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Scaling of radiated power to plasma contamination for neon seeded discharges on boronized TEXTOR-94

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Abstract

When neon is injected into a tokamak plasma with the aim of reducing the peak heat flow into the SOL by enhanced edge radiation, both P_{rad} and Z_{eff} increase. The ratio of the incremental P_{rad} to the incremental Z_{eff}, $\Delta P_{rad}/\Delta Z_{eff}$, can change on TEXTOR from 0.1 MW to about 2 MW depending on n_e, on $T_e(a)$ and on the transport regime. The measured $\Delta P_{rad}/\Delta Z_{eff}$ is higher for I-mode auxiliary heated (higher diffusion) than for OH discharges (lower diffusion), consistent with model calculations. For I-mode discharges $\Delta P_{rad}/\Delta Z_{eff}$ is a decreasing function of $T_e(a)$ and it scales approximately as $\bar{n}_e^2$. The I-mode regime on TEXTOR, which displays very good energy confinement scaling, can represent, for suitable conditions, a satisfactory compromise between a high τ_E and not excessive particle confinement.

Keywords: TEXTOR-94; Radiation; Impurity transport; Improved confinement mode

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1. Introduction

A possible solution for the problem of the power exhaust in a tokamak reactor might be provided by the injection of extrinsic impurities [1]. For a suitable impurity, selected according to the plasma parameters, a significant fraction of the heat flow can be converted into radiation at the plasma edge; the subsequent spreading of power over a large area will limit the peak heat flux to the targets to acceptable values.

In recent years a considerable experimental effort has been made on several devices to assess the viability of this method for present day tokamaks in view of a possible extension to reactor grade plasmas. Neon is being used extensively as an extrinsic radiator in limiter [2,3] as well as in divertor devices [4–6], while argon has been tested in ASDEX-U and JET. Restricting the present analysis to the use of neon, one sees that while a γ (γ = ratio of radiated to input power) on the order of 0.8–0.9 can be achieved in all devices relatively easily, a number of new problems and incompatibilities arise, particularly in the case of the divertor configuration. Comparing the results of the toroidal limiter tokamak TEXTOR-94 (in Tore Supra neon is injected mainly in the frame of the ergodic divertor experiments, resulting in different physics) with those of divertor devices the following main differences emerge:

(1) In TEXTOR-94 the edge radiating layer created by neon is more symmetrical in the poloidal direction than that created by the intrinsic impurities alone (mainly carbon for boronized walls), which is mainly localized in the vicinity of the limiter. On the contrary, on divertor devices the radiating layer becomes strongly poloidally asymmetric when neon is injected, especially in the vicinity of the X-point.

(2) The energy confinement time increases in TEXTOR-94 when neon is injected [2]; in divertor tokamaks even though the L-mode is improved, τ_E does not generally recover the H-mode scaling.

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(3) Although the ionic effective charge (Z_{eff}) increases in all devices, on TEXTOR-94 the additional contamination can be kept relatively low for certain conditions [7]. This was made possible by strongly raising the electron density and by optimizing the feedback systems of neon and of the stored diamagnetic energy.

Of these three points, which might be interdependent, the last one is discussed in this paper in detail. The quantity $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$, where P_{rad} is the total radiated power and Δ refers to the case with neon as compared to the case without neon, has been measured in a wide range of the TEXTOR-94 operational space. This quantity, Δ_Z^P, which will be called the 'quality of cooling', characterizes the impurity edge cooling with respect to the deuteron dilution; a high ratio $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$ indicates the simultaneous achievement of target protection and low additional plasma contamination. We have found for the first time a quantitative dependence of Δ_Z^P on the line averaged electron density ($\bar{n}_{\mathrm{e}}$) and on the edge electron temperature ($T_{\mathrm{e}}(a)$), considered as independent variables. The experimental data suggest, on the other hand, that Δ_Z^P is strongly influenced by the transport regime.

2. Experimental data

The diagnostics specific to the present experiments are: a 26 channel bolometric system [8] for the measurement of the total radiated power (poloidally resolved), helium and lithium thermal beams [9,10] for the measurement of the edge electron temperature and density profiles and a 2 channel visible continuum system for the measurement of the average Z_{eff}. In Fig. 1 the geometry of the two chord system for Z_{eff} measurements is shown: one chord (A) detects the visible continuum across the whole plasma cross section, while the other (B) detects only the signal arising from the plasma edge. The signal from this second chord is subtracted from the main signal according to a procedure described in Ref. [7]. This method allows partial compensation for the non-bremsstrahlung component of the visible continuum of the main signal.

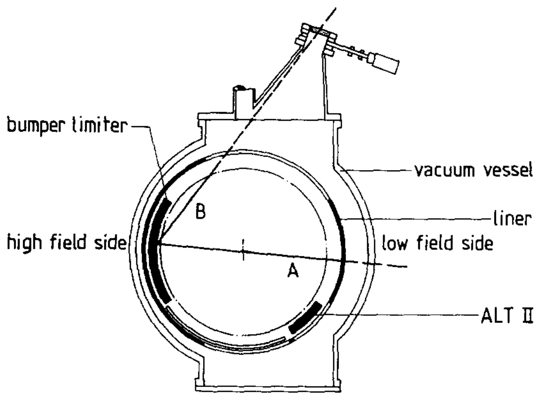

Fig. 1. Poloidal cross section of TEXTOR. The geometry of the two chord system for the measurement of Z_{eff} is shown.

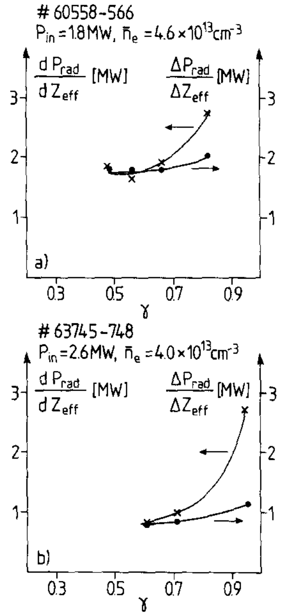

Fig. 2. $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$, the quality of cooling, and $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ are shown as a function of γ for two series of discharges. The combination of P_{in} and n_{e} in case (a) leads to a quality of cooling higher than in case (b).

The present study is based on ten series of discharges, seven pertaining to the I-mode regime [2] and three to Ohmic heated plasmas. In each series the input power (P_{in}) is approximately constant as well as the electron density profile, while the neon puffing rate (and γ) is increased shot by shot. In the first reference discharge of each series neon is not injected. The number of discharges per series can change from seven to three. By increasing the neon puffing rate P_{rad} and Z_{eff} increase while $T_{\mathrm{e}}(a)$ decreases; the diamagnetic energy generally increases [2].

One can define two different ratios which relate the incremental P_{rad} to the incremental Z_{eff}. In $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$ the incremental quantities refer always to the first reference discharge without neon (one compares P_{rad} of the second discharge with P_{rad} of the first, the third with the first and so on; the same with Z_{eff}) while in $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ one compares the second with the first, the third with the second and so on. These two ratios are obviously related: both derive from the same function $P_{\mathrm{rad}} = P_{\mathrm{rad}}(Z_{\mathrm{eff}})$. While in the first ratio, which is useful for practical purposes, discharges with very different γ and $T_{\mathrm{e}}(a)$ are generally compared, the second ratio refers to a local (in γ and in $T_{\mathrm{e}}(a)$) property of the quality of neon cooling, because discharges with similar γ are considered. This ratio is useful when the data are compared with temperature dependent quantities, such as the radiation function (see Section 3). Both ratios will be used in the following.

In Fig. 2 $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ and $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$ are displayed as a function of γ for two series of auxiliary heated discharges; case (a) refers to $P_{\mathrm{in}} = 1.8$ MW, $\bar{n}_e = 4.6 \times 10^{13}$ cm^{-3}, γ up to 0.82 and case (b) to $P_{\mathrm{in}} = 2.6$ MW, $\bar{n}_e = 4 \times 10^{13}$ cm^{-3}, γ up to 0.9–0.95. The reference discharges (without neon) are characterized by $Z_{\mathrm{eff}} = 1.2$ at $\gamma = 0.33$ in case (a) and by $Z_{\mathrm{eff}} = 1.8$ at $\gamma = 0.5$ in case (b). In both cases the two ratios increase with γ, but, in spite of the fact that $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ is comparable in the two cases at high γ, $\Delta P_{\mathrm{rad}}/\Delta Z_{\mathrm{eff}}$ in case (b) is always much lower than in case (a). This example shows the two main properties of the quality of neon cooling: (i) at medium-high $\bar{n}_e$, for auxiliary heated attached discharges, the quality of neon cooling can slightly increase with γ; (ii) a high quality of cooling can be reached only when $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ is high even at low γ. This can happen only for certain values of $\bar{n}_e$ and P_{in} (or alternatively of $T_e(a)$) and as we shall see, for certain transport regimes.

(i) The non-linear increase of the quality of neon cooling with γ depends on the correlated decrease of $T_e(a)$, as already shown [7]. This behavior had been previously observed during experiments of argon and methane injection in TEXTOR [11]. It is worth mentioning that at medium-high $\bar{n}_e$ the globally measured $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ for neon seeded discharges is a little higher than $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ of neon itself, $(\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}})_{\mathrm{Ne}}$, in a boronized machine. This is a consequence of the reduction of the intrinsic carbon density during neon injection since $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ of carbon is a factor of two lower than that of neon [7].

(ii) In Fig. 3 the data points of $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ pertaining to all the series of discharges are plotted versus γ. In spite of the wide range of variability of $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ (0.1–3 MW), only two qualitative information can be derived from this plot: (1) $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ is high for auxiliary heated discharges at high $\bar{n}_e$ and high γ, and (2) Ohmic discharges display a very low $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$, even at high γ. Only a different ordering of the data points can provide us with quantitative correlations.

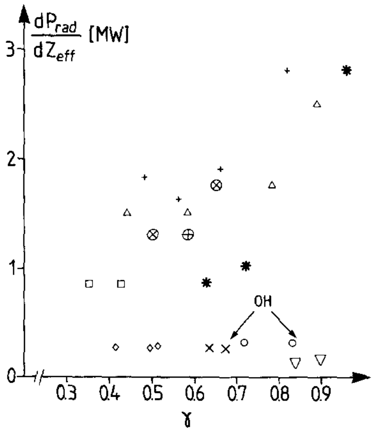

Fig. 3. The whole set of data points as a function of γ. From this plot only qualitative information can be obtained (see text). Symbols as in Fig. 4.

3. Normalization of the quality of cooling

For an impurity of atomic number Z [7,11]

$$P_{\mathrm{rad}} = \int n_e \sum_{0}^{Z-1} n_z L_z(T_e)\,\mathrm{d}V, \tag{1}$$

where all quantities are local quantities and $L_z(T_e)$ is the radiation function of the ion of charge z. Expressing the density of the different ions n_z in terms of their concentration relative to the density of the fully stripped ions in the plasma center, n_Z, for light impurities which radiate only at the plasma edge, where the average density is indicated by $\langle n_e \rangle_{\mathrm{ed}}$, one obtains:

$$P_{\mathrm{rad}} = n_Z \langle n_e \rangle_{\mathrm{ed}} \bar{L}_Z\big(T_e(a), \tau_p\big) V. \tag{2}$$

Here the average effective cooling rate $\bar{L}_Z$, which in a first approximation depends on $T_e(a)$, includes all the transport properties of the impurities and of the background plasma and V is the plasma volume where line radiation is emitted. Since the incremental Z_{eff} in the central plasma is given by $\mathrm{d}Z_{\mathrm{eff}} = \mathrm{d}n_Z(Z^2 - Z)/n_e(0)$ one has:

$$\frac{\mathrm{d}P_{\mathrm{rad}}}{\mathrm{d}Z_{\mathrm{eff}}} \frac{1}{\bar{n}_e^2} = K_p \frac{V}{Z^2 - Z} \bar{L}_Z\big(T_e(a), \tau_p\big), \tag{3}$$

where $n_e(0)\langle n_e \rangle_{\mathrm{ed}}$ has been set equal to $K_p \bar{n}_e^2$. K_p, which depends on the density peaking factor, is on the order of 1 for TEXTOR standard conditions. When comparing the experimental data points with Eq. (3) we disregard the role of K_p since the experimental Z_{eff} is evaluated using the average electron density, not the central one. Therefore the influence of the density peaking factor on the measured $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ is weak. We expect, then, the measured $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ divided by $\bar{n}_e^2$ to be basically a function of $T_e(a)$ and of the transport regime considered. We do not expect the actual power of $\bar{n}_e$ to be exactly 2 since the plasma volume where line emission occurs is also a function of $\bar{n}_e$. According to an analytical 1D model [12], the volume V scales as $\bar{n}_e^{-0.5}$; the resulting explicit dependence on n_e would be $\bar{n}_e^{1.5}$.

In Fig. 4 the data points of $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}}$ divided by $\bar{n}_e^2$ are plotted versus the measured $T_e(a)$. $(\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}Z_{\mathrm{eff}})/n_e^2$ is clearly divided into two branches; a higher one for auxiliary heated I-mode discharges and a lower one for Ohmic discharges. While for the OH discharges, due to the limited number of data points, no attempt can be made to find a scaling with $\bar{n}_e$ or $T_e(a)$, the data points for auxiliary heated discharges, when normalized to $\bar{n}_e^2$, appear to be a function of $T_e(a)$ alone. The quality of cooling does not depend only on the edge temperature and on the electron density, but, more strongly, also on the transport regime.

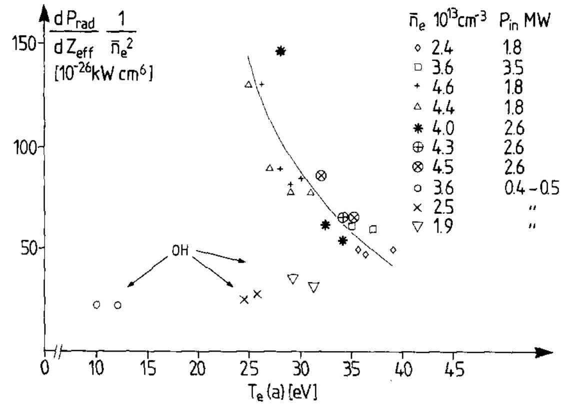

Fig. 4. $(dP_{rad}/dZ_{eff})/\bar{n}_e^2$ as a function of the measured $T_e(a)$. $(dP_{rad}/dZ_{eff})/\bar{n}_e^2$ is divided into two branches: a higher for I-mode discharges, a lower for OH. dP_{rad}/dZ_{eff} for I-mode scales approximately as $\bar{n}_e^2$.

This finding is in qualitative agreement with the results of the analytical radiation model mentioned above, which predicts a scaling of V with the square root of the cross field diffusion, for a given n_e.

Concerning the order of magnitude of the measured $(dZ_{eff}/dP_{rad})/n_e^2$, it is interesting to note that for $V = 1$ m^3 and $Z = 10$ the effective cooling rate, $\bar{L}$, resulting from Eq. (3) is on the order of 10^{-25} W cm^3 when $(dP_{rad}/dZ_{eff})/n_e^2$ is taken to be 100 KW 10^{-26} cm^6 (see Fig. 4). This is a reasonable value, when compared with theoretical findings (see, for example, Ref. [13]) and with other estimates based on experiments [14].

A more detailed comparison between the experimental data and theoretically computed $L(T_e, \tau_p)$ for neon [15] could provide quantitative information on the confinement time of neon, since the computed radiation function increases significantly when the confinement time of neon decreases. Such a comparison is, however, not straightforward. One has not only to take into account the difference between the globally measured dP_{rad}/dZ_{eff} and $(dP_{rad}/dZ_{eff})_{Ne}$, see Section 2, but also to relate the measured dP_{rad}/dZ_{eff} to the local temperature where peak radiation occurs and to specify the radiating volume for the different plasma conditions.

4. Conclusions

The measured marked difference in the quality of cooling between Ohmic and auxiliary heated I-mode discharges at similar $T_e(a)$, which persists when dP_{rad}/dZ_{eff} is weighted with $\bar{n}_e^2$, can only be explained by a difference in particle transport in the two regimes. Similar conclusions can be drawn from the computation of the effects on radiation produced by an ergodic layer at the plasma edge [14], and from theoretical considerations based on the radiation properties of a tokamak plasma under stationary burning conditions [16]. When the perpendicular diffusion increases, the radiating layer extends, giving rise to a higher P_{rad}, for a given impurity density in the central plasma.

The observed decrease of $(dP_{rad}/dZ_{eff})/\bar{n}_e^2$ with $T_e(a)$ could cause a problem in case of operation at very high $T_e(a)$. Since, however, on the one hand $T_e(a)$ is not a free parameter and on the other hand the dependence of the quality of cooling on n_e is strong, operation at high n_e could in general guarantee a high Δ_Z^P.

On TEXTOR-94 the best quality of cooling (higher than 2 MW) is achieved for I-mode discharges at $T_e(a) =$ 25–30 eV, corresponding to $P_{in} = 1.5$–2 MW and $\bar{n}_e =$ 4.5–5 10^{13} cm^{-3}: at γ in the order of 0.8, Z_{eff} is in the range 1.7–2. For such medium-high n_e discharges, τ_E is close to the value predicted by the ELM-free H-mode scaling [17]. For appropriate plasma conditions, the I-mode on TEXTOR-94 can represent, due to the favorable dependence of τ_E and of Δ_Z^P on n_e, a good compromise between the needs of high energy confinement and large P_{rad} at low neon concentration.

Not too high edge T_e and impurity confinement time, and high electron density appear to be the prerequisite for the viability of the concept of neon cooling for a reactor grade plasma.

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