TOTAL RADIATION LOSSES AND GLOBAL ENERGY BALANCE IN NEUTRAL-BEAM-HEATED ASDEX DISCHARGES

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ABSTRACT

Global energy balances of ohmically heated (≈400 kW) and neutral-beam-heated (<2.5 MW) divertor discharges in ASDEX are compared. The fractions of power losses attributed to different loss channels are almost independent of the heating power. Impurity radiation does not play any decisive role. The volume-integrated torus radiation losses, including CX neutrals, are between 20 and 30 % of total heating power. The toroidally inhomogeneous part of this torus radiation is a significant but not dominant contribution. Strong volumetric power losses are detected by bolometers from regions where particle recycling essentially occurs and builds up locally enhanced neutral particle densities: In discharges using a poloidal limiter power losses mainly due to CX neutrals and localized in the vicinity of the limiter account for about 40 % of the input energy. In divertor discharges radiation emission in front of the neutralizer plates grows exponentially with $\bar{n}_e$ and can dissipate more than 50 % of the power entering the divertor chambers in both the ohmic and neutral-beam heating cases. About half of the power flux with grazing incidence on the neutralizer plates seems to be reflected in the forward direction.

1. INTRODUCTION

In the ASDEX large poloidal divertor experiment particle exhaust and energy removal have been studied in detail for the ohmic heating case. The use of the divertor - as compared with metallic limiter discharges - reduces the impurity content and, consequently, the volume-integrated radiation losses from the main plasma by a factor of two to about 20 % of the heating power. Inside the divertor chambers high neutral-gas pressures can be built up, resulting in strong interaction between the molecular hydrogen gas and the cold high-density plasma. In this case, more than half of the diverted power is converted into volume emission of neutral hydrogen atoms with kinetic energies of a few eV /1/. The contributions of some of the inelastic atomic and molecular processes, such as ionization, to the volumetric power losses in the scrape-off plasma are expected to change drastically with increasing temperature. This paper therefore investigates the global energy balance of

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divertor discharges with strong neutral-beam heating and large power fluxes. Preliminary results have been reported in Ref. /2/.

2. GLOBAL ENERGY BALANCE

If not otherwise stated, we discuss ungettered double-null divertor discharges. Two neutral beams (H^o) are injected parallel to the ohmic-heating current (co-injection), delivering up to 3.1 MW (40 kV, 0.2 s) into the deuterium plasma. The experimental arrangement as well as the method applied to extrapolate the power losses measured in one divertor zone to those in all four zones (four neutralizer plates) are described in Ref. /1/. The thermographic system recording the surface temperature of the neutralizer plates is calibrated absolutely by means of thermocouples; the numerical calculation of power DEP absorbed by the plates from the surface temperature evolution takes into account the finite plate thickness /3/. The volume-integrated radiation and neutral particle losses in both the main plasma volume (RAD) and in all four divertor zones (RAD_{DIV}) are measured with metal resistor bolometers.

The global energy balance and its dependence on the total heating power (OH+NB) is shown in Fig. 1. When the heating power is raised from OH ≈ 0.4 MW to OH+NB ≈ 2.0 MW, all three power loss channels, RAD, RAD_{DIV} and DEP, increase nearly linearly by a factor of between 3.5 and 4.5. Above 700 kW the percentage contributions of both RAD and RAD_{DIV} to the power losses are almost independent of the heating power and amount to about 15 % each (I_p = 380 kA; $\bar{n}_e = 2.8 \times 10^{13}$ cm^{-3}). Figure 2 shows the variation of the global energy balance with the main plasma density $\bar{n}_e$ for neutral-beam heating. The main chamber radiation never exceeds 25 % of the heating power. The divertor radiation grows exponentially with $\bar{n}_e$, and at highest densities about 50 % of the diverted power is converted into radiation. As a consequence, the power deposition on the neutralizer plates decreases drastically. A power equal to 1.0 x DEP (±20 %) over large ranges of heating power (0.4 to 1.6 MW) and $\bar{n}_e$ (1.3 to 6 x 10^{13} cm^{-3}) is missing in the global balance. It is tentatively explained by the effect that the ions striking the target plates under nearly grazing incidence are quasielastically reflected in the forward direction /4/ and are thus not detected either by thermography or by bolometry.

Even in the case of low densities ($\bar{n}_e \approx 1.5 \times 10^{13}$ cm^{-3}) and a total heating power of more than 2 MW, the local radiation losses in the plasma centre remain below 0.1 W/cm^3, whereas the local power input amounts to several W/cm^3. The radial radiation profiles show a pronounced edge peak, while in the centre they are more or less flat (uncertainty of Abel inversion).

The slope $\lambda^{-1} = (2.6 \times 10^{13}$ cm$^{-3})^{-1}$ of the exponential increase of RAD_{DIV} with $\bar{n}_e$ ($RAD_{DIV} \sim \exp(\bar{n}_e/\lambda)$) does not depend on the heating power, and it is roughly half of that for the electron line density $\int n_{ed} dl$ and neutral gas pressure p_o in the divertor. The latter result is partly due to a reduction of the divertor plasma temperature T_{ed} with increasing $\int n_{ed} dl$ /5/, which again results in smaller rate coefficients as well as energy yields of atomic and molecular processes contributing to RAD_{DIV}. Reference /6/ contains a more detailed discussion of the physics of the scrape-off plasma in the divertor.

3. RADIATION COOLING IN THE LIMITER VICINITY

The question arises whether in limiter discharges, too, localized radiation losses in the vicinity of the limiter significantly contribute to the global energy balance. Charge exchange measurements showed that nearly 100 % of the ion recycling occurs at the poloidal limiter of ASDEX, causing a local enhancement of the neutral particle density /7/. A toroidal radiation profile around the limiter position was obtained by means of a bolometric scan from shot to shot (Fig. 3). The exponential decay length of the radiation agrees with that of CX measurements. Quantitaive correlation of the bolometric with the CX profile yields: 1. In addition to the toroidally uniform part of the radiation amounting to about 40 % of the heating power, radiation localized near the limiter acounts for 35 to 40 % of the input power, leaving about 20 % which is probably deposited on the limiter (no limiter calorimetry). 2. Using the fact that the toroidally uniform part of the bolometrically measured radiation includes about 10 % of CX neutrals, it can be deduced that the radiation in front of the limiter consists almost completely of CX neutrals with kinetic energies of above 100 eV.

4. NEUTRAL-BEAM-INDUCED CHARGE EXCHANGE LOSSES

In Ref. /8/ it was pointed out that the loss of plasma ions through charge exchange with the so-called beam halo may provide an important energy loss channel which depends on the toroidal angle φ. In order to measure these power losses locally enhanced near the beam port, three bolometers were placed along one of the two beam lines. The result is shown in Fig. 4. Owing to the rather limited number of data points (because of machine accessibility), which are tentatively fitted by a parabolic curve, only a rough estimate can be given: On the toroidal average, the non-uniform part of the radiation and neutral particle losses amount to about 20% of the uniform part.

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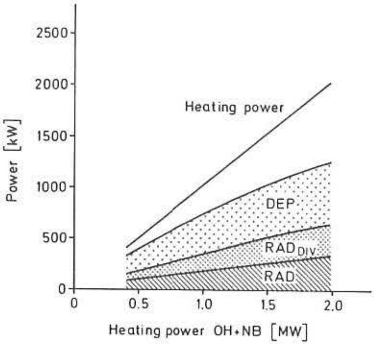

Fig. 1: Variation of global energy balance with total heating power (I_p=380kA, $\bar{n}_e$=2.8x10^{13}cm^{-3}).

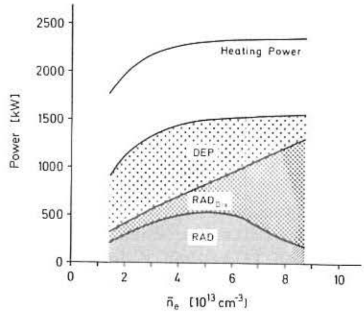

Fig. 2: Dependence of global energy balance on main plasma density $\bar{n}_e$ (I_p=380kA; OH+NB=2.1MW).

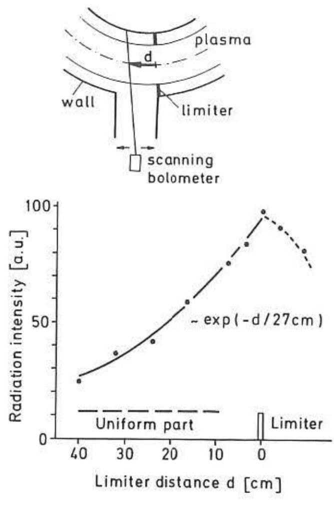

Fig. 3: Locally enhanced radiation losses in the vicinity of the poloidal graphite limiter (I_p=380kA; $\bar{n}_e$=2.8x10^{13}cm^{-3}).

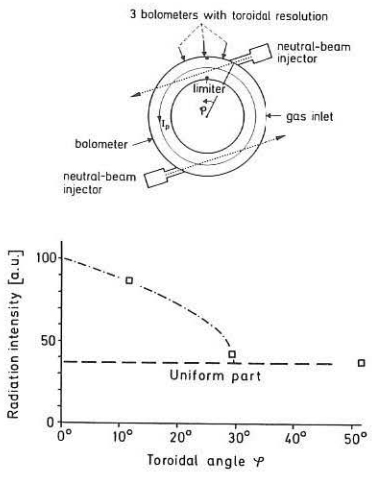

Fig. 4: Toroidal variation of the radiation in neutral-beam-heated discharges (I_p=380kA; OH+NB=2.4MW; $\bar{n}_e$=4.0x10^{13}cm^{-3}).