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Nonmonoenergetic Beam With Helical Čerenkov Radiation: Possible Technique to Determine Magnetic Field in a Hostile Electromagnetic Environment

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Modifications caused by the nonmonoenergetic beams to the recently described helical Čerenkov radiation (resulting from electron helical motion in a medium under the influence of magnetic field) are studied in a visible portion of the spectrum. The analysis is greatly simplified by utilizing a new analytical approximate expression for the number of emitted photons per unit path length for the usual "monoenergetic" helical Čereknov radiator. The effect of the nonmonoenergetic beam is that simultaneously with the helical Čerenkov radiation also the radiation into harmonics (above and below the helical Čerenkov effect threshold) may occur at the same radiation angle and at the same visible frequency. Hence, harmonic radiators may enhance the usual helical Čerenkov radiation. For the medium of silica aerogel with the index of refraction of 1.075 and the beam energy in the 2–3-MeV range interacting with the magnetic field of about 10 T, one estimates that in the visible portion of the spectrum an electron from a nonmonoenergetic beam will generate between 1 and 2 photons at the end of the 10-cm interaction length. This shows the possibility of detecting a magnetic field coming from an electromagnetic treat wave form, which in turn, represents a hostile electromagnetic environment. The importance of detecting this magnetic field comes from the fact that in an environmental medium it can disrupt optical signals. Here we show the way for measuring and quantifying such disruptions.

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1. POWER SPECTRA FOR THE HELICAL ČERENKOV EFFECT AND HARMONIC RADIATION ABOVE AND BELOW HELICAL ČERENKOV THRESHOLD

The helical Čerenkov effect (HCE) arises from electrons moving in a medium on helical trajectories under the influence of the uniform magnetic field that, for simplicity, is defined as $\vec{B} = \hat{z}B$, with B denoting the magnitude of the magnetic field and $\hat{z}$ its direction (Šoln 1992). The helical Čerenkov radiation with angular frequency ω will occur if (Šoln 1992)

$$n(\omega)\beta_z(0) \geq 1, \tag{1}$$

where $\beta_z(0) = v_z(0)/c$, with $v_z(0)$ denoting the parallel component of the electron velocity with respect to $\vec{B}$. Here and in what follows, $\beta = v/c$, $\beta_z = v_z/c$, $\beta_\perp = v_\perp/c$ with $v_\perp$ being the perpendicular component of the electron velocity with respect to $\vec{B}$ and $v^2 = v_z^2 + v_\perp^2$. One notices that v_z is also the velocity of the electron-guiding center. The power spectra for the HCE and for the harmonic radiation below and above the helical Čerenkov threshold are, respectively:

$$P(\omega;0) = \frac{e^2\omega v(0)_z}{c^2}\left\{\left[(\sin\theta_0)J_0(\xi_0)\right]^2 + \left[\left(v_\perp(0)/v_z(0)\right)J_1(\xi_0)\right]^2\right\}, \tag{2a}$$

$$\cos\theta_0 = \frac{1}{n(\omega)\beta_z(0)}; \tag{2b}$$

$$P(\omega;a) = \frac{e^2 v_z(a)\omega}{c^2}\Big\{\sin^2\theta_a\, J_a{}^2(\xi_a)$$
$$+ \left(v_\perp(a)/2v_z(a)\right)^2\left[\cos^2\theta_a\left(J_{a+1}(\xi_a) + J_{a-1}(\xi_a)\right)^2 + \left(J_{a+1}(\xi_a) - J_{a-1}(\xi_a)\right)^2\right]$$
$$- \left(v_\perp(a)/v_z(a)\right)\sin\theta_a\cos\theta_a J_a(\xi_a)\left[J_{a+1}(\xi_a) + J_{a-1}(\xi_a)\right]\Big\}, \tag{3a}$$

$$\cos\theta_a = \frac{1}{n(\omega)\beta_z(a)} - \frac{a\omega_c}{n(\omega)\omega\beta_z(a)},\quad a = 1,2,3,\ldots; \tag{3b}$$

$$P(\omega;-b) = \frac{e^2 v_z(-b)\omega}{c^2} \Big\{ \sin^2\theta_{-b}\, J_b^2\,(\xi_{-b})$$

$$+ \big(v_\perp(-b)/2v_z(-b)\big)^2 \Big[\cos^2\theta_{-b}\, \big(J_{b+1}(\xi_{-b}) + J_{b-1}(\xi_{-b})\big)^2 + \big(J_{b+1}(\xi_{-b}) - J_{b-1}(\xi_{-b})\big)^2\Big]$$

$$+ \big(v_\perp(-b)/v_z(-b)\big) \sin\theta_{-b} \cos\theta_{-b}\, J_b(\xi_{-b}) \big[J_{b+1}(\xi_{-b}) + J_{b-1}(\xi_{-b})\big]\Big\}, \tag{4a}$$

$$\cos\theta_{-b} = \frac{1}{n(\omega)\beta_z(-b)} + \frac{b\omega_c}{n(\omega)\omega\beta_z(-b)}\,,\ b = 1,2,3,.... \tag{4b}$$

The notation is such that

$$\xi_l = \frac{n(\omega)\omega R_l \sin\theta_l}{c},\quad R_l = \frac{v_\perp(l)}{\omega_c},\quad \omega_c = \frac{eB}{M\gamma(l)c},\quad l = 0,a,-b\,, \tag{5}$$

where, in general, R denotes the electron gyro-radius, M the mass of the electron, and $\gamma(l)$ is the electron relativistic factor. It is relations (2b), (3b), and (4b), of course, that kinematically define the HCE, harmonic radiation below, and above the helical Čerenkov threshold, respectively. For the sake of comparison, we also list the power spectrum of the ordinary Čerenkov effect (no magnetic field present; see, for example Šoln [1992]):

$$P(\omega;C) = \frac{e^2\omega v_c}{c^2}\sin^2\theta_c;\quad \cos\theta_c = \frac{1}{n(\omega)\beta_c}, \tag{6}$$

where v_c is the electron velocity and θ_c is the radiation angle.

2. NUMBER OF PHOTONS PER UNIT PATH LENGTH IN THE VISIBLE SPECTRUM

From now on, we shall assume that index of refraction n varies very slowly in the visible wavelength interval of interest; that is, for all practical purposes, n is independent of ω.

We start with the expression for the number spectrum per unit path length

$$\frac{d^2N_T(\omega;l)}{dLd\omega} = \frac{P(\omega;l)}{\hbar\omega v_z(l)} \equiv N(\omega;l), \tag{7}$$

where $l = 0$, a, −b, and, by definition, $l = C$ represents the ordinary Čerenkov effect when v_z is replaced by v_c. Next, the number of photons per unit path length that are emitted into angular frequency interval $d\omega$ and the wavelength interval $d\lambda$ are given, respectively, as

$$\frac{d^2N_T(\omega;l)}{dLd\omega}d\omega = N(\omega;l)d\omega = \tilde{N}(\lambda;l)d\lambda; \tag{8a}$$

$$\tilde{N}(\lambda;l) = \frac{P(\omega(\lambda);l)}{\hbar\lambda v_z(l)}. \tag{8b}$$

Because of $|d\omega/d\lambda| = \omega/\lambda$ (radiation is observed in a vacuum), we also have this very important relation,

$$N(\omega;l)\,\omega = \tilde{N}(\lambda;l)\,\lambda. \tag{9}$$

At this point, we introduce the "natural finite" wavelength and angular frequency intervals:

$$\Delta\lambda = \lambda_2 - \lambda_1 = \lambda_0, \lambda_{1,2} = \frac{\sqrt{5}\mp 1}{2}\lambda_0, \lambda_0 = \frac{\lambda_1 + \lambda_2}{\sqrt{5}}, \tag{10a}$$

$$\Delta\omega = \omega_1 - \omega_2 = \omega_0, \omega_{1,2} = \frac{\sqrt{5}\pm 1}{2}\omega_0, \omega_0 = \frac{\omega_2 + \omega_1}{\sqrt{5}}, \tag{10b}$$

where λ_0 and ω_0 are the center wavelength and center angular frequency, respectively. One can easily see that these definitions are numerically very close to what one uses in experiments (Martin and Shaw

1993). Furthermore, one also has that $\Delta\omega = 2\pi c/\Delta\lambda$. For latter references, we notice that to a good approximation $\sqrt{5} \cong (e+1)/(e-1)$, which will be useful later. However, one can also introduce the "infinitesimal" wavelength and angular frequency intervals:

$$\delta\lambda = \lambda_0, \tag{11a}$$

$$\delta\omega = \omega_0 . \tag{11b}$$

It will be seen that for the ordinary and helical Čerenkov effects the calculated (dN_T/dL)'s for radiation falling within either $\Delta\lambda$ or $\delta\lambda$ are practically the same.

For the ordinary and HCE, one has from relations (8) that the total number of photons per unit path length emitted within wavelength and angular frequency intervals $\Delta\lambda$ or $\Delta\omega$ to be, respectively

$$\frac{dN_T(\lambda_0,\, \Delta\lambda;\; l = 0, C)}{dL} = \int_{\lambda_1}^{\lambda_2} \tilde{N}(\lambda; l = 0, C)\, d\lambda , \tag{12a}$$

$$\frac{dN_T(\omega_0,\, \Delta\omega;\; l = 0, C)}{dL} = \int_{\omega_2}^{\omega_1} N(\omega;\; l = 0, C)\, d\omega . \tag{12b}$$

Of course, (12a) = (12b). Next we estimate the contributions from harmonics to dN_T/dL within $\Delta\omega$ or $\Delta\lambda$ intervals. Since harmonics occur at sharp frequencies (wavelengths), it is sufficient to estimate them for radiation that falls within infinitesimal $\delta\omega$ ($\delta\lambda$). Of course, $\delta\omega$ ($\delta\lambda$) is supposed to be within $\Delta\omega$ ($\Delta\lambda$). Having said that, consistent with relations (11), we have that for any harmonic index l

$$\frac{dN_T(\lambda_0, \delta\lambda; l)}{dL} = \tilde{N}(\lambda_0; l)\lambda_0 = \frac{dN_T(\omega_0, \delta\omega;\, l)}{dL} = N(\omega_0, l)\,\omega_0 . \tag{13a,b}$$

With these preliminaries, we first deal with the ordinary Čerenkov effect. Consistent with relations (6), (8), (10), and (12), we obtain

$$\frac{dN_T(\lambda_0, \Delta\lambda; C)}{dL} = 2\pi\alpha\sin^2\theta_c\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) = \tilde{N}(\lambda_0, C)\lambda_0 = \frac{dN_T(\lambda_0, \delta\lambda; C)}{dL}, \tag{14a}$$

$$\frac{dN_T(\omega_0, \Delta\omega; C)}{dL} = \frac{\alpha}{c}\sin^2\theta_c(\omega_1 - \omega_2) = N(\omega_0, C)\omega_0 = \frac{dN_T(\omega_0, \delta\omega; C)}{dL}. \tag{14b}$$

As we see, expressions (14a) and (14b) are exactly in the forms of relations (13a) and (13b), respectively.

To address the HCE and harmonic radiation, we first rewrite the argument of the Bessel Functions from (5) as

$$\xi_l = \left(n\gamma(l)\beta_\perp(l)\sin\theta_l\right)\frac{\omega(Mc/e)}{\mathrm{B}}. \tag{15}$$

In the visible spectrum, we have that typically $\omega \cong 4 \times 10^{15}\mathrm{s}^{-1}$. With $(Mc/e) \cong 5.56 \times 10^{-12}\mathrm{sT}$, we have that $\xi_l \cong (n\gamma(l)\beta_\perp(l)\sin\theta_l)\, 2 \times 10^4\mathrm{T/B}$ is going to be very large for "moderate" magnetic fields, $\mathrm{B} \leq 100$ T. Hence, we can utilize the asymptotic expressions for Bessel functions (Arfken 1985):

$$8x >> 4l^2 - 1:\; J_l^2(x) \cong \frac{1}{\pi x}\left[1 + (-1)^l \sin 2x\right]. \tag{16}$$

Since in the HCE only $l = 0,1$ come, we are allowed to use the asymptotic expressions for Bessel functions in form (16). With relations (2a), (7), (8), and (9), we obtain

$$N(\omega; l=0) = N_{eff}(\omega; l=0) + N_{osc}(\omega; l=0), \tag{17a}$$

$$\tilde{N}(\lambda; l=0) = \tilde{N}_{eff}(\lambda; l=0) + \tilde{N}_{osc}(\lambda; l=0); \tag{17b}$$

$$N_{eff}(\omega;l=0) = \frac{\alpha\left[(n\beta(0))^2 - 1\right]}{c\pi\xi_0\left(n\beta_z(0)\right)^2}, \tag{18a}$$

$$N_{osc}(\omega;l=0) = \frac{\alpha\sin 2\xi_0\left[\left(n\beta_z(0)\right)^2 - \left(n\beta_z(0)\right)^2 - 1\right]}{c\pi\xi_0\left(n\beta_z(0)\right)^2}, \tag{18b}$$

$$\tilde{N}_{eff,osc}(\lambda;l=0) = \frac{2\pi c}{\lambda^2} N_{eff,osc}\left(\omega(\lambda);l=0\right). \tag{18c}$$

It is evident that generally $|N_{osc}| < |N_{eff}|$. Furthermore, as λ varies from λ_1 through λ_0 to λ_2, N_{osc} experiences rapid oscillations in the variable ξ_0; as such, its contribution in the integral (12b) is negligible. Therefore, we obtain

$$\frac{dN_T(\lambda_0,\Delta\lambda;l=0)}{dL} = \tilde{N}_{eff}(\lambda_0;l=0)\lambda_0\ln(\lambda_2/\lambda_1)$$

$$\cong \tilde{N}_{eff}(\lambda_0;l=0)\lambda_0 = \frac{dN_T^{eff}(\lambda_0,\delta\lambda;l=0)}{dL}, \tag{19a}$$

$$\frac{dN_T(\omega_0,\Delta\omega;l=0)}{dL} = N_{eff}(\omega_0;l=0)\omega_0\ln(\omega_1/\omega_2)$$

$$\cong N_{eff}(\omega_0;l=0)\omega_0 = \frac{dN_T^{eff}(\omega_0,\delta\omega;l=0)}{dL}, \tag{19b}$$

where, of course, (19a) = (19b) term by term. Next, in relations (19), because of $|N_{osc}| < |N_{eff}|$, one may write N_{eff} $(l = 0)$ + N_{osc} $(l = 0)$ instead of just N_{eff} $(l = 0)$ and still obtain a good estimate for dN_T $(l = 0)/dL$; this we then denote as $dN_T^{est}(l = 0)/dL$.

Examples (19) suggest, then, that for harmonic radiation above and below the HCE threshold, rather than going through tedious calculations, one may simply estimate the number of photons per unit length emitted within $\Delta\omega$ or $\Delta\lambda$, respectively, as

$$\frac{dN_T^{est}(\omega_0,\Delta\omega;l=a_0,-b_0)}{dL} \cong \frac{dN_T(\omega_0,\delta\omega;l=a_0,-b_0)}{dL} = N(\omega_0;l=a_0,-b_0)\omega_0, \qquad (20a)$$

$$\frac{dN_T^{est}(\lambda_0,\Delta\lambda;l=a_0,-b_0)}{dL} \cong \frac{dN_T(\lambda_0,\delta\lambda;l=a_0,-b_0)}{dL} = \tilde{N}(\lambda_0;l=a_0,-b_0)\lambda_0, \qquad (20b)$$

where again (20a) = (20b) term by term and a_0 and b_0 are harmonic indices associated with the central angular radiation frequency ω_0 according to relations (3) and (4), respectively.

3. APPLICATIONS

On general grounds, it follows from relations (2) to (5) that as B becomes larger and/or $\beta_\perp(l)$ becomes smaller, the HCE will dominate over the harmonic radiation. In fact, for $\beta_\perp \neq 0$, and $B \to 0$, the HCE will gradually disappear, while the radiation into harmonics will become more dominant. At B = 0, all the harmonic radiation will sum up into the ordinary Čerenkov radiation, which, however, can also be calculated directly (Šoln 1992).

Let us go back to the nonmonoenergetic beam. Here, by definition, the estimated overall number of photons per unit path length is the superposition of the emitted total number of HCE photons per unit path length and the estimated total number of photons per unit path length into the harmonics above and below the HCE threshold. We shall assume that as one goes from one electron to another in the beam that $\beta_\perp(a) = \beta_\perp(-b) = \beta_\perp(0) = 0.3$, where l = 0,a,–b are indices associated with the HCE and harmonic radiation below and above the HCE threshold, respectively. Their constancy is, of course, an average value for $\beta_\perp$ across the beam; it is justified by the fact that $\beta_\perp$ does not enter into the definition of radiation frequency. Hence, the nonmonoenergetic beam quality will be specified by $\beta_z(l)$ which approximately varies between 0.92 and 0.94 with $\beta_z(0) = 0.934$ corresponding to the HCE (the energies of individual electrons are in the 2–3-MeV range). The helical motion of electrons is maintained through silica aerogel as a medium (the index of refraction in the visible spectrum is $n = 1.075$) by the magnetic field of B = 10 T. The radiation angular frequency in all three cases is simply the central angular radiation frequency in the visible portion of the spectrum, $\omega_0 = 3.77 \times 10^{15} s^{-1}$. Specifically, using relations (19), (20), (7), and (2) to (5), we have the following expressions for the number of photons per unit path length for each case:

$$l = 0, \beta_z(0) = 0.9340, \cos\theta_0 = 1/(n\,\beta_z(0)) = 0.9960, \gamma(0) = 5.1541:$$

$$\frac{dN_T(\omega_0,\Delta\omega;l=0)}{dL} \cong 0.104 \text{ cm}^{-1}; \qquad (21a)$$

$$l = a_0 \cong 120, \beta_z(a_0) = 0.9206, \cos\theta_{a_0} = \cos\theta_0, \gamma(a_0) = 4:$$

$$\frac{dN_T^{est}(\omega_0,\Delta\omega;l=a_0)}{dL} \cong 0.205 \text{ cm}^{-1}; \qquad (21b)$$

$$l = -b_0 \cong -71, \beta_z(-b_0) = 0.9393, \cos\theta_{-b_0} = \cos\theta_0, \gamma(-b_0) = 6:$$

$$\frac{dN_T^{est}(\omega_0,\Delta\omega;l=-b_0)}{dL} \cong 0.120 \text{ cm}^{-1}. \qquad (21c)$$

At the end of the L = 10-cm path length in the silica aerogel, the number of photons generated by an electron in the radiation angular frequency interval $\Delta\omega$ with the central radiation angular frequency $\omega_0 = 3.77 \times 10^{15} s^{-1}$ and at the central angle θ_0 are, respectively

$$N_T(\omega_0,\Delta\omega;l=0) = 1.04, \qquad (22a)$$

$$N_T^{est}(\omega_0,\Delta\omega;l=a_0) = 2.05, \qquad (22b)$$

$$N_T^{est}(\omega_0,\Delta\omega;l=-b_0) = 1.2, \qquad (22c)$$

where the parameters correspond to relations (21a,b,c).

We can take a simple average over $l = 0$, a_0,$-b_0$ of relations (21a,b,c) yielding

$$\frac{dN_T^{est}(\omega_0,\Delta\omega;average)}{dL} \cong 0.143\ \text{cm}^{-1}. \tag{23}$$

Comparing this expression with (21a), we see that the harmonic emission actually enhanced the helical Čerenkov radiation. Finally, from relation (23), we have

$$L = 10\ \text{cm},\ \text{B} = 10\ \text{T}:\ N_T^{est}(\omega_0,\Delta\omega;average) = 1.43, \tag{24}$$

so that an electron beam with, say, 10^8 electrons in cm^3 will generate about 1.4×10^8 photons in cm^3 at the end of a 10-cm path length in the silica aerogel. This can be observed experimentally.

Recently, a great deal of progress has been made in achieving magnets whose fields would reach 100 T (Boebinger, Passner, and Bevk 1995). With B = 100 T in relations (21a,b,c), the harmonic numbers and the number of photons per unit path length become, respectively: 0, 1.039 cm^{-1}; 12, 2.166 cm^{-1}; and -7, 0.408 cm^{-1}. One notices that only for the HCE, $l = 0$, the number of photons per unit path length scales linearly with B.

These examples show explicitly that the HCE with a nonmonoenergetic electron beam could be a vehicle for detecting a magnetic field in the hostile electromagnetic medium.

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