Schlieren Techniques for the Visualization of Current Sheets in Pulsed Electromagnetic Accelerators

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Abstract

Techniques for the visualization of current sheets, which rely on the refraction of light from an external source, are reviewed. In particular, experimental results from the application of shadowgraph, schlieren photography, and a modified shadowgraph technique to visualize current sheet canting in a pulsed electromagnetic accelerator are presented. It is shown that for the discharge parameters in this device, only the modified shadowgraph technique gives useful results.

1 Introduction

The classical description of the acceleration mechanism in a pulsed plasma thruster (PPT) involves the formation and propagation of a current sheet which entrains gas as it propagates along the acceleration channel, acting as an electromagnetic snowplow[1]. Therefore, a fundamental understanding of why current sheets can fail to maintain good propellant sweeping characteristics is essential to the development of more effective PPTs. We are involved in a long-term effort, which we call the Current Sheet Stability Experiment (CSSX), to understand the important aspects of the physics involved in the initiation, propagation, and ejection of current sheets in pulsed electromagnetic accelerators.

An experimental accelerator has been built to generate current sheets. The device was not built to be a functional thruster but, rather, a platform in which diagnostic access to current sheets was easily achieved. The details of this accelerator are described in section 2.1. The first phase of this project was to use advanced visualization techniques such as fast framing cameras and schlieren photography to gain a qualitative idea of how the discharge evolves in the experimental accelerator. The results of the photographic survey were presented in an earlier paper[2]. The major result of this work was the time-resolved optical visualization of complex current sheet dynamics including the effect of current sheet canting — the departure of the current sheet from perpendicular attachment to the electrodes to a skew, or tipped attachment. Severe canting, at angles of up to sixty degrees relative to the electrode normal, was observed. This canting may have adverse implications for PPT performance as it may create off-axis components of thrust, which constitute a profile loss. To take corrective action, it is first essential to understand the

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physical mechanism which causes canting to occur. Since the photographs in that study relied on monitoring optical ion emission, they do not necessarily show the position of the current sheet. A more direct method is to visualize the current sheet through light refraction as it passes through its steep electron gradients.

The term "schlieren techniques" refers to the broad class of optical diagnostics which exploit the fact that light from a source external to a test object (a flowing gas, for example), when made to pass through it, will be refracted by any density gradients which exist in the flow. After passing through the flow, with appropriate optical arrangements, the refracted and un-refracted light can be separated to yield an image with dark and light areas which correspond to disturbed and undisturbed regions of the flow, respectively. So, in the case of visualizing current sheets, the high electron density gradient associated with a thin, propagating current sheet should produce an image with high contrast in the areas which correspond to the spatial extent of the sheet. In the present work, it was hoped that visualization of the current sheet using schlieren techniques would give better spatial and temporal resolution of the position of the current sheet. This would allow for more accurate calculation of properties such as canting angle and sheet sweeping speed.

Schlieren techniques have been used by earlier researchers to visualize current sheets. Notably, both Lovberg *et al.* [3] and MacLelland *et al.* [4] used schlieren photography with parallel plate accelerators similar to the device used in the present work. We have applied techniques similar to theirs; however, we were not able to produce similar results. It was only after trying many different optical configurations that useful results were obtained. The purpose of this paper is twofold: to attempt to explain why we were unable to reproduce results using the same techniques as earlier researchers, and to describe a modified shadowgraph technique that ultimately gave useful information. While this paper does not present any new specific information about how pulsed plasma thrusters work, we hope that others attempting to apply schlieren techniques to devices with similar operating parameters will benefit from reviewing our experience.

The structure of this paper is as follows. First, the apparatus used in the experiment is described. The properties of the accelerator and vacuum facility are given. Also, detailed illustrations of the several schlieren setups used are shown. Next, in the experiment section, the images acquired using each of these configurations are shown and discussed. Finally, conclusions are made about the general suitability of schlieren techniques for the visualization of current sheets in devices with operating conditions similar to those in the CSSX accelerator.

2 Apparatus

The experimental apparatus used in the present work was a parallel plate pulsed plasma accelerator in a dielectric vacuum facility, a Nd:YAG laser mounted on an optics table, and several schlieren optical arrangements.

2.1 CSSX Accelerator I

The CSSX Accelerator I is a parallel plate pulsed plasma accelerator with glass sidewalls (a schematic illustration with relevant dimensions is shown in Fig. 1). The electrodes themselves are made of copper, while the glass sidewalls are made of Pyrex. The sidewalls reduce the region accessible to the discharge to 10 cm (width), whereas the electrodes themselves are 15 cm wide. The motivation for using Pyrex sidewalls is several-fold: first, they provide an excellent optical view of the discharge, second, they isolate the current sheet to a well defined spatial region, third, they isolate the discharge from electric field singularities which are associated with the sharp edges of the electrodes, and last, they isolate the discharge from the rapidly fringing magnetic field at the edges of the electrodes. The two latter benefits tend to make the discharge environment more conducive to the formation of spatially uniform current sheets.

The accelerator is powered by an eight stage pulse forming network (PFN). The values of the electrical components at each stage were chosen to give

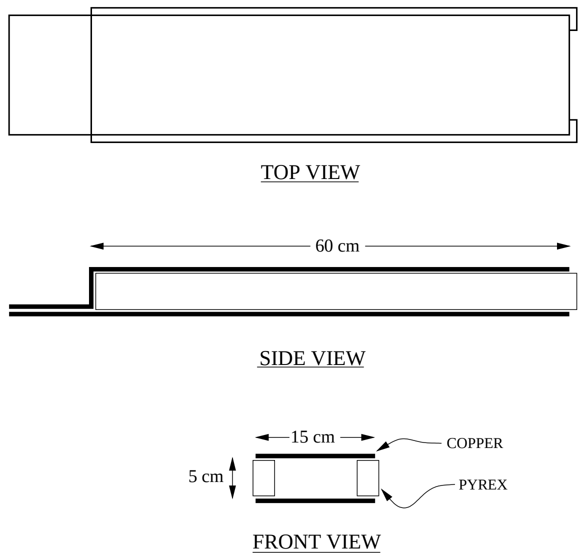

Figure 1: Schematic of CSSX Accelerator I.

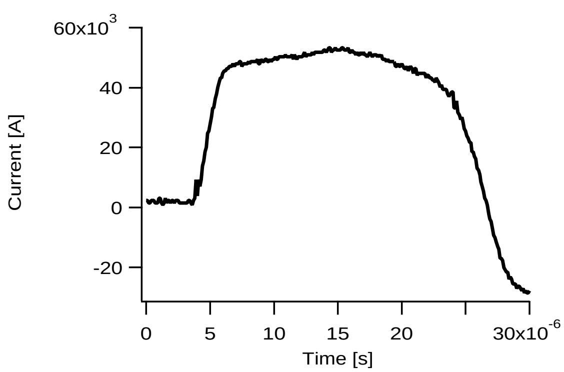

Figure 2: Typical current waveform (propellant: argon (p=100 mTorr) , voltage: 4 kV).

a nearly flat current profile with a pulse width that corresponds to the time it takes the current sheet to traverse the length of the accelerator. Each stage is composed of an 18 μF capacitor in series with a 100 nH inductor. The bank voltage was generally set to 5 kV, yielding a total discharge energy on the order of 2 kJ. The PFN was switched into the accelerator using an ignitron. The peak current was approximately 60 kA, with an initial rise rate on the order of 10^{10} A/s. The duration of each pulse was about 20 μs, which was followed by one cycle of damped ringing. A typical current trace is shown in Fig. 2.

Propellant loading was accomplished using the ambient fill technique. After the vacuum tank was pumped down to its base pressure, the entire tank was brought to the desired operating pressure with the chosen propellant (helium, argon, and xenon were used in the present study). This resulted in a uniform gas distribution within the accelerator prior to discharge initiation.

In general, the apparatus performed very well; current sheets were generated in the expected manner (i.e., formation at the breech and propagation to the exit) and the experiments were very repeatable.

2.2 Vacuum facility

The vacuum facility used in this experiment is described in detail by Jahn [5]. The vacuum vessel is a 1 m diameter, 2 m long cylindrical tank made entirely of Plexiglass (which has been shown to eliminate the electromagnetic interactions sometimes found in metallic vessels), with glass optical access windows. Gases are introduced into the tank using a regulated feed-through. The tank uses a diffusion pump with a freon-cooled trap to achieve a base pressure of 4×10^{-5} Torr. Sub-milliTorr pressures are measured with a CVC cold cathode gauge. All pressures above one milliTorr are monitored using a MKS Baratron vacuum gauge.

2.3 Laser

The light source used in all experiments was a Continuum Minilite II pulsed Nd:YAG laser. The laser is capable of generating 5 ns burst of radiation at 1064 nm and the first three harmonics. In all of the experiments described in this paper, the wavelength was set to 532 nm. At this wavelength, the laser is capable of delivering 25 J pulses at up to 15 Hz rep rate.

2.4 Schlieren Optical Arrangements

Schlieren techniques are well developed and have been used to visualize many different types of flows. The basic principles of the method can be found in the standard references[6]. Four optical arrangements were used in the present experiments – the

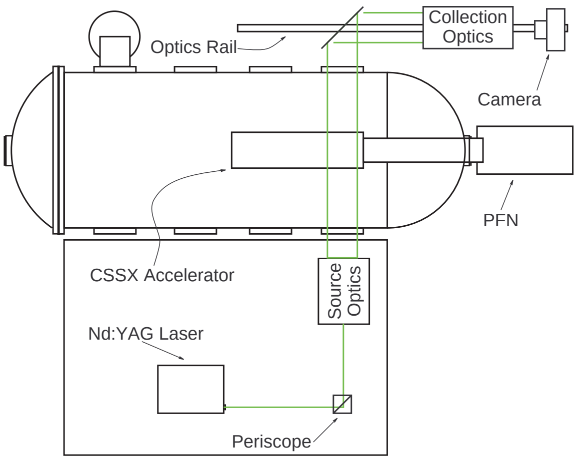

Figure 3: Schematic of schlieren optical layout.

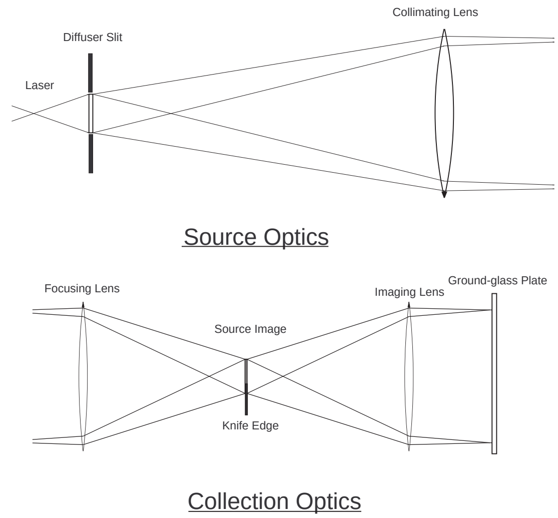

Figure 4: Schematic of schlieren photography source and collection optics.

conventional schlieren and three variations of the shadowgraph configuration. Figure 3 shows the general arrangement of the light source, vacuum chamber, accelerator, and light collection optics. Each specific configuration may be distinguished by the particular optical arrangement contained in the boxes labeled "source optics" and "collection optics." The details of the source and collection optics for each configuration are discussed below.

2.4.1 Schlieren Photography Configuration

The most complicated of the optical arrangements used was the schlieren photography arrangement. The source and collection optics for this configuration are shown in figure 4.

Schlieren photography involves imaging a finite sized source which radiates *isotropically*; a laser, which has a very small cross section and is highly collimated, violates both of the criterion for being a useful schlieren photography source. In order to use our laser as a light source, it was expanded and diffused through a masked opal glass silt (1mm x 10 mm). Six inch diameter lenses were used for both the collimating and focussing lenses. A razor was used as a knife edge and the centerline of the accelerator electrodes was imaged onto a ground glass screen.

2.4.2 Shadowgraph Configuration

The shadowgraph configuration is the simplest of the arrangements used. The source and collection optics for this configuration are shown in figure 5. Unlike in the schlieren photography arrangement, it desirable to have the smallest source size possible in the shadowgraph configuration. In our experiments we used a spatial filter with a 10 μm pinhole. Six inch diameter lenses were used for both the collimating and focussing lenses. The collection optics consist of only a focusing lens and ground glass plate. The magnification of the image is determined by the position of the plate relative to the focusing lens.

2.4.3 Modified Shadowgraph Configurations

In the modified shadowgraph scheme the source optics are the same as in the standard shadowgraph configuration. The difference lies in the collection optics, which use masks at the focus of the focusing lens to intercept refracted rays. Two different types of masks were used in the present study: a pinhole aperture and a "dot" mask. The pinhole aperture allows all of the unrefracted light to pass, resulting in a shadowgraph image with an illuminated background and dark striations, while the dot mask has the op-

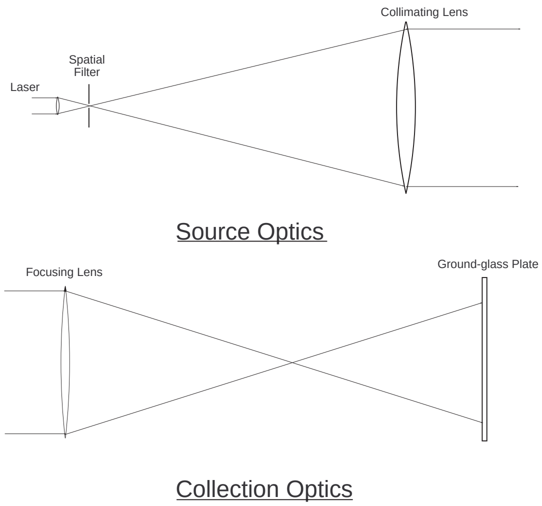

Figure 5: Schematic of shadowgraph source and collection optics.

posite effect – illuminated striations on a dark background.

2.4.4 Camera

The camera used in this study to acquire images was a Kodak DCS 460 digital camera. Acquired images were downloaded directly to a data acquisition computer.

3 Experimental Results

For reference, figure 7 shows a series of photographs acquired in our previous study[2]. The photographs show the evolution of the current sheet as it accelerates away from the breech.

In the following sections, we show images acquired using the schlieren techniques.

3.0.5 Schlieren Photography Configuration

Schlieren photographs were acquired near the breech and center of the accelerator using the apparatus described in the previous section. However, after repeated attempts, the schlieren photography configuration yielded no resolvable features in the discharge.

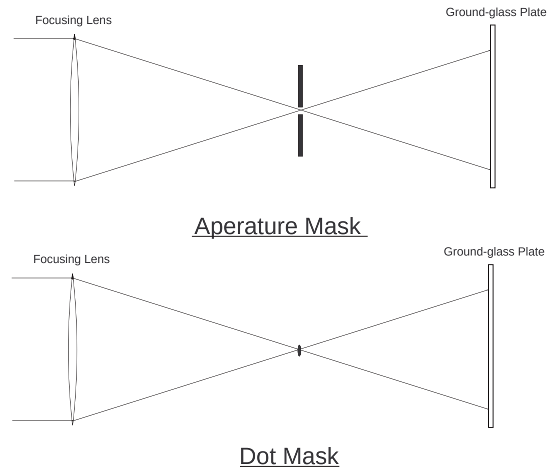

Figure 6: Schematic of modified shadowgraph collection optics.

3.0.6 Shadowgraph Configuration

Slightly better results were obtained using the shadowgraph configuration. Figure 8 shows an image obtained near the center of the accelerator. A faint image of the current sheet is visible along the bottom electrode (cathode). As was observed in the photographic study, the shadowgraph image indicates that the current sheet is highly canted. However, this image is too faint and small in spatial extent to provide any useful quantitative information.

3.0.7 Modified Shadowgraph Configurations

Both modified shadowgraph configurations illustrated in figure 6 were attempted. Use of the aperture mask yielded an image very similar to the image in figure 8. In the modified shadowgraph image the current sheet image was much darker, that is, better resolved. The spatial extent of the image, however, was no greater than that yielded by the standard shadowgraph.

Figure 9 shows a modified shadowgraph image that resulted from using the dot mask. The contrast of the image has been reversed to better clarify the structure. In this image we begin to see features reminiscent of the photographic survey. In particular, the image in figure 9 was acquired near the same spatial

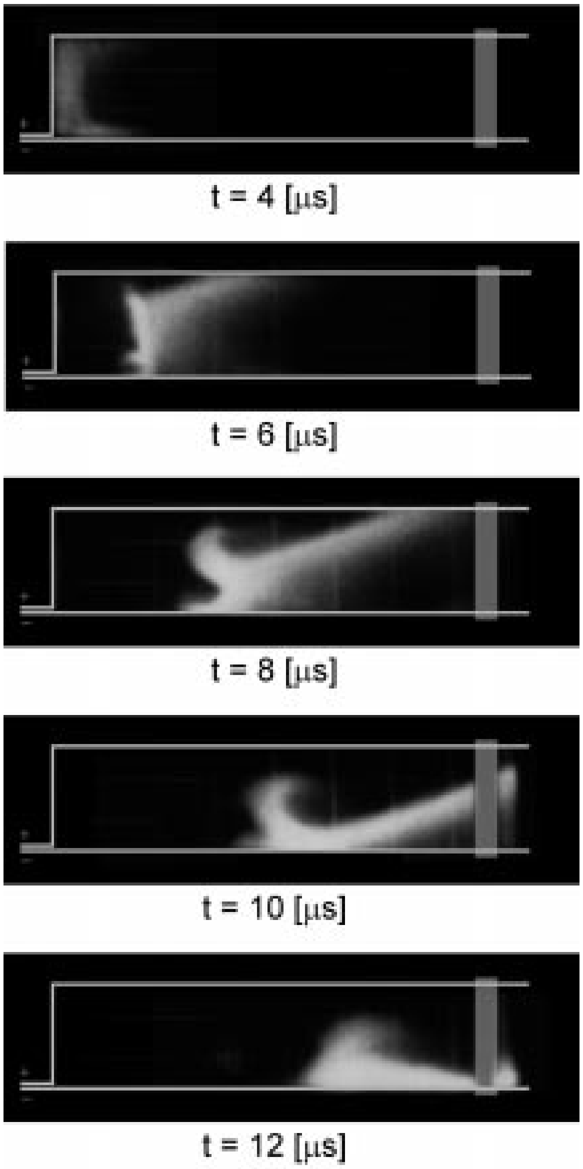

Figure 7: Series of photographs showing the evolution of the discharge near the breech[2](p=100 mTorr (Argon), V=5 kV).

position and at about the same time as the image in figure 7 labeled t = 8 μs. In both of these images we see that a sharp, linear structure emanates from a more diffuse structure near the cathode. The canting angle is severe; a canting angle of approximately sixty degrees can be interpreted from figure 9.

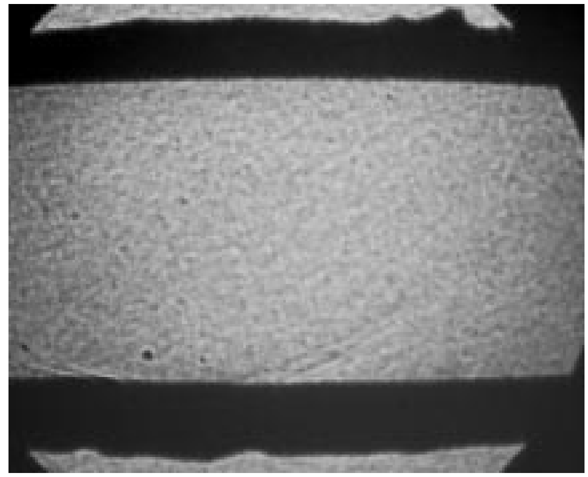

Figure 8: Shadowgraph image of current sheet near bottom electrode (Argon, 100mTorr, V = 4kV). The features may be compared with the photograph in figure 7 at t=10 μs.

4 Discussion and Conclusions

Several optical arrangements of the schlieren technique were employed in an attempt to image current sheets in a pulsed plasma accelerator. The schlieren photography technique yielded no useful data. The shadowgraph technique yielded barely resolved images of the current sheet near the cathode. The modified shadowgraph technique provided the best results and, in particular, the dot mask collection optics arrangement allowed a current sheet to be fairly well resolved across the entire field of view.

It still remains to discuss the reason why earlier researchers were able to use the standard schlieren photography configuration to obtain useful information, while we were not. We believe that the reason stems from the fact that the earlier researchers were operating at much higher power levels than we are in the present study. In both of the cited experiments, the initial capacitor voltages were set to over 15 kV, while our bank voltage never exceeded 5 kV. It is not unreasonable to expect that the current sheets in their experiments contained significantly higher electron densities than in our device, and hence provided greater potential for large angle refraction of the incident light.

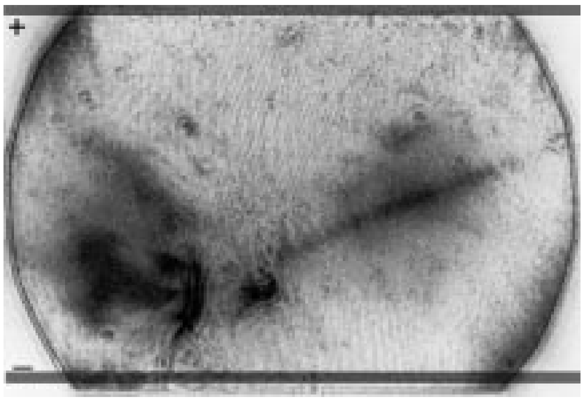

Figure 9: Modified shadowgraph image of current sheet near breach of accelerator (Argon, 100mTorr, V = 4kV).

Despite our inability to use the techniques of the earlier researchers, the modified shadowgraph technique which uses the dot mask appears to be capable of resolving the current sheet with sufficient detail to yield a measure of canting angle. Our future plans are to continue to refine this technique to obtain even greater contrast. Ultimately, we hope to establish a more complete visual survey for further study of the current sheet canting problem.

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