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# Radiation in impurity-seeded discharges in the JET MkI, MkIIA and MkIIGB divertors

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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 MkIIGB divertors are discussed, in particular in terms of their radiative properties. A reassessment of the radiation levels in about 235 discharges, seeded predominantly with nitrogen or neon, leads to the conclusion that radiation levels have been underestimated in some impurity-seeded plasmas in MkI and MkIIA. Apart from increased radiation levels, the consequences of the reassessment for the interpretation of impurity-seeded plasmas are limited. With the new estimates the understanding of the power balance and the fit to Matthews' scaling law for $Z_{\mathrm{eff}}$ are improved. The techniques for improved estimates of the total radiated power and radiated power in the divertor region are discussed and it is shown that weighted summation of bolometer line integrals is unreliable for impurity-seeded discharges in JET.

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## 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 [1–5], 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 MkIIGB divertor was recently carried out [2], showing that in several of the JET experiments the radiation level has been underestimated. To cover a larger dynamic range of plasma parameters, in this paper this reassessment is extended to over 100 nitrogen-seeded discharges, and to 135 discharges with and without impurity seeding by other species ($^4$He, Ne, Ar and Kr). Other parameters varied were heating method and power, gas injection rate and location, and plasma configuration.

Because the total radiated power and the power radiated due to the presence of the divertor play an important role in the analysis presented in this paper, the techniques used to determine these quantities are discussed in detail in Section 2. The radiative properties of impurity-seeded JET plasmas are described in Section 3. Here, also the differences with earlier results due to the reassessment and extended database to the MkIIGB

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[1] See appendix of J. Paméla et al., 'Overview of recent JET results and future perspectives,' in Proceedings of 18th IAEA Fusion Energy Conference, Sorrento, 2000 (IAEA, Vienna, 2001).

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divertor are discussed. Section 4 places the results into context.

## 2. Determination of the total radiated power

### 2.1. Methods to determine the total radiated power

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

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

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 $\Delta p$ is the distance between the lines of sight. Provided the lines of sight are parallel and the finite widths of the views 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 $\Delta p$ can only approximate $P_{\rm rad}$. The selection of appropriate weights $\Delta p$ 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 $P_{\rm rad}$ is obtained from a volume integral over tomographic reconstructions of the local emissivity in a poloidal cross-section. A standard constrained-optimization method with non-negativity constraint is used for tomographic reconstruction [6,7]. Experience at JET has shown that determining $P_{\rm rad}$ from the tomographic reconstruction using only main-vessel lines of sight is the most accurate way.

### 2.2. Methods to determine the total radiation in the divertor region

Tomography makes it possible to determine the radiated power 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 in practice. Divertor radiation defined as 'all radiation emitted below the X point' [8] 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 accurately separate the power radiated from inside and 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. Low ionization stages of impurities escaping from the divertor are likely contributors to this increased radiation above the X point. One might therefore define radiation from the divertor region $P_{\rm div}$ 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

$$P_{\rm h}(Z) = 2\pi\int_{Z_{\rm min}}^{Z}\int_{R_{\rm min}}^{R_{\rm max}} \varepsilon(R,Z')R\,{\rm d}R\,{\rm d}Z',$$

where $\varepsilon(R,Z)$ is the local emissivity (units W/m$^3$). Fig. 2 shows a typical example of $P_{\rm h}(Z)$ in JET. In diverted plasmas there is a profound bend of the curve at $Z \approx -1$ 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 $P_{\rm div} \approx P_{\rm h}(-1\ {\rm m})$ is meaningful and robust. Naturally, $P_{\rm rad} = P_{\rm h}(2\ {\rm m})$, where $Z \approx 2$ m is at the top of the plasma. We define the power radiated in the bulk plasma as $P_{\rm bulk} = P_{\rm rad} - P_{\rm div}$ (see solid circles in Fig. 2).

### 2.3. Differences in $P_{rad}$ estimates

As can be seen from Figs. 1 and 2, $P_{\rm div}$ can dominate over $P_{\rm bulk}$ in impurity-seeded plasmas (note also that the divertor *peak* emissivity can be more than one order of magnitude higher than the peak emissivity in the bulk

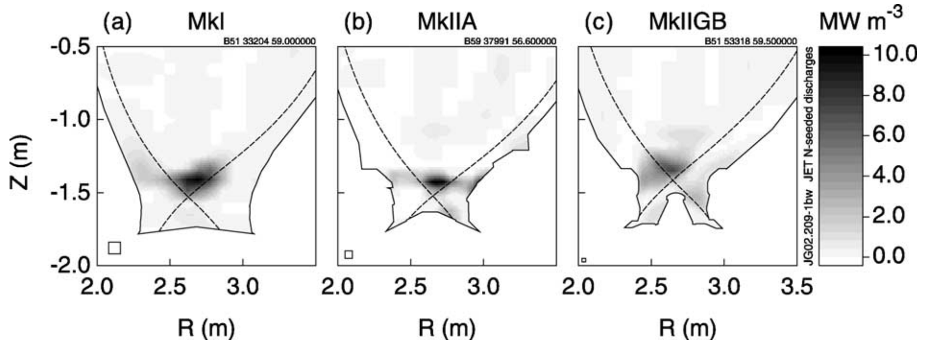

Fig. 1. Tomographic reconstructions (poloidal cross-sections) of the total radiation in nitrogen-seeded discharges in three JET divertors. The input data has been averaged over ELMs.

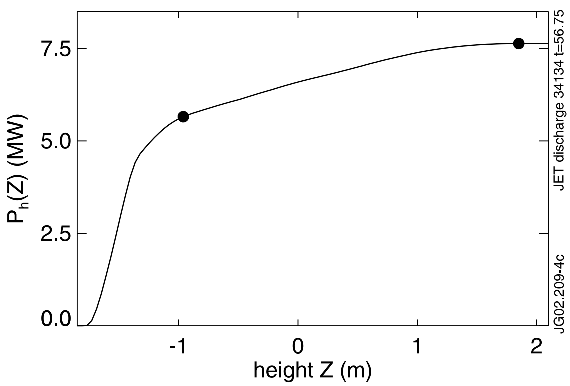

Fig. 2. The total power $P_h(Z)$ radiated below height $Z$, as a function of $Z$, for a typical nitrogen-seeded plasma with about 75% divertor radiation. Solid circles indicate the points taken for $P_{div}$ and $P_{rad}$. Typical X points are located around $Z = -1.5$ m, i.e. on the steep slope.

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 MkIIGB larger $\Delta p$ are required for channels that view the divertor. Fig. 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 $P_{div}/P_{bulk}$ is high. In MkIIGB, 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 computationally intensive, 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 [9]. This method may replace weighted summation in the future.

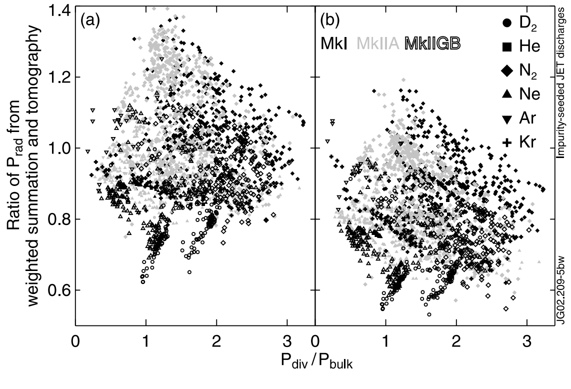

Fig. 3. Ratio of $P_{rad}$ from weighted summation to the best available estimate from tomography (many points per discharge). (a) Weights taking into account the divertor; (b) weights not taking into account the divertor.

## 3. Radiative behaviour for different impurities and JET divertors

### 3.1. Radiated power fraction

The radiated fraction $f_{rad}$, i.e. the ratio of $P_{rad}$ to the total input power, is an important parameter because a high $f_{rad}$ implies a low power flux to the divertor target. Fig. 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 $P_{div}/P_{bulk}$. Non-steady-state discharges have been excluded from Fig. 4; among these about 20% of the total sample of nitrogen and neon seeded discharges undergo a density-limit disruption.

Fig. 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). Increased radiation in the divertor rather than in the main-plasma edge may be attractive because it is less likely to affect the L-H mode power threshold. For nitrogen, $f_{rad}$ shows a linear increase with $P_{div}/P_{bulk}$, 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 seen. In MkIIGB $f_{rad} \sim 90\%$ has been obtained for periods of a few seconds, which is not apparent from Fig. 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 scalar plasma parameter has been identified. With this reassessment significantly higher $f_{rad}$ are obtained than previously assumed [1].

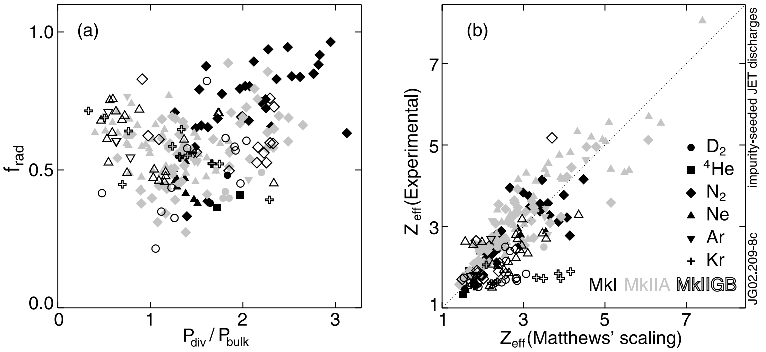

Fig. 4. (a) Time-averaged $f_{\rm rad}$ during a steady-state phase as a function of the average $P_{\rm div}/P_{\rm bulk}$ (one point per discharge). (b) Experimental $Z_{\rm eff}$ vs. the $Z_{\rm eff}$ predicted by Matthews' scaling law (one point per discharge).

For non-seeded plasmas the trend is similar, but $f_{\rm rad}$ is lower. For the other impurities the behaviour is rather different: there is a clear trend towards lower $f_{\rm rad}$ when $P_{\rm div}/P_{\rm bulk}$ increases. Clearly, with these impurities high $f_{\rm rad}$ is achieved when the main chamber radiation dominates.

The higher $P_{\rm rad}$ obtained by the reassessment also has consequences for other quantities. For example, a degree of detachment (DoD) can be defined as $I_{\rm s}^{\rm scal}/I_{\rm s}^{\rm meas}$ [10], where $I_{\rm s}^{\rm meas}$ is the ion saturation current measured by Langmuir probes and $I_{\rm s}^{\rm scal} \propto \bar{n}_{\rm e}^2/(1-f_{\rm rad})$. A reassessment of the DoD with the new $f_{\rm rad}$ 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 et al. [1,11] proposed a simple scaling law for $Z_{\rm eff}$ that has been shown to match data of impurity-seeded plasmas in several tokamaks, and which can be used to predict $Z_{\rm eff}$ in similar plasmas in ITER. The scaling law is

$$Z_{\rm eff} = 1 + \alpha P_{\rm rad} Z^{\delta}/(S^{\beta}\bar{n}_{\rm e}^{\gamma}), \qquad (2)$$

where $Z$ is the charge of the seeded impurity (in unseeded plasmas carbon is assumed to be the main impurity), $S$ is the main-plasma surface in m$^2$, $\bar{n}_{\rm e}$ the line averaged electron density in units $10^{20}$ m$^{-3}$, $P_{\rm rad}$ is given in MW, and $\alpha$, $\beta$, $\gamma$, and $\delta$ are fit parameters. In JET the experimental line-averaged $Z_{\rm eff}$ is derived from the Bremsstrahlung measurement; in the analysis one has to be careful to use a consistent $\bar{n}_{\rm e}$ for the experimental $Z_{\rm eff}$ and Eq. (2). Although fit parameters have been obtained for a multi-machine database [11] 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 [11]; $\alpha = 7$ is the only unknown, which contains the atomic physics.

As Eq. (2) is linearly dependent on $P_{\rm rad}$, we have verified whether the scaling law still gives an adequate description of re-assessed JET data. The same database of MkI and MkIIA discharges that were analysed in Ref. [1] was used, extended by several other discharges and discharges in the MkIIGB divertor, which were not available at the time. The result (Fig. 4(b)) is very similar to the previously published scaling [1,11]. In fact, with the improved estimate of $P_{\rm rad}$ the scatter of points is slightly reduced: the $\chi^2$ 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 $P_{\rm rad}$. In addition, the fit is slightly better than with the values for the fit parameters obtained in Refs. [1,11]. It is remarkable that Eq. (2) describes the data so well, in particular for nitrogen which mainly radiates in the divertor region (while Eq. (2) is consistent with a radiating shell in the main plasma [11]). 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 $Z_{\rm eff}$. The krypton-seeded discharges that deviate most from Matthews's scaling have high core and total radiation levels while the experimental $Z_{\rm eff}$ is modest. Clearly, the simple model of a radiating shell that gives constant $\alpha$ for all impurities is invalid. Indeed, taking a three times thicker radiating shell for these discharges, which is consistent with bolometer profile measurements, and thus reducing $\alpha$ by a factor of 3 gives a good fit.

## 4. Discussion

A reassessment of $f_{\rm rad}$ achieved in impurity-seeded plasmas in the JET MkI and MkIIA divertors has shown that the levels are significantly higher than previously thought [1,6] and more in line with other tokamaks, such as ASDEX-U [8]. Clearly, the weighted-summation method to estimate $P_{\rm rad}$ from bolometer line integrals is inadequate in impurity-seeded plasmas.

Previously reported levels of power loss through charge-exchange (CX) neutrals in the MkI and MkIIA divertor [6], with good agreement between bolometer measurements and code modelling, are still valid. In fact a better-matching power balance is obtained in detached plasmas, i.e. the known power loss (radiation, CX neutrals, heat flux to divertor targets) is closer to the known input power. In general, it seems that in nitrogen-seeded discharges $f_{\mathrm{rad}}$ is higher and the neutral loss lower in MkI than in MkIIA, as previously reported [6]. It is difficult to deduce whether this reduction is a consequence of divertor closure as the points of MkIIA and MkIIGB are rather scattered. Detachment, however, occurs at monotonically lower radiated fraction with increasing divertor closure [2]. The fact that very high $f_{\mathrm{rad}}$ 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 [12] and thus becoming low at the density limit, although this should still be confirmed with code modelling. Although $f_{\mathrm{rad}}$ 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 $Z_{\mathrm{eff}}$ has improved slightly and detachment as defined by the DoD has only changed little.

Nitrogen seeding is an effective way to increase $f_{\mathrm{rad}}$ in JET by predominantly radiating in the divertor region, while in many cases $Z_{\mathrm{eff}}$ can be kept low. Unfortunately, in most nitrogen seeded discharges, except for several MkIIA discharges, the confinement is lower than with neon seeding, when measured against a confinement figure of merit $Hf_{\mathrm{GDL}}$ [13], where $H$ is the $H$ factor for an ITER scaling such as IPB98(y,2) and $f_{\mathrm{GDL}}$ 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 [14]. 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, MkIIGB with septum removed, will be characterized in these experiments.

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