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Journal of Nuclear Materials 241–243 (1997) 450–455

journal of nuclear materials

Scaling radiative plasmas to ITER

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Abstract

In the radiative regime non-intrinsic impurities have been used to produce divertor power loads which would be considered acceptable when extrapolated to ITER. However, it has been a matter of concern that the maximum Z_{eff} currently deemed acceptable for ITER has been exceeded by a large margin in radiative plasma experiments in large divertor machines such as JET, JT60-U, AUG and DIII-D. This paper points out that without a suitable scaling law, comparisons of Z_{eff} between current machines and ITER are meaningless. Results from a multi-machine database are presented which show that there appears to be a remarkably simple and robust scaling which relates Z_{eff} to line averaged density, total radiated power and main plasma surface area. A similar scaling has been found in code simulations with EDGE2D and DIVIMP. The consequences for ITER are discussed.

Keywords: Impurity transport; Density limit; Scaling law; Radiation energy sink; Detached plasma

1. Introduction

Radiative detached plasmas are currently considered by ITER to be the preferred solution to the problems of reducing the peak power and erosion of divertor components to acceptable levels [1]. In current limiter and divertor experiments, non-intrinsic impurities have been used to increase the radiated power fraction to levels considered relevant for ITER [2–8]. Most of these discharges are close to or exceed the minimum requirement for energy confinement set by ITER [1]. Unfortunately, the impurity content is usually well above the ITER reference values which, excluding the contribution from helium ash, are: $Z_{eff} \leq 1.2$ and $n_D/n_e \geq 93\%$. For example, in high power JET or ASDEX-Upgrade (AUG) radiative discharges $Z_{eff} \approx 3$ is typical which means that the impurity contribution to Z_{eff} is about one order of magnitude higher than the ITER reference. However, this direct comparison of Z_{eff} values is meaningless without a scaling law based on theory, modelling or experimental results. In this paper first results are presented from multi-machine database whose primary purpose is to investigate the scaling of Z_{eff} in radiative discharges.

2. A multi-machine database for Z_{eff} scaling

Size scaling is crucial when extrapolating impurity content to ITER and this can only be explored within the context of a multi-machine database. Such a database has now been assembled and includes data from a variety of

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PII S0022-3115(96)00545-4

Table 1
Current contributors to the multi-machine Z_{eff} database indicating the type of gas injected and the number of points available

Tokamak	Injected species	Points
ASDEX	D_2	129
AUG	D_2, N_2, Ne, Ar	47
C-Mod	D_2, CD_4, N_2	101
DIII-D	Ne	4
JET(1992)	D_2	1
JET(MkI divertor)	N_2, Ne, Ar	78
JT60-U	D_2, Ne	57
TEXTOR	Si, Ne, (Si + Ne)	8

tokamaks and impurities as listed in Table 1. The main focus of the database is on discharges with fractional radiated powers in excess of 50%. Some, but not all, of the discharges might also be classified as detached. The lack of clear back transition in the radiative regime means that the distinction between L- and H-mode is rather blurred and has not been made in our analysis.

Unfortunately, the diagnostics and methods for deriving Z_{eff} are not identical for all machines: Some are central values (DIII-D, C-Mod) and the others are line averaged. In the tokamaks where Z_{eff} profiles are available this difference does not add substantially to the experimental uncertainties (AUG, JET). The DIII-D points come from charge-exchange spectroscopy whilst the other machines use visible bremsstrahlung.

The primary quantities which prove essential for the scaling are the total power radiated, P_{rad}, plasma surface area, S, line averaged density, $\bar{n}_e$, atomic number Z of the impurity and Z_{eff}. Fig. 1 shows Z_{eff} plotted as a function of P_{rad} for the database.

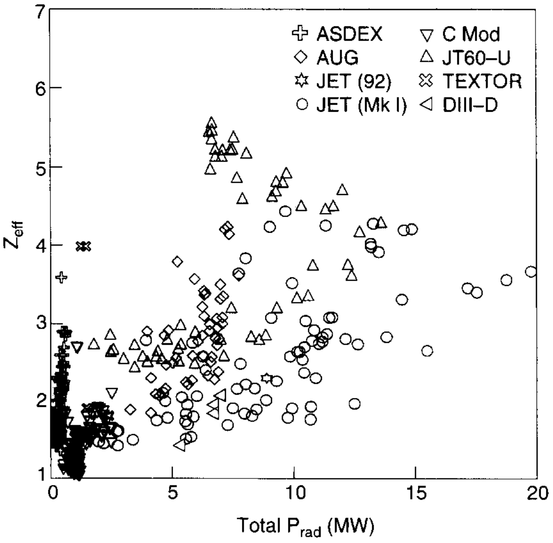

Fig. 1. Z_{eff} versus total radiated power P_{rad}.

3. Regressing the Z_{eff} database

To regress the Z_{eff} database we need to decide on a suitable functional form and identify the relevant parameters. If we start with the simplistic assumption that the radiation comes from a plasma volume V_{rad} where the electron and impurity densities are $n_{e,rad}$, $n_{z,rad}$ respectively:

$$P_{rad} = V_{rad} n_{e,rad} n_{z,rad} L_z + P_{CX} \tag{1}$$

where P_{CX} is the power loss due to charge exchange and L_z is the average radiated power coefficient in the radiating volume. The multi-machine database uses total radiated power from main chamber bolometer systems which are screened from divertor charge exchange losses but not line radiation, for this reason it will be assumed that $P_{CX} = 0$.

If we assume that the radiated power is coming from a uniform shell of thickness Δ then $V_{rad} = S\Delta$ where S is the main plasma surface area. This is a reasonable approximation for high Z radiating impurities such as argon but not for low Z impurities such as nitrogen [9]. Defining compression factors $C_n = n_{e,rad}/\bar{n}_e$ and $C_z = n_{z,rad}/\bar{n}_z$ to provide a simple relationship between the impurity and electron densities in the radiating zone and line averaged values, the following expression for the impurity ion concentration $f_z = \bar{n}_z/\bar{n}_e$ may be derived:

$$f_z = P_{rad}/\left(S\Delta C_n C_z \bar{n}_e^2 L_z\right) \tag{2}$$

The corresponding expression for Z_{eff} is:

$$Z_{eff} \approx 1 + Z(Z-1)f_z = 1 + Z(Z-1)P_{rad} \\ /\left(S\Delta C_n C_z \bar{n}_e^2 L_z\right) \tag{3}$$

the database does not contain information about Δ, C_n, C_z or L_z and so the regression has been applied with functions of the form:

$$Z_{eff} = 1 + \alpha P_{rad} Z^{\delta}/\left(S^{\beta} \bar{n}_e^{\gamma}\right) \tag{4}$$

where α, β, γ and δ are determined by a non-linear least squares fit to the multi-machine database with equal weight given to each point. The result of this is the following:

$$Z_{eff} = 1 + 5.6(\pm 0.7) P_{rad} Z^{0.19 \pm 0.05} \\ /\left(S^{1.03 \pm 0.02} \bar{n}_e^{1.95 \pm 0.04}\right) \tag{5}$$

where P_{rad} is in MW, S in m^2 and $\bar{n}_e$ in units of 10^{20} m^{-3}.

The multi-machine experimental data are plotted against this regression in Fig. 2. Also, shown is the desired operating point for ITER ($Z_{eff} = 1.2$ excluding He, $P_{rad} = 150$ MW, $S = 1253$ m^2, $\bar{n}_e = 1.3 \times 10^{20}$ m^{-3}).

The regressed Eq. (5) is so close to Eq. (3) with $Z(Z-1)/(\Delta C_n C_z L_z)$ constant that for most practical purposes of evaluation Eq. (6) may be more useful. However,

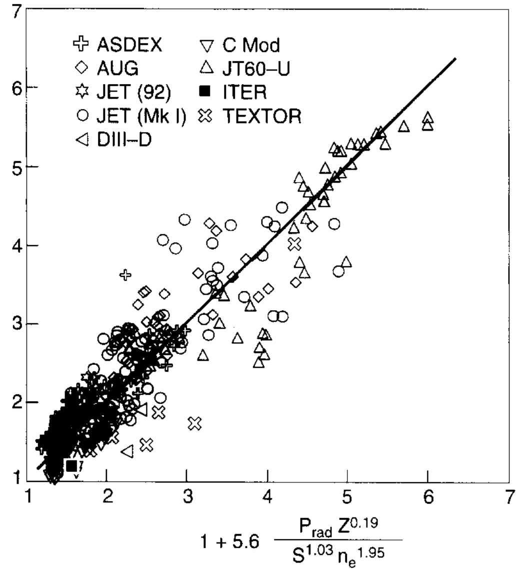

Fig. 2. Z_{eff} versus the scaling law of Eq. (5) for experimental data from C-Mod, ASDEX, AUG, DIII-D, JT60-U, TEXTOR and JET. The desired ITER operating point is also indicated.

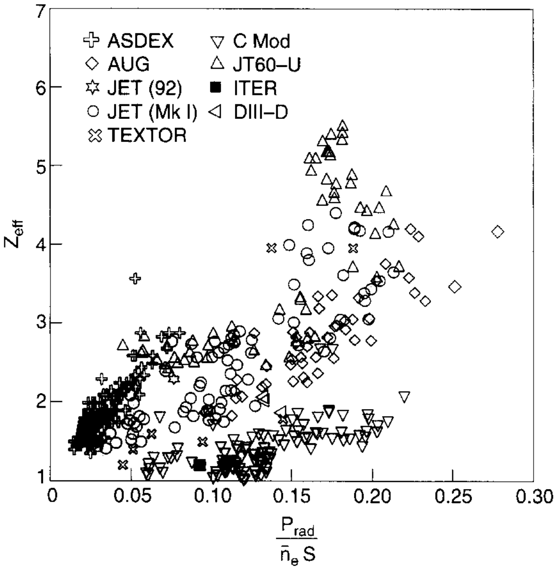

Fig. 3. Experimental Z_{eff} versus $P_{rad}/\bar{n}_e S$.

there seems no physical reason why the exponents should be exact integers.

$$Z_{eff} = 1 + 7P_{rad}/\left(S\bar{n}_e^2\right) \tag{6}$$

Scaling relations (5) and (6) provide a useful datum by which to judge the relative performance of radiative discharges although care must be taken that $\bar{n}_e$ and the density used in computing Z_{eff} have correlated errors. This is because the visible bremsstrahlung intensity used to compute Z_{eff} depends on the square of the density and so the errors can be made to cancel if the scaling is close to Eq. (6). The regression illustrated in Fig. 2 represents the mean and one can see that there are quite a few discharges with an incremental Z_{eff} which is half the predicted value. TEXTOR is the only limiter machine currently represented in the database [7]. On the basis of Fig. 2 one can see that TEXTOR performs at least as well as most divertor machines. The inverse square law dependence of incremental Z_{eff} on line averaged density has already been reported from TEXTOR [8].

At first sight the scatter in the data shown in Fig. 2 may make the regression appear unconvincing. However, the error bars in the exponents of the regressed expression are very small which is indicative of the wide range in parameters provided by the multi-machine database. It has been assumed that the pulses with deuterium only have radiation dominated by intrinsic carbon impurities and so Z has been set to 6 in these cases. This means that the range of Z within the database is only 3 (carbon to argon) whereas, the other parameters all vary by more than an order of magnitude as illustrated in Table 2.

The quality of the fit to the data is best illustrated by plotting the data against similar functions to the regressed expression with one parameter changed. Fig. 3 shows that when Z_{eff} is plotted as a function of $P_{rad}/\bar{n}_e S$ the data from each machine forms well separated groups. A plot of Z_{eff} against $P_{rad}/\bar{n}_e^2 R$ where R is the machine major radius produces a similar result.

4. Detachment

Partially detached and fully detached plasmas are indistinguishable within the Z_{eff} scaling Eq. (5). Fig. 4 shows

Table 2
Indicating the large range of key parameters within the multi-machine database

Parameter	Minimum	Maximum	Range (max./min.)
Plasma surface area S (m^2)	7.4	168	23
Total radiated power P_{rad} (MW)	0.17	19.8	116
Line averaged density $\bar{n}_e$ ($\times 10^{20}$ m^{-3})	0.11	2.04	18
Density squared $\bar{n}_e^2$ ($\times 10^{40}$ m^{-6})	0.012	4.16	347
Impurity atomic number Z	6	18	3

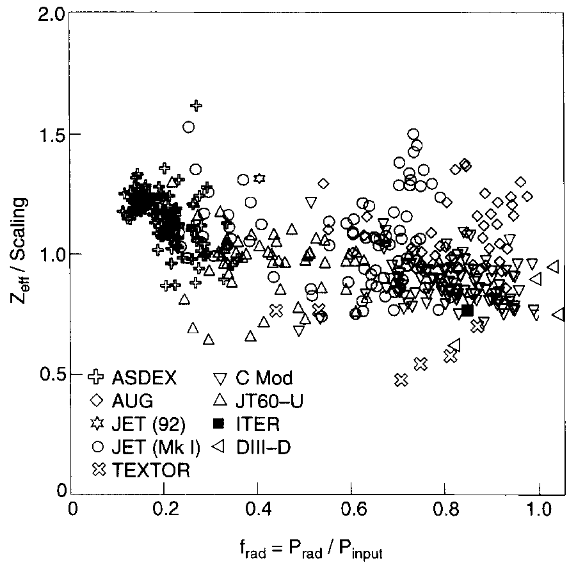

Fig. 4. $Z_{eff} / Z_{eff,predicted}$ versus fractional radiated power f_{rad}.

the ratio of Z_{eff} measured to that predicted by scaling Eq. (5) as a function of fractional radiated power, f_{rad}. Detachment is usually observed when $f_{rad} > 0.7$ [10] and there is no sign of degradation with respect to the scaling at this point. However, partially detached plasmas have less P_{rad} and so lower Z_{eff} which may make them attractive to ITER [11].

5. Comparison with codes

The Z_{eff} scaling has been investigated using the EDGE2D/NIMBUS 2D multi-fluid code [12]. The strength of EDGE2D is that the calculations are fully self-consistent. The main limitation of EDGE2D as used in the cases we will present is that it models only the scrape-off layer and a relatively thin layer inside the separatrix. It is therefore necessary to make an assumption about the relationship between the separatrix density and the line averaged density and to choose cases where most of the radiation occurs in the region covered by the model. For the cases presented here we assume that $n_{e,sep} = 0.3 \times \bar{n}_e$.

In Fig. 5 results from EDGE2D are compared with the empirical multi-machine scaling. The points are from a collection of runs performed on JET and ITER grids, for purposes other than testing the scaling. They cover a range of divertor configurations, plasma conditions and physics assumptions which are too great to detail here. There is agreement with the empirical scaling Eq. (5), in most cases within a factor of 2. The size scaling to ITER is also consistent with Eq. (5). This is encouraging since it suggests that the dependencies observed in the existing experimental data still hold when extrapolating to ITER.

The DIVIMP code [13] was used to model the behaviour of recycling and non-recycling impurities using grids covering the SOL and core plasmas which were generated for JET, CMOD, DIII-D and ITER. DIVIMP requires the provision of a plasma background into which the impurities can be injected and followed in a Monte-Carlo way. The plasma backgrounds were generated with an 'onion-skin' model, with densities and temperatures across the targets specified as boundary conditions. Typically, the target separatrix was set at 10 eV with an e-folding length of 0.1 m along the target; the target separatrix density was varied in the range 10^{19} m^{-3} to 10^{21} m^{-3}, also with a 0.1 m e-folding length. The cross-field diffusion coefficient was varied from 0.3 to 3 m^2 s^{-1}. Parallel conduction plus various levels of convection were assumed along the SOL. Core density and temperature profiles were adjusted in various ways. The separatrix electron density was however always assumed to be 0.3 times the line averaged value.

The DIVIMP results shown in Fig. 5 are consistent with the scaling Eq. (5) within a factor of 2 and are remarkably robust. Points were generated which fell an order of magnitude below this scaling by injecting a non-recycling impurity directly into the divertor. However, this rather extreme assumption is not reactor relevant and may rely to some extent on the trace impurity approximation used in the DIVIMP calculations.

DIVIMP has been used to study the surprising implication of Eqs. (3) and (5) that $Z(Z-1)/(\Delta C_n C_z L_z)$ is nearly constant. In the DIVIMP runs of Fig. 5, diagnostics were included which showed that values of Δ, C_n, C_z and L_z, averaged over the radiating zone, each varied by an

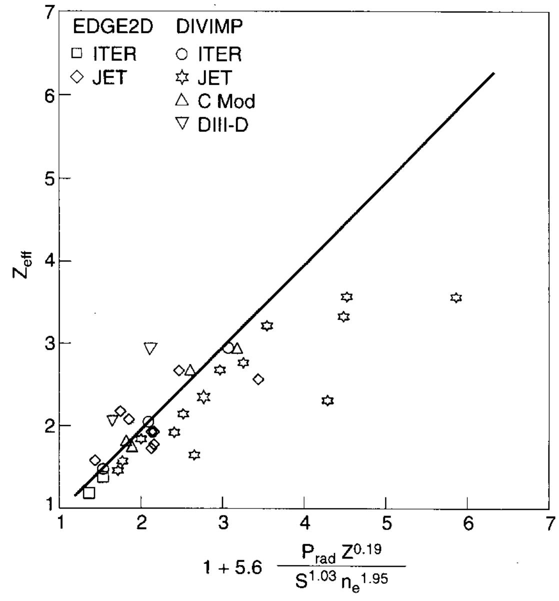

Fig. 5. Z_{eff} from a wide variety of EDGE2D and DIVIMP runs versus Eq. (5).

order of magnitude but $Z(Z-1)/(\Delta C_n C_z L_z)$ remains constant within a factor of 2. This finding is not presently understood and is the focus of further studies.

The simple assumption leading to Eq. (3) of a uniform radiating shell is incorrect both in the code runs and in some of the experimental results [9] where highly asymmetric SOL or divertor radiation can dominate. However, despite this, the simple assumption appears to get the right size scaling. This is a surprising result which currently has no satisfactory explanation although a part of the story may be found in [14].

6. Implications for ITER

Z_{eff} predicted by Eq. (5) for ITER is 1.6 whereas ITER would like $Z_{\text{eff}} < 1.2$ (excluding helium) implying that the ITER operating point is close to what can easily be achieved and is within the scatter of the existing data. Also, EDGE2D and DIVIMP results suggest that extrapolation to ITER is reasonable. The results also show no clearly preferred radiating species for Z_{eff} but dilution will therefore decrease with Z. There is also no clear evidence that divertor geometry or degree of detachment significantly influence the scaling. This raises the question as to whether ITER really needs a deep divertor. Forced convective flow in the SOL also seems not to influence the scaling of the real data or the code predictions, although there may be other benefits such as enhanced helium removal.

Although the scaling Eq. (5) shows that ITER should be close to meeting its goal in terms of Z_{eff}, this result relies on assuming an operating density of 1.2×10^{20} m^{-3}. This density corresponds to 1.6 times the Greenwald limit [15]. Unfortunately, there are no examples of radiative H-modes exceeding the Greenwald value within the existing database as shown in Fig. 6. If ITER were to reach only 0.8 times the Greenwald value, which seems typical of the larger machines, then the predicted Z_{eff} for ITER rises to 3.4.

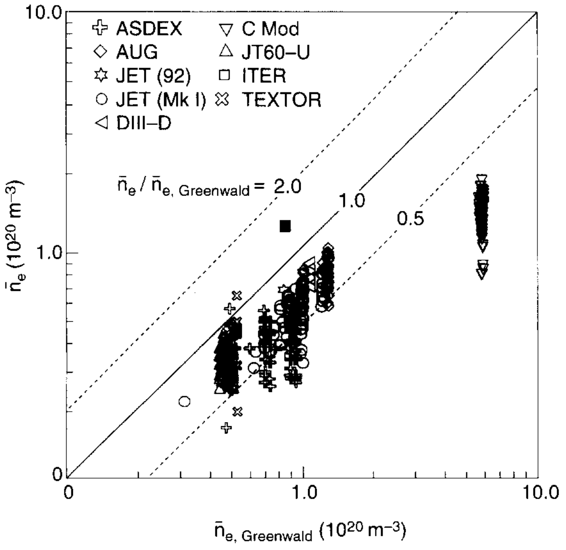

Fig. 6. Greenwald density value for radiative plasma database versus line averaged density.

Line averaged density was used in this scaling study because it is commonly available. However, edge density is probably more relevant since the line radiation is concentrated near the edge of the plasma. One consequence of this is that if the Greenwald density limit is exceeded in ITER by peaking of the core density profile then the scaling Eq. (5) may be invalidated. Low edge density implies that higher concentrations of impurities would be necessary to meet the required radiated power fraction although fuelling the core may help purge central impurities.

7. Conclusions

The scaling relation Eq. (5) appears to predict the incremental Z_{eff} due to impurities in current radiative plasma experiments and DIVIMP and EDGE2D code within a factor of 2 in most cases. It also suggests that the Z_{eff} required by ITER does not require huge improvement over current experimental results, provided the required operating density can be achieved. Unfortunately, the ITER operating density is currently specified to be well above the Greenwald density limit and there is no evidence so far that this can be achieved in a radiative H-mode.

The implication of the current scaling is that $Z(Z-1)/(\Delta C_n C_z L_z)$ is constant within a factor of 2 over a wide range of conditions. Since this is not understood, it is possible that experimental results may be found in the future which strongly violate the scaling. For example, the ideal radiating divertor with good impurity retention. The scaling presented here should be regarded as a preliminary framework within which to judge the relative performance of radiative discharges with respect to impurity content. There is plenty of scope for extending the database and improving the quality and consistency of the data it holds. Without such a scaling study, comparisons of Z_{eff} between different machines and ITER's requirements are completely meaningless.

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