Collision of Two Plasma Streams*

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(Received April 25, 1960)

It has been predicted that under certain conditions the counter-streaming of colliding plasma streams should be unstable and should be stopped in a very short distance with the translational energy being converted to the energy of ion or electron oscillations. The collision of two plasma streams satisfying one set of conditions, for which instability had been predicted, has been studied experimentally, and no evidence of instability has been observed. Study of the plasma dispersion equation indicates that much more rigorous conditions must be met before such instability should occur.

I. INTRODUCTION

VARIOUS authors[1–5] have predicted that if, under certain conditions, two tenuous streams of plasma should collide, their relative motion would be stopped by a collective plasma instability rather than by the collision of individual particles. This interaction involves the transfer of the translational energy of the plasma into electrostatic plasma oscillations in a time of the order of the ion plasma period $(M/e^2N)^{\frac{1}{2}}$ and in a distance of the order of $(M/e^2N)^{\frac{1}{2}}U$, where M is the mass of the ion, N is the number density, and U is the stream velocity.

In most cases that have been considered, the velocity dispersion of the electrons and ions of the colliding plasmas has been assumed to be small compared to the relative velocities of the two streams. While these conditions may occur on an astrophysical scale, they are difficult to duplicate in the laboratory. However, Parker has considered a case whose conditions can be more closely approached, experimentally.[2,3] This is the case where the ion dispersion is small compared to the stream velocity while the electron dispersion is large compared with the same velocity. In this case he predicts no interaction between the electrons in the two streams but an interaction should occur between the two ion streams. The effect of the electrons should be to reduce the ion plasma frequency by partially screening the ions; but, if the velocity dispersion of the electrons is large, they will not be able to follow the fluctuations in ion density exactly and the counter-streaming ions should interact.

II. EXPERIMENTAL

In conjunction with our experiments on plasma injection into high-compression mirror machines, we have developed a plasma source which produces a burst of $\sim 2\times 10^{17}$ deuterons over a period of several microseconds.[6] The deuterons have a Maxwellian distribution in a moving frame of reference with an average translational energy of $\sim$900 ev and a temperature of $\sim$45 ev. This is equivalent to a stream velocity of $\sim 30\times 10^6$ cm/sec and a mean random velocity parallel to the stream of $\sim 5\times 10^6$ cm/sec. The electrons have a translational velocity approximately the same as the ions, and measurements of their mean random energy show it is of the same order as the random energy of the ions.

These properties of this source suggested its use in a search for the type of instability predicted by Parker. The experimental layout is shown in Fig. 1. Two of the plasma sources were mounted at opposite ends of a vacuum chamber 20 feet in length and 18 inches in diameter. This chamber was in a longitudinal solenoidal magnetic field whose value could be varied over a range of 0 to 800 Gauss. Normally, when the sources were operating, the background pressure was less than 10^{-5} mm/Hg.

The main diagnostic tools were magnetic probes located at three stations along the chamber. With these probes changes in the field due the presence of plasma from one of the sources were easily detectable. Since the predicted interaction involves large increases in density in the interaction region, a probe buried in this region would be expected to detect field changes appreciably larger than the sum of the signals received from the two sources separately. An ion extraction probe was also used to determine whether the ions from one source were lost, deflected, or slowed down

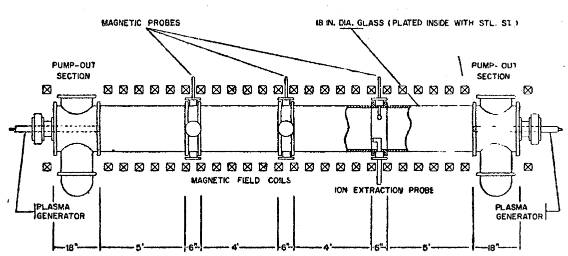

FIG. 1. Experimental layout, colliding plasmas.

* Work was performed under the auspices of the U. S. Atomic Energy Commission.
1 F. D. Kahn, J. Fluid Mech. **2**, 601 (1957).
2 E. N. Parker, Phys. Rev. **112**, 1429 (1958).
3 E. N. Parker, University of Chicago Report EFINS-59-1, 1959 (unpublished).
4 P. D. Noerdlinger, Bull. Am. Phys. Soc. **5**, 307 (1960).
5 P. J. Kellogg and H. Liemohn, Phys. Fluids **3**, 40 (1960).
6 F. Coensgen, W. Cummins, A. Sherman, and W. E. Nexsen, University of California Radiation Laboratory Report UCRL-5703, 1959 (unpublished).

when they passed through the plasma from the second source.

III. RESULTS

The plasma column produced by the source has a density of $\sim 10^{12}$ ions/cc in the interaction zone and has an average diameter greater than 10 cm. When account is taken of the shielding effect of the electrons (following Parker[3]) the ion plasma frequency corresponding to this density and temperature is in the neighborhood of 50 megacycles. Since the plasma period is the e-folding time of the predicted interaction, the instability should grow from noise in less than a microsecond after the streams collide, and the interaction zone should be of the order of 50 centimeters thick. This is much shorter than the apparatus and certainly much shorter than the Coulomb mean free path.

In our runs, which have involved probing the plasma at various radial positions and for values of the magnetic field over the 0 to 800 Gauss range, we have observed no sign of the predicted instability. Both the magnetic probe and extraction probe signals appear to be almost strictly additive, indicating that the two plasma streams pass through each other with practically no interaction. A large signal is often picked up by the magnetic probes when the streams collide and this was at first mistaken for an interaction, but further work identified this as a current of several hundred amperes magnitude flowing through the plasma from one end of the vacuum chamber to the other. Because of the low resistivity of the plasma along the field lines, currents of this magnitude can arise when parts of the plasma sources float above ground during the source discharge.

IV. DISCUSSION

The theory is one-dimensional and does disregard the presence of magnetic fields, but the magnetic field in the experiment is parallel to the stream velocity and intuitively it would seem that it would have little effect on the predicted electrostatic oscillations parallel to the stream. However, it should be pointed out that the interactions involve increases in density of ions which have a component of energy perpendicular to the field and therefore there is a coupling mechanism. The runs that were made in zero magnetic field involved plasma streams with much lower density and therefore with an interaction zone that was large compared to the size of the experimental apparatus. Therefore, we cannot discount the possibility that the instability is damped by the magnetic field before it is measurable.

According to Parker's work[2,3] the electron dispersion should be large enough for the instability to occur when the electron temperature and the ion temperature are of the same order of magnitude, a condition that is met by our plasma source. However, our own examination of the dispersion relationships (Appendix I) indicate contrary to Parker that for the instability to occur, the electron energy should be of the same order as the ion translational energy. This is, or course, a much more stringent condition. Until this range of electron energies is reached, the electrons apparently are able to mask almost completely any ion density fluctuation. Thus our results are not inconsistant with theory as we interpret it.

ACKNOWLEDGMENTS

We wish to acknowledge a very helpful discussion with I. B. Bernstein and the assistance of O. Kammerer in the operation of the experiment.

APPENDIX I

The stability of a plasma against longitudinal electrostatic oscillations is generally considered by examination of the dispersion relation[7,8]

$$\frac{K^2}{\Omega_p^2}=\int_{-\infty}^{\infty}\frac{f'(U)dU}{U-V}=\mathrm{P}\int_{-\infty}^{\infty}\frac{f'(U)dU}{U-V}-i\pi f'(V),$$

where P refers to "principal value of," $K=2\pi/\lambda$, the wave number of the oscillations, $V=\omega/K$, the phase velocity, $f'(U)$=first derivitive of the initial velocity distribution function$=f_e'(U)+m_e/m_i f_i'(U)$, $\Omega_p=(4\pi ne^2/m_e)^{\frac{1}{2}}$, the electron plasma frequency. For a real K we are interested in those values of U for which $f'(U)=0$. It has been shown[4] that the plasma is stable if and only if

$$\int_{-\infty}^{\infty}\frac{f'(U)dU}{U-V_m}<0,$$

where V_m are those values for which $f'(U)$ is zero and $f(U)$ is minimal.

For identical counterstreaming plasmas with stream velocities $\pm U_0$ and Maxwellian distributions (in the moving frame)

$$f_{e,i}(U)=\frac{1}{V_{e,i}(2\pi)^{\frac{1}{2}}}\left\{\exp\left[-\frac{(U-U_0)^2}{2V_{e,i}^2}\right]+\exp\left[-\frac{(U+U_0)^2}{2V_{e,i}^2}\right]\right\},$$

and

$$f_{e,i}'(U)=\frac{-1}{V_{e,i}^3(2\pi)^{\frac{1}{2}}}\left\{(U-U_0)\exp\left[-\frac{(U-U_0)^2}{2V_{e,i}^2}\right]+(U+U_0)\exp\left[-\frac{(U+U_0)^2}{2V_{e,i}^2}\right]\right\}.$$

[7] N. G. Van Kampen, Physica **23**, 641 (1957).
[8] O. Buneman, Phys. Rev. **115**, 503 (1959).

Also

$$\mathrm{P}\int_{-\infty}^{\infty}\frac{(U-U_0)\exp[-(U-U_0)^2/2V_{e,i}^2]}{(U-V_m)}dU$$

$$=\mathrm{P}\int_{-\infty}^{\infty}\frac{\xi\exp(-\xi^2/2)d\xi}{\xi-\lambda}$$

$$=\mathrm{P}\int_{-\infty}^{\infty}\frac{(U+U_0)\exp[-(U+U_0)/2V_{e,i}^2]}{(U-V_m)}dU,$$

where $\lambda_{e,i}=(U_0+V_m)/V_{e,i}=U_0/V_{e,i}$, since for this distribution $V_m=0$. Then,

$$\int_{-\infty}^{\infty}\frac{f_{e,i}(U)dU}{U}=\frac{-2}{V_{e,i}^2(2\pi)^{\frac{1}{2}}}\mathrm{P}\int_{-\infty}^{\infty}\frac{\xi\exp(-\xi^2/2)d\xi}{\xi-\lambda_{e,i}}$$

$$=\frac{-2}{V_{e,i}^2}h(\lambda_{e,i}).$$

It can be shown that

$$h(\lambda)=1-\lambda\exp(-\lambda^2/2)\int_0^{\lambda}\exp(p^2/2)dp.$$

The values of this function are tabulated in a slightly different notation by Ünsold.[9]

The condition for stability is therefore

$$h(\lambda_e)+\frac{m_eV_e^2}{m_iV_i^2}h(\lambda_i)>0,$$

or

$$g(\lambda_e,\,T_e/T_i)=h(\lambda_e)+\left(\frac{T_e}{T_i}\right)h\left[\left(\frac{m_i}{m_e}\right)^{\frac{1}{2}}\left(\frac{T_e}{T_i}\right)^{\frac{1}{2}}\lambda_e\right]>0.$$

[9] A. Ünsold, *Physik der Sternatmospharen* (Verlag Julius, Springer, Berlin, 1938), 1st ed., p. 163.

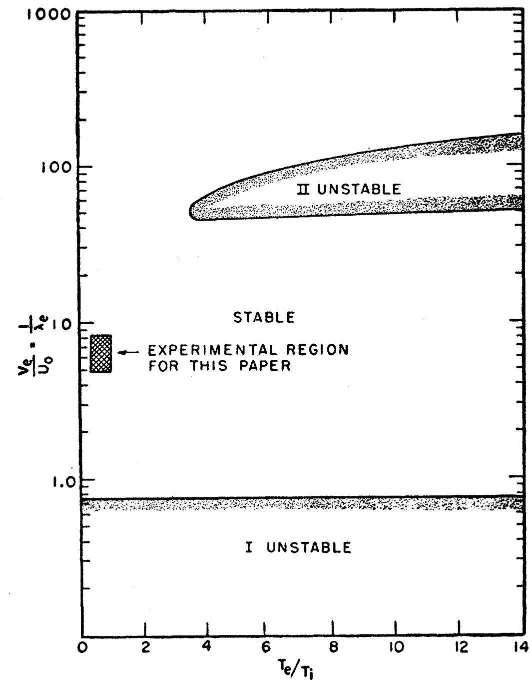

FIG. 2. Conditions for stability of identical counterstreaming plasmas.

The region of stability for identical colliding plasma streams is indicated in Fig. 2. The boundary for the stable region was obtained by setting $g(\lambda_e,\,T_e/T_i)=0$. The instability in region I will be due to the interaction of the electrons in streams whose translational velocity is larger than the electron random velocity, while the instability in region II will be due to the interaction of the ions. It appears that this interaction cannot occur until the random energy of the electrons is of the same order as the translational energy of the ions.