

Impurity Concentration as a Critical Parameter in a Diverted Scrape-off Layer

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Introduction

Essentially different central densities in a Tokamak discharge force different states of the divertor (e.g. [1],[2],[3]). At low densities the divertor plasma is attached and the impurity radiation is produced close to the plates. With rising density the divertor cools down and the radiation level increases until the radiation front retracts from the plate [9] leaving the immediate neighbourhood of the plate free of radiative losses. This development is accompanied by some reduction of the power flowing to the plate (e.g. [10]) usually called partial (energy) detachment [2]. If the density is increased further, this detachment develops until almost no power reaches the divertor plate (complete detachment). Whereas some experiments show a smooth transition through a chain of quasi-stationary states others are reported to exhibit a discontinuous jumping of the radiation front pointing to a bifurcation.

Simple 1D models ([4],[5],[6]) have identified the strong temperature dependences of both the parallel heat conduction and the radiation rate function of the impurities as essential ingredients to describe the divertor behaviour.

In this paper a very simple 1D model for the parallel electron heat conduction including a realistic radiation function and the sheath condition at the plate is applied to half of a SOL (midplane to one plate). The general aim is a better physical understanding demonstrated by convincing answers to questions like "What is the significance of using realistic radiative losses?", "Can we relate common processes (e.g. partial detachment, retraction of the radiation zone) to specific properties of the model?", or "What is the control parameter for the dynamics of the radiation zone?".

Furthermore, an analytical solution provides a fully transparent and retracable "benchmark" for more sophisticated 1D numerical models ([7],[8])

The Model

The model (fig. 1) is restricted to the 1D electron heat conduction parallel to the magnetic field lines with a strongly temperature dependent conduction coefficient

$$q(x) = -\kappa_0 T(x)^{5/2} \frac{dT(x)}{dx}$$

Power losses are assumed to be due to radiation from intrinsic impurities distributed along the whole parallel length

$$\frac{dq(x)}{dx} = -n_z(x) n(x) S[T(x)]$$

A prescribed temperature at the midplane, $T(x=0) = T_m$, is used as one boundary condition. The source of power is assumed to be localized at the same location and, therefore, introduced as the second boundary condition: $q(x=0) = q_m$.

The dependence of the radiation on local plasma parameters is described by modelling essential features (S_c and T_c) of the realistic radiation rate function (e.g. [11]) for Carbon in the SOL (fig. 2)

$$S(T) = S_c \frac{\theta(T - T_c)}{\sqrt{T/T_c}}$$

For simplicity it is assumed, that the impurity density n_z is proportional to the density of the background plasma and the impurity concentration does not depend on the length coordinate: $n_z(x) = c_z n(x)$. Furthermore, the electron pressure is taken to be constant all over SOL and divertor: $n(x)T(x) = p(x) = p_m$. To replace the pressure at midplane p_m , the reverse of the dimensionless Knudsen-number Kn is introduced $p_m = (\lambda_0/L_{||}) T_m^3 / K n_m$ which is known to vary over almost three orders of magnitude during experimental density ramps.

The Solution

The problem can be solved analytically to obtain the dependence of the local energy flux density on the local temperature

$$q(T) = q_m \sqrt{\frac{\max(T, T_c) - T_0}{T_m - T_0}}$$

with $T_0 = T(q=0) = T_m - T_c^7 / (2\alpha T_m^6)$, and the inverted parallel temperature profile

$$x(T) = L_{||} \sqrt{\frac{T_m - T_0}{\beta T_c}} \left\{ F[\max(T, T_c)] + \theta(T_c - T) \frac{2}{7} \frac{1 - (T/T_c)^{7/2}}{\sqrt{1 - T_0/T_c}} \right\}$$

where

$$F(\xi) := \left[(8T_m^2 + 10T_m T_0 + 15T_0^2) \sqrt{T_m(T_m - T_0)} - (8\xi^2 + 10\xi T_0 + 15T_0^2) \sqrt{\xi(\xi - T_0)} \right] / (24T_c^3) + \frac{5}{8} \left(\frac{T_0}{T_c} \right)^3 \left(\ln \frac{\sqrt{T_m} + \sqrt{T_m - T_0}}{\sqrt{T_c}} - \ln \frac{\sqrt{\xi} + \sqrt{\xi - T_0}}{\sqrt{T_c}} \right)$$

α and β are coefficients depending on $1/Kn_m$ and q_m .

At the divertor plate a sheath develops that requires a matching condition $q(T_d) = q_d$ for the heat flux. The letter is determined by $q_d = \delta \sqrt{T_d}$. This sheath condition applied to $q(T)$ establishes a relation between T_d and T_m for given $1/Kn_m$ and q_m . Postulating $T = T_d$ at the divertor plate, i.e. $x(T_d) = L_{||}$, determines the adequate midplane temperature T_m for given q_m and $1/Kn_m$. Unfortunately, the inverse profile $x(T)$ cannot be inverted analytically, so this last step has to be done numerically.

Results and Conclusions

For rising $1/Kn_m$ the divertor plasma cools down as expected and the temperature T_d at the plate falls (fig. 3). This process is accompanied by a rising radiative loss and, consequently, a reduction of the power flowing to the divertor plate. If T_d falls below the critical temperature T_c for the onset of the radiative losses the described model exhibits a retraction of the zone of maximum radiation away from the plate (figs. 4,5). In this range of $1/Kn_m$ the decrease of T_d can be rather dramatic. The retraction was found to have bifurcation character (development of a cusp) with respect to a critical impurity concentration c^* (about 4% for Carbon) as the control parameter (fig.3). For impurity concentrations below the critical value a smooth retraction takes place, whereas for higher concentrations the radiation front jumps upstream, showing a typical hysteresis for the re-attraction phase. The retraction of the radiation zone causes a decrease of the radiating volume (or length in a 1D model) that counteracts the strong rise of the losses and, consequently, decelerates the previously fast reduction of the power flux to the divertor plate. The related bend in $q_d(1/Kn_m)$ is usually interpreted as the stagnation of the divertor in a partially detached state (fig. 6). The model thus predicts an intimate relation between the retraction of the radiation zone and the partial (energy) detachment.

Additional Remark: Applied to the full SOL (from inner to outer plate), with an asymmetrically localized power source, the simple model leads to a qualitatively different branching of the power between the inner and outer parts of the SOL for impurity concentrations below or above the bifurcation value. This behaviour offers a new interpretation of the changes of the asymmetry of power deposition onto inner and outer plates, a crucial feature of a diverted tokamak discharge. If, for example, discharges with one orientation of the toroidal magnetic field show systematically a higher impurity concentration compared with discharges having the other orientation, the ratio of power fractions into the inner and outer divertor branch is qualitatively different. It should be pointed out that this model does not include any transport term having a direct dependence on the magnetic field direction.

References

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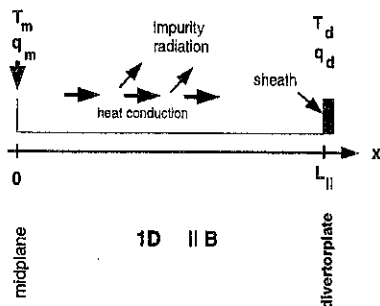


fig.1 the model (schematic drawing)

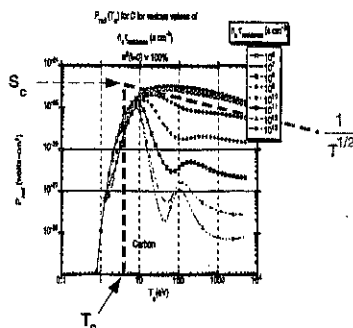


fig.2 the radiation function for C from [11] and the approximation used in the model

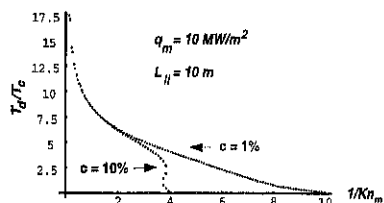


fig.3 divertor temperature versus reversed Knudsen number for different C concentrations

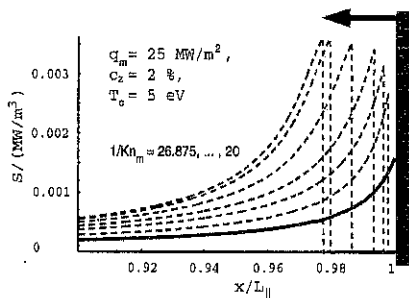
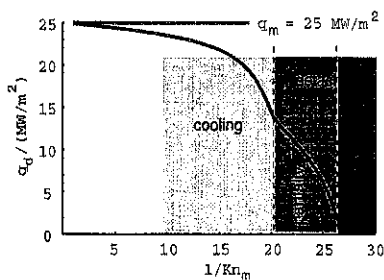
fig.4 retraction of the radiation front for rising $1/Kn_m$ 

fig.6 power density at the plate versus reversed Knudsen number

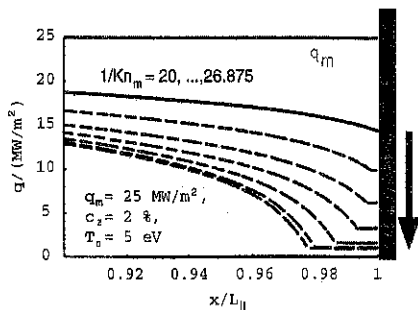


fig.5 profiles of the energy flux density for different reversed Knudsen numbers