Electron Beam from a Magnetoplasmadynamic Arc

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A long, tenuous, but well-collimated beam of luminosity is observed to emerge from the plume of a magnetoplasmadynamic arc operated in a fiberglass vacuum tank. Examination of the beam trajectory in the magnetic field of the earth, and in other externally imposed fields indicates that the beam consists of a stream of 100-V electrons emitted from the core of the arc, which excite background gas particles to luminosity along their path to the tank wall. Although this beam carries a negligible portion of the arc current, the particle energy corresponds to some two-thirds of the arc voltage, and the beam is capable of damaging material surfaces which it encounters. Formation and emission of such a well-collimated stream of electrons of this energy seems incompatible with present concepts of magnetoplasmadynamic arc structure, and may have implications for space thruster applications.

Operation of a magnetoplasmadynamic arc[1-3] in a large fiberglass vacuum tank[4] has revealed certain characteristics of the arc plume visibly different from those seen in metallic tanks. Most prominent of these is the appearance of a long, tenuous, but well-collimated beam of luminosity which emerges along the centerline from the more intense portion of the plume near the orifice, and projects far downstream in a gentle curve toward the tank sidewall (Fig. 1). The purpose of this paper is to present a phenomenological description of this beam, and to attempt some identification of it.

At the outset it is important to distinguish between the subject phenomenon and the more familiar "cathode jet" commonly observed in magnetoplasmadynamic arc operation over a broad range of conditions. The latter is a sharply defined, intense jet in the center of the plume, clearly emanating from the emission spot on the cathode surface, and tightly constrained by the axial external field. For example, if the emission spot should migrate around the cathode surface, that cathode jet may be seen to precess about the centerline along the surface of revolution defined by the field line through the cathode spot. In contrast, the more diffuse beam that interests us here is found to be sensitive to the bias field in only a secondary way, and over a substantial range of this parameter, it executes essentially the same trajectory through the tank, and strikes the wall at the same location.

For the more detailed description and analysis to follow, we refer to operation under the following nominal conditions: The accelerator consists of a $\frac{1}{4}$-in. tungsten cathode centered within a $\frac{5}{8}$-in. straight-bore, tungsten-clad orifice in a $1\frac{1}{2}$-in. face diameter, water-cooled, copper anode (Fig. 2). The cathode tip is a blunted cone of $\frac{3}{8}$-in. length, withdrawn $\frac{1}{2}$-in. upstream of the anode face. The bias coil

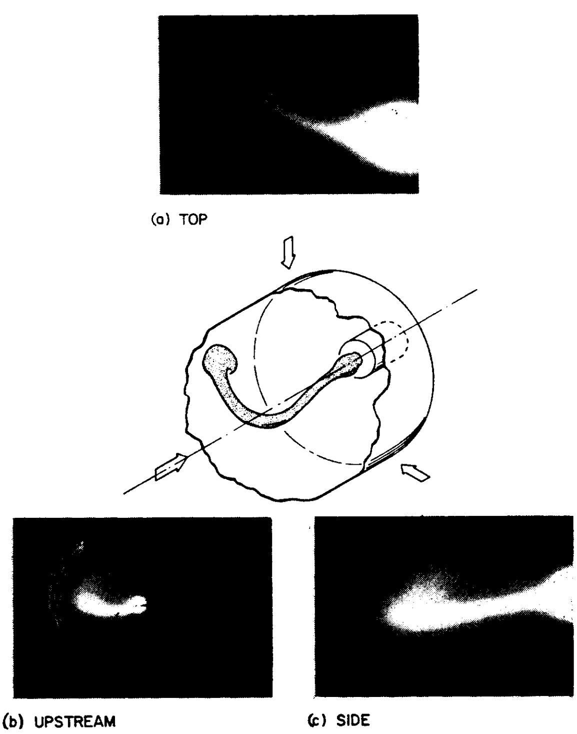


FIG. 1. Three views of beam from magnetoplasmadynamic arc.

[1] A. C. Ducati, G. M. Giannini, and E. Muehlberger, AIAA J. 2, 1452 (1964).
[2] K. E. Clark and R. G. Jahn, Astronaut. Acta **13**, 315 (1967).
[3] N. M. Nerheim and A. J. Kelly, Jet Propulsion Laboratory, California Institute of Technology Report No. 32-1196 (1967).
[4] A. C. Ducati, R. G. Jahn, E. Muehlberger, and R. P. Treat, NASA CR 62047 (1968).

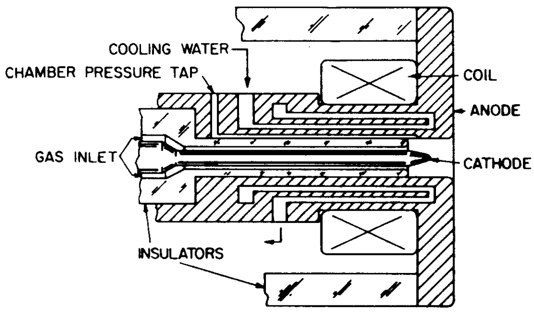


FIG. 2. Magnetoplasmadynamic accelerator.

consists of 28 turns of mean diameter $2\frac{1}{8}$-in. coaxial with the cathode, with centerplane $1\frac{1}{4}$-in. upstream of the anode face. At its centerpoint, this coil provides a nominal field of 1000 G, in the downstream direction. Arc voltage and current are set at 150 V and 50 A, respectively, and the hydrogen mass flow at 1.0 mg/sec. At this throughput, the fiberglass vacuum tank, which is 8 ft in diameter and 18 ft long, can be maintained at a background pressure of 1×10^{-4} Torr by its 52-in. diffusion pump.

Under these conditions, the subject beam appears as a diffuse, pink–blue column, 2- or 3-in. thick, bent into the configuration shown in Fig. 1. The major element of its trajectory is a nearly circular, clockwise arc in the top horizontal projection of radius 26 in., extending almost $\frac{1}{2}$ revolution from its emergence from the main plume to its intercept with the tank wall [Fig. 1(a)]. Superimposed on this is a nearly circular deflection in the projection plane transverse to the thruster axis, of radius 62 in., clockwise in the upstream view [Fig. 1(b)], which combines with the major horizontal curve to yield a hooklike projection in the vertical plane containing the axis [Fig. 1(c)]. Near its intersection with the wall, the beam appears to broaden somewhat, and then to splay out along the surface in all directions.

In view of the low pressures and correspondingly large mean free paths prevailing over most of the long trajectory, it seems reasonable to suspect a nearly collisionless beam of charged particles, undergoing deflection in the prevailing magnetic field. In this regard it is important to realize that the field from the small bias coil is essentially dipolar, and decays to negligible magnitude over most of the beam trajectory, leaving only the magnetic field of the earth to impose the observed beam deflection. Specifically, for the test conditions quoted, the bias field falls below that of the earth about 14 in. from the orifice, at which point the major beam deflection is just beginning. Assignment of the beam deflection

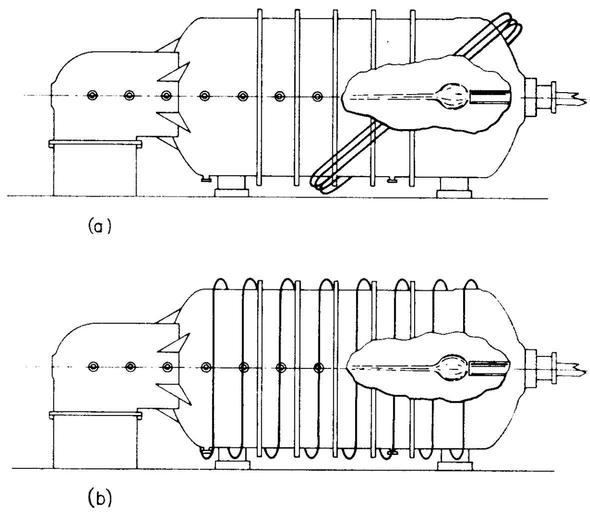


FIG. 3. Exterior coils on fiberglass vacuum tank: (a) to buck the magnetic field of the earth; (b) to change the north-south magnetic field component.

to the field of the earth is also suggested by the prominence of the effect in this dielectric vacuum tank, in contrast to metallic tanks which may carry return currents which tend to obscure weak exterior fields.

To check this hypothesis, a large coil was appropriately wound on the outside of the vacuum tank, for the purpose of canceling the earth-field component. In the Santa Ana area, this field has a horizontal intensity of 0.257 G, an inclination of 15° east of true north, and a dip angle of 59° to the horizontal.[5] The resultant magnitude is almost precisely 0.50 G. Since the axis of the vacuum tank points due south from the arc orifice, the inclined coil plane is set nearly orthogonal to the vertical plane through the tank axis, as shown in Fig. 3(a). With three turns of mean radius about 80 in., some 53 A should just cancel the magnetic field of the earth at the coil center. Experimentally, it is found that 45 A is the optimum value, at which condition the beam is essentially straightened, and projects well down the tank centerline before diffusing into invisibility [Fig. 4(c)]. Doubling of the optimum bucking-coil current deflects the beam to the opposite tank wall in a trajectory essentially symmetric to that seen in the magnetic field of the earth [Fig. 4(d)]. The discrepancy between the calculated and observed current values is readily closed by inclusion of the small contribution of the arc bias coil in this region, and by allowance for the nonuniformity of the bucking-coil field over the beam trajectory. The

[5] United States Department of the Interior, Geodetic Survey, Los Angeles, California (private communication).

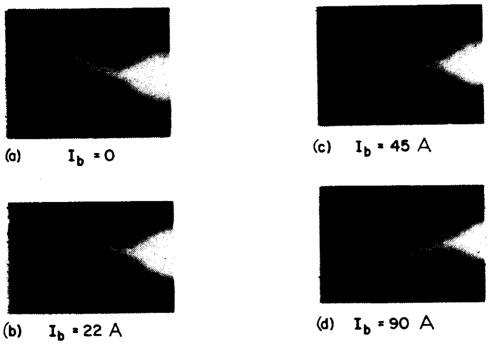
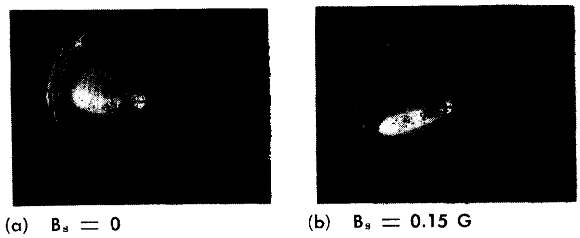


FIG. 4. Effect of bucking field on beam trajectory (top views).



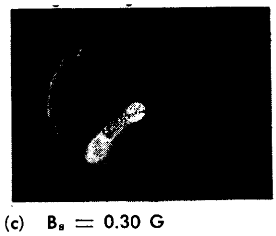


FIG. 5. Effect of axial field on electron beam (upstream view).

influence of the magnetic field of the earth on the beam thus seems established.

The sense of the deflection in these fields indicates that the beam consists of negatively charged particles emerging from the accelerator, and since there is no precedent for negative hydrogen ions in this environment, we henceforth presume that the particles involved are electrons. It then is instructive to estimate the energy of these electrons from the dimensions of their trajectories in known fields. For this purpose the arc bias field is difficult to employ since it is so highly nonuniform, but for the reason mentioned above, if we only consider elements of the trajectory beyond 15 in. from the orifice, this field component may be neglected, at least to first order.

With no other field than that of the earth prevailing, we deal with the classical situation of a charged particle injected with a given velocity vector **v** into a uniform, but inclined field $\mathbf{B}_e$. The resulting trajectory is a helix of radius

$$R = mv_\perp/qB_e \qquad (1)$$

transcribed with a circular period

$$\tau = 2\pi m/qB_e \qquad (2)$$

and having a turn spacing

$$s = v_\parallel \tau, \qquad (3)$$

where $v_\perp$ and $v_\parallel$ are the components of **v** perpendicular and parallel to **B**, respectively, and q and m are the charge and mass of the particle, all in the mks system. Under nominal operating conditions, only about $\frac{1}{2}$ turn of the helix is completed before the trajectory intersects the tank wall. Insertion of the observed radius, projected on the helix base plane, in (1) yields a value for the particle velocity of 5.73×10^6 m/sec; division of the observed trajectory length by the half-period gives the value 5.80×10^6 m/sec, with both estimates considered accurate to $\pm 10\%$.

An independent estimate of particle energy can be made by superimposing another uniform component of magnetic field, and observing the change in the beam configuration. The most convenient implementation has been to wind an evenly spaced solenoid on the outside of the vacuum tank, coaxial with it, to provide a reasonably uniform north–south component of magnitude comparable with, but less than the resultant earth field [Fig. 4(b)]. The first-order effects of this field component, B_s, are to change $v_\parallel$, and thus the helix turn spacing, and to tip the helix base plane. Axial views of the trajectory for three values of B_s are shown in Fig. 5. Briefly, it is found that 0.15 G is just sufficient to cancel the north component of the earth (plus the small contribution from the arc bias coil) yielding a transverse plane projection that is radially straight, i.e., the helix degenerates into a circle of zero pitch, in a plane containing the tank axis. Analysis of the curvature introduced into this projection by changes of ± 0.15 G from this value then yields indicated velocities of 5.62×10^6 m/sec and 6.68×10^6 m/sec, respectively, these estimated accurate to $\pm 15\%$.

Considering the relative and absolute accuracies of the various methods, we adopt a mean value of $v = 5.93 \times 10^6$ m/sec $\pm 10\%$, which corresponds to the particle energy

$$\epsilon = \tfrac{1}{2}mv^2 = 100 \text{ eV} \pm 20\%. \qquad (4)$$

In comparison with the arc terminal parameters quoted above, this corresponds to $\frac{2}{3}$ of the full arc voltage, and raises fundamental questions about the origin of this high-energy electron beam in the magnetoplasmadynamic arc environment.

Some indication of the source of the electron beam might be derived from systematic variation of the arc operating parameters about the nominal conditions, but this is not readily accomplished. For a given electrode geometry and gas type, the arc voltage, current, bias field, and gas flow rate are functionally interlocked in a particular arc mode; variation in one of these parameters predicates first-order change in at least one other. A common example is the increase in arc voltage with bias field at constant current. Occasionally, for obscure causes possibly involving the cathode emission pattern, an arc will elect a different mode of operation and display a different functional relation among its terminal parameters, whereon it is possible to duplicate all but one of the nominal conditions. In such rather irregular events, it has been possible to ascertain, for example, that a drop in arc voltage from 150 to 110 V produces a beam helix of correspondingly smaller radius and pitch, and that a drop in arc current from 50 to 20 A does not affect the beam geometry, per se. Similarly the principal effect of a bias field increase from 1000 to 3000 G is found to be a brightening of the main plume near the orifice, with little change in the character of the long beam emerging from it. Based on these isolated examples of the effect of single parameter change, the observed behavior of the beam under continuous variation of arc parameters in a given mode of operation appears consistent, e.g., an increase in bias field produces both a brightening of the near plume and an increase in beam helix size appropriate to the arc voltage increase predicated by the larger bias field, etc.

Variation of tank background pressure produces striking changes in the luminosity of the beam. Over the range from 10^{-4} to 5×10^{-3} Torr, the visible brightness of the beam increases by order of magnitude, suggesting that the luminosity is provided by background particles, excited by inelastic impact of the electrons in the beam. Above 5×10^{-3} Torr, the beam appears to have difficulty penetrating the background gas, first disappearing at its tail near the tank wall, and, by 3×10^{-2} Torr, retracting completely within the confines of the near plume. Above this pressure, no visible beam emerges but the near plume appears slightly displaced radially in the same direction as the beam deflection at lower pressures, as if by reaction to containment of the beam within itself. Obstruction of the beam in this pressure range is in agreement with simple mean free path calculations for 100 V electrons in molecular hydrogen, using established total cross sections.[6] Backgrounds of argon and nitrogen have also been bled into the tank, both of which define the beam more brilliantly in their characteristic hues, and both of which extinguish it in roughly the same high-pressure range.

One conceivable source of the observed beam would be a jet of "runaway" electrons, whose existence in the magnetoplasmadynamic arc environment has been suggested in other connections.[7] The plasma properties in the arc chamber, as best they are known, satisfy at least marginally the Dreicer[8,9] criterion for the onset of the runaway phenomenon, provided the medium contains only fully stripped ions and electrons. For the energies available here, this restricts the possibility to pure hydrogen; yet, when the arc is supplied with a 50% mixture of argon and hydrogen mass flow, or when it ingests argon or nitrogen from the tank background, its beam intensifies, rather than extinguishes. Further, the beam may be observed at arc powers below 2 kW, where it is doubtful that even pure hydrogen is fully dissociated and ionized.

Thus, it seems that the acceleration of the beam electrons must occur in a legitimately low-density region of the arc, say $n < 10^{12}$ cm^{-3}, where their mean free path is long compared with the acceleration path length. Based on arc chamber pressure measurements of 0.7 Torr, this would seem to indicate some portion of the plume well outside the orifice. Yet, it is difficult to conceive of an electric field configuration which can deliver $\frac{2}{3}$ of the arc potential in this region, and equally difficult to explain the excellent beam collimation, presumably provided by the bias magnetic field, in a region where the electron gyroradius is not substantially smaller than the beam width.

The remaining alternative is to postulate an unusually low-density corridor for electron acceleration from the cathode tip out through the anode orifice well into the plume, possibly sustained by a pumping action of the jet, or of the electron beam itself. Some suggestion that such a strong positive radial pressure gradient exists is provided by the immediate appearance in the core of the plasma of the foreign gases purposely injected into the tank during the backpressure experiments described above. In this concept the device would resemble an electron gun, or electrostatic sprayer, with pointed cathode and ring anode, and the current conduction near the cathode and anode might

[6] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Phenomena* (Oxford University Press, London, 1956), 2nd ed., Sec. 3.1.

[7] A. C. Ducati, R. G. Jahn, E. Muehlberger, and R. P. Treat, NASA CR 54703 (1966).

[8] L. Spitzer, Jr., *Physics of Fully Ionized Gases* (John Wiley & Sons, Inc., New York, 1962), 2nd ed., p. 139.

[9] H. Dreicer, Phys. Rev. **115**, 238 (1959); **117**, 329 (1960).

involve separate streams of electrons and ions, as first suggested by Stratton.[10]

Regardless of the details of its origin, the observed electron beam, if not properly obviated, could complicate the operation of a magnetoplasmadynamic arc as a space thruster. On the one hand, if the beam were to circle about some local or external magnetic field and return to the anode or to some other portion of the spacecraft, surface damage could result. As evidence of the vigor of this beam, its region of normal intersection with the vacuum tank wall has become visibly charred. Attempts to probe it electrostatically have suffered from rapid heating of the probe to incandescence. Even when straightened by the bucking field, its impact on probe supports far down the tank produces visibly glowing hot spots after only a few seconds. On the other hand, if the field geometry were to keep the beam from returning to the spacecraft, some neutralization provision might be required to balance the negative charge loss. In either case, the beam involves a disproportionately large power drain, since at its apparent specific impulse, its power to thrust ratio is very high.

Clearly the relative importance of any of these effects depends on the fraction of total arc current involved in this beam, and this is a difficult measurement to make accurately by any of the usual magnetic or electric probing methods because of the very small current density, relatively large background fields and charge densities, and the hostile thermal environment. That the current density is small follows first from elementary space-charge considerations. For example, assuming that the current distribution across the beam is reasonably smooth, that the background ionization provides negligible space-charge neutralization, and that the beam spreading is mainly electrostatic rather than thermal, the observed ratio of beam length to diameter indicates a total beam current of less than 10^{-3} A, and corresponding electron density between 10^5 and 10^6 cm^{-3}.[11] A rudimentary Langmuir probe survey has been made through the beam near its impingement on the wall, and this shows a departure from ion saturation current in the neighborhood of 70 to 80 V, and indicates a high-energy electron current component of a few milliamps. Without more detailed studies, it seems reasonably assured then that the beam carries only a small portion of the total arc current.

For application as a space thruster, the prosaic solution may simply be to avoid domains of operation where the electron beam emerges from the main plume, e.g., by different bias field strengths and configurations, higher chamber pressures, etc. Nevertheless, better understanding of this phenomenon may shed light on other aspects of the arc structure and acceleration mechanisms, and prove useful in dealing with other troublesome aspects of magnetoplasmadynamic arc operation, notably the excessive heat transfer to the anode surface, and the reentrainment of ejected gas.

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[10] T. F. Stratton, AIAA J. **3,** 1961 (1965).

[11] J. R. Pierce, *Theory and Design of Electron Beams* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1954), 2nd ed., Chap. 9.