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Petrasso, R.D

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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Revisiting shock-driven exploding pushers: Insights into plasma flows and fields, stopping power, nucleosynthesis, and kinetic effects

Richard D Petrasso
Plasma Science and Fusion Center
Massachusetts Institute of Technology
77 Massachusetts, Ave., Cambridge, MA 02139 USA
E-mail: petrasso@psfc.mit.edu

Abstract. Shock-driven exploding pushers (SEP) provide a platform for a variety of incisive studies of high-energy-density phenomena in basic science and in inertial-confinement fusion (ICF). Fusion in D3He-filled SEPs provides monoenergetic 3.0-MeV protons, 14.7-MeV protons, and 3.6-MeV alphas, which are used to “backlight” a wide variety of experiments for radiographs of plasma-flow dynamics and self-generated fields in plasma jet collisions; in magnetic reconnection; in Rayleigh-Taylor instability growth; and in direct- and indirect-drive ICF implosions. In addition, reactions in SEPs are being used to study the stopping power of ions in plasmas, to study reactions important for nucleosynthesis, and to identify and study kinetic phenomena and the breakdown of hydrodynamic descriptions of plasma behaviour.

1. Introduction

Though shock-driven exploding pushers (SEP) were used for the first implosions in inertial-confinement fusion (ICF), they subsequently received diminishing attention except, in part, as a tool for testing and calibrating diagnostics. But recent developments have demonstrated that SEP is a platform that provides novel opportunities for a variety of incisive studies of high-energy-density (HED) phenomena in both basic science and ICF. For example, fusion in D3He-filled SEPs provides monoenergetic 3.0-MeV protons, 14.7-MeV protons, 3.6-MeV alphas, and other particles (see figure 1). These particles, emitted nearly isotropically, are now used to “backlight” a wide variety of HED experiments at the Omega laser facility [1], resulting in radiographs of plasma-flow dynamics and self-generated fields in plasma jet collisions [2]; in magnetic reconnection [3,4]; in Rayleigh-Taylor instability growth [5]; and in direct- and indirect-drive ICF implosions [6,7,8]. This work is addressed below in Sec. 2. In addition, the monoenergetic particles are being used to study the stopping power of warm and cold classical, non-classical, and degenerate plasmas, as discussed in Sec. 3.

SEPs are also intrinsically interesting because of their own physics, which make possible the study of important topics such as nucleosynthesis and kinetic and/or multi-ion fluid phenomena. For nucleosynthesis, conditions of the SEP plasma can mirror conditions in the early Universe or in stellar interiors. A number of recent and planned SEP experiments (see Sec. 4) address reactions such as 3He+3He fusion (the 3rd and dominant energy-producing step in the Sun); T+3He fusion (relevant to early-universe light-element generation); and D-H fusion (the 2nd step in the solar p-p chain, but also important in the formation of protostars).
As for kinetic effects, the mean free paths of ions in SEPs can easily be comparable to or greater than the implosion scale size when the fuel plasma density is sufficiently low and the temperature sufficiently high. Such conditions lend themselves to investigating kinetic effects and the possible breakdown of hydrodynamics. Within this general domain, the issue of multi-ion fluid effects, as opposed to the “average” single-ion fluid approximation that is pervasively used in almost all hydro simulation codes, is the subject of active experimental and theoretical investigation (see Sec. 5). With these objectives in mind, a recent series of experiments on Omega has probed implosions in which the initial fuel density of D^3He was systematically varied from 0.14 to 3.1 mg/cm^3. In this context it is notable that in the shock convergence phase of ignition capsule implosions the density of the DT gas is 0.3 mg/cm^3, so conditions in ignition capsules during shock convergence, and just after the rebound, mirror many of the conditions found in SEP. Thus insights culled from SEP studies will be germane to the “kinetic” phase that occurs during ignition implosions.

2. Exploding pushers for monoenergetic-charged-particle radiography

For quantitatively probing laser-plasma interactions, and particularly resultant E and B fields, an imaging technology was developed with a monoenergetic-particle backlighter and a matched detection system [10] as shown in figure 2. The monoenergetic particles (figure 1a) are nuclear fusion products resulting from D^3He-filled, exploding-pusher implosions at OMEGA: 14.7-MeV protons, 3-MeV protons, and 3.6-MeV alphas generated from the nuclear reactions

\[ \text{D} + \text{^3He} \rightarrow \alpha (3.6 \text{ MeV}) + \text{p} (14.7 \text{ MeV}) \]  
\[ \text{D} + \text{D} \rightarrow \text{T} (1 \text{ MeV}) + \text{p} (3 \text{ MeV}) \]  

In figure 2, the backlighter implosion is driven and timed to simultaneously “illuminate” two laser-generated plasma bubbles that are generated by a 600 J laser beam striking a 5-µm-thick CH foil. The 14.7-MeV protons pass through both plasma bubbles and through a mesh (period 150 µm) that resides either just in front or behind the plasma bubbles. Deflections of the proton beamlets defined by the mesh map the field strengths via the Lorentz force onto the CR39 proton detector. The fact that, as shown in figure 2b, one bubble is magnified (top) while the other is de-magnified demonstrates that the deflections are due to B fields rather than E fields. Since the protons are mono-energetic, the integral of the path integrated B field can be determined exactly. In this instance the degeneracy between E and B field deflections is broken by “flipping” the bubble. Another method is to make radiographs with both 14.7 and 3.0 MeV protons on two separate 10x10 cm sheets of CR39 and use the differences in deflection for different proton energies to discriminate between E and B fields.
Figure 2. Illustration of how a proton radiograph of two laser-generated plasma bubbles and a mesh were used [11] to study self-generated fields at the bubbles by analysing deflections of mesh-produced proton beamlets. Analysis of radiograph (b) proved that the fields were magnetic and not electric, and produced a map of magnetic field strength (c).

In another application, illustrated in figure 3, backlighter protons were used to make proton radiographs of an ICF capsule imploded by x rays generated by the interaction of 30 laser beams with the inner wall of a gold hohlraum [8]. The time sequence of radiographs shows the evolution of a five-pronged, asterisk-like pattern surrounding the imploding capsule, which reflects the 5-fold symmetry of the laser beams striking the hohlraum Au walls. The patterns are due to electromagnetic fields and plasma jets formed between neighbouring, expanding plasma bubbles that are generated by “nearest neighbour” laser beam pairs.

Figure 3. The first imaging of fields in a hohlraum, which utilized proton radiography, produced images at different times relative to laser-drive turn-on [8].

3. Exploding pushers for studying stopping power
Charged-particle stopping in weakly- to strongly-coupled plasmas has been studied analytically and numerically for decades [12,13, and references therein]. Although extensive efforts have been made to theoretically describe the behaviour of the charged-particle stopping in ICF-relevant plasmas, a very limited set of experimental data exists to check the validity of theories and models. To the best of our knowledge, only one previous attempt has been made to study the characteristics of charged-particle stopping for ICF-relevant plasma conditions [14], and it used a single shock-driven exploding...
pusher. Measured energy spectra of the charged particles produced in reactions (1) and (2) were used to measure the energy lost by each charged particle while leaving the plasma, and it was possible to compare the measurements to predictions of individual stopping models (see figure 4). This effort represented important progress in establishing an experimental method, but it was limited to one implosion whose parameters were not fully characterized and therefore it could not unambiguously identify the most accurate stopping model(s). Recent experiments [15] resolve that issue by utilizing a greatly expanded database, quantitatively probing charged-particle stopping near the Bragg peak for a wide range of more accurately characterized plasma conditions. They quantitatively evaluate different charged-particle stopping formalisms that have been central to discussions in the current literature and that will be required for accurately modelling alpha transport and heating of the hot spot in ignition experiments.

Figure 4. Energy loss normalized by $Z^2$, as a function of $E/A$, as predicted by the Li-Petrasso formalism [12] and by the parameterization of molecular dynamics simulations [13]. These curves were generated for a plasma with an electron temperature of 500 eV and an electron number density of $10^{22}$ cm$^{-3}$. Using DD-T, D$^3$He-$\alpha$, DD-$\rho$ and D$^3$He-$\rho$, with substantially different velocities, characteristics of different charged-particle stopping formalisms around the Bragg peak can be investigated. The energies of the four charged fusion products are indicated in the figure (typical spectra are shown in figure 1a).

4. Exploding pushers in plasma nuclear physics
As described in Ref. [16] and illustrated in figures 5a and 5b, the first basic nuclear physics experiment in the context of an ICF facility involved measurement of the differential cross section for elastic neutron-triton ($n$-T) and neutron-deuteron ($n$-D) scattering at 14.1 MeV at OMEGA, utilizing CPS-2 (figure 1b). By simultaneously measuring elastically scattered $^3$H and $^2$H ions from a deuterium-tritium gas-filled, shock-driven exploding pusher, the cross section for elastic $n$-$^3$H scattering was obtained with significantly higher accuracy than previously achieved in accelerator experiments. The results compare well with calculations that combine the resonating group method with an ab initio, no-core shell model, which demonstrate that recent advances in ab initio theory can provide an accurate description of light-ion reactions.

Figure 5. (a) Measured differential cross section for elastic $n$-D scattering, normalized to a Faddeev calculation. (b) Measured and calculated differential cross section for elastic $n$-T scattering. The solid curve represents an ab-initio calculation, and the dashed curve represents an R-matrix calculated n-T cross section.
In very recent work, the first preliminary $^3$He-$^3$He proton spectrum ever obtained from a plasma was acquired from a $^3$He-gas-filled exploding pusher and measured with compact proton spectrometers [9]. Both the three-body continuum and the p+$^5$Li resonance at 9.3 MeV were observed at an average Gamow energy of ~95 keV [17] under conditions similar to those in first-generation, hydrogen-burning Population III stars. The $^3$He-$^3$He reaction is the third step in the p-p chain, which is important in our Sun and also dominates the initial stages of first-generation hydrogen-burning, Population-III stars (which have masses of tens to a hundred solar masses). These stars were responsible for the first synthesis of heavy nuclei in the universe, and understanding their evolution will be important for calculations of later stellar and galactic dynamics. Such stars will be studied directly by astrophysicists using the James Webb Space Telescope.

5. Exploding pushers for studying kinetic and multi-ion fluid effects

Exploding pushers are ideal for studying the transition from the hydro regime to the kinetic regime and also multi-ion effects in the hydro limit (such as for D$^3$He or for DT). In this context it is important to realize that all implosion simulation codes that are widely used are single-average-ion hydro codes. To explore these different regimes and different approximations, a series of exploding pusher experiments was undertaken (figure 6) in which the density of the D$^3$He fuel was varied from 3.1 (hydro regime) to 0.14 mg/cm$^3$ (kinetic regime). Over this density range the mean-free path of the ions at bang time transitioned from much shorter (at 3.1 mg/cm$^3$) to much longer than the imploding shell radius. Hydro simulations should increasingly deviate from experimental results as the fuel density is reduced, which was exactly what was seen. The DD and D$^3$He yields at high densities were in reasonable agreement with hydro simulations, but diverged strongly at the very lowest densities, where simulated yields were approximately 2 orders of magnitude too high [18,19].

Figure 6. Implosion experiments at Omega on 14 March 2013 explored the impact of varying the fuel density from 3.1 to 0.14 mg/cm$^3$, for investigating multi-species effects and, at the lower densities, kinetic effects.

Figure 7. Hydrodynamic predictions for burn histories of DD and D$^3$He. A new diagnostic will measure both burn histories to discriminate between these simulations and those from kinetic and multi-ion fluid codes.

Another area where deviations from hydrodynamic behaviour will be studied is the relative timing of ICF burn histories for DD and D$^3$He reactions. Figure 7 illustrates burn histories predicted by an average-ion hydro simulation for an SEP with 2.2-mg/cm$^3$ D$^3$He fill, but simulations of multi-ion fluid codes and kinetic codes predict substantially different results. To experimentally explore these effects, a new dual-particle temporal diagnostic for measuring any differences between DD and D$^3$He burn histories to ~ 10 ps accuracy [20] has just been tested with great success. Making such measurements on a single diagnostic is important because it avoids cross-timing uncertainties that are unavoidable when comparing measurements made with two different diagnostics.
6. Student development

Much of the work described here was carried out by MIT PhD students (see figure 8), who worked on diagnostic development and calibration as well as experiment design and analysis. They have done hands-on work at the MIT accelerator, at Omega, and at the National Ignition Facility (NIF).

![Figure 8. Several MIT staff, students, former students, and E. Moses (b), the former NIF director, at the MIT student-run accelerator used for diagnostic development. Former student D. Casey, now a scientist at LLNL, was the first student to write a PhD thesis with NIF data.](image)

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