Comment on "Cascade Focusing in the Beat-Wave Accelerator"

Gibbon and Bell[1] have reported on the results of a numerical analysis describing the conditions under which the laser beams in the plasma beat-wave accelerator (PBWA) will experience enhanced focusing. They found that the diffractive properties of the radiation-beam envelopes (of frequencies ω_1,ω_2) depend strongly on the initial frequency mismatch $\Delta\omega_0$ between the radiation beat frequency $\Delta\omega\equiv\omega_1-\omega_2$ and the ambient plasma frequency ω_{p0}, i.e., $\Delta\omega=\Delta\omega_0+\omega_{p0}$. When $\Delta\omega_0=0$, they observe the radiation-beam envelope to diffract more rapidly than it would in vacuum. For small negative values of $\Delta\omega_0$, they observe enhanced focusing of the radiation-beam envelope. Gibbon and Bell offered energy cascading as the explanation for their results; however, the underlying physical mechanism may be more clearly understood by considering the optical-guiding properties that the resonantly generated plasma wave has on the radiation beams in the PBWA.

The physical mechanism for producing optical guiding using a plasma wave (with phase velocity $\simeq c$) is similar to the mechanism for producing optical guiding using a density channel. This may be understood by considering the index of refraction η of a radiation beam (of frequency ω) in a plasma with a density profile $\rho(r)$, i.e., $\eta\simeq 1-\omega_{p0}^2\rho(r)/2\omega^2\rho_0$, where ρ_0 is the ambient density. A density channel will have $\partial\rho/\partial r>0$ and, hence, $\partial\eta/\partial r<0$, which is necessary for the radiation to be refractively guided. Similar guiding results from a plasma wave of the form $\delta\rho=\delta\rho_0(r)\sin(k_p\zeta)$, where $\zeta=z-ct$, $k_p=\omega_{p0}/c$, $\delta\rho_0>0$, and $\partial\delta\rho_0/\partial r<0$. Provided $\delta\rho_0$ is sufficiently large,[2] the radiation beam will be focused over regions where $\sin(k_p\zeta)<0$ (which correspond to decreases in the electron density). Conversely, in regions where $\sin(k_p\zeta)>0$ the radiation experiences enhanced diffraction. Thus, a plasma wave of sufficiently large amplitude breaks up an initially uniform radiation beam into "beamlets" (of length $\lesssim\pi/k_p$) centered about $k_p\zeta=-\pi/2\pm 2j\pi$ (j=integer) which remain optically guided as they propagate.

In the PBWA, optical guiding is more complicated since the plasma wave is resonantly generated[3] by the radiation beams, $\delta\rho\simeq\delta\rho_0(r)\sin(\Delta\omega\zeta/c+\theta)$, where $\theta(\zeta)$ is the nonlinear phase shift of the plasma wave. Assuming the envelopes of the radiation beams ω_1,ω_2 are identical and by averaging over a period of the beat wave $\Delta\omega$, the real part of the index of refraction is[2] $\eta\simeq 1-\omega_{p0}^2/2\omega^2-(\omega_{p0}^2\delta\rho_0/4\omega^2\rho_0)\sin\theta$, in the regime where relativistic effects[4] are negligible. Thus, refractive guiding is a strong function of $\theta(\zeta)$. For no frequency mismatch, $\Delta\omega_0=0$, initially (at the head of the radiation beams) $\delta\rho_0=0$ and $\theta=0$. As the plasma-wave amplitude grows, nonlinear effects cause θ to monotonically increase up to the point of saturation, $\theta=\pi/2$. When $\theta=\pi/2$, $\partial\eta/\partial r>0$ and the radiation beams experience enhanced diffraction. A small initial frequency mismatch[3] $\Delta\omega_0<0$ allows the saturation point to be prolonged and a larger amplitude of the saturated plasma wave may be achieved. The maximum amplitude at saturation, $\delta\rho_{\text{sat}}^{\max}$, is obtained for an optimal mismatch[3] $\Delta\omega_0^{\text{opt}}$. When $\Delta\omega_0=\Delta\omega_0^{\text{opt}}$, θ (initially, $\theta=0$) progressively decreases to the point where $\theta=-\pi/2$ ($\delta\rho_0=\delta\rho_{\text{sat}}^{\max}/2$) for which $\partial\eta/\partial r<0$ and, thus, enhanced guiding of the radiation beams is achieved.[2] This is in agreement with the numerical results of Gibbon and Bell. Physically, this may be understood by considering the small-scale structure of the radiation-beam envelope. At saturation, $\theta=\pi/2$, the plasma wave is phased such that the peaks of increased density in the plasma wave ($\Delta\omega\zeta/c+\theta=\pi/2\pm 2j\pi$) coincide with the intensity peaks of the combined radiation envelope,

$$|E_1+E_2|^2\simeq|E_1|^2+|E_2|^2+2|E_1||E_2|\cos(\Delta\omega\zeta/c)\,,$$

thus leading to enhanced diffraction of the radiation beat wave. For the case $\Delta\omega_0=\Delta\omega_0^{\text{opt}}$, the point at which $\theta=-\pi/2$ corresponds to the plasma wave phased such that the troughs (minima) of plasma density ($\Delta\omega\zeta/c+\theta=-\pi/2\pm 2j\pi$) coincide with the intensity peaks of the combined radiation envelope, thus indicating that the intensity peaks may propagate as optically guided beamlets.

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