Compatibility of the Radiating Divertor with High Performance Plasmas in DIII–D

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DIII–D NATIONAL FUSION FACILITY

GENERAL ATOMICS

273–06/TWP/rs

INTRODUCTION

Introduction

- <u>Issue</u>
  Protecting the divertor structure from excessive power loading
- <u>Possible solution</u>
  "Seed" the divertor with impurities in order to enhance the radiated power upstream of the divertor targets → more uniform dispersal of power loading → "Radiating divertor"
- <u>Trade-offs</u>
  Reducing divertor power loading vs. degrading plasma performance, e.g., impurity accumulation → displacement of fuel ions and degradation in τ_E
- <u>Reduction in impurity accumulation</u>
  Enhance deuterium flow in the scrape-off layer → Counters the thermal gradient force that pushes impurities out of the divertor

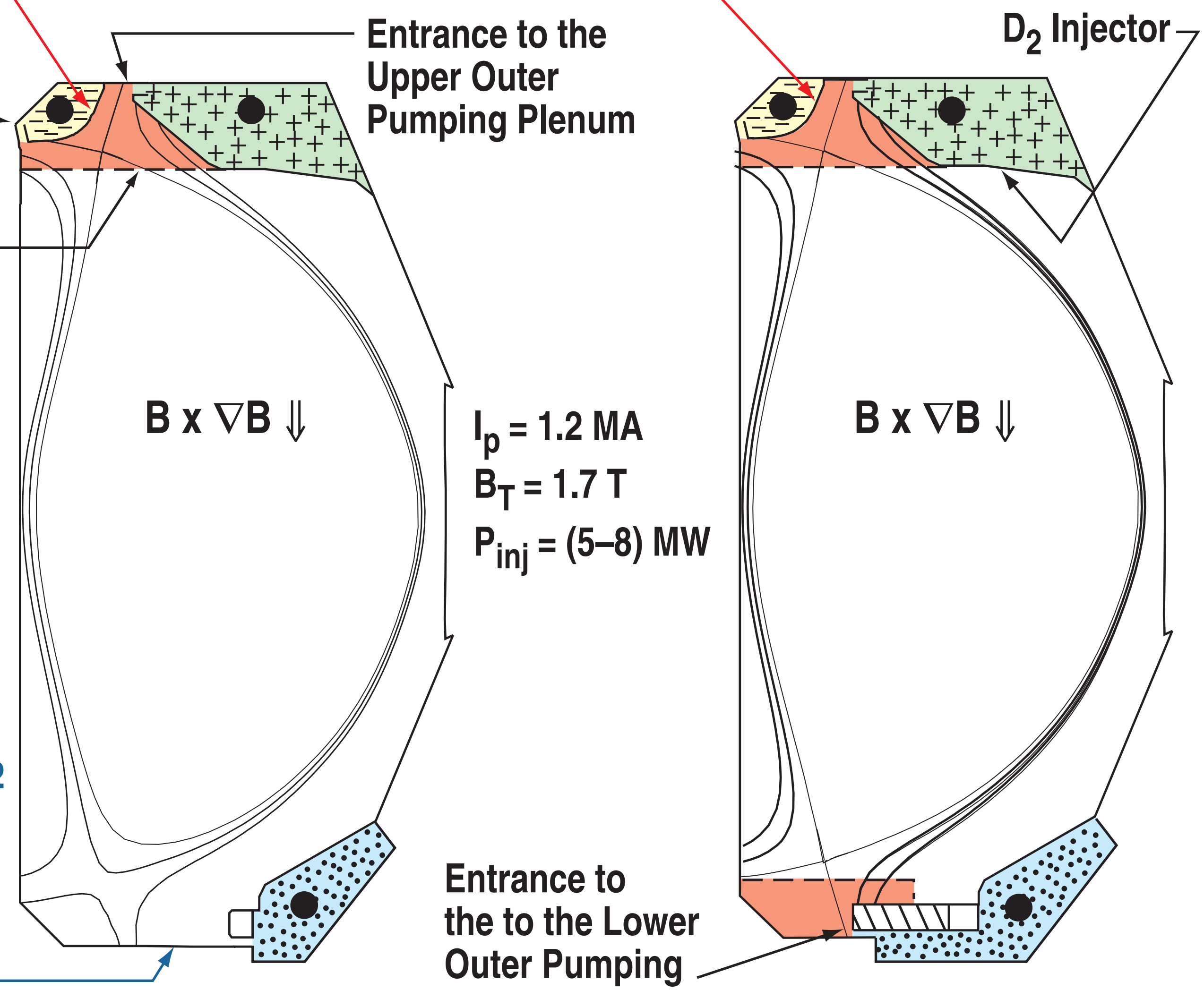
- ***<u>HOW DOES ALL THIS AFFECT "HIGH PERFORMANCE" PLASMA OPS?</u>***

Main Questions

- Is radiating divertor operation compatible with high performance "hybrid" discharges?
- How well can impurities be confined to the "closed" DIII–D divertor?
- How effectively does the radiating divertor reduce power loading at each divertor target?
- Do DNs behave differently than SNs under radiating divertor conditions?

EXPERIMENTAL ARRANGEMENT

DIII–D Puff and Pump Capability Enhanced by DN Pumping



- Argon injected directly into the private flux region
- Enhanced deuterium flow toward the divertor by injecting D_2 from the bottom of the vessel

Experimental Operating Conditions

- Hybrid plasmas are used in this study
  - Similar to ELMing H-mode plasmas with good confinement, e.g., $\tau_E/\tau_{ITER89P} \gtrsim 2$
  - Important difference: absence of sawteeth

    $\Rightarrow$ Improved stability and confinement properties
- 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 protecting the vessel interior
  - ARGON (injected)
    - Radiates effectively under hybrid plasma operating conditions
    - Relatively short $\lambda_{MFP} \rightarrow$ good candidate for confining to the divertor
- Inner and outer divertor legs are attached during puffing

ARGON AT TRACE LEVELS

SINGLE-NULL with B x ∇B DRIFT DOWN

Exhaust enrichment (η_{exh}) $\propto \Gamma_{D2}$ and $\eta_{exh,MAX} \approx 38$

Exhaust Enrichment is One Measure of How to Characterize the Retention of Injected Impurities in the Divertor

$$[\text{exhaust enrichment}] \equiv [f_{EXH}]/[f_{CORE}]$$

where

$$f_{CORE} \equiv [n_{Z,CORE}]/[n_{e,CORE}]$$

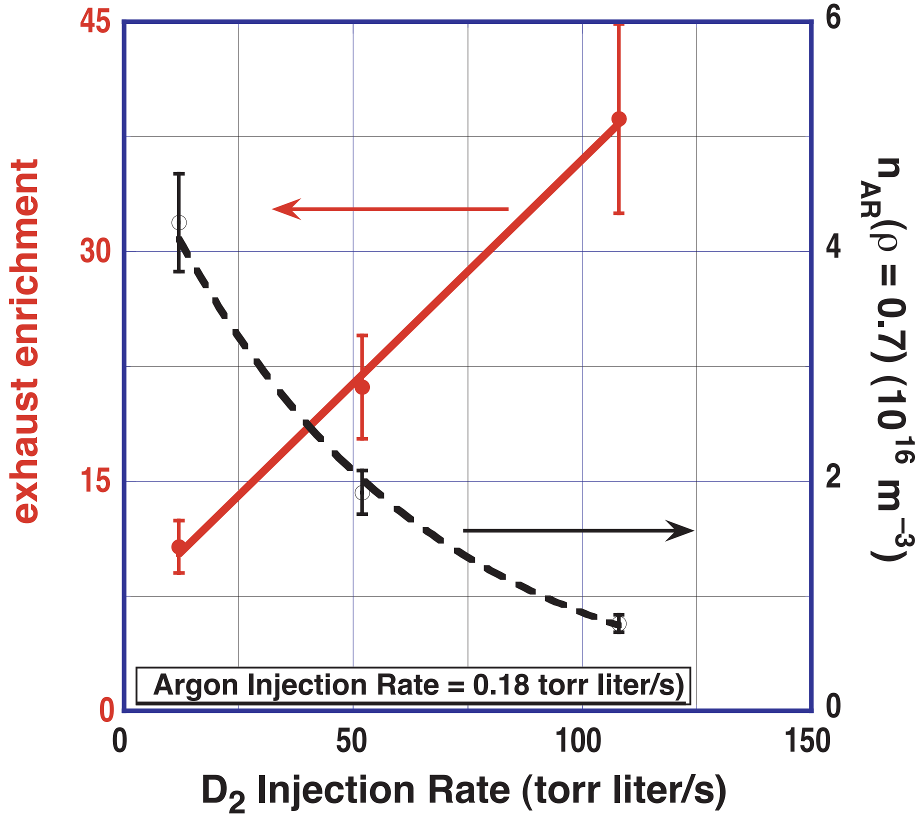
- $n_{e,CORE}$: **Thomson scattering**
- $n_{Z,CORE}$: **Charge-Exchange Recombination** (Ar^{+16} and C^{+6} profiles)

$$[f_{EXH}] \equiv [P_{Z,EXH}]/[2 \times P_{D2,EXH}]$$

- $P_{Z,EXH}$, $P_{D2,EXH}$: **Modified Penning gauge** (partial pressure of deuterium and argon inside outer baffle)

The Exhaust Enrichment of Trace Argon Increased by a Factor of 3 Over the Range of Γ_{D2} Considered

The argon density decreased by almost a factor of six over the Γ_{D2} range considered



Comparison with a previous DIII–D experiment with trace argon

	1998*	2005
Γ_{D2} (Torrℓ/s)	84	108
DIV. Config.	"OPEN"	"CLOSED"
$\overline{B} \times \nabla B$	Toward Xpt	Away from
Pumping	Outer	Inner + Outer
η_{EXH}	17	38

*M.R. Wade, et al, J. Nucl. Matter., 266–269 (1999) 44

Argon Enrichment Improves Significantly with Combined D_2 Injection and Pumping

	Case A	Case B	Case C
Γ_{D2} (Torr ℓ/s)	0	52	107
Γ_{AR} (Torr ℓ/s)	1.3	1.3	1.3
n_{AR}/n_e (ρ=0.7) (%)	0.092	0.034	0.013
η_{EXH}	11.4	24.3	35.1
$n_{e,ave}$ (10^{20} m^{-3})	0.47	0.58	0.61
$n_{e,DIV,OUT}$ (10^{20} m^{-3})	0.25	0.40	0.50
$n_{e,DIV,IN}$ (10^{20} m^{-3})	0.29	0.59	1.02

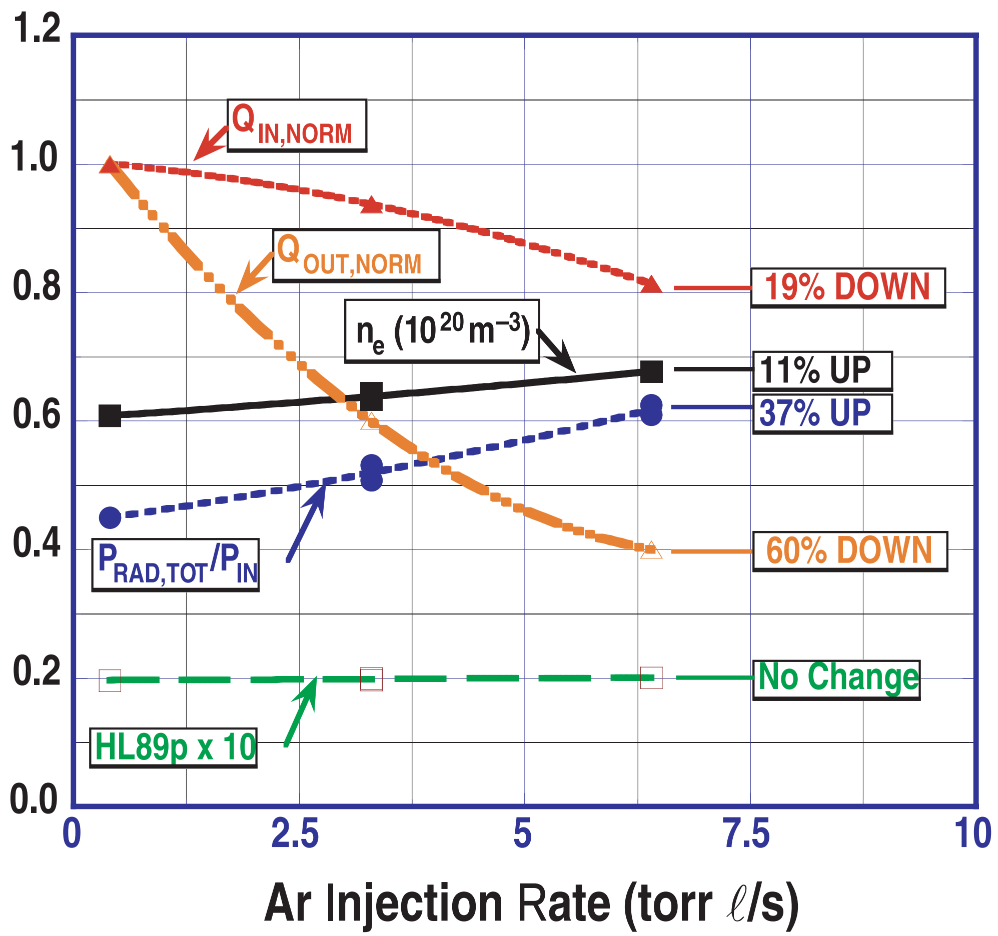
Note: We choose ρ=0.7, because MIST impurity transport analysis of the hybrid plasmas under investigation showed that helium-like argon at ρ=0.7 was by far the dominant charge state of argon → good approximation for the total argon density

ARGON AT PERTURBING LEVELS

SINGLE-NULL with $B \times \nabla B$ DRIFT DOWN

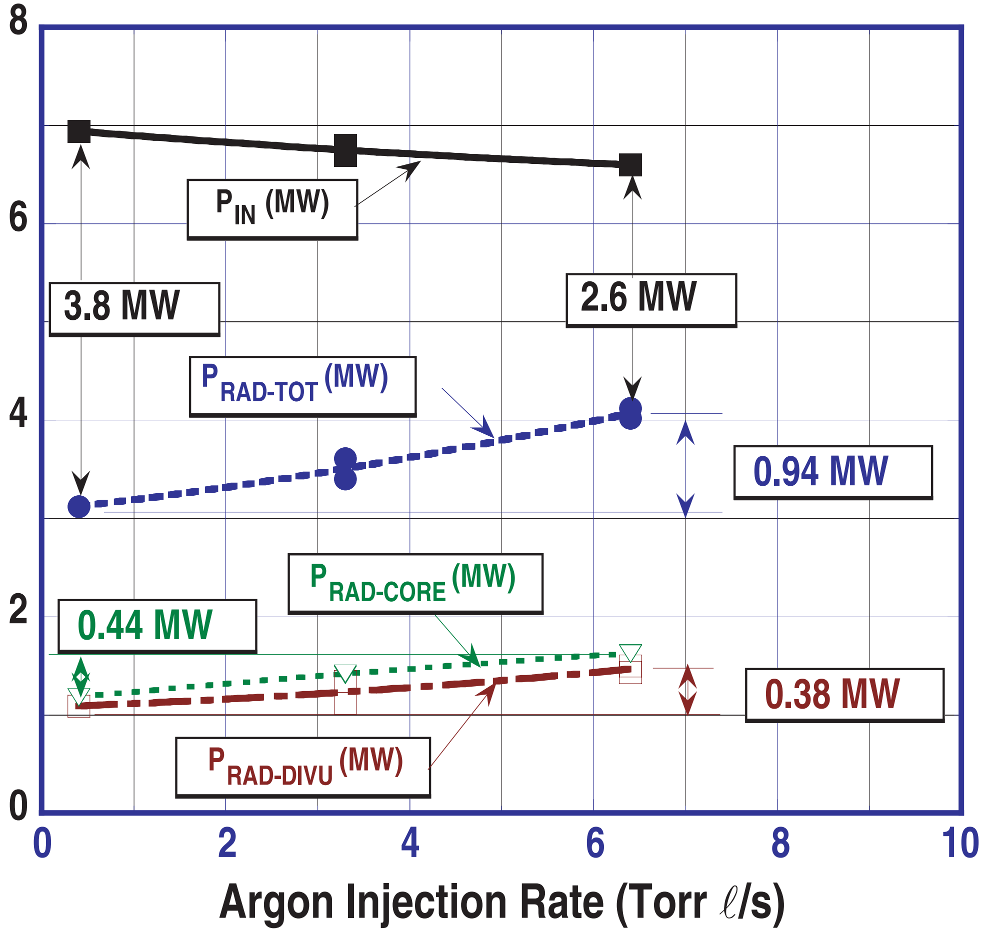
The heat flux reduction at the outer divertor target was much greater than that at the inner divertor target

The Peak Heat Flux at the Outer Divertor Target Decreased Much More than at the Inner Divertor Target, as the Argon Injection Rate Increased



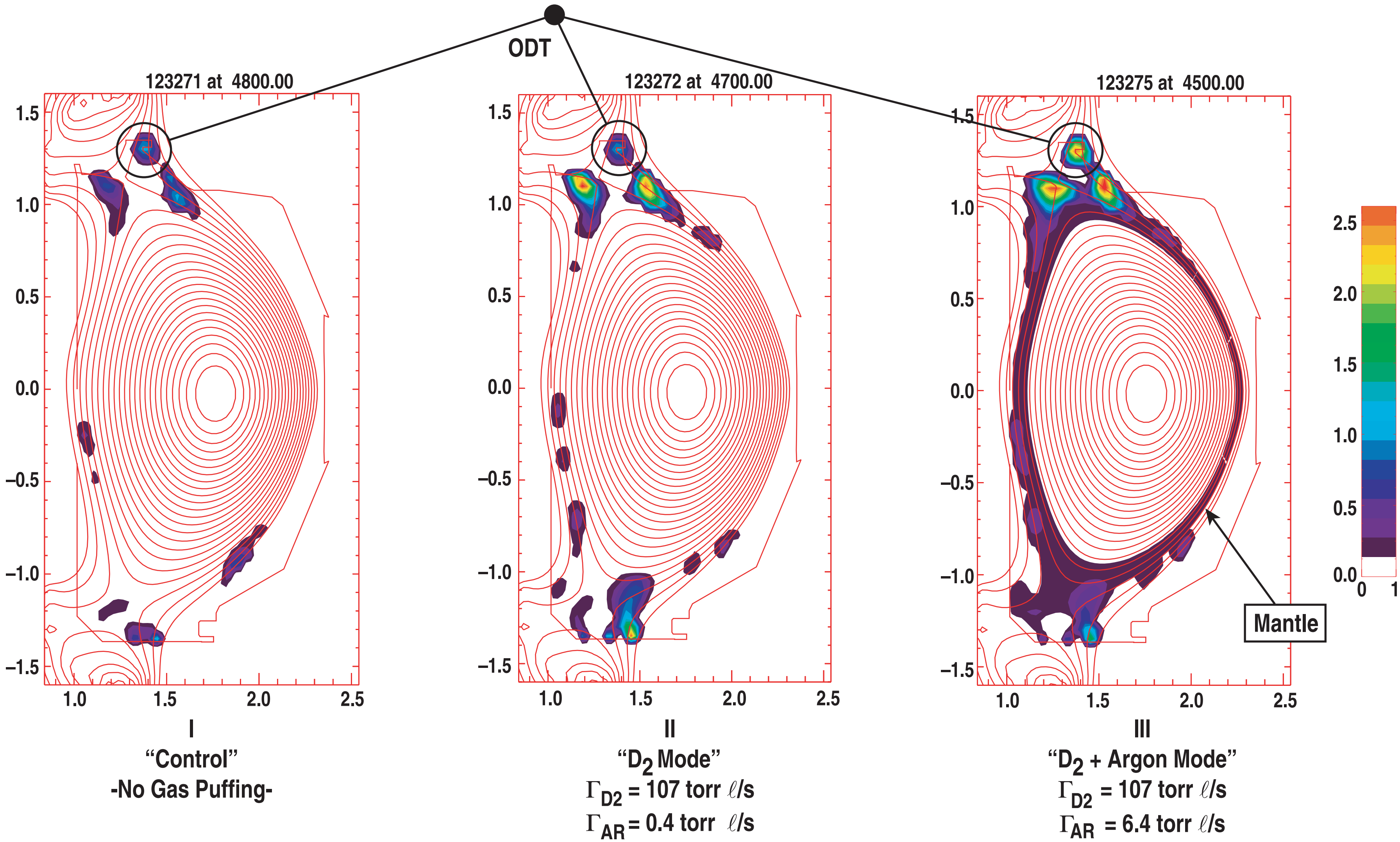
- Modest increase in density with a higher rate of argon injection
- Rise in total radiated power was co-incident with a sharp drop in peak heat flux at the outer divertor target but much less of a drop at the inner divertor target
- Maintain good energy confinement during argon injection

Roughly 40% of the Increase in the Total Radiated Power from High-level Argon Injection was Found in the Divertor

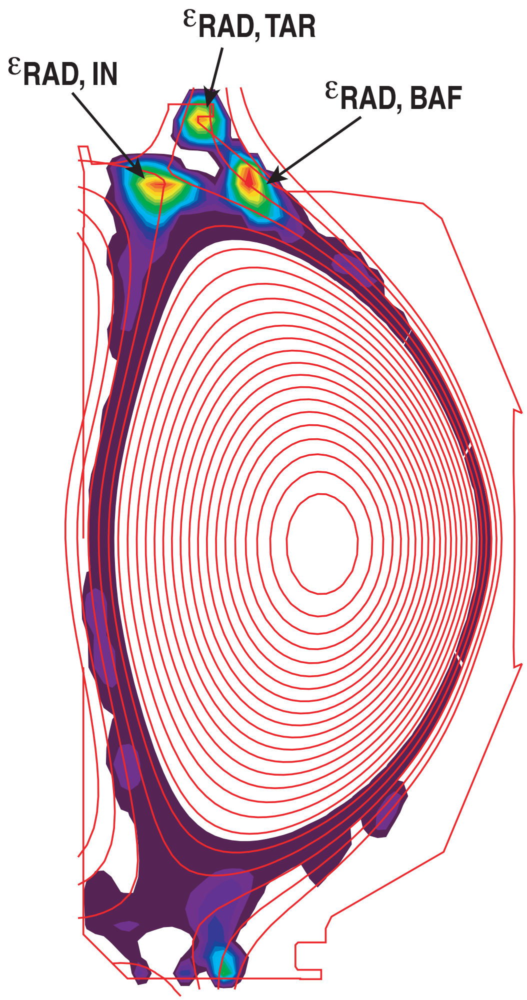


- The increase in both divertor and total radiated powers was linear in Γ_{AR} over the range considered
- About 45% of the increase in $P_{RAD\text{-}TOT}$ with high-level argon injection was found in the core

Argon Injection with Enhanced Deuterium Flow in the SOL was Effective in Raising the Radiated Power Near the Outer Divertor Target (ODT)



The Reduction in the Peak Heat Flux at the Outer Divertor Target may be Associated with the Increase in Radiated Power Near the Target



Comparison of peak emissivities for two cases

	$[\varepsilon_{RAD,IN}]_P$ $[MW/m^3]$	$[\varepsilon_{RAD,BAF}]_P$ $[MW/m^3]$	$[\varepsilon_{RAD,TAR}]_P$ $[MW/m^3]$	$[\hat{Q}_{OUT}]_P$	$[\hat{Q}_{IN}]_P$
D_2 Mode	2.95	2.80	1.10	1.0	1.0
D_2 + Ar Mode	2.85	2.95	2.70	0.37	0.81

- $[\varepsilon_{RAD,TAR}]_P$ increased by 2-3x for the D_2 + Ar mode
- $[\varepsilon_{RAD,BAF}]_P$ and $[\varepsilon_{RAD,IN}]_P$ were comparable in both cases

  - $[\hat{Q}_{OUT}]_P$ is the peak heat flux at the outer divertor target normalized to the "D_2 mode" case
  - $[\hat{Q}_{IN}]_P$ is the peak heat flux at the inner divertor target normalized to the "D_2 mode" case

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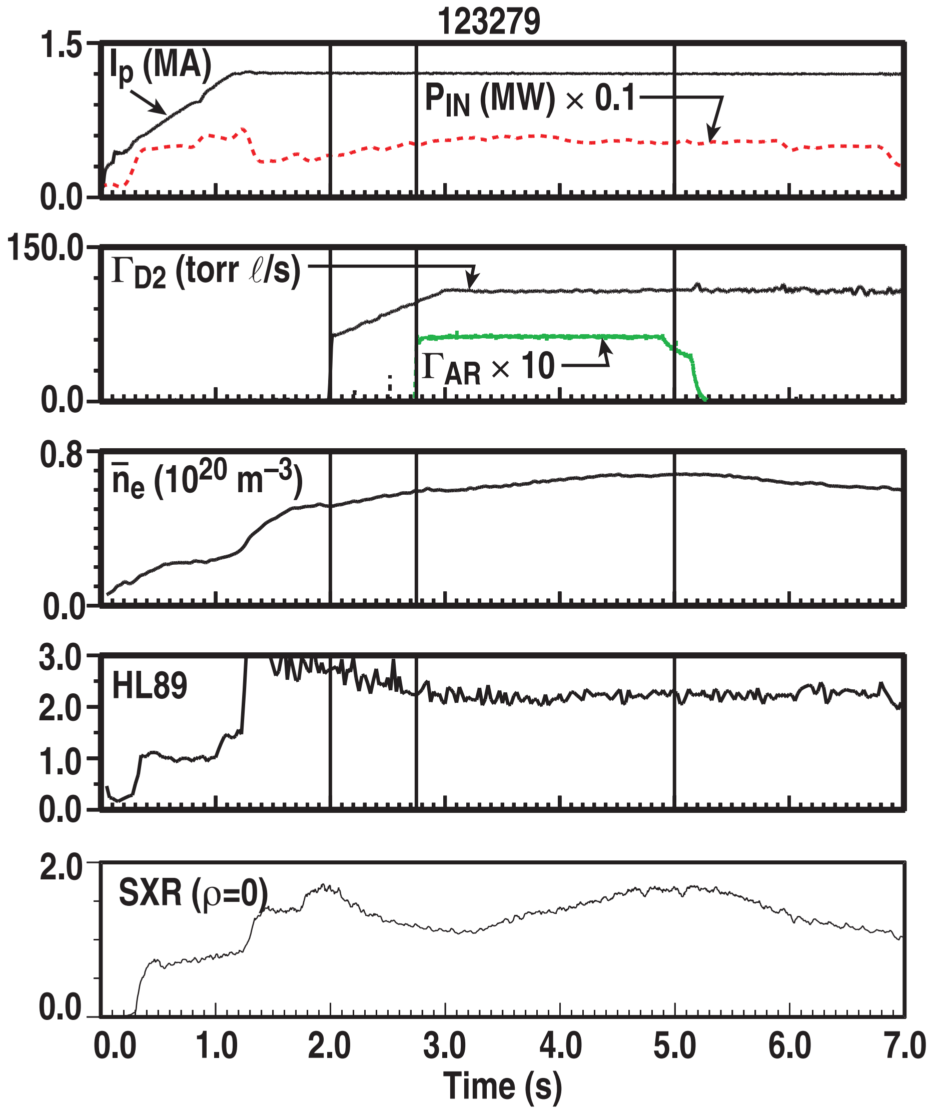
ARGON AT PERTURBING LEVELS

SINGLE-NULL with $B \times \nabla B$ DRIFT DOWN

η_{exh} was insensitive to Γ_{AR}

The Response of a Hybrid-class Plasma to D_2 Injection and to D_2+Argon Injection is Shown



t ≈ 2.0 – 2.8 s — D_2 injection only

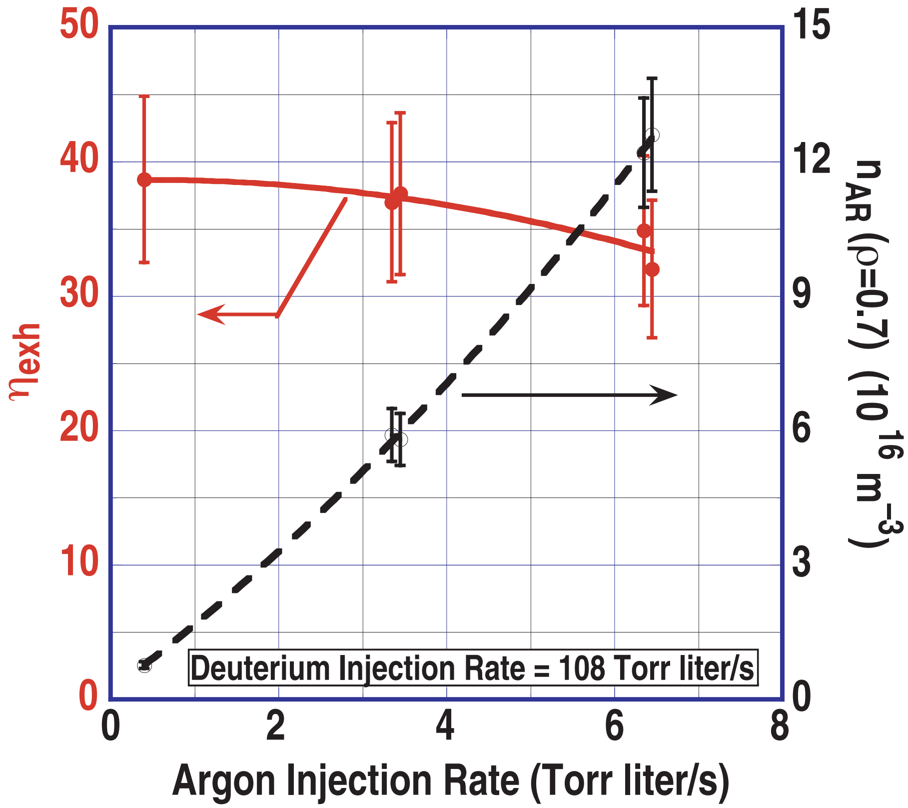
t ≈ 2.8 – 5.0 s — D_2 + argon injection

t ≈ 5.0 – 7.0 s — D_2 injection only

- Roughly 10% increase in line-averaged density after argon injection is initiated
- No change in the energy confinement time with the addition argon to D_2
- Minimal sawtooth activity

The Exhaust Enrichment was Insensitive to the Argon Injection Rate at Perturbing Levels

The Argon density increased a little faster than linear



Comparison of Exhaust Enrichment

	1998*	2005
Γ_{D2} (Torr. ℓ)	190	108
Γ_{AR} (Torr. ℓ)	3.8	6.4
$\bar{n}_e$ (10^{20} m^{-3})	0.80	0.67
P_{IN} (MW)	12	6.7
$\tau_E/\tau_{ITER89P}$	1.7	2.0
P_{RAD}/P_{IN}	0.72	0.63
$P_{RAD,CORE}/P_{IN}$	0.17	0.24
Z_{EFF}	1.85	2.1
η_{EXH}	≈5	32

*M.Wade, et al, J. Nucl. Matter., 266–269 (1999) 44

A Comparison of D_2 and Argon Gas Puffing Modes on "Hybrid" Plasma Behavior

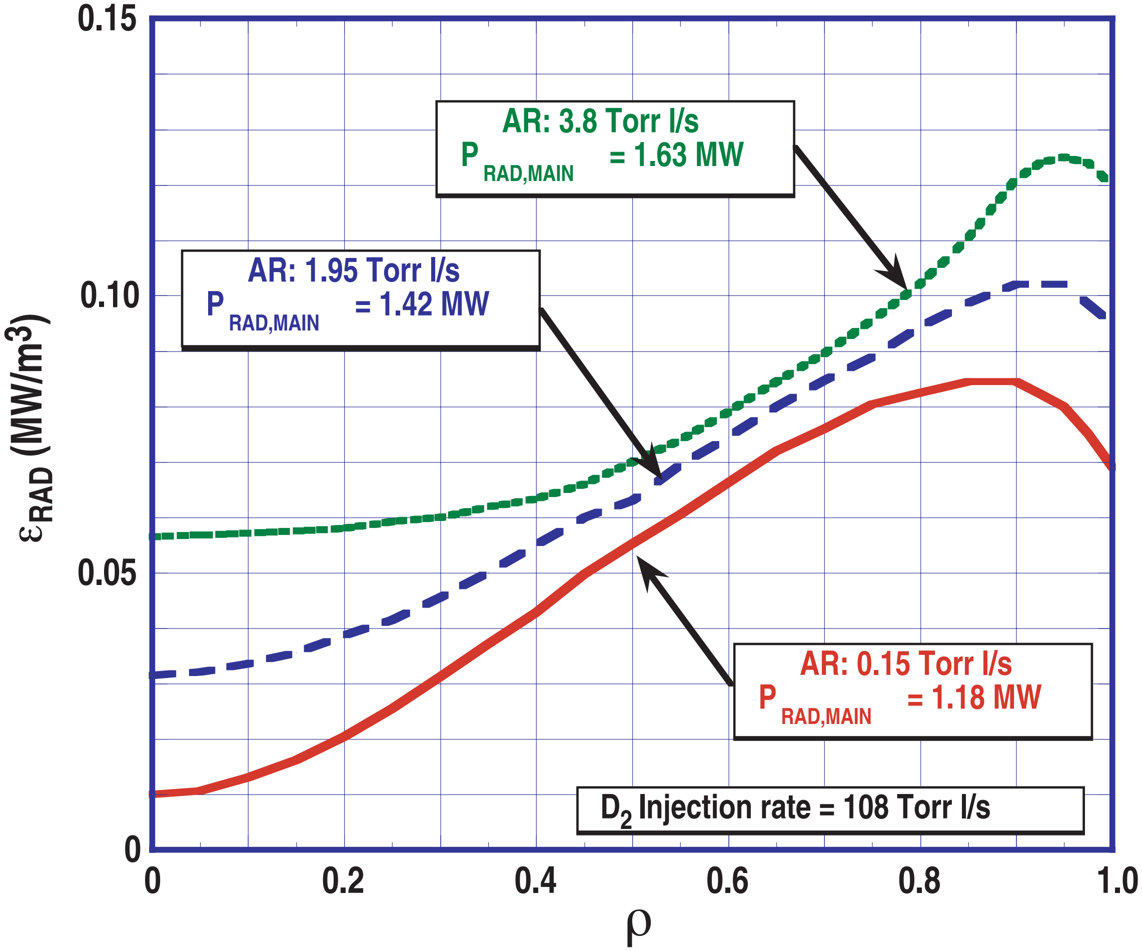
	[CASE 1]	[CASE 2]	[CASE 3]
Γ_{D2} torr liter/s	108	108	108
Γ_{AR} torr liter/s	0.4	3.4	6.4
$\bar{n}_e$ (10^{20} m^{-3})	0.61	0.64	0.67
$H_{ITER\ 89P}$	2.0	2.0	2.0
P_{IN} (MW)	6.9	6.8	6.6
$P_{RAD,TOT}/P_{IN}$	0.45	0.52	0.63
$P_{RAD,MAIN}/P_{IN}$	0.17	0.21	0.24
$P_{RAD,DIV}/P_{IN}$	0.16	0.18	0.22
$q_{P,IN}$ (MW/m^2)	1.6	1.5	1.3
$q_{P,OUT}$ (MW/m^2)	3.0	1.8	1.2
$T_{e,IN}$ (eV)	10	10	10
$T_{e,OUT}$ (eV)	22	15	10
ν_{ELM} (Hz)	≈ 80	≈ 75	≈ 70
$n_C/n_e[\rho = 0.7]$ (%)	2.1	2.1	2.2
$n_{AR}/n_e[\rho = 0.7]$ (%)	0.013	0.10	0.20
$Z_{EFF}[\rho = 0.7]$	1.65	1.87	2.15
η_{EXH}	38	37	33

ARGON AT PERTURBING LEVELS

SINGLE-NULL with B x ∇B DRIFT DOWN

Roughly 30% of $P_{RAD,CORE}$ was due to argon

The Primary Radiator Inside the Core Plasma is Mainly Carbon, Even at the Highest Argon Injecton Rate



Case 1: "trace argon"
>95% of the radiated power in the core was from carbon

Case 3: "perturbing argon"
25-30% of the radiated power in the core was from argon and the profile was still hollow

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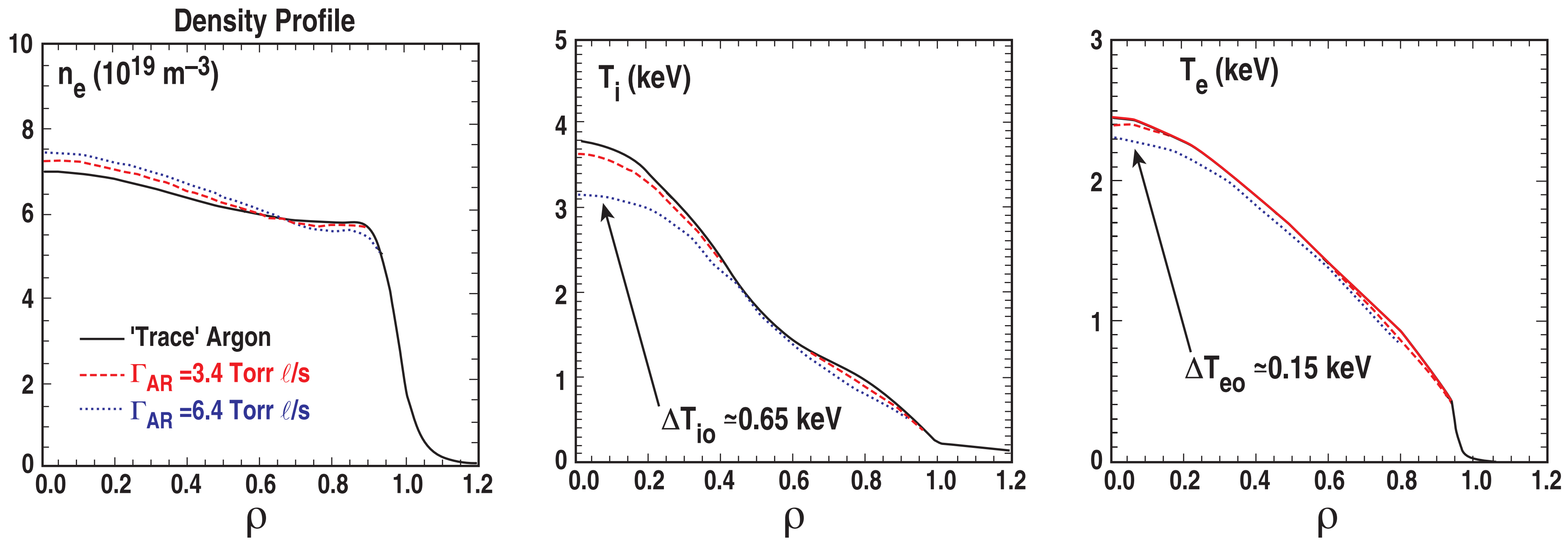
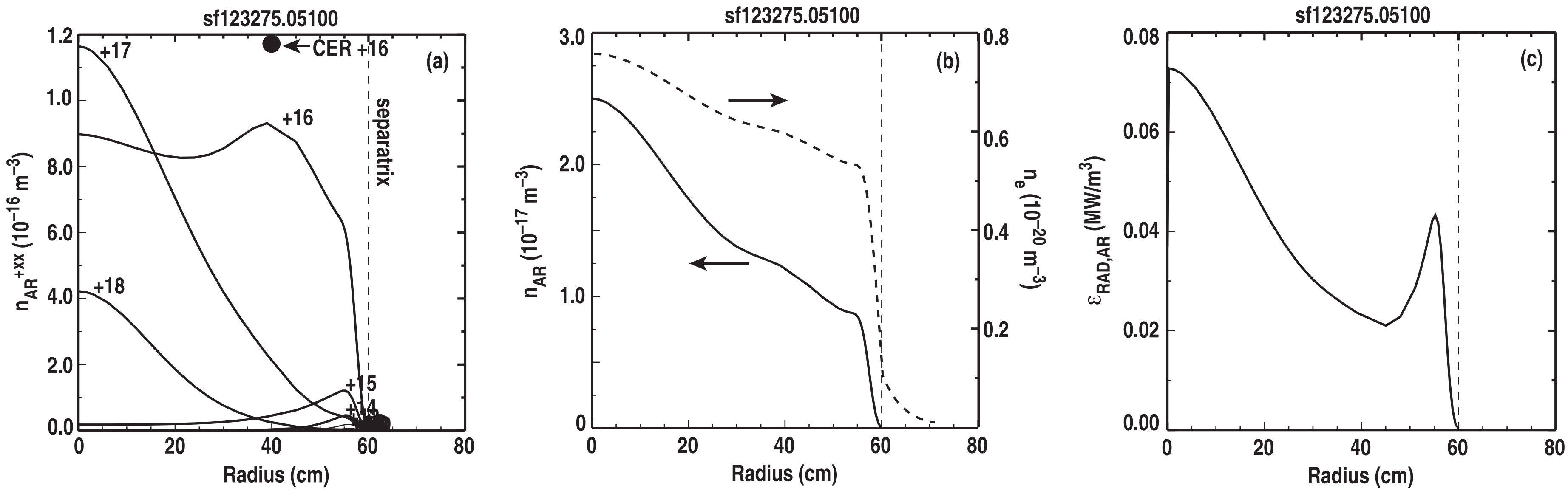
Note: For case 3, 4% of the **deuterium fuel ions** was displaced by the Ar at ρ=0

Increasing Γ_{AR} Reduced T_{i0} Much More than T_{e0}

- Density profile slightly more peaked at higher Γ_{AR}
- Total stored energy unchanged



MIST Analysis for "High Γ_{AR}" (case 3) Shows Important Features of Argon Behavior in the Main Plasma



Ar^{+16} state dominates into outer region of the plasma, but does not dominate near the center

The argon profile is more peaked than the background electron density profile

The emissivity profile from argon is peaked near the center and near the edge

ARGON AT PERTURBING LEVELS

SINGLE-NULL with B x ∇B DRIFT DOWN

The argon concentration was much higher near the outer divertor target than near the inner divertor target

An Alternative Method for Estimating the Relative Argon Concentration at the Inner and Outer Targets

$$\begin{pmatrix}\text{Argon flux at the} \\ \text{divertor target}\end{pmatrix} \equiv \Phi_{AR} = \sigma \times I_{ARII} \times [S/X_B]$$

where σ is the ratio of the whole multiplex to measured line 434.8 nm

I_{ARII} is the measured emission rate of ARII 434.8 nm

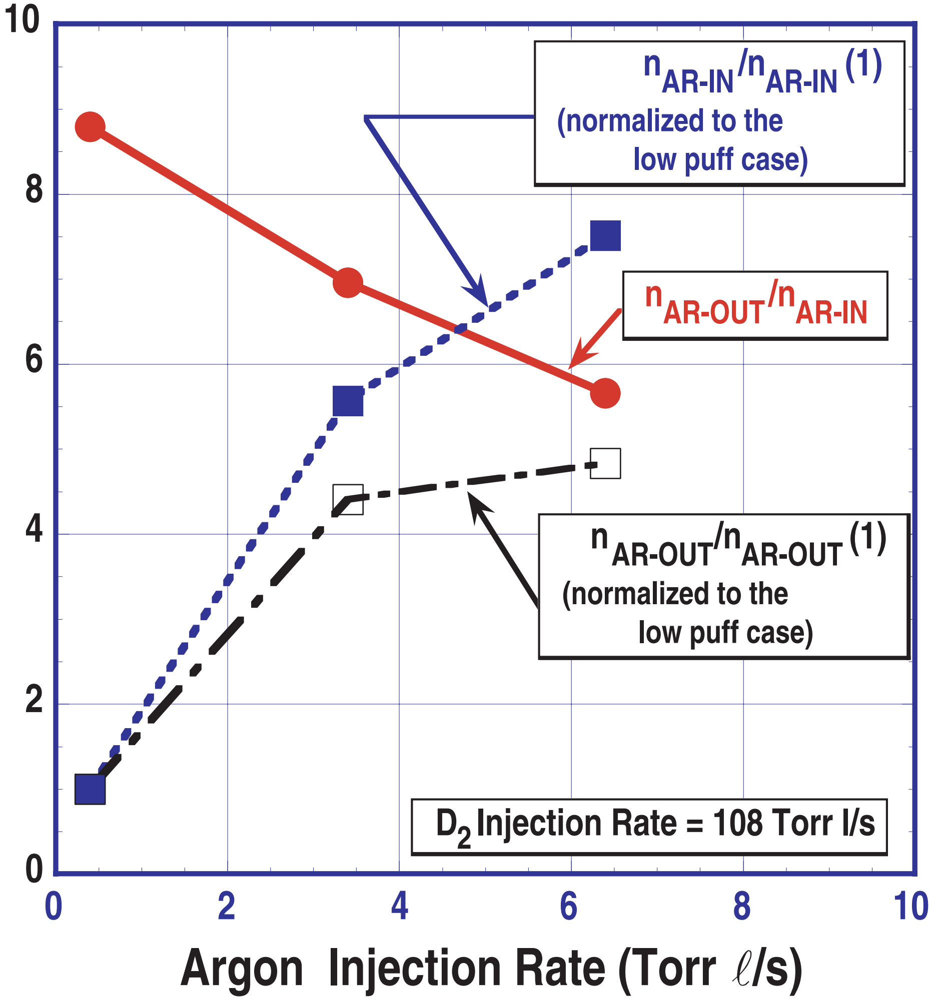
S/X_B is the ratio of ionization to excitation rates computed from a collisional radiative model [R.C. Isler, Nucl. Fusion 24 (1984) 1599]

Simple example:

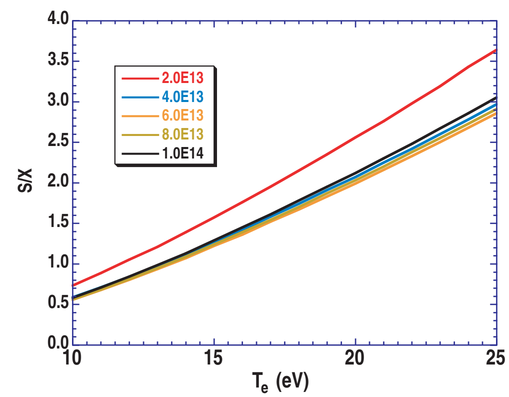
Because both T_e and n_e at the inner and outer targets were comparable at high Γ_{AR} (case 3):

$$\Phi_{AR,OUT}/\Phi_{AR,IN} \approx n_{AR,OUT}/n_{AR,IN} \approx I_{ARII,OUT}/I_{ARII,IN} \approx 6$$

The Argon Asymmetry Between the Inner and Outer Divertor Targets Decreased, as the Argon Injection Rate was Raised



- **The argon density at the inner target grew more rapidly than the argon density at the outer target, as Γ_{AR} was raised**
- **Conditions favoring argon entrainment in the outer divertor evidently deteriorated, as Γ_{AR} was increased**

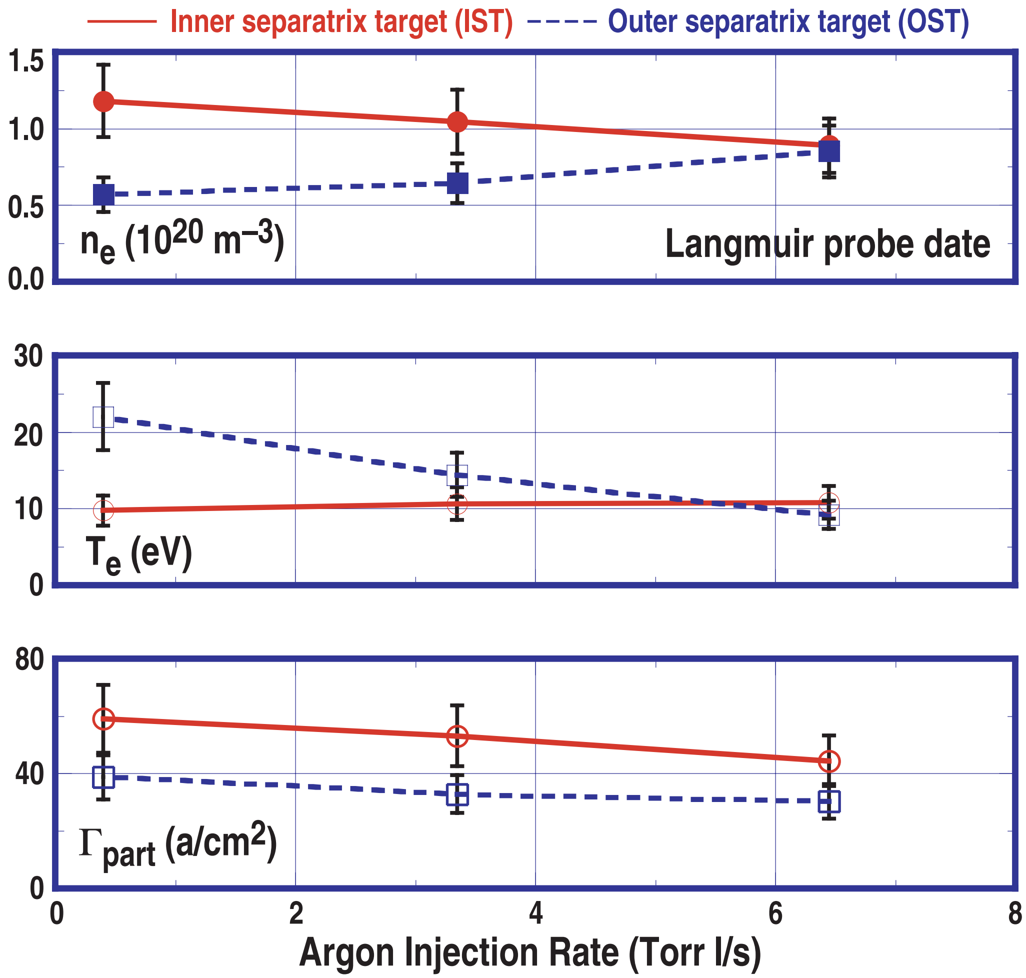


ARGON AT PERTURBING LEVELS

SINGLE-NULL with $B \times \nabla B$ DRIFT DOWN

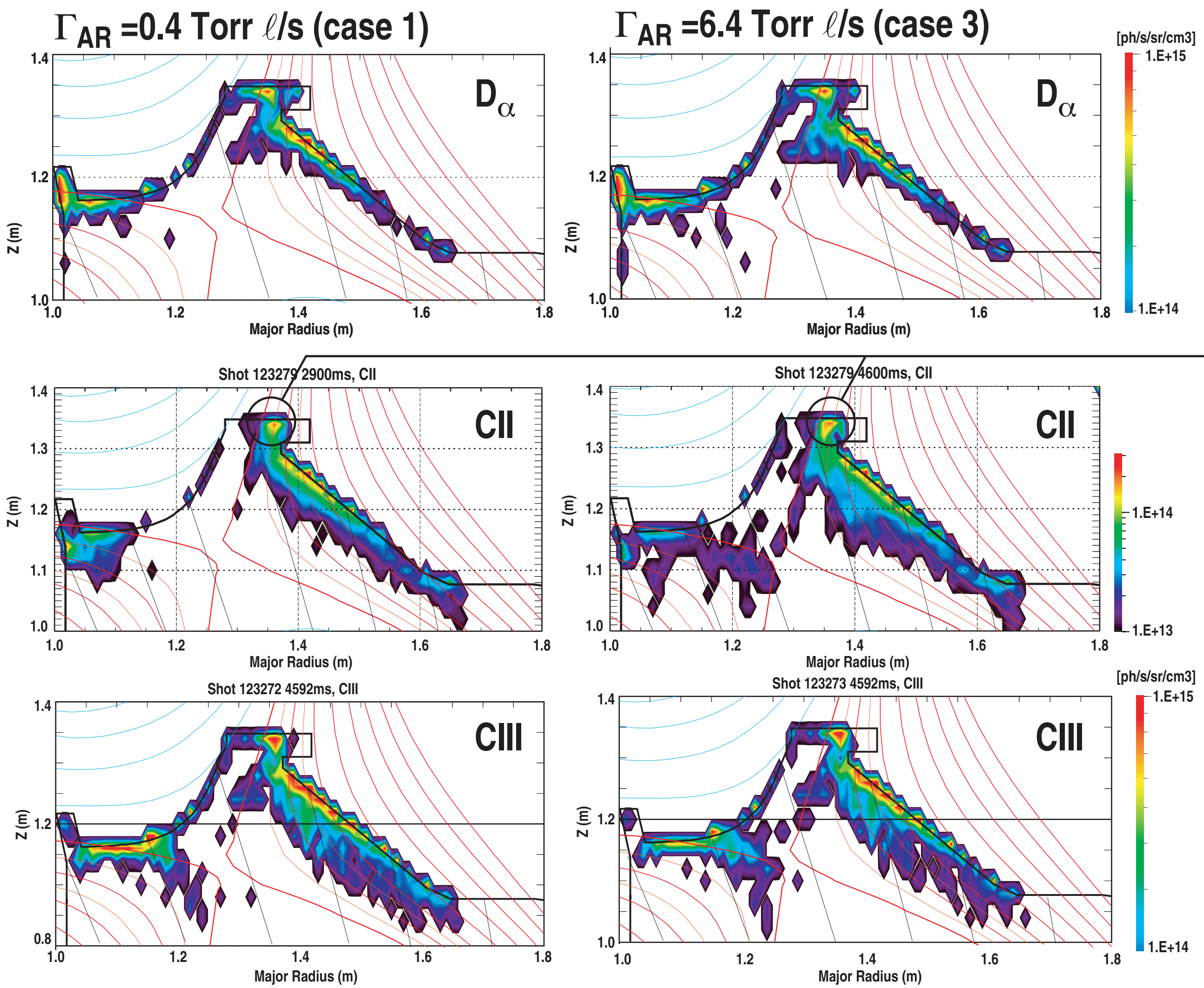
Carbon was the main contributor to $P_{RAD,DIV}$

Increasing the Argon Injection Rate Has its Most Pronounced Effect on the Electron Temperature at the Outer Divertor Separatrix Target



- n_e at the IST decreased ≈ 24%
- n_e at the OST increased ≈ 17%
- T_e at the IST was insensitive to the argon presence
- T_e at the OST decreased more than 2x
- Γ_{part} decreased 20-25% at both IST and OST

Adding Argon Had Little Effect on the Recycling (D_α) and CIII Distributions but Increased CII Radiation Localized Near the Outer Divertor Target



- D_α distribution in the outer divertor shows little change after argon is added
- Increase in CII radiation at the outer target post-argon injection
- Similar CIII distributions

  [CIII is a good indicator of the location of the dominant radiator CIV lines.]

Argon Was Not the Principal Radiator in Either the Divertor or the Main Plasma

- No direct measurement of the radiated power from argon, carbon, and deuterium
- "Trace" argon (i.e., Case 1) — *Expect radiated power to be carbon-dominated*
  - Little contribution to radiated power from argon
  - D_α radiation distribution is NOT consistent with bolometer data
  - CIII/CIV radiation distribution is consistent with bolometer data
- Perturbing argon (i.e., Case 3) — *Expect radiated power to still be carbon dominated*
  - CIII/CIV radiation distribution consistent with bolometer data
  - 50% increase in CII signal at the outer divertor target may in part be due to sputtering of the graphite tiles by argon ⇒ increase in radiated power at the target likely due to a combination of argon and sputtered carbon
  - *If* the entire increase in divertor radiation between case 1 and case 3 was due to argon, the upper limit of the argon contribution to total divertor radiation in case 3 would be ~0.29

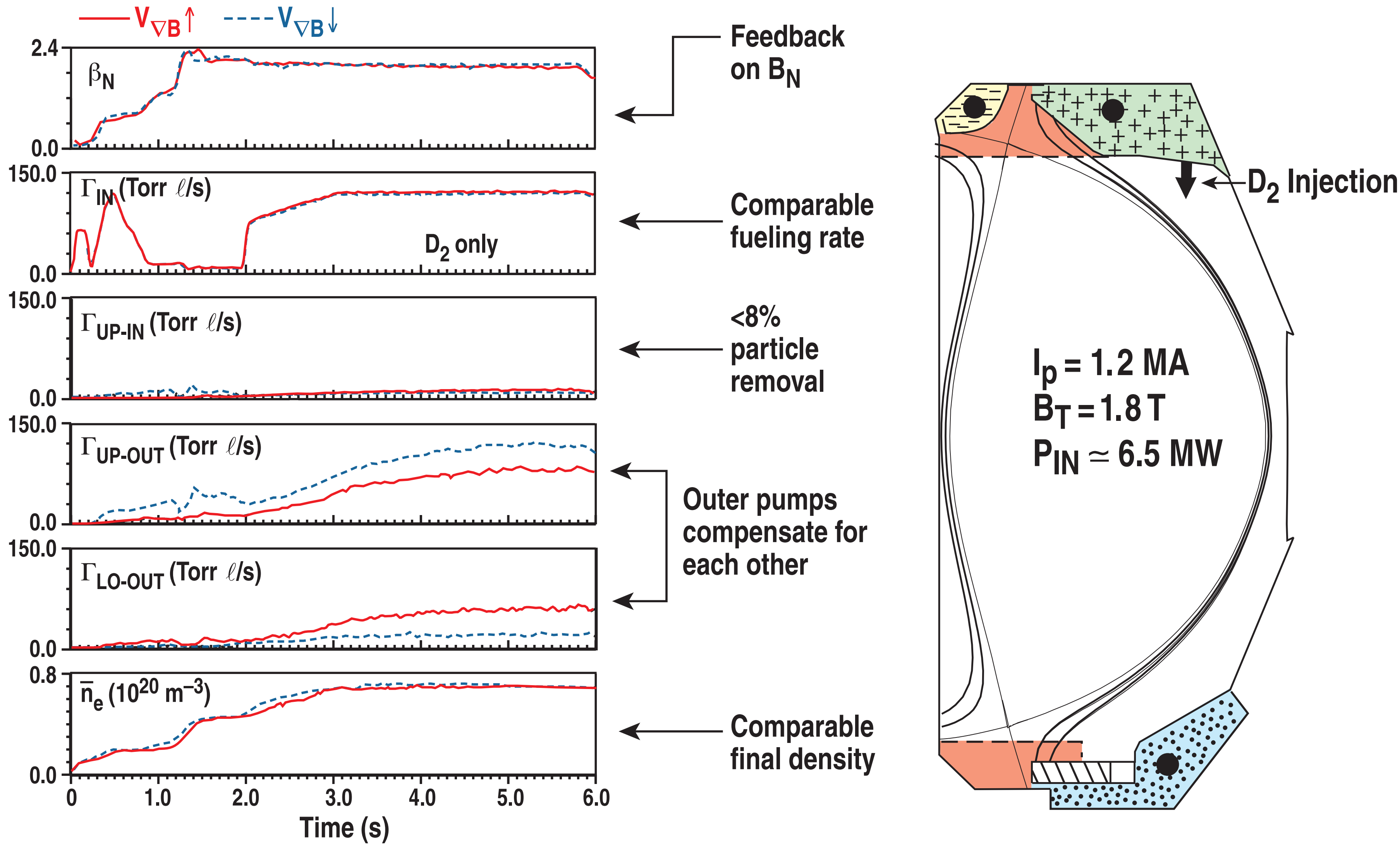
-Recent Data-

SINGLE-NULL *vs* *DOUBLE-NULL*

B x ∇B DRIFT DOWN

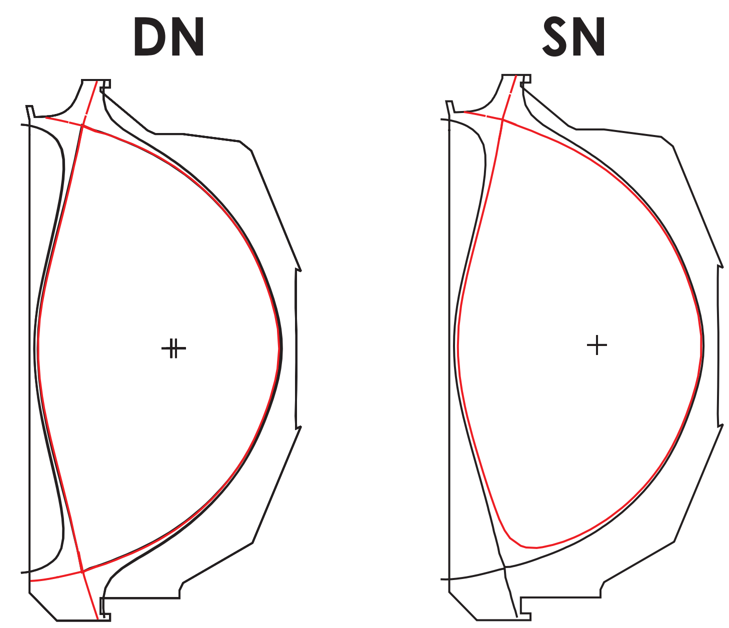
- **Argon entered the main plasma more rapidly in DNs**
- **DNs did not tolerate the higher Γ_{Ar} that SNs did**

The Modified Pumping Configuration Enhances the Feasibility of "Puff-and-Pump" Experiments in High-δ Double-null Plasmas



– Trace Argon Injection –
Argon Accumulation in the DN was Much More Pronounced than in the SN Where $B \times \nabla B$ is Down

	DN	SN
dRsep (cm)	0.0	+1.0
Γ_{AR} (Torr ℓ/s)	0.17	0.17
Γ_{D2} (Torr ℓ/s)	108	108
P_{INJ} (MW)	6.5	6.5
V_{ELM} (Hz)	≈130	≈130
$\bar{n}_e$ (10^{20} m^{-3})	0.7	0.6
n_{AR}	0.72	0.46

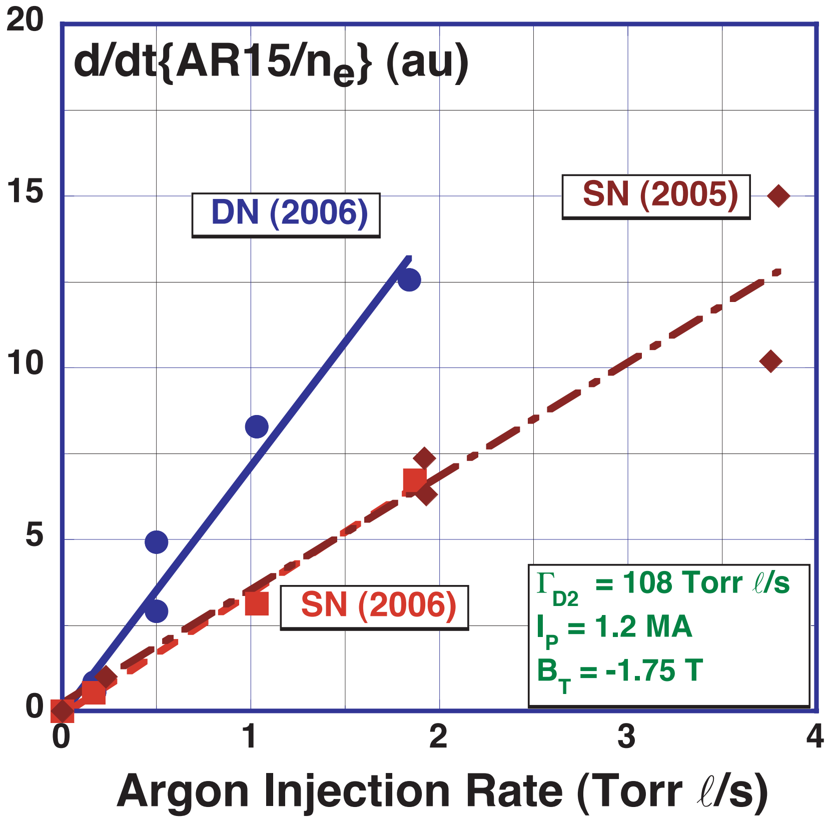


- All three pumps are operational
- D_2 and argon are injected from the midplane and from the upper private flux region, respectively

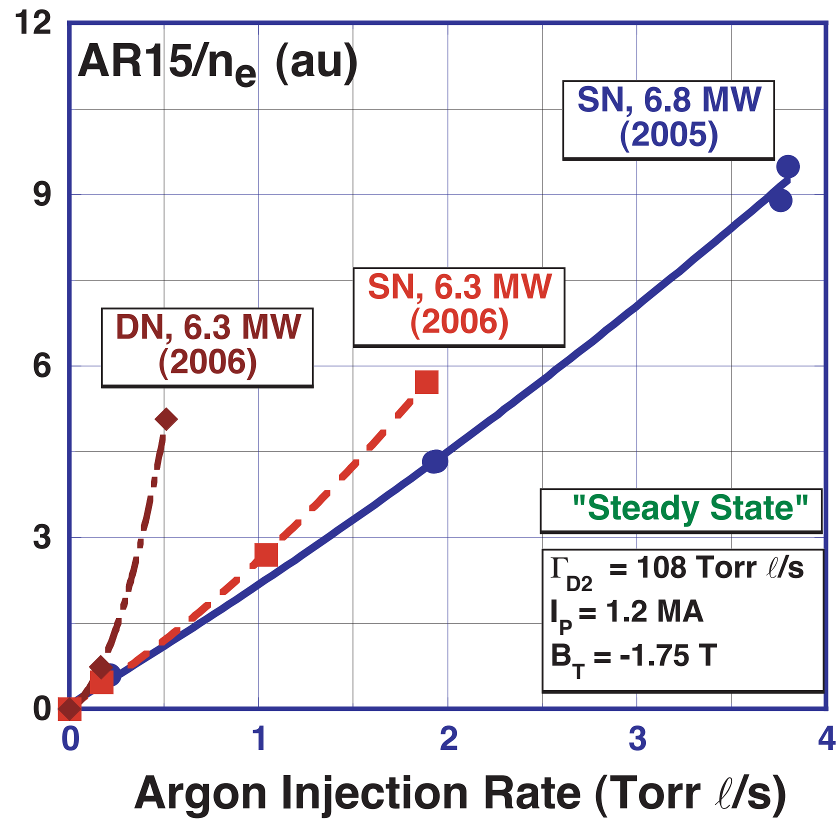
— For a given argon injection rate and B×∇B is down —

Argon Initially Accumulates Faster in DN than SN and Reaches Higher Steady State Values

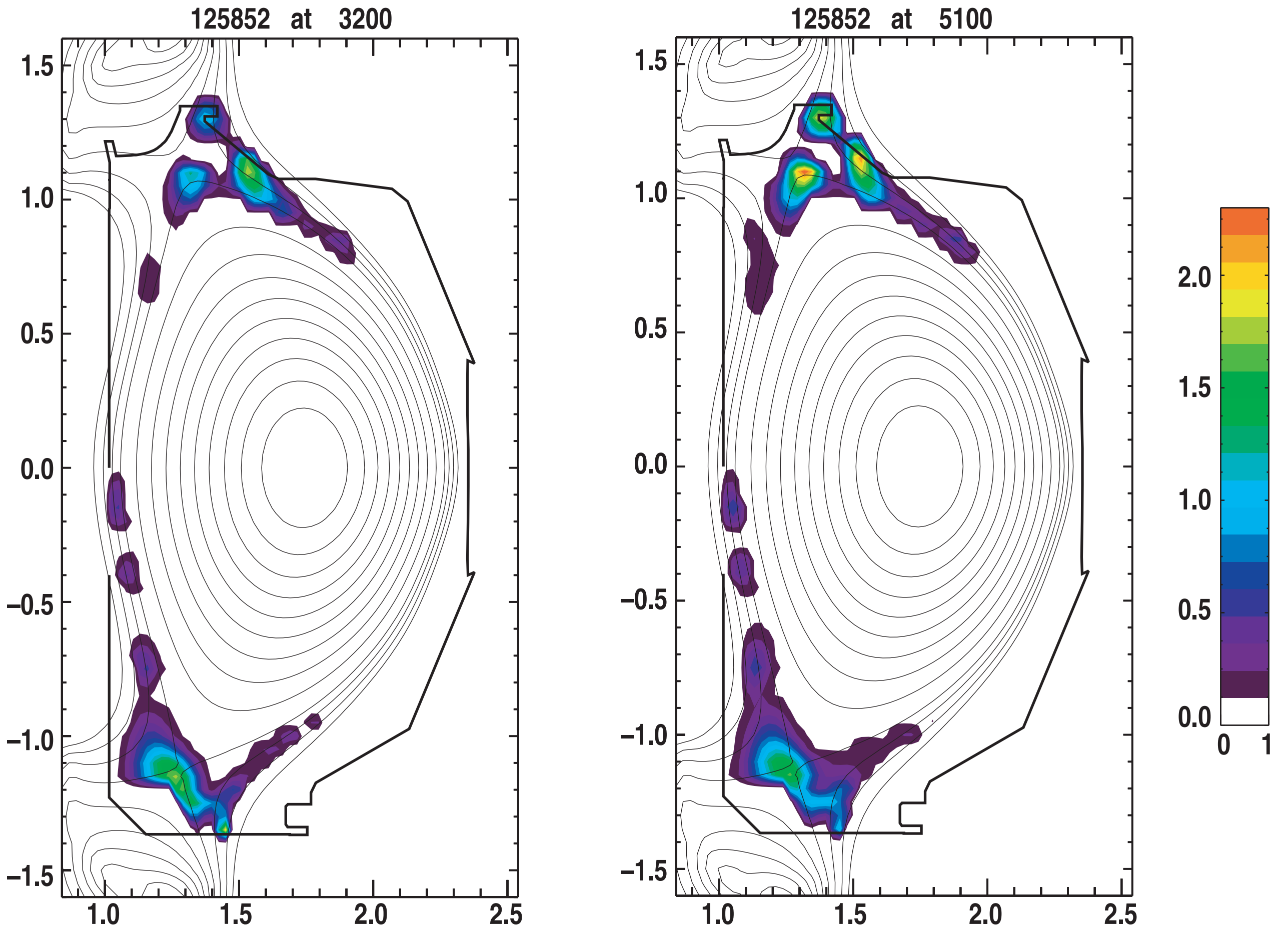
The initial rate at which argon accumulates in a DN is ≈2x that of a SN, given the same Γ_{AR} and Γ_{D2}



Argon accumulates in DNs to a much higher steady state value than in SNs, given the same Γ_{AR} and Γ_{D2}



The Argon Injection Increased Radiated Power Much More in the Upper Divertor Than in the Lower Divertor In the DN Configuration Where Bx∇B is Down



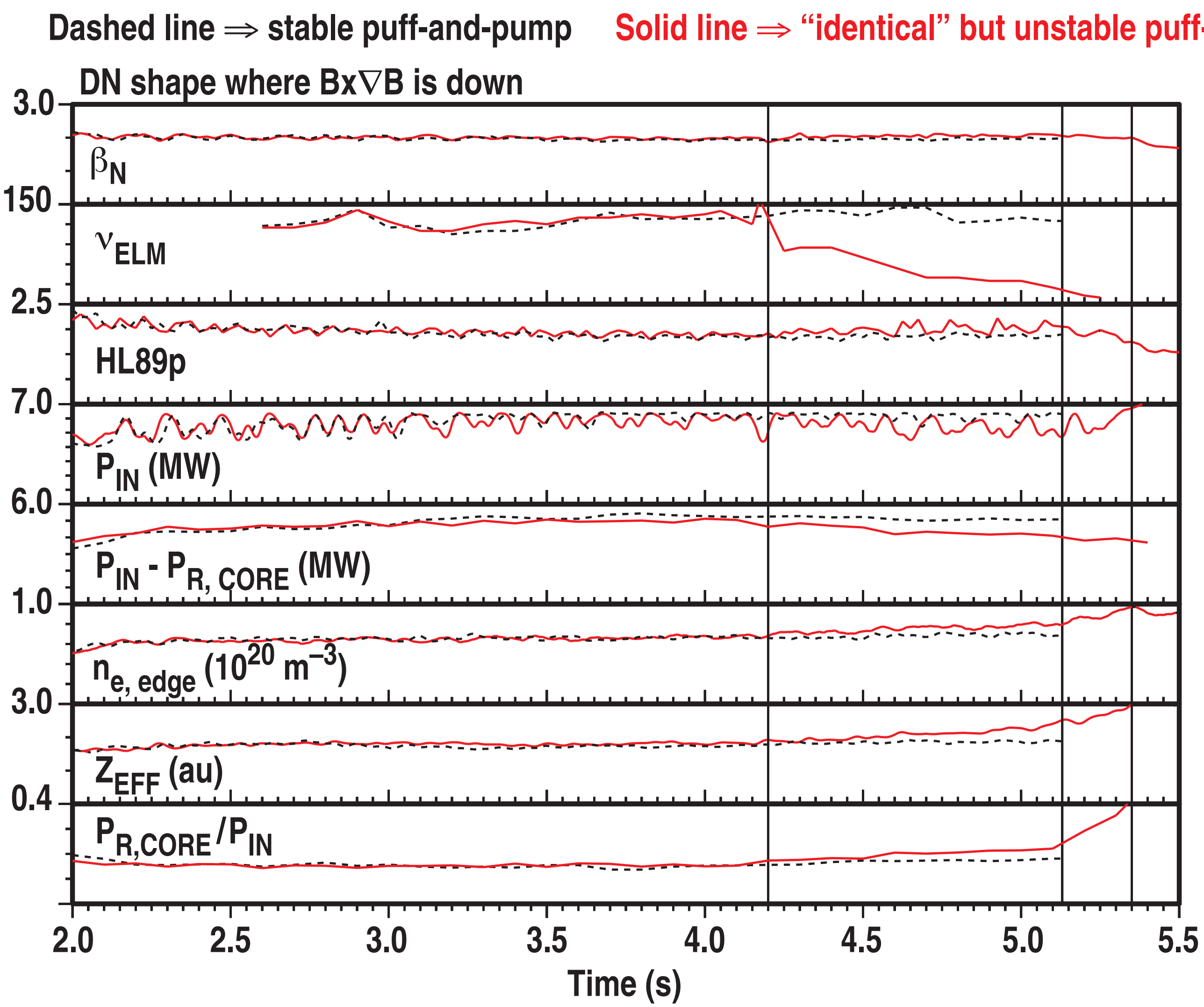
Γ_{D2} = 108 Torr ℓ/s
Γ_{AR} = 0

Γ_{D2} = 108 Torr ℓ/s
Γ_{AR} = 0.51 Torr ℓ/s

Γ_{AR} (tℓ/s)	0	0.51
P_{INPUT} (MW)	6.0	6.1
$P_{R, CORE}$ (MW)	0.85	1.09
$P_{R, SOL}$ (MW)	0.20	0.42
$P_{R, UP,DIV}$ (MW)	0.67	0.99
$P_{R, LO,DIV}$ (MW)	0.70	0.75

Note: Argon was injected into the upper divertor

Decreased ELMing Activity Triggered Processes Leading to the Eventual Loss of H-Mode During Puff-and-Pump Operation



- Constant plasma beta was maintained by feedback on NBs
- Continuous decrease in ν_{ELM} for t > 4.2 s
- HL89p increased after t = 4.2 s
- Less P_{NB} needed after t = 4.2 s
- Continuous decrease in power flow through separatrix for t > 4.2 s
- Continuous increase in n_e (edge) after t = 4.2 s
- Continuous rise in Z_{EFF} for t > 4.2 s
- Radiating fraction inside the core < 0.2 at t = 4.2 s

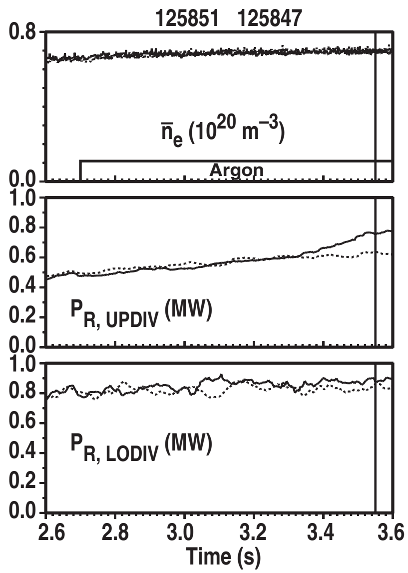
-Recent Data-

SINGLE-NULL ***vs*** ***DOUBLE-NULL***

B x ∇B DRIFT DOWN and UP

- **The distribution of the radiated power and the argon containment in the divertor changed when the B×∇B drift direction changed**

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



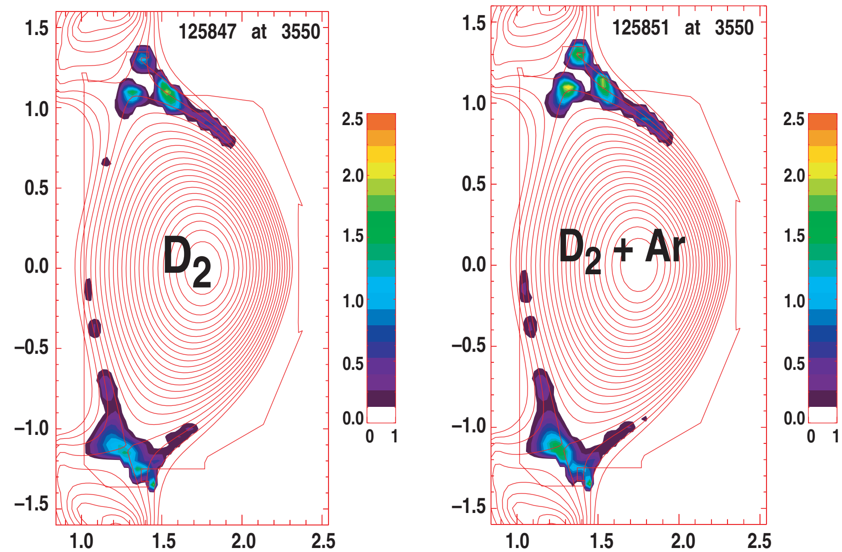
$B \times \nabla B \downarrow$

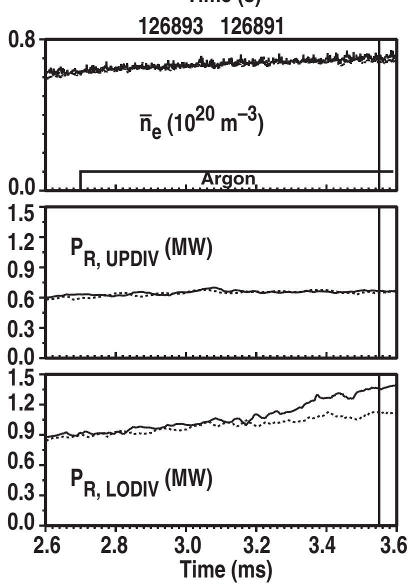
—— $D_2 + Ar$

········ D_2

$\Delta P_{R, UPDIV} \simeq +0.20$ MW

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





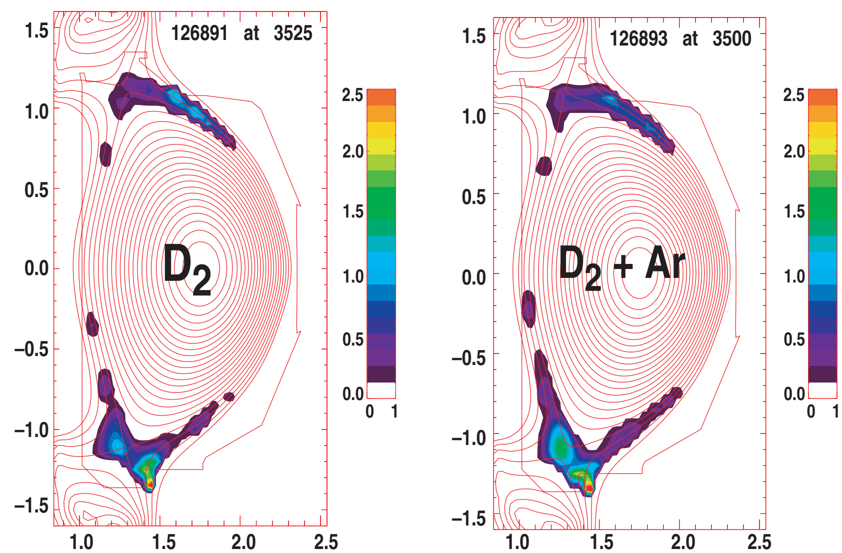
$B \times \nabla B \uparrow$

—— $D_2 + Ar$

········ D_2

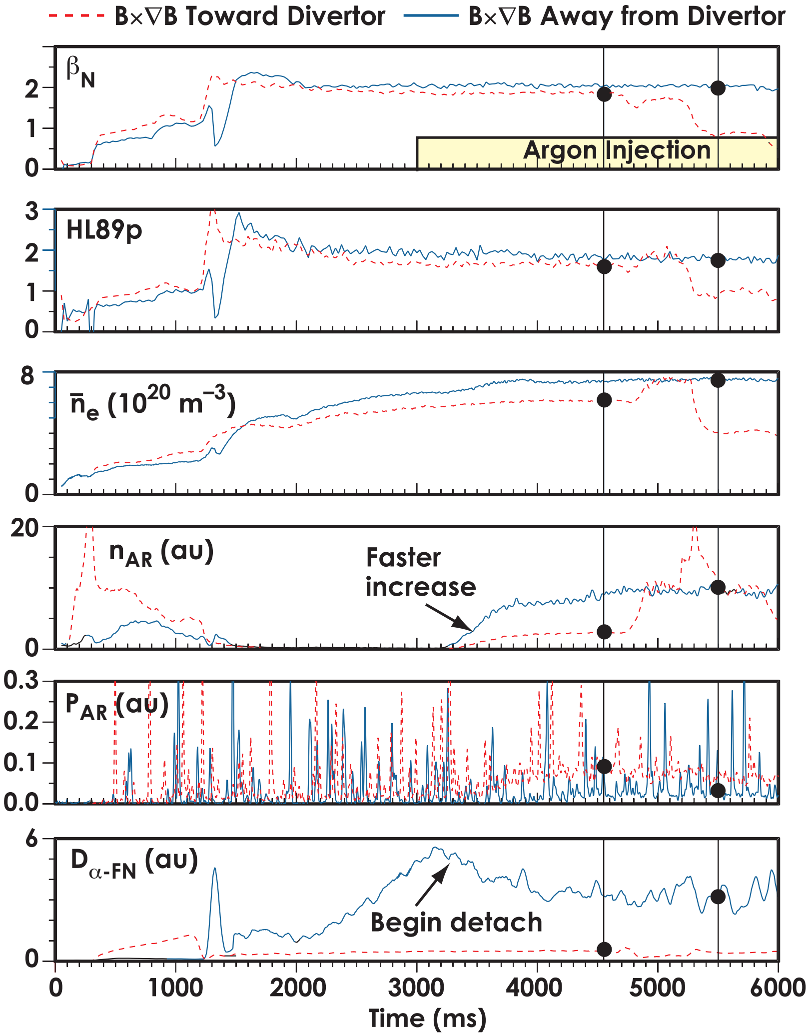
$\Delta P_{R, UPDIV} \simeq +0.02$ MW

$\Delta P_{R, LODIV} \simeq +0.23$ MW



– Upper Single Null Divertor Case –

Argon Escapes Much More Quickly from the Divertor Region and Reaches a Higher Steady State Concentration in the Core when the B×∇B Ion Drift is Toward the Divertor



Γ_{AR} = 0.85–1.00 Torr ℓ/s
Γ_{D2} = 108 Torr ℓ/s
Feedback on β_N with neutral beams

HL89p ≃ 1.7–1.9

Line-averaged density was steady at the two times of interest

"n_{AR}" was 2–3 × greater in the "B×∇B toward the divertor" case

The argon pressure in the upper baffle was much lower in the "B×∇B toward" case

Upper inner divertor in the "B×∇B toward" case showed evidence of detaching shortly after argon injection started

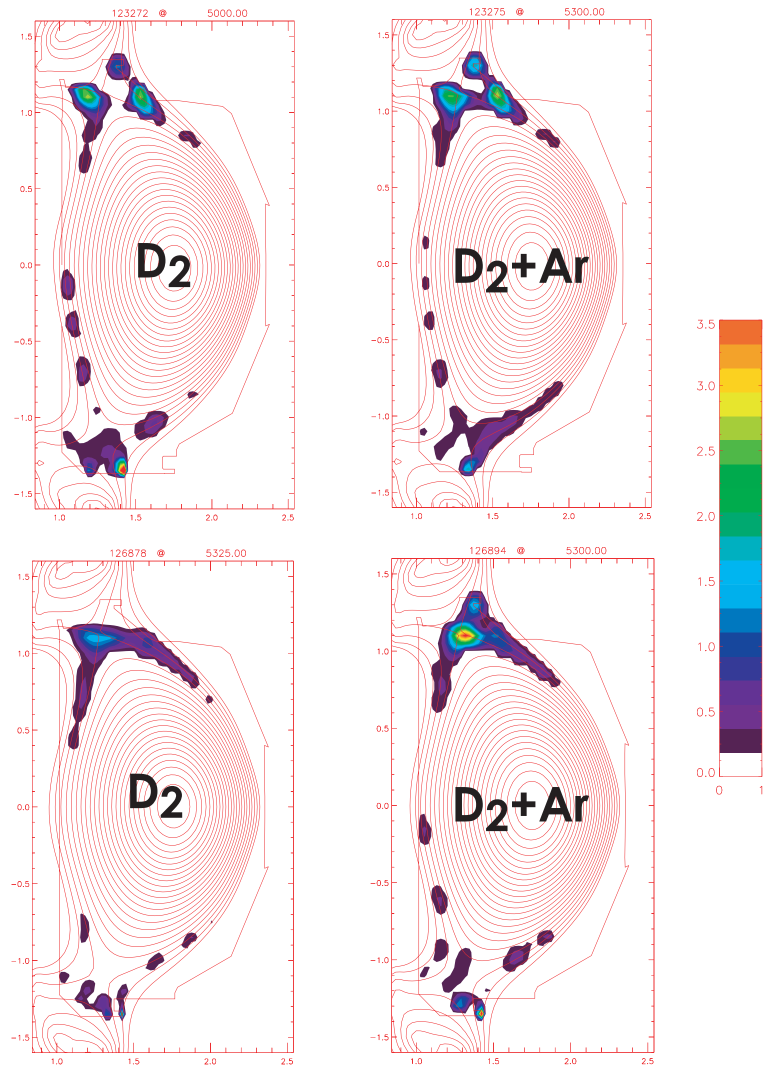
The Emissivity Distribution in the Divertor of SN Plasmas Changed Markedly When the B×∇B Ion Direction was Reversed

B×∇B toward lower divertor

- Three main radiating regions in the divertor were observed
- Outer divertor target region was most affected by argon injection

B×∇B toward upper divertor

- One main region of emissivity lay near the X-point during D_2 phase
- Radiated power from the X-point region continued to be dominant during argon injection



DISCUSSION

Discussion

Heat flux reduction in SNs (Bx∇B↓)

- $q_{P,OUT}$ was reduced ≈2.5X between case 1 and case 3, but $q_{P,IN}$ by only ≈20%
- Greater increase in ε_{RAD} near the outer divertor target than near the inner induces this "asymmetry"
- Greater concentration of argon near the outer divertor target induces greater change in ε_{RAD}

Argon asymmetry at the divertor targets in SNs (Bx∇B↓)

Several factors may have contributed to the asymmetric argon distribution between divertors

- Geometry: The argon source was located in the PFR near the outer divertor target and was adjacent to a major sink for the argon, i.e., the entrance to the outer baffle pumping plenum. For argon neutrals, direct flight across the PFR from the outer divertor target to the inner was blocked by the dome over the inner cryopump
- Particle drifts: The *ionized* argon in the PFR near the separatrices would be preferentially dragged from the inner target toward the outer divertor target by E_R x B-induced ionic flow across the PFR
- Induced D_2 flows in the SOL: Leakage of argon out of the closed outer divertor was impeded by the enhanced deuterium flow in the SOL directed into that divertor.
- Additional pumping: Argon that *does* make it to the inner target can be exhausted by the dome cryopump.

Discussion (continued)

Argon accumulation in the main plasma of SNs (B×∇B↓)

- n_{AR} was almost linear with Γ_{AR}
  => $n_{AR} \propto \Gamma_{AR}-\Gamma_L(\nu_{ELM})$, where $\Gamma_L(\nu_{ELM})$ is the time-averaged argon losses during ELMs
  - If $\Gamma_L(\nu_{ELM})$ is constant as Γ_{AR} increases, n_{AR} is linear with Γ_{AR}
  - As more argon accumulates in the main plasma, $P_{RAD,MAIN}$ increases → ν_{ELM} decreases [(i.e., H ≈80 Hz (case 1) to H ≈70 Hz (case 3)] → $\Gamma_L(\nu_{ELM})$ decreases → n_{AR} rises faster than linear in Γ_{AR}
- The 3/2 NTM did not prevent the n_{AR}-profile from becoming more peaked than the n_e-profile. Even so, $\varepsilon_{RAD}(\rho)$ was not peaked on axis and there was no observed degradation in τ_E

Comparison of two radiating divertor conditions in SNs

The above results can be compared with those from a previous, well-documented DIII-D puff-and-pump experiment, where argon was injected into the PFR of a standard ELMing H-mode plasma (*Wade et al.*)

- *Similarities:* I_P, B_T, q_{95}, and line-averaged density
- *Differences:* (1) No dome structure in the PFR and the divertor was more "open," (2) the particle pumping was done only at the outer divertor target, and (3) the E_R x B-induced ion particle flow across the PFR was directed *toward* the inner divertor target
- *Trace argon:* η_{exh}(*Wade*) was only ≈50% of that reported here, even though Γ_{D2} was higher in *Wade*
- *Perturbing argon:* (1) inner divertor leg "detached" and (2) η_{exh}(*Wade*) degraded significantly with Γ_{AR}

Discussion (continued)

Double-null vs single-null shapes ($B\times\nabla B\downarrow$)

- Argon penetrates DN much faster than it does for SN
- Expected: D2 fuelling in DN more efficient than SN ⇒ likely similar result for argon injection
  - Narrower SOL for DN on inboard side
  - Quiescent SOL for DN on inboard side (no ELMing)
  - Detached lower inner leg in DN

$B\times\nabla B\downarrow$ vs $B\times\nabla B\uparrow$

- Single-null: argon escapes divertor much more readily when $B\times\nabla B$ is toward the divertor
  - Inner divertor leg detaches more easily in $B\times\nabla B\uparrow$
  - Argon escape is easier with detached inner divertor leg
- Double-null: The increase in radiated power due to argon was stronger in the divertor opposite are $B\times\nabla B$ drift direction
  - Argon is not well contained in the upper divertor when $B\times\nabla B\uparrow$
  - Strong evidence that particle drifts are important in DN puff and pump experiments
  - Results suggest it will be difficult to achieve equal radiated power in both divertor

PRELIMINARY CONCLUSIONS

The Radiating Divertor Concept Shows Compatibility with Hybrid Regime Operation Under Certain Conditions

$B\times\nabla B\uparrow$ direction

- The puff and pump approach in SN was effective in reducing peak power loading at the outer divertor target but much less so at the inner target
- Argon presence was MUCH stronger in the outer divertor of the SN, possibly explaining why heat flux reduction was much stronger at the outer divertor target
- $\eta_{EXH} \propto \Gamma_{D2}$ at trace argon levels, in SNs and was weakly dependent on Γ_{AR} at fixed Γ_{D2}
- Argon accumulated in DNs at a much faster rate than in SNs, given the same Γ_{AR}

$B\times\nabla B\uparrow$ and $B\times\nabla B\downarrow$ directions

- Argon escapes to divertor more readily in SNs with $B\times\nabla B$ toward the divertor
- The increase in $P_{RAD,\,DIV}$ due to argon for DNs was stronger in the divertor opposite the $B\times\nabla B$ drift direction → difficulty in achieving equal radiated power in both divertors