Final technical report on the project

TIME EVOLUTION OF CAPSULE $\rho R$

and

PROTON EMISSION IMAGING OF CORE STRUCTURE

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TABLE OF CONTENTS

A. ρR EVOLUTION AT SHOCK-COALESCEENCE TIME AND AT BANG TIME: possible effects of ρR imprinting at shock-coalescence time ......................................................... 3
   i. Measurement with multiple proton spectrometers .......................................................... 3
   ii. Measurement with multiple proton spectrometers plus the proton temporal diagnostic .... 3
B. PROTON EMISSION IMAGING OF NUCLEAR BURN ........................................................... 5
C. STUDENT TRAINING AND EDUCATION IN HIGH-ENERGY-DENSITY PHYSICS AND ICF ................................................................. 6
D. GROUP PUBLICATIONS, 2002-2004 ................................................................................. 6
E. GROUP CONFERENCE PRESENTATIONS, 2002-2004 .................................................. 8
F. REFERENCES ........................................................................................................................ 11
A. pR EVOLUTION AT SHOCK-COALESCEENCE TIME AND AT BANG TIME:
possible effects of pR imprinting at shock-coalescence time

i. Measurement with multiple proton spectrometers

Following an earlier prediction [1], absolute measurements of low-mode pR asymmetry have now been made through spectra of both primary and secondary D³He protons (their energy losses leaving a capsule are proportional to pR for each spectrometer line of sight). Definitive observation of asymmetry was first made with secondary protons from D₂-filled capsules [2]; demonstration of the correlation between drive asymmetry and pR asymmetry was made with D³He-filled capsules [3], examined in more detail [4], and culminated [5] in the derivation and experimental verification of a scaling formula \( \frac{\delta \langle \rho \rangle}{\langle \rho \rangle} \approx 0.4 (C_r^{-1}) \) relating the rms amplitude of asymmetry in illumination \( I \) to the rms amplitude of pR asymmetry in terms of the radial convergence ratio \( C_r \) (showing that the growth in amplitude of these low modes is dominated by Bell-Plesset-like convergence effects). It has also been shown now [6,7] that the same scaling can be applied at individual angles and individual times during implosion, and that separate modes grow at approximately the same rate and maintain their phase at least until compression burn time (see Fig. 1).

![Diagram](a)(b)(c)(d)

**FIG. 1.** Effects of laser drive asymmetry on pR asymmetry and pR asymmetry growth have been inferred from D³He proton spectra measured at different directions such as those in (a), where each spectrum (3 out of 6 are shown) is decomposed into components from shock bang time (blue) and compression bang time (red). (b) Offsetting capsules from target chamber center resulted in illumination intensity \( I \) as a function of angle \( \theta \) away from the offset direction. \( I(\theta) \) resulted in pR(\( \theta \)) with the same phase, growing in amplitude without phase inversion as shown in (c) and (d). The relationship between the amplitudes of (b), (c) and (d) is consistent with the prediction in ref. [5] that pR asymmetry growth should proceed primarily through effects of the radial convergence ratio \( C_r \). The data in (b)-(d) are from OMEGA shot 31388 (18 atm D³He in a 27-\( \mu \)m CH shell; 23 kJ of laser energy). These data are from ref. [7].

ii. Measurement with multiple proton spectrometers plus the proton temporal diagnostic

The symmetry data inherent in multiple proton spectra have now been combined with direct measurements of proton production time evolution to produce more complete information about the time evolution of pR asymmetries [8]. This has been made possible by the development of the Proton Temporal Diagnostic (PTD), which was developed on OMEGA for studying the D³He burn history (see Fig. 2) [8,9]. The strength of the D³He shock burn, and its clear separation from the compression burn (unlike the case for DD or DT), allow
highly accurate timing measurements [8] makes possible the modeling of capsule structural evolution throughout the time interval from shock coalescence to compression burn.

FIG. 2. The proton temporal diagnostic (PTD) for measurements of the D^3He burn history. (a) The PTD front end. (b) Streaked image of scintillator output, recorded by a CCD camera attached to a streak camera. (c) Resulting time history of the D^3He burn, indicating both shock burn and compression burn for shot 31271. In (b), a train of optical fiducial signals (labeled “4”), is used for timing reference. Also indicated is the x-ray component (labeled 1), shock component (labeled 2), and compression component (labeled 3).

Because the Ti dependence of the D^3He reaction is much stronger than that of the DD reaction, shock bang time can be measured far more accurately from the proton rate in D^3He implosions than from the neutron rate from either DD or DT implosions. Shock bang is particularly important because it is unaffected by mix [10] and is also one of the best measures of drive efficiency. As an illustration, Fig. 3 shows an example of a proton rate history (measured by the proton temporal diagnostic, or PTD [9]), from a D^3He implosion, and 1-D LILAC simulations of the same implosion. Selection of an appropriate flux limiter (in this case 0.07) results in a simulation that matches the timing of shock bang and compression bang, but the yield does not agree even for the shock bang (at which time the 1-D calculation would be expected to be at its most accurate because of the absence of mix.

FIG. 3. The first measured D^3He burn rate histories provide clear shock bang timing and a new and stringent test of simulations. In this case, the measurement (solid red) is compared with two 1-D simulations with flux limiters of 0.06 and 0.07 (dashed lines) for a 24-µm thick CH shell implosion (shot 29839). The shock and the compression bang times are well matched by the 1-D calculation with flux limiter 0.07, but neither simulation (nor others not shown) can match the magnitude of the shock burn, for which there is no mix and 1-D should be expected to best replicate the experiment.

FIG. 4. The measured time evolution of ρR and ρR asymmetries (a) provides details of implosion dynamics hitherto unavailable. Evolution of ρR is inferred from the D^3He burn history (a) and individual proton spectra (b) from a single shot (two of six are shown) as described in Ref. [8].

By combining the D^3He burn rate with data from multiple proton spectrometers, the time evolution of ρR and ρR asymmetries can be inferred as illustrated in Fig. 4 [8]. It was shown that the ρRs grew from about 13 mg/cm^2 at shock bang time [8,10] (just before deceleration onset) to between 45 and 80 mg/cm^2 some 350 ps later at compression bang time. In this instance, the ρR growth is observed to be asymmetric, an occurrence that apparently depends strongly on illumination conditions [3,7,5]. In addition, it was
shown that ρR asymmetries exist at shock-bang time for nominally symmetric implosions, and that these asymmetries (l = 1) are amplified throughout the implosion without any phase changes. It was also shown that ρR asymmetries grow ~2 times as fast as the average ρR growth [8].

B. PROTON EMISSION IMAGING OF NUCLEAR BURN

Measured burn images and burn profiles provide compelling insight into implosion dynamics, including the combined effects of mix, hydro efficiency, and electron and radiation transport. To that end, we developed the multi-camera Proton Core Imaging System (PCIS) [11,12] on OMEGA (Fig. 5) for quantitative, 3-D spatial measurements of the fusion burn region in direct-drive implosions of D³He-filled capsules. Images from three orthogonal penumbral imaging cameras are processed with special algorithms [11] to find either the surface brightness of the burn region with arbitrary asymmetric structure (Fig. 5) [11,14,15] or the radial profile of D³He reactions per unit volume when burn is spherically symmetric (Fig. 6) [11,13]. Combined with our other diagnostic measurements of the time evolution of D³He burn, ρR as a function of angular position, and the time evolution of ρR, PCIS provides a unique tool for studying implosion dynamics and performance.

FIG. 5. 3-D imaging of D³He burn in an asymmetric OMEGA implosion shows the effects of drive asymmetry. The images show surface brightness of the burn region as seen simultaneously from three orthogonal directions by separate proton emission cameras [11,12]. Prolate burn asymmetry resulted from (intentional) laser drive asymmetry with lower than average illumination in two opposing directions. The pole view is along the axis of symmetry, both side views are orthogonal to it. Burn images are important, as they reflect the cumulative effects of drive, compression, and mix.

FIG. 6. Measurements of burn region size show the effects of different drive and capsule parameters for symmetric OMEGA implosions [13]. (a) Sample radial profile of D³He emissivity is approximately Gaussian, with a burn radius R_burn defined at the 1/e point. (b) R_burn vs. on-target laser energy for glass and CH shells. (c) R_burn vs. ρR for imploded capsules with 20-μm CH shells and different fill pressures. The smaller burn region for the lower pressure is related to compression and mix, as discussed in the text.

Figure 5 shows an example of how (intentionally) asymmetric laser drive results in an asymmetric burn region. Similar results for different types and amplitudes of drive asymmetry show clear correlations between drive conditions and burn asymmetry. Figure 6a shows a sample radial profile of burn for a symmetric OMEGA implosion, while Fig. 6b shows examples of how the size of
the burn region varies for different laser energies and shell types. The burn regions of imploded thin-
glass-shell capsules get larger with increasing laser energies; the burn regions of thick-plastic-shell
capsules are, not surprisingly, significantly smaller than those of glass-shell capsules imploded with
the same laser energy. Figure 6c shows that decreasing fill pressure can lead to diminished burn
region size, even though shell convergence (as indicated by \( \rho R \)) does not notably increase. This
is supported by our previous finding [14] from studies of similar DT implosions that a reduction of
pressure did not lead to much increase in radial convergence, in contrast to predictions of 1D codes,
and was probably an indication of increased fuel-shell mix; the reduction in burn region size at lower
pressures seen here may be another sign that mix is more extensive, cooling more of the outer fuel
region.

C. STUDENT TRAINING AND EDUCATION
IN HIGH-ENERGY-DENSITY PHYSICS AND ICF

The MIT group has outstanding graduate and undergraduate students training in ICF and
HEDP. They are involved in a wide range of projects from experimental to simulation to theory. The
graduate students are deeply engaged in every aspect of our research program, and spend
considerable time at LLE working on experiments and working with our collaborators from LLE and
from the National Labs. They report their results at the major conferences (DPP, Anomalous, IFSA,
HTPD), at National Laboratory workshops and seminars, and at seminars at MIT and LLE, and
they write up their work for submission to refereed physics journals. Each graduate student typically
has three major first-author publications as well as co-authorship on several (typically 5-7) other
major publications by the completion of their thesis. Presently we have five outstanding graduate
students: Mr. Ryan Rygg, Mr. Cliff Chen, Mr. Joe DeCiantis, Ms. Sabine Volkmer and Mr. Daniel
Casey. We anticipate that at least one more will join us this summer. Graduate students Ryan Rygg
and Joe DeCiantis both were awarded 1st Place Excellence Awards for their Graduate Research at
the last NNSA symposium.

We have found that the undergraduates are also quite eager to participate and to learn about
ICF. The Fusion Product Source gives them hands-on experience with many of the techniques we are
using at, or developing for, OMEGA and the NIF. In this past year 11 undergraduates have worked
in our group (Ms. Amy Slagle, Mr. Greg Belote, Mr. Gabriel Warshauer-Baker, Mr. Rory Rother, Mr.
Andy McLaughlin, Mr. Dylan Consla, Ms. Jessica Lam, Mr. Siddharth Sundar, Mr. Jon Williams,
Mr. Dan Dennis, and Ms. Molly Bright). Each had a project for which he or she had primary
responsibility.

D. GROUP PUBLICATIONS, 2002-2004

m1. F. H. Séguin, J. L. DeCiantis, J. A. Frenje, S. Kurebayashi, C. K. Li, J. R. Rygg, C. Chen, V.
P. W. McKenty, D. D. Meyerhofer, S. Roberts, T. C. Sangster, K. Mikaelian and H. S. Park,
“D3He-proton emission imaging for inertial-confinement-fusion experiments (invited)”, Rev. Sci.

m2. C. K. Li and R. D. Petrasso, “Stopping of Directed Electrons in High-Temperature Hydogenic

m3. C. K. Li, F. H. Séguin, J. A. Frenje, R. D. Petrasso, J. A. Delettrez, P. W. McKenty, T. C. Sangster,
Radha, S. P. Regan, W. Seka, “Effects of Nonuniform Illumination on Implosion Asymmetry in

J. M. Soures, “Measuring shock bang timing and \( \rho R \) evolution of D3He implosions at OMEGA”,

Séguin, “Dependence of shell Mix on Feedthrough in Direct Drive Inertial Confinement Fusion”,


E. GROUP CONFERENCE PRESENTATIONS, 2002-2004


1. M. Canavan et al., “A modified accelerator for ICF diagnostic development”.
2. J. L. DeCiantis et al., “The dependence of measured burn profiles on capsule and laser parameters”.
3. J. A. Frenje et al., “Measurements of time evolution of ion temperature in D³He implosions at OMEGA”.
4. C. K. Li et al., “Stopping, straggling and blooming of directed energetic electrons in hydrogenic plasmas”.
6. F. H. Ségouin et al., “Studying effects of drive asymmetry on burn asymmetry with proton emission imaging”.

34th Annual Anomalous Absorption Conference (2 - 7 May 2004, Gleneden Beach, OR):

7. C. K. Li et al., “Effects of Nonuniform Illumination on Implosion Asymmetry in Direct-Drive Inertial Confinement Fusion”.
11. J. DeCiantis et al., “Studying the Burn Region in ICF Implosions with Proton Emission Imaging”.


13. M. J. Canavan et al., “Diagnosing DT Cryogenic Fizzles at the NIF”.
14. J. DeCiantis et al., “Studying the Burn Region in ICF Implosions with Proton Emission Imaging”.

- 8 -
t15. J. Frenje et al., “A Magnetic Recoil Spectrometer (MRS) for $\rho R_{\text{fuel}}$ and $T_i$ Measurements of Warm, Fizzle and Ignited Implosions at the NIF”.

t16. C. K. Li et al., “First Spectrometry of Charged Particles from Indirect-Drive Capsule Implosions”.


t17. C. K. Li et al., “Effects of Nonuniform Illumination on Implosion Asymmetry in Direct-Drive Inertial Confinement Fusion”.


3rd International Conference on Inertial Fusion Sciences and Applications (7 - 12 Sept. 2003, Monterey, CA):

t36. C. K. Li et al., “$\rho R$ Asymmetry in Spherical Implosions of Inertial Confinement Fusion”.

- 9 -
38. J. A. Frenje et al., “A Novel Magnetic Recoil Spectrometer (MRS) for Precise $\rho R_{\text{fuel}}$ and $T_i$ Measurements of Warm and Cryo OMEGA Implosions, and Warm, Fizzle and Ignited NIF Implosions”.

39. P. W. McKenty et al., “Direct-Drive Cryogenic Target Implosion Performance on OMEGA”.

33rd Annual Anomalous Absorption Conference (22 - 27 June 2003, Lake Placid, NY):

40. C. K. Li et al., “Using Charged Particles to Measure $\rho R$ and $\rho R$ Asymmetries for Indirect-Drive Implosions”.

41. J. A. Frenje et al., “Measurement of Shock-Coalescence Timing and $\rho R$ Evolution of $D^3He$ Implosions at OMEGA”.

42. J. A. Frenje et al., “A Magnetic Recoil Spectrometer (MRS) for Precise $\rho R_{\text{fuel}}$ and $T_i$ Measurements of Warm and Cryo Targets at OMEGA and the NIF”.

43. F. H. Seguin et al., “Time Evolution of $\rho R$ Asymmetries in OMEGA Direct-Drive Implosions”.

44. R. Rygg et al., “The Effects of Implosion Asymmetry on Shock Coalescence in OMEGA Experiments”.

45. S. Kurebayashi et al., “Using Secondary Protons and Neutrons to Study $\rho R_{\text{fuel}}$”.

46. J. DeCiantis et al., “Imaging DD and D$^3$He Burn Profiles on OMEGA Implosions”.


47. C. K. Li et al., “Capsule Areal Density Asymmetries and Time Evolution Inferred from 14.7-MeV Protons in OMEGA Implosions”. (Invited talk)

48. R. D. Petrasso et al., “Proton Core Imaging Spectroscopy (PCIS) of OMEGA Implosions”.

49. F. H. Seguin et al., “Measurement $\rho R$-Asymmetry Time Evolution in Implosions at OMEGA”.


52. S. Kurebayashi et al., “Relationship of Secondary Nuclear Production to Implosion Characteristics at OMEGA”.


32nd Anomalous Absorption Conference (21 - 26 July 2002, Oahu, Hawaii):

54. R. D. Petrasso et al., “Capsule Areal Density Non-Uniformities and Evolution Inferred from 14.7-MeV Proton Line Structure in Omega $D^3He$ implosions”.

55. C. K. Li et al., “Effects of Fuel-Shell Mix upon Direct-Drive, Spherical Implosions on OMEGA”.

56. V. A. Smalyuk et al., “Areal-Density-Growth Measurements with Proton Spectroscopy on OMEGA”.

14th Topical Conference on High Temperature Plasma Diagnostics (8 - 12 July 2002, Madison, Wisconsin):

57. C. K. Li et al., “Charged-particle Spectroscopy on OMEGA Laser Facility”. (Invited talk)

58. J. A. Frenje et al., “A Magnetic Deuteron Recoil (MDR) Neutron Spectrometer for $\rho R_{\text{fuel}}$ Measurements of Cryogenic DT Targets on OMEGA and NIF”.

CEA-DOE workshop (Feb 2002, LLNL):

59. C. K. Li et al., “Recent Results of Implosion Physics Studies for Direct-Drive ICF experiments”.

60. T. C. Sangster et al., “OMEGA Direct-Drive ICF experiments”.

- 10 -
F. REFERENCES

12. J. D. DeCiantis et al., Rev. Sci. Instrum., to be submitted.
13. J. D. DeCiantis et al., Phys. Plasmas, to be submitted.