Study of Magnetic Helicity Injection via Plasma Imaging Using a High-Speed Digital Camera

S. C. Hsu and P. M. Bellan

***Abstract*—The evolution of a plasma generated by a novel planar coaxial gun is photographed using a state-of-the-art digital camera, which captures eight time-resolved images per discharge. This experiment is designed to study the fundamental physics of magnetic helicity injection, which is an important issue in fusion plasma confinement, as well as solar and astrophysical phenomena such as coronal mass ejections and accretion disk dynamics. The images presented in this paper are not only beautiful but provide a powerful way to understand the global dynamics of the plasma.**

***Index Terms*—Helicity injection, plasma imaging, spheromak.**

MAGNETIC helicity [1] is a quantity which describes the amount of twist or writhe in the magnetic field of a given volume. The injection or ejection of magnetic helicity from a plasma often figures prominently in its dynamics and overall stability. For example, the helicity content of certain magnetically-confined plasmas in fusion research (e.g., spheromaks) must be sustained somehow, i.e., via helicity injection. On the other hand, too much magnetic helicity content in a plasma can lead to violent global disruptions; an example of this is a coronal mass ejection [2]. The details of how magnetic helicity is injected into a plasma and its role in causing instabilities are poorly understood. The goal of this research is to study the process of magnetic helicity injection in a simple laboratory experiment.

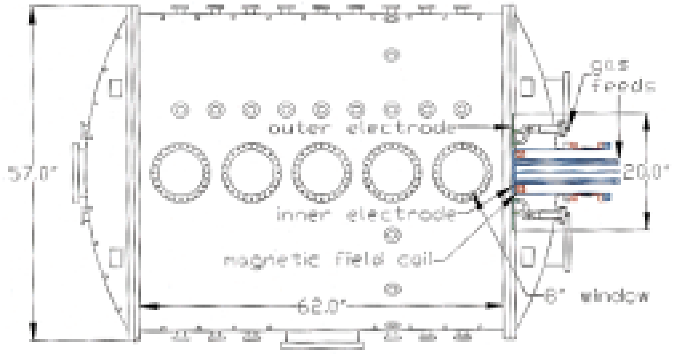

Fig. 1. Schematic of experimental setup showing large vacuum chamber and planar spheromak gun on right side of chamber. The CCD camera is located at the 8 in window, looking toward the gun electrodes at an angle.

Fig. 1 shows a schematic of the experimental setup. A coaxial spheromak gun with large planar geometry is installed on one end of a large vacuum chamber. A spheromak [1] is a plasma configuration in which the magnetic field is produced largely by dynamo-generated internal currents. The spheromak gun setup includes 1) inner (8-in diameter copper disk at left end of re-entrant port in blue) and outer (20-in outer diameter copper annulus in green) electrodes; 2) an external solenoid (in red) to produce a "bias" magnetic field; and 3) gas lines to deliver fast puffs of hydrogen gas to the region adjacent to the electrodes. After the bias field and gas puffs are introduced, a 120-μF high-voltage capacitor bank is discharged across the electrodes through an ignitron. Typically, the inner electrode is at negative polarity high voltage, and the outer electrode is connected to vacuum chamber ground. The optimum path for plasma breakdown is along vacuum magnetic field lines (produced by the external solenoid) which link the inner and outer electrodes. Arcing does not occur at the small gap between electrodes because the pressure-distance product at that point is far to the left of the Paschen curve minimum for breakdown. Typical parameters are $V_{\rm gun} \approx$ 4–6 kV, $I_{\rm gun} \approx$ 100–150 kA, $B \sim$ 0.2–1 kG, $T_{\rm e} \sim T_{\rm i} \sim$ 20 eV, and $n_{\rm e} \sim 2 \times 10^{14}$ cm^{-3}.

Fig. 2 shows a sequence of images illustrating the evolution of a hydrogen plasma generated by the planar coaxial gun. Henceforth, the frames will be referred to by number (1–8), with frame 1 corresponding to column 1, row 1; and frame 2 to column 2, row 1, etc. The images are taken using a Cooke Corporation HSFC-PRO multiple-frame charge coupled device (CCD) camera. Each frame is 1280 by 1024 pixels with 12-bit dynamic range and is shown using a false color table. Typically, the plasma is observed in unfiltered visible light, as in Fig. 2, through a Vivitar 17–28 mm f/4–4.5 zoom lens. However, by using filters, it has been verified that most of the light emission is from neutral hydrogen line transitions, but it should be noted that H–H$^+$ charge-exchange time is estimated to be very fast ($\ll$1 μs) in this experiment, and thus light emission may represent plasma ion dynamics fairly well. The exposure time of each frame in Fig. 2 is 20 ns and the interframe time is 1.5 μs, which is on the same order as an Alfvén transit time, and thus magnetohydrodynamic (MHD) processes can be resolved. The camera is capable of 500 million frames/s and exposure times as short as 5 ns. Light collected through the lens is split into four paths, each imaged onto a separate CCD array, each of which in turn stores two images at different times for a total of eight, i.e., frames 1 and 5, 2 and 6, etc., are from the same CCD array, respectively.

The viewing perspective is from the port with the 8-in window, which is labeled in Fig. 1, such that the gun electrodes appear on the right side of each frame. The circular gap between electrodes is visible most clearly in frame 6. In

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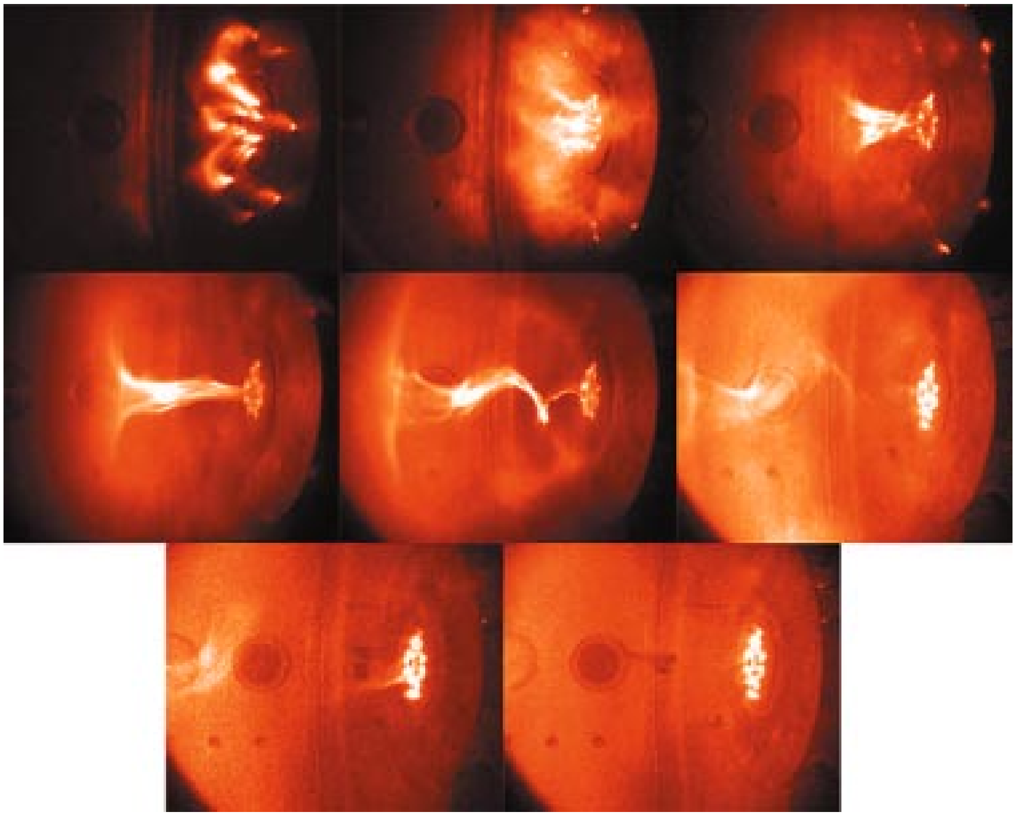

Fig. 2. Digital images from a single discharge taken by a Cooke Corporation HSFC-PRO CCD camera; false color is applied to the 12-bit images. The gun electrodes appear on the right side of each frame. The first frame (column 1, row 1) is at 4 μs after capacitor bank discharge, and the interframe time is 1.5 μs.

frame 1, gas breakdown has just occurred along eight discrete paths (defined by vacuum magnetic field lines) corresponding to gas injection locations. In frame 2, the discrete arcs have expanded and begun coalescing. Magnetic reconnection is expected to occur along the geometric axis of the device as the discrete flux tubes coalesce; this could in part be responsible for the particularly intense light emission there. In frames 3–4, a central column forms and expands in the direction of the geometric axis. In frame 5, the central column has developed a remarkable nonlinear helical perturbation on the Alfvénic time scale. This instability is likely an ideal MHD kink mode, as its onset agrees quantitatively with the Kruskal–Shafranov limit [3]. In frames 6–8, the central column detaches and moves out of the field of view of the camera. From the images, the plasma expansion away from the electrodes can be estimated to be approximately 7×10^6 cm/s, which is similar to the estimated Alfvén speed. By experimentally altering the ratio of gun current $I_{\rm gun}$ to initial bias magnetic flux $\psi_{\rm gun}$, different plasma configurations are realized. The plasma in Fig. 2 corresponds to an intermediate value of $\lambda_{\rm gun} \equiv \mu_0 I_{\rm gun}/\psi_{\rm gun}$. Lower values of $\lambda_{\rm gun}$ result in plasmas with stable and well-anchored central columns. Higher values of $\lambda_{\rm gun}$ result in plasmas which detach and form spheromak states, which was verified with magnetic field measurements in a prior experiment [4].

Multiple-frame plasma imaging is a powerful way to understand the global plasma dynamics and especially any modes which arise. The information gathered with this camera in one plasma discharge would require a minimum of eight discharges using a single-frame camera. And even then, the ability to follow mode dynamics would be lost. The multiple-frame camera could also be used for imaging ion spectral lines in other gases such as helium or argon, thus allowing time-resolved data on T_i (via Doppler broadening) or ion drift speed (via Doppler shift) to be obtained. Using a magnetic probe array as well as optical diagnostic techniques, quantitative details of the magnetic configuration and dynamics are being obtained. This information will help elucidate how energy and magnetic helicity are coupled from open field lines (emanating from the gun) into a spheromak which has a time-averaged closed field configuration.

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