Measurement of Plasma Current Sheet via Fiber-Optic Probe

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An understanding of plasma current sheet behavior is extremely important for both scientific research and technical projects. We present a new probe that uses optic fibers to observe the plasma light directly, over small distances. Optical exploration of a simple current sheet generated in a weakly-ionized plasma provides proof-of-concept and interesting data on current-sheet behavior, which are in agreement with theory.

Plasma current sheets are extremely important for many fields of study, including astrophysics, solar behavior, the study of Earth's auroras, and plasma-based spacecraft propulsion systems. Traditional observation of these structures has been limited to electrical and magnetic sampling (Langmuir probes, etc.). In this paper we measure properties of a current sheet by observing emitted light.

Light emitted by plasma is formed almost exclusively by the decay of atomic electrons excited by inelastic collisions with free electrons from the plasma. The intensity of light emitted as a result of this process is given by:

$$I = \int_{E_{min}}^{\infty} f(v)\sigma(v)dE \tag{1}$$

where $f(v)$ is the electron distribution function and $\sigma(v)$ is the cross-section for excitation. If we assume a reasonable distribution for $f(v)$, without disproportionately large numbers of electrons at higher energies (for example, a Maxwellian such as $f(v) = n_0 e^{\frac{-mv^2}{2kT_e}}$), and that the electron temperature stays relatively stable over the life of the plasma, [1] then the product $f(v)\sigma(v)$ scales with the density of the plasma. In other words, measuring the intensity of emitted light is one way of measuring plasma density.

The machine used for this experiment (Fig. 1) sustained a weakly-ionized ($\frac{n_e}{n_0} \approx 10^{-2}$) plasma and a magnetic field of approximately 60 gauss. The plasma was generated in pulsed mode (duration 1.6mS) from a radio-frequency (RF) source operating at approximately 2 MHz. A thoriated-tungsten filament provided seed electrons. Ion and electron temperatures were estimated at $T_i \leq 1$eV, $T_e \approx 6$eV respectively using a triple probe. [2] We inserted three objects into the plasma: a 20cm x 1cm metal grid, the fiber probe described below, and a combination Langmuir/triple probe for electrical measurements.

Shortly after the beginning of each shot, the grid is biased positive with respect to the chamber wall. For our plasma ($B = 60$ gauss, $\mu = 14$ (nitrogen). the ion

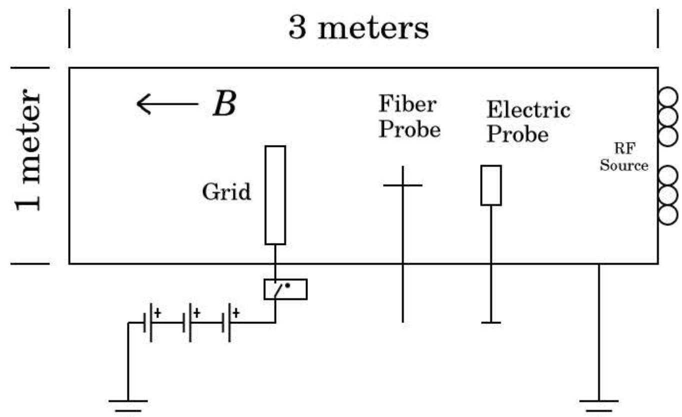

FIG. 1: Experiment chamber, containing a weakly-ionized nitrogen plasma. The current grid, which is activated by a transistor switch, removes electrons, carving a hole in the plasma, while the fiber probe faces the grid and observes the effects.

and electron thermal speeds are:

$$v_{th,e} = 4.2 \times 10^7 \sqrt{T_e} = 1.2 \times 10^8 \text{cm/sec} \tag{2}$$

$$v_{th,i} = 9.8 \times 10^5 \sqrt{\frac{T_i}{\mu}} = 2.6 \times 10^5 \text{cm/sec} \tag{3}$$

The electrons have an enormous themal velocity, and a small fraction of them travel down the field lines to disappear into the grid, within a microsecond. Because the ion thermal speed is much slower (by three orders of magnitude), they cannot react so quickly. Additionally, ions are constrained to "orbit" out of the region, as they cannot cross the field lines directly. In our plasma the ion gyroradius is:

$$R_{ci} = \frac{102}{B}\sqrt{\mu T_i} = 6.4\text{cm} \tag{4}$$

In contrast, the electron gyroradius is tiny:

$$R_{ce} = 2.38\frac{\sqrt{T_e}}{B} = 0.1\text{cm} \tag{5}$$

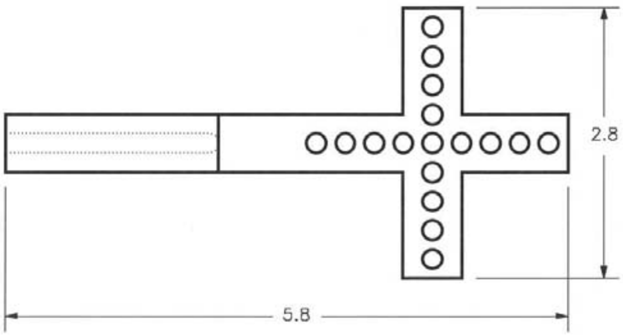

FIG. 2: Fiber-optic probe with 17 tips on two axes, originally designed for small-scale spatial correlations

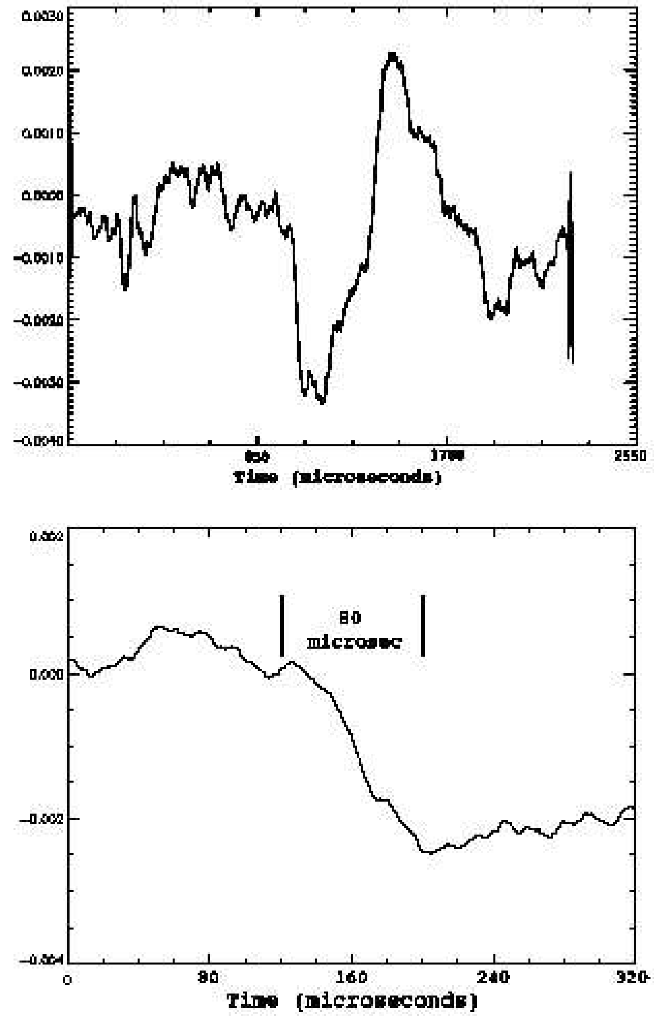

FIG. 3: (a) Profile of the hole over time as seen by a fiber lined up with the grid center. (b) Magnification showing the fall time (≈ 80 microseconds) it takes for the hole to form.

An ion gyroradius of 6.4 cm is comparable to the size of the grid. Over suitably long time scales, it should be possible for ions to migrate out of the grid region, forming an area of low density. The resulting density shift should produce a measurable change in emitted light.

The fiber-optic probe head shown in Fig. 2 consists of seventeen 200-micron fibers on 3mm centers, held in a rigid cross machined from a single piece of PEEK. The optic axis of each fiber is perpendicular to the surface of the head, and all fibers are held at the same height. Each fiber terminates on an individual photodiode, whose photocurrent is measured by a simple op-amp circuit with a gain of 1000. The output signal is AC-coupled through a low-pass filter, and has a maximum amplitude of about 50mV on our device. The fiber-to-fiber cross talk was measured and found to be negligible.

For the experiment, the fiber probe was oriented with the optic axis along the field, facing the grid at a distance of 60cm. The output from each of 16 working amplifiers was fed into a digitizer sampling at an effective rate of 25MHz. To cover the region of interest, we moved the probe linearly across the grid's shadow in 11 steps. We took 10 shots per unique location, and averaged the signals. Two runs, one with the grid off, and one with it on, allowed us to compensate for background shifts in plasma light emission. All plots presented here were generated by subtracting the no-grid signal, and have been smoothed to better present large-scale structures. An example plot of the light level as a function of time is shown in Fig. 3(a), for a particular fiber located in the middle of the region of interest. The light level drops markedly when the grid turns on, about 900 microseconds into the shot. 420 microseconds later, the grid turns off and the light level returns.

The magnification in Fig. 3(b) shows the plasma's reaction when the grid is first turned on. The light decay occurs in 80 microseconds. During this time, the electrons and ions can travel, respectively $L_e = 9.6 \times 10^3$ cm and $L_i = 20.8$ cm.

The ion length scales are in agreement with the theory of hole formation. When the grid is switched on, the electrons respond to the presence of the electric field by moving towards the grid. After a very small fraction of electrons have left the region, it begins to acquire a net positive charge. This has two effects; first, the electron flow out of the region is impeded, and second, ions begin to slowly spiral out of the region. The time required for the region to return to a stable equilibrium is governed by the ion movement.

More information about hole formation would come from observing the hole edges in space, over time. Fig. 4 shows the hole profile as a function of elapsed time and radial distance inside the machine. Here "0" marks the measurement point furthest from the machine wall. Unfortunately, the hole seems to have spread out so far over the 60cm distance between it and the grid that the edges of the hole are indistinct. In addition, this probe and

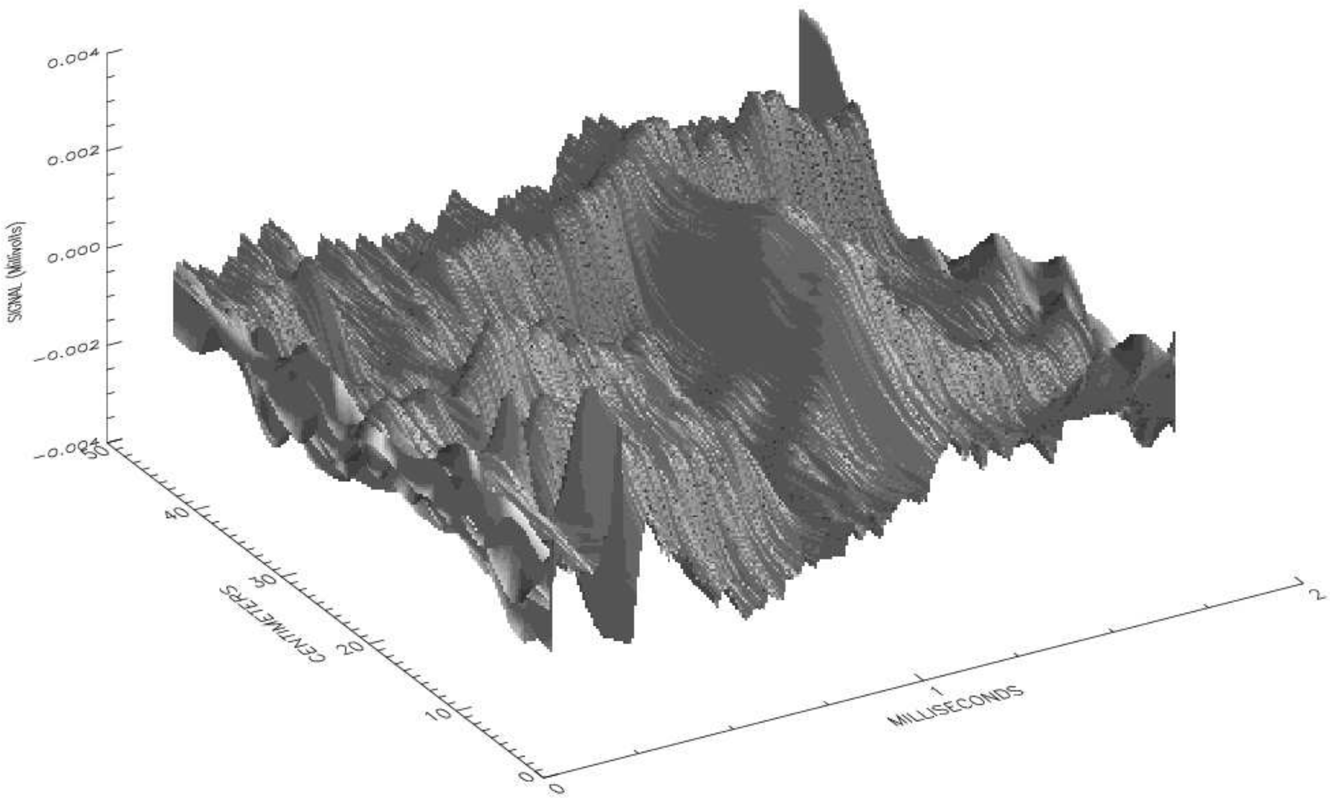

FIG. 4: Radial profile of the hole, in time.

associated electronics were designed for a plasma with density and light levels 1000 times higher, so the signal-to-noise ratio is a problem. We identify the shelf at 40cm as the near edge of the hole. The far edge of the hole is not visible, and whatever structure existed at the near edge of the hole has been lost in the gap between radial positions 10 and 11 (35-40cm). Similar problems were encountered with attempts to map the hole vertically using the nine fibers on that axis. We saw no clear structure, except that the that the hole seemed to fill in from the top and bottom rather than the sides when the grid was turned off. This observation is also consistent with the theory presented; ions take less time to spiral back into the hole across its 1-centimeter height than across its full 20-centimeter length.

More interesting data on this phenomenon could be gathered with higher magnetic field strengths, which would keep the hole stable over longer distances from the grid. The present machine design uses a simple RF source with a spiral antenna, which results in an electric field within the machine in the θ direction. High magnetic field strengths in the present design conflict with the RF source by forcing the electrons along an axial path, preventing the source from accelerating them to the energies required for breakdown. A more powerful plasma source would also be of interest in future experiments, particularly one that does not emit large quantities of electromagnetic interference.

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[1] M. Fassler, Private communication.
[2] M. Fassler.