*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, O-1.006 (2005)*

Propagation of high order harmonics in dense relativistic plasmas

W. Rozmus[1], A. Robinson, R. Evans, A. E. Dangor, K. Krushelnick
Blackett Laboratory, Imperial College, London, SW7 2AZ, UK
[1] on leave from Physics Department University of Alberta, Edmonton, Canada

Introduction. High intensity short laser pulse interactions with thin foil targets have been studied in simulations and experiments primarily as a source of fast ions. Ion acceleration occurs at the target back side and is produced by the space charge electrostatic fields set up by relativistic electrons escaping the plasma at the rear surface. Transport and generation of relativistic electrons in such plasmas are fundamental, not only to ion acceleration, but also to laser light absorption, plasma instabilities, and magnetic field generation. In this paper we show that high harmonic spectra which were measured on the front and back side of a dense target (between the 7th and 12th orders) include information about the physics of short pulse driven plasma including all of the listed above processes. This experiment [1,2] was performed using the VULCAN laser system at the Rutherford Appleton Laboratory producing pulses of τ_p=0.8ps duration at λ_0=1.053μm with energies up to 70 J and intensities 9 10^{19} W/cm^2 onto targets. Because of the contrast ratio (~ 10^{-6}) the interaction occurs between the main pulse and the already preheated foil plasmas at densities <20 n_{cr} as shown in hydrodynamical simulations [1]. The laser spot size was 20 μm, which was larger than the longitudinal size of the preheated foil estimated to be 5 μm from the hydrodynamical simulations. A short pulse plasma interaction leads to density profile steepening at the critical density surface due to the strong ponderomotive force. This enables application of the oscillating mirror model [3,4] to explain the generation of the observed harmonics. Unlike harmonics in recently published studies [5,6], they originate from the same source but display different spectral features when observed at the front and at the back side due to interaction with the relativistic plasma while crossing the target. References [5,6] have involved bunched relativistic electron beams which locally resonate with nonlinear plasma waves giving rise to harmonics at the same frequencies [5] or emit coherent transition radiation when crossing the back surface [6]. Dense plasma of the target was opaque to these harmonics. Alternatively, the shift towards higher order harmonics has been observed in [1] when the initial thickness of the foil and corresponding density of preheated plasma are increased. Only radiation with high enough frequencies for which the target is underdense has been observed in the back.

Index of refraction. Propagation of high frequency radiation in relativistic plasmas is described by the dispersion relation for two, cold (density - n_c, temperature - T_c) and hot (n_h, T_h), electron populations

$$\frac{k^2c^2}{\omega^2}=1+\sum_{\alpha=c,h}\frac{\omega_{p\alpha}^2}{\omega^2}\left[\int d^3p\,\frac{v_x}{1-kv_z/\omega}\frac{\partial f_\alpha}{\partial p_x}\right], \qquad (1)$$

where electromagnetic radiation is described by a plane wave (ω,k) propagating in the z-direction with an electric field pointing in the x-direction, $\omega_{p\alpha}=(4\pi e^2 n_\alpha/m_e)^{1/2}$ and f_α (α=c,h) are electron distribution functions. Describing the interaction experiment on the ps time scale with intensities approaching 10^{20} W/cm^2 and the initial thickness of the preheated foil plasma L_0~5μm we have assumed a relativistic electron distribution function in the Maxwellian form, $f_h=\exp[-c(m^2c^2+p^2)^{1/2}/T_h]/(4\pi m^2cT_hK_2(mc^2/T_h))$. Such a choice is consistent, for example, with the fast electron recirculation in a target [7]. The temperature T_h is given by the ponderomotive scaling [8] at approximately 4 MeV. With cold electrons described by the Maxwellian at T_c=1keV the dispersion relation (1) yields an approximate solution (cf. e.g. [9])

$$\left(\frac{kc}{\omega}\right)^2=1-\left(\frac{\omega_{pc}}{\omega}\right)^2-\frac{1}{3}\frac{mc^2}{T_h}\left(\frac{\omega_{ph}}{\omega}\right)^2, \quad \left(\frac{mc^2}{T_h}\ll 1,\ \frac{kc}{\omega}\le 1\right), \qquad (2)$$

where contributions to the index of refraction, $\eta=kc/\omega$, due to relativistic electrons are much smaller by comparison with the usual cold electron term. Thus, in thin foil plasmas heated by short pulse lasers which deposit energy into relativistic electrons the index of refraction (2) changes in time because of the variation in the composition of the target where the density of cold electrons is decreasing with the increase of n_h.

Generation of fast electrons. We characterize fast electron production in terms of basic relations involving energy conservation and scaling laws. At time t the number density of hot electrons occupying the region extending to $L_h(t)$ could be found from the absorbed laser energy, $3\,T_h\,n_h(t)\,L_h(t)/2=\int dt'\,I_{abs}(t')$, where $I_{abs}(t)=AI_0\sin(\pi t/\tau_p)$, A is an averaged absorption coefficient and τ_p defines pulse duration. During the target evolution the total number of electrons remains constant and within the one dimensional approximation is defined by $n_e\,L_0=n_h(t)\,L_h(t)+n_c(t)\,L(t)$, where L_0 is the initial dimension of the preheated foil, the length L(t) is defined by the cold electron expansion which follows ion motion and spreading out of the plasma. From the above relations we find the time varying cold electron density,

$$\left(n_e - \frac{4}{3\pi}\frac{\tau_p A I_0}{T_h L_0}\sin^2\left(\frac{\pi t}{2\tau_p}\right)\right)\frac{L_0}{L(t)} = n_c(t) \qquad (3)$$

Harmonics. The oscillating plasma mirror model [3,4] explains the source of higher harmonics in short pulse laser dense plasma interactions through the nonlinear dynamics of the critical surface using the cold electron fluid model approximation. The transverse surface current at the critical density reemits radiation at higher harmonics. For frequencies larger than 5ω_0 they can also propagate through the overdense plasma of the preheated foil and contribute to the spectra observed at the back side of the target [10]. Following [4] we describe the critical surface motion in terms of the superposition of oscillations at two frequencies ω_0 and 2ω_0. This leads to the oscillating mirror model spectrum in Fig 1. Positions of calculated harmonics are in good agreement with the observed spectrum at the front of the target. Harmonics observed in the back side display red shift, broadening and additional structure in the spectrum due to plasma effects. The amplitudes of different peaks in the experimental spectra are due to the sensitivity variation of the detector. The observed maximum intensity at approximately 10th harmonic is also the result of this variation in instrumental sensitivity.

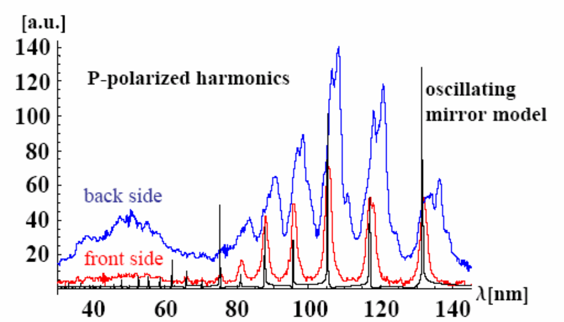

Fig.1 *High harmonics spectra in the back and front sides of the target in comparison with the oscillating mirror model.*

The line-shape. Higher harmonics, which propagate through a target provide an optical diagnostic of relativistic dense plasmas. Their spectral properties, such as red shift, reflect time variations of the index of refraction (2) occurring due to decreasing number density of cold electrons (3) during laser light absorption and plasma expansion. We use the spectral line corresponding to the 10th harmonic on the front side of the target to estimate the instrumental width on the order of < 1 nm by comparing the measurement with the oscillating mirror model calculations. The frequency shift of the p-polarized 10th order line behind the target is shown in Fig. 2. We estimate its magnitude by calculating the Fourier transform of the plane wave solution with the phase defined by $\varphi=\omega_{10}(t-L(t)\eta_{10}(t)/c)$, where $\omega_{10}=10\ \omega_0$, η_{10} is the index of refraction (2) calculated at $\omega=10\ \omega_0$ for the time varying density n_c (3). To estimate plasma extent we take $L(t) = L_0+c_s t$, where $c_s=(ZT_h/m_i)^{1/2}$ is the sound velocity characterizing self-similar plasma expansion on the back side of the target [11]. In fact to achieve as good an agreement as shown in Fig. 2 we have varied in time an expansion velocity in L(t) from 0.1 c_s to c_s during the pulse duration. By adding this additional time change to the pulse intensity and density variations we have obtained the frequency chirp of the harmonic line in agreement with the measurement.

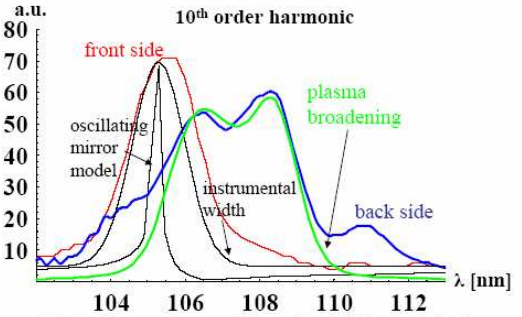

Fig.2 *Measured spectral lines of the 10th harmonic in the front and back sides of the target in comparison with the oscillating plasma mirror model and relativistic plasma effects*

Conclusions. We have explained spectral features of the harmonic radiation from the thin foil target in terms of physical processes characterizing relativistic electron plasma and expansion of multispecies targets. The talk and further studies will elucidate additional features of the harmonic spectra by relating them to the rarefaction shock and the strong self-generated magnetic field which explains measurement of the s-polarized harmonics.

References

[1] U. Wagner, P. Norreys, A. Gopal, *et al.* Central Laser Facility Annual Report, RAL (2003/2004);

[2] U. Wagner, M. Tatarakis, A. Gopal *et al*. Phys. Rev. E **70**, 026401 (2004).

[3] S. V. Bulanov, N. M. Naumova, and F. Pegoraro, Phys. Plasmas **1**, 745 (1994).

[4] R. Lichters, J. Meyer-ter-Vehn, and A. Pukhov, Phys. Plasmas **3**, 3425 (1996).

[5] U. Teubner, K. Eidman, U. Wagner, *et al*. Phys. Rev. Lett. **92**, 185001 (2004).

[6] H. Popescu, S. D. Baton, F. Amiranoff, *et al*. Phys. Plasmas **12**, 063106 (2005).

[7] A. J. Mackinnon, *et al.* Phys. Rev. Lett. **88**, 215006 (2002).

[8] S. C. Wilks, *et al.* Phys. Rev. Lett. **69**, 1383 (1992).

[9] V. P. Silin, Soviet Physics JETP **11**, 1136 (1960).

[10] P. Gibbon, D. Attenbernd, U. Teubner, *et al.* Phys. Rev. E **55**, R6352 (1997).

[11] V. Yu. Bychenkov, *et al.* Phys. Plasmas **11**, 3242 (2004).