Particle–in–cell simulations of the impact of retarding field analyser probe head geometry on ion saturation current measurements

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Received 26 April 2004

The Retarding Field Analyser (RFA) is essentially the only practical tool for the measurement of ion energies parallel to the total magnetic field in the tokamak scrape–off layer plasma. One such device has recently been successfully employed at JET [1]. Its bi–directional nature allows both measurements of ion temperature and plasma flow velocities. The latter are computed by collecting the ion saturation flux to negatively biased entrance slit plates which are set back inside a boron nitride protective housing. When comparing the RFA slit currents with those measured by a turbulent transport probe (TTP), the RFA fluxes are found to be a factor 4 to 5 lower for very similar plasma conditions. Using Particle–in–Cell (PIC) simulations, this contribution demonstrates unambiguously and quantitatively, that the RFA flux attenuation is induced by the magnetic pre–sheath formed in the orifice in front of the slit plates.

PACS: 52.70.Ds
Key words: retarding field analyser, magnetic pre–sheath, plasma flow, tunnel effect

1 Introduction

Ion temperature and velocity distributions in the plasma edge of the tokamak are notoriously difficult to measure. The Retarding Field Analyser (RFA) offers an approach which can access the plasma ions or electron distribution directly and has been successfully demonstrated in several tokamaks [2]–[4]. The probe is generally designed to measure the component of the charged particle velocity parallel to the magnetic field direction.

The principle of the RFA can be briefly described as follows: charged particles are transmitted through an aperture and are analysed by retardation in the electric field established through bias potentials applied to a number of grids (Fig. 1). In the edge plasma of

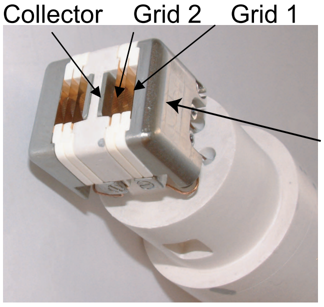

Fig. 1. Internal components of the JET bi–directional RFA [2] showing the entrance slit plates, retarding grids and collectors.

fusion devices the probe containing the RFA electrodes is aligned along the total magnetic field such that the parallel component of the charged particle velocity distribution is the sampled quantity. The entrance slit is wide enough to permit adequate flux transmission, yet sufficiently small to shield the aperture from the plasma. This implies slit widths of the order of the Debye length which is typically of the order of several tens of microns in the tokamak edge plasma.

In JET, the RFA system is positioned at the top of the torus just outboard of the plasma center line at a major radius of 3.25 m. When used as a Mach probe, slit plates positioned at right angles to the field lines on the either side of the probe body are biased at −150 Volts to collect ion saturation current $j_{\mathrm{sat,o}}$ and $j_{\mathrm{sat,i}}$ on plates facing the outer and inner divertor, respectively, along field lines. The slit plates, which can withstand high heat loads, are placed behind opening tunnels of area 24 mm^2 (Fig. 3), which are machined into the boron nitride probe protective housing and define a collection area. This boron nitride housing and the tunnel walls are coated with carbon to avoid sputtering of the insulating housing material onto the slit plates. The carbon layer has been, however, partially absorbed into the boron nitride probe head during baking making it hard to judge the electrical conductivity properties. The tunnel walls constitute an orifice which restricts the plasma flow to the slit plates – quantifying the amplitude of this effect is the subject of this contribution.

The Turbulent Transport Probe [TTP] is a second probe used for measurements in the JET SOL [5]. It is a 9 graphite pin Langmuir probe, with 5 pins positioned on the top of a 5 mm high boron nitride divide oriented at right angles to the field lines. These pins, together with 3 pins behind one side of the divide, are cylindrical with 1 mm diameter. A fourth, larger pin, is located on the other side of the divide. For parallel flow measurements, the pins on each side of the divide are biased at −200 V to collect $j_{\mathrm{sat,o}}$ and $j_{\mathrm{sat,i}}$. Both probes are located at the same poloidal position in the JET torus, but separated 180° toroidally.

Typical measurements of $j_{\mathrm{sat,o}}$ and $j_{\mathrm{sat,i}}$ from both the TTP and RFA are shown in Fig. 2 [6]. This example is for a 2 MA, 2 T normal field ohmic discharge with central density ramp from $< n_e >= 1.6 \times 10^{19}$ m^{-3} to 3.4×10^{19} m^{-3}. There is a clear discrepancy between the measurement of $j_{\mathrm{sat,o}}$ and $j_{\mathrm{sat,i}}$ using the two probes. The ion saturation current measured by RFA is 4 to 5 lower than the TTP value. It should be noted, however, that there is some uncertainty in the TTP j_{sat} values owing to uncertainty in the absolute values of the pin collecting areas due to finite Larmor radius effect.

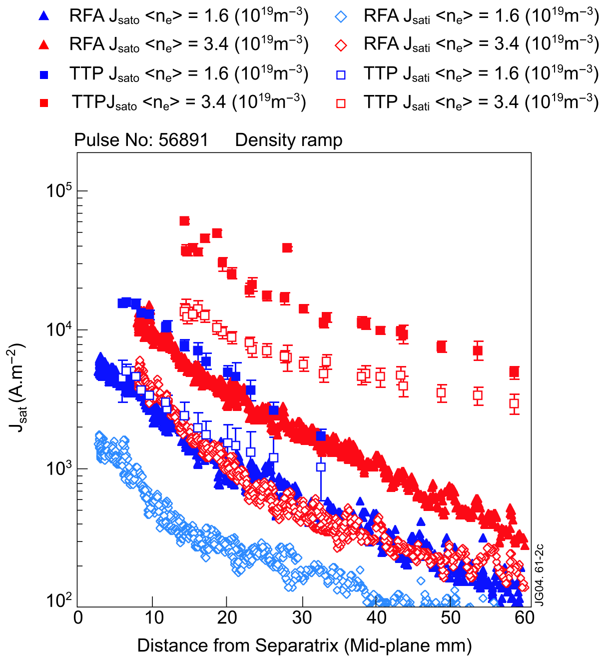

Fig. 2. Ion saturation curents, $j_{sat,o}$ and $j_{sat,i}$, as measured on each side of the RFA and TTP acting as Mach probes [6].

2 Numerical model

The attenuation of the plasma flow inside the tunnel and consequently the difference in ion saturation current measurement between RFA and TTP, is caused by a magnetic pre–sheath effect (see e.g. [8]). A very strong radial electric field established close to the tunnel wall demagnetizes ions and draws them to the walls as shown schematically in Fig. 3 [9],[10]. At the same time, the electrons are still magnetized due to their much smaller Larmor radius and continue to flow toward the slit plates. The thickness of the magnetic pre–sheath layer is in this case a complex function of the ion and electron temperatures (T_i, T_e), as well as plasma density and can only be computed numerically.

The two–dimesional Particle–in–Cell (PIC) code XOOPIC [11] has been used to simulate the RFA “tunnel” effect and its subsequent impact on the ion saturation current collected by the slit plates. The RFA tunnel in front of the slit plates is rectangular. These simulations are performed in a Cartesian coordinate system to allow easy interpretation of the rectangular geometry of the RFA tunnel. However, since XOOPIC is a 2D code, one of the tunnel dimensions must be assumed infinite in making the simulation. As shown in Fig. 4, the larger of the two rectangular dimensions is neglected (6 mm) and a 4 mm wide tunnel is simulated. Since the attenuation factor is greatest for a narrower tunnel, this represents the worst case scenario and will give an upper limit of the attenuation factor for one tunnel dimension. The geometry of the model is depicted in Fig. 5. Plasma particles (Maxwellian electrons and deuterons) are injected from the right hand side at a rate corresponding to a given ion saturation current density and flow along the magnetic field lines into the tunnel. The tunnel walls are assumed to be electrically conducting and biased at floating potential, with the left hand side of the model representing the conducting slit plate biased at −150 V. The ratio of the injected ion saturation current density to that reaching the slit plate gives the attenuation factor, δ, for the RFA tunnel.

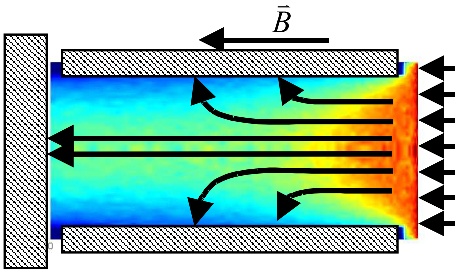

Fig. 3. The strong radial electric field gradient established in the tunnel demagnetizes the ion gyro–orbits. Ions are ripped from their guiding center trajectories and drawn to the wall.

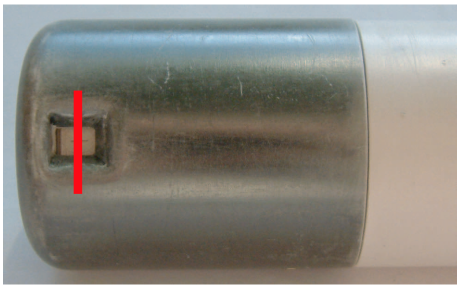

Fig. 4. Photograph of the probe head and the tunnel with slit plate. The vertical red line indicates the shorter of the two rectangular dimensions – this is the section across which the tunnel is simulated.

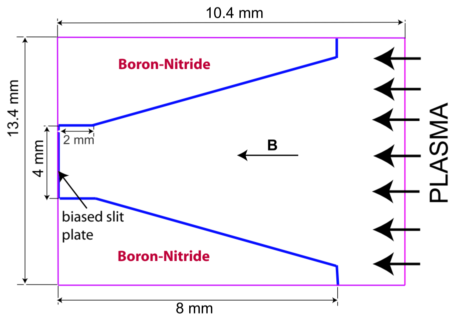

Fig. 5. XOOPIC model geometry.

In this paper the attenuation factor for different radial positions of the RFA (for different values of j_{sat}, T_e and T_i) is calculated. These parameters are extracted from experimentally obtained radial profiles [6] (Fig. 6, T_e, Fig. 7, j_{sat}). Ion temperatures are assumed to be $2 \times T_e$ – an observation well supported by experiment [7]. The profile marked “EDGE2D” in Fig. 7 is the result of code simulations using EDGE2D/Nimbus package in which the entire JET SOL is modelled using experimental profiles of n_e, T_e as a guide. Although the shape of the RFA j_{sat} profile is well matched, the RFA data need to be multiplied by a factor of 6.5 to bring code and experiment into agreement. Part of this factor is due to the tunnel effect.

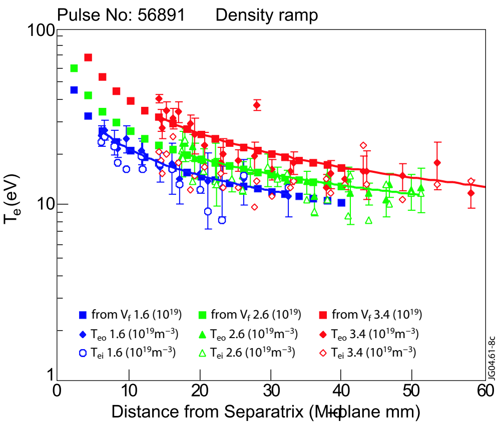

Fig. 6. Electron temperatures measured on probes facing outer divertor, T_{eo}, and inner divertor, T_{ei}, of scanning TTP probe, (points with error bars). The full lines are a fit to the data using standard sheath theory to relate V_f and T_e [6].

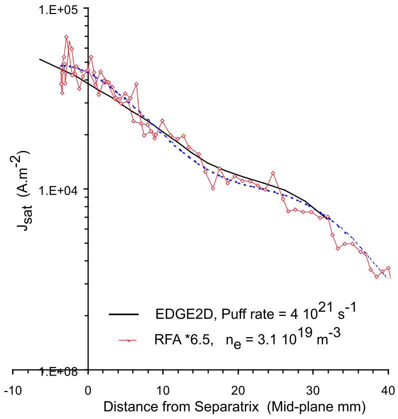

Fig. 7. A comparison of corrected ion saturation current to the RFA (unperturbed flux) with the EDGE2D prediction. The experimental data has to be multiplied by a factor 6.5 to match the code prediction.

3 Simulation results

Examples of the electron and deuterium density profiles along the tunnel axis are shown in the Fig. 8. They have been obtained for values of T_e and j_{sat} corresponding to distances of 2 mm and 32 mm from the LCFS. One can see that the main decrease of the density begins approx. 2 mm from slit plate; at larger distances the density is almost unaffected. Quasineutrality is well conserved except for the sheath region close to the slit plate, where the electron density quickly falls to zero and deuteron density to some particular value due to deuteron acceleration.

In Fig. 9 we shows the radial dependence of δ, each point representing a full XOOPIC simulation for values of j_{sat} and T_e extracted from Figs. 6,7. The attenuation factor decreases with radius from a value of 2.2 down to 1.5. A separate calculation shows that for the range of j_{sat} between $0.5 \div 1.1$ A cm^{-2} and given constant ion and electron temperature the values of attenuation factor change only from 1.5 to 1.6. Therefore, the decrease of δ in Fig. 9 is caused mainly by decreasing T_e and T_i with radius. This observation has important consequences for Mach number measurement using the RFA slit plates, when T_e is assumed to be constant along the field lines, but the probe measures two different values of ion saturation currents on opposite sides. The XOOPIC results show that the attenuation factor is insensitive to values of j_{sat} typical inside SOL. Therefore, the RFA Mach number measurements are unaffected by this tunnel effect except for very low values below 0.1 A cm^{-2} which occurs only very close to the vacuum vessel walls in JET. At these low values, the radial electric field generated close to the tunnel walls is less shielded due to lower plasma density, leading to an increase in the attenuation factor.

Assuming that the attenuation of the plasma flux occurs only in a localized region close to the tunnel walls of width much smaller than the width of the tunnel, the effect of the four walls can be added together to produce the total attenuation factor. Equivalent calculations using the longer dimension also indicate attenuation factors of ≈ 1.5. The total value of δ is thus in the range 3 – 4 and is in very good agreement with the difference between TTP

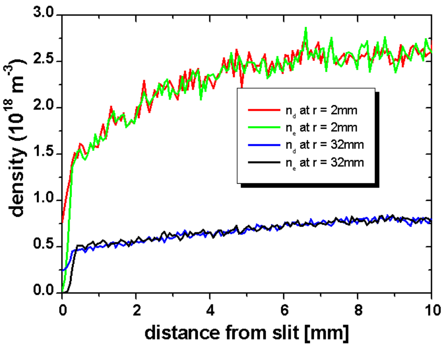

Fig. 8. Electron and deuteron density profiles along the tunnel axis for parameters: r_{LCFS} = 2 mm : T_{e} = 60 eV, J_{sat} = 3.3 A cm^{-2} and r_{LCFS} = 32 mm: T_{e} = 15 eV, J_{sat} = 0.5 A cm^{-2}

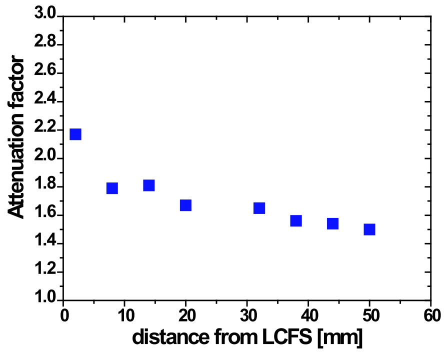

Fig. 9. Radial profile of the attenuation factor.

4 Possibilities for the geometry optimization

The kinetic simulations can be also used to investigate alternative geometries that might avoid this tunnel effect. An example of a possible new tunnel geometry is shown in the Fig. 10. The 4 mm wide tunnel is now only 1 mm long and broadens out to 11 mm as the slit plate is approached. Although the shape ought to reduce significantly the tunnel effect, the simulations show that the attenuation factor is the same as in the old geometry. The reason is shown in Fig. 11, where the axial density profiles are plotted for the old and new geometries. Evidently, even the 1 mm long tunnel is sufficient to suppress the plasma flow by the same factor. Making the tunnel even shorter would improve the situation but would not be technically desirable owing to resulting power handling problems.

5 Conclusions

Kinetic PIC simulations have demonstrated the strong influence of tunnel effects on ion saturation current measurements obtained with the JET Retarding Field Analyser probe. Radial profiles of attenuation factor have been computed, yielding values in the range of 3 to 4, in good agreement with observed differences between equivalent measurements from the RFA and TTP probes, where the latter is unaffected by the tunnel effect. The simulations also confirm that the tunnel effect does not compromise RFA Mach number measurements.

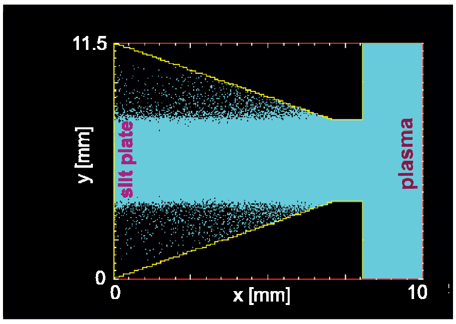

Fig. 10. Example of new tested geometry. Blue points represents the deuterons.

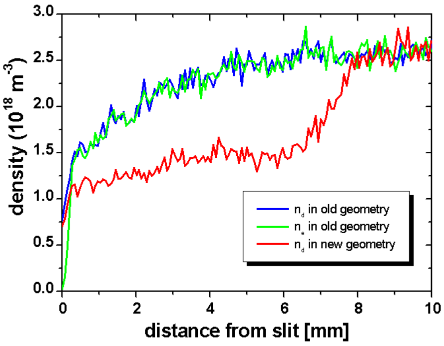

Fig. 11. Density profile along the tunnel axis. Green and blue lines represent the old geometry and red line corresponds to the new one.

The magnitude of the tunnel effect will also depend on the material conductivity. Simulations here have assumed fully conducting tunnel walls. Measurements will be made on the RFA probe head following removal from the JET tokamak to asses the conductivity of the thin graphite coating. Further simulations will be performed to account for an insulating surface. In that case it is expected that the tunnel wall will charge positively due to the large cross–field ion mobility and prevent further ion losses. The tunnel wall will effectively become reflecting for ions, and the current attenuation to the entrance slit should be reduced.

Simulations with alternative geometries demonstrate that even a very short tunnel can have a considerable attenuation effect. There is thus a strong argument for the current design which is optimised from the point of view of power handling. Indeed, the attenuation effect provides further protection by reducing the heat flux.

This work was supported by Grant Agency of the Czech Republic Grant 202/03/P062.

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