Plasma Radiation with Local Impurity Injection into a Magnetic Island of W7-AS Stellarator and at the separatrix of AUG Tokamak

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Introduction

Energy dissipation by impurity radiation at the plasma edge has become the preferred solution for reducing the heat loads of divertor plates in tokamaks and stellarators. However the magnetic configuration at the plasma boundary is quite different for the proposed ITER-tokamak and the W7-X-stellarator [1]. Whereas in ITER open magnetic field lines outside the separatrix are guided to a divertor chamber being locally separated from the main plasma magnetic islands at the plasma edge are intersected by target plates in the main chamber with relatively small radial separation from the separatrix in W7-X. While impurity radiation cooling in the tokamak edge configuration has been studied already extensively, the influence of magnetic islands on the properties of the edge plasma is still quite unknown. First investigations on the stellarator W7-AS are reported in this paper. For this purpose nitrogen pulses of a few ms duration have been injected into natural islands at the plasma edge of W7-AS discharges by a reciprocating erosion probe with a radial precision of injection of about 5 mm [2]. The cylindrical probe head consists of a boronnitrid casing of 5 mm diameter and length and a small electrode of titanium or carbon of 2 mm diameter and length on the front side. For comparison similar experiments with nitrogen injection were also made in the tokamak ASDEX-Upgrade. In this case a boronnitrid probehead of 30 mm diameter was exposed near the separatrix on the outboard side for 10 ms several times during a discharge using the midplane manipulator.

Modelling of Nitrogen radiation from a magnetic island

The power which can be stationarily radiated by nitrogen from a magnetic island region has been studied using a simple particle transport model. A continous impurity source at the centre of a circular plasma region, representing the island with density n_e, electron temperature T_e and impurity residence time of $\tau = r^2 / D$ is considered where D is the cross field diffusion coefficient. The temporal evolution of the impurity charge states in this region is calculated from the equation

$$dn_q/dt = n_e (S_{q-1}n_{q-1} - (S_q+R_q)n_q + R_{q+1}n_{q+1}) - n_q/\tau_q$$

with n_q being the density of the impurity species, q the ionization state; S and R are the rate coefficients for ionization and recombination, respectively. The radiated power density has been calculated from the relation $p = \Sigma L_q(T_e) n_q n_e$ in which L_q is the radiation rate function. Assuming $n_e = 1*10^{19} m^{-3}$, r = 2 mm and an atomic nitrogen source strength of $1*10^{22} m^{-3} s^{-1}$ the results shown in fig.1 are obtained. Considerable nitrogen radiation from a magnetic island can only be expected if T_e is about 15 eV and if furthermore the diffusion coefficient within the island is smaller than 0.2 m^2 / s. Using the values of fig.1 a radiated power from the magnetic island of a 5/9-configuration up to 400 kW are predicted in case of W7-AS.

Experiments in the stellarator W7-AS

The experiments were performed in NBI-heated discharges with a 5/9- island configuration and limiters on the inboard side [2]. The nitrogen was injected with the reciprocating probe in upstream position (bottom side). Due to the injection the electron temperature within the island of W7-AS measured by the probe itself decreased from values up to 80 eV to about 10 eV. The total radiation raised up to 90 % of the input power, however, particular enhancement of radiation from island region could not be observed. The spatial distribution of the radiation after injecting nitrogen was found to be only slightly dependent on the location of the injection (X- or O-point). Enhanced radiation mainly occurred on the inboard side. When the density was increased, plasma shrinking induced by impurity injection was observed to start at densities of about 1 x $10^{20} m^{-3}$. This shrinking was accompanied by partial transient plasma detachment from the inboard limiters. However, there are strong indications for poloidal asymmetries in connection with plasma shrinking. In fact, at plasma densities of 1.6 x $10^{20} m^{-3}$, the ion current measured by probes near the O-point decreased by more than an order of magnitude on the outboard side (upstream) and less than a factor of two in the equatorial plane on the inboard side (downstream). Strongly localized radiation zones at the inboard side (MARFE s) were induced by the impurity injection at this density. In contrast to tokamaks the radiating region is not toroidally symmetric but seems to follow a helical line within a modular section similar to the helical edge observed earlier on the outboard side of W7-AS [3]. The power load to the inboard limiters measured by thermography was reduced by less than 25 % when a Marfe was formed in front of these limiters. The close proximity of the radiating region to the limiters possibly prevent a stronger reduction of the limiter load.

Besides the radiation from nitrogen a considerable enhancement of radiation from intrinsic impurities occurred. This observation is explained by the increase of radiation with decreasing plasma edge temperature and a deeper penetration of intrinsic impurity atoms due to the low edge plasma density and temperature.

Experiments in the tokamak ASDEX-Upgrade

Nitrogen was repeatedly injected just inside the separatrix in a 2 MW neutral beam heated L-mode discharge with programmed increasing plasma density from 4 to $8*10^{19}$ m^{-3}. During the injections the electron temperature at the separatrix measured by ECE on the outboard side decreased to values between 30 eV and 10 eV depending on the density (see fig.3) while the line averaged plasma density was transiently affected by less than 10 %. Radiation measured by the bolometer at a toroidal distance of 2.5 m from the impurity source was enhanced mainly above the X-point and on the inboard side. The fraction of the total radiated power in the main chamber to the input power reached about 0.8. Divertor detachment is indicated by the CII-signal of the divertor spectrometer at all plasma densities. The particle and the power fluxes to the target plates measured by Langmuir probes and thermography were also found to be strongly reduced during the injection (not shown here). Most remarkable is the following observation: Despite the fact that the carbon flux released from the target plates of the divertor was strongly reduced the concentration of carbon and oxygen in the main chamber increased as evidenced by the signals from the monitor for these impurities.

Modelling of the plasma boundary of AUG

In order to model the AUG-experiment descibed above an artificial carbon or boron ion source inside the separatrix on the outboard side was introduced in the B2/Eirene-code for a discharge with a plasma density of $5*10^{19}m^{-3}$ at the separatrix and 3 MW heating power. The diffusion coefficient was assumed to be 0.2 m^2s^{-1}. With increasing strength of the artificial impurity source and decreasing edge temperature the carbon radiation has been found to shift continously from the divertor to the X-point. Generally, when a MARFE is formed with an electron temperature of 1-2 eV finite temperature gradients exist along the separatrix. Thus the electron temperature varies between 1 and 20 eV on the inboard side whereas the value on the outboard side is still 30 eV (see fig.4). This is consistent with the observed radiation pattern. Evidently, the intrinsic impurity fluxes of carbon and oxygen produced at the inner wall shield can penetrate much deeper into the plasma at temperatures below 10 eV; i.e. the screening of the SOL-plasma due to ionization is reduced. This reduced screening may explain the experimental observation of enhanced C and O concentration in case of strong nitrogen injection into the edge plasma of AUG.

Summary:

Despite the quite different magnetic configurations in the stellarator W7-AS and the tokamak AUG the radiation pattern is similar when the electron temperature at the separatrix is decreased to values lower than 30 eV. A particular radiation from island regions at the plasma edge is not observed even after injecting nitrogen into a magnetic island of the stellerator W7-AS. The experiments in AUG have revealed that a too extensive radiation cooling should be avoided in order to prevent an increase of the intrinsic impurities caused by loss of screening.

References :

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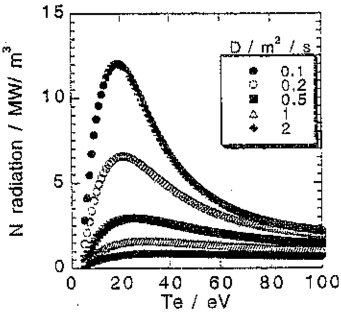

fig.1 : Calculated power density radiated during nitrogen injection into a magnetic island in dependence on the electron temperature with the diffusion coefficient as parameter

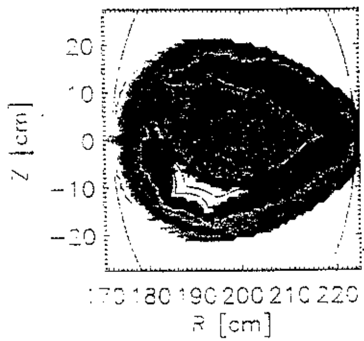

fig. 2 : 2D-plot of radiated power (bolometer) during nitrogen injection showing a MARFE on the inboard side below the equatorial plane of W7-AS

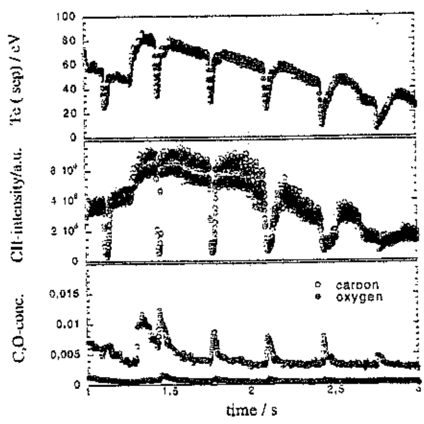

fig. 3 : Temporal traces of diagnostic signals of the AUG-discharge # 7738. From top to bottom:
electron temperature at the separatrix
C-II-signal of the divertor spectrometer,
C-and O-concentration inside the separatrix

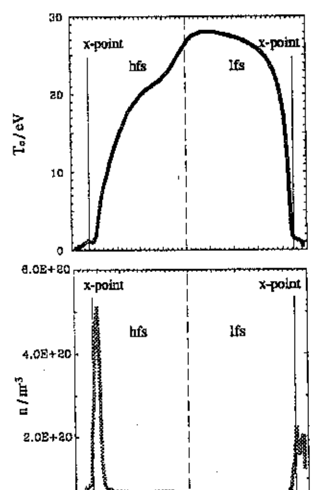

fig.4 : Electron temperature and plasma density at the separatrix in dependence on the poloidal position for a discharge with a MARFE near the X-point as calculated from B2/Eirene