A SCALING LAW FOR THE CONFINEMENT TIME OF NON RECYCLING INJECTED IMPURITIES IN JET AND TORE SUPRA

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Data bases have been set up for the particle confinement times τ_p of non recycling impurities injected in laser ablation experiments in the JET and Tore Supra tokamaks [1]. No dependence of τ_p on the charge of the injected element or on the background gas (D or ^{4}He) was found in these discharges.

1 DESCRIPTION OF EXPERIMENTS AND OF DATA SETS

The data analysed here are from L-mode plasmas produced in the limiter, single null X-point or double null X-point configuration. In all but two pulses (Tore Supra) sawtooth activity was present. The background gas was D_2 or ^{4}He. The total number of pulses in the data set used for statistical analysis is 133 (63 from Tore Supra and 70 from JET).

Operational ranges explored with our data sets	
• Tore Supra	• JET
◊ $R \sim 2.3$ m; $a_L \sim 0.75$ m; $\kappa \sim 1$	◊ $R \sim 3$ m; $a_L \sim 1.1$ m; $\kappa \sim 1.6$
◊ $V_P \sim 28$ m^3	◊ $V_P \sim 125$ m^3
◊ $I_P = 0.8 - 1.7$ MA	◊ $I_P = 2 - 7$ MA
◊ $B_T = 2.6 - 4.0$ T	◊ $B_T = 1.45 - 3.45$ T
◊ $<n_e> = 1. - 4.\ 10^{19}$ m^{-3}	◊ $<n_e> = 1. - 4.3\ 10^{19}$ m^{-3}
◊ P_{in} up to ~ 7 MW	◊ P_{in} up to ~ 15 MW

Correlation table for the joint data set

	log($<n_e>$)	log(B_t)	log(V_p)	log(I_p)	log(P/n_eV_P)
log($<n_e>$)	1				
log(B_T)	0.127	1			
log(V_p)	-0.225	-0.632	1		
log(I_p)	-0.155	-0.489	0.931	1	
log($P_{in}/<n_e>V_P$)	0.139	0.487	-0.579	-0.511	1

$<n_e>$= vol. averaged el. density
B_T = tor. magnetic field
V_P = plasma volume
I_p = plasma current
P_{in} = total heating power

From the above table it can be seen that there is a strong correlation between current and plasma volume. However the influence of I_P on τ_p can be independently analysed in the separate data sets from the two machines where the volume is not varying significantly. Information on the dependence of τ_p on the plasma volume can also be checked against experimental values of τ_p, as found in the published literature [1].

Elements injected	
• **Tore Supra** Mn(Z=25), Ni(28), Cu(29), Ge(32)	• **JET** Al(Z=13), Ti(22), Fe(26), Co(27) Ni(28), Ge(32), Zr(40), Mo(42),Ag(47)

Analysis technique to deduce τ_p	
• **Tore Supra** Eigenmode analysis of soft X-ray signals *select slowest eigenmode*	• **JET** Fit exponential decay to intensities of Li-, Be-, Na- or Mg-like $\Delta n = 0$ transitions

2 PREVIOUS SCALING LAWS

The scaling proposed by Marmar et al. for ohmic discharges from Alcator C [2]

$$\tau_A[\text{ms}] = 0.075\, a_L[\text{cm}]\, M_{bg}\, R[\text{cm}]^{0.75}\, Z_{eff}/\,(Z_{bg}\, q_{cyl})$$

predicts values for τ_p that are too high by factors ranging between ~2 and ~7 for Tore Supra and between ~3 and ~6 for JET. This scaling also indicates a dependence on the background plasma. This dependence cannot be verified from our database because practically all our data are obtained in D_2 or ^{4}He discharges and M_{bg}/Z_{bg} is constant.

The scaling proposed by Hawkes et al. for JET [3]

$$\tau_H[\text{ms}] = 90\, n_e[10^{19}\,\text{m}^{-3}]^{0.4}\, q_\psi^{\,0.5}$$

was based mostly on 3 MA ohmically heated discharges or discharges with low additional heating. No dependence on power or plasma current could therefore be indicated by that scaling.

3 SEARCH OF APPROPRIATE SCALING LAW FROM THE NEW DATA SETS

We looked for a monomial scaling law of the form $\tau_{sl} = 10^a \prod_{i=1}^{m} p_i^{k_i}$ where p_i indicates the generic parameter. Linear regressions were performed minimising the logarithmic standard deviation for the best fit. An analysis of sensitivity of τ_p to the different parameter has been performed. We started from the observation that the main ordering parameter of the impurity confinement time is, for both the data sets independently as well as for the combined dataset, $P_{in}/(\langle n_e\rangle V_p)$. Therefore we analysed the meaningfulness of possible dependencies on other parameters by comparing the standard deviations of different linear regressions. The only statistically signifincant parameters were found to be $P_{in}/(\langle n_e\rangle V_p)$, I_p and V_p. Our best choice for a scaling law for τ_p was found to be

$$\boxed{\tau_{sl}[\text{ms}] = 7.4\; V_p^{\,0.70\pm0.08}\; I_p^{\,0.31\pm0.09}\; (P_{in}/\langle n_e\rangle)^{-0.57\pm0.03}}$$

where P_{in} is measured in MW, I_p in MA, n_e in 10^{19}m^{-3} and V_p in m^3. The logarithmic standard deviation for this regression is $\sigma_{bf} = 0.068$.

Similar dependencies on I_P are found when one analyses the two data sets separately and uses I_P as a second parameter together with $P_{in}/<n_e>$ in the linear regression.

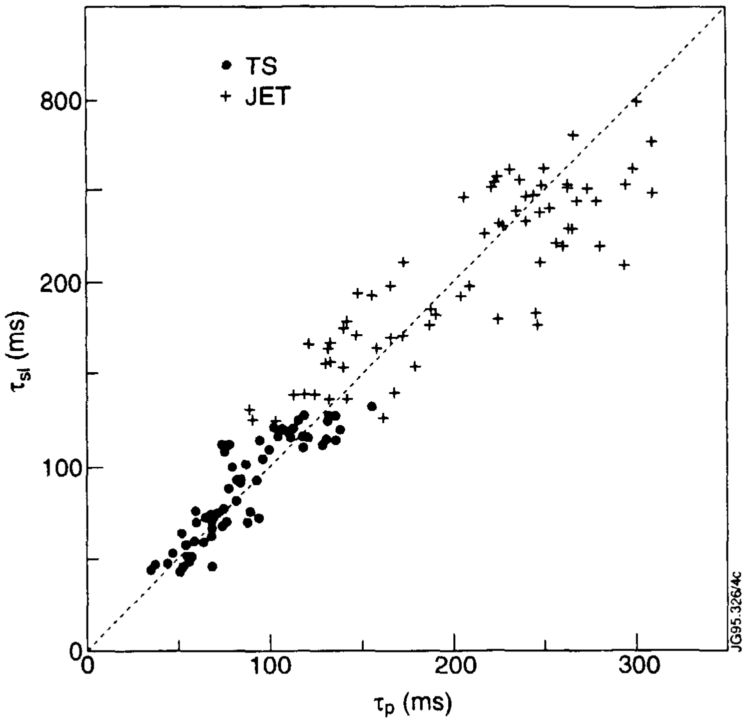

Fig. 1 Impurity confinement time τ_{sl} as predicted by the scaling proposed in this paper versus experimental τ_p-values (dots: TS, crosses: JET). The dashed line shows $\tau_{sl}=\tau_p$

4 CONSISTENCY WITH OTHER EXPERIMENTAL RESULTS AND WITH DIMENSIONAL CONSTRAINTS

The parametric dependence of the proposed scaling law is very close to that found independently for the two machines and appears to be broadly consistent with the experimental results obtained in ohmic discharges on other tokamaks (see fig. 5).

The proposed scaling law also satisfies the Connor-Taylor constraint [4] applicable to finite β collisional models:

$$5\,\kappa_B + \kappa_I + 8\,\kappa_n + 3\,\kappa_P - 4\,\kappa_R - 4\,\kappa_a + 5 = 0$$

where the κ's are the exponents in the scaling expression for B_T, I_p, n_e, P_{in} , R and a_L, respectively. The sums of the positive and negative terms are 9.87 (±0.26) and -10.11 (±0.96). Therefore the left hand side of equation above is equal to -0.24 (±1.10).

Constraints deriving from less general plasma models are not satisfied by this scaling law.

5 COMPARISON OF THE IMPURITY CONFINEMENT TIMES WITH THE GLOBAL ENERGY CONFINEMENT TIMES

The global energy confinement times τ_E for the same discharges is also available in our databases. τ_E is defined as the ratio of the diamagnetic energy to the total input power P_{in}, τ_E and τ_p are of the same order but different, their average ratio τ_E/τ_p being ~2.5.

The logarithmic linear regression of τ_E gives

$$\tau_{E\text{-}sl}\,[\mathrm{ms}] = 54\, I_p^{0.73\pm.12}\, V_p^{0.34\pm.11}\, n_e^{0.32\pm.08}\, B_T^{0.01\pm.14}\, P_{in}^{-0.41\pm.04} \qquad (\mathrm{MA}, \mathrm{m}^3, 10^{19}\,\mathrm{m}^{-3}, \mathrm{T}, \mathrm{MW})$$

and a standard deviation $\sigma_{bf} = 0.089$.

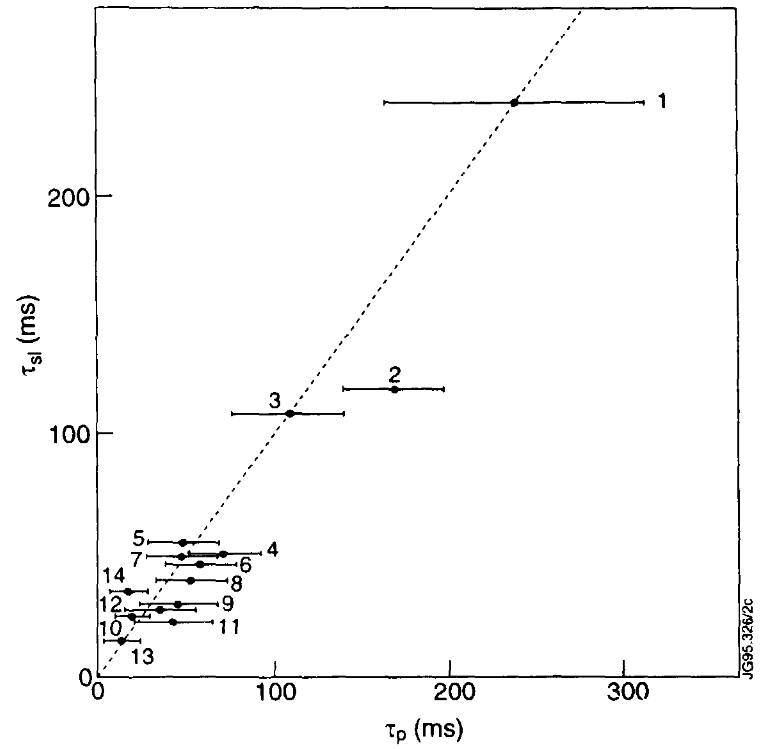

Fig. 2 Impurity confinement times predicted by the scaling law proposed in this paper τ_{sl} versus the experimental τ_p values for several tokamaks:[1] 1 JET, 2 TFTR, 3 Tore Supra, 4 Textor, 5 ASDEX, 6 PLT, 7 T10, 8 PDX, 9 DITE, 10 TEXT, 11 TFR, 12 FT, 13 Alcator C, and [5]14 Alcator C MOD. The horizontal bars show the range of the reported experimental values. All data refer to ohmic plasmas with deuterium as background gas

This scaling is not far from the ITER89-P [6] scaling law

$\tau_{E\text{-}ITER89}\,[\mathrm{ms}] = 38\ M_{bg}^{\ 0.5}\ I_p^{\ 0.85}\ R^{1.2}\ a_L^{\ 0.3}\ \kappa^{0.5}\ n_e^{\ 0.1}\ B_T^{\ 0.2}\ P_{in}^{\ -0.5}$ $(\sigma_{sl} = 130\ \mathrm{ms})$

or from the scaling proposed by Taroni et al. [7]

$\tau_{E\text{-}T}[\mathrm{ms}] = 73\ I_p\ R^{1.5}\ n_e^{\ 0.5}\ B_T^{\ -0.5}\ P_{in}^{\ -0.5}$ $(\sigma_{sl} = 100\ \mathrm{ms})$

Comparison of the above scalings for τ_E with the scaling for τ_p indicates that

- the ratio of τ_E/τ_p should increase with I_p and decrease with increasing plasma size and density.
- A more moderate trend to increase with increasing total input power is also expected.
- The dependence of τ_E/τ_p on B_T remains uncertain, as the trends of the two confinement times independently are.

The logarithmic linear regression of this ratio leads to

$$\boxed{\tau_E/\tau_p\ [\mathrm{ms}] = 6.4\ I_p^{\ 0.40\pm.16}\ V_p^{\ -0.32\pm0.15}\ n_e^{\ -0.17\pm.12}\ B_T^{\ 0.02\pm.20}\ P_{in}^{\ 0.16\pm.05}}$$

and to a logarithmic standard deviation $\sigma_{bf} = 0.123$. The high value of σ_{bf} found is due to the large relative uncertainty on τ_E/τ_p that is obtained as the ratio of two independently measured quantities.

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