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- **A Summary of the Beat-Wave Experiments at Ecole Polytechnique**
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- **On Triple Focusing Dipole Magnets.** D. Bernard and A. E. Specka, LPNHE, Ecole Polytechnique, IN2P3 & CNRS, 91128 Palaiseau, France

A SUMMARY OF THE BEAT-WAVE EXPERIMENTS AT ECOLE POLYTECHNIQUE

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Abstract

In a large set of experiments we have studied the physics of particle acceleration by laser beat-wave driven plasma-waves in the case of a Nd-glass laser with wavelengths close to 1 μm. The plasma is generated by multiphoton-ionization in deuterium. The plasma wave generated by the beat-wave has been observed by Thomson-scattering and its saturation attributed to the coupling with ion waves through the modulational instability. Electrons injected at 3 MeV have been accelerated in the plasma up to 4.3 MeV. The maximum energy gain is limited by the dephasing between the injected electrons and the plasma wave. The observed energy gain is compatible with a maximum accelerating electric field of 0.7 GV/m.

1 INTRODUCTION

The beating in a plasma between two copropagating electromagnetic waves can generate a longitudinal electron plasma wave with a high electric field and a relativistic phase velocity. This mechanism called beat-wave [1] is efficient if the electron plasma frequency ω_p is close to the difference frequency between the two laser beams. It is one of the proposed mechanisms for laser particle acceleration. Various experimental programs have been developed in order to study this mechanism and the possible resulting electron acceleration [2-7]. Among them, the program developed at UCLA and using a CO_2 laser at wavelengths near 10 μm is described in this issue. We will describe here the results obtained at Ecole Polytechnique with a Nd-glass laser at wavelengths near 1 μm. The different issues that were successively studied, and that we will describe here, include plasma formation [8], the generation and the measurement of the relativistic electron plasma wave, the physics relevant to its saturation [9,10] and the acceleration of an injected electron beam [7].

2 PLASMA FORMATION

In order for the plasma wave to grow significantly, one has to fulfill the resonance condition between the plasma frequency and the laser frequencies. The required precision on the plasma density depends on the laser wavelength and intensity. In absence of saturation, it is of the order of 1% to a few % respectively [11] for existing Nd-glass lasers ($\lambda \approx 1$ μm) and CO_2 lasers ($\lambda \approx 10$ μm). To obtain such a precision and homogeneity we generate the plasma by multiphon-ionization of deuterium. A laser beam is focused in the middle of a chamber filled with deuterium at a precise pressure [12]. Above threshold, the gas is fully ionized and the electron density is determined by the initial atomic density. We checked this in an experiment by measuring the electron density by Thomson scattering [8]. In this experiment we used a frequency doubled Nd laser beam at $\lambda \approx 0.5$μm, pulse duration 200ps (600ps) and energies up to 10J (30J). After ionization, the ponderomotive force of the laser beam pushes the electrons outwards and the ion and electron densities slowly decrease by a few percent per 100 ps.

3 GROWTH AND SATURATION OF THE PLASMA WAVE

All the beat wave experiments, with or without injection of an e^- beam, have been made with two laser beams at $\lambda \approx 1.0530$μm and $\lambda \approx 1.0642$μm, pulse duration of about 100ps and energies up to 10J per wavelength. In a first series of experiments we measured the growth and the saturation of the plasma wave generated by beat-wave. The two pulses are synchronized and focused in the middle of the chamber filled with deuterium. After ionization the plasma wave begins to grow. The direct observation of this wave by collinear Thomson scattering at 0° is not reliable because of a large signal due to a four-wave coupling mechanism in the gas surrounding the plasma [10,9].

When its amplitude is high enough, it couples with electron and ion waves, with longer k vectors, in the regime of modulational instability [9,10]. These waves are measured by Thomson scattering of a colinear probe beam at $\lambda = 0.53$ µm. In this configuration, the scattering angle on the direct waves is very small. Thus, the scattered spectra observed at 10° reveal the existence of long k vector electron **and** ion waves. This is the evidence of an efficient coupling of the primary plasma wave with other modes in the plasma. This mechanism saturates the growth of the primary wave very early in the laser pulse at a rather low level of density perturbation of 1% to 5%. The imaging of the secondary waves for a focusing length of 1 m shows the presence of beatwave over a length of 1 cm and a maximum diameter of the order of 300 µm.

4 ELECTRON ACCELERATION

In the last series of experiments we studied the acceleration of a relativistic electron beam injected in the plasma. The set-up is shown in Fig.1. The two laser pulses are focused by a 1.5 m or 1.2 m focal length lens in deuterium gas. At resonance, the deuterium density is $1.115\times10^{17}\text{cm}^{-3} \pm 2.3\%$ corresponding to a pressure equal to 2.272 mbar at 22°C. It can be adjusted with a precision of ±0.3%.

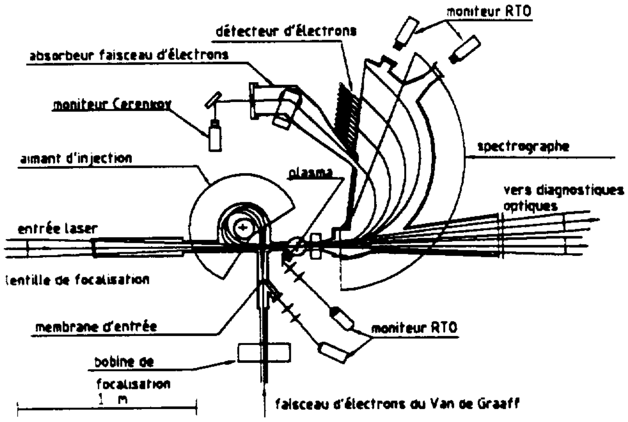

Figure 1 : Experimental set-up of the acceleration experiment.

The electron source is a pulsed Van de Graaff accelerator delivering electrons with a total energy of 2.5, 3.0 or 3.3 MeV and a relative energy fluctuation of 10^{-3}. The pulse duration is equal to 0.4 ms, so the beam can be considered as continuous during the life time of the plasma wave. The current is set to 170 µA corresponding to 1000 electrons per picosecond. The beam is focused on a thin (1.5 µm) aluminium foil separating the vacuum of the accelerator from the target chamber and reimaged at the plasma location by a triple-focusing magnet [13,14]. The geometrical parameters have been monitored by monitors detecting the optical transition radiation [15]. We found 25 µm [RMS] for the focal spot in vacuum, 45 µm for the focal spot in 2 mbar D_2, and 10 mrad [RMS] for the angular divergence.

The energy spectrum of the electrons after passing the plasma is measured by a magnetic spectrograph and an array of 10 scintillators read by photomultipliers [13]. The noise is mainly due to electrons scattered on the gas molecules. It amounts to 5 e^-/ns. The photomultiplier signals being gated by 5 ns electronic gates, this noise amounts to 25 e^- per channel.

In the following we will summarize the main results. A large number of shots have shown the presence of accelerated electrons. These are seen only when the two laser pulses are synchronized in time and near the theoretical resonant pressure .

The optimum effect of acceleration is expected when the phase velocity of the plasma wave is not too far from the velocity of the accelerated electrons. In our case the relativistic factor corresponding to the phase velocity is $\gamma_p = 94.5$ and the maximum injection energy corresponds $\gamma = 6.5$. This means that the electrons get out of phase while travelling in the plasma. This dephasing distance is given by : $l \approx \gamma_p\gamma_e^2\lambda$, where λ is the mean laser wavelength, and is equal to ≈ 4.2 mm. If the plasma is too long, the electrons get out of phase during acceleration and suffer successive acceleration and deceleration periods, thus decreasing the maximum energy gain. This latter is given to first order by [16] $\Delta\gamma = \Delta\gamma_{max}\times e^{-L/l_d}$ where $\Delta\gamma_{max} = eE_{max}\times\pi Z_R/mc^2$, Z_R is the Rayleigh length of the focused laser beam, $L = 2\times Z_R$ and $l_d = (2/\pi)\times l$. To check this effect we changed separately the plasma length L and the injection energy.

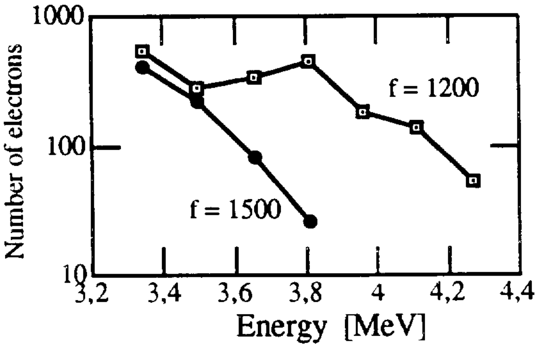

Figure 2 : Spectra of accelerated electrons obtained with a 1.5 m focal length (black symbols) and a 1.2 m focal length (open symbols). The injection energy is 3 MeV. The two lines are the best results obtained near the resonant pressure.

Figure 2 shows the electron spectra obtained with an injection energy of 3 MeV and focal lengths of 1.5 m and 1.2 m. It appears clearly that the energy gain is much larger in the shorter plasma. The most convincing evidence is obtained from Fig.3 where the focal length is fixed and the injection energy is varied from 2.5 MeV to 3.3 MeV. In the same plasma conditions, the maximum energy gain increases significantly when the injection energy increases, i.e when the dephasing length increases.

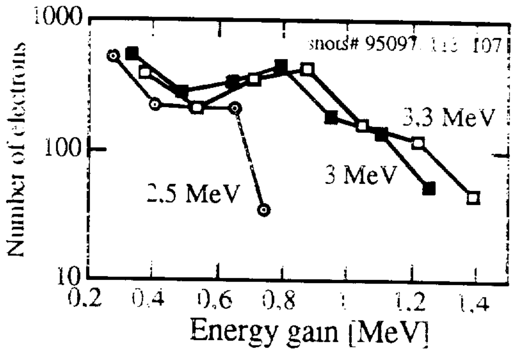

Figure 3 : Best spectra of accelerated electrons for three injection energies (2.5, 3.0 and 3.3 MeV). The focal length is 1.2 m.

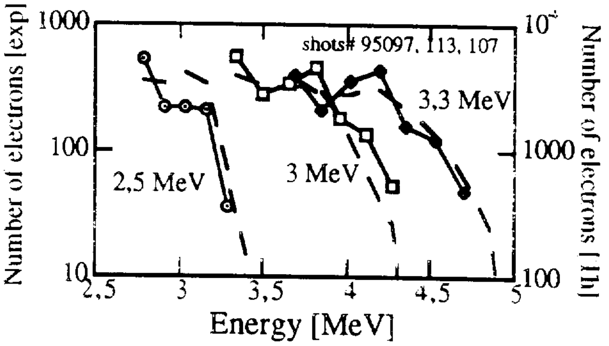

Figure 4 : Same spectra as in Fig.8. compared with the results of the acceleration model (dashed lines) for the parameters L = 2.8 mm and δ_{max} = 2.4%.

We compared the measured spectra with a simple 3D acceleration model assuming a gaussian laser beam with the measured focal spot and the Rayleigh length as a parameter [16]. The electron density perturbation δ is gaussian in radius with a maximum value δ_{max} at focus and Lorentzian dependence along the laser propagation axis. Because of the different values of the injection energy, we obtain a narrow range of parameters for which we get a good agreement with the experimental spectra. This is shown in Fig.4 with L = 2.8 mm and δ_{max} = 2.4% corresponding to a maximum electric field of 0.7 GV/m. The value of the electric field is in agreement with the Thomson scattering measurements and the theoretical predictions [9]. The acceleration length of 2.8 mm is much shorter than the time-integrated image (1 cm). Nevertheless we have also seen [9] that because the saturation time due to the modulational instability depends on the local laser intensity, the plasma waves only exist in a limited region at a given time. Both parameters are thus in reasonable agreement with our preceding measurements.

5 CONCLUSION

We have presented a summary of the results of the beatwave experiments at Ecole Polytechnique. All important physical points seem to be well understood : the growth of the plasma wave is limited by the modulational instability and the energy gain of the accelerated electrons is limited by the dephasing distance between the electrons and the phase velocity of the plasma wave. It is quite clear from these results and the results obtained elsewhere in a different regime that future beat-wave experiments should involve more powerful laser beams with possibly shorter pulses, and injection of electrons with higher energies.

6 ACKNOLEDGEMENTS

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