Impact of the Radiating Divertor Approach on Future Tokamaks

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For

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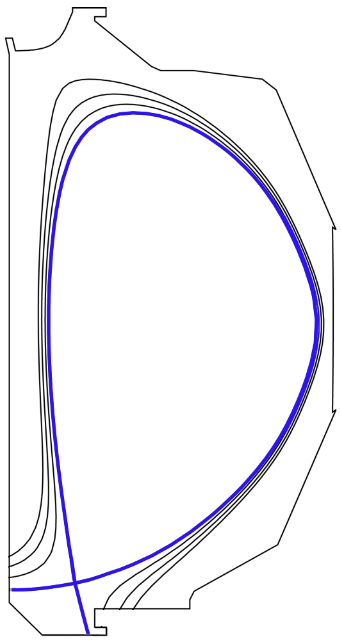
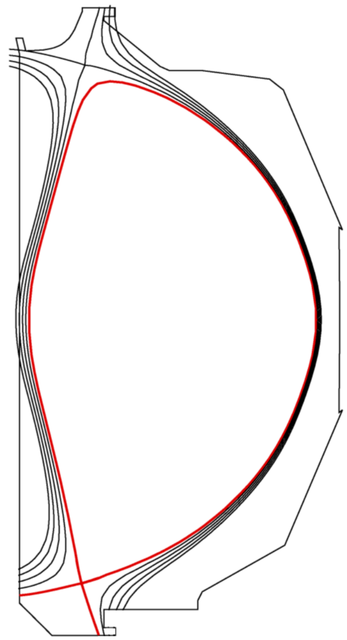
Recent DIII-D experiments have examined several tokamak scenarios under radiating divertor conditions



ITER Baseline Scenario (IBS)

Stable radiating divertor

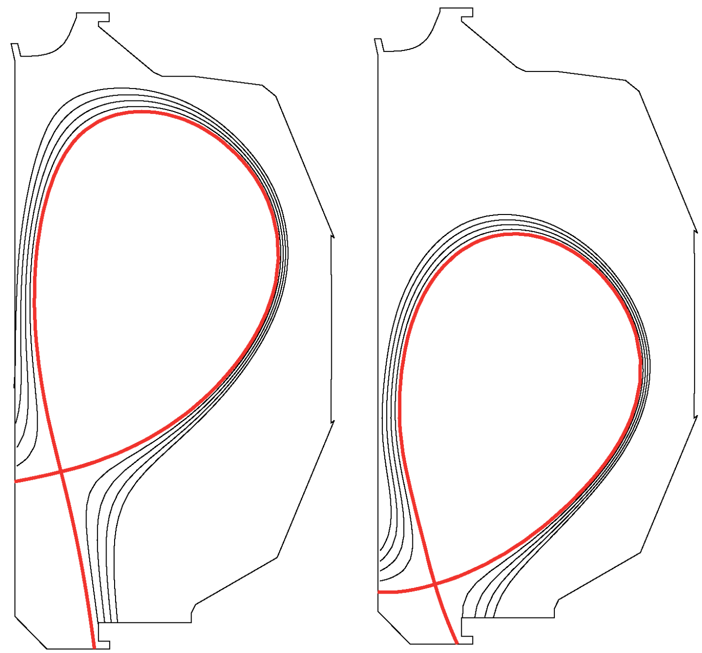
Low divertor heating



High Performance Double-Null plasmas

Maintain high performance properties

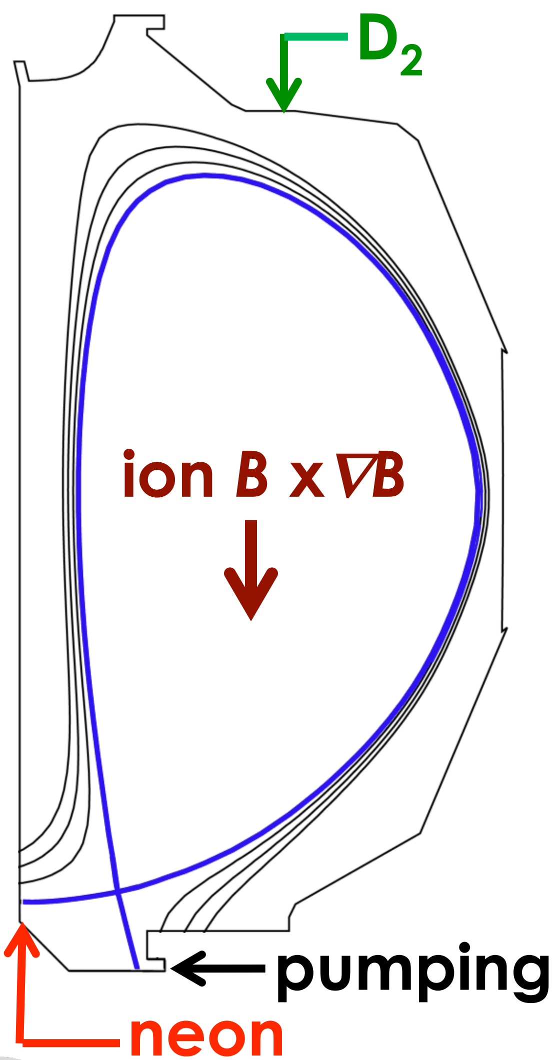
Low divertor heating



Long vs short outer divertor legs

A significant additional reduction in divertor heating under radiating divertor conditions by lengthening the parallel connection length $L_{||}$

The radiating divertor was applied to the ITER Baseline Scenario plasmas



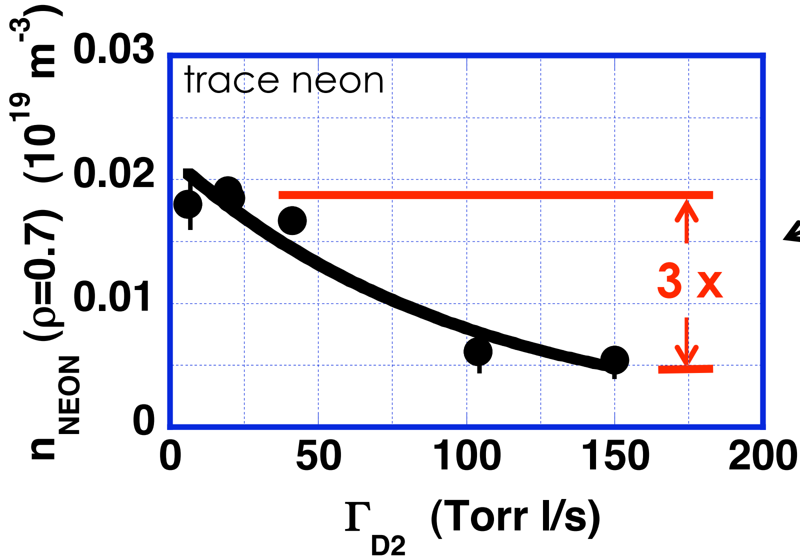
Setup

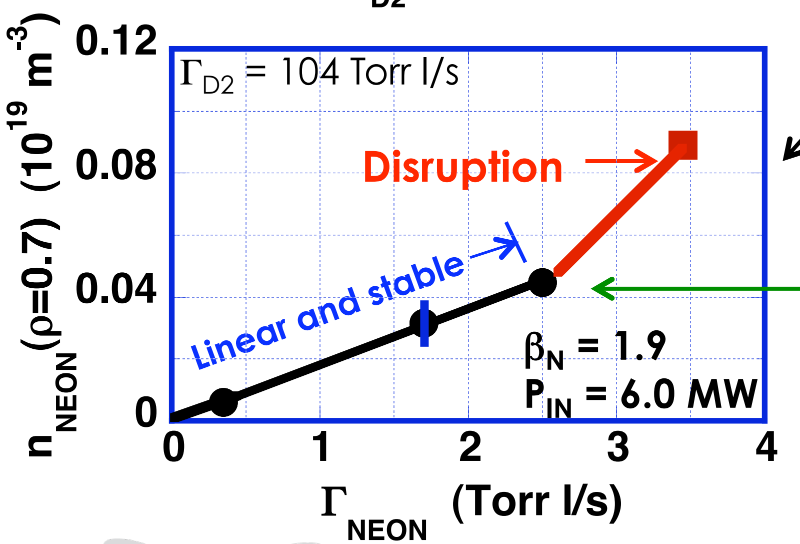
- ITER Similar Shape with $q_{95} \cong 3.15$
- $\beta_N = 1.9$ was maintained by neutral beam feedback

Results to-date

- Stable radiating divertor resulted in a high radiated fraction outside the core plasma and low divertor heat flux
- The peak ELM heat flux and core dilution were both reduced at higher deuterium flow and density
- Greater incidence of less benign tearing modes was observed at higher fueling rate and density

Neon accumulation inside the IBS core plasma was controlled by varying the D_2 and neon injection rates





- The neon accumulation in the core was strongly reduced with increased D_2 injection rate (Γ_{D2})
- The neon accumulation in the core was largely linear with the neon injection rate (Γ_{NEON})
- Stable radiating divertor case:

$P_{R,TOT}/P_{IN} = 0.79$

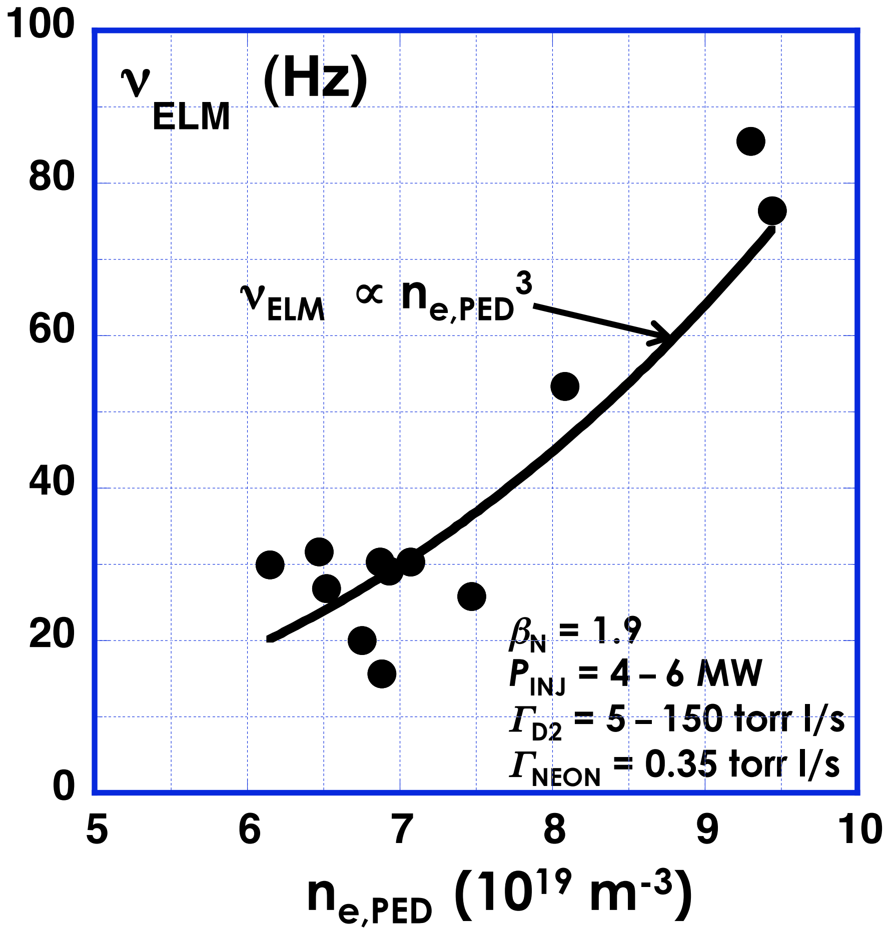
$P_{R,SOL+DIV}/P_{IN} = 0.64$

$q^{P}_{\perp,OD} \approx$ 2.2 MW/m² ⟶ 0.6 MW/m²

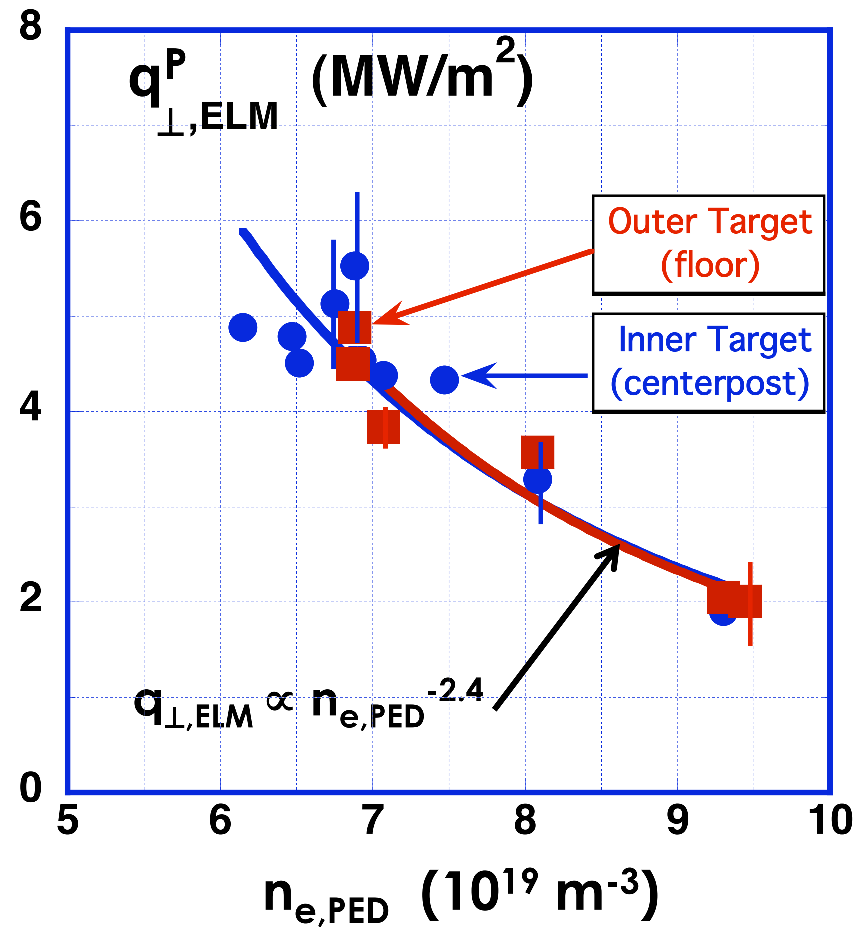
partially detached

An increase in ELM frequency in IBS was matched by a decrease in the ELM peak heat flux, as $n_{e,PED}$ was raised

These ELMs were characterized as type-1

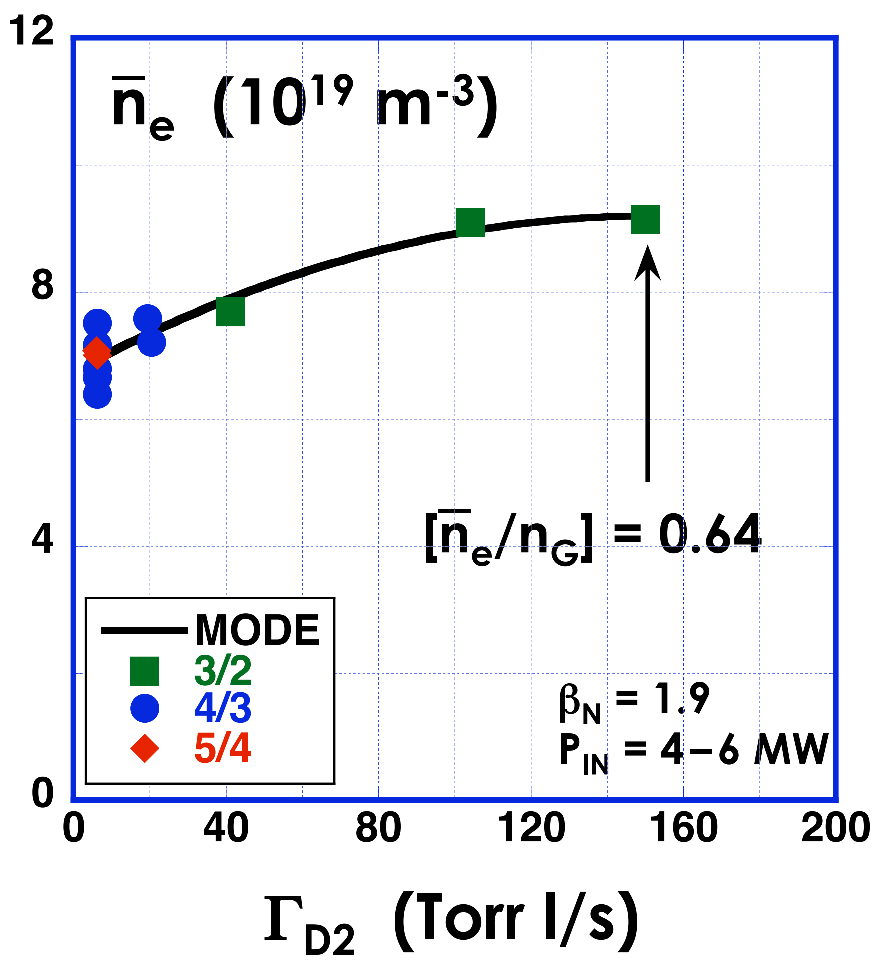


$q^P_{\perp,ELM}$ at the inner and outer divertor targets was comparable

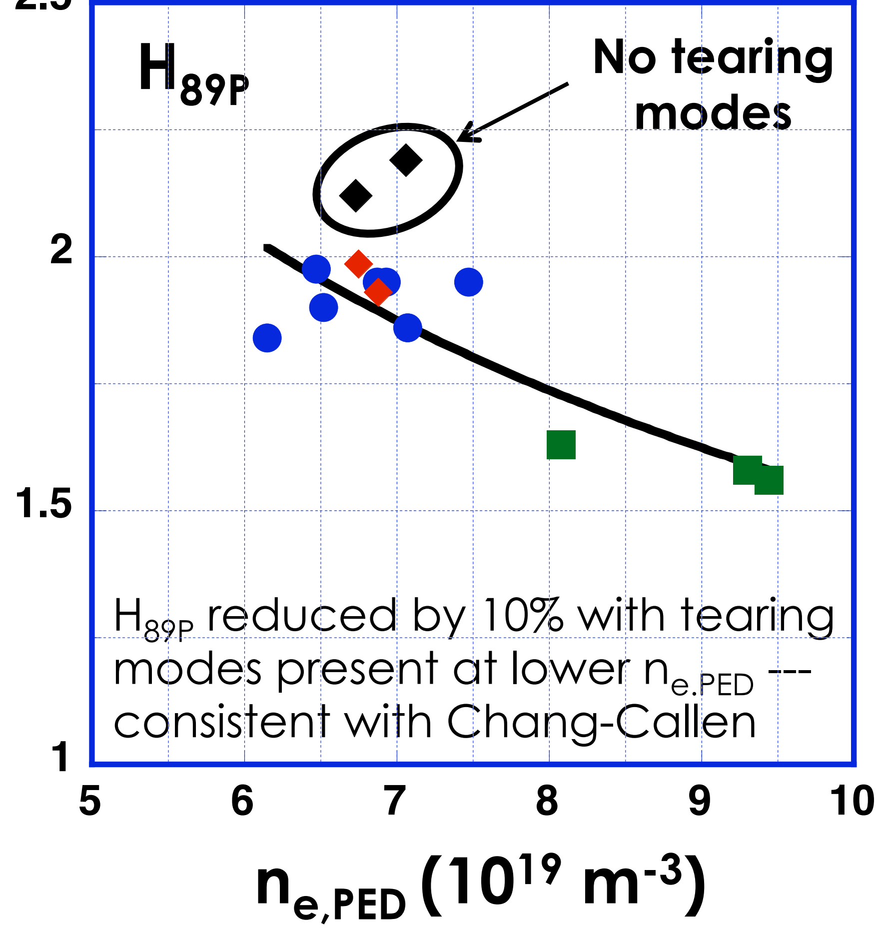


Greater incidence of less benign tearing modes in the IBS was seen at higher fueling rate and pedestal density

Steady $\bar{n}_e$ was well below n_G

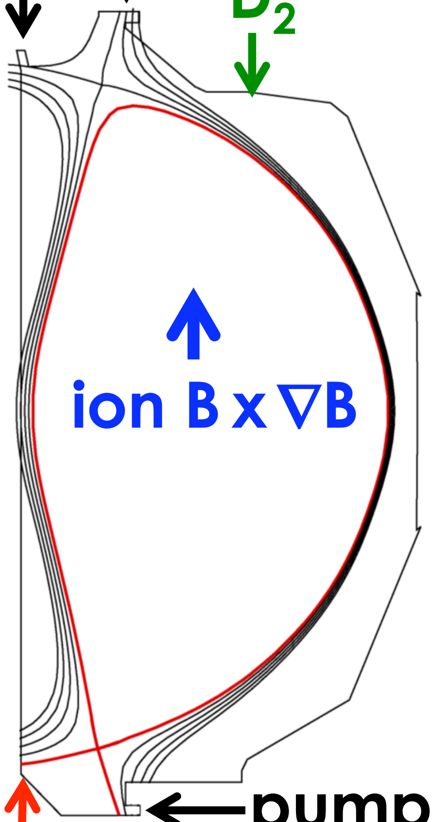


Tearing modes account for about half of drop in H_{89P} at higher $n_{e,PED}$, per Chang-Callen belt model*



*Chang,Z., Callen, J.D., Nucl. Fusion, **30** (1990) 219.

The radiating divertor was applied to high performance unbalanced double-null divertor (DND) plasmas



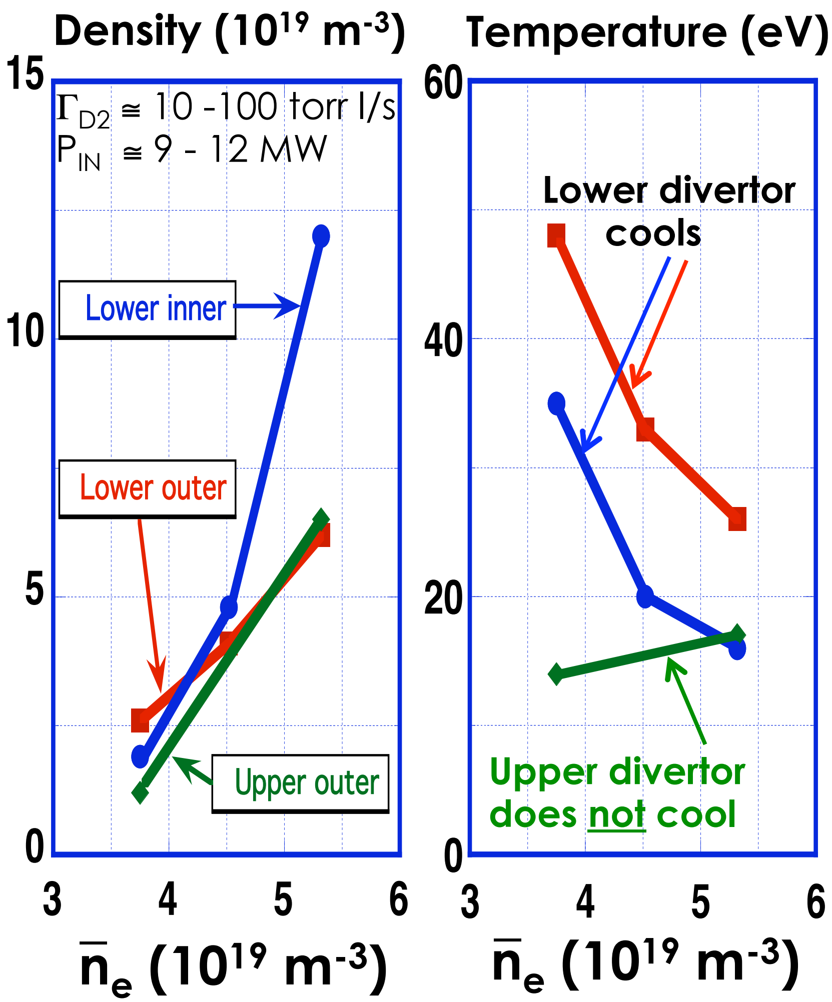
Setup

- An unbalanced double-null plasma was biased slightly toward the lower divertor (dRsep = -5 mm) in order to optimize particle control
- β_N = 2.9 was maintained by neutral beam feedback
- Applied ECH power was ≅3 MW for 3.5 s

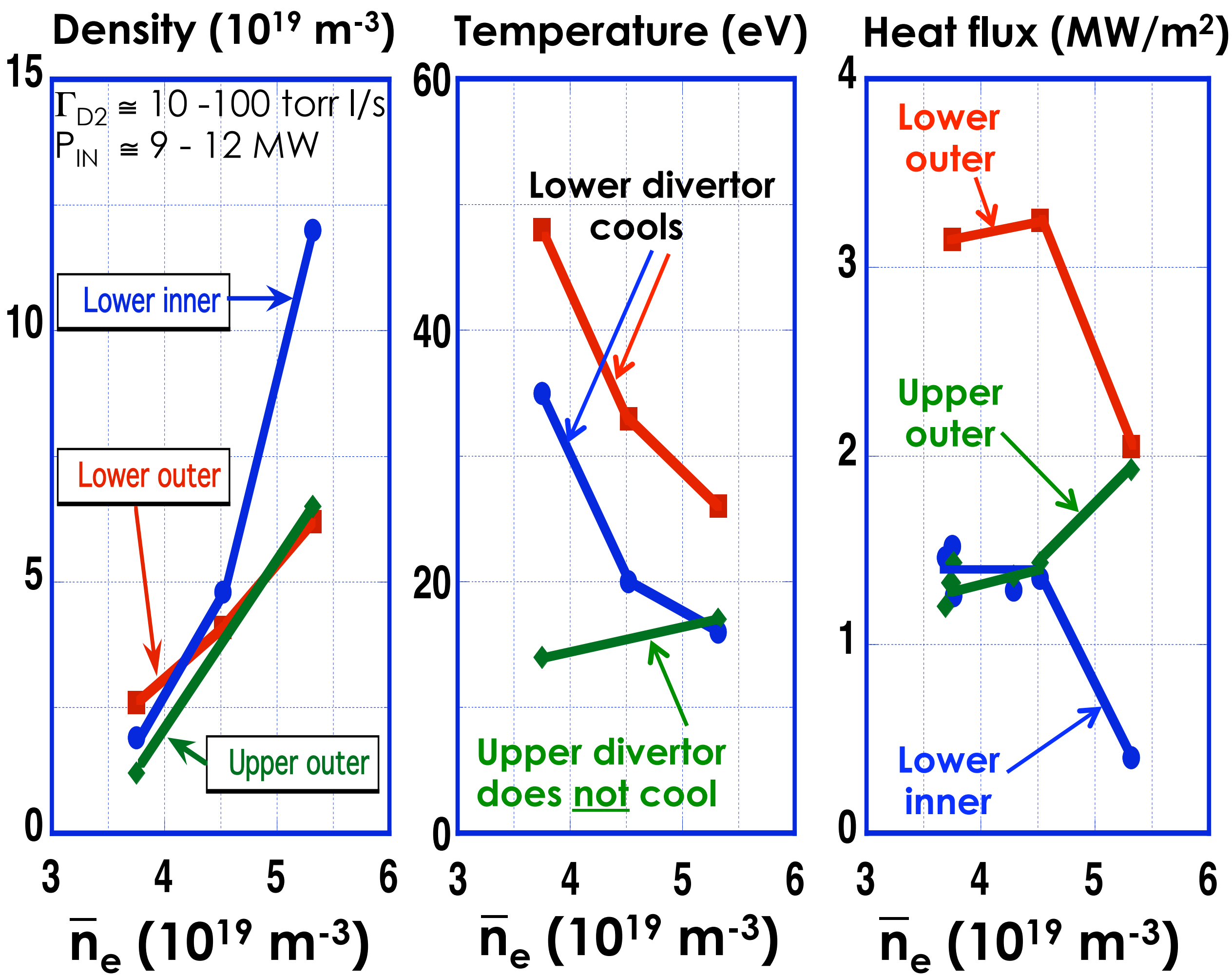
Results to-date

- Heat flux was substantially reduced in the lower (primary) divertor by a combination of D_2 and neon injection, and good energy confinement was maintained.
- Peak heat flux in the upper outer (secondary) divertor *increased* during D_2 and neon injection, if β_N was held constant.

Temperature in the lower divertor fell as $\bar{n}_e$ was raised, but it *increased* in the upper divertor, if β_N held constant



Peak heat flux in the lower divertor fell as $\bar{n}_e$ was raised, but it *increased* in the upper divertor, if β_N held constant



Hypothesis

With $\bar{n}_e$ increasing, must raise P_{IN} to maintain β_N

Find:

$\Delta P_{SOL} = \Delta P_{IN} - \Delta P_{R,CORE} > 0$

Lower (primary) Divertor:

$\Delta P_{SOL \rightarrow LD} < \Delta P_{R,LD}$

➔ Both temperature and peak heat flux decrease

Upper (secondary) Divertor:

$\Delta P_{SOL \rightarrow UD} > \Delta P_{R,UD}$

➔ Both temperature and peak heat flux increase

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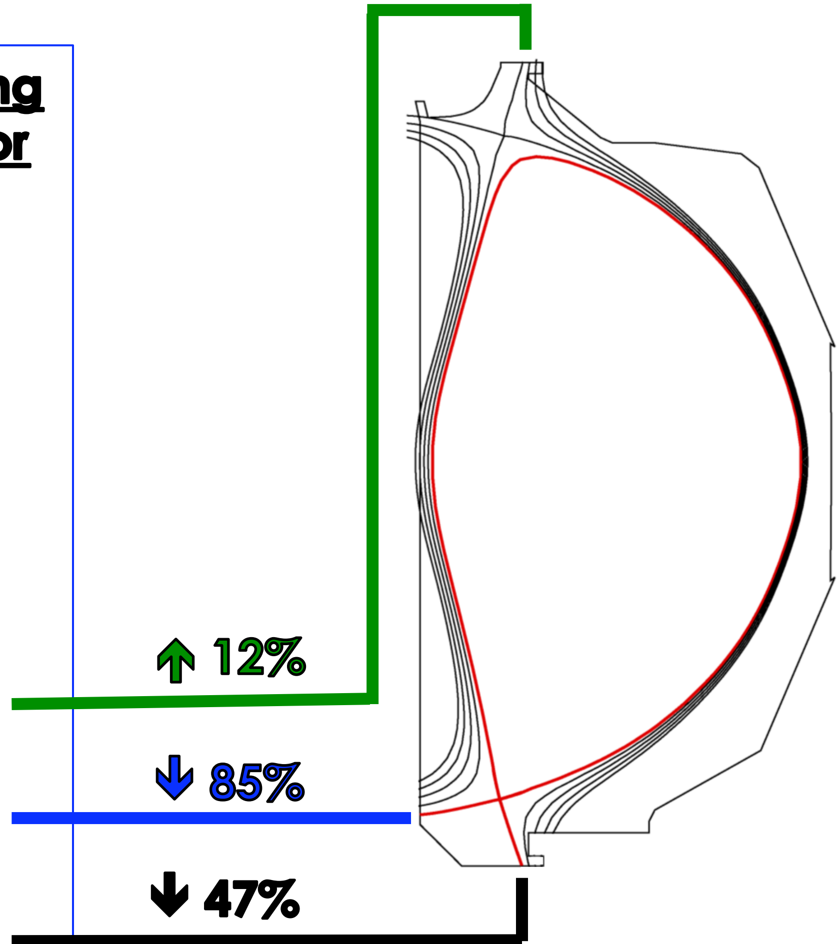
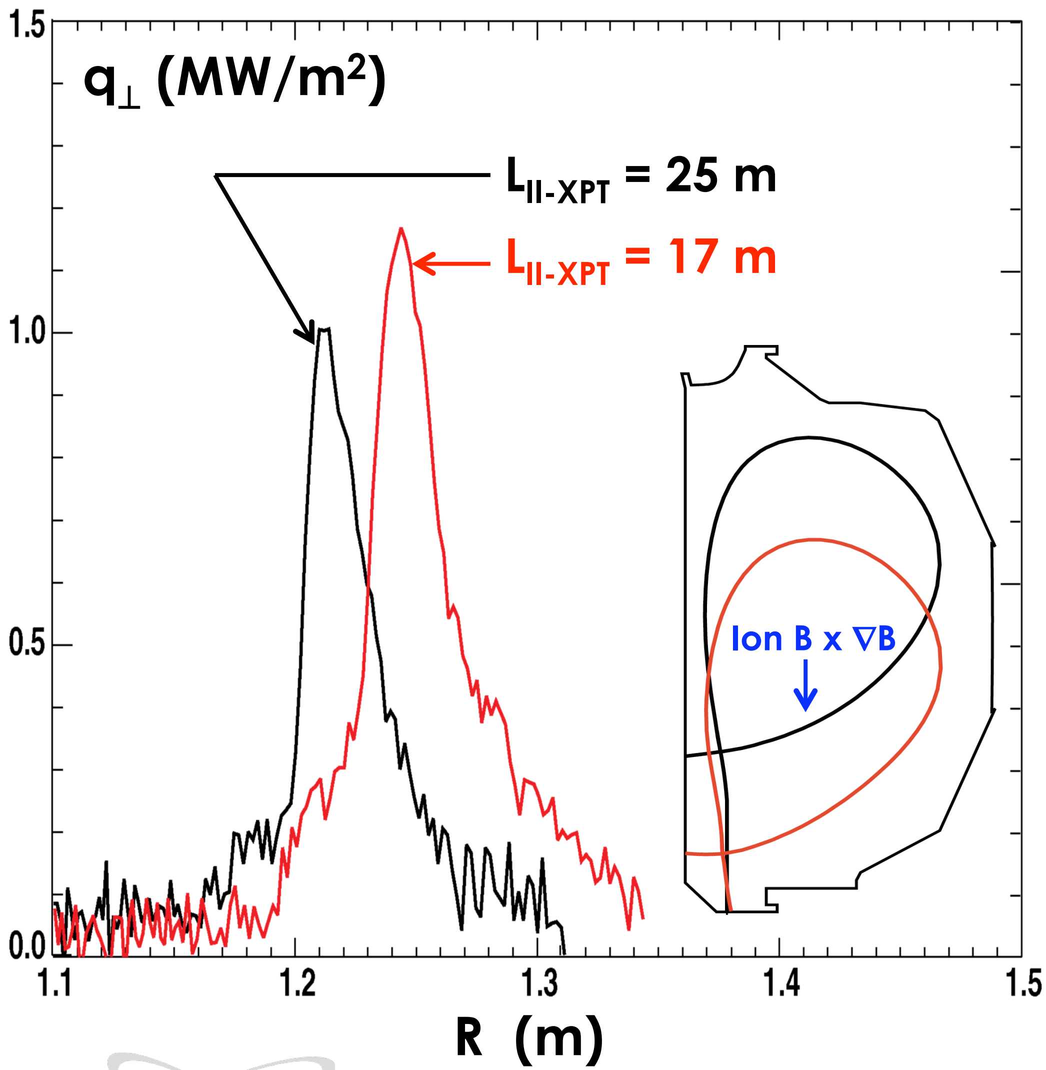
Neon and D_2 injection strongly reduced heat flux in the lower divertor of DND with little degradation in $H_{98(y,2)}$

	Standard Divertor	Radiating Divertor
$H_{98(y,2)}$	1.35	1.30
$\overline{n}_e/n_G$	0.41	0.56
$P_{NB} + P_{ECH}$ (MW)	8.8	10
$P_{R,TOT}/P_{IN}$	0.25	0.60
$q^P_{UP,OUT}$ (MW/m²)	1.20	1.35
$q^P_{LOW,IN}$ (MW/m²)	1.25	0.19
$q^P_{LOW,OUT}$ (MW/m²)	3.20	1.70



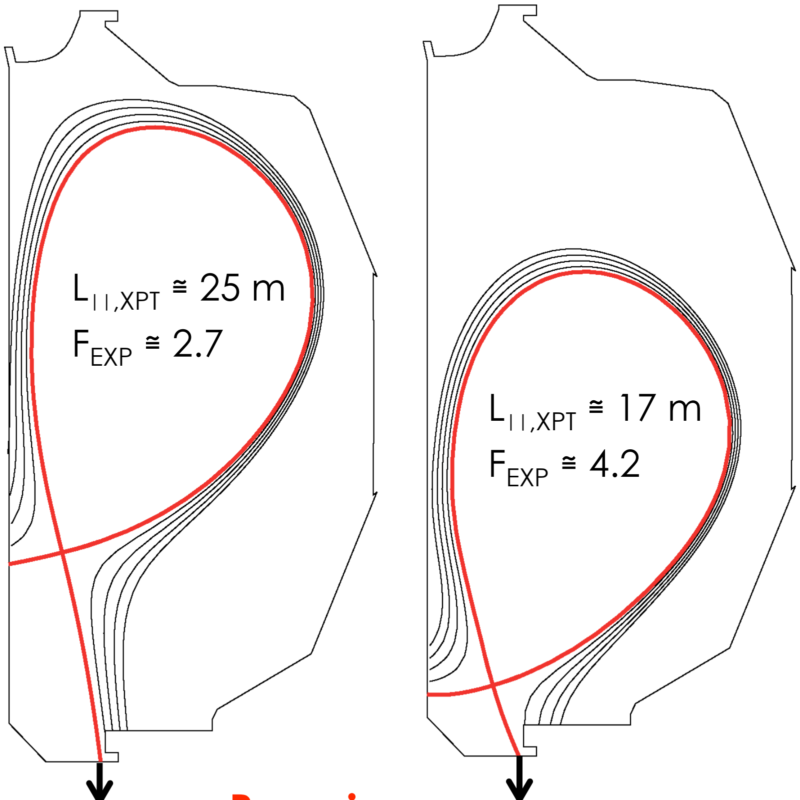
Increasing $L_{||}$ in the SOL broadened $q_{\perp}(R)$ profile and lowered the peak heat flux at the outer target



No gas puffing or pumping

- **Identical core plasma but different $L_{II\text{-}XPT}$**
- **Flux expansion at the outer target (F_{EXP}) differs:**
  - **5.6** for $L_{II\text{-}XPT}$ = 17 m
  - **3.2** for $L_{II\text{-}XPT}$ = 25 m
- **Similar FWHM ≈ 3.5 cm**
  - peak $q_{\perp}$ comparable
- **$L_{II\text{-}XPT}$ vs F_{exp}**
  - Modeling suggests that cross-field transport effects are in play

Increasing $L_{||,XPT}$ enhanced heat flux reduction during radiating divertor operation



1.8 ← Pumping Only → 1.8 MW/m²

1.0 ← Radiating Divertor → 1.3 MW/m²

<u>Similar configuration but now with active particle exhaust</u> (β_N = 1.9)

- **<u>Pumping Only</u> (P_{IN} = 6.5 MW):**
  - Peak heat fluxes comparable
  - Consistent with previous (unpumped) result
- **<u>Radiating Divertor</u> (P_{IN} = 9.0 MW):**
  - Expect increased neutrals and impurity presence along the SOL between X-point and target to enhance cross-field diffusion
  - Expect the longer $L_{||,XPT}$ case to produce a greater reduction in $q_{\perp}^{P}$
  - Modeling to begin shortly

Good progress in adapting radiative divertor to fusion relevant conditions was made

- **Radiating divertor operation in the ITER Baseline Scenario was effective in reducing both stationary and ELM peak heat flux.**

- **High performance was maintained and heat flux was significantly reduced in the primary divertor of an unbalanced DND during D_2 and neon injection.**
  - Temperature and heating in the secondary (outer) divertor increased, under the β_N = constant constraint.

- **Increasing $L_{||,XPT}$ under radiating divertor conditions produced a substantial additional reduction in the peak heat flux.**

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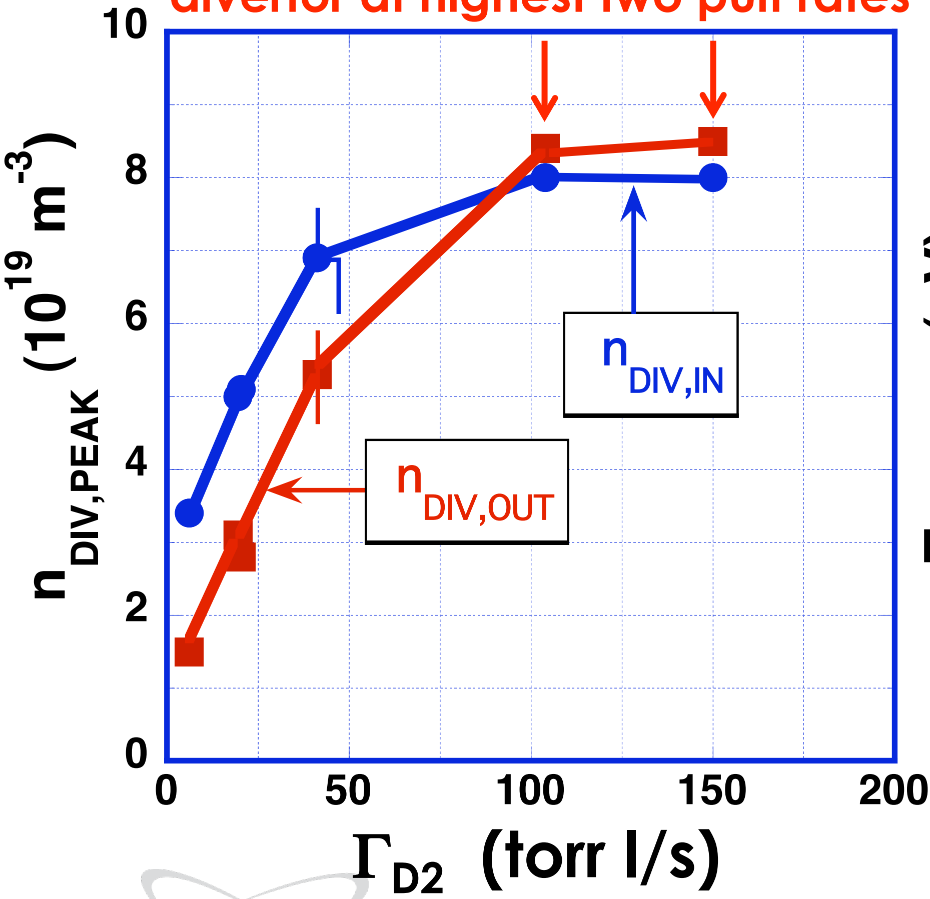
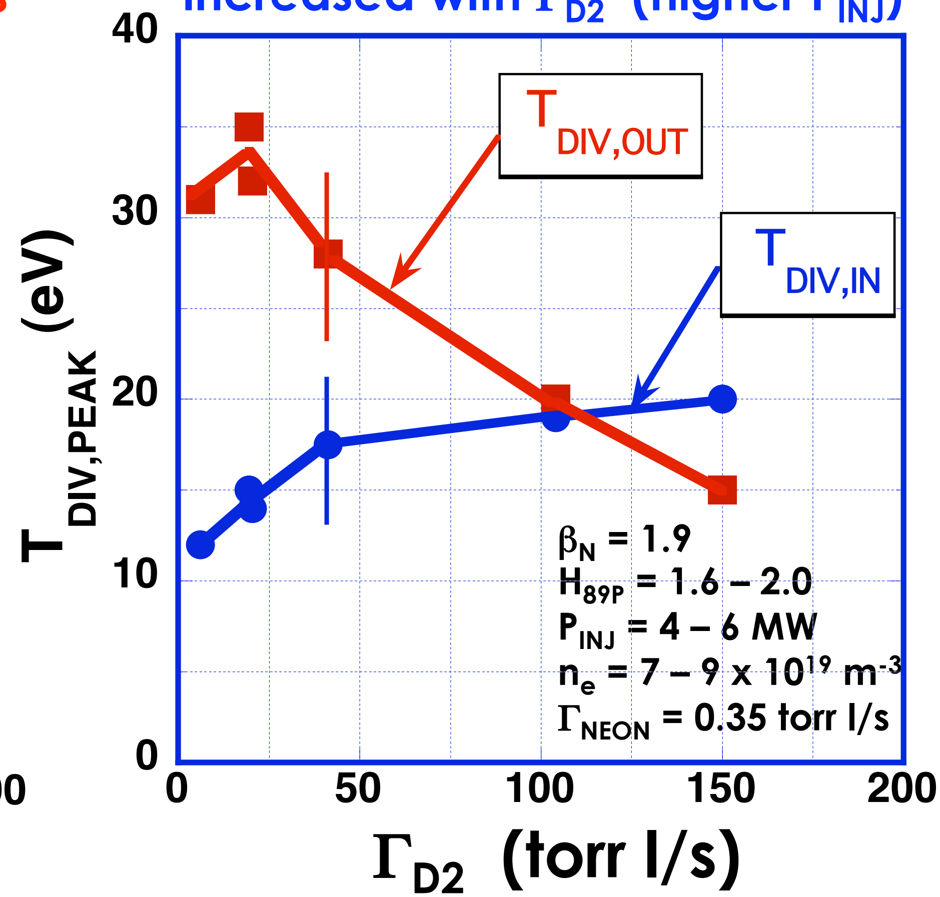
RESERVE FIGURES

Density and temperature near the inner and outer divertor targets evolve differently with Γ_{D2} at constant β_N

- Partial detachment at the inner divertor was observed in all cases
- Partial detachment of the outer divertor at highest two puff rates



- $T_{DIV,PEAK}$ of the outer divertor was strongly affected by higher Γ_{D2}
- Inner divertor temperature increased with Γ_{D2} (higher P_{INJ})

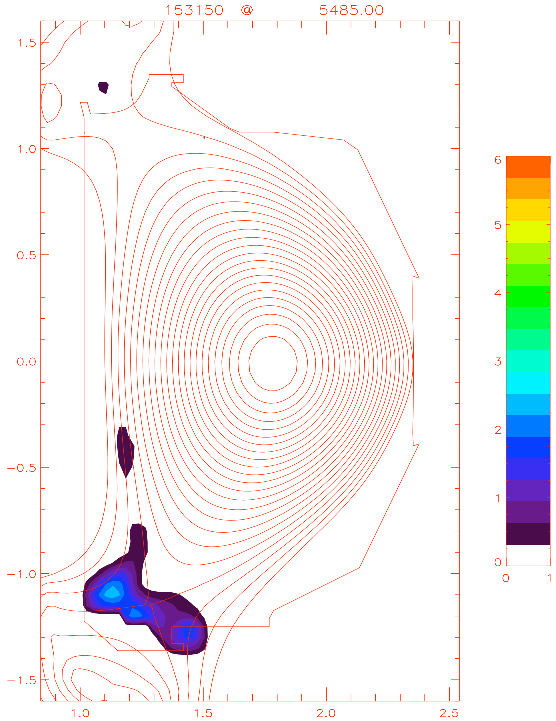


The centroid of the divertor radiated power shifts from the inner divertor to the outer divertor as Γ_{D2} is raised

$P_{IN\text{-}DIV} = 0.5 \times [P_{INJ} - P_{R,CORE}] - P_{R,IN\text{-}DIV}$

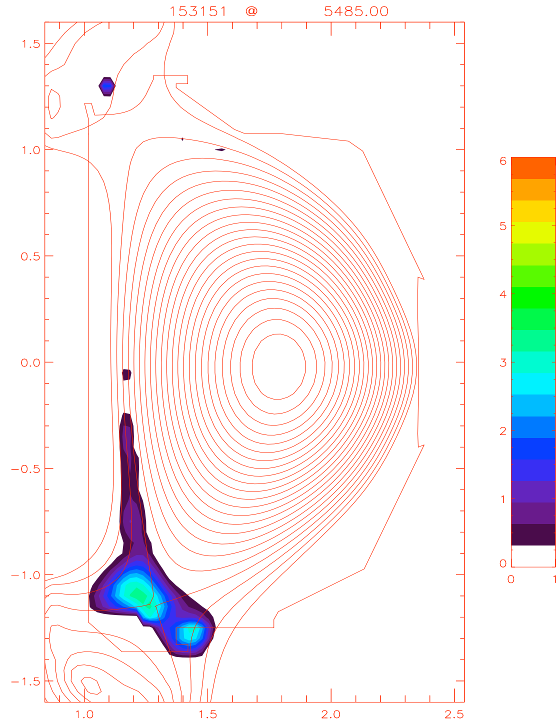
$P_{OUT\text{-}DIV} = 0.5 \times [P_{INJ} - P_{R,CORE}] - P_{R,OUT\text{-}DIV}$

$P_{IN\text{-}DIV}$ = 1.17 MW
$P_{OUT\text{-}DIV}$ = 1.23 MW



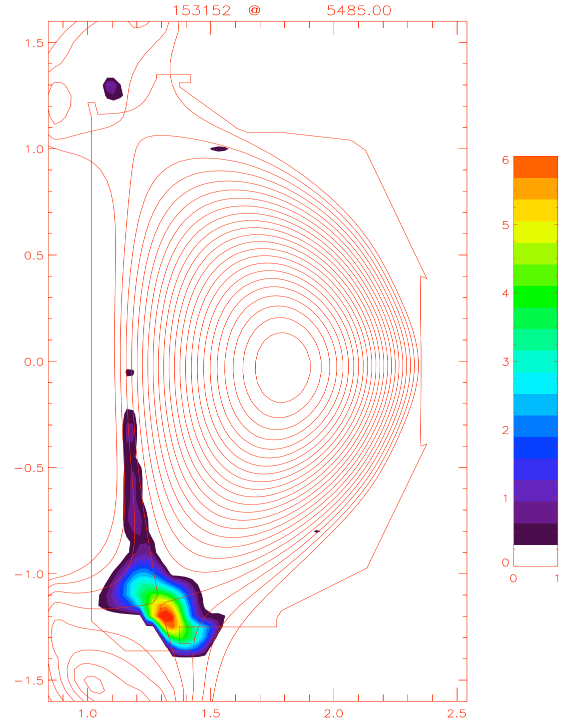
Γ_{D2} = 20 torr l/s

$P_{IN\text{-}DIV}$ = 1.70 MW
$P_{OUT\text{-}DIV}$ = 1.60 MW



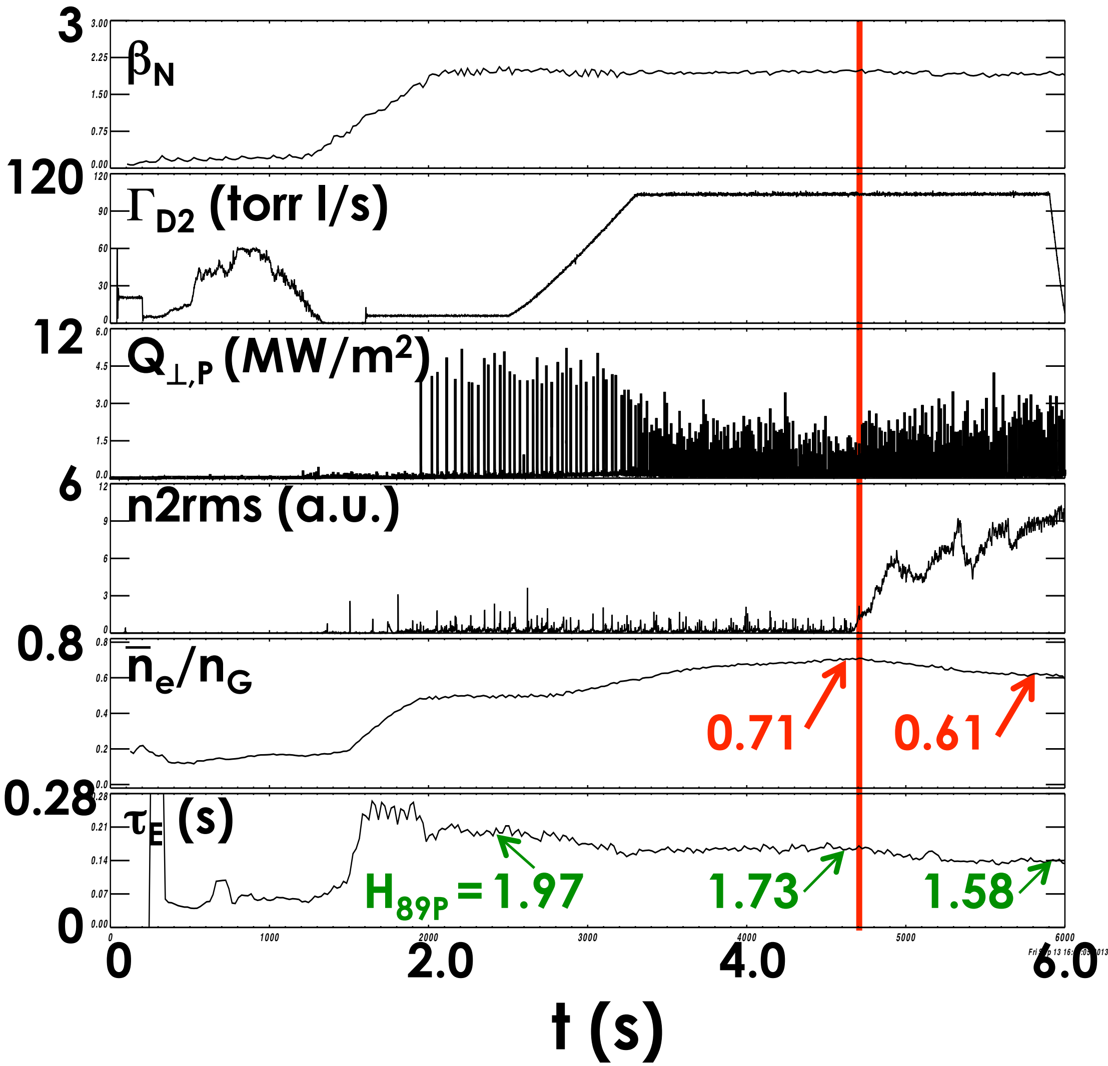
Γ_{D2} = 40 torr l/s

$P_{IN\text{-}DIV}$ = 1.80 MW
$P_{OUT\text{-}DIV}$ = 0.71 MW



Γ_{D2} = 104 torr l/s

Tearing modes triggered during heavy D_2 gas puffing degraded both particle and energy confinement



– β_N was maintained by NBs under feedback control

- Heavy deuterium gas injection for almost 3 s

- Peak heat flux at the inner target tracked ELM activity

- Substantial 3/2 tearing mode triggered at 4.7 s

- Density rolled over after the 3/2 tearing mode appeared

– τ_E dropped ≈10% after the 3/2 tearing mode appeared

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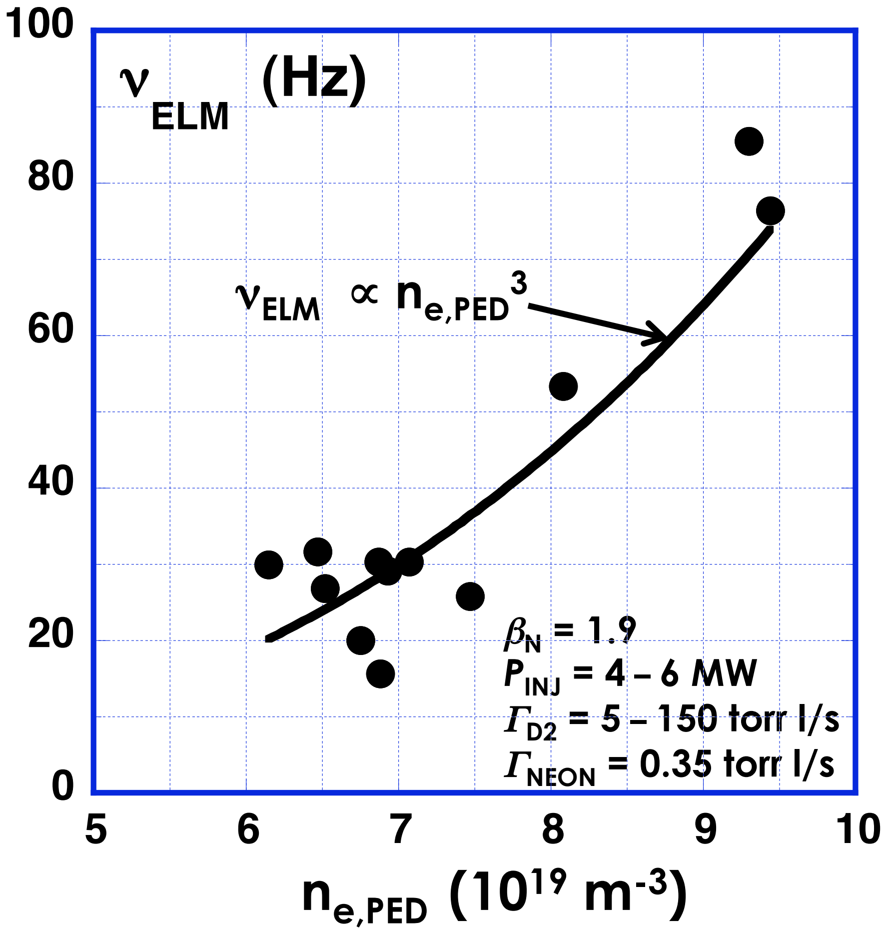
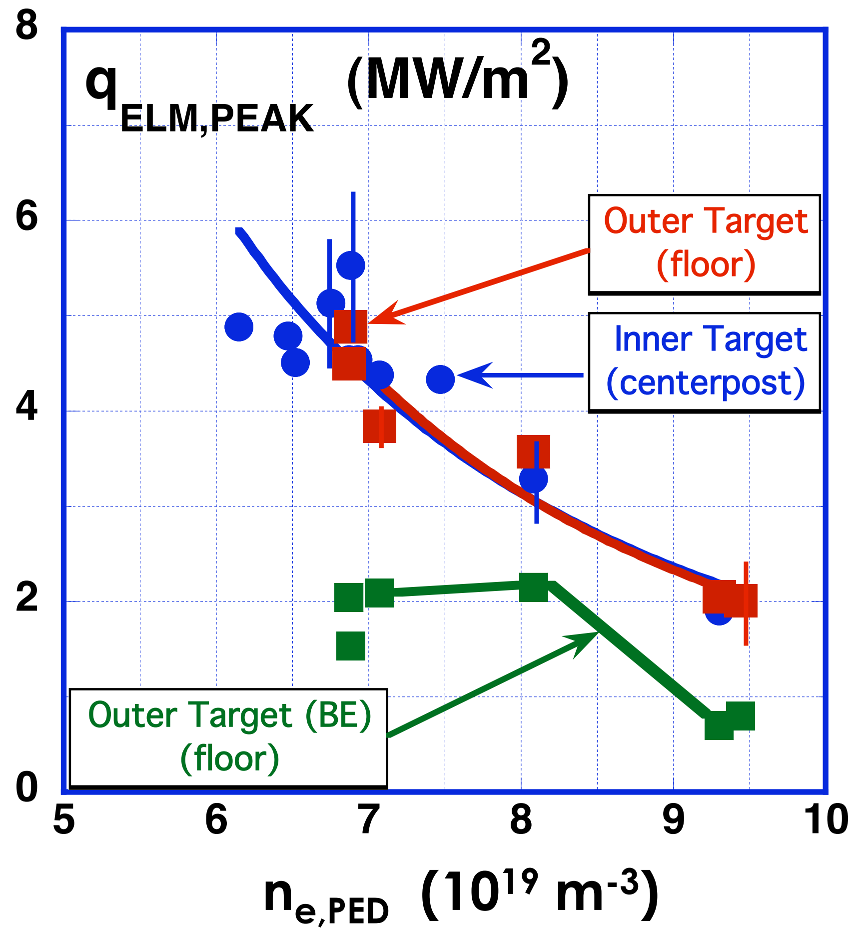
An increase in ν_{ELM} was matched by a decrease in the peak ELM heat flux, as $n_{e,PED}$ was raised

These ELMs are characterized as type-1

$q_{ELM,PEAK} \propto n_{e,PED}^{-2.4}$





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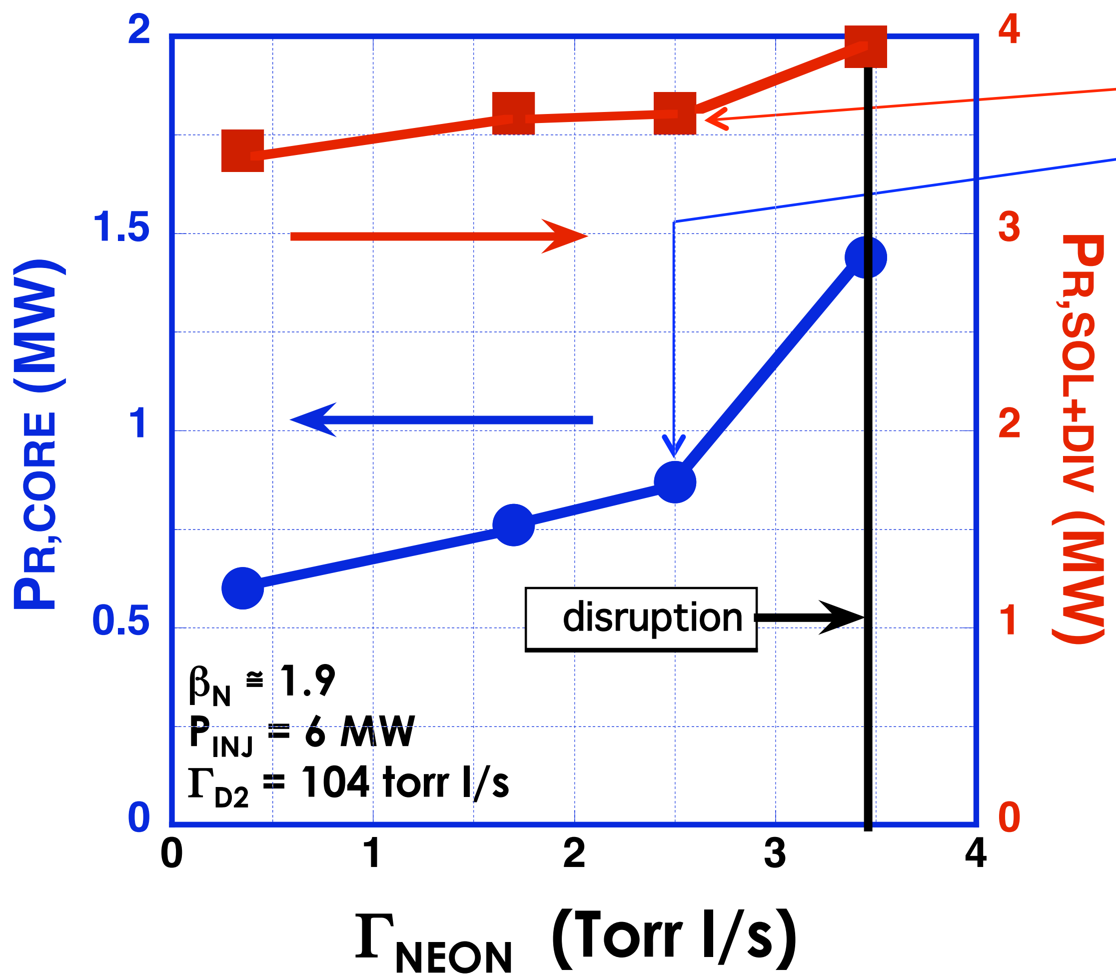
≅60% of the *increase* in the radiated power is found outside the main plasma during neon injection



Γ_{NEON} (t l/s)	0.35	2.50
$P_{R,SOL+DIV}/P_{IN}$	0.58	0.64
$P_{R,CORE}/P_{IN}$	0.10	0.15
$P_{R,TOT}/P_{IN}$	0.68	0.79

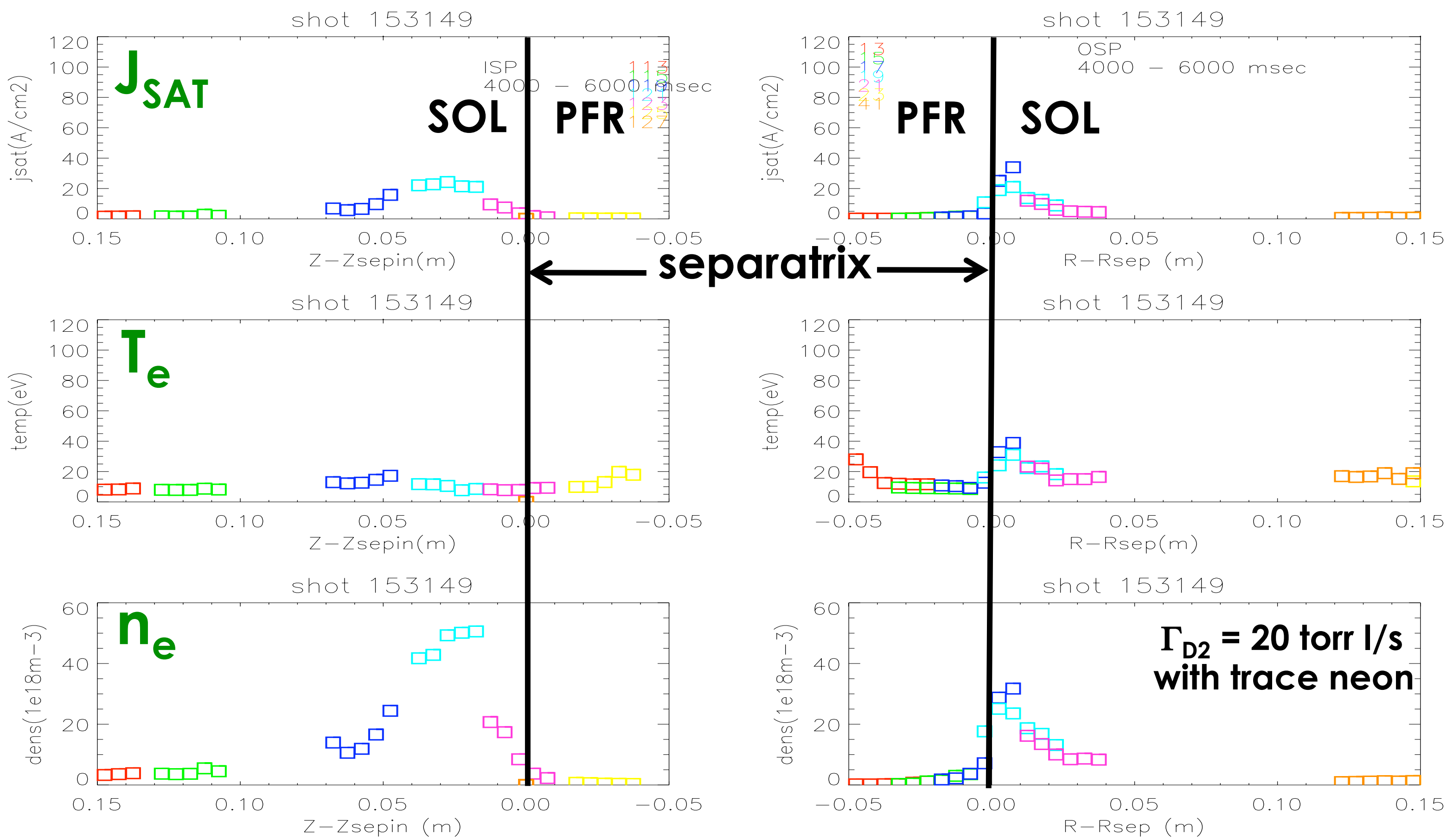
Z_{EFF} = **2.3 (CER)**

- $\Delta [Z_{EFF,CARBON}]$ ≅ **0.8**
- $\Delta [Z_{EFF,NEON}]$ ≅ **0.5**

Power split with increasing Γ_{NEON} consistent with previous results at different Ion Bx∇B, dRsep, impurity specie (argon), and pumping scheme, e.g., ref [1].

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

J_{SAT}, T_e, and n_e profiles suggest partial detachment at the ID target and attachment at the OD target



Inner divertor (centerpost)

Outer divertor (floor)

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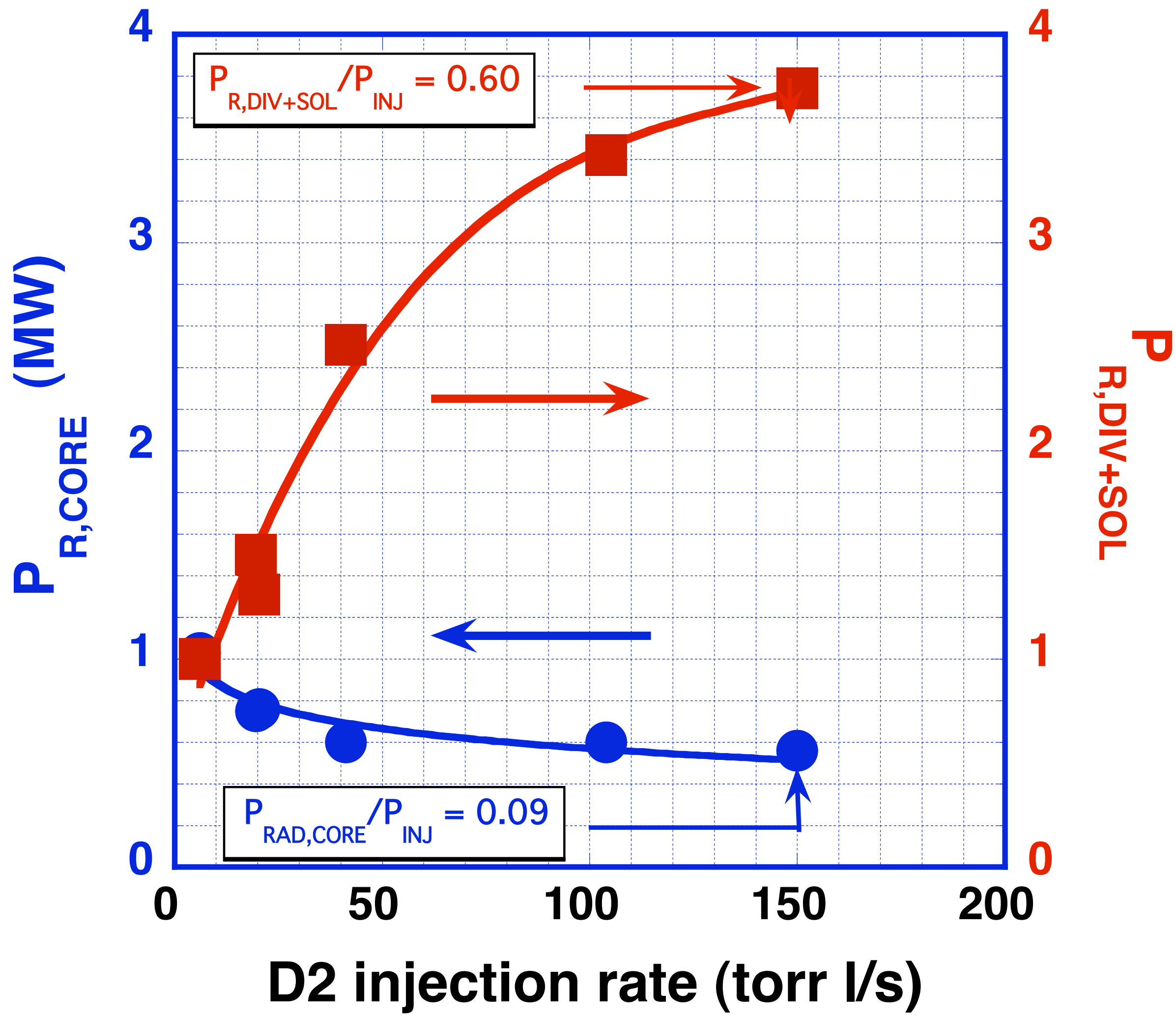
The increase in the radiated power during D2 gas puffing occurs entirely outside the main plasma



At lowest Γ_{D2}:

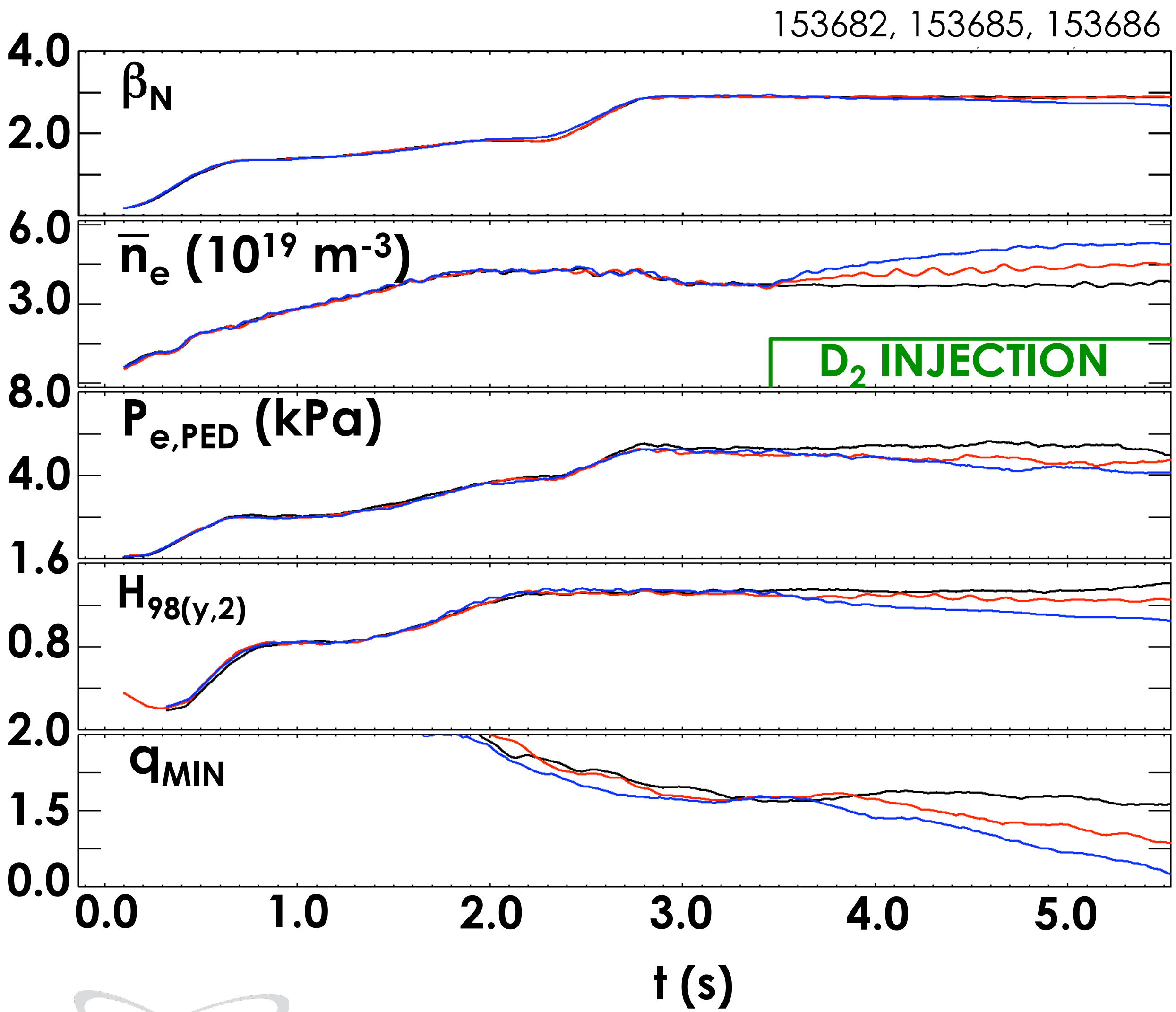
– ≅25% of the power input is radiated outside the main plasma
- $P_{R,TOT}/P_{INJ} \cong 0.50$

At highest Γ_{D2}:

- More than half of the power input is radiated outside the main plasma
- $P_{R,TOT}/P_{INJ} \cong 0.69$

$\bar{n}_e = 7 – 9 \times 10^{19}\ m^{-3}$
$\beta_N = 1.9 – 2.0$
$P_{INJ} = 4.1 – 6.2$ MW
$\Gamma_{NEON} = 0.35$ torr l/s

$H_{98(y,2)} > 1.3$ and $q_{MIN} \approx 1.5$ could not be maintained at the higher levels of density and Γ_{D2} studied



- β_N was held approximately constant at ≈ 2.9
- $\bar{n}_e/n_G$ = 0.40 – 0.60
- pedestal pressure decreased as $\bar{n}_e$ increased
- $H_{98(y,2)}$ decreased 15 – 20% over this Γ_{D2} range
- q_{MIN} difficult to maintain at high Γ_{D2}

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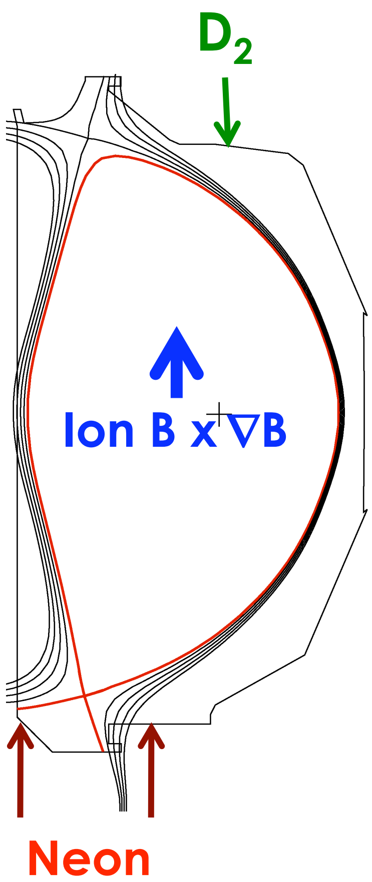
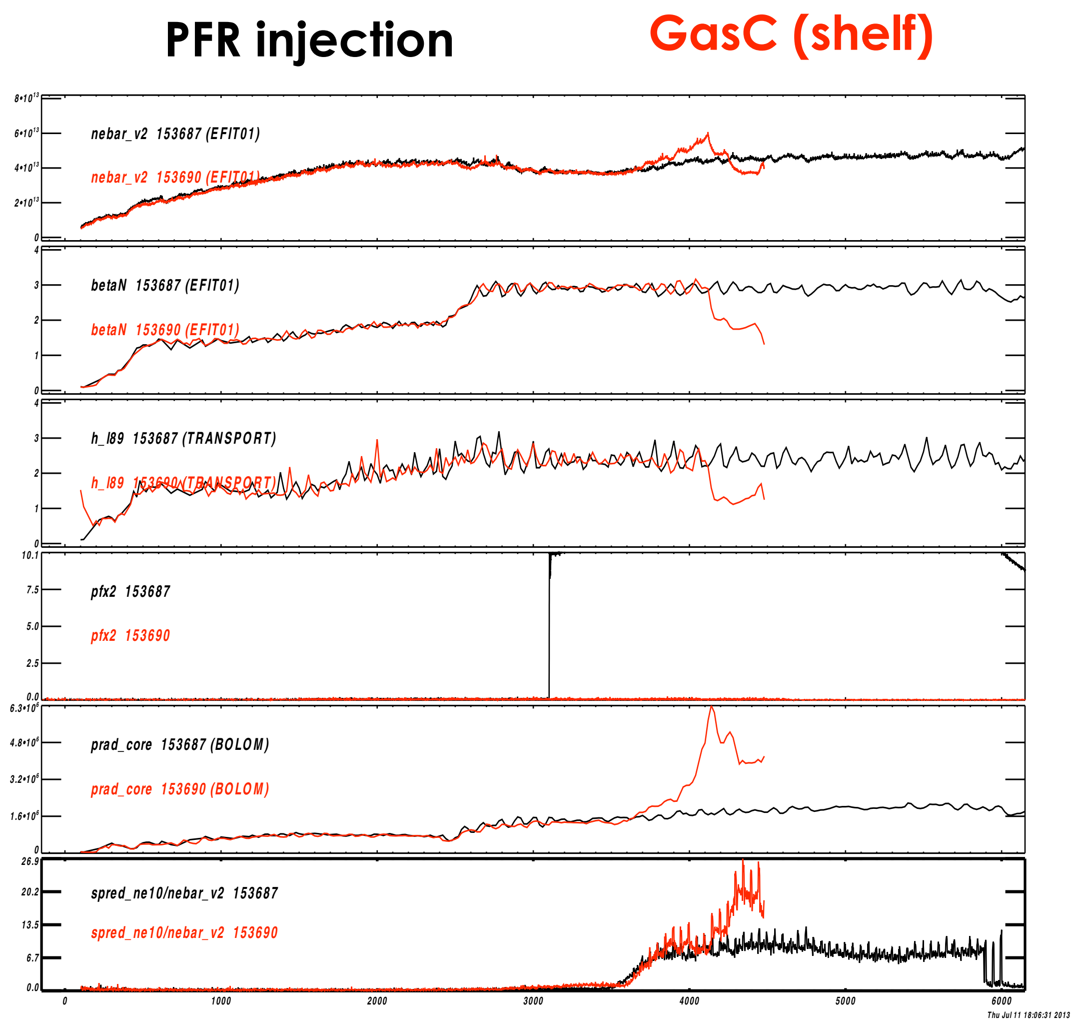
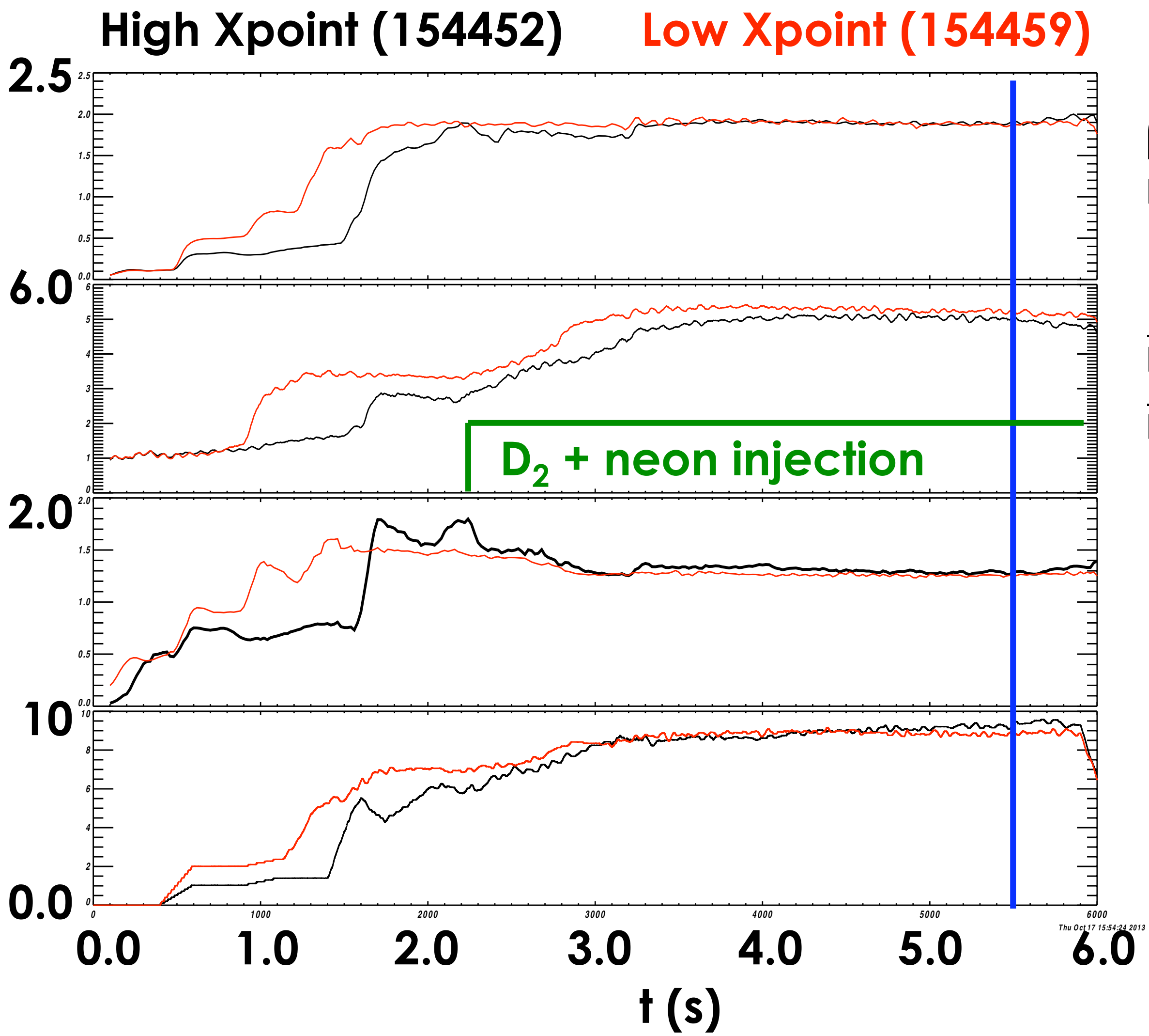
The poloidal location of impurity injection plays a major role in the success of the radiating divertor





Similar core properties for both high- and low Xpoint cases during puff-and-pump radiating divertor operation



β_N = 1.9 was maintained by neutral beam feedback

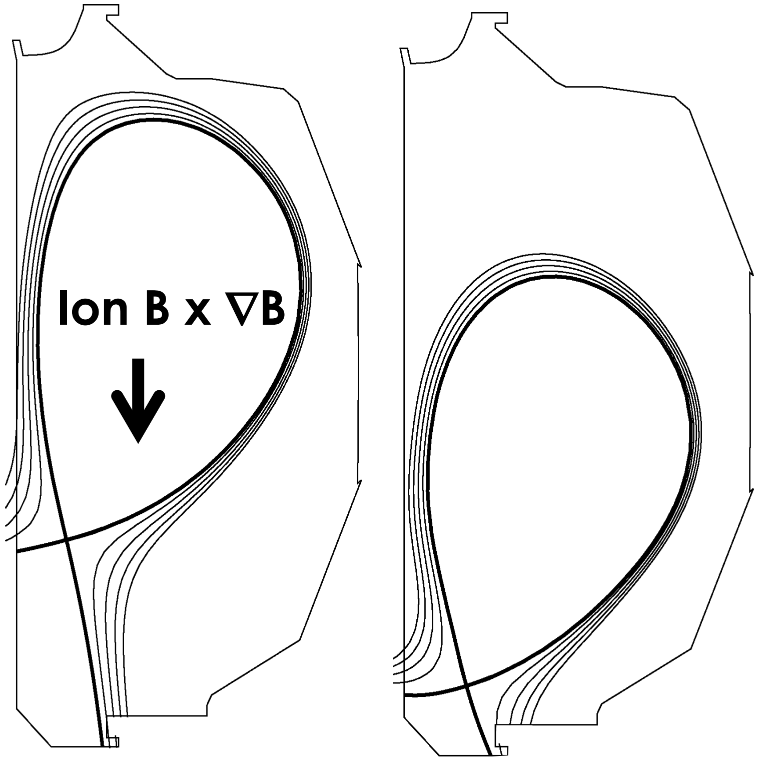
$\bar{n}_e \cong 5.1 \times 10^{19}\ m^{-3}$

$\bar{n}_e/n_G \cong 0.55$

$H_{89P} \cong 1.3$

$P_{IN} \cong 9$ MW

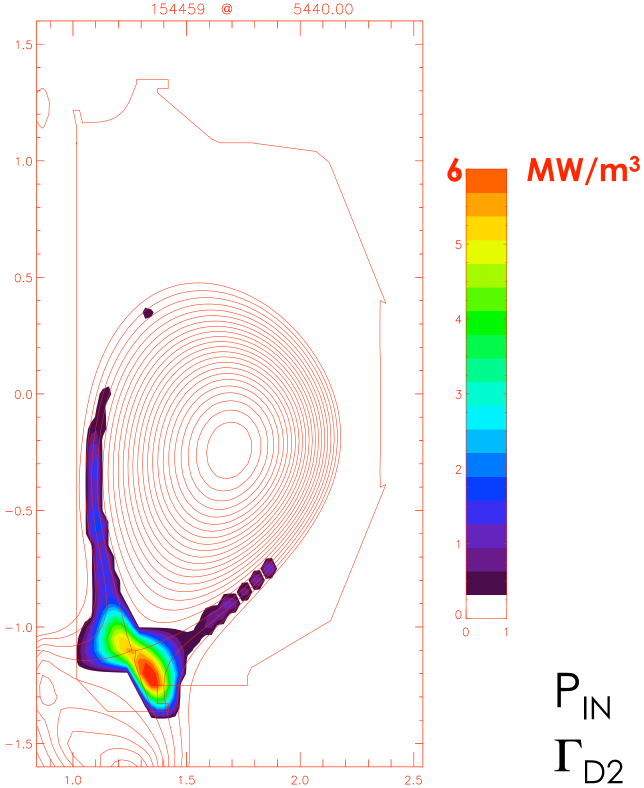
Longer $L_{||,XPT}$ led to a more pronounced drop in the peak heat flux during radiating divertor operation



	High X-pt		Low X-pt	
	no RD	RD	no RD	RD
$L_{||,XPT}$ (m)	**25**	**25**	**17**	**17**
β_N	1.9	1.9	1.9	1.9
F_{EXP}	**2.7**	**2.7**	**4.2**	**4.2**
Γ_{D2} (Torr l/s)	-	150	-	150
Γ_{NEON} (Torr l/s)	0.4	5	0.4	5
H_{89P}	1.48	1.28	1.55	1.25
P_{IN} (MW)	6.4	9.2	6.6	8.9
$P_{IN} - P_{R.TOT}$ (MW)	3.6	4.5	3.9	3.4
$\bar{n}_e/n_G$	0.35	0.55	0.35	0.55

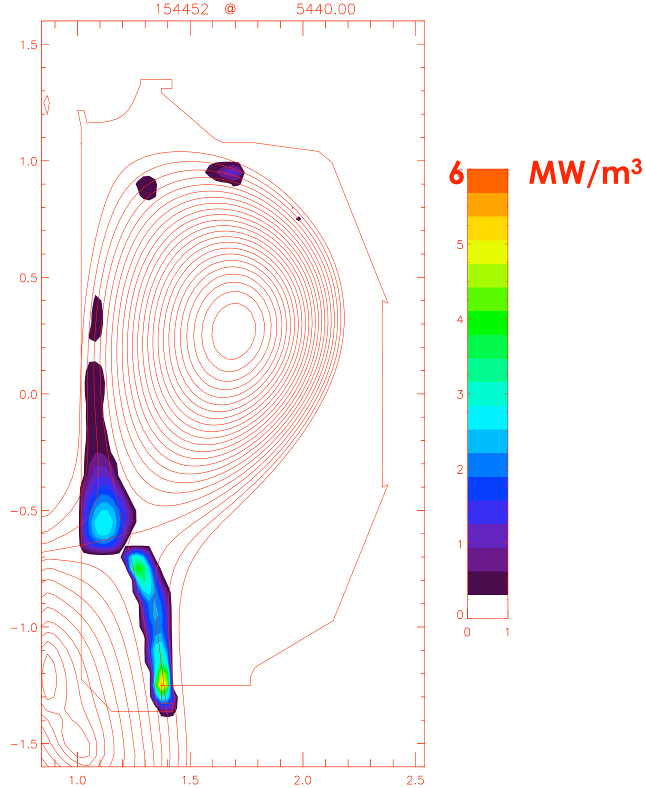
- **Consistent with previous expectations**
- **Cross-field transport enhanced along SOL of longer $L_{||,XPT}$ during radiating divertor?**

Radiated power for the high X-point was more evenly distributed than the low X-point case



$P_{RAD,TOT}$ = 5.40 MW
$P_{RAD,CORE}$ = 0.97 MW
$P_{RAD,SOL}$ = 1.03 MW
$P_{RAD,OD}$ = 2.33 MW
$P_{RAD,ID}$ = 1.07 MW

P_{IN} = 9 MW
Γ_{D2} = 150 torr l/s
Γ_{NEON} = 5 torr l/s



$P_{RAD,TOT}$ = 4.74 MW
$P_{RAD,CORE}$ = 0.99 MW
$P_{RAD,SOL}$ = 1.23 MW
$P_{RAD,OD}$ = 1.83 MW
$P_{RAD,ID}$ = 0.69 MW