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An Investigation of the Nature Properties of Plasma

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This study presents the characteristics of the plasma and the effect of the laser beam to best suit the plasma model behaviour. Special attention is paid to the “Genuine” Two Fluid Model and the pondermotive and transient forces. These models are translated into a numerical study of the parameters, such as the electric field density and temperature distributions once electromagnetic energy is supplied to the plasma. The parameters are presented graphically against time and distance into a small plasma fuel pellet. It is noted how field density and ions form undulations through the plasma. Types of plasma fuels are discussed with regards to their key parameters, such as density, volume and temperature. These characteristics were initially used in computations that were performed using the laser driven inertial fusion energy option based on volume ignition with the natural adiabatic self-similarity compression and expansion hydrodynamics [1].

1. Introduction

This is a very complex field of study, involving many fields of understanding, electromagnetic field theory, atomic structure and quantum mechanics (noticeably little used or mentioned in the literature). It deals with the mathematics of gradient fields, the resulting forces, moving charges and the theories of thermo-kinetic movement and especially employs non-linear mathematics. There is an overview at the beginning, of the forces involved, and the models of plasma structure. It is too vast an area of knowledge to plough into at this study, without showing such an overview. Coupled with the plasma structure are the values of temperature, energies and densities, etc involved. Numerical work is offered in this study dealing with the non-neutrality of plasmas. Specially, the internal ‘churning’ that goes on inside plasma, before and during any external fields, such as lasers supplied electromagnetic fields is offered to them.

2. Genuine Two Fluid Plasma Model

When the electron cloud is pushed by the non-linear force; the ions are subsequently dragged on by virtue of electrostatic fields. The equations

$$\mathbf{v} = \frac{m_i v_i + Zm\mathbf{v}_e}{m_i + Zm} \qquad (1)$$
$$\mathbf{j} = e\left(n_i \mathbf{v}_i - n_e v_e\right)$$

as a net velocity and for the current density have to be coupled with the Maxwell equations at the very least, the Poisson equation. The first thing to emerge from research is the fact plasmas are not free from internal electric fields at the high-frequency range of an irradiating laser. This was seen in studies of cosmic and geophysical plasma’s, by [2, 3]. This led to a real time, collisional, non-linear generalisation for these high-intensity laser fields. Transfer of energy from electrons to ions, and back again, by an adiabatic compression, had to be included. Energy from laser to electrons to ions is a vital step if a process allowing for nuclear fusion is to be realised.

To bring about fusion it is required that the nuclei of the deuterium are forced together so as to overcome the Coulomb force of repulsion. To bring them into proximity of a Fermi (10^{-15} metre). This means increasing the density of the ions, as it is the ions, which constitute the site of the nuclei. Examining some of the variables it can be seen the longitudinal electric field is zero at the outset, Fig. 1.

The electron fluid expands faster, thus developing an electric field. The electrons change direction, as discussed earlier, leading to an oscillation, which appears as the plasma frequency. This being electron density dependant. Given enough time the field becomes a uniform internal one of 10^6 Vcm^{-1} [4, 5]. Spatially this occurs over 10^{-3}cm. Once the laser is turned on at 0.6 psec, longitudinal Langmuir oscillation results. Their amplitude is about one-tenth the transverse laser field amplitude. Unfortunately non-conservative characteristics result when very strong oscillations occur due to the laser. This has been explored by workers such as [5, 6 and 7]. Indeed Umstadter found using a 25TW-pulsed laser produced 30 MeV electrons in vast numbers and the plasma acceleration mechanism resulted. [5] took the conservation equations and derived the following from the oscillation equation:

$$\frac{\partial^2 E}{\partial t^2} + v\frac{\partial E}{\partial t} + \omega_{p0}^2 E = E_{s0}\omega_{p0}^2 + \frac{4\pi e}{Me}\frac{\partial}{\partial x}\frac{E_L^2 + H_L^2}{8\pi} + 4\pi e v(n_i v_i - Z n_e v_e) \qquad (2)$$

Where

$$E_{s0} = \frac{4\pi e}{\omega_{p0}^2}\left[\frac{\partial}{\partial x}\left(\frac{3n_i kT_i}{m_i} + Z n_i {v_i}^2\right) - \frac{\partial}{\partial x}\left(\frac{3n_e kT_e}{m_c} + n_e {v_e}^2\right)\right]$$

$$\omega_{p0}^2 = 4\pi e^2\left(\frac{n_e}{m_c} + \frac{z^2 n_i}{m_i}\right)$$

The solution of which is the longitudinal electric field, the electrostatic of Langmuir, termed E_s

$$E_s = \frac{4\pi e}{W_p^2}\left[\frac{\partial}{\partial x}\left(\frac{3n_i kT_i}{m_i} + Z n_i {v_i}^2\right) - \frac{\partial}{\partial x}\left(\frac{3n_e kT_e}{m_c} + n_e {v_e}^2\right) + \frac{1}{m_e}\frac{\partial}{\partial x}\frac{E_L^2 + H_L^2}{8\pi}\right]\left(1 - \exp\left(-v t/2\cos\omega_e t\right)\right)$$
$$+ \frac{\omega_p^2 - 4\omega^2}{\left(\omega_p^2 - 4\omega^2\right)^2}\frac{4\pi e}{m_e}\frac{\partial}{\partial x}\left(E_L^2 + H_L^2\right)\cos 2\omega t + \frac{2v\omega}{\left(\omega_p^2 - 4\omega^2\right)^2}\frac{4\pi e}{m_i}\frac{\partial}{\partial x}\left(E_L^2 + H_L^2\right)\sin 2\omega t \qquad (3)$$

Fig. 1 shows the zero internal fields. At 1.1 picoseconds the field builds rapidly (over 0.2 picoseconds) and at the virtual surface of the tiny piece of plasma that is within the first 8 micrometres. The first field peaks at approximately 10^8 Vcm^{-1}, the field dropping off from 20 micrometres. The movement of the electrons surrounding their “trailing behind” ions builds the field over this distance. In reality a very short distance, nearly half an interatomic distance. Clearly the graph shows a polarity reversal at 7.5 micrometres and after time 1.2 to 1.5 picoseconds. This is evidence for the direction undertaken by the electrons and hence the ions. This is a ripple effect as can be seen by the diminished, but still visible, ripple from 10 to 20 micrometres. By 25 micrometres there appears to be little field, but a more sensitive probe should detect an ever-decreasing undulation of the field, given a larger piece of plasma.

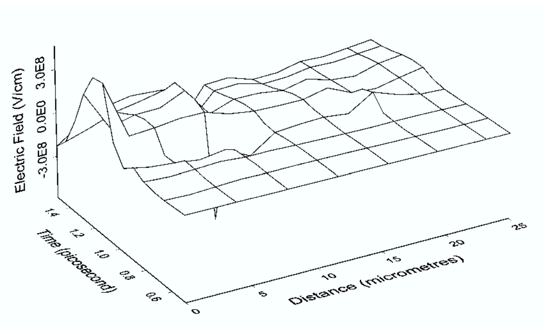

Fig. 1

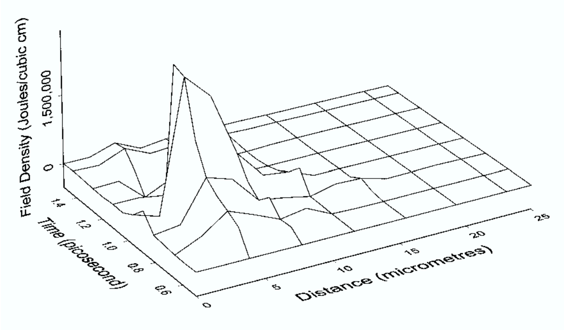

Fig. 2

Fig. 1. Electric field inside the plasma changing over time. The field being generated around the focus of the laser beam in the plasma. Fig. 2. Electric field density of the laser. The energy concentration is in Joules per cubic centimetre. A caviton can be seen at about 0.4 picosecond and at a distance of 3.5 micrometre

The actual electromagnetic energy density of the laser field is shown in Fig. 2. This graph gives an indication of how much energy is actually deposited by the laser and where/when is it available. Pulsation is again detected both over time and through distance. It an be seen to be time dependant starting at 0.6 psec, dropping off and reforming at 0.7, and so on. The maxima would correspond to strong penetration. Each ripple corresponds to acceleration stopping (Fig. 3a and 4).

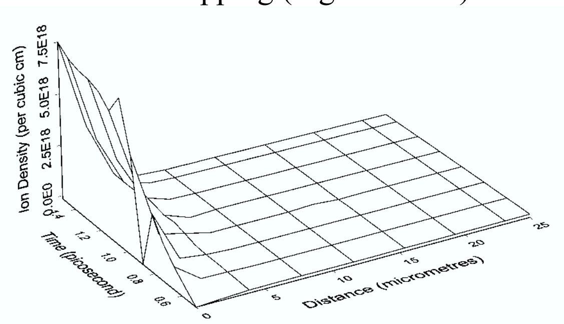

Fig. 3a

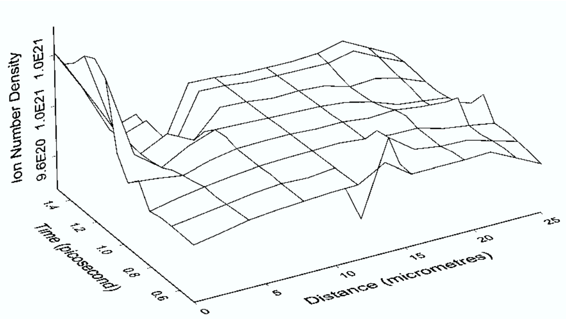

Fig. 3b

Fig. 3a. Ion density, per cubic centimetre. The number of ions being taken in order of 10^{18}. Fig. 3b. Ion number density shows the rippling effect better than ion density

By comparing Fig. 2 and Fig. 3a it can be seen the field values relate fairly well to the 'dip' in ion density at 5 or so micrometres. The wall of ions built up at the plasma surface accumulated over a few picoseconds. The movement to that position was against the direction of the laser beam. As noted a slight ripple is seen at a distance of 4-5 micrometres. Little effect is seen then until 12.5 or so micrometres on an almost unperceivable 'bump'. One would speculate that given more time and continuing irradiation this ion wall would migrate through the plasma. The pulse is better defined in Fig. 3b.

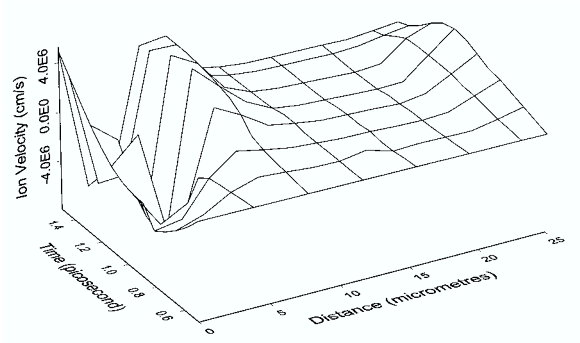

Fig. 4

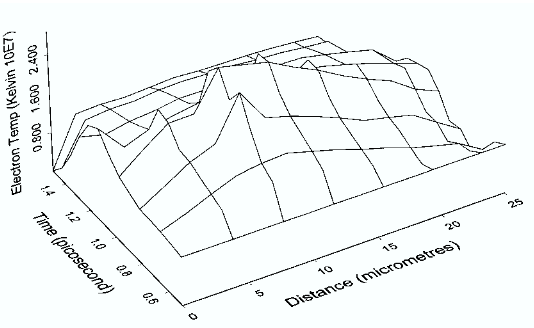

Fig. 5

Fig. 4. Ion velocity in centimetres, illustrating the surface effect of the initial activity with "calm period" leading to next rippling effect. Fig. 5. Electron temperature in units of 10^7 degrees Kelvin

Fig. 4 shows the vector nature of ion velocity. There is little movement until 0.6 picoseconds. Until that time, when the laser is activated the ions are uniformly travelling in all directions at relatively slow velocities. Fig. 5 shows a rise at 0.7 to 0.9 picoseconds on the surface. It is over the 0.7 to 1.0 picosecond the temperature rise for the electrons to migrate through the plasma. This creates a hot spot, a depth of 7.5 to 10 micrometres. This study has investigated the nature and properties of plasma by a mathematical approach. It focused in on the movement of electrons and ions in a fully ionised plasma. Electrostatic forces were added to the list of forces involved. The non-neutrality of in-homogenous plasma was examined. The distances between the particles and the effect of collisions between were viewed in terms of electric currents being evident in any plasma. Models, such as Schlüters two fluid model were examined along with the non-linear force. From Schlüters two fluid model emerged the "genuine" two fluid plasma model. The study used the two fluid model to examine internal electric fields, the plasma frequency and its relation to a laser's frequency. The simulations in the study analysed the key variables of ion density, velocity, electric field densities and temperature over time. These variables were also looked at with regards to the depth of penetration of the laser beam. This was viewed against the background of the oscillations set up in plasmas by the ions pursuing the moving electrons.

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