

# Visualization of Current Sheet Evolution in a Pulsed Plasma Accelerator

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**Abstract**—High-speed photography and magnetic field probes were used to visualize and study the formation and propagation of current sheets in a pulsed plasma accelerator. Magnetic field measurements complement photographic records, as the latter indicate the location of the plasma but not necessarily current, whereas magnetic field data provide an unambiguous picture of the current location, but do not directly yield the location of the plasma. The observed current sheet evolution was found to be rich in features and has produced fundamental insight into the phenomena of current sheet canting and trailing wake formation.

**Index Terms**—Current density, magnetic field measurement, photography, plasma engines, plasma sheaths, visualization.

**P**ULSED electromagnetic accelerators are devices which use intense bursts of electrical current ( $\mathcal{O}(10^4 - 10^6)$ A) to create high speed ( $\mathcal{O}(10^3 - 10^5)$ m/s) jets of plasma, and are used in many basic plasma science experiments [1], as well as in pulsed plasma thrusters (PPTs). The present study aimed to investigate current sheet dynamics, in order to better understand the acceleration mechanism in PPTs and ultimately provide guidance for improving their performance.

The plasma discharge in a PPT evolves as follows. First, the volume between two electrodes is filled with a working gas. High voltage (typically 1–15 kV) is then applied between the electrodes, the gas breaks down, and current begins to flow. As the current rises, a transverse magnetic self-field forms behind current sheet and interacts with the current to create an axially directed electromagnetic self-force, which causes the current sheet to accelerate away from the breech, sweeping up gas along the way. At the end of the electrodes, the gas entrained in the current sheet is ejected and an impulsive thrust is produced.

An experimental apparatus was constructed to investigate current sheet physics. The accelerator, shown at the top of Fig. 1, was a parallel-plate pulsed plasma accelerator with copper electrodes and Pyrex sidewalls. The sidewalls reduce the region accessible to the discharge to 10 cm (width), whereas the electrodes themselves were 15 cm wide and 60 cm long. Argon propellant loading was accomplished using an ambient fill: after the vacuum tank was pumped down to its base pressure, the entire tank was brought up to the desired operating

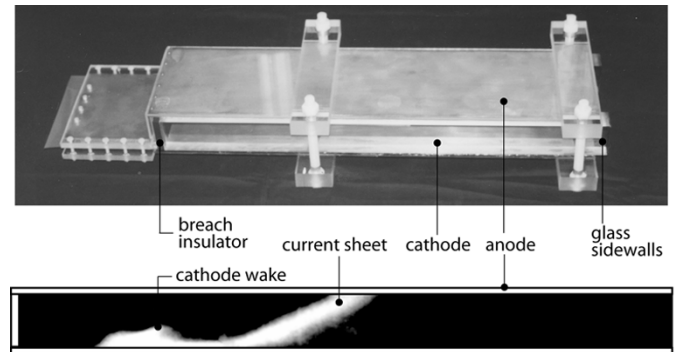


Fig. 1. (Top) photograph of the discharge chamber and (bottom) photograph of current sheet near the midsection of the accelerator (argon, 75 mtorr).

pressure (75–400 mtorr). This resulted in a uniform gas distribution within the accelerator prior to discharge initiation. The accelerator was powered by a pulse forming network, which provided a nearly flat current ( $\approx 60$  kA) profile for about 25  $\mu$ s.

A Hadland Photonics Imacon 792LC camera was used to obtain a series of photographs that show the spatial evolution of the current sheet during a current pulse. The framing rate was set to 500 kHz and the exposure time for each image was 400 ns. A narrow-pass line filter (488 nm, 10 nm full-width half-maximum) was used to allow only the light emitted by argon ions to enter the camera—to exclude the more diffuse glow of neutrals. The side of the accelerator was imaged through a chamber window. A typical photograph of an argon arc discharge in the accelerator, taken approximately 10  $\mu$ s after initiation, is shown at the bottom of Fig. 1. Lines have been drawn to indicate the position of the electrodes. The current sheet, which is the bright diagonal object that spans the gap between the electrodes, is seen to be highly canted relative to the electrode normal. Also, the current sheet is seen to leave plasma in its wake, along the cathode. Ideally, the current sheet would remain perpendicular to the electrodes as it propagates axially. In contrast, as time progresses, current sheets are observed to severely cant as they propagate. The effect of canting is to force the plasma entrained by the current sheet into the cathode, where it stagnates and is then left behind.

While the photographic records show rich features that have complex and dynamic evolution, it is difficult to ascertain which of these features actually carry current. Such an insight can be obtained by complementing the photographs with magnetic field measurements. Two magnetic field probes were used to map the evolution of the magnetic field. Time resolved measurements were made over a grid spanning the entire inter-electrode space [2]. This array of points consisted of seventy-two

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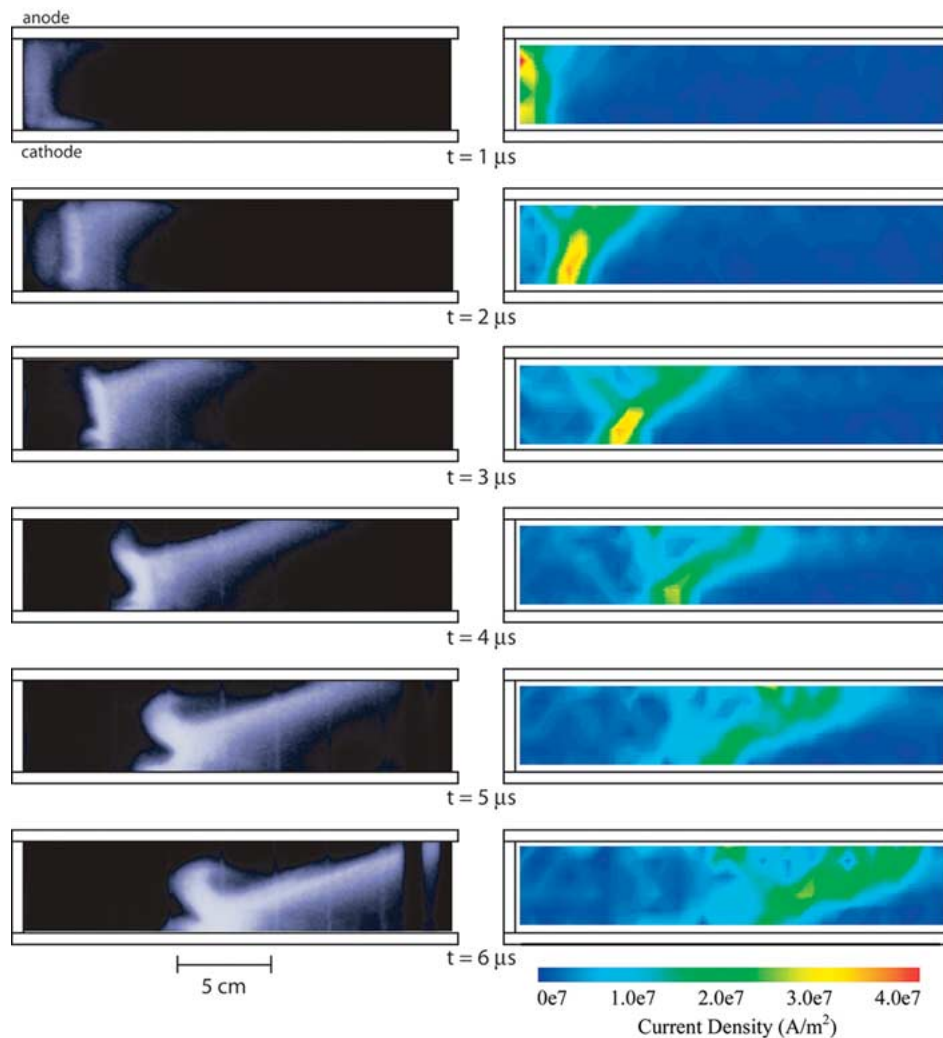


Fig. 2. Photographic (left, argon, 75 mtorr) and current density (right, argon, 100 mtorr) data showing the evolution of the current sheet near the breach.

axial by six transverse locations. Since only two probes were employed, data was obtained at just two out of 432 grid points during a single discharge. However, the repeatability of the discharge was excellent and allowed for the integration of this data into a composite set of frames.

The frames in Fig. 2 more clearly illustrate the transition of the arc from its planar initial state, to the fully canted current sheet. Here we show both photographic records and current density contours (as inferred from the magnetic field data), side by side at similar test conditions. As the current sheet leaves the back of the accelerator, it immediately begins to bifurcate. The initial anode attachment point recedes from the electrode, and a diagonal sheet forms. Within several microseconds the sheet attains the canted structure that it maintains for the remainder of its propagation. The base of the arc forms a hook-like structure which has been previously observed [3].

These visual data gave the fundamental insight that guided the detailed studies of the canting phenomenon and the nature and importance of the trailing wake. An experimental paper [4] showed that the degree of canting depends on the atomic mass of the propellant; lighter atoms were observed to yield less canting (the measured angles ranged from approximately  $10^\circ$  for hydrogen to  $70^\circ$  for xenon). A phenomenological model of the

canting process has been developed [5]. It is postulated that a density gradient forms near the anode with a characteristic length on the order of the ion Larmor radius. This allows for rapid penetration of the magnetic field along the anode, due to the Hall effect, leading to a canted current front ahead of the initial current sheet. The development of the wake has recently been explored as well [6].

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