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# Electromagnetic Radiation from Magnetized Wake of Laser Irradiated Gas Jet

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**Abstract:** In this work a mechanism for converting large amplitude magnetized wakefield due to laser irradiated gas jet into high power THz radiation is discussed. A two dimensional (2D) theory of the radiation is presented and the results are compared with experimental data.

Historically in 1934 Cherenkov discovered a new mechanism for electromagnetic radiation. A charged particle travelling in a uniform medium with a constant speed greater than the phase velocity of light in the medium emits Cherenkov radiation [1]. Recently charged particle is replaced by a short intense laser pulse. Similarly, the group velocity of the driving pulse should be greater than the phase velocity of the excited radiation in the medium. Cherenkov emission of THz radiation from short optical pulse in electro-optic media has been observed experimentally [2, 3]. Plasma is a dispersive media as well. Group velocity of the laser pulse in plasma is $v_g = c(1-\omega_p^2/\omega_0^2)^{1/2}$. Usually, $\omega_0$ the angular frequency of the laser pulse is much more greater than $\omega_p$, the plasma frequency and $v_g \simeq c$. By applying a modest dc magnetic field perpendicular to the direction of laser pulse propagation the electromagnetic component of the plasma wake due to the rotational motion of electrons around the magnetic field lines will generate. This enables the wake to propagate through the plasma and to couple out into vacuum as radiation at the plasma boundary.

The phase velocity of the excited waves is $v_{ph} = c/\sqrt{\varepsilon}$ where $\varepsilon$ is the dielectric constant of the plasma, therefore a Cherenkov like radiation can be generated when $\sqrt{\varepsilon} \geq 1$. In Fig. 1 the behavior of refraction index $\sqrt{\varepsilon}$ of magnetized plasma for extraordinary modes in different frequencies is shown. $\omega_L$ and $\omega_R$ are the cutoff frequencies and $\omega_H$ is the upper hybrid frequency. It is shown that the radiation frequency is restricted from $\omega_p$ to $\omega_H$, where $\varepsilon \geq 1$. Radiation frequency is very close to $\omega_p$, so

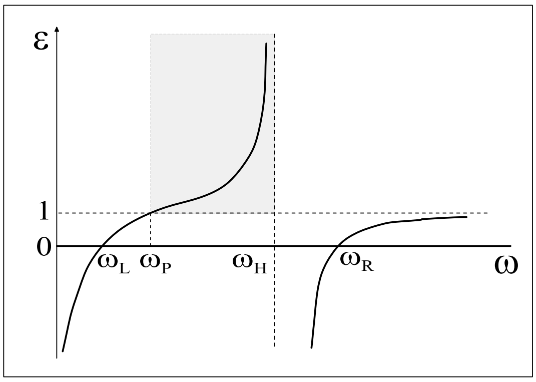


Figure 1: The dispersion of the extraordinary wave. Gray region shows the frequency range of the radiation.

tunable with plasma density. This mechanism not only can be used in plasma based accelerators as a powerful diagnostics to detect wakefield behavior but as it will be shown this mechanism is the kW source of THz radiation. From interaction on $fs$ laser pulses and magnetized plasma, this radiation has been observed experimentally [4, 5, 6, 7].

A direct analytical procedure to find all components of magnetized wakefield in one dimension is presented in Ref. [5]. For two dimensional case, one can start from the same equations but in the new form. A short laser pulse is considered to propagate in the $+z$ direction ($V_0 \approx C$) in a homogenous plasma of density $N$. The transverse laser profile depends only on coordinate $x$ and is independent of $y$. External dc magnetic field is applied in the $+y$ direction. So for the basic Maxwell's equations we have:

$$\frac{\partial E_z}{\partial x} + \frac{1}{V_0}\frac{\partial E_x}{\partial \xi} = \frac{1}{c}\frac{\partial B_y}{\partial \xi}, \tag{1}$$

$$\frac{1}{V_0}\frac{\partial B_y}{\partial \xi} = \frac{1}{c}\frac{\partial E_x}{\partial \xi} - \frac{4\pi}{c} eNv_x, \tag{2}$$

$$\frac{\partial B_y}{\partial x} = \frac{1}{c}\frac{\partial E_z}{\partial \xi} - \frac{4\pi}{c} eNv_z, \tag{3}$$

This set of equations should be completed by the equation for electron motion along the $x$ and $z$ axes, taking into account $\Phi$, the average ponderomotive potential of the laser pulse.

$$m\frac{\partial v_x}{\partial \xi} = -eE_x - e\frac{\partial \Phi}{\partial x} + \frac{e}{c}B_0 v_z, \tag{4}$$

$$m\frac{\partial v_z}{\partial \xi} = -eE_z + \frac{e}{V_0}\frac{\partial \Phi}{\partial \xi} + \frac{e}{c}B_0 v_x. \tag{5}$$

where $\xi = t - z/V_0$. By applying Laplace transformation with respect to $\xi$ and solving the equations we arrive at the following equation for the magnetic field transform $\widetilde{B}_y(x,s)$, in which $s$ is the Laplace variable:

$$\frac{\partial^2 \widetilde{B}_y}{\partial x^2} - \kappa^2 \widetilde{B}_y = F(x,s), \tag{6}$$

where $F(x,s)$ is the source given by:

$$F(x,s) = -\frac{1}{c}\frac{\omega_p^2 \omega_c}{s^2 + \omega_h^2}\Big(\frac{s^2}{c^2\beta^2}\widetilde{\Phi} + \frac{\partial^2 \widetilde{\Phi}}{\partial x^2}\Big) \tag{7}$$

$\widetilde{\Phi}$ is the Laplace transformation of the laser pulse envelope function, $\omega_p$ and $\omega_c$ are the plasma electron frequency and the electron cyclotron frequency as usual and $\omega_h = (\omega_p^2 + \omega_c^2)^{1/2}$ is the upper hybrid frequency of the extra-ordinary mode of magnetized plasma. For $\kappa$ we have

$$\kappa^2 = \frac{s^2}{c^2}\Big(1 + \frac{\omega_p^2}{s^2}\frac{s^2 + \omega_p^2}{s^2 + \omega_h^2} - \frac{1}{\beta^2}\Big) \tag{8}$$

where $\beta = V_0/c$. Real part of $\kappa$ should be taken positive to satisfy the radiation condition (namely all fields should be finite at infinity). From now on the approximation $\beta = 1$ is used to simplify the solution and laser pulse is assumed to be a square pulse with duration $\tau$ and pulse length $\ell$. To find the magnetic field we have to apply the inverse Laplace transformation. In this case the magnetic field can be found as the sum of outgoing and incoming plane waves of different frequencies propagating different angles.

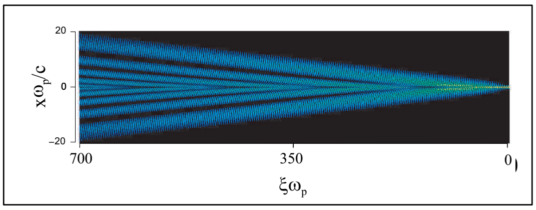


Figure 2: Distribution of the magnetic field $B_y$ behind the laser pulse.

$$B_y(x,\xi) \approx \frac{\omega_p^2\omega_c}{2c^3\sqrt{\pi}}\sum_{i=1}^{2}\frac{e^{-(1/4)g_i^2\ell^2}}{g_i}\frac{\omega_i^2+c^2g_i^2}{\omega_h^2-\omega_i^2}\sqrt{\frac{2\pi}{|g_i''x|}}\sin\left[\omega_i\xi - g_ix + \varphi(\omega_i) - \frac{\pi}{4}sgn(g_i''x)\right] \quad (9)$$

where $g_i = g(\omega_i)$ and $g_i''$ denotes the second derivative with respect to $\omega$ at $\omega_i$ and the sum is taken over the frequencies $\omega_i$. The field pattern with $\omega_c/\omega_p = 0.3$ and $\omega_p\ell/c = 0.5$ is plotted in Fig. 2. There is a conical structure, very similar to the feature of Cherenkov radiation and several whiskers are present. To get insight into the field structure we made an asymptotic evaluation of the integral using the well known phase stationary approach. It turns out that there are two stationary points, i.e. two frequencies, for a given coin with angle $\alpha$. It means that there is a superposition of two harmonic oscillation at the cone. Evidently, it gives beating along the cone. It explains the multi tail structure of the radiation. There is no beating however at the external cone of the radiation pattern. Characteristics of the external cone, such as frequency of the radiation, cone angle, and tilting of the wave fronts of the cone as well as radiation power is described at Ref. [8]. The power of the radiation due to $E_x$ in the forward direction $z$ is:

$$P_z \approx \frac{\ell^2\omega_p^2\omega_c^2}{16mc^2}|\widetilde{\Phi}_0(\omega_p)|^2 I, \quad (10)$$

where $I$ is a dimensionless factor. Numerical calculations shows that for $0.1 \leq \omega_p\ell/c \leq 3$ and $0.01 \leq \omega_c/\omega_p \leq 0.3$: $I \approx 2$ to 4. Taking laser intensity of $10^{17}$ W/cm$^2$, wave length of 800 nm, $\tau = 100$ fs, $\ell = 10$ $\mu$m, $\omega_p/2\pi$=2 THz, and $\omega_c/\omega_p$=0.01, which is the condition of experiments [5, 6, 7], shown in Fig. 3, the power of radiation in the $z$ direction in the mentioned experiments theoretically should be about 350 W.

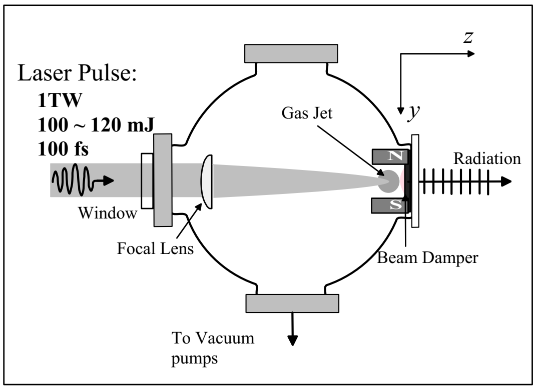


Figure 3: Experimental setup.

but in the mentioned experimental condition, measured power was about several tens of milliwatts.

Furthermore, experimental results show that wake field disappears faster than the calculated life time. The observed pulse duration is about 200 ps at FWHM, while the expected value is 80 ns. A sample of radiation is shown in Fig. 4. Now from the mentioned theoretical results this discrepancy can be explained. The frequency of the detected radiation is measured to be about 60 GHz$\approx \omega_p/15$, rather than $\omega_p$ [5]. It means that the detected radiation originated not from the plasma core but from a smooth transition layer between the plasma and vacuum. In this layer the plasma density should be about $\omega_p/15$. By substituting $\omega_p/15$ instead of $\omega_p$ into Eq. (10), we obtain $p_z \approx 100$ mW, which is very close to experimental data. Also the pulse width of the radiation which is in fact, the life time of plasma wakes, is the life time of that part of wakes which are in the frequency range of measured radiation, obviously smaller than the life time of the main part of plasma wakefield.

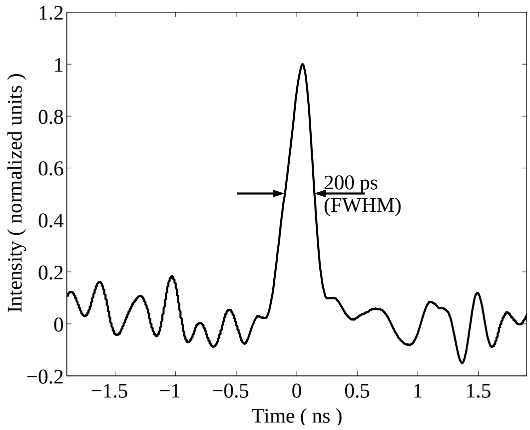


Figure 4: Sample of Radiation.

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