CERENKOV RADIATION FROM A MAGNETIZED PLASMA: A DIAGNOSTIC FOR PBWA EXPERIMENTS[i]

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Abstract

In the plasma beat wave acceleration scheme, the ponderomotive force of a two-frequency laser pulse resonantly drives a large amplitude ($E^{es}\approx3$ GV/m) relativistic electrostatic plasma wave. The electro-static (es) wave does not couple to the vacuum modes and its energy is dissipated in the plasma. With a static magnetic field $B_0\mathbf{z}$ applied perpendicularly to the laser beam propagation axis **x**, the two-frequency laser pulse couples to the L branch of the XO mode of the magnetized plasma through Cerenkov radiation. The electromagnetic component (em) of the XO mode couples to the vacuum mode. The plasma wave is not affected by the transverse magnetic field, and measuring the characteristic of the emitted radiation thus provides an in-situ diagnostic for the beat-wave-excited accelerating structure (amplitude, phase, and damping for example). Additionally, the mechanism of interest is a possible source for a gigawatt terahertz radiation source.

1 INTRODUCTION

In the last decade plasmas have entered two fields traditionally reserved to vacuum devices: the microwave sources and the electron accelerators. Self modulated laser wakefield (SM-LWFA) experiments have demonstrated accelerating fields larger than 100 GV/m, resulting in acceleration of electrons by up to 100 MeV in a millimeter [1]. Laser driven plasma beat wave acceleration (PBWA) experiments have shown accelerating fields up to 3 GV/m, resulting in acceleration of electrons by 30 MeV over a 1 cm length [2]. Using laser created, relativistically-propagating ionization fronts in a plasma frequency up-shifting of microwaves from 35 GHz continuously to 170 GHz has been demonstrated [3]. Direct conversion of the static electric field of an array of alternatively biased capacitors using the same ionization front has produced continuously tunable short pulses of radiation between 6 and 93 GHz [4]. Recently a new scheme taking advantage of the large electric field produced in the PBWA experiment has been proposed for generating mega- to gigawatts of THz radiation by applying a static magnetic field perpendicularly to the laser beam path. [5] The radiation is generated by coupling of the two-frequency laser pulse to the left branch of the extraordinary mode of the magnetized plasma through Cherenkov radiation. This scheme can be either used as a THz radiation source, or as a diagnostic for the PBWA experiment itself.

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2 CHERENKOV RADIATION FROM A MAGNETIZED PLASMA

First consider a two-frequency laser pulse exciting a plasma wave to a large amplitude in an unmagnetized plasma. In the dispersion or (ω,k) diagram the excitation is represented by the intersection between the laser pulse line $\omega=kv_{gl}$, where $v_{gl}=(1-\omega_{12}^2/\omega_{pe}^2)^{1/2}c$ is the laser pulse group velocity in the plasma, and the es plasma wave eigenmode of the cold plasma at $\omega=\omega_{pe}$. At this intersection point the phase velocity of the plasma wave is c but its group velocity is zero. The energy deposited in this mode by the laser pulse does not propagate outside of the plasma and is finally dissipated in the form of plasma heating. The plasma wave is at cut-off in the plasma and only a small volume around the plasma surface about one skin depth deep is expected to radiate in vacuum. Note that the laser pulse line never intersects with the electromagnetic (em) eigenmode of the plasma $(\omega^2=\omega_{pe}^2+k^2c^2)$.

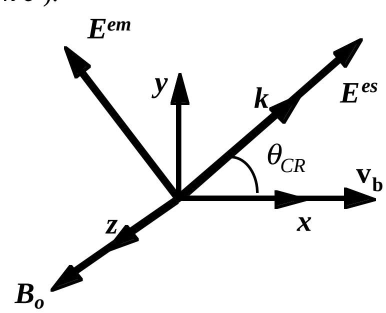

Figure 1: Geometry for the Cherenkov radiation in a magnetized plasma ($\boldsymbol{k}\in(\boldsymbol{x},\boldsymbol{y})$).

Applying a static magnetic field $\boldsymbol{B_0}$ modifies the nature of the plasma eigenmodes. In particular when $\boldsymbol{B_0}$ is perpendicular ($\perp$) to the laser beam path ($\boldsymbol{B_0}=B_0\boldsymbol{z}$, see Fig. 1) and for $\boldsymbol{k}\perp\boldsymbol{B_0}$ ($\boldsymbol{k}=k\boldsymbol{x}$) and $\boldsymbol{E}\perp\boldsymbol{B_0}$ ($\boldsymbol{E}$ the wave electric field), the dispersion relation is:

$$\frac{c^2k^2}{\omega^2}=1-\frac{\omega_{pe}^2}{\omega^2}\frac{\omega^2-\omega_{pe}^2}{\omega^2-\omega_H^2} \qquad (1)$$

where $\Omega_{ce}=eB_0/m_e$ is the electron cyclotron frequency, $\omega_H=(\omega_{pe}^2+\Omega_{ce}^2)^{1/2}$ is the upper hybrid frequency. The eigenmodes of the plasma are the left (L) and right (R) branch of the extraordinary or XO-mode (see Fig. 2) and have cut-off frequencies at $\omega_{R,L}=[\pm\Omega_{ce}+(\Omega_{ce}^2+4\omega_{pe}^2)]^{1/2}$ respectively. These two branches have two components to their electric field; an em component $\boldsymbol{E}^{em}=E^{em}\boldsymbol{y}$, and an es component $\boldsymbol{E}^{es}=E^{es}\boldsymbol{x}$. Their amplitude ratio is obtained from the dielectric tensor for the magnetized plasma: $E^{em}/E^{es}=\Omega_{ce}/\omega_{pe}$. Waves with $\omega<\omega_L$ or $\omega_H<\omega<\omega_R$ are evanescent in the plasma. The laser pulse line intersects with the L-XO branch of the magnetized plasma. Physically the ponderomotive force of the laser pulses pushes the electrons along the $\boldsymbol{x}$ axis creating $\boldsymbol{E}^{es}$, they rotate around the B_0 lines in the $(\boldsymbol{x,y})$ plane and generate $\boldsymbol{E}^{em}$. Note that the dispersion relation of eq. (1) remains valid for any $\boldsymbol{k}$ in the $(\boldsymbol{x,y})$ plane. Figure 2 shows that the laser pulse can couple to the L-XO mode through Cherenkov radiation at any angle $\theta_{CR}\leq 90°$, where the velocity of the disturbance (the laser pulse) $v_{gL}\approx c$ is larger than the phase velocity of the L-XO mode. Note that this corresponds to Cherenkov radiation from photon bunches rather than from particles. The Cherenkov condition $cos\theta_{CR}=1/\beta_{gl}n(\omega)$ where $\beta_{gl}=v_{gl}/c$, $v_{gl}=c(1-\omega_{pe}^2/\omega_{12}^2)^{1/2}\approx c$, and $n(\omega)=ck/\omega$ is given by eq. 1. Since the plasma is dispersive different frequencies are emitted at different angles. However, Fig. 2 shows that the group velocity of the L-XO mode decreases with increasing θ_{CR} while the emitted frequency increases from ω_{pe} to ω_H. Cherenkov radiation is thus emitted essentially in the forward direction (θ_{CR}=0) at ω_{pe} since a significant group velocity is necessary for the radiation to exit the plasma.

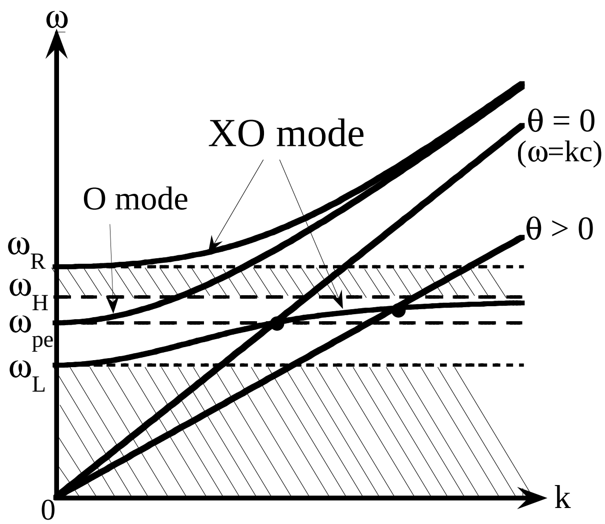

Figure 2: Dispersion relation for the magnetized plasma with $\boldsymbol{k}\perp\boldsymbol{B_0}$, $\boldsymbol{E}\perp\boldsymbol{B_0}$, and $\boldsymbol{k}$ in the $(\boldsymbol{x,y})$ plane (see Fig. 1). The dashedregion are evanescent regions. The Cherenkov condition is show by the dots at the two angles.

For $\boldsymbol{k}$ in the $(\boldsymbol{z,x})$ plane, the dispersion relation can be rewritten as a function of θ_{CR} [6], but the major conclusions remain the same as for $\boldsymbol{k}$ in the $(\boldsymbol{x,y})$ plane: the Cherenkov radiation is emitted essentially in the forward direction (θ_{CR}=0) at ω_{pe}. Figure 3 shows the frequency of the Cherenkov emitted as a function of the Cherenkov angle for the two cases $\boldsymbol{k}$ in the $(\boldsymbol{x,y})$ plane and $\boldsymbol{k}$ in the $(\boldsymbol{z,x})$ plane.

The dispersion relation (eq. 1) indicates that at θ_{CR}=0 the index of refraction for the L-XO n_{L-XO} mode is equal to one. In the case of a step function boundary between the plasma with density n_e and vacuum, the EM component of the L-XO mode couples to vacuum with a transmission coefficient equal to 1 (from n_{L-XO}=1 to n_{vac}=1) and thus $E_{vac}^{em}=E^{em}$. The es component of the L-XO mode is confined to the plasma. The power density radiated in vacuum is thus given by the Poynting vector: $S=\varepsilon_0(\Omega_{ce}/\omega_{pe})^2(E^{es})^2c/2$. In the case of a continuous plasma/vacuum boundary, both ω_H and ω_R decrease with the plasma density, and the forward wave at the bulk plasma frequency ω_{pe} has to cross the evanescent region shown on Fig. 2. For the case of a linear plasma density variation over the boundary an analytic expression for the attenuation coefficient can be derived.[5] The electric field is attenuated by a factor ≈3 by a linear decrease of the plasma density over three plasma wavelengths. In practice the attenuation can be minimized by abruptly terminating the plasma by, for example, using a gas jet, or by bringing the magnetic field to zero over the smallest possible distance. In the forward direction the group velocity of the L-XO mode is given by $v_{g-XO}=(\Omega_{ce}/\omega_{pe})^2c$. Once depositedin the plasma by the laser pulse the energy will convect out of the plasma for a time given by the minimum between the transit time for the energy through the plasma of length L_p: (L_p/v_{gL-XO}), and the life time of the plasma wave. This determines the pulse-length of the radiation emitted in vacuum.

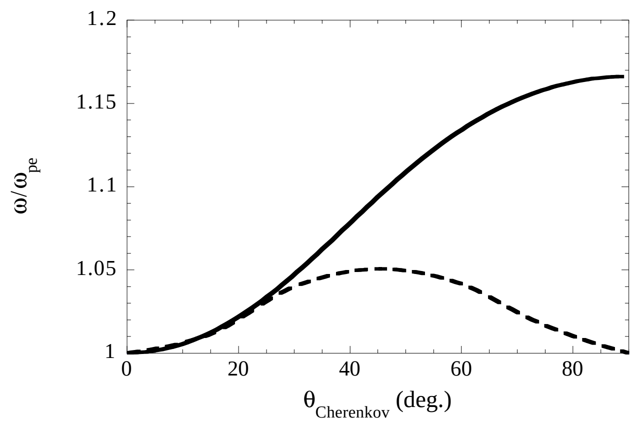

Figure 3: Frequency of the Cherenkov radiation (normalizedto ω_{pe}) as a function of the Cherenkov angle θ_{CR} in the case where $\boldsymbol{k}$ is in the $(\boldsymbol{x,y})$ plane (solid line), and $\boldsymbol{k}$ is in the $(\boldsymbol{z,x})$ plane (dashed line), for $\boldsymbol{E\perp B_0}$ and $\Omega_{ce}/\omega_{pe}=0.6$ and $\omega_H\approx 1.17$.

All of the analytical results describedabove have been verified by 2-D particle in cell (PIC) simulations. These simulations also show that the excitation of the plasma wave by the laser pulse is not degraded over the unmagnetized case for B_0 up to values corresponding to $\Omega_{ce}/\omega_{pe}\approx$0.8. For larger values of B_0 the ratio of E^{em}/E^{es} becomes smaller than the analytical value of Ω_{ce}/ω_{pe}.

3 THE PBWA EXPERIMENT

In the Neptune laboratory PBWA experiment [7] a high power (≈100 J in ≈100 ps or ≈1 TW), two-frequency CO_2 laser pulse (ω_1, ω_2 corresponding to λ_1=10.592 µm and λ_2=10.296 µm) is focusedby an off-axis parabola in a cell containing a static fill of gas (H_2 or D_2) or metallic vapor (Li, Na, or Cs). The spot size of the focused “flat-topped” beam w_0 (radius at 1/e for the fields) at best focus is 280 µm (1.4 times diffractionlimited) with an effective Rayleigh range $z_R=2\pi w_0/\lambda_{12}$=2.4 cm where λ_{12} is the average of λ_1 and λ_2. The laser intensity is large enough to strip each atom of the gas/vapor from its first electron through field ionization. The gas/vapor pressure is adjusted so that the electron plasma frequency $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$ (n_e is the plasma density ≈10^{16} cm^{-3}) is exactly equal to the frequency differencebetween the two laser frequencies: $\omega_{pe}=\omega_2-\omega_1$. The ponderomotive force associated with the beat envelope of the two-frequency laser pulse resonantly drives a large amplitude es plasma wave or beat wave $\delta n_e/n_e\approx$0.3, where δn_e is the plasma density perturbation, which corresponds to $E_x^{es}\approx$3 GV/m. A 17 MeV electron bunch from a rf-photo-injector with a radius $\sigma_x \approx \sigma_y \approx$30-50 μm is injected into the plasma wave and is accelerated to ≈100 MeV and dispersed in energy by a double-focusing electron magnetic spectrometer. The plasma wave characteristics in time, space, frequency, and wavenumber are measured by Thomson scattering of a 532 nm laser pulse. In the upcoming experiment, the H gas fill is be replaced by a Na or Cs heat-pipe oven. An open oven geometry [8] is chosen to allow for access to the plasma from the side for the different diagnostics. The Na and Cs vapor require a lower laser intensity to be field ionize because their ionization potential (5.1 and 3.9 eV respectively) is lower than that of H (13.6 eV). This allows for ionization and excitation of the plasma wave over a longer length and increases the electrons energy gained. Calculations show that the energy gain increases from 55 MeV over about one z_R in H to about 85 MeV over about $2z_R$ in Li [9]. Their ion mass is larger than that of H which renders the plasma more robust to ion motion and instabilities. A dipole magnet generates the transverse static magnetic field and has an strength of around 6 kG ($\Omega_{ce} << \omega_{pe}$). The field $\boldsymbol{B_0}$ can be applied either over the whole length of the plasma when the electrons are not injected, or only over the last 5 mm when the electrons are injected in the plasma, so that the plasma wave diagnostic and the electron acceleration are obtained at the same time. The plasma frequency is ≈1 THz, and the wavelength of the radiation (≈300 μm) is about equal to the plasma diameter. The radiation will thus strongly diffract from the plasma volume. It is collected by a parabolic mirror and sent out of the vacuum box through a silicon window (see Fig. 4). The temporal shape of the emitted pulse is monitored using a Schotkky-barrier diode. The signal amplitude as a function of time is proportional to the relative plasma wave amplitude as a function of time ($\Omega_{ce} << \omega_{pe}$), while its absolute amplitude is proportional the accelerating field.

The output power expected at 1 THz is 1 MW for B_0=6 kG (for a step plasma/vacuum boundary). This scheme can thus be used to produce powerful THz radiation for remote sensing or for seeding of an FEL. In the Neptune Laboratory experiment neither the plasma boundary, nor the magnetic field are expected to have a sharp boundary. Consequently the power produced in the plasma by Cherenkov radiation is expected to be considerably attenuated at the boundary. However, detecting the emitted radiation will be diagnostically extremely important for the acceleration experiment itself.

4 SUMMARY

A static magnetic field is applied transversely to the laser beam path in the PBWA experiment. The laser pulse emits Cherenkov radiation through coupling to the L branch of the XO mode of the magnetized plasma. The radiation is emitted essentially in the forward direction, at the plasma frequency (≈1 THz). The radiation parameters will be used as a diagnostic for the PBWA experiment. Method to allow for the high power THz radiation generated in the plasma to be transmitted through the plasma/vacuum boundary will also be investigated.

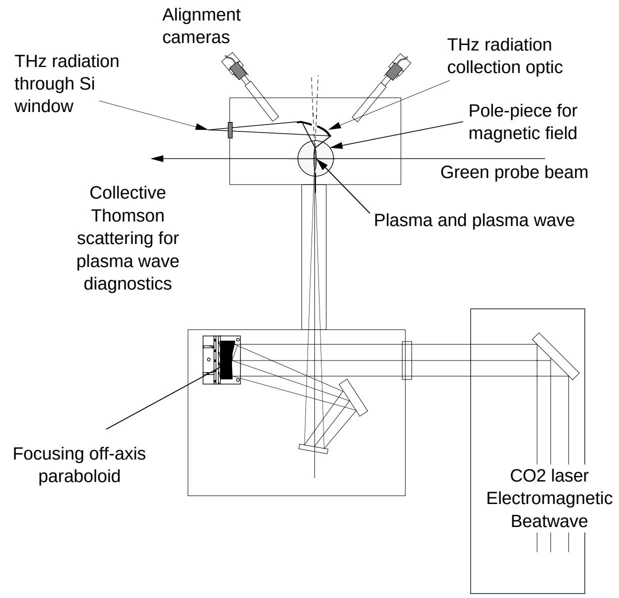

Figure 4: Experimental arrangement for the Cherenkov experiment in the Neptune Laboratory. The THz radiation propagates in the forward direction and is reflected towers the diagnostics, through a silicon window.

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