§58. Investigation of Proton Energy Deposition in Compressed Cu Doped CD Shell

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The experiment for this project used the GEKKO XII and LFEX laser systems to investigate the proton fast ignition (pFI) concept of inertial confinement fusion (ICF). The essence of the concept is separation of the fuel compression and heating stages by using separate high energy (GXII in this case) and short pulse (LFEX) lasers. The latter irradiates a standoff target surface inside a cone directed toward the shell center, sending an intense beam of protons at approximately the time of peak compression.

A major objective of this project was to measure the protons' spectra and angular distribution with and without an imploded shell at the end of the cone. The newly upgraded LFEX laser provides the opportunity to make these measurements with a kilojoule energy- one of the highest energy short pulse lasers in the world.

The target consisted of a Cu-doped CD shell (550 μm OD with 5 μm CH ablator layer and 1.8 μm Cu(2.5%):CD layer) with a Au cone (45° full, h=1mm) embedded at one direction. The shell was illuminated uniformly by 9 GXII lasers (1.3 ns, λ = 0.53 μm) with 300 J each. Using the GEKKO XII driver pulse-shapes utilized in the electron fast ignition campaign, we expected to assemble the CD shell (doped with Cu at 2% atomic density of CD) to an areal density of $\rho r \sim 0.07$ g/cm^2 with a peak density of ~7 g/cm^3.

The LFEX beam (4 beamlets, 1000 J energy total, 6 ps FWHM duration, λ = 1.056 μm, $I > 3\times10^{18}$ W/cm^2) was injected into the cone and focused onto a cone-protected hemisphere foil with a 60 μm focal spot to generate protons from the hemisphere located 500 μm from the shell center.

The timing of the injection of the LFEX beam relative to arrival of the GXII beams onto the shell was chosen based on simulations of the implosion time of the shells and our previous proton fast ignition experiments at the same facility. An x-ray streak camera was used to watch the implosion evolution. An x-ray pinhole camera confirmed that the shell collapsed concentric to the original shell and inline with the cone to within 50 μm. Joint shots were taken at three different LFEX injection timings relative to the bang time: -250, -100, and +50 ps.

The primary diagnostic was a trio of proton spectrometers in the forward direction, 20° above, 0°, and 40° below the axis. They recorded the absolute proton spectra with high resolution covering the range 150 KeV<E_p<38 MeV. Electrons were also measured with the same spectrometer. Fig. 1 presents raw data from the three proton spectrometers from an LFEX-only shot (left) and a joint shot with an imploded shell (right). The proton beam from LFEX by itself had 17 J with a slope temperature of 2.3 MeV on axis and 1.8 and 2.0 MeV from the upper and lower spectrometers, respectively. This measurement will guide future experiments and be used as input in simulations.

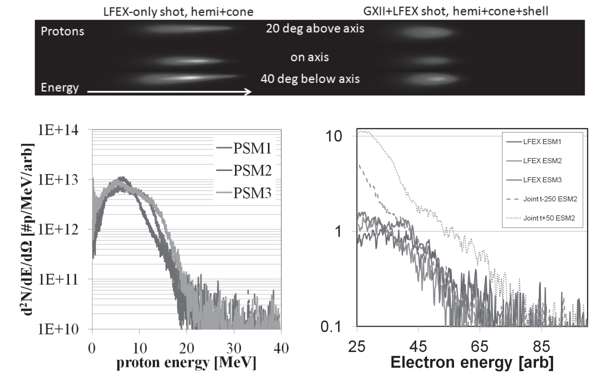

FIG. 1: a) Proton spectrum measured from the source after exiting the Au cone at three angles on a single LFEX shot with 1029 J in 6 ps. b)The same measurements taken in a joint GXII+LFEX shot showing much lower proton signal. c) The analyzed spectra from a). d) Fast electron spectra for select data showing increased LFEX coupling to fast electrons when the implosion took place.

On the joint shots, the proton signal was significantly reduced too much to be explained by stopping power from the imploded core alone. This could indicate that the implosion heated or disturbed the curved foil prior to the LFEX injection. The fast electron spectra (Fig. 1d) agree with this conclusion as coupling to fast electrons increased with increasing delay, which is consistent with a preplasma on the front surface. It is now believed that this was caused by un-converted 1.06 μm GXII light reaching the LFEX target inside the cone. To mitigate this in the future, the cone height will be extended to 5.5 mm.

The coupling to the imploded target was also measured. Diagnostics for this purpose were a Cu Kα imaging system and HOPG spectrometer both to measure emissions from the Cu dopant atoms. For shots without LFEX, the spectrum included Cu Kα (8048 eV) and He-like lines (8150-8400 eV), indicating the CH ablator was exhausted and the GXII lasers directly interacted with the Cu-doped layer. The Cu Kα signal was only slightly increased (a factor of <2) for each of the joint shots compared to the implosion-only shot, and it was highest for the shot with delay -100 ps, which could indicate coupling by <1 MeV protons, which take many 10s of ps to travel from the source to the core. Neutrons were also detected only on the -100 ps delay shot ($Y_N \sim 10^6$ vs. 10^4 from the implosion only).

For this campaign, the shielding for the monochromatic x-ray imaging system was improved to reduce the high background observed in the 2013 campaign. The result was a decrease in background by nearly an order of magnitude. The Cu Kα emission was observed in a GXII shot but the background was still too high to observe it in the joint shot.