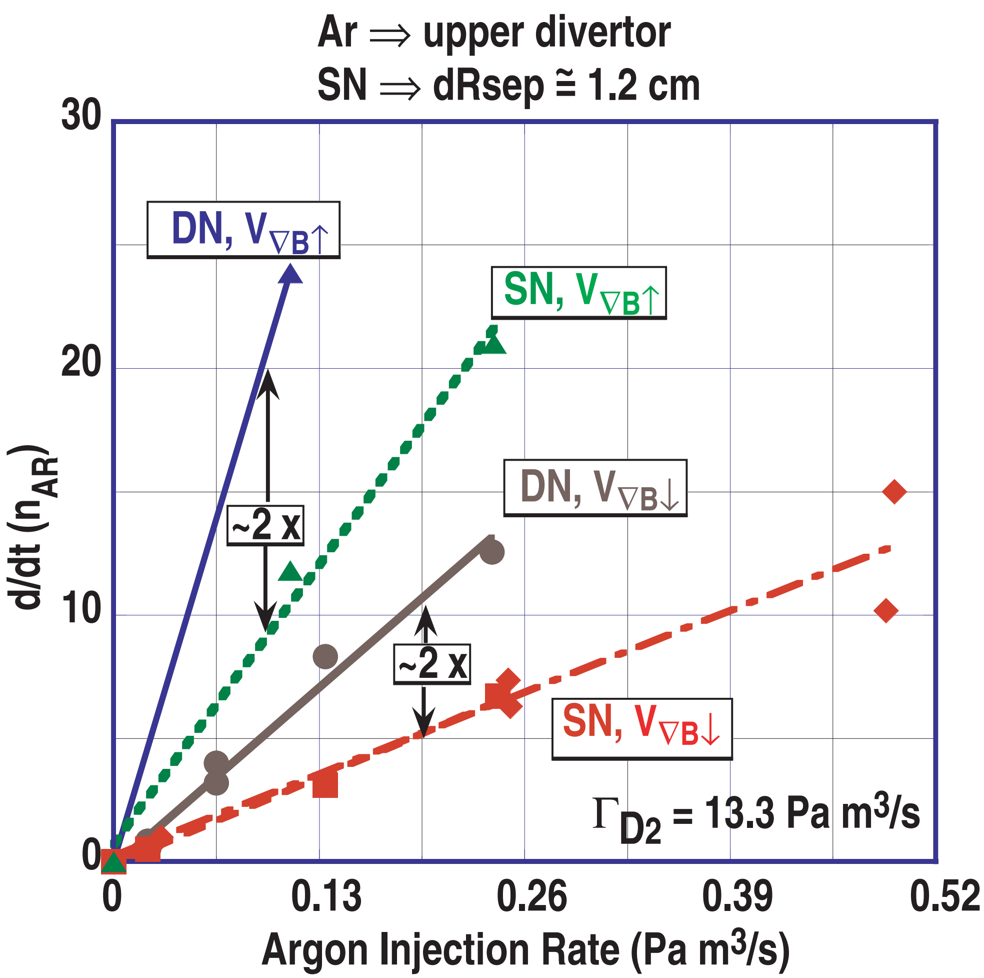

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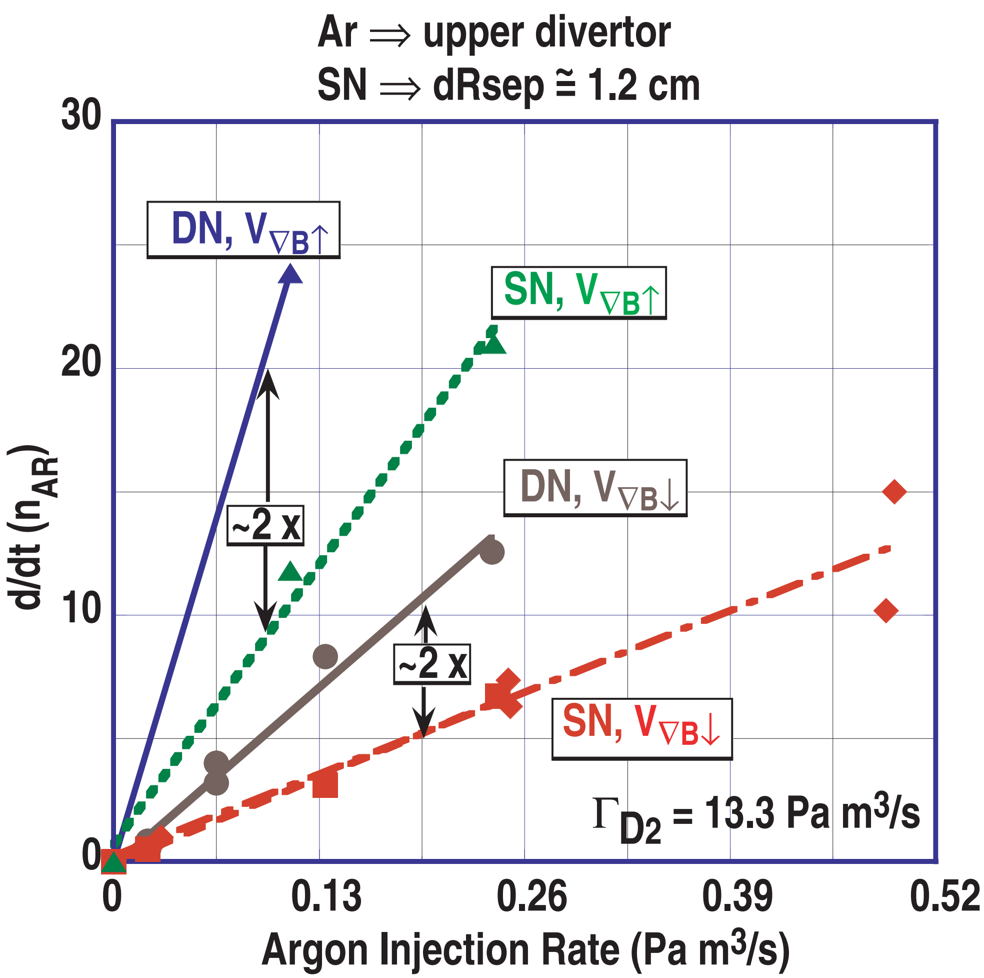

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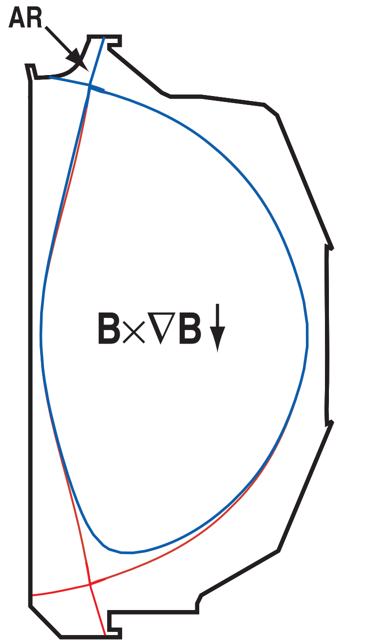
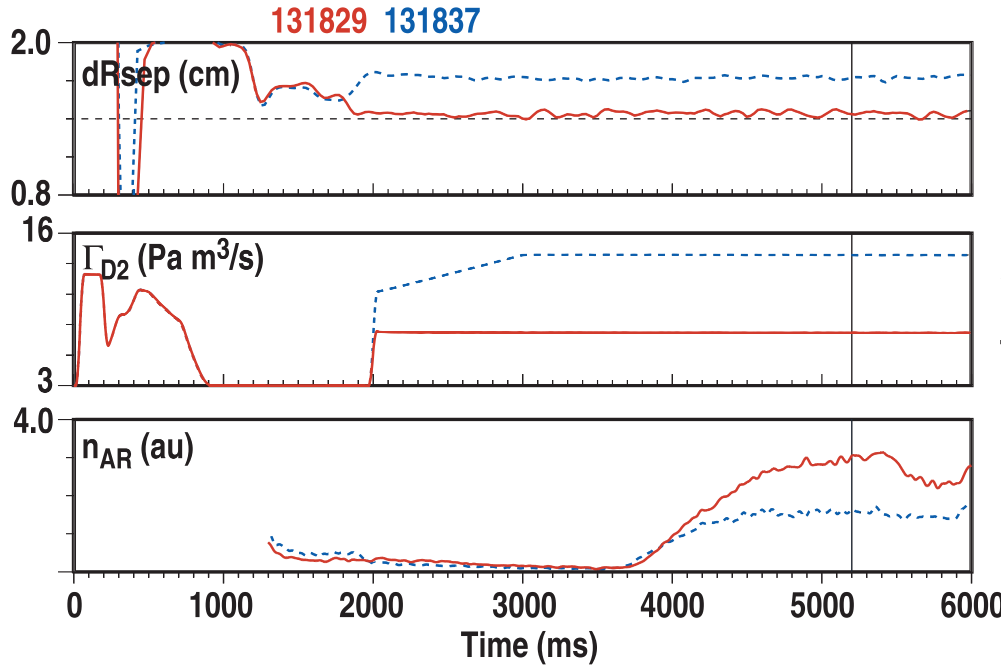
- The same can be said for DNs
- Argon accumulated faster in the core of DNs than in SNs with the same B×∇B direction
- Argon pumping fraction in upper divertor
  - SN, B×∇B↓: 85%
  - DN, B×∇B↓: 75%
  - SN, B×∇B↑: 35%
  - DN, B×∇B↑: 20%

The DN H-Mode Plasma Had About Twice the Argon Accumulation in the Main Plasma as the SN, When n_{PED}, τ_E, and P_{RAD} Were Matched





Γ_{D2} (SN) > Γ_{D2} (DN) for matched plasmas

n_{AR} (DN) ≃ 2 n_{AR} (SN)

$n_{PED} \simeq 0.57\times10^{20} m^{-3}$

$H_{89P} \simeq 2.0$

$P_{RAD} \simeq 2.5$ MW

$\beta_N = 2.0$

$P_{INJ} = 5.8$ MW

$\Gamma_{AR} = 0.06$ Pa m^3/s

dRsep = 0, +1.2 cm

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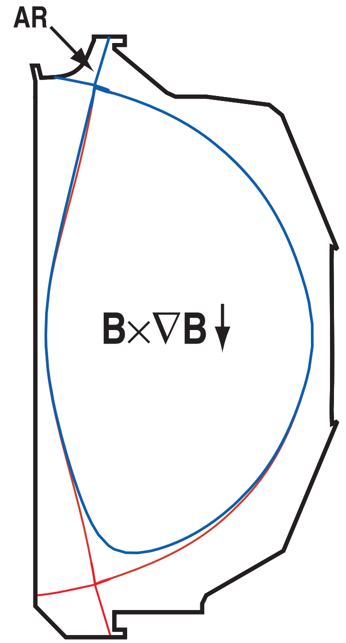

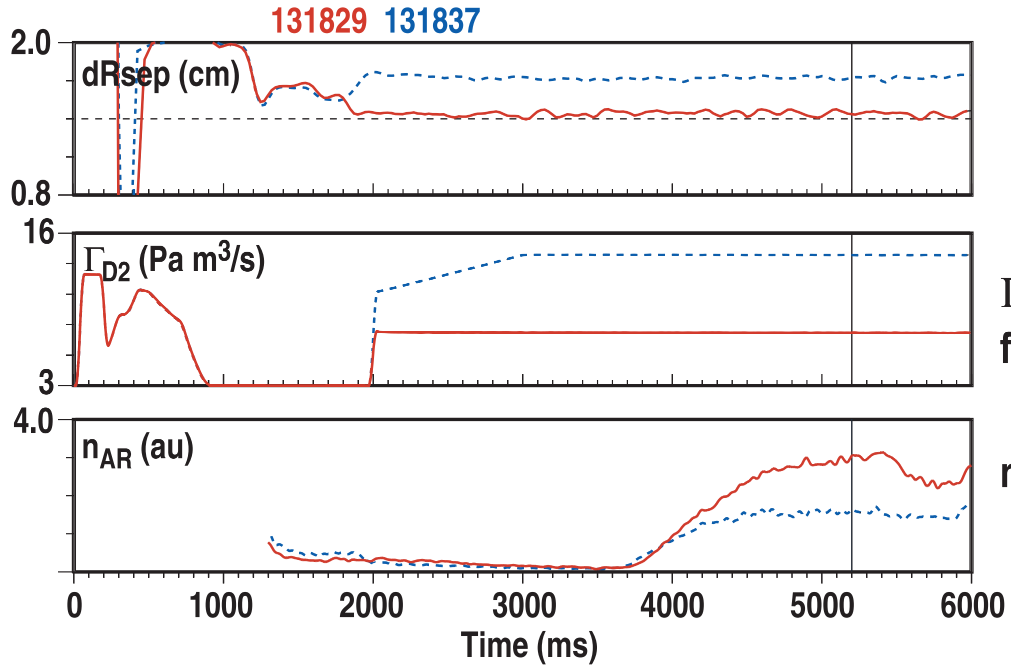

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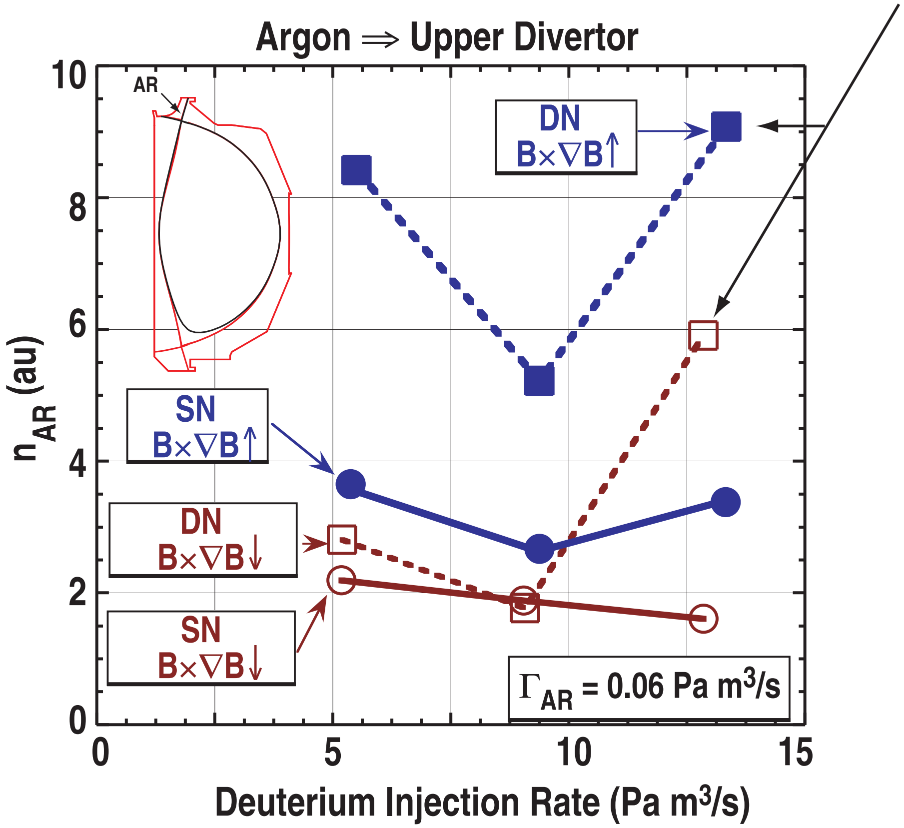
"Advantages" in SN:

- **Greater D-flow on the HFS for "SN"**
- **Narrower SOL on HFS for "DN"**
- **More quiescent on HFS for "DN"**

⇒ advantage: "SN"

Gas Puffing to Inhibit Impurity Build Up Works Best for SNs with B×∇B Away from the X-Point



- **Both DN uses show a pronounced rise at high Γ_{D2}**
  - Virtual detachment of upper inner divertor leg

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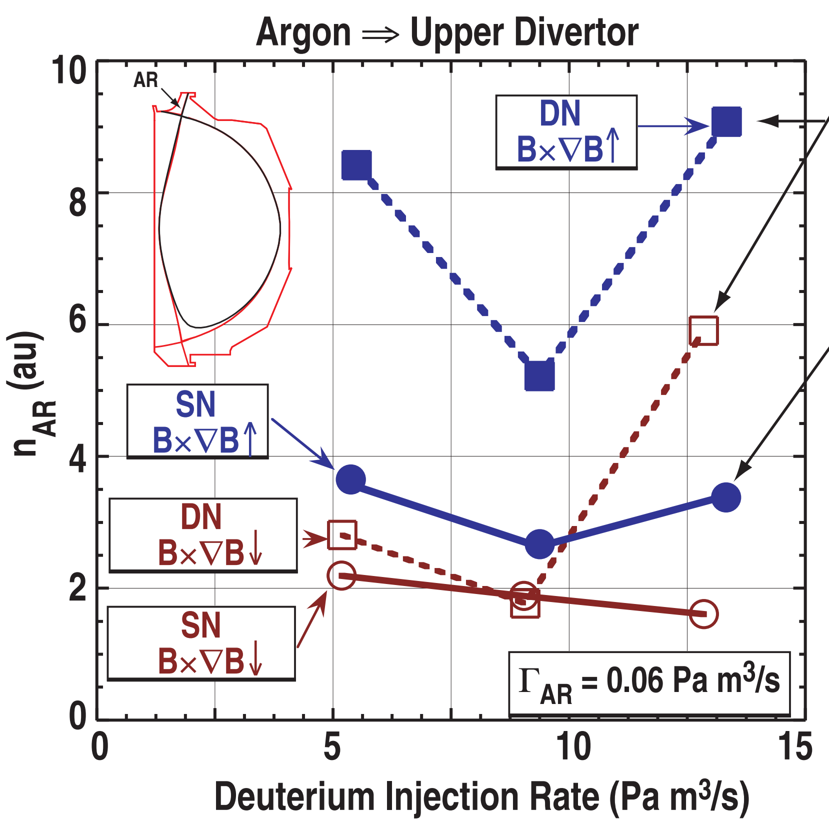

- **Both DN uses show a pronounced rise at high Γ_{D2}**
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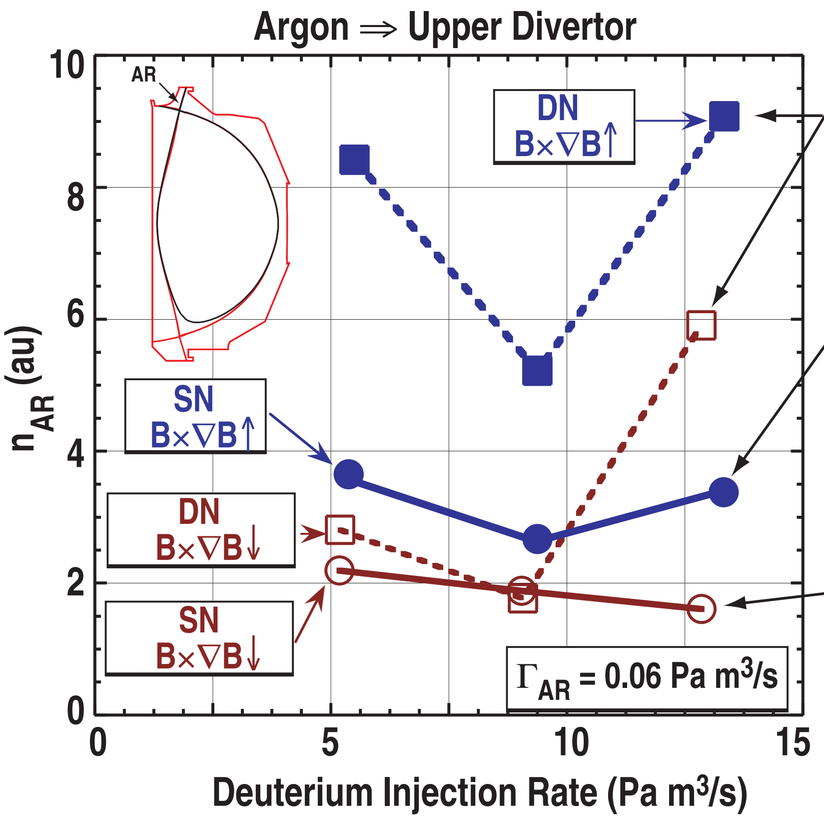

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  - Virtual detachment of upper inner divertor leg
- **SNs with B×∇B toward the divertor shows a less pronounced reversal of n_{AR}**
  - E_r×B drift in the private flux region toward inner target
- **SNs with B×∇B away from divertor appears best suited in keeping argon out of core plasma**
  - E_r×B drift in private flux region toward the outer target