Plasma Modelling for PSI-1

H. Kastelewicz[1], D. Reiter[2], R. Schneider[3], D. Coster[3], H. Meyer[3]

[1]Humboldt-Universität, Berlin, Germany
[2]IPP, Forschungszentrum Jülich GmbH, EURATOM Association, Germany
[3]Max-Planck-Institut für Plasmaphysik, EURATOM Association, Germany

Introduction

In the axisymmetric device PSI-1 an electric high-current arc is used to produce a magnetically confined plasma column of 1.8m length and about 5 to 10 cm diameter outside of the anode.

Because of the particular ring-shaped design of the anode-cathode system and the effect of the magnetic field the plasma is actually generated off-axis within a narrow shell near the inner anode surface. As a consequence, pronounced hollow radial profiles are built up for the plasma density and temperature which may essentially be modified downstream the plasma column due to radial diffusion, axial streaming and the interaction with the neutrals background (recycling).

Previous modelling of the plasma by the authors using the B2–Eirene code package / 1 / have been resrticted to the plasma column outside the anode since the actual version of the B2 code does not allow for electric fields and currents. In these calculations the radial plasma profiles at the anode exit (electron and ion densities, electron and ion temperatures, ion velocities) are boundary conditions of the code which must be prescribed in any way.

In order to avoid this large set of mostly unknown boundary parameters, the anode-cathode region has been included in the present model in a simplified manner by prescribing explicitely the electron energy source due to the discharge current. The latter is strongly localized (bound to the magnetic field) and may reasonably be estimated. The plasma state is thus directly related to external discharge parameters (input power, gas influx rate).

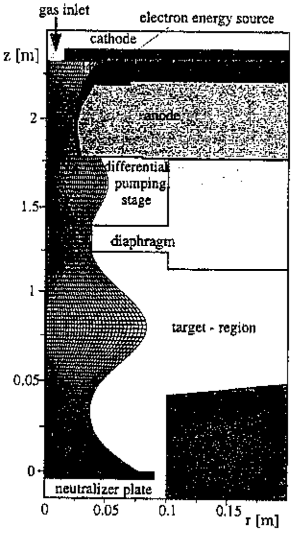
PSI-1 model

Fig. 1 shows an axial cross-section of the device and the geometrical assumptions of the model.
Like in the experiment, the neutral gas (atoms or molecules) flows in through a concentric hole in the cathode bottom and is pumped in the target chamber and the differential pumping stage according to given pumping efficiencies. Under steady-state conditions (which are considered here), both, the net influx and the pumping rates are equal.

The B2 calculational grid is defined by the magnetic flux surfaces and its orthogonals and incloses axially the whole plasma volume between the cathode bottom and the neutralizer plate. As boundary conditions in the radial direction the decay length ($\lambda = 1cm$) of the ion densities, the electron and ion temperatures and the parallel velocities are prescribed; in the parallel direction (neutralizer plate, outer anode surface, cathode bottom) Bohm conditions are used.
The anomalous radial transport is described by the transport coefficients: $D_i = 0.5m^2/s$ (ion diffusion), $\kappa_{e,i}/n_{e,i} = 1.0m^2/s$ (heat conduction), $\eta_i/m_i n_i = 0.2m^2/s$ (viscosity).

In order to simplify the boundary conditions, the inner anode surface is assumed to be identical with a magnetic flux surface (axial co-ordinate line) and the geometrical structure of the cathode is neglected. Both approximations should hardly influence the plasma results, particularly in the column outside the anode. On the other hand, the assumed electron energy source (see Fig. 1), in this approximation, excludes parallel components of the discharge current hitting the anode surface and is not representative, therefore, for the total discharge power.

In this paper the source will be characterized by a constant electron temperature $T_{e,source}$ in the specified region or by the corresponding energy $P_{e,source}$ transfered there to the plasma electrons. The electron temperature in the source region and the neutral gas influx rate are the only external parameters of the model.



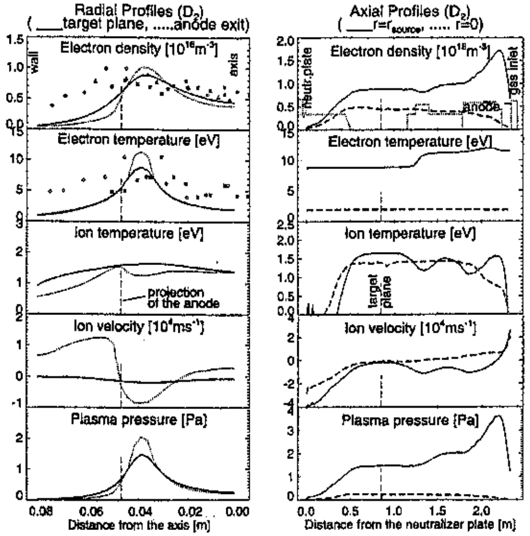


Fig. 1
Model system of the plasma generator PSI-1

Fig. 2 Radial and axial plasma profiles for a D_2 plasma
The radial profiles at the anode exit (dotted lines) are projected along the magnetic field lines to the target plane. The axial profiles are along the magnetic flux surface just through the source region (full line) and at the column axis (dashed line).

Deuterium Plasma

We consider a steady state deuterium plasma for the following parameters:

Net gas influx rate: $F_{D_2} = 0.63 \times 10^{19} s^{-1}$

Electron source temperature: $T_{e,source} = 12eV \quad (P_{e,source} = 860W)$

The total ion and energy fluxes leaving the anode exit are in this case $F_{D^+} = 8 \times 10^{18} s^{-1}$

and $F_e = 250W$. The corresponding fluxes onto the neutralizer plate are $F_{D^+} = 1.7 \times 10^{19} s^{-1}$ and $F_e = 140W$ showing an enhanced ion flux due to local recycling. Some axial and radial profiles of essential plasma parameters are given in figs. 2.

In the target plane one gets radial plasma profiles which are in good agreement with experimental data (fig. 2). Comparing n_e in the target plane and at the anode exit one finds only a rather small flattening of the hollow profile. The relaxation effect of radial ion diffusion along the plasma column is largely compensated by two processes: (i) considerable ionization rates in the outer column layers with high electron temperature and (ii) near the symmetry axis, axial ion loss to the neutralizer plate but also – in the case of a deuterium plasma – to the anode side.

In this case an axial ion flow inversion back into the anode occurs near the column axis. The reason is a pressure gradient which is built up by "ion sources" due to radial inward diffusion and "sinks" at the neutralizer plate and the cathode bottom. If this flow reversal is artificially blocked or inverted by appropriate boundary conditions of the code (cf. / 1 /), a much steeper density profile at the anode exit ($n_{e,max}/n_{e,axis} \approx 5$) would be required to produce a profile like that of fig. 2 for the target plane.

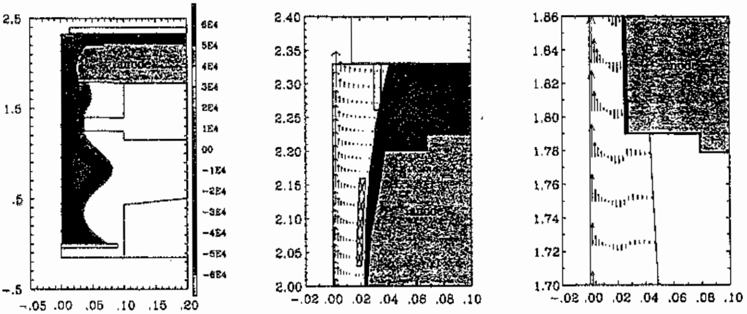


Fig. 3
Contour plot and arrow plot of the axial ion velocity showing flow reversal back to the anode.

Neutrals

The D and D_2 densities have steep gradients in the anode-cathode region but rather flat profiles in the column outside the anode due to the long mean free path of the neutrals. In the target chamber n_D increases radially in inward direction while n_{D_2} deceases due to the dissociation of molecules and the action of the wall (source for molecules and sink for atoms). The densities vary radially as $n_D \approx (1 \div 1.6) \times 10^{17} m^{-3}$ and $n_{D_2} \approx (2 \div 1.3) \times 10^{18} m^{-3}$, which roughly corresponds to an dissociation degree of 10% in the plasma column. The atom density agrees with mesurements with the two-photon spectroscopy but is smaller than results obtained by passive H_α spectroscopy. This discrepancy need still to be clarified. Uncertainties result in particular from the dissociation rates of vibrationally excited molecules.

The D_α radiation of the atoms has a clear hollow profile (as a consequence of the hollow T_e profile) with a maximum intensity of about $P_\alpha = 30W/m^3$ in the target chamber.

Argon Plasma

The experimentally achieved densities for an argon plasma are usually higher than for deuterium. We consider here the following high-density case, but the principal results apply also for lower densities:

Net gas influx rate: $F_{Ar} = 7.8 \times 10^{19} s^{-1}$

Electron source temperature: $T_{e,source} = 12eV, \quad (P_{e,source} = 25kW)$

The total ion and energy fluxes out of the anode are $F_{Ar^+} = 1.3 \times 10^{19} s^{-1}$ and $F_e = 1.5kW$ and onto the neutralizer plate $F_{Ar^+} = 3.5 \times 10^{19} s^{-1}$ and $F_e = 250W$. The total radiated energy is $P_{rad} = 22kW$, the most part being radiated between anode and cathode.

In contrast to the deuterium plasma no hollow profiles for the electron density are found (even just outside the anode exit) and no ion flow inversion is built up. This is partly due to the more effective radial relaxation (smaller axial velocities) and the contribution of higher charge stages. Typical for the argon plasma is a very steep density decrease in the anode region.

In the target chamber the *neutral density* is nearly constant, $n_{Ar} \approx 1.0 \times 10^{19} m^{-3}$, and comparable with the ion density.

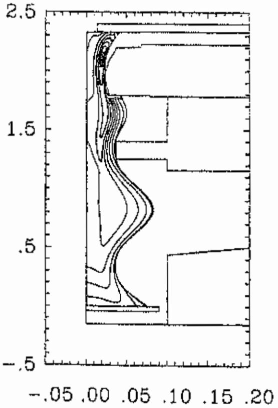


Fig. 4 Contourplot of the Ar line radiation (log. scale)

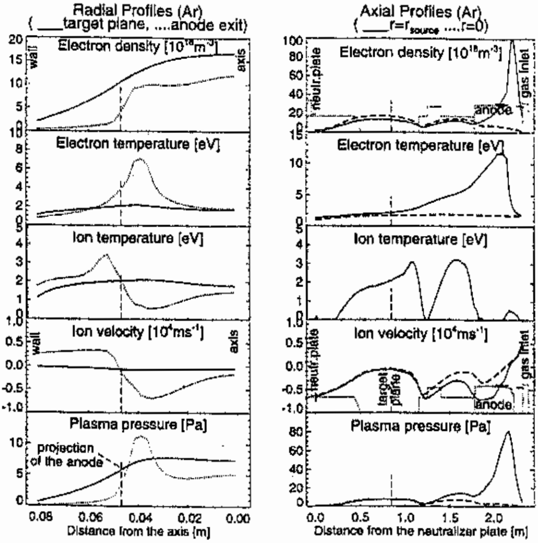


Fig. 5 Radial and axial plasma profiles for an Ar plasma

Reference

/ 1 / H. Kastelewicz, D. Reiter, R. Schneider et al., 23rd EPS Conf. on Fusion and Plasma Physics (Kiev,1996) p II-803