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X-ray High-Resolution Spectroscopy for Laser-Produced Plasma

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Abstract

The study of the emission spectrum gives information about the material generating the spectrum itself and the condition in which this is generated. The wavelength spectra lines are linked to the specific element and plasma conditions (electron temperature, density), while their shape is influenced by several physical effects like Stark and Doppler ones.
In this work we study the X-ray emission spectra of a copper laser-produced plasma by using a spherical bent crystal spectrometer to measure the electron temperature. The facility used is the laser TVLPS, at the Tor Vergata University in Rome. It consists of a Nd:Glass source (in first harmonic - 1064 nm) whose pulse parameters are: 8 J in energy, time duration of 15 ns and a focal spot diameter of 200 μm. The adopted spectrometer is based on a spherical bent crystal of muscovite. The device combines the focusing property of a spherical mirror with the Bragg's law. This allows to obtain a great power resolution but a limited range of analysis. In our case the resolution is on average 80 eV. As it is well-known, the position of the detector on the Rowland's circle is linked to the specific spectral range which has been studied. To select the area to be investigated, we acquired spectra by means of a flat spectrometer. The selected area is centered on 8.88 Å. To calibrate the spectrum we wrote a ray-tracing MATLAB code, which calculates the detector alignment parameters and calibration curve. We used the method of line ratio to measure the electron temperature. This is possible because we assumed the plasma to be in LTE condition. The temperature value was obtained comparing the experimental one, given by the line ratio, with the theoretical one, preceded by FLYCHK simulations.

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1. Introduction

The study of the X-ray emission of plasma has an important role in physics. From the atomic point of view we can acquire information about the atomic structure of the atom shells. Moreover, X-ray emissions from plasma are useful to understand plasma conditions like electronic temperature and density. This is interesting to understand astrophysical plasmas, but also, in laboratory-produced plasmas. Several effects occur in laser-produced plasma at different laser intensities. At low laser intensities the study of optical emissions can provide useful information about the physical conditions (Laser Induce Breakdown Spectroscopy). At higher intensities back-ground temperature increases and

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soft X-ray emission spectrum of the material provides information about temperature and density. The interaction of high electromagnetic field can accelerate charged particles like electrons. In this case suprathermal electrons can collides with the inner shell of the atoms and the result is Kα radiation emission from solid material. Kα radiation is crucial to study the propagation of suprathermal electrons in matter for many fields, like the Inertial Confinement Fusion ($\check{S}m\acute{i}d$ et al. (2013); Antonelli et al. (2011)). Moreover in laser-produced plasma the typical density is similar to the solid density or higher. In this conditions Stark effect becomes important, influencing the emitted line shape. The presence of strong magnetic fields can have, as result Zeeman effect spitting the emission lines. Furthermore the high velocities of the ion in the expanding plasma corona produce a Doppler shift. X-ray spectroscopy acquires an important role to study all these effects. Different techniques were developed in this fields. In this work we present a particular spectrometer based on a spherically bent crystal. Its particularity is the combination of the properties of Bragg's diffraction and spherical mirror. The result is depicted as a 2D image, with energy resolution in one axis and spatial resolution in the other one.

2. Plasma models

The interaction of the laser light at a certain intensity ionizes the material. Two conditions must be satisfied to generate ions with ionization potential E_i in a plasma:

$$T_e \gtrsim \eta E_1 \tag{1}$$

where T_e is the electron temperature of the plasma and $\eta \simeq 0.1$ for LTE, while $\eta = 0.2$ for corona equilibrium (Vainshtein et al., 1979). The second condition is:

$$\Delta t \gtrsim \delta t_i \tag{2}$$

where Δ_t is the lifetime of the plasma and $\delta t_i = [N_e < v\ sigma_i >]^{-1}$ is the ionization time for the given ions, N_e is the electron density and $< v\sigma_i >$ is the rate of ionization by electron impact.

The energy of the laser beam photons is low, so the efficiency of the direct ionization of the matter is low. Ionization is the result of the collision between the electron and the atom with the absorption of a photon. This mechanism is possible only if there are free electrons in the point where the laser hit the matter. This process is called collissional absorption. The plasma created by the interaction start to expand in normal and opposite direction with respect to the surface of the target. The ablation pressure generate an inward shockwave in the material. At high laser energy and intensity the shockwave can achieve pressures in the order of Mbar. This is the base of the idea of the ICF. This kind of pressure were characterized in many experiment related to the study of the equation of state of many material for astrophysical interest and for fusion science. X-ray comes out from the interaction region between laser and target. For a given laser wavelength the specific density, where the wave vector becomes zero, is called critical density and it is given by:

$$n_c = \frac{1.11 \times 10^{21}}{\lambda_0^2} cm^{-3} \tag{3}$$

where λ_0 is the wavelength of the laser in μm. In general the soft X-ray emission from a laser-produced plasma comes from this specific region. The level population distribution of atoms in a plasma is closely related to thermodynamic parameters such as plasma temperature and density. So this is important in the analysis of plasma spectra in order to quantify internal parameters like energy, density (electronic and ionic) and opacity.

To describe the relation between these plasma parameters and the population kinetic exist different theoretical models according to different thermodynamic conditions.

2.1. Local Thermodynamic Equilibrium

The Local Thermodynamic Equilibrium (LTE) model describes a plasma state where each atomic process are in *detailed balance*. This means that the rate of every atomic process (except the radiation process) are perfectly balanced