Poloidal anisotropies in ICRH tokamak plasma

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Abstract

Using a bi-Maxwellian model of the distribution function for minority ion species in the presence of ICRH, implying the asymmetry of minority ion temperatures in perpendicular and parallel directions relative to magnetic field, the asymmetry in pressure is analysed. The analytical model is applyed to some values similar to that of experiments on a Hidrogen plasma with He-3 minority ions.

1 Introduction

The auxiliary heating of plasma, in particular Ion Cyclotron Resonance Heating (ICRH), induce a temperature asymmetry and can affect the poloidal asymmetry of impurity densities, [1], [2]. With the aim of describe plasma behavior, the distribution function play a central role in both fluid and kinetic theory of plasma fusion theory.

For the sake of simplicity, the most used model of the reference distribution function (RDF) of species α in plasma is the Maxwellian distribution function, which offer the advantage of a simpler solution for the kinetic equations and macroscopic description of the plasma in first approximation. But the Maxwellian form of the distribution function is isotropic in velocity space and cannot describe the asymmetries present in a fusion tokamak plasma.

To encompass the pressure anisotropy in equilibrium plasma, one usual choice for the distribution function is a bi-Maxwellian form, [3], [4], even this not contain the whole complexity of magnetized fusion plasma. Other interesting expression of the distribution function was proposed in [5] corresponding to FAST- plasma heated by ICRH and simulated by using Hybrid Magnetohydrodynamic Gyrokinetic Code (HMGC), [6].

In the present paper we show how the ICRH affect the temperature and pressure asymmetry in tokamak plasma using a bi-Maxwellian distribution function for minority species and exemplify on a temperature radial profile similar to that measured in shot 79352 at JET, [7].

2 Model of the distribution function

The Maxwellian velocity distribution in a single direction is

$$f(v_i) = \left(\frac{2\pi T_i}{m}\right)^{-1/2} \exp\left[-\frac{m v_i^2}{2T_i}\right]$$

in a unit system with the Boltzmann constant $k_B = 1$. In magnetized plasma the velocities $v_\perp$ and $v_\parallel$ may be associated with different temperatures, respective $T_\perp$ and $T_\parallel$. An example is the case of plasma heated by ICRH, where the particles are accelerated only in perpendicular direction. The distribution in velocity space resulted by combining the Maxwellian distributions corresponding to $f\left(v_\parallel\right)$

$$f\left(v_\parallel\right) = \sqrt{\frac{m}{2\pi T_\parallel}} \exp\left[-\frac{mv_\parallel^2}{2T_\parallel}\right]$$

and $f\left(v_\perp\right)$

$$f\left(v_\perp\right) = \sqrt{\frac{m}{2\pi T_\perp}} \exp\left[-\frac{mv_\perp^2}{2T_\perp}\right]$$

is the *bi-Maxwellian* distribution on a given flux surface, as proposed in [1],

$$F\left(\overrightarrow{x}, v_\parallel, v_\perp\right) = n_c \left(\frac{m}{2\pi}\right)^{3/2} \frac{1}{T_\perp \sqrt{T_\parallel}} \exp\left(-\frac{mv_\parallel^2}{2T_\parallel} - \frac{mv_\perp^2}{2T_\perp}\right) \tag{1}$$

with

$$\int F\left(\overrightarrow{x}, \overrightarrow{v}\right) d\overrightarrow{v} = n_c\left(\overrightarrow{x}\right)$$

where the integration is over a flux surface and n_c is the number of particles on this flux surface.

In an axisymmetric toroidal geometry the magnetic field $\mathbf{B}$ is written as

$$\mathbf{B} = \frac{\mathcal{B}_0(r)}{q(r)} \frac{r}{R_0} \mathbf{e}_\theta + \frac{\mathcal{B}_0(r)}{1 + (r/R_0)\cos\theta} \mathbf{e}_\zeta$$

with

$$\mathcal{B}_0(r) = B_0 \sqrt{1 + r^2 R_0^{-2} q^{-2}}$$

where $\mathbf{e}_\theta$ and $\mathbf{e}_\zeta$ are unit vectors in poloidal, respective toroidal directions, r is the minor radius (radius in the circular poloidal section) and θ is the poloidal angle. For a large aspect ratio tokamak, the magnetic field strength can be approximated as

$$B(r,\theta) = B_0 \frac{R_0}{R} \quad , \quad R = R_0 + r\cos\theta \tag{2}$$

When a particle gyrocenter moves along a magnetic field line, $v_\parallel$ and $v_\perp$ changes and so the fraction of perpendicular kinetic energy and parallel kinetic energy change along the guiding center orbit. In consequence the temperatures $T_\perp$ and $T_\parallel$ will change from a flux surface to another. So the distribution function will be

$$F\left(r, v_\parallel, v_\perp\right) = n_c(r) \left(\frac{m}{2\pi}\right)^{3/2} \frac{1}{T_\perp(r)\sqrt{T_\parallel(r)}} \exp\left(-\frac{mv_\parallel^2}{2T_\parallel(r)} - \frac{mv_\perp^2}{2T_\perp(r)}\right) \tag{3}$$

3 Pressure anisotropies induced by ICRH

In the ICRH process the minority ion species will be heated and their perpendicular kinetic energy will be increased in the ICRF wave absorption layer. Lets note with R_c the radius corresponding to middle of absorption layer and B_c the magnetic field strength at $R = R_c$,

$$B_c = B_0 \frac{R_0}{R_c}\ , \quad R_c = R_0 + r_c, \quad r_c = a\cos\theta_c$$

Corresponding to JET dimensions, the major radius R_0 and minor radius a will be taken as $R_0 = 2.9$ m and $a = 1$ m. Because the magnetic field strength varies as $1/R$, in the points with $R > R_c$ the magnetic field strength B is lower then B_c and name this domain *lfs* (*low-field side*). In the points with $R < R_c$ the magnetic field strength B is larger then B_c and name this domain *hfs* (*high-field side*).

Consider that in the absence of ICRH will no anisotropic temperatures, $T_\perp = T_\|$ and the distribution function is Maxwellian. The ICRH process will lead to anisotropic temperatures and, by consequence to anisotropic pressure:

$$P_\| = n_c T_\| (r)\, H_\| \tag{4}$$

$$P_\perp = n_c T_\perp (r)\, H_\perp \tag{5}$$

Using the notations,

$$T_{\perp a}(r,\theta) = T_\perp (r)\left[\frac{B_c}{B(r,\theta)} + \frac{T_\perp(r)}{T_\|(r)}\left(1 - \frac{B_c}{B(r,\theta)}\right)\right]^{-1} \tag{6}$$

$$T_{\perp b}(r,\theta) = T_\perp (r)\left[\frac{B_c}{B(r,\theta)} - \frac{T_\perp(r)}{T_\|(r)}\left(1 - \frac{B_c}{B(r,\theta)}\right)\right]^{-1} \tag{7}$$

the expressions of $H_\|$ and $H_\perp$ are different in *hfs* and *lfs*. So, in hfs (when $B > B_c$) in domain $-a \le r\cos\theta < r_c$, [3]

$$H_{\|,hfs} = \frac{T_{\perp a}(r,\theta)}{T_\perp(r)} \quad , \quad H_{\perp,hfs} = \left(\frac{T_{\perp a}(r,\theta)}{T_\perp(r)}\right)^2 \tag{8}$$

and in *lfs* (when $B < B_c$) in domain $r_c \le r\cos\theta \le a$, [3]

$$\begin{aligned} H_{\|,lfs} &= \frac{T_{\perp a}(r,\theta)}{T_\perp(r)} \\ &+ \left(\frac{T_\perp(r)}{T_\|(r)}\right)^{3/2}\left(1 - \frac{B(r,\theta)}{B_c}\right)^{3/2}\left(\frac{T_{\perp b} - T_{\perp a}}{T_\perp(r)}\right) \end{aligned} \tag{9}$$

$$\begin{aligned} H_{\perp,lfs} &= \left(\frac{T_{\perp a}(r,\theta)}{T_\perp(r)}\right)^2 \\ &+ \left(\frac{T_\perp(r)}{T_\|(r)}\right)^{1/2}\left(1 - \frac{B(r,\theta)}{B_c}\right)^{1/2}\left[\frac{T_{\perp b} - T_{\perp a}}{2T_\perp(r)}\frac{B(r,\theta)}{B_c} + \frac{T_{\perp b}^2 - T_{\perp a}^2}{T_\perp^2(r)}\right] \end{aligned} \tag{10}$$

The radial profile of the temperature must be taken from the experimental measurements. As an example we take a temperature radial profiles, see figure 1, similar to those obtained in JET (shot 79352, [7]) by CXRS (Charge eXchange Recombination Spectroscopy) [8].

In the absence of auxiliary heating the velocity space for the ion minority is supposed isotropic, and so $T_{i,\|}(r) = T_{i,\perp}(r) = T_i(r)$. In this case the radial variation of $T_i(r)$ is shaped as

$$T_i(r) = 1.23\exp\left[-\frac{190}{R_0^2}(R-2.88)^2\right] + 0.56\exp\left[-\frac{133}{R_0^2}(R-3.23)^2\right] \quad (11)$$
$$+0.11\exp\left[-\frac{665}{R_0^2}(R-3.52)^2\right] + 0.23\exp\left[-\frac{190}{R_0^2}(R-3.72)^2\right]$$

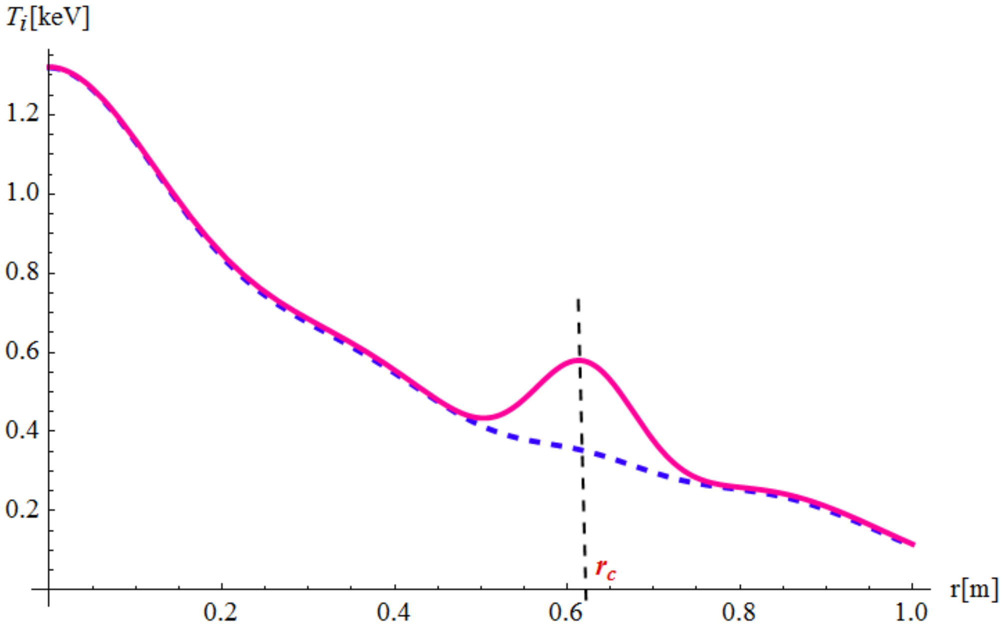

Figure 1. Radial profile of the minority ion species (He-3) temperature's in the absence of ICRH (blue dashed line) and at the short moment after coupling ICRH (solid red line). The vertical dashed line at $r = r_c$ mark the middle of the ICRH power deposition.

and represented in figure 1 by dashed line for $R_0 = 2.9\ m$. The ICRH modify only $T_{i,\perp}(r)$ as figured by solid line in figure 1 and shaped as

$$T_{i,\perp}(r) = 1.23\exp\left[-\frac{190}{R_0^2}(R-2.88)^2\right] + 0.57\exp\left[-\frac{133}{R_0^2}(R-3.23)^2\right] \quad (12)$$
$$+0.33\exp\left[-\frac{1140}{R_0^2}(R-3.52)^2\right] + 0.24\exp\left[-\frac{190}{R_0^2}(R-3.72)^2\right]$$

Modeling the temperatures $T_{i,\parallel}(r)$ and $T_{i,\perp}(r)$ by (11) and respective (12), the anisotropies coefficients $H_\parallel(r,\theta)$ and $H_\perp(r,\theta)$ are plotted in figure 2 and respective figure 3.

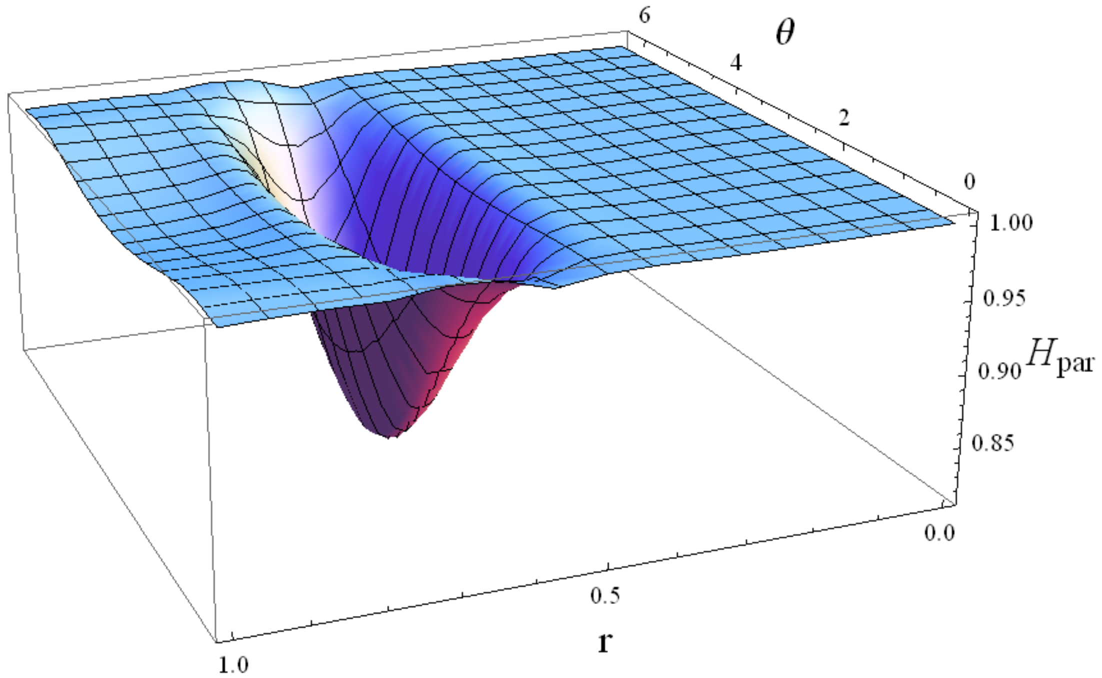

Figure 2. Graphical representation of the coefficient $H_{\|}$ given in (8) and (10) as function of r and θ.

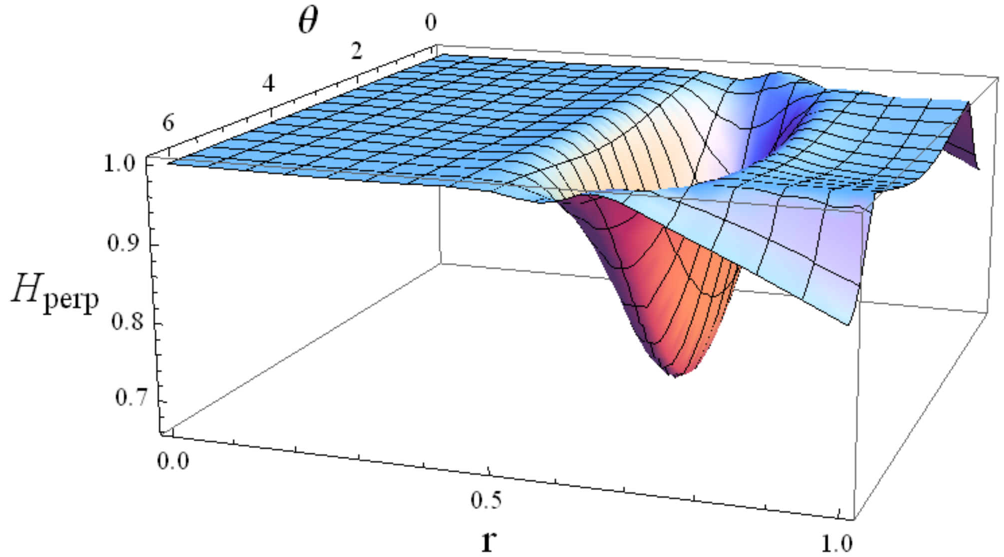

Figure 3. Graphical representation of the coefficient $H_{\perp}$ given in (8) and (10) as function of r and θ.

The quantities $P_{\|}/n_c$ and $P_{\perp}/n_c$ are plotted in figure 4 and respective figure 5.

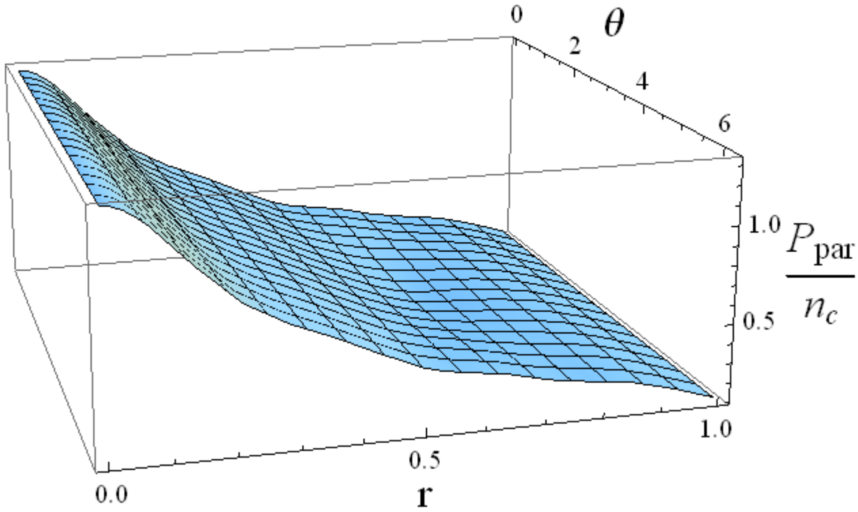

Figure 4. Graphical representation of $P_{\|}/n_c$ as function of r and θ.

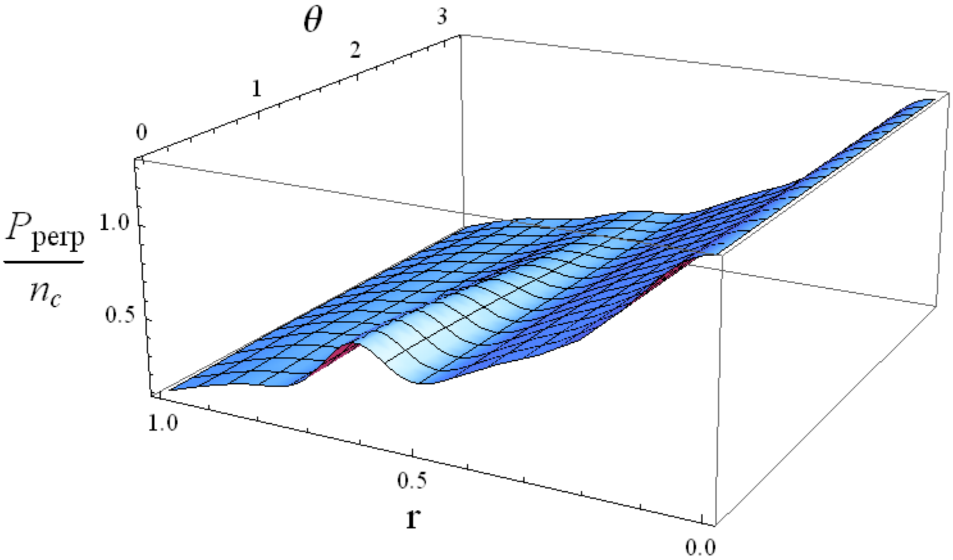

Figure 5. Graphical representation of $P_{\perp}/n_c$ as function of r and θ.

4 Comments and conclusions

The auxiliary ICRH of tokamak plasma induce an asymmetry in temperature of minority ion species on parallel and perpendicular directions relative to magnetic field in a flux surface. Because of the strong rotation of plasma in toroidal direction (rapid movement along magnetic field line), the ICRH process will not create a poloidal asymmetry in parallel pressure $P_{\|}$, as can be seen in figure 4: at a given value of r the quantity $P_{\|}/n_c$ do not change with θ.

Contrary, the ICRH process will induce a poloidal asymmetry in perpendicular pressure $P_{\perp}$, as can be seen in figure 5. This can be seen more clearly in figure 6. This asymmetry will induce a poloidal rotation which contribute to a better confining of plasma.

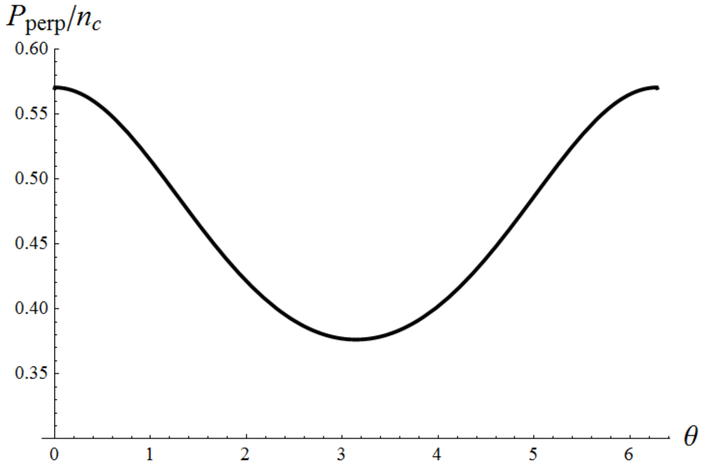

Figure 6. Variation with poloidal angle θ at $r = r_c = 0.63$ of the perpendicular pressure.

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