TRANSITION RADIATION OF THE MODULATED ELECTRON BEAM IN DUSTY PLASMA

I.O.Anisimov, Eu.V.Martysh, I.M.Voronov

Taras Shevchenko National University of Kyiv, Radio Physics Faculty,
64 Volodymyrska St., 01033, Kyiv, Ukraine

Transition radiation of the modulated electron beam from the accidental inhomogeneities caused by the dust particles is calculated. This radioemission is proposed for the dust particles' diagnostics. Numerical estimations show that the magnitude of this radioemission is much higher than thermal radioemission of the plasma core.

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1. INTRODUCTION

It is well known that hot plasma part of tokamaks exists up to the last closed magnetic surface. This part is called the confinement region. Although at the edge of the confinement region the plasma temperature is lower than in the center of the plasma torus, it seems still to be high for macro-particles (dust) which may appear for some reason in this region to survive for a long time [1]. Usually dust particles can survive for a long time in plasma with temperature less than 20eV. But there are regions behind the last magnetic surface where the temperature of plasma is even lower and these regions can influence the confinement of plasma inside the last closed magnetic surface.

There are the experimental evidences that dust exists in these regions inside the edge plasma and is not located on the walls. This evidence is indirect since it comes from analyses of the dust collected after the discharge [2]. But the size and shape distributions of dust particles and their material constitution indicate that during the discharges dust must be confined in the low-temperature parts of the edge plasma and it exposed to the low-temperature plasma during the whole discharge.

The usual method for detection of dust particles is Mie scattering by laser radiation. This method has not been used in tokamaks for many reasons [1]. So, we have a question - what kind of diagnostics of dust plasma parameters is the best to use in a edge plasma? The idea of this work is to use the transition radiation of the modulated electron beam from the plasma inhomogeneities caused by the dust particles. Electron beams are already used for magnetic field configuration diagnostics [3]. On the other hand registration of the thermal radioemission in the microwave band was traditionally used on the set of fusion devices [4]. The charged dusty particles perturb the plasma concentration. The charged particle (charged bunch) motion in such plasma results to the transition radiation of the electromagnetic waves. This effect was observed in the laboratory experiments [5-6]. The magnitude of non-resonant transition radioemission is directly proportional to the bunch current and to the perturbations of the plasma dielectric permittivity profile. Consequently the information about the dust particles can be obtained in the real time mode. The main types of the fusion plasma self-radiation are the cyclotron radiation and recombination radiation. Maximums of the spectrums of these types of radiation lie in the short waves band relatively to the transition radiation.

The non-resonant transition radiation of the electron bunch in the planarly-stratified plasma with the magnetic field parallel to the concentration gradient and the resonant transition radiation of this bunch in the planarly-stratified isotropic plasma were calculated in our previous works [7-10]. The possibility to find out the information about the plasma concentration profile from the transition radiation spectrum was demonstrated. The stability conditions of the electron bunch current and the smallness of its influence on the plasma were found out [11]. Formation of clusters from high-excited atoms near border between fusion plasma and hard wall was demonstrated in [12]. Role of recombination processes with dusty particles was investigated in [13] to microwave radiation from complex plasma.

2. MODEL DESCRIPTION AND BASIC EQUATIONS

Charge compensated cylindrical modulated electron beam of the radius a is injected into the cold isotropic plasma. The plasma is considered to be accidentally inhomogeneous. It is known [1] that magnetic field in the edge plasma is much smaller than in the plasma core. So in the zero-order approximation we can neglect the effect of magnetic field on the electron beam. Beam arises in the plane $z=0$ and moves along z axis. Its alternating component of the current density can be treated as a given function:

$$\vec{j}(r,z,t)=\begin{cases} e_z j_m \exp(-z/L)\exp\left(i\omega t-i\kappa z\right), & r\le a,\quad z\ge 0;\\ 0, & r>a,\quad z<0, \end{cases} \qquad (1)$$

where $\kappa=\omega/v_0$, v_0 and ω are the beam velocity and modulation frequency respectively ($\omega>\omega_p$, ω_p is the Langmuir frequency of the background plasma), L is the beam's relaxation distance. Current density tends to zero if $z\to+\infty$. Waves equations for electromagnetic field excited by the current (1) in plasma with time independent and spatially accidental dielectric permittivity $\varepsilon(\varphi,r,z)$ have the form:

$$\Delta E(\varphi,r,z,t)-graddiv\vec{E}-\frac{\varepsilon(\varphi,r,z)}{c^2}\frac{\partial^2\bar{E}(\varphi,r,z,t)}{\partial t^2}=$$

$$=\frac{4\pi}{c^2}\frac{\partial j}{\partial t};$$

$$\Delta\bar{H}(\varphi,r,z,t)-\frac{\varepsilon(\varphi,r,z)}{c^2}\frac{\partial^2 H(\varphi,r,z,t)}{\partial t^2}+$$

$$+\frac{1}{\varepsilon(\varphi,r,z)}\left[grad\ \varepsilon(\varphi,r,z)\times rot\ \vec{H}(\varphi,r,z,t)\right]=$$

$$=\frac{4\pi}{c}\left(\frac{1}{\varepsilon(\varphi,r,z)}\left[grad\ \varepsilon(\varphi,r,z)\times \vec{j}\right]-rot\ \vec{j}\right). \qquad (2)$$

System's solution (2) is based on infinitesimal condition for relative permittivity alteration of the background plasma:

$$\varepsilon(\varphi,r,z)=\varepsilon^{(0)}+\varepsilon^{(1)}(\varphi,r,z),$$

$$\left|\varepsilon^{(1)}(\varphi,r,z)\right|<<\varepsilon^{(0)}=\varepsilon_0. \qquad (3)$$

3. THE SPECTRAL INTENSITY OF THE PLASMA INHOMOGENEITIES CAUSED BY THE DUST PARTICLES

It is assumed that dust particles are equal and distributed accidentally in the plasma volume. The disturbances of the plasma dielectric permittivity caused by the dust particles are treated as the small perturbations (3).

The spatial spectrum intensity is estimated generalizing the model of the accidental pulses' sequence [14] (every dust particle is located accidentally and independently from other particles, spatial location point and dusty particles' total quantity are statistically independent):

$$G(\vec{k})=2\pi n_d\left|\Phi(\vec{k})\right|^2, \qquad (4)$$

where n_d is the dust particles' concentration, Φ is the spatial spectrum density of separate dust particle.

The contribution of separate dusty particle into the spatial disturbance of the plasma dielectric permittivity vanishes exponentially at the characteristic Debye length r_d. After normalization the spatial spectrum intensity of the dusty plasma inhomogeneities can be given in the form:

$$G(|k|)=\frac{16\sigma_\varepsilon^2 r_d^3}{\pi\left(|k|^2 r_d^2+1\right)^4}. \qquad (5)$$

Dispersion σ_ε of the accidental function $\varepsilon_1(\varphi,r,z)$ can be written through the parameters of the dust particles:

$$\sigma_\varepsilon^2=\frac{9}{8}\frac{Z^2 n_d}{r_d^3 n_c^2}, \qquad (6)$$

where Z is the dusty particle's charge and $n_c(\omega)$ is the critical plasma concentration at the modulation frequency.

4. TRANSITION RADIATION CAUSED BY THE DUST PARTICLES IN PLASMA

Non-resonant transition radiation is caused by the scattering of the beam's electromagnetic field on the accidental inhomogeneties of the dusty plasma. This radioemission can be calculated from the first-order approximation equation (2) with the field of modulated electron beam in the right side. The solution of this equation was substituted in the form of Fourier series by φ, Fourier integral by z and Fourier – Bessel integral by r. Than the inverse transforms were carried out.

Due to the three-dimensional spatial inhomogeneity radiated waves are both p- and s-polarized. The radial component of the energy flux for these components can be written in the form:

$$\Pi_R^{(p)}(R,\Theta)=\frac{2\pi L(j_m a\sin\Theta)^2}{\varepsilon_0^{5/2}cR^2}\int_0^\infty K_r dK_r G(K_r,\kappa-k\cos\Theta)\times$$

$$\times\int_0^\pi d\psi\,\frac{J_1^2\left(\sqrt{K_r^2-2kK_r\sin\Theta\cos\psi+k^2\sin^2\Theta}\,a\right)}{K_r^2-2kK_r\sin\Theta\cos\psi+k^2\sin^2\Theta}\times$$

$$\times\left\{\frac{\kappa\cos\Theta K_r(K_r-k\sin\Theta\cos\psi)+(\kappa^2-k^2)(k\sin^2\Theta+\kappa\cos\Theta)}{K_r^2-2kK_r\sin\Theta\cos\psi-k^2\cos^2\Theta+\kappa^2}\right\}^2$$

$$\Pi_R^{(s)}(R,\Theta)=\frac{2\pi L(\kappa k j_m a\sin^2\Theta)^2}{\varepsilon_0^{5/2}cR^2}\int_0^\infty K_r^3 dK_r G(K_r,\kappa-k\cos\Theta)\times$$

$$\times\int_0^\pi d\psi\,\frac{J_1^2\left(\sqrt{K_r^2-2kK_r\sin\Theta\cos\psi+k^2\sin^2\Theta}\,a\right)}{K_r^2-2kK_r\sin\Theta\cos\psi+k^2\sin^2\Theta}\times$$

$$\times\frac{\sin^2\psi}{\left\{K_r^2-2kK_r\sin\Theta\cos\psi-k^2\cos^2\Theta+\kappa^2\right\}^2}, \qquad (7)$$

where $k=\varepsilon_0^{1/2}\omega/c$.

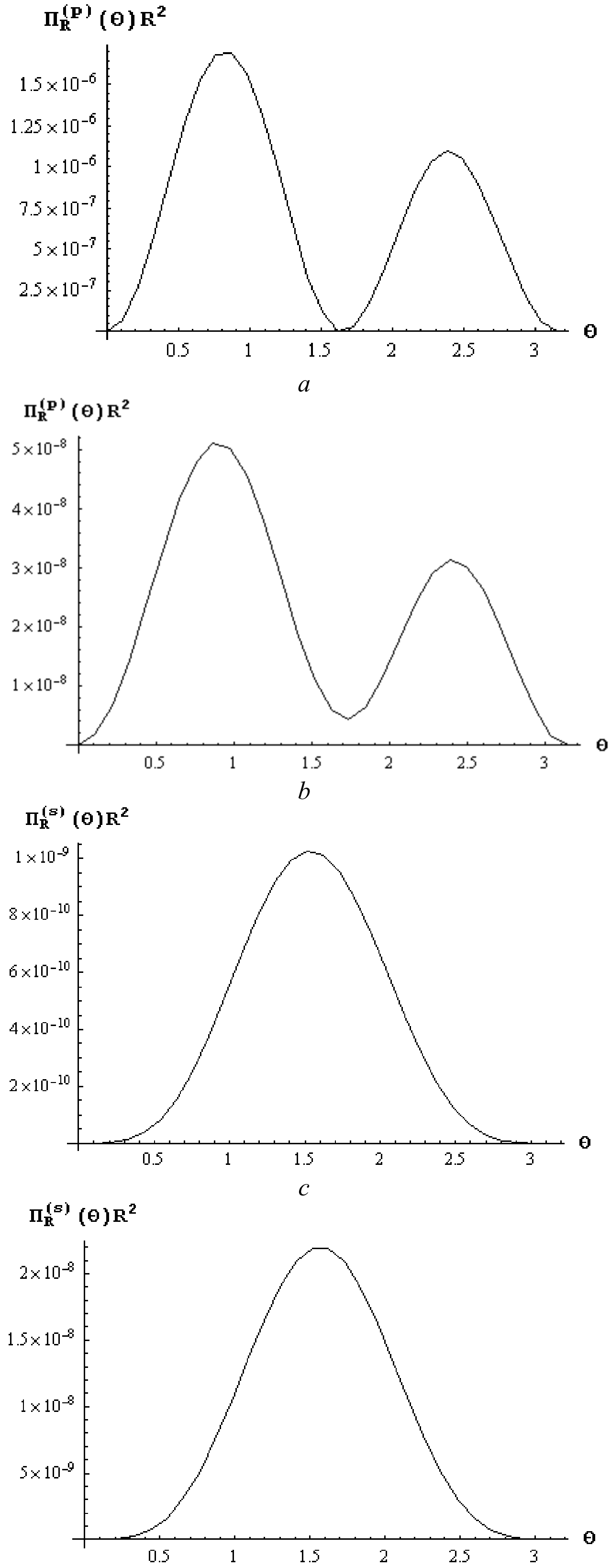
Transition radiation is determined by the overlapping of the beam's spatial spectrum and spatial spectral intensity of the inhomogeneities. Its magnitude is directly proportional to the product of the dust particles concentration and their square average charge.

5. DISCUSSION

The radiation patterns for p- and s-polarised components calculated for typical parameters are presented on Fig.1*a-d*. The graphics show that radiated power for p-polarized waves is mainly directed forward and backward (Fig.1*a-b*). For s-polarized component it is mainly directed perpendicularly to the beam velocity. Position of maximum radiation point matches spatial resonance condition for characteristic propagation vector for radiated electromagnetic field, vector component for modulation frequency and wave vector for spatial spectrum intensity of the dusty plasma inhomogeneities. Radiated power is more for p-polarized waves. Total power is about 0.1-1 μW for radial component of p-polarizated transition radioemission (s-polarizated radiation is lower of 1-2 orders). This power is enough to be detected by the radio receiver. Natural blackbody thermal radiation is about 10^{-13} J/m^2 and it is lower in absolute comparison with transition radiation for typical conditions.

For large velocities ($v_0>0.1c$) the radioemission intensity is decreased when the beam velocity is increased. It is the result of growth of the transversal size of the transition radiation formation zone. If this size is large relatively to the average distance between the dust particles, radioemission vanishes due to the averaging of the contributions with the accidental phases. For small velocities radioemission is decreased when the beam velocity slow down.

Transition radioemission of the modulated electron beam can be used for information obtaining about complex plasma inhomogeneity caused by the strongly charged dusty particles. So the diagnostics based on transition radiation is possible method to study the parameters of dusty plasma systems.



a

b

c

Fig.1. Radiation patterns of p-polarized (a - $v_0/c=0.1$, b - $v_0/c=0.9$) and s-polarized (c - $v_0/c=0.1$, d - $v_0/c=0.9$) transition radiation depending on the angle θ (radian) for $\omega_p=2\cdot10^{10}s^{-1}$, $\omega=6\cdot10^{10}s^{-1}$ $j_m=1A/cm^2$, $r_d=0.02cm$, a=0.5cm, L=1m, $\sigma_\varepsilon^2=5\cdot10^{-8}$, $Z=7\cdot10^4$.

In our calculation the effect of the beam on the background plasma was negated. For plasma with the typical parameters and beam of energy 100 *KeV* and current 1 *A* it is possible for electron bunches of duration less than 1 μs.

Of course the model treated in this article is very simplified. More accurate treatment must take into account real geometry of the system, influence of magnetic field, dusty particles' distribution on size, etc.

REFERENCES

1. V.N. Tsytovich, J. Winter. *Physics – Uspekhi,* **41**, 815-822 (1998).

2. J.Winter, G.Gebauer, "Dust in magnetic confinement fusion devices and its impact on plasma operation", *Proc. 13th PSI*, San Diego, 1998, p.p.731-732.

3. W.Horton, Y.-H. Ishikava. *Chaos and Structures in Nonlinear Plasmas.* World scientific publishing, 1996.

4. V.D.Rusanov. *Modern methods of plasma studies.* Gosatomizdat, Moscow 1962. (In Russian).

5. S.M.Levitsky, Yu.I.Burykin, *Ukr. Phys. Journ.,* **17**, 1198-1201 (1972). (In Russian).

6. I.O.Anisimov, S.M.Levitsky, A.V.Opanasenko, L.I.Romanyuk, *Journ. Techn. Phys.,.* **61**, p.p.59-63 (1991) (In Russian).

7. I.O.Anisimov, *Ukr. Phys. Journ.*, **41**, p.p.798-801 (1996). (In Ukrainian).

8. I.O.Anisimov, K.I.Lyubich, *Ukr. Phys. Journ.,* **42**, p.p.959-966 (1997). (In Ukrainian).

9. I.A.Anisimov, *Geomagnetism and aeronomy*, **35**, p.p.40-45 (1995). (In Russian).

10. I.O.Anisimov, K.I.Lyubich. *J. Plasma Phys.*, **66**, p.p.157-165 (2001)

11. I.O.Anisimov, K.I.Lyubich, *Journ. Phys. Studies* **4**, p.p.61-67, (2000). (In Ukrainian).

12. Martysh E. V., Mal'nev V.N. "Formation of highly excited atom clusters in the plasma edge", *25-th EPS Conference on Controlled Fusion and Plasma Physics*, Abs. of ICP, part I, Prague, 1998, p.161.

13. E.V.Martysh , "Dusty particles – possible source of Rydberg states in ionosphere", *VIII Ukrainian Conference on plasma Physics and Controlled Fusion*, Book of Abstacts, Alushta, Crimea - Ukraine, 2000, p.87.

14. S.A.Akhmanov, Yu.E.Djakov, A.S.Chirkin. *Introduction to the statistical radio physics and optics*. Nauka, Moscow, 1981. (In Russian).