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Novel diagnostics for the study of electron transport in solid materials

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Abstract

The study of fast electrons generated in laser-matter interactions and their transport through matter is of great interest for the fast ignition concept in the inertial confinement fusion. A typical experimental approach is the interaction of intense laser radiation with foil targets. The transport of the electrons through the foil can be studied with several techniques including X-ray emission measurements and direct measurements on electrons leaving the foil. Some laser-matter interaction features can be monitored using spectroscopy in the visible range.

Here we will focus our attention on some of the experimental techniques that have been used in laser-foil experiments at ILIL laboratory in Pisa and in a VULCAN Petawatt experiment at RAL. In particular we will describe high resolution X-ray spectroscopy with a bent crystal, K-alpha flux measurements, direct measurements of the angular distribution and spectrum of the electrons, and spectroscopy of the $3/2\omega$ and 2ω harmonics of the laser radiation.

Introduction

During the interaction of ultrashort, high power laser pulses with solid targets, laser energy is efficiently transferred to the electrons and a significant fraction of electrons with energies well above the background electron temperature is generated. These so-called fast electrons enter the target-material, where they deposit part or all of their energy. The generation of the fast electron population and its transport through the target material involve complex physical phenomena [0]. First of all, the laser-solid interaction conditions depend on the on the temporal profile of the laser pulse and in particular on the prepulse structure [0, 0]. Depending on the interaction regime, different physical processes are predominantly responsible for the generation of fast electrons and thus the energy and the angular distribution of the fast electrons can differ significantly for different interaction conditions. In addition, the transport of the fast electron beam through the target material is accompanied by the generation of huge electromagnetic fields, so a purely collisional model cannot usually account for all the observed phenomena.

A typical experimental approach to the study of the generation and the transport of fast electrons in solids is the study of the interaction of intense laser radiation with foil targets. Due to the complexity of the physics involved, a good knowledge of the laser parameters is desirable in these experiments as well as a large variety of diagnostics in order to get information on the laser-matter interaction regime and on the electron transport through matter. Here we will focus our attention to some of the experimental techniques that are used in dedicated laser-foil experiments at ILIL laboratory in Pisa and in a VULCAN Petawatt experiment at RAL. In the first section, we report on X-ray emission measurements including X-ray spectroscopy with a bent crystal and spectrally resolved X-ray flux measurements with a CCD working in the single-photon regime. The second section is dedicated to the direct detection of electrons and protons leaving the rear side of the target foil. The third section is about spectroscopy in the visible spectral range in order to monitor the laser-matter interaction conditions.

Characterization of the X-ray emission induced by fast electrons

Amongst other processes, electrons moving into the target material produce inner-shell ionization of the atoms. Radiative decay gives then rise to the emission of K-shell lines from the target material. From the spectra of the K-shell emission, one can get information about the ionization stages and therefore about the heating of the target [0].

Such spectra can be obtained with bent crystals giving high resolution spectra ($\Delta\lambda/\lambda$ can be of the order of 10^{-4} or better). These kind of spectrometers can work in a wide range of X-ray energies and offer the advantage that the spectral resolution is relatively independent on the X-ray source size [0]. In addition, a 1D image of the X-ray source in the plane orthogonal to the dispersion plane is obtained. In Fig. 1 experimental results obtained with a spherically bent Mica crystal from the interaction of a 2TW laser pulse with a 10 μm thick Ti foil at an intensity of about 10^{16} W/cm^2 at ILIL laboratory in Pisa are shown. The data in Fig. 1a) was obtained with a bent Mica crystal spectrometer working in the 7th order of diffraction. Fig. 1b) shows the spectrum obtained from the data in Fig. 1a) and Fig. 1c) shows the lineout of the Kα_1 emission in the vertical direction (see rectangle). The source (integrated over 100 pulses of the driving laser) has a FWHM of 350 μm.

The same experimental technique can be applied in quite different experimental conditions. In Fig. 2 an X-ray spectrum around the Ni Lyα line obtained from the interaction of the VULCAN Petawatt laser pulse at an intensity of 10^{21} W/cm^2 with a multilayer target containing a central Ni layer (fig. 2) are shown. In this experiment the bent Mica crystal was used in the 11th order of diffraction. Bent crystal spectrometers require a significant photon flux.

A different experimental technique which is useful even for low photon flux, is based on a CCD camera working in single-photon mode and a custom-made algortihm for data analysis, described in detail in [0]. This diagnostic allows to obtain the X-ray photon flux and preliminary spectral measurements with a spectral resolution of typically 100 eV in a quite immediate way. This technique has been applied succesfully in our experiments in Pisa [0].

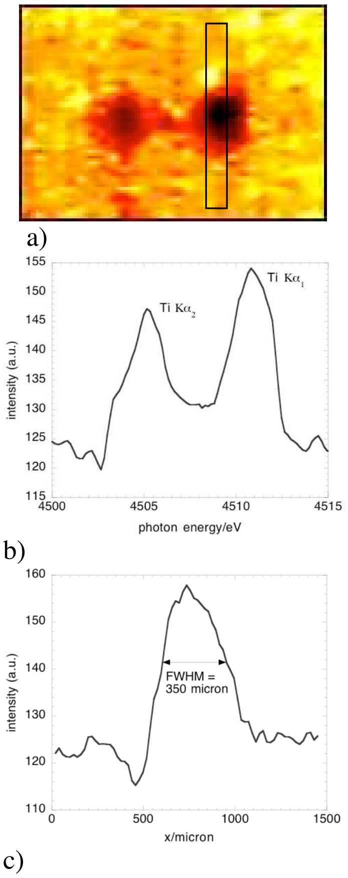

Figure 1: X-ray Kα emission from the interaction of a femtosecond laser pulse with a Ti foil at an intensity of about 10^{16} W/cm^2 (details see text).

Energy and angular distribution of the electrons

For the direct detection of electrons and protons leaving the rear side of the target foil we use a home-made detector, SHEEBA [0], based on a stack of radiochromic films, which change their colour getting blue, where electrons, protons or other ionizing particles release energy inside the sensitive layer. While protons have a pronounced Bragg peak, that is they release nearly all their energy in one radiochromic film layer, the energy of the electrons is released in several consecutive layers. An algorithm based on the Montecarlo code Geant4 is therefore used to reconstruct the electron spectrum from the signals detected by the single radiochromic film layers. With respect to other types of electron spectrometers, with SHEEBA the whole electron beam can be detected and its angular distribution can be measured. In addition, radiochromic films have a relatively high detection threshold ($10^6 - 10^7$ photons/mm^2). These characteristics make SHEEBA a detector suitable for measurements of electrons in ultrashort laser-matter interactions, where a large number of electrons is generated. Measurements performed with SHEEBA are reported in [0].

Laser harmonics and half-harmonics emission

In the experiments in Pisa and at RAL the optical radiation emitted in the direction of the reflection of the laser beam has been analyzed spectrally. We observed 3/2 ω emission which is a signature of Two Plasmon Decay instability and/or Stimulated Raman Scattering, both occuring close to the quarter critical density. We also observed 2 ω emission which is in turn a signature of interaction taking place at the critical density [0]. Fig. 3 shows the spectrum of the specular reflected radiation (dispersed by means of a prisma) from the interaction of the 2TW, 67 fs laser pulse at ILIL in Pisa with a 10 μm thick Ti foil.

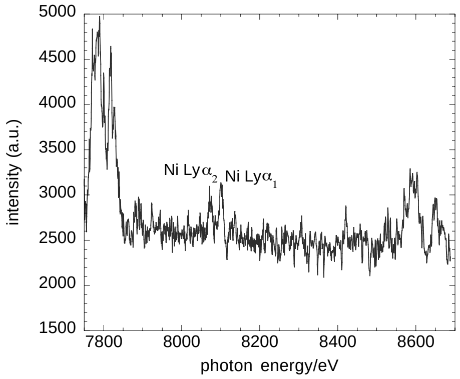

Figure 2: X-ray spectrum around the Ni Lyα doublet (details see text).

Conclusions

In this paper some experimental techniques suitable for the study of fast electron transport in matter in ultrafast laser-solid foil interaction experiments have been briefly described. These diagnostics can help to obtain a better understanding of the physical phenomena involved in the transport of fast electrons in dense matter.

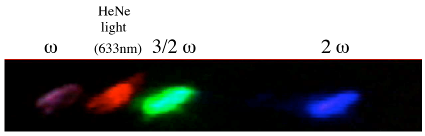

Figure 3: Spectrum of the reflected radiation. From the left to the right infrared radiation (visible due to fluorescence in the diffusive device), the HeNe alignment laser, 3/2 ω and 2 ω emission are visible.

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