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

by
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for
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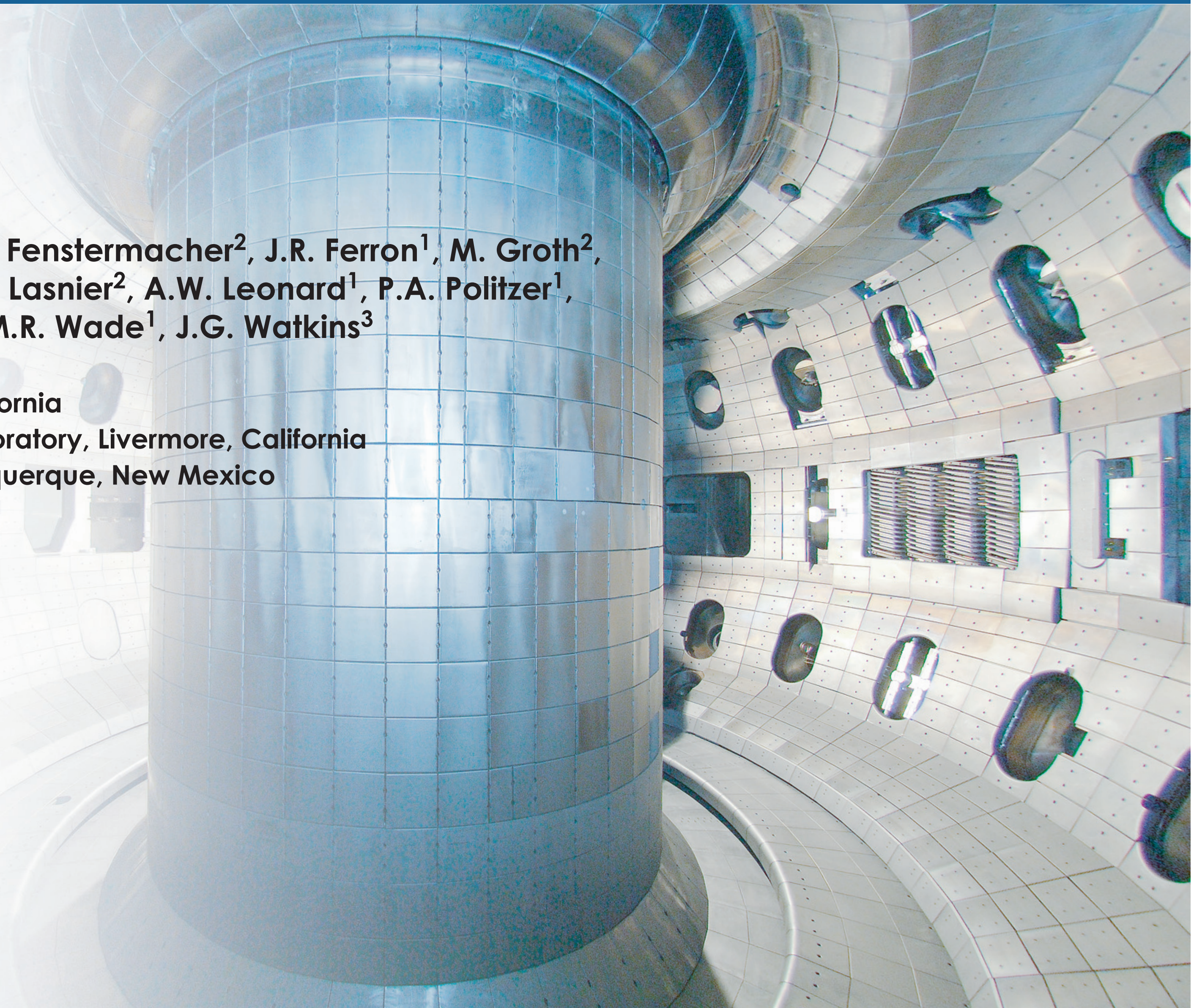

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Section 1

INTRODUCTION

Introduction

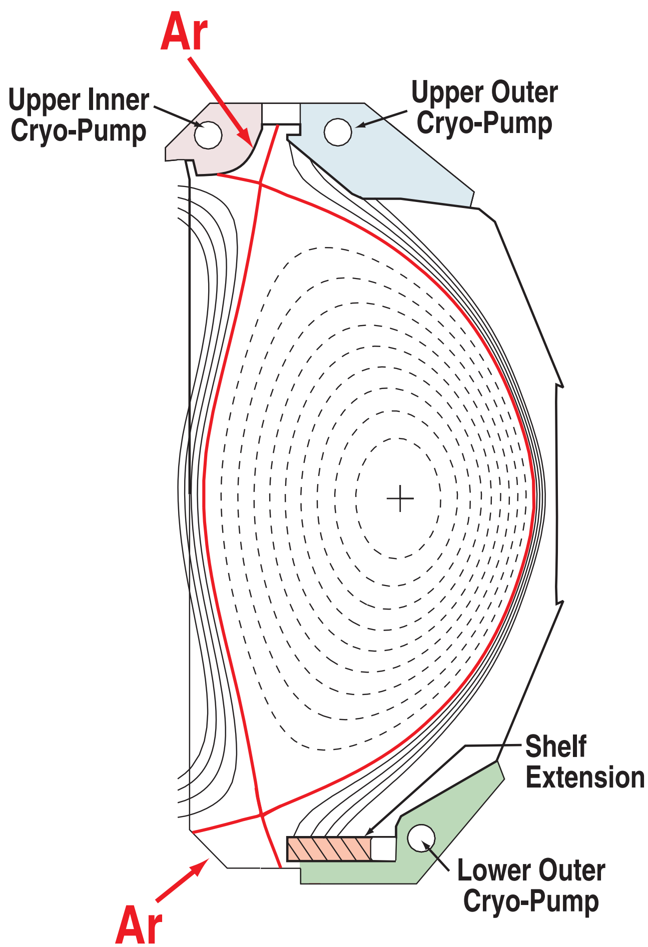
- ***Puff-and-pump* is a promising approach for reducing localized heating on the divertor structures of future highly powered tokamaks, such as ITER**
  - "Seed" impurities, which are injected into the divertor(s) and are impeded from escaping the divertor(s) by an enhanced particle flow into the divertor, can significantly raise the radiated power upstream of the divertor targets
  - Provides a more uniform dispersal of the incoming power
- **The *puff-and-pump* approach was successfully applied in DIII-D for one set of operating conditions**
- **The *puff-and-pump* approach is applied over a much wider range of operating conditions**
  - Ion Bx∇B drift direction
  - Divertor "closure"
  - Magnetic balance – Double Null (DN)

Experimental Operating Conditions

- ELMing H-mode plasmas are used in this study
  - H_{89P} = 1.5–2.1 [H_{89} (y,2) ≃ 0.9–1.2]
  - $\bar{n}_e/n_G$ ≃ 0.4–3.7
  - q_{95} ≃ 4.0–4.5
  - P_{IN} = 5–8 MW
  - |dRsep| ≲ 1.5 cm

- There are two main impurity species in the core plasma
  - CARBON (intrinsic)
    - Dominant intrinsic impurity in DIII–D discharges
    - Generated by erosion of the graphite armor
  - ARGON (injected)
    - Radiates effectively under H-mode plasma operating conditions
    - Relatively short λ_{MFP}

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



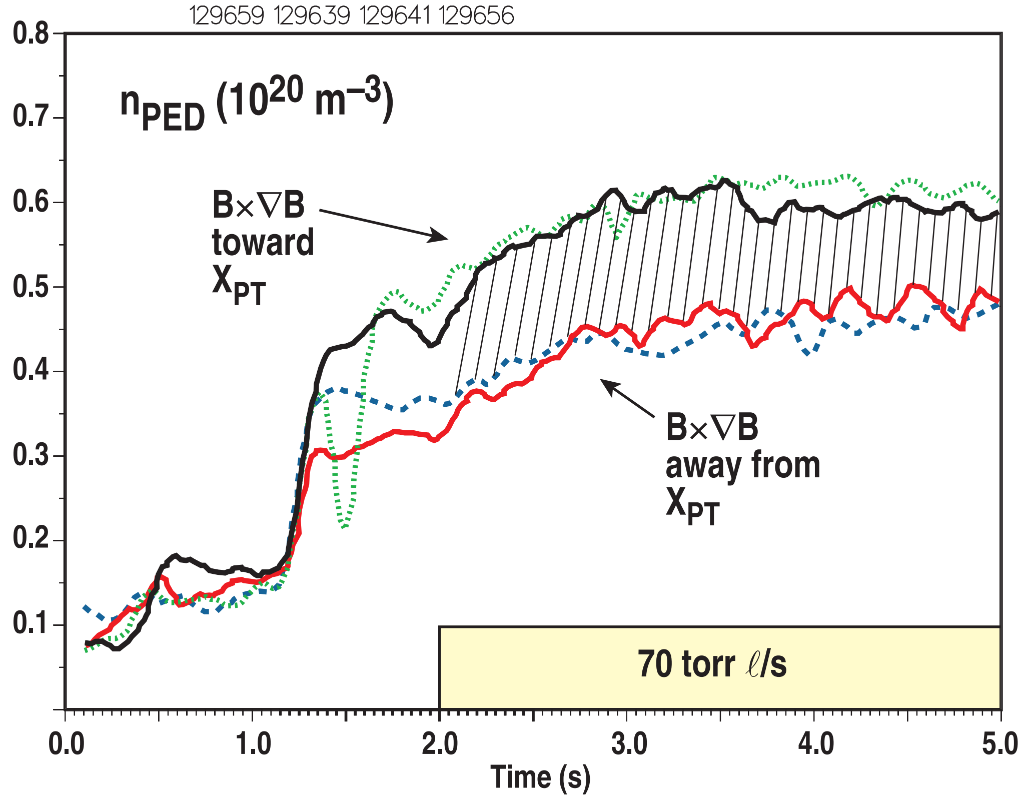
- **Experimental arrangement**
  - The upper divertor is more "closed" than the lower divertor
  - Three cryopumps are independently controlled
  - The seed impurity (argon) can be injected into the private flux regions of either divertor
  - Argon pressure measurements are made in the upper outer plenum
  - $|dRsep| \lesssim 1.5$ cm for all shots in this study

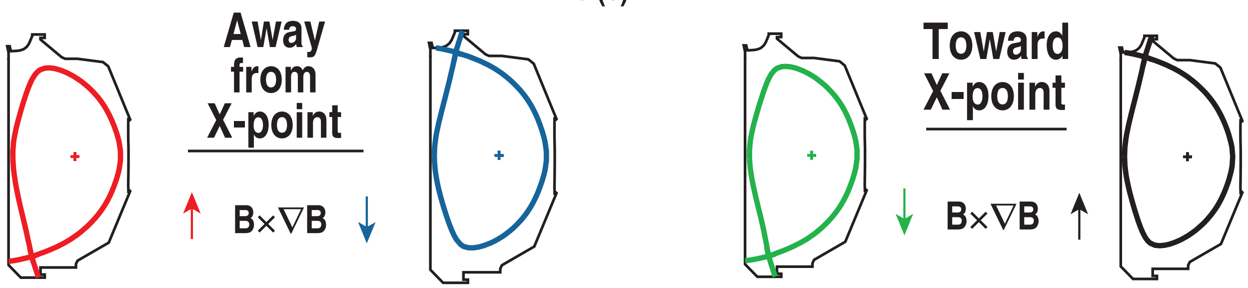
    * "SN" → $|dRsep| \gtrsim 1$ cm
    * "DN" → $dRsep = 0$

Section 2

The ion B×∇B drift direction is much more important to D_2 fueling than differences in DIII–D divertor geometry

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

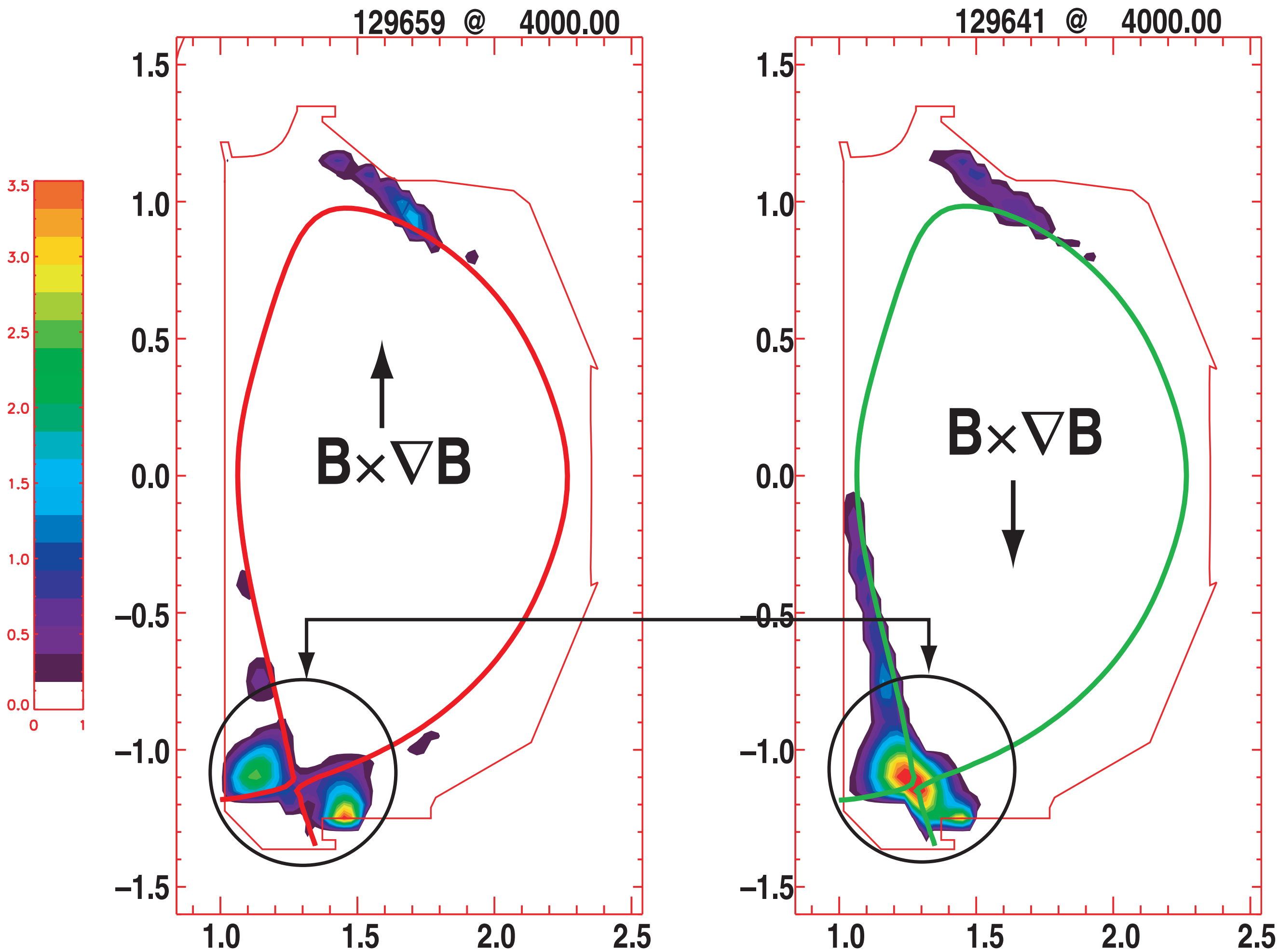




- To match exhaust characteristics, only the outer pump in the dominant divertor is activated
- This result is consistent with previous work highlighting the importance of particle drifts in plasma fueling*

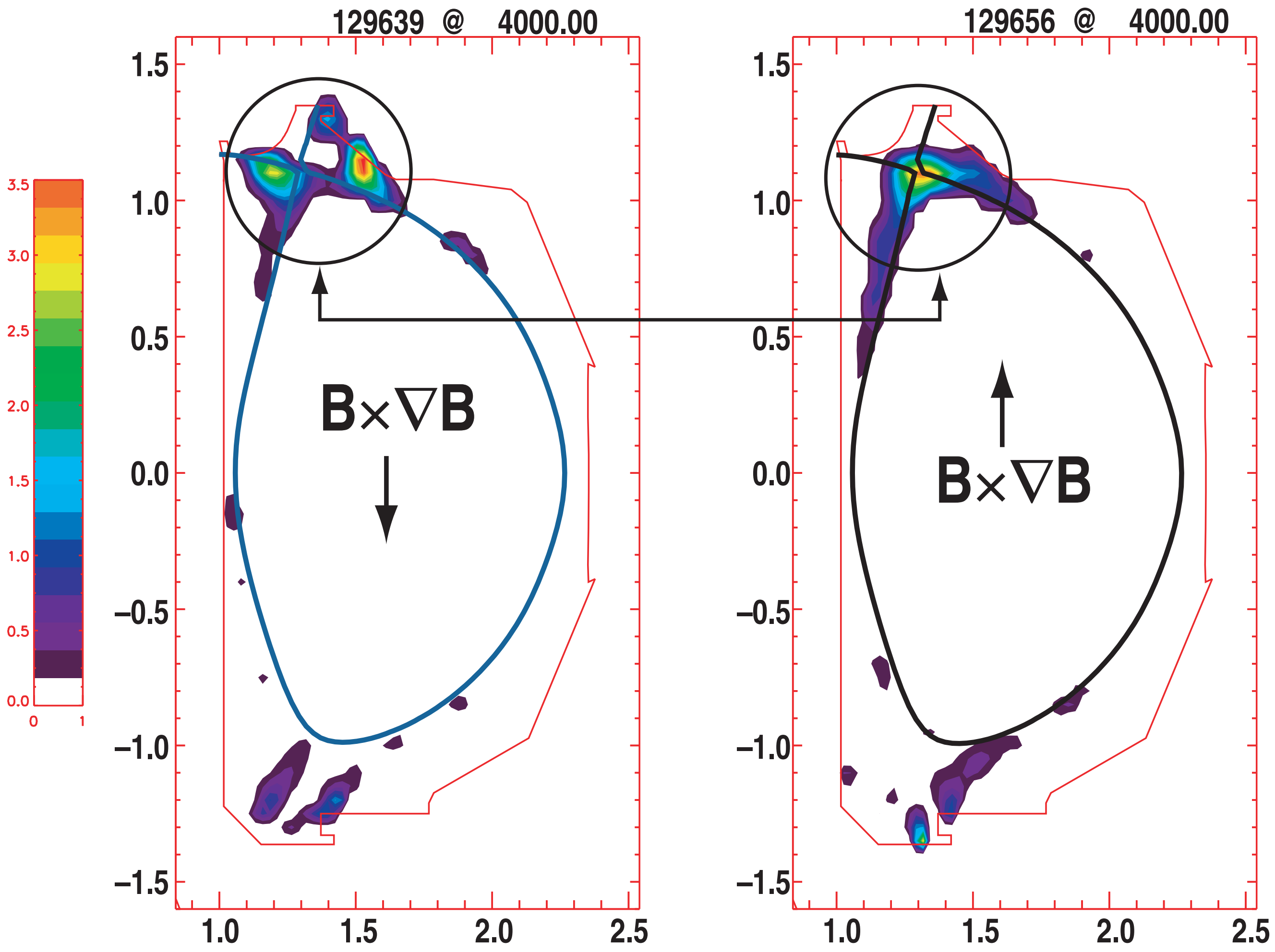
*M. Groth, *et al.*, J. Nucl. Matter **290-293** (2005) 452

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



Same divertor but different ion B×∇B drift directions

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



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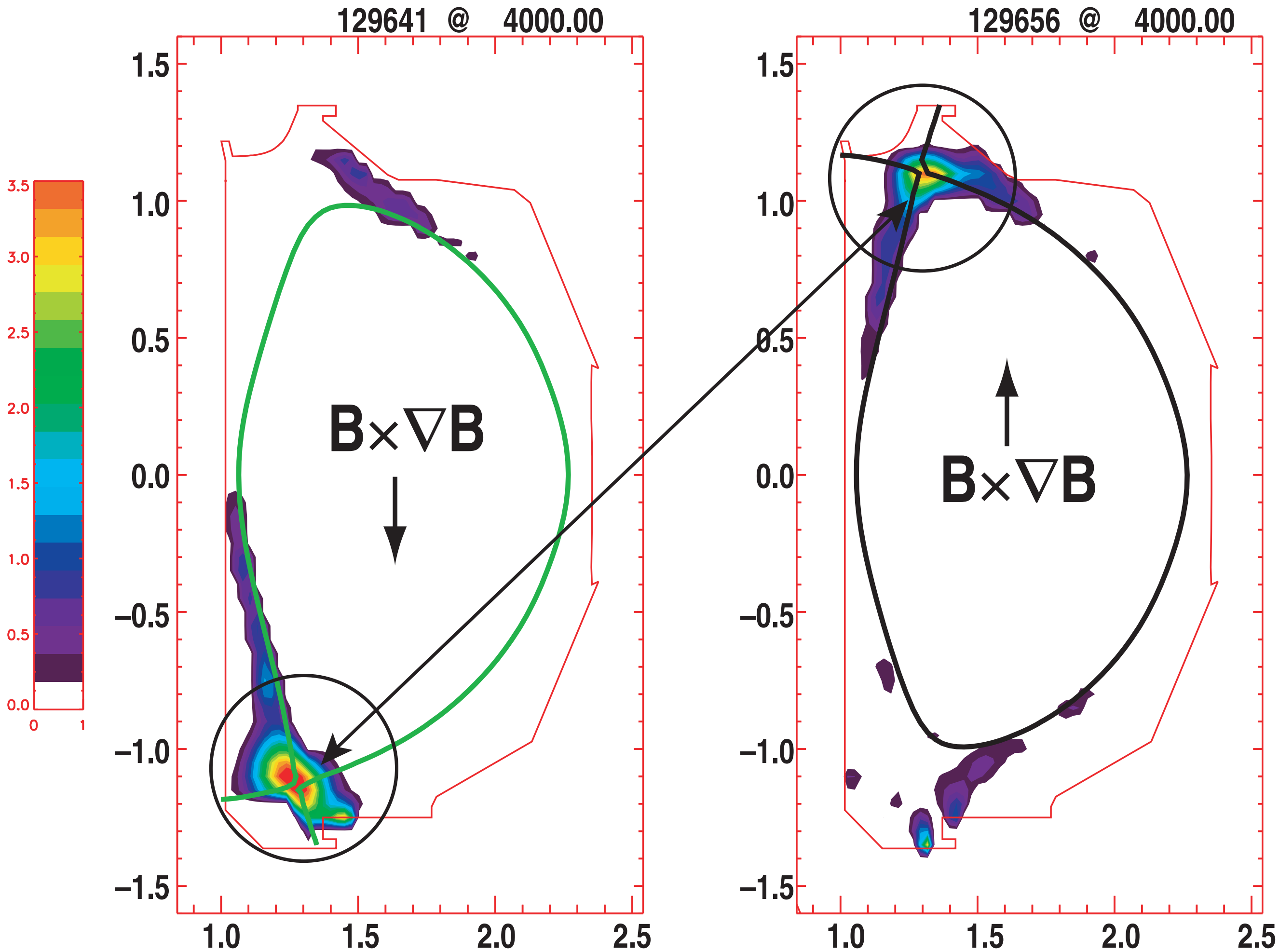
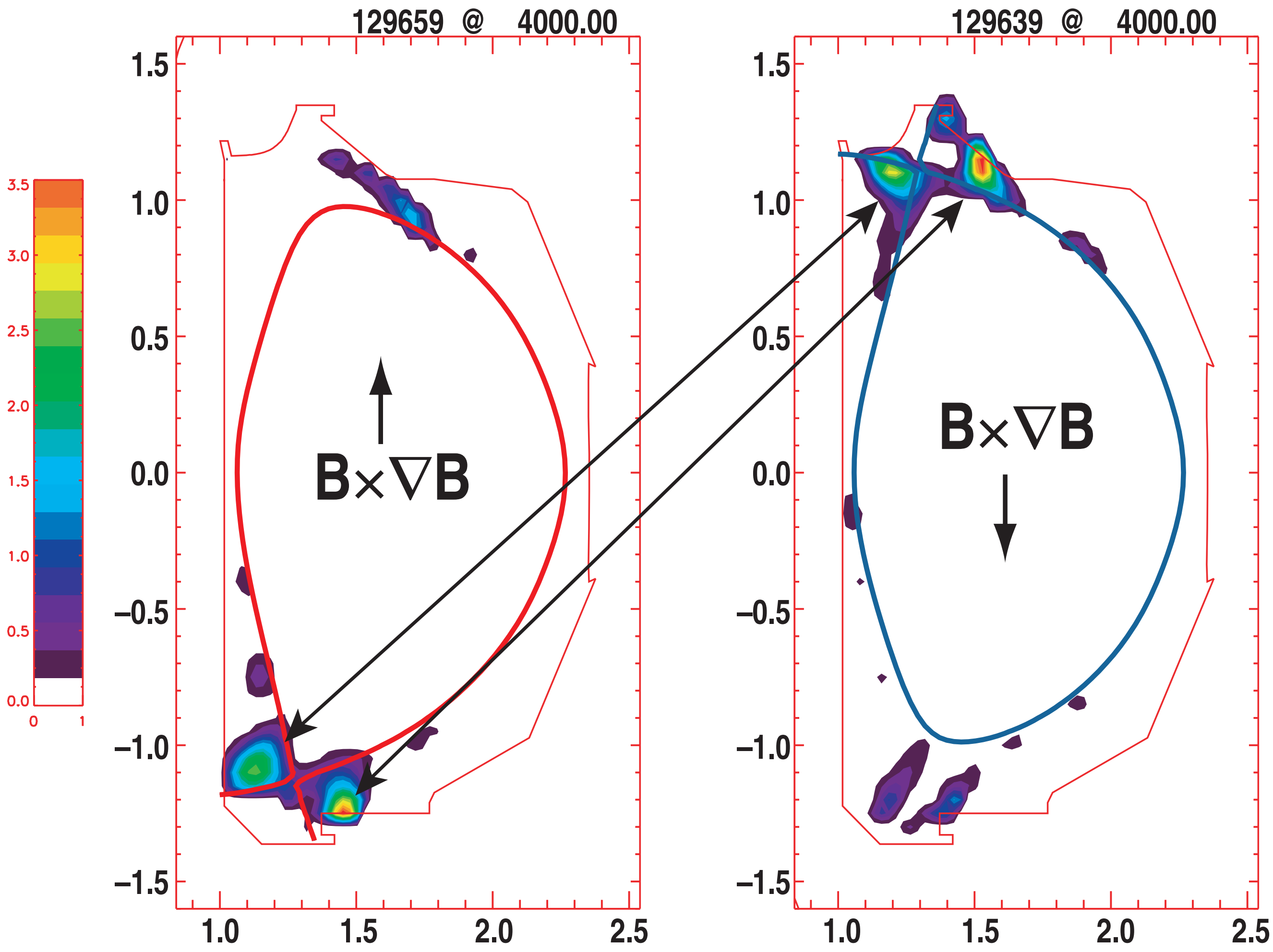


Different divertor but the ion B×∇B drift direction is toward the X-point

⇒ Similar radiated power in divertor region

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



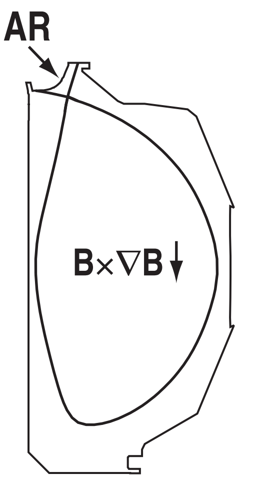
Different divertor but the ion B×∇B drift direction is away from the X-point

⇒ Similar radiated power in divertor region

Section 3

The best results were obtained when the ion $B \times \nabla B$ drift was directed away from the dominant divertor

Best Case: An Increased D2 Injection Rate Produced A Lower Core Argon Density, and Good Exhaust Enrichment is Maintained at Perturbative Radiating Divertor Conditions



dRsep = +1.2 cm

I_P = 1.2 MA

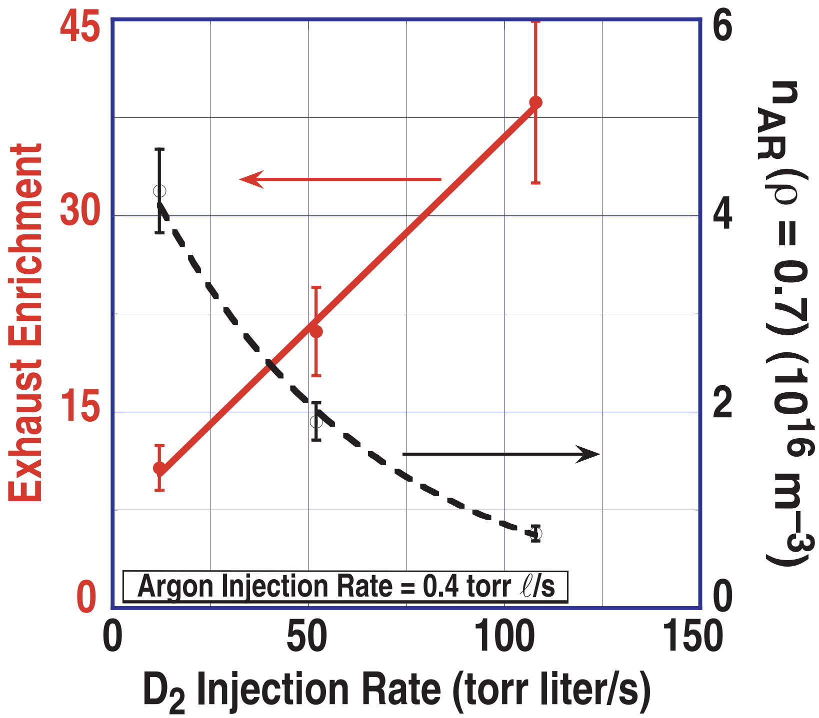
B_T = 1.8 T

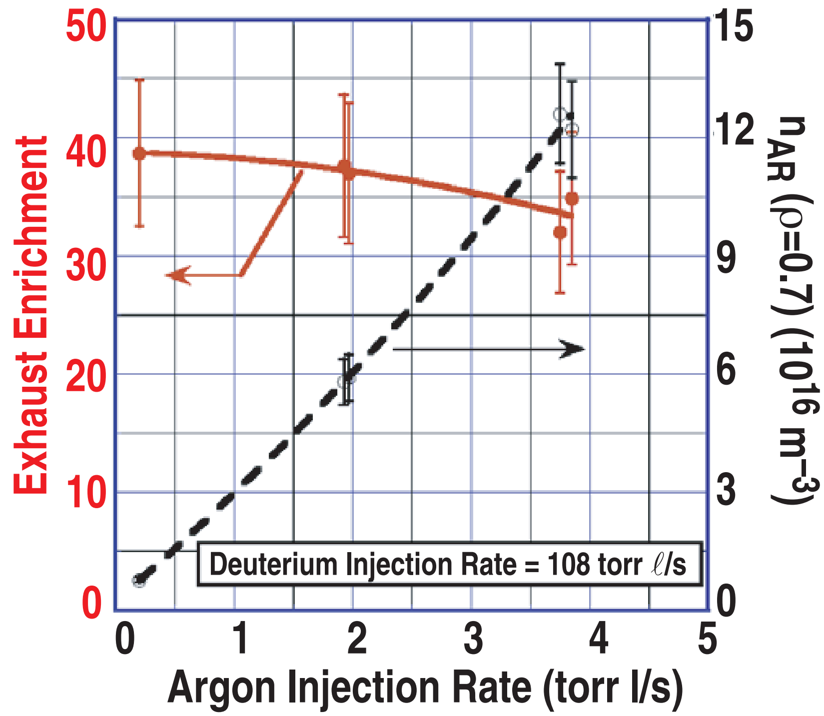
P_{IN} = 6–7 MW

$\beta_N \simeq 2.4$

$H_{89P} \simeq 2$

$\frac{\bar{n}_e}{n_{GR}} \leq 0.65$





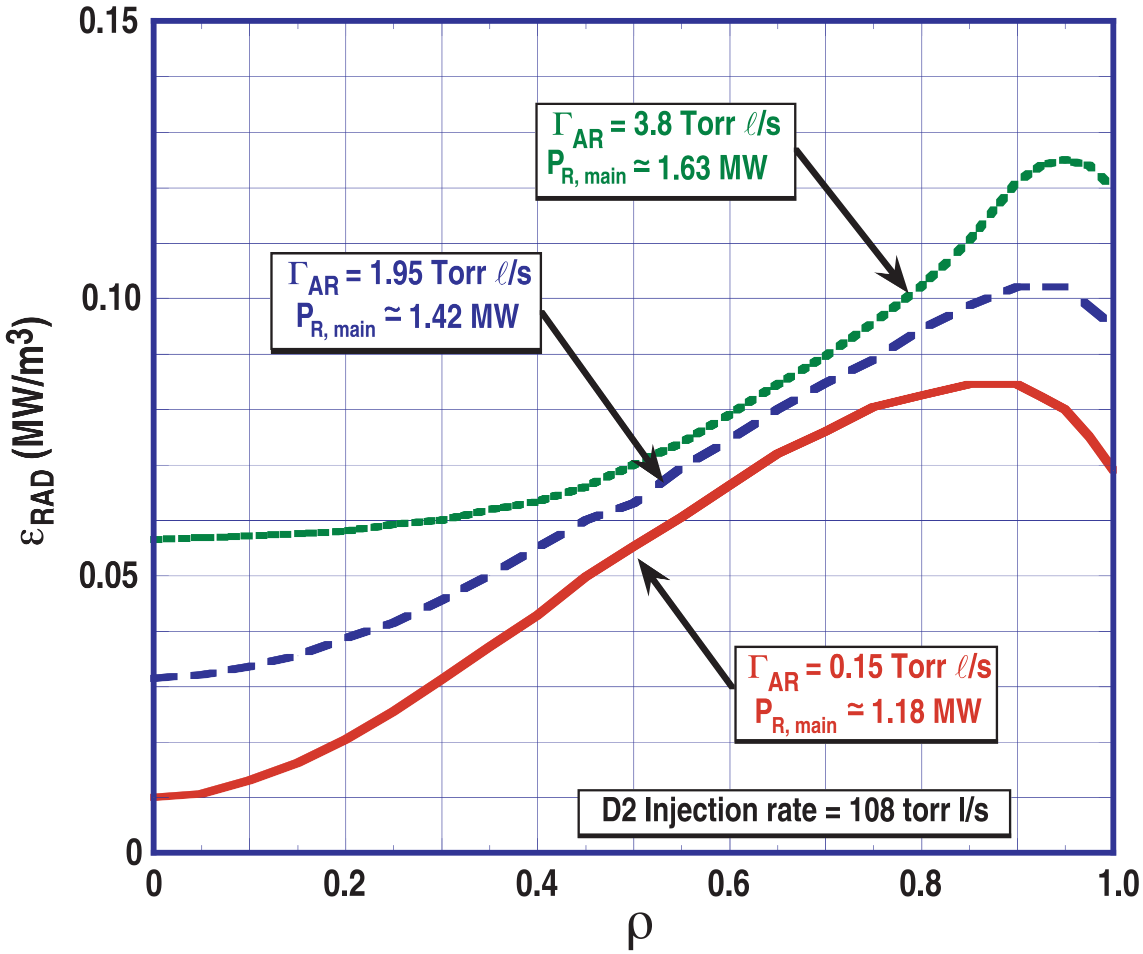
$$\text{Exhaust Enrichment} \equiv \frac{f_{AR,exh}}{f_{AR,core}}$$

At the highest argon injection rate:

– Heat flux reduced ~2.5x

– Both divertor legs attached

Increase in Radiated Power in the Main Plasma is Due Almost Entirely to the Increase in Argon



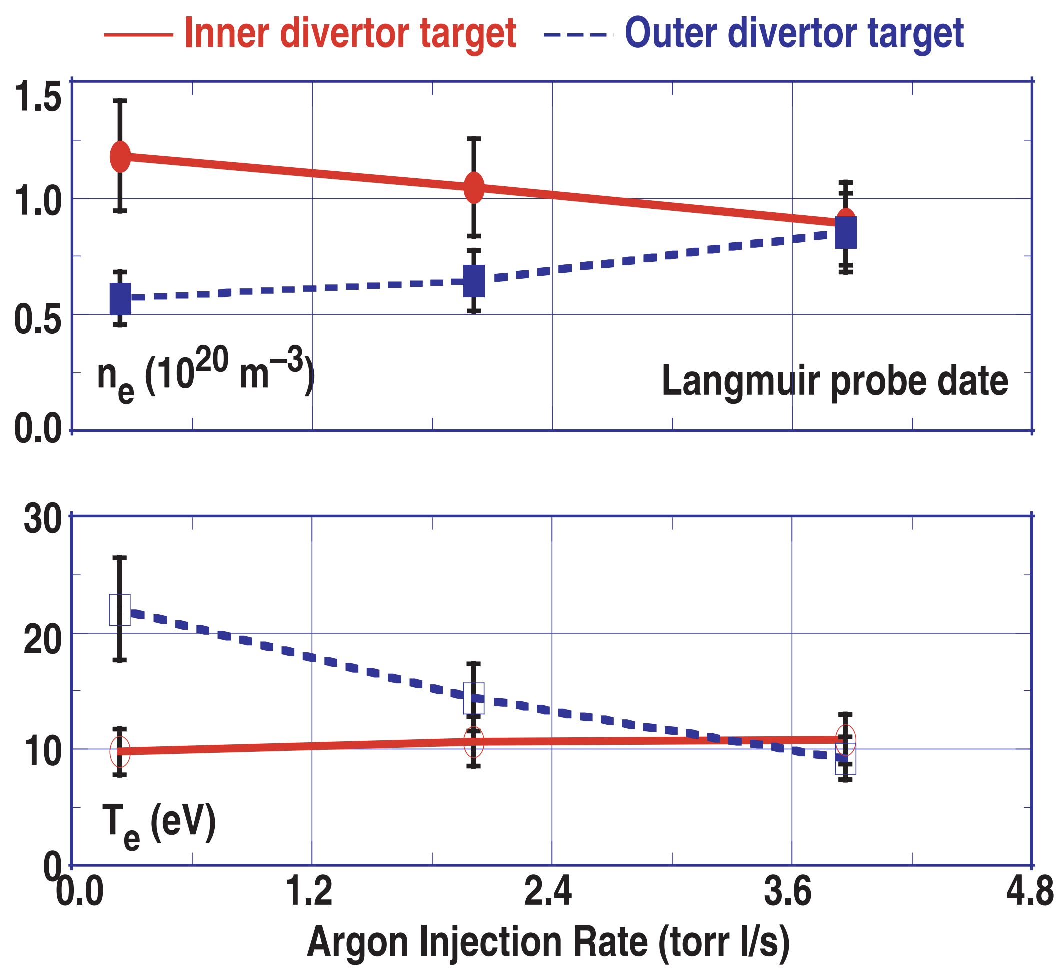
$\Gamma_{AR} \simeq$ 0.15 torr ℓ/s case

- >95% of the radiated power in the core was from carbon
- $\bar{n}_e$ – 6.1×10^{19} m^{-3}

$\Gamma_{AR} \simeq$ 3.8 torr ℓ/s case

- 25-30% of the radiated power in the core was from argon and the profile was still hollow
- $\bar{n}_e$ – 6.7×10^{19} m^{-3}

Inner Divertor Shows No Sign of Detaching with Increasing Γ_{AR}, but the Outer Divertor Cools Significantly

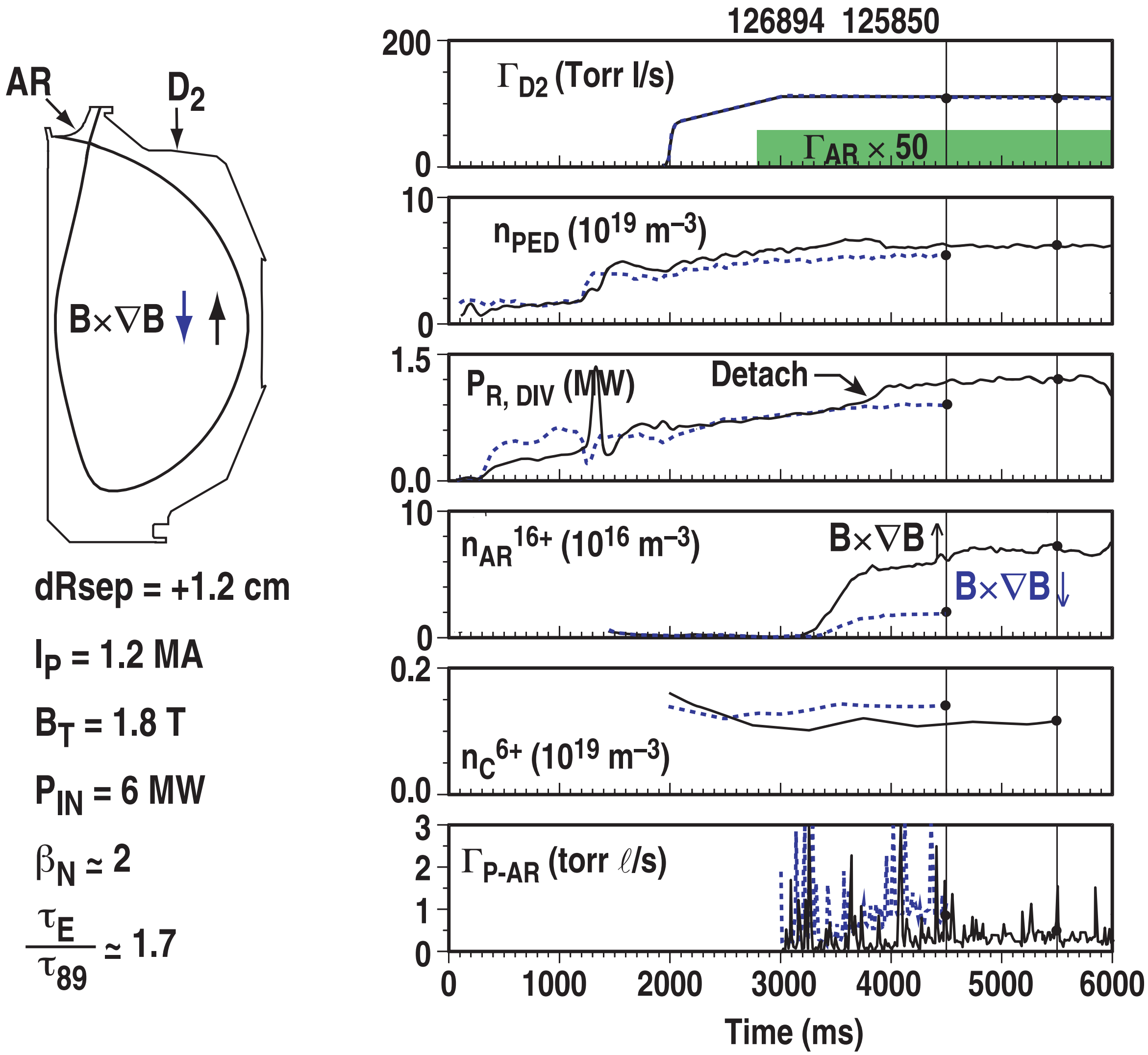


- n_e at the inner divertor target decreased ≈ 24%
- n_e at the outer divertor target increased ≈ 17%
- T_e at the inner divertor target was insensitive to the argon presence
- T_e at the outer divertor target decreased more than 2x

Section 4

Particle drifts in the SOL and divertor play a major role in plasma behavior for SN H-mode plasmas

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**
- **Higher n_{PED} for B×∇B toward the X-point**
- **Divertor radiated power**
  - Partial detachment of inner divertor leg for B×∇B↑
  - B×∇B↓ attached at all times
- **~3× argon in core for B×∇B↑**
- **Little change in core carbon during argon puff**
- **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↑**

⇒ **Consistent with 1998 experiment**

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

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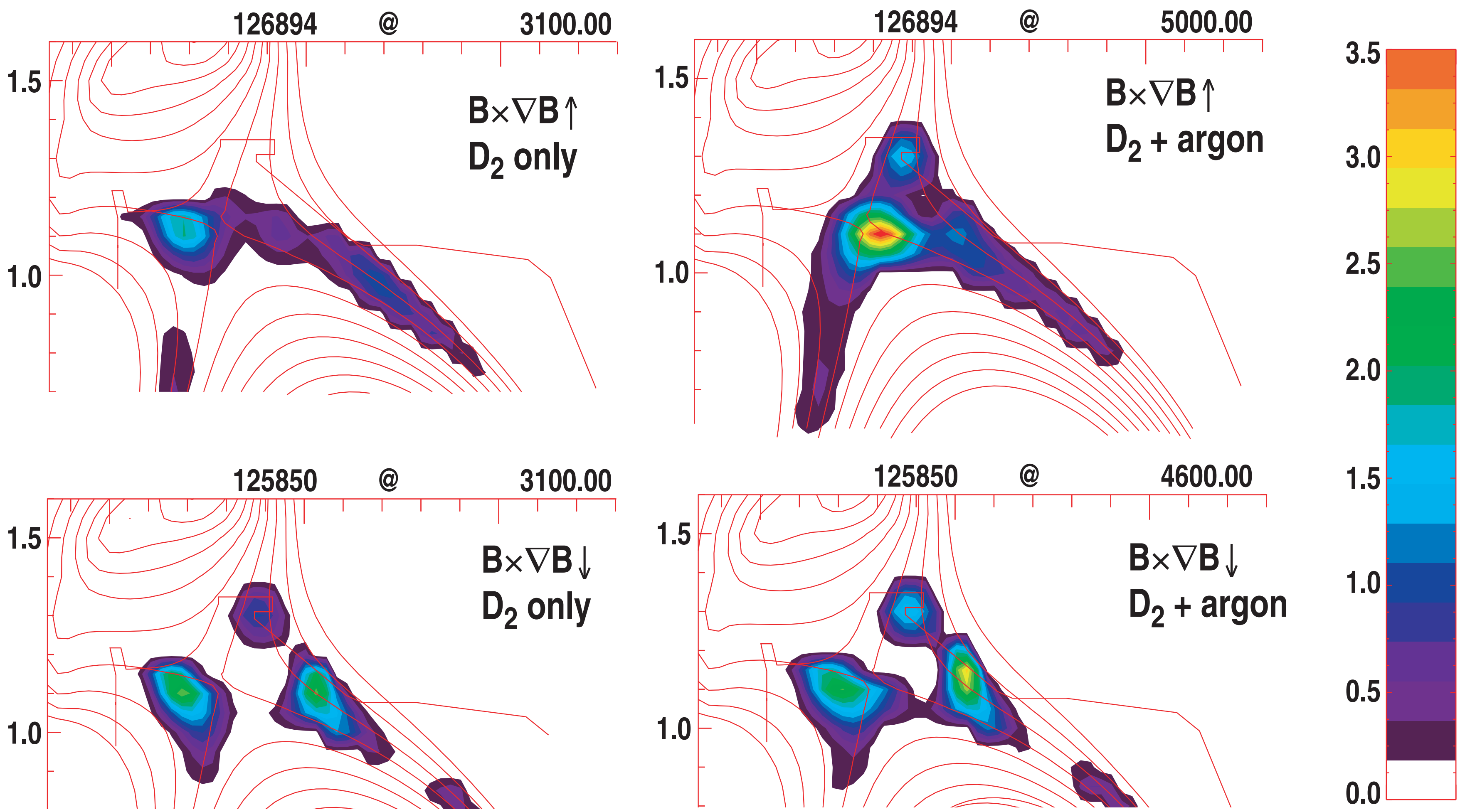
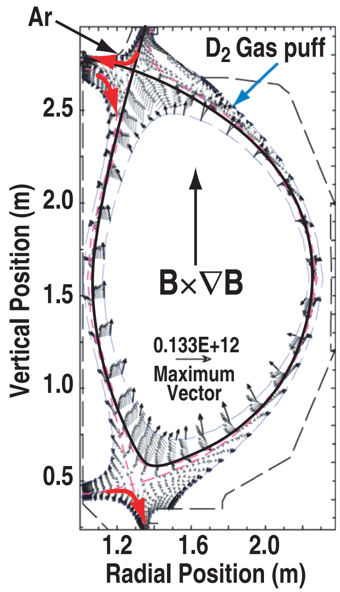
Radiated Power Disribution in Divertor of the SN Changed Significantly when B×∇B was Reversed

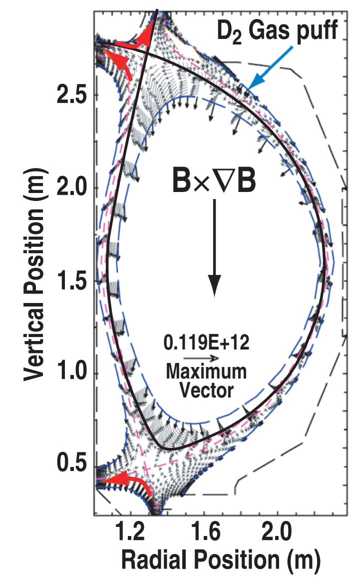


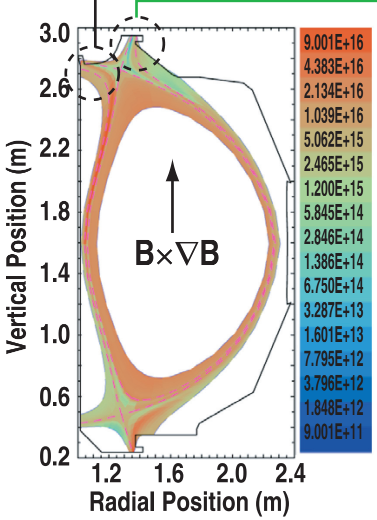
UEDGE Modeling is in Qualitative Agreement with Experiment

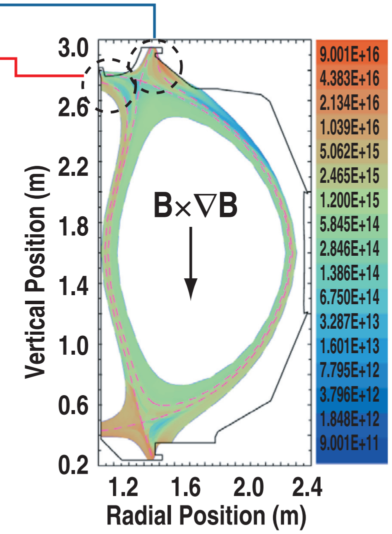


- **$E_r \times B$ in private flux region of upper divertor**
  - Rapid detachment of inner leg for B×∇B↑ (seen in exp.)
  - No detachment of outer leg
  - Argon exhaust rate by upper outer pump ~2.5 greater for B×∇B↓ (consistent with exp.)
  - Harder to detach inner leg, even for a highly perturbating argon injection rate

- **20x build up of argon in the mantle (~3 x in experiment)**

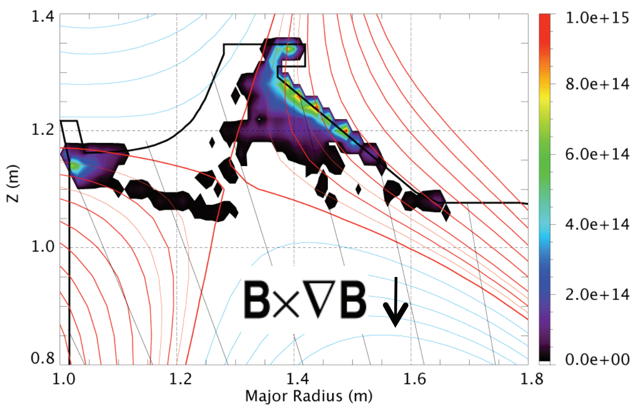


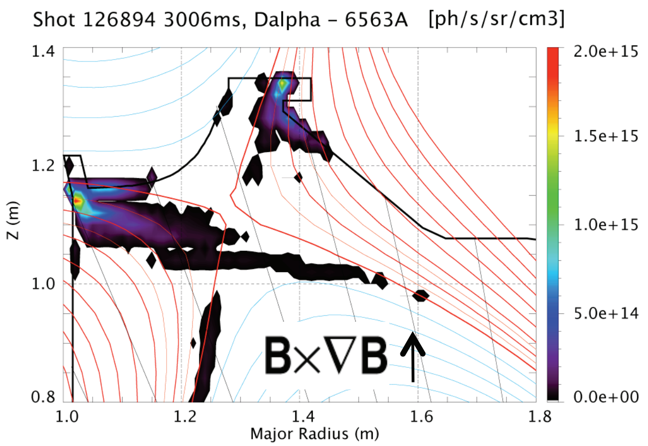




UEDGE Modeling with Particle Drifts is Qualitatively Consistent with the Observed D_α Distribution

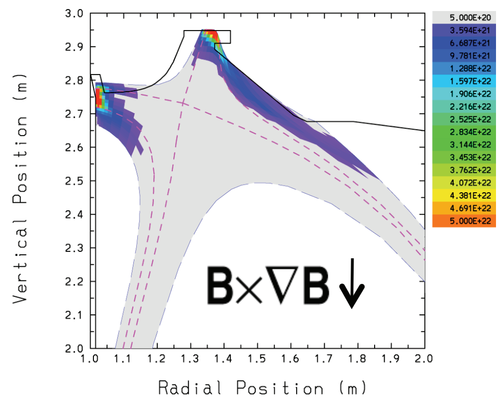
D_α

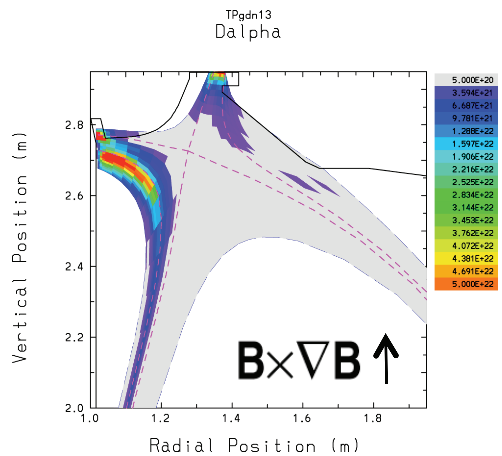




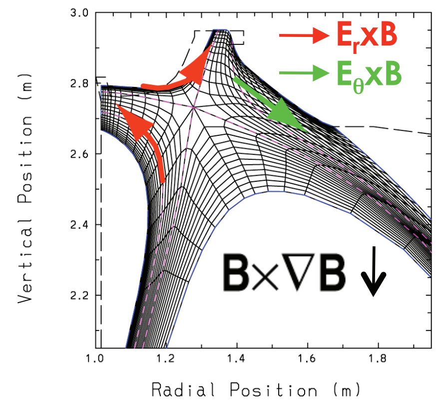
EXPERIMENT

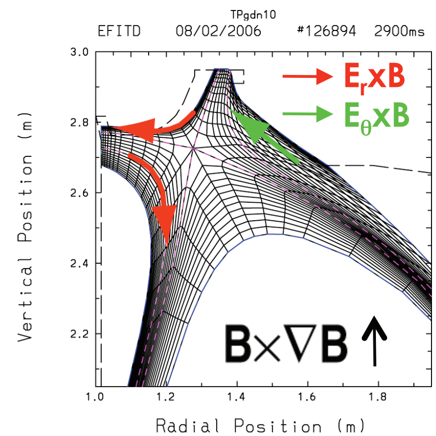
D_α





Plasma Flows





UEDGE (2-D Fluid Code) → **Finite dRsep near DN** / **Full drifts w/H-mode**

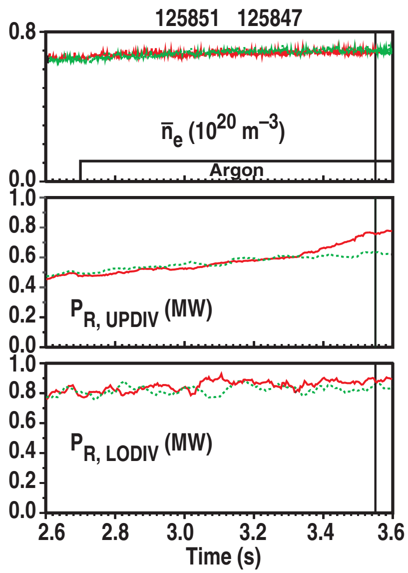
Discussion of Section 4

- **UEDGE transport analysis has highlighted the importance of particle drifts in producing the observed behavior in recycling and seed impurity behavior. The $E_r \times B$ ($\propto \nabla_r T_e$) drift is largely responsible for plasma flow across the PFR**
  - Toward the inner strike point for ion B×∇B drift case toward the X-point
    - → Much of the injected argon is swept toward the inner divertor target
    - → Increases local radiated power and possible detachment
  - Toward the outer strike point for ion B×∇B drift case away from the X-point
    - → Much of the injected argon is swept toward the outer divertor target
    - → Stronger argon exhaust rate by the outer divertor cryopump
    - → The inner target relatively insensitive to Γ_{AR}
- **Less pumping of argon by the upper outer divertor cryopump implies that unpumped argon leaks out of the divertor at a higher rate for the ion B×∇B drift case toward the X-point and serves as a source of argon fueling for the main plasma**
  - $E_r \times B$ drift toward the lower divertor in the high field side SOL also facilitates escape of argon from the upper divertor for cases with ion B×∇B drift toward the X-point

Section 5

Particle drifts in the SOL and divertors also play a major role in plasma behavior for DN H-mode plasmas

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



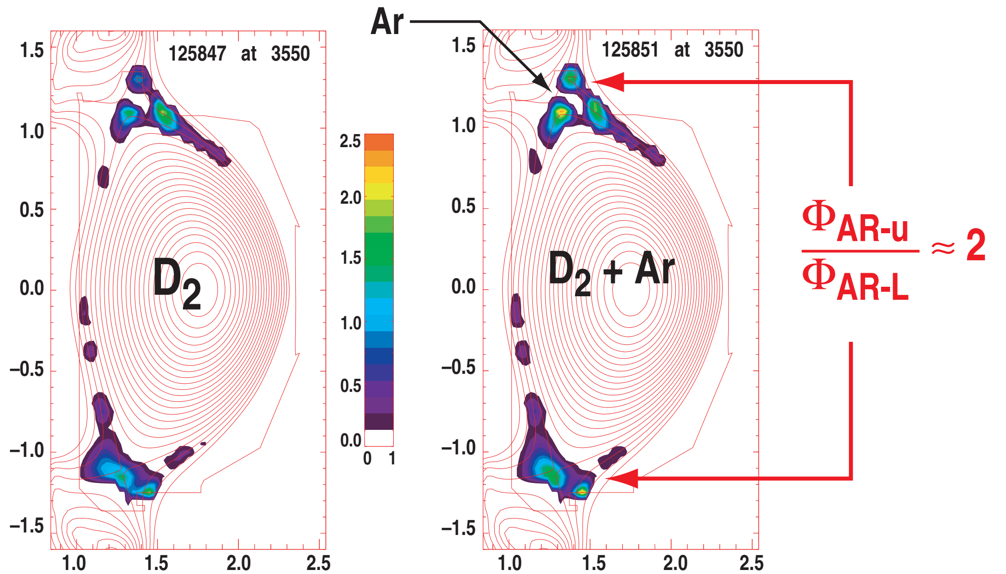
$B \times \nabla B \downarrow$

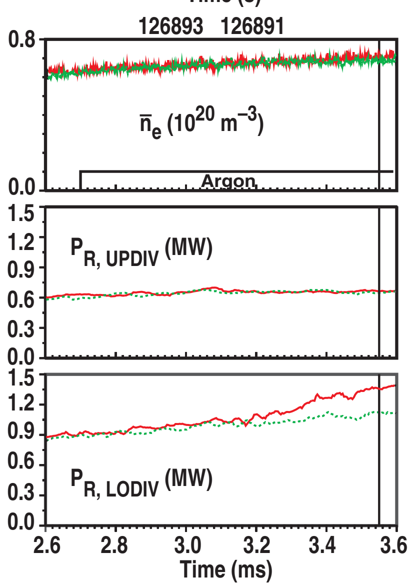
D_2

D_2 + Ar

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

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





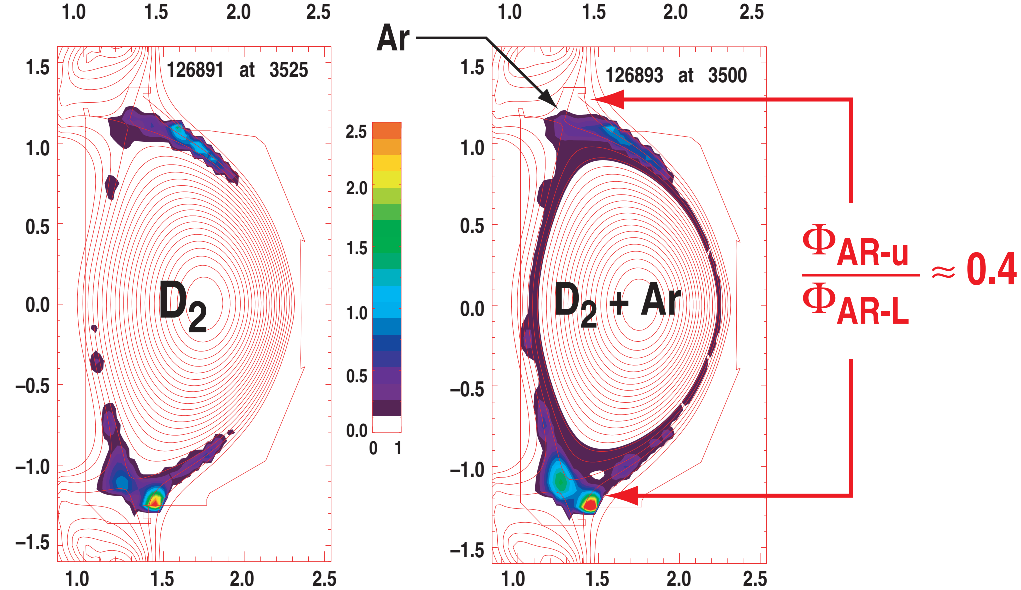
$B \times \nabla B \uparrow$

D_2

D_2 + Ar

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

$\Delta P_{R,\,LODIV} \simeq +0.27$ MW



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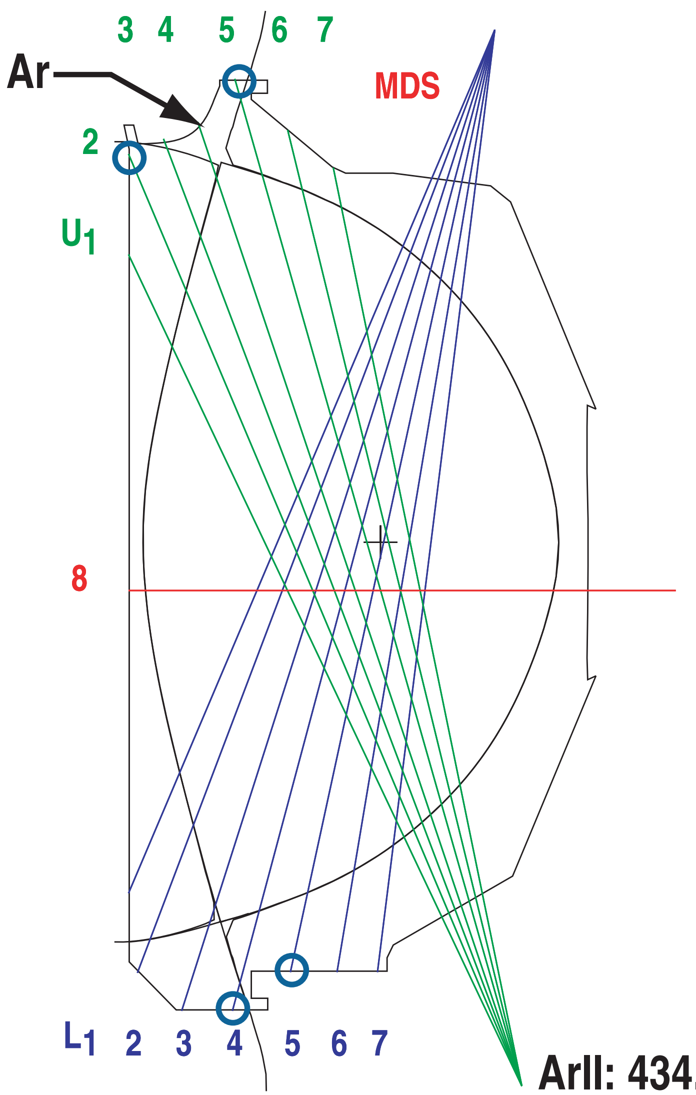
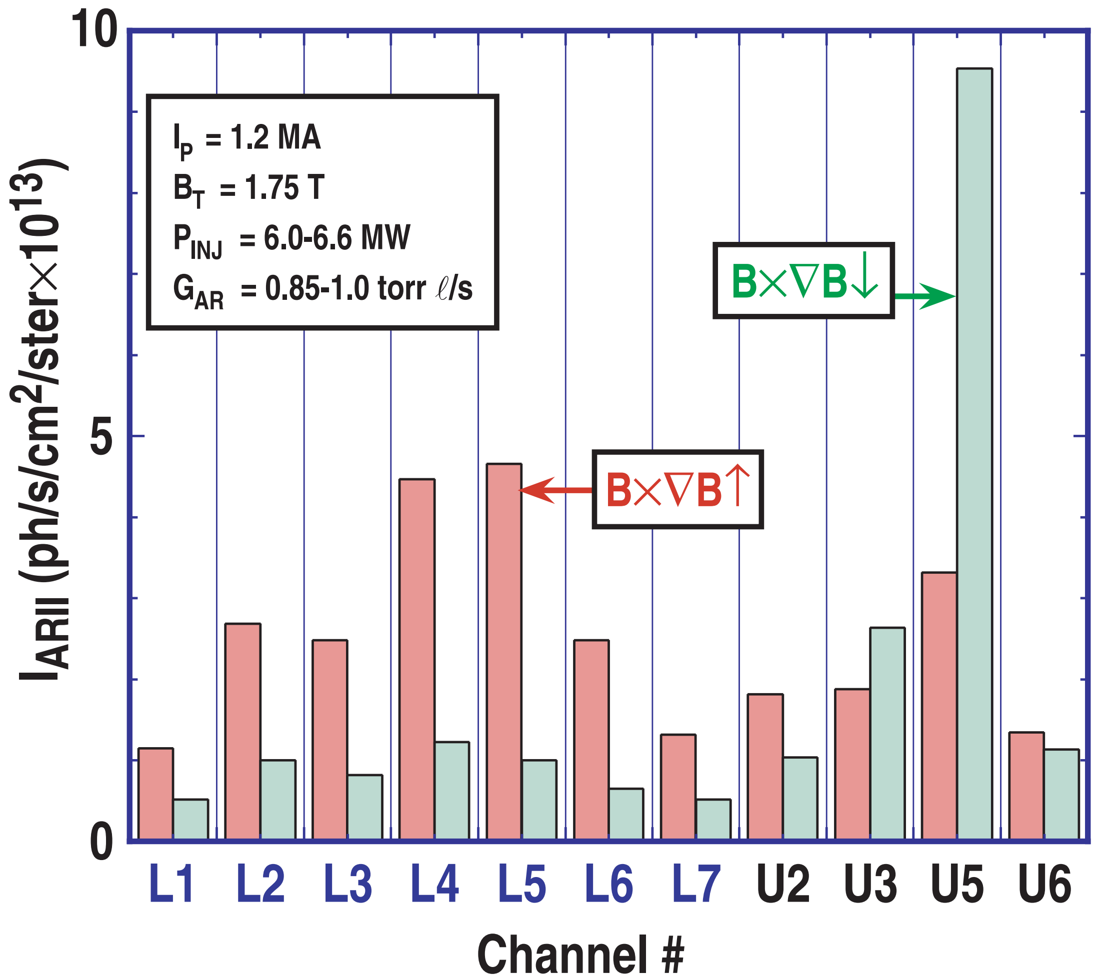
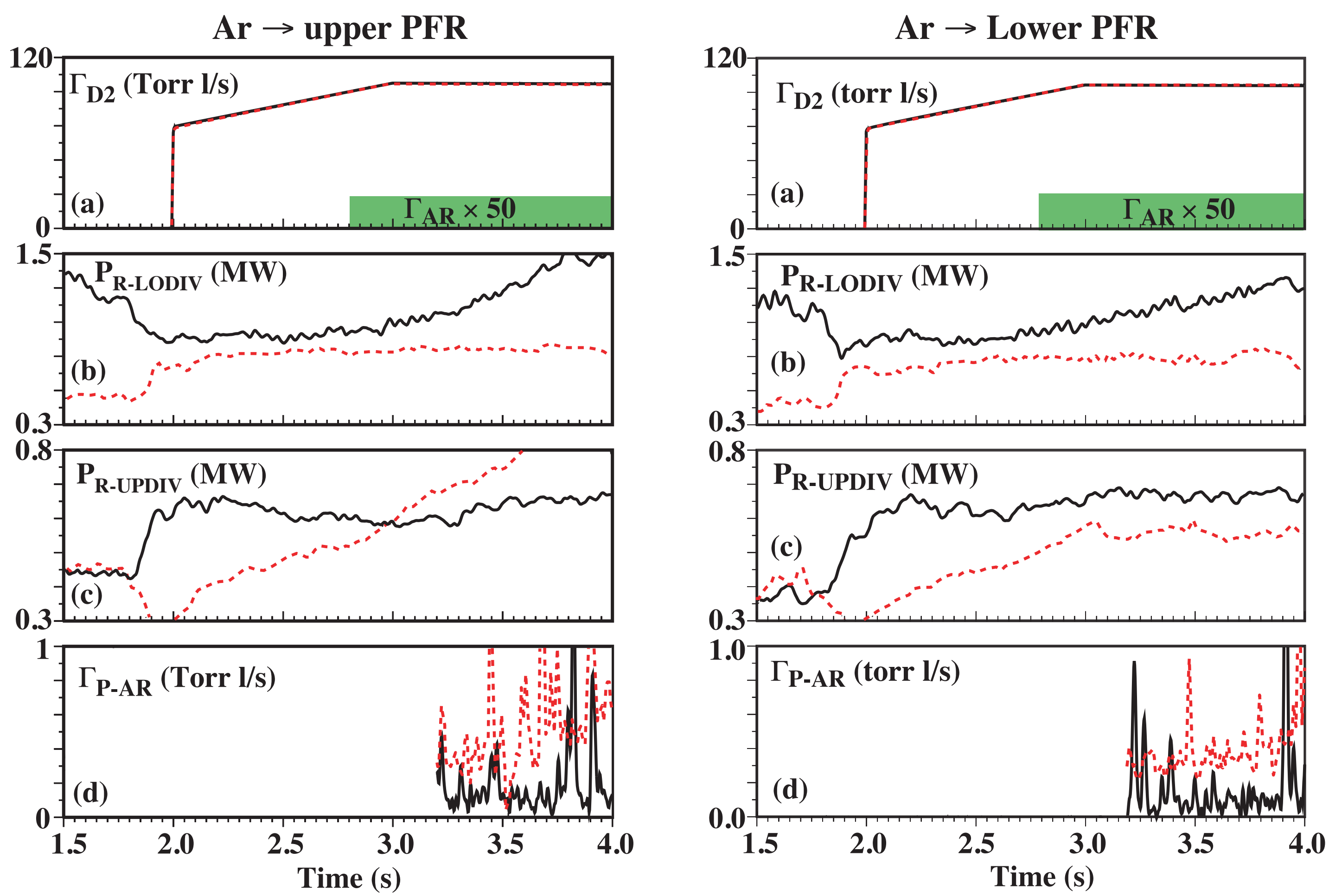
Argon Accumulated in the Divertor Opposite the B×∇B Direction





During Argon Injection Radiated Power Increased More in the Divertor Opposite Ion Bx∇B Drift Direction, Regardless of the Divertor into Which Argon was Injected



(———) Bx∇B↑

(- - - - -) Bx∇B↓

Response stronger for Bx∇B↑

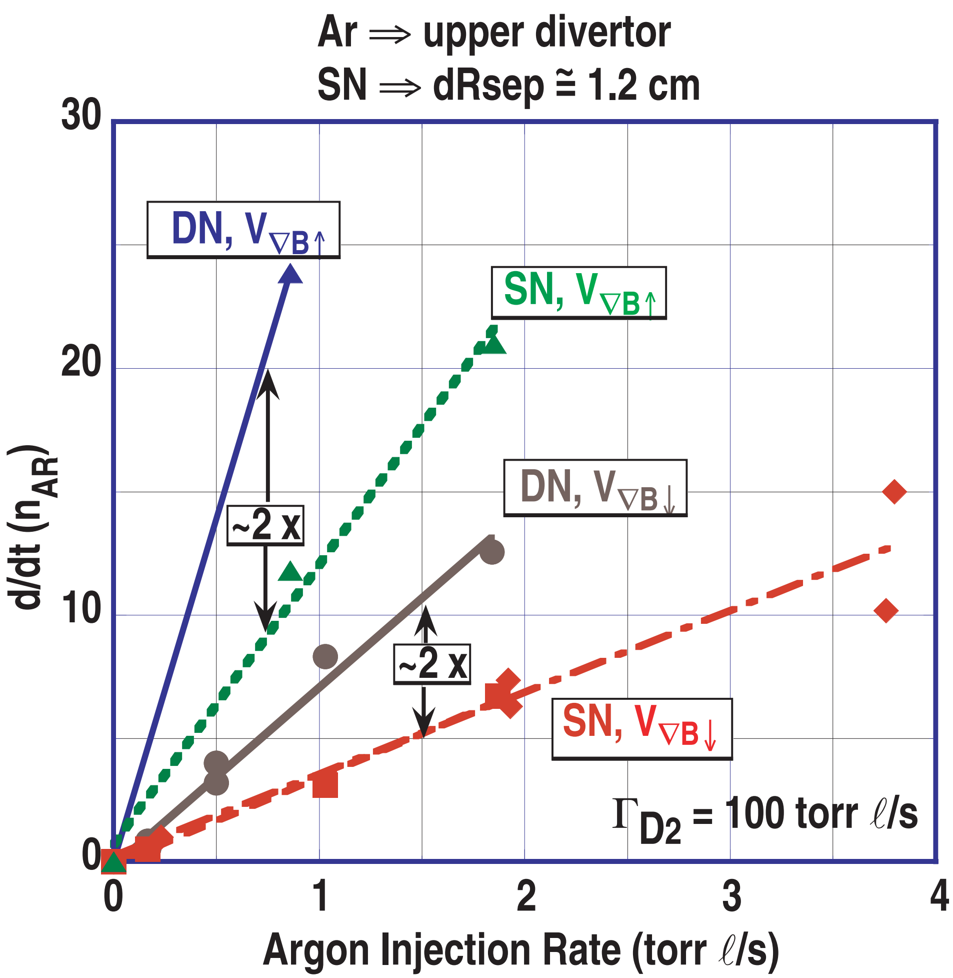
Response stronger for Bx∇B↓

Argon pumping from upper outer divertor stronger when Bx∇B↓

Section 6

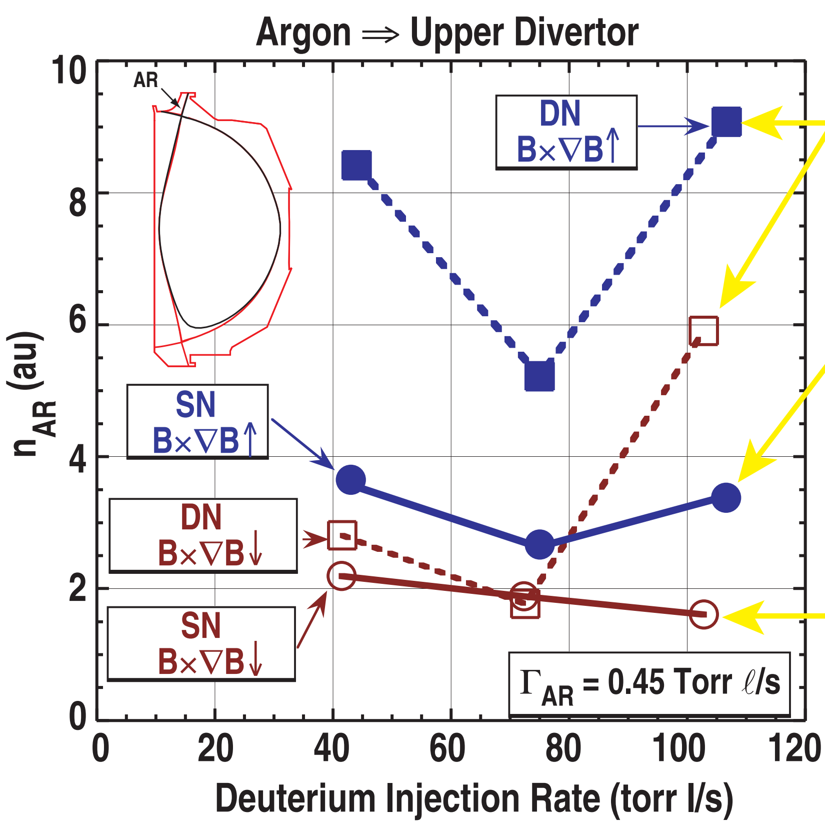
Comparisons of SN and DN performances during puff-and-pump show strikingly different behaviors

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



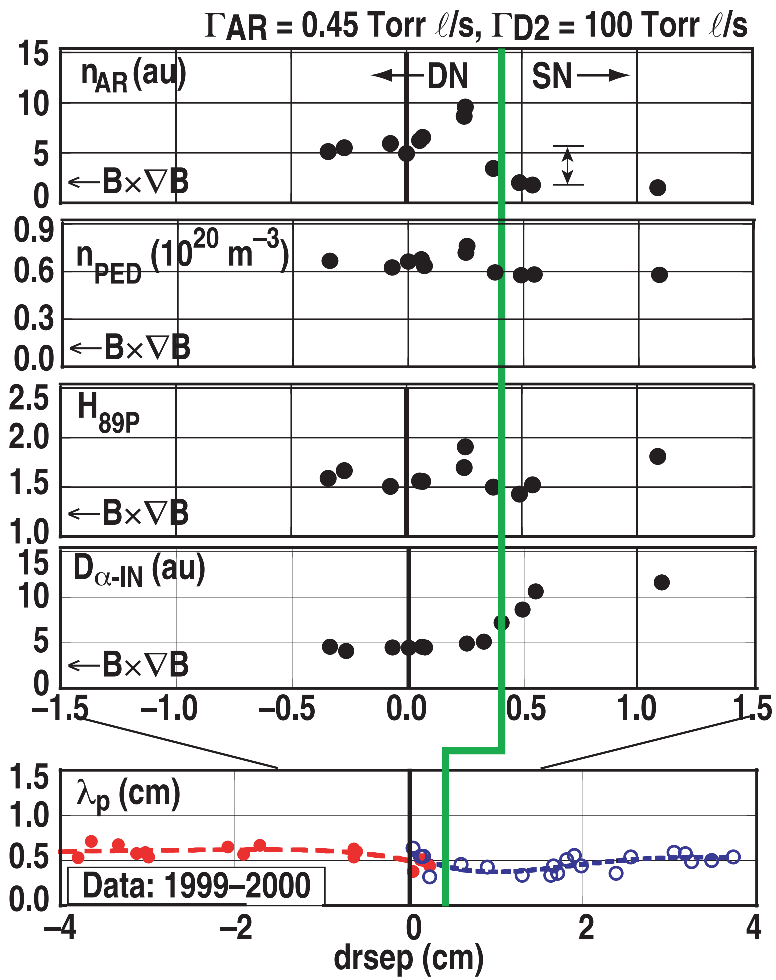
- Argon accumulated faster in the core of SNs when the B×∇B direction is toward the divertor with the argon source
- The same can be said for DNs
- Argon accumulated faster in the core of DNs than in SNs with the same B×∇B direction
- The higher the pumping fraction of argon, the lower the argon concentration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

Use of "Puff and Pump" May be More Limited for DNs as Well as for SNs with B×∇B Toward the Upper Divertor



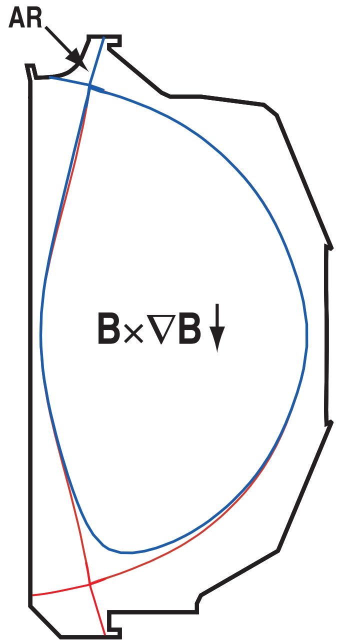
- **Both DN cases show a pronounced rise at high Γ_{D2}**
  - Virtual detachment of upper inner divertor leg
- **SNs with B×∇B toward the divertor shows a less pronounced reversal of n_{AR}**
  - E_r×B drift in the private flux region toward inner target
  - E_r×B drift toward lower divertor on HFS
- **SNs with B×∇B away from divertor appears best suited for puff and pump**
  - E_r×B drift in private flux region is toward the outer target

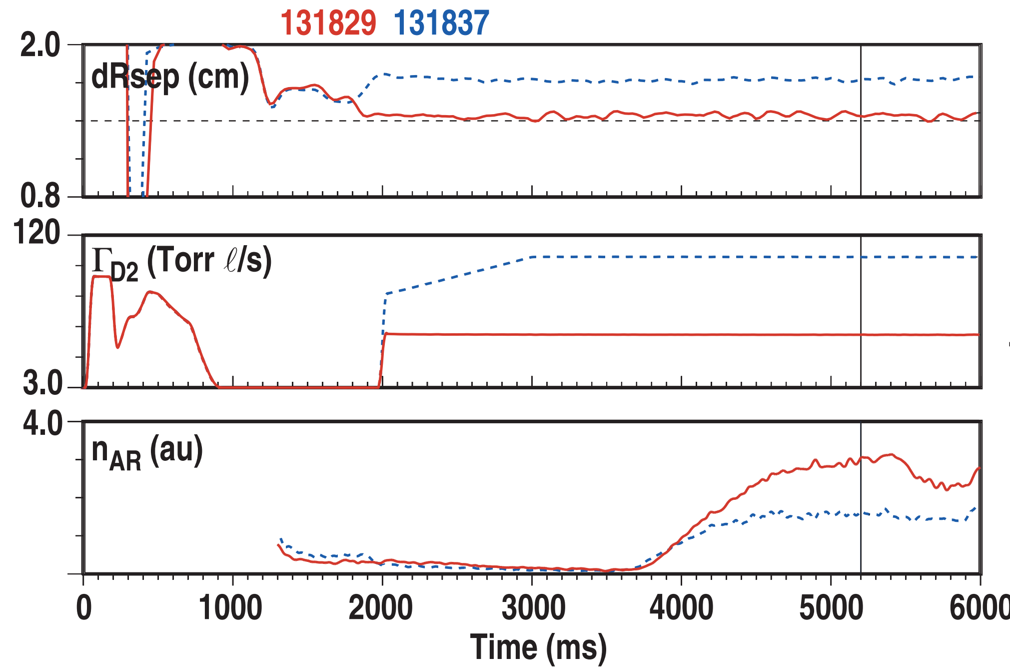
Significant Reductions in Argon Density in the Main Plasma is Observed as DN Transitions to SN



- n_{AR} dropped by a factor of ~3× between dRsep = 0 and dRsep = +0.5 cm
- n_{AR} and n_{PED} roughly tracks H_{L89} for dRsep < +0.5 cm
- Increase in $D_{\alpha\text{-IN}}$ is associated with decrease in n_{AR} ⇒ DN/SN transition
- Transition region near $|dRsep| \simeq 0.4$ cm $\simeq \lambda_p$

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

$\Gamma_{AR} = 0.45$ Torr ℓ/s

dRsep = 0, +1.2 cm

- Greater D-flow on the HFS for “SN”
- Narrower SOL on HFS for “DN”
- More quiescent on HFS for “DN”

$\Rightarrow$ advantage: “SN”

Summary of Section 6

- Since the same particle drifts are in play, DN behavior shows similar trends to that of SN behavior in that the leakage of argon from the upper divertor is significantly greater when the ion Bx∇B drift is toward the X-point
- The argon buildup in the core plasma of DNs was higher than in comparable SNs with the same ion Bx∇B drift direction
- Raising Γ_{D2} is most effective in keeping argon out of the core plasma when the ion Bx∇B drift direction is away from the x-point of a SN plasma
- DN behavior transitions to SN behavior for puff-and-pump operation when dRsep → 0.4 cm ≃ λ_p

Discussion of Section 6

- **Since the same particle drifts are in play, DN behavior shows similar trends to that of SN behavior in that the leakage of argon from the upper divertor is significantly greater when the ion Bx∇B drift is toward the X-point**
  → More injected argon would be available to "fuel" the main plasma
  → Argon accumulation in the divertor opposite the ion Bx∇B drift direction
  → Difficulty of balancing radiated power between the two divertors
- **The argon buildup in the core plasma of DNs was higher than in comparable SNs with the same ion Bx∇B drift direction**
  - Power flow to inner target for DNs much less than for SNs
    → The electron temperature and density at the inboard SOL target of a DN is characteristically much less than that of a comparable SN
    → Relatively simple to detach DN on the high field side
    → More direct way for neutrals to escape to the high field side for DNs compared with SNs
  - Narrower, cooler, and more quiescent SOL for DNs on the high field side than for SNs
    → Favors higher argon "fueling" rate for DNs or SNs

Discussion of Section 6 (Continued)

- **Raising Γ_{D2} is most effective in keeping argon out of the core plasma when the ion B×∇B drift direction is away from the X-point**
  - But is less effective when the ion Bx∇B drift direction is toward the X-point due to the cooling of the plasma at the inner divertor targets as Γ_{D2} increases, making it more transparent to argon neutrals
  - And is least effective for DN plasmas.
    Increasing Γ_{D2} from the LFS has little effect in enhancing particle flow to the divertor targets on the high field side due to the severing of the HFS SOL from the LFS SOL
- **DN behavior transitions to SN behavior for puff-and-pump operation when dRsep → 0.4 cm ~ λ_p**
  - Significantly reduced argon in the core plasma compared with DN for dRsep ≥ +0.4 cm only when the ion Bx∇B drift direction is downward
  - When the heat flux width λ_p is comparable to dRsep, a significant fraction of the power flowing into the low field side SOL can now reach the inner divertor target, leading to stronger recycling (and attachment) at the inner divertor target
    → Increasing dRsep further would lead to only marginal increase in recycling activity
    → Harder for neutrals to leak into SOL on the HFS if the inner target is attached

Conclusions

- **For tokamaks characterized as largely single-null, such as ITER, results presented here point to the importance of considering particle drifts in assessing the projected success of puff-and-pump**
  - For achieving and maintaining a detached inner divertor leg using seed impurities as a "trigger",
  - For preventing the seed impurity from contaminating the main plasma, and
  - For operating as an unbalanced DN, as might occur in more triangular, high performance ITER plasmas

- **Understanding how SN or DN H-mode plasmas behave under puff-and-pump operation requires the inclusion of particle drifts in the analysis**