THE EFFECT OF DIVERTOR MAGNETIC BALANCE ON H–MODE PERFORMANCE IN DIII–D

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We report on recent experiments for which the magnetic balance of highly triangular ($\delta \approx 0.8$), unpumped H–mode plasmas was systematically varied. Changes in divertor heat loading and particle flux were observed when the magnetic configuration was varied from a balanced double-null (DN) divertor to a slightly unbalanced DN divertor. For attached plasmas, the variation in heat flux sharing between divertors is very sensitive near DN. This sensitivity can be shown to be consistent with the measured scrape-off length of the parallel divertor heat flux, $\lambda_{q||}$. At magnetic balance we find that the peak heat flux toward the divertor in the grad-B direction is twice that of the outboard divertor. Most of the heat flux goes to the outboard divertor legs in a balanced double-null, where the peak heat flux in the outer divertor may exceed that of the inner divertor by tenfold. The variation of the peak particle flux between divertors is less sensitive to changes in magnetic balance. These particle and heat flux “asymmetries” in DN plasmas are consistent with the presence of E×B poloidal particle drifts in the scrape-off layer and private flux region. Regardless of how the divertors were magnetically balanced, D_2 gas puffing always reduced energy confinement to the range $\tau_E/\tau_{E89P} \approx 1.3$–$1.6$. When reached, τ_E/τ_{E89P} remained nearly constant, even as these plasmas were fueled to near their respective density limits.

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INTRODUCTION

Much of tokamak research to-date has focused on the single-null (SN) divertor. Yet, since plasma shaping (e.g., elongation κ and triangularity δ) can affect important plasma characteristics, such as energy confinement and plasma β-limit, it is uncertain that future tokamaks will (or should) adopt configurations based on the SN.

HIGH TRIANGULARITY MAY FAVOR THE DOUBLE-NULL (DN) SHAPE

- $P_{e,ped} \Uparrow$ with δ
- $\tau_E \Uparrow$ with $P_{e,ped}$

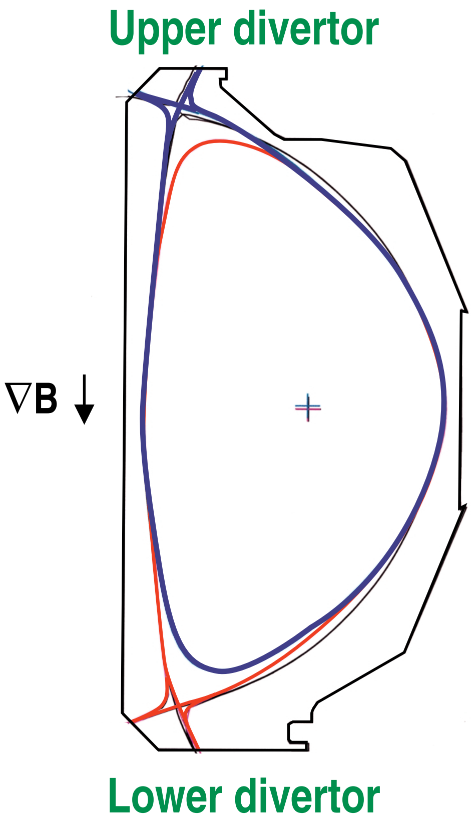
$\Rightarrow$ May make the DN attractive, since both nulls can be maintained “inside the box”.

HOW MUCH “MAGNETIC (IM) BALANCE” IS NEEDED FOR DIVERTED PLASMAS TO DISPLAY EITHER SN OR DN BEHAVIORS?

In this poster we report on recent DIII–D experiments which looked into this question, particularly with respect to:

- Heat and particle flux sharing by the divertors,
- Response of the plasma to deuterium gas fueling.

SEPARATRIX CONFIGURATIONS ARE VARIED FROM LOWER SN→DN→UPPER SN IN THIS STUDY



Common Parameters:

I_p = 1.37 MA

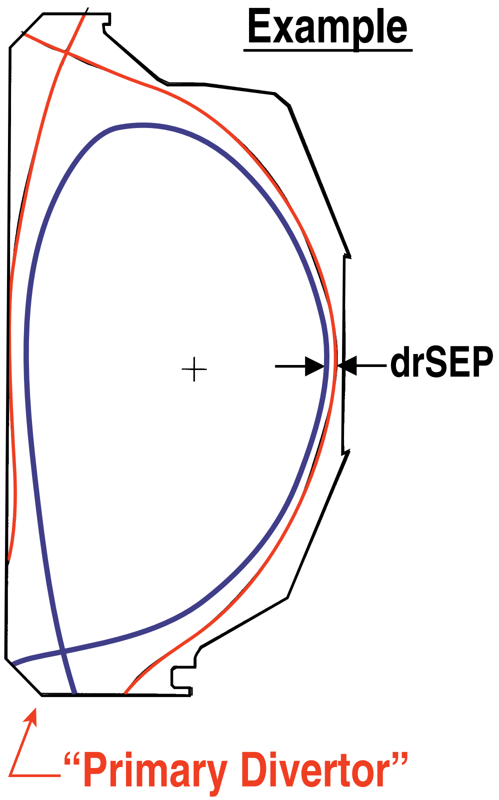
B_t = 2.0 T

P_{in} = 4 - 8 MW

$q_{95} \approx$ 4.5

δ_{avg} = 0.8 (DN)

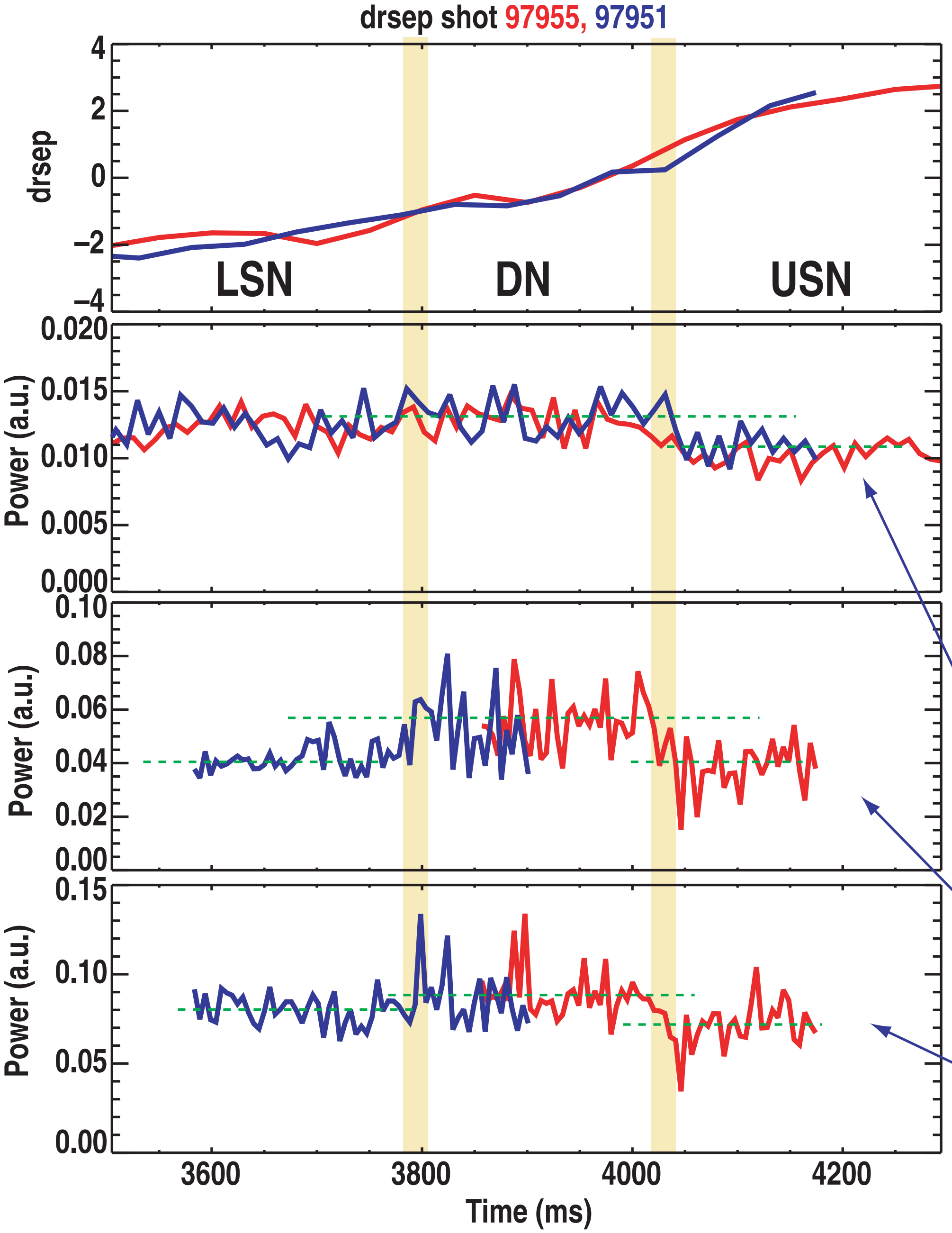
δ_{avg} = 0.6 (SN)



drSEP → { The radial distance between the upper divertor separatrix and the lower divertor separatrix, as determined at the outboard midplane } →

- drSEP > 0 (USN)
- drSEP = 0 (DN)
- drSEP < 0 (LSN)

OBSERVE SMALL INCREASE IN SOL FLUCTUATION LEVEL IN DOUBLE NULL CONFIGURATION



- Longer SOL connection lengths in SN (versus DN) can connect good and bad curvature regions
- Turbulence modeling indicates that fluctuations may be lower in SN due to modes averaging over both good and bad curvature regions (X. Xu, LLNL)
- Density fluctuations monitored using reflectometry

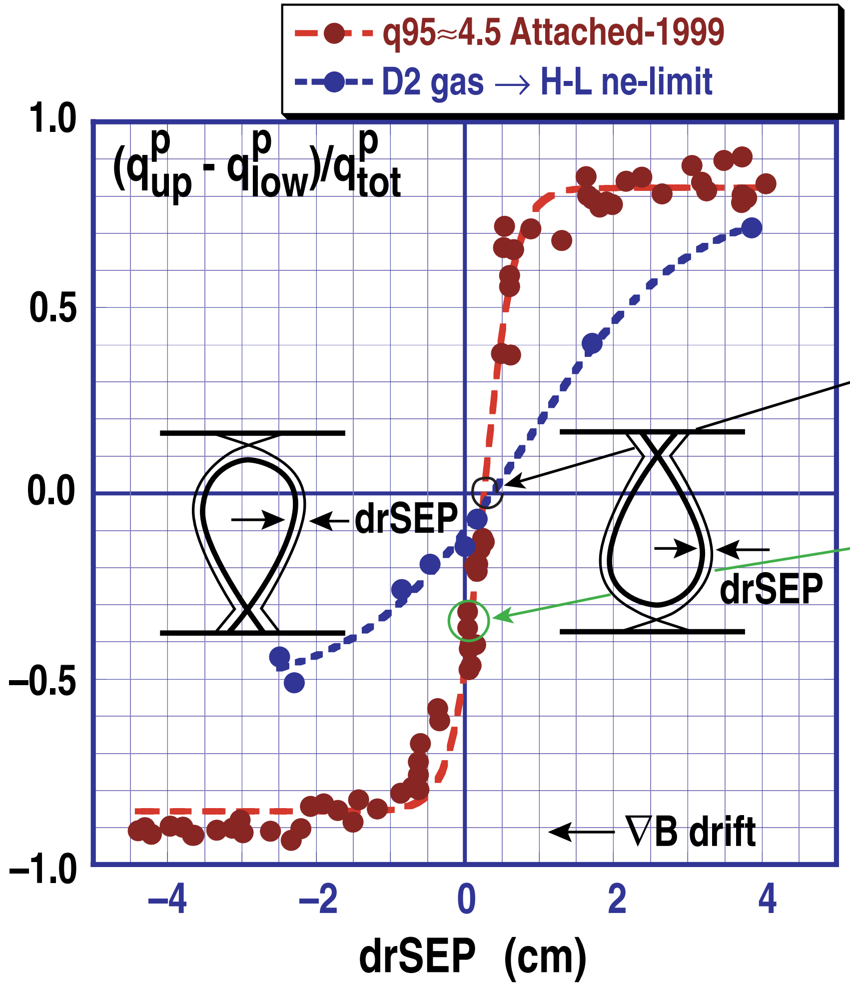
~ separatrix

SOL

far SOL

— OUTBOARD DIVERTOR —

THE VARIATION IN HEAT FLUX SHARING IS LARGE FOR SMALL CHANGES IN drSEP NEAR DN



ATTACHED

- Heat flux “domination” shifts from one divertor to the other within ≈ 1 cm
- Peak heat flux balance at drSEP ≃ 0.25 cm
- Balanced DN: $q^p_{low} \simeq 2 \times q^p_{up}$

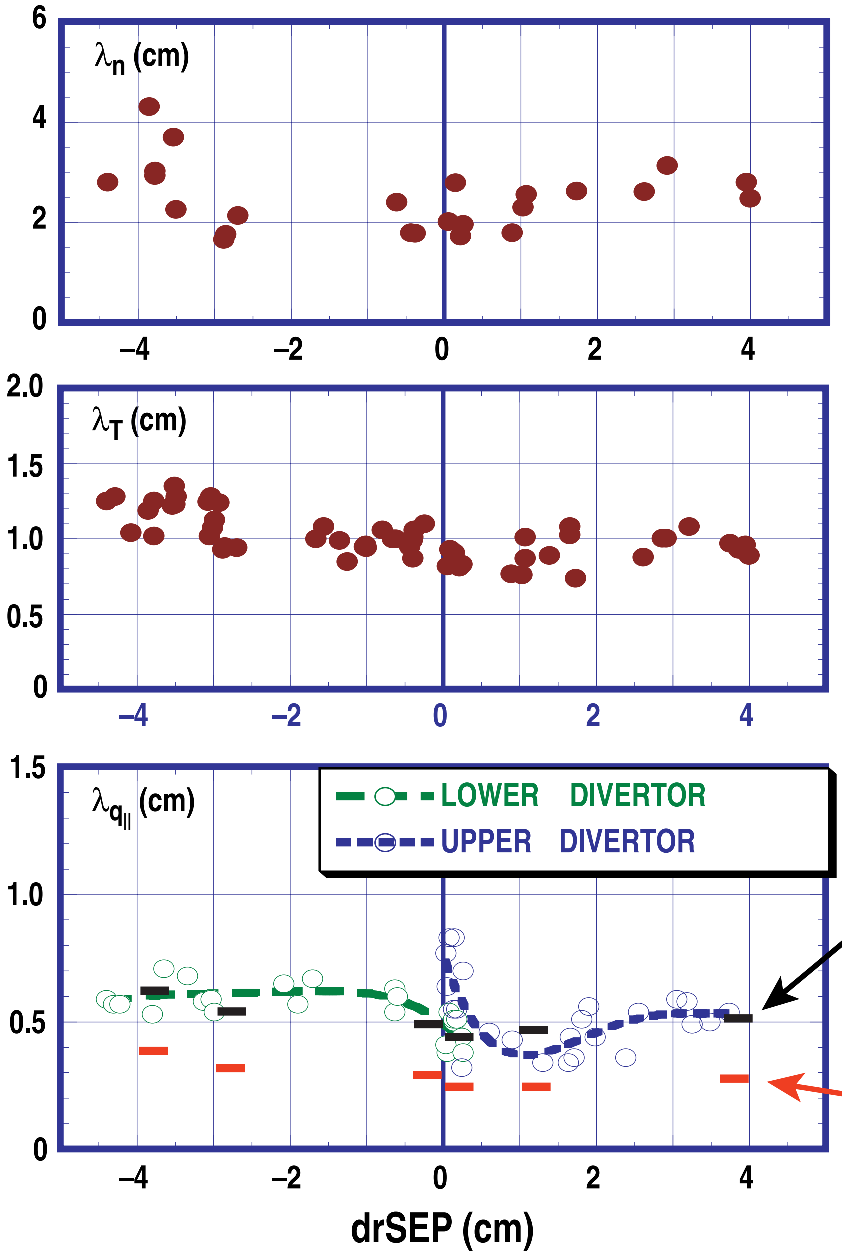
DETACHED

- Transition is broader at high density (e.g., $n_e \simeq n_{e,H-L}$)

  — $q^p_{low} \simeq 1.2 \times q^p_{up}$

— OUTBOARD SCRAPE-OFF LAYER —

THE SCRAPE-OFF WIDTH OF THE PARALLEL DIVERTOR HEAT FLUX ($\lambda_{q_{||}}$) IS INSENSITIVE TO drSEP IN ATTACHED PLASMAS



"Upstream" λ_n & λ_T are mapped to the outer midplane

- $\lambda_n \approx$ 2-4 cm
- $\lambda_T \approx$ 0.8-1.3 cm

$\rightarrow \lambda_n \approx (2\text{-}3) \times \lambda_T$

Divertor heat flux is mapped from the primary divertor to the outer midplane

- Large heat flux shift occurs within a drSEP range $\approx 2 \times \lambda_{q_{||}}$
  (See above figure)
- **Flux Limited Regime:**

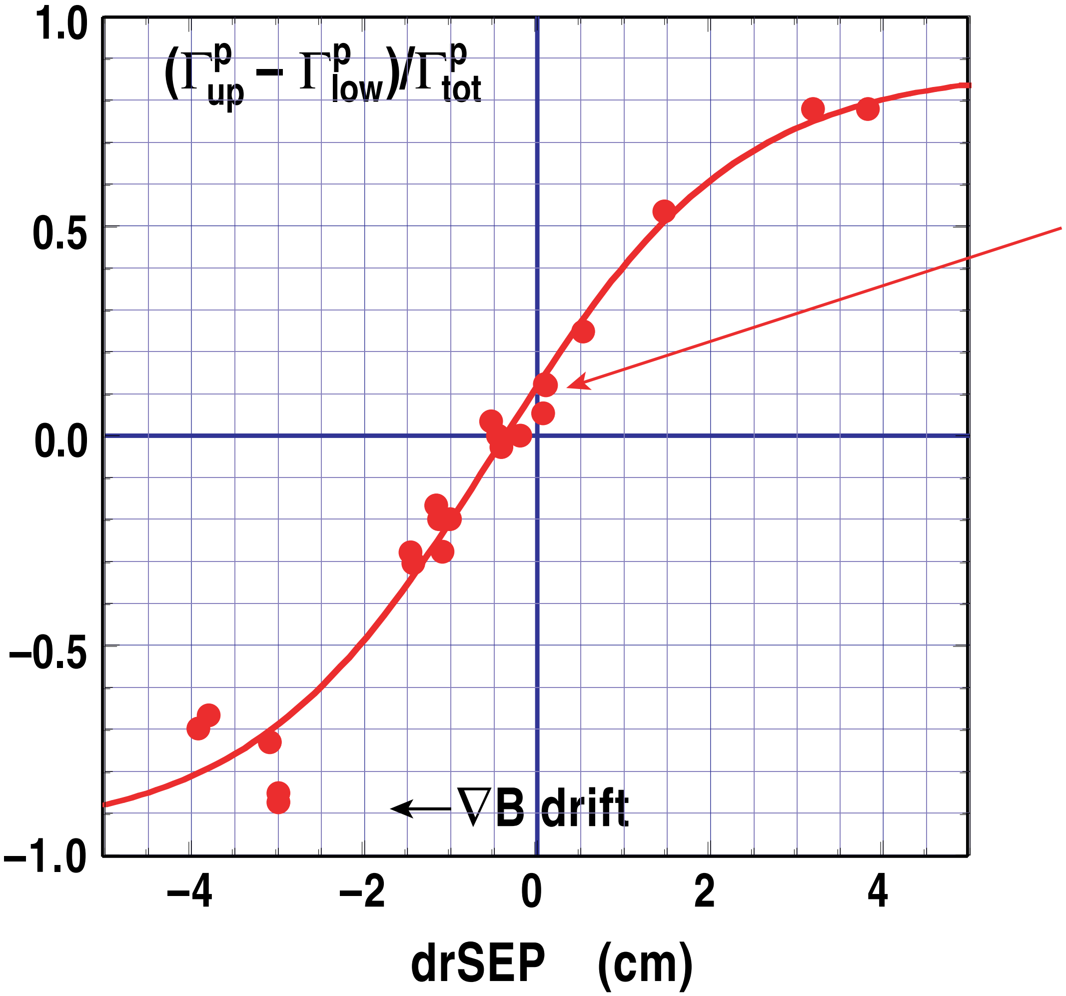
$$\lambda_{q_{||}} = \frac{1}{\dfrac{1}{\lambda_n} + \dfrac{1.5}{\lambda_T}}$$

Conduction Regime

$$\lambda_{q_{||}} = \frac{2}{7} \times \lambda_T$$

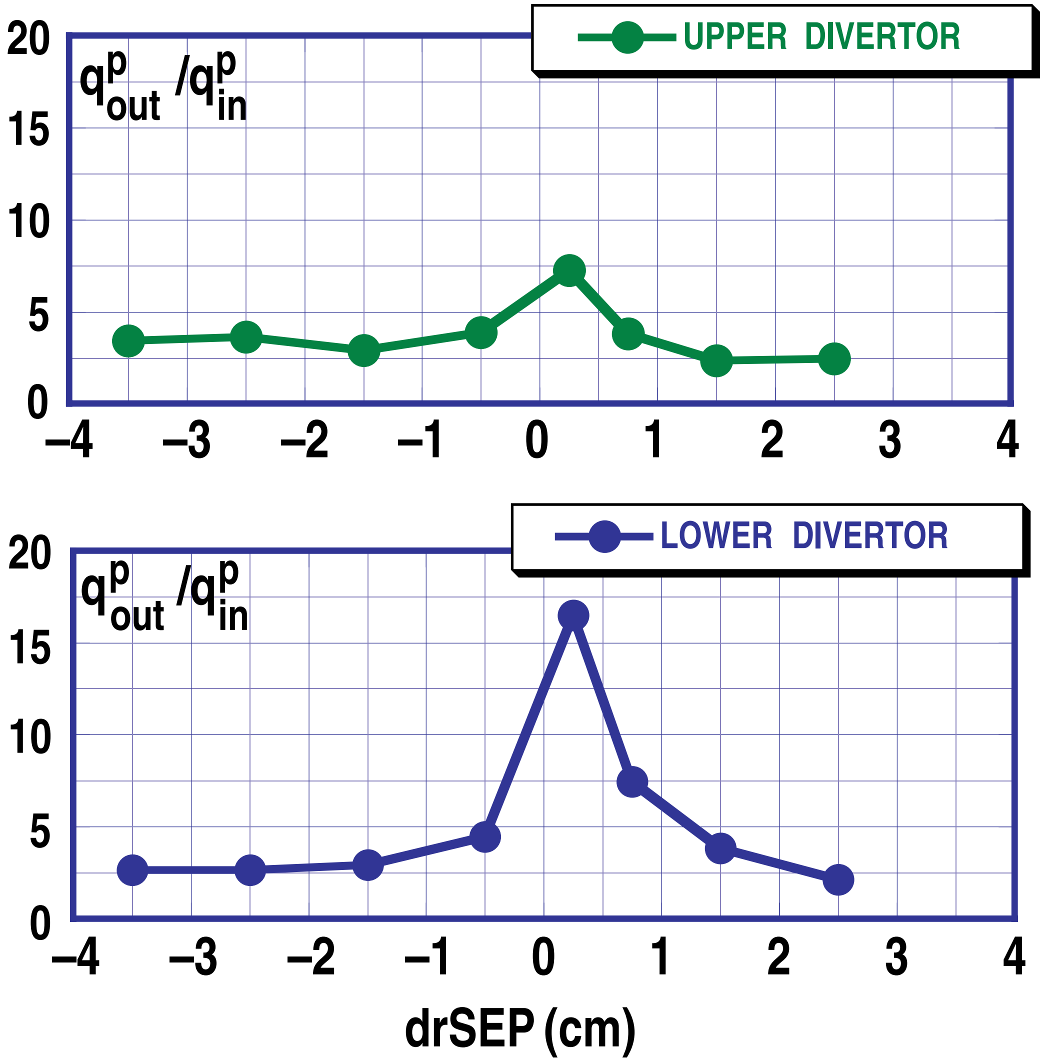
— OUTBOARD DIVERTOR —

THE SLOWER VARIATION OF PARTICLE FLUX WITH drSEP IS LIKELY DUE TO DIVERTOR PROCESSES



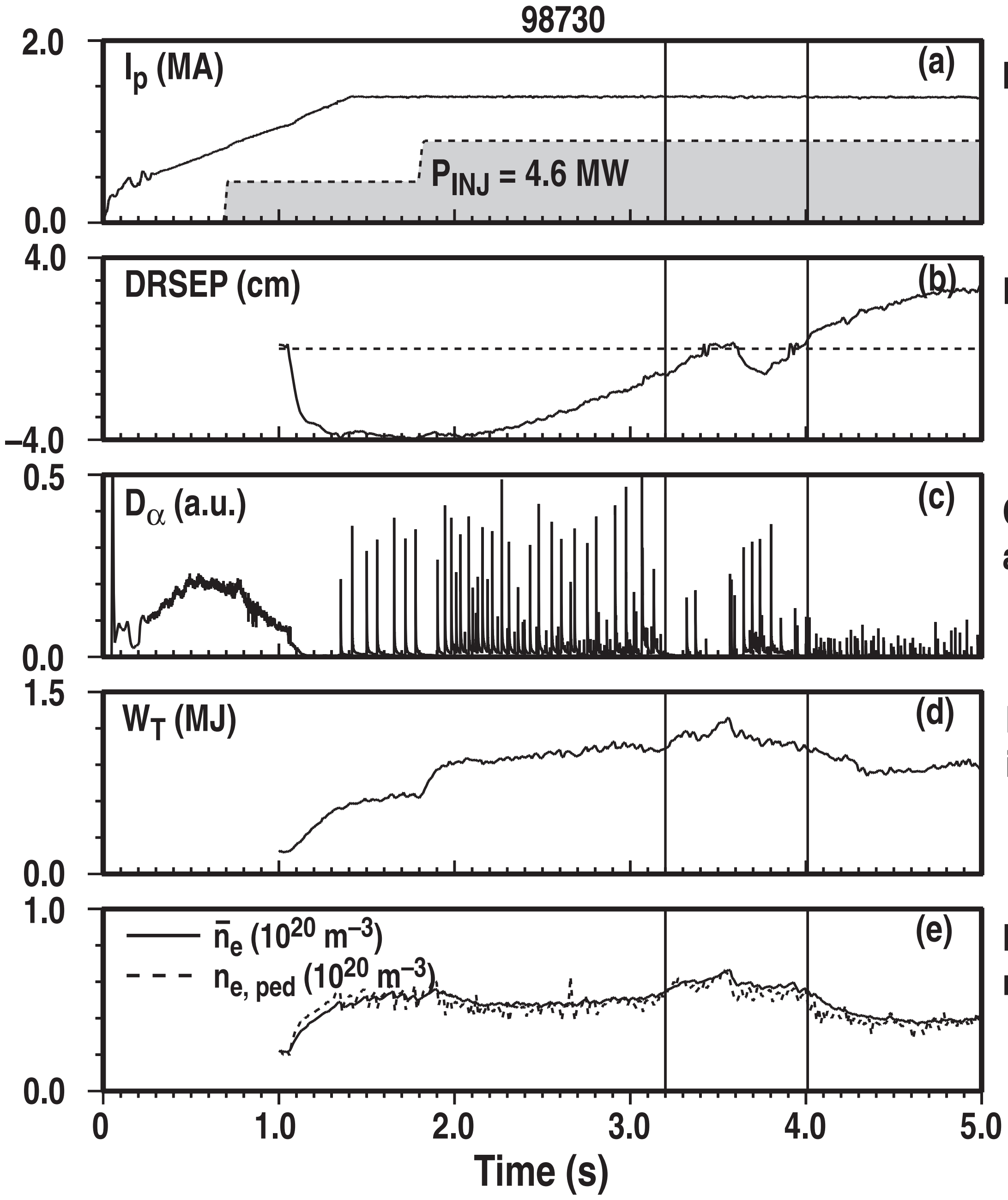
- Determined using Langmuir probes + strike point sweeping
- Balanced DN: $\Gamma_{up}^{p} \approx 1.2 \times \Gamma_{low}^{p}$
- Might expect a slower variation of Γ with drSEP than $q_{||}$
  - $\Gamma \propto n\sqrt{T}, \rightarrow \lambda_{\Gamma} \simeq 1$ cm
  - Figure implies: $\lambda_{\Gamma} \simeq 3$ cm

MOST OF THE HEAT FLUX GOES TO THE OUTBOARD DIVERTOR LEGS IN A BALANCED DN DIVERTOR



- $q^p_{out}/q^p_{in} \approx 2.5$ over most of drSEP in both upper and lower divertors.
- $q^p_{out} >> q^p_{in}$ for drSEP ≈ 0 in both upper and lower divertors.
  - Difference in the peaks believed due to E×B poloidal drift effects (See Discussion)

"DYNAMIC" SCAN IN DRSEP SHOWS THAT PLASMA BEHAVIOR NEAR DRSEP = 0 IS HIGHLY SENSITIVE TO CHANGES IN DRSEP



I_p = 1.37 MA

LSN → DN → USN

Changes in DRSEP affect ELMing

Plasma energy increases for DN

Higher edge density near DRSEP = 0

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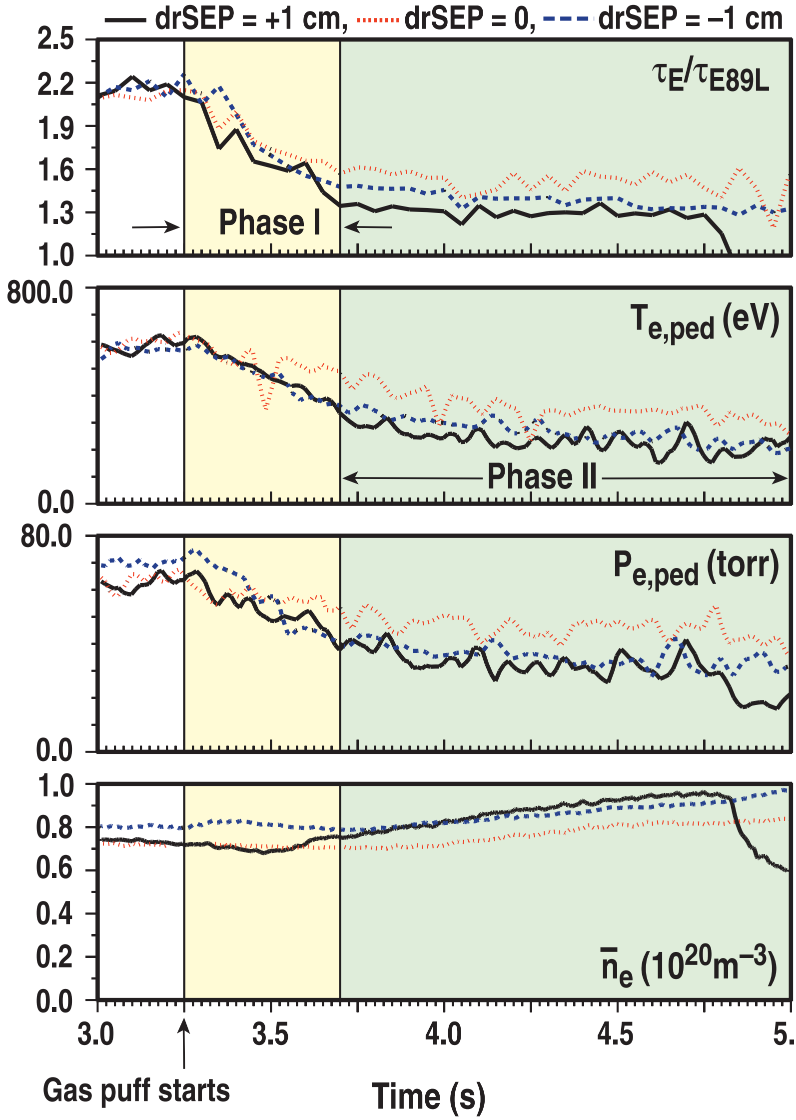
CONFINEMENT AND PEDESTAL CHARACTERISTICS DEGRADE WITH GAS PUFFING AT ALL VALUES OF drSEP

- For drSEP = –1cm (LSN), 0 (DN), +1 cm (USN)
  - ★ τ_E/τ_{E89p}, $T_{e,ped}$, and $P_{e,ped}$ decrease together after gas injection [Phase I]
  - ★ τ_E/τ_{E89p} $P_{e,ped}$ are essentially unchanged during Phase II
  - ★ Density does not increase until Phase II
- Applies to high triangularity, high BT, and unpumped H–mode discharges



Phase I: ↓
Phase II: →

Phase I: ↓
Phase II: →

Phase I: ↓
Phase II: →

Phase I: →
Phase II: ↑

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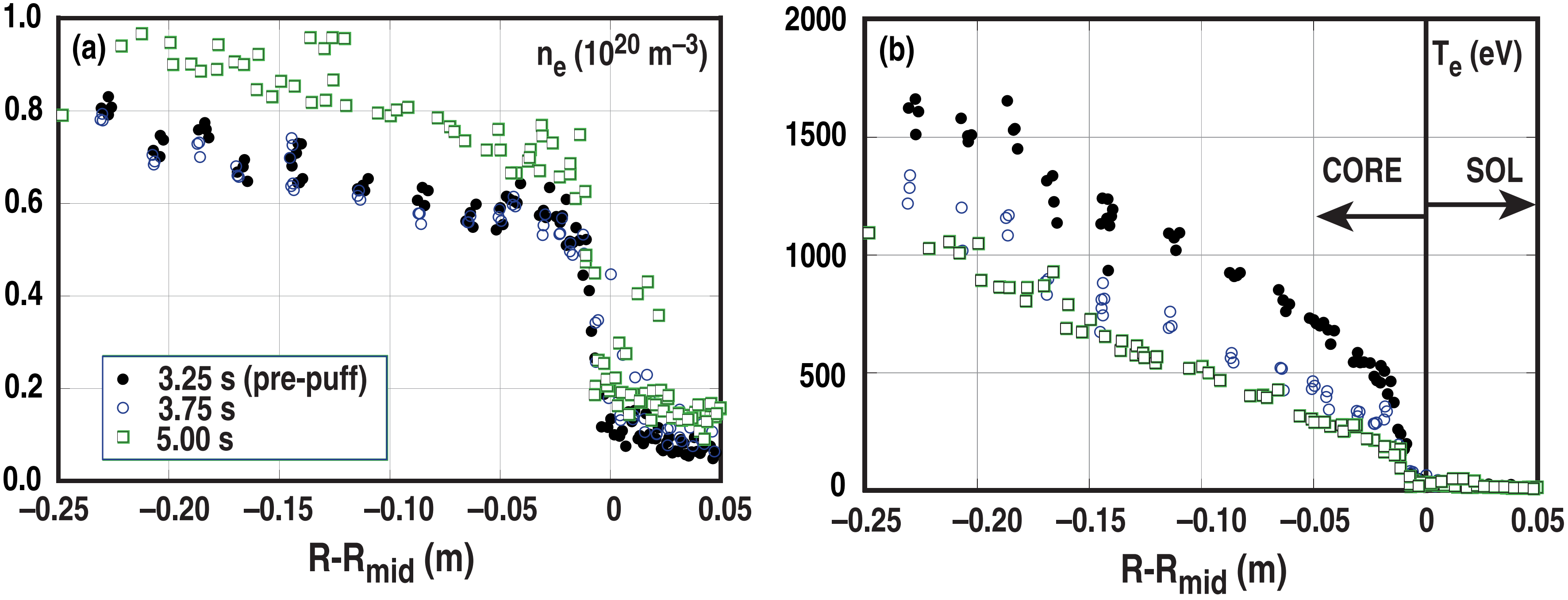
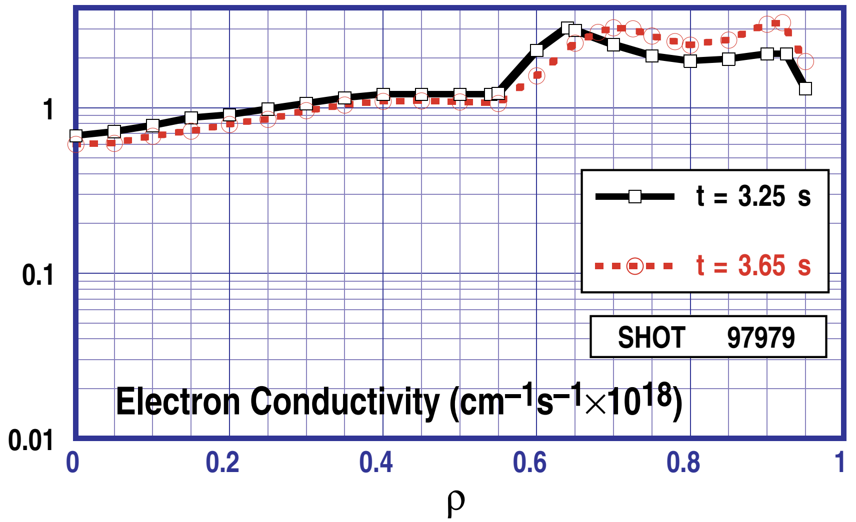
THE n_e–AND T_e PROFILES SHOW DISTINCTLY DIFFERENT BEHAVIOR DURING PHASE I AND PHASE II

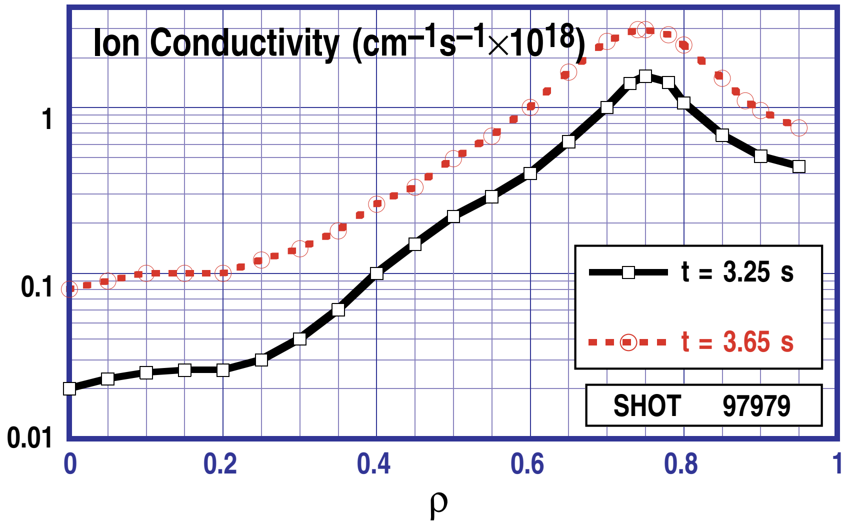
- The n_e-profile shows little change during phase I
- Most of the decrease across the T_e-profile occurred during phase I
- The product $n_e \times T_e$ is approximately constant during phase II (“plateau”)



DEUTERIUM GAS PUFFING APPEARS TO LEAD TO HIGHER THERMAL CONDUCTIVITY OF THE ION CHANNEL

- Before gas puffing (3.25 s):
  - Electron conductivity dominates
  - Ion conductivity comparable only at r/a ≈ 0.75
- After 0.4 s of deuterium gas puffing (end of phase I)
  - Ion conductivity increases by a factor of 2-4 across the profile
  - Ion conductivity is comparable to electron conductivity from r/a ≈ 0.6-0.9
  - Electron conductivity is mostly unchanged after gas puff



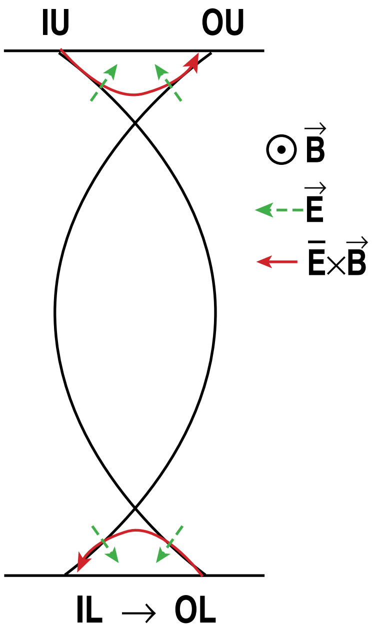


DISCUSSION

Our data is consistent with E×B poloidal particle flows playing a major role in the observed particle and heat flux asymmetries in the DNs discussed in this paper. At present, however, the modeling of these symmetry-breaking particle drifts self- consistently in the DN configuration is only at a rudimentary level in available 2-D fluid modeling edge transport codes, such as UEDGE [1]. On the other hand, 2-D fluid modeling has been used successfully to study the importance of E×B drifts in less complicated (SN) configurations in DIII–D [2]. In fact, recent E×B poloidal particle flow across the private flux region (PFR) were measured in DIII–D divertor plasmas and found to be in agreement with the particle flow predicted by UEDGE modeling [3]. This agreement gives confidence that our basic understanding of E×B edge plasma drifts is grounded well enough to understand our DN data on a qualitative level.

[1] T.D. Rognlien, et al., Plasma Phys. 34 (1994) 362.
[2] T.D. Rognlien, et al., J. Nucl. Mater. 266-269 (1999) 654.
[3] J.A. Boedo, et. al., Phys. Plasmas 7 (2000) 1075.

UP/DOWN ASYMMETRIES IN DN



- The ELECTRIC FIELD (E) which drives the drift arises mainly from the radial gradient in Te in the PFR.
- FLOW DIRECTIONS:
  Lower divertor: OL → IL
  Upper divertor: IU → OU
- Expect $\Gamma_{OU} > \Gamma_{OL}$ (as observed), resulting in $n_{OU} > n_{OL}$.

- $\left\{\frac{q_{OL}}{q_{OU}}\right\} \approx \left\{\frac{n_{OU}\times T_{OU}^{1.5}}{n_{OL}\times T_{OL}^{1.5}}\right\} \approx \left\{\frac{n_{OU}}{n_{OL}}\right\}^{0.5} > 1 \leftarrow$ **OBSERVED**

  where we assume pressure balance between OL and OU divertors.

- By the same arguments: $\left\{\frac{q_{IL}}{q_{IU}}\right\} < 1$
- From the adove: $\left\{\frac{q_{OL}}{q_{IL}}\right\} > \left\{\frac{q_{OU}}{q_{IU}}\right\} \leftarrow$ **OBSERVED**

Preliminary UEDGE modeling of a DIII–D-like DN discharge with the E×B drift turned on by Rensink [4] qualitatively supports this interpretion.

[4] M. Rensink, (private communication, 2000).

OUT/IN ASYMMETRIES IN DN

A. Geometric contributions with poloidally uniform $\chi_\perp$ alone may not explain strong asymmetry

$$\frac{q_{OUT}}{q_{IN}} \approx \frac{\chi_\perp \times \nabla T_{OUT} \times A_{OUT}}{\chi_\perp \times \nabla T_{IN} \times A_{IN}}$$

where $\chi_\perp$ is diffusivityacross separatrix and taken as poloidally uniform at the separatrix

∇T is the temperature gradient across the separatrix, where $|\nabla T_{OUT}| \approx 2 \times |\nabla T_{IN}|$

A is the surface area of plasma either outboard or inboard of X-points, with $\frac{A_{OUT}}{A_{IN}} \approx 1.7$

$\Rightarrow \frac{q_{OUT}}{q_{IN}} \approx$ 3-4 NOT OBSERVED $\Leftrightarrow \frac{q_{OUT}}{q_{IN}} \approx$ 7-17

B. Factors that can raise OUT/IN ratio over “geometric” prediction

- Divertor radiated power can affect inboard divertors move than outboard divertors
- “Poor” curvature on the outboard side may induce a higher $\chi_\perp$ on the outboard side compared with that of the inboard side [5].
  - Little power can flow around to the inboard side from the “lossy” outboard side, resulting in high values of q^p_{out}/q^p_{in}
  - There is some experimental support for “worse” transport on outboard side in going from SN to DN

[5] X. Xu, 13th U.S. Transport Task Force (TTF) Workshop, 2000.

SUMMARY & CONCLUSION

- We have shown that the peak heat flux balance (up/down and in/out) is highly sensitive to variation in magnetic balance near the DN configuration in attached plasmas
  - Sensitivity is characterized by $\lambda q_{||}$
  - Consistent with E×B poloidal drift playing an important role in these observed asymmetries

    ⇒ Strong in/out heat flux asymmetries for DNs may relax the cooling requirements for handling the power flowing to the inboard divertors and simplify the engineering of the inboard divertor

- Particle flux to the outboard divertors is less sensitive to changes in magnetic balance

  ⇒ Magnetic balance control may be less critical to particle pumping

- Degradation of τ_E with gas injection was seen for all values of drSEP