BEAT-WAVE ACCELERATOR EXPERIMENTS AT ECOLE POLYTECHNIQUE

F. AMIRANOFF, A. DYSON, J.R. MARQUES, C. STENZ,
LULI, Ecole Polytehchnique, Palaiseau, France.
P. BENKHEIRI, L. EVEILLARD, F. JACQUET, P. MINE,
LPNHE, Ecole Polytechnique, Palaiseau, France.
G. MATTHIEUSSENT
Laboratoire PGP, Université Paris XI, Orsay, France.

ABSTRACT

The beating of two copropagating laser beams in a plasma may generate a plasma wave which can accelerate particles to very high energies. In order to obtain high electric fields, of the order of 1 GV/m, the plasma frequency must be matched to the frequency difference between the two laser beams. For beat-wave experiments using a Nd:glass laser the precision on the plasma density and homogeneity must be better than 1%. New techniques for optical alignment and gas purity control have been developed for this purpose. We present results on the formation of plasmas by multiphoton ionization of N_2, H_2 and D_2. We discuss the design of an experiment to detect the acceleration of electrons.

The plasma waves created by resonantly beating two intense laser beams can produce ultrahigh electric fields that propagate with velocities close to c. By phase locking charged particles in such a wave they may be accelerated to very high energies within a short distance.

We intend to perform a series of beat-wave experiments using a Neodymium glass laser giving the wave lengths λ_0 = 1.053 µm (YLF) and λ_1 = 1.064 µm (YAG). These two copropagating laser beams are to be focused to a peak intensity $I = 10^{14}$ W cm^{-2} in a plasma of electron number density $n_0 = 10^{17}$ cm^{-3}. The matching of the driving frequency $\Delta\omega = \omega_0 - \omega_1$ to the plasma frequency ω_p, requires the homogenity of the plasma electron density n_0 to be within 1%. For this purpose a gas containment vessel has been constructed using ultra high vacuum techniques. To eliminate the introduction of impurity gasses, the vessel is permanently sealed and for this reason novel optical alignment techniques have been developed without the use of an alignment target.

I - GAS CONTAINMENT VESSEL AND ALIGNMENT METHOD

The gas containment vessel is essentially cylindrical in shape, of length 1.3 m and diameter 25 cm. It is constructed of stainless steel type Z2 CNDS 17-12 (316 L) to a high vacuum specification; the joints used for the diagnosis ports are of viton. A heating system enables the temperature of the inner surface to be raised to about 100°C in order to reduce subsequent outgassing.

A base pressure of 10^{-7} mbar is achieved with a stability better than 10^{-3} mbar/3 hours. The temperature of the fill gas can be regulated to within 0.1°C by a water circulation system. The pressure of the fill gas is measured using a capacitive pressure head connected to an electronic readout system which compensates for temperature effects on the pressure measurement. The accuracy of the system is 10^{-3} mbar at a pressure of 2 mbar. The temperature of the fill gas is measured using thermocouple devices placed at various positions on the vessel, giving an absolute accuracy of about 0.3°C.

The above conditions for pressure and temperature allow about 5 hours of operation before a change of fill gas is necessary to satisfy the required precision on the gas pressure of better than a few per mil at 2 mbar.

The vacuum vessel and the alignment techniques which we shall now describe, have been tested in multiphoton ionisation experiments at both 1.053 µm (YLF) and 0.53 µm (frequency doubled YLF). We present preliminary results for 0.53 µm wavelength. The plasma formed by the laser beam is diagnosed by collecting the Thomson scattered light from the same beam. Two diagnostic channels each one composed of a spectrometer with an entrance slit of 100 µm in diameter, coupled with a streak camera, are placed at opposite sides of the gas vessel on the same optical axes, i.e. at complementary angles.

The focussing of optical components is achieved using a centroid diode PIN-SC/100 from United Detector Technology. The analogue signal from each side (1 cm long) of the square sensitive surface of the diode is amplified, digitised and fed into a micro-processor readout system. This gives the center of mass of an alignment laser beam with a spatial accuracy of about 5 um.

The principle of the focussing technique is shown in Fig. 1. A small rotating quartz prism is inserted in the beam of a low power commercial c.w. laser to give a rotating pencil beam of effective aperture Δ. Intermediate coupling lenses with an overall magnification of unity focus the rotating pencil on to the plane of a centroïd diode. When the coupling optics are defocussed a circular trace of the rotating pencil beam is obtained on the diode. Focussing is achieved by varying the positions of the focussing lenses until a stationnary spot is obtained. This technique is applied for alignment of optical axes of the two diagnostic channels. For the main high power laser beam similar techniques are used : the rotating pencil beam is obtained from a rotating mask placed in the beam of a low power c.w. laser of full beam diameter that follows the same optical path as the main high power laser beam.

The overall process is as follows : a centroid diode D1 is placed at the image position of the plasma in an equivalent plane formed using a thin partially reflecting glass plate (Fig. 2). In the diagnostic channel at 170° from the plasma axis, the alignment laser is focussed on the entrance pupil of the spectrometer. For this purpose a centroid diode D2 is used at a position conjugate of the pupil by a removable mirror (Fig. 3a). The focussing point at the entrance slit of the spectrometer acts as an effective object for subsequent focussing by the channel collecting optics onto the diode D1 defining the plasma position. The alignment of the diagnostic channel at the complementary angle is achieved using the transmitted rotating pencil beam directly. Focussing of this channel is performed using a diode D3 placed in the equivalent plane of the spectrometer entrance slit formed by the insertion of a removable mirror (Fig. 3b). With these methods, the main high power laser beam is focussed by an f/10, 1 m focal length doublet with an accuracy of 500 µm and with a lateral position better than 10 µm. By changing the relative positions of the main focussing lens and the part of the plasma viewed by the diagnostic channels it is verified that the alignment method does indeed give the best intersection.

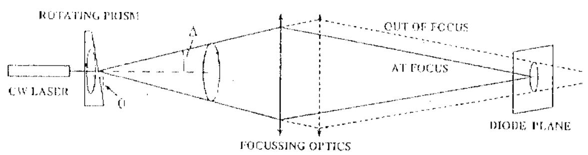

Figure 1

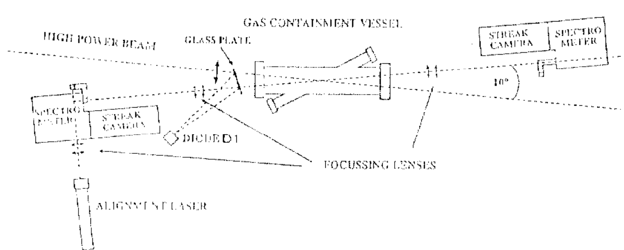

Figure 2

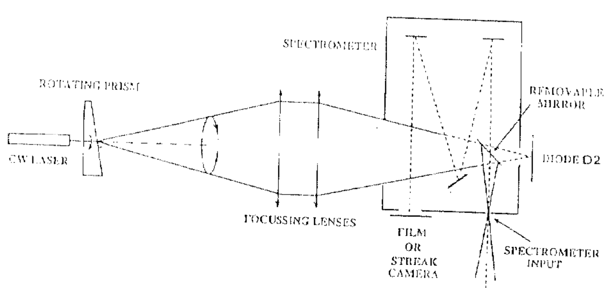

Figure 3a

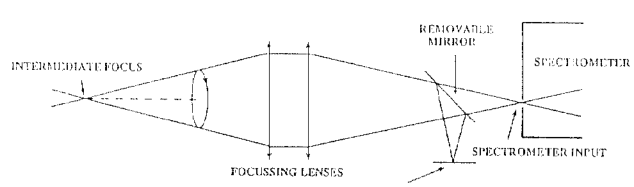

Figure 3b

II - EXPERIMENTAL DETAILS AND RESULTS

The experiments were performed using the neodymium glass laser at LULI, Ecole Polytechnique. This gives laser pulses of either 60J, 600ps at 1.053 µm (YLF) or 20J, 600 ps at 0.53 µm using a frequency doubling crystal. The laser beam is focussed into the gas containment vessel filled with either N_2 or H_2 or D_2 gas at pressures of a few torr. Focussing is achieved using a 1m focal length f/10 doublet giving a focal spot of about 100 µm diameter and a peak irradiance of 10^{15} Wcm^{-2}(YLF) or $3x10^{14}$ Wcm^{-2} (frequency doubled YLF). This results in multiphoton ionisation of the fill gas and the plasma formed is diagnosed by collecting the Thomson scattered light from the same laser beam. The diagnostic channels each consist of a spectrometer which collects the light scattered by the plasma using intermediate coupling lenses of overall magnification unity and effective aperture f/10. The spectrally dispersed light from the spectrometer is monitored using a Hadland Imacon 500 series optical streak camera and intensifier. The camera is fitted with either an S1 tube for the experiments at 1.053 µm or an S20 tube for the experiments at 0.53 µm. Despite the use of the optimum tube the camera is about 100 times more sensitive to 0.53 µm light and it is necessary to run the intensifier at maximum gain when using 1.053 µm light. We present preliminary results for 0.53 µm wavelength.

The two diagnostic channels are placed on opposite sides of the gas containment vessel on the same optical axis to give a small (10°) and a large (170°) scattering angle. The channel at large angle with a scattering parameter $\alpha = 1/k\lambda_D \approx 0.5$ (where k is the scattered wave number and λ_D the Debye length) gives spectral profiles with FWHM proportional to $\sqrt{T_e}$ where T_e is the thermal electron temperature, from the data we find an electron temperature of the order of 15 eV. The channel at the small angle with a scattering parameter $\alpha = 1/k\lambda_D \approx 5$, gives spectral profiles depending on the electron and ion temperature and the electron number density of the plasma; the scattering is in the collective regime and one expects the observed spectrum to consist of an ion feature plus two electron satellite peaks at $\pm\ \omega_p$ from the central ion line. This permits the electron number density of the plasma can be measured.

The results for nitrogen show that multiple ionisation occurs (the electron number density increases with time) and so this gas is unsuitable for beat-wave experiments.

By comparison with the fill gas number density which can be regulated to within about 0.1%, data on H_2 and D_2 show clearly that the plasma is fully ionised at the start of the laser pulse and that the plasma density at the center of the laser spot decreases (Fig. 4). The averaged observed slope of the electron number density of the plasma is 5% for 100 ps. Fig. 5 shows a simulation of the hydrodynamic evolution of plasma taking into account the radial ponderomotive force due to the laser beam and the thermal pressure of the plasma. On Deuterium data with larger ion mass we observe a less pronounced slope.

TYPICAL MODEL RESULTS

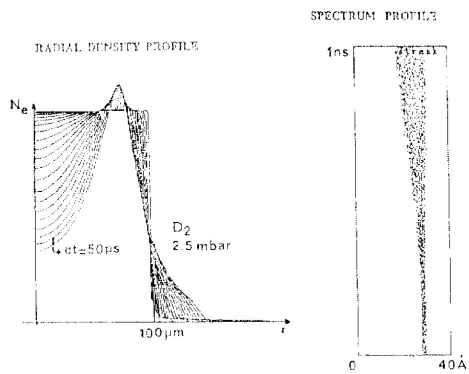

Figure 4

DENSITY EVOLUTION WITH TIME

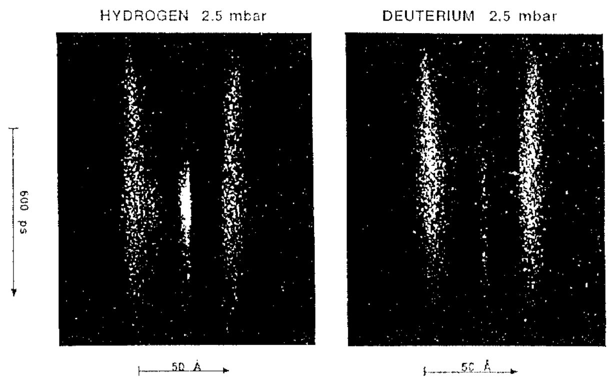

Figure 5

III - CONCLUSIONS AND FUTURE

Multiphoton ionisation of H_2 and D_2 is adequate for plasma formation. Ultra high vacuum techniques and alignment methods using a rotating pencil beam have been successfull in controlling the density uniformity of the created plasma. The observed hydrodynamic evolution shows that an homogeneous laser focal spot and short pulses ($\lesssim$ 100 ps) are needed and we expect that deuterium should be better due to the larger ion mass. Analysis of the experiment with the 1.053 μm wavelength is under progress. In the future we intend to perform a series of beat wave experiments using a neodymium glass laser giving the wavelengths 1.064 μm (YAG) and 1.053 μm (YLF). The plams wave is resonantly produced with a phase velocity v such that $\gamma = (1-v^2/c^2)^{-1/2} = \omega_0/\omega_p \approx 100$. Assuming a modest plasma wave amplitude $\delta n/n \approx 1\%$ we expect an accelerating field of 3 MV/cm suitable to accelerate electrons. The injected electron beam we intend to use is produced by the Van de Graaff accelerator of the SESI laboratory at Ecole Polytechnique. The beam is essentially monoenergetic (E = 3 MeV and $\Delta E/E \approx$ 1°/oo) when the terminal is at a stable potential, with a DC current of 200 μA. Tests have already been made and the electrons focussed to a spot less than 0.6 mm in diameter on an aluminium window of width 13, 8 and 3 μm. The scattering angle induced by the diffusion is less than 20 mrd for one half of the electrons and 8 μm width. This window should serve as an interface between the accelerator vacuum line and the gas containment vessel filled with D_2 at a pressure of 1.7 mbar. A beam line has been constructed using a solenoid to reduce the focal spot of the electron beam on the window to be less than 100 μm. An electron spectrometer and a new gas containment vessel are presently under design.