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DRAFT

Shock timing technique for the NIF

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Abstract

Among the final shots at the Nova laser was a series testing the VISAR technique that will be the primary diagnostic for timing the shocks in a NIF ignition capsule. At Nova, the VISAR technique worked over the range of shock strengths and with the precision required for the NIF shock timing job – shock velocities in liquid D_2 from 12 μm/ns to 65 μm/ns with better than 2% accuracy. VISAR images showed stronger shocks overtaking weaker ones, which is the basis of the plan for setting the pulse shape for the NIF ignition campaign. The technique is so precise that VISAR measurements may also play a role in certifying beam-to-beam and shot-to-shot repeatability of NIF laser pulses.

52.35.Tc,52.58.Ns,47.40.Nm,07.60.Ly

Typeset using REVTEX

I. INTRODUCTION

The biggest problems with inertial fusion are drive symmetry and shell stability; imploding a fraction of a milligram of DT to a ρr over 2 g/cm^2, so inertial confinement works, won't be easy.

This paper is about the secondary problem of shock timing; symmetry and stability aren't the only challenges we face in the ignition campaign at the National Ignition Facility (NIF). The NIF ignition target requires a pulse shape with a complicated low power foot, designed to send a carefully timed series of shocks through the frozen DT shell. If the shocks are too closely spaced, they coalesce within the DT ice; if too widely spaced, the DT ice decompresses between shocks. Either way, the DT winds up on a high adiabat and fails to reach high ρr at the end of the implosion [1].

The plan for achieving the proper shock timing (that is, the proper pulse shape) for a NIF ignition capsule relies on a diagnostic instrument called VISAR [3] (velocity interferometry system for any reflector). A VISAR very accurately measures the speed of the leading shock in liquid hydrogen; the cold liquid is transparent, while shocked hydrogen is a highly reflective metal [4]. Section II explains how we will use the leading shock measurements to adjust the laser pulse shape, converging to the proper pulse for driving an ignition capsule after several timing shots. Section III discusses the Nova VISAR experiments from March to May of 1999 that demonstrate both the accuracy and dynamic range we need to carry out our NIF shock timing plan.

II. NIF SHOCK TIMING PLAN

Four shocks traverse the DT ice main fuel layer in indirectly driven NIF ignition capsules [2]. The first three quarters of the laser pulse launches this shock sequence in a complicated series of steps. The strength and timing of the shocks depends on the power and timing of the steps in the laser pulse, but the precise relationship is very difficult to compute. Absorption

of the laser, conversion to X-rays, and X-ray ablation are all complicated processes. Our simulations for any one process will never be better than a few percent, and some parts may well be off ten percent or more. The combined modeling uncertainties probably exceed the tolerance of an ignition capsule to errors in pulse shape. We need an experimental procedure to find the proper pulse shape.

A typical ignition pulse, shown in Fig. 1, has many adjustable parameters. The height of the first step sets the crucial first shock strength; once this is set, the timing of the steps that launch the second and third shocks become the most critical parameters. As a rule of thumb, none of the four shocks may coalesce within the DT ice layer, and all four must break out of the ice layer in a tight sequence. Since each shock overtakes the previous one, if the DT ice layer were thicker, the shocks would begin to coalesce at a depth just inside the actual ice layer thickness. A reasonable design criterion is for the first three shocks to coalesce at a single point and time – about 85 μm from the ablator interface, when the actual ice thickness in the capsule is 80 μm. The fourth shock can overtake the others somewhat later.

This coalescence criterion for the first three shocks does not represent an optimum in any sense, but it does guarantee good shock timing. The overtake depth is actually a free parameter; the capsule will be well-timed over a range of coalescence depths of several microns.

In order to time the shocks for a NIF ignition capsule, we will use an experimental analogue of the technique we use to tune capsules with simulations. Instead of a series of simulations where we adjust the pulse shape until the shocks break out from the DT ice in a tight sequence, we will perform a series of shock timing shots, monitoring shock coalescence with a VISAR, and adjusting the pulse shape until the first three shocks coalesce at the proper depth.

Fig. 2 compares the shock timing target to the ignition target. There are three important differences: First, the shock timing package is planar, although the ablator material and thickness are the same as the spherical capsule. Second, the hydrogen is liquid D_2 in the

timing package, and solid DT in the capsule. Third, the timing package is on the hohlraum wall, while the capsule is centered. To compensate for these differences, we can choose a slightly different coalescence depth for the planar liquid D_2 than we would for the curved solid DT. (The current best guess is that the D_2 coalescence depth should be equal to the DT ice layer thickness, rather than a few microns greater.) The hohlraum designs will obviously be slightly different as well; we may need to accentuate those differences to nudge the X-ray drive at the wall of the shock timing hohlraum closer to the X-ray drive at the center of the ignition hohlraum. NIF ignition capsules are robust enough to tolerate the minor timing errors introduced by imperfections in these compensating adjustments.

This plan neglects the fourth shock for two reasons: First, simulations indicate that the difference between planar and spherical geometry begins to be significant by the fourth shock. Second, the combined shock generated by the fourth shock coalescence will be too strong to monitor with the VISAR. The fourth shock launch differs somewhat from the first three; it is partly launched by the rise of the drive pulse to its peak, but partly by the first rarefaction (from the shock crossing the D_2 interface) reflecting off the ablation front. Hence, the timing of the fourth shock is only partially controlled by changing the pulse shape; the other part is just the natural onset of acceleration of the shell, determined by its thickness. In simulations, it is relatively easy to get the fourth shock timed correctly, when the first three are good. If we suspect the fourth shock timing is preventing ignition on NIF, a few shots with different timing would suffice to scan through all plausible launch times.

The first step in a NIF shock timing campaign will be to select the ablator material and thickness. (We are working on experimental techniques for making this choice.) About six to eight shots with shock timing packages will suffice to find the pulse shape parameters which cause the first three shocks to coalesce at the selected depth in the liquid D_2 (the DT ice thickness in the capsule): The first two or three shots will adjust the strength of the first shock, and spread the second and third out beyond the required spacing. The next step is to move the timing of the second shock back, so that it overtakes the first at the required depth; this will take another two or three shots. The final step is to pull back the timing

of the third shock until it coalesces at the same point as the first two. Only the position of the leading shock needs to be measured to carry out this program; the VISAR is an ideal instrument for the job.

A lot of design work remains to be done for the NIF shock timing campaign: How do we design the shock timing hohlraum to best match ignition capsule drive? What coalescence depth in the liquid D_2 gives the best timing for the capsule?

However, the Nova experiments prove that a VISAR diagnostic can measure the entire range of shock speeds with the precision required for the shock timing job. Fig. 3 shows the leading shock speed in the liquid D_2 for a detuned NIF ignition pulse (the three shocks are too spread out, as they will be during the first step of the timing series). The first shock speed is 20 μm/ns; after the second shock overtakes it, the leading shock speed jumps up to 38 μm/ns; after the third shock joins, the leading shock is moving at 69 μm/ns. The required coalescence depth is 80 μm, with ± 2 μm precision. The figure also shows VISAR data from three Nova shots; VISAR sees the overtake events very clearly, and the shock speeds observed on Nova essentially span the range that the NIF observations require.

After the fourth shock, the leading shock speed jumps to well over 100 μm/ns; the radiation precursor in front of such a strong shock will probably ruin the VISAR shock speed measurement, although information about the timing of the overtake might be available.

III. NOVA VISAR EXPERIMENTS

The Nova targets were halfraums (that is, hohlraums with only a single laser entrance hole) heated by the five west beams of Nova, as sketched in Fig. 4. There were two different pulse shapes, a 2 ns "square" pulse and a 6 ns "PS100" pulse, with wide range of drive energies for each pulse shape. About a dozen shots gave high quality VISAR data.

The VISAR diagnostic consists of an 808 nm probe laser, which passes through the liquid D_2, reflects off the shock front (or, early in time, the D_2-ablator interface), then returns to a pair of interferometers. One leg of each interferometer includes a time delay, so that the

light reflected from the shock at any time interferes with the light reflected at a slightly later time. In essence, the time delayed leg of the interferometer is shorter than the undelayed leg by the distance the shock travels in the delay time τ. Accounting for the shortening of the vacuum wavelength $\lambda = 808$ nm by the refractive index $n = 1.13$ of liquid D_2, the phase difference between the two legs is $2vn\tau/\lambda$. (There is a small, subtle, additional correction [3].) Hence, the phase difference is proportional to the shock velocity v.

One interferometer had delay time τ of 15.8 ps, the other interferometer had $\tau = 51.7$ ps. The instrument with the longer delay time is more sensitive, and makes the high precision shock speed measurement. However, at 6.79 μm/ns/fringe, the high precision interferometer has a phase shift of many fringes for shock speeds of 65 μm/ns. The purpose of the instrument with the shorter delay is to determine the integer part of the fringe shift for the high precision instrument. Only one plausible shock speed is consistent with the fractional part of the fringe shifts recorded by the two interferometers.

A VISAR is an imaging interferometer: The image of the target forms where the two legs recombine and interfere. By slightly tilting the beam splitter that recombines the legs, the phase difference can be translated into spatial fringes; the fringe spacing is proportional to the tilt. Finally, a streak camera with its slit perpendicular to the spatial fringe pattern records the image: Phase and position at the target are combined on one axis of the final image, while time is the other axis. Fig. 5 is the high resolution VISAR image made on shot 29040809. The triangular shape of the region where the fringes are visible results from the increasing curvature of the shock front (and the ablator) as it moves away from the initial interface position. Late in time, only a small spot near the center of the shock remains parallel enough to the original interface to reflect the probe all the way back to the streak camera. Shock breakout and overtake events show up as discontinuities in the fringe pattern. The low precision VISAR image made on the same shot determines the integer part of any fringe discontinuities.

We do not have usable X-ray drive data for these shots, and most of the PS100 laser power data is compromised (remember that these were some of the final shots before Nova was

dismantled). Furthermore, the VISAR data strongly suggests an additional problem that complicates the question of the drive on these shots: Water ice may have condensed out of the vacuum chamber on the interior of some these cryogenic hohlraums, unpredictably altering the X-ray drive by as much as 10 eV. Unrelated cryogenic Nova experiments definitely had water condensation problems, and two of the VISAR shots showed a 15% difference in shock speed, despite being identical shots on the same day with only a 1.6% difference in incident energy according to the laser diagnostics, and no other indications of problems (such as beam clipping).

Nevertheless, the Nova VISAR data stand on their own merits. The VISAR technique definitely works with an indirectly driven ablator, at least up to drive temperatures of 150 eV. Most of the Nova shots had aluminum ablators, but one shot had a polyimide ablator, so either metal or plastic ablators work. Shock coalescence events, where a stronger shock overtakes the leading shock, show up beautifully in the VISAR images; the basic idea for the NIF shock timing plan is sound. In these indirect drive experiments, the VISAR recorded shock speeds in liquid D_2 ranging from 12 μm/ns to 65 μm/ns, corresponding to drive temperatures ranging from 80 eV to 150 eV. Finally, the Nova VISAR data demonstrated an accuracy of about 0.3 μm/ns (1/20 fringe), at least up to velocities of 30 μm/ns.

Four of the shots with good VISAR data included an LiF anvil in the liquid D_2, placed a precisely measured distance from the ablator surface. The impact of the shock on the LiF shows up as a sudden drop in the velocity measured by the VISAR. (The shock transmitted into the LiF is too weak to change the transparency of LiF, so the VISAR continues to reflect from the D_2-LiF interface after impact. Changes in the optical properties of the shocked LiF compromise the recorded interface velocity, however.) The time integral of the VISAR velocity from shock breakout to LiF impact must equal the known distance from ablator to LiF; any discrepancy represents inaccuracy in the VISAR measurement. Table I shows the results of these four experiments.

High resolution VISAR data from the first three LiF anvil shots demonstrate one to two percent measurement accuracy. With this Nova instrument, the error in the coalescence

depth of 80 μm required for the NIF shock timing series would be 1 μm, or at most 2 μm, which is all that will be necessary. This level of accuracy is consistent with directly driven VISAR experiments, as well.

The low resolution VISAR should be a little over three times less accurate. In the fourth LiF anvil shot, the high resolution VISAR failed, and the low resolution VISAR gave 8% less than the measured distance to the anvil. This is near the 6% error that would be consistent with a claim of 2% accuracy for the high precision instrument, but there is another possible explanation for that discrepancy: The other three shots had much lower drive; the highest was 29052003 at about 120 eV, while shot 29041305 went up to about 145 eV drive. In simulations, the X-ray preheat of the LiF on shot 29041305 causes it to expand by several microns, while LiF preheat is completely negligible for the other shots. Hence, the distance traversed by the shock before impact on 29041305 may actually have been somewhat less than the preshot distance from ablator to LiF. Thus, preheat makes direct verification of VISAR accuracy at high drive difficult. However, shot 29052003 is already a stronger shock than the first shock at NIF, and the LiF impact accuracy for that shot is unambiguous.

Even though the drive is uncertain, the Nova VISAR data compares well to simulations of the shocks. Multiplying a drive shape and spectrum from a crude hohlraum simulation by a factor chosen to match the measured shock strength at breakout time gives a satisfactory comparison for all of the 2 ns drive data. Fig. 6 shows the shock speed as a function of time for the four 2 ns drive shots with aluminum ablators. The laser turned off at 2 ns, before any of these shocks even broke out into the D_2, which is why the shock speed decreases with time. The simulations match this decay rate quite well, with the possible exception of 29032204. The shock was so weak for that shot, that the reflection required by the VISAR is probably marginal. Certainly, VISAR cannot measure shock speeds in liquid D_2 any smaller than 29032204.

The shots with the 6 ns PS100 pulse shape are more interesting. In that case, the drive is sometimes long enough to launch a second shock. The D_2 is hardly denser than vacuum compared to the aluminum (or plastic) ablator. Therefore, when the first shock

breaks into the D_2, a strong rarefaction wave runs back through the ablator. When this wave reaches the ablation front, the ablator begins to accelerate. If the acceleration persists, the ablator reaches a speed higher than the speed that the interface originally jumped into the D_2, launching a second shock into the D_2, which eventually overtakes the first. The VISAR records the shock coalescence as a sudden increase in the speed of the leading shock. Although the mechanism for launching this second shock is not the same as in a NIF shock timing package, the hydrodynamics in the D_2, which the VISAR measures, is identical: A second shock runs down and catches the first. (The mechanism of the second shock launch in the Nova experiments is similar to the fourth shock launch in a NIF ignition capsule.)

Shock overtake events occurred in shots 29040809 and 29052003, as the VISAR data in Fig. 7 shows. (Two other shots gave good shock coalescence data.) The figure also shows that matching the observed shock speed as a function of time with a simulation is much more challenging than for the 2 ns data. The exact time of the overtake and the strength of the combined shock depend on the details of the X-ray pulse shape. The gray curves in Fig. 7 represent simulations using several different X-ray drive histories; Fig. 8 plots the corresponding drives. One drive shape shown for each shot matches the observed shock speed reasonably well, but the shock speed measurement does not uniquely determine the drive history.

Either more elaborate hohlraum models, or more elaborate experiments, or both might corroborate the details of the X-ray drive shapes that match these VISAR data. But consider an alternate view: The details of the X-ray drive do not matter, either at Nova or at NIF. The point of the NIF pulse shape is to make the first three shocks coalesce at a particular depth in the DT ice, not to reproduce some calculated X-ray drive history. The planar liquid D_2 shock timing package is a good surrogate for the capsule, so a pulse that makes shocks coalesce at the proper depth in the shock timing package will be very close to the proper shape for driving the capsule. The VISAR has the accuracy and dynamic range to find that proper pulse shape by experiment. *Ab initio* simulations with comparable accuracy are unnecessary.

IV. SUMMARY

In the Nova VISAR experiments, we measured shock velocities in liquid D_2 from 12 μm/ns to 65 μm/ns with better than 2% accuracy. This is good enough to carry out our NIF shock timing plan, so that we can experimentally find and verify the correct pulse shape to drive an ignition capsule. VISAR experiments continue at the Omega laser in collaboration with the Laboratory for Laser Energetics. We recognize the difficulty of designing a hohlraum that produces the same X-ray drive on a planar shock timing package as the ignition hohlraum produces on a capsule, given the same laser pulse. However we resolve this hohlraum design issue, the VISAR diagnostic will allow us to directly verify that the shocks launched by some particular pulse shape actually coalesce at the proper depth in cryogenic hydrogen. Since that coalescence is the whole reason for the fancy pulse shape in the first place, VISAR measurements give us exactly the feedback we need to experimentally find the proper pulse shape for a NIF ignition capsule.

The extraordinary precision of the VISAR shock speed measurement may have uses beyond shock timing, as well. With VISAR we can reliably distinguish shock strength differences of a few percent; with care we can build targets which are identical to even better tolerance. Hence, a VISAR diagnostic could check that a laser is delivering identical pulses for months or years; this precision is comparable to or better than the best laser diagnostics, and independent of any evolutionary changes in either the laser or its diagnostics. A target-based repeatability measurement could also serve as a power balance diagnostic. Also, in conjunction with high precision laser diagnostics, we could perhaps study whether random shot-to-shot shock strength variations exceed the variations in incident laser power. Any such application of VISAR would become much more attractive if it were non-cryogenic experiment. So far, VISAR has tracked directly driven shocks in water, plastic, and LiF; cryogenic D_2 is still the only indirectly driven material.

To some extent, the big problems of drive symmetry and shell stability come down to whether our best effort will be good enough to achieve ignition. However, we continue to

work on diagnostic techniques that will allow us to adjust both the laser and target for optimal symmetry and stability. If we can find experiments which are as direct a measure of symmetry and stability as VISAR is of shock timing, we have a chance of ignition at the NIF. Success depends on schemes for experimental feedback and iteration in all these areas.

ACKNOWLEDGEMENTS

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TABLES

TABLE I. Thickness of D_2 layer compared to integral of VISAR speed from shock breakout to LiF impact. Uncertainties are scatter among lineouts at various positions, not our estimate of absolute accuracy.

Shot	Layer (μm)	Hi-res VISAR	Lo-res VISAR
29042703	116	117±1	123±10
29050407	113	115±2	125±5
29052003	222.5	221±3	223±5
29041305	148	-	136±2

FIGURES

FIG. 1. A typical laser pulse for an indirect drive ignition capsule has many adjustable parameters. Three crucial ones are the power of the first step, and the timing of the second and third steps.

FIG. 2. A VISAR shock timing target differs somewhat from the NIF ignition capsule it mocks up. The ablator material and thickness are identical, but the shock timing package is planar. A thick liquid D_2 layer in the shock timing package replaces the DT ice layer in the ignition capsule. The LiF anvil is optional and does not affect the interesting part of the shock propagation.

FIG. 3. The Nova VISAR experiments cover the full range of shock strengths required for the NIF shock timing plan. Shock overtake events, which are the heart of the shock timing plan, show up nicely in VISAR data. The pulse in the simulated NIF shock timing data is mistimed so that the first three shocks coalesce sequentially, rather than simultaneously.

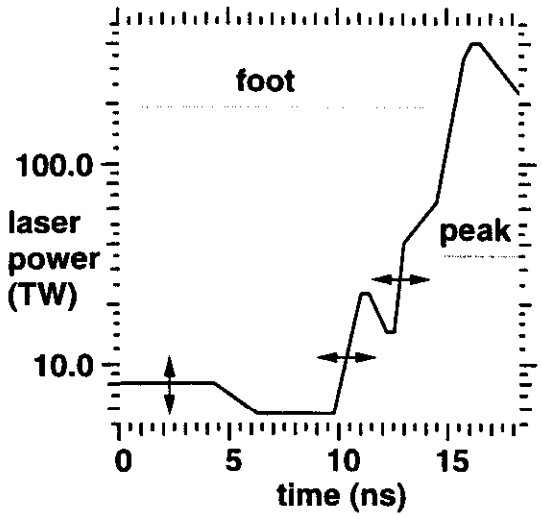
FIG. 4. Nova VISAR targets (March-May 1999) were very similar to the proposed NIF shock timing targets.

FIG. 5. The 6.79 μm/ns/fringe VISAR image from shot 29040809 is typical high quality VISAR data. Horizontal is both position on the target and phase; vertical is time. The discontinuities at 2 ns and 5.3 ns are shock breakout and coalescence, respectively. Increasing curvature of the shock front as it propagates causes the triangular envelope of the fringes.

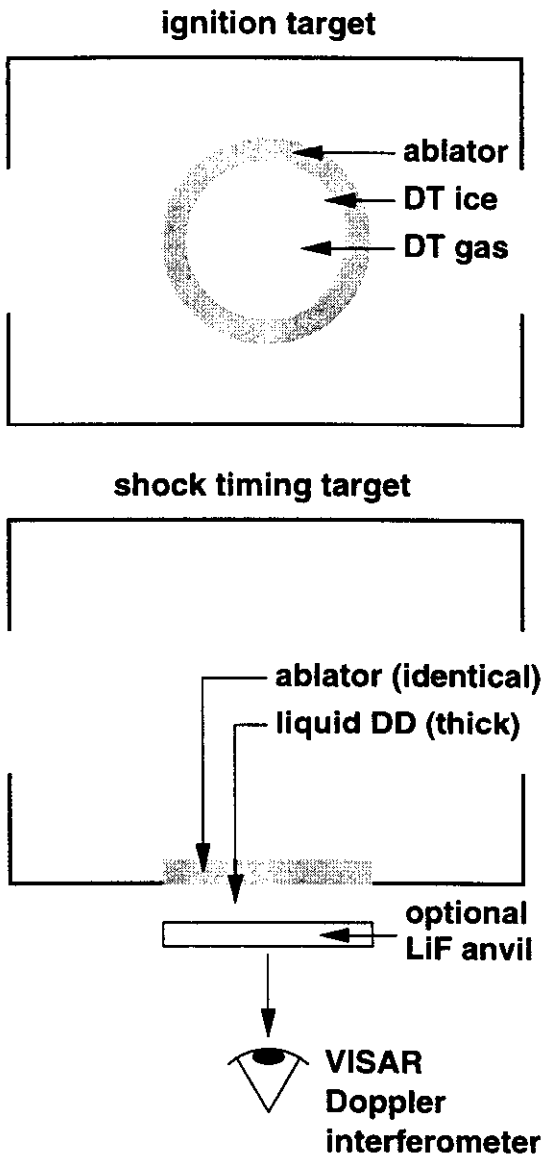
FIG. 6. The dark curves are VISAR data from 2 ns square pulses for four shots; the higher the drive energy, the faster the shock. Lineouts at several positions are plotted for each shot. The light curves are simulations. X-ray drive multipliers force the initial shock strength to match the data in each case, so only the breakout time and decay rate are fair measures of simulation accuracy.

FIG. 7. The dark curves are VISAR data from 6 ns PS100 pulses for two shots; the higher the drive energy, the faster the shock. Lineouts at several positions are plotted for each shot. The light curves are simulations. The various simulations correspond to the different X-ray drive histories shown in Fig. 8.

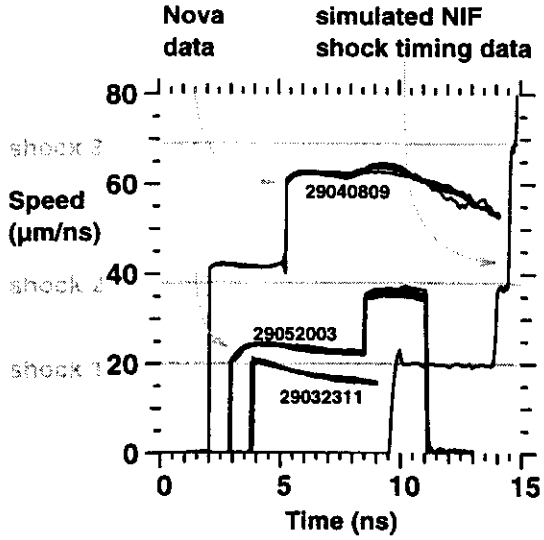
FIG. 8. The three upper curves are the X-ray drives corresponding to the three simulations of shot 29040809 plotted in Fig. 7; the two lower curves correspond to the two simulations of shot 29052003. The dark curves match the VISAR shock overtake times best. The overtake time and combined shock strength are sensitive to details of the drive shape.



Munro, Fig. 1


ignition target
ablator
DT ice
DT gas
shock timing target
ablator (identical)
liquid DD (thick)
optional
LiF anvil
VISAR
Doppler
interferometer

Munro, Fig. 2


Nova
data
simulated NIF
shock timing data
80
60
40
20
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Speed
(μm/ns)
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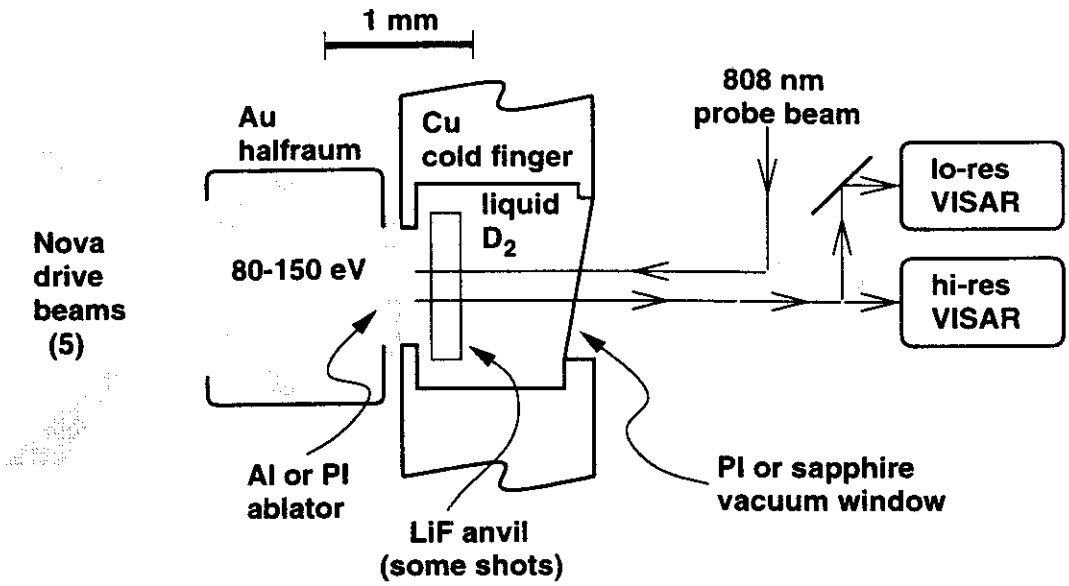
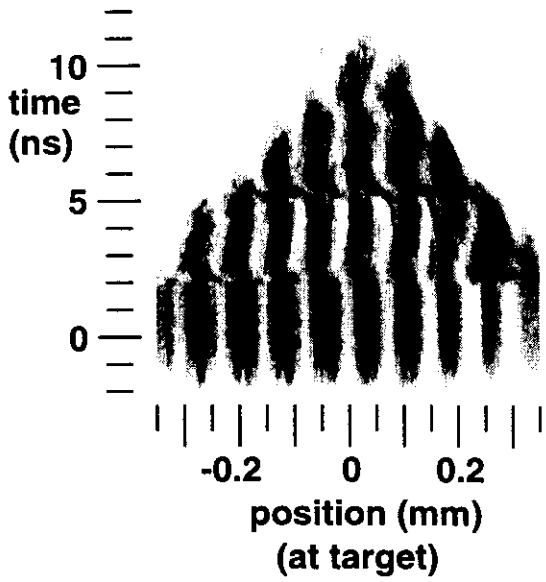
29052003
29032311
0
5
10
15
Time (ns)

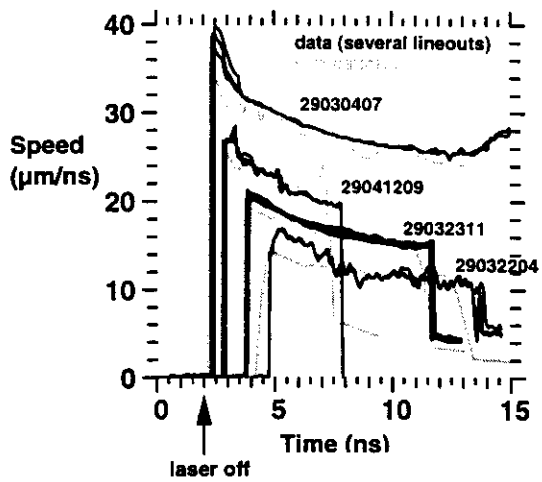
Munro, Fig. 3


1 mm
Au
halfraum
Cu
cold finger
808 nm
probe beam
lo-res
VISAR
liquid
D_2
Nova
drive
beams
(5)
80-150 eV
hi-res
VISAR
Al or Pl
ablator
LiF anvil
(some shots)
Pl or sapphire
vacuum window

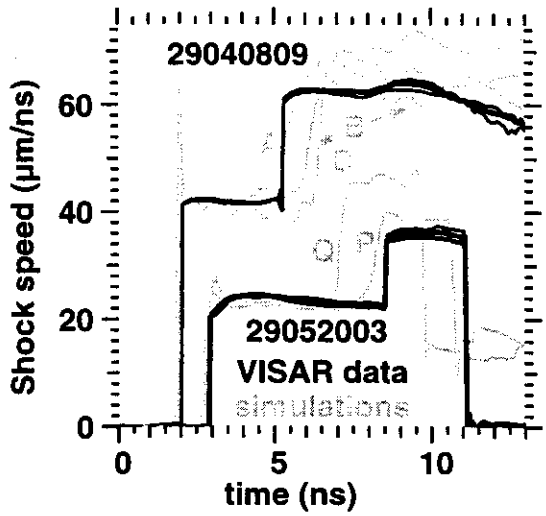
Munro, Fig. 4



Munro, Fig. 5


40
30
20
10
0
Speed
(μm/ns)
data (several lineouts)
29030407
29041209
29032311
29032204
0
5
10
15
Time (ns)
laser off

Munro, Fig. 6


29040809
29052003
VISAR data
simulations
Shock speed (μm/ns)
time (ns)
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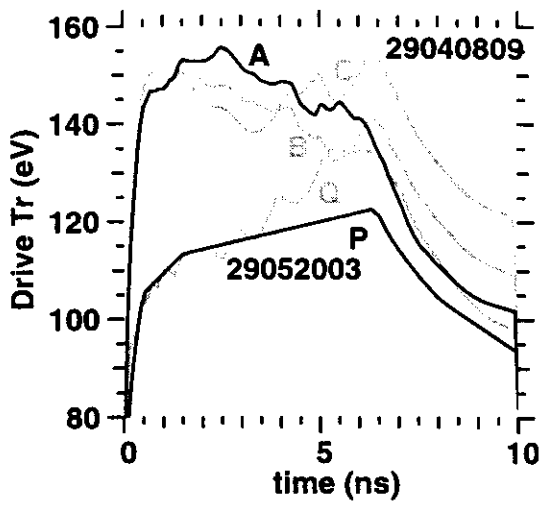
20
40
60
0
5
10

Munro, Fig. 7


160
140
120
100
80
Drive Tr (eV)
0
5
10
time (ns)
A
29040809
P
29052003

Munro, Fig. 8