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Spatial radiation profiles in the ASDEX Upgrade divertor for detached plasmas

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Abstract

In this paper we describe impurity line emission measurements in the divertor of ASDEX Upgrade during high power neutral beam heated discharges. We focus on detached conditions where the dominating part of the radiation comes from the X-point region. Spatially resolved line emission in the VUV and visible spectral region of the intrinsic carbon and additionally puffed impurities (neon and nitrogen) is presented. A simple interpretation of the line emission profiles is given and they are also compared to the results of bolometry.

Keywords: ASDEX Upgrade; VUV spectroscopy; Divertor detachment; MARFE

1. Introduction

At high power input into the scrape-off layer (sol) and low density, divertor temperatures are high, resulting in high power load to the target plates. With increasing density or higher impurity content in the sol the radiation losses increase and the power load is more and more reduced (detachment). To decrease it to a tolerable level in ITER, the complete detached H-mode (CDH) with neon puffing is proposed where even ELMs are dissipated in the divertor [1]. Depending on the density or impurity level detachment differs in the position of the thermal front which is the region with a steep temperature gradient where the ionization of impurities occurs [2]. Often it is localized near the magnetic X-point, resulting in a concentration of the total divertor radiation there.

A closely related phenomenon is the MARFE: a localized axisymmetric high density region with a high radiation level [3]. In divertor tokamaks like ASDEX Upgrade or DIII-D they appear near the magnetic X-point [4]. MARFEs occur above a threshold of the line-averaged midplane density when the divertor is already detached.

Because the bolometrically measured total power radiated in the divertor shows a similar pattern in both cases we focus on divertor spectroscopy to describe both phenomena from an experimental point of view. We present the divertor line emission of intrinsic and puffed impurities in detached H-mode and L-mode discharges. Different degrees of detachment, called partial and full detachment, as well as MARFEs can be clearly distinguished by the radiation pattern of the emitting ions.

2. Diagnostics

Divertor spectroscopy in ASDEX Upgrade is based on two systems, a combined scanning system for the VUV and visible range (boundary layer spectrometer [5]) viewing the targets almost perpendicularly and a visible system (divertor spectrometer [6]) viewing tangentially to the outer plate. Fig. 1 shows the scanning range for the divertor observation and the fixed 16 lines of sight of the divertor spectrometer. For the VUV instrument, an absolute calibration is not yet available. Thermography provides power deposition profiles on the plates. Bremsstrahlung at 4.7 μm is also detected by this system in the X-point region when a MARFE appears. Here the blackbody radia-

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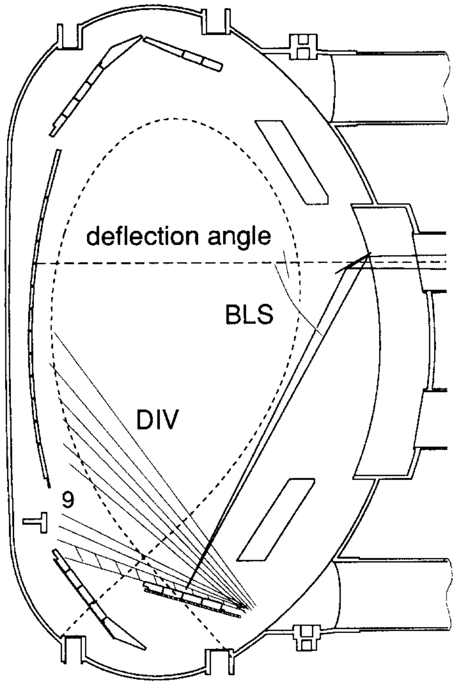

Fig. 1. Arrangement of the boundary layer spectrometer (BLS) and the divertor spectrometer (DIV) at ASDEX Upgrade.

tion does not interfere because these lines of sight do not strike the foot points at the target plates. Total radiated power is measured by bolometer arrays and the plasma parameters by Langmuir probes flush mounted in the target plates.

3. Results

3.1. Carbon radiation in a density limit discharge

Emission of intrinsic carbon, mainly responsible for the power loss in the divertor, was studied in the hydrogen discharge shown in Fig. 2. Neutral beam heating is gradually increased up to a 5 MW plateau. Due to the density ramp-up the plasma falls back to the L-mode after a short H-mode phase. The plasma starts to detach at 1.95 s as indicated by the reduction of CIII intensity in front of the plate and by the decrease of particle flux. This detachment is continuous, with no apparent bifurcation. At 2.1 s, the bremsstrahlung in the X-point region strongly increases, indicating the formation of a MARFE.

Carbon emission (CII 133.5 nm, CIII 117.5 nm, CIV 154.8 nm) in the corresponding phases is shown in Fig. 3. In the attached phase the carbon radiation is concentrated in front of the plates. No X-point radiation is observed. In the outer divertor the shift of the emission maxima with the charge number is well resolved. The distance between CII and CIV amounts to 2.5° (6 cm). In the detached phase the radiation of all carbon species strongly increases. Simultaneously, the emission zones of CIII and CIV extend to the X-point. In the marfe phase, however, there is no radiation from the inner divertor. Now it comes mainly from the marfe region at the X-point. In comparison to the preceding phase without the marfe, CII intensity is low whereas the emission of CIII and CIV is only slightly diminished.

The results of the divertor spectrometer are shown in Fig. 4, where the CIII emission at 465 nm is plotted versus the elevation from the outer target. The profiles are given for the attached phase from 1.6–1.8 s, the detached phase at 2.05 s and at 2.2 s with the MARFE. In the attached divertor the CIII emission peaks immediately in front of the target. At 2.05 s it fills the whole divertor. This state we call partially detached because the thermal front now lies in the divertor. As already observed with the boundary layer spectrometer, carbon emission is much stronger compared to the preceding attached phase. During the MARFE, a maximum in the CIII emission appears near the X-point with a reduced intensity near the plate.

A rough interpretation of this behavior must consider the temperature dependence of the line emission. With the transition to detachment, the temperature falls below 5 eV as measured by the Langmuir probes. Two competing tendencies influence the carbon emission. Lowering T_e would reduce the released carbon flux and consequently the line emission. But simultaneously, the excitation will

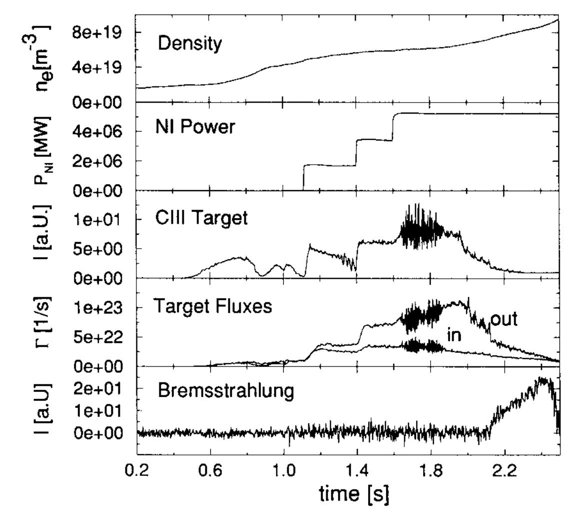

Fig. 2. Time traces of a 5 MW neutral beam heated discharge in ASDEX Upgrade (#7758): line-averaged density. neutral beam power, CIII intensity 1 mm in front of the outer target, plasma fluxes to the inner and outer divertor from Langmuir probes and bremsstrahlung from the X-point region. Detachment starts in the inner divertor at 1.86 and in the outer divertor at 1.95 s. The strong increase of the bremsstrahlung after 2.1 s indicates the formation of a marfe.

be more and more effective at low temperature in comparison to the ionization. Therefore the emission increases because the ions emit more photons until they are ionized during their life time. We conclude that during partial detachment the increased number of the emitted photons per ions cannot be compensated by a flux reduction. Therefore the carbon release is not remarkably influenced. However, in the MARFE phase the situation is reversed in that the carbon flux is strongly reduced resulting in the low emission in the divertor (see the CII signal in Fig. 3). The MARFE effectively switches off the carbon source from the plate. It resides at least partly on closed flux surfaces where carbon is provided from wall sources. Both conclusions are directly confirmed by numerical simulations [7].

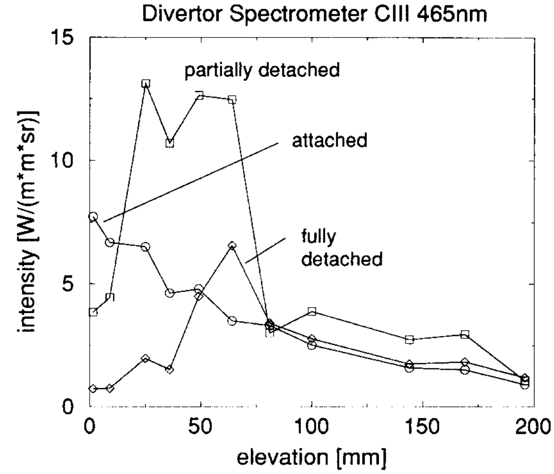

Fig. 4. Divertor spectrometer: Visible carbon emission (C(III), 465 nm) as a function of the elevation under attached (1.6 and 1.8 s), partially detached (at 2.05 s) and fully detached (MARFE, at 2.2 s) divertor conditions (#7758).

3.2. Divertor detachment by nitrogen puffing

In a series of 5 MW neutral beam heated H-mode deuterium discharges nitrogen was puffed into the divertor. To compensate for the high wall sticking probability of nitrogen, two valves were used with a toroidal distance of 180°. During the puff the plasma detaches with attached phases during ELMs. The spatial emission of the nitrogen ions (NII 91.6 nm, NIII 99.1 nm, NIV 92.3 nm and NV 124 nm) integrated over ELMy and ELM-free phases is shown in Fig. 5 for two different influxes. At low gas puffing rate ($1.5 * 10^{21}$ particles/s) the emission zones of the ions are separated according to their charge numbers, which is directly visible in the outer divertor. At high puffing rate ($3 * 10^{21}$ particles/s) the emission of all ions peaks at the X-point.

In Fig. 6 we compare the corresponding carbon emis-

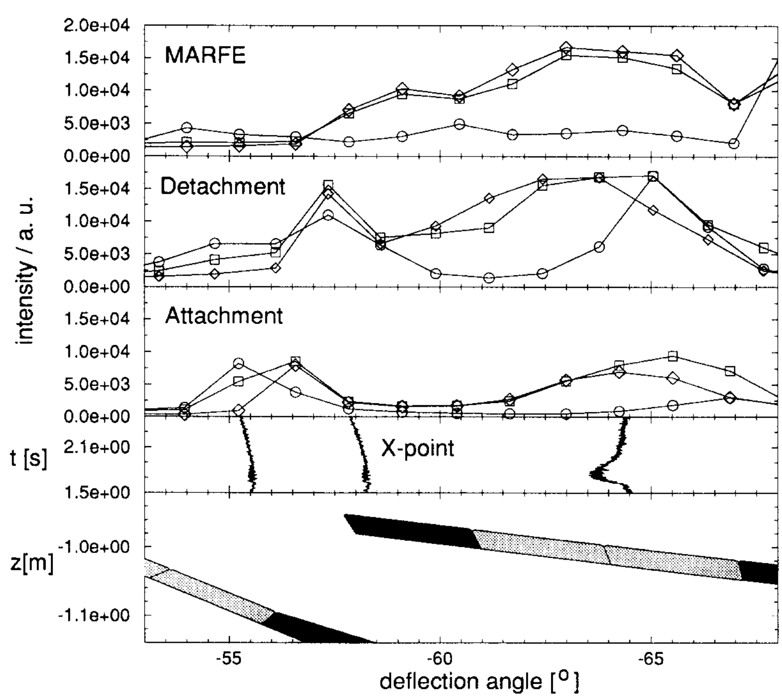

Fig. 3. Boundary layer spectrometer: carbon emission (CII: circles, CIII: squares, CIV: diamonds) as a function of the deflection angle (see Fig. 1) at different phases of the density limit discharge (#7758). The target plates and the positions of the strike points as well as X-point are given for comparison.

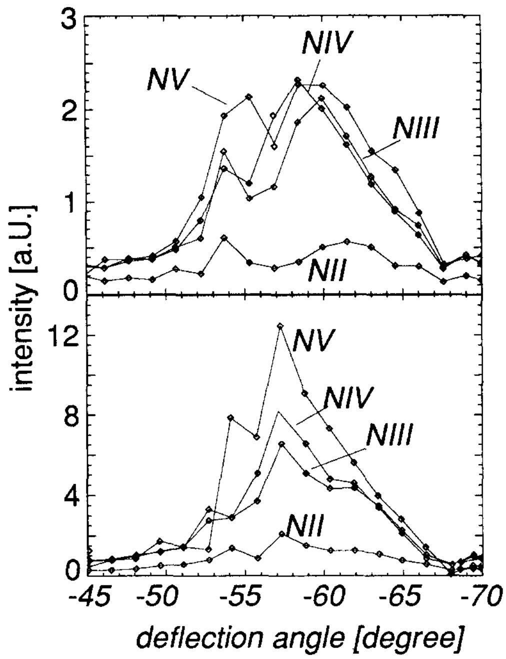

Fig. 5. Nitrogen emission profiles of a 5 MW neutral beam heated H-mode discharge during divertor puffing for two different fluxes. At a flux of $1.5 * 10^{21}$ particles/s (#6543) the emission maxima of the ions are shifted upwards, what is directly visible from the signals in the outer divertor (on top). At $3 * 10^{21}$ particles/s (#6544) the emission of all ions is maximum at the X-point (at bottom).

sion profiles measured with both spectrometers. The divertor spectrometer gives the CIII intensity at 465 nm between ELMs as function of the distance from the outer plate. They are very similar to those observed in the density limit discharge (see Fig. 3). At low blow rate the emission fills out the whole divertor whereas at high blow rate the divertor is fully detached. This points to the different positions of the thermal front either in the divertor (partially detached) or at the X-point (fully detached). From the CII emission at 90.2 nm measured with the boundary layer spectrometer we estimate the particle flux. During partial detachment the emission is nearly unchanged compared to the preceding phase without the nitrogen puff. At full detachment the CII signal and consequently the carbon influx is low. Mainly nitrogen contributes to the power losses in this case. An increase of bremsstrahlung usually supposed as a sign for the condensation in the MARFE is not observed. Therefore we have full detachment without the formation of a MARFE and this may be related to the different radiation characteristics of nitrogen.

3.3. Neon emission in the divertor

Neon puffing experiments were carried out in 5 MW neutral beam heated discharges leading to a partially detached divertor similar to the nitrogen case described above. The puffing valve was localized near the midplane. Line emission of the different neon ions was studied by the VUV branch of the boundary layer spectrometer. The emission of NeIV (54.2 nm), NeV (57 nm), NeVI (56.1 nm) and NeVIII (78 nm) in the divertor is shown in Fig. 7. Ions in medium charge states exhibit maxima in both divertors. In the case of NeVIII, they cannot be separated for geometrical reasons, i.e. the radiation emanates from the X-point region. This emission profile also exhibits a second maximum at 65 degrees which is related to the radiating neon shell in the plasma bulk (as also observed e.g. in the TEXTOR tokamak). In principle, recombination of the He-like state cannot be excluded as a source for NeVIII, but this occurs in the whole boundary layer. The localized appearance of NeVIII emission near the X-point together with the simultaneous observation of the lower ionization stages proves that neon which was neutralized at the target plates can be ionized up to the Li-like state in the divertor. Summing up over all the charge states results

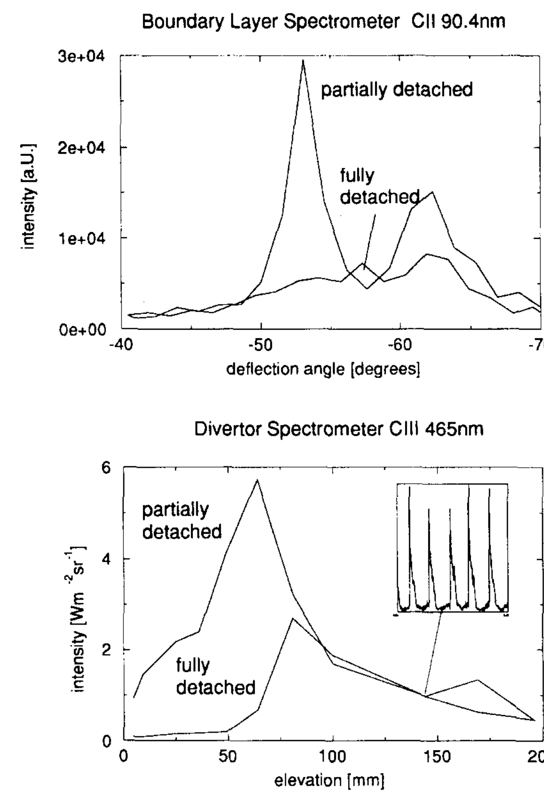

Fig. 6. Comparison of divertor carbon emission profiles for strong (#6544) and moderate (#6543) nitrogen puffing. The boundary layer spectrometer shows a CII signal nearly proportional to the carbon influx from the plate (on top). In the fully detached case the influx is strongly suppressed. The divertor spectrometer shows the CIII emission in the detached state (at bottom). During partial detachment carbon emission fills out the whole divertor whereas in the fully detached case it is located near the X-point.

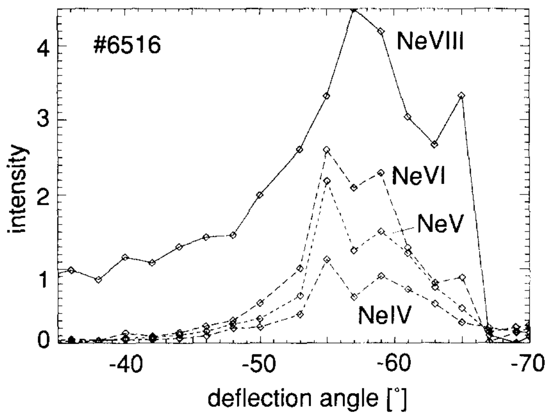

Fig. 7. Emission of NeIV, NeV, NeVI and NeVIII in the divertor during neon injection into the boundary (#6516). The divertor plasma is in a partially detached state.

in significant power radiated from the neon ions in the X-point region.

Fig. 8 shows a 2D contour plot of the total radiated power measured by the bolometer arrays. Inside the separatrix the power is uniformly radiated from an emission shell. In the divertor, however, the radiated power is strongly peaked at the X-point in agreement with the appearance of the highly ionized neon species. During partial detachment the impurity influx from the plates continues nearly unchanged so that neon as well as carbon contribute to the power losses in this case.

4. Summary

The line emission of impurities which represents the main power loss channel in the divertor was studied by

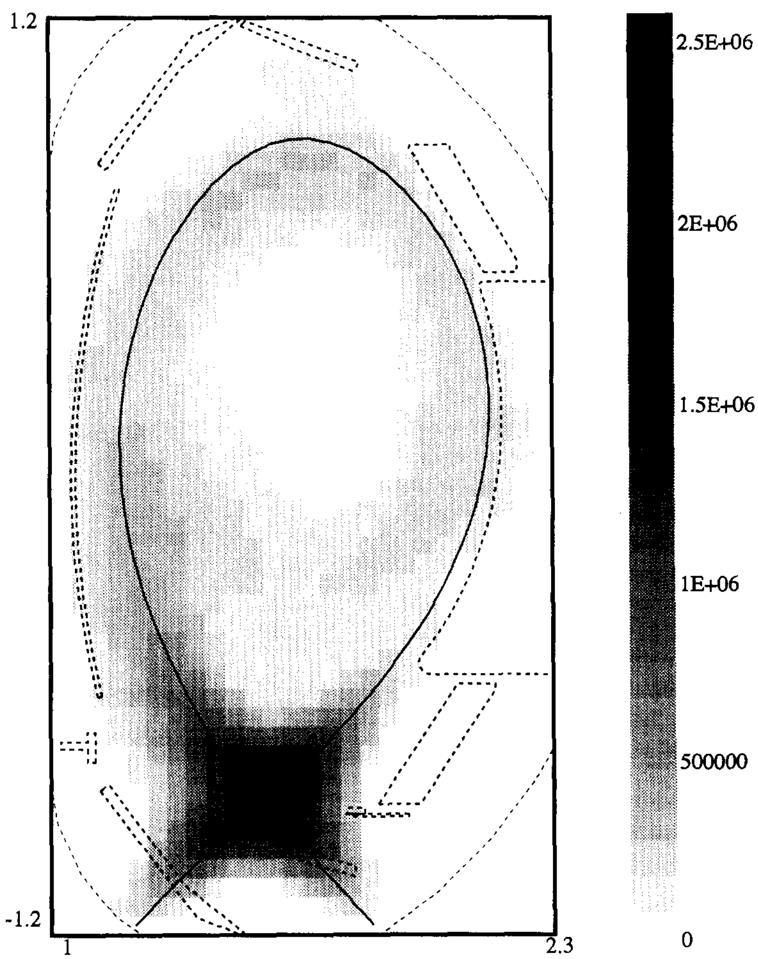

Fig. 8. Poloidal distribution of the radiated power reconstructed from the results of the bolometer arrays during neon injection (#6516 at 2.2 s). Power loss is strongly peaked at the X-point which is in agreement with the observation of highly ionized neon species in that region.

visible and VUV spectroscopy under detached conditions. Three different cases of a detached divertor have to be distinguished:

– During partial detachment the thermal front is localized in the divertor. Atoms released from the target or puffed into the divertor (neon, nitrogen) are ionized there resulting to a broad emission distribution. Despite the low temperatures the carbon release from the targets is not strongly reduced. The appearance of highly ionized neon species in the X-point region shows that neon is effectively transported.

– The case where the thermal front is localized near the X-point is called full detachment. Divertor radiation is low and the main emission comes from the X-point. Strong nitrogen injection provides a good example for this case.

– The third phenomenon is the MARFE observed in L-mode at very high densities. Even though the carbon influx from the target plates is reduced as can be seen from a decrease of the CII emission, the total radiation (mainly from CIII and CIV) remains at high level as the MARFE resides on closed flux surfaces.

By means of impurity puffing the radiated power and the degree of detachment can be controlled varying the puffing rate. Full detachment can be obtained without the formation of a MARFE.

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