LINER COMPRESSION AND INSTABILITIES AND SHOCKS AT HIGH CURRENTS WITH THE PEGASUS AND RANCHERO SOURCES

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Abstract

We have done implosion experiments with cylindrical liners at currents ranging from 3 to 25 million amperes (MA). The low current (3-6 MA) experiments are done at the Pegasus capacitor bank facility and the high current (~25MA) ones are done with an explosive flux compression generator (Ranchero) in Ancho canyon at Los Alamos. Visible light and x-ray images provide details of the implosion but provide different results in both axial and radial views. Axial views taken with visible light framing cameras show that measurements of shock front velocity in imploding gas filled (Xe or Ar) aluminum liners appear to be different. Also, axial x-ray images give different shock velocities. Radial views show significant material "blow-off" as seen with the visible light framing camera. This paper will discuss these differences and how they effect the hydrodynamics and instability growth in liner implosions. We will also discuss the details of the diagnostic techniques that are necessary in this harsh experimental environment.

I. INTRODUCTION

For several decades, pulsed power experiments[1] have led to research in instability growth in high temperature and density plasmas generated by a thin foil (~2000-50000 Angstroms thick) implosion. At the present time emphasis has been placed on hydrodynamic effects and the growth of instabilities in thick (~1mm thick) cylindrical loads that are in most cases made from various types of aluminum. Common to all these experiments is the application of a large current pulse to a cylindrically symmetric load, with the resulting Lorenz force compressing the load to produce hydrodynamic motion and/or high temperature, high-density plasma. These experiments have been carried out at two facilities at Los Alamos; the ones at low current (several million to ten million amperes) on the Pegasus capacitor bank; and at a higher current (above twenty million amperes) at Ancho canyon where experiments are done with explosively driven magnetic flux compression generators. In a recent experiment with the Ranchero generator we developed 25.7 million amperes and were able to deliver 15 million amperes into the load. With a new, longer (1.4 Meter), Ranchero generator we expect to deliver approximately 30MA into the load. The current levels that explosive generators can produce are equivalent to that of Atlas and can therefore provide answers to potential problems that can influence the design of the Atlas machine.

Diagnosing experiments in the severe environments of explosives and high energy pulsed power has always been a difficult task. We have developed methods for collecting data, protecting and saving diagnostics in the environment of several hundred pounds of high explosives. Imaging, both visible light and X-ray, have been the main sources of data for research on instability growth in plasma and liner implosions. Numerical modeling[2], based on the observation of time sequences of visible light images, has resulted in the successful prediction of magneto hydrodynamic instability growth in plasmas. New numerical models have extended successful predictions of hydrodynamic effects to thick liner implosions. Atchison[3] et al. have discussed detailed comparisons with radiographic data and 2-D calculations.

In these experimental campaigns, depending on the objectives, liners of various thickness and sizes are used. Also, initial perturbations, sine waves of specific wavelength and amplitude may be machined onto either the outside or inside surfaces and they may be in axial or azimuthal orientation. Sometimes different perturbations that act as a seed for the instability growth may be placed in different locations on the same load. This gives us the ability to see different instability growth from dissimilar, initial perturbations on the same experiment. Most of these experiments will have starting liner diameters from about 3.5cm to 5cm and with a goal of attaining a velocity of around 20km/sec.

Some of the reasons for these experiments are to study Rayleigh-Taylor instabilities, the Bell-Plesset convergent instabilities, hydrodynamic effects, and flows in 3-D, and others other physics issues that are not relevant to this paper. In addition, they serve as proof of principle experiments and a source for diagnostic development for the Atlas system. Atlas will generate high energy density conditions by running ~30 MA of current through a cylindrical liner and a large amount of damage can incur to diagnostics and the load area at these current levels.

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Therefore, prior knowledge that we will learn from Ranchero experiments, can be applied to the Atlas design to minimize problems associated with the destructive effects at these high energies.

II. EXPERIMENTS

The data discussed in this paper was obtained from several experiments from both the Pegasus and Ancho canyon facilities. The emphasis in this report is totally based on imaging and the observation of shocks and instability growth of imploding liners. The pictures shown in this paper were obtained with electronic high speed framing cameras (Imacon 468 and 790) and the flash x-ray images were obtained directly on film. Numerous experiments were carried out with thin (~1000nm thickness) foil implosions and they provided data for code development. Figs. 1 shows comparisons of actual data and 2D computer simulations by Darrel Peterson[2] of Los Alamos. The features on the surface that are reproduced by the calculations are the amplitudes and the wavelength modes that dominate the implosion. The computer model requires an initial perturbation of amplitude δ, whose value is chosen such that the calculated final radiation pulse is in agreement with the experimental radiation pulse. However, the foils that were used in these experiments have not been perfect and include wrinkles that may serve as initial perturbations. Fig 2 shows a sequence of images 167 ns apart from two experiments. We observe superimposed on the wrinkles the onset of a new set of instabilities that run azimuthally around the foil. These appear to be totally independent of the initial wrinkles and are the ones that grow into the large instabilities that are apparent in later frames. The two images shown have different initial conditions but show the growth of the same types of late time instability. The observed images suggest that, at least in the thin foil case, the instability is initiated by something other than the initial perturbation and require more study. In thick, solid, cylindrical loads, the growth of the instabilities seem to be totally related to surface perturbations. Many of the experiments have machined structures on the surface, which are the seed to instability growth. In order to have a reference, however, experiments that used smooth cylinders with no intended perturbation were carried out. The sequence of images in figure 3 shows

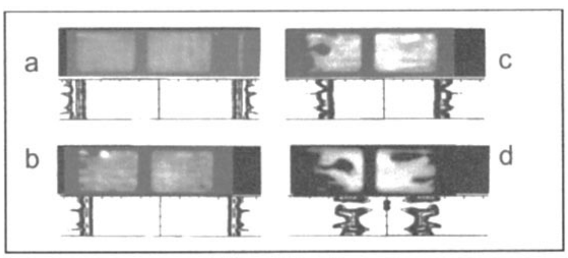

Figure 1 Comparison of data from the 4.9mg foil implosion with numerical simulations. The isodensity contours from simulations agree well with the data.

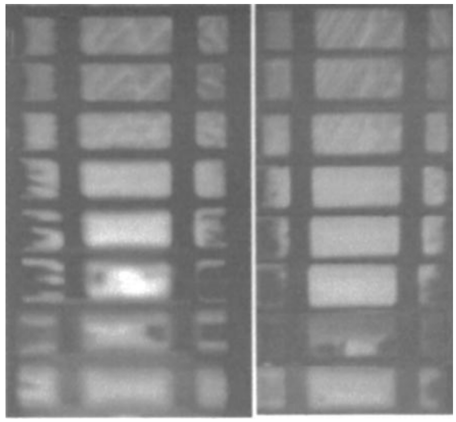

Figure 2 The two thin foil implosion experiments show different initial wrinkles. Nevertheless, the instabilities that grow are independent of these perturbations. Instead, a new set of instabilities develop azimuthally, and grow into the large ones.

data from two identical experiments with significantly different current. In this figure a sequence of images were taken of a 0.4 mm thick aluminum cylinder with a 4.8 cm radius. The camera used an inter-frame time of 500ns and an exposure time of 100ns. The effect of this difference is apparent in the surface "blow-off" of the two experiments. compression of the metal cylinders due to a significantly different current and the effect it has on the surface. An experiment done at low current is shown on the left and in this case, the change of radius almost follows theoretical calculations. Compression in the higher current experiment on the right, however, deviates significantly from calculations. X-ray radiographs taken of the implosions suggest that a different phenomenon is taking place in the high current experiment. The outer surface "blow-off" that is seen in the figure on the right suggests anomalous current flow and heating of the cylinder. Also, it suggests that that the "blow-off" may be coming off the surface as a sequence of thin layers.

Experiments done at even higher currents suggest that

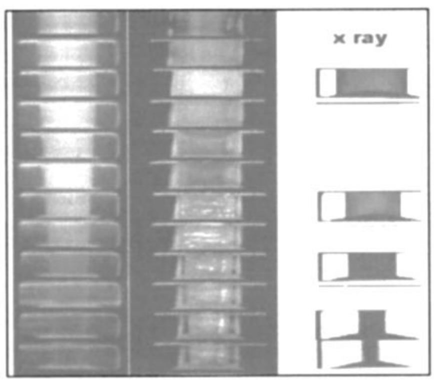

Figure 3 The sequence of visible light camera images of two experiments on the left were taken at the same time relative to initial current. On the second set we see surface "blow-off" at a higher current. X-ray images at roughly equivalent times are shown on the right

the outer surface becomes extremely unstable, and a significant amount of material is blown off and left behind. The x-ray diagnostics are not sensitive to the lower density surface "blow-off" and therefore, give a more truthful view of the implosion which is in good agreement with theoretical predictions. Our experience has shown that at very high currents it becomes virtually impossible to see surface detail on pictures taken of the liner with visible light framing cameras. As an example, we show a picture in figure 4 and contrast it with a representative example done with x-ray radiography. The x-ray radiograph shows a picture late in the implosion where ~50 micron size initial surface perturbations have grown drastically. It is a concern that at higher currents in the Atlas and Ranchero current regime the surface "blow-off" may obliterate the details of the instability evolution.

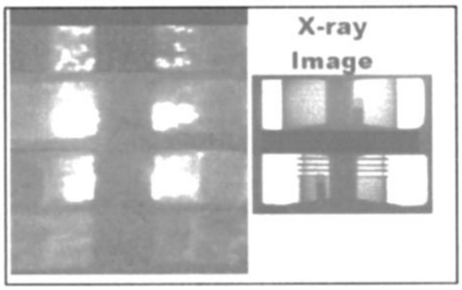

Figure 4 Examples of visible imaging at high current shown on the left and due to the surface plasma, it is impossible to see the actual liner. As a reference, x-ray images are shown on the right that had equivalent current and ~10micron size initial perturbations.

In another series of experiments, two concentric aluminum liners are used, The outside one carries the current, implodes, and collides and generates a shock in the inner one. In these types of experiments we can study at instability growth and Rayleigh Taylor mix in convergent geometry. In our experiments, the inner cylinder has axial "flutes" of different wavelength and amplitude, machined on the inside surface and these are located at special places on the circumference and were to serve as a "seed" perturbation. Also, the inner cavity is filled with either Argon or Xenon gas at one atmosphere. When the shock wave interacts at the target vacuum or gas interface, ejecta can be blown off but if a gas fill is used, light will also be emitted from the gas at the shock region of the interface. Therefore it is possible to tell where the shock front and Al-gas interfaces are. In some experiments we have also used a laser "back-lighter" to determine the location of the interior wall of the inner cylinder during compression. A flash x-ray is also taken at this time. Electronic framing cameras are used to record the progress of the implosion and the images will show the location of the shock front and the Al-gas interface.

Correlation between calculations, comparison with x-ray information and visible light image has not always been consistent. In figure 5 we show a sequence of

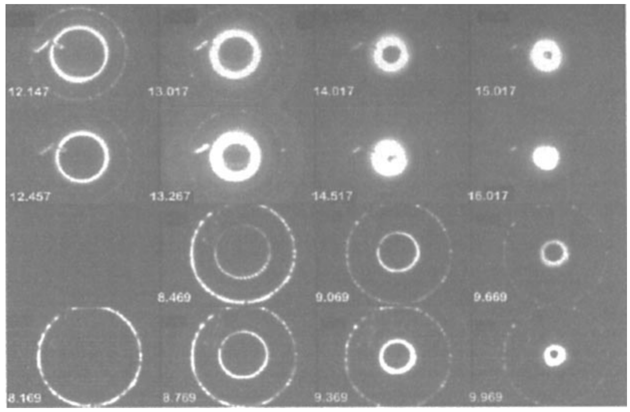

Figure 5 The upper sequence of images was taken with Xe in the center and a 140Kbar shock pressure; the lower one with Ar in the center and a 500Kbar shock pressure.

images taken with visible light framing cameras during two separate experiments. The first experiment generated a shock pressure of 140Kbar and had Xe at one atmosphere in the center. The second experiment had Ar at one atmosphere and had a shock pressure of 500Kbars. Determination, from the images, was made of the location of the shock front and the Al-gas interface. In the images (figure 5) are a sequence of rings, the front of the ring (inside diameter) is the shock front; the outer diameter of the ring is the Al-gas interface. When the determination of the Al-gas interface is done in this fashion, we notice that correlation with the x-ray data gives a different rate of compression. Effects of this can be seen in the images in figure 5. The data that was obtained with the Ar gas fill inside the inner cylinder and correlates almost perfectly with x-ray data and calculations. Also, it is much easier to see the growth of instabilities when Ar gas is used as seen in the early frames in the second experiment of figure 5.

A third experiment was done that had a laser "back-lighter" with one atmosphere of Ar gas and this experiment generated a shock pressure of 140 Kbars. Figure 6 shows a sequence of these images. It is easy to get confused by the structure observed. The front edge of the dark region is ejecta being blown from the surface and not the shock front, and is moving at twice the speed of the shock front. The opacity of this material is high

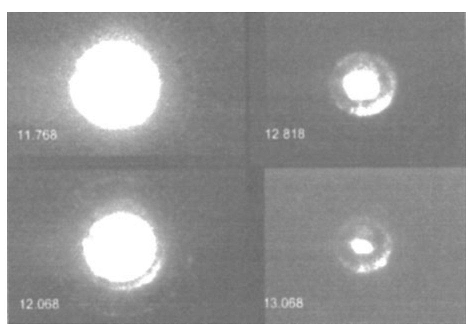

Figure 6 A sequence of the implosion taken with a laser "back-lighter". These show ejecta being accelerated to the center in front of the shock front.

enough that the laser beam was drastically attenuated The structure that is seen is also observed clearly in the x-ray images and is located where initial perturbations were machined. Figure 7 shows an x-ray image and a visible light image that was taken earlier in time. The visible light images show the effect of the instability much earlier.

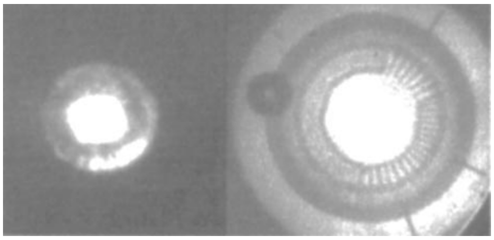

Figure 7 The ejecta that can be seen in visible light image (left) gets to the center much earlier than the x-rays show for the bulk motion.

In the future, the main diagnostic for the study of instability growth will be x-ray radiography. The construction of the loads will require thick, metal current returns and will make visible access impossible and therefore the need for high energy (.150-3MV) x-rays. The programmatic requirements are for multi-frame dynamic radiography with a resolution of ~100 microns. The experiments in Ancho canyon also require that the radiography be done in the environment of several hundred pounds of high explosive.

In our first Ranchero experiment that had a liner load, we were able to take three radiographs at different times. Several layers of film with intensifying screens were used. These were housed in protective, one inch thick steel containers, with a thin aluminum front window. Even then, some damage was observed on the film as can be seen in the figures. The 450 KV x-ray sources were destroyed in the experiment. The film was recovered and the data is shown in figure 8. In figure 9 we show the

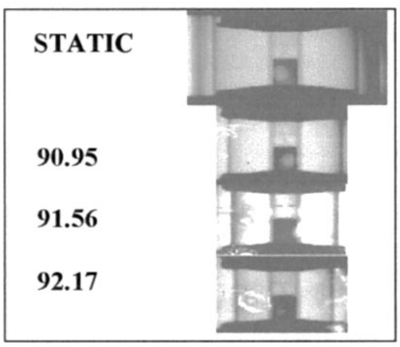

Figure 8 The three x-ray images with the appropriate experimental time. Damage due to the explosives is seen on the film.

Ranchero system that delivered 15.7MA through the load. The picture shows the complete system with diagnostics, the vacuum system and the generator. The experiment

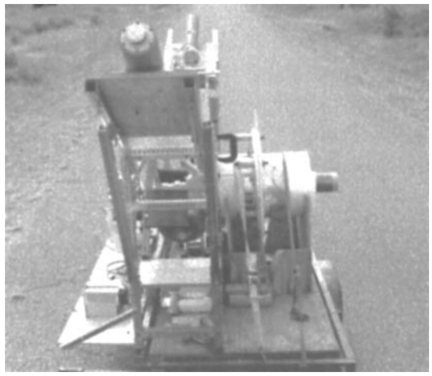

Figure 9 The Ranchero system. The x-ray sources are seen on the top. The load area can be see to the left of the generator.

was hauled to the firing point on a trailer, which is also sacrificed in the experiment. In a very recent experiment we were able to generate ~35MA with our long Ranchero generator[4]

III. CONCLUSIONS

Instabilities play a very important role in implosion physics. Many applications of electromagnetic solid liner implosions require that the state of the liner remain intact, be predictable and smooth. Ordinary fabrication processes can generate a surface that becomes totally unstable. The only way to study the details of instability growth is via imaging. We have been successful in these efforts in studying growth of instabilities in plasmas that have led to the correct theoretical models. We have used visible light and x-ray imaging to observe hydrodynamic effects, "blow-off" of ejecta, and instability growth in solid and fluid liners, and the experiments have led to many surprises. One of the main future challenges will be to develop x-ray sources with a small spot size, time resolved multi-frame imaging and high fluence to penetrate complex structures.

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