A mechanism of ion temperature peaking by impurity pellet injection in a heliotron plasma

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Abstract. Experiments on the Large Helical Device with injection of carbon pellets into discharges of low density have demonstrated a significant reduction of the ion heat conduction in the plasma core and increase of the central ion temperature by a factor up to 2. These results are interpreted in the framework of a transport model elaborated on the basis of those applied previously to explain the confinement improvement by impurity seeding into tokamak devices TEXTOR and JET. Calculations performed reproduce well the strong peaking of the ion temperature profile with increasing carbon density n_Z and the consequent drop in the confinement as n_Z exceeds a certain critical level. The importance of different elements in the model, such as braking of the main ion rotation by friction with impurity ones, the shape of the density profiles, is investigated. A qualitative assessment of the applicability under the fusion reactor conditions, e.g. of much higher plasma density and heating power, is done.

1. Introduction

The improvement of the ion energy confinement by seeding of different impurity species, such as nitrogen, neon, argon, have been observed in diverse tokamak devices, e.g., ISX-B [1], ASDEX and ASDEX-U [2, 3], TEXTOR [4], JET [5, 6], DIII-D [7], JT-60U [8]. The results of recent experiments performed on the heliotron Large Helical Device (LHD) [9, 10] have demonstrated that this phenomenon is not specific for the tokamak type of magnetic fusion devices: the injection of carbon pellets into the LHD led to a pronounced peaking of the ion temperature profile and strong increase, up to a factor of 2, of the central T_i magnitude.

This allows to reduce further the core anomalous transport in discharges where an internal transport barrier is generated by a high enough heating power [11]. The similarities of observations both on tokamaks and on helical devices reveal the fundamental nature of the confinement improvement induced with impurities in hot fusion plasmas. Therefore the understanding of mechanisms of impurity injection on the anomalous heat transport in the LHD are of a significant importance for magnetic fusion investigations in general.

In [4,12,13] the results of experiments with impurity seeding in tokamaks have been interpreted by considering the impact of the effective plasma charge Z_{eff} on the toroidal ion temperature gradient (ITG) instability that is usually discussed as the main source of the anomalous ion transport. The curvature of magnetic field lines is the main cause of toroidal ITG modes and one has to expect the development of this instability and accompanying anomalous transport in helical devices also. In the next section of the present paper the previous analysis of ITG instability is generalized for plasmas with two ion species, i.e. the main background one of a hydrogen isotope and one charge state of impurity. In the third section the method to solve numerically the ion heat transport equation with a heat conduction depending strongly non-linearly on the temperature gradient, as in the case of ITG, is outlined. In section 4 the results of computations are compared with the experimental data from LHD. Finally conclusions are drawn.

2. Experimental background

A significant peaking of the ion temperature T_i in the plasma core can be obtained in the LHD after injection of carbon pellets, see figure 1 and [9]. The degree of the ion energy confinement improvement is related most strongly to the amount of the injected carbon, see figure 1, and approaches its maximum, where the central value of T_i is nearly doubled, at an impurity density n_Z of $5-10\cdot 10^{17} m^3$, dependent on the injection scenario, see figure 2. The experiments in question have been done to achieve a maximum ion temperature [11]. In a good agreement with the ISS04 energy confinement time scaling for stellarators [14], with a total heating power in the LHD of $20MW$ it is possible to get a $T_i \approx 3 - 4keV$ at a relatively low plasma density of $1 \div 2 \cdot 10^{19} m^{-3}$ only, see figure 3. This is much lower than a level of $10^{20} m^{-3}$ required in a future reactor and a significant increase of the power as well as the usage of diverse means to reduce the anomalous transport, in particular, the impurity pellet injection discussed here, would allow to approach this level.

The recent LHD experiments to study the isotope effect in the ion particle and energy confinement have demonstrated that the impurity presence is of importance for the internal transport barrier (ITB) quality [15]: in a deuterium plasma the ITB can be sustained longer than in a hydrogen one because the formation of the impurity hole requires more time due to lower impurity transport. Also the shape of the radial profile of the electron density n_e plays a role for the reduction of the ion heat conduction: a slightly hollow $n_e(r)$ results in a stronger confinement improvement, see figure 3.

Under the conditions of a low plasma density in the experiments in question the increase of impurity radiation losses by the pellet injection does not contribute dramatically to the global power balance. As one can see in figure 4, even the injection of pellets sufficient to double the central T_i the total power radiated did not exceed 10% of the input one. By extrapolating the impurity pellet scenario to a higher plasma density, one of the main concerns is, however, the plasma thermal collapse [16]. The application of a resonant magnetic perturbations (RMP), generating a broad magnetic island at the plasma edge, has been proven to be a promising approach to overcome this difficulty [17]. In the LHD experiments analyzed in the present paper the RMP has not been applied.

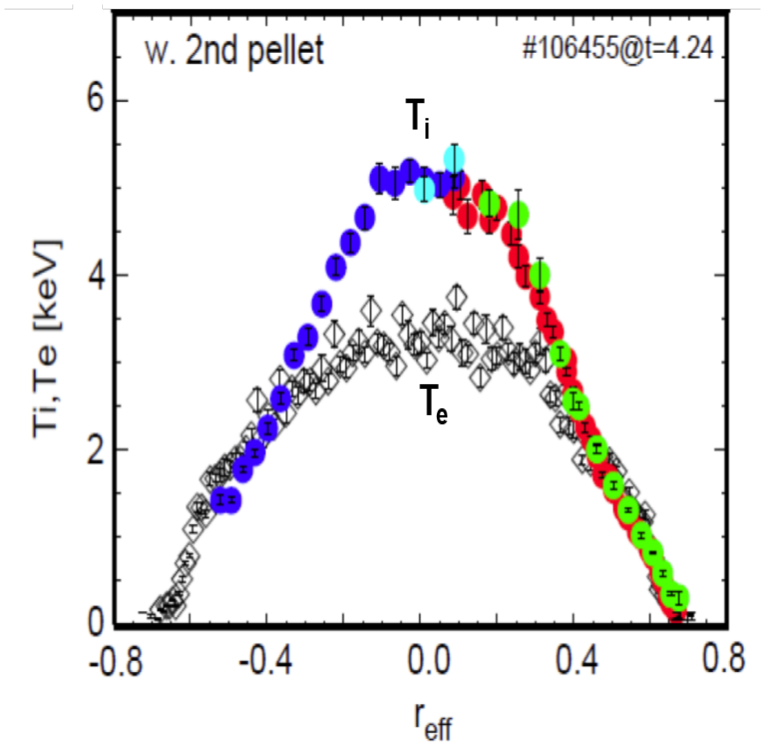

Figure 1. The electron and ion temperature profiles measured in the LHD discharge #106455 after injection of two carbon pellets; $r_{eff} = \pm r/r_s$, with r being the minor radius of a circular toroidal shell with the same volume as the flux surface in question, r_s is that of the last closed surface, the sign $+/-$ correspond to the outboard/inboard position on the surface.

3. Anomalous contribution to ion heat conduction from unstable ITG modes

The contribution of a toroidal ITG instability to the ion anomalous heat conduction κ_{an} is assessed by applying a mixing length approximation [18], which is less sophisticated by more transparent than normally done Gyrokinetic simulations of turbulence in a high ion temperature plasma in the LHD [19]. By following [18], consider an ITG Fourier mode with the frequency ω, poloidal wave vector k, generating the perturbation $\widetilde{\varphi}$ of the electrostatic potential. Small perturbations of the density n_Z and temperature T_Z, $\widetilde{n}_Z$ and $\widetilde{T}_Z$, respectively, of ions with the charge Z are governed by the following linearized equations for particle and heat balances:

$$\left(\bar{\omega} + \frac{\tau}{Z}\right)\frac{\widetilde{n}_Z}{n_Z} + \left(\varsigma_Z\bar{\omega} - \epsilon_Z + 1 + \delta_Z\right)\frac{e\widetilde{\varphi}}{T_e} + \frac{\tau}{Z}\frac{\widetilde{T_Z}}{T_Z} = 0, \tag{1}$$

$$\left(\bar{\omega} + \frac{5}{3}\frac{\tau}{Z}\right)\frac{\widetilde{T_Z}}{T_Z} - \frac{2}{3}\bar{\omega}\frac{\widetilde{n}_Z}{n_Z} - \left(\epsilon_T - \frac{2}{3}\epsilon_Z\right)\frac{e\widetilde{\varphi}}{T_e} = 0, \tag{2}$$

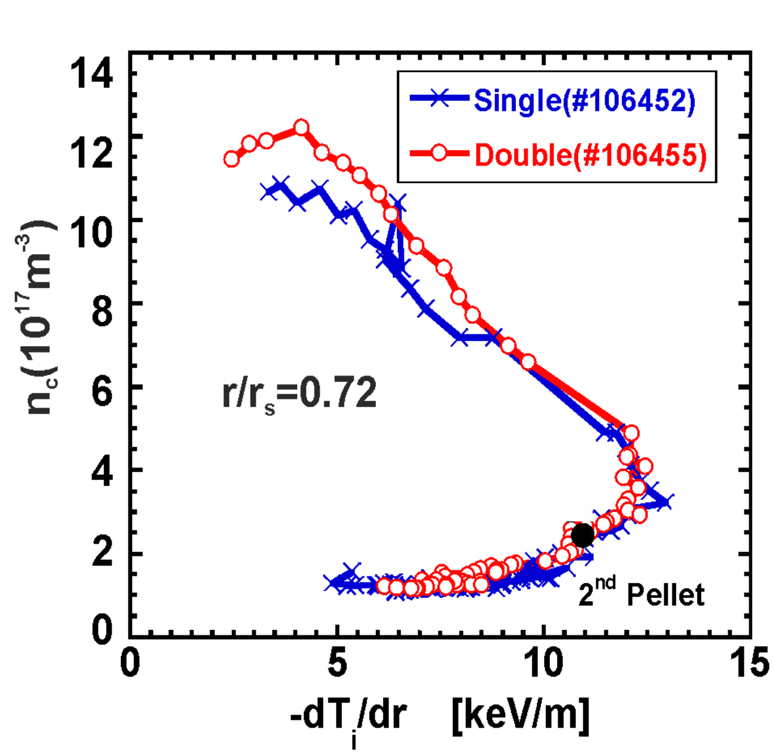

Figure 2. The ion temperature gradient at the foot of the core region vs. the carbon impurity density, by injection of a single and double pellets into the LHD plasma., (At the position in question, $r/r_s = 0.72$, the ion temperature does not practically change with the pellet injection and the parameter $\epsilon_T = -\frac{d\ln T_i}{dr}\frac{R}{2}$, being of the importance for an ITG-instability analysis, see below, varies nearly proportionally to the ion temperature gradient and $\epsilon_T \approx -0.87\frac{d\ln T_i}{dr}$). [9]

where

$$\bar{\omega} = \frac{\omega}{\omega_{De}},\ \omega_{De} = \frac{2kcT_e}{eBR},\ \tau = \frac{T_i}{T_e},\ \epsilon_Z = -\frac{d\ln n_Z}{dr}\frac{R}{2},\ \epsilon_T = -\frac{d\ln T_i}{dr}\frac{R}{2},$$

$$\varsigma_Z = k^2\rho_Z^2,\ \delta_Z = \varsigma_Z\left(\epsilon_T + \epsilon_Z\right)\tau/Z,$$

with $\rho_Z = \sqrt{T_e m_Z}/\left(ZeB\right)$ being the Larmor radius of the Z-ions; henceforth it is assumed that the unperturbed temperature of impurity ions is equal to that of the background hydrogen ions, T_i. The impact of ion parallel motion, which involves the magnetic geometry characteristics, such as the safety factor q, the q shear, magnetic ripples etc., is neglected in the equations (1) and (2) so these are applicable both to tokamak and to stellarator configurations. For the conditions in question of hot core plasmas this does not lead to a large error in the ITG-instability growth rate [20]. If one impurity ion species only, i.e. carbon nuclei in the case under consideration, is taken into account, the plasma quasi-neutrality condition is as follows:

$$\widetilde{n}_i + Z\widetilde{n}_Z = \widetilde{n}_e, \qquad (3)$$

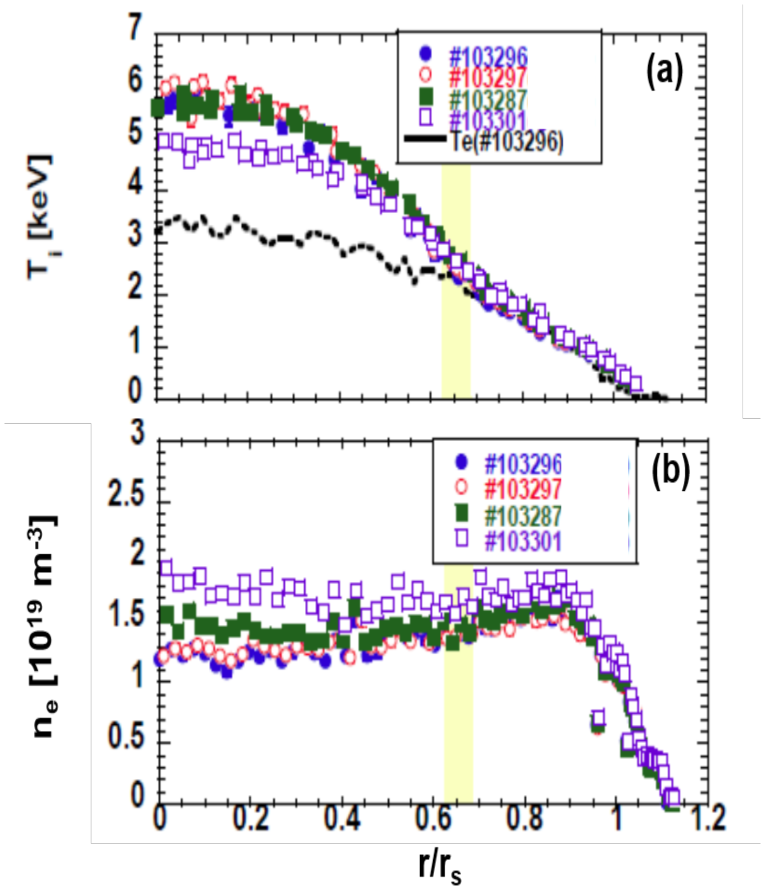

Figure 3. The radial profiles of the electron and ion temperatures (a) in several LHD discharges with different shape of the electron density (b).

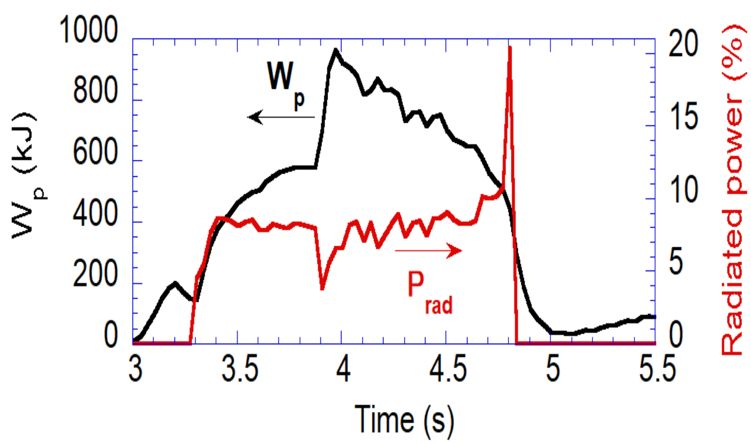

Figure 4. The time traces of the total plasma energy content W_p and radiation fraction $P_{rad}/Heating\ power$, in the LHD shot 106455 with the RMP application at a high plasma density.

The relation between the perturbation of the electron density $\widetilde{n}_e$ and $\widetilde{\varphi}$ follows from the parallel force balance:

$$T_e \widetilde{n}_e = e n_e \widetilde{\varphi}, \tag{4}$$

The perturbation frequency $\bar{\omega}$ is governed by a quartic polynomial algebraic equation, following from the requirement that the above system of linear equations for the amplitudes of small perturbations has a non-trivial solution:

$$a_4 \bar{\omega}^4 + a_3 \bar{\omega}^3 + a_2 \bar{\omega}^2 + a_1 \bar{\omega} + a_0 = 0, \tag{5}$$

where

$$a_4 = 1 + \xi_i \varsigma_i + Z \xi_Z \varsigma_Z, \; a_3 = \tau_1 + \frac{\tau_1}{Z} + \xi_i \left(\frac{\varsigma_i \tau_1}{Z} + b_i \right) + Z \xi_Z \left(\varsigma_Z \tau_1 + b_Z \right),$$

$$a_2 = \frac{\tau_1^2}{Z} + \tau_2 + \frac{\tau_2}{Z^2} + \xi_i \left(\frac{b_i \tau_1}{Z} + \frac{\varsigma_i \tau_2}{Z^2} + c_i \right) + Z \xi_Z \left(b_Z \tau_1 + \varsigma_Z \tau_2 + c_Z \right),$$

$$a_1 = \frac{\tau_1 \tau_2}{Z} \left(1 + \frac{1}{Z} \right) + \frac{\xi_i}{Z} \left(c_i \tau_1 + \frac{b_i \tau_2}{Z} \right) + Z \xi_Z \left(c_Z \tau_1 + b_Z \tau_2 \right),$$

$$a_0 = \tau_2 \left(\frac{\tau_2 + \xi_i c_i}{Z^2} + Z \xi_Z c_Z \right),$$

with $\xi_i = n_i/n_e$, $\xi_Z = n_Z/n_e$ being the ion concentrations, $\tau_1 = 10\tau/3$, $\tau_2 = 5\tau^2/3$, $b_Z = 1 + \delta_Z - \epsilon_Z + \frac{5}{3}\frac{\tau}{Z}\varsigma_Z$, $c_Z = \frac{\tau}{Z}\left(\frac{5}{3} + \frac{5}{3}\delta_Z + \epsilon_T - \frac{7}{3}\epsilon_Z\right)$, $b_i = 1 + \delta_i - \epsilon_i + \frac{5}{3}\tau\varsigma_i$, and $c_i = \tau\left(\frac{5}{3} + \frac{5}{3}\delta_i + \epsilon_T - \frac{7}{3}\epsilon_i\right)$; all values with the subscript i are related to the main ions of the hydrogen isotope with the charge $Z = 1$.

According to a mixing length approximation [18] the contribution to the heat conductivity from unstable drift modes can be estimated as $\chi_{an} \approx (\mathrm{Im}\omega)_{\max}/k_{\max}^2$, where $(\mathrm{Im}\omega)_{\max}$is the maximum value of the mode growth rate as a function of k and $k_{\max}$ - the value of k at which $(\mathrm{Im}\omega)_{\max}$ is approached. This approximation does not account for the reduction of the instability grows rate with the shear of the rotation induced by the radial electric field, $\Omega_{E\times B}$ [21]. The important role of $\Omega_{E\times B}$ for the temperature peaking in tokamaks induced by impurity injection has been demonstrated in [23] for JET L-mode discharges with neon seeding. It has been also shown that the main contribution to the time averaged radial electric field (do not mix with fluctuations triggered by ITG instability) is due to poloidal diamagnetic rotation induced by the radial temperature gradient, and $\Omega_{E\times B} \approx \frac{1}{eBr}\left|\frac{dT_i}{dr}\right|$. Finally, with the dimensionless wave number $\varsigma = k_{\max}^2 \rho_i^2$ one gets the following assessment for the anomalous ion heat conduction due to the ITG instability:

$$\kappa_{an} = \left(n_i + n_Z \right) \chi_{an} = \kappa_* \left(1 - \frac{Z_{eff} - 1}{Z} \right) \left[\frac{\mathrm{Im}\bar{\omega}\left(\varsigma\right)}{\sqrt{\varsigma}} - \frac{\tau \psi \epsilon_T \rho_i}{\varsigma r} \right], \tag{6}$$

Here $\kappa_* = 3 n_e T_e^{1.5} \sqrt{m_i} / \left(e^2 B^2 R \right)$, $Z_{eff} = \left(n_i + Z^2 n_Z \right) / n_e$ is the effective plasma charge and the relations $n_i = n_e \left(Z - Z_{eff} \right) / \left(Z - 1 \right)$, $n_Z = n_e \left(1 - \xi_i \right) / Z$ have been used; the factor $\psi = \xi_i + \xi_Z \sqrt{A_Z/Z}$, with A_Z being the atomic weight of the impurity ions, takes into account the braking of the main ion diamagnetic rotation by collisions with the impurity ones.

In spite of its simplicity the present model for ITG-instability reproduces well important features of calculations with the gyrokinetic Vlasov code GS2 [22]. In particular, if the stabilizing effect of $\Omega_{E\times B}$ is not taken into account both approaches provide similar values of 0.5-0.6 for $k_{\max}\rho_i$. In future studies the present model will be extended to calculate impurity transport, see [20], to do a more thorough comparison with the results of GS2 modeling.

In figure 4 the ratio κ_{an}/κ_* is shown versus Z_{eff} for hydrogen plasmas with carbon nuclei with $Z = 6$ as the dominant impurity species, $n_e = 1.5 \cdot 10^{19} m^{-3}$, $\tau = 1$, $\epsilon_T = 5$ and several combination of ϵ_i and ϵ_Z. One can see the ion heat conduction reduces significantly with Z_{eff}. This is due to the decrease of the diamagnetic drift, induced by the density and temperature perturbations, with the ion charge [18, 24], which ismimicked in Eqs. (1) and (2) by the terms proportional to τ/Z. Since $\widetilde{n}_Z, \widetilde{T}_Z$ change mostly in the poloidal direction, this type of drift motion is radially directed and dominates the anomalous heat transfer generated by ITG modes.

Thus ITG growth rate reduces with increasing impurity density because the impurity ion charge Z is significantly larger than that of the main ions and, thus, the terms in Eqs. (1) and (2) responsible for the instability are smaller. However, by approaching of Z_{eff} to Z the anomalous ion heat conduction starts to grow with the impurity density. This could be explained by (i) the change of the ITG instability threshold with Z, (ii) the reduction of $\Omega_{E\times B}$ and (iii) the increasing $k_{\max}$ which is more and more dominated by the Larmor radius of the impurity ions and $k_{\max} \sim 1/\rho_Z \sim Z/\sqrt{A_Z} \sim \sqrt{Z}$. Therefore the factor ς increases and this affects the former term in the relation (6) weaker than the latter one, by reducing additionally the impact of the $E \times B$-shear.

4. Ion heat conduction equation

In the core of the LHD plasma the poloidal cross-sections of the magnetic flux surfaces are close to elliptic ones. The plasma parameters are nearly homogeneous on the surfaces and can be described as functions of the effective radius $r = \sqrt{yz}$, with y and z being the minor and major axes of the cross-section. The ion temperature is governed by the following heat conduction equation:

$$\frac{1}{r}\frac{d}{dr}\left(-r\kappa_i\frac{dT_i}{dr}\right) = Q^i_{heat} - Q_{ie}, \tag{7}$$

where the $\kappa_i = \kappa_0 + \kappa_{an}$ is the ion perpendicular heat conduction with the value κ_0 defined from the requirement that the magnitude of $T_i\,(r=0)$ calculated for the state with the maximum peaking of the temperature profile in the presence of carbon impurity reproduces the experimental one; Q^i_{heat} is the ion heating power and $Q_{ie} = \alpha\,(T_i - T_e)$- that of the heat transfer from ions to electrons through coulomb collisions. The

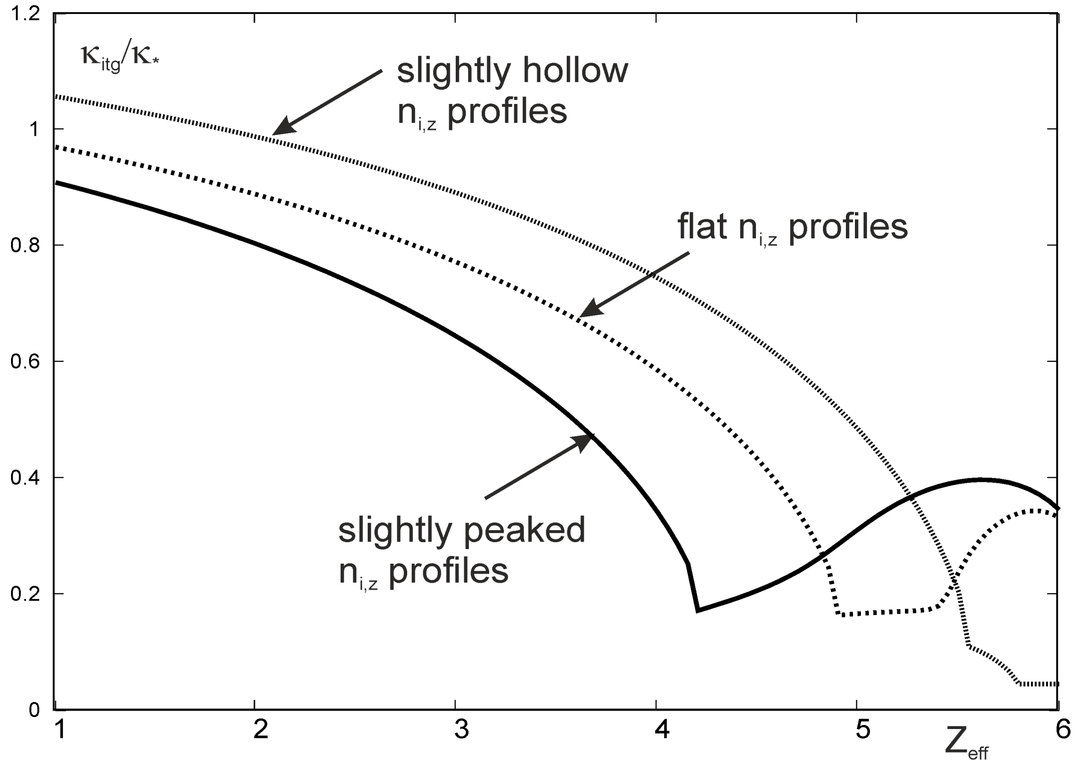

Figure 5. The anomalous ion heat conduction due to ITG unstable modes versus the plasma effective ion charge computed for slightly peaked, $\epsilon_{i,Z} = 1$, flat, $\epsilon_{i,Z} = 0$, and slightly hollow, $\epsilon_{i,Z} = -1$, ion density profiles.

anomalous contribution to the ion heat conduction due to ITG unstable modes, κ_{an}, depends itself on the ion temperature gradient. Figure 5 displays κ_{an} versus ϵ_T for $\epsilon_{i,Z} = 1$ and different magnitudes of Z_{eff}, with other parameters assumed the same as by calculating the results presented in Fig.4. One can see that at some critical values of ϵ_T the anomalous heat conduction changes abruptly. As it has been demonstrated in [25], by solving equation (7) with a standard approach, e.g., a finite difference one, this can lead to numerical instabilities. This situation is exaggerated by the fact that the radial position of such a discontinuity in κ_{an} is unknown in advance.

An approach to handle transport models, predicting abrupt changes of the heat conduction with the temperature gradient, has been elaborated in [25]. This is based on the introduction of the new variable:

$$\Theta(r) = \frac{1}{r^2} \int_0^r \Omega T_i \rho d\rho, \tag{8}$$

where the function $\Omega(r)$ is chosen by analyzing the T_i-dependence of the right hand side (rhs) of equation (7). One can straightforwardly get:

$$T_i = \frac{1}{\Omega} \left(r \frac{d\Theta}{dr} + 2\Theta \right), \tag{9}$$

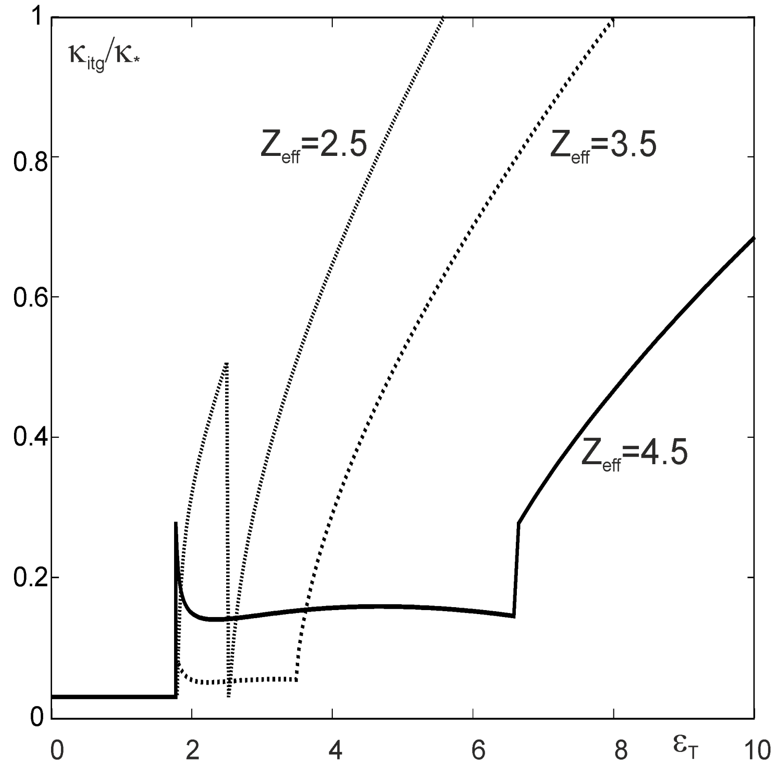

Figure 6. The anomalous ion heat conduction due to ITG unstable modes versus the parameter $\epsilon_T \sim dT_i/dr$ computed for different values of Z_{eff}.

$$\frac{dT_i}{dr} = \frac{r}{\Omega}\left[\frac{d^2\Theta}{dr^2} + \left(\frac{3}{r} - \frac{d\ln\Omega}{dr}\right)\frac{d\Theta}{dr} - \frac{2}{r}\frac{d\ln\Omega}{dr}\Theta\right]. \tag{10}$$

By integrating equation (7) from $r = 0$, one gets an equation for $\Theta(r)$. In the present case, where T_i is involved into the rhs of (7) only through Q_{ie}, $\Omega = \alpha$ and:

$$\frac{d^2\Theta}{dr^2} + \left(\frac{3}{r} - \frac{d\ln\alpha}{dr}\right)\frac{d\Theta}{dr} - \left(\frac{2}{r}\frac{d\ln\alpha}{dr} + \frac{\alpha}{\kappa_i}\right)\Theta = -F, \tag{11}$$

with free term $F = \frac{\alpha}{\kappa_i r^2}\int_0^r \left(Q^i_{heat} + \alpha T_e\right)\rho d\rho$.

One can see that on the contrary to equation for T_i the one above for Θ does not contain $d\kappa_i/dr$, becoming infinite in the points of κ_{an}, and, thus, of κ_i discontinuity. Therefore, as it was shown in [25] it can be integrated without numerical troubles by standard numerical methods for the second order ODE. From the relations (9), (10) it follows that the boundary condition at the plasma axis for T_i, $dT_i/dr\,(0) = 0$, transforms into $d\Theta/dr\,(0) = 0$. The boundary condition at the outer border of the computational region, $r = r_*$, corresponds that the T_i- profile does not change with impurity injection for $r > r_*$ and, thus, $T_i(r_*)$ is fixed.

5. Results

5.1. LHD experiment

Computations have been performed for the conditions of the LHD shot 106455 where the amount of impurity has been varied by injecting two carbon pellets with a certain time interval; in calculations this variation has been mimicked by changing Z_{eff}. The input parameters for the transport model have been assessed by analyzing the experimental profiles: $\kappa_0 = (5.7 - 2.5r^2/r_*^2)\, 10^{19} m^{-1} s^{-1}$ with $r_* = 0.4m$; the plasma density is slightly hollow, $n_e\,(r) = (1.2 + 0.3r^2/r_*^2)\, 10^{19} m^{-3}$; according to transport analysis [9] the deposition power changes very slightly with the pellet injection and henceforth $Q^i_{heat} = 0.8(1 - 0.66r/r_*) MW\, m^{-3}$ is adopted for all conditions. Figure 6 shows the assumed electron temperature profile, which practically did not change by impurity injection, and the ion temperature profiles calculated with different magnitudes of Z_{eff}. One can see that the computed T_i-profiles mimics quantitatively and qualitatively well the experimental ones, see Figure 1. The central temperature value increases with the impurity content up to $Z_{eff} \gtrsim 3$ but drops noticeably if Z_{eff} approaches to a level of 4. This in line with the results in Fig. 2 predicting the deteriorating effect of a too high impurity concentration on the ion energy confinement. The optimum carbon density of $8 \times 10^{17} m^{-3}$, corresponding to the maximum central T_i, is in rough agreement with the experimental data presented in Fig.2. The agreement between calculations and measurements becomes better if one takes into account that in the discharges a significant contribution to Z_{eff} was from He seeded into H plasma for other experimental aims.

The shear of the drift rotation induced by the radial electric field E_r, $\Omega_{E\times B}$, is traditionally considered as of a very importance for the suppression of drift micro-instabilities triggering anomalous transport in magnetic fusion devices [21]. The analysis in [23] has shown that under conditions in question the main contribution to E_r is from the diamagnetic rotation component induced by the ion temperature gradient. In the present model this is taken into account by the last term in the square brackets in the relation for κ_{an}. With increasing density of impurity the flow of the main hydrogen ions is braked by the friction through coulomb collisions with the impurity ions whose rotation velocity is smaller by a the factor $1/Z$. This must be of importance for the deterioration of the ion heat transport at high n_Z. In the relation (6) for κ_{an} this is described by the reduction of the factor ψ with decreasing ξ_i. To demonstrate the significance of the $\Omega_{E\times B}$ effect computations have been done with $\psi = 1$ corresponding to $Z_{eff} = 1$. The results presented in Fig. 7 demonstrate that in such a case, in a disagreement with observations [9], there is no deterioration in the ion heat transport, at least up to $Z_{eff} = 4$.

One of the main peculiarities of the plasma parameter profiles in the heliotron LHD is an essentially flat or even slightly hollow electron density profile. Under conditions in question with carbon pellet injection plasmas with a hollower $n_e(r)$ reveals a stronger reduction in the ion heat transport channel, see Fig. 3. This is in line with the reduction

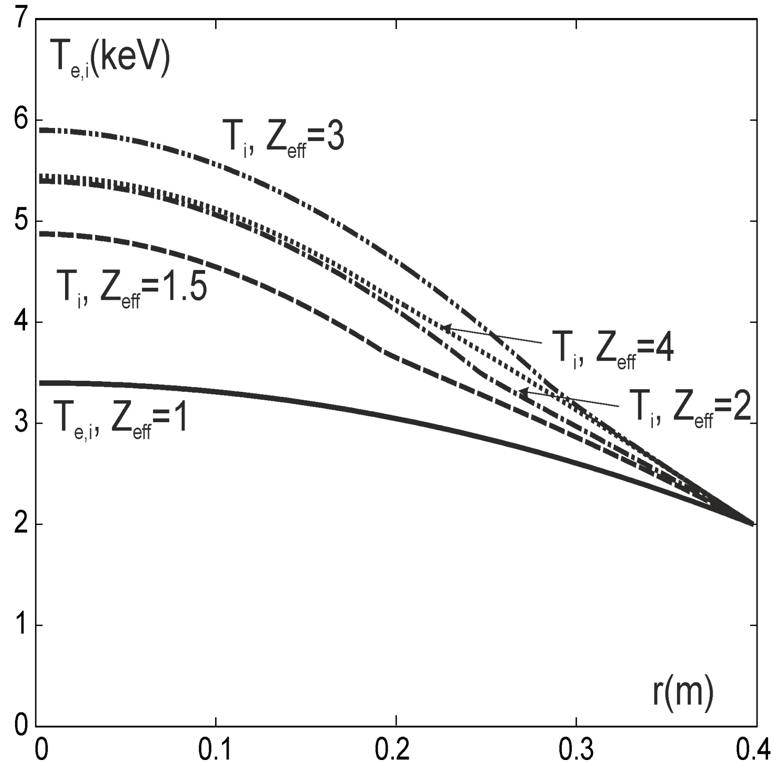

Figure 7. The radial profiles of the ion temperature computed with different magnitudes of Z_{eff}.

of ITG growth rate by a hollow density profile observed in recent gyro-kinetic Vlasov simulations [26]. To prove that also the model elaborated in the present paper reproduces these experimental findings calculations were performed with an ideally flat density, $n_e(r) = 1.5 \cdot 10^{19} m^{-3}$, and the T_i-profiles obtained for different Z_{eff} are shown in Fig. 8. One can see that the confinement improvement in this case is noticeably smaller than for hollow density profiles and deteriorates very fast with $Z_{eff} > 3$. The main effect of the hollow n_e-profile is a smaller plasma density in the core. This results in a lower κ_* and, see Eq.(6), a smaller κ_{an}.

Finally, we consider the role of the ion component cooling through coulomb collisions with electrons given by the term Q_{ie}. Due to the mass relation collisions between the main and impurity ions are much more effective for heat transfer than those with electrons. Therefore collisions of impurity ions with electrons is of importance for both ion components. If as above these collisions are taken into account, $Q_{ie} \sim (1+\xi_i)/2$. On the contrary, by neglecting the contribution of $Z-e$ collisions $Q_{ie} \sim \xi_i$ and Fig.9 shows the ion temperature profiles obtained in this case. They very marginally differ from those shown in Fig. 6 found by taking $Z-e$ collisions in Q_{ie} into account. This fact does not mean, however, that the factor in question is not important generally. Its role may be more significant under reactor conditions with a much higher electron density.

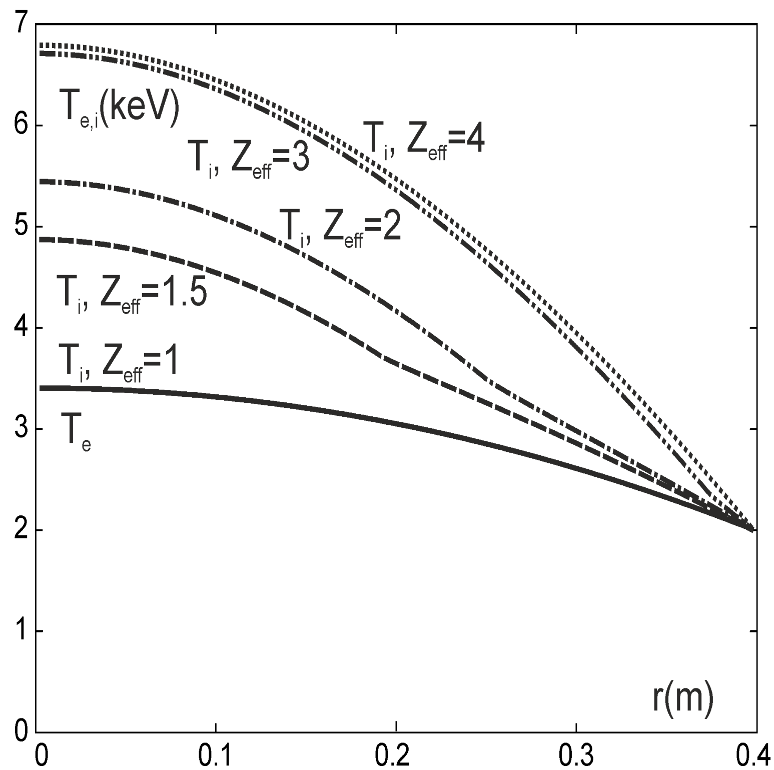

Figure 8. The radial profiles of the ion temperature, computed by neglecting the braking of the main ion rotation due to friction with impurities.

5.2. Extrapolation to reactor conditions

A lot of experimental facts both presented and cited, in particular, in this paper show a positive influence of impurities on the anomalous ion heat transport, by leading to the suppression of the ITG induced turbulence. The fact that these findings were done on tokamak and helical fusion devices suggest a fundamental nature of these phenomenon being of value by itself. Nonetheless, its practical usefulness for the future reactors is still a matter of debates. The main arguments against impurity injection are the suspicions that the increase of Z_{eff} will lead to (i) the plasma dilution and, thus, the reduction of the fusion output and (ii) the growth of the edge radiation provoking disruption in tokamaks and thermal collapse in helical devices.

To analyze the Z_{eff} effect on the fusion power we start from the plasma power balance:

$$\frac{(n_e + n_i + n_Z)\,T}{\tau_E} \sim P_{fus},$$

where T is the plasma temperature assumed the same for all charged components; for the energy confinement time τ_E we assume the ISS04 scaling [14] and modify this to take into account the effect of impurity on the anomalous transport which, according

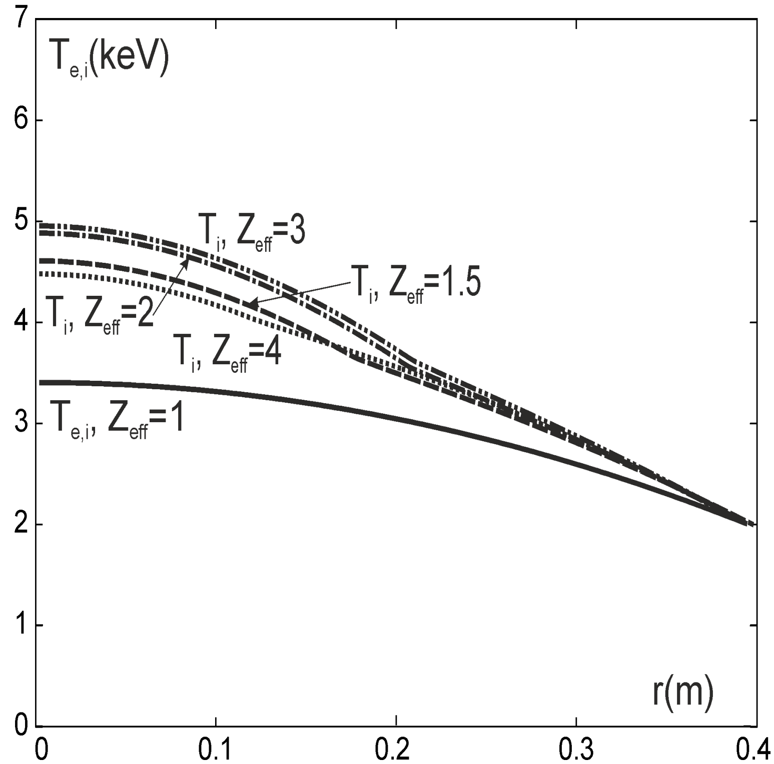

Figure 9. The radial profiles of the ion temperature computed with flat ion density profiles.

to the present study, decreases roughly as $1/\sqrt{Z_{eff}}$; thus

$$\tau_E \sim \frac{n_e^{0.54}}{P_{fus}^{0.61}} \sqrt{Z_{eff}};$$

and in the important temperature range $5keV \lesssim T \lesssim 20keV$ the fusion power

$$P_{fus} \sim n_i^2 T^2.$$

By combining the relations above and using the plasma quasi-neutrality condition, providing $n_i = n_e \frac{Z-Z_{eff}}{Z-1}$, $n_Z = \frac{n_e}{Z} \frac{Z_{eff}-1}{Z-1}$, one gets:

$$T \sim f_{ZT} n_e^{1.45}, \; P_{fus} \sim f_{ZP} n_e^{4.9}, \quad (12)$$

with $f_{ZT} = \varphi_Z \psi_Z^{3.54}$, $f_{ZP} = \psi_Z^{9.1}$, $\psi_Z = \varphi_Z \frac{Z-Z_{eff}}{Z-1}$ and $\varphi_Z = \frac{2Z\sqrt{Z_{eff}}}{2Z+1-Z_{eff}}$.

Figure 10 shows the factor f_{ZP} as a function of the effective plasma ion charge for 3 impurity species, namely, helium, carbon and neon.One can see that, on the one hand, the accumulation of He ash will, as expected, lead to drop of the fusion power. On the other hand, the presence of seeded C and Ne impurities results in a significant increase, in spite of the plasma dilution, in the power input, at least if the ISS04 energy confinement time scaling can be extrapolated to reactor conditions. The increase of f_{ZP} with Z_{eff} for the effective ion charge not much larger than 1 is through the factor φ_Z and reveals the dependence of τ_E on the heating power. The decrease of f_{ZP} for larger Z_{eff} is the dilution effect. Although it is a very qualitative indication it motivates

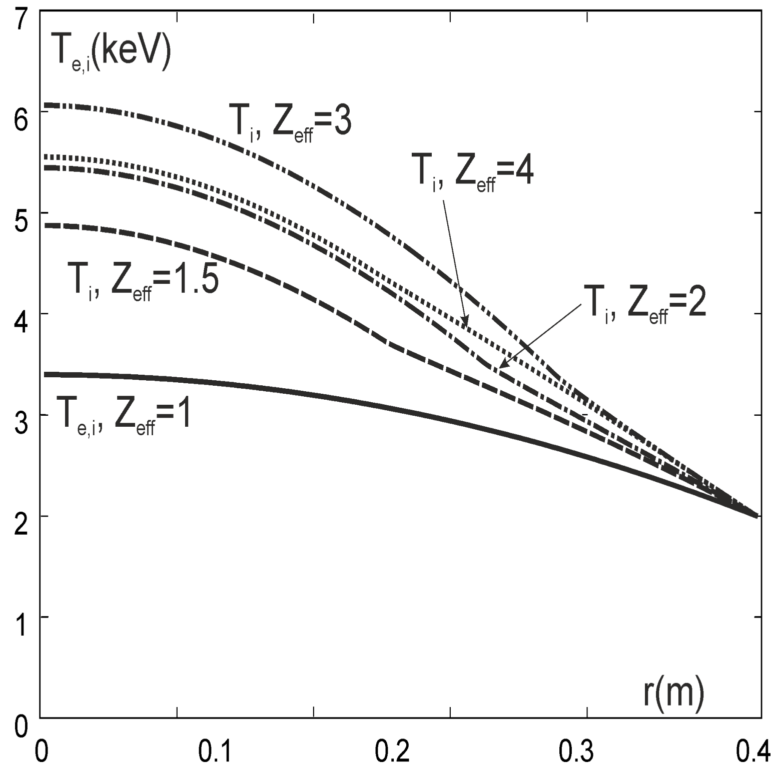

Figure 10. The radial profiles of the ion temperature, computed by neglecting the cooling of the ion components through coulomb collisions between impurities and electrons.

to continue the exploration of the impurity influence on the energy confinement in the plasma of fusion devices.

The role of impurity radiation energy losses has been neglected in the analysis above. As it has been mentioned in the LHD experiments of a low plasma density discussed in the present paper these did not exceed $10-15\%$of the heating power. However, it is important to consider what will be happened by going to a higher density required in a reactor, of $10^{20}m^{-3}$, by simultaneously maintaining Z_{eff} at a fixed level. The radiation power from the plasma core, P_{rad}^{core}, is mostly due to Bremsstrahlung and recombination of impurity nuclei and increasing as $n_Z n_e \approx n_e^2/Z^2$. By using the ADAS-data [27] one gets that for C and Ne impurities $P_{rad}^{core}/n_e^2 V_{pl} \approx 3{\cdot}10^{-36} Wm^3$ at a plasma temperature of $15keV$, i.e. by a factor of 30 smaller than $P_{fus}/n_e^2 V_{pl} \approx 10^{-34} Wm^3$. Thus, also under the reactor conditions the core radiation of injected impurity should not be a large problem. Nonetheless, it is well-known that in modern devices the line radiation of incompletely stripped impurity ions dominate radiation losses and for impurity species in questions these are Li-like ion states, C^{3+} and Ne^{7+}, respectively. These species reside at the plasma edge and are not in a corona equilibrium, being essentially affected, in particular, by transport phenomena, see, e.g., [28]. A firm assessment of their radiation, P_{rad}^{edge}, is not so trivial as for impurity nuclei in the plasma core and requires a special consideration out of scope of the present study. Here we note only that a simple proportion $P_{rad}^{edge} \sim n_e^2$

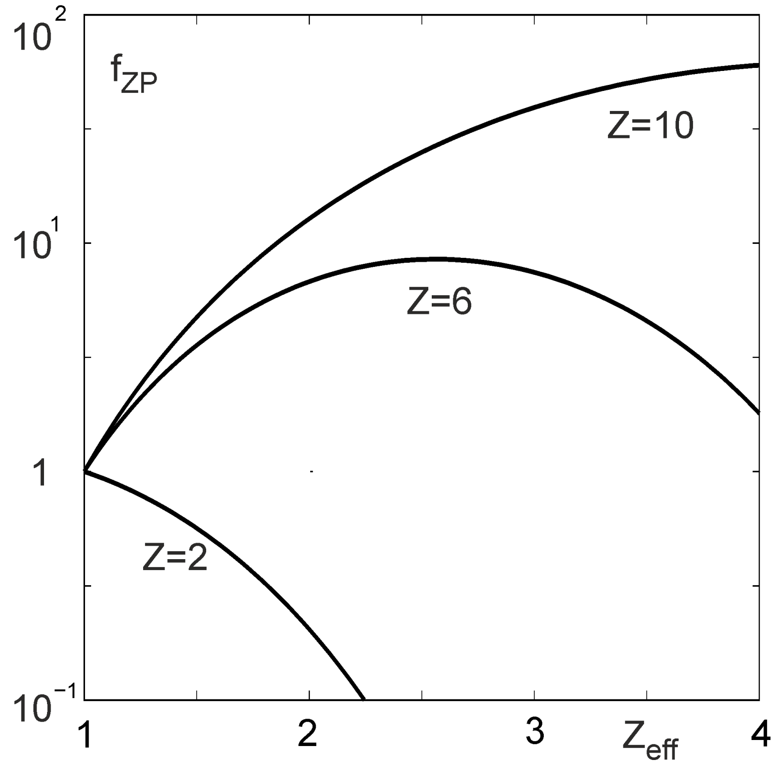

Figure 11. The factor f_{PZ}, characterizing the impact of the impurity presence in a fusion reactor on its power output, as a function of the plasma effective ion charge for different impurity species, assessed by assuming the ISS04 scaling for the energy confinement time in stellarators.

obviously can not be applied in this case. For example, the measurements on LHD [29] have demonstrated that by increasing the line averaged density n_e from $2 \cdot 10^{19} m^{-3}$ to $7 \cdot 10^{19} m^{-3}$ the total radiation losses, dominated by P_{rad}^{edge}, have grown by a factor of 2 only. At the same time, being enhanced to a certain fraction of the input power, the edge impurity radiation can provoke thermal instabilities resulting in a plasma collapse. To avoid such a trouble in the LHD the application of a resonant magnetic perturbation at the plasma edge has been verified as an effective tool [17]. It has allowed to get a stable detached plasma at a high reactor relevant density of $10^{20} m^{-3}$ with the radiation losses approaching closely to the input power. To our mind this method deserves further deeper study and elaboration, especially, by taking into account that RMP is now widely exploited on magnetic fusion devices of different concepts. In future experiments one has to try to apply RMP also by attempting to explore the impurity injection scenario for the confinement improvement at a higher plasma density.

6. Conclusions

Recent experiments on the heliotron LHD with injection of carbon pellets have demonstrated that the reduction of anomalous heat transport in the presence of impurities, found previously in diverse tokamak devices, is not specific for this type of fusion devices only. At an optimal level of the carbon density of $5 - 10 \cdot 10^{17} m^{-3}$ a pronounced peaking of the ion temperature profile and strong increase, up to a factor of 2, of the central T_i magnitude has been observed in the LHD. The similarity of the impurity influence both in tokamaks and in helical devices testify about a fundamental nature of this phenomenon. Therefore the approach used before to interpret the confinement improvement in TEXTOR and JET has been elaborated further and applied here to explain the observations on the LHD. It is based on the impact of the ion charge on the growth rate of a toroidal ion temperature instability considered usually as the main trigger of the anomalous transport in magnetic fusion devices.

The results of calculations are generally in line with the experimental findings. They reproduces both qualitatively and quantitatively the drop of the ion anomalous heat conduction and peaking of the ion temperature with Z_{eff}, increasing up to a critical level, and the drop of the ion confinement if this level is exceeded. Our computations also demonstrate a significant importance of the shear of the drift rotation induced by the radial electric field. Under conditions in question E_r is mostly driven by the diamagnetic flow induced through the ion temperature gradient. If the braking of this flow by the friction with impurity ions is neglected the ion temperature peaking with increasing impurity concentration is significantly higher than in the experiments. Moreover, there is no critical Z_{eff}, by overcoming which the energy confinement starts to deteriorate. The model elaborated reproduces also the stronger impurity effect on the T_i peaking for hollow density profiles compared to flat ones as it is observed in the LHD. Calculations show that coulomb collisions between impurities with electrons do not play a noticeable role for the ion heat balance. This cooling channel may become more important by going to a higher plasma density relevant to a fusion reactor. The present consideration demonstrates that both experiments on helical devices, such as the LHD, allowing a good control and reproduction of experimental conditions, and their interpretation can make an important contribution to fusion studies in general, in particular, by investigating impurity impacts on the plasma performance.

Although there are qualitative indication that the impurity injection approach can work also under reactor relevant conditions, for a firm extrapolation of the LHD results further developments of the present model are necessary. In particular a time dependent calculations for the entire plasma volume, by including a description of the impurity source through the pellet ablation and transport of the material ablated, the evolution of the electron density seems to be of importance. This has been demonstrated in the LHD experiments with carbon pellets of different radii, see [9].

To validate the present model further comparison with different measurement data have to be done in future investigations. It concerns, e.g., turbulence spectrum, the generation mechanism of the radial electric field leading to $\Omega_{E\times B}$ stabilization of ITG modes. Here it is assumed as generated mostly by the ion temperature gradient and this assumption has to be checked by comparing with measurements by the charge-exchange diagnostics providing the contributions from the toroidal, poloidal and diamagnetic rotation components to E_r separately. In a reactor the α- particles will be intrinsically presented and an elaboration of our approach for the case of 3 and more ion species is of interest. This is also of importance to include into the considerations heavier impurities such as neon, argon, tungsten, studied in present experiments too.

The present study shows that the impurity injection can be a promising scenario to improve the energy confinement in heliotron fusion device. Nonetheless a skeptical attitude by many researches to a deliberate introduction of impurities into a fusion reactor is understandable. This stimulates us to further investigations of this approach in diverse respects such as:

(i) optimization of the impurity pellet injection method, e.g., by doing this at the high field side to use the polarization drift;

(ii) combination with other successful schemes to improve ion confinement, e.g., hydrogen pellet injection in W7-X [30] which provides a peaked profile of the plasma density (the density peaking has been proven as an effective method to suppress ITG-instabilities already in TEXTOR RI-mode [4]);

(iii) application RMP at the plasma edge to control the radiation losses and prevent a plasma thermal collapse [17, 29]

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