ACCELERATION OF INJECTED ELECTRONS IN A LASER BEATWAVE EXPERIMENT*

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Abstract

A 10-ps beam of 12 MeV electrons was loaded in a 1-cm long plasma beat wave accelerator driven by a TW CO_2 laser pulse. CO_2 laser pulses and electron bunches were deterministically synchronized with an uncertainty of 20 ps. At the resonant electron plasma density of ~10^{16} cm^{-3} the electrons have been accelerated to 22 MeV with a gradient of ~1 GeV/m.

INTRODUCTION

Laser-plasma accelerators of particles, which have a potential to become next-generation high-gradient accelerators, rely on laser excitation of large amplitude relativistic plasma waves (RPWs) for acceleration. Two main considerations drive a significant interest to this type of devices: availability of laser power sources producing multi GV/m electric fields and the fact that plasmas can sustain these very strong fields. Since the interaction length of a focused laser beam is limited fundamentally by diffraction, multistage acceleration is required to achieve the kinetic energy of interest for high-energy physics. In this context it is important to inject a well-characterized electron beam into a pre-formed plasma accelerating structure and explore methods for extracting and characterizing a high-quality beam.

Here we report on a high-gradient acceleration of externally injected electrons in a plasma beatwave accelerator (PBWA) driven by a CO_2 laser. RPWs are excited by beating electromagnetic waves where difference between the laser frequencies, $\Delta\omega=\omega_1-\omega_2$, is equal to the plasma frequency, ω_p [1,2]. The energy gain reached 10 MeV for approximately a 1-cm long PBWA. The interaction length and intensity is strongly limited by ionization-induced refraction of the laser beam [3]. Possible ways to overcome this limitation in the PBWA's length are discussed.

EXPERIMENTAL SET-UP

The experiment is being done at the Neptune Laboratory at UCLA. The layout of the PBWA set-up is shown in Fig. 1. A TW CO_2 laser system producing two-wavelength pulses at 10.3 μm and 10.6 μm was used to drive the plasma beatwave. This pair of lines determined value of the resonant electron plasma density of $n_e \approx 9.4 \times 10^{15}$ cm^{-3}. The laser beam was focused by a F/18 lens giving a spot size $w_0 \approx 200$ μm and a Rayleigh range of $2Z_R \approx 26$ mm. A 12 MeV electron beam with parameters listed in Table 1 was focused down to 150 μm

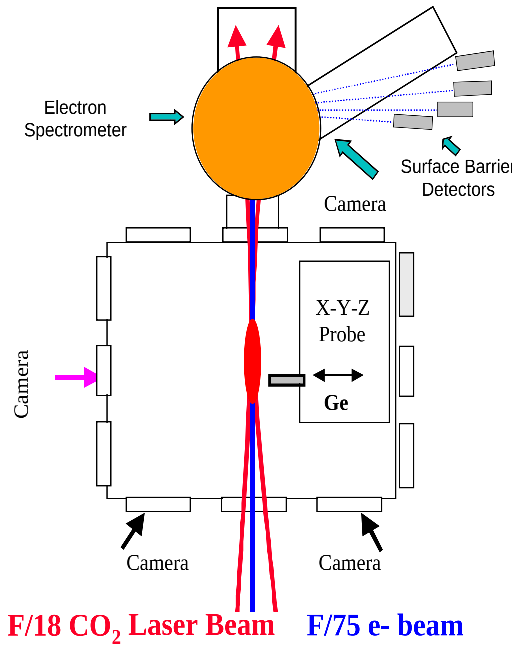

Figure 1: Layout of the PBWA set-up.

(σ_{rms}) and injected into the plasma. The energy spectrum of electron beam was analyzed using a Browne-Buechner spectrometer in combination with a fluorescer screen (for energies E=12-15 MeV) and a set of Si surface barrier detectors (E>15 MeV). With the current set-up 3-5 electrons with maximum energy up to 50 MeV were detectable.

Table 1: Electron Beam Parameters

Bunch Length (FWHM)	10 ps
Emittance	12 mm-mrad
Energy	12 MeV
Charge	100 pC

Synchronization

In order to inject a 10-ps electron bunch at the very maximum of the plasma wave amplitude driven by a 160-ps CO_2 laser pulse, they must be synchronized on a picosecond scale. Synchronization is possible because the same 1 μm pulse is used to produce electrons on a photocathode and to switch a short 10-μm pulse for amplification in a MOPA CO_2 laser system [4]. A two-step technique was used for synchronization: cross-correlation between 10 μm photons and electrons

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measured with an unamplified laser pulse followed by compensation of a constant time delay gained in active medium of the final CO_2 amplifier.

Electron-beam-controlled transmission of 10-μm radiation in Ge [5] was utilized for the cross-correlation measurement. For this purpose the pulse was sent through a 1-mm thick germanium plate at the laser focus and time dependence of the 10-μm transmission was recorded. The latter was realized by a computer controlled optical delay line. A typical result of cross-correlation measurement is presented in Fig. 2. There is a part in the dependence corresponding to a time window when an e-bunch reaches

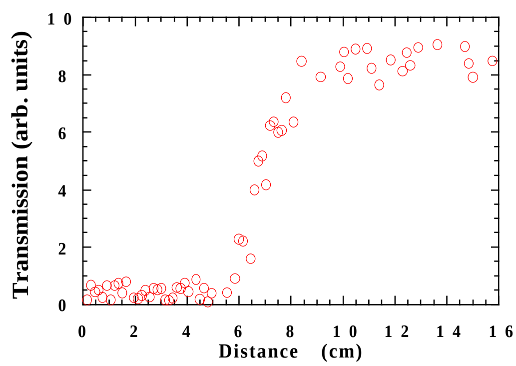

Figure 2: Cross-correlation measurement.

the Ge plate first and 10-μm radiation is fully attenuated. The plasma formation happens on a time scale similar to the duration of the plasma creating electron-bunch. Therefore, accuracy of the cross-correlation measurements is limited by a 10-ps bunch length. A total width of the recorded cross-correlation curve is ~ 270 ps, which agrees very well with a CO_2 laser pulse length measured by a streak camera.

These measurements were done with a 10- μm laser pulse propagating through a 3 X 2.5-m long multiatmosphere CO_2 amplifier with no inversion of population. It is known that the resonant behavior of the refractive index (n) in the vicinity of a homogeneously broadened molecular transition results in an increase of n in the inverted medium. This leads to decrease of the group velocity of the laser pulse with gain in comparison with no-gain conditions. Series of measurements revealed that a 120±20 ps pulse delay was gained in our case [6]. In the experiment we compensated for the delay after the cross-correlation measurement. Thus a total uncertainty of 20 ps is achieved in synchronization of CO_2 laser pulses and electron bunches, which was adequate for a 160-ps laser pulse.

PLASMA BEATWAVE PRODUCTION AND CHARACTERIZATION

A typical 2.5-cm long plasma, generated in a backfill of H_2 at resonant density of ~10^{16} cm^{-3} is shown in Fig. 3.

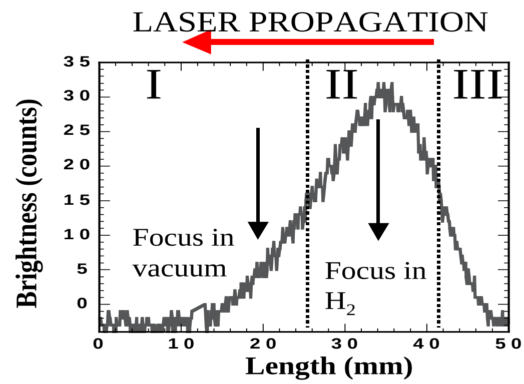

Fig 3: Lineout of H_2 plasma at 160 mTorr.

The plasma was produced at a distance larger than Z_R from the focus in vacuum. Note, that position of focus in vacuum for a high-power beam was determined by ionizing Ar with a fraction of the total power corresponding to an appearance intensity of 2.5×10^{14} W/cm^2. The plasma lineout in Fig.3 clearly demonstrates asymmetry caused by ionization-induced refraction [3]. Optimal peak power of the laser beam in the experiment was 0.5 TW. This power did not exceed the field ionization threshold for H_2 (1.37×10^{14} W/cm^2) by a factor of two. Increasing both the laser power and plasma density resulted in shifting the plasma further upstream, making losses caused by refraction more severe.

RPW's driven by a two-wavelength CO_2 laser pulse were detected and characterized by a collinear Thomson scattering (TS) technique using a green probe beam [7]. An F/4 optic was used for focusing the 532.1 nm probe beam. This allowed to sample only approximately 1 mm of the 2.5-cm long plasma and, by scanning the sampling point, to map the RPWs longitudinally. The latter information was very important for the asymmetric plasmas distorted by ionization-induced refraction of the laser beam. TS signal resolved both in frequency in time for the zone II in Fig. 3 is presented in Fig.4. A short, ~

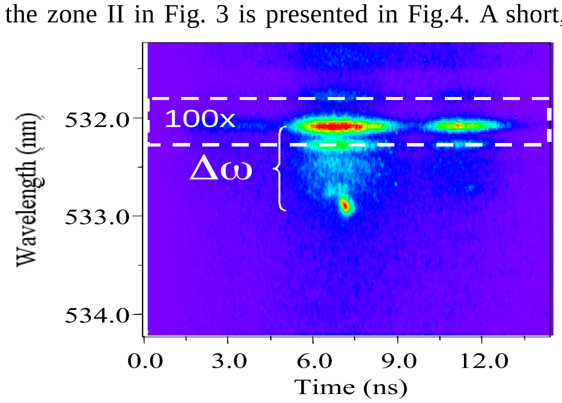

Figure 4: Streak camera image of the TS signal.

100 ps sideband shifted by 8.1 Å from the wavelength of the probe light was the result of scattering from the RPW. The 8.1 Å shift of the scattered light corresponds exactly to the Δω separation between the two frequencies of the CO_2 laser beatwave. Another conclusion drawn from

these measurements is that TS signal and, therefore, the wave amplitude is a strong function of the plasma brightness. It is not a surprise, since the plasma beatwave efficiently couples energy of an electromagnetic wave of the laser field into an electrostatic plasma wave with almost zero group velocity, additionally increasing heating of the plasma. The amplitude of the RPW $\varepsilon=\Delta n_e/n_e$, where Δn_e is the magnitude of the perturbation of the electron density associated with the wave, was estimated from the absolute amount of scattered light to be ~0.1 around focus in H_2 (zone II). However, the plasma wave amplitude dropped to 0.01-0.02 in both peripheral zones I and III limiting the effective length, where a large amplitude RPW was excited, to ~1 cm.

ELECTRON ACCELERATION

One of the main difficulties of measuring ionizing radiation and electrons in particular is that the commonly employed detectors are sensitive to a variety of radiation sources. To decrease the background caused by stray hard X-rays produced by bremsstrahlung, each surface barrier detector was placed in a thick lead housing with an aperture equal to 8 mm (detector size). Detectors were also shielded by 1-3 mm of Cu cutting off all X-rays below 0.1 MeV at the peak of SBD's sensitivity. A series of null tests were performed under various conditions, which could, in principle, produce false signals on our detectors. They are transverse blowing of the e-beam by the laser beam or plasma producing scattered 12 MeV electrons, acceleration of electrons by a Raman instability in the plasma rather than the beatwave, and the acceleration of background plasma electrons rather than the injected electrons from the photoinjector. All null tests using both single- and two-wavelength laser pulses confirmed that detected above the noise signal is result of acceleration in the PBWA. As seen in Fig. 5, the highest energy gain was ~10 MeV. In the experiment the e-beam was not matched both longitudinally and transversely to the plasma wave, therefore 100% energy spread was obtained.

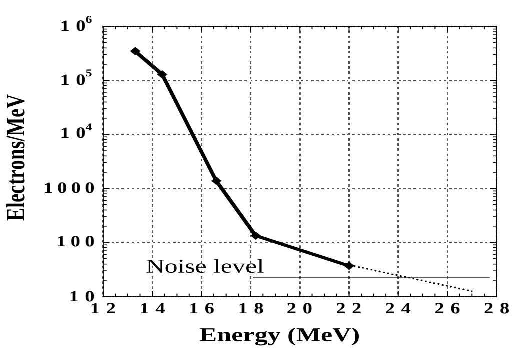

Fig 5: Single-shot electron spectrum.

The diameter of the accelerating structure was larger than the plasma wavelength of 340 μm making the longitudinal contribution of the electron density perturbation at least three times larger than the radial contribution [8]. In this case a 1-D formalism based on Gauss's law can be applied to estimate the maximum energy gain $W_{max}=0.96\varepsilon(n_e)^{0.5}L$, where L is the efficient beatwave length. For a beatwave length of 1 cm and the wave amplitude $\varepsilon=0.1$, the energy gain W_{max} =10 MeV. This energy gain is in a good agreement with one obtained in the experiment. Thus it is ionization-induced refraction of the laser beam by the plasma that limits the beatwave length and, therefore the net energy gain.

We consider several possible solutions for the refraction problem. One can try to guide the laser pulse in a gas filled hollow waveguide [9] in order to confine the laser beam in the focal region. Another solution is to create an ion channel by using a longer laser pulse with a duration longer than the characteristic time of ion motion, thus initiate a self-guiding process [10,11]. Experimental results on enhanced acceleration by laser beatwave in a self-induced ion channel will be reported elsewhere [12].

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