Interpretative analysis of particle confinement time on MAST

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1. Introduction

In contrast to analysis of global energy balance, majority-ion confinement time on tokamaks is usually obscured by the difficulty of determining source rates, which are a complicated blend of direct inputs and pumping with recycling. A total quantity \( \tau_p(s) \) may be expressed:

\[
\frac{dN_i^{\text{tot}}}{dt} = - \frac{N_i^{\text{tot}}}{\tau_p} + S = - \frac{N_i^{\text{tot}}}{\tau_p^*} + S_{\text{add}} \sim \frac{dN_i}{dt} = - \frac{N_i}{\tau_i} + \varepsilon_i^{\text{recycle}} S_{\text{recycle}} + \varepsilon_i^{\text{add}} S_{\text{add}}^{-},
\]

where \( N_i^{\text{tot}} \) is the total fuel-ion content and \( N_i \sim N_i^{\text{tot}} \) is their number within the confined region; \( S \equiv S_{\text{recycle}} + S_{\text{add}}(s^{-1}) \) is total source rate consisting of recycling and externally-added components respectively; \( 0 \leq \varepsilon_i \leq 1 \) are efficiencies with which these contribute to the core plasma; and \( \tau_i = a^2 / D_1 \) is consequently a time more representative of diffusion across this zone. When all added fuelling is switched off \( (S_{\text{add}} = 0) \), \( N_i^{\text{tot}} \) cannot decline faster than net effective confinement time \( \tau_p^* = \tau_p / (1 - R) \geq \tau_p \), where \( 0 \leq R = \tau_p S_{\text{recycle}} / N_i^{\text{tot}} \leq 1 \) is an overall recycling coefficient. Similarly:

\[
\tau_i \sim \frac{N_i}{\tau_p^*} [\varepsilon_i^{\text{recycle}} S_{\text{recycle}} - (1 - \varepsilon_i^{\text{add}}) S_{\text{add}}^{-}] \sim \tau_p N_i - \tau_p^* [(1 - \varepsilon_i^{\text{recycle}}) S_{\text{recycle}} + (1 - \varepsilon_i^{\text{add}}) S_{\text{add}}^{-}] \geq \tau_p.
\]

Derivation of \( \tau_i \) requires a sufficiently detailed description of particle input, effluxes and recycling. A global model adapted for the large ratio of vessel to plasma volumes (~10 : 1) on MAST has been developed\(^1\), in particular distinguishing between molecular and atomic processes and allowing for an extended gas envelope around the plasma fed directly by outboard puffing. An initial survey of discharges with such input has been undertaken, by adjusting for each one both model \( \tau_i \) and wall recycling coefficient as functions of time in order to match experimental signals for volume-average electron density \( n_e^{-}(m^{-3}) \) and estimated global D\(\alpha\) emission

\[
4 \pi A_p \xi_{\text{D}0} = \{ \Gamma_0 D^2 / (S/XB) D^2 + \Gamma_1 D^2 / ("S/XB") D^2 \}.
\]

Here \( A_p (m^2) \) is the separatrix surface area, \( \xi_{\text{D}0} \) (photons m\(^{-2}\) sr\(^{-1}\) s\(^{-1}\)) is main-plasma D\(\alpha\) radiance, \( \Gamma_0 (s^{-1}) \) are ionizing fluxes of respective neutral particles, and ratio of atomic rate coefficients\(^2\) \( (S/XB) D^2 \approx 14 \). One issue is that effective molecular emission factor \( ("S/XB") D^2 \) does not reduce to such a simple number owing to terms proceeding first through molecular ionization \( (e^- + D_2 \rightarrow 2 e^- + D_2^+) \). Sensitivity to this parameter is considered in following results.

2. Core deuteron confinement time \( \tau_d \)

A sample of 67 MAST outboard-puffed plasmas has been modelled, comprising mainly double-null-diverted with some centre-column-limited cases, while encompassing both Ohmic and neutral-beam-heated operation. Gas inputs were separately calibrated using a validated ionization gauge for injection into the vessel with no plasma or fields applied. Core fuelling efficiencies \( \varepsilon_i \) crucially represent neutral-particle penetration across the separatrix, but become distinguishable\(^1\) since they affect absolute \( \langle n_e \rangle \) most, whereas \( \partial \langle n_e \rangle / \partial t \) is more sensitive to \( \tau_i \).
Over the ranges examined, \( e_1^\text{recycle} = e_1^\text{add} = 0.1 \) were found to be adequate throughout, perhaps consistent with fuelling always from the tank reservoir. Good matches to observed \( (n_e)(t), 4\pi A_p(t) \xi_{\text{in}}(t) \) were then found to be possible by adapting \( \tau_i(t) \) plus just atomic desorption coefficient \( \rho_{\text{ad}}(t) \), i.e., each atom striking wall surfaces has a probability \( 0 \leq \rho_{\text{ad}} \leq 1 - \rho_D \) of returning as half of a thermal molecule, where reflection coefficient \( \rho_r = 0.5 \) (and similarly for ions \( \rho_{\text{id}} = \rho_i = 0.5 \)) is assumed \cite{1}. In the absence presently of active sinks on MAST, pumping is therefore simulated by the fraction \( 1 - \rho_D - \rho_{\text{ad}} \) of atoms adsorbed at the walls. Initially \((\text{S/XB})^{D2} = (\text{S/XB})^D\) has also been adopted, as suggested in other recent studies \cite{3}, but primarily because this implies minimum possible molecular density in the vacuum tank \( n_{D2} \) (m\(^{-3}\)), thus upper bounds on \( \tau_i \) and persistence of wall sinks.

A typical calculation is shown in Fig.1, actually an Ohmic DND discharge. The sudden step-down of gas puffing \( \Phi_{\text{out}} \) (electrons s\(^{-1}\)) at 0.18 s in this instance provokes a rapid rise in particle confinement, illustrating that generally \( \tau_i \) tends to be highest when fuelling is lowest, and vice versa. In complete gas turn-off experiments \( \tau_i \) can even become arbitrarily large, as plasma density is sustained for very small sources, so that its value is only defined with substantial uncertainty. These 3 such plasmas are consequently excluded from subsequent regressions. Principal-component analysis over the whole remaining dataset finds strong correlations between computed \( n_{D2} \), line-average electron density \( \pi_e \) (m\(^{-3}\)), and \( \Phi_{\text{out}} \), so only one of these can be chosen as a regressor; \( \pi_e \) is also anti-correlated with confined plasma volume \( V_p \) (m\(^3\)). Furthermore magnetic field \( B_t \) (T) varies too little for any dependence upon it to be identified. For the NBH cases alone, which were all in L-mode with auxiliary power \( P_{NB} \) (MW), \( \Phi_{\text{out}} \) exhibits almost exact anti-correlation with plasma current \( I_p \) (kA). Taking these restrictions into account, regressions separately on the (37) Ohmic and (27) NBH results during steadiest phases yield :-

\[
\tau_i^{(\text{Ohmic})} (\text{ms}) \approx 3.2 \times 10^{12} \left( I_p \right)^{-0.11} \left( \Phi_{\text{out}} \right)^{-0.50}, \quad \tau_i^{(\text{NBH})} (\text{ms}) \approx 3.5 \times 10^{21} \left( P_{NB} \right)^{-0.32} \left( V_p \right)^{0.53} \left( \Phi_{\text{out}} \right)^{-0.91} \left( e_1 = 0.1 \right).
\]

Interestingly these recall the negative current and power dependencies of neo-Alcator and L-mode energy confinement time \( \tau_E \) respectively. However, an equally large fraction of the variance over all (64) cases, irrespective of heating scheme or configuration, is removed by the single variable fit :-

\[
\tau_i (\text{ms}) \approx 5.3 \times 10^{14} n_{D2}^{-0.70} \left( e_1 = 0.1 \right).
\]

![Fig.1 Example model fit to experiment for a MAST Ohmic DND plasma \((e_1 = 0.1 \text{ and assuming } (“\text{S/XB}”)^{D2} = (\text{S/XB})^D)\).](image-url)
3. Wall pumping

In Fig. 1 a monotonic rise of inferred \( \rho_{ad} (t) \) throughout the pulse is seen, which is typical of results obtained. This is consistent with expected depletion of wall sinks as adsorbed wall inventory \( N_w(t) \) (atoms m\(^{-2}\)) accumulates. Starting value \( \rho_{ad0} \) (\( N_{w0} \)) at \( t = 0 \) is roughly inversely correlated with the duration of prior inter-shot helium-glow-discharge cleaning, but depends also on the history (density, power) of immediately preceding discharges. Plotting \( \rho_{ad}(t) \) against computed \(^1\) \( N_w(t) \), exemplified for a selection of results in Fig. 3, hence allows maximum capacity \( N_{wc} \geq N_w(t) \) setting the point at which pumping runs out (\( \rho_{ad} = 1 - \rho_{ad} = 0.5 \)) to be deduced. Saturation of wall sinks broadly indicates a linear rise of desorption

\[
\rho_{ad} (N_w) \approx \rho_{ad0} + (1 - \rho_{ad0}) \left( \frac{N_w - N_{w0}}{N_{wc} - N_{w0}} \right) ,
\]

which would actually imply available surface sites are occupied by impinging atoms at the greatest rate possible \(^1\). In MAST, regular boronization with trimethylborane is used to improve surface conditioning, such that adsorbing layers consist largely of an amorphous mixture of carbon and boron. From Fig. 3, \( N_{wc} \approx 1.0 \cdot 1.5 \times 10^{20} \) D m\(^{-2}\), so for \( f \) deuterium atoms accepted per wall-surface particle, then approximately \( J \sim (N_{wc} / f) (V_m / N_A)^{D2} \approx 6 / f \) monolayers are able to participate in pumping during a discharge, where \( V_m = (V_m^C + V_m^B) / 2 \) (m\(^3\)) is the mean molar volume of C and B and \( N_A \) is Avogadro’s number. This rather limited capacity would be an impediment to more prolonged plasmas on MAST, unless their density were kept low, or significantly more efficient fuelling methods (eg pellet injection) were employed, or both. Recall \( N_{wc} \) will also be reached more quickly if physically \((“S/XB”)^{D2} > (S/XB)^D\), since \( n_{D2} \) and associated wall fluxes are then higher for a given \( n_e \). However, an
in-vessel divertor with closure and cryopumping will be installed in a future upgrade of MAST, providing for pumping and plasma density control \cite{1} which practically will never degrade.

4. Conclusions

Interpretative global modelling of majority-particle balance on MAST suggests core confinement time $\tau_i$ varies inversely with outboard gas-puffing rate, being higher when $\Phi_{\text{out}}$ is lower, and vice versa. In addition, steady-state $\tau_i$ is governed chiefly by surrounding molecular density $n_{\text{D2}}$ in the large vacuum tank, $\tau_i \propto n_{\text{D2}}^{-0.7}$, irrespective of configuration or heating scheme. Such susceptibility is close to expectations for constant core fuelling efficiency $e_i$ as construed, plus roughly constant content $N_i$, since $\frac{\partial N_i}{\partial t} = 0 \Rightarrow N_i / \tau_i = e_i S \propto n_{\text{D2}}$. The large alteration in $\tau_i$ inferred (Fig.2), which is much greater than modelling uncertainties, therefore probably does reflect a genuine change in particle behaviour, viz ion efflux tends to rise for a given $(n_e)$ with stronger fuelling from the surrounding gas envelope. A similar trend is hinted by estimated energy confinement time, at least for higher values of $n_{\text{D2}}$. This emphasizes the importance of minimizing tank-gas density to optimize performance, something which can be accomplished for a given steady plasma density only by improving core fuelling efficiency \cite{1} (and not by stronger pumping), eg using inboard puffing, or ideally deep pellet injection. The main qualification is that so far $n_{\text{D2}}$ has only been calculated. Measurements during MAST pulses will become available with a screened fast ionization gauge, now being implemented. The wide variation in $n_{\text{D2}}$ already predicted for existing conditions (Fig.2) will be checked, helping to verify the global model and to resolve D$\alpha$ emission by molecules ("S/XB")$^{\text{D2}}$. Maximum inventory of wall pumping will also be confirmed. Longer term, plasma density control in sustained high-density discharges will be ensured by supplementing limited wall sinks with a closed, cryopumped divertor.

References

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