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# Modification and control of divertor detachment in Alcator C-Mod

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**Abstract**

The effect of adding different impurity gases and ICRF heating on divertor detachment has been compared for Ohmic, L-mode and high-$q_{\|}$ ($\geq 300$ MW/m$^{-2}$), H-mode plasmas. The relative effect of all these external controls on divertor and core radiation is evaluated. Recycling gases (Ne and Ar) are found to primarily affect the main plasma as opposed to the divertor region. The lower $Z$ non-recycling gases, $N_2$ and $CD_4$ are more efficacious in this regard. $N_2$ was found effective in inducing detachment for high-$q_{\|}$, H-mode plasmas. An additional advantage of $N_2$ over the higher $Z$ gases is that its injection resulted in the smallest degradation in H-mode energy confinement ($\sim$ 10%).

*Keywords:* Alcator C-Mod; Improved confinement mode; Detached plasma; Impurity transport; Divertor plasma

## 1. Introduction

Detached divertor operation has become an accepted technique for reducing heat loads to the divertor plates (e.g., Refs. [1-3]). The primary methods of achieving divertor detachment have been through 2 routes, increasing the core plasma density and the addition of impurities. It is apparent that efforts must be made to exert finer control over the characteristics of detachment in order to optimize the positive characteristics (reduction in heat flow to the divertor plates) while minimizing the negative characteristics — increased impurities and radiation in the core plasma, poorer energy confinement.

Similar studies have involved the use of neutral beam heating and fairly open divertor geometries [4-6]. The results of ASDEX-UG experiments favor injection of Ne over $N_2$ because the reduction in core confinement is minimized and because $N_2$ leads to compound ELMs [4]. Experiments at the JET [5] tokamak have determined that $N_2$ maximizes the divertor radiation in comparison to Ne. In all cases it is found that the resultant core $Z_{eff}$ is high ($\sim$ 3).

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Experiments have been undertaken on the Alcator C-Mod tokamak to modify the onset density and the characteristics of divertor detachment. The injection of impurities and ICRF power have each been found to be useful controls over detachment. Results are presented for Ohmic and RF-heated plasmas (fundamental H-minority, both L- and H-mode), all with $B_{tor} = 5.3$ T. Recycling and non-recycling impurity gases have been utilized with varying degrees of success.

## 2. Experiment description

Alcator C-Mod is a high-field tokamak with an unusual closed divertor geometry and molybdenum divertor plates [1]. The high toroidal magnetic field allows achievement of very high divertor and core plasma densities. $T_e$ at the divertor plate $\sim 5$ eV is generally found to be the threshold below which divertor detachment occurs [1,2,7]. More detailed characteristics of divertor detachment and the available diagnostics are found elsewhere [1,7,8]. Various divertor geometries are available for study in Alcator C-Mod. For this work all equilibria have strike points on the vertical plates [9].


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A number of impurity gases were employed in these studies: the recycling gases, Ar and Ne; and the non-recycling gases $CD_4$ and $N_2$. Because the results from $CD_4$ and $N_2$ were similar we will concentrate on the $N_2$ results here. Likewise Ne will have primary emphasis for the recycling gases.

The power balance in Alcator C-Mod is determined from the results of a number of diagnostics. The total input power, $P_{IN}$, is the sum of Ohmic and injected ICRF powers. The radiated power from the main plasma, $P_{rad,main}$, is the sum of a 'symmetric' part which is assumed constant on a flux surface and an 'asymmetric' part which is inside the separatrix near the X-point ($P^{in}_{Rad,div}$). The former is measured by a toroidally-viewing bolometer array located on the midplane of the torus [8]. The latter measurement is determined through the tomographic inversion of the bolometer brightness from 20 chords viewing the divertor region at different angles [8]. The combination of high resolution provided by both the bolometry and magnetics reconstruction (EFIT [10]) allows the division of 'divertor' radiation into amounts inside ($P^{in}_{Rad,div}$) and outside ($P^{out}_{Rad,div}$) the separatrix. The power flowing into the SOL is then

$$P_{SOL} \equiv P_{IN} - P_{rad,main}. \quad (1)$$

Comparison of probe measurements of $n_e$ and $T_e$ in the SOL and at the divertor surface [7] are used to determine whether pressure loss has occurred along a flux surface (detachment). Each flux surface is labeled by its distance outside the separatrix at the midplane ($\rho$ in mm).

## 3. Experimental results

### *3.1. Neon puffing to lower the detachment onset density (Ohmic)*

Neon has been found to be effective in reducing the onset density for detachment in Ohmic plasmas. The results of such experiments are shown in Fig. 1 for 800 kA discharges with $\bar{n}_e$ increasing throughout the pulse. Neon was injected in varying amounts early in the discharge and the resultant detachment onset density and core brightness of Li-like Ne recorded. The MIST impurity transport code [11] is employed to determine the core level of Ne from the Ne-VII brightness. The detachment onset density could be decreased by almost a factor of 2. The Ne injection is not without adverse effects; $Z_{eff}$ and radiation in the core plasma both increased ($\Delta Z_{eff} < 0.8$). The location of the impurity puff is not an important factor for recycling gases; it need not be injected in the divertor [12].

The neon puff increases core radiation while at the same time suppresses the radiation in the divertor region *outside the separatrix* Fig. 2. Shown are 2 discharges with

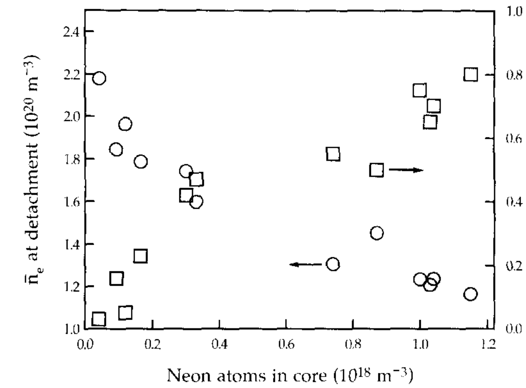


Fig. 1. Scaling of the detachment onset density (○) with increasing amounts of Ne in the core plasma. The change in $Z_{eff}$ (□) from bremsstrahlung is shown as well. All data are for 800 kA ohmic plasmas.

identical conditions up until the neon injection at 420 ms (valve voltage). Note that when detachment occurs the balance of radiation further shifts inside the separatrix. This radiation shift at detachment reflects the standard process of detachment in Alcator C-Mod [1].

Experiments with Ohmic plasmas have shown $N_2$ and $CD_4$ to be similarly useful in bringing about detachment.

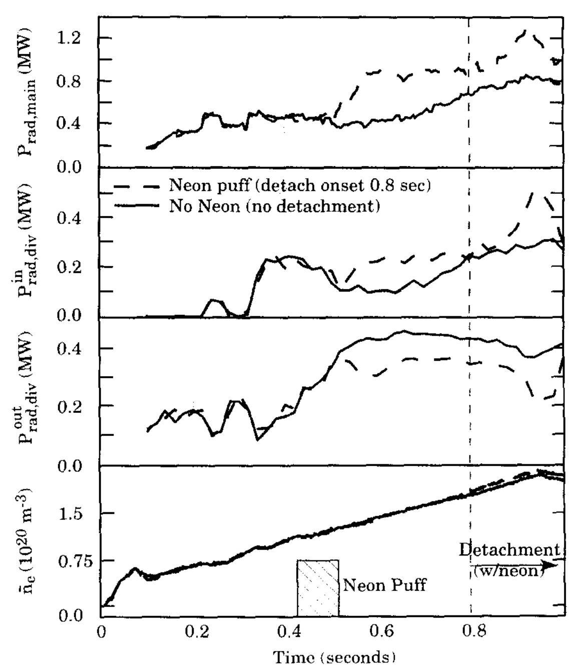


Fig. 2. An example of the effect of Ne injection on the balance of divertor radiation in shots from the set shown in Fig. 1 (———— no neon, — — — neon).

The primary differences between these lower $Z$ gases and Ne/Ar are: (1) more radiation is in the divertor region (see Section 3.2); and (2) the effect on $P_{\mathrm{Rad,main}}$ is minimal before detachment (little is needed) [12].

### 3.2. Effect of auxiliary heating

Increased radiative losses reduce the power flow to the divertor and thus can reduce the detachment onset density. Experiments have also been carried out to determine the usefulness of adding power flow to control detachment *without* addition of extrinsic impurities. As for the Ohmic plasmas discussed above, the core energy confinement can be characterized as L-mode.

Fig. 3a–c shows the effect of increasing the power flow into the SOL, through ICRF heating, for an already detached divertor plasma. Shown in this figure are the divertor characteristics at three different flux surfaces in the SOL; $\rho = 0$, 2 and 4 mm (not detached) in distance from the separatrix as previously defined. The divertor plasma characteristics shift towards reattachment as $P_{\mathrm{SOL}}$ is increased. At $\rho = 4$ mm, the increase in $P_{\mathrm{SOL}}$ primarily trades increasing $T_e$ for decreasing $n_e$ as the pressure holds fairly constant. When $T_e$ at $\rho = 2$ mm reaches $\sim 5$ eV the corresponding density peaks and starts to decrease as the separatrix density continues to rise. Even for an increase in $P_{\mathrm{SOL}}$ of a factor of 5, the pressure is still not peaked at the separatrix ($\rho = 0$ mm). This corresponds to $T_{\mathrm{e,separatrix}}$ still not reaching the detachment threshold of $\sim 5$ eV.

Radiation in the divertor is counteracting much of the effect of increasing $P_{\mathrm{SOL}}$, Fig. 3d. It is apparent that as $P_{\mathrm{SOL}}$ is increased, $P^{\mathrm{out}}_{\mathrm{Rad,div}}$ increases at a similar, but slower, rate. Shown for comparison is a line corresponding to $P^{\mathrm{out}}_{\mathrm{Rad,div}} = P_{\mathrm{SOL}}$. Typical error bars are shown indicating the significant uncertainties due to the tomographic inversion, calibration and the knowledge of the separatrix location. Note that as $P_{\mathrm{SOL}}$ increases above $\sim 0.6$ MW, $P^{\mathrm{in}}_{\mathrm{Rad,div}}$ strongly decreases indicating that the divertor radiation peak has moved back outside the separatrix. This movement corresponds to the increase in $T_{\mathrm{e,plate}}$ on the $\rho = 2$ mm flux surface shown in Fig. 3c and precedes the increase in $T_{\mathrm{e,plate}}$ at the separatrix.

### 3.3. H-mode plasmas – Combined auxiliary heating and impurity puffing

Experiments have also been carried out with 1 MA H-mode plasmas using a combination of auxiliary heating and impurity puffing controls. The better core energy confinement is accompanied by a decrease in $\lambda_{q_{\parallel}}$ (the cross-field e-folding distance in the SOL for the parallel heat flow) from 3–6 mm in L-mode to 1–2 mm in H-mode. This, combined with the high $P_{\mathrm{SOL}}$, results in

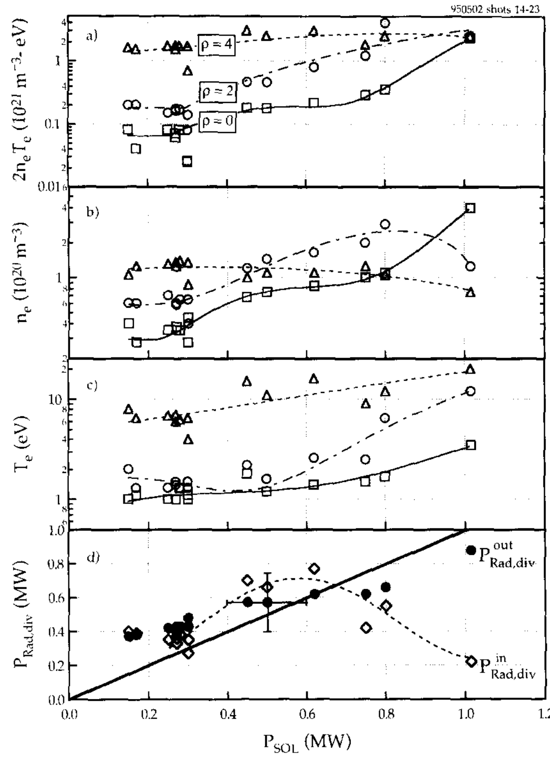


Fig. 3. Scaling of divertor plasma parameters for a series of 800 kA ICRF-heated discharges with no impurity puffing. Fits to the experimental data are shown to guide the eye. Data for three flux surfaces referenced to the plasma midplane; $\rho = 0$ (□), 2 (○) and 4 mm (△) are: (a) divertor pressure; (b) divertor $n_e$; (c) divertor $T_e$; and (d) $P_{\mathrm{Rad,div}}$ both inside (◇) and outside (●) the separatrix. The line is for $P_{\mathrm{Rad,div}} = P_{\mathrm{SOL}}$.

parallel heat flows that are typically 0.5 GW/m$^2$, of order that predicted for ITER. Because of this difference, experiments to determine the effect of the different gases Ar, Ne and $N_2$ on the SOL and divertor dynamics were repeated ($CD_4$ was not included).

In general, it was found that for these high-$q_{\parallel}$ plasmas, only the lower $Z$ non-recycling gas, $N_2$, offered the right balance of effects on the core and divertor plasmas needed to induce divertor detachment. Fig. 4 illustrates the relative efficacy of the different gases. In each case, Ne (Fig. 4a) and $N_2$ (Fig. 4b) puff levels are increased over 3 shots. All of the Ne-injection discharges are attached while only the 'No puff' discharge in the $N_2$ set is attached. The onset of detachment is $\sim 0.86$ s. The auxiliary heating power was 2.8 and 3.1 MW for the Ne and $N_2$ datasets, respectively ($P_{\mathrm{IN}} \sim 4.0$ MW for both). Both gases increase core radiation, reducing $P_{\mathrm{SOL}}$. However, while the $N_2$ injection increases $P^{\mathrm{out}}_{\mathrm{Rad,div}}$ by $\leq 40\%$, Ne injection, if anything, decreases $P^{\mathrm{out}}_{\mathrm{Rad,div}}$. Ar injection is similar in effect to the Ne in that only $P_{\mathrm{Rad,main}}$ is increased and no detachment is induced.

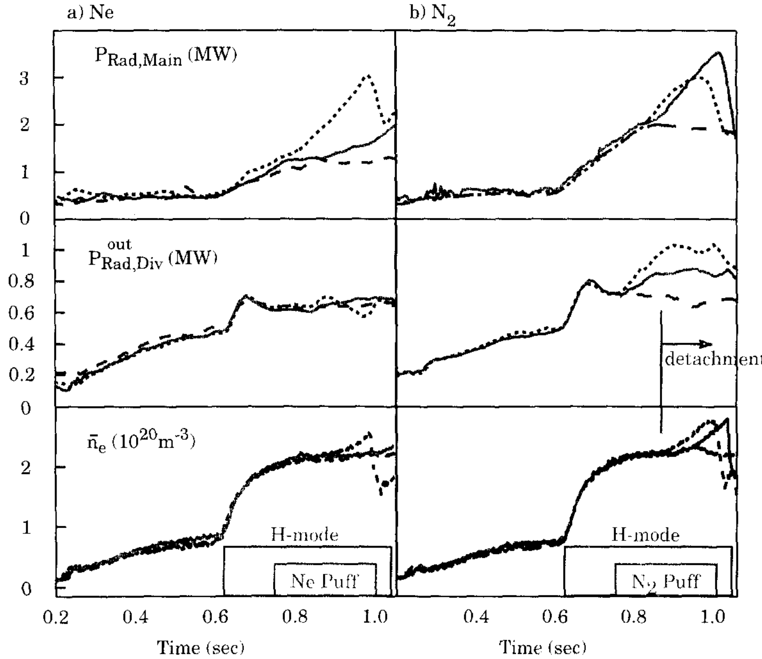


Fig. 4. Comparison of the effects of impurity gas puffing on H-mode plasmas. (a) Ne (— — — no puff, ————-, 3.75 Torr l and - - - 6.25 Torr l) and (b) $N_2$ (— — — no puff, ————-, 9.4 Torr l and - - - 17 Torr l) The RF power is turned off at different times.

It is also of interest to compare the effect of these different gases on other main plasma characteristics. Energy confinement ($E_{plasma}/P_{IN}$) is displayed in Fig. 5 normalized as $H_{ITER89\text{-}P} = \tau_E/\tau_{ITER89\text{-}P}$ ($H_{ITER93\text{-}ELMy} \sim H_{ITER89\text{-}P}$). As $P_{Rad,main}/P_{IN}$ increases for any gas, the core confinement is degraded. However, the degradation for Ne and Ar is larger than for $N_2$. Increases in $Z_{eff}$ (0.3–0.5 for Ne and Ar, 0.5–1.1 for $N_2$) accompanied the degradation in confinement and increases in $P_{Rad,main}$.

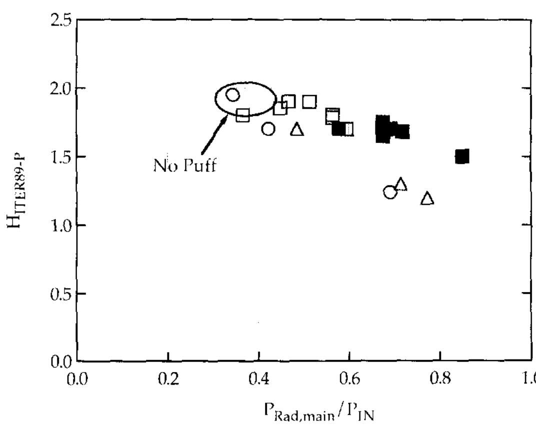


Fig. 5. Comparison of the core energy confinement H-factor for puffing with Ne (○), Ar (△) and $N_2$ (□ at the start of detachment, ■ after detachment reaches an equilibrium). The H-factor shown is the same for ITER89-P and for ITER93-ELMy.

## 4. Discussion

In previous studies $T_{e,plate} < 5$ eV has been shown to be a controlling factor in the detachment onset [1,2,7,13]. In simple 1D fluid SOL heat transport models [7,14] we can write down a relationship between the plasma parameters and the power flowing in the SOL, $q_{\|}$. Assuming a minimal temperature gradient and that radiation losses occur along a flux surface only in the region from the X-point, $S_X$, to the plate, $S_{plate}$, then one can solve for the dependence of $T_{plate}$ on the connection length, $L$, upstream and core parameters:

$$T_{plate} \propto \frac{q_{\|,X}^{10/7}(1 - f_{rad,flux})^2}{L^{4/7} n^2_{upstream}} \propto \frac{P_{SOL}^{10/7}(1 - f_{rad,global})^2}{L^{4/7} \lambda_{q\|}^{10/7} n^2_{upstream}} \quad (2)$$

where $f_{rad,flux}$, the fraction of parallel heat flux lost to radiation, is defined by $q_{\|,x}(1 - f_{rad,flux}) = q_{\|,plate}$ and globally by $f_{rad,global} = P^{out}_{Rad,div}/P_{SOL}$. Eq. (2) expresses both a relationship of $T_{plate}$ to SOL parameters along a given flux surface and a more global description involving $P_{SOL}$.

Eq. (2) confirms the three primary avenues to controlling $T_{e,plate}$ and thus detachment: (1) increasing the core plasma density ($n_{upstream}$); (2) decreasing $q_{\|}$ ($P_{SOL}$); and (3) increasing $P^{out}_{Rad,div}$. The results of this study show that use of Ne and Ar relies completely on reducing $q_{\|}$ for inducing detachment while $CD_4$ and $N_2$ decrease $q_{\|}$ *and* increase $f_{rad}$. We see from this equation that $f_{rad}$ is the stronger control. In contrast to present results, other tokamaks [4–6,15] have found that Ne and Ar affect $P_{Rad,main}$ *and* $P_{Rad,div}$. This may be due to differences in plasma characteristics, definitions of 'divertor' radiation or the C-Mod (bolometry) spatial resolution. It would also be expected that Ne and Ar are less effective in inducing divertor radiation due to lower cooling rates for the range in $T_e$ found in the divertor [16].

The difficulty in using such coarse measures as $P_{SOL}$ and $P^{out}_{Rad,div}$ are illustrated by Fig. 6 for the H-mode plasmas discussed in Section 3.3 (Fig. 5). The movement of discharges in this operational space is very different for the higher versus lower $Z$ gases. We see that the $f_{rad,global}$ for the $N_2$ detachment *onset* and high Ne/Ar gas puff cases (which remain attached) are similar. If Eq. (2) held in the global sense outlined then the recycling gas cases should have detached before the $N_2$ detachment onset (lower $P_{SOL}$ for the recycling gases). This is not the case. The implication is that the relative volumetric loss increase on a particular flux surface, $f_{rad,flux}$, for the $N_2$ case must be higher than for the recycling gases. In addition, we see that increasing $P^{out}_{Rad,div}$ is more efficient in causing detachment than reducing $P_{SOL}$; less increase in $P^{out}_{RAd,div}$ is required. From the viewpoint of the core plasma we should ideally control $f_{rad}$ with low $Z_{eff}$. A better understanding of divertor impurity transport and screening from the core is needed (see [12]).

A second difference between L- and H-mode plasmas is the effect of detachment on the divertor radiation. As shown in Figs. 2 and 3d, a large fraction of the divertor radiation shifts inside the separatrix after detachment for L-mode plasmas. For the high-$q_{\|}$ H-mode case this movement does not occur. Fig. 4b is typical of this behavior; $P^{out}_{Rad,div}$ does not decrease after detachment. A possible explanation is that the level of impurities is different in L- and H-mode plasmas. However, the shift in radiation occurs in Ohmic plasmas even with very low impurity levels ($Z_{eff} \leq 1.2$). We speculate that the more likely cause is measured increases in both core impurity transport times and $T_e$ just inside the separatrix. Both of these effects lead to a drop in the radiative cooling rate [16] in this region. In addition, higher $T_e$ enhances parallel conduction ($\propto T^{5/2}$) thus minimizing any gradients driven by a localized radiation source.

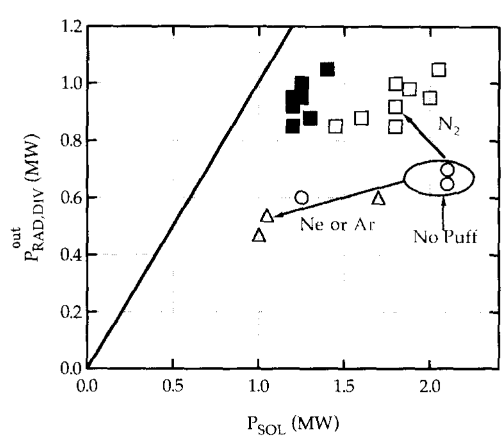


Fig. 6. Operational space for same H-mode plasmas as Fig. 5. Shown for comparison is a line corresponding to $P^{out}_{Rad,div} = P_{SOL}$. The arrows indicate the general movement of discharges for the different cases.

Another characteristic difference between the effect of the different gases on H-mode plasmas is in the degradation in core confinement. Increases in $P_{Rad,main}/P_{IN}$ correlate with decreases in core confinement in all cases. The injection of the higher $Z$ gases leads to a larger degradation in $\tau_E$ (for *attached* plasmas), compared to $N_2$ (for *detached* plasmas), for the same $P_{Rad,main}/P_{IN}$. This may be due to differences in radiation emissivity profiles for the main plasma. Radiation inside the separatrix could lead to decreases in $T_e$ at the edge (thermal barrier region) and thus poorer confinement. N injection results in an emissivity peak at larger minor radii than Ne/Ar in C-Mod and elsewhere [4,5].

## 5. Summary

The recycling gases Ne and Ar have been found effective in inducing detachment for L-mode plasmas but not for H-mode plasmas with ITER-like high-$q_{\|}$. The effect of these gases in both cases is to reduce the power flowing in the SOL through increases in core radiation. Divertor radiation, if anything is reduced. The lower-Z gases, $N_2$ and $CD_4$ are found to be more efficacious in this regard because they bring about increased $P^{out}_{Rad,div}$ as well as $P_{Rad,main}$. Small increases in divertor radiation appear to be very effective in bringing about detachment. The core energy confinement of H-mode plasmas is more adversely affected by the injection of higher $Z$ gases than by $N_2$. In all cases $\Delta Z_{eff}$ is large.

The high-spatial resolution provided by the 20-channel divertor bolometer arrays have improved the characterization of the divertor radiation in both detached and attached plasmas. For L-mode plasmas the peak in the divertor radiation moves inside the separatrix, above the X-point after detachment. The radiation pattern is affected only slightly by detachment in the high-$q_{\|}$ H-mode plasmas studied here. This is important in that it opens the possibility that a reactor plasma such as ITER can effectively use the divertor volume after detachment.

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