Onset of Rotating Disturbance in Linear Hall-Current Accelerator

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Onset of a low-frequency (1–100 KHz), azimuthally rotating, helical instability at a critical magnetic field was observed in a crossed-field geometry. The experiments were performed in an axisymmetric Hall-current accelerator employing an axial electric field and a nearly uniform radial magnetic field. Dependence of the critical magnetic field on pressure and type of propellant is shown. The origin of the instability is found to be in a critical region near the cathode, and it is shown that the instability can be suppressed throughout the interelectrode region by controlling the magnetic field in the critical region only. An attempt is made to relate the experimental results to the theoretical work of Simon on crossed-field instabilities.

Introduction

THE existence of rotating nonuniformities in linear Hall-current accelerators has been substantiated in a large number of previous experiments.[1–5] The nonuniformity rotates in the azimuthal direction at a low frequency (1–100 KHz) and is believed to be associated with an instability in the plasma. Some of the earlier experiments have shown the dependence of the frequency on magnetic field, pressure, and arc current, but an onset at a critical magnetic field has not been reported for this device.

In most of the earlier experiments considerable attention was given to the magnetic field uniformity in the anode region of the device and over a major part of the interelectrode distance. The cathode, however, was located outside the uniform field region. The instability was thought to originate in the anode region. In Ref. 5 the effect which the radial and axial components of magnetic field in the anode region had on the instability was investigated. It was then thought that the axial component of magnetic field near the anode controlled the instability. The possibility of such an effect was supported by the independent theoretical work of Ref. 6. However, the requirement of independent radial and axial magnetic-field components in the anode region produced in the cathode region a highly nonuniform field which could not be controlled. In an effort to understand the effect which the magnetic field near the cathode had on the instability, the present geometry was set up, with uniformity of the radial magnetic field extending over the entire anode-to-cathode region. In this geometry an onset of the instability for a critical value of radial magnetic field has been observed. The cathode region is shown to be the area of origin of the instability, and the instability can be suppressed throughout the region between the electrodes by controlling the radial magnetic field near the cathode only.

B_r-critical is found to vary with pressure in a manner predicted by the recent work of Hassan.[7] The density gradient in the critical region near the cathode is found to become quite large prior to and following onset, and its direction is such as to agree with the necessary condition for crossed-field instabilities found by Simon.[8] This necessary condition was recently confirmed by Hassan for instabilities in the MPD arc.[7] There are, of course, other models which treat the phenomena associated with nonuniformities in the linear accelerator and the MPD arc, e.g., the work of Fay and Cochran,[9] and the work done by Smith[10] on electrothermal instabilities, but a direct comparison between the present results and these theories has not as yet been made.

Apparatus

A schematic of the linear hall accelerator is shown in Fig. 1. The anode is a water-cooled copper ring, 5.5 cm i.d. and 7.5 cm o.d. The cathode is a 1-mm-diam tungsten wire which is shaped into an almost closed circle of 7 cm diameter. The cathode was placed in the center of an annulus of 5 cm i.d. and 9 cm o.d. The cathode is heated either with a d.c. current of 70 amp or with a 60-Hz, a.c. half-wave rectified current with a peak current of 70 amp. Similar wire cathodes were used in the majority of the earlier experiments with the linear Hall accelerator. The heating current in such cathodes produces an approximately $1/r$ magnetic field which, in the region close to the cathode, can be of the order of the applied magnetic field. Because of the nonuniformity of the applied magnetic field in the cathode region in the earlier experiments, it was not possible to determine the effect which the field of the cathode wire had on the instability. The present experiment employs an external field which is nearly uniform throughout the anode to cathode region and so makes possible a determination of this effect.

The anode-to-cathode distance is 11 cm and a nearly uniform radial magnetic field is produced in this region by use of a central iron core and an external coil placed about 20

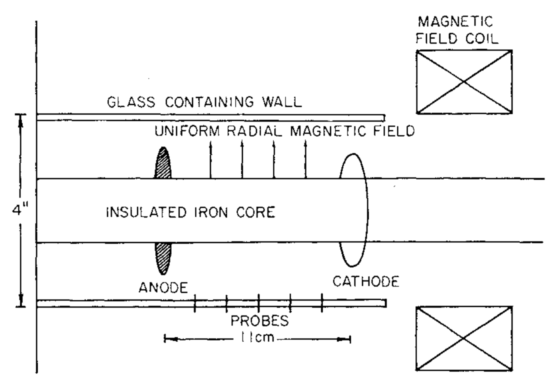

Fig. 1 Linear Hall current accelerator.

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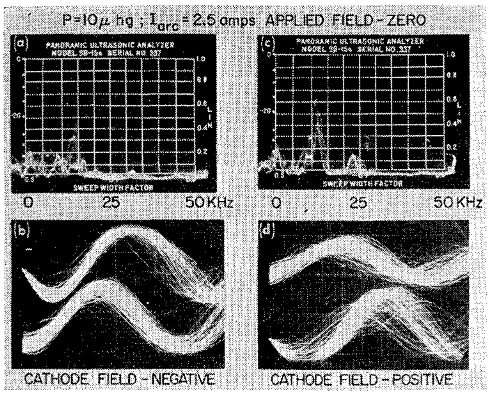

Fig. 2 Frequency spectrum and direction of rotation of voltage oscillations.

cm from the cathode. The maximum value of the radial magnetic field was about 180 gauss. This externally applied field fell off approximately as $1/r$ away from the iron core, and the values given are those at the mid-point of the annulus. The axial component of the external field was small, less than 10% of the value of the radial component, throughout the discharge region. In a separate experiment, the axial component was increased independently and was found to have no effect on the results discussed below. The iron core was covered by a boron nitride insulator.

Stationary probes constructed of tungsten wire (0.2 mm diam and 1.5 mm long) were inserted at various axial and azimuthal positions through a quartz tube containing the discharge. All probes were displaced approximately 0.5 cm inward from the quartz tube.

Probe signals were fed into a Panoramic Spectrum Analyzer, a Tektronix type 555 dual-beam oscilloscope, and/or an X-Y recorder. Measurements were made of the floating potential and the ion saturation current. The measurements were made in argon, xenon, helium, and nitrogen at pressures ranging from 1 to 200 mtorr. The majority of data were taken with an arc current of 2.5 amps.

Results and Discussion

Use of a d.c. cathode heating current of 70 amp produces a magnetic field around the cathode wire which was calculated to be about 300 gauss at the surface of the wire, falling off to about 15 gauss 1 cm from the surface of the wire. With zero external magnetic field (defined as B_r) oscillations were observed throughout the interelectrode region. (Pressure is 10 mtorr in argon and arc current is 2.5 amps unless otherwise noted.) Figure 2a shows the frequency spectrum of this oscillation at a probe located 2.5 cm from the cathode. The phase shift between two probes at the same axial position (2.5 cm from the cathode) and displaced 90° azimuthally is shown in Fig. 2b and shows the perturbation to be rotating azimuthally with an $m = 1$ mode. (Cathode positive and cathode negative refer to the radial component of the magnetic field of the cathode wire on the upstream (anode) side of the cathode. This component is defined as B_{rc}. Positive means radially outward.)

Reversal of the cathode heating current with consequent reversal of the associated self-magnetic produced the results shown in Figs. 2c and 2d. The oscillation exhibits the same frequency, but the direction of rotation has reversed due to the reversal in the magnetic field of the cathode wire.

As mentioned in the foregoing, the frequency-spectra and phase-shift measurements shown in Fig. 2 were made by using a probe located 2.5 cm from the cathode. A probe located 2.5 cm from the anode showed the presence of oscillations which had the same frequency as those at the cathode probe but with $m = 0$. Similar measurements at higher B_r to be described later showed an $m = 1$ helical perturbation at all probes. This variation of mode at $B_r = 0$ and B_{rc} finite is still under investigation.

If a 60-Hz, a.c., half-wave-rectified heating current was used, it was possible to examine the probe signals during that portion of the cycle when the heating current and its associated magnetic field were zero, but the cathode was still hot enough to emit thermionically. It was found that for zero external field, B_r, the plasma was quiescent, and without oscillations. As B_r was increased from zero an onset of coherent oscillations was observed at $B_r \simeq \pm 15$ gauss. The direction of rotation was in the drift or $E \times B$ direction.

It was further found that the existence of a quiet state depends only on the existence of a subcritical field near the cathode and not throughout the device. This was shown by making use of the self-magnetic field of the d.c. cathode heating current. The current was applied such that B_{rc} was positive. The external radial field B_r was applied negatively so that it subtracted from B_{rc}. The resulting spectra and phase-shift measurements are shown in Fig. 3. Figure 3a shows the spectrum at $B_r = -10$ gauss, showing the frequency to have decreased slightly from the $B_r = 0$ condition. At $B_r = -20$ gauss, the perturbation disappeared abruptly with the discharge becoming quiet throughout the interelectrode region, as shown in Fig. 3b. (The signal at zero frequency is a zero marker internally generated by the analyzer.) The quiet state shown in Fig. 3b persisted as B_r was varied further to about -40 gauss, at which value the coherent oscillation reappeared, as shown in Fig. 3c. Further variation of B_r increased the frequency of rotation. The phase-shift measurements of Figs. 3d and 3e show that the direction of rotation was opposite for these two conditions.

If B_r was applied positively such that it added to B_{rc}, no quiet state was observed and the coherent oscillation observed at $B_r = 0$ increased in frequency as B_r was increased.

The conclusion to be drawn from the observations is that the onset of the instability, its direction of rotation, and its frequency are controlled by the total magnetic field $B_r + B_{rc}$ in a critical region close to the cathode. The approximate location of this region can be deduced as follows: for the d.c. cathode measurements, with B_{rc} positive, the plasma is quiet in the range $-20 \geq B_r \geq -40$ gauss, with onset occurring for the two end values. Since the critical field required for onset is symmetrical about a zero magnetic field for the a.c. heated cathode measurements, it is assumed that the same is true for the d.c. heated cathode. The zero point is taken to be the center of the quiet range, $B_r = -30$ gauss. So, for $B_r = -30$ gauss, it is necessary that $B_r + B_{rc} = 0$, thus locating the center of the critical region at a distance of about 1.5 cm from the cathode.

The influence which the confining walls have on the onset of the instability has also been examined. In the results described above, the cathode was placed inside the

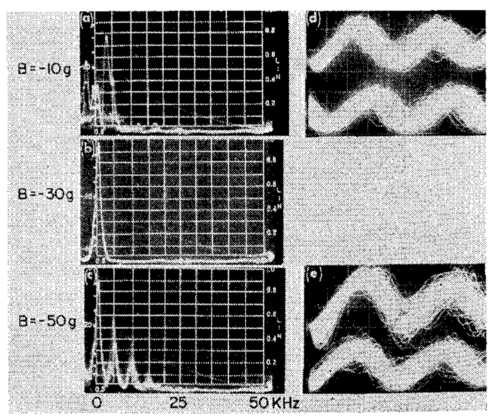

Fig. 3 Frequency spectrum of voltage oscillations.

glass tube, about 4 cm from the end of the tube. The confining surfaces, glass tube on the outside and boron nitride insulator on the inside, were each about 1 cm from the cathode wire. In an additional experiment, the cathode was placed about 4 cm downstream of the end of the glass tube so that the only confining surface was the inside boron nitride insulator. For this configuration a double quiet state was observed, one for positive B_r and one for negative B_r (with B_{rc} held to one direction). The second quiet state was apparently due to cancellation of B_{rc} on the downstream side of the cathode. The fact that this second quiet state disappears when the cathode is confined by both the boron nitride insulator and the outside glass tube indicates that the walls may act as a buffer to the electrons emitted on the downstream side of the cathode.

The pressure dependence of B_r-critical is shown in Fig. 4 for different gases using the a.c. heated cathode. B_r-critical is seen to increase with increasing pressure (or, equivalently, increasing mass flow) for all gases. This increase is seen to be significantly greater for the heavier gases (A, Xe) than for the lighter gases (He, N_2). The dependence of B_r-critical on pressure and type of propellant in the linear device shows a marked similarity to onset data obtained in the coaxial MPD arc at higher power and mass-flow levels.[11] (The linear device uses an externally heated cathode, but Kribel[16] finds that operating an MPD arc with an externally heated cathode produces results similar to those obtained when operating with a self-sustained arc.) The pressure dependence of B_r-critical is in qualitative agreement with a recent analysis done by Hassan[7] for the MPD arc.

The frequency of rotation after onset in the linear device is shown in Fig. 5 as a function of B_r for three different pressures in argon. Following onset, the frequency is seen to increase with increasing B_r. For the lower pressures, a maximum is reached followed by a slight decrease in frequency for increasing B_r. It is further observed in Fig. 5 that for a given B_r, the frequency of rotation is higher for lower pressures, which is similar to observations made in high-power MPD arcs.

In Fig. 6, the ion saturation current collected by a probe located 1.5 cm from the cathode is shown as B_r is varied from 0 to -80 gauss. The variation in ion saturation current can be caused by variations in ion density, electron temperature, and/or directed ion velocity. The presence of the large magnetic field of the cathode wire in the region near the cathode suggests that it is the trapping of charged particles in this region which produces the large variation in ion saturation current. In what follows then, it will be assumed that variations in ion saturation current are essentially ion density variations and that the variations in electron temperature and directed ion velocity over this narrow region are much smaller than these ion density variations. For the measurements of Fig. 6 the d.c. heated cathode was used. The plasma was stable in the range from $B_r \simeq -12$ to $B_r \simeq -30$, the dashed line representing the approximate value of B_r in the center of the stable region.

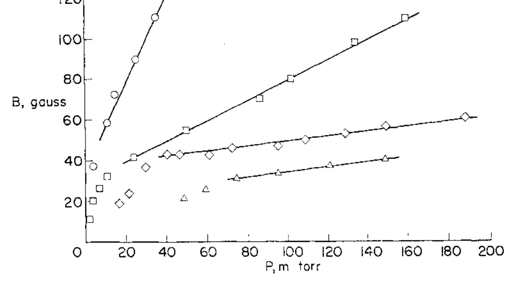

Fig. 4 Critical field vs pressure.

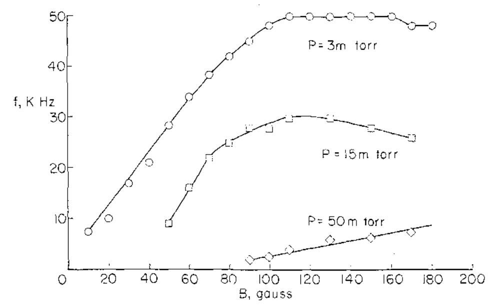

Fig. 5 Frequency vs *B* in argon.

In order to study the transition of the plasma from a stable mode to an unstable mode, consider the ion density profile (Fig. 6) as B_r was varied from the center point of the quiet region. As B_r was increased or decreased the density was seen to increase until onset occurred at $B_r \simeq -12$ and $B_r \simeq -30$. Following onset at $B_r \simeq -30$, the density was seen to increase with increasing B_r, but less rapidly than in the stable mode. The onset at $B_r \simeq -12$ was accompanied by an abrupt change in density. The density peak reached at onset was followed by a steep decline which leveled off at $B_r \simeq 0$. Increasing B_r in the positive direction to $+80$ gauss (not shown in the figure) showed the density to be slightly increasing in a manner similar to that for large negative B_r. Density changes at the anode, over the same range in B_r, showed neither the amplitude nor the abruptness observed near the cathode.

The dependence of arc voltage on B_r for constant current is shown in Fig. 7 for the range $B_r = 0$ to $B_r = -70$ gauss. The data of Fig. 7 were taken at $P = 50$ mtorr and are typical of $V - B_r$ characteristics at other pressures. In general, it was observed that the width, in B_r, of the stable region of the plasma increased with increasing pressure. For $P = 50$ mtorr the plasma was stable from $B_r \simeq -20$ to $B_r \simeq -60$ gauss, the dashed line representing the approximate center of the stable region.

The onset at $B_r \simeq -20$ gauss was accompanied by a sharp change in voltage of about 15% of the total voltage. As B_r was varied from -20 to -60 gauss (in the stable region) the voltage changed slightly, the change becoming more steep as onset was approached at $B_r \simeq -60$ gauss. There was no abrupt change in voltage accompanying the onset at $B_r \simeq -60$ gauss, and following onset the change in voltage was almost linear with B_r.

The abrupt change in voltage for small B_r occurs when the field of the cathode wire controls the instability (direction of rotation is $E \times B_{rc}$). The onset at $B_r \simeq -60$ gauss occurs when the external field controls the instability (rotation following onset is in direction of $E \times B_r$). In this sense, the *V-B* characteristics at large values of applied field, where no abrupt changes occur, is probably more typical of the *V-B* characteristic of the MPD arc. Measurements made in the MPD arc have not revealed any abrupt changes in voltage accompanying onset.[11]

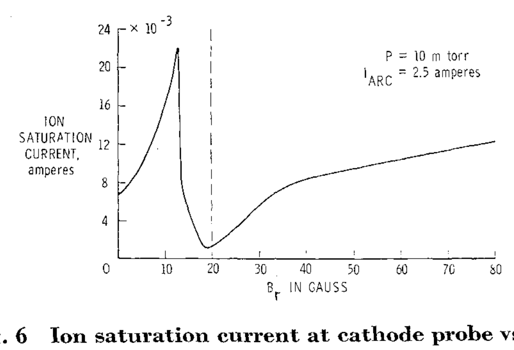

Fig. 6 Ion saturation current at cathode probe vs B_r.

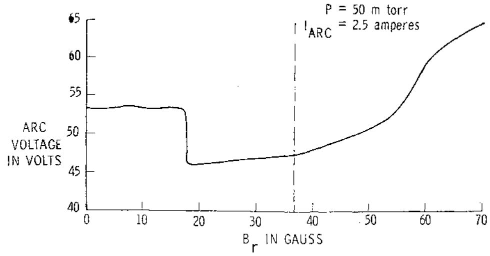

Fig. 7 Arc voltage vs B_r.

Figure 8 shows the ion density distribution over the interelectrode region. For this measurement a series of ten probes spaced 1 cm apart was used. The first probe was located 1 cm from the anode and the tenth was located at the cathode. For a given value of B_r, a switching arrangement sampled each probe successively, the signals being fed into an X-Y recorder.

In Fig. 8 the data for $B_r = -20$ and $B_r = -15$ gauss show the density distribution for a stable plasma, $B_r = -20$ gauss being approximately the center of the stable region at this pressure (10 mtorr). It is seen that for $B_r = -20$ gauss the density gradient is on the average negative (anode-to-cathode being positive). However, in the critical region approximately 1.5 cm from the cathode where the onset occurs (see previous discussion), the density gradient is seen to be slightly positive. For $B_r = -15$ gauss the plasma is still stable; there is only a small change in the density gradient in the anode region, but in the critical region near the cathode the positive density gradient becomes significantly larger. For $B_r = -10$ gauss the plasma is unstable and the density gradient in the critical region has become even steeper in the positive direction. For all further variation in B_r such that the plasma remains unstable, the density gradient in the critical region near the cathode remains steep and positive.

This observation is important because it indicates a possible connection between the experimental results and the theoretical work of Simon.[8] Simon's work specifies that a necessary condition for the onset of crossed-field instabilities is that $E_A(dn/dz) > 0$, where E_A is the applied electric field and (dn/dz) is the axial density gradient. The experiment shows 1) that a critical field is required for onset; 2) that the critical field is required only in a critical region about 1 to 2 cm from the cathode; and 3) that in this critical region near the cathode the density gradient becomes large and positive just prior to onset and remains so following onset. Since it can be assumed further that E_A is positive in this region, the necessary condition of Simon's theory is satisfied in the critical region. A firm conclusion could not be drawn, however, without a measurement of E_A in the critical region since the exact manner of variation of E_A in this region is not known.

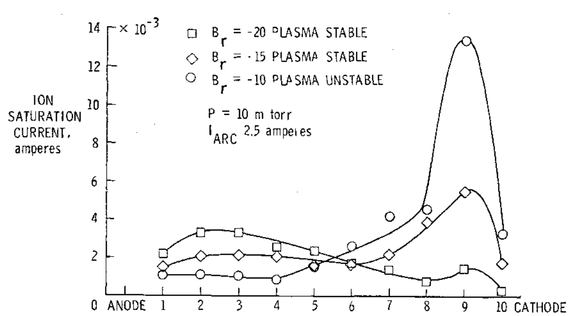

Fig. 8 Ion saturation current vs axial position for stable and unstable plasma conditions.

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