Recent Results on the Beat Wave Acceleration of Externally Injected Electrons in a Plasma

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In the Plasma Beat Wave Accelerator (PBWA), two laser beams of slightly different frequencies resonantly beat in a plasma in such a way that their frequency and wavenumber differences correspond to the plasma wave frequency and wavenumber. The amplitude modulated electromagnetic wave envelope of the laser pulse exerts a periodic nonlinear force, the ponderomotive force, on the plasma electrons, causing them to bunch. The resulting space-charge wave has a phase velocity that is nearly equal to the speed of light if the laser frequencies are much greater than the plasma frequency. If an electron bunch is now injected with a velocity close to this, it can be trapped and accelerated much in the same way as a surfer riding an ocean wave.

The UCLA program on the PBWA seeks to demonstrate extremely high-gradient acceleration of externally injected test particles by a relativistic plasma wave excited using the beat wave technique. The longitudinal electric field associated with such a wave is given by $\varepsilon\sqrt{n_0}$ V/cm where ε is the density modulation (n_1/n_0) and n_0 is the plasma electron density in cm^{-3}. Thus, for $\varepsilon = 0.1$ and $10^{15} < n_0\ (\mathrm{cm}^{-3}) < 10^{17}$, accelerating fields of $\simeq 0.3 \leq$ E (GeV/m) ≤ 3 are possible. It is the purpose of our current experimental program to demonstrate such ultra-high gradient acceleration over a reasonable distance.

Our experiment comprises of four major parts: the CO_2 laser driver to act as the electromagnetic energy source; the plasma to convert the transverse oscillating field of the laser into the longitudinal oscillating field of a plasma wave to accelerate particles; a preaccelerated bunch of electrons for injection into the plasma wave; and diagnostics to detect the accelerated electrons, plasma wave and plasma conditions. In Table I we give experimental parameters for the laser, the electron beam, the plasma and the plasma wave that is driven by the laser beams. These parameters will be used throughout the rest of the paper unless otherwise noted.

Plasma density n_o	8.6×10^{15} cm^{-3}
Plasma wave wavelength λ_p	360μm
Lorentz Factor γ_{ph}	33
Plasma frequency ω_p s^{-1}	5.2×10^{12}
Dephasing Length	$\approx$ 30 cm
Laser wavelengths	10.591μm, 10.289μm
Typical electron quiver velocities	0.17, 0.07
Risetime of laser pulse (ps)	150 ps
Injection energy of electrons	2.1 MeV
Average current (mA)	15 mA
Electron pulse width (ns)	10 ns

Table I. Experimental Parameters

In the experiments the plasma was produced by tunnel ionization of static-fill of hydrogen gas at various pressures.[1] The plasma wave was indirectly diagnosed by Thomson scattering of a probe laser beam and by monitoring the Raman backscatter spectrum of the incident laser light. The accelerated electrons were momentum selected by a dipole magnet and then entered a cloud chamber. By applying a perpendicular magnetic field to the cloud chamber the accelerated electrons can be energy analyzed.

We found that no electrons were observed when none were injected or when the laser was operated on a single frequency. However, electrons up to the detection limit of 9.1 MeV were observed when 2.1 MeV electrons were injected in a plasma wave excited (over a narrow range of static gas pressures close to the resonance), by a dual frequency laser beam.[2] The accelerated electron signal was found to be correlated with indirect measurements of the amplitude of the plasma wave using Thomson and Raman scattering. The energy gain of the electrons suggests plasma wave amplitudes of at least 8% over a 10 mm interaction length.

Thomson scattering measurements indicate plasma wave amplitudes up to 15-30%, offering the possibility of measuring even greater energy gains in future experiments.

These experiments have shed light on what is important in future experiments. First, that tunnel or multi-photon ionized plasmas are homogeneous enough for coherent, macroscopic acceleration. Second, the laser pulse should be short to reduce the ion effects (typically $\tau < 3\nu_{pi}$) and the modulational instability. Third, the peak laser intensity should be such that $I\lambda^2 \sim 2 \times 10^{16}$ $\mathrm{W/cm^2 \cdot \mu m^2}$ in order to get substantial beat wave amplitudes. These considerations will play an important role in the design of a future 100 MeV/1 GeV plasma beat wave accelerator experiment.[3]

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References

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