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Experimental investigation of fast electron transport through Kα imaging and spectroscopy in relativistic laser-solid interactions

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Abstract

The study of the basic physical processes underlying the generation of fast electrons during the interaction of high-intensity short laser pulses with solid materials and the transport of these fast electrons through the target material are of great importance for the fast ignition concept for inertial confinement fusion and for the development of ultra-short X-ray sources.

We report on the experimental investigation of fast electron transport phenomena by means of the spatial and spectral characterization of the X-ray emission from layered targets using bent crystal spectrometers and a new diagnostic technique based on a pinhole-camera equipped with a CCD detector working in single-photon regime for multi-spectral X-ray imaging [1]. In particular, differences of fast electron transport features depending on the atomic number and/or the resistivity of the target material have been studied.

The experiments were carried out at relativistic laser intensities, both in the longer ($\simeq$ps) pulse interaction regime relevant for fast ignition studies [2] and in the short-pulse ($\simeq$100 fs) interaction conditions related to basic physics studies as well as to the development of ultrashort Kα X-ray sources.

Introduction

During the interaction of a high power short laser pulse with solid matter a great number of so-called fast electrons, that is electrons with energies much higher than the electron temperature, is produced [3]. The forward propagating fast electrons enter the underlying target material, where the fast electrons deposit their kinetic energy partially or entirely through different physical meccanisms including collisions with the target atoms or ions, electric and magnetic field generation and the onset of instabilities. A detailed knowledge of the fast electron transport properties is of fundamental importance for many applications, such as the design of novel-type short pulse X-ray sources and the inertial confinement fusion in the scheme of the fast ignitor, where the fast electron beam is required to travel through a high density plasma to deposit its energy efficiently in the core of the compressed target [4].

From an experimental point of view, indirect measurements are mainly employed for the characterization of the fast electron beam transport. In particular, the Kα emission, generated through collisional inner-shell ionization of the target atoms by the fast electrons and subsequent radiative transitions, is widely employed as a diagnostic tool. Typically, multi-layer targets containing one or more tracer layers for the X-ray emission measurements are used.

We present here some aspects of the experimental techniques based on K shell emission measurements, which have been used in two different interaction regimes for the study of electron energy transport phenomena. The joint experiments described have been carried out with the 8 TW laser system at the IOQ Jena and with the VULCAN Petawatt laser beam at RAL. In the short pulse ($\simeq$100 fs) interaction regime in Jena a novel diagnostic technique based on the use of a pinhole camera equipped with a CCD working in single photon regime has been employed [5]. With this technique 2D Kα source images can be obtained simultaneously from all different target layers. In the longer pulse high energy regime ($\simeq$1 ps) of the VULCAN laser experiment a variety of diagnostics has been set up. Amongst other diagnostics, high resolution spectroscopy with a bent Mica crystal spectrometer and 2D monochromatic imaging of X-ray line emission with a spherically bent Quartz crystal have been performed.

Multi-spectral monochromatic X-ray imaging

The experiment carried out at the IOQ Jena was performed with the 8TW Ti:Sa laser system. Multi-layer targets were irradiated at an intensity of 5×10^{19} W/cm^2. In this experiment 2D Kα images have been obtained simultaneously from all target layers (three in our case) with a novel diagnostic technique described in detail in [1].This technique is based on the use of a pinhole camera equipped with a CCD working in single photon regime. The energy of the detected photons can be reconstructed and the landing position of each photon is stored. The photons lying in the spectral range of interest are then selected. After applying this procedure to a few hundreds of data acquisitions, the selected photons are summed up maintaining their original position on the CCD chip. Thus it is possible to obtain an image of the X-ray emission (averaged over the shots of the driving laser) at the selected photon energy with a spectral resolution of about 150 eV and a spatial resolution of a few microns. These nearly monochromatic images can be reconstructed for any photon energy in the range from 1 keV to a few tens of keV. Therefore it is possible to obtain simultaneously 2D Kα source images from all target layers.

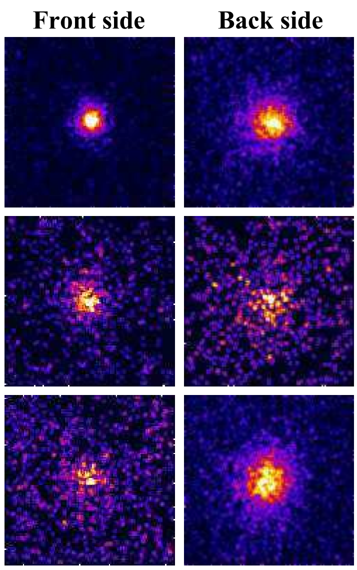

Figure 1: X-ray front and back pinhole camera images of the K shell emission obtained from the analysis of 350 data acquisitions. The target consisted of three layers: Cr(*top), Ni(center) and Fe(bottom).*

Fig. 1 shows a typical set of images obtained from the irradiation of a Cr-Ni-Fe target. The photons in the spectral range of the Kα and the Kβ photon energies have been selected for each target layer for a total of 350 data acquisitions. The left column shows the images from the pinhole camera looking at he laser-irradiated target surface and the right column shows the back pinhole camera images. From the top to the bottom row the images from each of the different target layers are shown respectively: the laser-irradiated 1.2 μm thick Cr layer (top), the 11 μm thick Ni middle layer (center) and the 10 μm thick Fe layer (bottom). The size of the images is 165 μm in both directions in the object plane. The micron size spatial resolution enables the detection of the spatial structure of the X-ray emission. In fact, considering the images taken at the same photon energy seen from either side of the target, differences of the Kα source size are clearly visible in fig 1. An explanation of the underlying physical processes is beyond the scope of this paper. For a quantitative analysis of the data other X-ray emission processes such as e.g. bremsstrahlung emission as well as reabsorption effects should be taken into account.

In general, with the described experimental technique the propagation of the fast electron beam can be reconstructed through the whole target. The development of this experimental technique has been performed on a multi-shot basis, summing up the contributions from some hundred of pulses of the driving laser, but the extension of this technique to a single-shot diagnostic is currently under study. In order to achieve this task, a higher number of photons has to be collected in a single acquisition. This can be done either by increasing the magnification of the pinhole camera image or by the use of a pinhole array instead of a single pinhole in order to acquire simultaneously a large number of single-photon images.

Temperature measurements through high resolution spectroscopy

In the following a short description of some aspects of the experiment carried out at the VULCAN laser facility at RAL is given. In the experiment, fast electron transport was studied on millimeter-sized layered targets and on so-called mass-limited targets. The latter targets were expected to be efficiently heated during the interaction [6], therefore a diagnostic device capable of giving information on the target temperature was chosen. As part of a set of diagnostics, 2D monochromatic X-ray imaging with a Quartz crystal of the line emission from the tracer layer and high resolution spectroscopy with a spherically bent Mica crystal in the spectral range around the imaged line emission have been performed. The 2D images give information about the spatial structure of the line emission, and thus, in the case of line emission from highly ionized matter, they give spatial information about the heated region. Information about the temperature is obtained from the measured X-ray spectra. Therefore the measured spectra are compared to synthetic spectra calculated for a set of temperatures and electron densities.

Conclusions and acknowledgments

In summary, we reported on X-ray diagnostic techniques for fast electron transport studies in interaction regimes relevant to the fast ignition approach to inertial confinement fusion. In the short pulse regime, a novel multi-spectral X-ray imaging technique has been used in order to simultaneously obtain monochromatic images of the K shell emission from each target layer, whereas in the high energy long pulse regime temperature measurements have been performed using high resolution spectroscopy.

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