Examination of Bow-Shock Formation in Supersonic Radiatively Cooled Plasma Flows

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***Abstract*—Radiative high-Z plasma bow shocks driven by a 200-kA current are investigated by using high-resolution dark-field laser Schlieren imaging and a Mach–Zehnder interferometer. Results demonstrate stationary high-density compressible bow shocks and provide data on the plasma Mach number and electron density.**

***Index Terms*—Laser imaging, plasma flows, shock.**

SHOCK formation and evolution are prevalent in many systems including inertial -confinement fusion and astrophysics. Recently, we have carried out experiments on a small university-scale pulsed-power device, where we generate supersonic highly radiative high-Z plasma flows. These flows can be used to create stationary shocks in the laboratory observable for ~100 ns. Typical conditions of the ejected plasma are $T_e \sim 15$ eV and $n_e \sim 10^{18}$ cm^{-3} [1]. Using this system, we can acquire a wealth of data on the evolution of shocks over time, as well as make accurate measurements and adjustments of the initial conditions of the plasma.

In this paper, we used an inverse wire array configuration [2]. The operation of the array is similar to a standard wire array; however, by having the current on the ablating wire flow in the opposite direction, a repulsive force is generated (see Fig. 1). We present the preliminary work for examining bow shocks created by the supersonic plasma flow impacting an object. The inverse array is formed by current flowing from the anode ring up a 10-μm tungsten wire that is hung from a 4-mm circular plate connected to the top of the central return cathode.

Our current driver, i.e., GenASIS, is a linear transform driver [3] that delivers a load current of 200 kA at 75 kV and has a rise time of ~150 ns. To probe the plasma, we employed a neodymium–yttrium-aluminum-garnet laser frequency doubled to 532 nm, with a pulsewidth of 5 ns. The beam is split, and we can achieve a Mach–Zehnder interferometer that allows us to map the density of the plasma and apply a dark-field Schlieren technique that uses a 600-μm spherical stop to reveal density gradients in the plasma [7]. The minimum and maximum acceptance angles for the system are 0.04 and 0.014 rad, respectively, which result in the detectable density range of 5.5×10^{18} to 4×10^{21} cm^{-3}, assuming a parabolic density profile. Images were taken with a 16-bit charge-coupled device camera with a spatial resolution less than 20 μm.

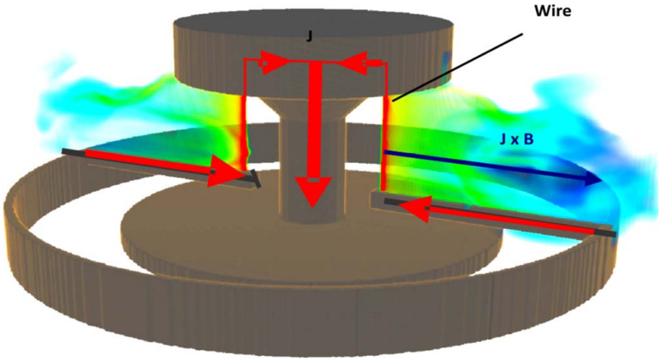

Fig. 1. Diagram of inverse wire array showing radially accelerating plasma due to $J \times B$ forces.

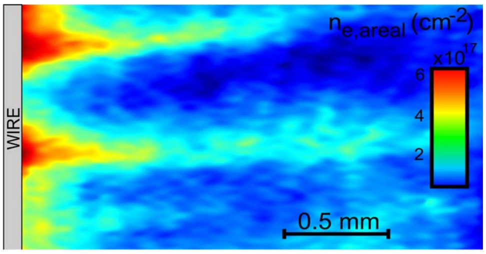

Fig. 2. Electron density mapping of the image generated by interferogram.

Fig. 2 is the unfold of an interferogram of the plasma ablated from a wire radially outward, with distinctive flare structures common to all wire array systems [4], [5]. Using interferograms, one can map n_e integrated along the path of the laser using the Fourier analysis package in IDEA image analysis software [6] to analyze fringe shifts due to the ejected plasma. The density difference between ablation flares and troughs is only roughly a factor of 2 to 3 [7]. By the time flares reach an appreciable distance from the wire, the plasma density is almost uniform. Plasma densities at the wires can reach ~10^{18} cm^{-3} and decrease to ~10^{17} cm^{-3} further away from the wire. Previous work indicates that the ablated plasma velocity is 10^7 cm/s [4], the ionization as $Z = 5$ for tungsten and $T_e = 15$ eV results in a sound speed of approximately 8×10^5 cm/s. It is therefore estimated that a bow shock with a Mach number of 12 could be generated by placing an object in the path of this fast moving plasma. In the time scale relevant

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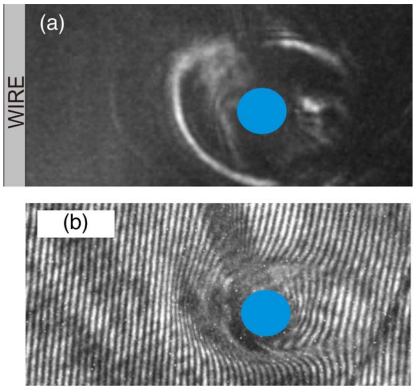

Fig. 3. (a) Schlieren image of a shock created by supersonic plasma impacting a 500-μm horizontal wire. (b) Interferometer image of the same shock.

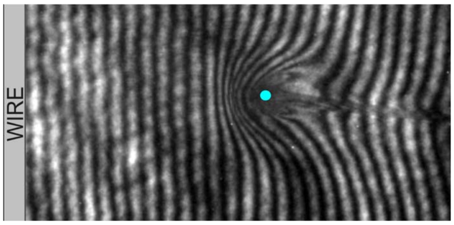

Fig. 4. Initial interferometry work of the plasma shock impacting a 200-μm horizontal wire at 233 ns after peak current.

to shock transit time (approximately a few nanoseconds), the plasma flow density is quasi-stationary, as shown in [4].

The Schlieren image of a shock formed by a 500-μm wire object [see Fig. 3(a)] shows the large electron density gradient on the edge of the shock. The Rankine–Hugoniot density jump condition $\rho_2/\rho_1 < (\gamma+1)/(\gamma-1)$ ($\gamma = 5/3$ for monatomic gas) is limited to 4 under strong shock conditions. However, due to radiative cooling, the plasma flow compressibility increases, forming shocks with much larger mass density increase. Using the image from the interferometer [see Fig. 3(b)], the post shock electron density is evaluated to be ten times greater than the upstream conditions. This increase in electron density occurs in less than 0.2 mm, and the resulting shock angle gives us a Mach number greater than 5. As the material is heated in the shock, an increase in ionization is expected, which impacts the expected mass density increase. To correctly measure the mass density jump across a bow shock, a spatially resolved extreme ultraviolet spectroscopy will be used in the future work to measure the inflow and the shock ionization state. The interferogram (see Fig. 4) also shows the preliminary work on future shock experiments with different-sized objects (in this case, a 200-μm wire).

In summary, a small university-scale pulsed-power setup can be used to generate stationary shocks, which can be extensively measured and studied to better understand bow-shock mechanics in radiatively cooled flows.

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