Ion orbits and ion confinement studies on ECRH plasmas in TJ-II stellarator

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Abstract

It has been observed that the ion temperature profile of low density ECR heated TJ-II plasmas is almost flat and that energetic ions are present well outside the last closed magnetic surface. The heat diffusivity obtained for such ion temperature profiles is very high and, therefore, transport cannot be described by Fick’s law. Ion trajectories with different pitches and starting points have been estimated and it has found that a feasible explanation for such flat mean energy profile is that ion orbits are wide enough to communicate distant parts of the plasma radius, thus giving an effective flat ion temperature profile, for these low density plasmas. The distribution function is also obtained without considering collisions and non-Maxwellian features are found.

1. Introduction and motivation.

Ion temperature profile is obtained in magnetic confinement devices by charge-exchange neutral particle analysers (CX-NPA) that measure energy spectra of CX neutrals that escape from the plasma. The temperature is deduced from the measured spectra, taking into account that the particles that are collected by the analyser at every chord can come from different radial positions. A single ion temperature profile must be obtained performing a series of reproducible discharges in order to have enough statistics to obtain the temperatures from the spectra [1].

It has been observed that the ion temperature profile of several ECR heated stellarator plasmas is almost flat and it is even possible to find energetic ions well outside the last closed magnetic surface, provided that plasma density is low enough. These phenomena have been found, for instance, in TJ-II Flexible Heliac [2, 3] and in LHD Heliotron [4]. Of course, the heat diffusivity obtained for such ion temperature profiles is very high and transport cannot be described by Fick’s law.

The neutral fluxes and their corresponding energies were measured for ECR heated plasmas in TJ-II by means of two charge-exchange neutral particle analysers. These plasmas are characterised by having low densities (under the cut off of microwaves), hot electrons in the core and cold ions. The absolute fluxes of hot neutrals go down as the minor radius increases, but their mean energies remain roughly constant even outside the last closed magnetic surface [3]. The hypothesis that was advanced to explain such findings was that the ion orbits are wide enough to communicate distant parts of the plasma radius, thus giving a flat ion temperature profile, for the low density plasmas considered in that experiment. Some recent calculations show that ion orbits are pretty wide in tokamaks [5], which makes feasible the former explanation. The size of the orbits is determined by the energy of the
ions, which are heated mainly in the plasma core by collisions with hot electrons. On the opposite, these hot ions will heat electrons in the edge.

The present work is devoted to estimate directly the ion fluxes and distribution function by calculating ion trajectories with different energies, pitches and starting points, disregarding the collisions, for the moment. In this way, the global collisionless ion flux has been estimated in TJ-II, as well as the ion energy spectra at different radial and toroidal positions. The validity of the previous explanation is established for the detected energy spectra of the CX-neutrals escaping from the plasma.

2. Ion trajectories and non-local transport

The usual neoclassical transport codes, like DKES (Drift Kinetic Equation Solver) [6], work under the hypothesis that diffusion coefficients only depend on local quantities, i.e., considering that the plasma background characteristics that a given particle sees when travelling in the plasma do not change strongly along the trajectory during the time between two collisions. For instance, DKES code only works disregarding the superbanana and potato orbits. The monoenergetic neoclassical coefficients, which depend on collisionality and electric field, are estimated with this assumption and, after a deconvolution with the Maxwellian distribution function, the final neoclassical coefficients are calculated. The fluxes are then obtained from density and temperature profiles as functions of the electric field. The final electric field is obtained by applying the ambipolarity condition and forcing electron and ion flux to be equal. Then the fluxes and the neoclassical transport coefficients for the particular plasma conditions are estimated.

The problem appears when the typical radial width of the orbits of the particles is large enough to visit far regions of the plasma with very different collisionalities and electric fields. In such a case, only the global fluxes make any sense (see e.g. [7]) since the transport coefficients should depend on the electric field and collisionality values that the particle suffers along the trajectory. The validity of the local ansatz will depend on the structure of the magnetic field of the device and is not valid particularly when the radial excursion of the particle between two collisions is large. This usually happens when the ripple of the magnetic field is strong enough as it occurs in TJ-II.
The trajectories of ions in TJ-II are computed by considering the actual 3D geometry and the usual drifts due to electric field and gradient of magnetic field are considered:

\[
\vec{v}_D = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{m_i}{2e}(2v^2 - v_\perp^2)\frac{\vec{B} \times \nabla B}{B^3}
\]

The TJ-II magnetic configuration has been described by a tridimensional grid [8]. Equilibrium previously calculated with VMEC code (see e.g. [9]) has been described by a grid whose cell structure is made of toroidal layers (24 for every semi-period, i.e., limited by toroidal planes detached 1.9°). Every layer consists of an orthogonal uniform grid that covers totally the plasma. The number of cells at every layer is 25 x 25. The physical magnitudes as density, temperature and magnetic field are taken in the centre of every cell. The walls of the cells are adjacent, without overlapping or hollows between them. The reminder of the plasma can be simulated from a single octant using the symmetry properties of TJ-II (four periods with stellarator geometry). The electric field under consideration is only the perpendicular one, since we assume that the electrostatic potential is constant at every magnetic surface. Under these assumptions, particles will keep constant kinetic energy during their trajectories, therefore, the perpendicular velocity will be the key variable to understand the kinematics.

The electric field that has been introduced for the estimation of the trajectories can be seen in Figure 1. It is pretty similar to the experimentally measured by Heavy Ion Beam Probe (HIBP) [10] for effective radii \(\rho < 0.9\) and by Langmuir probes for \(\rho > 0.9\) [11]. The field is taken from the experimental data since it is very difficult to estimate in a self consistent way, considering that one needs to know the electron and the ion fluxes. The plasma is in the electron root for \(\rho < 0.7\) and in the ion root at outer positions. The electric field influences the ion trajectories strongly, as will be shown below. Therefore, the results are strongly dependent of electron density and potential profile in this collisionless regime.

The flux can be directly estimated just adding the contributions of all the single

![Figure 3. Left panel: Radial coordinate and magnetic field along a trajectory of a passing ion. Right: The same for a trapped ion.](image-url)
particles. For the calculations presented here, $30 \times 10^6$ hydrogen ions are launched with energies, pitches and positions randomly chosen. The energies of the particles are distributed following a Maxwellian distribution function with $T=100$ eV, which is of the order of the measured ion energy in TJ-II \cite{2}, and their pitch distribution is uniform. The physical positions of the particles are also chosen randomly distributed according to the measured TJ-II density (see Figure 2).

Figure 3 shows the orbit of a passing ion that starts close to magnetic axis with energy $E=100$ eV. It can be seen that the radial excursion in one collision time is $\Delta \rho \approx 0.4$. The orbit of a trapped ion with the same energy is also shown in Figure 3, where $\Delta \rho \approx 0.6$. From these pictures, it is clear that thermal ions describe wide radial excursions at these low densities before suffering a collision, and the transport can be hardly described in terms of particle and heat diffusivities in these conditions. Moreover, ions of different energies are mixed at every radial position and, therefore, energy spectra will be similar and temperature profile will be approximately flat, unless ion collisionality increases and the size of radial excursions of ions is limited. The experimental data show that ion temperature shows a gradient in NBI plasmas in TJ-II \cite{12}. In fact, in the NBI phase, plasma density increases and so does the collisionality. In this situation, electron temperature decreases and is more similar to the ion one. The more equal the ion and electron temperatures, the more efficient the energy transmission between the two species is, therefore, ion orbits will play a less important role in transport and more peaked ion temperature profiles are expected and found experimentally. In fact, These peaked ion temperature profiles can be seen in reference [\cite{Error! Marcador no definido.}], where a density scan is shown in NBI plasmas in TJ-II. It is found that the higher the plasma density the more peaked the ion temperature profiles are.

The value of the electric field is also a key ingredient for governing ion confinement as far as ions suffer rare collisions. The evolution of trajectories in Fig. 3 shows two clear different zones. The inner one, where the ion is in the electron root zone and where the confinement is poor due to the effect of the positive electric field that tends to push the ion outwards. The outer zone that is in the ion root, with negative and weaker electric field, in which the higher ripple is the responsible of confinement degradation.

![Figure 4. Distribution function of parallel velocity at $\rho=0.6$. Triangles: Maxwellian; line: without electric field; dots: with electric field.](image)

The trajectories of the ions have been estimated using a fourth order Runge-Kutta method, although for the present grid it is enough to use a leap-frog method. Those trajectories are followed during two typical collision times in order to extract the importance of collisionless evolution, in comparison with the effect of collisions.
The integrated radial flux divided by density is obtained just adding the ion velocities that are in a radial corona at a given time and dividing by the total number of particles. The integrated toroidal flux, that is roughly null as expected is also estimated by adding the velocities of the particles that are located between two toroidal planes. Finally the distribution function is obtained by dividing the velocity space in perpendicular and parallel intervals for a given plasma volume and counting the particles inside.

4.- The results

All the ion orbits are followed during a time interval equivalent to two collision times in the centre. Then, it is possible to see the relative importance of orbits in confinement, by evaluating all the relevant transport quantities in a collision time. In particular, if the radial excursions are wide enough, ions are able to communicate distant zones in the plasma.

The distribution function is estimated just counting particles of different parallel and perpendicular velocities at every magnetic surface (or plasma radial corona). Non-Maxwellian features appear although no heating or collisions with electrons are considered. The deviation of the Maxwellian can only be attributed to the TJ-II geometry effects. Obtaining the distribution functions in this way is equivalent to solving Drift Kinetic Vlasov Equation. Although collisions will tend to reduce the deviation of Maxwellian, a strong effect of geometry on the evolution of distribution function can be expected. The distribution function of parallel velocity at ρ=0.6 can be seen in Figure 4 that shows a strong deviation of the bulk distribution function as well as the appearance of a tail at moderate energies. Figure 5 shows the radial particle flux with and without electric field integrated on every magnetic surface. It can be seen clearly that the flux increases strongly close to the edge.

Figure 5. Total radial flux integrated by the magnetic surfaces, with electric field (dots) and without it (line).

In absence of collisions, ion transport give rise to inhomogeneous density on every magnetic surface, as can be seen in Figure 6. This is, indeed a source of parallel and perpendicular transport.

5.- Conclusions

The usual local ion transport calculation methods are doubtful in low density plasmas in TJ-II Flexible Heliac. The size of the orbits performed by the ions in the complex TJ-II geometry is so wide that far regions of the plasma are connected, making the local ansatz not valid for neoclassical transport estimations. This is demonstrated by following a large number of particles and estimating the non-local ion fluxes.

This is a feasible explanation for the observed flat ion temperature profiles and for the existence of ions well outside the last close magnetic surface. For low collisionality plasmas, the influence of magnetic structure on transport and confinement properties is very important. The local ansatz for neoclassical calculations can be violated if the radial
excursions between collisions are wide enough that the particles see very different collisionalities and electric field.

Non-Maxwellian features are found due to the magnetic structure and the dependence of confinement properties on pitches and energies. As far as collisions are rare, this gives some asymmetries and plasma inhomogeneities. The effect of collisions must be included in order to solve the DKE in TJ-II plasmas and see what of the transport features observed in the collisionless regime are still occurring in different collision regimes.

Acknowledgment.

The authors would like to thank the Barcelona Supercomputer Centre the use of Mare Nostrum computer.

References