Effect of Sheath Curvature on Rayleigh-Taylor Mitigation in High-Velocity Uniform-Fill, *Z*-Pinch Implosions

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Recent gas puff experiments on the 7-MA Saturn machine identified a curved surface at the plasma-vacuum interface during the run-in phase of the implosion. Incorporating this topology into a corresponding two-dimensional magnetohydrodynamic calculation revealed that this curvature plays a surprisingly dominant role in mitigating Rayleigh-Taylor (RT) growth prior to stagnation. Calculations with both Saturn and representative PBFA-Z parameters show that sheath curvature contributes to the reduction in RT growth by convecting the instability to the edges of the pinch faster than it can grow. [S0031-9007(97)03377-2]

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Traditional *Z*-pinch implosions are known to be susceptible to the Rayleigh-Taylor (RT) instability [1,2], especially for thin foil loads [3]. To improve the implosion quality, gas puff loads with thicker shells were subsequently developed. However, experiments have never demonstrated acceptable radiation performance with large diameter, high-velocity annular implosions [3,4]. For example, Saturn [5] data with annular gas puffs have shown significant instability growth and poor radiation emission at diameters of 4.5 cm [6,7]. Many techniques have been suggested to reduce RT development in conventional loads without substantially degrading the compression ratio of the pinch. Such techniques include uniform fills [8,9], puff on puff [10–12], B_z or shear stabilization [13–15], and tailored density profiles [16,17]. Uniform fills, in particular, have been investigated both experimentally and theoretically.

In a recent set of experiments on the 8-MA Saturn generator, the effect of uniform fill loads on stability was examined using neon-argon and krypton-argon gas mixtures [18]. These experiments demonstrated an improvement in implosion quality compared to corresponding annular loads. In addition, a unique feature associated with the uniform-fill loads was identified. Based on images from a high resolution, space- and time-resolved pinhole camera, a curved sheath was clearly seen at the plasma-vacuum interface during the observable portion of the implosion phase. This "hourglassing" [19] effect is shown in the experimental pinhole camera images of Fig. 1 and is attributed to the divergence of the gas flow coupled with an axial mass gradient. This is similar to the long wavelength effects that produce zippering [20,21]. It is evident from the figure that the hourglassing is fairly severe, and is maintained throughout the implosion.

The detection of hourglassing in this set of experiments has led to speculation concerning the role, if any, that sheath curvature may play in instability growth or reduction. To examine this issue, a number of 2-dimensional magnetohydrodynamic (MHD) calculations were performed using the MACH2 [22] code. In these calculations, the injected gas distribution was simulated by a uniform density, right circular cylinder, with a concave outer surface and height of 2.0 cm. Imposing the curved outer surface of the load as an initial condition provided a means to study the effects of hourglassing on RT growth over a wide range of amplitudes. The curved surface was simulated by a circular arc, a reasonable approximation to the observed curvature, using the mesh generating tools of MACH2. A number of perturbation schemes were considered to seed the instability, including random density perturbations and a 2 mm periodic imposed surface perturbation. A 5% random cell-to-cell density perturbation defined throughout the cylinder was chosen here; this has been found to produce amplitude and wave structure comparable to that observed in experiment. To follow the evolution of the instability, the calculations were run in an

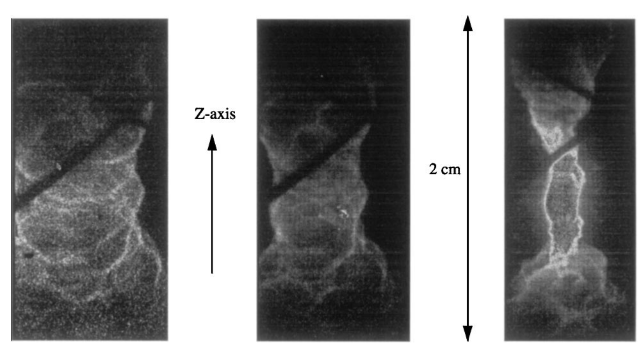

FIG. 1. Pinhole camera images of a krypton uniform-fill implosion. The sheath curvature is evident throughout the implosion. Uniform neon shows similar results. (The dark bands in the images are anode wires.)

Eulerian mode. Figure 2 illustrates one of the initial configurations used for a 4.5 cm nozzle calculation based on Saturn neon-krypton gas puff parameters. The electrodes which confine the top and bottom of the load are considered to be perfectly conducting walls. The cell resolution along the pinch axis was 0.2 mm, providing resolution down to 1 mm wavelengths; these wavelengths are often the most detrimental to the implosion dynamics [4,23].

To specifically investigate curvature effects on RT growth, four initial configurations of a krypton uniform-fill load with varying degrees of curvature were considered. In each calculation the total mass was nominally 500 μg with a mean load diameter of 4.5 cm. The peak current delivered to the load was typically between 7 and 8 MA depending on inductance, with implosion times and velocities comparable with experiment. The degree of curvature ranged from 0.0 (no curvature) to 5.0 mm, as defined by the maximum displacement of the load surface from that of a flat cylinder at a radius of 2.0 cm (refer to Fig. 2). Figure 3 shows the density profile just prior to stagnation in each of the four cases. The peak mass density at this time went from 5.1×10^{-4} g/cm^3 in the 5.0 mm arc to 2.9×10^{-4} g/cm^3 in the flat cylinder. It is clear from this figure that the instability becomes less pronounced as the original curvature of the load is increased. In fact, the 5 mm arc shows almost no short wavelength RT structure. This improvement in stability is observed throughout the entire implosion. Additional calculations with a neon load demonstrate a similar result. There, the mitigating effect appears more dramatic; the loss of multiple bubble-spike structures is readily observed in moving from a flat load surface to one that is curved. Furthermore, the instability has decreased in amplitude and has increased in wavelength, with accumulation of mass at the electrode surface.

The behavior exhibited in these calculations suggests that the RT reduction may be caused by material flow along the sheath, convecting the instabilities toward the computational wall boundaries. Numerical diagnostics support this, revealing that during the run-in phase of the implosion, the curved sheath introduces material flow along the plasma surface away from the center of the arc towards the electrodes. Mass flow with curved sheaths has also been demonstrated in plasma focus geometries [24]. Recent work by Shumlak and Hartman [25] and by Arber and Howell [26] has shown that velocity shear can have a stabilizing effect in the static $m = 1$ instabilities. A similar process may be occurring with the hourglassing, as indicated by these simulations.

To examine the issue of load curvature further, a set of calculations has been performed to look at instability convection using parameters indicative of the PBFA-Z accelerator [27]. PBFA-Z, which is designed to drive higher mass loads over longer implosion times, requires much larger load diameters to reach the same implosion velocities achieved with Saturn. Such high-velocity, large diameter implosions will be even more susceptible to RT growth; for example, simulations based on PBFA-Z annular loads indicate that a 4.0 cm diameter, 1 mm thick shell becomes extremely unstable during the run-in phase, while an 8.0 cm diameter shell is completely disrupted before any of its mass reaches the stagnation axis. Replacing the annulus with a uniform fill at 4 cm dramatically improves the performance of the pinch, while at 8 cm, the pinch is still highly unstable. These preliminary calculations have been extended to include implosions at 4.0, 6.0, and 8.0 cm diameters with varying degrees of curvature. The load mass in each case was 3.4, 1.5, and 0.86 mg, respectively. The implosion was driven by an equivalent-circuit PBFA-Z voltage wave form with a typical load current between 12 and 14 MA, and implosion times on the order of 100 ns;

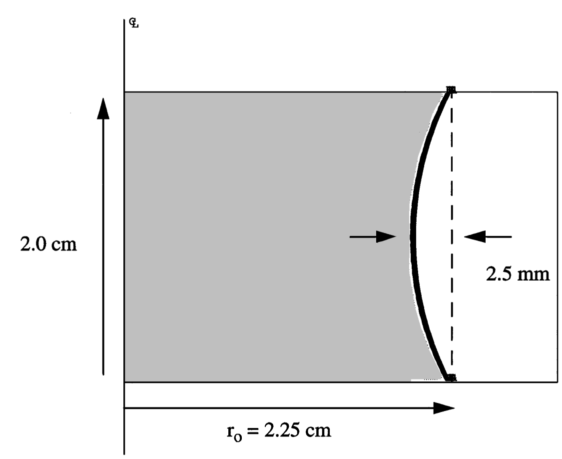

FIG. 2. Initial density profile for a 4.5 cm diameter krypton gas puff calculation. The degree of curvature at the outer load surface, as defined by the displacement from a flat surface, is 2.5 mm for this case.

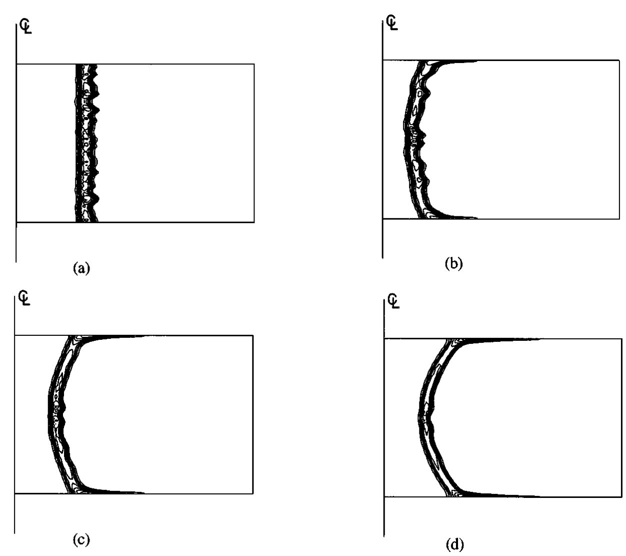

FIG. 3. Krypton density isocontours at 90 ns into the implosion for (a) a uniform-fill cylinder with a flat surface (0.0 mm), (b) a 1.0 mm circular arc, (c) a 2.5 mm circular arc, and (d) a 5.0 mm circular arc.

aluminum was used as opposed to the krypton discussed earlier.

The results of simulations performed on a 4.0 cm diameter load are summarized in Table I. Here, four degrees of curvature were examined; 0.5, 1.0, 2.5, and 5.0 mm. As with the Saturn calculations, improvement was seen with increased hourglassing. The number of observed spike structures decreased from ten to two in moving from a flat surface to a 2.5 mm arc, with substantial broadening of the spikes and an overall decline in amplitudes. This is consistent with an increase in axial mass flow as the curvature becomes more severe. In the case of a flat surface, the growth of instabilities is a direct consequence of mass streaming from bubble regions into neighboring spikes; in other words, there is a continual loss of mass from the bubble regions. With increasing curvature, this flow pattern changes as a net axial velocity moving from the arc center towards the electrodes flows in addition to the original RT mass motion. This results in accumulation of mass at the electrodes and spreading of the instabilities near the center region of the arc. For the 2.5 mm arc, there is always a net velocity across each spike region. This is illustrated in Fig. 4 which shows axial mass velocity along the load surface for a flat cylinder and a 2.5 mm arc. Much of the RT structure which was observed in the flat cylinder is no longer visible in the 2.5 mm case.

Computational diagnostics which measure the shear velocity flow along the curved load surfaces provide evidence which suggests axial velocities on the order of 10% or more of the radial velocity are needed to slow RT growth. This value is similar to that obtained by Shumlak and others concerning flow stabilization of the kink instability. With the 4.0 cm load, substantial RT mitigation was observed for the 1 mm arc, with further improvement as the degree of curvature was increased. The same trends were seen with the 6.0 and 8.0 cm diameter loads, with substantial RT mitigation apparent with the 2.5 mm arc and 5 mm arc, respectively. For these larger diameter, lower mass loads, a higher curvature is required to match the increased radial velocities.

In conclusion, this work has demonstrated the general importance that curved loads have on mitigating RT growth during the run-in phase of a Z-pinch implosion. A curved surface introduces an axial flow along the outer edge of the load which washes out the RT instability, leading to improved pinch quality at stagnation. Whether the reduction in RT growth is the result of velocity shear or material advection along the interface toward the electrodes is uncertain. These issues, along with the role the electrodes play in the simulations are under investigation. The degree of curvature required depends on the implosion velocity, which is determined by the load mass and diameter, as well as various accelerator parameters. This result has important design implications for PBFA-Z, where loads made of foam and similar materials could be manufactured to take advantage of this effect.

TABLE I. Curvature effects on a 4.0 cm diameter aluminum load.

Load curvature (mm)	V_{radial} (cm/μs)	V_{axial} (cm/μs)	λ (mm)
0.0	43	0.1	1.4–2.8
0.5	43	4.3	1.7–3.3
1.0	41	6.2	1.9–3.9
2.5	36	9.2	2.4–4.3
5.0	33	10.4	2.8–4.3

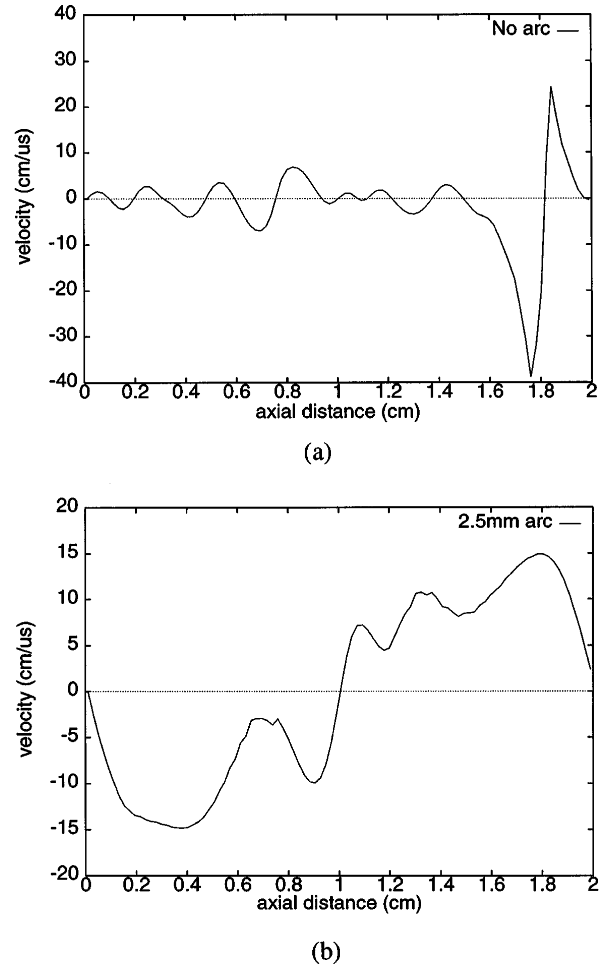

FIG. 4. Axial velocity as a function of axial distance for (a) flat surface and (b) 2.5 mm arc. Velocities were measured near the surface in each case. The large fluctuation in velocity above 1.7 mm (top edge of grid) in case (a) results from slicing across a bubble (vacuum) region.

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