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ABSTRACT

Radiative cooling by seeded impurities is a way to reduce the power load on divertor targets. Impurity-seeding experiments carried out in the JET MkI, MkIIA and MkII GB divertors are discussed, in particular in terms of their radiative properties. A reassessment of the radiation levels of about 235 discharges (seeded predominantly with nitrogen or neon) leads to the conclusion that radiation levels in some impurity-seeded plasmas in MkI and MkIIA have been underestimated. The techniques applied to obtain improved estimates of the total radiated power and radiated power in the divertor region are discussed and it is shown that weighted summation is unreliable for impurity-seeded discharges in JET. The consequences of the reassessment on the interpretation of impurity-seeded plasmas is limited. However, the understanding of the power balance and the fit to Matthews' scaling law for Z_{eff} are improved.

1. INTRODUCTION

The reduction of the power load on divertor target plates is an important issue for future fusion reactors. Such a reduction may be achieved by radiative cooling due to seeded impurities. Impurity-seeding experiments have been carried out in many tokamaks, including JET (see Ref. 1 for experiments in the JET MkI and MkIIA divertors). A reassessment of a small number of nitrogen-seeded discharges in the JET MkI, MkIIA and MkII GB divertor was recently carried out [2], showing that in several of the JET experiments the radiation level has been underestimated. In this paper this reassessment is extended to over 100 nitrogen-seeded discharges, and to 135 discharges with and without seeding by other impurity species (^4He , Ne, Ar and Kr). Other parameters varied were heating method and power, gas injection rate and location, and plasma configuration.

2. DETERMINATION OF THE TOTAL RADIATED POWER

2.1. METHODS TO DETERMINE THE TOTAL RADIATED POWER

The total power P_{rad} radiated by the plasma can be estimated from bolometer measurements in one or more poloidal cross-sections and by assuming toroidal symmetry. One way to estimate P_{rad} is by weighted summation over the channels i that cover a complete poloidal cross-section

$$P_{\text{rad}} = 2\pi(R_0 + p_i) \sum_i f_i \Delta p, \quad (1)$$

where p_i is signed distance to the vessel centre, f_i is the line integral measurement (in units W/m^2), R_0 is the major radius, and Δp is the distance between the lines of sight. Provided the lines of sight are parallel and the beam widths are sufficiently wide to avoid gaps, Eq. (1) is very accurate. At JET a vertically viewing camera has the lines of sight spread over a fan and Eq. (1) with appropriately chosen weights Δp can only approximate P_{rad} . The selection of appropriate weights Δp is not trivial in diverted plasmas: the weights should be adjusted in relation to divertor radiation, which can be significant (Fig. 1).

A more-accurate assessment of P_{rad} is obtained from a volume integral over tomographic

reconstructions of the local emissivity in a poloidal cross-section. A standard constrained optimization tomographic reconstruction with non-negativity constraint is used [3,4]. Experience at JET has shown that determining P_{rad} from the tomographic reconstruction made using only main-vessel lines of sight is the most accurate way available. Although tomographic reconstructions using all lines of sight give significantly more spatial structure in the divertor region, this apparently goes at the expense of the accuracy of integral quantities, probably because small errors and inconsistencies in divertor measurements lead to relatively large artefacts in main-plasma radiation.

2.2. METHODS TO DETERMINE THE TOTAL RADIATION IN THE DIVERTOR REGION

Tomography makes it possible to determine the total power radiated in various regions in the plasma, such as in the divertor. It is not trivial to find a physically meaningful definition of “divertor radiation” that can be determined accurately. Divertor radiation defined as “all radiation emitted below the X point” [5] is problematic. From tomography simulations with peaked emission profiles close to the X point one can demonstrate that the spatial resolution of the JET bolometers is insufficient to determine whether radiation is from inside or outside the separatrix. Furthermore, Fig. 1 shows that the definition using the X point is rather arbitrary and that the presence of the X point causes an increase in radiation in the scrape-off layer, and possibly inside the last closed flux surface, above the X point. Therefore, one might define radiation from the divertor region P_{div} as “all radiation induced by the presence of an X point.” The total power, radiated below a height Z (see Fig. 1 for the definition of Z) is given by

$$P_h(Z) = 2\pi \int_{Z_{\text{min}}}^Z \int_{R_{\text{min}}}^{R_{\text{max}}} \epsilon(R, Z') R dR dZ'$$

where $\epsilon(R, Z)$ is the local emissivity (units W/m^3). Figure 2 shows a typical example of $P_h(Z)$ in JET (solid curve). In virtually all diverted plasmas there is a profound bend of the curve at $Z \approx -1\text{m}$, which only depends weakly on actual X-point height, and a mostly linear rise for higher Z (despite the plasma width changing with height). Because of these characteristics, defining $P_{\text{div}} \approx P_h(-1\text{m})$ is meaningful. Naturally, $P_{\text{tot}} \approx P_h(2\text{m})$, and we define the power radiated in the bulk plasma as $P_{\text{bulk}} = P_{\text{tot}} - P_{\text{div}}$.

2.3. DIFFERENCES IN P_{RAD} ESTIMATES

As can be seen from Figs. 1 and 2, P_{div} can dominate over P_{bulk} (note also that the divertor peak emissivity can be more than one order of magnitude higher than the peak emissivity in the bulk plasma). Because of the calculation speed, an estimate of P_{rad} is obtained in all JET discharges by weighted summation with fixed weights, which may be inadequate in highly radiative plasmas. For unseeded low-density plasmas in MkI and MkIIA a weighting that does not take into account the divertor gives satisfactory results, whereas in similar plasmas in MkII GB larger Δp are required for channels that view the divertor. Figure 3 compares these two weighted-summation estimates with the best estimate of P_{rad} from tomography for several timeslices of many impurity-seeded

discharges. There is a scatter of up to 60% and there are differences between the divertors and impurity species. In the MkI and MkIIA plasmas with nitrogen seeding the estimate with weights that do not take into account the divertor (Fig. 3(b)) is reasonable, except when $P_{\text{div}}/P_{\text{bulk}}$ is high. In MkII GB, the weighting that takes into account the divertor (Fig. 3(a)) gives better estimates for nitrogen, as in low-density deuterium plasmas. However, for neon, argon and krypton, both methods underestimate P_{rad} , and there is no significant dependence on P_{div} . This result illustrates that in impurity-seeded plasmas one should not rely on estimates of P_{rad} from weighted summation of the lines of sight of the JET bolometer system. In the subsequent analysis in this paper P_{rad} and P_{div} from tomography (using main-vessel lines of sight) have been used. Because tomography is slow, this method cannot be used for routine analysis. Good results have however been obtained with fast neural networks using all main-vessel lines of sight and trained with the tomography results [6]. This method may replace weighted summation in the future.

3. RADIATIVE BEHAVIOUR FOR DIFFERENT IMPURITIES AND JET DIVERTORS

3.1. RADIATED POWER FRACTION

The radiated fraction f_{rad} , i.e. the ratio of P_{tot} to the total input power, is an important parameter because a high f_{rad} implies a low power flux to the strike points. Figure 4(a) shows the time-averaged f_{rad} obtained during steady-state phases of impurity-seeded discharges (and some non-seeded) in the JET database as a function of $P_{\text{div}}/P_{\text{bulk}}$. Discharges that have no steady-state phase have not been included; among these about 20% of the total sample of nitrogen and neon seeded discharges undergo a density-limit disruption.

Figure 4(a) illustrates that nitrogen is the most effective impurity to achieve high f_{rad} and that the power is mainly radiated in the divertor region (in particular a radiating zone close to the X point, Fig. 1). For nitrogen, f_{rad} shows a linear increase with $P_{\text{div}}/P_{\text{bulk}}$, irrespective of the divertor. Note that the exact location of the radiation peak, inside or outside the separatrix, cannot be deduced from the bolometer measurements as the spatial resolution is insufficient. From the available data it seems that the highest f_{rad} were obtained in the MkI divertor (although very high fractions are obtained in all divertors before a density-limit disruption). The nitrogen data for the other divertors is rather scattered and no clear trend between the divertors is visible. In MkII GB f_{rad} as high as 90% has been obtained for periods of a few seconds, which is not apparent from Figure 4(a) because of the chosen averaging windows. The scatter may be the result of the large variation of plasma parameters in the database, but no dependence on any particular plasma parameter has been identified. With this reassessment significantly higher f_{rad} are obtained than previously assumed [1].

For non-seeded plasmas the trend is similar, but f_{rad} is lower. For the other impurities the behaviour is rather different: there is a clear trend towards lower f_{rad} when $P_{\text{div}}/P_{\text{bulk}}$ increases. Clearly, these impurities radiate most effectively outside the divertor.

The higher P_{rad} obtained by the reassessment have also consequences for other quantities. For example, a Degree of Detachment (DoD) can be defined, which depends on f_{rad} . A reassessment of

the DoD does not require any changes in interpretation: the radiated fraction required for a given DoD decreases with increasing divertor closure [2].

3.2. MATTHEWS' SCALING OF Z_{eff}

Matthews [1,7] proposed a simple scaling law for Z_{eff} that has been shown to match data of impurity-seeded plasmas in several tokamaks, and which can be used to predict Z_{eff} of similar plasmas in ITER. The scaling law is

$$Z_{\text{eff}} = 1 + \alpha P_{\text{rad}} Z^\delta / (S^\beta \bar{n}_e^\gamma), \quad (2)$$

where Z is the charge of the seeded impurity (in unseeded plasmas one can assume that carbon is the main impurity), S is the main-plasma surface (in m^2), \bar{n}_e the line averaged electron density (in units 10^{20}m^{-3}), P_{rad} is given in MW, and α , β , γ , and δ are fit parameters. In JET the experimental line-averaged Z_{eff} is derived from the Bremsstrahlung measurement; in the analysis one has to be careful to use a consistent \bar{n}_e for the experimental Z_{eff} and Eq. (2). Although fit parameters have been obtained for a multi-machine database [7] and for JET MkI and MkIIA plasmas [1], the resulting parameters are very close to $\beta = 1$, $\gamma = 2$, and $\delta = 0$ that correspond with a simple physical model [7] and $\alpha = 7$ is the only unknown, which contains the atomic physics.

As Eq. (2) is linearly dependent on P_{rad} , we have verified whether the scaling law still gives an adequate description of JET data after the reassessment of P_{rad} . The same MkI and MkIIA discharges that were analysed in Ref. 1 were used, extended by several other discharges and discharges in the MkII GB divertor. The result (Fig. 4 (b)) is very similar to the previously published scaling [1,7]. In fact, with the improved estimate of P_{rad} the scatter of points is slightly reduced: the χ^2 of the fit to Eq. (2) with $\alpha = 7$, $\beta = 1$, $\gamma = 2$, and $\delta = 0$ is about 16% lower than with the old estimate of P_{rad} . In addition, the fit is slightly better than with the values for the fit parameters obtained in Refs. 1 and 7. It is remarkable that Eq. (2) describes the data so well, in particular for nitrogen for which most power is radiated in the divertor region (Eq. (2) assumes a radiating shell in the main plasma). A number of discharges with krypton seeding were included in the present analysis, for which the scaling of Eq. (2) predicts far too high a Z_{eff} . The krypton-seeded discharges that deviate most from Matthews's scaling have high core and total radiation levels while the experimental Z_{eff} is modest. Clearly, the simple model of a radiating shell that gives constant α for all impurities is invalid. Indeed, assuming a three times thicker radiating shell for these discharges and thus reducing α by a factor of 3 gives a good fit.

4. DISCUSSION

A reassessment of f_{rad} achieved in impurity-seeded plasmas in the JET MkI and MkIIA divertors has shown that the levels are significantly higher than previously thought [1,3] and more in line with other tokamaks, such as ASDEX-U [5]. Previously reported levels of power loss through charge-exchange (CX) neutrals in the MkI and MkIIA divertor [3], with good agreement between bolometer measurements and code modelling, are still valid; in fact a better-matching power balance

is obtained in detached plasmas. In general it seems that f_{rad} is higher and the neutral loss lower in nitrogen-seeded MkI discharges than in MkIIA, as previously reported. It is difficult to deduce whether this reduction is a consequence of divertor closure as the points of MkIIA and MkII GB are rather scattered. Detachment, however, occurs at monotonically lower radiated fraction with increasing divertor closure [2]. The fact that very high f_{rad} are obtained close to the density limit in all divertors is not in contradiction with the finite CX neutral losses mentioned above. In L-mode discharges it has been observed that the CX neutral losses decrease with increasing density or detachment [8] and thus becoming low at the density limit, although this should still be confirmed with code modelling. Although f_{rad} is higher than previously assumed, the consequences of the reassessment for the interpretation of impurity-seeded discharges are limited: for example, the fit to Matthews' scaling law for Z_{eff} has improved slightly and detachment as defined by the DoD has only changed little.

Nitrogen-seeding is an effective way to increase f_{rad} in JET by predominantly radiating in the divertor region, while in many cases Z_{eff} can be kept low. Unfortunately, in most nitrogen seeded discharges, except for several MkIIA discharges, the confinement is less good than with neon seeding, when measured against a confinement figure of merit $H \times f_{\text{GDL}}$ [9], where H is the H factor for an ITER scaling such as IPB98(y,2) and f_{GDL} the fraction of the Greenwald density. It has been possible to optimize confinement in radiative-mantle discharges with neon and argon seeding by careful adjustment of the seeding levels [10]. Experiments are planned with nitrogen seeding to improve stationarity by feedback on the radiation level and to improve the confinement. Furthermore, the latest JET divertor, MkII GB with septum removed, will be characterized in these experiments.

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REFERENCES

- [1]. G.F. Matthews et al. Nucl. Fusion **39** (1999) 19
- [2]. J. Rapp et al., "ELM mitigation by nitrogen seeding in the JET Gas Box divertor," accepted for publication in Plasma Phys. Control. Fusion
- [3]. L.C. Ingesson et al., in Proc. 24th EPS Conf. on Controll. Fusion and Plasma Phys., Ed. M. Schittenhelm et al., Europhysics Conference Abstracts Vol. 21A (EPS, 1997), Part I, pp. 113
- [4]. L.C. Ingesson et al., Nucl. Fusion **38** (1998) 1675
- [5]. J.C. Fuchs et al., J. Nucl. Mat. **290–293** (2001) 525
- [6]. O. Barana, A. Murari, P. Franz, L.C. Ingesson, G. Manduchi, Rev. Sci. Instrum. **73** (2002) 2038
- [7]. G.F. Matthews et al., J. Nucl. Mat. 241–243 (1997) 450
- [8]. L.C. Ingesson et al., in Proc. 28th EPS Conf. on Controll. Fusion and Plasma Phys. (Funchal 2001), Ed. C. Silva et al., Europhysics Conference Abstracts Vol. 25A (EPS, 2001), pp. 1633
- [9]. L.D. Horton et al., Nucl. Fusion **39** (1999) 1
- [10]. G.P. Maddison et al., "Radiating-edge plasma experiments on JET," subm. Nucl. Fusion

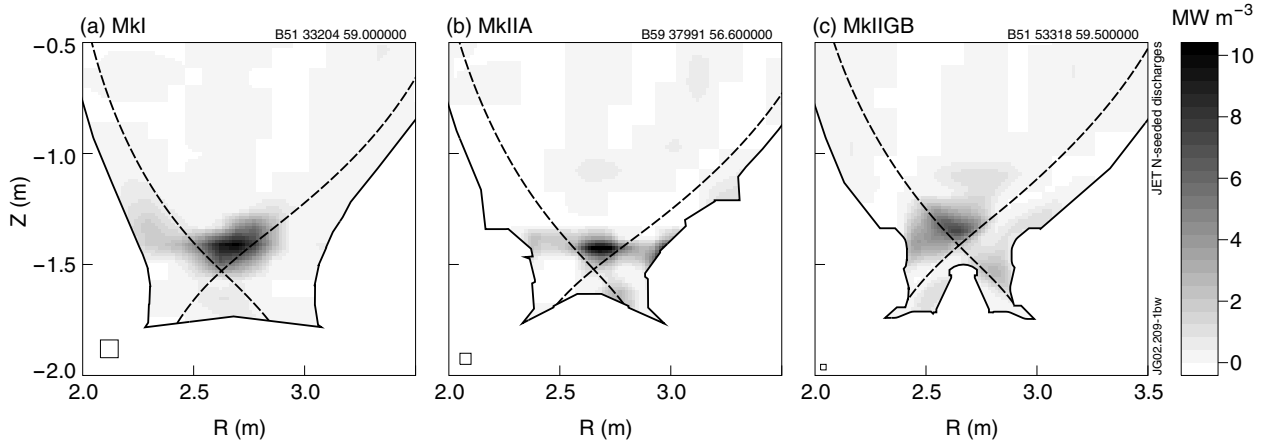


Figure 1: Tomographic reconstructions of the total radiation in nitrogen-seeded discharges in three JET divertors. The input data has been averaged over ELMs.

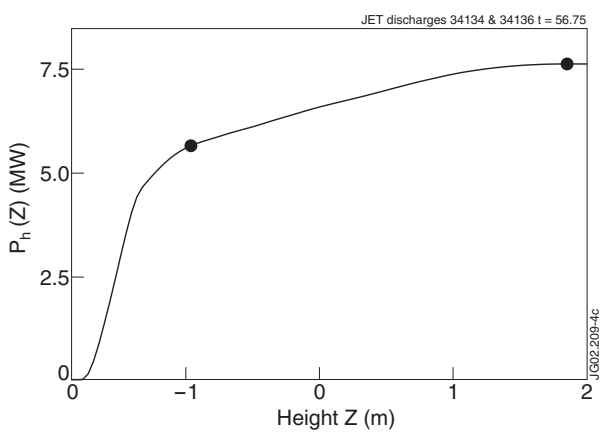


Figure 2: The total power $P_h(Z)$ radiated below height Z , as a function of Z , for a typical nitrogen-seeded plasma with about 75% divertor radiation. Solid circles indicate the points taken for P_{div} and P_{tot}

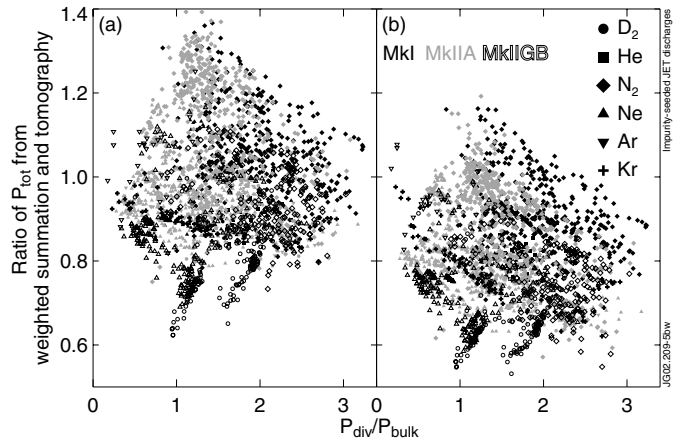


Figure 3: Ratio of P_{rad} from weighted summation to the best available estimate from tomography (many points per discharge). (a) Weights taking into account the divertor; (b) weights not taking into account the divertor.

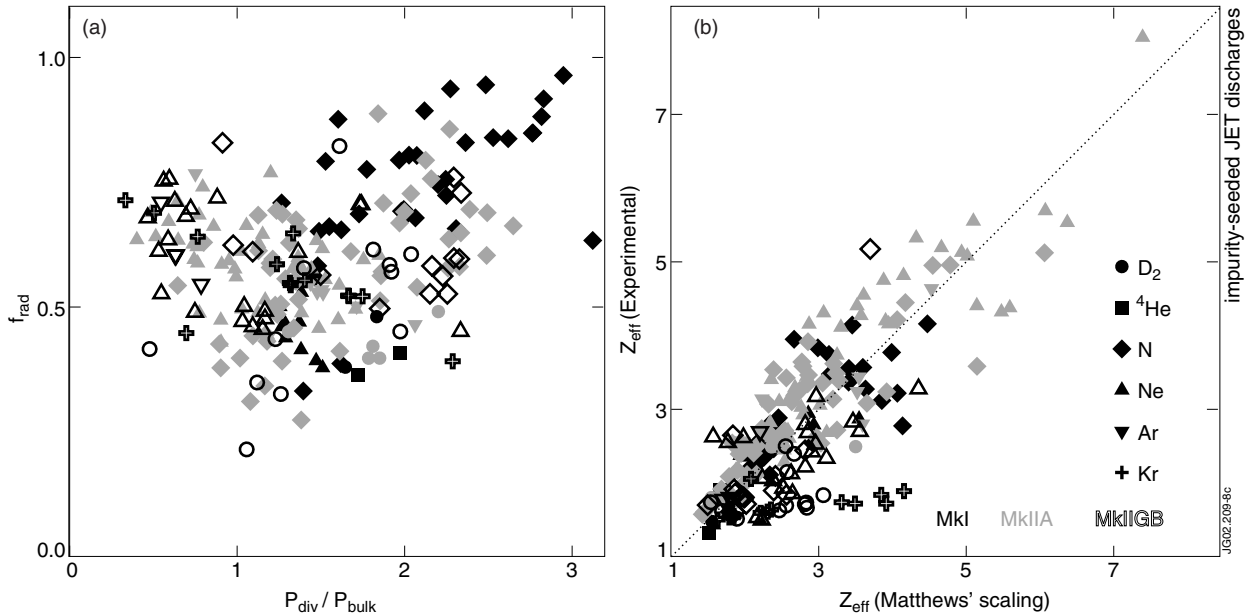


Figure 4: (a) Time-averaged f_{rad} during a steady-state phase as a function of the average P_{div}/P_{bulk} (one point per discharge). (b) Experimental Z_{eff} vs. the Z_{eff} predicted by Matthews' scaling law (one point per discharge).