Observation of nonlinear propagation of relativistic and short laser pulses in under-dense plasma

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We present here the experimental observation of depletion of laser pulse due to nonlinear plasma wake excitation, which results in frequency downshift. The experiment was performed using the Astra-Gemini laser system; a laser pulse of 800nm wavelength and pulse length of ~50fs is focused by an f/20 off-axis parabola to an intensity of ~4x10^{18} W/cm^2 onto a He gas jet. The backing pressure of the He jet varied from 15 to 95bar. The emitted radiation is observed by a top-view optical spectrometer (perpendicular to the laser propagation axis). This radiation is collective, and it is not emitted from the laser pulse centre, but from cavity edges. It is observed that the average wavelength is increasing as the laser propagates through under-dense plasma for different incident laser energy and pressure of gas, due to relativistic and nonlinear effects (pulse depletion, in particular). Preliminary 2D PIC simulations reveal that the wavelength of collective radiation at 90° to the laser propagation axis dominates over other types of radiation and the wavelength gradually grows along the laser propagation axis, in agreement with the experiment.

The study of the propagation of ultra-short and intense (>10^{18}W/cm^2) laser pulses in plasmas is of fundamental importance and demonstrates a variety of nonlinear phenomena. The understanding of the interaction in this regime demands a detailed study of relativistic and nonlinear mechanisms such as relativistic self focusing [1], plasma channelling [2], dynamics of plasma channels caused by coulomb explosion [3] and nonlinear depletion of energy by the excitation of plasma waves [4]. Plasma waves excited by ultra short and intense laser pulses are the basis of highly promising electron acceleration schemes [5].

In this paper, we present the experimental observation of frequency downshift of intense femtosecond laser pulses during their propagation through underdense plasma.

The experiment was performed using the Astra Gemini [6] Ti: Sapphire laser at the Rutherford Appleton laboratory. A laser pulse of wavelength 804 nm, pulse duration of 54 fs with energy varying from 3 to 10 J is focused to an intensity of order of 10^{18} W/cm^2 onto a He gas jet. A conical supersonic helium gas jet has the orifice diameter of 0.5 mm; the smaller diameter nozzle is used to avoid very high-energy electron acceleration. The electrons are deflected by a permanent magnet (0.7 T, 30 cm). The densities are estimated from the neutral gas density assuming double ionization of He atoms; this assumption is justified by the high intensity of the laser pulse, which exceeds the threshold of the barrier suppression ionization by a few orders of magnitude.

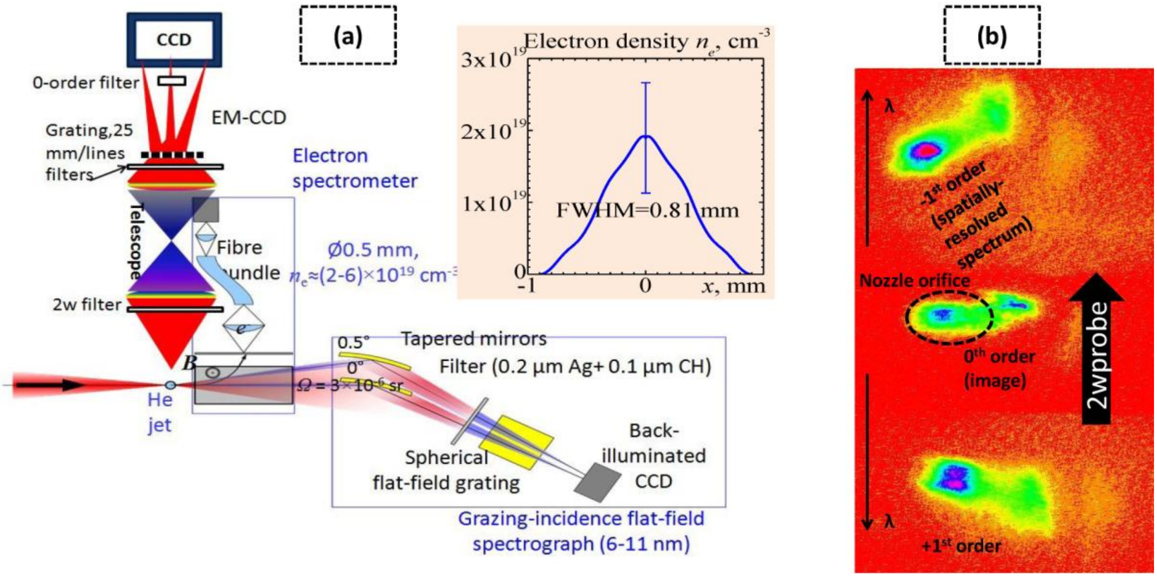

Figure 1:- (a) the experimental setup schematic, inset shows He plasma density profile; (b) the raw image detected by top view optical spectrometer, circle on the 0^{th} order showing the nozzle orifice.

The neutral gas density profiles are measured with an interferometer. The FWHM of the density distribution is 0.8 mm, the peak density varied from (1.0±0.4)×10^{19} cm^{-3} to (4.0±1.7)×10^{19} cm^{-3}. An optical spectrometer is installed perpendicular to the laser propagation axis, as shown in the experimental setup (Figure 1 (a)). The arrow shows the laser beam direction. The top-view optical spectrometer (TOS) consists of an imaging system, 25 grooves per millimetre grating, a band pass filter (400-550nm), and a CCD. The figure 1(a) shows a typical raw image obtained with the top view spectrometer.

In this section, the results obtained from the top-view optical spectrometer are presented and discussed. The figure 2 (a) shows that the wavelength is increasing for different pressures at specific laser energy; the figure 2(b) depicts the up-shift in wavelength at a specific pressure for different laser energies. The wavelength upshift (frequency downshift) does not depend on the incident laser energy and pressure of He gas jet. On the other hand, no variation in wavelength is observed at very low energies (mJ) of the incident beam, confirming the nonlinear nature of the phenomenon. The relativistic and nonlinear phenomena involved in the laser plasma interaction and their effects on laser pulse are described as follow.

When the intense laser pulse is focused on a supersonic flow of gas, in the early stage the gas is ionized by tunneling or multi photon ionization. As the intensity ramps up, the electrons stripped from atoms start quivering at velocities close to velocity of light (*c*). The electron quivering momentum significantly exceeds $m_e c$, where m_e is the electron rest mass and c is the speed of light. The relativistic change in the electron mass alters the plasma frequency, which results in modification of refractive index of the plasma. As the laser

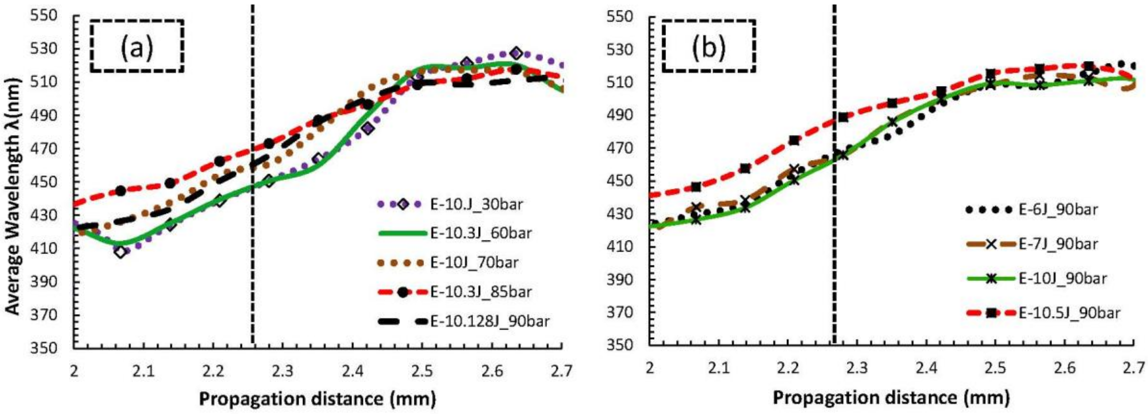

Figure 2: Variation of average wavelength with respect to the laser propagation distance for (a) different gas jet pressures at specific laser pulse energy of 10J; (b) different laser energies at particular pressure of 90 bar. The dashed line shows the centre of the gas jet.

intensity profile is peaked on axis, the refractive index is maximal on axis, which causes the wave front to curve inward and the laser beam to converge (self-focus) with the corresponding increase of intensity. The phase velocity of the laser is related to the refractive index, so the local changes in the phase velocity modify the temporal and spatial profiles of the laser intensity. In the mean time, the laser's radial ponderomotive force pushes the electrons away from laser axis, creating electron cavitation [7], which gives rise to modulating refractive index. The intensity modulation, along with ponderomotive and relativistic self focusing and channelling, lead to various nonlinear phenomena such as self modulation, Raman scattering, and nonlinear depletion of laser pulse energy. The energy depletion of the intense laser in the course of the interaction is due to the plasma wave excitation [4, 8] and the rate of energy deposition is dependent on laser parameters and plasma density [8]. Hence, the evolution of the laser pulse proceeds in two phases; plasma is modulated within the laser pulse leading to steepening [4] and pulse compression; and frequency red-shifts as the energy is deposited into the plasma [8].

In summary, we observe optical radiation in the direction perpendicular to the laser axis. This radiation is generated from the walls of the cavitated ion channel, where the electrons density is at its maximum. The radiation frequency gradually downshifts as the laser propagates in the plasma, due to the energy depletion. Energy depletion by plasma wave excitation results in acceleration and heating of electrons and the downshift in frequency can eventually lead to spatially locked electromagnetic solitons [4].

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