RADIATION BEHAVIOUR OF GAS AND PELLET REFUELLED HIGH DENSITY DISCHARGES IN ASDEX

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Abstract. Pellet and gas refuelled high density divertor discharges in ASDEX are investigated with regard to their radiation behaviour and energy balance. Exclusively ohmically heated deuterium plasmas in a non-carbonized (NC), carbonized (C) and titanium gettered (DP) vacuum vessel are considered. In gas refuelled plasmas the radiation power profiles are hollow with a central emissivity $\epsilon(0) \leq 10\text{mW/cm}^3$ in C and $\epsilon(0) \leq 40\text{mW/cm}^3$ in NC and DP discharges. In C discharges P_{RAD}/P_{Ω} rises from 0.2 at $\bar{n}_e = 3.2 \cdot 10^{19}m^{-3}$ to 0.3 at the density limit. In NC and DP plasmas higher values from 0.3 to 0.45 are observed. Radiation from the X-points can amount to 14 % of P_{Ω}. In pellet refuelled discharges a central peaking of the emissivity ϵ is observed. A sudden transition from negligible or slow impurity accumulation to a fast rise could be detected in many discharges. In NC and DP pellet discharges a self-triggering of impurity accumulation was found. Measured inward drift velocities range from 60 cm/s to 130 cm/s at r=15 cm.

1. Global radiation behaviour and energy balance. This paper mainly deals with parametric studies of the total plasma radiation with a particular emphasis on X-point radiation from gas and pellet refuelled high density discharges in ASDEX. Three radiation zones are discernible with the bolometric diagnostics. The main plasma including the scrape-off layer, the regions around the two X-points and the divertor plasma [1].

Total X-point and main plasma radiation can be separated from two independent measurements of the total radiation in the main plasma chamber. Firstly with the wide-angle bolometers and secondly with the bolometer array both taking into account the X-point radiation with various weighting factors. Radial profiles of emissivity are derived by standard Abel-inversion technique.

Ohmically heated pellet and gas refuelled high density divertor discharges in deuterium are investigated with regard to their radiation behaviour and energy balance during current flattop. Carbonized (C), non-carbonized (NC) and titanium gettered (DP) discharges with safety factors q_a between 2.7 and 2.9 and plasma currents between 300 KA and 380 KA are considered here.

In gas refuelled discharges dW_p/dt the time derivative of stored plasma energy Wp is negligible small whereas during pellet injection dW_p/dt amounts up to 20 % of P_{Ω} and has to be taken into account in the power balance. The normalized total radiation of the main plasma $P_{RN} = P_{RAD}/(P_{\Omega} - \frac{dWp}{dt})$ as a function of the line averaged electron density $\bar{n}_e$ during various gas refuelled discharges is shown in Fig. 1a.

In carbonized plasmas P_{RN} amounts to 0.2 at $\bar{n}_e = 3.5 \cdot 10^{19}m^{-3}$. NC and DP plasmas radiate about 0.35 at $\bar{n}_e = 3.5 \cdot 10^{19}m^{-3}$ owing to a higher content of metals, mainly of iron. At higher densities near the density limit gas refuelled discharges with $q_a > 2.7$ (no sharp limit was detected) show a nonlinear increase of P_{RN} with rising $\bar{n}_e$. This behaviour can be attributed mainly to a decrease of the electron temperature near the separatrix due to enhanced recycling losses and line radiation of low-Z impurities (C_{III}-lines). A correlation between edge peaking of radiation power profiles (carbonized and gettered plasmas) and nonlinear behaviour of P_{RN} with $\bar{n}_e$ can be deduced from Figs. 1a and 3.

The formation of a zone of enhanced radiation near the separatrix is observed just 10–20 ms before a density limit disruption occurs. Owing to an electronic integration time constant $\tau = 10ms$ the time resolution of the bolometric diagnostics is too poor to reveal details of the radiation profile evolution. This type of poloidal symmetric thermal instability which differs from the usual Marfe evolves on a longer time scale in JET due to its larger dimensions [2]. The normalized X-point radiation $P_{XN} = P_X/(P_\Omega - dW_p/dt)$ (Fig. 1b) enhances with increasing $\bar{n}_e$ similar as P_{RN} does. Maximum values of P_{XN}=0.14 are obtained and have to be considered in the energy balance. A titanium gettered discharge (#19514) serves as an example for a low $q_a = 2.1$ high density plasma. P_{RN} remains nearly constant until the density limit is reached and P_{XN} increases linearly with $\bar{n}_e$. The formation of a zone of enhanced edge radiation could not be detected.

In ASDEX a considerable increase of the line average density $\bar{n}_e$ and of the Murakami parameter $\bar{n}_e R/B_T$ was achieved by injecting series of deuterium pellets with a centrifuge [3,7]. We consider here only discharges with high central peaking of the density profiles during pellet injection.

A nonlinear enhancement of P_{RN} with rising $\bar{n}_e$ is observed in pellet refuelled (C, NC and DP) discharges qualitatively similar to gas refuelled plasmas. Starting from values characteristic to gas refuelled plasmas P_{RN} continuously rises until about 0.45 at the density limit (Fig. 2a). The relative increase of P_{RN} is highest in C discharges in contrast to gas refuelled discharges. Central peaking of the electron density and radiation power profile in pellet discharges is responsible for this behaviour. P_{XN} decreases with increasing $\bar{n}_e$ (Fig. 2b) owing to the high central radiation which reduces the power outflux in the scrape-off layer.

A correction of P_{RN} with the total radiation inside the inner half minor radius $P_{RAD}(a/2)$ yields nearly no variation of the corrected P_{XN} with $\bar{n}_e$. Near the density limit P_{XN} is usually smaller in pellet discharges than in gas refuelled discharges.

In pellet and gas refuelled discharges the normalized divertor radiation $P_{DN} = P_{DIV}/(P_\Omega - dW_p/dt)$ rises with $\bar{n}_e$ up to $\bar{n}_e \approx 5.5 \cdot 10^{19} m^{-3}$. Above $\bar{n}_e = 5.5 \cdot 10^{19} m^{-3}$ P_{DN} saturates which indicates the achievement of a high recycling regime in the divertor [1]. Near the density limit P_{DN} continuously decreases with $\bar{n}_e$ owing to the steady increase of the radiation in the main plasma P_{RN} and, thus, decreasing heat flux into the divertor.

The energy confinement time $\tau_E = W_p/(P_\Omega - dW_p/dt)$ shows a similar behaviour as P_{DN} near the density limit. The plasma energy W_p is derived from the diamagnetic signal, from kinetic data (twice the energy content of electrons) and from the equilibrium beta. Li is derived from the electron temerature profiles assuming neoclassical resistivity and neglecting diffusion of the poloidal magnetic field. All three energies agree better than within 10% and indicate the same trend with $\bar{n}_e$. The power on the divertor plates P_{cond} is measured with the thermographic diagnostics. Only a small fraction of the heating power is deposited on the divertor plates. The normalized power on the divertor plates $P_{CN} = P_{cond}/(P_\Omega - dW_p/dt)$ is smaller than 0.1 and reduces further near the density limit (Fig. 4).
We conclude: a nonlinear rise of P_{RN} with $\bar{n}_e$ is observed in both gas and pellet refuelled C, NC and DP discharges with maximum values of $P_{RN} \approx 0.45$ at the density limit. X-point radiation plays an important role in the energy balance ($P_{XN} \leq 0.14$). Gas and pellet discharges show a different behaviour of P_{XN} with $\bar{n}_e$.

2. Profiles and impurity transport. The signal rise of the central channels of the bolometer camera originates either from a Marfe which is a low tempertaure thermal instability located at the plasma boundary [4] or from enhanced radiation from the plasma centre. A Marfe is accompanied by a strong increase of the line intensities from low ionization stages of low Z impurities, e.g. CIII lines ($T_e \approx 10eV$). In contrast radiation peaking at the plasma centre is indicated by a simultaneous rise of intensity of central soft X-ray channels and of Fe XVI lines. Considering spectroscopic, soft X-ray and bolometer signals we can separate Marfes from radiation peaking at the plasma centre.

Normalization of the radiation emitted from the outer half of the minor plasma radius to the total radiation P_{RAD} yields a quantitative parameter indicating the profile shape (Fig. 3). All gas refuelled discharges (with sawtooth activity during current flattop) show edge peaked radiation profiles. The central radiation power density in C discharges is less than $10mW/cm^3$ and in NC and DP discharges it is somewhat higher $\leq 40mW/cm^3$ but still negligible related to the central ohmic heating power $P_\Omega(0) \approx 200mW/cm^3$.

In low $q(q_a \leq 3)$ pellet discharges the central peaking of the density and the radiation power profile is correlated. During a typical discharge there is first a phase of negligible or slow impurity accumulation, which may suddenly turn into a fast accumulation at the plasma core. Three different scenarios for this transition are experimentally observed: a) one pellet is missing during a series of pellets (Fig. 5), b) after pellet injection if no density limit disruption occurs, c) in NC and DP discharges the q on axis may considerably rise above 1.0 owing to a pronounced flattening of the T_e-profile with rising central radiation power density (Fig. 6). A self-triggering of accumulation occurs then if $P_{RAD}(0)/P_{\Omega}(0) \geq 1$ (see also [6]).

Case a) is demonstrated in Fig. 5 for a discharge with density feed back. From t=1.5s until t=2.1s the T_e- and n_e-profiles remain nearly unchanged with a small rise of $n_e(0)(\leq 20\%)$. Strong sawtooth activity is observed during pellet injection which obviously prevents an accumulation of impurities averaged over a pellet cycle. After a last sawtooth possibly triggered by the pellet at t=1.89s a fast accumulation starts inside a minor radius r=10cm (Fig. 7). One finds from the chord-intensity profile in Fig. 7 a transport of impurities from the outer plasma regions $r > 10cm$ to the plasma core. It seems that the impurity accumulation is immediately stopped by the next pellet (Figs. 5,5a). A neoclassical theory [5] predicts from $\frac{dp_i}{dr}$ an inward drift velocity $v_D = 100cm/s$ at r=15 cm. At this position the maximum gradient of the pressure profile of plasma ions is observed. An inward drift velocity of $v_D = 65cm/s$ at r=15 cm is derived for case a) [5] which is in good agreement with theory. One can speculate that pellets change the outward transport of impurities by triggering sawteeth resulting in a higher cycle averaged diffusion coefficient. More details are given in [5].

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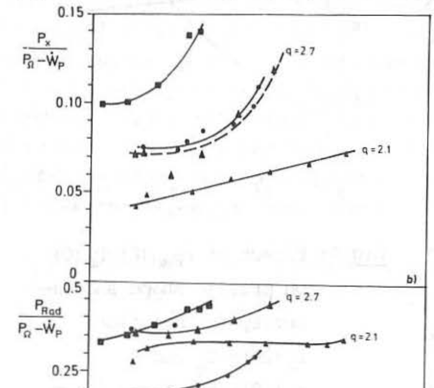

Fig. 1a, 1b: Gas-refuelled

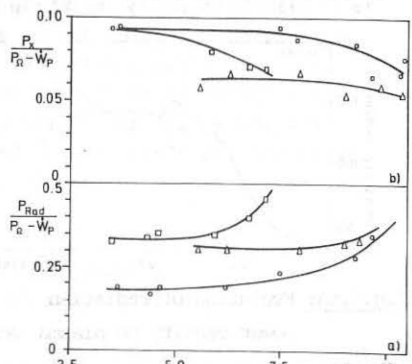

Fig. 2a, 2b: Pellet-refuelled

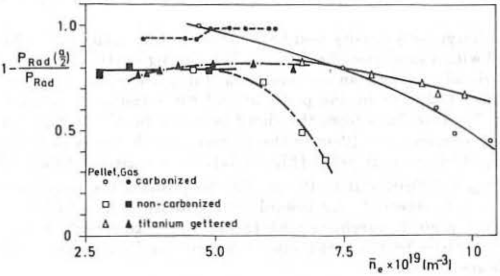

Fig.3: $P_{Rad} - P_{Rad}(\frac{a}{2})$ related to P_{Rad}.
$P_{Rad}(\frac{a}{2})$ = radiation from outer plasma column $\frac{a}{2} \leq r \leq a$

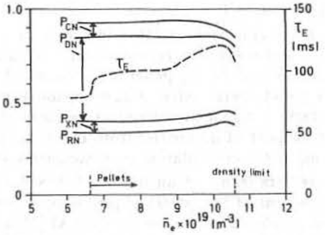

Fig.4: Energy balance for a pellet refuelled DP-plasma.

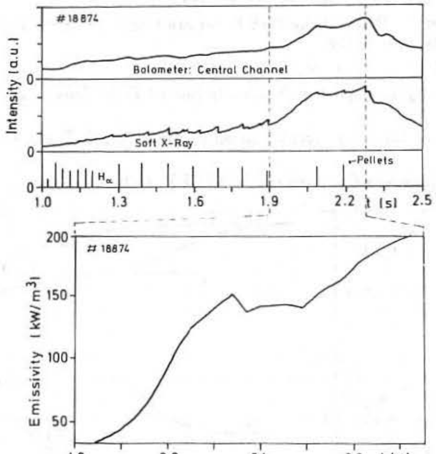

Fig.5,5a: Evolution of radiation power density on plasma axis.

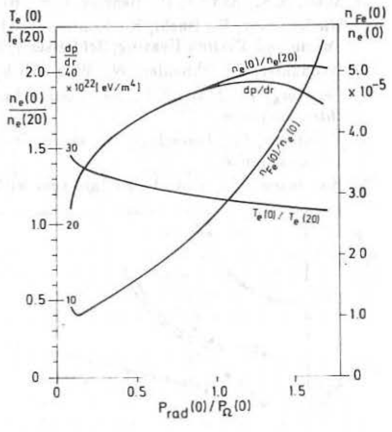

Fig.6: Effect of $P_{Rad}(0)/P_\Omega(0)$ on profile shape and impurity accumulation
$T_e(20) = T_e$ and
$n_e(20) = n_e$ at r = 20 cm

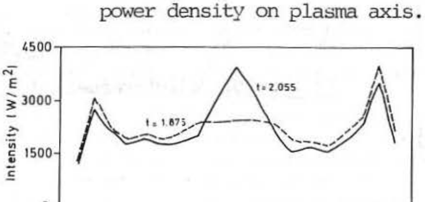

Fig.7: Radial profiles of chord-intensity before and during accumulation