of integrated radial potential in Fig. 3(b) are derived from a simple classical model which assumes (a) that electrons are rigidly attached to magnetic-field lines until such time as their field line passes through one of the cylinders, and (b) that an electron beam of 12 mA is trapped for the first 10 μsec. The mechanisms controlling the efficiency with which the electron beam is trapped on leaving the gun are not well understood. Assumption (b) may be regarded as determining two parameters, such as the minimum and final potential in Fig. 3(b). The agreement of the shape of the curves indicates that the electrons are tied to field lines.

By injecting the electron current in a narrow pulse significantly delayed from onset of the magnetic field, one can in principle create an electron cloud which is not in contact with either conducting wall. In linear geometries, such electron distributions are known to be unstable against long-wavelength diocotron instabilities (otherwise known as slipping stream or Kelvin-Helmholtz instabilities). In cylindrical geometries Levy[2] has predicted that such distributions can sometimes be stabilized by close proximity to conducting walls. In our experiments, utilization of the foregoing delayed-injection mode has sometimes led to observations of rf noise near the characteristic diocotron frequency ($\omega_0 \approx E/Ba$) accompanying a radial-potential history whose interpretation would require electrons to move away from the field line on which they were injected. These results suggest that both unstable and stable configurations exist and can be produced by this technique. Possible applications of this concept are discussed in the text of an adjoining paper.

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[1] W. Knauer and E. R. Stack, in Transactions of the Tenth National Vacuum Symposium, Boston, 16-18 October 1962 (Pergamon Press, New York, 1963).

[2] R. H. Levy, "The Diocotron Instability in a Cylindrical Geometry," Avco-Everett Research Laboratory Research Report No. 202, December 1964 (to be published).

PRODUCTION OF BeV POTENTIAL WELLS*

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It may be possible to produce large electrostatic potential wells by a method which avoids the usual breakdown limitations. The well would be produced by a cloud of electrons suspended in a magnetic field. Experimental and theoretical evidence bearing on the stability of such clouds are discussed by Janes.[1] Estimates to be presented below suggest that the BeV range may be accessible with large equipment. Ions introduced into the potential well would be both accelerated and contained. If the number of ions which can be contained in this way is limited by the accumulation of positive space charge, it would be possible to produce an over-all reaction rate of the order of 10^{16} nuclear reactions per second. While the concept of achieving high-energy nuclear reactions at such enormous rates is very appealing, it should be borne in mind that the entire concept is still in its infancy. Thus, although preliminary low-voltage experiments[1] and stability analyses[2] are very promising, serious obstacles to achieving these conditions may yet be discovered.

The over-all configuration is sketched in Fig. 1. An electron cloud is contained along the circular axis of a torus by a magnetic field parallel to this axis. This cloud produces a potential minimum along the circular axis and an electric field in the direction of the minor radius. Individual electrons rotate in the $\vec{E}\times\vec{B}$ direction around the circular axis at the E/B velocity. The electron cloud can be introduced into such a system by injecting the electrons onto magnetic-field lines as the magnetic field is built up.[1] The magnetic-field lines then carry the electrons into the system replacing the belt in a Van de Graaff.

The ordinary breakdown limitation of surface discharges is obviated since there is no insulator separating two electrodes. Furthermore,

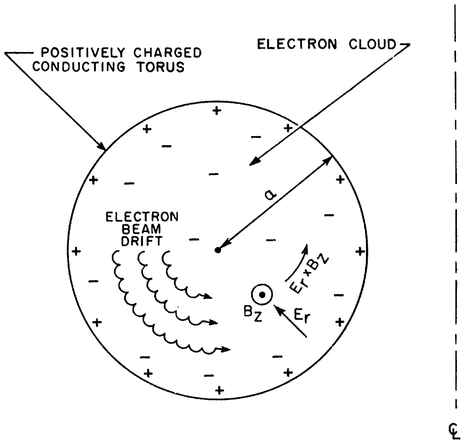

FIG. 1. Illustration of the toroidal geometry discussed in the text.

the limit associated with field emission of electrons from the negative terminal is also eliminated. If the breakdown limit is associated with ion extraction from the outer wall, electric fields in excess of 10^8 V/cm should be attainable.

The equilibrium for containment of the electron cloud is obtained by balancing the electric and magnetic stresses on the individual electrons $(\vec{E}+\vec{v}\times\vec{B}=0)$. Coupled with Gauss's and Ampere's laws, this reduces to a balance of the sum of the magnetic and electrostatic stresses. For low electron densities, or more precisely if ω_p/ω_c (plasma frequency/cyclotron frequency) $\ll 1$, inertial stresses are negligible. If $E/B \ll c$, the magnetic field is unaffected by introducing the electron cloud. As E/B approaches the speed of light the magnetic field is decreased in the region of the electron cloud. In order to demonstrate quantitative relationships for this containment, lines of constant magnetic-field intensity, electric-field intensity, and electron density have been plotted in Fig. 2 on coordinates of E/B velocity (expressed in rest-energy terms) and total depth of the potential well. The figure is drawn for a torus of one-meter minor radius, and all quantities are measured at the outer edge of the plasma. Larger apparatus sizes would lead to larger voltages.

Ions injected into the system will be accelerated to an energy equal to the depth of the potential well or to an energy corresponding

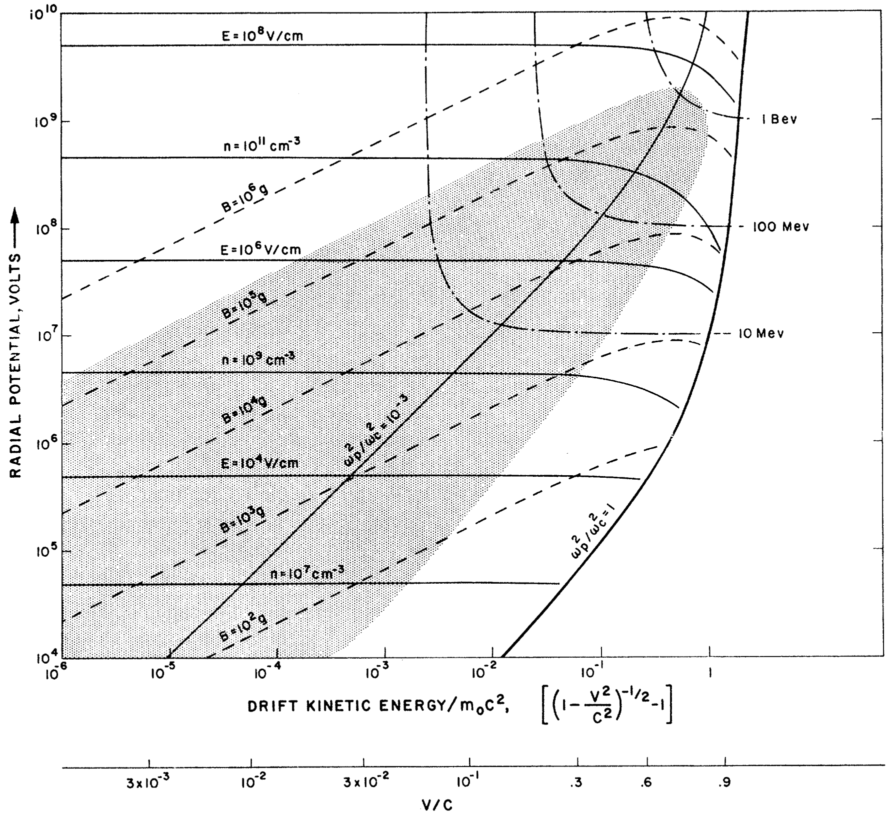

FIG. 2. Map of 1-m electron plasma containment device. The shaded region is thought to be accessible.

to the E/B velocity, whichever is lower, as indicated by the dotted lines in Fig. 2. The ion density which can be built up before the potential well is destroyed by positive space charge, or before neutral plasma forms of instability become important, may be comparable to the initial electron density.

Figure 2 has been terminated along a line ($\omega_p^2/\omega_c^2 = 1$) for which the electron gyro radius based on the E/B velocity, r_e, is equal to the minor radius, a, since this is an absolute limit to containment of the electrons by the magnetic field. Low-voltage experiments[1,3] suggest that there may be an instability if ω_p^2/ω_c^2 becomes greater than about 0.05. The lower boundary of the shaded region represents a crude estimate of a limitation imposed by this instability. The upper boundary of the shaded region is determined by the upper stress limit to the strength of magnetic field which can be achieved ($\sim 2\times 10^5$ G). The shaded area then represents an estimate of the accessible region.

The upper corner of this region corresponds to ion densities in excess of 10^{11} cm^{-3} and ion energies comparable with 1 BeV where the total meson production rate should exceed 10^{16} per second based on a cross section of 10^{-25} cm^2 and a system volume 10^8 cm^3. Since the ions move in random directions, the center-of-mass velocity may be small and in many of the above cases can lead to available c.m. energies in excess of the threshold for heavy antiparticle production. Since the cross sections for antiparticle production are of order 10^{-28} cm^2, one might expect a total yield of antiparticles in the range of 10^{13} per sec.

Since antiprotons will primarily be created near the center where E/B is small, there is some possibility of containing them in the magnetic field despite their negative charge.

These considerations represent a considerable extrapolation from understood regions. Preliminary experiments[1] have been carried out at voltages less than 10 kV, with E/B velocities less than one-hundredth the velocity of light, and with somewhat different geometries. Similarly, theoretical stability analyses[2] have been restricted to neglecting the electron mass ($\omega_p/\omega_c \ll 1$), $E/B \ll c$, and assuming no spread in electron velocity at a point. Thus, although the experiments have verified the inductive-charging principle and have demonstrated a stable range, no definitive statement can be made regarding extrapolation to the conditions discussed above. In very gross terms there is some reason to expect greater stability in this case than has been found for neutral plasmas. Since the plasma is charged, disturbances in the plasma make significant fields at the container walls. Either the natural image charges or fields obtained by adjusting the wall impedance can produce fields in the plasma which stabilize the disturbance. These image charges apparently stabilize in the region which has been studied.[2]

We may also note that an interesting facility can be obtained on a much smaller scale and with less extrapolation from known conditions. The upper limit of voltages obtainable with a Van de Graaff, ~10 MeV, can be reached with a torus of 10-cm minor radius, at magnetic fields of 5×10^4 G including the restriction $\omega_p^2/\omega_c^2 < 0.05$. At this condition E/B is still small compared to the speed of light ($\sim 10^{-1}$).

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[1] G. S. Janes, preceding Letter [Phys. Rev. Letters 15, 135 (1965)].

[2] R. H. Levy, "The Diocotron Instability in a Cylindrical Geometry," Avco-Everett Research Laboratory Research Report No. 202, December 1964 (to be published).

[3] W. Knauer and E. R. Stack, in Transactions of the Tenth National Vacuum Symposium, Boston, 16-18 October 1962 (Pergamon Press, New York, 1963).