Target debris collection studies for inertial confinement fusion (ICF) experiments

G.P. Grim, T. N. Archuleta, P.A. Bradley, M.M. Fowler, A.C. Hayes, G. Jungman, A.W. Obst, R.S. Rundberg, D.J. Vieira, Y. Q. Wang, and J.B. Wilhelmy,
Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, USA
E-mail: gpgrim@lanl.gov

Abstract. At the recently completed National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, the initial set of diagnostics to be deployed are focused on measuring neutrons and γ's generated by \( d(t, n)α \) reactions in the imploded capsule. Although valuable for understanding pre-ignition experiments, this abbreviated diagnostic suite provides an incomplete picture of the plasma conditions obtained. Prompt radiochemical techniques, based on induced neutron and charged particle reactions within the imploded target, provide a novel and interesting new perspective. To enable these techniques requires the collection and assay of activated target material. In Nov. 2008, experiments were performed using the Omega Laser at the University of Rochester to study the efficiency of collecting debris from directly driven targets. Results from these experiments indicate that target debris was successfully collected, and the debris thermalization and transport scheme enhanced the debris collection up to 347% over direct collection.

1. Introduction
Prompt radiochemistry may be used in ICF experiments to study hydrodynamical mixing of the ablator and fuel[1, 2], as well as implosion dynamics, such as ablator velocity, through measurement of \(^9\text{Li}\) production in Be targets, or ablator radius and thickness, by measuring suitably normalized production of \((n,p)\) or \((n,2n)\) reactions on ablator contaminants such as Si, or Cu. To enable these measurements, techniques must be developed to ensure efficient collection of activated target material from the implosion, as well as, in-situ assay of lifetimes as short as 100 ms.

Collection of activated debris products from ICF implosions has had some degree of success in the past[3, 4, 5, 6]. To lay a foundation for understanding these issues in the NIF environment, we have performed a set of debris collection experiments on the Omega laser at the University of Rochester, Rochester, NY. The goals were to gain understanding of the dynamics of debris generation and transport in an ICF experiment, and to develop strategies to optimize the collection of this debris. Below we present results from these experiments.

2. Target debris collection
In experiments performed using the Nova laser, it was observed that debris generated by the ablated and highly compressed target posses kinetic energies too great to collect on materials.
directly viewing the target[3]. At the Omega laser, this situation may be ameliorated by moving materials away from the target. At the NIF, it is anticipated that X-rays generated by laser target interactions for 1.1 MJ shots, will ablate the target chamber wall, at least along the direction of the laser entrance holes[7]. Thus, developing a strategy for addressing this phenomena is important to enable reliable debris collection in ICF experiments.

2.1. Debris thermalization and transport experiment

Fig. 1(a) illustrates the architecture of a debris collection experiment performed at the Omega laser in Nov. 2008. Debris striking a “reflector” foil, in close proximity to the target, will thermalize while ablating a sufficiently thick layer of the ablator, which will entrain the target material and transport it as a thermal vapor to a “collector” foil, elsewhere in the chamber. In the experiments fielded, a 5.03 cm diameter reflector foil was positioned 14 cm from target chamber center (TCC) and was contoured to have a 40.6 cm radius of curvature. A 10 cm collector opposed the reflector at a distance of 65 cm from TCC. To facilitate a number of different assay techniques, different collector materials were used and varied from shot to shot. These materials consisted of Si, Sn, Ta, and Au. The fractional solid angles subtended from TCC by the reflector and collectors was 0.81% and 0.15% of 4π.

Plastic CH targets were used in the experiments. All capsules were specified to have an outer diameter of 875 µm and a 15 µm wall thickness. The capsules were filled with 15 atmospheres of equimolar DT gas. To measure the collected debris we manufactured 90% enriched \(^{13}\)CH targets and used the \(^{13}\)C/\(^{12}\)C (\(\delta^{13}\)C) ratio as our primary signature. Direct assay of \(^{13}\)C was possible for concentrations above \(1E14\) cm\(^{-2}\). The target masses were nominally 39.4 µg for \(^{13}\)C enriched targets, and 36.6 µg for the natural abundance targets. If the target debris were distributed uniformly, the CH concentrations impinging the reflector and collector surfaces should be \(6.9E14\) cm\(^{-2}\) and \(3.2E13\) cm\(^{-2}\) respectively.

To determine the materials present on the surface of the collectors, we used Rutherford backscattering spectrometry (RBS), nuclear reaction analysis (NRA) and time-of-flight secondary ion mass spectrometry (ToF-SIMS). To measure \(\delta^{13}\)C, the \((d,p)\) reaction on C was used. Details of this analysis are being published in a separate manuscript, but the primary signature for C isotopes results from the characteristic protons energies produced in \(^{12}\)C\((d,p)^{13}\)C and \(^{13}\)C\((d,p)^{14}\)C reactions. These energies are 3.25 MeV for the \(^{12}\)C\((d,p)^{13}\)C reaction and 6.19 MeV for the \(^{13}\)C\((d,p)^{14}\)C reaction. Collector foils were exposed to a 4 mm\(^2\), 1.4 MeV deuteron beam produced in the Ion Beam Materials Laboratory (IBML) at Los Alamos National Laboratory. The range of 1.4 MeV deuterons in Sn is approximately 10 microns.

Fig. 1(b) shows an example of the data collected from the NRA analysis. The data are proton spectra from the \((d,p)\) reaction produced by 240 µC of deuteron beam impinging a 0.25 mm thick Sn foils. A 25 µm Al foil was placed in front of the surface barrier detector which further reduced the characteristic proton energies for \(^{12}\)C and \(^{13}\)C signatures to 2.7 MeV and 5.9 MeV, respectively. The relationship between the number of counts in each carbon peak, \(^{12,13}\)A, and the respective concentrations, \(^{12,13}\)\(n\), is given by the formula:

\[
\frac{^{13}A}{^{12}A} = \frac{\sigma_{13}(d,p)^{13}n}{\sigma_{12}(d,p)^{12}n},
\]

where, \(\sigma_{12,13}(d,p)\), are the \((d,p)\) reaction cross sections on the respective carbon isotopes. Due to the simultaneous measurement the geometric and intrinsic detection efficiencies are identical for both reactions. A “clean” Sn foil was used to determine the \(\sigma_{13}(d,p)/\sigma_{12}(d,p)\) ratio by assuming the concentration ratio was equal to 0.011. Absolute concentration calibration was performed by implanting 40 keV \(^{13}\)C ions from 1E14 cm\(^{-2}\) to 5E16 cm\(^{-2}\) on the surface of a
clean Sn foil. The range of 40 keV C ions in Sn is nominally $\sim$20 nm, thus to determine potential contributions from bulk carbon by the deuteron beam, $(d,p)$, measurements were performed on the back surface of the foils and used to correct for this effect. The $(d,p)$ analysis technique simultaneously measures both $^{12}$C and $^{13}$C, thereby allowing for a direct measurement of $\delta^{13}$C after correction with the cross section ratio above. The calibration studies indicate that the practical $^{13}$C detection limit for this technique is $\sim 1E14$ cm$^{-2}$, provided that particle energy interference from other light isotopes can be avoided.

All implosions were generated by direct drive, using 23 kJ of laser energy delivered in a 1 ns square pulse. The data in Fig. 1(b) show a clear $^{13}$C signal is present in foil. Visual inspection of the pre and post shot foils shows a visibly significant presence of Au. Due to the proximity of the mass of Sn to that of Au, RBS analysis could not be used on this foil, but a Si wafer positioned 65 cm from TCC, and opposing a similar reflector foil, was observed to have a Au concentration of 3.8E15 cm$^{-2}$ present on the surface exposed to the Au reflector.

Table 1 summarizes the NRA data collected and analyzed to date. The data presented in the first row summarizes the calibration data. The $\delta^{13}$C ratio was assumed to be 0.0110, and the shown carbon concentrations were based on the $^{13}$C calibration data. Foil Sn-4 was measured on its front and back surfaces. The front surface was exposed to three successive enriched $^{13}$CH target implosions. The back surface was protected from direct exposure through a seal and enclosure. The $\delta^{13}$C ratio observed on the back surface was consistent with natural abundance carbon, while the front surface observation was 29.4% larger. The concentrations of $^{12}$C and $^{13}$C have decreased, from back to front, by 36.7% and 17.9%. This decrease in concentrations levels is due to heating of the foils by X-rays and target debris ions arriving ahead of the reflected thermal debris. Further, this decrease indicates that the carbon present on the foils is consistent with a few monolayer surface contamination, probably due to processing and preparation of the foils. This same behavior is observed in TOF-SIMS analysis of SiOH concentrations on the surface of clean Si wafers used in the experiments. The concentration of SiOH decreased by a factor of 50 from wafers used in the experiment to those not used. Finally, to confirm that the increased $^{13}$C observed on Sn-4 was not due to some other source, a natural abundance $^{nat}$CH.

Figure 1. Sketch of the target debris collection scheme deployed on the Omega laser facility and the NRA analysis of a Sn foil. A 5.03 cm diameter Au “reflector” foil, with 40.6 cm radius of curvature is located 14 cm from the target. The center radial of the foil points through target chamber center to a “collector” foil located 65 cm from the target. Proton spectra from the $(d,p)$ reaction produced by 240 $\mu$C of beam on a Sn foil exposed to three successive enriched $^{13}$CH target implosions.
target was imploded and debris collected on foil Sn-2. The measured δ\(^{13}\)C on the surface of the exposed foil is consistent with natural abundance. Thus, the excess \(^{13}\)C observed on foil Sn-4 must be due to the \(^{13}\)C in the enriched \(^{13}\)CH target used in the experiment.

Using the measured \(^{12}\)C concentration on Sn-4 to determine the amount of background \(^{13}\)C present, leaves an excess \(^{13}\)C concentration of 1.27 ± 0.08 × 10\(^{14}\) cm\(^{-2}\) from the target implosions. Under the assumption that the target debris is uniformly distributed, this implies an increase in collection efficiency due to reflection of between 47% and 342%. This range of values is due to the lack of data confirming whether the debris is from one, two, or three shots that the foil was exposed to. Since the concentration level is consistent with monolayer deposition on the foils, and the observed back-to-front concentration decreases for both C and SiOH are independent of the number of shots, it is likely that the increase due to reflection is at the higher end of the quoted range.

3. Summary
We have performed a debris collection experiment using directly driven targets at the Omega laser, based on thermalization, entrainment and focused transport to a collector substrate. We have observed statistically significant concentrations of target debris in the data analyzed and in enhancement of our collection efficiency over direct collection from 47% to 347%.

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