Experimental Study of the Criteria for Rod Explosion in Pulsed Power Discharges

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When a high current is driven through a conductor, an azimuthal magnetic field is generated, resulting in compression of the conductor by the Lorentz force. This phenomenon, known as a Z-pinch, can be utilized to compress plasma to high temperatures and densities for nuclear fusion experiments [1]. Separately, it has been reported that a silicon rod placed in a liquid medium can be explosively disintegrated by a pulsed current, producing nanoparticles [2–6]. Motivated by these observations, this study investigates the conditions under which a rod is either compressed or exploded during high-current pulsed discharge.

Experiments were conducted using a 1-kJ pulsed power system capable of delivering a peak current up to 100 kA with a rise time of ~ 1.5 μs to drive a silicon rod in vacuum [7]. The rod had a rectangular cross section measuring 1 mm × 1 mm and an effective length of 25 mm. Diagnostics included time-resolved shadowgraphy, schlieren imaging, and interferometry, using a Nd:YAG Q-switched laser (wavelength 532 nm, pulse width ~5 ns) as a backlighter. Shown in Figure 1 are the schlieren image and the interferometer image of an exploding rod taken at the moment of peak current.

Contrary to previous observations in liquid media [2–6], the silicon rod survived the pulsed discharge. Analysis of the interferometry images revealed that the ablative plasma reached a peak number density of approximately 10^{18} m^{-3}, with a corresponding plasma diameter of ~5 mm as inferred from schlieren images. Using Bennett's relation [8], the plasma temperature was estimated to be ~30 eV. The Spitzer resistivity of the ablative plasma was found to be approximately 10^{-2} Ω·m, substantially lower than the resistivity of solid silicon (10^{2} Ω·m). This suggests that the majority of the current flowed through the low-resistivity plasma rather than through the solid rod, resulting in limited ablation and survival of the silicon rod after discharge.

To further validate this interpretation, experiments were repeated with a tin rod, characterized by a much lower solid-state resistivity of ~10^{-7} Ω·m. The tin rod, with a 1.2-mm diameter circular cross section, completely exploded after the pulsed current application. In this case, the resistivity of the tin rod was lower than that of the surrounding tin plasma (assumed to have a similar temperature and density as the silicon plasma), causing the current to continue flowing through the tin rod and leading to its complete disintegration.

A similar mechanism is inferred for the explosion of silicon rods in liquid media [2–6]. In such cases, the ablative plasma is rapidly cooled by the surrounding liquid, leading to a significant increase in its resistivity. Consequently, the current is redirected through the solid rod, resulting in its complete explosion.

In conclusion, we demonstrated that by controlling the resistivity of the rod and the ablative plasma, the current path can be manipulated. If the current predominantly flows through the rod, complete explosion occurs. Conversely, if the current flows primarily through the ablative plasma, the rod experiences minimal ohmic heating and can survive the pulsed discharge. This understanding provides a basis for controlling material behavior under extreme current-driven conditions.

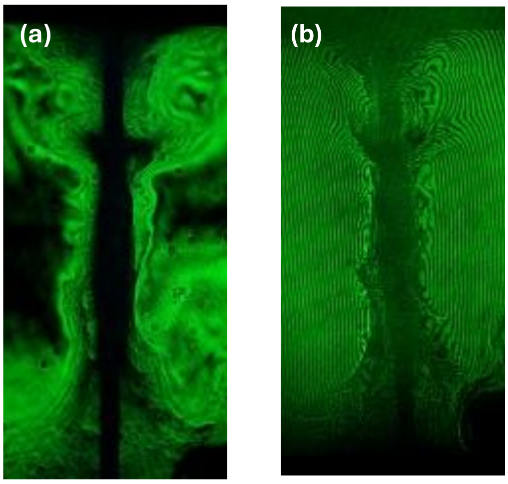

Figure 1: (a) Schlieren image and (b) interferometer image of an exploding rod taken at the moment of the peak current. The width of the ablative plasma was obtained by the schlieren image (a), while the density was retrieved from the interferometer image (b).

References
[1] C. W. Hartman, *et al*, Nucl. Fusion **17** (1977) 909.
[2] Chuhyun Cho, *et al*, Jpn. J. Appl. Phys., **50** (2011) 106201.
[3] Umer Farooq, *et al*, J. Nanosci. Nanotechnol., **14** (2014) 9340.
[4] Longhai Zhong, *et al*, J. Appl. Phys. **132** (2022) 113303.
[5] Chuhyun Cho, *et al*, J. Korean Phys. Soc. **57** (2010) 1807.
[6] C. H. Cho, *et al*, Surf. Coat. Technol. **201** (2007) 4847.
[7] P.-Y. Chang, *et al*, Rev. Sci. Instrum. **93** (2022) 043505.
[8] Thomas J. M. Boyd and J. J. Sanderson, The physics of plasmas.