ABSTRACT

Recent experiments on DIII–D point to the importance of two factors in determining the rate at which deuterium particles can be pumped at the divertor target(s): (1) the divertor magnetic balance, i.e., the degree to which the divertor topology is single-null (SN) or double-null (DN), and (2) the direction of the toroidal field, i.e., clockwise or counter-clockwise around the torus. Changes in divertor magnetic balance near the DN shape have a much stronger effect on the pumping rate at the inner divertor target(s) than on the pumping rate at the outer divertor target(s). The behavior in the particle pumping observed at the inner and outer divertor target(s) in the DN and near-DN shapes were qualitatively consistent with the redistribution of particles expected in the presence of $B\times\nabla B$ and $E\times B$ drifts in the scrapeoff layer (SOL) and divertor(s)

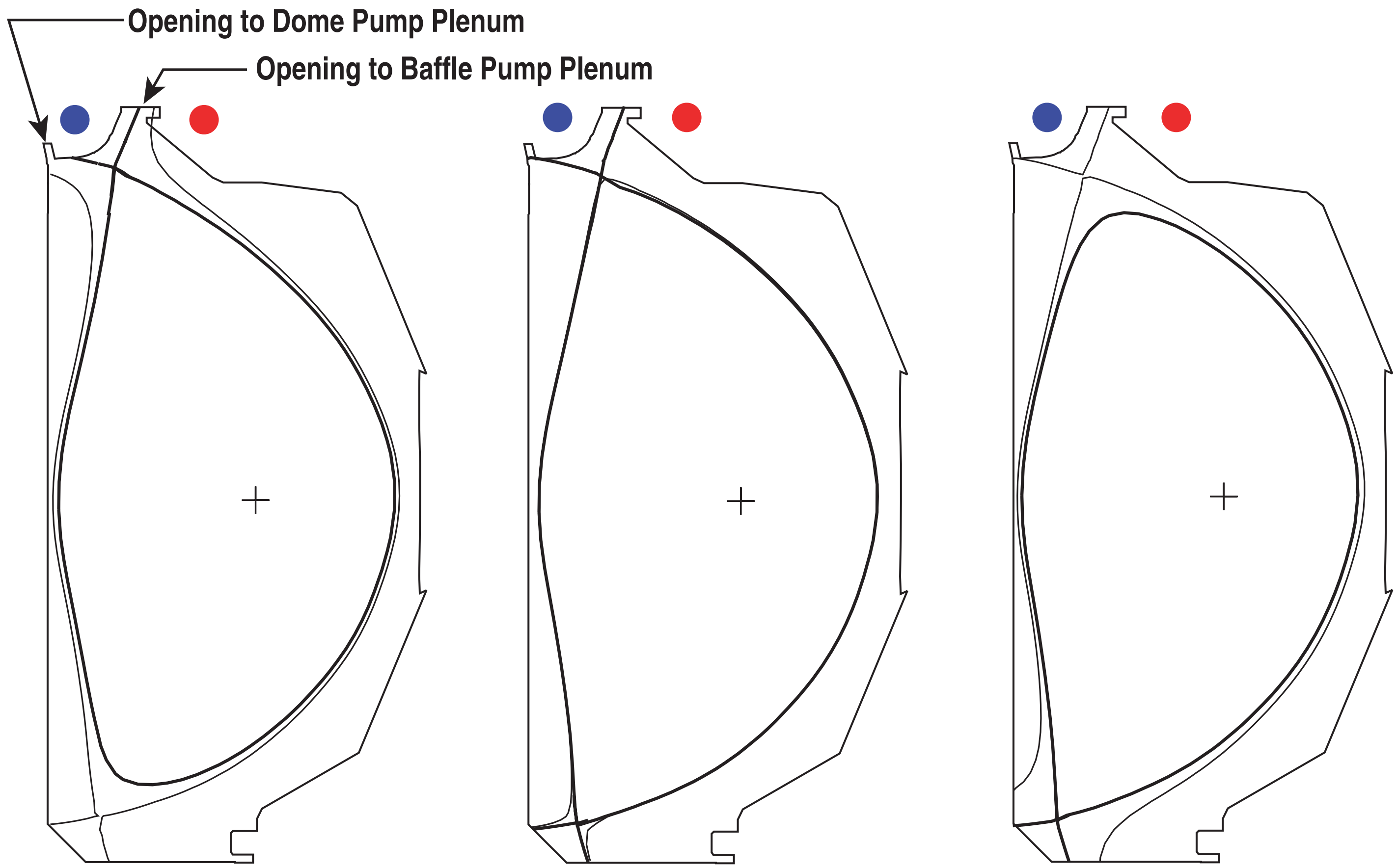
MAIN POINTS

Changes in magnetic balance near the double-null (DN) divertor shape for H–mode plasmas have important consequences for particle exhaust

- Divertor topology near DN has a much stronger effect on pumping the inner divertor target than on the outer divertor divertor target
- The particle pumping observed at the inner and outer divertor target(s) were qualitatively consistent with the re-distribution of particles expected in the presence of $B\times\nabla B$ and $E\times B$ drifts in the scrape-off layer and divertor(s),
  - i.e., the direction of the toroidal field has a strong effect on the ratio of the inboard pumping rate to the outboard pumping rate
- Changes is recycling activity in front of the entrance to the pumping plenum is a good indicator of changes occurring in the particle exhaust rate
- Paricle exhaust by pumping on either the inner or the outer divertor legs depends strongly on pedestal density

— PUMPED PLASMA STUDY —

ACTIVE PARTICLE EXHAUST OCCURS ONLY IN THE UPPER DIVERTOR VIA THE DOME-AND BAFFLE PUMP SYSTEMS



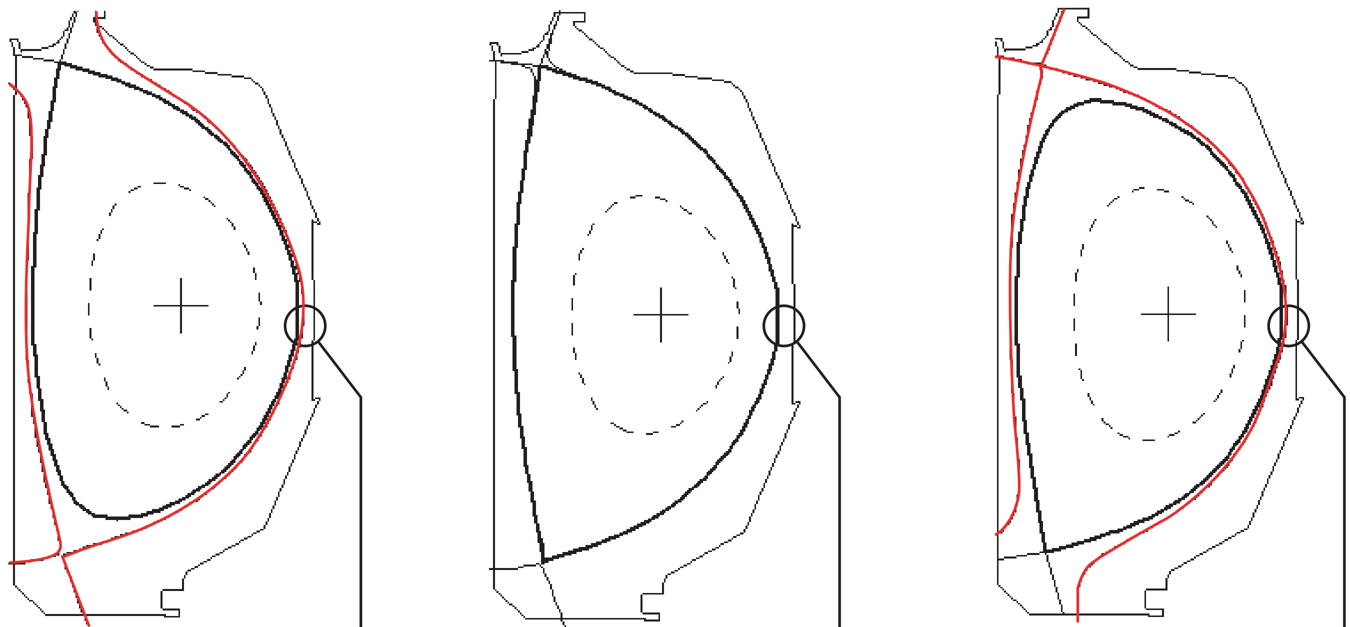
USN (dRsep = +1.2 cm) | DN (dRsep ≅ 0) | LSN (dRsep = –1.2 cm)

I_P = 1.2 MA
B_T = 1.9 T
P_{INJ} = 6-11 MW
$\frac{\tau_E}{\tau_{E89P}}$ = 2.1 - 2.5

- The "dome" pump exhausts particles at the upper <u>inner</u> divertor target
- The "baffle" pump exhausts particles at the upper <u>outer</u> divertor target

MAGNETIC BALANCE IS QUANTIFIED BY *dRsep*

dR_{sep} → { The radial distance between the upper divertor separatrix and the lower divertor separatrix, as determined at the outboard midplane } → { $dR_{sep} > 0$ (USN) $dR_{sep} = 0$ (DN) $dR_{sep} < 0$ (LSN) }

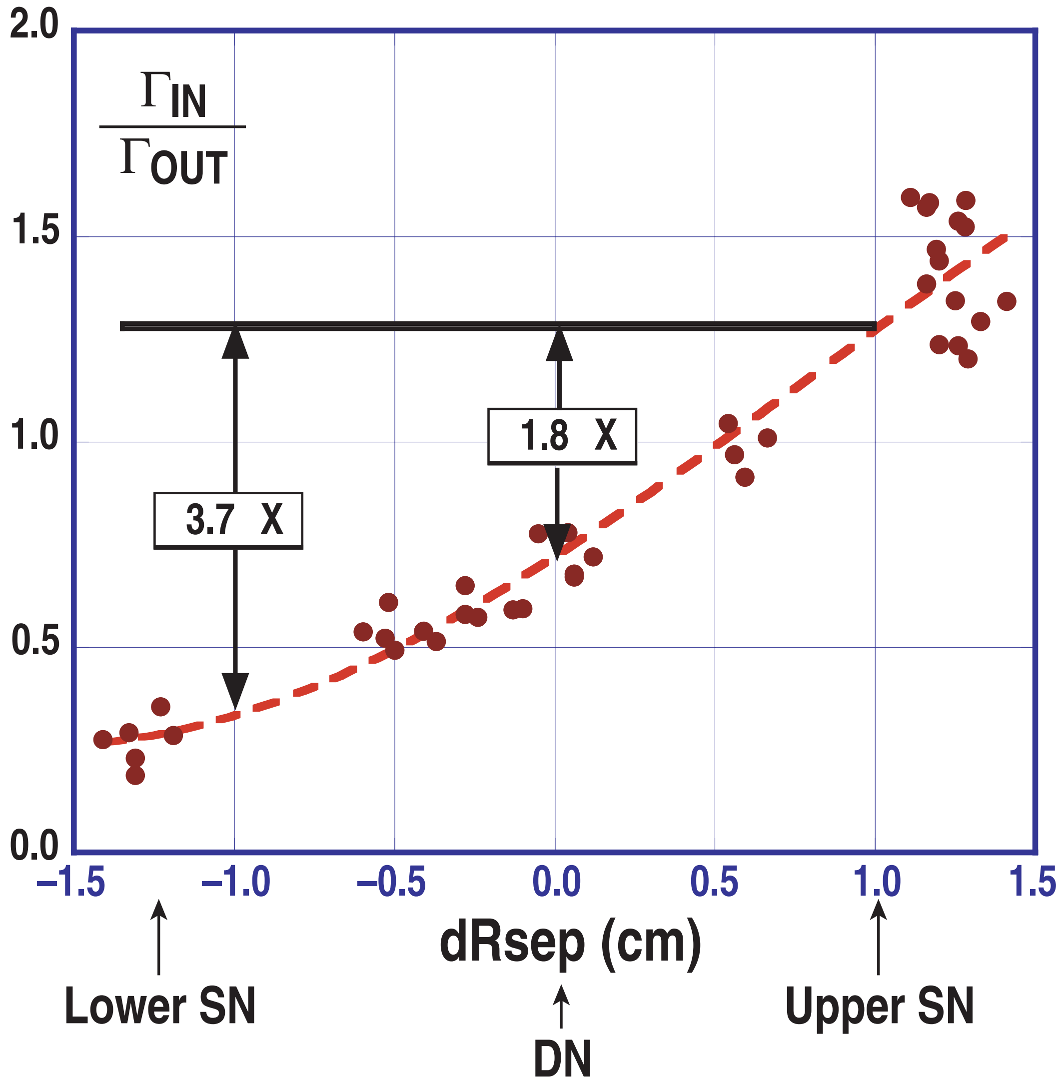


UPPER SINGLE-NULL
dR_{sep} = +2.0 cm

DOUBLE-NULL
dR_{sep} = 0.0 cm

LOWER SINGLE-NULL
dR_{sep} = –2.0 cm

THE RELATIVE IMPORTANCE OF INBOARD PUMPING TO OUTBOARD PUMPING DROPS RAPIDLY FOR dRsep = +1 cm → –1 cm



- "Γ_{IN}" is the particle exhaust rate at the upper inner divertor target
- "Γ_{OUT}" is the particle exhaust rate at the upper outer divertor target

Note: the $\vec{B} \times \nabla B$ ION DRIFT direction is toward the upper divertor for the data shown here

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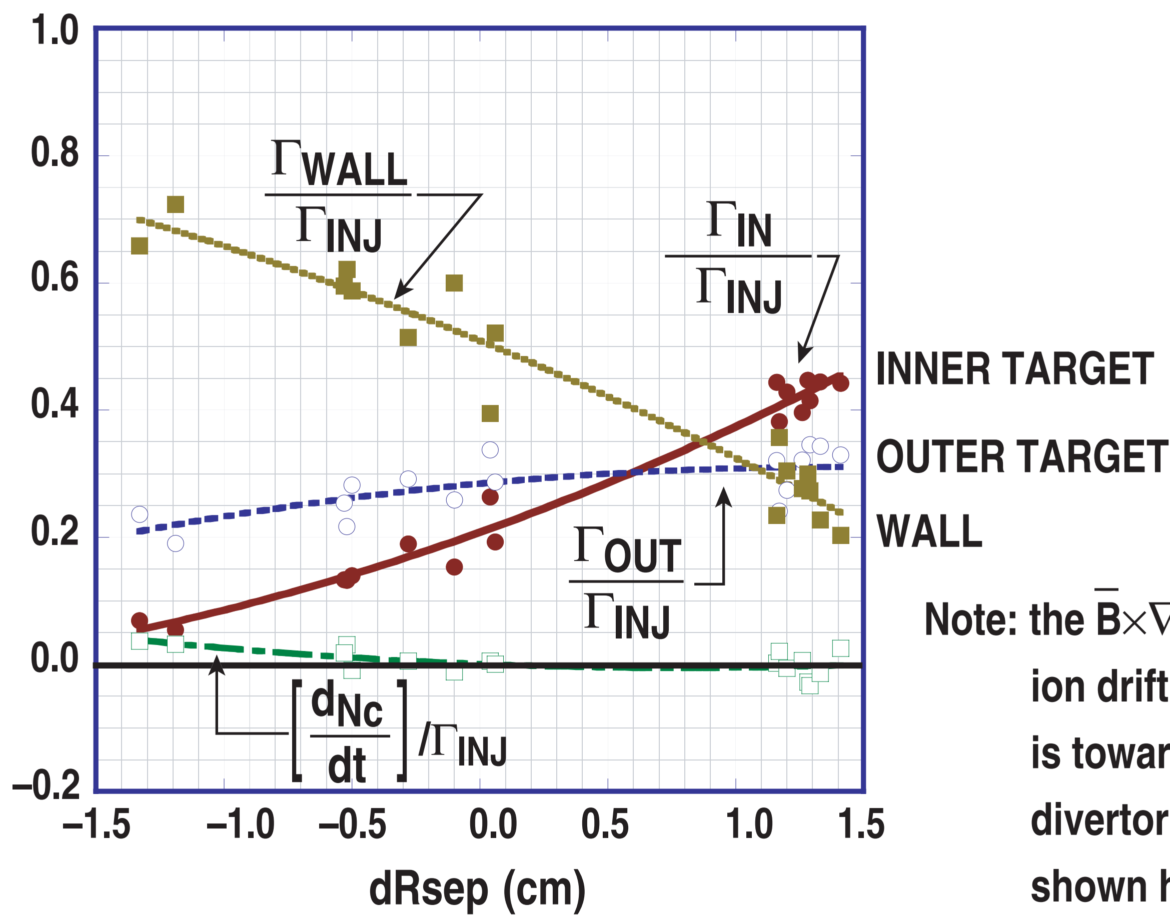
PUMPING AT THE OUTER DIVERTOR TARGET IS INSENSITIVE TO CHANGES IN dRsep BETWEEN 0 AND +1.5 cm BUT PUMPING AT THE INNER DIVERTOR TARGET IS SENSITIVE

$$0 = \Gamma_{INJ} - \Gamma_{IN} - \Gamma_{OUT} - \Gamma_{WALL} - \frac{dNc}{dt}$$ (Particle Balance)



Note: the $\bar{B}\times\nabla\bar{B}$ ion drift direction is toward the upper divertor for the data shown here

- Narrow density window: $n_{e,PED} = (0.37–0.40)\times10^{20}\ m^{-3}$

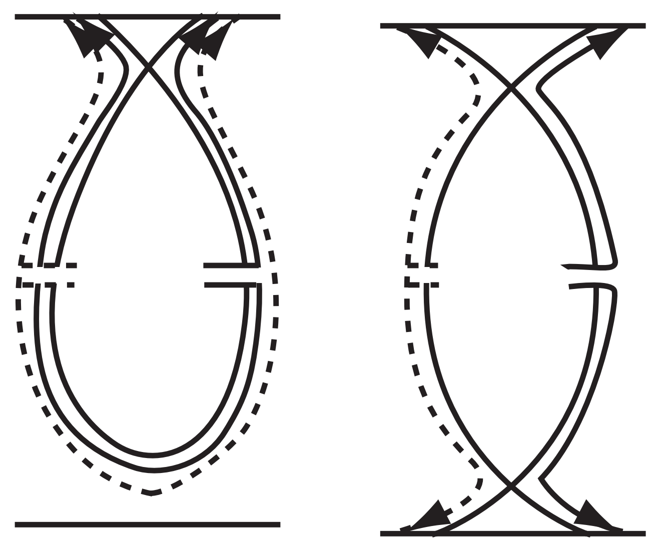
122-04/TP/jy

THE SENSITIVITY OF THE PUMPING RATE AT THE INNER DIVERTOR TARGET TO CHANGE IN MAGNETIC BALANCE CAN BE UNDERSTOOD IN TERMS OF WHERE PARTICLES FROM THE CORE ENTER THE SCRAPE-OFF LAYER

- Particles/s flowing into the SOL (LFS) ≈ (3 –4] × # particles/s flowing into the SOL (HFS)
  - Smaller plasma surface area on the high-field side (HFS)
  - Steeper radial gradients in edge core density on the (LFS)

- Upper outer divertor:
  - dRsep = +1 cm ⇒ 0 has only a minor impact on the direct particle flow into the upper outer divertor

- Upper inner divertor:
  - dRsep = +1 cm ⇒ 0 severs the direct route from the LFS to the upper inner divertor, starving the inner divertor of a major source of fueling



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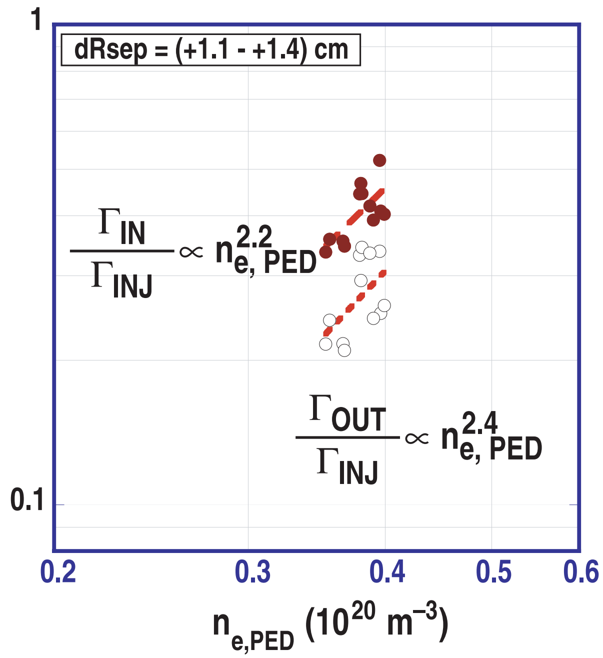
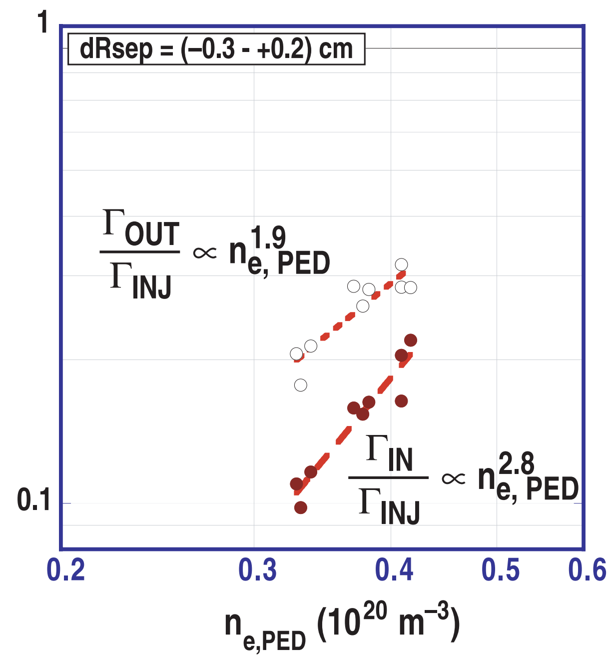
THE PUMPING RATES AT THE INNER AND OUTER TARGETS DEPEND STRONGLY ON PEDESTAL DENSITY FOR BOTH SN AND DN





	n_{ped} at 100% Pumping
SN:	$0.46 \times 10^{20} m^{-3}$
DN:	$0.56 \times 10^{20} m^{-3}$

$\Gamma_{PUMP} \propto I_{sat} \propto n_u^2 \propto n_{e,ped}^2$

- $\Gamma_{PUMP} \propto I_{sat}$: λ_{ei} > Distance to pump entrance
- $I_{sat} \propto n_u^2$: Two-point model
- $n_u^2 \propto n_{e,ped}^2$: Assume tightly linked

Where

$\lambda_{ei} \rightarrow$ electron-ion ionization mfp, $I_{sat} \rightarrow$ particle flux at target, $n_u \rightarrow$ upstream density on separatrix

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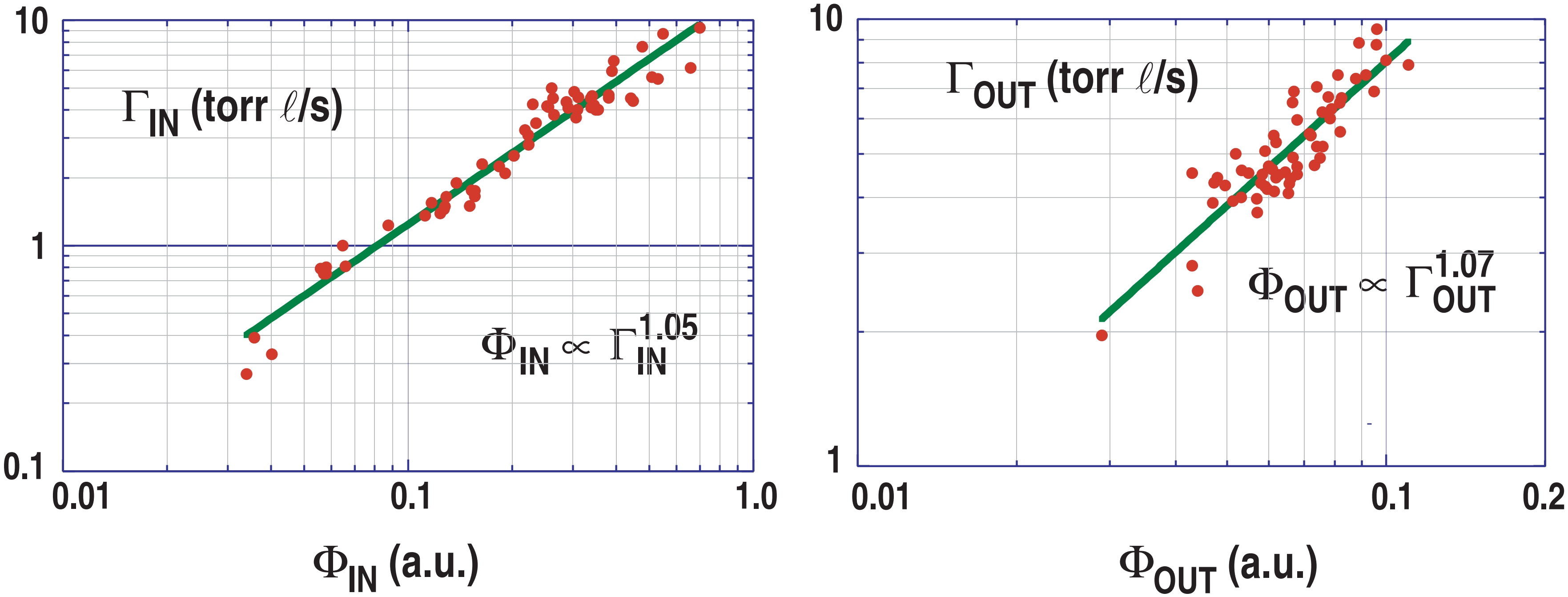
— LOW DENSITY, HIGH PERFORMANCE PLASMAS —

THERE IS A LINEAR RELATIONSHIP BETWEEN RECYCLING RADIATION (Φ) AND PARTICLE EXHAUST AT THE INNER AND OUTER PUMPS



- $\Gamma_{IN} \propto I_{sat,IN} \propto \Phi_{IN}$
- $\Gamma_{OUT} \propto I_{sat,OUT} \propto \Phi_{OUT}$

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THE BASIC TWO-POINT MODEL PREDICTS A QUADRATIC DEPENDENCE OF THE PARTICLE EXHAUST WITH DENSITY AT THE PLASMA EDGE

- The basic equations of the basic Two-Point model are:
  - $2\, n_t T_t = n_u T_u$ — Eq. (1) $\Rightarrow$ Pressure balance
  - $[T_u]^{3.5} = [T_u]^{3.5} + 3.5\, q_{||} L/\kappa_{0e}$ — Eq. (2) $\Rightarrow$ Power balance
  - $q_{||} = \gamma\, n_t kT_t C_{st}$ — Eq. (3) $\Rightarrow$ Sheath heat transmission

where

- u,t $\Rightarrow$ Subscripts denote upstream and divertor quantities
- κ_{0e} $\Rightarrow$ Electron parallel conductivity coefficient
- γ $\Rightarrow$ Sheath heat transmission coefficient
- L $\Rightarrow$ Distance between the divertor target and stagnation point along a separatrix field line
- C_{st} $\Rightarrow$ Ion speed of sound at the target

THE BASIC TWO-POINT MODEL PREDICTS A QUADRATIC DEPENDENCE OF THE PARTICLE EXHAUST WITH DENSITY AT THE PLASMA EDGE (Continued)

- From Eqs. (1–3), the particle flux density (Γ_t) at the divertor target is:

$$\Gamma_t \propto \frac{(n_u)^2\, L^{0.57}}{(q_{||})^{0.43}} \qquad \text{Eq. (4)}$$

- If we assume that the pedestal density n_{PED} and n_u are tightly linked, then:

$$\Gamma_t \propto \frac{(n_{PED})^2\, L^{0.57}}{(q_{||})^{0.43}} \qquad \text{Eq. (5)}$$

- Thus, we would expect that:

$$\Gamma_{EXHAUST} \propto \Gamma_t \propto (n_{PED})^2 \qquad \text{(see figure)}$$

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THE RATE AT WHICH PARTICLES ARE PUMPED IS PROPORTIONAL TO THE RATE AT WHICH PARTICLES STRIKE THE DIVERTOR TARGETS

- **Particles neutralized at the divertor target reach the pump entrance (and are subsequently pumped) without undergoing re-ionization, if**

$$\lambda_{ei} > D$$

where λ_{ei} is the mean free ionization length of neutrals distance, and D is the distance from the strike point to the cryopump entrance

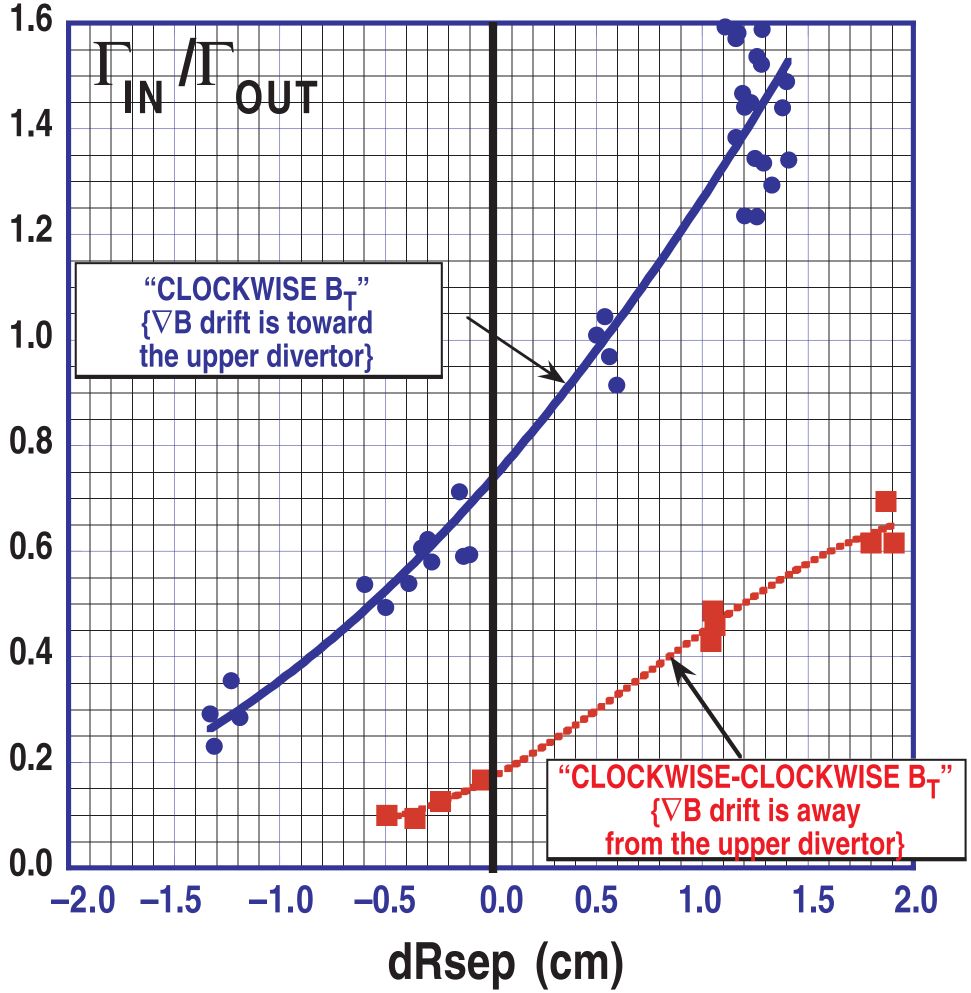
- **This suggests that the rate of particles pumping would largely depend on divertor geometry and the ion particle flux profile***

- **Since λ_{ei} > D for the low density, high performance plasmas discussed here, we expect that the number of particles pumped by the cryo-pumps be proportional to the number of particles striking the divertor target, so that,**

$$\Gamma_{EXHAUST} \propto \Gamma_t \qquad \text{Eq. (6)}$$

* R. Maingi, J.G. Watkins, M.A. Mahdavi, and L.W. Owen, "Pump Plenum Pressure Dependence on Divertor Plasma Parameters and Magnetic Geometry in the DIII–D Tokamak," GA-G23057 Report, (March, 1999)

THE DIRECTION OF THE TOROIDAL MAGNETIC FIELD HAS A STRONG EFFECT ON THE RATIO OF INBOARD PUMPING TO OUTBOARD PUMPING IN THESE HIGH ENERGY CONFINEMENT DISCHARGES



Measurements are made by the inner and outer cryo-pumps in the upper divertor

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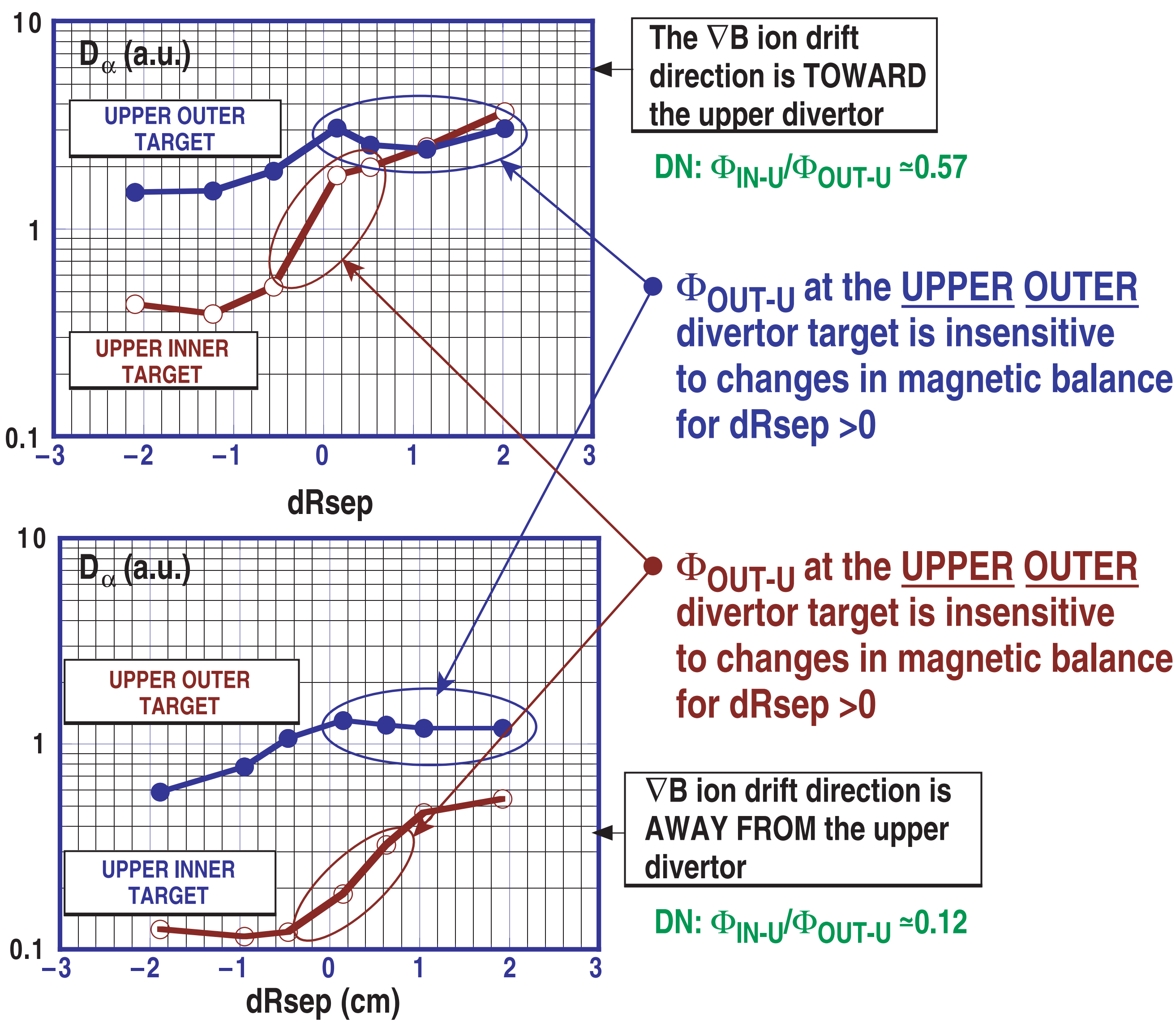
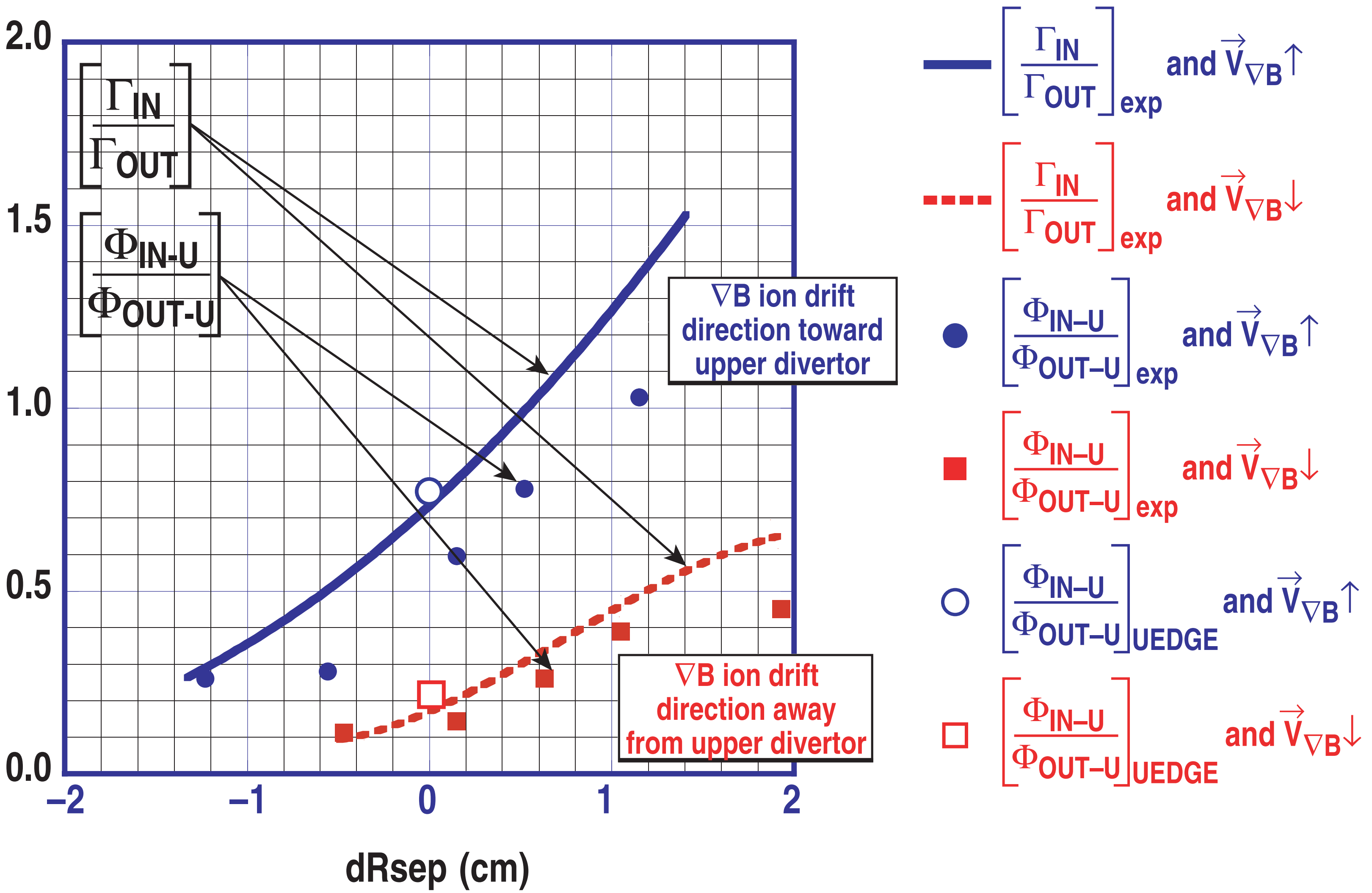
—FOR CASES WHERE THERE IS NO ACTIVE PUMPING—

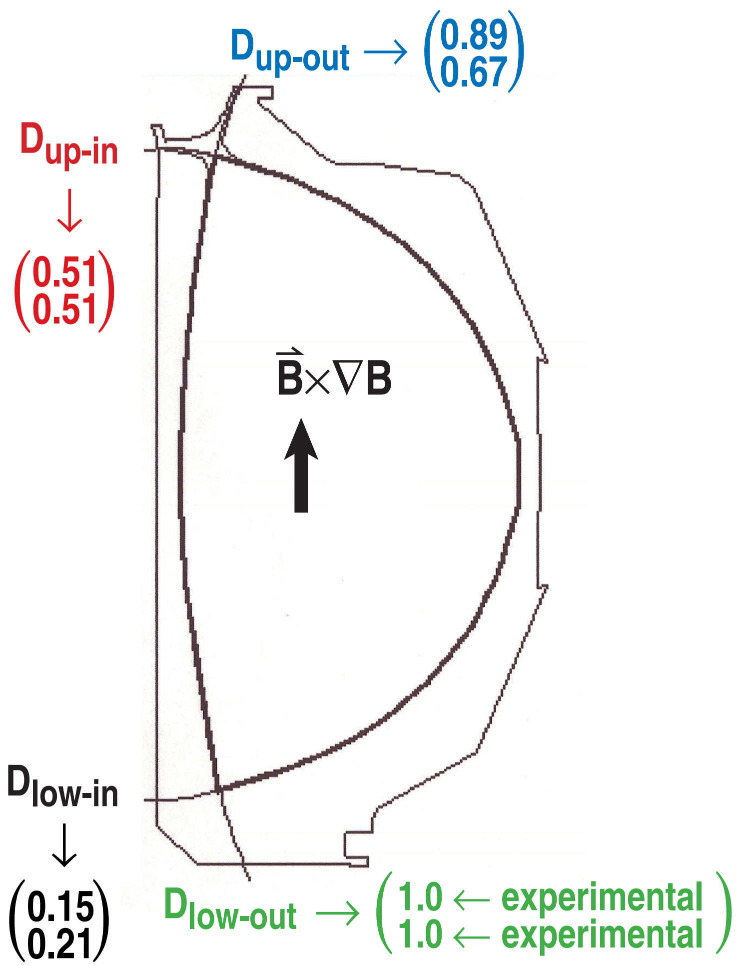
THE RECYCLING RADIATION AT THE INNER AND OUTER STRIKE POINTS IN THE UPPER DIVERTOR DEPENDS STRONGLY ON BOTH MAGNETIC BALANCE AND THE B×∇B DRIFT DIRECTION



THE EXHAUST RATIO FOR THE PUMPED CASES AND THE RECYCLING RATIO FOR UNPUMPED CASES SHOW SIMILAR BEHAVIORS WITH CHANGES IN dRsep AND ∇B ION DRIFT DIRECTION



UEDGE MODELING OF THE RECYCLING DISTRIBUTION IS REASONABLY CONSISTENT WITH THE DATA



Recycling Ratios in DN

	Experiment	UEDGE
$D_{up\text{-}out}/D_{up\text{-}in}$	1.7	1.3
$D_{low\text{-}out}/D_{low\text{-}in}$	6.7	4.8
$D_{up\text{-}in}/D_{low\text{-}in}$	3.4	2.4
$D_{up\text{-}out}/D_{low\text{-}out}$	0.9	0.7

UEDGE indicates that the E×B poloidal drift is important to understanding these results

THERE ARE SEVERAL SIMILARITIES IN BEHAVIOR BETWEEN Γ_{IN} AND Φ_{IN-U} AND BETWEEN Γ_{OUT} AND Φ_{OUT-U}

- The dependence of Φ_{IN-U}/Φ_{OUT-U} on dRsep mirrors that of Γ_{IN}/Γ_{OUT}

- The dependence of Φ_{IN-U}/Φ_{OUT-U} on the direction of the $B\times\nabla B$ ion drift direction also mirrors that of Γ_{IN}/Γ_{OUT}

- Γ_{IN} and Φ_{IN-U} both depend strongly on dRsep near DN

- Γ_{IN} and Φ_{IN-U} are both insensitive to changes in dRsep for dRsep > 0

THESE SIMILARITIES IN BEHAVIOR SUGGEST THAT THE SAME UNDERLYING PHYSICS APPLY TO BOTH PUMPED AND UNPUMPED CASES

- UEDGE modeling of the SOL and divertor of a similar but non-actively pumped DN plasma has shown that the observed asymmetries in $\Phi_{IN\text{-}U}/\Phi_{OUT\text{-}U}$ was consistent with the presence of E×B and B×∇B particle drifts
  - The electric field is mainly generated by the radial gradient in Te with respect to the flux surfaces in the private flux region and its direction is always away from the Xpoint
  - If the B×∇B ion drift direction is upward in the DN, UEDGE indicates that the E×B drift transports ions through the PFR from the outer- to the inner target in the upper divertor, leading to enhanced recycling at that inner target. Reversed in the lower divertor
  - The UEDGE predictions for $\Phi_{DOME\text{-}U}/\Phi_{BAF\text{-}U}$ in both upper and lower divertors in the DN are shown as open circles and open squares, and are consistent with the experimental values of $\Phi_{DOME\text{-}U}/\Phi_{BAF\text{-}U}$
- Similarity in behavior of $\Phi_{DOME\text{-}U}/\Phi_{BAF\text{-}U}$ and Γ_{IN}/Γ_{OUT}

⇒ Drift particle physics may also be important to Γ_{IN}/Γ_{OUT}

- UEDGE modeling of an actively pumped DN plasma is ongoing

CONCLUSIONS

- Our preliminary analysis of the DIII–D particle pumping data suggests that particle removal at the divertor targets depends on both the magnetic balance and the directions of the particle drifts in the SOL and divertor

- These processes are particularly important for understanding particle exhaust for the DN configuration, where severing the inboard SOL from the outboard SOL dramatically reduced the total direct particle flow to the inner targets and where particle drifts in the SOL and divertor(s) appeared to further redistribute particles between the inner and outer target(s)