Electrothermal Instability Mitigation by Using Thick Dielectric Coatings on Magnetically Imploded Conductors

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Recent experiments on Sandia's Z facility have confirmed simulation predictions of dramatically reduced instability growth in solid metallic rods when thick dielectric coatings are used to mitigate density perturbations arising from an electrothermal instability. These results provide further evidence that the inherent surface roughness as a result of target fabrication is not the dominant seed for the growth of magneto-Rayleigh-Taylor instabilities in liners with carefully machined smooth surfaces, but rather electrothermal instabilities that form early in the electrical current pulse as Joule heating melts and vaporizes the liner surface. These results suggest a new technique for substantially reducing the integral magneto-Rayleigh-Taylor instability growth in magnetically driven implosions, such as cylindrical dynamic material experiments and inertial confinement fusion concepts.

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In this Letter we demonstrate a novel technique that substantially reduces the amplitude of plasma instability growth in a Z-pinch liner implosion. A Z-pinch implosion is formed by applying an axial flow of electrical current to a cylindrical conductor or annular shell formed by a number of different techniques, including arrays of wires and directed jets of gas [1]. The axial (z-direction) current flow results in a self-generated azimuthal magnetic field which in turn cylindrically compresses matter by the $\vec{j} \times \vec{B}$ (Lorentz) force. Z pinches have a number of practical applications and have been used to study a wide range of high energy density physics, such as material equations of state, material strength, phase transitions, radiation-driven hydrodynamic phenomena, radiation effects on materials, and inertial confinement fusion research [2]. One factor that limits the scope of Z-pinch research in these areas is the fact that they are predominately susceptible to the magneto-Rayleigh-Taylor (MRT) instability [1,3–6] at the outer liner-vacuum interface. This instability is analogous to the well-known fluidic Rayleigh-Taylor instability where a low-density fluid (magnetic driving pressure) is pushing against a dense fluid (plasma liner). We have been actively studying single-mode [7,8] and multimode [9,10] instability growth relevant to a magnetized liner inertial fusion (MagLIF) concept [11,12] in order to better understand the nature of MRT instability growth in these types of systems and to benchmark our simulation codes.

One common approach to mitigating MRT instability growth is to reduce the initial seed for the instability growth by machining a smoother and more uniform initial surface on the liner. This approach has proven effective with radiation-driven inertial confinement fusion capsules in the National Ignition Campaign [13]. However, radiographic image data from a previous MRT growth experiment [Fig. 9 of Ref. [6]] showed that instability growth was not linearly proportional to the amplitude of the initial perturbations. In this experiment, imposed sinusoidal perturbations ($\lambda = 200\ \mu$m, amplitude $= 10\ \mu$m) grew linearly to an amplitude of 500 μm, while at an identical time perturbations from an unperturbed "smooth" surface with an initial amplitude of 60 nm rms grew to an amplitude of 70 μm, a factor over 20 times greater. These results suggest that, at these small scales, making the liner surface smoother does not lead to improved instability performance. Another physical mechanism must be setting the initial seed or configuration for MRT growth.

Recently, we have proposed a new theory for the initial seed of MRT instability growth in pulsed power-driven liners machined with smooth, high-quality surface finishes [14]. This theory suggests that MRT instability growth is not seeded from the characteristic liner surface roughness, but rather a form of electrothermal instability. Electrothermal instabilities can arise whenever the electrical resistivity of a material depends on temperature. In the condensed state of metals, electrical resistivity increases with temperature ($(d\eta/dT) > 0$). Any small nonuniformity, such as a small variation in η, results in temperature perturbations that form striations perpendicular to the flow of current [1,14–18]. These perturbations can become large enough to produce density perturbations which then seed MRT instabilities. Several methods have been proposed for mitigating this form of electrothermal instability growth in Z-pinch liner implosions [19]. Here, we present an alternative approach and experimentally demonstrate successful

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mitigation of the detrimental effects of the electrothermal instability. Image data obtained in these experiments clearly show a reduction in the integral amount of MRT instability growth.

Our approach uses a dielectric coating similar to past exploding wire experiments [20,21]. Unlike those experiments, it is not our intent to modify the characteristic energy deposition into the metal. Instead we use a comparatively massive dielectric coating applied to the surface of a solid metal rod. We predicted thick dielectric coatings would reduce instability growth in two ways. First, the massive dielectric coating acts to hydrodynamically tamp the expansion [19] of the Joule-heated outer metallic surface layers. This slows the metal surface expansion and keeps the density relatively high compared to the case without the dielectric coating. Since in linear theory the electrothermal instability growth rate is inversely proportional to density [14,17], the growth rate is effectively reduced. The hydrodynamic tamper also acts to reduce the amount of mass movement when electrothermal temperature perturbations become large enough to induce pressure variations sufficient to redistribute mass. As a result, the growth of density perturbations can be substantially reduced during the initial heating of the liner surface. This ultimately lowers the initial seed for MRT instabilities as the rod begins to be compressed by the increasing magnetic pressure.

Figure 1 shows several magnetohydrodynamic simulations from HYDRA [22] which illustrate the effect of dielectric coatings with different thicknesses near peak expansion of the surface of the rod. Large density

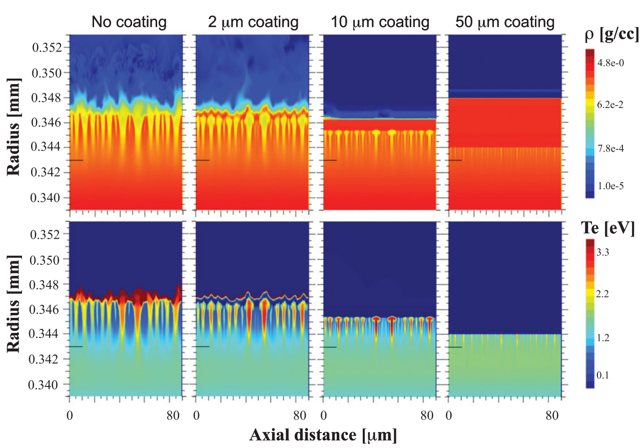

FIG. 1 (color). Simulated density and electron temperature contours showing the difference in perturbation growth predicted with several different thicknesses of dielectric coating on an Al rod at identical times when the drive current is approximately 7 MA. The coating is not observable in the temperature plots with the chosen contour levels since the coating carries very little current and remains comparatively cold in these simulations. Note that a small black line on the left side of each image represents the initial position of the coating-liner interface.

perturbations in the Al are evident in the uncoated case while coated cases show progressively less instability growth as the thickness of the coating is increased. Upon examination of the Al and coating interface, located at the outer tips of the density perturbations, the effectiveness of the hydrodynamic tamping can be clearly observed as the radial position of the interface is progressively reduced and closer to the initial radius as the coating thickness increases. As expected, no significant perturbations are observed in the dielectric coating since it is stable to the striation form of the electrothermal instability. MRT instability growth in the coating should also be negligible since the material remains mostly solid and has undergone very little acceleration up to this point.

It is also evident in the temperature plots of Fig. 1 that electrothermal temperature perturbations in the Al persist in all of the coated and uncoated rod simulations. However, it can also be seen that coated rod simulations exhibit smaller growth rates while maintaining higher densities in the outer Al surface layers. Continuing to increase the initial dielectric coating thickness asymptotically reduces instability growth in our simulations. Only modest improvement is observed with initial coating thicknesses greater than 50 μm since hydrodynamic tamping is sufficient to inhibit redistribution of mass from electrothermal instabilities. Since thicker coatings also add additional mass, an optimum exists around this same value that mitigates the effects of electrothermal instability growth and does not significantly slow the implosion velocity. Depending on the material model and transport coefficients implemented for the dielectric, thermal conduction eventually deposits enough energy to heat the coating sufficiently to carry a tiny fraction of the total current. At this point, the current carrying portions of the dielectric coating become MRT unstable as they begin to be compressed along with the Al.

The hydrodynamic tamping effect of the dielectric was tested experimentally by examining instability growth on a 6.86-mm diameter solid metal rod which was driven to 20 MA in 100 ns by Sandia's Z accelerator. The current pulse, shown in Fig. 2(a), was measured with an array of differential B-dot probes [23] located upstream of the rod at a radial position of 6 cm as well as with a downstream velocity interferometer system for any reflector (VISAR)-based current diagnostic at a radial position of 1.1 cm. The metal rod, shown in Fig. 2(b), consisted of two distinct sections. The top section was a solid piece of Al 1100 alloy that was counterbored and joined to a bottom section of solid pure Be using an internal threaded bolt. The multi-component rod was then diamond turned on a lathe as a single piece to produce a uniform and consistent surface finish ($\sim$60 nm rms) over the entire target. Half the azimuthal portion of the rod was covered with a relatively thick 40-μm dielectric film cut from a polypropylene sheet and joined to the metal rod with an epoxy layer that varied from 20 to 30 μm in thickness. This was done so that

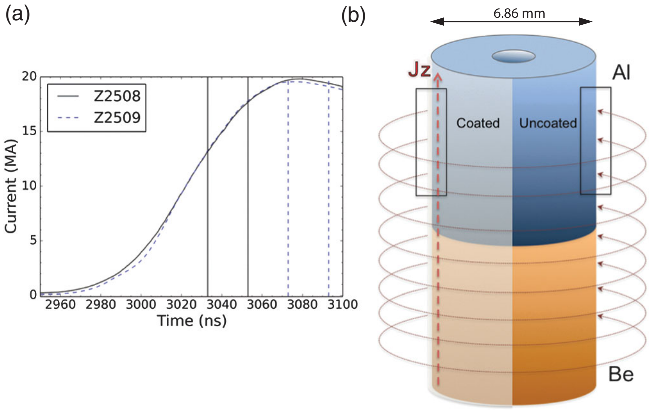

FIG. 2 (color). (a): Measured load region B-dot current for the two experiments performed, with vertical lines representing the time x-ray radiographs were taken. (b): Pictorial diagram of the multicomponent rod with a dielectric coating that covers both the Al and Be sections while only extending π radians azimuthally. The experimental field of view was normal to the R-Z plane and encompassed the entire rod. The regions represented by the black rectangles are the portions of the experimental field of view that are analyzed and presented in this Letter.

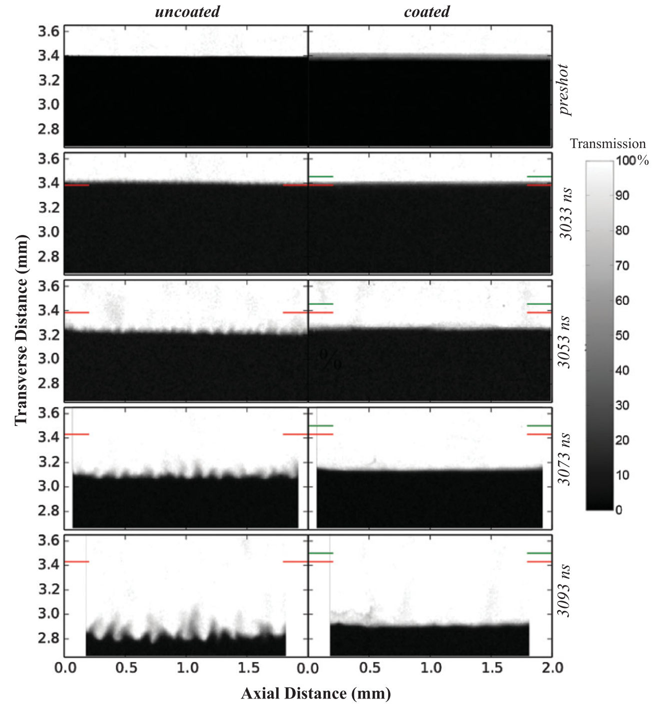

FIG. 3 (color). Cropped and zoomed monochromatic 6151 eV x-ray transmission images of the instability growth observed on the coated (right) and uncoated (left) sections of the Al rod at times $t = 0$ ns, $t = 3033$ ns, $t = 3053$ ns, $t = 3073$ ns, and $t = 3093$ ns. Red lines indicate the initial position of the Al surface and green lines indicate the initial position of the dielectric coating surface. Note that the diameter of the rod used in the first experiment was slightly smaller (OD $= 6.768$ mm) due to a target fabrication problem.

instability growth on the coated half of the rod could be observed simultaneously with the growth on the uncoated half of the rod using a two-frame 6151 eV monochromatic x-ray imaging system [24,25] that is aimed to view the rod at 3° above and below the horizontal axis. Layer deposition methods for the coating may permit a more uniform and bubble-free coating, but were not used here due to cost and time constraints. The result was adequate; the dielectric and epoxy layer contained some bubbles and edge curling, but smooth sections were large enough that the target could be appropriately rotated such that no large bubbles appeared in the field of view of the backlighter imaging system.

Figure 3 shows a sequence of the x-ray radiographs obtained over the course of two separate experiments. These images have been cropped to show only the outer surface of the coated and uncoated Al sections [represented by the black rectangles in the pictorial diagram of Fig. 2(b)] to facilitate direct comparison. Each of the radiographs exhibit clearly resolvable instability growth on the uncoated section of the rod. By contrast, the coated section of the rod shows little to no measurable instability growth. This remarkable result persists beyond peak current and peak acceleration of the rod surface, as evidenced in later frames where MRT instabilities are fully developed on the uncoated side of the rod. The dielectric coating appears to also have been effective in mitigating instability growth in the Be half of the targets; however, the significantly lower opacity of Be complicates the analysis since it becomes comparable with the dielectric opacity. We intend to discuss our analysis of the Be section in a future publication.

Fourier transforms of lineouts of the radiographs for both the coated and uncoated Al rod surfaces are shown in Fig. 4. The first radiograph was taken at a time when the level of instability growth is expected to be only marginally resolvable by the 15-μm resolution of the imaging system. This frame shows at least (the amplitude of instability growth on the coated side is below the resolvable limit) a 2× reduction of instability growth on the coated side of the rod for wavelengths between 50 and 80 μm. It should be noted that by frame 2, the coated half of the rod exhibits a 5–10× instability reduction for most wavelengths above 50 μm. By frame 3, most wavelengths exhibit a 10× reduction factor that persists at least until the last frame was taken at $t = 3093$ ns. Even though the instability amplitude is only marginally resolvable in the coated section in all but the last frame, clear differences in the amount of instability growth are evident in the earliest frames. If the dielectric coating was effective in reducing the seed for MRT instability growth, substantial differences in the amount of instability growth should be observed in the earliest frames before significant motion. The level of instability growth reduction also appears to be relatively constant. This is consistent with the seed for MRT instability growth being reduced in the

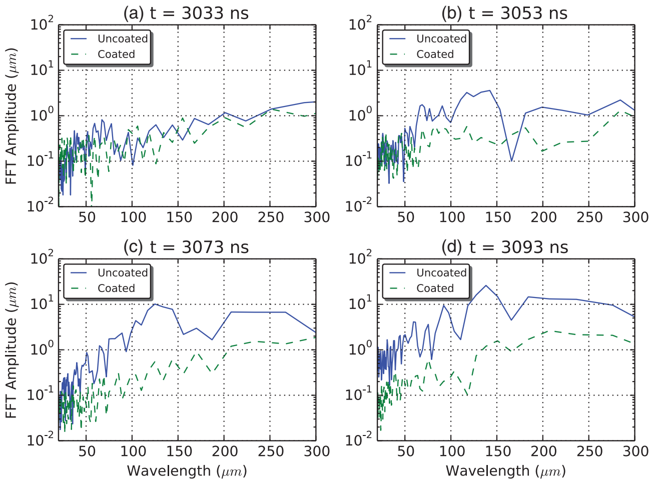

FIG. 4 (color). Fourier transforms of radiograph lineouts from the coated (green) and uncoated (blue) sections taken from the Al section of the rod at times $t = 3033$ ns (A), $t = 3053$ ns (B), $t = 3073$ ns (C), and $t = 3093$ ns (D). The coated section of the rod exhibits significantly less instability growth by approximately a factor of 10 to as much as a factor of 50 in dominant wavelengths.

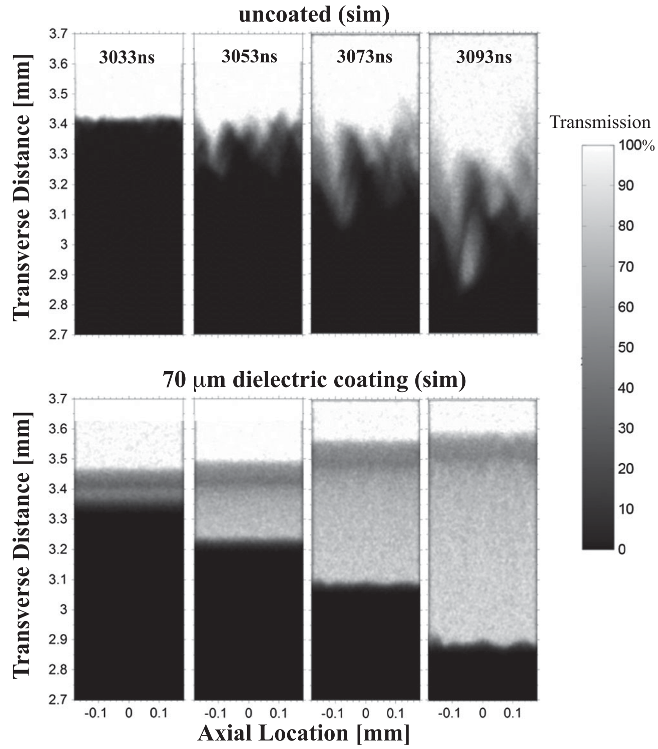

FIG. 5. Preshot simulated transmission radiographs of an Al rod with a 70-μm dielectric coating (bottom) and without a coating (top) shown at the same times as the experimental radiographs in Fig. 3. While the dramatic reduction in instability growth with the thick dielectric coating was correctly predicted qualitatively, these simulations clearly underpredict the fraction of current flowing in the coating which consequently allows the coating and Al to progressively separate.

earliest phases of the implosion due to the mitigation of electrothermal instabilities [14,19].

Preshot simulations, as shown in Fig. 5, are in qualitative agreement with these experiments although there are notable differences. First, instability growth in both the coated and uncoated simulations is about twice as large as observed experimentally. This difference may be attributed to inconsistent initial conditions. Experimental targets were measured to have slightly smoother surface characteristics than was initially assumed in the simulations. Secondly, two-dimensional simulations can overpredict MRT growth rates due to the imposition of perfect azimuthal correlation [26]. The other notable difference in the simulations is the clear separation of the dielectric coating from the Al as time progresses since the bulk of the dielectric coating remains relatively force free. Since these simulations are performed in a resistive magnetohydrodynamics code, we concede that we may be ignoring some surface physics that may contribute to earlier breakdown and conduction of electrical current in the coating itself. However, even though the experiments clearly show that the coating carries a much greater fraction of the total current, the dielectric material is not unstable to the striation form of electrothermal instability growth since the material does not exhibit a positive $d\eta/dT$ dependence. Furthermore, exploratory simulations that intentionally modify the electrical resistivity in the coating such that it does carry a larger fraction of the current show smaller amplitudes of instability growth due to more effective hydrodynamic tamping.

One alternative explanation for the reduction in instability growth observed in Figs. 3 and 4 is that the presence of the coating effectively reduces the density gradient scale length [27–29] of the instabilities. Since the coating is carrying a non-negligible fraction of the total current, the current distribution and density distribution near the surface could be broadened significantly. While this effect may be playing a role at some level in these experiments, it is most likely a small contribution. The simulations shown in this Letter have a significantly smaller fraction of current flowing in the coating and has steeper density and acceleration gradients compared to the case without the coating. Yet the simulations still qualitatively show similar reductions in instability growth with thick dielectric coatings as the experiments.

The results of these experiments may have profound implications for future magnetically driven liner implosions, such as Z pinches, cylindrically driven dynamic material experiments [30], and especially inertially confined fusion concepts such as MagLIF [11,12]. While these results are extremely encouraging, additional experiments are still needed to confirm the effectiveness of this technique in annular imploding liners that undergo significantly greater acceleration and implode to high convergence ratios. We are currently planning to perform these types of experiments on nominal MagLIF imploding liners where, in previous experiments without a dielectric coating, significant MRT growth has been observed leading up to stagnation [10].

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