L.2: Understanding fast electron generation and transport through Cu K_α x-ray measurements

The generation and transport of MeV fast electrons in ultrashort high intensity laser foil interaction is being studied worldwide to understand the fundamental aspects of laser energy coupling in dense plasma. It is also relevant to fast ignition concept of laser fusion as well as for development of MeV proton source and ultrashort duration x-ray source. For laser intensity > 10^{18} W/cm^2, fast electrons are predominantly generated by *J*x*B* mechanism with emission direction along laser propagation direction. Fast electrons transport through the thin foil target is strongly affected by the surface sheath fields that inhibit the escape of electrons and confines the fast electrons through refluxing and re-acceleration processes. However, these aspects are not well explored experimentally. We have studied the fast electron generation and transport in thin foil through high resolution measurements of K_α x-rays generated by the fast electron while propagating in dense matter.

The experiment was performed using 150 TW, Ti:sapphire laser system at RRCAT. The *p*-polarized laser beam (duration ~30 fs) was focused to a focal spot size of ~ 4.5 µm x 5.5 µm (FWHM) on 7 µm thick Cu foil to an intensity of ~ 10^{19} W/cm^2. A cylindrically bent crystal spectrograph was indigenously developed to measure high resolution Cu K_α emission in spectral range of 8.0 – 8.1 keV with a resolving power of > 500. X-ray spectra were recorded on an indirect x-ray CCD camera.

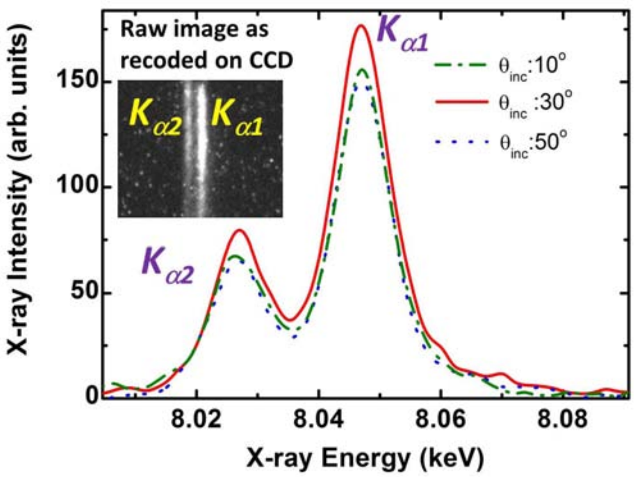

Fig. L.2.1: K_α x-ray spectra recorded at angle of incidence of 10°, 30° and 50°.

Figure L.2.1 shows typical x-ray emission spectrum ($K_{\alpha 1}$ and $K_{\alpha 2}$ lines) recorded in single shot for laser angle of incidence of 10°, 30° and 50°. A typical raw image of the x-ray spectra is also shown in the inset. For the laser intensity of ~10^{19} W/cm^2, the dominant absorption (electron acceleration) mechanism is *J*x*B* heating. This was also supported by direct measurement of escaping fast electrons along laser propagation direction. It can be noted that the x-ray intensity does not show much variation (< 10%) with the angle of incidence.

The absolute K_α x-ray flux was estimated to be ~ 2.4 x 10^9 photons per shot, which corresponds to the laser energy to K_α conversion of ~2.6 x 10^{-5}. The conversion of laser energy to fast electrons was also estimated to be ~1% by comparing models of x-ray generation from fast electrons. From direct measurements, the conversion efficiency of laser to escaping fast electrons (> 70 keV) was found to be ~ 10^{-2} %. The observed difference in conversion efficiency suggests that the most of the electrons were confined inside the target due to refluxing and produce x-rays with higher flux.

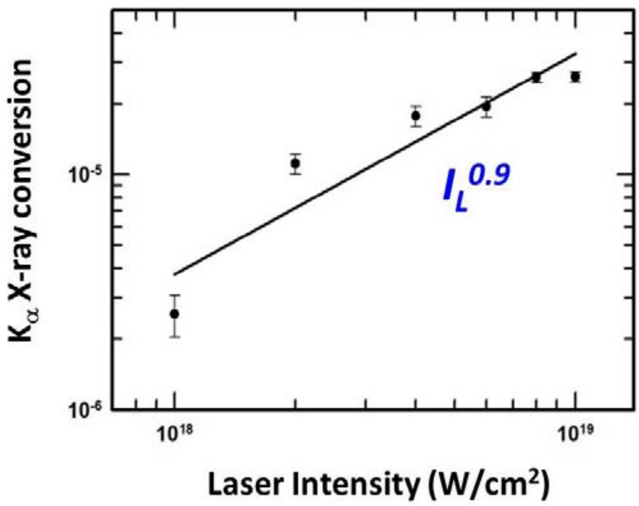

Fig. L.2.2: Laser energy to K_α x-ray conversion as function of laser intensity. Laser intensity was varied by changing the laser energy.

It can be noted from the Figure L.2.2 that the K_α conversion increases with the increasing laser intensity with scaling of ~ $I_L^{0.90}$. This is contrary to the expected behaviour as target thickness (7 µm) is much smaller than electron stopping range (tens of µm) for energy of several hundred keV. This reestablishes that K_α photons are mainly generated by the refluxing electrons. The refluxing efficiency is expected to be > 90% for present condition. As fast electron energy increases with the laser intensity, the number of K_α photon generated by refluxing electron also increases. A simple semi-analytical model was proposed to explain the observed x-ray scaling, which also suggests that x-rays are mainly generated by the electrons produced by *J*x*B* heating. Further, K_α measurement as a function of different layered targets demonstrates the dominant role of refluxing in x-ray conversion. Re-acceleration of fast electrons for longer pulse duration was manifested in slower x-ray conversion scaling of ~$I_L^{0.13}$ at constant laser fluence. Interestingly, a strong laser polarization (*p* and *s*) dependence of K_α x-ray conversion was also observed.

Ref.: T. Mandal, V. Arora, A. Moorti, and J. A. Chakera, Plasma Physics and Controlled Fusion 63, 095009 (2021).

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