Coupling between JET Pedestal $n_e$-$T_e$ and Outer Target Plate Recycling:
Consequences for JET ITER-Like-Wall Operation

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Introduction: With the tungsten target plates of the JET ITER-Like-Wall (ILW) phase, carbon radiation will be reduced and must be replaced by that of seeded impurities to prolong target plate lifetime. Investigations to this end of ELMy-H (EH) & Advanced Tokamak (AT) scenarios using N$_2$ and Ne along with D$_2$ fuelling have been carried out in matrix fashion (fig. 1, top), whereby the aim was to cover a large variation in divertor power loading $P_{div}$ and temperature $T_{e,div}$ regardless of core performance. The intended effect of impurity seeding is to increase radiation $P_{rad}$ in order to mitigate $P_{div}$ and that of D$_2$ to enhance recycling to further reduce $T_{e,div}$, both being necessary for ILW-compatibility. $P_{rad}/P_{in}$ ranged over 48-66% (EH) and 31-60% (AT). Details on $P_{rad}$ and $P_{div}$ are given in a companion paper /1/. This data set is used to study the interrelationships between the pedestal temperature $T_{e,ped}$ & density $n_{e,ped}$ and the ion flux $\Gamma_i$ to the outer target plate. An advantage of these studies is the wider range of $n_{e,ped}$ and $T_{e,ped}$ afforded by the use of impurities (fig. 2). Different type-I ELM regimes also prevail: For EH, $\nu_{ELM}$ initially decreases with D$_2$ (~20->10Hz). Impurities can provoke compound ELMs ($\nu_{ELM}$≥ 3Hz) as well as augment $\nu_{ELM}$ (to 50Hz).

v_{\text{ELM}} (AT) largely spans the range \(\sim 50 - 200\text{Hz}\) increasing with \(D_2\) for the subset selected.

2. Experimental Results: All quantities reported are averaged over \(\sim 1\text{s}\), i.e. over many ELM cycles. This is readily done using \(T_e\) from the ECE radiometer, with the values deviating less than 50eV (<5%) from those gained from the High Resolution Thomson Scattering (HRTS) system. As radiometer values were not always available, \(T_e\) from HRTS is cited, read at the 90% flux surface. Inter-ELM \(T_e\)-excursions in compound ELM phases can more than 200eV (only with Ne in EH) with an average deviation from the mean of \(\pm 100\text{eV}\), otherwise \(\sim 50\text{eV}\). The edge vertical interferometer channel (tangent to 90% flux surface) also enables good time averaging, has a low noise level and none of the potential calibration uncertainties associated with Thomson scattering. It is very closely related to \(n_e\) from HRTS and is taken to define \(n_e^{\text{ped}}\), with a typical uncertainty of \(\pm 10^{18}\text{m}^{-3}\). A rough estimate of \(\Gamma_i\) is obtained from the \(D_\alpha\) line intensity summed over the outer target plate \(\Phi_{\text{div}}\) using \(S/XB\approx30\), i.e. \(\Gamma_i\approx 30 \Phi_{\text{div}}\).

An estimate of \(T_{e,\text{div}}\) is derived from \(P_{\text{div}}\) (IR camera) and \(\Gamma_i\): \(T_{e,\text{div}}=P_{\text{div}}/\left(8\times1.610^{19}\times\Gamma_i\right)\), \(8=\)energy transmission factor. Langmuir probe results from other EH discharges indicate this quantity need be multiplied by 2 to obtain the peak \(T_e\). Values for \(T_{e,\text{div}}\), energy confinement time \(\tau_E\), \(T_{e,\text{ped}}\) and \(n_{e,\text{ped}}\) are plotted vs. \(\Gamma_i\) in fig. 3. Note, \(\Gamma_i\) is largely determined by \(D_2\) (fig. 1).

![Fig. 3: top to bottom, all vs. ion flux to target plate \(\Gamma_i\); \(T_{e,\text{div}}\) computed from \(P_{\text{div}}\) (IR camera) and \(\Gamma_i\); energy confinement time \(\tau_E\); \(T_{e,\text{ped}}\) and \(n_{e,\text{ped}}\). Left ELM-H; Right AT.](image-url)
Higher $\Gamma_i$ means lower $\tau_E$, with impurities often making matters worse (fig. 3), in particular at lowest $\Gamma_i$ where a dramatic drop in $n_{\text{ped}}$ can occur (also in $T_{\text{e ped}}$ for AT Ne-seeding), associated with an impurity-driven increase in $v_{\text{ELM}}$. Seeded Ne or N$_2$ leads to an obvious enhancement of $P_{\text{rad}}$ only at lower $\Gamma_i$ (-> lower D$_2$) for the present carbon-dominated environment (50->61% for EH, 30->60% for AT) /1/. Evidently $T_{\text{e ped}}$ is not reduced by $P_{\text{rad}}$ cooling as one might expect (fig. 3); it does decrease uniformly with higher $\Gamma_i$, showing minor impurity variations. In contrast, $n_{\text{ped}}$ initially increases with $\Gamma_i$ ($D_2$ fuelling), then rolls over.

3. Discussion: SOLPS code calculations for a density scan at constant power (5MW, inner & outer strike points on horizontal target) may be used to examine how the values of $\Phi_{\text{D}}$ code and $\Gamma_i$ code are related /2/. The result is for $T_{\text{e div}}>4$eV $\Phi_{\text{D}}$~$\Gamma_i^{0.76}$, i.e. S/XB = $\Gamma_i$ code/$\Phi_{\text{D}}$ code is not constant (due in part to the S/XB $T_e$ dependence). Nonetheless, $D_\alpha$ code still mirrors $\Gamma_i$ code over a wide range of $T_{\text{e div}}$, implying that the assumption S/XB=30 is a credible approach to gain a first estimate of the experimental $\Gamma_i$ from the measured $\Phi_{\text{D}}$. Taking the separatrix density $n_{\text{es}}$ from HRTS, using a Tanh fit in the gradient region and assuming the separatrix position is correctly given by EFIT, yields the relationship $\Gamma_i\sim n_{\text{es}}^{2.5\pm0.3}$ for both EH & AT. This signifies that $\Gamma_i$ is a very sensitive probe for changes in $n_{\text{es}}$, $n_{\text{es}}$ being more difficult to measure with precision due to the steep gradients in the edge region and uncertainty in separatrix location.

Fig. 4 illustrates that $\Gamma_i$ (e.g. $n_{\text{es}}$) is closely correlated with $n_{\text{ped}}/\tau_E$, meaning an enhancement in $\Gamma_i$ dictates an increase in $n_{\text{ped}}$ and/or a decrease in $\tau_E$ must prevail ($\tau_E$ is intertwined with the $D_2$- & impurity-levels). Another correlation exists between $\Gamma_i$ and $n_{\text{ped}}/T_{\text{e ped}}$ (fig. 4). A least-squares regression (not accounting for errors in $n_{\text{ped}}$ & $T_{\text{e ped}}$) yields good fits (given in the fig. 5 caption) to $\Gamma_i$ over the entire operational ranges for both ELMy-H and AT scenarios.

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Fig. 4: Ion Flux $\Gamma_i$ to outer target plate vs. $n_{\text{es}}^{\text{ped}}/\tau_E$ (top) & $n_{\text{es}}^{\text{ped}}/T_{\text{e ped}}$ (bottom). Left ELMy-H; Right AT.
These encompass an order of magnitude change in $\Gamma_i$ and a factor of $\sim 2$ for $n_e^{\text{ped}}/T_e^{\text{ped}}$. The exact form of the fits is not of importance here, rather the demonstration of the very coherent interplay among $\tau_e^{-1}$-$n_e^{\text{ped}}$-$T_e^{\text{ped}}$ and $\Gamma_i$, illustrated in figs. 4 and 5, i.e. a coupling over the edge transport barrier (ETB) region between the core/pedestal and $\Gamma_i$ to the outer target plate (and thus $n_e$). In addition, the estimated $n_{es}$ values won from HRTS are found to be nearly linear with $n_e^{\text{ped}}/\tau_e$ for both EH & AT (not shown). These are new observations of fundamental nature, implying that any change in $\Gamma_i$ is automatically accompanied by a change in $\tau_e^{-1}$-$n_e^{\text{ped}}$-$T_e^{\text{ped}}$ along the operational curves defined by the points of figs. 4 & 5 and vice versa.

![Ion Flux](image)

**Fig. 5: $\Gamma_i$ vs fit: Left ELMy-H (9.3$10^{13}$ $n_e^{\text{ped}}$11$10^{11}/T_e^{\text{ped}}$13$10^{15}$); Right AT(1.17$10^{30}$ $n_e^{\text{ped}}$08$10^{21}/T_e^{\text{ped}}$22$10^{18}$)[m$^{-3}$,eV]**

**4. Conclusions:** The discovered link among $\tau_e^{-1}$-$n_e^{\text{ped}}$-$T_e^{\text{ped}}$ and $\Gamma_i$ (e.g. $n_{es}$) suggests a phenomenon such as “stiff profiles” could be in action in the ETB, perhaps in combination with a critical gradient related to ELM onset conditions. This remains to be examined. Stiff ETB profiles have been observed on ASDEX-Upgrade, with $\eta_e$~2 being common [3/]. In any case, the observed coupling, whatever its origin, has ramifications when producing ILW-compatible conditions at the target plate: Enhanced $\Gamma_i$ will be obligatory to suppress $T_{e}^{\text{div}}$ to tolerable levels (exact value to be determined at the start of ILW operation) and also to secure reasonable plasma operation in the presence of mandatory seeded impurities. Higher $\Gamma_i$ is achievable only through $D_2$ fuelling - leading to higher $n_{es}$ - and through the coupling to higher $n_e^{\text{ped}}/\tau_e$ or $n_e^{\text{ped}}/T_e^{\text{ped}}$. This chain of events appears unavoidable.

A corollary is that the increase in neutral pressure associated with higher $D_2$ does not necessarily lead to a lower $\tau_e$ because of penetration to the pedestal and reduction of $T_e^{\text{ped}}$. Rather, the change in pedestal parameters is a result of constraints imposed by the established interconnections in association with the change in $n_{es}$. Similarly, an alteration in pedestal confinement – due to modes, for example, present in some of the selected discharges /1/ or due to the addition of impurities – will also effect a modification of $n_{es}$ and $\Gamma_i$.

**5. References**

1. G Maddison et al., Paper P2.160 this conference
2. D Coster, private communication

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