

Plasma of extreme energy density by intense XUV beams

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We present hydrodynamic simulations performed with MULTIfs for first experiments at the TESLA-Test-Facility (TTF) at DESY in Hamburg. It is shown that the XUV(eXtreme Ultra Violet)-FEL(Free-Electron-Laser) will generate solid density matter with keV temperatures and up to Gbar pressures in thin targets. Further for 30eV photons the foil can be used as femtosecond switch, where the switching-time depends on the intensity of the laser pulse.

Introduction:

We report on new possibilities to generate solid-density plasma at extreme energy density by intense XUV beams becoming available at DESY/Hamburg in 2005 [1]. The TTF2 will provide 100 fs pulses containing up to 10^{14} photons with energies in the range of 20 – 200 eV. When focussed to spots of 1 μm diameter, the pulses will reach intensities up to 10^{18} W/cm² and generate uniform thin plasma layers of solid-density with temperatures up to some keV and Gbar pressures. During the 100 fs interaction time, the target material will be in an extreme state of non-equilibrium, and the hydrodynamic expansion is negligible. Scattered photons will allow to study the structure of very uniform small plasma volumes in unprecedented detail. Important diagnostics for this will be Thomson and Compton scattering. We expect these XUV beams to become a major new tool in the study of dense ICF plasmas and offers new possibilities to study equations of state (EOS) and opacities over a wide range of the phase diagrams for various materials. The new XUV and later the X-ray Free Electron Laser (XFEL) source at DESY will exceed the brilliance of existing sources by about 8 orders of magnitude. In Table 1 we consider the beam parameters expected at DESY for the TTF and the XFEL [2]. In 2001, 15 eV FEL photons were already demonstrated in the first phase of TTF1. In the second phase of TTF2, now expected to be operational in 2005, beams with photon energies of 20 -200 eV will become available, and the present time horizon for XFEL photons up to 12 keV is 2011.

TABLE 1	TTF2	XFEL	LCLS
Wavelength	6 – 60 nm	0.1 nm	0.15 nm
Photons/pulse	10^{14}	2×10^{12}	4×10^{11}
Pulse duration	100 fs	100 fs	200 fs
Pulse energy	0.3 mJ	4 mJ	0.5 mJ
Pulse power	1 GW	37 GW	2.5 GW

Heating near plasma frequency:

The TESLA Test Facility (TTF2) is expected to provide photons in the XUV region between 10 - 100 eV. The corresponding frequencies lie in the region of the plasma frequency ω_p of solid-density plasmas. As illustrated in Fig. 1, this is also the region of peak coupling between photons and solid-density matter. For lower photon energies ($\omega_L < \omega_p$), the material density is over-critical, and the light cannot propagate. For higher photon energies ($\omega_L > \omega_p$), thin foils are transparent, but the photon cross-sections decrease.

The maximum energy deposition in solids therefore occurs just in this region, and TTF2 can reach plasma states in the same parameter range as the final XFEL, be it in thinner target foils (typically 50 - 100 nm).

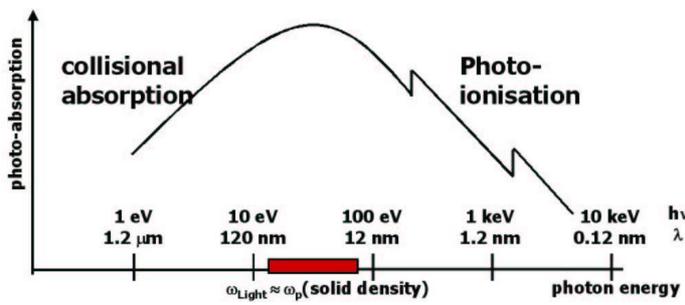


Figure 1: Schematic drawing of photo-absorption versus photon energy. In solid targets, maximum energy deposition occurs for photon energies of 10 - 100 eV, where also the plasmon energies of solid-density plasma are located. For medium- and high-Z metals, collisions of free electrons with ions are the main absorption mechanism; absorption by photo-ionisation sets in for $h\nu > 100\text{eV}$.

Another point is that the absorption also depends on temperature like it is illustrated in Fig. 2.

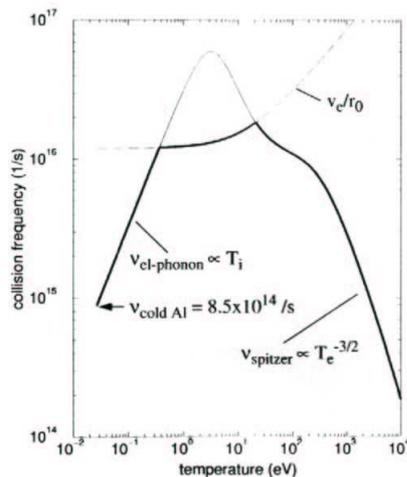


Figure 2: Collisional frequency of solid Aluminium in dependence of temperature for $T_e=T_i$ [4].

We show simulations with the 1D-hydrodynamic code MULTIfs [4,10] for a 30 eV , 10^{16} W/cm² and 10^{18} W/cm² XUV pulse as defined in Fig. 3. We see that temperatures up to 500 eV and pressures up to 500Mbar for an intensity of 10^{16} W/cm² and 5keV temperature for an intensity of 10^{18} W/cm² are obtained within this conditions (see Fig. 4). Recognize that the

XUV-FEL beams can generate solid-density plasma covering the full temperature range relevant for inertial fusion applications.

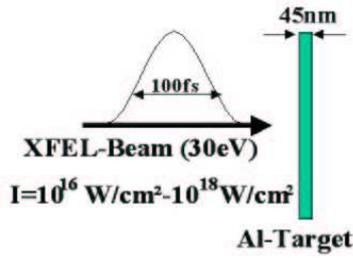


Figure 3: Definition of photon pulse and target foil used in the subsequent simulations

The uniformity of the plasma layers is of central importance. They expand in a planar way making accessible a large range of densities. We anticipate that pump-probe experiments for measuring material opacities and equation-of-state properties will become possible covering temperatures of 1 eV – 1 keV and densities in the range of $10^{-3} < \rho/\rho_0 < 1$.

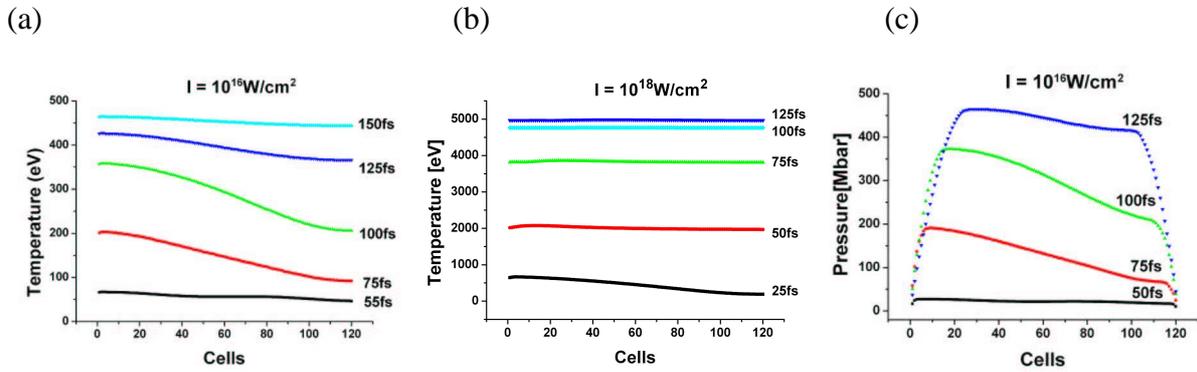


Figure 4: Temperature derivation of the electrons in an Al-target at an intensity of (a) 10^{16} W/cm^2 (b) 10^{18} W/cm^2 . (c) Pressure profiles at different times for an intensity of 10^{16} W/cm^2 .

At these intensities, the aluminium is ionised up to Al^{11+} and the plasma frequency stays just below the photon frequency so that the pulse can propagate (see Fig. 5). Raising the intensity to 10^{18} W/cm^2 , also the K-shell electrons are ionised and the plasmon energy $h\nu_p$ rises to 32 eV (Fig. 5b) such that light transmission is cut off and recovers only at later times (Fig. 7), when the foil density drops due to hydrodynamic expansion.

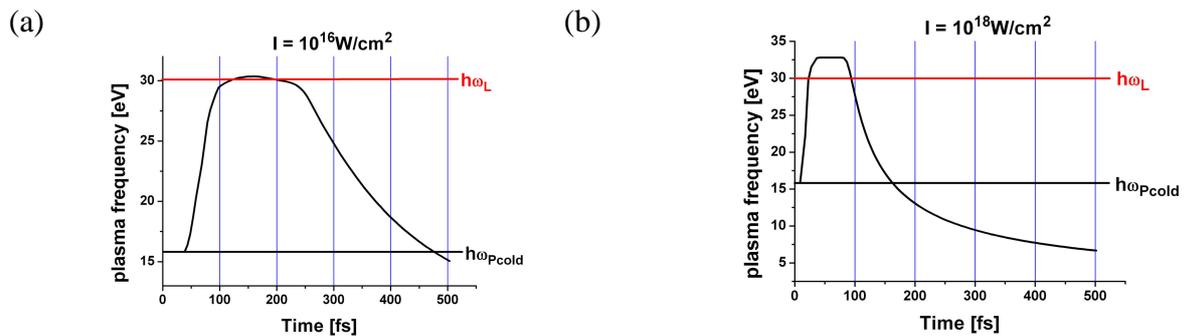


Figure 5: Temporal development of the plasma frequency for an intensity of (a) 10^{16} W/cm^2 and (b) 10^{18} W/cm^2 .

In Fig. 6 and 7 it is shown that the radiated foil can be used as a femtosecond switch when heating the foil cuts transmission when ω_p reaches ω_L . It is seen that the transition from reflection to the transmission occurs very rapidly. The switching-time depends on intensity. If the intensity is higher the ionisation is faster and therefore the plasma frequency reaches the photon frequency earlier. That allows to slice the incident pulse into pieces with short rise times and large contrast ratios. While the transmission drops from nearly 100% to less than 10% the absorption and also the reflection at the front surface of the foil is increasing.

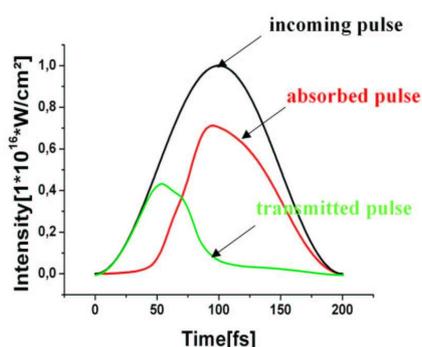
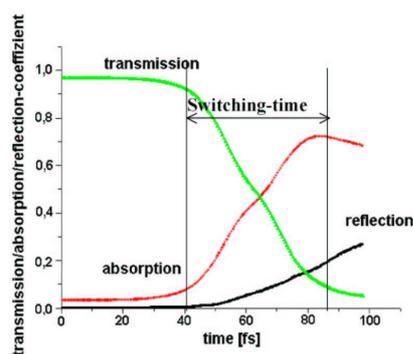


Figure 6: Time dependence of the transmission, reflection and absorption of the pulse for an intensity of 10^{16} W/cm^2 . Switching-time is 45fs.

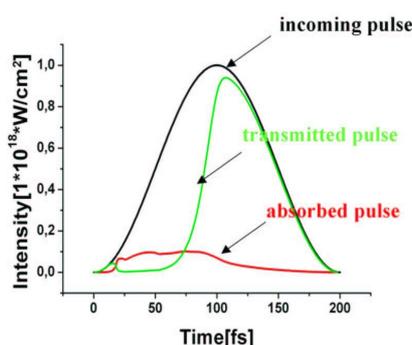
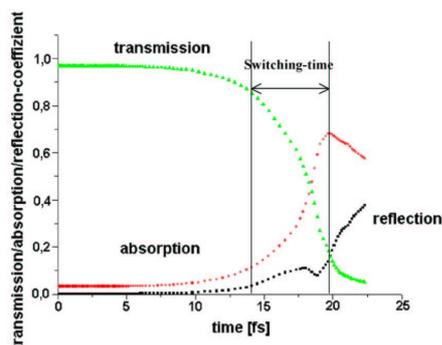


Figure 7: Time dependence of the transmission, reflection and absorption of the pulse for an intensity of 10^{18} W/cm^2 . Switching-time is 7fs.

These fast switching properties may be of interest in applications. A possible application for this switching behavior is to cut out a part of the 100fs-long main pulse. Therefore you will get very short pulses in the order of a 10fs. Or you can use the switch as a plasma mirror for XUV-rays.

References:

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