Ion Energy Influence on Confinement in TJ-II Stellarator

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Introduction

In a previous work, the neutral fluxes and their corresponding energies were measured for ECR heated plasmas in the flexible heliac TJ-II [1]. The measurements were carried out by means of two charge–exchange neutral particle analysers for radial positions $r/a > 0.6$ and showed that the absolute fluxes of hot neutrals go down as the minor radius increases, but their mean energies remain roughly constant. This fact holds even when the charge-exchange neutral particle analyser is measuring outside the last closed magnetic surface [2]. The widths of ion orbits were suggested as an explanation for these measurements, which have been observed repeatedly in ECRH plasmas. In TJ-II NBI heated plasmas the ion temperature profile becomes peaked with a parabolic shape. In both types of plasmas (ECRH and NBI) the ion temperature at the edge is roughly the same, between 70-100 eV, depending on the density.

A first attempt to explain the flat temperature profile in ECRH plasmas concerned the width of ion orbits but they were not calculated explicitly. In this study we calculate the width of the orbits in a particular case as a first approximation to a future work that will take into account collisions and electric field. Particles have been launched from suitable plasma places to calculate and follow their paths in the appropriate magnetic field geometry.

Calculations

The ion orbits have been calculated in the 42_100_68 magnetic configuration, those used in Ref [2]. This magnetic configuration has a volume of about 1 m^3 and an averaged minor radius of about 20 cm. It also has a high value of rotational transform ($\iota(0)=2.118$, $\iota(a)=2.239$). The particles were launched from 8 different poloidal positions and four radial positions ranging from the plasma centre to outside the LCFS. Also we varied the energy of the launched particles, from almost zero ($4.7\cdot10^{-2}$ eV) to 4.7 MeV, covering by far the energy range of particles detected by the CX-NPA that are used to calculate ion temperature. The pitch angle of the particles was also varied from $v_\perp/v= 0$ to $v_\perp/v=0.999$, i.e. from totally parallel to almost totally perpendicular velocity, but focusing in the very perpendicular ones which are those collected by the analyzer. These parameter ranges amount to 2688 particle orbits calculations.

The particles were followed along their trajectories taking into account only the ∇B drifts. As we deal with low-density plasma, the collisions are not taken into account for the moment and there is no way of changing the energy of the particles. The minimum and maximum radial position, toroidal and poloidal angle as well as the length of the trajectory and the time that the particle was in the plasma were recorded. The final of a single orbit is taken when the particle escapes out from the plasma or at the collision time, since this is the typical time for a particle to change its energy and trajectory. Before doing the calculations, the collision time for each particle energy was calculated all along the radius. The minimum collision time for every energy was selected as the life-time for the particles of this energy. Collision time was calculated for an ion test particle in the background plasma (see e.g. [3]):

$$\tau_{12\perp}^{-1} = \frac{q_1^2 q_2^2 n_2}{2\pi\varepsilon_0^2 m_1^2}\log(\Lambda)\frac{1}{v_1^3}\phi\left(\frac{v_1}{v_{T2}\sqrt{2}}\right) \qquad \text{(eq. 1)}$$

$$\tau_{12\parallel}^{-1} = \frac{q_1^2 q_2^2 n_2}{4\pi\varepsilon_0^2 m_1^2}\log(\Lambda)\left(1+\frac{m_1}{m_2}\right)\frac{1}{v_{T2}^2}\frac{1}{v_1}G\left(\frac{v_1}{v_{T2}\sqrt{2}}\right), \qquad \text{(eq. 2)}$$

where q_i are the charges of the particles, n_2 the density of the background plasma, m_i the mass of the particles, $log(\Lambda)$ the Coulomb logarithm, v_1 the velocity of the test particles, v_{T2} the thermal speed of the particles from the background plasma, ϕ the error function and G the Chandrasekhar function G. The values for the considered background thermal plasma were taken from the Thomson Scattering of one of the shots used to calculate the ion temperature at the edge.

Results and discussion

In general and independtly of the pitch angle and initial energy, the majority of the particles reach the Last Closed Flux Surface before a collision time although they travel a long way inside the plasma.

Almost all of the particles launched with some amount of perpendicular velocity escape from the plasma independently of their initial position or energy. Only some very low energy particles in certain poloidal angles remain in the plasma. This is not surprising because the TJ-II is not optimized for neoclassical transport. In fact, the particles explore a quite different magnetic fields and radial positions, depending on where they are born. For very low

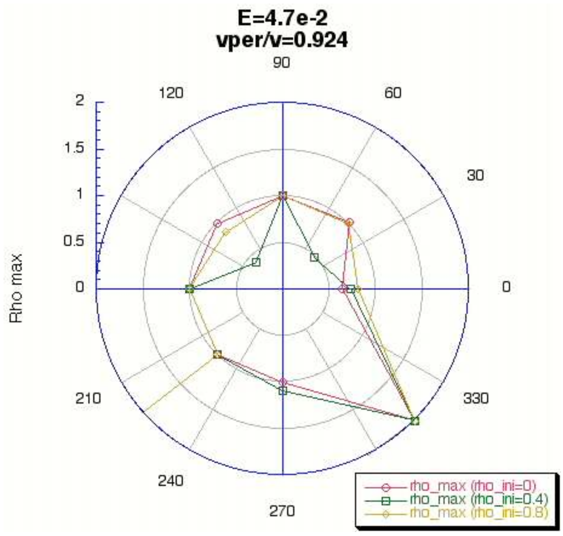

Figure 1. Polar plot of the maximum effective radius reached by particles of very low energy and high perpendicular velocity starting from different radius. The particle is considered to escape when it arrives at ρ=1.

energy, the particles that do not escape are those that are born in a poloidal angle that corresponds to high magnetic field for the corresponding toroidal cut which allows for a larger population of passing trajectories. Figure 1 shows the polar diagram of the maximum radius achieved by these particles of lowest energy and with finite perpendicular velocity. In other positions the particles can easily enter a banana orbit that makes it easier escaping from the plasma. The more parallel the velocity the more particles remain in the plasma. When the energy is over 100 eV all the particles escape from the plasma, since the collision time is increased.

For particles without perpendicular velocity the situation is slightly different. When the particles are born in effective radius of ρ=0.4 or ρ=0.8, the only particles that do not escape are those with energy $4.7\cdot10^{-2}$ eV, as before. But for particles born close to magnetic axis, there are more particles that remain in the plasma, also depending on the poloidal angle. In this case, all the particles with poloidal angle 0 and energy below 0.5 MeV remain in the plasma, as can be seen in figure 2.

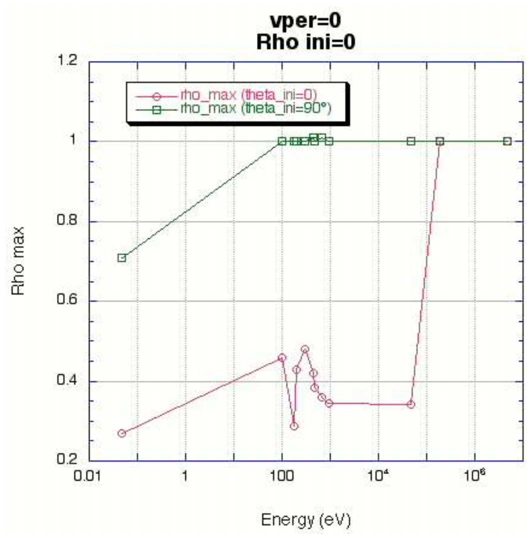

Figure 2. Maximum effective radius reached by particles with only parallel velocity and born in the centre of the plasma for two different poloidal angles.

All the particles have been launched from the same toroidal angle, the one corresponding to the CX-NPA position in TJ-II. Most of these particles perform a toroidal path of at least π/2 radians covering a quadrant of the machine. As it is a 4 period device, looking at a quarter of the machine is the same as looking at the entire device.

Conclusions

The calculations presented here show that a large amount of particles escape from the plasma before having a collision, performing excursions along the full minor radius. This result supports our former idea that the wide orbits of the ions are responsible for the flat ion temperature profile measured in TJ-II stellarator ECRH plasmas. With these results we show that a particle born in the centre of the plasma can travel up to the edge without colliding, so when measuring the ion temperature, no matter where the spectrometer is looking at, it will count the same energy distribution of particles everywhere. This is especially true for high pitch angle particles, which are those collected by the CX-NPA. However, even if the diagnostic measured particles with higher $v_{\parallel}$ we would expect a flat ion temperature profile according to the calculations. Therefore, the width of the orbits in TJ-II is a feasible explanation to the flat ion temperature measured in this stellarator in low-density plasmas. The ion orbits connects very distant parts of the plasma, implying that the energy distribution of the particles is the same in any minor radius, as was shown in ref. [2]. In consequence the temperature measured using the CX-NPA is the same at every position of the spectrometer.

There are light differences on the radius achieved by the launched particles which depend on the poloidal position were the particle is born, due to the complicated magnetic field structure of TJ-II. Most of the particles that do not escape are those of very low energy, which are not taken into account for the ion temperature calculation. Also there are some differences with the pitch angle of the particle: the higher the perpendicular velocity of the particle, the larger the probability for escaping from the plasma, as expected.

Further work must be done in order to take into account different magnetic configurations. Also more particles will be launched in order to complete the space and energy scan of the particles. Another task will be to include collisions so that the conditions of the plasma during NBI can be considered. These are very different from ECRH plasmas and a peaked ion temperature profile has been observed. The effect of electric field should also be incorporated in the calculations, since a strong influence of the electric field in the ion drifts is expected.

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