In this chapter we present x-ray emission measurements from an intense laser-solid target interaction. Nickel targets are irradiated at intensity levels of $10^{15}$ W/cm$^2$ in an ambient vacuum of $10^{-6}$ Torr. From the x-ray spectrum obtained, the hot electron temperature is calculated.

7.1 Introduction

In chapter 6 we have discussed the mechanisms of x-ray emission from ultrafast laser induced plasmas in solid density materials. In this chapter we present the results obtained from the interaction of an ultrafast laser pulse with a Nickel target in an ambient vacuum of $10^{-6}$ Torr.

7.1.1: Bremsstrahlung emission

When a fast electron is decelerated in the Coulomb potential of an ion a continuum emission takes place, which is known as the bremsstrahlung emission [1]. If the electron had an initial velocity $v$ and the impact parameter is $b$, the interaction time is $\tau = 2b/v$. The radiated spectrum is dominated by the corresponding frequency, $\nu \approx v/4\pi b$. On the basis of maximum acceleration during a single electron-ion impact, the energy radiated can be written as [2]
\[ \Delta E = \frac{4}{3} \frac{Z^2 e^6}{m^2 c^3 b^3 v} \]  - (7.1)

This expression can be integrated over a range of parameters to account for many electron-ion collisions per unit time. The number of electron-ion collisions per unit time, with an ion density \( n_i \), with an impact parameter ranging from \( b \) to \( b + db \), is \( 2\pi n_i v b db \). This yields the power radiated per electron as

\[ w = \frac{4}{3} \frac{Z^2 e^6}{m^2 c^3} 2\pi n_i \int_{b_{\text{min}}}^{b_{\text{max}}} \frac{db}{b^5} \]  - (7.2)

where the maximum impact parameter possible \( b_{\text{max}} \) is the Debye length and the minimum value \( b_{\text{min}} \) is given by the de Broglie wavelength. To evaluate the spectral distribution of bremsstrahlung emission, equation 7.2 can be written in terms of frequency and integrated as

\[ w = \frac{4}{3} \frac{Z^2 e^6}{m^2 c^3} \frac{8\pi^2 n_i}{\nu} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma \approx \frac{4}{3} \frac{Z^2 e^6}{m^2 c^3} \frac{8\pi^2 n_i}{\nu} \gamma_{\text{max}} \]  - (7.3)

It is assumed that \( \gamma_{\text{max}} \gg \gamma_{\text{min}} \) since \( b_{\text{max}} \gg b_{\text{min}} \) and \( \gamma = mv^2/2h \), the frequency corresponding to the de Broglie wavelength. Now, considering a Maxwellian distribution of electron velocities

\[ f_e = n_e \left( \frac{m}{2\pi k_B T_e} \right)^{3/2} \exp \left( -\frac{mv^2}{2k_B T_e} \right) \]  - (7.4)

the bremsstrahlung spectral intensity can be obtained as,

\[ W_B' = \frac{1}{\sqrt{3}} \int_{2b_{\text{min}}/m}^{\infty} A_f e^{4\pi v^2} dv = \frac{32\pi}{3} \left( \frac{2\pi}{3k_B T_e m} \right)^{3/2} Z^2 n_i^2 e^6 \exp \left( -\frac{hc}{\lambda k_B T_e} \right) \]  - (7.5)

Thus it is possible to obtain the energy-resolved bremsstrahlung spectrum if the temperature of the electron distribution is known.
7.1.2 Hard x-ray bremsstrahlung as signature of hot electrons

It has been shown before that the hot electrons generated in the laser plasma radiate via bremsstrahlung \cite{3}. Since the electrons are heated to extreme energies (tens and hundreds of keV) the radiation emitted also is of similar energy. This radiation falls in the hard x-ray regime of electromagnetic spectrum. Studying the hard x-ray bremsstrahlung, therefore, provides important information about the hot electrons that generate the radiation, and their distribution in the plasma.

Hard x-ray bremsstrahlung is used as a diagnosis for the behavior of hot electrons. In particular, the temperature of different hot electron distributions can be inferred from the x-ray emission. Distributions with different temperatures are usually the products of different absorption and acceleration mechanisms discussed before. By following the scaling laws of hot electrons one can identify the mechanisms prevailing in the parameter space of the laser-matter interaction.

From equation 7.5, a bremsstrahlung spectrum caused by hot electron distribution of temperature \( T_e \) can be written as

\[
N(E) \propto \frac{1}{T_e^{\nu_2}} \exp \left( -\frac{E}{kT_e} \right)
\]  

(7.6)

where \( E \) is the energy of the photon emitted. By fitting this function to an experimentally obtained energy-resolved bremsstrahlung spectrum, the temperature \( T_e \) of the hot electron distribution can be obtained. As \( T_e^{\nu_2} \) is a relatively slowly varying function with respect to the exponential term, a mere exponential fit yields the temperature, without much error \cite{4}.

7.2 Experimental

We used 100 fs laser pulses from the Ti:Sapphire CPA laser, focused using a 60 cm plano-convex lens to the target inside the vacuum chamber. A pulse energy of 10 mJ was used which resulted in peak intensities of about \( 10^{15} \) W/cm². The experimental setup is described in detail in chapter 5. The target manipulator and controller were configured such that there was sufficient separation (~ 200 \( \mu \)m).
between adjacent laser spots on the target. This ensures that the laser sees a fresh spot at each shot.

A calibrated NaI(Tl) detector was used to collect the spectra. The detector and calibration details can be found in chapter 5. The BK7 windows of the chamber set a low energy cutoff of around 15 keV. The detector was kept at a distance of about 75 cm from the target. In the present experiment, x-rays in the range of 30 to 200 keV are measured. The cosmic ray background noise was reduced by using appropriate time gating. We used an unpolished Nickel target (99.95 % purity, ACI Alloys) of 5 cm x 5 cm size for the measurements. The bremsstrahlung emission measured in the 30 keV - 200 keV region is shown in figure 7.1. The laser was $p$-polarized and was incident on the sample at an angle of 45 degrees. The spectrum was collected over 5000 laser shots.

![Figure 7.1: Bremsstrahlung emission from an unpolished nickel target kept at a 10$^-6$ Torr vacuum irradiated with 100 femtosecond pulses at an intensity of 10$^{15}$ W/cm$^2$.](image)

The hot electron temperature can be calculated from this data by fitting an exponential to the emission spectrum using equation 7.6. The value of the hot electron temperature thus obtained is 5 ± 1 keV. The fitted curve is given in figure 7.2.
Figure 7.2: Bremsstrahlung emission from the unpolished nickel target, fitted to an exponential decay using equation 7.6.

7.3 Conclusions

We have measured the x-ray emission from an ultrafast laser induced plasma in a Nickel target. The unpolished target is moved between successive laser shots using a target manipulator and controller, so that the plasma is generated from a fresh surface every time. The hot electron temperature calculated from the bremsstrahlung emission spectrum is $5 \pm 1$ keV.
References


