structure measurements can be carried out even in the absence of alignment.

---

† Work supported in part by the U. S. Energy Research and Development Administration and the National Science Foundation.

[1] J. Macek, Phys. Rev. A 1, 618 (1970).

[2] H. J. Andrä, Phys. Rev. Lett. 25, 325 (1970).

[3] E.g., ^{1}H I, Ref. 2; ^{3}He I, K. Tillman, H. J. Andrä, and W. Wittman, Phys. Rev. Lett. 30, 155 (1973); ^{4}He I, H. G. Berry, J. L. Subtil, and M. Carré, J. Phys. (Paris) 33, 947 (1972); ^{6,7}Li II, H. G. Berry, E. H. Pinnington, and J. L. Subtil, Phys. Rev. 10, 1065 (1974); ^{9}Be II, O. Poulsen and J. L. Subtil, Phys. Rev. 8, 1181 (1973).

[4] D. G. Ellis, J. Opt. Soc. Amer. 63, 1232 (1973).

[5] U. Fano and J. Macek, Rev. Mod. Phys. 45, 453 (1973).

[6] H. G. Berry, L. J. Curtis, D. G. Ellis, and R. M. Schectman, Phys. Rev. Lett. 32, 751 (1974); H. G. Berry, L. J. Curtis, and R. M. Schectman, Phys. Rev. Lett. 34, 509 (1975), and Phys. Lett. 50A, 59 (1974).

[7] R. H. Lambert and F. M. Pipkin, Phys. Rev. 129, 1233 (1963), optical pumping of an atomic beam.

[8] J. Desesquelles, M. J. Gaillard, and J. Silver, to be published.

[9] These parameters are proportional to the Fano-Macek parameters of Ref. 5. The relations given in Berry, Curtis, Ellis, and Schectman, Ref. 6, need to be corrected by a factor of $\frac{2}{5}$, i.e., $A_0^{\mathrm{col}} = \frac{2}{5} \times (\frac{3}{10})^{1/2} \rho_0^{\,2}$.

Plasma Leakage Through a Low-β Line Cusp*

Noah Hershkowitz,† K. N. Leung, and Thomas Romesser‡
Department of Physics, University of California, Los Angeles, California 90024

(Received 7 May 1975)

The half-width of the leakage aperture of plasma through a low-β line cusp is found to be twice the hybrid gyroradius $(r_e r_i)^{1/2}$ with r_e and r_i as the electron and ion gyroradii. This steady-state width is shown to develop in a time less than the ion gyroperiod.

Cusped magnetic fields have been widely suggested as being useful for confinement of both high- and low-β thermonuclear plasmas[1] (where β is the ratio of the plasma pressure to the magnetic pressure $B^2/8\pi$). Although the motion of charged particles in magnetic cusps has received considerable attention, a satisfactory description of how plasma leaks through cusps has not yet emerged. In particular, there seems to be considerable disagreement between theory and experiment.[1,2] Most theories predict a loss aperture for plasma whose radius r_L is (1) somewhere between the electron gyroradius r_e and the hybrid gyroradius $(r_e r_i)^{1/2}$ for high-β plasma ($\beta \approx 1$), and (2) $\approx r_i$ (the ion gyroradius) for ions in a low-β ($\beta \ll 1$) plasma.[1-3] Most high-β experiments have found $r_L \approx r_i$ although a recent experiment has found either $(r_e r_i)^{1/2}$ or $\approx r_e$.[2] As far as low-β line cusps are concerned, we know of no previous attempts to determine the loss aperture. In this Letter, we present experimental results for low-β ($\approx 2\times10^{-5}$) magnetic line cusps which indicate that the half-width of the steady-state leakage aperture for plasma is $\approx 2(r_e r_i)^{1/2}$. The time developments of the ion and electron leaks are also reported.

Data were taken in a device shown schematically in Fig. 1 which resembles a double plasma device[4] with a "picket fence" placed across the central plane. The line cusp field is produced by an

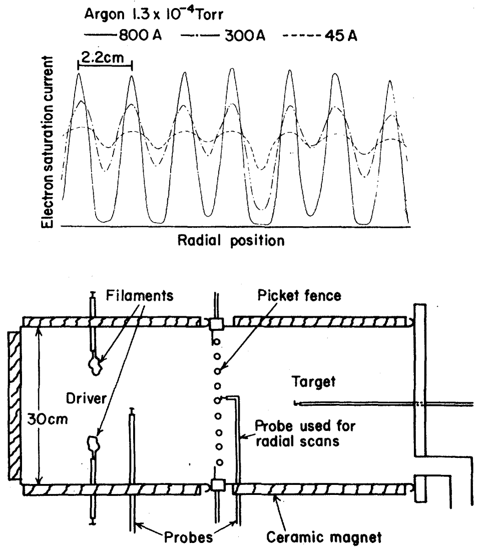

FIG. 1. Schematic diagram showing the picket fence and the multidipole device. Typical radial scans (electron saturation current) as a function of picket-fence current are shown. $B \approx 200$ G for 800 A. Probe-generated noise was not significant.

array of parallel water-cooled conductors (0.48 cm diameter separated by 2.2 cm) with current in adjacent conductors flowing an alternating directions. With 800 A current a maximum field $B \approx 250$ G was obtained at the center of the cusps.

Plasma is produced by 70-eV ionizing primary electrons from filaments located only in the "driver" chamber. Permanent magnets arranged in a full line-cusp geometry confine primary electrons (for over 100 bounces) and plasma ions and electrons (for several bounces) in the driver chamber.[5] Magnets are not placed on the end of the target chamber, thus reducing the confinement of primary electrons so that little plasma is produced there.

We investigated He, Ar, and Xe plasmas with steady-state "driver" densities $(1-5)\times 10^{10}$ cm^{-3} depending on the gas used and the fence currents. Typical operating pressure was 1×10^{-4} Torr ($\approx 5 \times 10^{12}$ neutral atoms/cm^3). Plasma and primary electron density and electron temperature T_e were measured with Langmuir probes while ion temperature T_i was measured with a gridded energy analyzer with a resolution better than 0.1 eV.

The effective width of the "hole" at the line cusp was determined from radial scans of a Langmuir probe behind the picket fence (see Fig. 1). For sufficiently high fence currents the transmitted flux (both electron and ion) has a Gaussian-like appearance (as shown in Fig. 1), with a peak behind the center of each cusp, so a width (half-width at half-maximum, HWHM) could be determined directly. As fence current was reduced, the flux from neighboring cusps overlapped. Direct width measurement was no longer satisfactory but we still could measure numerically the integrated flux. The ratio of the flux to plasma density normalized to the value of this ratio with zero fence current (the transmission T) is then a measure of the fractional width of the "hole." An effective half-width can be defined as half the open width of the hole multiplied by T.

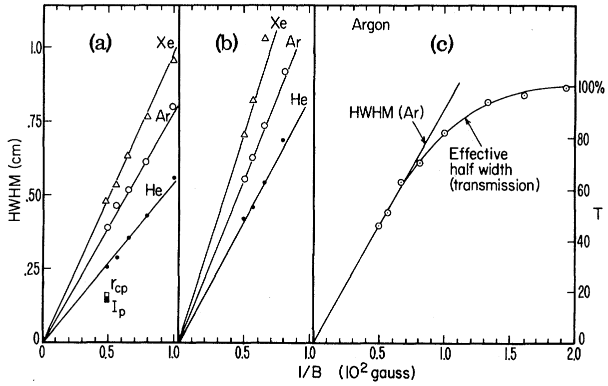

FIG. 2. Measured half-widths (HWHM) versus B^{-1} as determined from (a) electron saturation current, (b) ion saturation current, and (c) integrated (normalized) flux. The straight line labeled HWHM is taken from (a).

Results of direct width measurements for He, Ar, and Xe plasmas, by a cylindrical probe (0.03 cm diam$\times$0.5 cm length) located approximately 0.5 cm from the plane of the picket fence, with its axis oriented parallel to the wires, are shown in Figs. 2(a) and 2(b). The magnetic field B that is given is measured at the center of the cusps. The B field varies by less than 18% with radial probe position so *relative* density measurements should not be significantly influenced by the field.

It is apparent that the widths of the holes are linear functions of B^{-1} over the range of B investigated and that the width increases with increasing mass. A comparison of the measured electron and ion widths multiplied by B (i.e., the slopes of the straight lines) with other measured and calculated parameters is given in Table I. We find that for He, Ar, and Xe plasmas, the measured leakage half-widths W are directly proportional to the hybrid radii $r_H \equiv (r_e r_i)^{1/2}$ and that the ratio $W/r_H \approx 2$. However, since T_e/T_i is approximately the same for all three plasmas, we cannot rule out $(r_e c_s/\Omega_i)^{1/2} \approx 1.7 r_H$, where c_s is the sound velocity.

Data from the ion saturation current shown in Fig. 2(b) indicate an ion width slightly wider than the electron width and qualitatively similar in

TABLE I. Calculated and measured experimental parameters.

Ion	T_e (eV)	T_i (eV)	$r_e B$ (cm G)	$r_i B$ (cm G)	$r_H B$ (cm G)	WB (cm G)	W/W_{He}	W/r_H
Helium	4.7	0.6	5.2	158	28.6	54	1.0	1.9
Argon	3.0	0.3	4.1	353	38.1	80	1.5	2.1
Xenon	2.6	0.23	3.8	560	46.4	98	1.8	2.1

behavior. The effective widths obtained from normalized total flux measurements generally agree with those obtained from direct measurements of the half-width. Widths obtained by the two procedures in the argon plasma are shown in Fig. 2(c). A measurement of the *primary* electron width (labeled I_p) obtained from an argon plasma at 10^{-5} Torr is also given in Fig. 2(a). The measured primary half-width is close to the primary electron gyroradius r_{cp}. This behavior is expected from single-particle calculations[3] and is not surprising since the primary electron energy is much greater than T_e.

In addition to the width of the aperture, there are two other aspects to the steady-state data: the spatial electrostatic potential profile and the presence of plasma noise in the vicinity of the cusp. We find that the plasma potential goes negative by an amount comparable to T_e going from the driver to the target chamber *through* the cusp *along* the magnetic field, the difference increasing as the neutral pressure is decreased. Smaller variations $\lesssim T_i$ are observed across magnetic field lines in planes parallel to the fence (located a few millimeters away) with most of the change occurring in regions which contain very reduced plasma density (i.e., the shadows of the fence). Plasma noise in the neighborhood of the lower hybrid resonance frequency was observed near the cusp. The frequency of the noise was found to depend on the density and B and to scale roughly as the inverse of the square root of the mass ratio. It was independent of the primary electron energy and the plasma electron temperature (which could be varied by about a factor of 2).[6]

The steady-state data can be summarized as follows: The electron half-width is $\approx 2(r_e r_i)^{1/2} \approx (r_e c_s/\Omega_i)^{1/2}$, and ion half-widths are slightly larger. Primary electrons are found to have a half-width approximating their gyroradius. Most of the change in the plasma potential occurs along the magnetic field lines through the cusp going negative from driver to target by an amount $\approx T_e$ and plasma noise was associated with the cusp.

Transient measurements were made at short times after the "turn-on" of the plasma in addition to steady-state measurements. At $t = 0$ the primary electron bias voltage was pulsed on. Langmuir probe traces were taken using the gated output of a sampling plug-in whose delay time could be varied. Three kinds of measurements were made at fixed delayed times: Langmuir probe traces at fixed probe positions, ion saturation current as a function of radial position behind the cusps, and electron current as a function of radial position. At 1.5×10^{-4} Torr in argon, the Langmuir probes indicate the following sequence of events: Primary electrons uniformly fill the driver chamber within 10 μsec. For the next 20 μsec, plasma ions and only relatively high-energy electrons (tens of eV) are present at the center of the cusp. At 30 μsec we begin to detect cold electrons at the center of the cusp with temperatures comparable to those observed in steady state.

The time evolution of the ion and electron hole widths are shown in Fig. 3. At the earliest times ions are observed to have widths *greater* than in steady state although the density is very small and the uncertainty in width is considerable. This width *decreases* to the steady-state width after 30 μsec. Electrons are seen to start out with a width which is comparable to the primary electron gyroradius. After 30 μsec essentially steady-state conditions are reached. The early-time hole widths are consistent with the observation of only high-energy electrons for those times. In steady state we have already found that primary electrons leak through a narrow width (the order of the primary electron gyroradius). The small widths do allow us to place an upper limit on the width resolution of the probe, which clearly demonstrates that the measured widths at later times are not a probe sheath effect even though electron gyroradii are comparable to the probe diameter and the electron Debye length. Plasma noise similar to the steady-state noise is detected at early times.

It is tempting to identify the observed width with previous calculations which have predicted

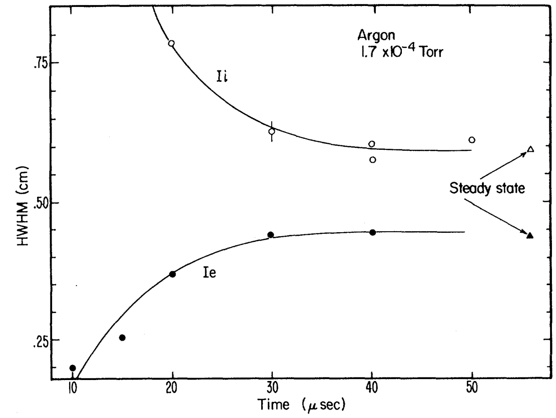

FIG. 3. Time development of the electron and ion half-widths for argon with $B = 190$ G.

hybrid widths.[1] However, such calculations apply to high-β situations. One might argue that far from the cusp a high-β situation exists. For our plasma this occurs with $B \approx 1$ G. Since lines of B from this region connect to a region in the center of the cusp whose width is much smaller than any of the measured widths in this experiment, it is unlikely that high-β phenomena are involved.

The time-dependent data have been shown to be generally consistent with the steady-state data. The hybrid half-width is seen to develop early in the evolution of the plasma. A comparison of the time for the width to reach its steady-state value, ~30 μsec, with the characteristic times of the plasma shows how short this time is. With $n \sim 10^8/\text{cm}^3$ at $B = 250$ G, the ion plasma period is 3 μsec and the ion gyroperiod is 105 μsec. This steady-state width is reached in ten ion plasma periods and in less than half an ion gyroperiod. The plasma itself takes about 800 μsec or 27 times as long to reach its steady-state density. We know of no theory which can explain these results.

We are greatly indebted to Professor J. M. Dawson, who suggested this experiment. We thank Professor B. D. Fried, Professor K. R. MacKenzie, Professor A. Y. Wong, and Mr. T. K. Samec for helpful discussions, and J. Theobald for technical assistance.

---

*Work supported in part by U.S. Air Force Office of Scientific Research Grant No. 73-2445.

†On leave from University of Iowa, Iowa City, Ia. 52242.

‡Present address: TRW Systems, Redondo Beach, California.

[1] I. Spalding, in *Advances in Plasma Physics*, edited by A. Simon and W. B. Thompson (Interscience, New York, 1971), Vol. 4, p. 79 (an extensive review article containing many references).

[2] A. Kitsunezaki, M. Tanimoto, and T. Sekiguchi, Phys. Fluids 17, 1895 (1974).

[3] T. Samec, K. N. Leung, K. R. MacKenzie, and B. D. Fried, Bull. Amer. Phys. Soc. 19, 928 (1974), and private communication.

[4] R. J. Taylor, K. R. MacKenzie, and H. Ikezi, Rev. Sci. Instrum. 43, 1675 (1972).

[5] K. N. Leung, T. K. Samec, and A. Lamm, Phys. Lett. 51A, 490 (1975).

[6] N. Hershkowitz and K. N. Leung, Appl. Phys. Lett. 26, 607 (1975).

Observation of Flat-Top Velocity Distributions of Electrons in Turbulently Heated Plasmas

K. Adati, H. Iguchi, Y. Ito,* T. Kawabe,† K. Kondo,‡ O. Mitarai,§ K. Muraoka, and R. Sugihara
Institute of Plasma Physics, Nagoya University, Nagoya, 464 Japan
(Received 26 March, 1975)

Velocity distributions of the electrons have been measured by a Thomson-scattering method with an eight-channel polychoromator in the initial stage of a linear turbulent-heating experiment. Flat-top distributions were observed associated with high-frequency fluctuations ($\omega \lesssim \omega_{pi}$) just before the onset of fast heating of the electrons. Those results were compared with computer simulations and theoretical analysis based on quasilinear process.

We report experimental observations of flat-top velocity distributions of the electrons in the initial stage of turbulent heating of a plasma by means of Thomson scattering of ruby-laser light with an eight-channel polychromator. High-frequency fluctuations just below the ion-plasma frequency (ω_{pi}) were observed to grow at almost the same time as the flat-top distributions appeared. These facts were considered as an indication of a quasilinear process in the turbulent heating of the plasma.

In turbulent plasmas, wave-particle interactions are quite strong and distortions of the velocity distributions of the electrons and the ions from Maxwellian have been expected.[1-3] Since the phase velocity of ion-acoustic waves in the plasma is less than the thermal velocity of the plasma electrons, the enhanced diffusion in velocity space is expected to bring a flat-top velocity distribution of the electrons, while for the ions hot tails would be formed. Computer simulation[4-6] showed the appearance of the flat-top velocity distribution of the electrons and hot tail of the ion distributions. They showed that the formation of