Deuterons and Neutrons from Cryogenic Deuterium Ribbons at Vulcan Petawatt

C. Ho[1], H. Ahmed[1,2], A. McIlvenny[1], P. Bonnay[4], T. Chagovets[3], D. Chatain[4], S. Ferguson[1], D. Garcia[4], A. Girard[4], L. Giuffrida[3], B. Greenwood[3], F. Grepl[3], C. Lazzarini[3], G. Milluzzo[1], F. Nawaz[3], M. Notley[2], F. Schillaci[3], V. Scuderi[3], F.Souris[4], M. Tryus[3], A. Velyhan[3], D. Margarone[1,3] , M. Borghesi[1] and S. Kar[1]

[1] *Centre for Plasma Physics, Queen's University Belfast, Belfast BT71NN, UK.*

[2] *Central Laser Facility, Rutherford Appleton Laboratory, Oxfordshire OX11 0QX, UK*

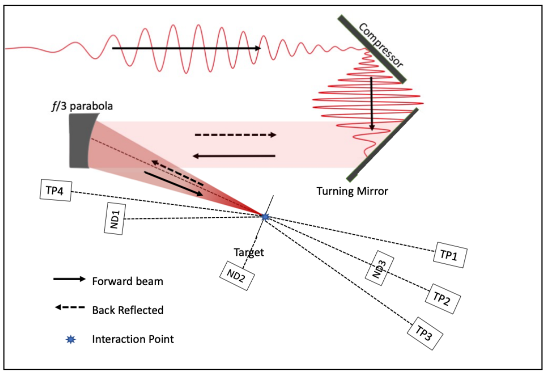
[3] *ELI–Beamlines Center, Institute of Physics, Czech Academy of Sciences, Za Radnici 835, 252 41 Dolni Březany, Czech Republic*

[4] *Université Grenoble Alpes, CEA IRIG-DSBT, F-38000 Grenoble, France*

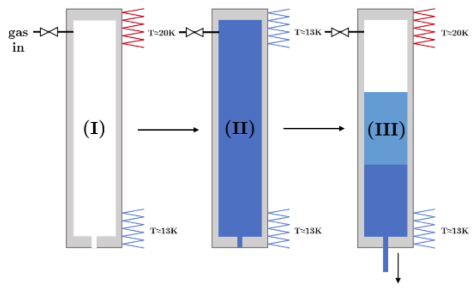
Abstract: The sustained interest in laser-driven neutron sources comes from their compactness and affordability while opening the possibilities for a wide range of applications, potentially complementing the research carried out at large-scale spallation facilities. An experiment was carried out at the Vulcan Petawatt facility (CLF, UK) to generate bright, ultra-short neutron bursts employing cryogenic ribbons of solid deuterium. Cryogenic targets can in principle produce single species, debris-free ion beams suitable for a wide range of applications. Deuterium ions up to 25 MeV/nucleon were detected in the forward direction, correspondingly with high energy neutrons in high fluxes being produced. Due to the low density of the target (∼200 mg/cc) and the significant radiation pressure at the delivered laser intensities ($5 \times 10^{19} - 5 \times 10^{20}\ W/cm^2$), considerable compression of the deuterium plasma at the front surface is expected and accelerating bulk deuterium by the hole-boring mechanism. The neutrons are subsequently produced by the d(d,n)^{3}He fusion reaction in the target bulk driven by ions produced by the hole-boring front. Preliminary particle-in-cell simulations support the experimental results to explain the underlying physics involving ps-class lasers at linear polarisation.

Introduction: Hole-boring [1] is the regime of radiation pressure acceleration (RPA) relevant to semi-infinite targets, where the ions from the front surface of the target are accelerated. Electrons are pushed into the skin layer by the ponderomotive pressure, which is balanced by the electrostatic pressure created by the charge separation. Ions reach the edge of the skin layer and escape with twice the velocity of the hole-boring front. The process continues until the end of the laser pulse. The accelerated ions travel through the target bulk generating neutrons through D-D reactions [2].

Experimental Setup: The experiment carried out at Vulcan petawatt used a 100um thick, 1mm wide cryogenic deuterium (cryo-d) ribbon. Multiple thompson parabola and neutron time of flight detectors were used to measure the ion and neutron spectra at various angles (fig.1a). To produce the cryogenic targets as shown in fig. 1b, deuterium gas was pumped into a cell and cooled using liquid helium, forming a solid deuterium plug at the bottom of the gas cell. The top of the cell was then heated creating a pressure differential that pushed the solid deuterium through the nozzle, forming a constantly flowing deuterium ribbon, suitable for use at high repetition. Unfortunately, the ribbon moved in and out of focus during the experiment, varying the intensity from $5\times10^{19}-5\times10^{20}\ W/cm^2$. Interferometry images were taken using a transverse probe beam, in order to measure the position of the ribbon on shot and therefore calculate the intensity.



(a) *Schematic of the Experimental Setup [3]*



(b) *Schematic Showing Three Stages of Cryogenic Target Production [4]*

Figure 1: Experimental Setup

Results:

i) Ions. Analysis of the ion spectra show that, despite our expectation of a pure deuterium beam a proton signal was present. However, the proton signal for cryo-d was much lower than from CH and CD targets (fig.2). The proton signal likely originates from hydrocarbon contaminants, or deuterium break up reactions. Furthermore, the deuterium signal from the cryo-d had a significantly higher flux and cut off energy in comparison to a CD target as shown in fig.2.

Theoretically, with increasing intensity we expect an increase in the hole boring velocity [5], $\beta_b = \sqrt{\Xi}/(1+\sqrt{\Xi})$ where $\Xi = I/(\rho c^3)$, and therefore an increase in the ion energies. The experimental deuterium cut off energy also showed a similar trend with increasing intensity (fig.2).

ii) Neutrons. As shown in fig.3, experimental data shows cryo-d produced a significantly higher neutron flux (by orders of magnitude) and neutron energies compared to CD foils (fig.3). The neutron flux generated from the in-target fusion mechanism has been shown to increase with increasing intensity [2]. However, the experimental results (fig.3) show the neutron flux plateaus at a mid-range intensity value, implying there is an ideal intensity to optimise neutron generation in this target. This unexpected flux scaling with intensity will be investigated using simulations.

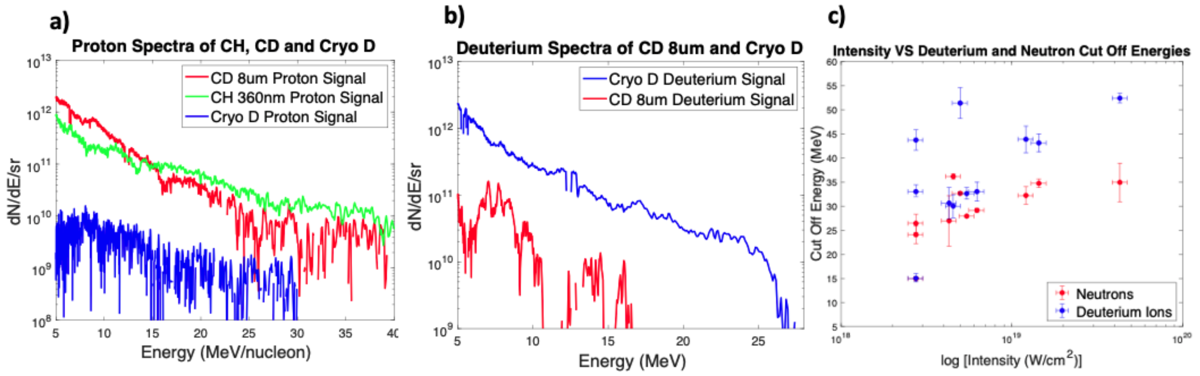


Figure 2: *a) Proton spectra for CD, CH and cryo-d. Showing an unexpected proton signal is present in the cryo-d. b) Deuterium spectra from CD and cryo-d targets. Showing the strongest signal from the cryo-d targets is deuterium. c) Deuterium and neutron cut off energies versus varying intensity*

Fig.2 shows the neutron energy increases with increasing intensity as expected from reaction kinematics, however the theoretical neutron scaling (plotted in grey) with ion energy (fig.3) shows that the experimental neutron energies are lower than expected compared to the ion energies achieved.

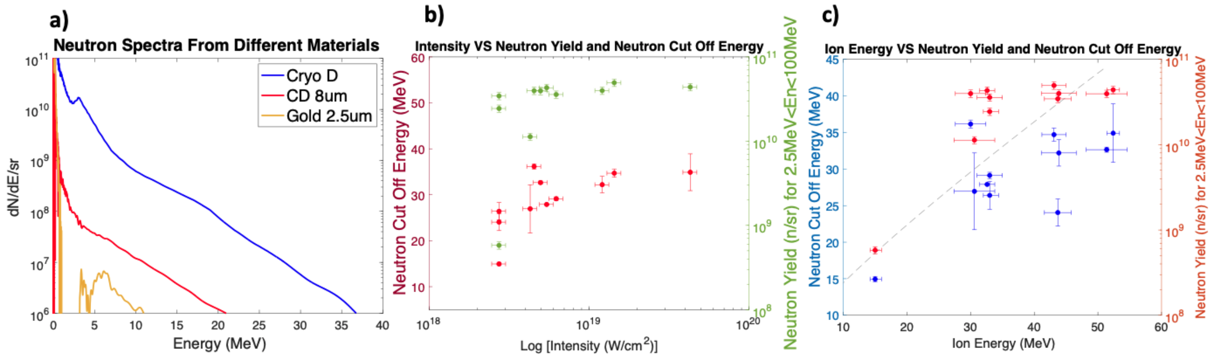


Figure 3: *a) Neutron spectra from cryo-d, CD and gold. Showing cryo-d has the highest neutron energy and flux in comparison. b) Neutron flux and energy against intensity. c) Neutron flux and cut off energy versus ion energy. The theoretical neutron energies can be estimated, [6]* $E_n = E_d/4(\sqrt{2} + \sqrt{(3Q/E_d)})^2$ *where* E_n *is the neutron energy and* E_d *is the deuterium ion energy.*

iii) Preliminary Particle-In-Cell Simulations. Particle-in-cell (PIC) simulations using SMILEI were used to investigate the neutron flux generation with respect to the laser pulse. Analysis of the laser electron density and neutron phase space, show that the majority of the neutrons are generated in the target bulk, rather than the hole-boring front (fig. 4). This may be because the neutron yield is dependent on the burn time of the reaction [7] $Y_n \cong \tau_{burn}/2 \int n_d^2 \langle\sigma v\rangle dV$. The hole-boring process lasts for the duration of a laser pulse, however the ions slowly make their way through the target bulk generating neutrons through in target fusion reactions for much longer than the duration of the laser pulse. These are preliminary simulations with a shorter pulse duration and a thinner target than the experimental setup. Multi-dimensional, full-scale simulations (including a target thickness scan) will be carried out to optimise this target for future use.

Conclusion: Despite having an unexpected proton signal in the ion spectra, the cryogenic deuterium target produced a strong deuterium signal. However, compared to the theoretical predictions, the neutron energies are lower than anticipated. The neutron flux was expected to increase with intensity however, instead it plateaus implying that there is an optimum intensity for neutron flux generation in these targets. Preliminary PIC simulations showed that most of the neutrons are generated towards the end of the pulse and continue long after the pulse has ended, as the ions slowly make their way through the target bulk. Multi-dimensional, full-scale simulations will be used to optimise the neutron flux from these cryogenic deuterium targets and investigate the underlying physics in these targets.

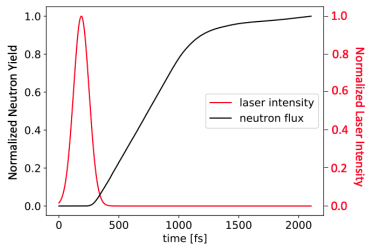


Figure 4: *Total neutron yield with time (black) obtained from simulations.*

References

[1] Macchi, A, et al. 2009,"Theory and simulation of ion acceleration with circularly polarized laser pulses", *C. R. Physique*, vol.10, no.2, pp. 207-215.

[2] Alejo, A, et al. 2016,"Recent advances in laser-driven neutron sources", *Il Nuovo Cimento C*, vol.6

[3] McIlvenny, A 2020, *Multispecies ion acceleration from intense laser interactions with thin foils*, PhD Thesis, Queen's University Belfast, Northern Ireland

[4] Martin, P 2020, *Schemes of Ion Acceleration Employing High Energy, Petawatt Laser Pulses*, PhD Thesis, Queen's University Belfast, Northern Ireland

[5] Robinson, A. P. L, et al. 2009, "Relativistically correct hole-boring and ion acceleration by circularly polarized laser pulses", *Plasma Phys. Control. Fusion*, vol.51

[6] Kar, S, et al. 2016, "Beamed neutron emission driven by laser accelerated light ions", *New J. Phys.*, vol.18

[7] Ditmire, T, et al. 1999, "Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters", *Nature*, vol.398