

# HARMONIC GENERATION DUE TO ELECTRON-ION CORRELATED SCATTERING IN SUPERSTRONG LASER FIELDS IN PLASMAS

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A problem of modification of an induced radiation spectrum in super strong laser field has not attracted attention because of the absence of coherent radiation in weak field and small modification of the stimulated bremsstrahlung at low frequency (near external field frequency). The same result in weak field has been found in both model: classical and quantum [1].

Our statement is that in rather strong fields the correlation between collision time and laser field phase is of basic importance. The major idea is as follows. Due to repeatedly returns of a rapidly oscillating electron to an ion the resulting collision time may be strongly correlated with phase of external wave field and provide coherent part of induced radiation. Even there is a more surprising effect: coherent part of radiation has maximum at frequency much larger than frequency of laser field. This effect is essentially important for great coherent frequency increasing in superstrong field.

We have solved numerically the classical equation of an electron motion in a Coulomb field of an ion and homogeneous alternating electrical field  $\mathbf{E}$  varying on harmonic law. The equation can be written in dimensionless variables [2,5]

$$\mathbf{R} = -\frac{\mathbf{R}}{R^3} + \mathbf{n} \cos(\Omega t), \quad (1)$$

that is convenient for consideration of strong fields. The following notation are introduced here ( $Z$  is the ion charge,  $\omega$  is the laser field frequency)

$$r_E = \sqrt{eZ/E}, \quad \omega_E = \sqrt[4]{eE^3/m^2Z}, \quad v_E = \sqrt[4]{Ze^3E/m^2}, \quad \Omega = \omega/\omega_E \quad (2)$$

It is important to note that the considered problem is described by one dimensionless parameter  $\Omega$ . It depends on the frequency and intensity of the laser field in a combination  $\Omega \sim \omega^4/E^3$ . It means, that a limiting case of quasistatic field ( $\Omega \rightarrow 0$ ) is equal to case of superstrong laser field.

A radiation cross-sections, characterising the bremsstrahlung intensity, for the coherent and incoherent case have the form (more detail see [3]):

$$\chi_n(\omega) = \frac{2}{3c^2} \sum_n \iint |\dot{\mathbf{a}}_n|^2 d\boldsymbol{\rho} d\varphi \cdot \delta(\omega - n\Omega), \quad (3)$$

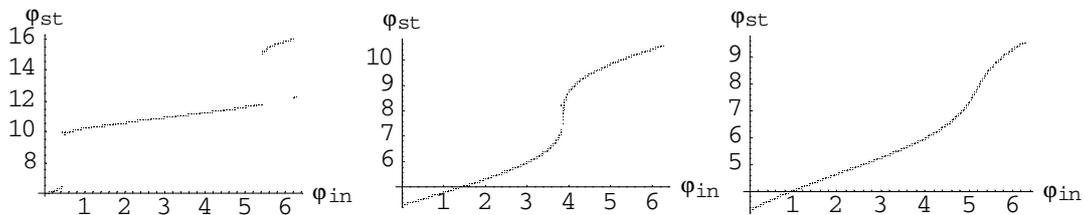
$$\chi_{coh}(\omega) = \frac{2}{3c^2} \sum_n \left| \iint d_{zn} d\varphi d\boldsymbol{\rho} \right|^2 \delta(\omega - n\Omega). \quad (4)$$

Here  $d_{zn} = \int_{-\infty}^{\infty} d_z(\tau) e^{in\Omega\tau} d\tau$  is the dipole moment spectrum,  $d\rho$  is the area in the plane normal to the direction of the incident beam close to the vector of the impact parameter  $\rho$ . It is easy to see that the coherent radiation cross-section is simple and rather evident extension of incoherent radiation cross-section.

Basic calculations were carried out for longitudinal ( $\mathbf{v}_{in} \parallel \mathbf{E}$ ) and transverse ( $\mathbf{v}_{in} \perp \mathbf{E}$ ) collisions for several intermediate magnitudes of angles.

### Phase grouping

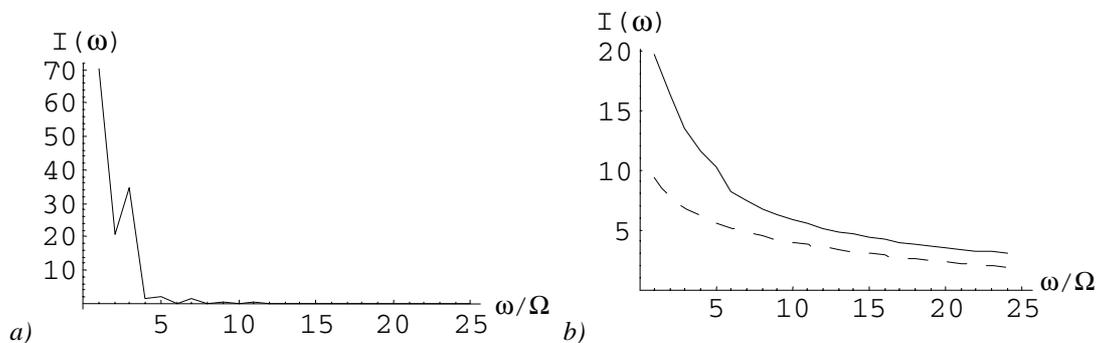
The most interesting result was found during the numerical simulations in superstrong laser field ( $\Omega \ll 1$ ). Time of collision is correlated with phase of external wave field (Fig.1) that we call “phase grouping”. The most intensively this effect observes for small drift velocities (fewer oscillating velocity). A mechanism of the phase grouping looks like distributed analogue bunching in klystron, used for microwave generation.



**Fig. 1.** Collision's phase vs. initial phase for  $\Omega = 0.32$  and  $\nu = 5, 10, 15$  (left to right).

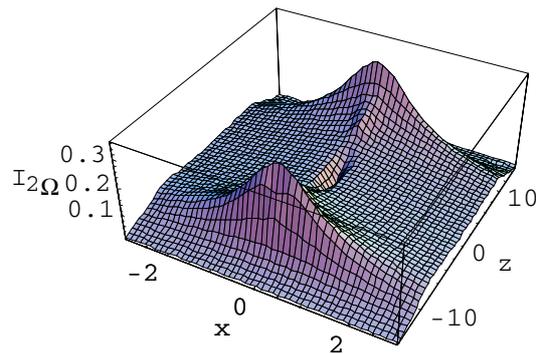
### Induced radiation

Correlation between collision time and external field's phase provides a coherent component of induced radiation. The coherent radiation propagates along the external wave direction and has maximum in spectrum at frequency  $\omega_E$  (Fig. 2a). It's important that in super strong fields, peak's frequency  $\omega_E$  is much larger than the external field frequency  $\omega$ . Existence of intense peak of coherent radiation at high frequency can effective increase the extern frequency  $\omega$  by “coherent” way!



**Fig. 2.** Coherent (left) and incoherent (right) radiation cross-section vs . frequency for  $\Omega = 0.32$  and  $\nu = \nu_{\sim} / 2$ . Dash – without external field.

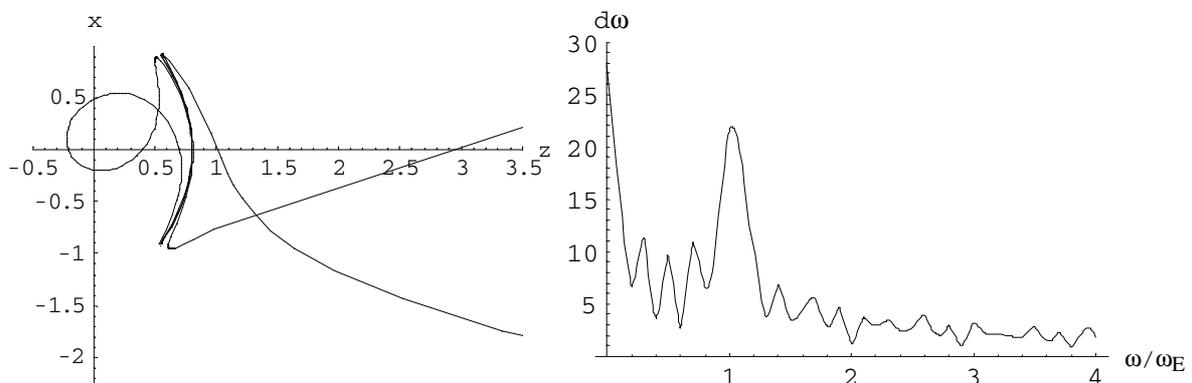
Spectrum of incoherent radiation is modified by analogue to the coherent one, it strongly increases at frequency smaller  $\omega_E$  (Fig. 2b). Intensity cross-section at high frequencies lightly increases relatively classical value without field due to existence of “representative” electrons [2,4]. The representative electrons from area of impact parameter much larger than Rutherford area strongly collide. As a result, the area of intense radiation and incoherent radiation cross-section increase. Numerical simulations show that dominant part of collisions with intense radiation (especially at small harmonics) lies in the area of collision with quasistatic external field (Fig. 3).



**Fig. 3.** Radiation intensity on frequency  $2\Omega$  vs. impact parameter for  $\Omega = 0.32$  and  $\nu = \nu_{\sim} / 2$  (transverse collisions).

### Static field

An electron motion in Coulomb and static external field can be solved analytically using Levi-Civita coordinate [6]. Figure 4 shows typical trajectory of an electron colliding in static field and its spectrum. It's easy to see “transversal” oscillating at the frequency  $\omega_E$ . Correspondent maximum of induced radiation is visible at frequency near  $\omega_E$ .



**Fig. 4.** Particles trajectory and its spectrum in static field.

In the simplest approximation, the value of dipole moment spectrum can be written as follows

$$d_{\omega} \sim \sum_n e^{-\lambda n} \delta(\omega - (2n+1)\omega_E) \quad (5)$$

Figure 4 shows that an intensity spectrum of induced radiation in our case strongly different from the case of weak fields. The most difference is the second peak existence. It is important to note that the intensity of this peak is of the same order then as the first one. On the other hand this peak is appeared due to the fast “transversal” oscillations only. Because of this one can hope to find an effective mechanism of pumping of electromagnetic waves with appropriate frequencies.

The presence of a maximum of radiation is at frequency  $\omega_E$ . The value of this frequency and the width of the maximum of radiation increase with amplitude of the electromagnetic wave. Obviously, it is related to the increasing of a particle localization time near the atom, and the reduction of minimum distance between a particle and atom.

In conclusion we note that marked variations in the traditional concept occur only in rather strong fields, namely when,  $r_{\perp} \gg r_e = \sqrt{eZ/E} \rightarrow \omega_E \gg \omega$  (more detail see [2]) or in dimensional variables

$$\omega \ll \omega_E \approx 2 \cdot 10^{10} \cdot Z^{1/4} \cdot (P[Wt/cm^2])^{3/8}. \quad (6)$$

### Acknowledgements

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### References

- [1] M.H. Mittleman: Introduction to the Theory of Laser-Atom Interactions. Plenum Press, New York and London, 1993.
- [2] G.M. Fraiman, V.A. Mironov, A.A. Balakin, submitted to Sov. JETP.
- [3] J.D. Jackson: Classical electrodynamics. John Willey & Sons, inc., New York-London, 1962.
- [4] G.M. Fraiman, V.A. Mironov, A.A. Balakin: “Correlated effects due to electron-ion collisions in superstrong laser fields in plasmas”, *ICPP 1998*.
- [5] G.M. Fraiman, V.A. Mironov, A.A. Balakin: “Bound states of coulomb system in superstrong laser fields in plasmas”, *ICPP 1998*.
- [6] E.L. Steifel, G. Scheifele: Linear and regular celestial mechanics. Springen-Verlag, Berlin - Heidelberg - New York, 1971.