SOL Power and Pressure Balance in Alcator C-Mod

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1 Introduction

In this paper we compare the results of a simple model of scrape-off layer (SOL) power and pressure balance, with detailed plasma measurements in the Alcator C-Mod tokamak. The model is based on the commonly used 'Two-Point Model', but includes significant additions (described in detail in a recent review article [1]). The present paper should be considered as a companion to an earlier publication [2], where similar data from the ASDEX-Upgrade tokamak was presented.

2 Power Balance

We assume that power flows along field lines in the SOL with a density q_u from the upstream stagnation location to the divertor by electron heat conduction,

$$T_u^{7/2} - T_t^{7/2} \simeq \frac{7 q_u L}{2\kappa_0} \tag{1}$$

where L is the connection length ($\simeq 8m$), T is the plasma temperature (we assume $T_i = T_e$), κ_0 is a constant and 'u' and 't' denote the upstream (we assume outer mid-plane) and (outer) target plate locations, respectively.

In Eqn. 1 we have assumed that the parallel power is nearly constant over most of the length of the flux tube. This is approximately valid, as detailed calculations have indicated, even in cases with high radiation on open surfaces, since such radiation tends to be localized near the divertor where densities are elevated. Although simple analytic estimates of such radiative loss based on 1-D modelling can be used [1, 2], assuming for example, constant impurity radiation coefficients and impurity fractions, the associated error is significantly larger than other uncertainties implicit in the simple modelling. We therefore take the experimentally determined radiative loss near the divertor as an input to the model, i.e. q_{rad}.

The boundary condition at the target plate is

$$q_t = n_t c_{St} (\gamma T_t + \epsilon_{pot}) \tag{2}$$

where, q_t is the parallel power density at the target plate ($q_t = q_u - q_{rad}$), c_{St} is the ion acoustic speed and $\gamma = 7$ is the sheath power transmission factor. ϵ_{pot} is the potential energy associated with each ion reaching the plate, including atomic and molecular recombination ($\epsilon_{pot} \simeq 16eV$).

3 Neutral Dynamics

We allow for the loss of plasma pressure by ion neutral friction in a thin recycling region close to the divertor plate. The pressure loss factor, f_m, is given by,

$$f_m \equiv \frac{2n_tT_t}{n_uT_u} = 2(\frac{\alpha}{\alpha+1})^{\frac{\alpha+1}{2}} \tag{3}$$

where,

$$\alpha \equiv \frac{<\ \sigma v\ \ >_i}{<\sigma v>_i + <\sigma v>_m} = f(T_t) \tag{4}$$

where $< \sigma v >$ are the rate coefficients for ionization (i) and momentum loss (m), including both elastic and charge-exchange collisions, given by [3]. Eqns. 3 and 4 were originally derived for gas discharge theory [4]. We assume an isothermal plasma temperature in the recycle region.

The neutral density in the recycle region n_H is related to the parallel scale-length of the region L_H, according to [1],

$$n_HL_H = F(T_t) \equiv \frac{c_{St}}{<\sigma v>_i + <\sigma v>_m}\left(\frac{\alpha+1}{\alpha^{1/2}}\arctan\alpha^{-1/2} - 1\right) \tag{5}$$

The parallel scale-length is determined using,

$$L_H = \frac{\lambda_H}{sin\theta} \tag{6}$$

where θ is the field line pitch angle at the plate and λ_H is the poloidal penetration distance from the plate of recycled neutral atoms based on charge-exchange diffusion [5],

$$\lambda_H = \left(\frac{8T_t}{3\pi m <\sigma v>_i<\sigma v>_m}\right)^{1/2}\frac{1}{n_r} \tag{7}$$

where $n_r = 2n_t/f_m$ is the density at the entrance of the recycle region.

Typically in experiments, rather than n_H in the plasma, one diagnoses the molecular gas adjacent to the divertor fan,

$$\phi_{mol} = \frac{\phi_H}{2} = \frac{1}{8}n_H\overline{c}_H \tag{8}$$

where the ϕ's are the molecular ('mol') and atomic ('H') flux densities and $\overline{c}_H$ is the mean thermal speed of atoms in the fan based on the plasma temperature T_t. We have assumed that atom fluxes out of the fan are balanced by molecular fluxes back into the fan and that other net particles sources and sinks are small in comparison to this exchange.

4 Experiment

The model is compared with experimental results from the Alcator C-Mod tokamak. The SOL plasma density and temperature are measured at the upstream and outer target plate locations with Langmuir probes. The molecular flux density outside of the plasma fan in the divertor is determined using an absolutely calibrated capacitance manometer. The radiated power in the divertor is deduced using multiple chords of bolometer cameras. The experimental results presented here consist of Ohmic discharges at various densities without boronization with $I_p = 0.8MA$, $B_t = 5.4T$ and vertical outer plate geometry.

In Fig. 1 we compare the experimentally determined pressure loss factor f_m at the outer plate on a number of flux surfaces (denoted by their ρ values, mapped to the outside mid-plane) with the prediction of Eqns. 3 and 4. Reasonable agreement between model and experiment is obtained, with strong pressure loss for $T_t < 5eV$ and no pressure loss for $T_t > 10eV$. In particular, the rapid decrease in f_m at low T_t is strong evidence that atomic physics processess are responsible. In the case of neutral friction, this results from the rapid decrease in ionization rate $< \sigma v >_i$ compared with charge-exchange rate $< \sigma v >_m$. Fig. 1, however, may also be consistent with other atomic processes being responsible, for example, volume recombination, which also has a strong temperature dependence and whose signature has recently been observed in C-Mod [6, 7].

The fact that f_m values on different fluxes surfaces are coincident, is perhaps surprising, given the 1-D nature of the model. This is reasonable, however, since plasma flow in the recycling region is primarily along field lines, from ionization source close to the plate to the surface sink, with cross-field transport of plasma being of minor importance.

The full model is now compared with experiment in Fig. 2, as a function of line-average density $\overline{n}_e$ for conditions on a flux surface near the separatrix, $\rho = 1mm$. Two fitting parameters are used in this modelling – the radiated power, as mentioned above, is taken from experiment, and the relation between the upstream density and $\overline{n}_e$, where we make the approximation $n_u = \overline{n}_e/3$. Thus, the 'good fit' between model and experiment in Figs. 2a and 2b is artificial. From global power balance and measurements of the mid-plane radial plasma profiles, $q_u \simeq 75MWm^{-2}$, which is assumed fixed in the modelling, approximately consistent with experiment.

Fig. 2c, 2d, 2e give the model prediction and experimental results for the target plate conditions, n_t, T_t and p_t, and the upstream conditions T_u and p_u, where $p_{t,u}$ are the total electron pressures. The data clearly exhibits three characteristic regimes – the linear/sheath-limited regime at low density, the high recycling regime at moderate density and the detached regime at high density [1, 8]. The linear regime has nearly isothermal conditions between the upstream location and the target plate, with $n_t \propto \overline{n}_e$ and no pressure loss along field lines. In the high recycling, large parallel temperature gradients develop, the target density rises rapidly with discharge density, $n_t \propto \overline{n}_e^3$, and no pressure loss is observed, since $T_t > 10eV$. In the detached regime, the T_t drops below 5 eV and significant pressure loss becomes possible, which results in a 'roll-over' of the target plate density n_t.

The model also gives the molecular flux density outside of the fan, ϕ_{mol}. One notes this continues to rise, throughout all regimes, following in the linear regime $\phi_{mol} \propto \overline{n}_e$, $\phi_{mol} \propto \overline{n}_e^3$ in the high recycling and continuing to rise in the detached regime. It may be, at first sight, surprising that atomic and molecular fluxes should continue to increase in the detached regime, despite a decrease in plasma ion density (and fluxes) at the target plate. The high neutral density is explained, after consideration of ion particle continuity, by the need to supply enough ionization in the face of a strong decrease in the ionization rate at low plasma temperatures [1, 9].

References

References

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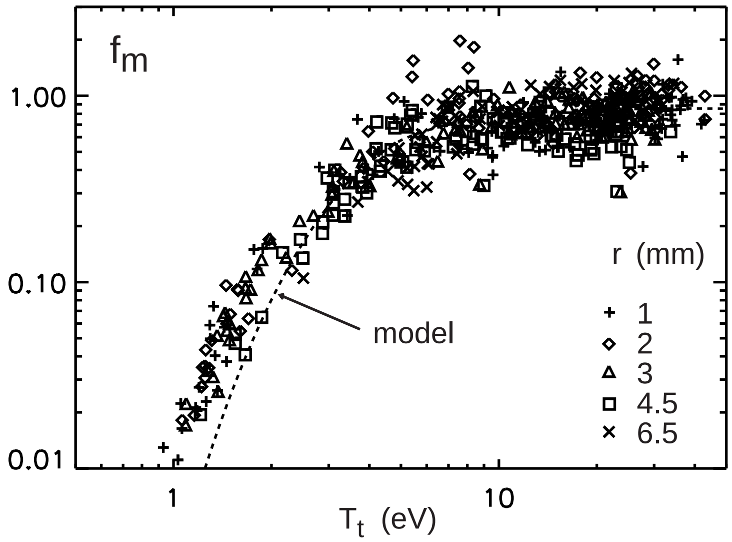
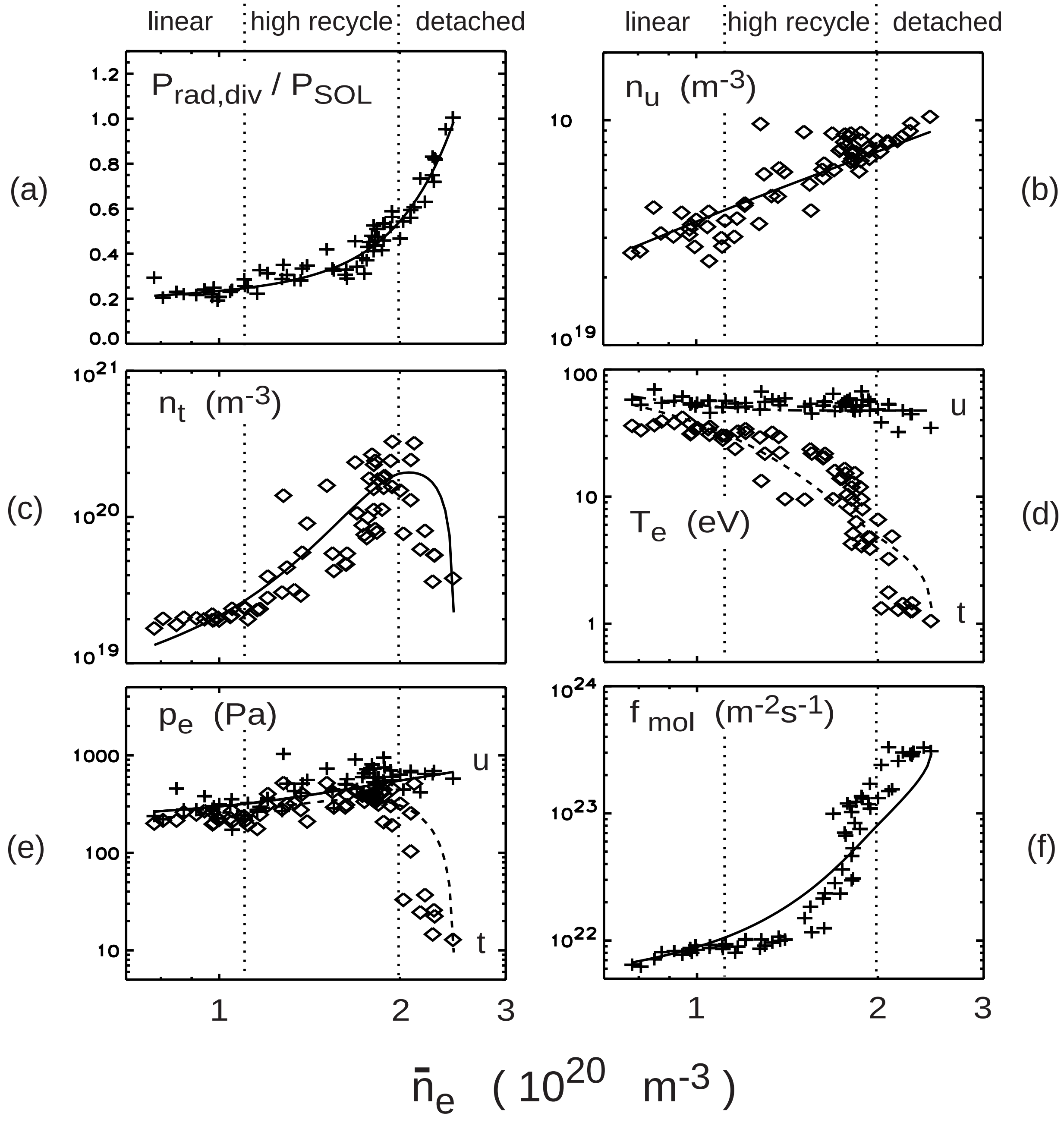
Fig. 1



f_m
1.00
0.10
0.01
1
10
T_t (eV)
model
r (mm)
1
2
3
4.5
6.5

Fig. 2



linear
high recycle
detached
linear
high recycle
detached
(a)
$P_{rad,div} / P_{SOL}$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
(b)
n_u (m^{-3})
10
10^{19}
(c)
n_t (m^{-3})
10^{21}
10^{20}
10^{19}
(d)
100
10
1
u
T_e (eV)
t
(e)
p_e (Pa)
1000
100
10
u
t
(f)
f_{mol} ($m^{-2}s^{-1}$)
10^{24}
10^{23}
10^{22}
1
2
3
1
2
3
$\bar{n}_e$ (10^{20} m^{-3})