A Numerical Study of CX and Radiation Losses in a Divertor Channel

S Weber[1], R Simonini, A Taroni.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.
[1] Permanent address: University of Oxford, Department of Theoretical Physics, Oxford, UK.

A Numerical Study of CX and Radiation Losses in a Divertor Channel

S. Weber*, R. Simonini, A. Taroni
JET Joint Undertaking, Abingdon, Oxon OX14 3EA, U.K.

INTRODUCTION

A new 2-dimensional code, EDGE2D/N, has been set up to investigate the physics of a simple divertor configuration. The aim is not model validation by means of detailed simulations of particular shots but rather the study of basic physics phenomena playing a role in the divertor. Special interest is given to the relative importance of transport, power losses due to hydrogenic atomic processes (charge-exchange (CX) and ionization) and hydrogen radiation in divertor relevant plasma regimes. In particular we analyse quantitatively the relevance of hydrogen atomic losses, following the ideas of Rebut and Watkins /1/. Calculations for JET as well as for ITER relevant cases have been performed.

THE MODEL

The FORTRAN source of EDGE2D/N is produced by a pre-processor written in REDUCE. The code solves the 2-dimensional plasma transport equations in a channel simulating the SOL in a deep slot divertor leg (Fig.1). For JET the length and width of the channel are 0.4 *m* and 0.1 *m* respectively, for ITER the corresponding values are 4 *m* and 0.1 *m*. Transport is classical in the parallel direction and anomalous in the perpendicular (radial) direction. Hot and cold neutrals are treated with a two-group diffusion approximation. Source terms due to CX, ionization and recombination have been included. Different possibilities for neutral recycling are examined. Following /1/ the plasma is neutralized and pumped at the target and refed from the separatrix-side (private region) or the wall (Fig.1). Partial recycling at the target has also been considered. Standard plasma boundary conditions are used at the target. An input power of 10 *MW* (with 5 *MW* in ion and electron channels) for JET is given at the channel entrance with an exponential fall-off away from the separatrix. The powers are increased by a factor of 10 in the case of ITER. Reference values for the thermal and particle diffusivities χ_i, χ_e and $D_\perp$ are: $\chi_i = \chi_e = 1.0\, m^2s^{-1}$, $D_\perp = 0.3\, m^2s^{-1}$. The hot neutrals have the local ion temperature and the cold neutrals are assigned a fixed temperature ($\lesssim 3\, eV$). The average energy loss ξ_i in eV per electron ionization event (including hydrogen radiation) is given by /2/: $\xi_i = 17.5 + (5 + 37.5/T_e)\log_{10}(10^{21}/n_i)$ with n_i in m^{-3} and T_e in eV. Following /1/ we assume that, on average, ionization and CX energy transfer due to the hot neutrals balance.

RESULTS AND CONCLUSIONS

The following tables give a summary for JET and ITER cases. n_i is taken as the maximum value at the channel entrance. The "net CX loss" takes into account the contribution to ions of cold neutral ionization. All powers are given in *MW*.

*)permanent address: University of Oxford, Department of Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, U.K.

ITER private region-recycling:

cold neutral influx s^{-1} $[10^{23}]$	n_i m^{-3} $[10^{19}]$	net CX loss	ioni-zat. + rad. losses ele.	total rec. losses	total atomic losses	ele. power flux to target	ion power flux to target	ele. power flux to wall	ion power flux to wall
6.0	3.2	28.16	1.43	0.0005	29.59	48.57	21.70	0.09	0.06
7.5	6.8	22.52	2.14	0.003	24.67	48.44	26.69	0.09	0.12
10.0	12	19.31	3.20	0.02	22.52	50.05	27.12	0.13	0.18
12.5	15	18.51	4.12	0.02	22.66	51.20	25.8	0.16	0.22

ITER wall imposed flux:

cold neutral influx s^{-1} $[10^{23}]$	n_i m^{-3} $[10^{19}]$	net CX loss	ioni-zat. + rad. losses ele.	total rec. losses	total atomic losses	ele. power flux to target	ion power flux to target	ele. power flux to wall	ion power flux to wall
3.4	4.4	16.03	0.63	0.001	16.67	49.83	33.15	0.16	0.20
12.5	5.6	15.97	3.07	0.006	19.04	49.37	30.91	0.34	0.34
42.5	8.9	8.40	11.94	0.29	20.62	47.76	28.30	1.66	1.66
105	19	-1.90	23.43	1.52	22.96	44.78	26.19	3.03	3.04

JET private region recycling:

cold neutral influx s^{-1} $[10^{23}]$	n_i m^{-3} $[10^{19}]$	net CX loss	ioni-zat. + rad. losses ele.	total rec. losses	total atomic losses	ele. power flux to target	ion power flux to target	ele. power flux to wall	ion power flux to wall
0.7	3.3	1.71	0.16	0.0000	1.87	4.85	3.28	0.001	0.001
1.1	6.6	1.48	0.27	0.0001	1.75	4.78	3.47	0.001	0.001
1.7	14	1.36	0.49	0.0004	1.85	4.79	3.35	0.001	0.001
2.2	18	1.36	0.66	0.0008	2.02	4.80	3.18	0.001	0.001

JET wall imposed flux:

cold neutral influx s^{-1} $[10^{23}]$	n_i m^{-3} $[10^{19}]$	net CX loss	ioni-zat. + rad. losses ele.	total rec. losses	total atomic losses	ele. power flux to target	ion power flux to target	ele. power flux to wall	ion power flux to wall
4.8	5.8	0.35	0.90	0.0005	1.25	4.61	4.13	0.002	0.003
6.0	7.0	0.32	1.07	0.0007	1.39	4.57	4.03	0.002	0.003
20.5	12	0.12	2.07	0.003	2.19	4.41	3.39	0.003	0.005
60	18	-0.24	3.27	0.01	3.04	4.24	2.71	0.007	0.006

In the tested range of densities recombination remains negligible. Recycling of neutrals from either the separatrix or wall side presents two rather different scenarios. In the case of separatrix-side recycling the outflow of plasma at the target equals the inflow of cold neutrals. The outflow of neutrals to the wall is negligible in comparison. On the other hand if a cold neutral influx is imposed from the wall the outflow of neutrals to the wall is in general a large fraction of the injected flux and larger than the plasma flux to the target. The considerably higher flux of neutrals from the wall compared to that from the private region (even though plasma densities and total losses don't differ much), accounts for the fact that only a fraction of the cold neutrals gets ionized, the rest returning as neutrals. For high densities (ca. $1.5 - 2 \cdot 10^{20}\, m^{-3}$) the temperature along the separatrix is about a factor $2 - 4$ lower for separatrix-side recycling than for wall recycling and decreases in the case of ITER from 280 eV to 60 eV (along the separatrix). For lower densities (ca. $3 - 5 \cdot 10^{19}\, m^{-3}$) the variations are smaller, decreasing from 360 eV to 240 eV. CX is more effective where the plasma temperature is high and therefore to exploit this to a maximum, neutrals have to be injected from the separatrix-side. In contrast, the atomic losses in the case of wall recycling are mainly due to ionization.

Trends of results are similar for JET and ITER cases (Figs 2-4 refer to one particular ITER case). If ITER recycling from the private region is considered, for the range of densities tested, the atomic losses vary around 22-29% of the input power. At very high density (ca. $4.8 \cdot 10^{20}\, m^{-3}$, not in the table) the atomic losses increase again up to 35% of which about two thirds are due to CX. It is more favourable to have some recycling at the target in addition to separatrix-side recycling. In this case the density of the plasma is considerably lower for the same atomic losses. For example in the JET case having 30% separatrix and 70% target recycling lowers the density along the separatrix by a factor of two (from $1.4 \cdot 10^{20}\, m^{-3}$ to $7 \cdot 10^{19}\, m^{-3}$) while increasing the atomic losses from 18.5% to 22%. At the same time the neutral flux decreases from $1.7 \cdot 10^{23}\, s^{-1}$ to $1.2 \cdot 10^{23}\, s^{-1}$.

Concentrating the recycling in the upstream half of the channel is not beneficial: at $n_i = 1.4 \cdot 10^{20}\, m^{-3}$ the losses go from 18.5% to 16.8%. Similarly doubling the channel length gives only a slight increase of the total atomic losses (at $1.4 \cdot 10^{20}\, m^{-3}$ from 18.5% to 21.7%). In order to maximize atomic losses and improve the efficiency of the scheme, the neutral influx (from the separatrix-side) would have to be tailored (e.g. increasing the plasma density as the temperature decreases along the channel). A better scheme probably would imply injection of impurities upstream. In this case recirculation of the neutrals is intended mainly to trap the impurities in the divertor region.

For the range of densities considered here, which extends to rather high values, about 20-30% of the incoming power can be dissipated via atomic losses (including hydrogen radiation). When the density is of the order of $3 \cdot 10^{19}\, m^{-3}$ or less the temperature remains high even if the atomic losses are comparable to cases at high density. To lower the plasma temperature throughout the channel a very high density ($> 2 \cdot 10^{20}\, m^{-3}$) and separatrix-recycling are necessary. These calculations indicate that hydrogen atomic losses are probably not efficient enough to lead to plasma extinction for realistic values of the plasma density and channel length. The energy losses scale well from JET to ITER, which allows a test of the concept at JET.

REFERENCES

/1/ Watkins, M.L., Rebut, P.-H., 19th Europ. Conf. on Contr. Fusion and Plasma Phys., Innsbruck, Austria 1992

/2/ Harrison, M.F.A., Harbour, P.J., Hotston, E.S., Nuc. Tech./Fusion 3 (1983) 432

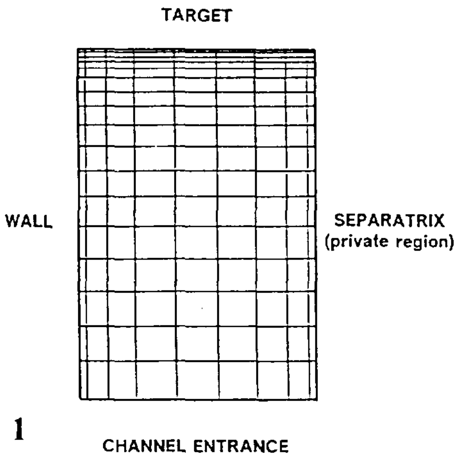
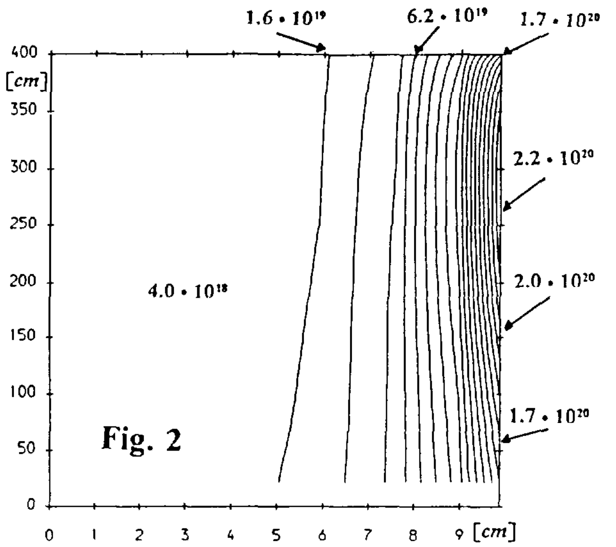
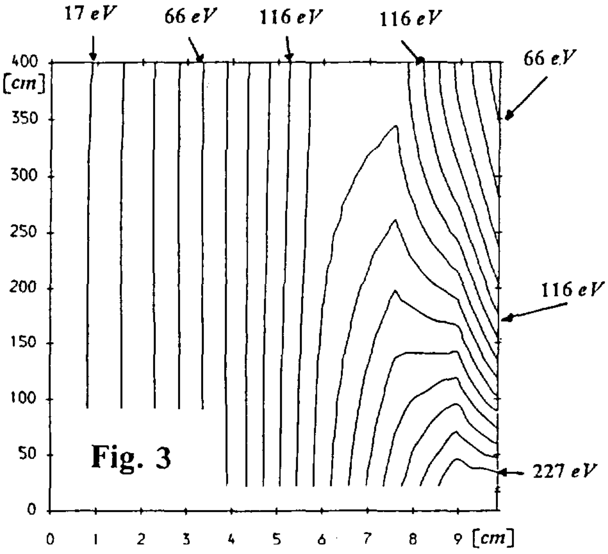


Fig. 1





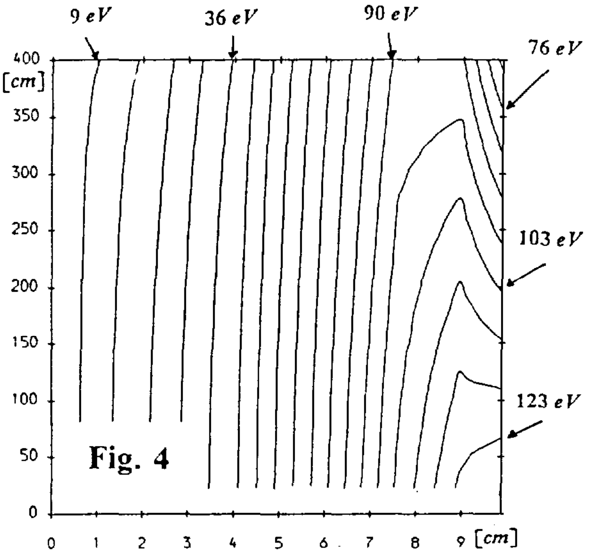


Figure 1. The computational plasma channel: a slab geometry with a non-uniform mesh and a constant magnetic pitch of $h_p = 0.1$ is used

Figure 2. Plasma density: ITER separatrix-side recycling for $n_i = 1.5 \cdot 10^{20}\,m^{-3}$ - $\Delta n_i = 1.15 \cdot 10^{19}\,m^{-3}$

Figure 3. Ion temperature: ITER separatrix-side recycling for $n_i = 1.5 \cdot 10^{20}\,m^{-3}$ - $\Delta T_i = 12.4\,eV$

Figure 4. Electron temperature: ITER separatrix-side recycling for $n_i = 1.5 \cdot 10^{20}\,m^{-3}$ - $\Delta T_e = 6.7\,eV$