Results from Radiating Divertor Experiments with RMP ELM Suppression

by
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INTRODUCTION AND REVIEW

Background and Motivation

- **Eliminating ELMs from plasmas using the Resonant Magnetic Perturbation (RMP) "I-coil" approach presents an attractive possibility for solving the "ELM-issue" in ITER and future highly powered tokamaks**
  - Yet, even if this approach eliminates impulsive damage to the divertor structure from ELM pulses, the steady-state, peak power loading at the divertor targets can still be unacceptably high
- **Radiating divertor solutions have reduced peak power loading at the divertor targets without concomitant degradation of ELMing H-mode plasma properties**
- **When combining RMP with radiating divertor scenarios, it is far from clear whether it is possible to maintain favorable H-mode operation, to prevent the injected impurities from contaminating the main plasma, and to maintain acceptable ELM suppression, all *simultaneously***

MAIN GOAL

**EXPLORE THE COMPATIBILITY OF USING
THE RMP ELM-SUPPRESSION TECHNIQUE
UNDER RADIATING DIVERTOR CONDITIONS**

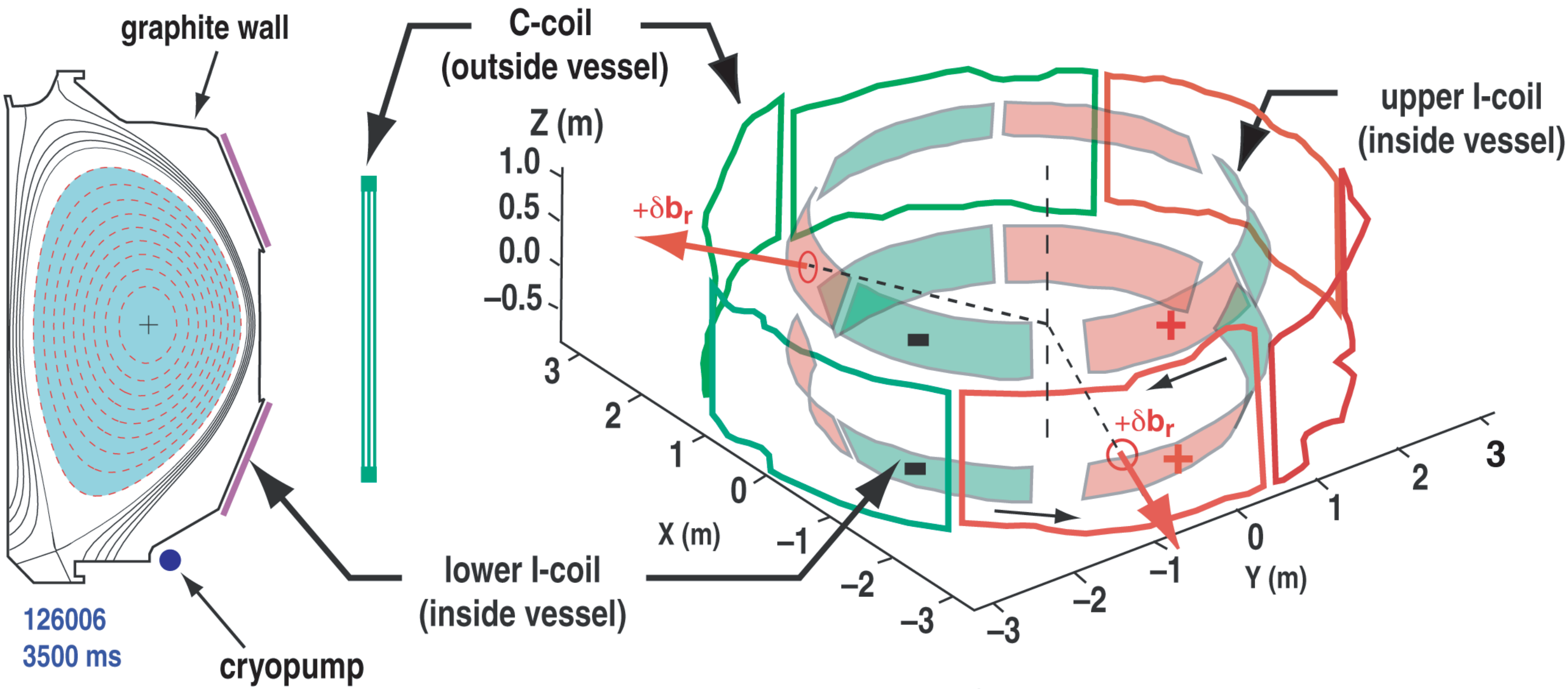
Experimental Operating Conditions

- **ELMing H-mode plasmas are used in this study**
  - $H_{98(y,2)} = 0.8–1.3$
  - n_e/n_G – 0.2-0.6
  - q_{95} – 3.5
  - P_{IN} = 5–8 MW
  - $I_{COIL} \leq 6$ MA, even parity, 60° toroidal phase

The ion Bx∇B drift direction is toward the X-point, unless otherwise specified

- **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}

Two Sets of Non-axisymmetric Coils Produce a Variety of RMPs in DIII-D

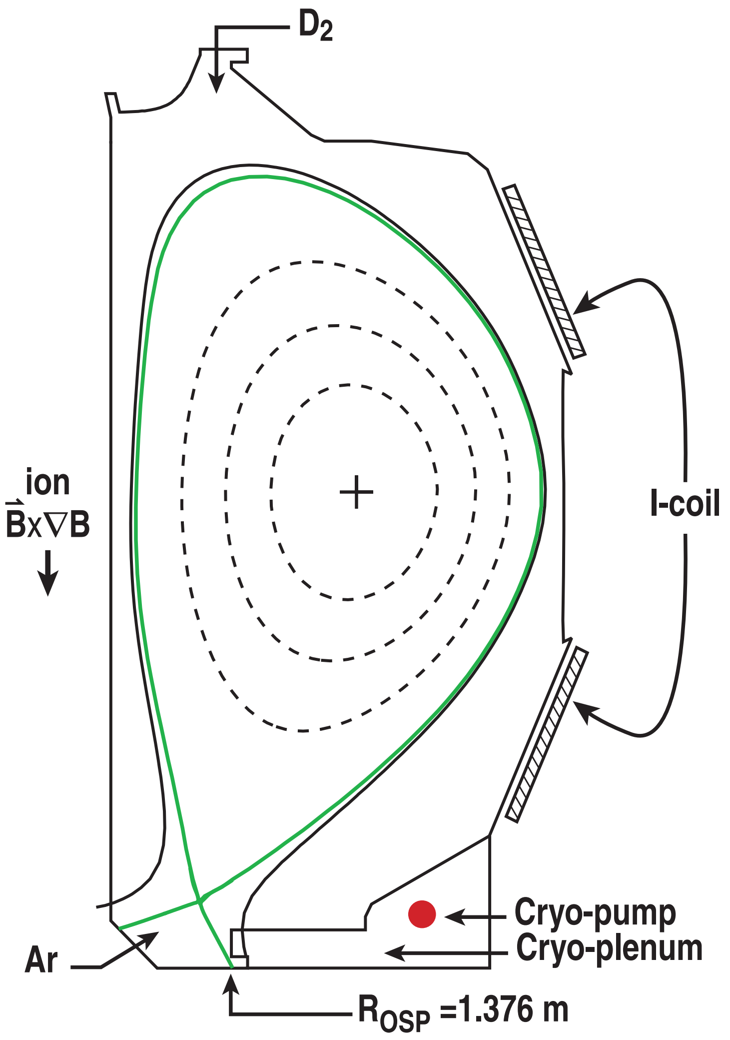


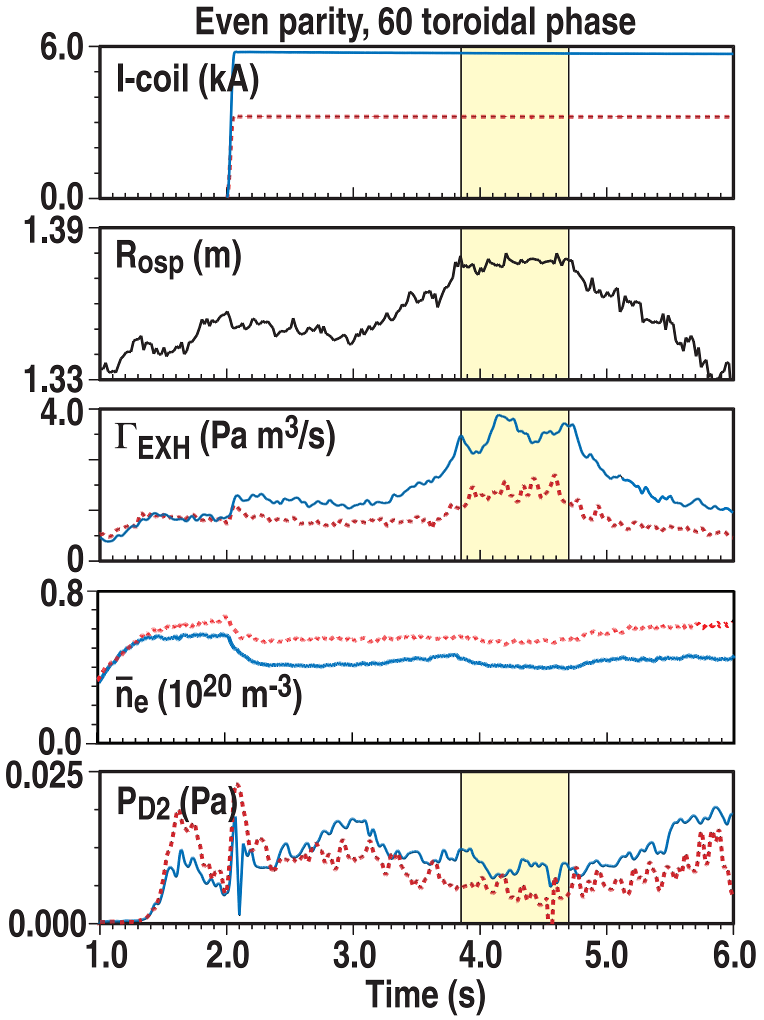
n=3 I-coil and n=1 C-coil configuration
(with up-down symmetric, even parity, I-coil)

- The 4-turn C-coil and single-turn upper/lower I-coil can be configured for n=3 RMP experiments or n=1 field-error correction

GENERAL FEATURES OF PLASMA OPERATION WITH RMP IN DIII-D

Maximum Particle Exhaust During RMP Occurred when the Outer Divertor Strike Point was Adjacant to the Plenum Entrance in Both “Low” and “High” I-coil Cases





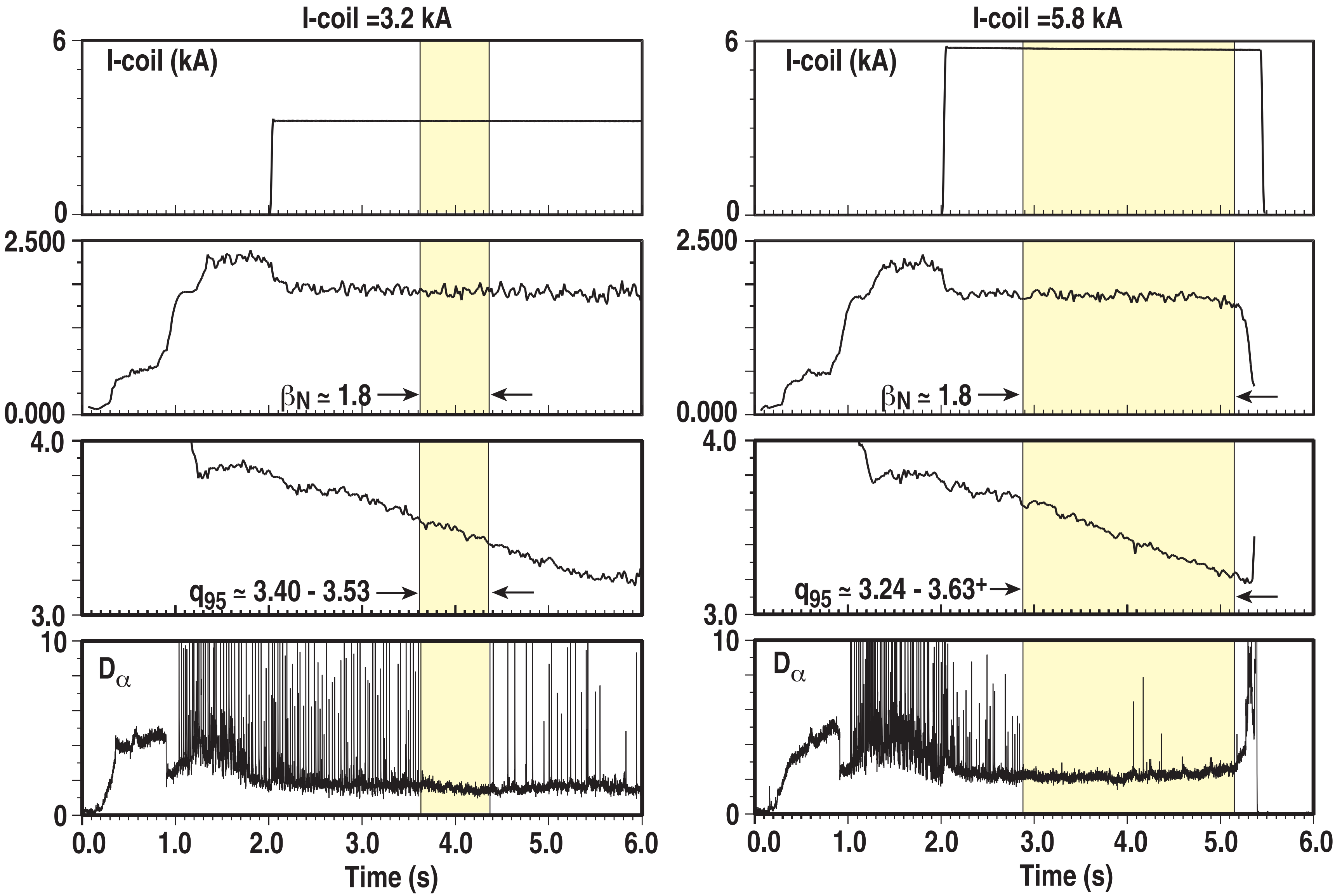
I_p = 1.42 MA
B_T = –1.8 T
P_{INJ} = 4.5-60 MW

Peak in particle exhaust: Rosp =1.376 m

Decreased density near peak in particle exhaust

Neutral pressure in the upper divertor (non-pumping) plenum drops with increasing Γ_{EXH} in the lower divertor

The Higher Value of the I-coil Current Gives a Much Wider Range in q_{95} for ELM Suppression



Ion ∇B drift is toward the X-point

Even parity

60 toroidal phase

I_p = 1.3-1.6 MA

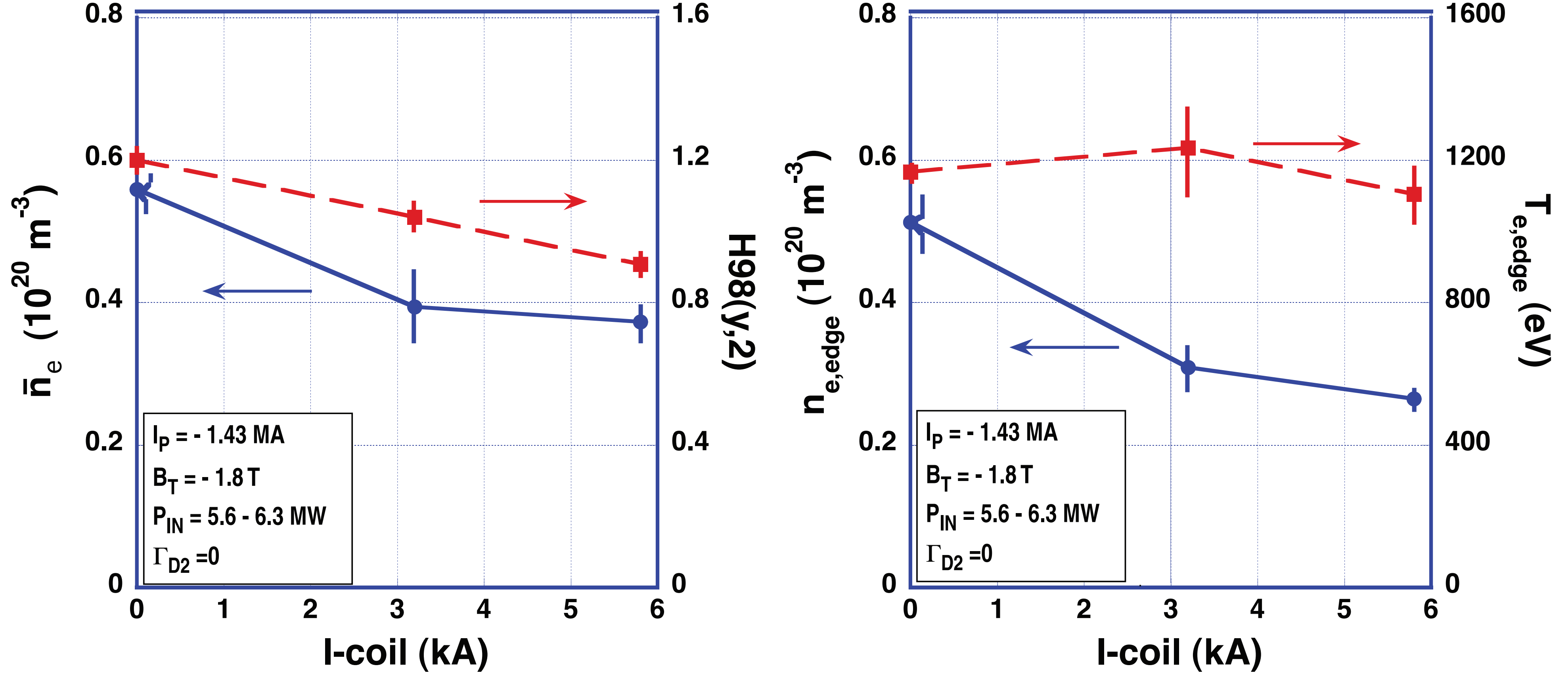
B_T = −1.78 T

R_{osp} ≃1.38 m

$H_{98(y,2)}$ ≃0.93-1.06

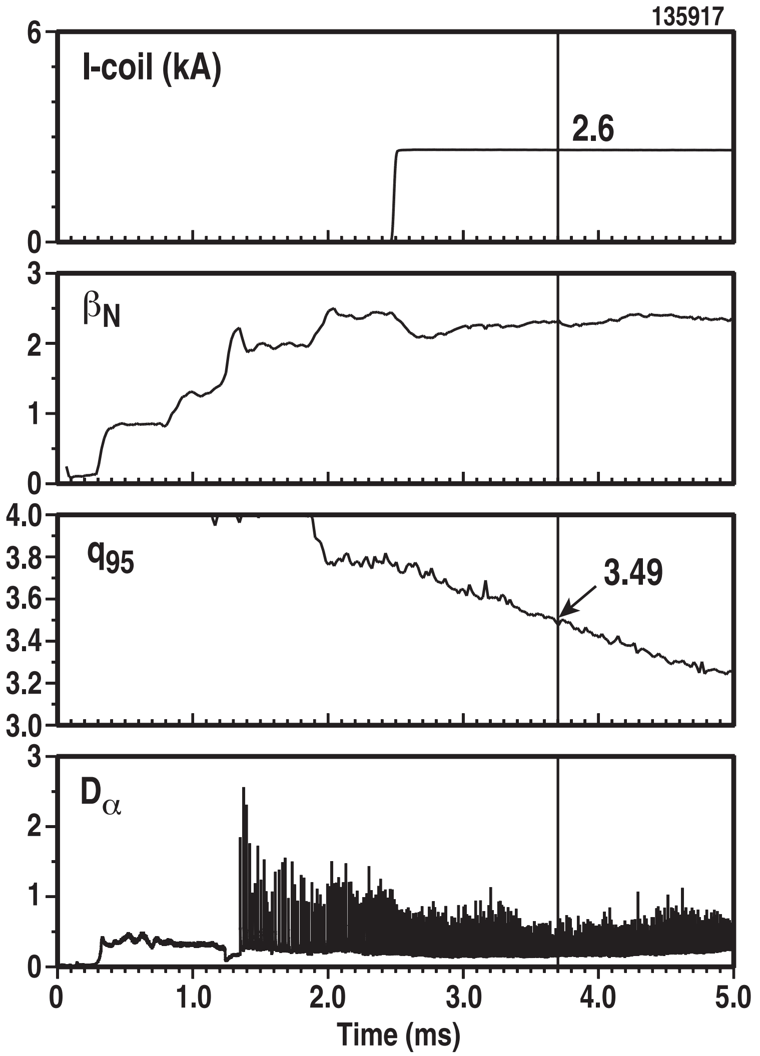
Raising the I-coil Current Reduces $\bar{n}_e$, H98(y,2), and $\bar{n}_e$,edge but has only Minor Effect on $T_{e,\ edge}$

ION Bx∇B is toward the X-point

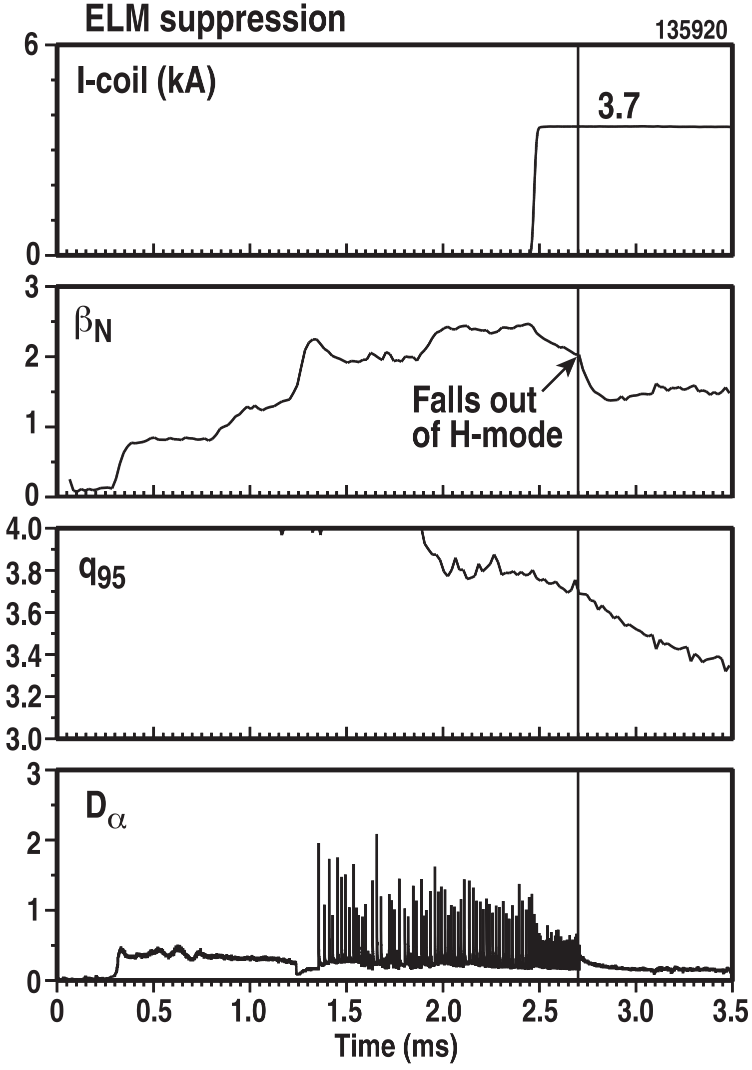


Suppressing ELMs by RMP is More Difficult when the Ion $B \times \nabla B$ Drift is Directed *Away from* the X-point

No resonance observed near $q_{95} = 3.5$ during q_{95} - scan

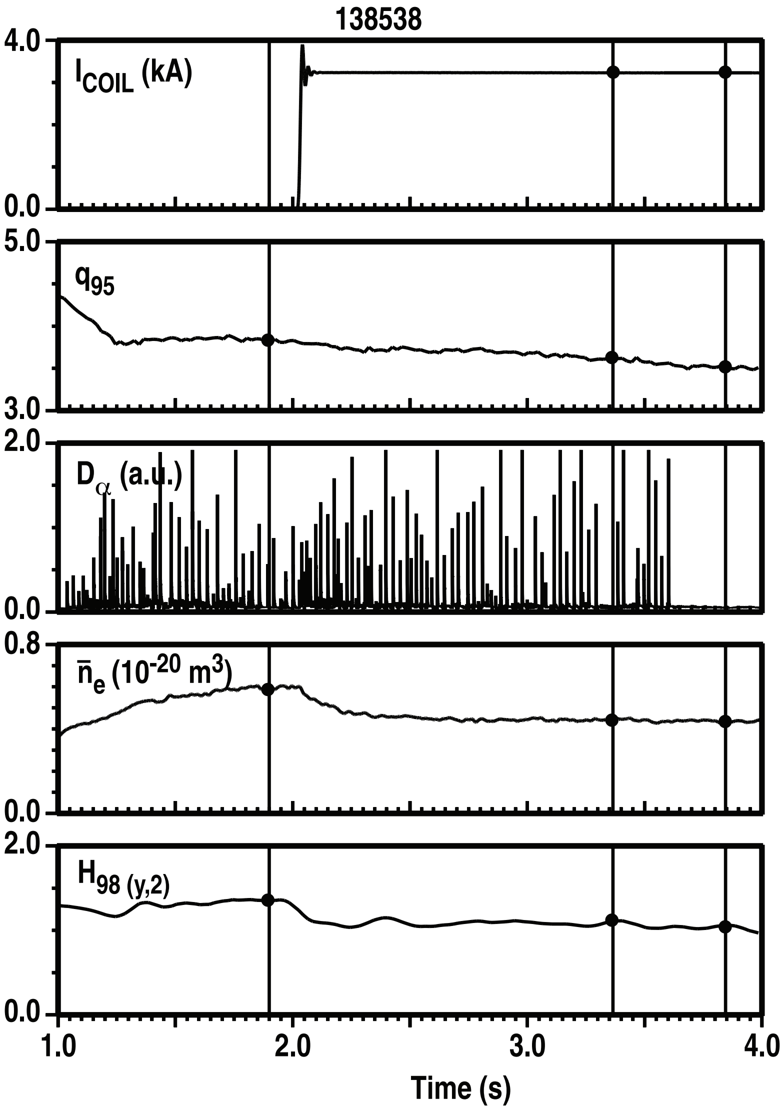


Increasing I-coil current produced an H-L back-transition but still no ELM suppression



- Operating too near the L-H power threshold
- Subject of a future investigation

Little Change in $\bar{n}_e$ and $H_{98(y,2)}$ is Observed Between Resonant and Off-resonant Application of the I_{COIL}



Three timeslices

- Pre-I_{COIL}
- I_{COIL} ON (non-resonant)
- I_{COIL} ON (resonant)

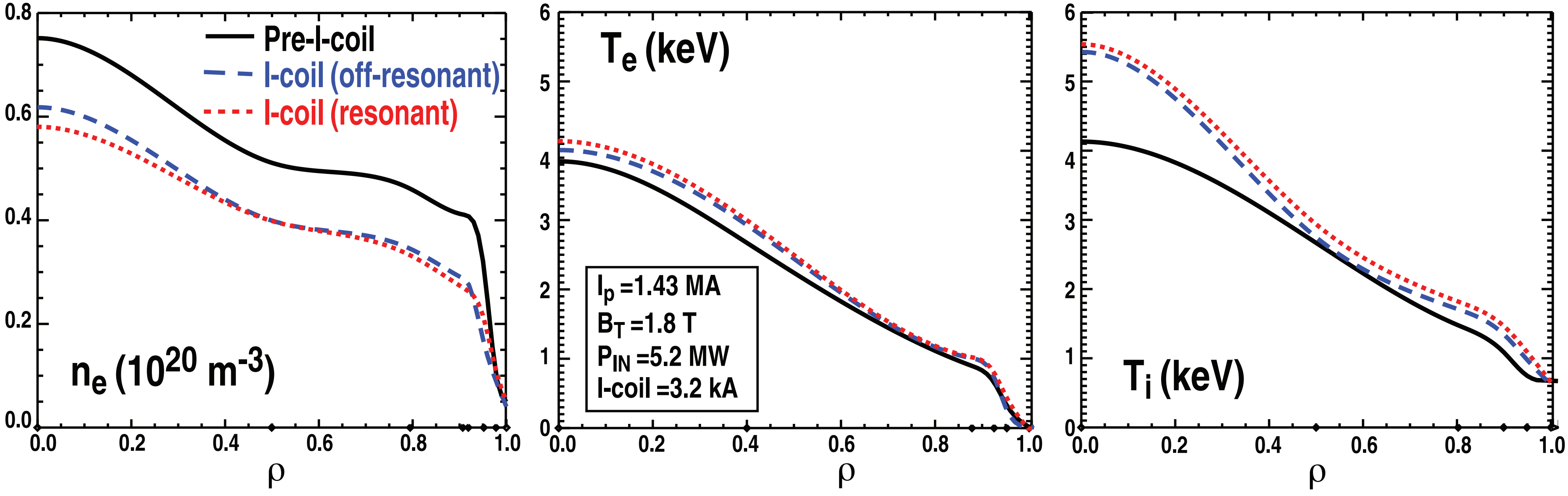
A slow scan in q_{95} induces non-resonant and resonant (ELM-suppressed) periods during the discharge

Virtually the entire 25% drop in n_e occurred shortly after the I_{COIL} was turned on

Virtually the entire 20% drop in $H_{98\ (y,2)}$ occurred shortly after the I_{COIL} was turned on

Activation of the I-coil Produced Major Changes in the n_e and T_i Profiles but Not in the T_e Profile

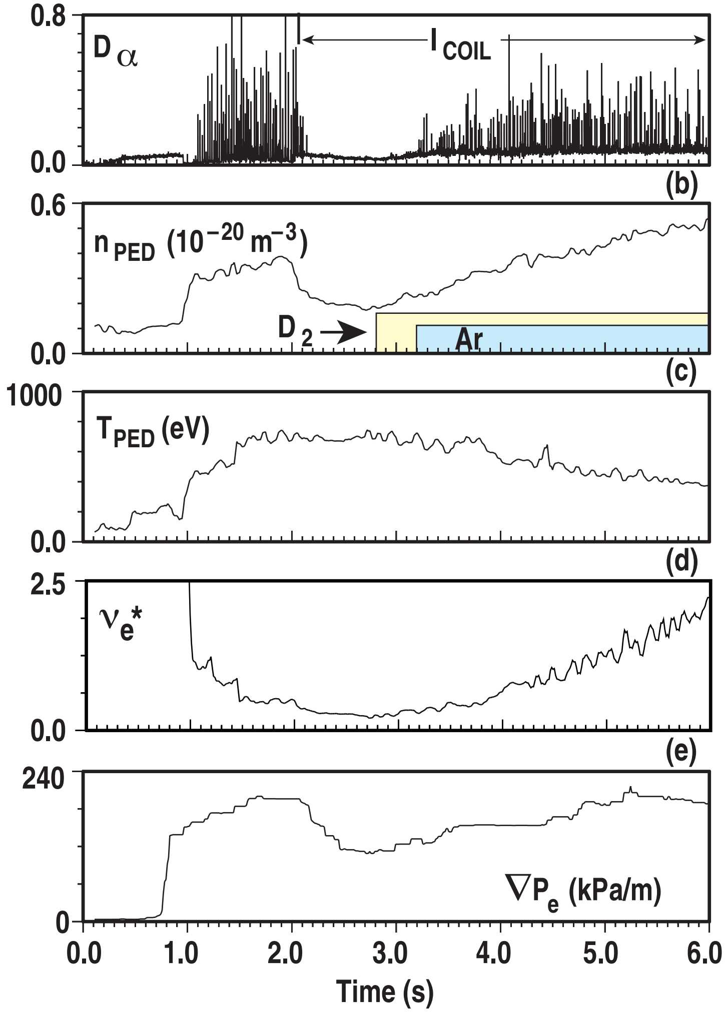
- **Relatively little variation in the profiles between resonant (ELM-suppressed) and off-resonant cases was observed**
- **Application of the I_{COIL} produced a fairly uniform reduction in the density profile, while largely "freezing" the T_e-profile**



RMP ELM SUPPRESSION + PUFF-AND-PUMP RADIATING DIVERTOR OFFERED A LIMITED DENSITY OPERATING SPACE UNDER DIII-D PLASMA CONDITIONS

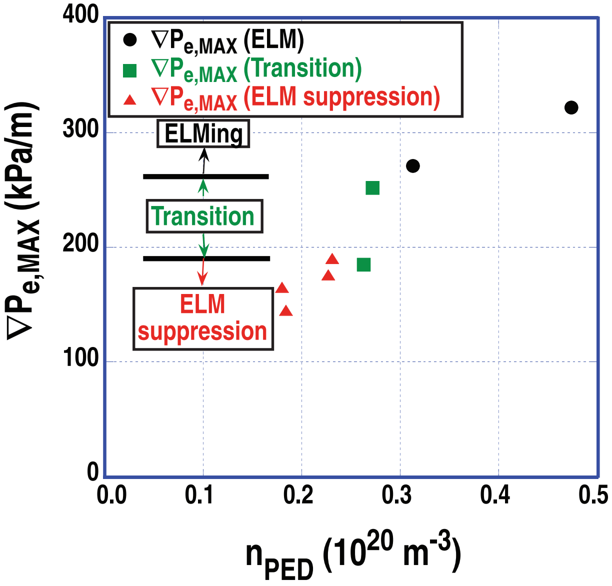
ELMing Activity Returns as n_{PED}, Edge Electron Pressure Gradient, and Electron Collisionality During D_2 and Ar Puffing Increase

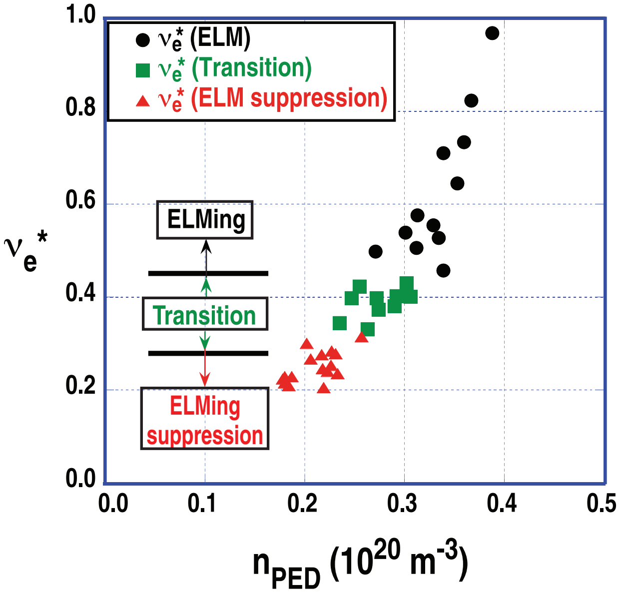
I_{coil} = 5.8 kA, P_{IN} = 6 MW, Γ_{D2} ~ 10 Pa m^3/s, Γ_{Ar} ~ 0.05 Pa m^3/s



- **Return of type-1 ELMs shortly after the activation of gas puffing during RMP-activation**
- **≈ 50% drop in n_{PED} when I_{COIL} was activated but strong recovery of n_{PED} with gas puffing**
- **Little change in T_{PED} with RMP activation but T_{PED} eventually decreased during gas injection**
- **Both ν_e^* and ∇P_e showed a pronounced drop after the I_{COIL} was activated, but both increased when gas puffing was turnd on**

The Range in Pedestal Density for ELM-suppressed Operation is Relatively Small for these DIII-D Plasmas





- **Modest increase in pedestal ∇P_e corresponds to the resumption of Type-1 ELMing**
  - Consistent with peeling-ballooning mode analysis ELITE

- **Type-1 ELMs return where $\nu_e^* > 0.3$**

NOTE: We cannot extrapolate these results to ITER, because for ITER BOTH:

– Pedestal $\nu_e^* \approx 0.1$ in ITER (favorable to ELM suppression), and

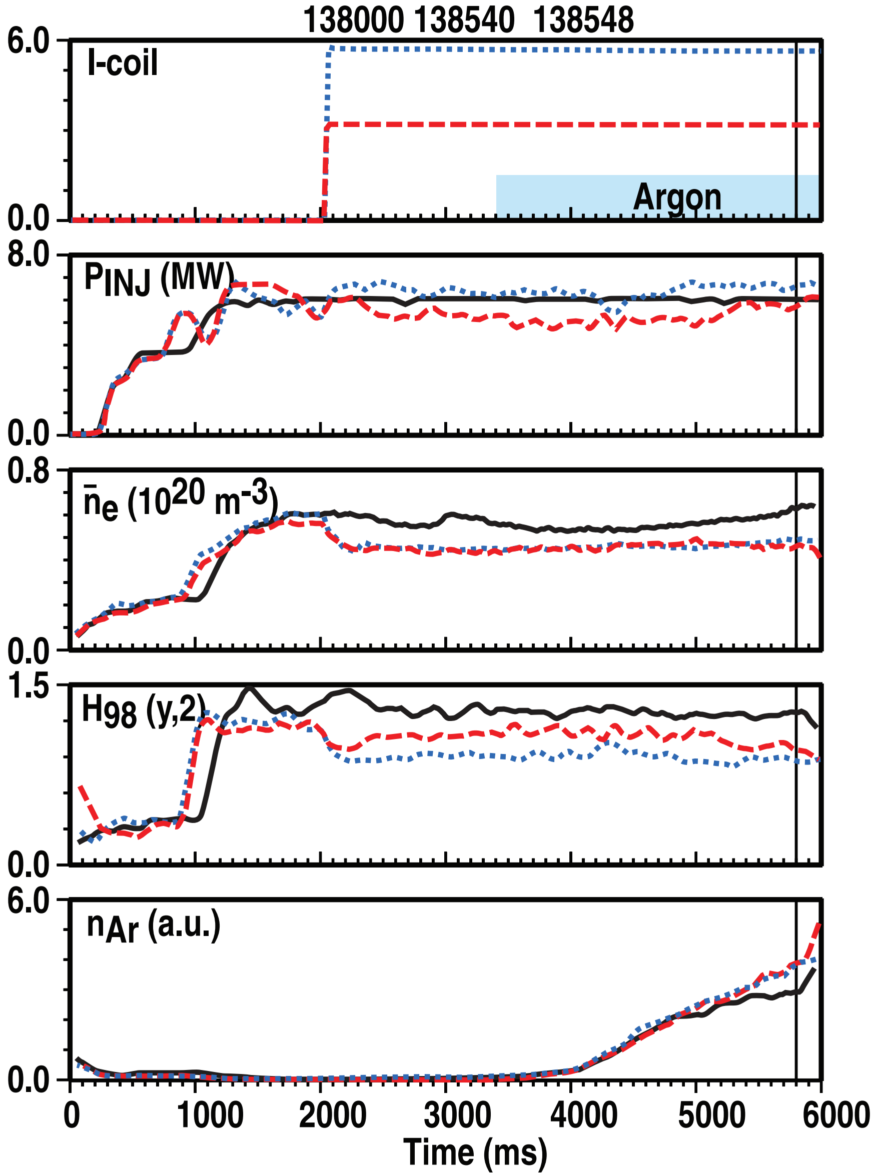
– Higher divertor densities expected for ITER (favorable to the radiating divertor puff and pump approach)

can be achieved SIMULTANEOUSLY, and this is not possible for DIII-D and other present day tokamaks

⇒ Expect greater compatibility in coupling RMP ELM suppression with the puff and pump radiating divertor under ITER plasma conditions

ARGON ACCUMULATION SHOWS MINOR DIFFERENCES BETWEEN RMP/NON-RMP H-MODE PLASMAS

Applying RMP to H-mode Plasmas Affects Density, Confinement, and Argon Accumulation



$\Gamma_{D2} = 0$, $\Gamma_{Ar} \simeq 0.05$ Pa m^3/s

P_{INJ} is fairly constant during most of the discharge

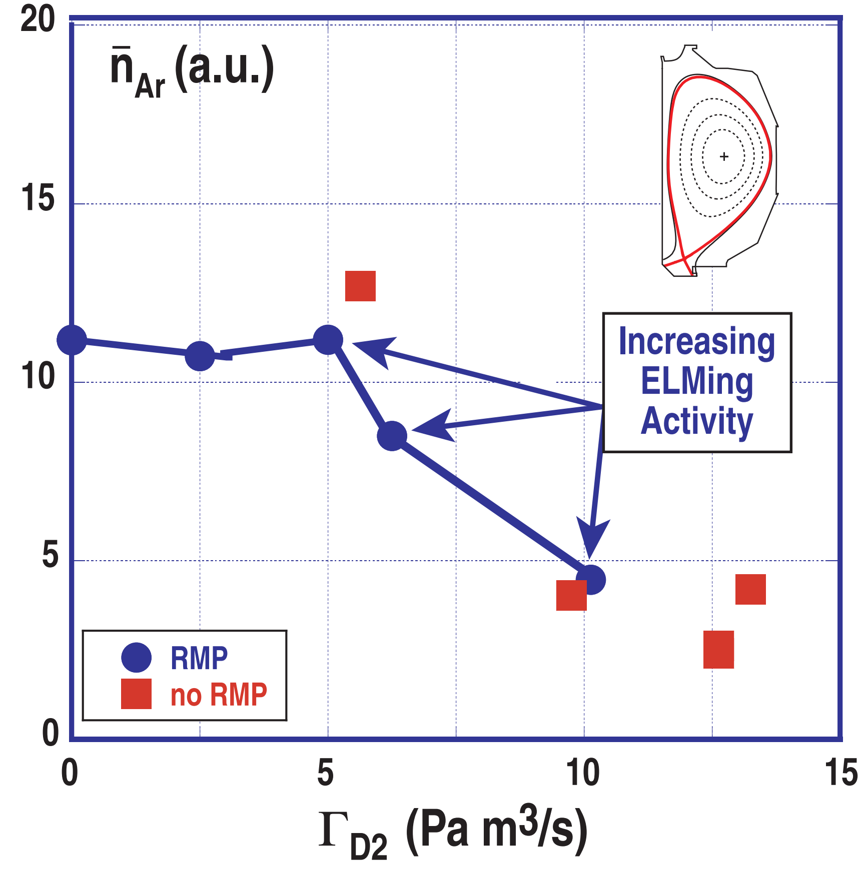
Pumpout when I-coil was activated

$$H_{98}(y,2) = \begin{cases} \rightarrow 1.25 \text{ (ELMing)} \\ \rightarrow 1.00 \text{ (3.2 kA)} \\ \rightarrow 0.88 \text{ (5.8 kA)} \end{cases}$$

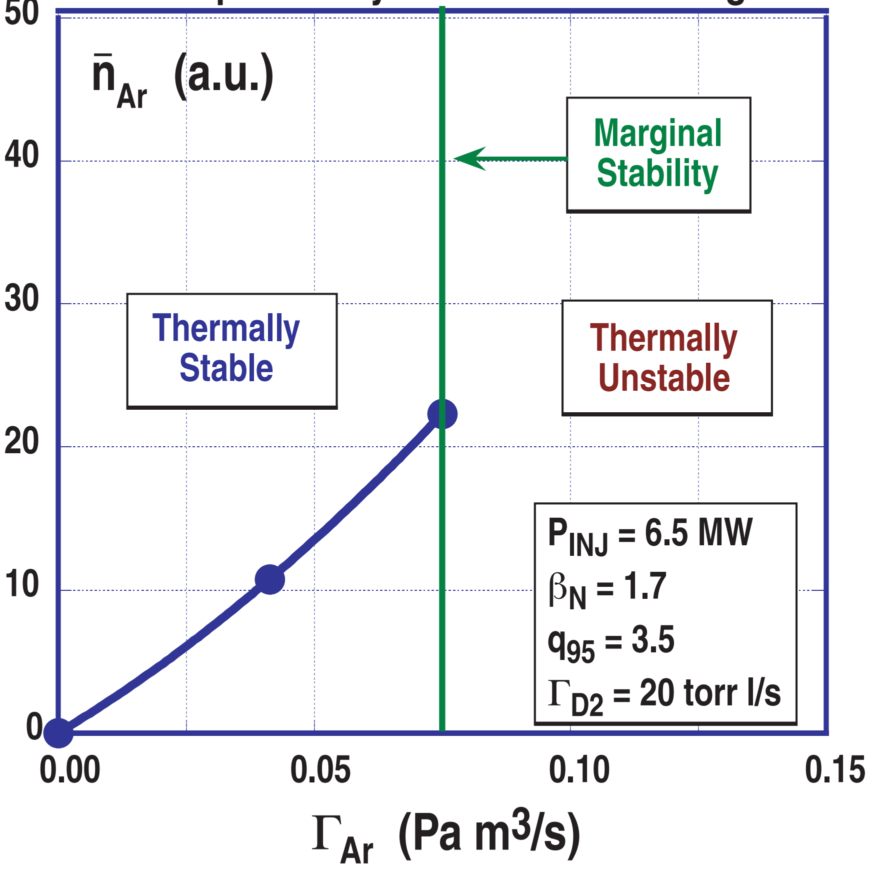
Argon accumulation was ~20-25% higher in I-coil cases

There are Important Simularities in Argon Accumulation Between RMP and non-RMP Discharges

Decrease in $\bar{n}_{Ar}$ with increasing Γ_{D2} in both RMP and non-RMP cases



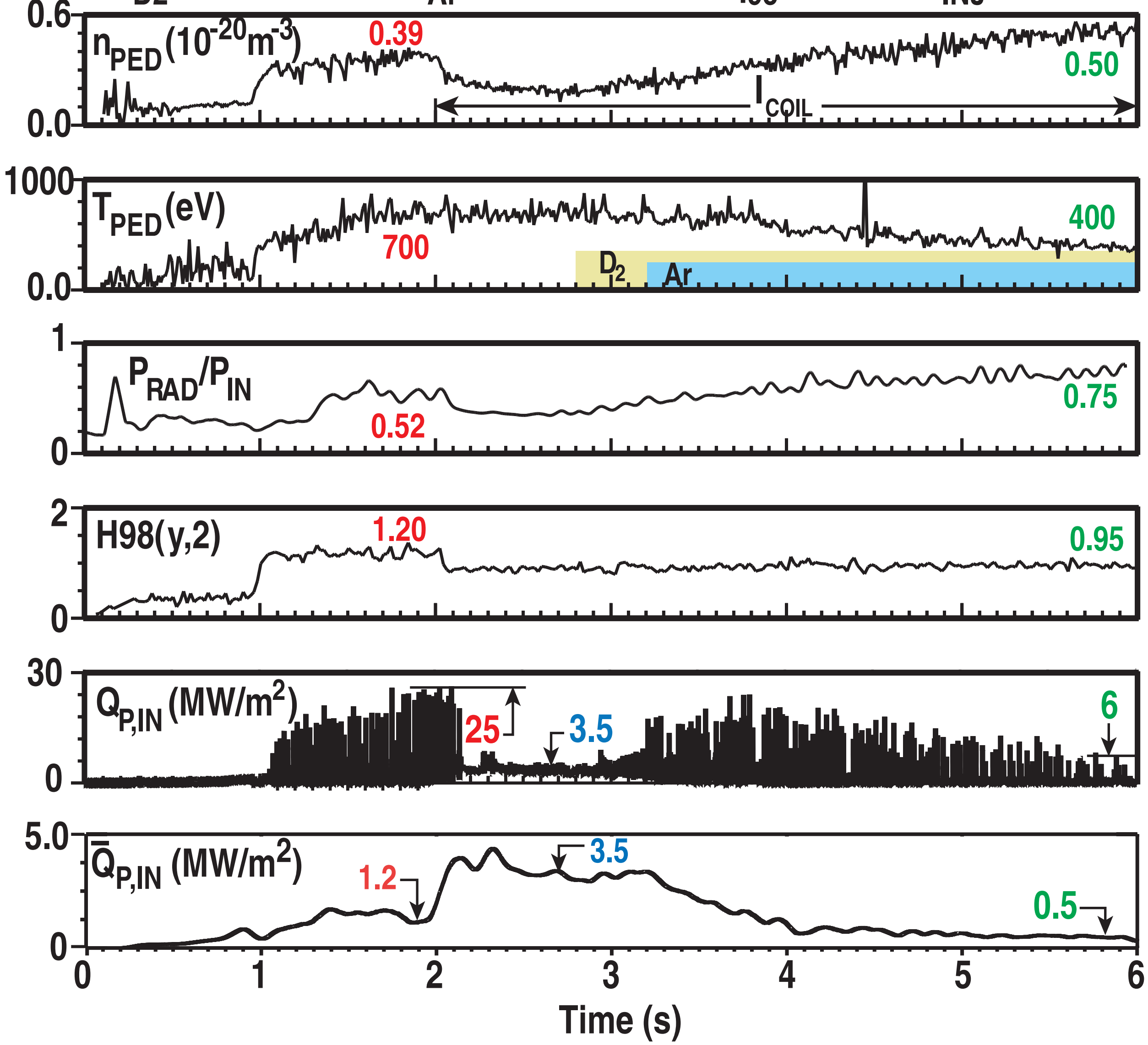
The near-linear behavior in argon accumulation with Γ_{AR} (and constant Γ_{D2}) parallels results obtained previously in non-RMP discharges



RMP ELM MITIGATION LEADS TO SIGNIFICANT REDUCTION IN TRANSIENT AND AVERAGE HEAT FLUX AT THE DIVERTOR TARGET

ELMs Return During Gas Injection but Significant Mitigation is Possible Even at Moderate Density

Γ_{D2} = 10 Pa m^3/s Γ_{Ar} = 0.05 Pa m^3/s $q_{95} \simeq 3.5$ $P_{INJ} \simeq 5.9$ MW



n_{PED} dropped with I_{COIL} activation but was ~25% higher by the end of the shot (t=5.8 s)

T_{PED} was unchanged with I_{COIL} activation but decreased during the gas puffing phase

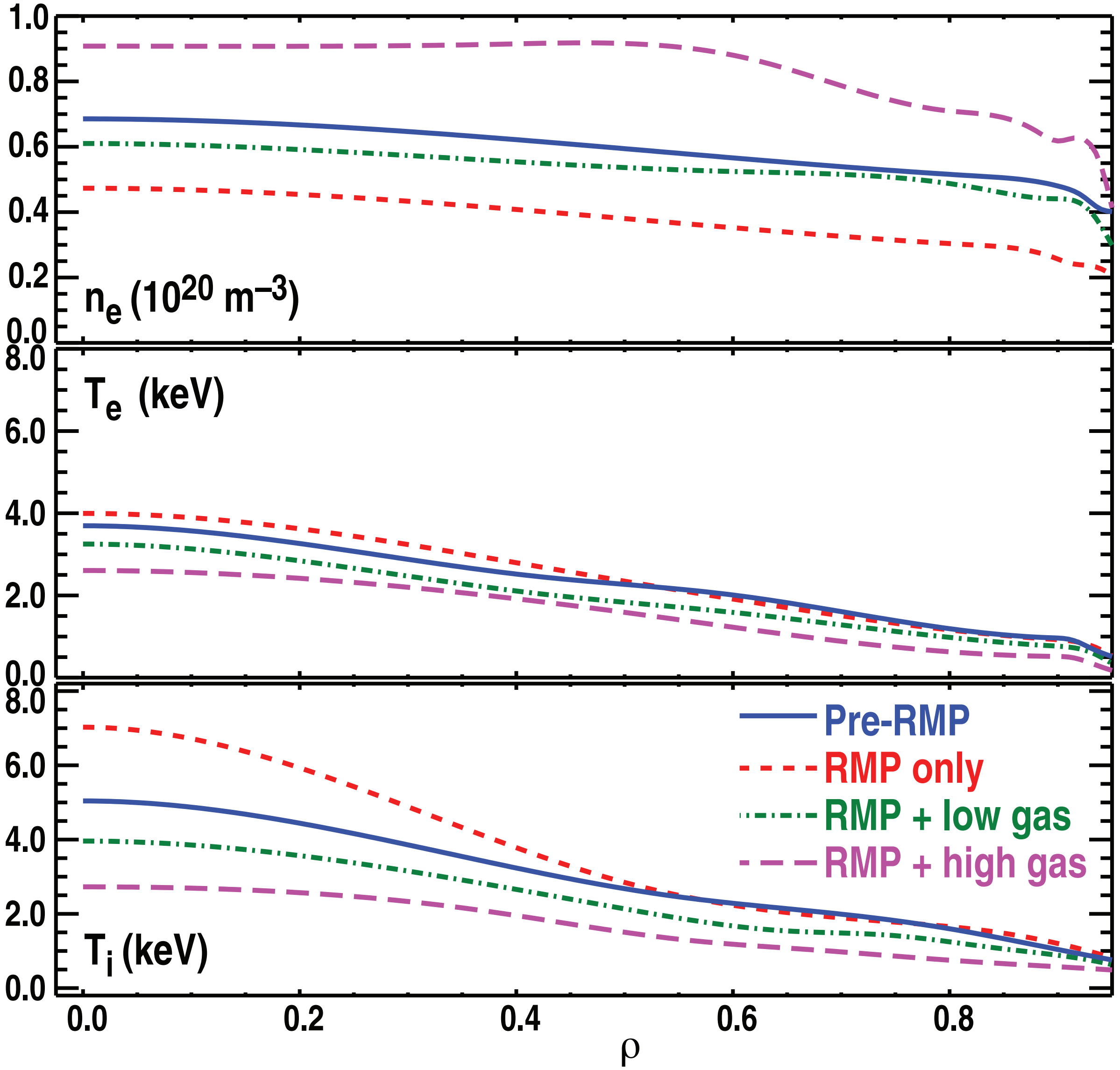
$$\frac{P_{RAD}}{P_{IN}} \cong \begin{cases} 0.52 \text{ (pre-}I_{COIL}\text{)} \\ 0.75 \text{ (t} \approx 5.8 \text{ s)} \end{cases}$$

H98(y,2) was insensitive to change in n_{PED} during gas puffing with RMP

Peak heat flux at the inner target at t = 5.8 s was reduced ~4x from pre-I_{COIL}

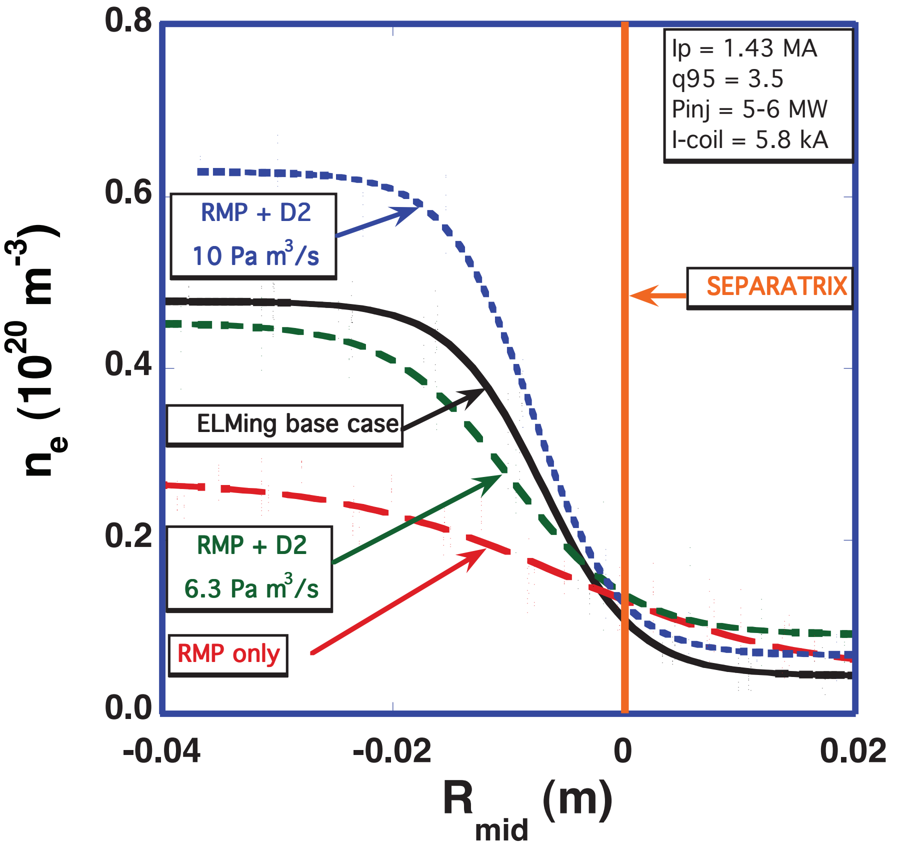
Time-average peak heat flux at the inner target was reduced ~2.4 for the same times

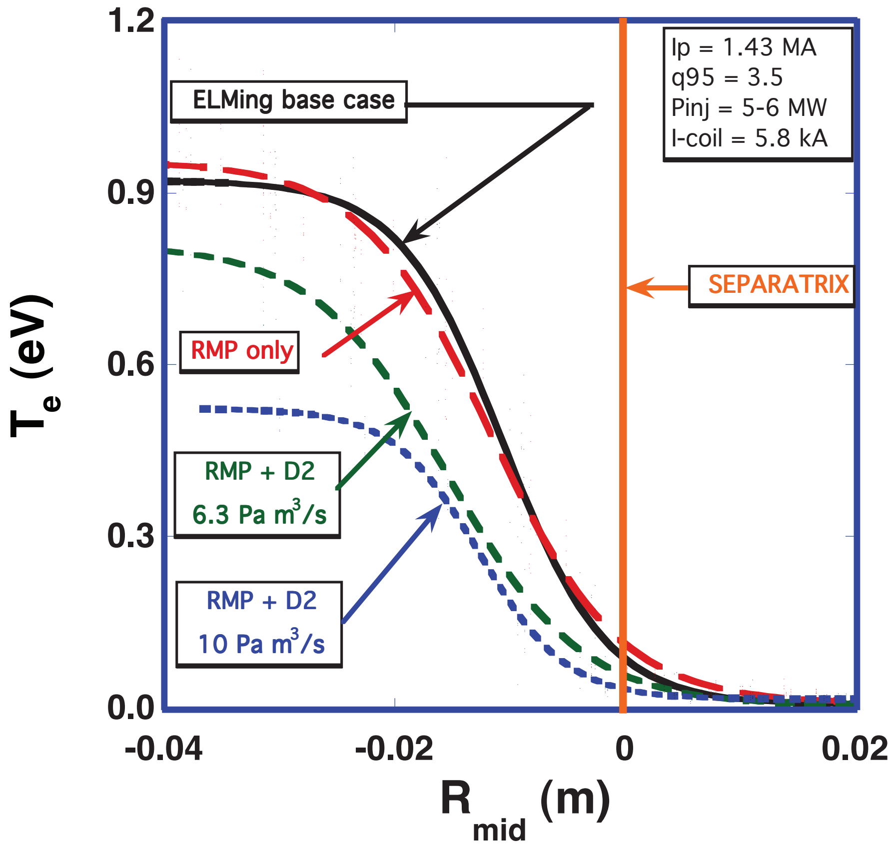
Active Control over the Density and Temperature Profiles in the Core is Possible using RMP and Gas Puffing



- A combination of RMP + gas puffing opens up a wide range in operating density
- T_i - profile change was more pronounced than T_e - profile after RMP was applied
- Both T_e and T_i were ~10-20% lower for the RMP case in comparison with the pre-RMP case at similar pedestal density

Active Control over Pedestal Density and Temperature is Possible Using RMP and Gas Puffing



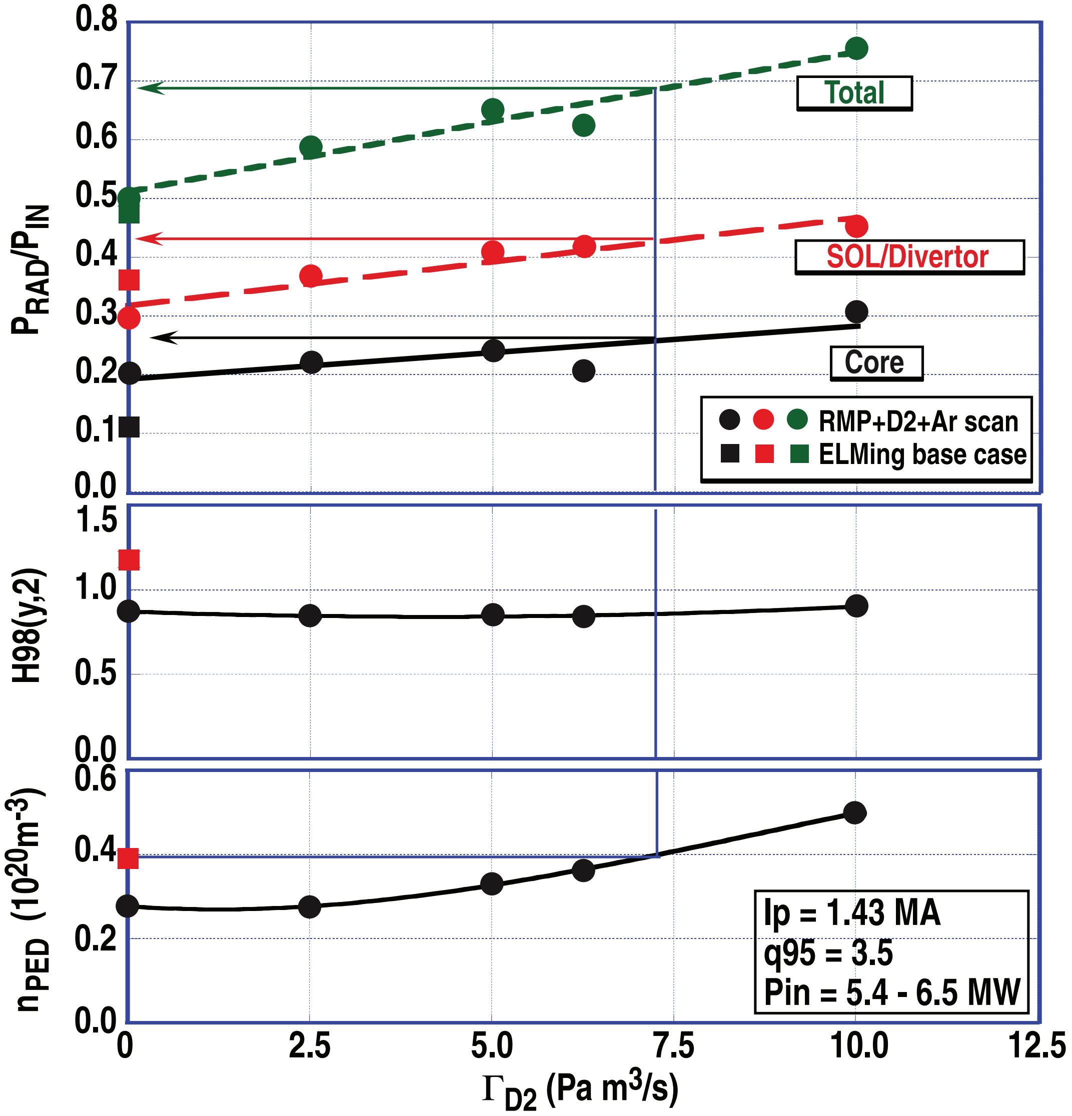


- n_{PED} for the ELMing base case was bracketed by RMP + gas puffing combinations
- Thicker density in SOL with RMP compared with the base case

- T_{PED} and T_{SEP} was significantly lower with RMP + gas puffing than for the base case at the same $n_{e,\ PED}$

  ⟶ Lower divertor temperature and heat flux

The Fraction of Total Radiated Power is Significantly Greater for Cases with RMP+D2+Ar than for Corresponding Standard Elming H-mode Plasmas at the Same Pedestal Density



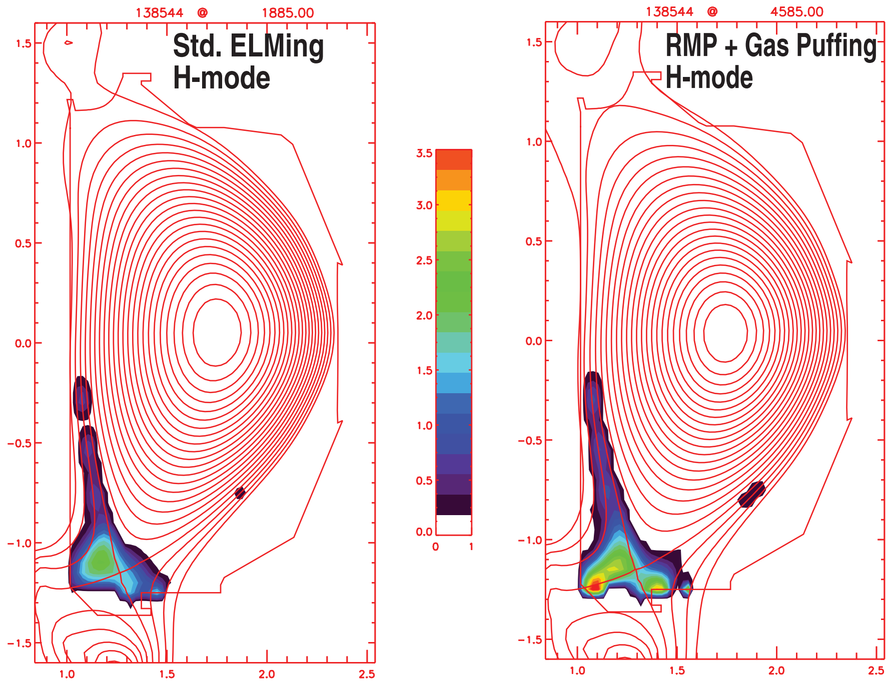
RMP vs base case at same n_{ped}

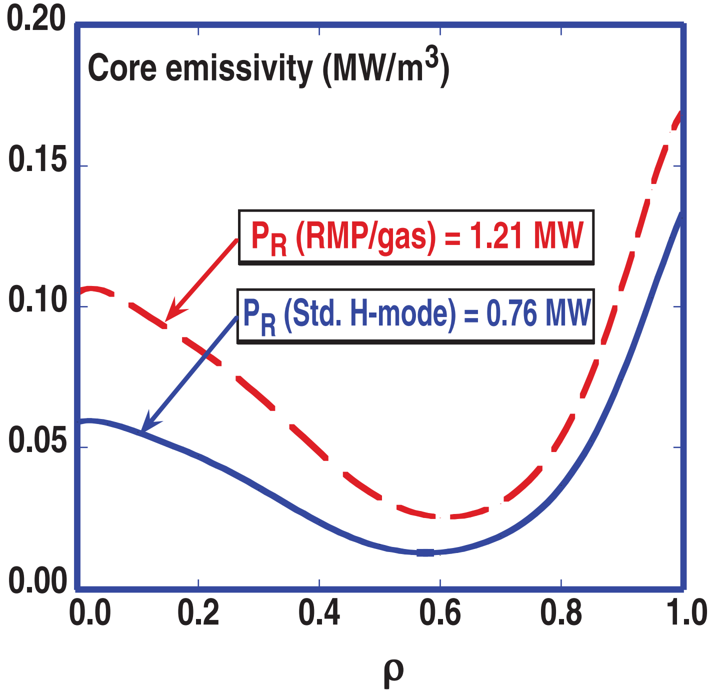
- ~50% *increase* in the total radiative fraction with RMP + gas puffing
- ~ $\frac{1}{3}$ of this *increase* was from the SOL/divertor
- H98(y, 2) dropped ~25% with RMP but was still ~0.9
- H98(y, 2) with RMP was insensitive to changes in n_{ped} and gas puffing rate
- Factor of two range in n_{ped} in this study

The Total Radiated Power was ≈ 40% Greater in the RMP/gas Puffing Case as the Standard H-mode Case at the Same n_{PED}

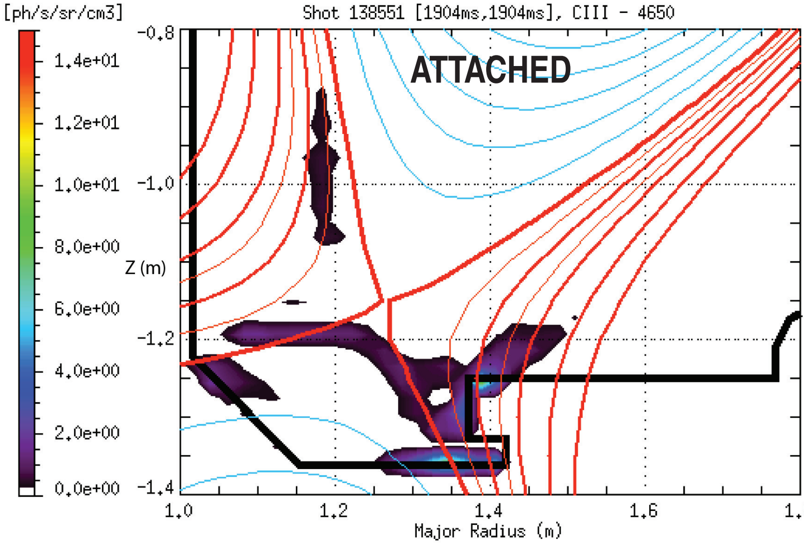
	Std. H-mode	RMP/gas
n_{PED} (10^{19} m^{-3})	3.9	3.9
P_{IN} (MW)	5.4	6.0
$\frac{P_{R,DIV/SOL}}{P_{IN}}$	0.38	0.49
$\bar{q}_{IN,\ DIV}$ ($\frac{MW}{M^2}$)	1.2	0.55

- Radiated power in the core plasma was considerably higher in the RMP/gas puffing case, but was still only ~20% of power input

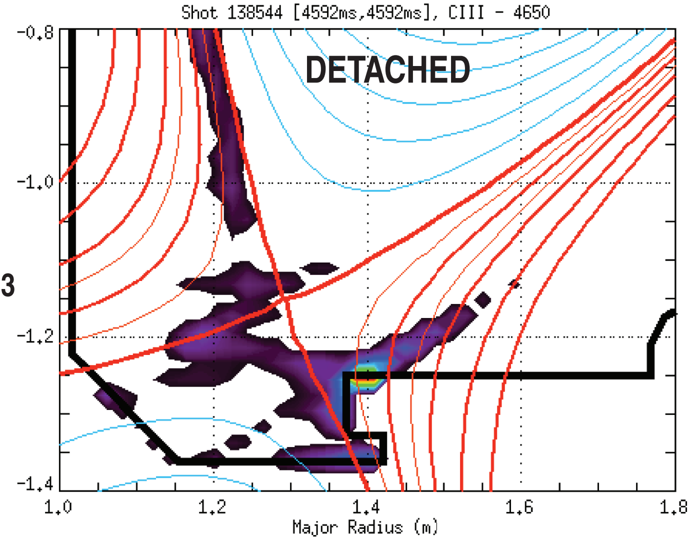




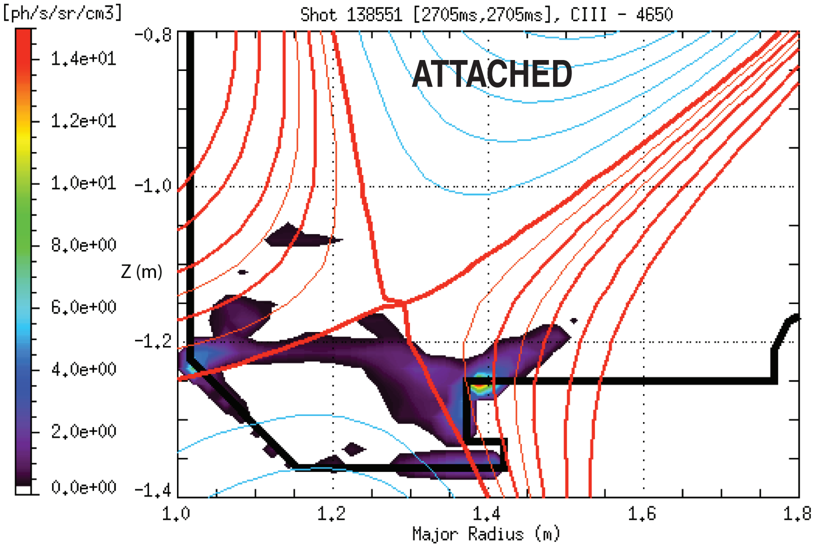
The Evolution of CIII Light (4650 Å) Shows Detachment of the Inboard Leg can Occur at Lower Density using RMP + Gas Puffing


Shot 138551 [1904ms,1904ms], CIII - 4650

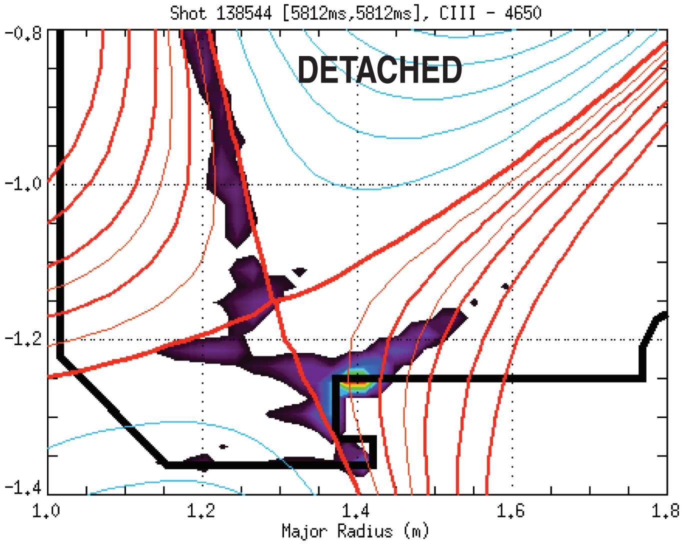
I_{COIL} = 0
WO/gas
$n_{PED} \simeq 4x10^{19}$ m^{-3}


Shot 138544 [4592ms,4592ms], CIII - 4650

I_{COIL} = 5.8 kA
W/gas
$n_{PED} \simeq 4x10^{19}$ m^{-3}


Shot 138551 [2705ms,2705ms], CIII - 4650

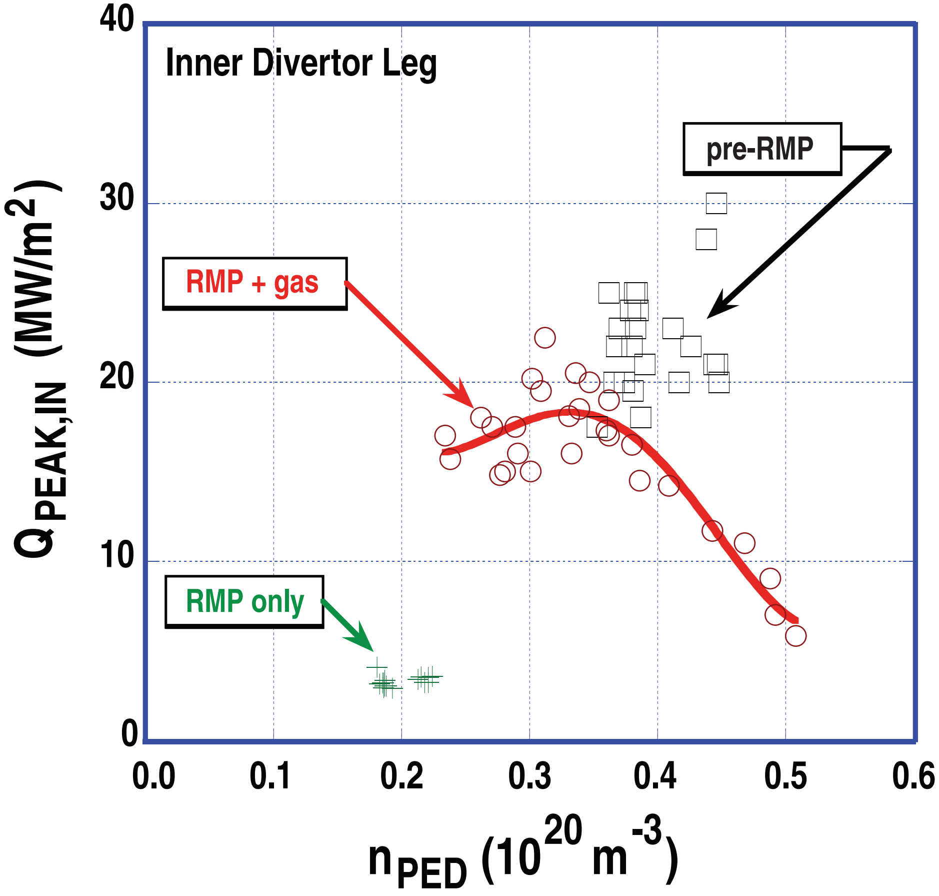
I_{COIL} = 5.8 kA
WO/gas
$n_{PED} = 1.9x10^{19}$


Shot 138544 [5812ms,5812ms], CIII - 4650

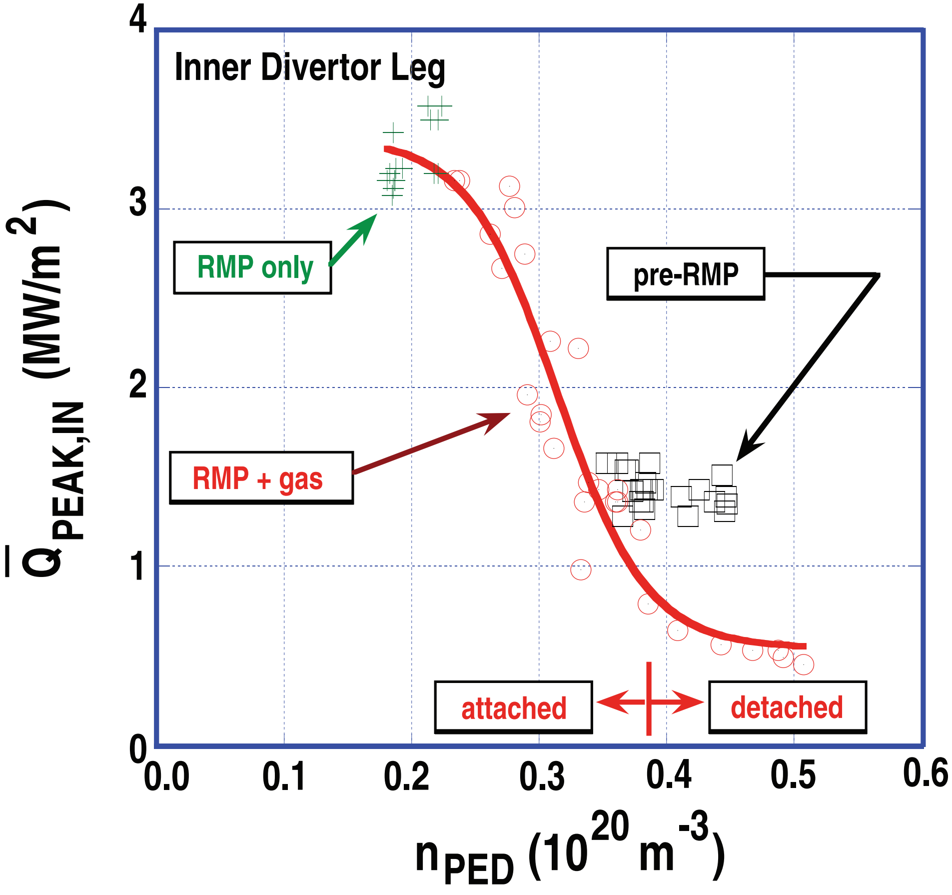
I_{COIL} = 5.8 kA
W/gas
$n_{PED} = 5.1x10^{19}$m^{-3}

RMP + Puff-and-Pump Offers Possibilities for Reduction in both Peak Heat Flux on ELMS and Average Peak Heat Flux

The addition of RMP reduced the ELM peak heat flux ~30% compared with pre-RMP cases at similar Pedestal Density



Considerably lower time averaged peak heat flux at the inner divertor target was achieved with RMP + gas puffing compared with pre RMP



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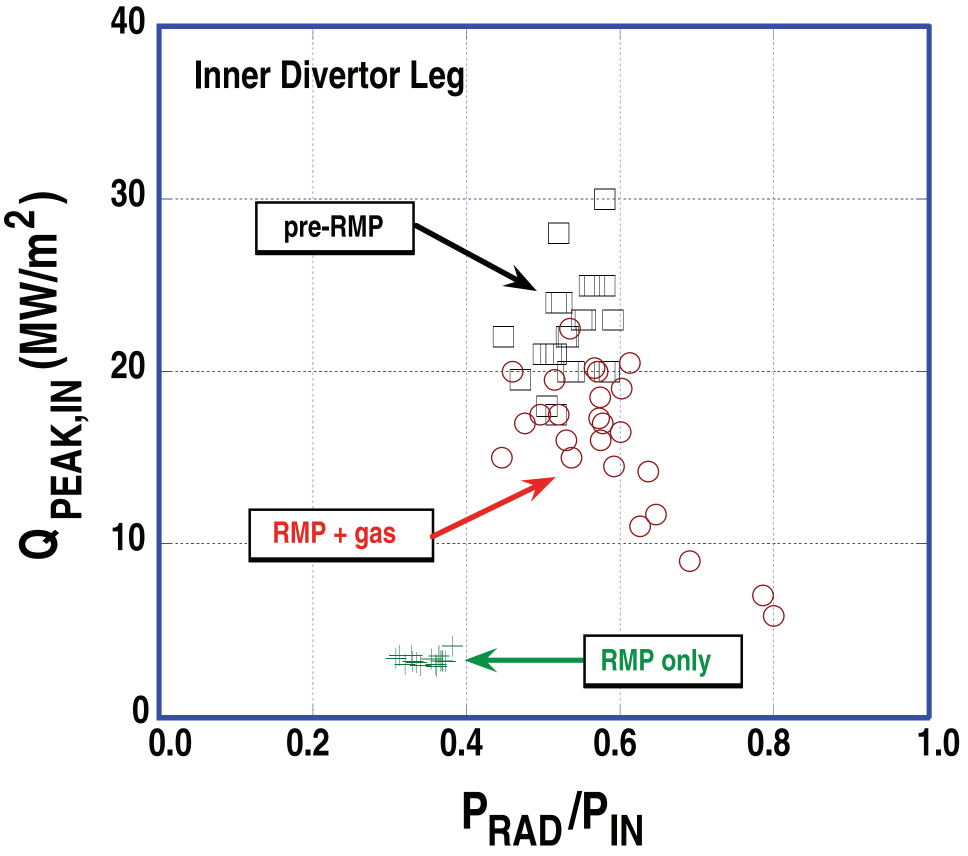
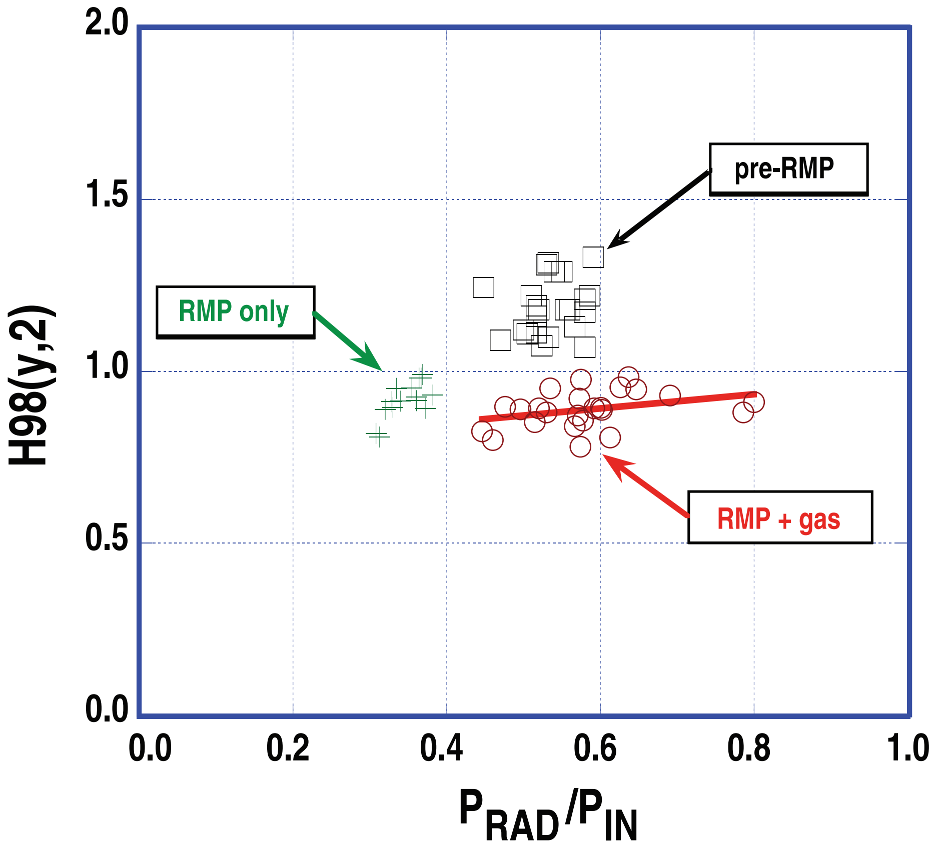
RMP + Puff-and-Pump Offers Possibilities for both ELM Suppression and Mitigation

The addition of RMP reduced the ELM peak heat flux ~30% compared with pre-RMP cases at similar radiative fraction



The addition of RMP reduced the average of the H98(y,2) ~25% compared with pre-RMP cases at similar radiative fraction



Detachment can be Facilitated using a Combination of RMP and Puff-and-pump

- **Simple two-point modeling of the SOL (1) in the conduction-limited regime:**

$$T_T = 5.4 \times 10^{35} \times (1-f_{R,SOL})^2 \times T_U^5/(Z_{EFF} \times L \times \gamma \times n_U)^2$$

where

T_U (eV) ≡ electron temperature at the midplane outer separatrix

n_U (10^{19} m^{-3}) ≡ electron density at the midplane outer separatrix

T_T (eV) ≡ electron temperature at the inner divertor separatrix target

γ ≡ power transmission coefficient ≈ 7

L (m) ≡ connection length from outer midplane separatrix to the inner divertor target ≈ 44 m

$f_{R,SOL}$ ≡ ratio of radiated power in the SOL/divertor to the power flow into SOL

Z_{EFF} ≡ representative Z_{EFF} in the SOL/divertor

- **T_T is very strongly dependent on T_U, so that changes in T_U has hugh leverage on T_T**
- **Changing $f_{R,SOL}$ as exerts appreciable leverage on T_T**

(1) P. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*, Institute of Plasma Physics Publishing, (2000) Chapter 5

Detachment can be Facilitated using a Combination of RMP and Puff-and-pump (Continued)

	Standard ELMing H-mode	Corresponding RMP + pump-and-pump ELMing H-mode
$\bar{n}_{e,}$ $(10^{19}\ m^{-3})$	5.8	5.9
n_{PED} $(10^{19}\ m^{-3})$	4.0	3.8
n_U $(10^{19}\ m^{-3})$	1.2	1.4
T_U (eV)	85	40
$f_{R,SOL}$	0.48	0.57
Z_{EFF}	2.35	1.85
T_T (eV)	8.6	<1

- **Strong dependence of T_T on T_U insures a significantly lower T_T for the RMP/puff and pump case**
  - Applying RMP resulted in particle pump-out in the core plasma
  - Gas puffing with both deuterium and argon pushed the core density back to its pre-RMP pedestal and line-averaged values
  - When the *initial* n_U was reached, T_U was significantly lower than initially. And the core, SOL, and divertor were more radiative, leading to $f_{R,SOL}$ being higher
    - ⇒ T_T for the standard ELMing was well above target temperatures consistent with detachment (e.g., ≈ 2 eV), while T_T for the RMP/puff and pump plasma fell within detachment temperatures

Experimentally, the former was not detached and the latter was detached

The Lower Edge Temperature Makes the RMP/puff-and-pump Approach Effective in Reducing the Average Peak Heat Flux at the Divertor Target While Maintaining Fixed Density

- Again, we use the 1-D two-point modeling approach and find:

$$\bar{q}_{\perp} = q_{||} \times \sin(\alpha) = 0.286 \times [\kappa_{0e}/(L \times Z_{EFF})] \times (T_U)^{3.5} \times \sin(\alpha)$$

where $\bar{q}_{\perp}$ = peak heat flux at the divertor target (W/m^2)

α = angle between $\vec{B}$ and the target divertor surface $\approx 2°$

$\kappa_{0e} \approx 2000$

Note the very strong dependence of $\bar{q}_{\perp}$ on T_U, so that even a small drop in T_U can lead to a significant drop in of $\bar{q}_{\perp}$

Comparing experimental and theoretical $q_{\perp}$ for the above previous two cases:

	Standard ELMing H-mode	Corresponding RMP + pump-and-pump ELMing H-mode
$\bar{q}_{\perp}$ (MW/m^2) → experimental (IR)	1.2	0.55
$\bar{q}_{\perp}$ (MW/m^2) → theoretical	1.1	0.10

Note that radiative contribution to $\bar{q}_{\perp}$ for RMP/PP case ≈0.3 MW/m^2

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Main Conclusions

- **The "window" for which there can be simultaneous ELM suppression and effective radiating divertor was elusive for discharges evaluated in this report**
  - The re-appearance of ELMs during gas puffing is consistent with the peeling-ballooning mode instability
- **RMP + gas injection has been shown to be effective in ELM mitigation**
  - Modest cost in energy confinement time
  - Opens up a wider range in density operation
- **We observed similar rates of argon accumulation in RMP and comparable non-RMP ELMing discharges**