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Generation of Uniform Plasmas for Beat Wave Experiments

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Abstract

The laser plasma "beat wave" mechanism for the generation of ultra-high electric fields requires plasmas of several metres length with density uniformity of about 1%. Multiphoton ionisation of molecular hydrogen gas at a pressure of a few torr provides a scalable mechanism for generating these plasmas. We describe measurements of electron density, temperature and uniformity of plasmas generated by a frequency-doubled Neodymium glass laser, at an irradiance of about 10^{14} Wcm^{-2} . The plasma density corresponds to 100% ionisation and is measured to be uniform to within the measurement errors over a length of 8mm.

Introduction

The ever escalating size and cost of modern particle accelerators has led the High Energy Physics community to seek new techniques for particle acceleration. One of the most interesting of the new ideas is the "beat wave" mechanism, originally proposed for plasma diagnosis and heating but subsequently adapted to relativistic particle acceleration (Tajima and Dawson 1979). In essence the beat wave scheme requires that two parallel laser beams of slightly different frequencies ω_1 and ω_2 are focussed into a plasma whose resonant frequency $\omega_p = \omega_1 - \omega_2$. A longitudinal electrostatic (Langmuir) wave is driven resonantly and under suitable conditions may achieve an amplitude of tens or hundreds of GeV/metre. Since this is a resonant process of moderately high "Q" the plasma density is required to be accurate to about 1% or better over the entire length of the accelerator, perhaps as much as 100metre. In order to avoid excessive collisional damping of the Langmuir wave the plasma temperature should be greater than about 20eV, while to minimise the trapping of background plasma electrons and the energy inefficiencies the temperature should not be too much higher than this minimum. To produce useful accelerating fields (Lawson 1983), plasma densities of $10^{16} - 10^{18} \text{ cm}^{-3}$ are envisaged, while in order to drive the beat wave on a fast time scale (ie less than the ion plasma period) and avoid plasma instabilities (Bingham, Mori and Dawson 1985), laser intensities greater than 10^{14} Wcm^{-2} are necessary.

Preliminary experiments in this field (Clayton et al 1985, Ebrahim et al 1986) have used DC arc discharges, Z or theta pinches, or air breakdown plasmas. These plasmas are recognised as having inadequate homogeneity and reproducibility for potential accelerator applications. In this paper we report on a technique for the production of exceptionally uniform plasmas with the appropriate density and temperature by multiphoton ionisation of molecular hydrogen. The technique is scalable to plasmas of arbitrary size and automatically provides the required plasma conditions wherever the laser intensity is large enough to drive the beat wave. The energy used to produce the multiphoton ionisation is less than 1% of the energy needed to drive the beat wave.

Multiphoton Ionisation and Gas Breakdown

Since the early days of Q-switched lasers a large body of experimental data has accumulated on the related subjects of multiphoton ionisation (essentially a single atom/molecule interacting with the high intensity light wave) and laser induced gas breakdown (the collisional avalanche following absorption of laser energy in a gas). The distinction between the two processes is one of time scale, if the laser pulse is long compared with the collision time then breakdown effects will predominate, while in the opposite limit true multiphoton ionisation will be seen. Reviews of gas breakdown physics (Grey Morgan 1975) and of multiphoton ionisation (Chin and Lambropoulos 1984) give appropriate bibliographies in these fields. For laser pulse durations of order

10^{-9} sec and gas pressures of about 1 torr the collision time approximately equals the laser pulse duration. Little work has been performed in this range but the work of Dewhurst, Pert, and Ramsden (1974), and of Krasnyuk et al (1970) is noteworthy.

In subsequent discussion of our work we describe it as multiphoton ionisation since we believe this to be the dominant ionisation process even though it is followed by some collisional heating. This will be discussed more fully in the conclusions section.

Two earlier experiments demand specific mention. One of the first experiments on multiphoton ionisation (Voronov et al 1965) studied the ionisation of molecular hydrogen using a ruby laser ($\lambda=694.3\text{nm}$). The experiment used a relatively long pulse duration (20nsec) but was at a low pressure to avoid collisional ionisation. The positive ions were identified by time of flight mass spectrometry, and detected using an electron multiplier. For irradiances I around 10^{12} - 10^{13}Wcm^{-2} , the total number of ions detected scaled as $I^{6.7}$ and the ions were predominantly the molecular ion H_2^+ . At the higher end of the irradiance range increasing amounts, up to 10%, of the atomic ion H^+ were detected. With shorter wavelengths the general trend of multiphoton ionisation data is to show greater ionisation rates at irradiances around 10^{14}Wcm^{-2} , although the power law dependence is less steep, corresponding to the lower degree of non-linearity of the process.

Ebrahim et al (1986) used a gas breakdown plasma in air for their elegant demonstration of particle acceleration in laser driven beat waves. They used a CO_2 laser, for which the multiphoton ionisation phenomenon is not well understood (about 100 photons are typically required for ionisation), and in which the dominant process following the creation of a few initial ions is probably collisional ionisation. Since their background gas was air it was difficult to produce full ionisation (requiring more than 1000eV for Oxygen) and the plasma density varied in time and space with the laser heating. The use of hydrogen in our experiment has the great advantage that ionisation is completed very rapidly and density change then occurs only through hydrodynamic motion.

Experimental Arrangement

The experiments were conducted at the SERC Central Laser Facility using the Vulcan Neodymium glass laser. The $1.054\mu\text{m}$ light from the laser was frequency doubled in a KDP crystal and focussed using either 1 metre or 2 metre focal length lenses of 10cm aperture into a glass vacuum vessel containing hydrogen gas at a pressure of 0.5-4torr (actually a Z-pinch, but the pinch discharge was not fired). The laser energy was typically 10 Joules in 100psec or 20Joules in 1nsec. The size of the focal spot was measured with an equivalent focal plane camera to be about $400\mu\text{m}$ with the 2metre focussing lens and $200\mu\text{m}$ with the 1 metre focussing lens used for the long pulse measurements. Focussed irradiances were

about 10^{14} Wcm^{-2} .

The green light acted as a Thomson scattering probe beam and the scattered light was collected at four different angles (20, 60, 120 and 160 degrees) and hence four different values of the scattering parameter $\alpha = 1 / k\lambda_D$. Light from diametrically opposed channels was fed into the same spectrometer by means of a concave spherical mirror as shown in Fig1. Light emerging from the spectrometers was fed into two optical streak cameras whose time dispersion separated the direct and reflected light components. The streak camera output was recorded on HP5 photographic film and a calibration wedge was recorded individually for each data shot. The overall layout of the scattering and other diagnostics is shown in Fig1. The spectral and temporal resolutions were respectively about 5Å and 100psec.

For the long pulse experiments (1nsec) the gas pressure was measured by a Vacustat gauge, similar in principle to a McLeod gauge, for the short pulse (100psec) experiments, which were carried out a few months later a substantially more accurate MKS Baratron gauge was used.

Experimental Results

The results of this experiment consist of four simultaneous time resolved Thomson scattered light spectra. The 20 degree scattering channel is predominantly sensitive to electron density and gives the electron density by direct measurement of the frequency separation of the plasma satellites. The 160 degree channel is mostly sensitive to electron temperature but in the other two channels the shape of the scattered light spectrum is dictated by both parameters and a fitting procedure is required. Typical scattered light signals from all four channels with a 100psec laser pulse are shown in Fig 2a and 2b. Fig 3 shows the 20 degree (high α) scattering signal with a 1nsec laser pulse. It is clear from this data that there is little change in density or temperature during the 1nsec laser pulse and the same was true for all our measurements. The duration of the scattered light signal indicates that the plasma is formed very early in the laser pulse, but there is no absolute time reference.

The photographic data is corrected for film response, spectrometer and streak camera spectral sensitivity and finally fitted in a least squares sense to theoretical Thomson scattering profiles for a thermal plasma. Electron density and temperature are the fitting parameters and the absolute system sensitivity is uncalibrated. Examples of this fitting procedure are shown in Fig 4 for scattering angles of 60, 120 and 160 degrees. In all of the data obtained, the four scattering angles can always be fitted by a single density and temperature and there is no evidence of plasma turbulence or of non-Maxwellian distributions.

For all the data, the electron density did not vary with the laser irradiance. Attempts to operate at lower irradiances and measure an ionisation threshold were limited only by the lack of scattered light.

The measured electron density as a function of gas fill pressure is shown in Fig 5. The electron density is proportional to the fill pressure, and corresponds to 100% ionisation to within the measurement error.

Fig 6 shows the results of defocussing the input lens by +4, -4mm axially, while keeping the scattering volume fixed in space. This has the effect of measuring the electron density variations along the axis of the main focussing lens. The densitometer scans show that there is no measurable variation of ω_p at the 2% level, corresponding to a 4% uncertainty in n_e .

The electron temperature is measured to be about 8-10eV for all the data independent of the laser irradiance. There is some suggestion that higher gas fill pressures correspond to higher temperatures.

The overall size of the multiphoton ionised plasma was determined by looking at the Thomson scattered light, transmitted through the spectrometer in zero order, and using a very large entrance slit size. The stigmatic imaging of the spectrometer then gave a two dimensional image in the output plane, and the streak camera was operated in focus mode, when it is used simply as an image intensifier. The image obtained in this way is shown in fig 7, together with the image from the equivalent focal plane camera. The transverse size of the plasma image (about 400 μ m) corresponds to the size of the focussed light beam. Since the plasma is viewed in the light scattered from the laser beam these measurements can give only a minimum plasma size, since plasma outside the focal region will not give rise to any scattered light.

Discussion

We have modelled the plasma heating with a simple one dimensional (cylindrically symmetric) computer code, modelling absorption, thermal conduction, ion-electron equilibration, and hydrodynamic expansion. The laser is incident along the axis and has a Gaussian radial intensity profile. The model assumes at $t=0$ that the plasma is ionised, at a temperature of 1eV or less. The classical absorption cross section is modified to allow for the reduction in collision frequency (Rand 1964, Pert 1972) when the electron oscillating velocity, in the light wave $v_{osc} = eE/m\omega$ exceeds the thermal speed $v_e = (k_B T_e/m)^{1/2}$.

$$v_{eff} = v_{class} \left(\frac{v_e^3}{v_o^2 + v_e^2} \right)^{3/2}$$

and the electron thermal conductivity is limited by the electron "free streaming" limit:

$$Q = \left(\frac{1}{Q_{\text{class}}} + \frac{1}{Q_{\text{fs}}} \right)^{-1}$$

The free streaming flux is defined as:

$$Q_{\text{fs}} = f n_e k_B T_e v_e$$

where k_B is Boltzmann's constant and f is an adjustable constant which normally is 0.1 for best agreement with more rigorous calculations based on the Fokker-Planck equation (Bell, Evans and Nicholas 1981).

The model gives very good agreement with the measured temperatures using the standard value of flux limit and the modified inverse bremsstrahlung cross section. Ignoring the free streaming limit causes the electron temperature in the model to be too low, while ignoring the strong field bremsstrahlung correction causes the model to give too high a temperature. If both the free streaming limit and the strong field corrections are omitted then the model predicts too great a sensitivity to changing laser irradiance. This can be regarded as tentative evidence for the correctness of the strong field bremsstrahlung model.

The model does not include the effects of 'above threshold' ionisation (Lompre et al 1985, Kruit et al 1983) which creates the initial electrons with energies of a few electron volts. The computer model can be artificially started with an arbitrary initial electron temperature, but because of the strongly velocity dependent absorption the final temperature (ie after 100-200psec) is hardly altered. Our measurements of electron temperature can therefore say nothing about the velocity of the electrons immediately following multiphoton ionisation.

Since the electron density following 100% ionisation is only 10^{-4} of the critical density, the refractive index of the plasma is very close to unity. This means that there is virtually no self-focussing of the laser light which propagates almost under free-space conditions. The uniformity of the plasma created by multiphoton ionisation is then limited only by the uniformity of the initial gas fill pressure and by hydrodynamic motion following the laser heating. At a temperature of 10eV, and assuming a beam waist of 400 μ m, the acoustic transit time is about 4nsec. The results of the computer model indicate that even this is an overestimate of the plasma motion since the strong field bremsstrahlung results in a very flat temperature profile extending out beyond the beam radius. In the computer model the electron density changes by less than 10^{-4} in a 1nsec laser pulse.

Conclusions

We have studied the laser ionisation of molecular hydrogen, using Thomson scattering techniques to measure the time and space resolved density and temperature. Our results show that the gas is fully ionised within a time which is very short compared with the laser pulse duration

and is ionised over a length of at least 1cm using 2metre focussing optics. The uniformity of the plasma is very high and appears to be more than adequate for performing future beat wave experiments. The measured temperature is less than is needed to avoid collisional damping of the plasma beat wave, but this is offset by the reduced collision frequency caused by the large oscillatory velocity of the electrons in the electric field of the laser.

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Figure Captions

- Fig 1 Schematic arrangement of the experiment.
- Fig 2 Time resolved Thomson scattering signals at four different scattering angles.
- Fig 3 High α scattering with the 1nsec duration laser pulse.
- Fig 4 Computer generated Thomson scattering profiles for $n_e = 1.1 \times 10^{17} \text{ cm}^{-3}$ and $T_e = 9\text{eV}$
(a) at 60 degrees, (b) at 120 degrees and (c) at 160 degrees
- Fig 5 Measured electron density as a function of hydrogen gas fill pressure. The full line corresponds to 100% ionisation.
- Fig 6 The measured high α (20 degree) Thomson scattering signals at three positions along the axis of the focussing lens.
- fig 7 An image of the plasma in Thomson scattered light at 60 degrees, and an image of the laser equivalent focal plane.

500 μ m

SCATTERED
LIGHT AT 60°

LASER EQUIVALENT
FOCAL PLANE