Response to "Comment on 'Nonlinear Compton scattering and electron acceleration in interfering laser beams'"

I. V. Pogorelsky
Brookhaven National Laboratory, 725C, Upton, New York 11973
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Response is made to Y. I. Salamin's preceding Comment [Phys. Rev. ST Accel. Beams **3**, 059001 (2000)]. We confirm the areas of applicability of the original and Salamin's general solutions and discuss new applications of the developed formalism.

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In his Comment, Salamin [1] proposes a generalized format for the exact solution of the equations of motion of relativistic electrons in the field of two plane electromagnetic waves attained by Amatuni and Pogorelsky [2]. The revised form of the solution, otherwise equivalent to one derived in [2], facilitates an explicit treatment of the problem of two copropagating electromagnetic waves that are different in frequency. As soon as the equivalency of the revised solution [given by Eqs. (4), (14)–(16) in [1]] to the original solution [expressed by Eqs. (5), (10)–(12) in [2]] is established [by Eq. (27) in [1]], there is no room for controversy and the apparent argument merely converges to coherency. The goal of the remaining part of this response is to outline areas of applicability of the obtained general solutions and to draw paths for an extended application of the developed formalism to the phenomena within and beyond the scope discussed in Refs. [1] and [2].

Further, responding to Salamin [1], we admit that the original expressions Eqs. (10) and (11) in [2] do become uncertain for copropagating waves. This necessitates using asymptotic rules to handle this case. The same is actually stated at the end of Sec. II of Ref. [2]. The authors of Ref. [2] did not elaborate on the case discussed in Ref. [1] since the initial purpose of their study was to uncover the phase sensitive effects (x-ray radiation and the electron energy modulation) occurring when the relativistic electron passes a standing electromagnetic wave.

A practical motivation for the Amatuni and Pogorelsky study [2] was to develop a novel tool to diagnose electron microbunches grouped to laser wavelength. Such microbunching is essential for attaining a monoenergetic regime of direct electron acceleration in laser field. Microbunches grouped to the 10 μm period have been produced via an inverse free-electron laser process and demonstrated by the coherent transition radiation method at the BNL accelerator test facility (ATF) [3]. The first attempt to phase such "dotted" electron beams into the inverse Cherenkov laser accelerator module is under way at the ATF [4,5].

As stated in the preceding paragraph, the goal of developing a novel method of microbunch diagnostics was accomplished by deriving phase sensitive expressions for intensity of the nonlinear component of electron Thomson scattering and for electron energy modulation [2].

Needless to say, the solution of the general equations of the electron motion in interfering waves, in addition to the standing wave case, allows excursions to other two-wave combinations. Among them is the problem considered in [1] of a relativistic electron exposed to copropagating waves of different frequency that is applicable to the so-called vacuum beat wave accelerator (VBWA) [6].

Not undermining the validity of the solutions attained in [1] and [2], the author wishes to use this occasion to comment on the applicability of the developed formalism to real world situations.

Both of the referenced papers address the solution of the electron motion in interfering plane waves. Furthermore, in order to obtain the net acceleration effect in copropagating waves or phasing effects in counter-propagating waves (standing wave) the electron-laser interaction length shall be terminated by some sort of screen or cavity mirror. Both assumptions (plane waves and cavities) look impractical when the laser field is appreciably strong to induce relativistic quiver electron motion. Indeed, ultrahigh electromagnetic field, attractive for novel methods of electron acceleration, implies focusing of the laser beam. The effect of the focused Gaussian beam on the relativistic electron is different from plane waves due to development of first order accelerating electrical field components along the axis and because of the possibility of electron transverse escape from the laser focus via a violent quiver motion. A limited Rayleigh length in focused laser beams is an important factor in explaining the existence of the residual net acceleration in the VBWA scheme [6]. There are also at least two problems with limiting screens or mirrors. Technically, they are subject to damage by focused laser beams. Evanescent transient fields developed at the material's surface upon electron beam transition and laser reflection complicate the physical picture and can obscure fine effects predicted by the abstract model which does not take into account material boundaries. Thus, further analytical efforts are required to converge from plane wave solutions of [1] and [2] to solutions for more realistic Gaussian beams.

This was the authors' intention mentioned [2] to explore analytically and computationally the standing wave produced within the waist of counterpropagating focused laser beams.

These and other related plans are now derailed by the untimely passing of my co-author Andrei Amatuni. He was the driving force behind the theoretical exertion presented in [2]. As a tribute to Amatuni, and to further enhance the present discussion, the utility of the derived general solutions are illustrated by a couple of excursions done by Amatuni after publishing the reviewed work [2].

The first example concludes a study of phase dependent parameters in Thomson scattering when the relativistic electron crosses a cavity filled with a standing electromagnetic wave. Based on the exact solutions [2], Amatuni derived the spectral and angular distributions of radiation during electron flight across the cavity of length L given by

$$\frac{dE}{d\theta d\omega'} = \frac{e^2L^2\eta^4}{32\pi}\cos^2\theta_y \sin^2\theta\left(1 - \frac{1}{2}\sin 4\zeta_{1i}\right) \times \left(\frac{\omega'^2}{\omega}\right)\omega'^2, \tag{1}$$

where the dimensionless amplitude of a single wave is $\eta = eE_0/2\omega \ll 1$ and θ_y is the angle between the direction of emitted radiation and the wave polarization vector. The initial phase, ζ_{1i}, defined at the moment and point of the electron penetration into the cavity is present in Eq. (1). It is now possible to use the derived intensity distribution to diagnose electron microbunches.

The second excursion from the exact solution [2] results in the novel idea of vacuum laser acceleration. In this case Amatuni elaborated on the concept of electron quiver expulsion from the laser focus, demonstrated in experiment [7]. It has been shown that when laser power is above the threshold value [8], quiver amplitude of the electron exceeds the radius of the focal spot of a Gaussian laser beam and the electron is scattered away from the focus.

Amatuni considered the case when the laser power is less than the threshold value and electron ejection from the laser focus is due to the second electromagnetic wave. He considered the second wave having the same linear polarization as that of the laser beam and propagating normally to the direction of the laser and electron beams. The potentials and the dimensionless amplitudes of the two waves are, correspondingly, $\alpha_y^{(1,2)} = (E_0^{(1,2)}/\omega_{1,2})\sin\zeta_{1,2}$, $\zeta_1 = \omega_1(t - x)$, $\zeta_2 = \omega_2(t - z)$, and $\eta_{1,2} \equiv eE_0^{(1,2)}/\omega_{1,2}$, $\eta_1^2 \gg 1$, $\eta_2^2 \ll 1$. Using results of the work [2], Amatuni found an expression for the electron trajectory $x_\mu(\tau)$ in the field of the two waves. The proper time of flight interval τ_0 corresponds to the condition $x(\tau_0) = Z_R$, where Z_R is the Rayleigh length of the laser beam. The electron will be ejected from the laser focus if $y_{max}(\tau_0) \geq w_0$, where w_0 is the radius of the laser focus spot. In the case when $\tau_0 > 2\pi e/\omega_1 m$, the following electron ejection condition is obtained:

$$\frac{\eta_1}{\eta_1^*} + \frac{\eta_2}{\eta_2^*} \geq 1, \qquad \eta_1^* = \frac{w_0}{4\tau_c} = \frac{\pi}{2\gamma}\left(\frac{w_0}{\lambda_1}\right), \qquad \eta_2^* = \pi\gamma\left(\frac{w_0}{\lambda_2}\right)\left(1 + \frac{1}{2}\eta_1^2\right), \tag{2}$$

where $\eta_{1,2}^*$ are the threshold values of the dimensionless amplitudes. It follows that if $\eta_1 < \eta_1^*$, the electron is ejected from the focus by a second weak electromagnetic wave with the wavelength $\lambda_2 \leq 2Z_R$, that can be in the microwave or even rf range. The requirement on the initial electron energy is

$$1 < \gamma < \min\left\{\frac{\eta_2}{\pi(\frac{w_0}{\lambda_2})(1 + \frac{1}{2}\eta_1^2)}, \frac{2^{1/2}\pi(\frac{w_0}{\lambda_1})}{(1 + \frac{1}{2}\eta_1^2)}\right\}. \tag{3}$$

A contribution of Salamin [1] provides hope that other researchers will continue Amatuni's work.

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