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THOMSON BACKSCATTERING FROM DENSE RELATIVISTIC ELECTRON LAYERS SURFING ON FEW-CYCLE MULTI-TW LASER PULSES

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Abstract

The generation of dense relativistic electron layers by high-contrast few-cycle multi-TW laser pulses is described and their use as relativistic mirrors to produce ultra-bright attosecond light pulses. The method is illustrated in Fig. 1. Nanometer-thick foils are irradiated to blow out all electrons. They move as dense layers with γ-factors of 10 -100 over distances of a few laser wavelengths without substantial expansion. This is shown by 1D and 2D PIC simulation. These layers are dense enough for coherent Thomson backscattering of counter-propagating probe light. Though they are typically transparent to the scattered light, the reflection occurs coherently. As a major new result, we report the fraction of reflected light energy in 1D geometry. The reflected probe light is compressed and upshifted in frequency by factors $4\gamma^2$. This leads to single attosecond pulses in the VUV and X-ray regime. The brightness of these pulses is estimated.

1. The blow-out regime

Here we consider laser pulses of relativistic intensity having electric fields $E_L / E_0 = a_0 \gg 1$. The normalization is $E_0 = mc\omega_L / e$ with laser frequency $\omega_L = k_L c$, light velocity c, electron mass m and charge e. Few-cycle pulses with $a_0 \gg 1$ are now available experimentally [1].

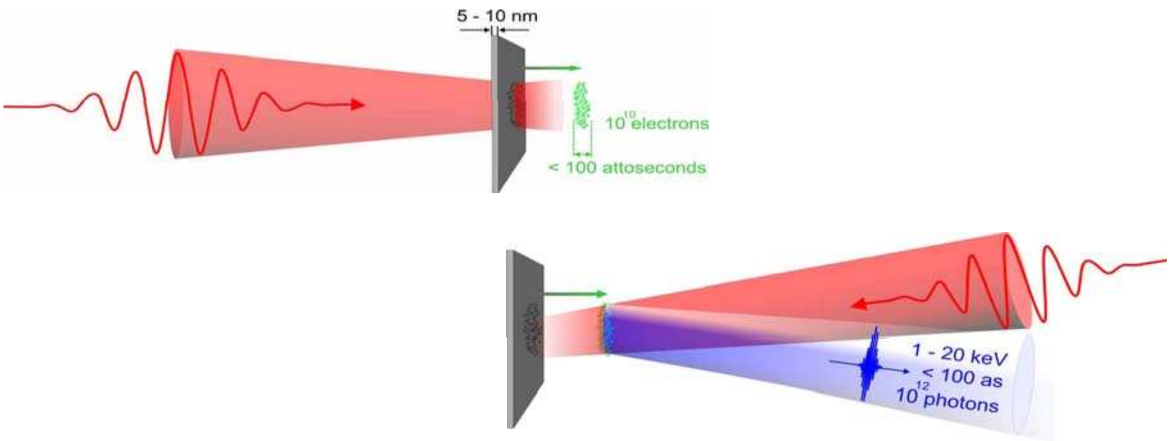

Fig. 1 Schematic view of laser-driven electron blow-out from a nano-meter thick foil and subsequent Thomson backscattering of a second probe pulse.

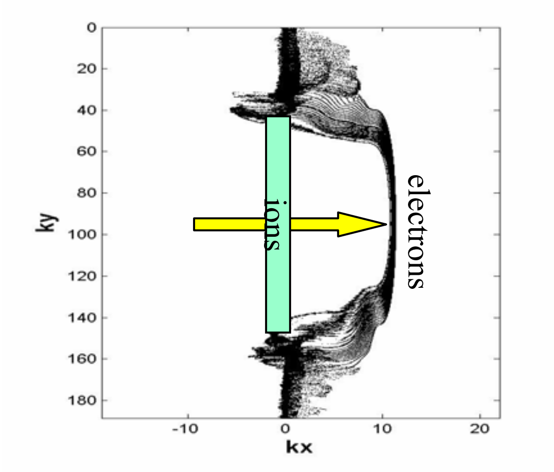

Fig. 2
Electron density distribution of 10 nm foil after about 2 cycles of laser irradiation (yellow arrow) with a step pulse at $a_0 = 60$. In the central region, electrons have separated from ions (green) and move close to the velocity of light with $\gamma \approx 80$ (2D-PIC simulation).

These pulses push electrons mainly in forward direction due to $(u/c)\times B_L$ interaction. Electron blow-out as seen in Fig. 2 then creates an electrostatic field

$$\varepsilon_0 = E_s / E_0 = N k_L d \tag{1.1}$$

where d is the initial foil thickness, $N = \omega_p^2 / \omega_L^2 = n_e / n_{crit}$ the normalized electron density, and $\omega_p = (4\pi e^2 n_e / m)^{1/2}$ the plasma frequency. The condition for complete blow-out is

$$\varepsilon_0 \ll a_0 \tag{1.2}$$

We have performed 2D-PIC simulations. The case of a foil with d =10 nm, N = 318, $\varepsilon_0 = 25$, irradiated by a 10 PW pulse with $a_0 = 60$ and focal radius $k_L w_0 = 50$, is shown in Fig. 2. The simulation reproduces results published by Kulagin [2]. It is seen that foil electrons completely separate from the ions in the central region and form a dense layer, carrying charge of more than 10 nC and moving with $\gamma \approx 80$. Though the layer rarefies in lateral direction, it survives over a time period of a few laser cycles.

The longitudinal structure of the electron sheath and its dynamic evolution have been studied in more detail by 1D PIC simulation. The results presented in Fig. 3 correspond to a half-wave laser pulse with $a_0 = 10$ and an initial foil with $N = 20$, $d = 5$ nm, $\varepsilon_0 = \pi/4$. Electron density and laser electric field are shown after 4.8 laser cycles of interaction. It is seen that the electron sheath is transparent to the light, but is carried along picking up light energy. All electrons are separated from the (ion) foil. The sheath has somewhat expanded from the initial 5 nm, forming a 30 as electron pulse. The density profile shows peaks at front and rear side, but the bulk density has dropped by a factor 3, now corresponding to $3\cdot 10^{17}$ electrons/cm^2 at an energy of 30 MeV and an energy spread of 3%. The average electron energy reaches a maximum of 40 MeV after about 10 laser cycles and then falls again (Fig. 2c). This temporal behaviour of the foil can be understood in the following way: Each electron moves essentially as a single particle, pushed by the Lorentz force depending on its phase relative to the light

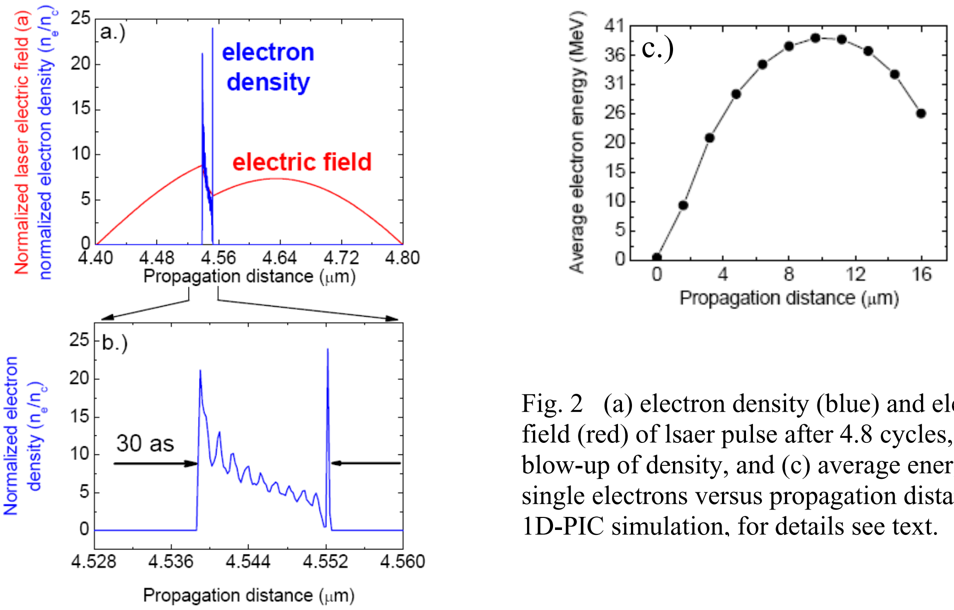

Fig. 2 (a) electron density (blue) and electric field (red) of lsaer pulse after 4.8 cycles, (b) blow-up of density, and (c) average energy of single electrons versus propagation distance. 1D-PIC simulation, for details see text.

wave. The analytic solution for a single electron leads to a momentum evolution of $p_x = mca_0^2 \cdot 2\sin^2(\tau_e/2)$ with the electron phase $\tau_e = \omega_L t_e - k_L x_e$. This corresponds to a peak electron energy of $2mc^2a_0^2 \approx 100\,\mathrm{MeV}$ after about 38 laser cycles. The electrostatic field of $E_x = \varepsilon_0 E_0 \approx 3 \cdot 10^{12} V/m$ tends to reduce the sheath acceleration and is responsible for the reduced peak energy of about 40 MeV, found in the PIC simulation.

3. Coherent Thomson backscattering

The electron sheaths discussed above may serve as relativistic mirrors. An example is shown in Fig. 4. *All quantities refer to the lab frame.* A layer of thickness d moving with $\gamma = 5$ converts light incident with wavelength $\lambda_L = 800\,\mathrm{nm}$ to $\lambda_L/4\gamma^2 = 8\,\mathrm{nm}$ and also reduces the pulse length by a factor $4\gamma^2 = 100$. Here we derive the fraction of reflected laser pulse energy, first treating coherent backscattering in the rest frame, and then transforming back to the lab frame. We find

$$R = \frac{N^2}{16\gamma^4} \sin^2(2\gamma^2 k_L d) \tag{1.3}$$

This result is confirmed by 1D-PIC simulation. The square dependence on density $N = n_e/n_{crit}$ highlights coherent backscattering. The oscillations with foil thickness d correspond to destructive interference of backscattered radiation from layers at different depth. In 1D geometry, only electrons located in layers thinner than half the wavelength of incident radiation ($\lambda_L/4\gamma$ *in the rest frame*!) backscatter coherently in normal direction. Coherent backscattering sets in when many electrons reside in such a layer. For the parameters of Fig. 4, one finds approximately $(10^8 N/\gamma^2) \cdot F/\lambda_L^2 \approx 10^8$ such electrons, assuming a transverse foil cross-section of $F \approx 5\lambda_L^2$.

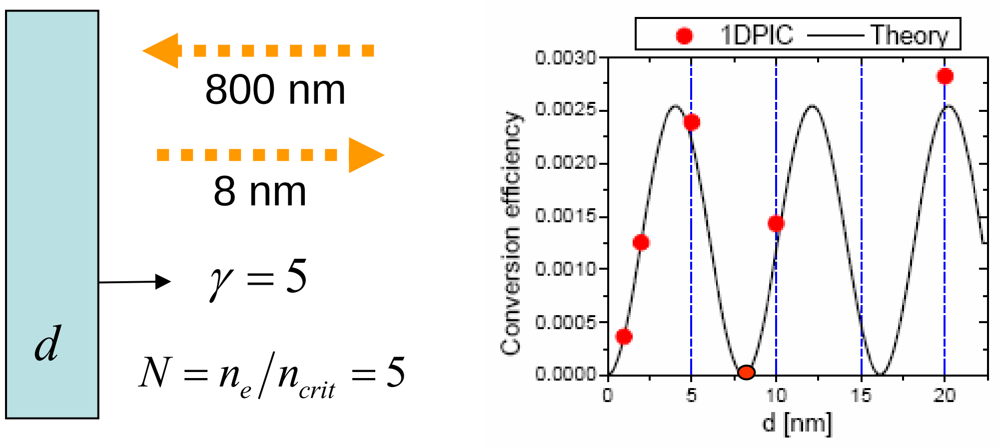

Fig. 4 Parameters of moving foil and backscattered radiation (left side) and 1D PIC results of backscattered energy fraction versus foil thickness, confirming eq. (1.3).

For the relativistic electron sheaths discussed in section 2, the condition for at least partial coherent backscattering is well fulfilled. The coherent radiation is backscattered into a solid angle $\Delta\Omega \approx (\lambda_L / 8\gamma^2)^2 / F \cdot 10^6 \mathrm{mrad}^2$, and the number of photons backscattered per unit of time, area, and solid angle from incident light of power P_0 is found as

$$B \approx \frac{N^2}{32\gamma^4} \frac{P_0 \Delta t}{(4\gamma^2 \hbar\omega_L)(\Delta t / 4\gamma^2) F} \frac{(2 \cdot 4\gamma^2)^2 F}{\lambda_L^2 \cdot 10^6 \mathrm{mrad}^2} \approx 10^{31} N^2 \frac{P_0}{\mathrm{TW}} \frac{\mathrm{photons}}{\mathrm{s} \cdot \mathrm{mm}^2 \cdot \mathrm{mrad}^2}$$

Here the energy reflection rate is estimated as $R \approx (N^2 / 16\gamma^4) / 2$. This level of brilliance is comparable with that of XFELs [3], though the expected pulses are much shorter, extending over attoseconds rather than femtoseconds, and have a much broader spectral width.

Presently, experiments are planned to detect and analyze the coherent backscattered radiation discussed in this contribution.

References

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