§50. Investigation of Intense Proton Beam Transport in Solids and Compressed Matter

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This project is investigating transport of intense proton beams in solids and compressed matter. The proton beam is generated by the world's most powerful laser, the 2 petawatt LFEX short pulse laser. The study is important to understanding how protons can be used to deliver heating in the proton fast ignition (pFI) concept of inertial confinement fusion (ICF). In this project, we studied the generation of a proton beam, how it transported through a Cu foam, and where the foam was heated. The Cu foam made by General Atomics has a density of 1.1 g/cm^3, about 12% of solid Cu, so that a large volume can be optically thin to its own K-shell x-rays.

Two Cu foam target types were used as shown in Fig. 1: a cylinder that was 1mm long, which has a stopping range of 7 MeV for protons and a sphere that was compressed by GXII (nine beams, 330 J/beam, λ = 532 nm) to achieve similar areal density to the cylinder according to 2D radiation hydrodynamic simulations.

The LFEX beam (4 beamlets, 1 kJ energy on target, 1.5 ps FWHM duration, λ = 1056 nm, I > 2×10^{19} W/cm^2) was focused onto a cone-protected partial hemisphere high-density C foil located 500 μm from the open cone tip to generate the protons. Proton and electron spectra were measured using particle spectrometers in three forward directions, as well as a Thomson parabola. The Cu foam was observed using two monochromatic x-ray imaging systems, an x-ray spectrometer covering 7-9 keV, and an x-ray streak camera.

The absolute proton spectra (Fig. 2) are affected significantly by the additions of the cone structure and the cylinder. Stopping by the cylinder is manifest in the difference between the green and red curves. The monochromatic Cu Kα imagers observe heating by both electrons and protons (Fig. 3 left).

When the LFEX laser was fired in addition to the GXII compression drivers using the spherical Cu foam targets, 60% more Cu Kα emission was observed by the HOPG x-ray spectrometer and 40% enhancement was seen in the Kα camera (Fig. 3 right). The difference in these values could be an indication that the sample was heated to $\gg$100 eV, changing the line emission.

Collection of these impactful data was a major accomplishment. Particle-in-cell simulations are underway to gain additional insight. Simulations with various proton stopping models[3] will be compared for their ability to match the experimentally measured energy loss (green to red curves in Fig. 2) and absorption in the Cu (Fig. 3). Verification of such models through benchmarking in this way is an imperative step for proton Fast Ignition.

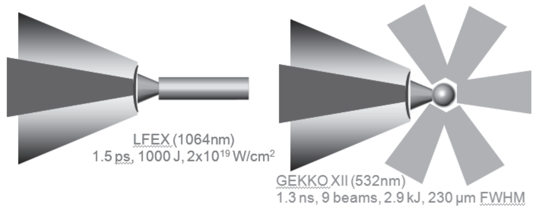

FIG. 1: target types with novel Cu foam transport samples. The cylinder was undriven while the 200 μm diameter Cu foam ball with ~18 μm CH ablator was irradiated by GXII (cone displayed cutaway to show the C foil).

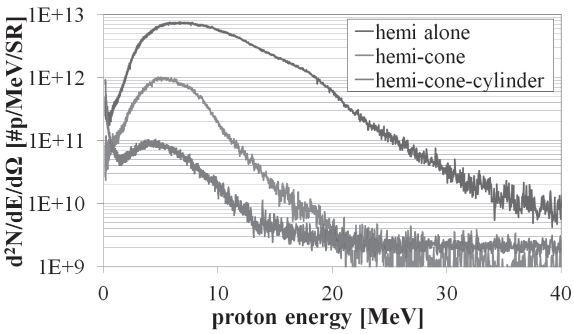

FIG. 2: proton spectra measured with the magnetic spectrometer along the laser and cylinder axis. The beam is strongest for a lone hemi (blue). When a cone is added, losses to the outer structure[2)] reduce the number and maximum energy of protons (green). Stopping in the cylinder reduces the proton beam energy further (red).

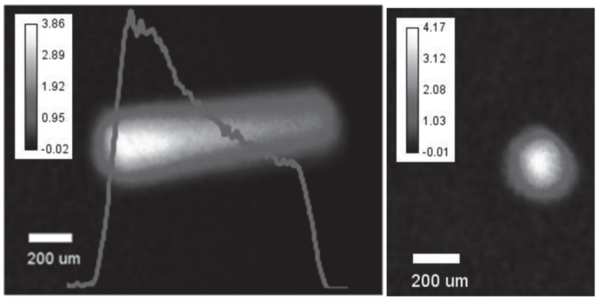

FIG. 3: images of Cu Kα emission from the two target types. The laser comes from left. The cylinder target (left) yields an emission profile indicating shallow heating from the protons with high stopping power and deeper heating by electrons. The sphere target (right) emitted 40-60% more in a joint shot than a shot with only GXII.

1) C. McGuffey et al., invited talk at the Fast Ignition Workshop in Yokohama in May 2016.
2) M.E. Foord, et al., *Phys. Plasmas* **19** 056702 (2012).
3) J. Kim et al., *Phys. Rev. Lett.* **115**, 054801 (2015).
4) J. Kim et al., *Phys. Plasmas* **23**, 043104 (2016).