Recent Results on the Beat-Wave Acceleration Experiment with Nd Lasers at Ecole Polytechnique

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Abstract

We describe an experiment aimed to accelerate particles with a beat-wave generated in a D_2 plasma by two Nd-YAG and Nd-YLF laser wavelengths. The 3 MeV incident electrons are produced by a Van de Graaff accelerator. The electron and laser beams are aligned with an optical transition radiator. The accelerated particles are analysed by a magnetic spectrograph and detected by an array of scintillators and photomultipliers. Preliminary results show a clear signal of a few hundred electrons accelerated to about 3.4 MeV.

1 INTRODUCTION

Among new methods to accelerate particles with a large electric field, the beat-wave technique [1] has been investigated by several groups for the last decade. In this scheme two high-intensity laser pulses are focused in a vessel containing hydrogen gas and create a fully ionized plasma. The beating of the two waves provides a longitudinal electric field which oscillates with the frequency difference of the two lasers. If this frequency difference is equal to the plasma frequency, a resonance effect results, and the charge separation produces a field up to several GV/m. A relativistic particle with the right phase can catch the wave and gain energy. An optimum effect is expected when the Lorentz factor of the wave, determined by its phase velocity, is close to the Lorentz factor of the particle.
Recently it has been demonstrated that externally injected electrons were accelerated up to several MeV, using a two-frequency carbon dioxide laser beam [2, 3]. With the same technique, the acceleration of background plasma electrons has also been reported [4]. In the Ecole Polytechnique experiment presented here, we have already published results concerning plasma creation and beat-wave generation [5]. In this article we describe the updated experimental set-up, which includes the electron beam injection and the accelerated electrons analysis.

2 PLASMA GENERATION

Two synchronized laser oscillators, Nd-YLF (1.053 μm) and Nd-YAG (1.064 μm), deliver two pulses of 90 ps and 160 ps duration (FWHM) respectively. These pulses are then amplified separately, up to an energy of 10 J each, with a time delay of 1 ns, in the LULI laser chain. They are transported to the experimental room, over a distance of 150 m. The beam is under vacuum and its alignment is performed with remote-controlled mirrors and screens. Measurement of the beam quality shows no deterioration due to this transport. The two pulses are synchronized in time and recombined by means of rotating plates and polarizers. They are then focused by a 1.5 m focal length lens into the vessel filled with D_2 gas.
At resonance, the deuterium density is 1.07×10^{17} cm^{-3}, corresponding to 2.187 mb at 22^{0}C. At the focus of the lens the plasma dimensions are about 100 μm (FWHM) wide and 1 cm length. The light intensity is higher than 4.10^{14} W.cm^{-2}. Preceding experiments [6] have shown that the gas is fully ionized by multiphotoionization, so that the initial plasma density is equal to the atomic density. The amplitude of the plasma wave was measured to be 1 to 5 % [5], limited by modulational instabilities [7]. The corresponding electric field was between 0.3 and 1.5 GV/m. Simulation and measurement indicate that the duration of the plasma wave is about 60 ps.
In the present experimental set-up two optical diagnostics are used. The laser light transmitted through the plasma is imaged on a CCD camera, giving an image of the focal spot. At an angle of 5° with respect to the beam line, a system consisting of a spectrometer, a streak camera and a CCD camera gives a time and frequency-resolved measurement of light scattered by the plasma. This Thomson diagnostic provides a signature of the beat-waves: the resonant behavior of the electron and ion waves is clearly correlated with the pressure curve [7] .

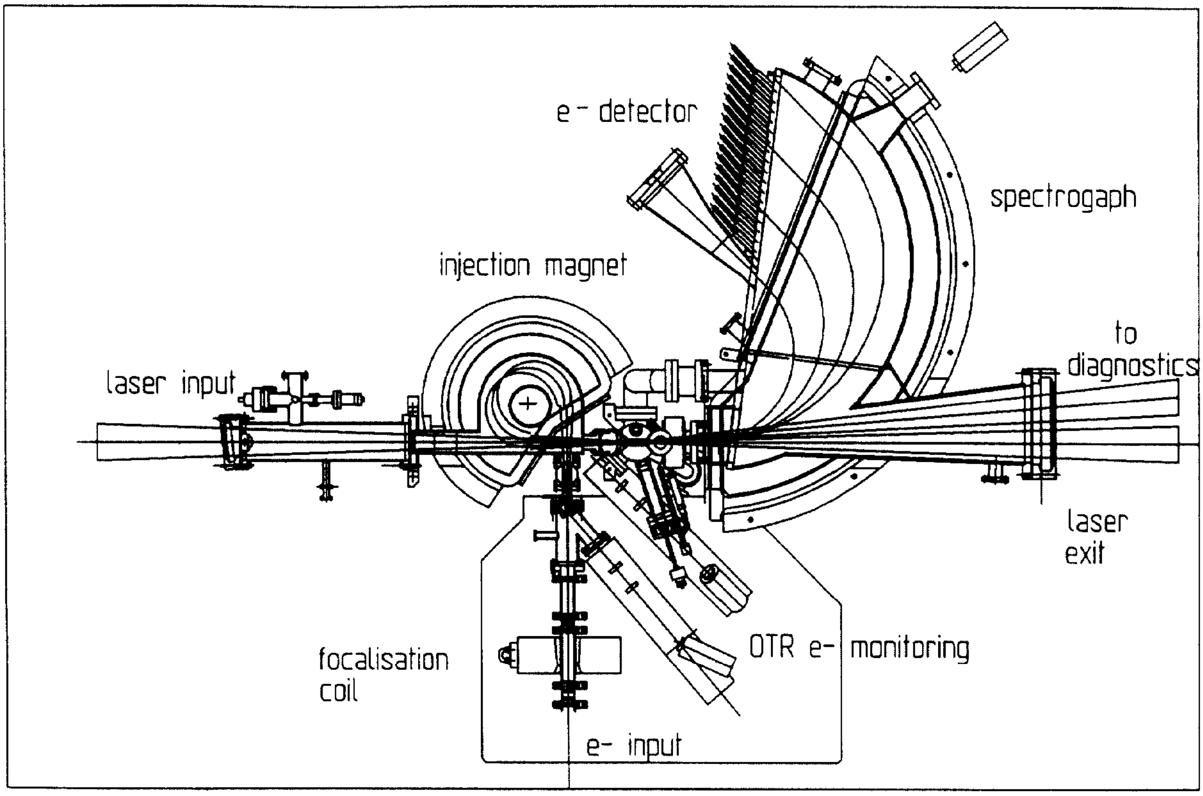

Figure 1: Experimental setup for the beat-wave acceleration

3 ELECTRON BEAM AND ALIGNMENT

The 3 MeV electron beam (2.5 MeV kinetic energy) is given by a Van de Graaff accelerator with an energy resolution of 5 keV. It can deliver a continuous beam or pulses at a 10 or 50 Hz repetition rate, or a single pulse synchronized with the laser shot. For pulses, the minimum (maximum) intensity and duration are respectively 10 μA and 100 μs (315 μA and 460μs). After an achromatic magnetic line, the beam is focused on a 1.5 μm aluminium foil and enters the plasma vessel. An Optical Transition Radiation (OTR) device monitors the size of the spot on the foil [8]. After subtracting quadratically the intrinsic resolution of the system (10 μm), the measured size of the spot (one standard deviation) is 20 μm. The angular divergences of the beam before and after the aluminium foil are 3 mrad and 10 mrad (standard deviation), respectively.
The injection magnet (figure 1) is an α-type achromatic and stigmatic system with a magnification factor equal to one. An other OTR device, using a removable foil, monitors the image spot, at the position where the center of the plasma is to be produced. This system is also sensitive to the laser light. It is used to tune the spatial coincidence of the laser and electron beam waists before each shot.
The magnetic spectrograph is a quadrupole-dipole combination, stigmatic at the injection energy. It has a large energy range (3 to 6 MeV) and an angular acceptance larger than the vertical size of the scintillators. The electron beam is cleaned by dedicated collimators, $\pm$60 mrad before plasma and $\pm$80 mrad after plasma. The 3 MeV electrons are directed towards a dump consisting of low Z material: aluminium and water. The back side is a transparent window through which the image of the beam is monitored by its Cerenkov light in water.

4 DETECTION APPARATUS

The energy resolution of the spectrograph is 0.15 MeV per channel, and its acceptance ranges from 3.27 to 4.84 MeV. The electron detector is an array of 10 scintillators, 2x2.2x5 cm^3 in dimension, separated by 1 mm lead septa. The decay constant of the scintillating material used (NE111A plastic) is 1.6 ns. The light is recorded by Hamamatsu R1635 photomultipliers, 10 mm diameter, 0.8 ns rise time. The pulse heights are measured by CAMAC driven ADC's, in coincidence with the laser pulse. To take advantage of the short signal, 5 ns long linear gate modules are inserted after the photomultipliers, before the ADC's. One or two channels can also be recorded on storage oscilloscopes. The time coincidence is tuned by observing directly on the photomultipliers an attenuated light pulse from the laser through optical fibers.

The energy calibration of the detector is performed by measuring the cosmic muons, which deposit 4.4 MeV per event. This is checked by observing the end spectrum of a ^{60}Co gamma ray source and the 3 MeV electrons scattered by the gas. By varying the applied high voltage and using fast amplifiers, the dynamic range extends from one to a thousand electrons, 2.5 MeV kinetic energy equivalent each.

5 EXPERIMENTAL RESULTS

Laser and electron pulses were triggered simultaneously so that the laser shot arrived at the peak intensity of the 120 μs electron pulse. All the results reported here were taken with an electron beam intensity of 80 μA. This was the maximum value tolerable to avoid saturation of the photomultipliers. At this intensity a background equivalent to 10 to 30 MeV per ns was measured in the detector channels. This background, associated with the electron beam, is mainly due to the scattering of electrons in deuterium for the two channels closer to the 3 MeV line. For the more energetic channels, other sources like the dump or the vessel must be predominant.

During eight laser shots we observed signals on channel 1 (centered at 3.24 MeV) at a level of 50 to 500 electrons, and on channel 2 (centered at 3.50 MeV) up to 80 electrons. On the higher energy channels it was not possible to observe any significant indication over the background, either on oscilloscopes or on ADC's. Three pressures, 2.189, 2.222 and 2.300 mb, were used.

Simultaneous optical diagnostic of the beat-wave by Thomson scattering was positive for the eight shots. As a cross check we performed several shots for which no acceleration was expected, but which could generate a fake signal: YLF alone, beats without electron beam, time delay between the two frequencies. No event was observed, which could simulate accelerated electrons.

6 CONCLUSION

We have observed the acceleration of externally injected electrons by a relativistic plasma wave. This is the first evidence of such a phenomenon when the plasma is excited by beat-waves of a two-frequency Nd:glass laser. Nevertheless the optimum conditions are not fulfilled since the Lorentz factor of the injected electrons, equal to 6, is much smaller than the Lorentz factor of the relativistic plasma wave, equal to 96. Moreover the phase of the wave is randomly distributed with respect to each incident particle.

The present result, obtained with a very low statistics of laser shots, is only qualitative. No optimization of the beats was possible, by tuning the parameters of the laser, and by scanning in deuterium pressure. The detector calibration is still preliminary. Developments are under progress, to reduce the electron and gamma background, coming from the gas vessel and from the dump. These improvements would permit to increase the sensitivity up to single electrons for the highest energy channels, and to work with a higher electron beam intensity. We expect in a near future to be able to measure the complete energy spectrum of the accelerated particles and to compare to simulations taking into account the experimental parameters.

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