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EDITORS

M. Lontano
Istituto di Fisica del Plasma "Piero Caldirola," C.N. R., Milano, Italy

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F. Pegoraro
Dipartimento di Fisica, Universitá di Pisa, Pisa, Italy

E. Sindoni
International School of Plasma Physics "Piero Caldirola," Milano, Italy

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HIGH INTENSITY 30 FEMTOSECOND LASER PULSE INTERACTION WITH THIN FOILS

A.Giulietti, A. Barbini, P.Chessa* ,
D.Giulietti#, L.A.Gizzi, D.Teychenné#

Istituto di Fisica Atomica e Molecolare del CNR
Via del Giardino, 7, 56127 Pisa, Italy

 # Dipartimento di Fisica, Università di Pisa, Italy
* *Laboratoire d'Optique Appliquée, - ENSTA , Palaiseau , France*

Abstract. An experimental investigation on the interaction of 30 femtosecond laser pulses with 0.1 and 1.0 µm thick plastic foils has been performed at intensities from 5×10^{16} to 5×10^{18} W/cm^2. The interaction physics was found to be definitely different whether the nanosecond low intensity prepulses led to an early plasma formation or not. In the first case high reflectivity and very low transmittivity were observed, together with second and three-half harmonic generation. In absence of precursor plasma, with increasing intensity, reflectivity dropped to low values, while transmittivity increased up to an almost complete transparency. No harmonic generation was observed in this latter condition, while ultra-fast ionisation was inferred by the blue-shift of the transmitted pulse. Finally, intense hard X-ray emission was detected at the maximum laser intensity level. Current theories or numerical simulations cannot explain the observed transparency. A new model of magnetically induced optical transparency (MIOT) is briefly introduced.

INTRODUCTION

Since the last generation of powerful femtosecond lasers was available, a new, exciting class of experiments has begun. The virtual lack of hydrodynamic expansion during the pulse interaction with solids makes it possible to achieve the completely unexplored physical domain of extremely high fields in solid-density ionised matter. From an experimental point of view, a serious problem that can prevent interaction of short pulses with solid-density plasmas may arise from the laser prepulse originating from amplified spontaneous emission (ASE) in the laser amplifier chain. If the intensity on target due to the prepulse (typically of nanosecond duration) is higher than the threshold intensity for plasma formation on target, a precursor plasma is formed which prevents the main femtosecond pulse to interact directly with the solid. In a previous experiment ([1]), it was shown that the use of targets consisting of thin plastic foils may avoid formation of precursor plasma, enabling the interaction of the main femtosecond pulse with high density laminar plasmas characterised by ultra steep gradients.

In this paper we report novel experimental results on the interaction of 30fs laser pulses delivered by the Ti:Sapphire system of the Laboratoire d'Optique Appliquée, focused onto either 0.1 or 1.0 µm thick plastic foils at intensities ranging between 5×10^{16} and 5×10^{18} W/cm^2. The effect of the prepulse was accurately tested for each series of measurements. The interaction physics, and consequently the observed effects, resulted definitely different, whether the nanosecond low intensity prepulses led to an early plasma formation or not. In condition of precursor plasma (*preplasma*) formation by the prepulse, the high intensity femtosecond pulse interacted with the preplasma and was strongly reflected. In this condition the fraction of the laser light transmitted through the target, if any, was merged into the experimental background level, while generation of both 2ω and 3/2ω harmonics of the laser light was observed. The space-resolved spectra of those harmonics showed interesting features.

A completely different scenario was observed in absence of preplasma, when the femtosecond pulse could interact with the unexploded foil. The most surprising result concerns the transmittivity ([2]). We found that when the laser intensity on target is greater than 10^{17} W/cm^2, the transmittivity goes above the experimental background level of ≈1% and increases dramatically with laser intensity, approaching full transparency at intensities above 10^{18} W/cm^2. To our knowledge, this is the first time that such effect is observed in the laser interaction with a solid density plasma. As the transmittivity increases, the reflectivity drops and reflection is mostly restricted to the boundaries of the laser spot on target. This fact produces an interesting effect of spatial filtering of the transmitted pulse. At intermediate intensity the partially transmitted light shows a definite blue shift due to self phase modulation, from which the time scale of the ionisation was estimated. No harmonics were detected in absence of preplasma. Also the spectrum of the X-rays emitted during the interaction was considerably affected by the presence or absence of the preplasma. As the analysis of a large number of data related to the X-ray measurements is still in progress, this part of our measurements could not be included in the present paper.

It is very important to point out that the current theory of laser interaction cannot account for the almost full transparency of 0.1 and 1.0 µm plastic foils to laser radiation at 3×10^{18} W/cm^2. Several effects have been considered that predict enhanced propagation, including anomalous skin effect([3]), self induced transparency ([4]), hole boring([5,6]). Hole boring and self-induced transparency have been mostly studied for density higher than, but comparable with the critical density, while in our experiments the electron density is close to the solid density, in absence of preplasma. Self-induced transparency needs ultra-relativistic fields, while we observed quasi-transparency at an intensity corresponding to a weakly relativistic field. In what concerns the anomalous skin effect, a description of this process in plasmas has been given by Weibel ([7]). Recently the anomalous skin-effect in solid-density plasmas has been considered both analytically ([8]) and numerically ([9]). Transmittivity is predicted higher than the in the case of normal skin effect, but still very lower than what we have measured. In the last section of this paper we briefly introduce an original theoretical model ([10]) of magnetically induced optical transparency (MIOT). The model assumes the existence of a static magnetic field of high intensity parallel to the oscillating magnetic field, and accounts for the observed high transmittivity of solid density plasmas to ultra-short pulses of weaklyrelativistic intensity. The generation of such an intense magnetic field may be ascribed to the electron motion in the dense matter under the action of the ultra-short e.m. wave-packet.

EXPERIMENTAL TECHNIQUE

The experiment was performed using the advanced Ti:Sapphire laser system recently developed at LOA. The 815nm, 30fs laser pulse was focused f/7.5 onto either a 0.1 or a 1.0 µm thick plastic foil target, using an off-axis parabolic mirror, with an angle of incidence on target of 20 degrees. The laser pulse was linearly polarised with the electric field in the plane of incidence (*P*- polarised). The focal spot was 10µm in diameter; the intensity on target was varied from 5 10^{16} to 5 10^{18} W/cm^2, by varying the energy in the pulse. The transmitted pulse was studied by using a diffusing screen placed beyond the target, on the laser propagation direction, at a distance 1.8 times the focal length of the focusing optics. A de-magnified image of the screen was formed onto a CCD array and on the entrance slit of a spectrometer. A second CCD array was placed on the output focal plane of the spectrometer. An additional channel was set up on the specular reflection direction, with the object plane located at the target plane. Also this channel was equipped with both an imaging CCD and a spectrometer with CCD, giving a space resolved spectrum of the reflected light. In addition, we monitored the soft X-ray emission (≈1-10keV) by means of a PIN diode and the hard X-ray yield (up to several MeV) by using six NaI(Tl) crystal scintillators, coupled to photomultiplier tubes.

The laser system was characterised by an ASE lasting approximately 10ns, forming a “pedestal” to the main pulse. The measured contrast ratio, i.e., the ratio between the power delivered in the fs pulse and that delivered in the ASE was ≥ 10^7. A severe test on the effect of the ASE on target was performed by firing the laser system, without injecting the fs pulse in the amplifier chain. In this condition, for a distinct set of measurements, we observed no damage on target over the whole range of ASE intensities. In this case we concluded that in full shots the target does not explode before the arrival of the femtosecond pulse. This test is indeed, for two distinct reasons, a proof “a fortiori”. Firstly, since no energy is spent in the amplification of the fs pulse, the level of ASE is greater than in the case of operation with fs pulse injection. Secondly, only the leading part of the ASE pulse prior to the arrival of the main fs pulse is relevant in determining the interaction conditions of the main pulse. Atomic excitation and partial ionisation in the target due to ASE cannot be excluded, but definitely the target does not explode prior to the high power pulse impact. So, we can state that the set of measurements described below as "interaction with no preplasma" are the actual result of interaction of the short pulse with the unexploded foil.

INTERACTION IN PRESENCE OF PRECURSOR PLASMA

In a few series of shots the prepulse was able to explode the thin target, allowing the formation and expansion of a preformed plasma, which then interacted with the 30 fs pulse. In this condition the short pulse was not transmitted though the plasma, while a considerable fraction of the pulse energy was specularly reflected. A typical monochromatic (at the laser wavelength) image of the target plane taken in the specular direction is shown in Fig. 1. The image evidences the distribution of the laser reflecting centres in the plasma. The pattern is similar to the far field pattern of the laser beam, including the diffraction rings. However in the reflected pattern there are two central maxima in place of one. This may be due to some misalignment in the focusing optics or to non-uniformity of the preformed plasma. Since the central part of the pattern was not reproducible shot by shot, the second explanation seems more likely.

In the same interaction condition also 2ω and 3/2ω harmonics generated specularly were observed. Space resolved spectra showed that blue and red shift of the second harmonic light originates in different regions, and may give useful information on the interaction of the ultra-short pulse with the precursor plasma. On the other hand, the observation of the 3/2ω harmonic is clear evidence that the plasma has expanded and developed an $n_c/4$ layer with a finite scalelength.

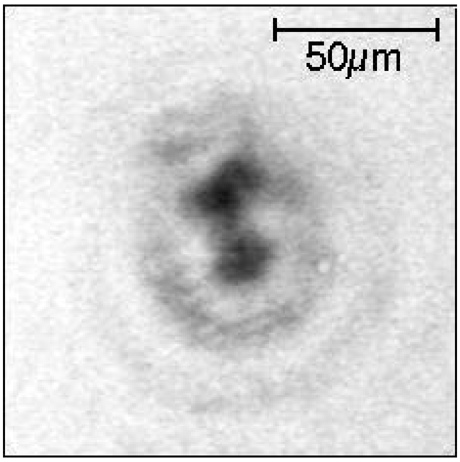

Figure 1. Monochromatic image (at the laser wavelength) of the target plane. The image was obtained in the specular direction in presence of precursor plasma. Laser intensity: 3×10^{18} W/cm^2; foil thickness: 1.0 µm.

INTERACTION WITH NO PRECURSOR PLASMA

A completely different scenario was found when the prepulse was not able to explode the foil before the arrival of the 30 fs pulse. No 2ω nor 3/2ω harmonics were observed. The most striking feature discovered in this condition of direct interaction of the short pulse with the solid foil was a high level of transmittivity above a given threshold of the laser intensity.

Transmittivity vs. laser intensity

The dependence of transmittivity as a function of the incident laser intensity is presented in the plot of Fig. 2. Open dots refer to 0.1 µm thick targets, the solid dot refers to the 1.0 µm case. Each data point was obtained by taking into account several interaction events for each laser intensity and by averaging the results. The error bar was estimated by the standard deviation of the set of data considered. The *background* line reported on the graph indicates the level at which the transmitted energy is comparable with the ASE energy (close to 1% of the main pulse energy) and consequently below this level the measurements cannot be entirely related to the main pulse. According to the plot of Fig.1, the transmitted fraction at incident intensities below 10^{17} W/cm^2 lies within the experimental background level. However, as the incident intensity increases, the transmitted fraction increases dramatically and the target becomes basically transparent at 3 10^{18} W/cm^2.

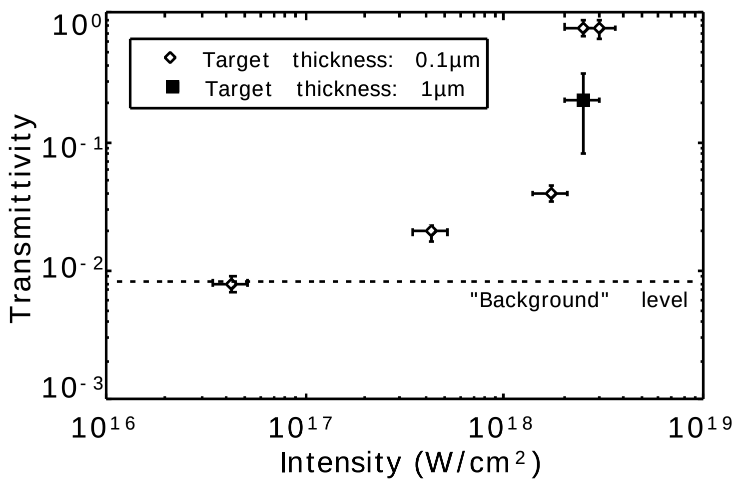

Figure 2. Transmittivity as a function of the intensity of the 30fs laser pulse. Open dots: 0.1 µm foil; solid dot: 1.0 µm foil. The background level indicates the level at which the energy in the pedestal (ASE) is comparable with the transmitted energy.

Transmittivity vs. target position

The transmittivity at the intensity of 2.5 10^{18} W/cm^2 was measured for different target positions along the laser propagation axis. The results are plotted in Fig.3, where the position "0" corresponds to the nominal focus of the parabolic mirror. Open dots refer to 0.1 µm thick targets, solid dots refer to the 1.0 µm case. The maximum transmittivity is observed when the target is beyond the nominal focus. The range of positions allowing high transmittivity in the case of 1.0 µm thick foil is of the order of few 1-2 Rayleigh lengths.

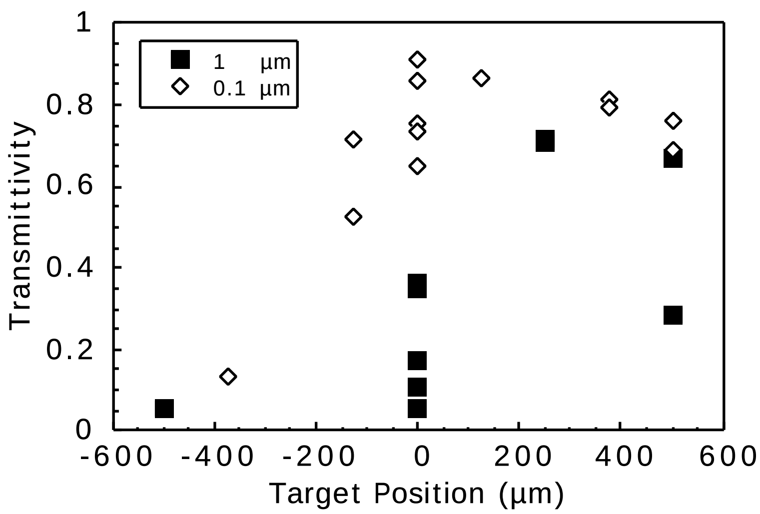

Figure 3. Transmittivity of the 30fs laser pulse, at an intensity of 2.5 10^{18} W/cm^2, for different target positions. Open dots: 0.1 µm foil; solid dots: 1.0 µm foil.

The reflected pulse

The pulse reflected in absence of preformed plasma was spectrally analysed and no 2ω nor 3/2ω harmonics were detected. Images of the target plane were also obtained. A typical monochromatic image taken in the specular direction at 3 10^{18} W/cm^2 is shown in Fig. 4. It is interesting to compare this pattern with the one of Fig.1, obtained at the same intensity, but in presence of the preformed plasma: the pattern of Fig.4, corresponding to no precursor plasma and high transmittivity, shows reflection mostly at the boundary of the laser spot, and is somehow complementary to the pattern of Fig.1, in which the dominant reflection comes from the centre of the spot.

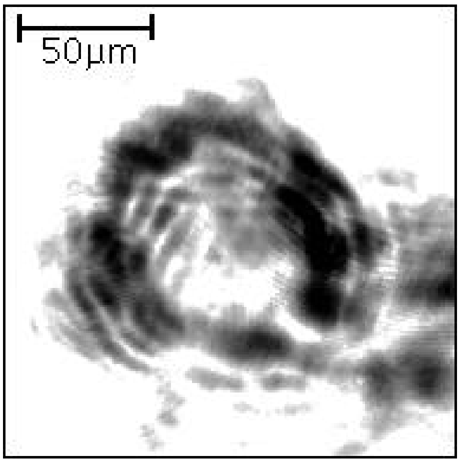

Figure 4. Monochromatic image (at the laser wavelength) of the target plane. The image was obtained in the specular direction in absence of precursor plasma. Laser intensity: 3×10^{18} W/cm^2; foil thickness: 0.1 µm.

The transmitted pulse

The near-field pattern of the transmitted pulse was also recorded. Pictures a) and b) of Fig. 5 show the transmitted pulse after propagation beyond the focus at high intensity (3 10^{18} W/cm^2); straight lines are spatial markers. Picture a) was obtained without target, and shows the near field of the unperturbed pulse; picture b) shows the near field of the pulse after interaction with a 0.1 µm thick plastic foil. Pictures c) and d) of Fig. 5 were obtained by two dimensional Fourier transform of the intensity patterns a) and b) respectively. It is evident that the spatial modes of higher order are suppressed by the 30 fs pulse interaction with the target, resulting in an effective spatial filtering of the high intensity laser light.

Evidence of ultra-fast ionisation

The transmitted pulse was also spectrally analysed at different intensities with and without target. The spectra of the pulse propagated without target have a bandwidth close to the Fourier limit for a pulse with a 30fs FWHM gaussian temporal profile. The spectra of the pulse after interaction with the foil target show that the interaction process produces a clear blue shift at moderate (5 10^{16} W/cm^2) and intermediate (4

10^{17} W/cm^2) intensities, while the spectrum of the pulse transmitted at the highest intensity (3 10^{18} W/cm^2) is basically unaffected. The spectral properties of the transmitted pulse were found to be stable shot to shot, except at the intermediate intensity, were shot-to-shot variations in shift and width were observed. The blue shift in the spectrum of the transmitted pulse is a clear signature of ultra-fast ionisation.

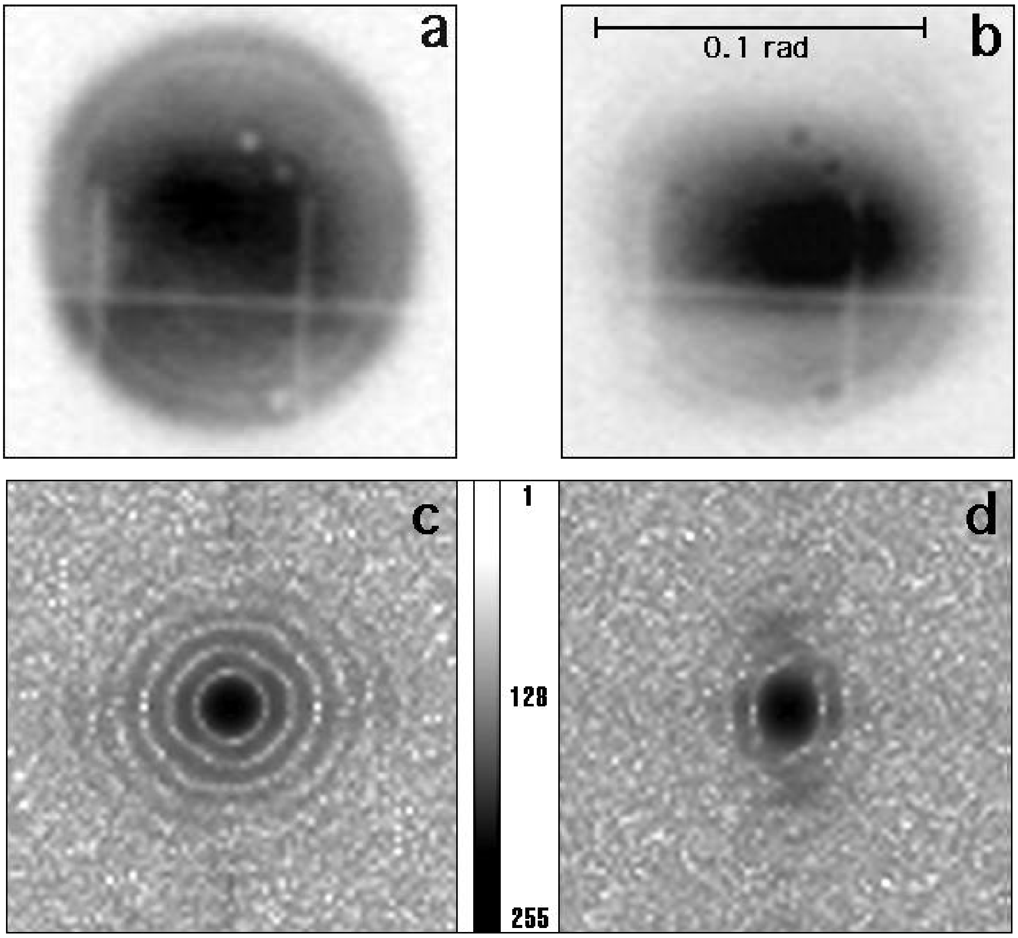

Figure 5. **a**) Near field pattern of the pulse propagated without target; **b**) with 0.1 µm foil. Laser intensity: 3 10^{18} W/cm^2. **c**) and **d**) are two-dimensional Fourier transforms of pictures a) and b) respectively. The log of the modulus of the FT is shown as a grey- scale.

This is well supported also by the amount of the blue shift, which is about 13 nm at 5×10^{16} W/cm^2, and about 20 nm at 4×10^{17} W/cm^2. Let us attribute the shift to self-phase modulation of the laser pulse, namely to the ultra-fast decrease in the refractive index due to the laser induced ionisation. Considering a change $\Delta\mu \approx -1$ in the refraction index, due to the transition from zero electron density to the critical density, we can evaluate the time scale Δt of such a transition from the approximate expression of the frequency shift produced by self-phase modulation ([11]):

$$\delta\omega \approx (L/c)(\Delta\mu/\Delta t)\,\omega_0.$$

Taking the interaction path L equal to the foil thickness 0.1 µm, we found $\Delta t \approx 20$ fs and $\Delta t \approx 13$ fs for the low and intermediate intensity, respectively. The definite consistency of these values, confirms that an ultra-fast ionisation actually occurs. The absence of shift in condition close to the full transparency, namely at 3×10^{18} W/cm^2, suggests that in this case the ionisation involves a negligible portion of the pulse, while the spectral variability observed at intermediate intensity may be due to the proximity of a sort of threshold for the effect leading to the transparency.

Magnetically induced optical transparency

The observed high transmittivity cannot be explained by the current theories on propagation of high intensity light in dense plasmas. Self-induced transparency due to the relativistic change of the electron mass is a marginal effect in our condition of weakly relativistic intensity ($a_0 = 1.2$, where $a_0 = eE_0/m\omega c$ is the relativistic parameter). The transmission due the anomalous skin effect has been evaluated by Matte et al. for thin foils ([7]) . Those calculations give for the conditions of our experiment a transmittivity of 10^{-6} up to 10^{-5}, much lower than the values we have measured. In what concerns the possibility of hole-boring due to the action of ponderomotive forces, it has been proved to be effective for plasma of density below or slightly above the critical density. However this kind of effect is ruled out in our condition of solid density plasma, in which enormous Coulomb restoring forces prevent electrons from depleting the 10 µm wide focal region.

The creation of extremely intense magnetic fields in the interaction between the laser pulse and the foil may trap electrons and induce transparency. Even though the actual mechanism of creation of such a magnetic field has to be still clarified, it may be useful to shortly discuss the effect of a static magnetic field in the propagation of the short pulse through a solid density plasma. In particular, if we assume the presence of a quasi-static magnetic field parallel to the oscillating magnetic field of the e.m. wave ([10]), with some suitable physical assumptions that are not discussed here, the single electron motion may be studied, and the refractive index may be qualitatively evaluated. We find that the equation of motion of the electron will be a typical Hill equation, with no analytical solution, unless we restrict ourselves to a limited range of values of the leading parameters. We consider the relativistic parameter a_0 of the laser wave, and the normalised cyclotron frequency $\Omega = \omega_c/\omega = eB_s/m\omega c$. We fixed a_0 to its maximum value of our experiment, say 1.2, and we looked for the electron motion, in the direction of the oscillating electric field $\mathbf{E}_\omega$, for various values of Ω, during the 30 fs pulse. Two classes of solutions were found: the first one regular and with limited values of the momentum transferred by the e.m. field to the electron; the second one chaotic and with the momentum dramatically growing in time. We also considered the refractive index of the plasma

$$\mu = \sqrt{1 - \frac{n_e}{n_c}\,\frac{\beta_\psi\ \mathbf{a}}{|\mathbf{a}|^2}}$$

expressed in terms of the normalised electron velocity along $\mathbf{E}_\omega$, $\beta_\psi = \mathbf{v}_\psi/c$, and the normalised vector potential $\mathbf{a} = e\mathbf{A}/mc$.

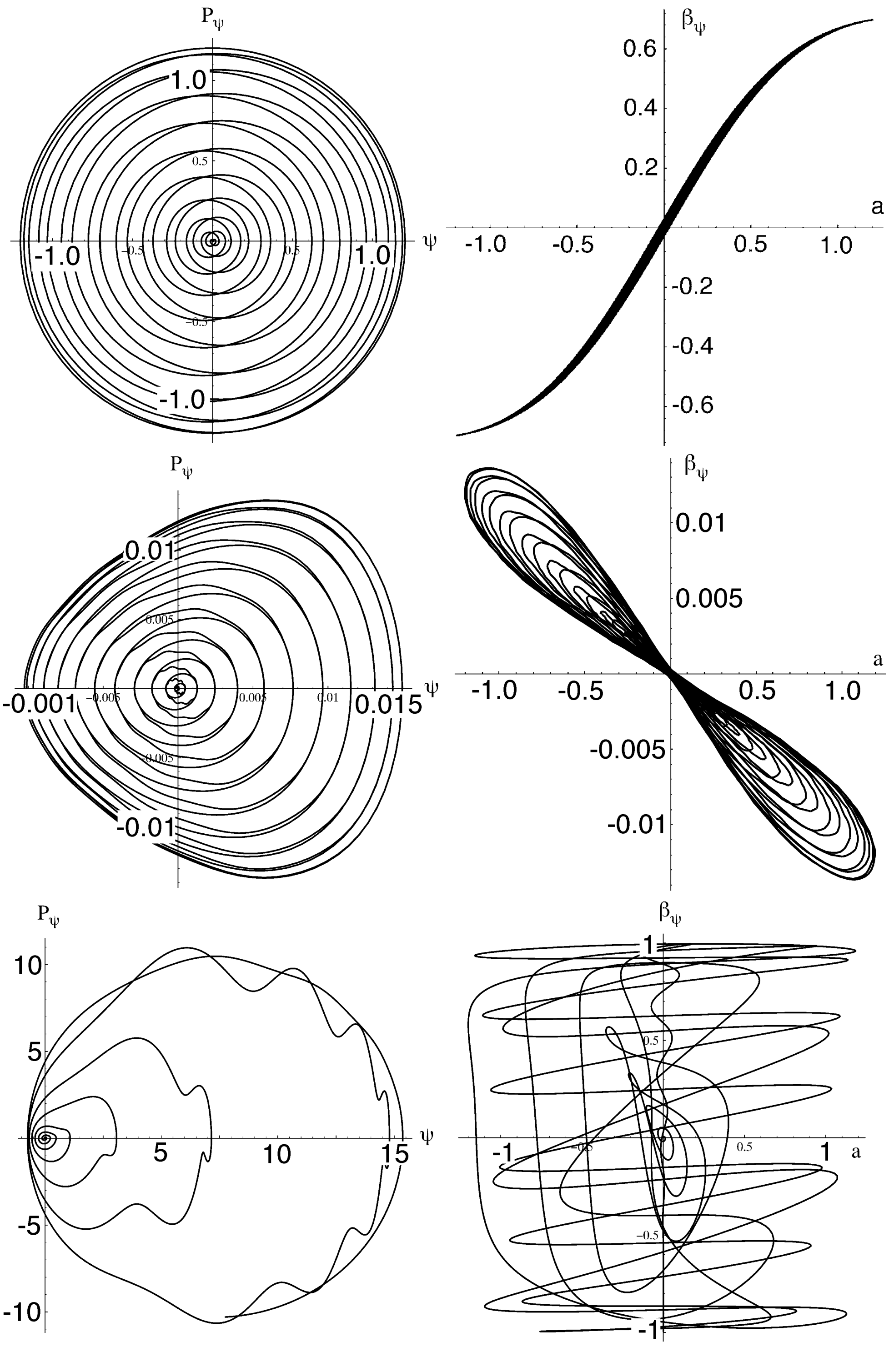

Figure 6. Left hand side: phase-space diagrams of the electron motion during the 30 ps pulse whose peak intensity corresponds to a_0 = 1.2. **Right hand side:** β versus a diagrams. **Top:** $\Omega = 0$. **Middle:** $\Omega = 10$. **Bottom:** $\Omega \approx 1$.

Transparency may occur only if μ is real. In the case of negligible magnetic field, the refractive index reduces to $\mu = (1 - n_e / \gamma n_c)^{1/2}$ where γ is the relativistic Lorenz factor; then μ can be real only if $\gamma n_c > n_e$, as for the relativistically self-induced transparency. For high magnetic fields the refractive index may be written in the form $\mu = \{1 - (n_e / n_c) [1 / (1 - \Omega^2)]\}^{1/2}$, and it is real if $\Omega > 1$, regardless of the value of the electron density n_e.

This latter is the most interesting case in order to interpret the anomalous transparency of a solid density plasma to a weakly relativistic femtosecond pulse that we have observed. Fig. 6 shows some numerical results for 30 ps pulses whose peak intensity corresponds to $a_0 = 1.2$. The top refers to the case $\Omega = 0$ and shows a regular motion of the electron with the maximum moment transferred by the wave of the order of 1. Transparency is not allowed, as β and **a** keep parallel during the pulse. The middle corresponds to $\Omega = 10$; the electron motion is still regular but the transferred moment is reduced to 1/100 of the original value: electrons are trapped by the magnetic field. Transparency is allowed as β and **a** are ant-parallel. Another relevant case is shown in the bottom part, corresponding to $\Omega \approx 1$. In this case the transferred momentum increases dramatically during the pulse, reaching 10 times the normal value, just after some seven optical cycles. In this conditions electrons may be accelerated to relativistic energies.

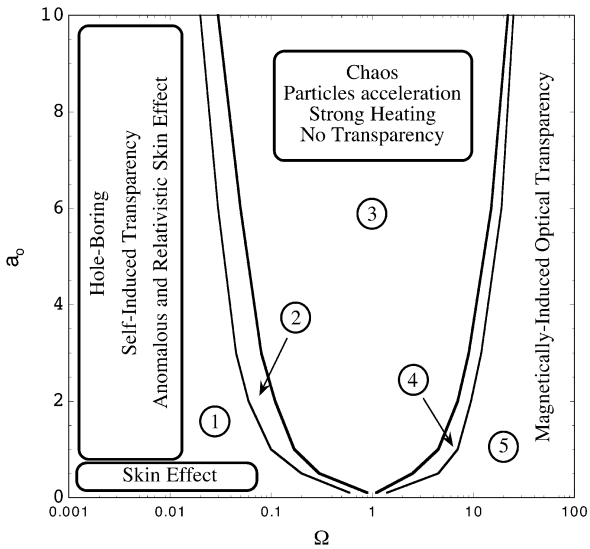

Figure 7. Schematic representation of the possible optical transparency and electron acceleration effects in terms of oscillating electric field (proportional to a_0) and static magnetic field (proportional to Ω).

The case represented in the middle of Fig.6 is particularly interesting for the interpretation of our experimental data. It has to be considered that $\Omega = 10$ corresponds to a quasi-static magnetic field exceeding 10^9 G, much higher than any magnetic field measured in a plasma so far. It may be the consequence of the ultra-fast volume ionisation in a the solid, even though the real mechanism of production of such a field has still to be understood. In this case a new type of self-induced transparency will occur at lower laser intensity than expected by pure relativistic effects. This scenario is schematically represented in Fig. 7, were different physical phenomena occurring in the interaction of intense laser pulse with matter are labelled. Most of the theoretical work has been devoted so far to the effect of extremely high laser intensity (a_0 >> 1). Our work suggest that also the region of high magnetic fields has to be investigated. A special consideration has to be also devoted to the resonant condition $\Omega \approx 1$, for which the cyclotron frequency associated to the magnetic field is close to the optical frequency of the laser pulse. The resonance condition may be suitable for particle acceleration.

CONCLUSION

The experimental technique using very thin plastic foils allows for the first time real interaction of an ultra-intense laser field with solid matter. In this unexplored condition ultra-fast volume ionisation was observed and above a given intensity threshold the highly ionised foil was found to be almost transparent to femtosecond pulses. The observed transparency is not explained by the current theories. The experimental results suggest that once the matter is highly ionised in times comparable with an optical cycle, its response cannot be described in terms of ordinary plasma behaviour. The tentative assumption of the creation of a very intense magnetic field in the interaction region seems to account for the anomalous transparency and the hard X-ray emission we have observed.

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