from stages of ionization corresponding to intermediate temperatures either in the corona or in the solar flares. Even the radiation from the high temperature (30,000°) part of the chromosphere has been found to be weaker than expected. This has led to a picture of the chromosphere in which the higher temperature is limited to a great number of small jets, called spicules.

One of the most interesting satellite observations of the EUV has been the observation made by the NASA group with a spectrometer on the orbiting solar observatory.[6] They find that the intensities of some of the EUV lines, in particular the resonance lines of FeXVI, increase sharply at the time of a solar flare. Since this instrument looks at the whole sun, while the flare only covers a small fraction of the sun, the increase in the flare region really must be very large. It will be extremely interesting to compare optical observations of the flare spectrum with the data from the orbiting solar observatory.

I have tried to give a general outline of coronal problems which may be studied simultaneously from the ground and from above the atmosphere. It is to be hoped that this study will prove a fruitful source of new knowledge about the solar atmosphere.

References

[1] Firor, J. and Zirin, H., "Observations of five ionization stages of iron in the solar corona," Astrophys. J. **135,** 122–137 (1962).

[2] Detwiler, C. R., Purcell, J. D., and Tousey, R., "The extreme ultraviolet spectrum of the sun," Mem. Soc. Roy. Sci. Liége **IV,** 253–263 (1960).

[3] Tousey, R., "Techniques and results of extraterrestrial radiation studies from the ultraviolet to x-rays," *Space Age Astronomy,* edited by A. J. Deutsch and W. B. Klemperer (Academic Press, New York, 1962).

[4] Zirin, H., Hall, L. A., and Hinteregger, H. E., "Analyses of the solar emission spectrum from 1300 to 250A as observed in August 1961," *Space Research* (North Holland Publishing Co., Amsterdam, to be published), Vol. III.

[5] Chubb, T. A., Friedman, H., and Kreplin, R. W., "X-ray emission accompanying solar flares," Mem. Soc. Roy. Sci. Liége **IV,** 216–277 (1960).

[6] Behring, W. and Neupert, W., "Preliminary solar flare observations with a soft x-ray spectrometer on the orbiting solar observatory," *Space Research* (North Holland Publishing Co., Amsterdam, to be published), Vol. III.

JUNE 1963 AIAA JOURNAL VOL. 1, NO. 6

Instabilities in a Coaxial Plasma Gun

T. J. Gooding,* B. R. Hayworth,† and R. H. Lovberg‡

General Dynamics/Astronautics, San Diego, Calif.

Configuration instabilities have been observed in a gas triggered coaxial plasma gun. Probe measurements of the azimuthal component B_θ and axial component B_z of the magnetic field indicate that the current distribution is initially azimuthally symmetric but collapses into a spoke, at a time close to current maximum. Optical data, taken with a Kerr cell camera, confirm this observation. The instability is found to depend on the gas distribution in the gun at the instant of firing and can be avoided by "tailoring" the gas density profile.

Introduction

The radial current sheet in a coaxial gun is hydromagnetically unstable against sweeping up into a single spoke or pinch on one side of the barrel. One hopes to operate such a device in a manner that will not allow this instability to grow to disastrous proportions before the acceleration is complete. The fatal attributes of such a spoke are that 1) it sweeps up very little of the gas that uniformly fills the barrel cross section and 2) it develops very violent secondary instabilities of its own which consume large amounts of energy in driving the randomly directed fluctuations.

An experimental study of a gas triggered coaxial plasma gun is presented in which two operating modes are obtained, depending on the pressure distribution in the gun at the instant of firing. One mode is characterized by a uniform current sheet propagating along the axis of the gun at velocities $\sim 10^7$ cm/sec; the current distribution in the alternate mode is initially symmetric but subsequently collapses into a spoke in a time short compared to the acceleration period. This spoke is observed with magnetic probes, measuring the azimuthal component B_θ and the axial component B_z of the magnetic field, and with a Kerr cell camera. A detailed discussion on the propagation of the uniform current sheet is presented in Ref. 1. Observations on the unstable mode are presented in this report, together with a brief description of the plasma gun.

Description of the Gun

The general arrangement of the gun and typical operating conditions are shown in Fig. 1. Ten low inductance ca-

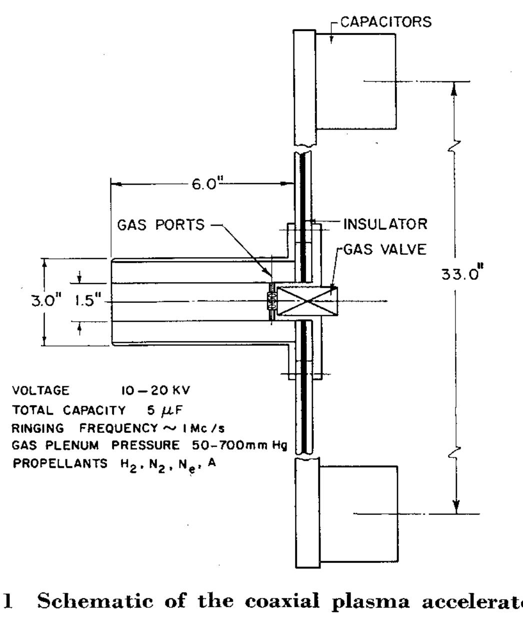


Fig. 1 Schematic of the coaxial plasma accelerator

Presented at the ARS 17th Annual Meeting and Space Flight Exposition, Los Angeles, Calif., November 13–18, 1962. This work was supported by NASA under Contract NAS-3-2501.

* Senior Staff Scientist, Group Leader Experimental Plasma Physics, Space Science Laboratory.

† Senior Physicist, Space Science Laboratory. Member AIAA.

‡ Consultant, Space Science Laboratory.

pacitors, each 25 kv, 0.5 μf, are mounted in a circular array on a steel flange. The gun assembly is mounted in the center of this flange. The propellant gas is fed through a solenoidal gas valve mounted inside the inner barrel of the gun. The mode of operation is to charge the capacitors, pulse the valve, and simply wait until the gas pressure builds up to the breakdown point and the gun fires. The gas distribution along the axis of the gun is varied by changing the pressure in the plenum chamber behind the gas valve. Magnetic probes are inserted through a vacuum window and moved along the axis of the gun at a radius midway between the two barrels.

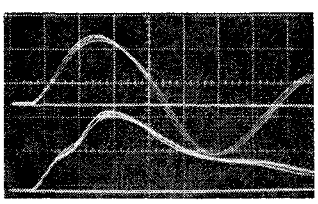
Several guns have been used, differing primarily in the location of the gas ports and the insulator arrangement. The data shown in this report are characteristic of all the guns and no attempt will be made to relate specific data to a particular gun. (For details, see Ref. 1.)

Experimental Results

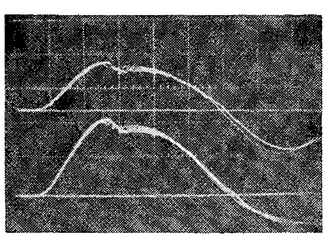
A. Magnetic Probes

The current waveform in the gun shows a striking variation with the pressure of the propellant gas behind the valve. In Fig. 2 three-shot overlays of the current waveform (upper trace) and the time distribution of B_θ (lower trace), measured at an axial position *between* the gas ports and the insulator, are shown for three plenum pressures. In this case the propellant gas is N_2 and the gun is operated at 10 kv. At low pressures the waveform is nearly an ideal damped sinusoid with a very small change in period during the ringing. At high pressures the current waveform shows considerable increase in inductance during the first half-cycle and "breaks" near current maximum.

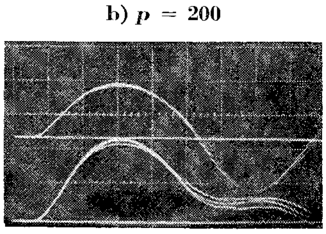
The B field distribution exhibits the well-known phenomena of "self-crowbarring," in which a second current sheet forms on the insulator subsequent to the main discharge. This is illustrated schematically in Fig. 3, where I_1 and I_2 are the currents behind and ahead of the crowbar point, respectively. If insulator crowbarring does not occur, the B_θ trace, at a z position between the insulator and the



a) p = 150



b) p = 200



c) p = 300

Fig. 2 Time distributions of I (upper trace) and B_θ (lower trace); $I \sim 75{,}000$ amp/cm, $B_\theta \sim 3800$ gauss/cm, $t = 0.2$ μsec/cm, p = plenum pressure in torr

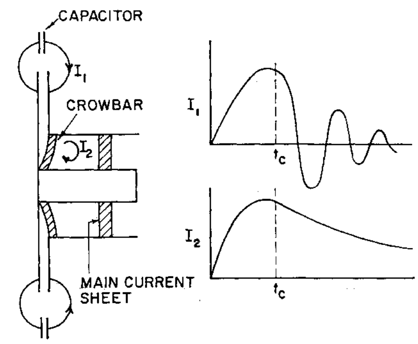


Fig. 3 Illustration of crowbarring at the insulator

initial breakdown, should duplicate exactly the total current waveform. If crowbarring takes place, however, the B_θ signal at that instant will stop oscillating along with the external current and will decay.

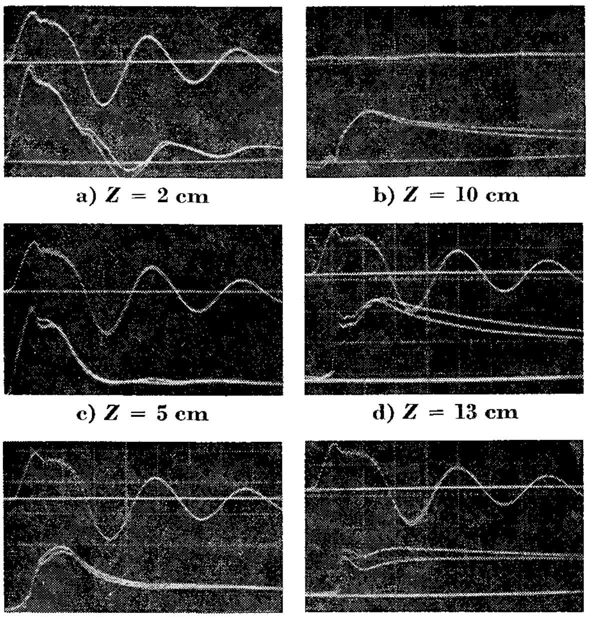
The B_θ distributions shown in Fig. 2 indicate that at very low pressures the initial breakdown occurs near the insulator; at slightly higher pressures the magnetic field exactly duplicates the capacitor current until late in the second quarter-cycle indicating that breakdown occurred over the gas ports; at the highest pressure crowbarring is delayed until late in the second half-cycle. This may be explained by observing that at high pressures, and consequently high inflow rates, breakdown pressure over the ports is reached at an earlier time than for slower flow, and, hence, the amount of gas which has reached the rear insulator actually will be smaller than for the low pressure cases. (Stated in equivalent terms, at the time a certain quantity of gas has entered the gun, it will spread over a larger region for slow inflow than if it were injected rapidly.)

A particular problem arises in interpreting the current trace for the high gas pressure operation. It is clear that high accelerator efficiency would be observable as a current waveform asymmetry. What one has in Fig. 2 is a distortion far too large to be accounted for by kinetic motion of the current sheet along the gun. On the basis of this current distribution alone it can be inferred that one is encountering either a suddenly increasing resistance and/or a dL/dt, which arises from configuration instabilities.

A series of B_θ measurements at various axial positions along the barrel provide a clear picture of what is occurring. Six of the probe traces are shown in Fig. 4. These data actually are taken from a gun in which the gas ports had been moved further from the insulator. This behavior is, however, characteristic of this mode of operation.

The positions at z = 2 cm and z = 5 cm, which are behind the gas ports, show the expected rise with total current (upper traces) and the usual crowbarring. At z = 8, which is near the ports, the rise is slightly delayed, a result that might be expected when the current first flows upstream of the probe and then has to move past the probe tip. The next three traces, z = 10, 13, 17 cm, however, yield a very unusual result. Each, individually, has a very sharp rise that usually is produced by the passage of a thin current layer moving at high speed. However, the rise is simultaneous at all three positions so that the motion of a current front down the barrel cannot be the cause. Also, it can be seen that in all positions downstream from the gas ports, the field rise is exactly coincident in time with the break in the current trace.

These results can be explained by a rather simple interpretation that the authors of this paper have since verified photographically. It is that initially, breakdown and current flow occur symmetrically, so that no magnetic field exists between the current sheet and the muzzle. Then the current configuration becomes unstable and, in a period of less than 0.1 μsec, sweeps up into a single spoke on the op-



a) Z = 2 cm b) Z = 10 cm
c) Z = 5 cm d) Z = 13 cm
e) Z = 8 cm f) Z = 17 cm

Fig. 4 Time distribution of I (upper trace) and B (lower trace); z = axial position of the B_θ probe, $t = 0.5$ μsec/cm, $I \sim 100{,}000$ amp/cm, $B \sim 3800$ gauss/cm ($\times \frac{1}{2}$ for $z \geq 13$ cm)

posite side of the barrel from the probe. Fields from this current channel appear instantly (on our time scale) at all points in the barrel. These configurations are sketched in Fig. 5.

The break in I at this time results from the fact that when the current sheet sweeps up into a spoke, dL/dt becomes exceedingly large. Over this short time interval, V is nearly constant, R is relatively negligible, and so

$$V = L(dI/dt) + I(dL/dt) = \text{const}$$

Since dL/dt is very large and positive, the forementioned equality is maintained by a negative swing of dI/dt. This behavior is characteristic of pinched discharges and has been reported by almost all workers in this field.

The "noisy" current plateau subsequent to the instability has a possible explanation of the following sort: when the spoke forms, it assumes all of the attributes of an ordinary pinch, including the wide spectrum of instabilities. Given the currents and densities typical of our experiment, one may expect the growth times of "kinks" and "sausage" instabilities to be perhaps less than 10^{-7} sec. The result would be a rapid disruption of the column, followed by a restriking of the arc, and the formation of new instabilities, ad infinitum. Now, the formation of any instability in the spoke produces, again, a dL/dt, which, as a factor in the term $\frac{1}{2} I^2 \, dL/dt$, accounts for the energy transferred from the field to kinetic energy of the instability in question. However, the disorganizing effect of the instability renders this process irreversible, such that the energy dumped into this term is lost as heat. Consequently, dL/dt, as far as the circuit is concerned, appears as a resistance, and the question as to whether R or dL/dt is responsible for the flattening of the current wave loses much of its relevance; they both produce an identical effect.

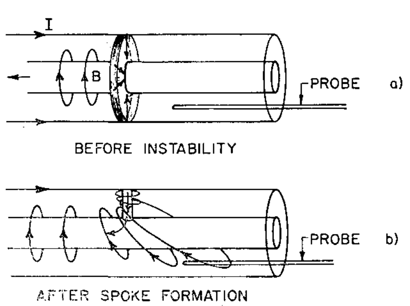
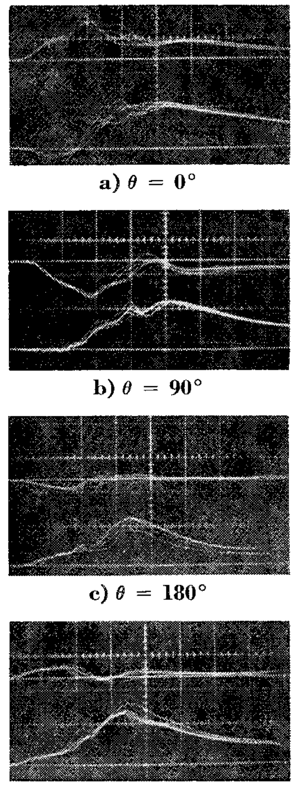


Fig. 5 Schematic of the magnetic field distributions; a) symmetric current distribution, and b) spoked current distribution



a) θ = 0°
b) θ = 90°
c) θ = 180°
d) θ = 270°

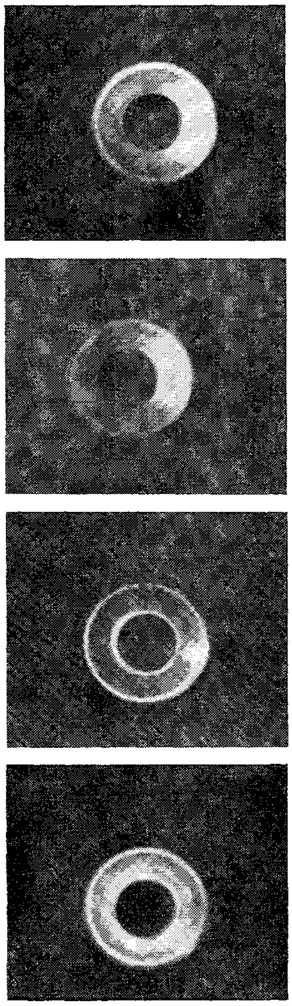
Fig. 6 Time distribution of B_θ (lower trace) and B_z (upper trace); θ = azimuthal position, the axial position z = 6.5 cm, B_θ = 5040 gauss/cm, B_z = 4840 gauss/cm, and t = 0.5 μsec/cm

In order to verify the "spoking" hypothesis, a probe that contains two coils was constructed, one oriented to couple B_θ, and the other for B_z. Clearly, an azimuthally symmetrical discharge will produce no B_z component at all, whereas a spoke, as an extreme case, sets up very strong z fields at points having the same z coordinate as the spoke, but slightly different θ (see Fig. 5). The probe was built so that it could be rotated in azimuth while being kept at the same z, and (approximately) the same r. Figure 6 is a particularly good example of the field distributions of a spoke. It can be observed that B_z at $\theta = 0$ and 90° is fairly large, and of opposite sign in the two positions. At 180° and 270°, B_z is small, and again of opposing signs. This combination of outputs would be produced by a spoke at about $\theta = 45°$, as one may verify again with the aid of Fig. 5. It is noteworthy that here, the spoke seems to occur at the same position on every discharge, where one would otherwise expect instabilities to form at random azimuths in the absence of directional effects in the electrodes.

B. Kerr Cell

The discharge was photographed using an Electro-Optical Systems Kerr Cell Camera with a 50 nanosec exposure time. The Kerr cell was triggered from a pick-up coil placed near the capacitors, and timed relative to the discharge via a variable delay inserted in the trigger pulse cable.

Figure 7 shows typical photographs of the discharge taken near current maximum. The interpretation of these photo-



a)
b)
c)
d)

Fig. 7 Kerr cell photographs of the discharge

graphs is always hazardous since there is no depth perception and it is not clear whether the luminosity is due to propellant, insulator, or electrodes. The photographs a) and b) correspond to the operating mode characterized by an initially uniform sheet collapsing into a spoke; c) and d) are examples of the other mode where the discharge is uniform but crowbarring occurs during the first half-cycle. The spoke on these pictures is believed to be the crowbar occurring on the insulator behind the uniform discharge.

The azimuthal position of the spoke repeated from shot to shot, and when the two barrels were rotated it was found that the spoke rotated according to the rotation of the inner barrel, i.e., the spoke is anchored to the inner electrode. Originally stainless steel barrels were used in the gun. It was thought that induced magnetic effects in the steel might be the source of this anchor, so copper electrodes were fabricated but again the discharge spoked, the spoke rotating with the inner barrel. With the copper electrodes however, the azimuthal position of the spoke did vary somewhat and the effect is perhaps less severe with copper than steel.

Gas Distribution Measurements

The gas distribution in the barrel was measured using a fast ionization gauge. Knowing the time delay between the gas valve trigger pulse and the onset of breakdown, the gas distribution just before breakdown was determined for various pressures. With a high plenum pressure the distribution was peaked over the gas ports, as expected. At lower pressures the gas was distributed uniformly, and at very low pressures the distribution was essentially constant throughout most of the gun volume.

Conclusions

The conclusions may be summarized as follows:

1) The pressure at which the propellant gas is injected into the barrel is the single most sensitive parameter affecting instability occurrence. If it is about a certain "critical" value, a very fast, violent spoking occurs. For lower pressure, the discharge tends to be symmetrical for the acceleration period.

2) The use of stainless steel for electrodes is to be avoided, since, even though nominally nonmagnetic, continued discharging on the electrodes sets up small magnetic "spots," and these drastically affect the breakdown characteristics of the tube.

3) A rough qualitative criterion for stability against spoking seems to be that the rate of neutral gas flow into the advancing sheet should not decrease in time at a faster rate than the driving pressures $B^2/2\ \mu_0$. This requires that the *distribution* of gas in the barrel prior to the shot should not be too peaked; such peaking naturally occurs for high injection pressures, as mentioned in item 1. It further implies that the sheet should not be allowed to *accelerate*, but rather, move at a constant or even a slightly decreasing speed.

A gas distribution that gives very uniform azimuthal current density has been achieved through the use of multiple gas ports spaced along the inner barrel in the axial direction. These have variable openings, thus allowing a "tailoring" of the pre-shot density profile.

Reference

[1] Lovberg, R. H., Hayworth, B., and Gooding, T. J., "The use of a co-axial gun for plasma propulsion," General Dynamics/ Astronautics Space Science Lab. Rept. AE62-0678; final report on Contract NAS-5-1139 (May 1962).