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ABSTRACT

The AGEX II Technical Quarterly publishes short technical contributions on aboveground experiments that use pulsed power and laser drivers. The Quarterly is intended to provide rapid exposure of timely technical ideas and results as well as a means for documenting AGEX II progress and scientific quality for the AGEX II community. Suitable topics include experimental results, diagnostic apparatus, theoretical design, and scaling, among others. This volume is the second in a series, preceeded by LALP 94-81.

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ACRONYMS AND SYMBOLS

ACRONYM/SYMBOL	MEANING
AGEX	aboveground experiments
CCD	charged coupled device
CONFUSE	a computer code
emf	electromotive force
FROG	frequency-resolved optical gating
FWHM	full-width at half-maximum
KDP	potassium dihydrogen phosphate
LASNEX	Los Alamos inertial confinement fusion design code
LRC	inductor, resistor, capacitor
RADGEN	a computer code
VNIIEF	All Russian Scientific Research Institute of Experimental Physics

Instabilities in Taylor-Sedov Blast Waves

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ABSTRACT

The stability of Taylor-Sedov blast waves in low-density gases was investigated. Theoretical results have shown that the stability of propagation in uniform gases depends on the adiabatic index of the gas. This was verified with a LASNEX simulation. Both stable and unstable propagation was observed in experiments at the Trident laser facility. The experimental verification of the adiabatic index criterion for stability is not yet completed.

INTRODUCTION

In a series of papers¹⁻³ in the *Astrophysical Journal*, Vishniac and Ryu showed theoretically that under certain conditions the propagation of shock waves can be unstable even in a uniform gas. The criterion for instability was an adiabatic index (g) below 1.2, where $g = C_p/C_v$ of the gas into which the wave propagates. Here C_p and C_v are the molar specific heats at constant pressure and volume. A low g can occur at certain densities and temperatures when excitation, ionization, and radiation processes increase the number of degrees of freedom.

In the above papers, the instability was modeled by starting with a spherical harmonic perturbation on the radius of the expanding wave.

$$R \propto t^{2/5} \left(1 + b t^s Y_l^m(\theta, \phi) \right)$$

The hydrodynamic equations linearized in the perturbation were solved for the growth rates of the perturbation as a function of l . The equations do not depend on m , and b is a constant. The results show a positive s for a range of l values and $\gamma < 1.2$. For example, a peak growth rate of $s \approx 0.5$ for $l \approx 30$ is calculated for $\gamma = 1.1$.

In a subsequent paper, J. Grun et al.⁴ demonstrated an instability of Taylor-Sedov blast waves propagating through a uniform gas. In this experiment, blast waves were generated by laser-driven ablation on a polystyrene foil in 5 torr of gas. For nitrogen, the blast waves appeared to be stable, expanding with the characteristic Taylor-Sedov $t^{2/5}$ law. In the case of xenon, no stable propagation occurred. This result was attributed to the above-mentioned instability. Presumably, the radiation

from the laser/foil interaction or the blast wave itself heats the background gas sufficiently to result in a γ below 1.2 in xenon but not in nitrogen. From these results and previous measurements, J. Grun et al.⁴ quoted a $\gamma = 1.3 \pm 0.1$ for nitrogen and a $\gamma = 1.06 \pm 0.02$ for xenon.

The intent of our experimental program is to verify the Vishniac theory in more detail by mapping out the transition from stable to unstable propagation in a gas by changing its γ . We accomplish this by varying the temperature of the gas using different ablator foils or secondary sources to control the radiation spectrum which heats the gas. For example, the γ of the noble gases can be driven from $5/3$ at room temperature to below 1.2 near 1 eV.

LASNEX TEST

To test whether this instability is observed in our hydrocalculations, we performed LASNEX computer simulations of Taylor-Sedov blast waves propagating in $\gamma = 1.4$ and $\gamma = 1.06$ gases.⁵ The calculation followed a spherical blast wave for several millimeters in 5 torr of gas. We chose the initial energy input to approximate the expansion of the wave in Ref. 4. For the $\gamma = 1.4$ case, the propagation was stable with an initial perturbation of $0.01 P_{l=30}$ in the energy, whereas the $\gamma = 1.06$ case resulted in a growing instability for a initial perturbation of $10^{-4} P_{l=30}$. Figures 1 and 2 show the results. A perturbation of $10^{-6} P_{l=30}$ is required to remain stable within the region of interest for the $\gamma = 1.06$ case.

Figure 1. Lasnex calculation of a spherical Taylor-Sedov blast wave in a gas with $\gamma = 1.4$ and a perturbation of $.01 P_{l=30}$.

Figure 2. Lasnex calculation of a spherical Taylor-Sedov blast wave in a gas with $\gamma = 1.06$ and a perturbation of $10^{-4} P_{l=30}$.

Close inspection of Fig. 2 shows that the angular wiggles of the instability do not exhibit the 15 zero crossings expected from a $P_{l=30}$ polynomial in one quadrant.

LASNEX solves the nonlinear hydroequations that lead to significant mode coupling and hence to a more complicated perturbed structure. The growth rate of the perturbation calculated by LASNEX is within 10% of that given by the linearized theory of Vishniac and Ryu. Without knowledge of this effect, this instability in a LASNEX calculation could easily have been mistaken for a numerical instability rather than a real hydrodynamic effect.

EXPERIMENTAL SETUP

The experiments were performed at the Trident laser facility, which has three available beams and is ideal for this kind of experiment. Beams A and B are used to drive the blast wave. Each beam can have a maximum energy of up to ~ 100 J at 527 nm in a several-ns pulse. For this experiment, beam C is used to image the blast waves in a dark-field-shadowgraph setup. The beam is operated in either single-pulse mode or as a train of 100-ps pulses separated by 30 or 60 ns with a total energy of 1 J at 1054 nm. Operating in pulse train mode allows multiple framing of the blast wave and permits determination of the blast wave's temporal development.

Figure 3. Schematic of the experimental setup.

A schematic of the apparatus used for these experiments is shown in Fig. 3. The target consists of either a 6- μm Mylar foil or a 6- μm gold foil mounted on a washer. Before each shot, a new target is positioned in the Trident target chamber. The chamber is then evacuated to a few millitorr and filled with the desired gas to the desired pressure. The blast wave is created by simultaneously illuminating the center of the target with the A and B beams of the laser. The beams are focused onto the target with $f/6$ optics to give a spot size of ~ 800 μm .

To image the blast wave, the target is illuminated with the collimated C beam. For single-pulse imaging, the time delay between when the A and B beams hit the target and when the C beam reaches the target is adjusted to give a suitable image. For multiple-pulse imaging, the delay is set so that the first C beam pulse reaches the target at the same time as the A and B beams. The direction of the illumination is perpendicular to the target normal. The shadowgraph-imaging system is aligned along the C beam axis. The first lens, L_1 , is a simple 1.5-m-focal-length optic located 1.5 m from the target. An ~ 2 -mm solid disk supported on a thin stalk is

located at the opposite focus of the lens to act as a block. Unscattered C beam light is focused onto the disk and kept from propagating through the rest of the system. However, C beam light scattering from the blast wave and the target is collimated by the first optic and passes by the block. A second lens, L_2 , is placed after the disk to focus this light onto the image plane of a Pulnix TM-7CN charged coupled device (CCD) camera. The second lens is a Nikon $f/5.6$, 75- to 300-mm zoom lens and is positioned so that its focus coincides with the blocking disk. Several green-blocking filters and 1054-nm band-pass filters are placed in front of L_2 to prevent any scattered light from the A and B beams from reaching the camera. The camera image is digitized and stored using a Spiricon laser beam analyzer. For such an imaging system, the intensity of the image is a function of the second derivative of the index of refraction of the scattering media. Thus, the system is well suited for imaging the blast wave which has a strong density gradient.

RESULTS

The stability of blast wave propagation in nitrogen, xenon, neon, and helium was investigated. None of the blast waves in nitrogen, neon, and xenon resulted in a clean "hemispherical" wave without some extra structure. The most unstable propagation occurs in xenon. Figures 4 and 5 show single- and multiple-frame shadowgraphs, respectively, of a blast wave initiated in xenon from a Mylar foil.

Figure 4. Single-frame shadowgraph of a blast wave in 5 torr of xenon initiated with 38 J at 152 ns.

Figure 5. Multiple-frame shadowgraph of a blast wave in 0.5 torr of xenon with 66 J at 30-ns intervals.

In both cases the propagation is highly unstable. For the lower pressure, the wave propagated farther from the origin than expected from the density scaling in the Taylor-Sedov theory. To invoke the energy scaling requires the further assumption that the fraction of the incident laser energy coupled into the blast wave is independent of the laser energy. This assumption has not been demonstrated.

To obtain a stable blast wave, we investigated helium. With its high excitation and

ionization energy, helium should be more difficult to drive into a low γ state. Figure 6 shows a multiple-frame shadowgraph of a blast wave in 5-torr helium driven by a Mylar foil with 90 J of laser energy. The frame spacing is 30 ns. The waves are not quite circular. This pattern is probably due to the foil ablation coupling to the gas, which favors the foil normal. The observed spacing between the wave fronts separated by 30 ns follows the Taylor-Sedov $t^{2/5}$ expansion to within 1.5%.

To observe an instability in helium, we initiated a blast wave using a gold foil. The x-ray yield from the laser/gold-foil interaction is higher than that from the carbon foil and hence should deposit more energy into the gas and lower its γ . The blast wave shown in Fig. 7 is clearly unstable and its structure is very different from the stable wave in Fig. 6. Whether or not the origin of the instability is due to driving γ below 1.2 is not proven. Future plans for this experiment include a spectroscopy-based measurement of the gas temperature ahead of the blast wave to determine the state and hence the γ of the gas.

Figure 6. Multiple-frame shadowgraph of a stable blast wave in 5 torr of helium initiated with 90 J on Mylar foil framed at 30-ns intervals.

Figure 7. Multiple-frame shadowgraph of a blast wave in 2 torr of helium initiated with 205 J on gold foil framed at 30-ns intervals.

CONCLUSION

We have demonstrated that Taylor-Sedov blast waves can be driven from stable to unstable propagation by varying the conditions in the gas. More experiments with diagnostics to measure the conditions in the gas prior to the arrival of the wave are required to determine the nature of this instability. This preliminary experiment has shown that the Trident laser facility is an ideal facility to perform this type of measurement involving drive energies of up to a few hundred joules timed relative to a multiple-pulse diagnostic beam.

The authors wish to thank the Trident team for their support during this experiment.

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Single-Shot Measurement of the Amplitude and Phase of Ultrashort Laser Pulses in the Violet Spectral Region

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ABSTRACT

Using single-shot, self-diffraction, frequency-resolved optical gating (FROG), we measure the complete electric field amplitude and phase of 405-nm second-harmonic pulses from an amplified Ti:sapphire system. The single-shot FROG device gives both qualitative and quantitative information that is useful for analyzing and optimizing the grating compressor in the chirped-pulse-amplification system.

Advances in ultrashort pulse laser systems have fueled the recent interest in developing practical methods to completely characterize the intensity and phase of ultrashort laser pulses.¹⁻³ Of these, only frequency-resolved optical gating (FROG) has been demonstrated for single-shot operation,^{1,4,5} using polarization gating as the nonlinear detector. We demonstrate the first use of a single-shot FROG device using self-diffraction as the nonlinear effect. FROG is used to study the generated second-harmonic pulses from an ultrashort pulse, terawatt-class Ti:sapphire laser system. Self-diffraction FROG has been demonstrated previously, but only for the multishot case.⁶ Because the ultrashort pulses travel through minimal dispersive elements in the self-diffraction geometry, this method has advantages over the polarization-gate geometry for both very short pulses, for which any dispersion can significantly alter the pulses, and for pulses in the violet and ultraviolet, where material dispersion is larger and nonlinear absorption effects in the optics are detrimental.

Recent demonstrations of frequency conversion of ultrashort pulse, terawatt-class Ti:sapphire laser systems have provided short-wavelength femtosecond pulses for a variety of applications.⁷⁻¹⁰ To our knowledge, there have been no direct measurements of the temporal evolution of the second- and third-harmonic pulses generated by these systems. (The second harmonic has been measured by a cross-correlation technique with the fundamental,⁷ and the third harmonic has been used to seed KrF amplifiers with outputs that have been characterized with a third-order autocorrelator.^{8,9}) Using self-diffraction FROG, we can determine the complete intensity and phase evolution of the pulses produced by frequency conversion in these systems.

The experimental setup for the single-shot, self-diffraction FROG device is illustrated in Fig. 1. A 50% beam splitter produces the two replicas of the pulse, which then cross at a small angle in a 1-mm quartz window. A 10-cm-focal-length cylindrical lens focuses the two beams on the sample, providing a continuous temporal delay across the sample between the pulses coming from the two arms. The sample is imaged onto the input slit of an imaging spectrometer with a 25-cm-focal-length lens. A beam stop in the focal plane of the imaging lens blocks all but the first-order diffracted signal.

Figure 1. Experimental apparatus for single-shot, self-diffraction FROG. The self-diffracted signal in the sample plane is imaged onto the input slit of an imaging spectrometer that resolves the signal at each point in time. Inset: Because most of the diffracted light comes from the times $\tau/3$ of one pulse and $-2\tau/3$ of the other pulse, the diffracted pulse, when spectrally analyzed, indicates the frequencies from both of these regions of the pulse.

A CCD camera collects the dispersed signal light on a single-shot basis, displaying signal intensity as a function of wavelength and delay (referred to as the FROG trace). Because of the small beam-crossing angle that is needed to avoid very small signal levels caused by phase mismatch, the available delay range for the self-diffraction geometry is limited, and we were only able to achieve a delay range across the sample of ~ 1 ps with angles $< 1^\circ$. Because of the high intensity of our pulses, good signal levels are produced at the relatively large crossing angle of 3.6° , thus providing more than a 6-ps delay across the sample for a 1-cm beam.

The laser pulses for the experiment are produced by second-harmonic generation of the output from a chirped-pulse-amplification Ti:sapphire system.⁷ This system produces 50-mJ, 150-fs pulses at 810 nm after the pulse compressor. Second-harmonic generation in a 1.5-mm-thick potassium dihydrogen phosphate (KDP) crystal produces up to 15 mJ at 405 nm. The energy of the pulses into the FROG apparatus is attenuated to below ~ 1 mJ to avoid nonlinear effects in the optics. The pulse compressor can be adjusted by changing the distance between the gratings and the input angle of the compressor while observing changes in the FROG trace.

Figure 2 shows the FROG trace of the second-harmonic output from this system when the pulse compressor is optimized, and Fig. 3 shows the FROG trace of the second-harmonic for a case when the separation of the gratings along the optical path was changed by $\sim 500 \mu\text{m}$. The self-diffraction FROG trace is related to the spectrogram of the pulse⁶ and graphically displays the instantaneous frequency as a function of time, subject to a slight correction because the signal pulse contains the frequencies from two different regions of the input pulse as shown in Fig. 1.

Figure 2. Experimental single-shot, self-diffraction FROG trace of the second harmonic of the Ti:sapphire system.

Much qualitative information can be obtained solely from the graphic representation of the FROG trace. A negative linear chirp on the pulse in Fig. 3 is clearly indicated by the tilt of the signal in the FROG trace, which shows that the wavelength increases as a function of time (decreasing frequency vs. time). In addition, temporal broadening and spectral narrowing are evident as compared to the trace in Fig. 2. The FROG trace in Fig. 2 shows a very slight tilt, which is possibly a residual second- or third-order dispersion from the laser system. The complex electric fields of the pulses are determined using an algorithm based on generalized projections and multidimensional minimization.¹¹ Figure 3 shows the derived temporal intensity and phase for the FROG traces in Figs. 1 and 2. For the optimized pulse, the pulse width of the second harmonic is 135 fs, full-width at half-maximum (FWHM), and the phase is roughly linear, indicating a nearly

Figure 3. Experimental single-shot, self-diffraction FROG trace of a chirped pulse from the second-harmonic of the Ti:sapphire system. The pulse was obtained by adjusting the length between the two gratings in the pulse compressor.

transformed, limited pulse. The pulse width of the 810-nm pulses before doubling was measured with a second-harmonic, single-shot autocorrelator and was found to be ~165 fs, FWHM. The shorter second-harmonic pulse is expected because of the square dependence of the frequency doubling on input intensity (the crystal is short enough that group velocity dispersion does not significantly broaden the pulses). The chirped pulse has a pulse width of 240 fs, and the parabolic shape of the temporal phase evolution indicates a negative linear chirp.

For a chirped-pulse-amplification system, it is very useful to examine the phase as a function of frequency because the effects of the stretcher/compressor system can be expressed as a frequency-dependent-phase function, $\phi(\omega)$, where the second-order term of the expansion in powers of frequency, $\phi^{(2)}(\omega)$, is the group velocity dispersion. Figure 4 shows the derived spectral intensity and the phase of the pulse measured in Fig. 2 in the frequency domain. The linear phase indicates a nearly transformed limited pulse, with a slight residual third-order dispersion. The spectrum is slightly asymmetric with a 1.98-nm (0.023 rad/fs) bandwidth, FWHM, which is the transform-limited bandwidth for a Gaussian pulse.

Figure 4. The derived temporal electric field amplitude and phase evolution for the experimentally measured FROG traces in Figs. 2 and 3.

The derived spectral intensity and the phase of the chirped pulse measured in Fig. 3 are given in Fig. 5 along with a calculation of the group velocity dispersion for a change in the compressor grating distance of 500 μm , giving a change in the group velocity dispersion, $\Delta\phi^{(2)}(\omega)$, of 4500 fs^2 . (The compressor is a double-pass configuration with two 2000 lines/mm diffraction gratings separated by 74 cm, which creates a total group velocity dispersion, $\phi^{(2)}(\omega)$, of $1.33 \times 10^7 \text{ fs}^2$ at 810 nm.) The calculated phase of the pulse is in very good agreement with the experimental data.

In conclusion, the single-shot, self-diffraction FROG device is a useful diagnostic for the second-harmonic pulses from an ultrashort-pulse-amplified Ti:sapphire system. The grating compressor for the chirped-pulse-amplification system could be optimized by observing the FROG display in real time. Analysis of the FROG data provides a quantitative measure of the group velocity dispersion in the system. In the future, we plan to incorporate ultrafast pulse-shaping techniques into the Ti:sapphire system and to use this FROG system as a diagnostic tool to determine the amplitude and phase of the pulses.

Figure 5. The derived electric field amplitude and phase evolution in frequency for the experimentally measured FROG trace in Fig. 2.

Figure 6. The derived electric field amplitude and phase evolution in frequency for the experimentally measured FROG trace in Fig. 5.

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The VNIIEF Magnetic Bubble Approach to an X-Ray Source

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ABSTRACT

Both analytic and cursory numerical investigations indicate that the All Russian Scientific Institute for Experimental Physics (VNIIEF) magnetic bubble approach to x-ray generation has potential advantages. An experimental test of this concept is currently being conducted at VNIIEF.

Our present approach to hydrodynamics-based thermal x-ray generation involves the acceleration of a thin liner to a high-inward-radial velocity and stagnation on axis to achieve a high enough temperature to provide soft x-radiation from the liner material. A simple relation shows the importance of a high velocity. Equating the inward kinetic energy to the internal energy upon stagnation on axis yields $T = v^2/2C_v$, where T is the temperature and C_v is the specific heat at constant volume. This is the case for negligible energy in the radiation field, and a more general result could be obtained if the details of the stagnation process were considered. However, for the purpose of estimating the velocity required for a given temperature, this result is adequate. To achieve about 300 eV, about 40 cm/ μ s is needed.

Several problems arise in trying to realize this approach to x-ray generation. First, to achieve the high velocities that are needed, very thin liners must be used. For very thin liners the current must achieve its maximum value very quickly to reach the high velocity desired. This requires fast switching of large currents. Second, the liner is Rayleigh-Taylor unstable so it is very sensitive to the fabrication process and the assembly of the experiments.

Recently, personnel at the All Russian Scientific Institute for Experimental Physics (VNIIEF) proposed a variation on the collapse of a cylindrical target as a means of producing a burst of x-radiation. Their proposal is to create a magnetic "bubble" which expands axially as it is driven toward an axis of convergence so that the increasing magnetic pressure is no longer acting on an increasing mass per unit area (aerial density, ρr).

ANALYSIS

A very simple analysis of the acceleration of a cylinder by an azimuthal magnetic field ($B_0 = \mu_0 I / 2\pi r$) leads to an equation for the velocity v of the cylinder at a given radius r :

$$v^2 = KL(1 \ln R/r)/\pi,$$

where $K = \mu_0 I^2 / 2\pi M$, I is the current (assumed constant here), R the initial radius, L the cylinder length, μ_0 is the permeability of free space, and M is the mass of the cylinder. This analysis assumes that the cylinder is thin.

The magnetic bubble proposed by VNIIEF is not a spherical bubble. Rather, it would be roughly circular in shape in the (r, z) plane, but cylindrically symmetric. It is expanded and imploded by an azimuthal field created by the current flowing through it so that the volume between the starting surface of rotation and the instantaneous surface is continually increasing. For the analysis that follows, we assume that the mass of the bubble spreads evenly along a circular shape. While this assumption is very simple, even spreading may not be accurate, nor may the assumption of circular shape be accurate, but our assumption serves as a convenient basis for a simple analysis. Specifically, the radius $(R-r)$ of the circle (with a center at a $z = 0$ and a fixed distance R from the axis) increases so that part of the mass collapses on axis and part is constrained to travel along a constant R path. The part in between is shaped by the accelerating field. To see what the maximum, inwardly radial velocity is, it is only necessary to track the velocity of the radially directed part. Assuming that the bubble is thin and that it maintains a circular shape in (r, z) starting with a half circumference of the circle equal to L , i.e., $\pi(R-r_0)$ for the same mass M , the relation for the square of the velocity becomes:

$$v^2 = K\pi\{R \ln(r_0/r) - (r_0 - r)\}$$

along the path $z = 0$. Here, r_0 is the initial, and r is the instantaneous distance of the circle from the axis. K is the same as defined above. R is the radial distance of the center of the circular shape of the bubble from the axis. Initially the circle radius $(R-r) = (R-r_0)$ is small, but approaches R as the bubble expands laterally and collapses on the axis. After the bubble collapses, it is no longer circular in shape of course, but the analysis is not meant to extend beyond collapse at $z = 0$.

Both of the above equations suggest that near collapse (i.e., as r approaches zero) the velocity increases without limit. However, a finite thickness should set a different maximum velocity for each case because the minimum r should be the thickness, and that thickness would be less for the case of the bubble because of its thinning due to expansion and also due to the greater acceleration. Setting $L = \pi(R-r_0)$ for the same mass M , the ratio of the squares of the velocities becomes:

$$(R-r_0) \ln(R/r) : [R \ln((R-r_0)/r) - (r-r_0)]$$

For $r = r_0$, the bubble velocity is zero, as is the cylinder velocity for $r = R$. For a modest decrease in r ($< r_0$), the inward velocity of the bubble exceeds that of the cylinder. As the $z = 0$ part of the bubble approaches the axis ($r \sim R/20$), the bubble

velocity exceeds the cylinder velocity by more than 2.5 times at the same radius. Figure 1 shows the functions:

$$\sqrt{R \ln \frac{R-r_0}{r} - (r-r_0)} \quad \text{and} \quad \sqrt{(R-r_0) \ln(R/r)}$$

for $R = 2$ cm and $r_0 = 1.9$ cm. For the case of $R = 20$ cm, $r_0 = 19.5$ cm, $M = 5$ g, and $I = 100$ MA, at $r = 2$ cm the bubble attains 62 cm/ μ s, but the liner only reaches 12 cm/ μ s.

Figure 1. Analytic functions for relative velocities of cylindrical shell (solid line) and magnetic bubble (dashed line).

CALCULATIONS WITH RADGEN

To better assess the magnetic bubble idea, a very simple explicit code, RADGEN, was written to follow the dynamic development of the bubble. The code assumes that the magnetic pressure acts normal to the surface of the expanding bubble. So far, only initially circular 2-D bubble shapes with a small initial radius ($R-r_0$) have been used. The actual 3-D shape is a rotation of the 2-D (r,z) shape about the axis of symmetry. For the 3-D bubble, the ρr increases due to convergence toward the axis but decreases as the bubble expands in (r,z). In the code a string of mass points was accelerated normal to the local surface as defined by each mass point and its two (r,z) neighbors. The dynamic load represented by the expanding magnetic bubble is part of a circuit that provides the driving current for the bubble.

Figure 2. RADGEN implosion of a cylindrical shell. The dashed curve result used only two mass points to represent the cylindrical shell while the others used ten mass points.

Figure 3. Implosion velocity computed by RADGEN for cylindrical shell.

For comparison the simple code has been used to treat both a cylinder and a bubble. The cylindrical case is shown in Fig. 2 with an expanded z scale. The acceleration would be the same for a long cylinder with the same mass per unit length. The velocities of the implosion are shown as a function of the position r in Fig. 3. Note that the finely zoned cylindrical calculations show a very early onset of instability. This instability is partly numerical as demonstrated by the fact that the growth starts at the outer edge where the boundary condition is different from the simple reflection used at the inner edge. However, it is also consistent with what one would expect for Raleigh-Taylor instability.

The expanding magnetic bubble implosion is shown in Fig. 4. Here the z scale is not expanded. Figure 5 shows the velocity along $z = 0$ for the magnetic bubble as a function of r . It appears that the (r, z) outflow along the expanding bubble surface may be stabilizing. However, more refined calculations show an onset of instability similar to that of the cylindrical case. The late time velocities for the bubble are generally about a factor of more than two times higher ($\sim 2.5\times$) than for the equivalent cylinder. While the bubble appears to evolve from its initial circular shape, VNIIEF's approximation of the (r, z) shape as a circle with an offset center seems to be fairly reasonable. The velocities attained by the bubble do not exceed those of the cylinder by as much as the simple analysis above would suggest, but the results from the simple code are in reasonable agreement with that analysis. Part of the deviation from the analytic results may be due to the fact that in the calculations, the current is not constant (dashed curve in Fig. 5).

The energy in the implosion goes as Mv^2 , and according to the earlier relation used to estimate the velocity required to achieve a given radiation temperature, the temperature goes as v^2 . The magnetic bubble appears to sacrifice total energy for increased velocity and hence a higher radiation temperature. The bubble collapse on axis is not instantaneous as is the case for an idealized cylindrical shell. Rather, the faster moving part at $z = 0$ collapses first, followed by the slower parts. One would expect an initial burst of radiation at high temperatures with a prolonged decay having continually decreasing radiation temperatures, depending on the details of the experimental geometry (i.e., whether or not walls limit the bubble volume, hence inductance). Also, one would expect jetting along the axis. While the total radiative energy may be greater for the cylindrical case, the useful radiative energy may be greater for the bubble case simply because the temperature is expected to be much higher, leading to better transport characteristics.

Figure 4. Shaping of magnetic bubble starting with an initial circular shape.

Figure 5. Implosion velocity computed by RADGEN for magnetic bubble. Also, the current that drives the bubble expansion is shown as a dashed curve.

The expanding bubble constitutes an increasing inductance (L) in the circuit, and the consequential back electromotive force (emf) opposes the driving current. Mokhov, Yakubov, and Garanin showed designs with walls that limited the bubble expansion laterally. In principle this should limit the rate of increase of the load inductance, but it cannot eliminate it. The expanding bubble front would continue to thin as the portion that encounters the wall stagnates against the

wall. The pr of the mass being accelerated goes as $M/(R-r)r$, so that it first decreases, but later begins to increase. This is in contrast to the cylindrical case for which M/rL always increases. Irv Lindemuth pointed out that when the bubble is driven by explosive-pulsed power rather than a capacitive (C) discharge (as with the simple LRC external circuit used for the calculations presented here), the explosive-pulsed power inductance is decreasing, and that the overall inductance in the circuit including the load probably decreases. Even though the increasing inductance of the load may not create a problem in regard to the drive current, VNIIEF and our people all agree that it does create a potential problem in the region near the origin of the bubble. This is because there the back emf creates a high electric field that could result in a breakdown that short-circuits the path of current through the bubble so that the acceleration stops. VNIIEF proposed to create the magnetic bubble by using a slow liner that loses contact to initiate the arc that forms the bubble. This would provide an ever-widening gap so that the increasing back emf would not create such a rapidly increasing electric field as would be the case for a fixed gap spanned by the arc that created the magnetic bubble. More importantly, the use of a slow liner should eliminate the need for fast switching of very high currents because the slow liner allows the current to rise to near the maximum provided by the driver before the arc forms the bubble.

ADDITIONAL THEORETICAL AND COMPUTATIONAL WORK NEEDED

The question of bubble symmetry still needs to be addressed. The analysis and simple code model are axially symmetric, but there is a possibility that the arc that would form the bubble would be initiated first at only one point in azimuth. In the joint liner implosion experiment at Arzamas-16, there was an insulation failure that resulted in an asymmetric implosion. We need to do some work that addresses this possibility. Whether or not the bubble is formed asymmetrically depends not only on the symmetry of the slow liner, but also on the impedance in the region where the slow liner loses contact with the wall. Because of the inductance and resistance rise due to geometry for a more constricted current path, the conductivity in any azimuthally localized region would have to decrease in a more than compensatory fashion for a large asymmetry to occur. Additional analysis or even a 3-D magnetohydrodynamics code may be necessary to answer the question of whether one should expect that uniform arcing should occur and lead to an azimuthally symmetric bubble. However, the experiment scheduled for February may provide the earliest answer.

The simple code discussed above relies on an ability to define a normal to the local surface defined by the adjacent mass points. Two methods that have been tried include defining a center of a circle using triplets of points and using a weighted mean of the normals to the two straight lines between the point of interest and its two neighboring points. Neither of these approaches is entirely satisfactory. Higher-order methods have not been tried. A better definition of the normal as well as a definition of limiting walls, as suggested by VNIIEF, would help generalize the code. In addition, modeling the bubble plasma behavior and the explosive-pulsed-power driver in the same calculation would also provide a more general understanding of the VNIIEF idea.

The bubble and cylindrical liner calculations are not on the same footing when considering the growth of the instability that appears in Fig. 2. This is because the mass points that define the liner remain close together allowing short wavelengths to grow at a rapid rate. In contrast, bubble calculation (with the same number of points) initially supports the short-wavelength growth, but soon does not as the mass points spread along the bubble. It would be useful to explore the stability of the magnetic bubble more thoroughly. An initial attempt to do so by greatly increasing the number of mass points defining the bubble showed wrinkling along the cylindrical boundary where the motion is disturbed, but the part of the bubble closer to the axis remained smooth. More work is needed on this problem.

Irv Lindemuth's CONFUSE code has a much more extensive circuit model than the simple LRC circuit used in RADGEN, but it used only a simple $F=MA$ dynamic load. Since RADGEN has a more detailed dynamic load, we intend to combine the two codes in some fashion for the sake of doing parameter studies of the magnetic bubble idea.

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