# Electron acceleration in stimulated Compton scattering

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A method for laser acceleration of electrons is proposed. Two intense electromagnetic waves of approximately equal frequencies are propagating in directions which are close to each other and also close to the direction in which the electrons are moving. The relationship among the frequencies and the geometry, the average energy acquired by the electrons, the distance over which there is a significant acceleration, and the distance over which saturation occurs are all determined. Ways to optimize the method are discussed. Estimates indicate that this method holds promise for accelerating electrons.

The problem of laser acceleration of electrons has recently attracted a great deal of interest.[1–3] Several specific schemes have been proposed, including an inverted free-electron laser with a wiggler.[3]

In the present letter we wish to analyze the acceleration of electrons in an inverse Compton laser. The general case of a Compton laser, of arbitrary geometry, was studied in Ref. 4. The most interesting configuration from the standpoint of electron acceleration is that in which both of the electromagnetic waves and the electron beam are moving in approximately the same direction. In this case the frequencies of the two waves must be nearly equal (more on this below), so that we can expect high intensities for both waves in the IR and optical ranges.

We assume that one of the two electromagnetic waves (with frequency $\omega_1$) is propagating in the same direction as the electron beam, while the second wave (with frequency $\omega_2$) is propagating at some small angle from that direction. The frequencies $\omega_1$ and $\omega_2$ are related to each other by the customary relation between the frequencies of the absorbed and emitted photons in a Compton scattering.[5] In our configuration, with $\epsilon = \gamma mc^2 \gg mc^2 \gg \hbar\omega_{1,2}$, $\gamma\theta \ll 1$, this relation is

$$\frac{\Delta\omega}{\omega} = \frac{\omega_1 - \omega_2}{\omega_1} = \gamma_{\text{res}}^2 \theta^2 , \tag{1}$$

where $\gamma_{\text{res}}$ is the resonant value of the relativistic factor $\gamma$, given by

$$\gamma_{\text{res}} = \epsilon_{\text{res}} / mc^2 .$$

Applying the results of Ref. 4 to the configuration under consideration here, we find the average change in the energy of an electron after it has traversed an interaction region of length $L$

$$\frac{\Delta\epsilon}{\epsilon} = \frac{\gamma^2}{16\pi} \frac{\lambda}{L} \mu^4 \frac{d}{du}\left(\frac{\sin^2 u}{u^2}\right), \tag{2}$$

  

where $\lambda = 2\pi c/\sqrt{\omega_1\omega_2}$, and

$$u = -\frac{L\pi}{\lambda}\frac{\theta^2}{2}\left(1 - \frac{\gamma_{res}^2}{\gamma^2}\right) \quad (3)$$

is a measure of the deviation from the resonant frequency. We have $\Delta\epsilon > 0$ if $u < 0$ or $\gamma > \gamma_{res}$, $[(d/du)(\sin^2 u/u^2)]_{max} \approx 0.5$. This value is reached at $u \approx -\pi/2$ or $\theta^2 = (\Delta\omega/\omega\gamma^2) + (\lambda/L)$. Here

$$\mu = \frac{eLE}{\epsilon}\sqrt{\frac{\Delta\omega}{2\omega}} \quad (4)$$

is the saturation parameter, and we have $E = \sqrt{E_1E_2}$, where $E_{1,2}$ are the electric field amplitudes of the two waves.

Expression (2) holds if $L \lesssim L_{sat}$, where $L_{sat}$ is the saturation distance, at which we have $\mu(L_{sat}) \approx 2$.

The increase in the energy of the electron is maximized at $L \approx L_{sat}$; this maximum increase is given by

$$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{max} = \frac{\Delta\epsilon(L_{sat})}{\epsilon} \simeq \frac{\lambda}{L_{sat}}\frac{\gamma^2}{2\pi} = \sqrt{\frac{\Delta\omega}{2\omega}}\frac{eE\lambda}{4\pi mc^2}. \quad (5)$$

The outlook for the use of this scheme at the present level of its theoretical description should be evaluated on the basis of the values of the parameters $L_{sat}$ and $(\Delta\epsilon/\epsilon)_{max}$: If $L_{sat}$ is not too large, and if $(\Delta\epsilon/\epsilon)_{max}$ is not too small, for a reasonable value of the field $E$, this fact could be taken as an indication that it would be possible to make use of stimulated Compton scattering in the configuration considered here for an effective acceleration of electrons. For an estimate we assume $\lambda = 10^{-3}$ cm, $\Delta\omega/\omega = 0.1(\lambda_1 = 9.6\ \mu m,\ \lambda_2 = 10.6\ \mu m)$, $E = 3\times 10^9$ V/cm ($I = 10^{16}$ W/cm$^2$), $\lambda = 5$, and $\theta = 0.15$. In this case we find $L_{sat} \approx 0.5$ mm and $(\Delta\epsilon/\epsilon)_{max} \approx 10\%$.

To combat the saturation, we might, as in the case of a free-electron laser,[6] switch to a system with varying parameters. For example, if the angle $\theta$ decreases $\propto 1/\gamma$ as an electron penetrates into the interaction region (along the $X$ axis), resonant condition (1) remains in force despite the increase in the electron energy $\epsilon$. Another possibility of the same type would involve an increase in the field $E$ along the $X$ axis, which would increase the effective mass of the electron and lead to a replacement of $\gamma_{res}^2$ in Eq. (1) by

$$\gamma_{res}^2 \Big/ \left(1 + \frac{e^2E^2\lambda^2}{4\pi^2 m^2 c^4}\right). \quad (6)$$

with $I = 10^{16}$ W/cm$^2$, the second term in the denominator in (6) is $\approx 2/3$, i.e., completely feasible. It appears that either of these possibilities could be realized through a suitable choice of focusing conditions for the radiation.

We believe that these estimates are encouraging; we would especially like to call attention to the comparatively small value of $L_{sat}$.

The efficiency of this method might be at least comparable to the efficiencies of other laser acceleration methods. Let us compare this new method with, for example, the method of acceleration by means of a longitudinal plasma beat wave, which arises when two collinear waves with approximately equal frequencies $\omega_1$ and $\omega_2$ propagate through a plasma.[3]

We know that the maximum increase in the energy of an electron in this scheme, $2\gamma^2 mc^2$, is reached over a distance $\sim\gamma^3\lambda$. This estimate corresponds to the ideal situation in which the electron oscillation velocity in the field of the plasma wave is close to the velocity of light. It follows from the experiment of Ref. 8, however, that the fields which are attainable in practice are roughly two orders of magnitude weaker, corresponding to an energy increase $\sim 10^{-2}\cdot 2\gamma^2 mc^2$. With $\gamma = 5$, this change in energy agrees with the estimate from (5). An acceleration to high energies by the method of the plasma beat wave would require maintaining the synchronization over a large distance, but this requirement might pose some serious difficulties: It would be necessary to prepare a large number of plasmas with different densities, and in different regions it would be necessary to have pairs of waves with different relations between the frequencies $\omega_1$ and $\omega_2$. With increasing energy, there would be a sharp increase in the acceleration length, which would unavoidably result in a decrease in the energy increment over a practical distance. (There are other difficulties.) In the acceleration method proposed here, which makes use of a stimulated Compton scattering, the synchronization can apparently be maintained by means of a varying geometry. This measure would of course require further research, but in principle it would be quite simple to implement. Furthermore, at high field intensities ($I \approx 10^{16}$ W/cm$^2$), the expansion of the plasma out of the focal region under the influence of ponderomotive forces could be substantial, resulting in a decrease in the plasma density, a disruption of the synchronization, and a termination of the acceleration. The stimulated-Compton approach is also free of that shortcoming.

In summary, an experimental study of this new acceleration method appears possible and worthwhile. There is also a need for a further theoretical study of the problem in order to obtain a description of the conditions for acceleration to high energies in a system with varying parameters.


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