d038

B2 - Eirene Simulations for a Deuterium Plasma at PSI-1

H. Kastelewicz, D. Reiter(*), R. Schneider, D. Coster, H. Meyer
Max-Planck-Institut für Plasmaphysik, EURATOM Association, Germany
(*) IPP, Forschungszentrum Jülich GmbH, EURATOM Association, Germany

1. Introduction

PSI-1 is a linear, axisymmetric device (Fig.1) which generates a plasma column of about 1.8m length and 5 to 10 cm diameter by means of a high current arc confined by an axial magnetic field ($0.05 \leq B/T \leq 0.1$). It is primarily designed to study outstanding problems of plasma-surface interactions at high ion flux densities relevant for fusion devices. The plasma column (outside of the anode) is axially limited by a target plate (carbon) and radially bound by diaphragms (carbon) for differential pumping ($10^{-2} \leq p/Pa \leq 1$) or by walls (stainless steel) of different radii ($10 \leq r/cm \leq 20$). Plasma density and temperature are in the ranges $10^{11} \leq n_e/cm^{-3} \leq 10^{14}$, $T_e \leq 10eV$ / 1 /.

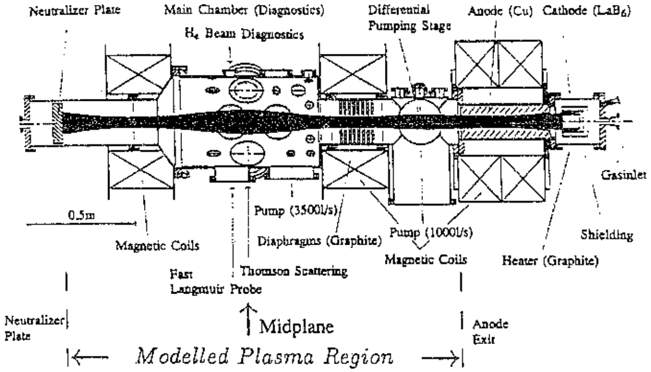


Fig. 1: Plasmagenerator PSI-1 (experimental arrangement)

2. Model System

The plasma is numerically modelled in the region between the anode exit and the target plate limiting axially the column using the coupled package of the B2 2D hydrodynamic plasma code and the Eirene 3D neutral Monte-Carlo-code / 2,3 /. Eirene provides a correct kinetic description of the neutrals recycling from the surfaces or streaming in from the anode (partially ionized plasma) and the gas pumping; the essential interaction processes with the surfaces and the plasma are taken into account.

The B2 calculational grid is defined by the magnetic flux surfaces. The ion motion in the axial direction (parallel to the field lines) is described by hydrodynamic equations and in the radial direction (orthogonal to field lines) by an anomalous diffusion with a diffusion coefficient in the range $D_i \approx (0.1 \div 1)m^2/s$. For the radial heat conductivities $\kappa_{e,i}/n_{e,i} = 1m^2/s$ and the viscosity $\eta_i/m_i n_i = 0.2m^2/s$ are assumed. Boundary conditions must be specified for the ion density, the ion and electron temperatures (or the corresponding particle and energy fluxes) and the ion velocity parallel to field lines.

The boundary conditions at the anode exit defined by the arc are the driving parameters of the model. Up to now, they have not been derived yet from experiments (or theoretical simulations of the arc) and, therefore, will be considered as adjustable parameters. In order to simulate a particular experiment in PSI-1 they must iteratively be calculated by comparing code results with measured profiles in the diagnostic plane (midplane).

For the boundary conditions at the wall side of the grid a decay length of 1cm for all plasma profiles is assumed and at the target plate and the outer anode surface Bohm conditions are used.

We calculate steady states for a deuterium plasma. In steady state, the "external" D$^+$ ion (and D atom) source at the anode exit is balanced by the loss of deuterium neutrals through the two pumps; the energy influx from the anode equals the energy deposited onto the different surfaces by electron and ion thermal conduction and convection and by the neutrals.

3. Results

Plasma state

In the present model, the essential parameters controlling the plasma are the boundary conditions (radial plasma profiles) at the anode exit. Calculations have been done assuming radially constant profiles for the plasma density, temperature and axial velocity to study the general properties of the system as well as hollow n_e, T_e profiles which are more appropriate to simulate the actual experimental situation in PSI-1 where, at present, concentric ring-shaped structures are used for both the anode and cathode.

Figs.2a) and 2b) show the radial density and temperature profiles in the midplane for various (radially constant) anode temperatures T_e, T_i but the same density $n_e = 5 \cdot 10^{18} m^{-3}$ ("soft" B2 boundary condition) and Mach number $M = 0.1$ of the parallel velocity assuming two different radial diffusion coefficients $D_i = 1m^2/s$ and $D_i = 0.2m^2/s$.

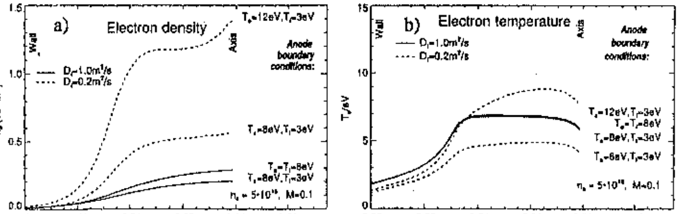
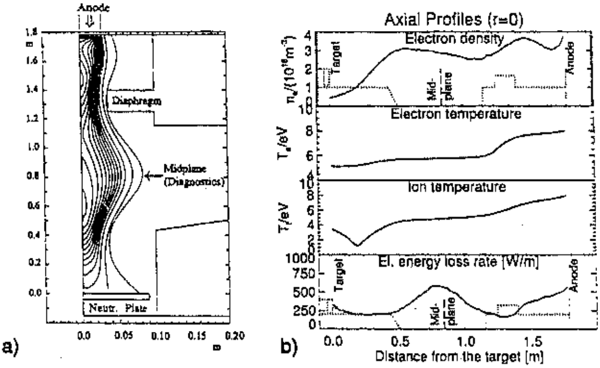


Fig. 2: Radial plasma profiles (midplane) for various anode parameters and diffusion coefficients

The sensitive dependence of the plasma density on the anode temperature T_e shows that plasma recycling basically determines the plasma state. The arc provides an energy source and an initial particle influx from the anode exit, but obviously, the plasma column is actually produced afterwards by the interaction with the neutral background. Better confinement and, as a consequence, enhanced plasma recycling is also the reason for the strong increase of the plasma density with decreasing radial diffusion coefficient D_i.

The (constant) radial temperature profile prescribed at the anode exit is hardly changed along the column because of the high parallel heat conductivity. It is remarkably modified only in the high-recycling regime where a slight hollow profile is formed due to enhanced ionization cooling near the axis of the column.

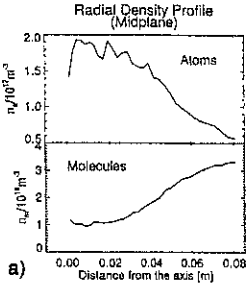
Because of the long mean free path of the neutrals ($\approx 0.5m$) under the typical conditions of PSI-1, practically the whole plasma is involved in the recycling process. Figs.3 show the density contour plot and some axial profiles for the low temperature case ($T_e = T_i = 8eV$ at the anode exit, $D_i = 1m^2/s$). The electron density has axial maxima which do not coincide with the places of maximum plasma compression due to the inhomogeneous magnetic field. This is a consequence of the strong recycling zones (plasma sources) which arise in these regions, although they are far away from the main neutral sources at the target plate and the outer anode surface. The ionization and electron energy loss rates per cm column length (radially integrated rates, Fig.3b) are maximum in the regions of greatest plasma radius. This also causes a steep axial T_e drop near the diaphragm.
Local recycling at the target plate, however, increases nonlinearly with T_e and would dominate for boundary anode temperatures above $\approx 12eV$. In this case an additional density maximum develops in front of the target plate.

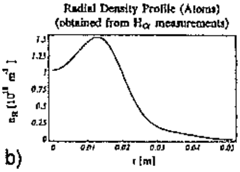


Figs. 3:
a) Electron density contour plot
b) Axial plasma profiles

Neutrals

The deuterium atomic and molecular densities and temperatures are obtained from the Eirene code which takes into account the essential surface processes (reflection, absorption and re-emission of molecules) as well as the collision processes with the plasma (dissociation, ionization, charge exchange, elastic collisions).
The D_2 density has clear maxima in front of the target plate and near the walls where the molecules are produced with wall temperature by thermal re-emission. D atoms originate from surface reflection of ions or atoms or from the dissociation of molecules (Franck-Condon atoms) and posses a much higher mean energy (about 3eV). Their mean free path ($\approx 0.5m$) is larger than the radial dimension of the plasma ($5 \div 10cm$), so they experience many wall reflections and tend to form an almost uniform neutral background in the axial direction.
In the radial direction one obtaines complementary density profiles for D and D_2 (Figs.4a) which show that the radial dependence is caused by D sources and D_2 sinks, respectively, which arise from the dissociation of molecules. Similar profiles are found experimentally (Fig.4b).





Figs. 4:

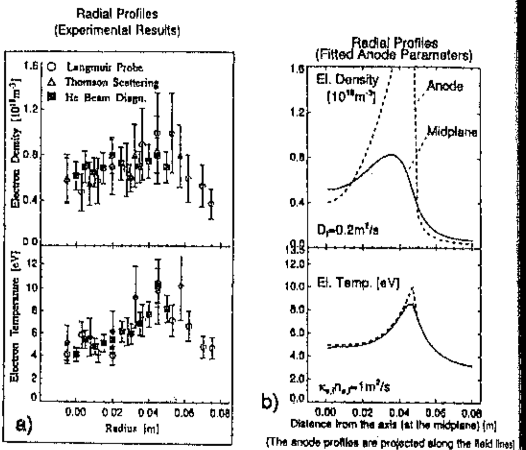
a) Calculated density profiles (midplane) for $T_e = T_i = 8eV$ at the anode exit and $D_i = 1m^2/s$

b) Density profile of H atoms derived from H_α diagnostics

Fitted code solution

The various diagnostics in PSI-1 yield hollow density and temperature profiles due to the special configuration of the cathode-anode system which cannot be modelled satisfactorily with radially constant anode boundary conditions. Fig.5b shows a set of anode n_e, T_e profiles (dashed curves) chosen to fit the measured profiles in the midplane (Figs.5a). $T_i = 3eV$ is assumed. Good agreement can be achieved for the T_e profile which is transformed from the anode to the midplane almost without distortion because of the high parallel heat conductivity.

The density profile , however, is largely smoothed out. For $D_i = 0.2m^2/s$ assumed in this case a good fit can be obtained for the plasma region inside the geometric projection (along field lines) of the anode exit (although for an extremely hollow profile at the anode), but in the outer region the density decreases too fast (compared with the experimental results) and a higher value for D_i would be required. ($D_i = 1m^2/s$ yields already a monotoneously decreasing profile in the midplane.) This discrepancy needs still to be clarified (variable D_i , check of the experimental data for larger radii).



Figs. 5

Measured plasma profiles (a) and code solution for fitted parameters (b)

References

/ 1 / Behrendt, H. et al., 1994 Proc. 21th EPS Conf. on Contr. Fusion and Plasma Physics (Montpellier) p III-1328

/ 2 / Reiter, D., J. Nucl. Mat. 196-198 (1992) 80

/ 3 / Schneider et al., J. Nucl. Mat. 196-198 (1992) 810