B2 – Eirene Density and Energy Scans for ASDEX Upgrade Shots

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Introduction

The coupled B2–Eirene multi-fluid code has been used to simulate the plasma evolution for a density-ramp deuterium discharge in ASDEX–Upgrade starting from the low density region which is hard to realize experimentally up to the density limit.

In particular, the two critical phenomena, ***detachment*** and ***marfe formation*** are considered in detail, both beeing related to the negative derivative of the impurity radiation characteristic and the nonlinear dependence of the parallel thermal conductivity on the electron temperature. During detachment the plasma changes from a high temperature ***divertor state*** to a low temperature one (bifurcation effect / 1 /); marfe formation – indicating the density limit – is connected to ***closed flux surfaces*** and leads to an unstable plasma state. The latter, however, can dynamically be stabilized by appropriately controlling the density.

The calculations refer to the MHD equilibrium and the plasma parameter region of the discharge #7758. The actual discharge is simulated by the steady states of the plasma in the corresponding density range.

Numerical Model

Like in the experiment the density is feedback controlled via a neutral gas puff and pumps (with fixed pump efficiencies) at the midplane and at the divertor region, respectively. The impurity production (carbon and small amounts of boron) is self-consistently described in Eirene by physical and chemical sputtering.

The calculational region extends far enough into the main plasma so as to describe also essential phenomena inside the separatrix like impurity radiation zones or marfe formation and to provide homogeneous boundary conditions for the B2 code at the inner grid boundary.

The energy influx from the central plasma across the inner grid boundary P_{in} ($= 2MW,\ \underline{3MW},\ 4MW,\ 7MW$) is an external parameter of the model. The particle influx is assumed to vanish there. As boundary conditions for the B2 code at the side walls a radial decay length of $1cm$ for the densities, temperature and parallel fluxes is used and Bohm-like conditions at the target plates.

The anomalous radial transport coefficients of the model are assumed to be constant: $D_i = (\underline{0.2},\ 0.5,\ 1.0)m^2/s$ (diffusion coefficient), $\kappa_{e,i} n_{e,i} = 1m^2/s$ (thermal conductivity), $\eta_i/m_i n_i = 0.2m^2/s$ (viscosity).

In this model the separatrix electron density ($n_{e,mid}$) at the outer midplane is used as reference density.

Density Scan

For the following density scan (Figs.1 and 2) $P_{in} = 3MW$ and $D_i = 0.2m^2/s$ are assumed.

At a critical value ($n_{e,mid} \approx 3.1 \times 10^{19} m^{-3}$), ***the inner divertor detaches:*** The electron temperature drops from $T_e \approx 50eV$ to $T_e \approx 2eV$ while the density inreases accordingly (enhanced recycling). The outer divertor remains at $T_e \approx 15eV$ and cools down more gradually with further increasing density. The total outer target particle flux reaches a maximum and decreases monotonously up to marfe onset at $n_{e,mid} \approx 6.8 \times 10^{19} m^{-3}$ The total impurity radiation is then about $0.6P_{in}$. A steady state marfe can dynamically be sustained at lower density by carefully controlling the gas puff (hysteresis).

Divertor Plasma – Density Scan (P_{in}=3MW)

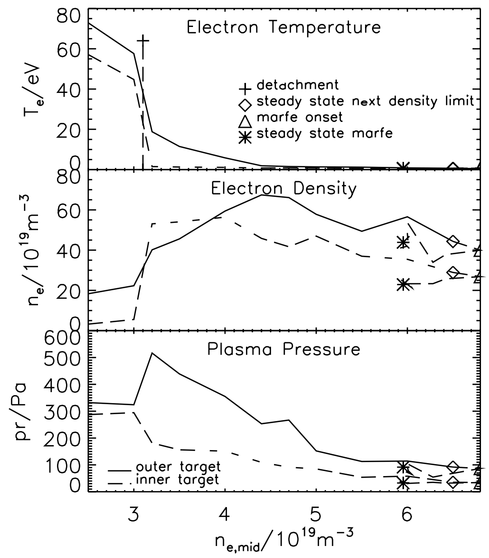

Fig.1 Maximum values at the target plates

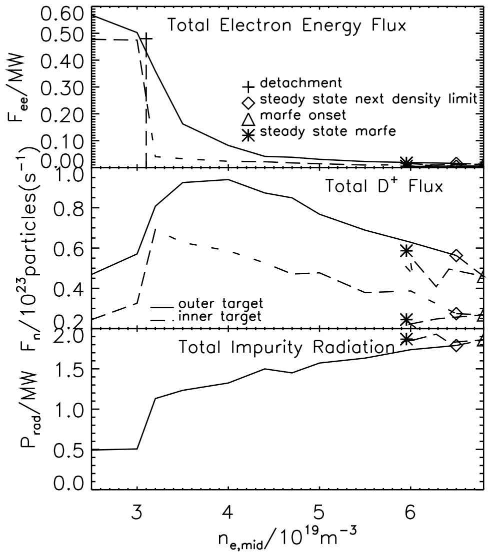

Fig.2 Total target fluxes and radiation

Transition to Detachment

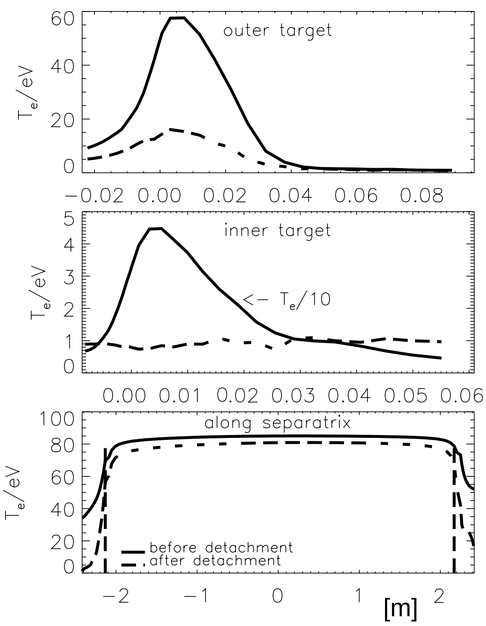

Fig. 3 Electron Temperature, radial and poloidal profiles

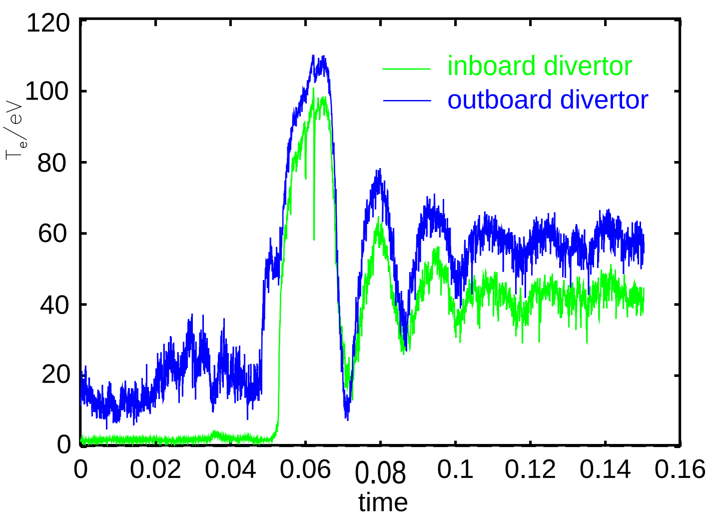

Fig.4 Temporal evolution of the maximum electron temperaure at the target plates during the change from the detached to the attached plasma state

Detachment may be be related to a bifurcation point of the plasma solution as has been shown in / 1 / within the framework of a 1–d model. It is a consequence of the particular characteristic of the impurity radiation function (which has a negative derivative) and the non-linearity of the heat flux ($\kappa_{\parallel}^{e} \propto T_e^{5/2}$).

The temporal evolution of T_e for this transition as obtained from the code calculation and the change of the T_e profiles at the target plates and – in poloidal direction – along the separatrix is shown in Figs. 3 and 4.

Transition to the marfe plasma state

Marfe formation occurs when the energy balance cannot be fullfilled locally on the outermost closed flux surfaces near the x-point which is the plasma region within the separatrix having the lowest electron temperature.

A thermal instability develops due to the decreasing thermal conductivity and the increasing impurity radiation if T_e goes down:

$$decrease\ of\ T_e \begin{cases} \nearrow\ increase\ of\ n_e\ \ (p \approx const\ ., closed\ flux\ surface!) \searrow \\ \searrow\ increase\ of\ P_{rad}\ (negative\ slope\ of\ rad.\ function) \nearrow \end{cases} decrease\ of\ T_e$$

The crucial condition for T_e inside the separatrix near the x-point is $T_{e,x} \approx (10 \div 20) eV$.

The steep density gradients of the marfe cause radial particle fluxes (to the inner as well as to the outer side of the plasma) which must be compensated by parallel fluxes from both poloidal sides to the marfe. This changes drastically the flux pattern (see Figs. 5, 6).

n_e Contour Plot and D1+ Particle Flux (Arrows)

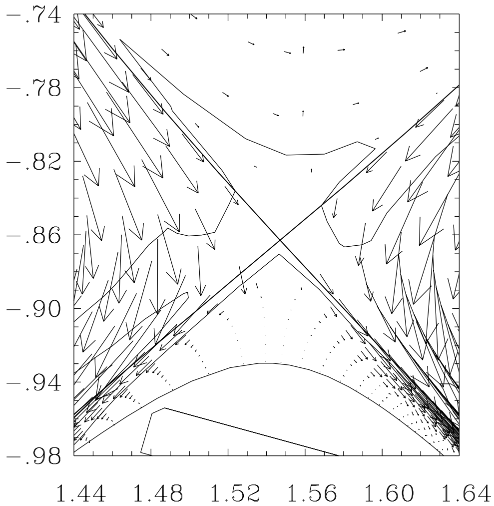

Fig. 5 Steady State Next Density Limit

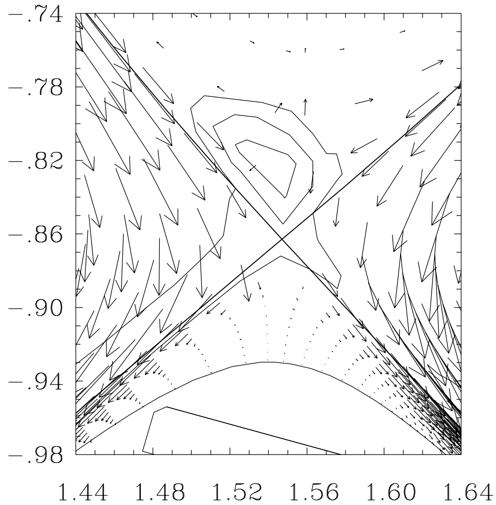

Fig. 6 Steady State Marfe

This marfe dynamics / 2 / (leading to a localized region of high density and low temperature relative to the surrounding medium) does not work in the SOL because of the parallel fluxes to the target plates. The cold region of the SOL would simply be extended.

Marfe formation is characterized by a strong local increase of the impurity radiation from the x-point region. However, only the radiation coming from inside the separatrix is due to the marfe.

Marfe Density Limit

Fig. 7 shows the electron temperature above the x-point as function of the midplane separatrix density for different energies and diffusion constants. In addition a curve $T_{e,x} \propto \sqrt{n_{e,mid}}$ $(T_{e,x}/eV = 11 \times \sqrt{n_{e,mid}/10^{19} m^{-3}})$ is fitted in order to compare with the “collisional” limit / 3, 4 / which is a necessary condition for marfe formation:

$$q_{95}(R/m) = \frac{10^{17} \left(T_{e,mid}/eV\right)^2}{n_{e,mid}/m^{-3}} \quad \longrightarrow \quad T_{e,mid}/eV \approx 23 \sqrt{n_{e,mid}/10^{19} m^{-3}}$$

R is the major radius and q_{95} the safety factor at the 95% flux surface. Fitting to $T_{e,mid}$ would yield $T_{e,mid} = 17/11 \times T_{e,x}$.

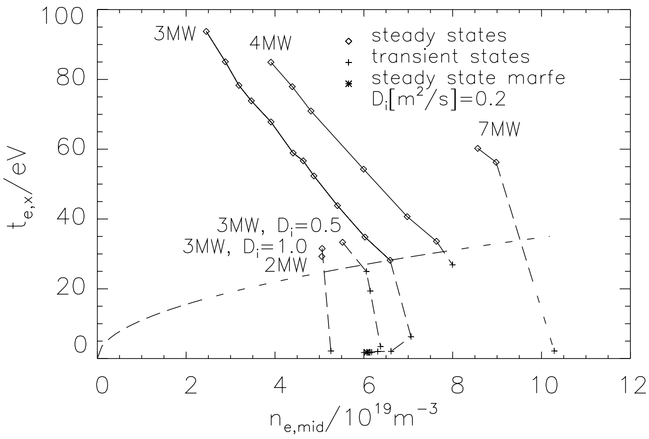

Fig.7 Electron Temperature above the x-Point in dependence on the Midplane Separatrix Density

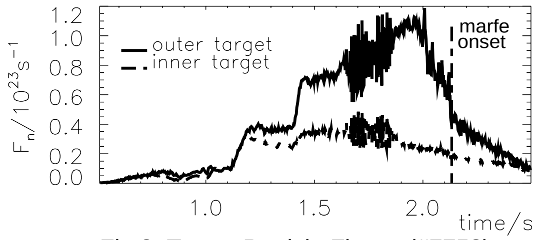

Fig.8 Target Particle Fluxes (#7758)

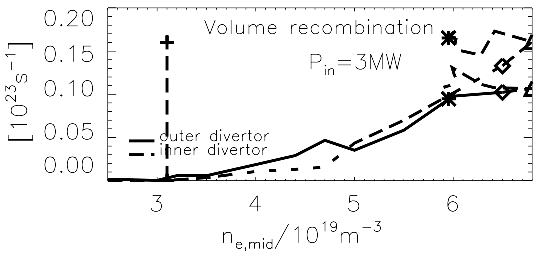

Fig.9 Volume Recombination Rates in the Diveror Regions

The steady marfe plasma states considered in these calculations are characterized by a relatively small ratio (< 0.4) between the volume recombination rate (Fig. 9) and the particle target fluxes (Fig. 2), i.e. the target flux reduction is essentially determined by impurity radiation cooling / 5 /. Contrary to this, the strong final decrease of the experimental flux curve in Fig. 8 is primarily due to volume recombination.

Conclusions

The simulations show that detachment occurs already at very low plasma densities usually not realized in experiments with additional heating. It is a step-like process where primarily the inner divertor is involved in. The outer divertor cools down more continuously during the density ramp. The experimentally observed “roll-over” of the outer target particle flux during the density ramp has been verified.

The upper density limit determined by marfe formation is reached when the radiation front has moved upwards from the target plates to the x-point and the electon temperature on the innermost closed flux surfaces above the x-point has sufficiently cooled down. Volume recombination is important but not the dominant particle loss process at marfe onset. A marfe can be stabilized by appropriately controlling the gas puff.

References

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