

# Ion density perturbation driven by electromagnetic turbulence and ICRH

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The perturbation of the ion density is evaluated using a fluctuating distribution function obtained as solution of the drift kinetic equation in passing particle regime. The radio-frequency heating is taking into account by pitch-angle-scattering part of the quasilinear radio-frequency operator. The radial variation of ion density perturbation is studied for terms generated by both the turbulence and ion cyclotron resonance heating (ICRH). The supplementary term of the ion density perturbation obtained here must be included in the quasi-neutrality condition usually used to determine the dispersion relation of the instability, crucial in the study of the turbulence.

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## 1. Introduction

The issue of anomalous transport in tokamak plasmas rests a major problem in physics of plasma fusion [1]. The auxiliary heating of plasma using ion cyclotron resonance waves is largely adopted in present fusion machine and is also previewed for ITER. Consequently, the ion transport due to instabilities in the presence of ICRH is of great interest [2]. The quasi-neutrality condition represents one of the fundamental equations used to describe the transport processes in plasma [3]. The goal of this paper is to analyse the ion density perturbation of the heated species because it enter in the quasi-neutrality equation.

The paper is organized as follow. In Section 2 the perturbed distribution function is written as a solution of the kinetic equation in drift approximation in toroidal geometry with axisymmetric magnetic field and assuming a Maxwell equilibrium distribution function. In Section 3 is evaluated the density perturbation driven by turbulence in absence of ICRH and in Section 4 the density perturbation driven by turbulence and ICRH. Relative magnitude and variation of different terms in density perturbation are discussed in Section 5 and some conclusions are presented in Section 6.

## 2. Perturbed distribution function

In this paper we consider non-Ohmic multi-component plasma which is weakly turbulent due to a fluctuating electric field  $\delta\vec{E} = -\nabla\delta\phi - (1/c)\partial_t\delta\vec{A}$  and a fluctuating magnetic field  $\delta\vec{B} = \nabla\times\delta\vec{A}$ . Consider also that one of its species  $\alpha$  is heated at the ion cyclotron resonance.

The distribution function is the sum of two contributions: one, denoted  $F^\alpha$ , corresponds to ensemble averaged part

and the second, denoted  $\mathcal{F}^\alpha$ , corresponds to the fluctuating part of the distribution function.

$$f^\alpha = F^\alpha + \mathcal{F}^\alpha \quad (1)$$

The particle's velocity  $\vec{v}$  is decomposed as,  $\vec{v} = v_\parallel\vec{b} + \vec{v}_\perp$ , where  $\vec{b} = \vec{B}/B$ . The fluctuating part of the distribution function  $\mathcal{F}^\alpha$  is the sum of a gyrophase averaged part denoted  $\bar{\mathcal{F}}^\alpha$  and a gyrophase dependent part  $\tilde{\mathcal{F}}^\alpha(\gamma)$ :

$$\mathcal{F}^\alpha = \bar{\mathcal{F}}^\alpha + \tilde{\mathcal{F}}^\alpha \quad (2)$$

The kinetic equation for  $\tilde{\mathcal{F}}^\alpha$  in drift approximation is

$$\partial_t\tilde{\mathcal{F}}^\alpha + v_\parallel\nabla_\parallel\tilde{\mathcal{F}}^\alpha + v_D\nabla_\perp\tilde{\mathcal{F}}^\alpha + L_0^\alpha\tilde{\mathcal{F}}^\alpha + \delta\mathcal{L}^\alpha F^\alpha = Q(\tilde{\mathcal{F}}^\alpha), \quad (3)$$

where  $L_0^\alpha$  is the Lorentz force operator originates from the equilibrium, respective  $\delta\mathcal{L}^\alpha$  from the fluctuating electromagnetic fields,

$$L_0^\alpha \equiv \frac{e_\alpha}{m_\alpha} \left( \vec{E} + \frac{1}{c} \vec{v} \times \vec{B} \right) \cdot \frac{\partial}{\partial \vec{v}}, \quad \delta\mathcal{L}^\alpha \equiv \frac{e_\alpha}{m_\alpha} \left( \delta\vec{E} + \frac{1}{c} \vec{v} \times \delta\vec{B} \right) \cdot \frac{\partial}{\partial \vec{v}}$$

and  $Q$  is the quasi-linear radio-frequency operator. From convenience we replace the velocity  $\vec{v}$  by variables:  $x$ , the kinetic energy scaled by thermal energy,  $\lambda$ , the ratio of magnetic moment to kinetic energy and  $\gamma$  the gyro-phase angle. In the following we assume equilibrium distribution function to be Maxwellian:

$$F_M^\alpha = n_\alpha \left( \frac{m_\alpha}{2\pi T_\alpha} \right)^{3/2} \exp(-x) \quad (4)$$

The perturbed quantity  $\delta a$  such as  $\delta \bar{f}^\alpha$ ,  $\delta \phi$  and  $\delta \bar{A}$  are expressed in terms of Fourier integrals

$$\delta a = (2\pi)^{-4} \int d\vec{k} \int_{-\infty}^{\infty} d\omega \delta a_{\vec{k},\omega} \exp[i(\vec{k} \cdot \vec{x} - \omega t)] \quad (5)$$

where  $\vec{k}$  is the wave vector and  $\omega$  is the wave frequency. From eq. (3) we obtain (with  $k_{\parallel} = \vec{k} \cdot \vec{b}$  and  $\vec{b} = \vec{e}_r + \vec{e}_\theta \eta / q$  where  $\vec{e}_r, \vec{e}_\theta, \vec{e}_\zeta$  are unit vectors in respective radial, poloidal and toroidal directions):

$$v_{\parallel} \frac{\partial \delta \bar{f}_{k\omega}}{\partial t} + v_{\parallel} \frac{e_{\alpha} F_M}{T_{\alpha}} \frac{\partial \delta \phi_{k\omega}}{\partial t} = i(\omega - \omega_D) \delta \bar{f}_{k\omega} - i \frac{v_{\parallel}}{c} \frac{e_{\alpha} F_M}{T_{\alpha}} \bar{\omega}_{*k} \cdot \bar{\delta A}_{k\omega} \quad (6)$$

$$- i(v_{\parallel} k_{\parallel} - \bar{\omega}_{*k} \cdot \vec{b}) \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} - \vec{e}_r \cdot \vec{v}_D \frac{\partial \delta \bar{f}_{k\omega}}{\partial r} + Q(\delta \bar{f}_{k\omega})$$

where  $\bar{\omega}_{*k} = \frac{c T_{\alpha}}{B e_{\alpha}} \frac{\partial \ln F_M^{\alpha}}{\partial r} (\vec{e}_r \times \vec{k})$  and  $\omega_{*k} = \bar{\omega}_{*k} \cdot \vec{b}$

In the following we assume an axisymmetric model for magnetic field (standard model) defined as in [4]:

$$B(r, \theta) = \frac{B_0 \sqrt{1 + \eta^2 q^{-2}}}{1 + \eta \cos \theta}, \text{ where } \eta = r / R_0 \text{ with } R_0 \text{ the major}$$

radius of the toroidal device,  $\theta$  the poloidal angle and  $q$  the safety factor. In this case, with circular poloidal cross section, the smallness of radial component of  $\vec{v}_D$  make possible to disregard the term with  $\vec{e}_r \cdot \vec{v}_D$  and keep terms with  $\omega_{*k}$ , despite the drift velocity ( $\vec{v}_D$  contains all the particle drift velocities) is much grater than diamagnetic velocity involved in  $\omega_{*k}$ .

In the absence of heating,  $Q(\delta \bar{f}_{k\omega}) = 0$ , integrating eq.(6) on obtain in the passing particle regime

$$\delta \bar{f}_{k\omega} = - \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} + i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} (\omega - \omega_D) \delta \bar{f}_{k\omega} \quad (7)$$

$$- i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} (v_{\parallel} k_{\parallel} - \bar{\omega}_{*k} \cdot \vec{b}) \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} - i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} \frac{e_{\alpha} F_M}{T_{\alpha}} \bar{\omega}_{*k} \cdot \bar{\delta A}_{k\omega}$$

The first term in the right hand part (rhp) represents the adiabatic response. If in the rhp of eq.(7) we use for  $\delta \bar{f}_{k\omega}$  its solution in preceding order approximation we obtain a series development of the solution. Keeping only first two terms of this series we have

$$\delta \bar{f}_{k\omega} = - \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} - i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} (\omega - \omega_D) \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} \quad (8)$$

$$- i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} (v_{\parallel} k_{\parallel} - \bar{\omega}_{*k} \cdot \vec{b}) \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} - i \int_{v_{\parallel}} \frac{dl}{v_{\parallel}} \frac{e_{\alpha} F_M}{T_{\alpha}} \bar{\omega}_{*k} \cdot \bar{\delta A}_{k\omega}$$

Considering, as a crude approximation, that all quantities are constant along the trajectory, we may approximate the integral on  $dl$  (along the trajectory) by simpler expression  $\pi q R$  [5] and obtain:

$$\delta \bar{f}_{k\omega} = \delta \bar{f}_{k\omega}^{(0)} + \delta \bar{f}_{k\omega}^{(1)} \quad (9)$$

where

$$\delta \bar{f}_{k\omega}^{(0)} = - \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} \quad (10)$$

$$\delta \bar{f}_{k\omega}^{(1)} = - i \pi q R \frac{(\omega - \omega_D - \omega_{*k} + v_{\parallel} k_{\parallel})}{v_{\parallel}} \frac{e_{\alpha} F_M}{T_{\alpha}} \delta \phi_{k\omega} \quad (11)$$

$$- i \pi q R \frac{e_{\alpha} F_M}{c T_{\alpha}} \bar{\omega}_{*k} \cdot \bar{\delta A}_{k\omega}$$

### 3. Density perturbation driven by turbulence

Density perturbation driven by turbulence is obtain from the definition

$$\delta n_i^{\alpha} = \int d\vec{v} \delta \bar{f}^{\alpha} \quad (12)$$

For the Fourier transform of perturbed density we have,

$$\delta n_{i,k\omega}^{\alpha} = \int d\vec{v} \delta \bar{f}_{k\omega}^{\alpha} \quad (13)$$

Using eqs. (9)-(11) we obtain the density perturbation driven by turbulence expressed by the first two terms of a series expansion as

$$\delta n_{i,k\omega}^{\alpha,(0)} = -4\pi \frac{T_{\alpha}}{m_{\alpha}^2} \sqrt{\frac{m_{\alpha}}{2T_{\alpha}}} \iint dx d\lambda \frac{B\sqrt{x}}{\sqrt{1-\lambda B}} F_M^{\alpha} e_{\alpha} \delta \bar{\phi}_{k\omega} \quad (14)$$

$$\delta n_{i,k\omega}^{\alpha,(1)} = -i2\pi^2 q R \left( \frac{2T_{\alpha}}{m_{\alpha}} \right)^{3/2} \int_0^{\lambda_c} dx \int_0^{\lambda_c} d\lambda \frac{B\sqrt{x}}{\sqrt{1-\lambda B}} F_M^{\alpha} \quad (15)$$

$$\times \left\{ \frac{e_{\alpha}}{T_{\alpha}} k_{\parallel} \delta \bar{\phi}_{k\omega} - \frac{\omega e_{\alpha}}{c T_{\alpha}} k_{\parallel} \bar{\delta A}_{\parallel,k\omega} + \frac{1}{B} \frac{\partial \ln F_M^{\alpha}}{\partial r} (\vec{e}_r \times \vec{k}) \cdot \bar{\delta A}_{k\omega} \right\}$$

Here the phase space variables  $x$  and  $\lambda$  are defined as

$$x = \frac{m_{\alpha} v^2}{2T_{\alpha}}, \quad \lambda = \frac{1}{B} \frac{v_{\perp}^2}{v^2} \quad (16)$$

Here the limits of integration on  $\lambda$  correspond to passing particle regime and  $\lambda_c = 1/B_{\max}$ .

In the following we introduce notation

$$\eta_{\alpha} = -L_n \frac{\partial \ln T_{\alpha}}{\partial r}, \quad \frac{1}{L_n} = - \frac{\partial \ln n_{\alpha}}{\partial r} \quad (17)$$

The integration over the variable  $x$  is expressed in terms of the Gamma function (see for example):

$$\int_0^\infty dx x^{n-1/2} \exp(-x) = \Gamma(n+1/2) = \frac{(2n-1)!!}{2^n} \Gamma(1/2) \quad (18)$$

where  $n$  is an integer and  $\Gamma(1/2) = \sqrt{\pi}$ .

After direct calculation we obtain from eqs. (15) and (16),

$$\frac{\delta n_{t,k\omega}^{\alpha}}{n_\alpha} = \frac{\delta n_{t,k\omega}^{\alpha(0)}}{n_\alpha} + \frac{\delta n_{t,k\omega}^{\alpha(1)}}{n_\alpha} \quad (19)$$

$$\frac{\delta n_{t,k\omega}^{\alpha(0)}}{n_\alpha} = -\frac{2}{\sqrt{\pi}} C_1^t \delta \bar{\phi}_{k\omega} \quad (20)$$

$$\frac{\delta n_{t,k\omega}^{\alpha(1)}}{n_\alpha} = -i4\pi^{3/2} [C_{es}^t \delta \bar{\phi}_{k\omega} + C_\zeta^t \delta \bar{A}_{k\omega,\zeta} + C_\theta^t \delta \bar{A}_{k\omega,\theta}] \quad (21)$$

with the following estimation of the coefficients:

$$C_1^t = \frac{e_\alpha}{T_\alpha} \Gamma(3/2) \left(1 - \sqrt{1 - B/B_{\max}}\right) \quad (22)$$

$$C_2^t = \frac{1 - \sqrt{1 - B/B_{\max}}}{BL_n} \left[ \left(1 - \frac{3}{2} \eta_\alpha\right) \Gamma(3/2) + \eta_\alpha \Gamma(5/2) \right] \quad (23)$$

$$C_{es}^t = \frac{qR}{2\pi} C_1^t \left( k_\zeta + \frac{\eta}{q} k_\theta \right) \quad (24)$$

$$C_\zeta^t = -\frac{qR}{2\pi} \left( \frac{\omega}{c} C_1^t + k_\zeta + \frac{\eta}{q} k_\theta \right) \quad (25)$$

$$C_\theta^t = \frac{qR}{2\pi} \left( C_2^t k_\zeta - \frac{\omega}{c} \frac{\eta}{q} C_1^t \right) \quad (26)$$

Equation (20) expresses the usual “adiabatic” response

which in leading order became  $\frac{\delta n_{t,k\omega}^{\alpha(0)}}{n_\alpha} = -\frac{e_\alpha}{T_\alpha} \delta \bar{\phi}_{k\omega}$ .

#### 4. Density perturbation driven by turbulence and ICRH

Fluctuating distribution function dependent on rf heating operator is written as

$$\mathcal{G}_{Q,k\omega}^\alpha = \int \frac{dl}{v_\parallel} Q(\mathcal{F}_{k\omega}^\alpha) \quad (27)$$

In the following we consider the quasilinear radio-frequency operator expressed by its pitch angle scattering part

$$Q_{PAS}(\mathcal{F}_{k\omega}^\alpha) = \frac{m_\alpha}{BT_\alpha} \frac{\sqrt{1-\lambda B}}{x} \frac{\partial}{\partial \lambda} \lambda \frac{2D_\perp \delta(\omega_h - n\Omega_\alpha - k_{h\parallel} v_\parallel)}{\sqrt{1-\lambda B}} \frac{\partial \mathcal{F}_{k\omega}^\alpha}{\partial \lambda}$$

Here the perpendicular diffusion coefficient  $D_\perp$  is defined

$$\text{as, see for example [6], } D_\perp = \frac{\pi n \Omega_\alpha}{2n_\alpha m_\alpha} \langle P \rangle$$

Here  $\langle P \rangle$  is the flux surface averaged absorbed rf power density. In the following we assume  $\langle P \rangle$  has a Gaussian profile [7] given by

$$\langle P \rangle = P_0 \exp \left[ -\frac{(\eta - \varepsilon \cos \theta_{res})^2}{\Delta \eta^2} \right] \quad \text{where } \theta_{res} \text{ is the}$$

poloidal angle corresponding to the central vertical axes of the resonance layer and  $\Delta \eta$  is the width of absorption layer, see for example [9]. We assume for  $\Delta \eta$  the

$$\text{expression } \Delta \eta = \frac{k_{h\parallel}}{\omega_h} \sqrt{\frac{2T_\alpha}{m_\alpha}} (1 + \varepsilon \cos \theta_{res}).$$

The limits of integration of the variable  $x$  are

$$x_0 \leq x \leq x_c = \frac{x_0}{1 - B/B_{\max}} \quad \text{with } x_0 = \frac{m_\alpha}{2T_\alpha} \frac{(\omega_h - n\Omega_\alpha)^2}{k_{h\parallel}^2}$$

After direct calculation we obtain the density perturbation due to ICRF heating and turbulence in the form

$$\frac{\delta n_{Q,k\omega}^\alpha}{n_\alpha} = -i4\pi^{3/2} [C_{es}^h \delta \bar{\phi}_{k\omega} + C_\zeta^h \delta \bar{A}_{k\omega,\zeta} + C_\theta^h \delta \bar{A}_{k\omega,\theta}] \quad (28)$$

with

$$C_{es}^h = -\omega C_1^h - c \left( k_\theta - \frac{\eta}{q} k_\zeta \right) C_2^h \quad (29)$$

$$C_1^h = \frac{D_\perp}{R} C_0^h, \quad C_2^h = \frac{D_\perp}{L_n} (C_n + \eta_\alpha C_T) \quad (30)$$

$$C_\theta^h = \omega C_2^h, \quad C_\zeta^h = -\frac{\eta}{q} \omega C_2^h \quad (31)$$

$$C_0 = \frac{q^2 R^2}{B_{res}} \frac{(m_\alpha / 2T_\alpha)^{5/2}}{x_0^2 k_{h\parallel}} \quad (32)$$

$$C_0^h = \frac{e_\alpha R B_{res}}{T_\alpha} C_0 \left[ \frac{1}{x_0} \Gamma(2, x_0, x_c) - \Gamma(1, x_0, x_c) \right] \quad (33)$$

$$C_n = C_0 \left[ \frac{1}{x_0} \Gamma(2, x_0, x_c) - \Gamma(1, x_0, x_c) \right] \quad (34)$$

$$C_T = C_0 \left[ \frac{1}{x_0} \Gamma(3, x_0, x_c) - \left( 1 + \frac{3}{2x_0} \right) \Gamma(2, x_0, x_c) + \frac{3}{2} \Gamma(1, x_0, x_c) \right]$$

The generalized incomplete gamma function is defined as

$$\Gamma(a, x_1, x_2) = \int_{x_1}^{x_2} t^{a-1} \exp(-t) dt \quad (35)$$

For the evaluation of the density perturbation we shall use an approximate expression for the dispersion relation [6]

$$\omega_h^2 = n^2 \Omega_i^2 \left/ \left( 1 + \frac{\omega_{pi}^2}{k_{h\parallel}^2 c^2} \right) \right. \quad (36)$$

where  $\omega_{pi}$  is plasma ion frequency.

We assume the following ion density and temperature profiles,

$$n_i = n_{i0} \left( 1 - \frac{\eta^2}{\varepsilon^2} \right), \quad T_i = T_{i0} \left( 1 - \frac{\eta^2}{\varepsilon^2} \right)^2 \quad (37)$$

with  $T_{i0} = 8.6 \text{ keV}$ ,  $n_{i0} = 10^{14} \text{ cm}^{-3}$ , plasma major radius  $R_0 = 620 \text{ cm}$ , plasma minor radius  $a = 200 \text{ cm}$ , resonant poloidal angle  $\theta_{res} = 4\pi/9$  at  $r = a$ , toroidal magnetic field on axis  $B_0 = 5 \text{ T}$ . As a representative order for the turbulence frequency we consider  $\omega = 100 \text{ kHz}$ .

With these parameters values in fig.1 is plotted  $\langle P \rangle / P_0$  for  $k_{h\parallel} = 1 \text{ cm}^{-1}$  (dashed line), respective  $k_{h\parallel} = 2 \text{ cm}^{-1}$  (solid line).

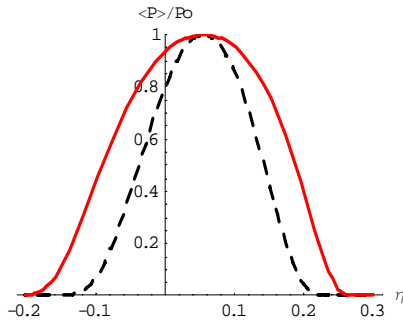


Fig.1. Ratio between the flux surface averaged absorbed rf power density  $\langle P \rangle$  and its maximum value  $P_0$  as function of the dimensionless radius.

## 5. Discussion

The quaineutrality condition

$$\sum_{\alpha} \delta n_{\alpha} = 0 \quad (38)$$

The resultant density perturbation evaluated as

$$\frac{\delta n_{k\omega}^i}{n_{\alpha}} = \frac{\delta n_{t,k\omega}^{\alpha}}{n_{\alpha}} + \frac{\delta n_{Q,k\omega}^{\alpha}}{n_{\alpha}} \quad (39)$$

is reading as

$$\frac{\delta n_{k\omega}^i}{n_{\alpha}} = -\frac{2}{\sqrt{\pi}} C_1^i \delta \bar{\phi}_{k\omega} - i4\pi^{3/2} \left( C_{es} \delta \bar{\phi}_{k\omega} + C_{\zeta} \delta \bar{A}_{k\omega,\zeta} + C_{\theta} \delta \bar{A}_{k\omega,\theta} \right) \quad (40)$$

with

$$C_{es} = -\omega C_1^h + C_{1\theta} c k_{\theta} + C_{1\zeta} c k_{\zeta} \quad (41)$$

$$C_{\zeta} = -\omega C_{1\zeta} - C_2 c k_{\theta} \quad (42)$$

$$C_{\theta} = -\omega C_{1\theta} - C_2 c k_{\zeta} \quad (43)$$

and

$$C_1^h = \frac{D_{\perp}}{R} C_0, \quad C_2 = \frac{qR}{2\pi c} C_2^i \quad (44)$$

$$C_{1\zeta} = \frac{qR}{2\pi c} C_1^i + \frac{\eta}{q} \frac{D_{\perp}}{L_n} (C_n + \eta_{\alpha} C_T) \quad (45)$$

$$C_{1\theta} = \frac{\eta R}{2\pi c} C_1^i - \frac{D_{\perp}}{L_n} (C_n + \eta_{\alpha} C_T) \quad (46)$$

In the following the safety factor is assumed monotone function on  $\eta$ :

$$q = 1.25 + \frac{2}{3} \frac{\eta^2}{\varepsilon^2} + \frac{9}{4} \frac{\eta^3}{\varepsilon^3} \quad (47)$$

The coefficient  $C_{es}^h$  given in eq.(29) is plotted in fig.2 for two different values of  $k_{h\parallel}$ . We remark that  $C_{es}^h$  is negative for  $k_{h\parallel} < 1.2 \text{ cm}^{-1}$  and positive for  $k_{h\parallel} > 1.3 \text{ cm}^{-1}$ .

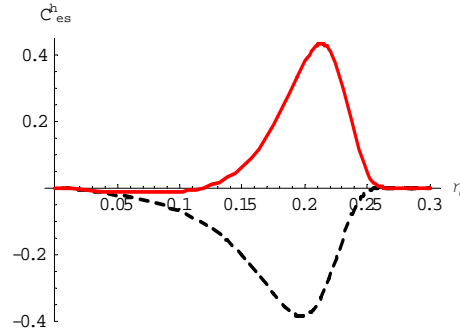


Fig.2. The coefficient  $C_{es}^h$  for  $k_{h\parallel} = 1.2 \text{ cm}^{-1}$  (dashed line) and  $k_{h\parallel} = 1.3 \text{ cm}^{-1}$  (solid line) with  $k_{\theta} = 10 \text{ cm}^{-1}$ ,  $k_{\zeta} = 1 \text{ cm}^{-1}$  and  $\omega = 100 \text{ kHz}$ .

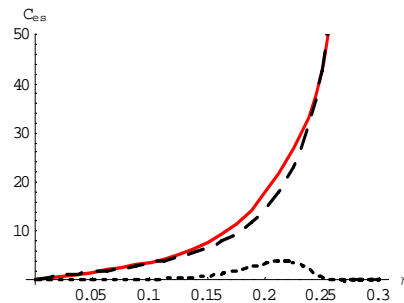


Fig.3. The coefficients  $C_{es}$  (solid line),  $C_{es}^h$  (small-dash line) and  $C_{es}^i$  (large-dash line) for  $k_{h\parallel} = 1.2 \text{ cm}^{-1}$  with  $k_{\theta} = 10 \text{ cm}^{-1}$ ,  $k_{\zeta} = 1 \text{ cm}^{-1}$  and  $\omega = 100 \text{ kHz}$ .

The coefficients  $C_\theta^h$ ,  $C_\zeta^h$  are very small comparative with  $C_{es}^h$ , respectively  $C_\theta^h \approx 10^{-6} C_{es}^h$  and  $C_\zeta^h \approx 10^{-7} C_{es}^h$ . Consequently the effects due to fluctuating vector potential are neglectable comparative with electrostatic potential fluctuations.

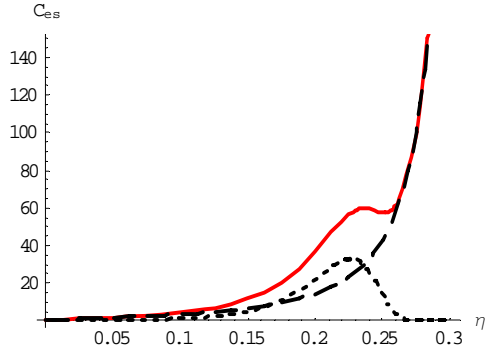


Fig.4. The coefficients  $C_{es}$  (solid line),  $C_{es}^h$  (small-dash line) and  $C_{es}^t$  (large-dash line) for  $k_{h,\parallel} = 1.3 \text{ cm}^{-1}$  with  $k_\theta = 10 \text{ cm}^{-1}$ ,  $k_\zeta = 1 \text{ cm}^{-1}$  and  $\omega = 100 \text{ kHz}$ .

## 6. Conclusions

The total combined effect of the electrostatic turbulence and ICRF heating on the density perturbation can be evaluated through  $C_{es}$  given in eq. (42). In figs.(3)-(4) we plot comparatively  $C_{es}$  (solid line),  $C_{es}^h$  (small-dash line) and  $C_{es}^t$  (large-dash line) for  $k_{h,\parallel} = 1.2 \text{ cm}^{-1}$  and  $k_{h,\parallel} = 1.3 \text{ cm}^{-1}$ . The effect of the heating on the density perturbation becomes significantly for  $k_{h,\parallel} > 1.5 \text{ cm}^{-1}$  and increase rapidly with  $k_{h,\parallel}$  but varies slowly with  $k_\theta$  and  $k_\zeta$ . In the present model based on the drift approximation the inductive terms are not very significant.

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