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Swirls Produced in a "Crowbarred" Rotating Plasma*

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The purpose of this note is to describe the observation of hydromagnetic-swirl development in a rotating gaseous plasma after it is subjected to an electromagnetic braking action.

Hydrogen at an initial pressure of 100μ Hg is contained in a copper cylinder 5-3/4 in. in diameter and 34 in. long. The cylinder is located in a uniform magnetic field that is directed along the cylinder axis. The ends of the cylinder are closed by Pyrex glass plates; an electrode located coaxially with the copper cylinder is mounted in one of these plates. A schematic diagram of the apparatus is shown in Fig. 1.

A hydromagnetic ionizing wave of the type described by Kunkel[1] is initiated by applying a radial electric field between the central coaxial electrode and the cylinder. This wave propagates down the tube to produce the plasma. Previous results have shown that the plasma thus produced is at least 90% ionized, and is rotating about the cylinder axis due to the $\underline{j} \times \underline{B}$ forces. When the ionizing front reaches the glass plate at the opposite end of the cylinder, a low-impedance shunt "crowbar" is connected between the coaxial electrode and the copper cylinder. The primary effect of this shunt is to impose on the plasma the condition

$$\int_{r_1}^{r_2} E_r(r)dr = 0 . \qquad (1)$$

Here $E_r(r)$ is the radial electric field, and r_1 and r_2 are the radii of the coaxial electrode and of the cylinder, respectively. Under the conditions imposed in these experiments the magnetic field is sufficiently strong so as to couple all macroscopic plasma motions along common field lines. Thus, to within times comparable to the Alfvén transit time, the plasma at all points on a given field line is expected to have the same (transverse) macroscopic velocity. The inductance of the external circuitry of the shunt is sufficiently high to require about 10 or 15μ sec for the rotational energy of the plasma to be dissipated in the external resistance. Since the rotational velocity $v_r(r)$ of the plasma is proportional to $E_r(r)$, Eq. (1) implies

$$\int_{r_1}^{r_2} v_r(r)dr = 0 . \qquad (2)$$

Equations (1) and (2) do not imply that $E_r(r) = v_r(r) = 0$ for all r. Indeed, prior to the application of the crowbar the plasma is rotating differentially. This differential rotation is due to the combined effects of the $1/r$ dependence of the radial current and the viscous drag at the cylinder wall and at the cylinder defined by the set of field lines intersecting the center electrode. The radial current density during the crowbar action must vary as $1/r$, resulting in a force with the same radial dependence. Because the braking impulse cannot match the plasma momentum for all r, Eq. (2) requires $v_r(r)$ to have both positive and negative values after crowbar. Plasma immediately adjacent to the outside cylinder wall and to the cylinder defined by the central electrode is expected to be held at nearly zero velocity by frictional forces, whereas that in the interior at smaller radii is reversed in direction, and at larger radii is slowed but not stopped. Swirling, resulting from such velocity distributions, is not unexpected, so long as the motion is consistent with the requirements of Eqs. (1) and (2).

Figure 2 is a sequence of 12 framing-camera photographs taken with the camera looking along the axis of the cylinder. An axial magnetic field of 16kgauss was applied to the plasma. The numbers below each photograph are the elapsed times (in μsec) after the front-propagating radial field was applied. The duration of each exposure was 0.70 μsec. The average angular velocity of the plasma before crowbar was about 8×10^{5} rad/sec; it is counterclockwise in the photographs. The crowbar shunt was applied to the electrodes at 20μsec, and the current through the shunt had fallen to a negligible value by 30 μsec. The swirls develop markedly after this time—in such a manner as to maintain the validity of Eq. (2).

Similar photographs taken with an H_β filter show the light to be of hydrogenic origin. Other photographs taken off the cylinder axis show that the swirls extend through the length of the tube.

The swirling motion of the plasma shown in Fig. 2 should induce local electric fields, with $\underline{E} = \underline{v}\times\underline{B}$. If these fields are made to equal zero throughout the plasma volume, the swirl motion should be strongly inhibited. Figure 3 is a second set of framing-camera photographs taken with the camera looking along the cylinder axis, with a conducting grid placed just inside the glass end plate, where it can be in contact with the plasma. This grid should hold $E_r(r) = 0$ on a scale comparable to the grid-wire spacing throughout the plasma after the plasma makes good electrical contact with it. It is apparant from Fig. 3 that no swirling motion occurred after the electrode current became zero at 30 μsec.

In addition to the mechanism outlined above, it is also possible that hydromagnetic instabilities associated with radial temperature or pressure gradients could be important in producing the observed swirls.

We wish to thank Willis C. Goss and Richard L. Woodcock for loaning the framing camera and assisting with its use.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

†First Lieutenant, U. S. Air Force. The opinions expressed by this author are his own and do not necessarily reflect those of the United States Air Force or of the Department of Defense.

1. W. B. Kunkel and R. A. Gross, Lawrence Radiation Laboratory Report UCRL-9612, May 1961 (unpublished).

FIGURE LEGENDS

Fig. 1. Schematic diagram of apparatus.

Fig. 2. Framing-camera photographs showing swirl development. Numbers below each photograph are the elapsed times (in μsec) after application of the radial field. Crowbar occurred at about 20 μsec. (The dark region at the right of each picture was caused by vignetting.)

Fig. 3. Framing-camera photographs taken with conducting screen in place. Numbers below each photograph are the elapsed times (in μsec) after application of the radial field.

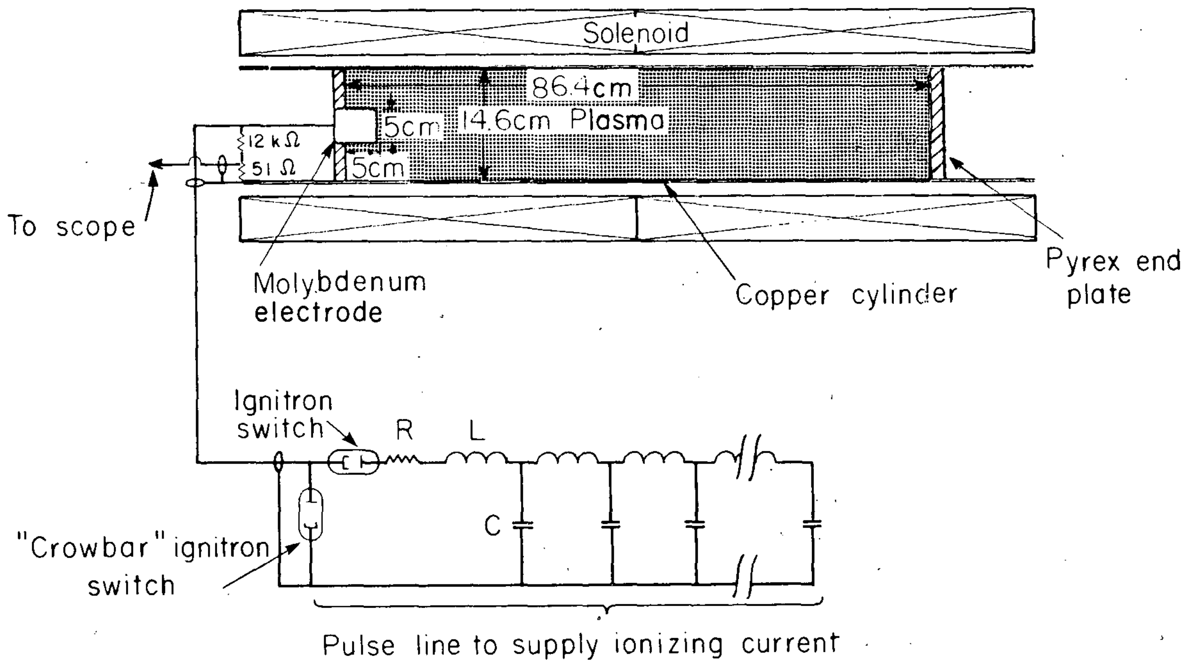

Fig. 1

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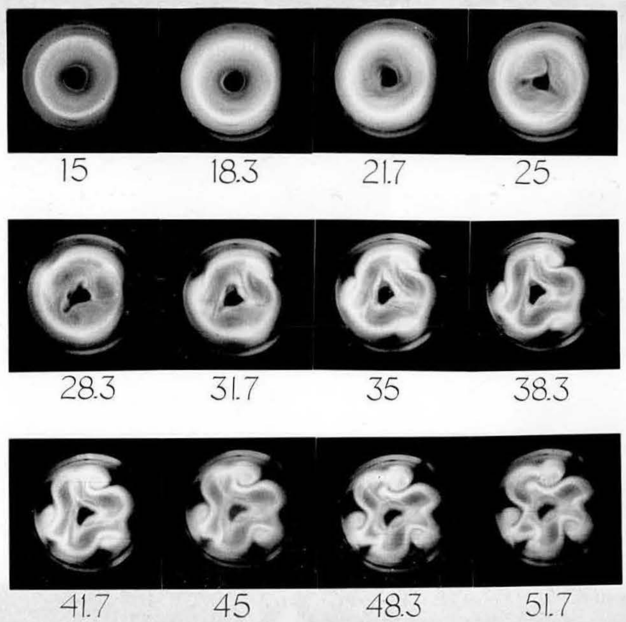

Fig. 2.

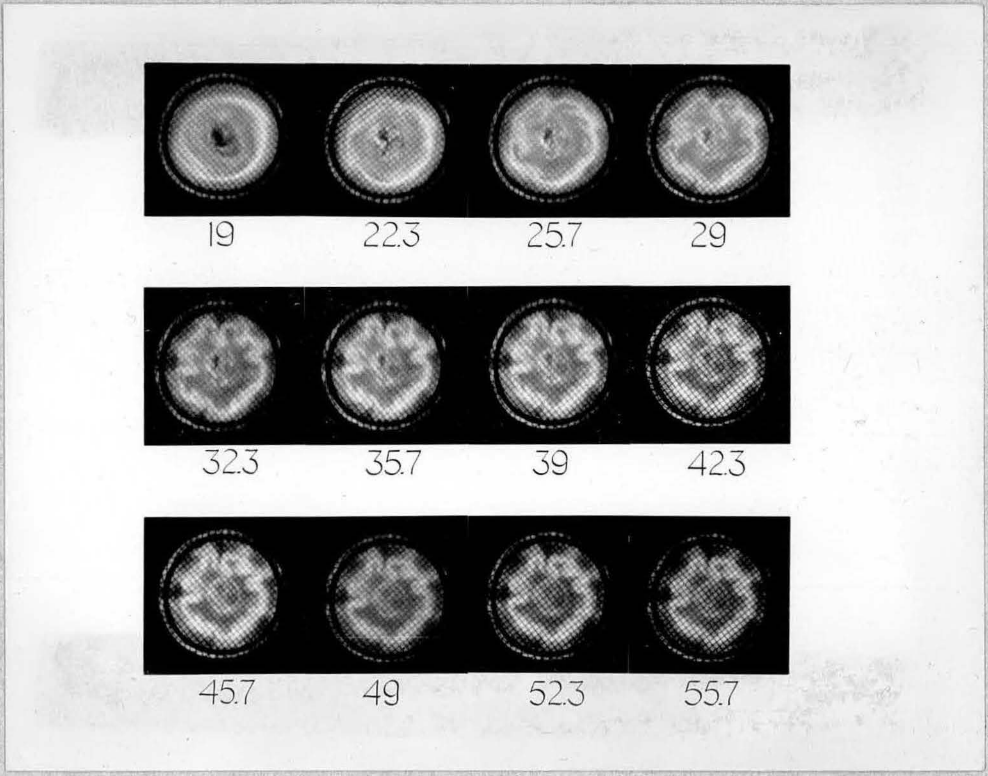

Fig. 3