Diffusion coefficient and convective velocity profiles of Ni-impurity in JET plasmas with ICRH

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Abstract. The influence of the RF heating on the Ni-impurity transport is studied from comparative analysis of two discharges in JET: the reference discharge #69808 without RF power and discharge #68383 with the maximum ICRF power of 8.3 MW which is applied to electrons in Hydrogen Minority Heating scheme. With this goal we use multi-fluid Weiland model with trace impurity approximation and input profiles of density and temperature from the two shots. For the most instable determined eigen modes are calculated diffusivity, convective velocity and peaking factor for the two shots, respectively.

1. Introduction
Experiments have shown that auxiliary heating can influence impurity accumulation and transport and, by consequence, the plasma confinement. In JET, various type of discharges at ITER relevant collisionality had shown that the density profile of Ni (Z=28) impurity is flattening when ion cyclotron resonance heating (ICRH) is applied [1]. Influence of ICRH on the impurity density profile was intensively studied but the present understanding of impurity transport and accumulation is still insufficient to predict the behaviour of elements over wide Z range. Also, some dicrepancies between calculated peaking factor and experimental measurements rest to be explained and clarified. The remainder of the paper is organized as follows. In section 2 are given the essential characteristics of the theoretical model as the impurity density perturbation and impurity particle flux due to ITG/TE modes in plasmas (obtained in [2] by using multi-fluid Weiland model). In section 3 analltical expressions of the profiles are given to fit the experimental data for impurity and electron density and temperature profiles from shots 69808 and 68383 in JET ([3], [4]). The reference discharge 69808 is without RF power and the discharge 68383 is with the maximum ICRF power of 8.3 MW in H Minority Heating. The influence of the heating on the density perturbation profile is taken into account by the specific profiles of electron density and electron/impurity temperature profiles for the two shots. Eigenvalues for the ITG mode in the inner region of the plasma are determined in section 4. The final section is dedicated to the conclusions and evaluation of the diffusivity, convective velocity and normalized impurity density peaking factor for Ni in the most unstable eigen-mode determined previously.

2. Characteristics of the model
The Weiland multi-fluid model with trace impurity approximation is used to describe ITG/TE mode turbulence and the impurity species. The equation for the impurity/ion density
perturbation due to ITG modes in plasmas with radio-frequency heating, obtained in [2] read as

\[ \tilde{n}_z = \left( \tilde{\omega} \left( \frac{R}{2L_{nz}} - 1 \right) - \tau^*_z \left( \frac{R}{2L_{nz}} - \frac{7}{3} \frac{R}{2L_{nz}} + \frac{5}{3} \right) + \frac{Z}{A_z q_s^2} \left( \tilde{\omega} + \frac{5\tau^*_z}{3} / \tilde{\omega} - 2\tau^*_z \right) \right) \frac{\tilde{\phi}}{N} \]  

(1)

where \( N = \tilde{\omega}^2 + 10\tau^*_z \tilde{\omega}/3 + 5\tau^*_z/3 \). Here \( \tilde{\phi} = e\phi/T_e \) is the normalized potential, \( \tilde{n}_z = \delta n_z/n_z \) is the normalized impurity perturbation, \( \tilde{\omega} = \omega/\omega_{De} \) the normalized frequency (where \( \omega_{De} \) is the electron magnetic drift frequency). The other notations are \( \tau^*_z = T_z/ZT_e \), \( 1/L_{nj} = -d\ln n_j/dr \), \( 1/L_{Tj} = -d\ln T_j/dr \), \( A_z = m_z/m_i \), \( q_s = 2q_k\rho_s \), \( \rho_s = c_s/c_i \), \( c_s = \sqrt{T_e/m_i} \).

The quasilinear impurity particle flux

\[ \Gamma_{nz} = -D_z \nabla n_z + n_z V_z \]  

(2)

is given by - see eq.(8) in [2],

\[ \Gamma_{nz} = \frac{k_{q} \rho_s \tau^*_z}{|N|} |\tilde{\phi}_k|^2 \left\{ \frac{R}{2L_{nz}} \left( \tilde{\omega}^2 + 14 \tilde{\omega} \tilde{\omega}_r + \frac{55 \tau^*_z}{9} \right) - \frac{R}{2L_{Tz}} \left( 2\tau^*_z \tilde{\omega}_r + \frac{5\tau^*_z}{3} \right) \right\} \]  

(3)

where \( N_1 = \tilde{\omega} - 2\tau^*_z \). In (2) \( D_z \) and \( V_z \) are the impurity diffusivity and convective velocity, respectively.

3. Input profiles

In the following are given the profiles which will be used as input data. They fit the profiles given in [3] for the reference discharge #69808 without RF power and discharge #68383 with the maximum ICRF power of 8.3 MW applied to electrons in Hydrogen Minority Heating scheme in JET. A subscript \( h \) will distinguish the quantities in the presence of ICRH from those without RF heating. The impurity considered here is Ni (Z=28). With \( x = r/a \), the impurity density profiles \( n_z \), \( n_{z-h} \), electron density \( n_e \), \( n_{e-h} \), impurity temperature \( T_z \), \( T_{z-h} \), electron temperature \( T_e \), \( T_{e-h} \) and safety factor \( q \) and \( q_h \) profiles are given, respectively, in (4)-(12) and plotted in figures 1-5. The values for \( n_{0e}, T_{0z} \) and \( T_{0e} \) are given as \( n_{0e} = 3.5 \times 10^{19} \text{ m}^{-3}, T_{0z} = 9.4 \text{ keV}, T_{0e} = 5.66 \text{ keV} \).

\[ n_z = n_{0z} \left\{ 0.54 - \frac{x}{2} + 0.4 \exp \left[ -30 \left( x - 0.01 \right)^2 \right] + 0.14 \exp \left[ -15 \left( x - 0.34 \right)^2 \right] \right\} + 0.13 \exp \left[ -20 \left( x - 0.8 \right)^2 \right] + 0.12 \exp \left[ -200 \left( x - 0.95 \right)^2 \right] \]  

(4)

\[ n_{z-h} = n_{0z} \left\{ 0.38 \exp \left[ -10x^2 \right] + 0.43 \exp \left[ -30 \left( x - 0.39 \right)^2 \right] + 0.28 \exp \left[ -12 \left( x - 0.6 \right)^2 \right] \right\} + 0.33 \exp \left[ -8 \left( x - 0.7 \right)^2 \right] + 0.4 \exp \left[ -10 \left( x - 0.8 \right)^2 \right] \]  

(5)

\[ n_e = n_{0e} \left\{ 0.91 - 0.91 x^2 + 0.1 \exp \left[ -15 \left( x + 0.1 \right)^2 \right] + 0.07 \exp \left[ -10 \left( x - 0.85 \right)^2 \right] \right\} \]  

(6)

\[ n_{e-h} = n_{0e} \left\{ 0.8 - 0.78 x^3 + 0.07 \exp \left[ -30x^2 \right] + 0.08 \exp \left[ -20 \left( x - 0.3 \right)^2 \right] \right\} + 0.03 \exp \left[ -80 \left( x - 0.7 \right)^2 \right] + 0.1 \exp \left[ -100 \left( x - 0.9 \right)^2 \right] \]  

(7)
\[ T_z = T_0 \left\{ 0.37 - 0.4x + 0.64 \exp[-9x^2] + 0.06 \exp[-16(x-0.6)^2] \\
+ 0.12 \exp[-20(x-0.9)^2] \right\} \] (8)

\[ T_{z-h} = T_0 \left\{ 1.04 \exp[-4(x+0.14)^2] + 0.21 \exp[-5(x-0.7)^2] \right\} \] (9)

\[ T_e = T_{0e} \left\{ 0.6 - 0.7x + 0.4 \exp[-14(x-0.08)^2] + 0.2 \exp[-30(x-0.35)^2] \\
+ 0.18 \exp[-20(x-0.65)^2] + 0.2 \exp[-90(x-0.92)^2] \right\} \] (10)

\[ T_{e-h} = T_{0e} \left\{ 0.93 - 1.04x + 0.97 \exp[-10(x+0.1)^2] + 0.45 \exp[-30(x-0.35)^2] \\
+ 0.24 \exp[-20(x-0.65)^2] + 0.28 \exp[-90(x-0.92)^2] \right\} \] (11)

\[ q = 1.5 + x^2 + 4x^3 + 2x^4, \quad q_h = 1 + x^2 + 4x^3 \] (12)

**Figure 1.** Ni-impurity density profiles in #69808 (full line) without RF power and discharge #68383 with ICRF power applied to electrons in Hydrogen Minority Heating (dashed line).

**Figure 2.** Electron density profiles in #69808 (full line) without RF power and discharge #68383 with ICRF power applied to electrons in Hydrogen Minority Heating (dashed line).

**Figure 3.** Ni-impurity temperature profiles in discharge #69808 (full line) and discharge #68383 (dashed line).

**Figure 4.** Electron temperature profiles in discharge #69808 (full line) and discharge #68383 (dashed line).

4. Quasineutrality condition and ITG eigenmodes
In order to represent the radial variation of the impurity density perturbation for the two shots we need to find the eigenfrequency modes for ITG instability. This imply to solve equation
resulting from the quasineutrality condition

\[-e \delta n_e + \sum_i e_i \delta n_i = 0 \tag{13}\]

where summation over \(i\) concern to summation over all ion/impurity plasma species. The resulting dispersion equation, which is of great complexity, was solved in different approximations; see for example [5]. In the following we assume one ion species with charge number \(Z_i\) and one impurity species (Ni) with charge number \(Z = 28\). In this case quasineutrality condition \((13)\) read as

\[\frac{\delta n_e}{n_e} = Z_i f_i \frac{\delta n_i}{n_i} + Z f_z \frac{\delta n_z}{n_z} \tag{14}\]

where

\[f_z = \frac{n_z}{n_e}, \quad f_i = \frac{n_i}{n_e} \tag{15}\]

From neutrality condition

\[Z_i n_i + Z n_z = n_e \tag{16}\]

and \((15)\) we obtain the density ion profiles - see figure 6,

\[n_i = \frac{n_e - Z n_z}{Z_i} \tag{17}\]

In the following the discussion will focus on the inner region of plasma with \(0 < r/a < 0.6\), where the contribution from trapped electrons will be neglected and the quasineutrality condition is approximated as

\[(1 - f_i) \frac{\delta n_{ef}}{n_{ef}} = (1 - Z f_z) \frac{\delta n_i}{n_i} + Z f_z \frac{\delta n_z}{n_z} \tag{18}\]

where \(\delta n_z\) is the impurity density perturbation, \(\delta n_i\) - ion density perturbation, \(\delta n_{ef}\) - circulating electrons density perturbation and \(f_i\) - fraction of trapped particles. The dispersion equation will be obtained from \((18)\) by introducing \(\tilde{n}_z = \delta n_z/n_z\) and \(\tilde{n}_i = \delta n_i/n_i\) from \((1)\) and \(\tilde{n}_{ef} = \delta n_{ef}/n_{ef}\) for free electrons, with assumption of quasi-adiabatic behavior,

\[\frac{\delta n_{ef}}{n_{ef}} = \frac{e}{T_e} \frac{\delta \phi}{\delta \phi} \tag{19}\]
Also, the ion (Hydrogen) temperature profile is assumed the same with impurity temperature profile. In this case, from the dispersion equation result four eigenvalues

\[ \tilde{\omega} = \tilde{\omega}_{re} + i\tilde{\gamma} \] (20)

Between the four eigenmodes we choose the unstable mode with the real and imaginary part represented in figure 7 and figure 8, respectively. As can be seen, in the presence of RF heating the growth rate \( \tilde{\gamma} \) becomes smaller than in the case without RF heating which means a more ‘quiet’ ITG instability.

5. Discussions and conclusions

The Ni-impurity diffusivity \( D_z \) and convective velocity \( V_z \) are calculated from (3) for ITG mode eigenvalue \( \tilde{\omega} \) with previously determined characteristics plotted in figure 7 and 8 for a fixed turbulence scale \( k_\theta \rho_s = 0.2 \) and with potential fluctuation level \( |\phi_k| = (\gamma/\omega_{sc}) (1/k_\theta L_{ne}) \) - see for example [5].

In figures 9 and 10 are shown the radial profiles of \( D_z \) and \( V_z \) in the two shots. We note that in the region with \( 0 < r/a < 0.5 \) the diffusivity in the presence of RF heating is smaller than diffusivity in absence of RF heating, with a very small value of \( D_{z-h} \) in the interval \( 0 < r/a < 0.3 \) and a maximum value at \( r/a = 0.47 \) that correspond to the position where start the plateau for \( n_{z-h} \). In the case without RF heating the diffusivity \( D_z \) rich its maximum at \( r/a = 0.43 \) and is
much greater than $\frac{D_{\perp}}{h}$ for $0 < r/a < 0.4$. As for the diffusivity, the presence of RF heating reduced nearly to zero the magnitude of the convective velocity in the region with $0 < r/a < 0.3$. Hence, in the central region of the plasma the transport due to ITG instability is practically suppressed as was confirmed by experimentally observations.

![Figure 11. Normalized impurity density peaking factor in discharge #69808 (full line) and discharge #68383 (dashed line).](image)

The normalized impurity density peaking factor $-\frac{RV_z}{D_z}$ (assuming a source-free plasma) of Ni-impurities as function of radial coordinate is shown in figure 11. The density peaking factor in the case without RF heating decrease linearly with $r/a$ in the region with $0 < r/a < 0.5$. In the case with RF heating the density peaking factor decrease with $r/a$ also for $r/a < 0.5$ but with a plateau for $0.2 < r/a < 0.3$. The results obtained in the present approximation are relevant for ITG mode in the region with $r/a < 0.5$ and can be used as a starting point for more precise calculations in iterative procedure.

**Acknowledgments**

This work has been carried out within Contract of Association EURATOM-MECTS Romania. Acknowledgements to Professor Tünde Fülöp and Hans Nordman for discussions.

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