WEAK ION SOUND TURBULENCE AND ISOTOPE ANOMALY IN ELECTRON CYCLOTRON RESONANCE ION SOURCE PLASMAS

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The production of highly charged ions is very efficient in highly ionized microwave heated plasma in an electron cyclotron resonance ion source (ECRIS). Recent experimental results have revealed that better production of highly charged ions is connected with appearance of weak ion sound turbulence arising due to decay instability of pumping wave in an ECRIS. In some theoretical papers different ions heating due to ion sound turbulence in an ECRIS was studied. Under appropriate conditions due to ion sound turbulence in mixture of two different gases light ions could be heated faster than heavy ions. Since confinement of ions will be the better the lower ion temperature, the differential ion heating enhances losses of preferentially heated light ion component, reducing at the same time losses of the less effectively heated heavy ions. This mechanism appears to be able to explain most of phenomena observed in experiments with "gas mixing effect". The present article considers the "isotope effect" in an ECRIS plasmas within the model of ion turbulent heating.

PACS: 52.35.-g

1. INTRODUCTION

The ECRIS discharge plasma is confined in an open magnetic trap (magnetic mirror trap with magnetic hexapole for achieving a minimum B structure and sustained by a high frequency electromagnetic wave, usually injected along the magnetic field from the high field side (Fig.1) [1]. The production of highly charged ions in the ECRIS essentially occurs in a sequence of ionization steps caused by electron impact. In order to make the production efficient, it is necessary to provide electrons with wide range energies due to effective rf electron heating that occurs at the condition of electron cyclotron resonance. Usually the physics of heating in ECRIS systems is considered in the simple mirror (SM) geometry without taking into account effects of minimum B structure [2].

The physics of plasma heating in systems similar to ECRIS is mainly controlled by the interaction of the incoming (pumping) wave with the electrons, the role of ions being more passive [2]. However for the various regimes of ECRIS plasma transport depends strongly on the ion temperature [3]. Therefore the ion heating is an important process and influences strongly on the ion source performance.

The ion temperature T_q^Z of a ion species with charge state q is determined by the ion energy balance equation, which reads in a simplified form [4, 5]

$$\frac{d(\frac{3}{2}n_q^Z T_q^Z)}{dt} = \frac{3}{2}\frac{n_e(T_e - T_q^Z)}{\tau^{e/i}} - \frac{3}{2}\frac{n_q^Z T_q^Z}{\tau_q^Z}. \qquad (1)$$

On the right hand side of this equation the first term is the power taken by the ions due to collisions with the electron population, $\left(\tau^{e/i}\right)^{-1}$ is the electron-ion energy equipartition rate for ions of the charge state q, n_e is the electron density, T_e – electron temperature; the second term stands for the ion energy diffusion loss rate, τ_q^Z is the ion confinement time. Since an energy exchange between ions is much faster than between electrons and ions all ions are expected to have the same temperature: $T_q^Z \equiv T_i$.

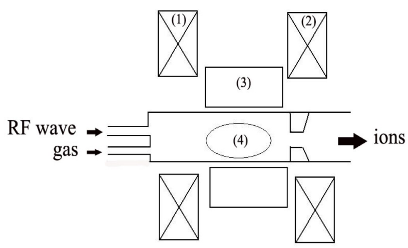

Fig.1. Scheme of an ECR ion source: 1, 2 – electromagnetic coils, 3 – hexapole (permanent magnets), 4 – plasma cavity

The beneficial effect of mixing a lighter gas in the plasma for the production of highly charged heavy ions (so - called "gas-mixing effect") was discovered fifteen years ago (see [6] and references therein). The reasons of this phenomenon are still under discussion. Antaya was probably the first who supposed that in the mixture of heavy and light ions the latter may take away the energy from the heavy ions in elastic collisions thus cooling them ("ion cooling" model) [7]: by elastic collisions the electrons heat the light ions not as effective as the highly charged heavy ions. Elastic ion-ion collisions equalize the various ion temperatures. The lowly charged ions have a short life time; they are lost from the source taking away the energy also of the heavy ions. Thus the life time of the heavy ions is increased and their mean charge should increase in the source.

Studying the mixture of nitrogen isotopes $^{15}N/^{14}N$ in ECRIS 2 the authors of Ref. [8] concluded that the model of "ion cooling" is not sufficient for explanation of the "isotope effect" observed at the same time as "gas mixing effect" [6]. They obtained an especially simple form for the low density case, where one gets immediately the ratio of the extraction currents for a mixture of

ВОПРОСЫ АТОМНОЙ НАУКИ И ТЕХНИКИ. 2006. № 5.
Серия: Плазменная электроника и новые методы ускорения (5), с.80-85.

two isotopes characterized by their nuclear mass numbers A:

$$\eta_{q+} = \alpha\left(\sqrt{\frac{A_1}{A_2}}\right)^{q-1}. \qquad (2)$$

Here we have replaced the indices A by 1, 2, the $A_{1,2}$ are the respective mass numbers. From (2) the current ratio for singly charged ions is expected to be almost equal to the gas mixture ratio α in the discharge chamber, so the value of $\chi = \eta_{q+}/\eta_{1+}$ can be compared with the value given by (2). The latter is only 1.15 for N^{5+}, which is too small compared to the observed χ that is as high as 1.5 for the mixing of nitrogen isotopes $^{15}N/^{14}N$.

The authors of Ref. [8] also remark that the exclusive dependence of the ion confinement times on the square root of the masses is not sufficient to explain the anomaly. They proposed to explain the isotope anomaly via different ion temperatures, or more precisely with a different mass dependent heating mechanism (predominantly for the lighter component) caused by ion Landau damping. The confirmation of the occurrence of this mechanism is the observation of low-frequency noises in correlation with the anomaly corresponding to well-known ion sound. They suggested that due to linear Landau damping the ion sound noises heats light ions more effectively than heavy ones and thus could influence essentially the heavy ions resident time in the plasma and consequently better output of higher charged heavy ions. Therefore a small deviation in the temperatures of various ions could result in an essential difference in the extracted currents.

As it was mentioned above the authors of Ref. [8] explain the "isotope effect" via the linear Landau damping of ion sound on ions that is however exponentially low at the observed velocities of ion sound. Therefore we proposed to consider a non-linear Landau damping of ion sound (non-linear ion sound scattering) on ions as a mechanism of ion heating and developed the model of ion turbulent heating of ions having different relation of a charge to mass [3,9,10].

It should be pointed out that peculiarities of ion turbulent heating due to non-linear Landau damping of ion sound in two-ion components plasma (plasma with two sorts of ions) have been investigated during the latest decade (see [11] and the references therein) for the case of the electron current driven instability. Using the results of general theory of non-linear wave-particle interaction for one component plasma (plasma with one sort of ions) [12, 13] the authors of Ref. [11] for the first time obtained the expression of ion sound spectrum in two component plasma taking into account self-consistent modification of electron and ion distribution function. At the consideration of ion turbulent heating they have shown that the turbulent heating rate is different for different ions. It should be pointed out that the specific feature of the ECRIS is that we could regard the electron distribution function as unchangeable and study the behavior of ions separately from electrons.

The appearance of low frequency noises in accompanying the electron heating by electromagnetic waves with frequencies close to the electron cyclotron frequency in plasma is a consequence of the decay instability [15,16]. The decay of the pumping electromagnetic wave launched along the magnetic field lines occurs in such a way that the wave vectors of the generated electrostatic waves are almost opposite to each other and the waves propagate under the small angle θ to the direction of the magnetic field lines This is the consequence of the conservation law for the total wave momentum and the fact that the electrostatic wavelengths are much shorter than those of the electromagnetic pumping wave. The condition of decay is

$$\Omega = \omega_h + \omega_s, k = k_s + k_h. \qquad (3)$$

Here $\Omega \le \omega_{ce}$ is the pumping wave frequency, which must be close to the local electron cyclotron frequency ω_{ce}; $\omega_h = \omega_{ce}(1 - \frac{\omega_{pe}^2}{\left|\omega_{pe}^2 - \omega_{ce}^2\right|}\sin^2\theta)$ is the hybrid frequency, ω_{pe} is the electron plasma frequency, and ω_s the ion sound frequency, the latter being much lower than ω_{ce}.The condition of the decay (3) can be satisfied only for a wave vector k_h directed almost parallel to magnetic field, since the hybrid frequency is close to the electron cyclotron frequency only in this case. Thus $\sin\theta$ is very small.

The value of minimum unstable external electric field $E_{\min}$ in one component plasma was obtained in the paper [17] where for the first time the parametric excitation of potential waves in a completely ionized plasma near electron cyclotron resonance by high frequency electric field was studied. The author of Ref. [15,16] shown that this process is equivalent to the two potential wave non-linear decay of pumping wave. The maximum growth rate of the decay instability γ_d corresponds to a frequency shift $\Delta = \Omega - \omega_h = \omega_s$ and is given by [15,16,17]

$$\gamma_d = \frac{1}{2}\sqrt{\omega_s\omega_{ce}} \cdot \sqrt{\frac{\omega_{pe}^2}{2\Omega^2} \cdot \frac{E^2}{4\pi n_e T_e}}, \qquad (4)$$

the angle θ is limited to the range

$$0 \le \sin\theta < \frac{1}{2} \cdot \frac{\left|\omega_{pe}^2 - \omega_{ce}^2\right|}{\omega_{pe}\omega_{ce}}. \qquad (5)$$

It means that the electrostatic waves are unstable inside a small cone around the direction of the magnetic field lines with $\theta < \theta_0$, $\theta_0 = \pi/6$. This non-linear interaction of three waves namely the pumping electromagnetic wave, the hybrid wave and an ion sound wave broadens the wave spectra and randomizes the phases of the waves [16].

According to the paper [17] it's possible to get the minimum threshold of decay instability for the case of multi components plasma at the condition $\cos\theta \approx 1$, $\omega_s = \omega_{pi}$:

$$\frac{E_{\min}^2}{4\pi n_e T_e} = 4\frac{\omega_{pi}}{\omega_{pe}}\frac{2\Omega^2}{\omega_{pe}^2}\sqrt{\frac{\pi}{2}}\frac{\nu_{ei}}{\Omega}, \qquad (6)$$

Here ν_{ei} is the electron–ion collision frequency, ω_{pi} is the ion plasma frequency. It can be seen that the threshold appears to be rather small for standard experimental parameters of ECR both in one component plasma [15] and two component plasma [18].

The form of ion sound turbulence spectrum was first given by Kadomtsev and Petviashvili [14] for the case of a current driven instability and studied by Tsitovich for the case when weak ion sound turbulence is driven by the high frequency electromagnetic wave [13]. In both cases the results are similar: the ion sound spectrum expands to waves with very long wavelengths, the steady state is provided by non-linear scattering of the ion sound wave towards small frequencies.

Using the results of the papers [11,12,13,14] we got the expression for ion sound spectrum for one and two components ECRIS plasmas [3,9,10]. According to Ref. [13] we had to consider two regions in k – space: the first is the region of generation, where the growth of ion sound waves is balanced by nonlinear Landau damping and the second one, the region of inertia, where energy flow into the lower ion sound frequencies is balanced by linear Landau damping on electrons (Fig.2).

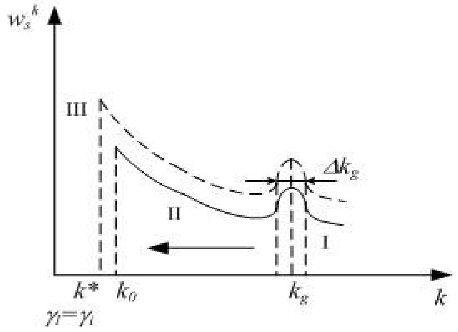

Fig.2. Schematic shape of ion sound spectrum: I – region of generation, II – region of inertia, III – region of adsorption

The density of ion sound energy is given by a classical form [13]

$$W = \int W_{\vec{k}} \frac{d\vec{k}}{(2\pi)^3} = \int \frac{1}{\omega(\vec{k})} \frac{\partial \omega^2 \varepsilon(\omega)}{\partial \omega}\bigg|_{\omega=\omega(\vec{k})} \frac{E_{\vec{k}}^2}{4\pi} d\vec{k} = \int N_{\vec{k}} \omega(\vec{k}) \frac{d\vec{k}}{(2\pi)^3}. \tag{7}$$

Here $\varepsilon(\omega)$ is the plasma permittivity. The dimension of the spectral energy $W_{\vec{k}}$ coincides with the dimension of energy. According to Planck the number of waves could be introduced as $N_{\vec{k}} = W_{\vec{k}} / \hbar\omega(\vec{k})$, where the Planck constant $\hbar$ is set equal 1. Thus the product of $N_{\vec{k}}\omega(\vec{k})$ has the dimension of energy and the number of waves is not dimensionless anymore. Usually the number of waves depends on the absolute value of the wave vector k and of the angle θ, i.e. $N_{\vec{k}} = N_k(\cos\theta)$ [11,12,13,14]. Since the growth rate has its maximum close to the small angle θ_0 we follow the idea of Kadomtsev and Petviashvili [14] and express the angular dependence of the ion sound spectrum by

$$N_k(\cos\theta) = N_k \delta(\cos\theta - \cos\theta_0), \tag{8}$$

It turned out that the ion sound spectrum in k – space has a saw-tooth form and depends considerably on microwave generator power and the characteristic parameter of the magnetic field lines (Fig.3).

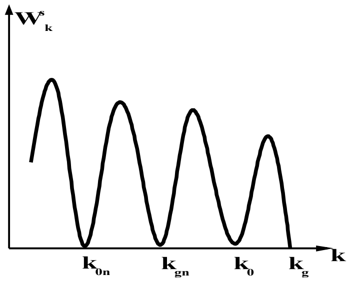

Fig.3. Shape of ion sound spectrum for the case $k_g - k_0 << k_g$

The appearance of additional areas of ion sound generation in k – space could be explained as follows: the phases of the ion sound waves are randomized in the area between $k_g \approx r_{De}^{-1}$ and k_0. Here k_0 corresponds to the case then $N_k = 0$, r_{De} – thermal electron Debye length. Therefore the growth rate here will be much less than the growth rate for fixed phases. In the region $k < k_0$ ion sound noise develops. The situation here corresponds to the decay instability with fixed phases, where the growth rate is determined by (4) with $\omega_s = \omega_s(k_0)$. Thus additional stages of the instability starts from new $k_{gn} \le k_0$ and will cause a spectral broadening from $k_{gn} + \Delta k_{gn}$ up to k_{0n}. It should be pointed out that in the area of long wave lengths where the rate of ion sound damping on electrons (γ_l) becomes smaller than the ion sound damping due to ion-ion collision (γ_i) the spectrum is cut off due to efficient ion sound absorption by ion-ion collisions. The ion sound damping due to ion-ion collisions turns out different for one component and two component plasma [19,20].

From the collisionless part of quasilinear equation for the ion distribution function which includes the induced (non-linear) scattering of ion sound waves on different ions we obtained the equations of ion turbulent heating. It should be pointed out that the same technique was applied to investigate the ion turbulent heating both in case then ion sound turbulence was driven by current instability [11] and in case of ion-sound kinetic parametric instability in helicon plasma source [21]. The simple calculation shown that under appropriate conditions due to ion sound turbulence in mixture of two different gases light ions could be heated faster than heavy ions [3,9,10]. Since confinement of ions will be the better the lower ion temperature, the differential ion heating enhances losses of preferentially heated light ion component, reducing at the same time losses of the less effectively heated heavy ions. This mechanism appears to be able to explain most of phenomena observed in experiments with “gas mixing effect”. In this paper we calculated the probability of induced ion sound scattering on ions for isotope case. Further we'll study the ion turbulent heating for isotope case as for mixture of two different gases.

2. INDUCED ION SOUND SCATTERING ON IONS IN TWO COMPONENTS PLASMA

2.1. THE CASE OF GAS MIXTURE

As discussed before we describe ECRIS plasma in a gas mixture as a two-ion-components plasma, i.e. plasma with two sorts of ions α and β considerably. Then the ion sound frequency ω_s will be expressed via the ion plasma frequencies of both ions $\omega_{pi\alpha}$ and $\omega_{pi\beta}$

$$\omega_s = \left(\frac{\omega_{pi\alpha}^2 + \omega_{pi\beta}^2}{1 + \frac{1}{k^2 r_{De}^2}}\right)^{1/2}, \quad \omega_{pi} = \left(\omega_{pi\alpha}^2 + \omega_{pi\beta}^2\right)^{1/2}, \qquad (9)$$

$$q_\alpha n_\alpha + q_\beta n_\beta = n_e.$$

Here n_α and n_β denote the densities of ions of kind α and β, respectively. The dispersion properties of plasma as well as non-linear plasma processes are determined by the thermal electrons in the bulk of the plasma.

The kinetic equation describing the induced scattering of ion sound waves on ions is given as

$$\frac{\partial N_{\vec k}}{\partial t} = N_{\vec k} \int_{-\infty}^{+\infty} N_{\vec k_1} v_{\vec k \vec k_1 \alpha}\, d\vec k_1 + N_{\vec k} \int_{-\infty}^{+\infty} N_{\vec k_1} v_{\vec k \vec k_1 \beta}\, d\vec k_1 . \qquad (10)$$

where

$$v_{\vec k, \vec k_1 \alpha} = \int w_{p\alpha}(\vec k, \vec k_1) \left\{ \frac{\partial f_\alpha}{\partial p} \cdot (\vec k - \vec k_1) \right\} \frac{d^3 p}{(2\pi)^6}. \qquad (11)$$

Here $f_\alpha(p)$ is distribution function of ions of sort α supposed to be Maxwellian, $w_{p\alpha}(k, k_1)$ is the probability of induced ion sound scattering on ions [11]

$$w_{p\alpha}(\vec k, \vec k_1) = \frac{4\delta\left(\left(\omega(\vec k) - \omega(\vec k_1)\right) - (\vec k - \vec k_1)\cdot \vec v\right)(2\pi)^9}{\left(\omega(\vec k)\right)^2 \left|\frac{\partial \varepsilon_k^l}{\partial \omega}\right|_{\omega = \omega(\vec k)} \left|\frac{\partial \varepsilon_{k_1}^l}{\partial \omega}\right|_{\omega = \omega(\vec k_1)}} \left|\Lambda_{\vec k \vec k_1 \alpha}\right|^2, \qquad (12)$$

$$\Lambda_{\vec k \vec k_1 \alpha} = \frac{e^2 q_\alpha}{(2\pi)^3 \omega(\vec k_1)} \frac{\vec k \cdot \vec k_1}{k k_1} \left(\left(\frac{q_\alpha}{M_\alpha} \left(\frac{2\vec k \cdot \vec v}{\omega(\vec k)} \right) \right) + \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right) \frac{\delta \varepsilon_{k-k_1\beta}^i}{\varepsilon_{k-k_1}^l} \right).$$

Here $\Lambda_{\vec k \vec k_1 \alpha}$ is the amplitude of induced ion sound scattering on ions, $\delta\varepsilon_{k-k_1\beta}^i$ is the contribution of ions of sort β in plasma permitivity. Replacing index α for β in the expressions (11), (12) one can get $v_{\vec k \vec k \beta}$. After some calculations we find that

$$v_{\vec k \vec k_1 \alpha} = \frac{e^2}{\omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \frac{1}{\pi} \frac{q_\alpha^2}{M_\alpha^2} \omega_{pi\alpha}^2 v_{T\alpha}^2 \delta'(\omega'') \left[\vec k, \vec k_1\right]^2 + \omega_{pi\alpha}^2 v_{T\alpha}^2 \frac{\omega(k)\omega'' e^2}{4\pi \omega_{pi}^4} \frac{q_\alpha}{M_\alpha} \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right) \times$$

$$\times \operatorname{Re}\left(\frac{\delta\varepsilon_{k-k_1\beta}^i}{\varepsilon_{k-k_1}^l} \right) \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \delta'(\omega'') 2k^2 \left(\frac{k}{k_1} - \frac{k_1}{k} \right) + \frac{\omega^2(k)}{4\pi\omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \delta'(\omega'') k''^2 \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right)^2 \times \qquad (13)$$

$$\left(\frac{v_{T\alpha}^2}{r_{D\alpha}^2} \left(\frac{\delta\varepsilon_{k-k_1\beta}^i}{\varepsilon_{k-k_1}} \right)^2 \right).$$

Here $k'' = k - k_1$, $k \approx k_1$, $\omega'' = \omega(k) - \omega(k_1)$, $v_{T\alpha}, v_{T\beta}$ are the thermal ions velocities, $r_{D\alpha}$ is the Debye length of ions of kind α. Neglecting the second term in the formula (13) finally we can get

$$v_{\vec k \vec k_1} = v_{\vec k \vec k_1 \alpha} + v_{\vec k \vec k_1 \beta} = \frac{e^2}{\pi \omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \delta'(\omega'') \left[\vec k, \vec k_1\right]^2 \times \left(\frac{q_\alpha^2}{M_\alpha^2} \omega_{pi\alpha}^2 v_{T\alpha}^2 + \frac{q_\beta^2}{M_\beta^2} \omega_{pi\beta}^2 v_{T\beta}^2 \right) +$$

$$+ \frac{\omega(k)\omega(k_1) e^2}{4\pi\omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \delta'(\omega'') k''^2 \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right)^2 \frac{v_{T\alpha}^2 r_{D\alpha}^2 + v_{T\beta}^2 r_{D\beta}^2}{\left(r_{D\alpha}^2 + r_{D\beta}^2\right)^2}. \qquad (14)$$

If the density of light ions β is less than the density of heavy ions α then under the following condition

$$\omega_{pi\alpha}^2 v_{T\alpha}^2 > \omega_{pi\beta}^2 v_{T\beta}^2,$$

$$\left(\frac{q_\beta A_\alpha}{q_\alpha A_\beta} - 1 \right)^2 \frac{r_{De}^2}{r_{D\alpha}^2} >> \frac{\omega_{pi\alpha}^2}{\omega_{pi\beta}^2} \qquad (15)$$

taking into account (14) finally we can write the kinetic equation (10) as follows:

$$\frac{\partial N_{\vec k}}{\partial t} = N_{\vec k} \int N_{\vec k_1} \frac{\omega(k)\omega(k_1) e^2}{4\pi\omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \delta'(\omega'') k''^2 \times \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right)^2 \frac{v_{T\alpha}^2 r_{D\alpha}^2 + v_{T\beta}^2 r_{D\beta}^2}{\left(r_{D\alpha}^2 + r_{D\beta}^2\right)^2} d\vec k_1. \qquad (16)$$

According to a general lemma of the non-linear plasma theory [13] one can get the spectrum of low frequency noises from the ion sound energy balance equation. In the region of generation this equation is as follows:

$$\frac{\partial N_{\vec k}}{\partial t} = 2\Gamma_{\vec k} N_{\vec k} + N_{\vec k} \int N_{\vec k_1} \frac{\omega(k)\omega(k_1) e^2}{4\pi\omega_{pi}^4} \left(\frac{\vec k \cdot \vec k_1}{k k_1} \right)^2 \times \delta'(\omega'') k''^2 \left(\frac{q_\alpha}{M_\alpha} - \frac{q_\beta}{M_\beta} \right)^2 \frac{v_{T\alpha}^2 r_{D\alpha}^2 + v_{T\beta}^2 r_{D\beta}^2}{\left(r_{D\alpha}^2 + r_{D\beta}^2\right)^2} d\vec k_1. \qquad (17)$$

Assuming in the region of generation a stationary state of the spectrum we get from equation (17) [3,9,10]

$$N_k = \frac{\omega_{pi}^4 \tilde{\gamma}_g}{\xi_2}\left(\frac{e}{M}\right)^{-2}\left(\frac{q_\alpha}{A_\alpha} - \frac{q_\beta}{A_\beta}\right)^{-2} \frac{\left(r_{D\alpha}^2 + r_{D\beta}^2\right)^2}{v_{T_\alpha}^2 r_{D\alpha}^2 + v_{T_\beta}^2 r_{D\beta}^2} \frac{(k_g + \Delta k_g - k)}{k_g^6}. \tag{18}$$

Here $\xi_2 = \left(-\frac{1}{3}P_2^2(\cos\theta_0) + \frac{1}{5}P_3^2(\cos\theta_0) + \frac{2}{15}\right)$,

$P_n(\cos\theta)$ are Legendre polynomials; M is proton mass, $\Gamma_{\vec{k}} = \tilde{\gamma}_g = G\tilde{\gamma}_d = G\gamma_d(k_g, \cos\theta_0)$, $G = d_1 / L$, d_1 is the extension of the region where decay instability occurs, L is the length of the magnetic trap.

The spectrum in the inertial region is given as [3,9,10]

$$N_k = \sqrt{\frac{\pi}{8}} \frac{1}{k^4} \frac{\omega_{pi}^6 r_{De}}{\omega_{pe} \tilde{\xi}_2}\left(\frac{e}{M}\right)^{-2}\left(\frac{q_\alpha}{A_\alpha} - \frac{q_\beta}{A_\beta}\right)^{-2} \times$$

$$\times \frac{\left(r_{D\alpha}^2 + r_{D\beta}^2\right)^2}{v_{T_\alpha}^2 r_{D\alpha}^2 + v_{T_\beta}^2 r_{D\beta}^2} \ln\left|\frac{k}{k_0}\right|. \tag{19}$$

Here $\Gamma_{\vec{k}} = \gamma_l = \sqrt{\frac{\pi}{8}} \frac{\omega_{pi}}{\omega_{pe}} \frac{\omega_s}{\cos\theta_0}$, $\tilde{\xi}_2 = \xi_2 \cos\theta_0$.

Matching the expressions of spectrum in these two regions at $k = k_g$ (k_g is the point in k-space where generation of ion sound occurs) we can find the relation between k_g and the unknown parameter k_0

$$\ln\left(\frac{k_g}{k_0}\right) = \sqrt{\frac{8}{\pi}}\left(\frac{G\tilde{\gamma}_d}{\omega_s(k_g)}\right)\frac{\Delta k_g}{k_g}\frac{\omega_{pe}}{\omega_{pi}} \equiv \frac{\Delta_k}{k_g}. \tag{20}$$

2.2. THE ISOTOPE CASE

It should be pointed out that the condition (15) is not observed for isotope case. Thus the case of isotope should be studied separately because all terms in the expression (14) should be taken into account.

Actually for the case of two isotopes we can rewrite the condition (15) as follows:

$$\left(\frac{\Delta A}{A}\right)^2 >> \frac{1}{\eta}\frac{T_1}{T_e}\frac{T_2}{T_1}\frac{\left(\eta + \frac{T_2}{T_1}\right)^2}{\left(\eta + \left(\frac{T_2}{T_1}\right)^2\right)}. \tag{21}$$

Here subscripts 1 and 2 denote first and second isotopes responsibly, $\eta = \frac{n_2}{n_1}$, $A_1 \equiv A$, $A_1 - A_2 = \Delta A$.

In most cases the temperatures of isotopes are almost equal to each other, i.e. $T_i = T_1 = T_2$. Then the satisfaction of the condition (21) is determined by the value of small parameter $\frac{T_i}{T_e}$ and the value of η. It is seen that for all isotopes the contrary condition is valid

$$\frac{T_1}{T_e}\frac{T_2}{T_1}\frac{\left(\eta + \frac{T_2}{T_1}\right)^2}{\left(\eta + \left(\frac{T_2}{T_1}\right)^2\right)} > \eta\left(\frac{\Delta A}{A}\right)^2. \tag{22}$$

To find the probability of induced ion sound scattering on ions for isotope case one should take into account the smallness $\left(\frac{\Delta A}{A}\right)^2$ in the second term of (14). Thus expanding expression (14) by the smallness $\left(\frac{\Delta A}{A}\right)$ we can get the kinetic equation (10) for isotope case.

$$\frac{\partial N_{\vec{k}}}{\partial t} = N_{\vec{k}}\left[\frac{(T_1 + \eta T_2)}{4\pi^2 n_1 M_1^2 (1+\eta)^2}\int N_{\vec{k}_1}\left[\vec{k}\times\vec{k}_1\right]^2 \delta'(\omega'')\frac{\left(\vec{k}\cdot\vec{k}_1\right)^2}{k^2 k_1^2} d\vec{k}_1 + \right.$$

$$\left. + \frac{\eta(T_1^2\eta + T_2^2)}{16\pi^2 n_1 M_1 (1+\eta)^2 (T_1\eta + T_2)^2}\left(\frac{\Delta M}{M_1}\right)^2 \int N_{\vec{k}_1}\omega^2(k)\left|\vec{k} - \vec{k}_1\right|^2 \frac{\left(\vec{k}\cdot\vec{k}_1\right)^2}{k^2 k_1^2} d\vec{k}_1\right]. \tag{23}$$

CONCLUSIONS

From the collisionless part of quasilinear equation for the ion distribution function using the expressions of ion sound spectrum and the probability of induced ion sound scattering obtained from equation (23) as for gas mixture case (see part 2.1) one could get the difference in the rates of isotope heating. It should be pointed out that as it was shown in Ref. [8] even a small difference between isotope temperature (in order of 3%) could provide the increase of light isotope extraction current and consequently better confinement of heavy ions in an ECRIS plasmas.

This work was supported by INTAS-01-0373, INTAS 97.0094, Federal Program "Integration", (№Я0068/2137) and scientific and technical program "Education industry" (№ 1535).

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СЛАБАЯ ИОННО-ЗВУКОВАЯ ТУРБУЛЕНТНОСТЬ И АНОМАЛИИ ИЗОТОПОВ В ПЛАЗМЕННОМ ИОННОМ ИСТОЧНИКЕ НА ЭЛЕКТРОННОМ ЦИКЛОТРОННОМ РЕЗОНАНСЕ

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Получение высоко зарядных ионов очень эффективно в высоко ионизированной нагретой микроволнами плазме в ионном источнике на электронном циклотронном резонансе (ИИЭЦР). Последние экспериментальные результаты показали, что лучшее получение высоко зарядных ионов связано с возникновением слабой ионно-звуковой турбулентности, возникающей благодаря распадной неустойчивости волны накачки в ИИЭЦР. В некоторых теоретических работах были изучены нагрев различных ионов за счет ионно-звуковой турбулентности в ИИЭЦР. При подходящих условиях, благодаря ионно-звуковой неустойчивости в смеси двух различных газов, легкие ионы могут быть нагреты быстрее, чем тяжелые ионы. Удержание ионов лучше при низких ионных температурах, различие в нагреве ионов усиливает потери преимущественно нагретой компоненты легких ионов, уменьшая в то же время потери менее эффективно нагреваемых тяжелых ионов. Появление этого механизма способно объяснить большинство явлений, наблюдающихся в экспериментах с «эффектом газовой смеси». Настоящая статья рассматривает «изотоп-эффект» в плазме ИИЭЦР в модели ионного турбулентного нагрева.

СЛАБКА ІОННО-ЗВУКОВА ТУРБУЛЕНТНІСТЬ ТА АНОМАЛІЇ ІЗОТОПІВ У ПЛАЗМОВОМУ ІОННОМУ ДЖЕРЕЛІ НА ЕЛЕКТРОННОМУ ЦИКЛОТРОННОМУ РЕЗОНАНСІ

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Одержання високо зарядних іонів дуже ефективне у високо іонізованій нагрітій мікрохвилями плазмі в іонному джерелі на електронному циклотронному резонансі (ІДЕЦР). Останні експериментальні результати показали, що краще отримання високо зарядних іонів пов'язане з виникненням слабкої іонно-звукової турбулентності, яка виникає завдяки розпадній нестійкості хвилі накачки в ІДЕЦР. В деяких теоретичних роботах були вивчені нагрів різних іонів за рахунок іонно-звукової турбулентності в ІДЕЦР. При підходящих умовах, завдяки іонно-звуковій нестійкості у суміші двох різних газів, легкі іони можуть бути нагріті швидше, ніж важкі іони. Утримання іонів краще при низьких іонних температурах, різниця у нагріві іонів підсилює втрати переважно нагрітої компоненти легких іонів, зменшуючи в той же час втрати менш ефективно нагріваємих важких іонів. Поява цього механізму здатна пояснити більшість явищ, що спостерігаються в експериментах з «ефектом газової суміші». Ця стаття розглядає «ізотоп-ефект» у плазмі

ІДЕЦР у моделі іонного турбулентного нагріву.