data on the quadrupole moment variation are required to confirm such a conclusion.

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[1]J. E. Mack and H. Arroe, Ann. Rev. Nucl. Sci. 6, 117 (1956); P. Brix and H. Kopfermann, Rev. Mod. Phys. 30, 517 (1958).

[2]G. Breit, Rev. Mod. Phys. 30, 507 (1958); H. Kopfermann, Nuclear Moments (Academic Press, Inc., New York, 1958), pp. 167-188.

[3]A. S. Reiner and L. Wilets, Nucl. Phys. 36, 457 (1962).

[4]G. L. Rogosa and G. Schwarz, Phys. Rev. 98, 1 (1955).

[5]E. J. Seppi, H. E. Henrikson, F. Boehm, and J. W. M. DuMond, Nucl. Instr. Methods 16, 17 (1962).

[6]M. S. Wertheim and G. Igo, Phys. Rev. 92, 1434 (1953). (Their result has been recomputed with $R_0 = 1.2$ F and with shielding corrections extended to the case of the $1s_{1/2}$ electron; see reference 7.)

[7]R. T. Brockmeier, thesis, California Institute of Technology, 1965 (unpublished).

[8]D. D. Smith, G. L. Stukenbroeker, and J. R. McNally, Jr., Phys. Rev. 84, 383 (1951); A. R. Striganov and L. A. Korostyleva, Zh. Eksperim. i Teor. Fiz. 2, 277 (1955) [translation: Soviet Phys.-JETP 2, 277 (1956)].

[9]L. Wilets, D. L. Hill, and K. W. Ford, Phys. Rev. 91, 1488 (1953).

[10]J. O. Newton, Nucl. Phys. 3, 345 (1957); 5, 218 (1957).

[11]R. E. Bell, S. Bjørnholm, and J. C. Severiens, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 32, No. 12 (1960).

[12]L. Wilets, in Encyclopedia of Physics (Springer-Verlag, Berlin, Germany, 1958), Vol. 38, Pt. 1, p. 96.

[13]D. S. Falk and L. Wilets, Phys. Rev. 124, 1895 (1961).

[14]See, for example, N. J. Ionesco-Pallas, Nuovo Cimento 15, 323 (1960).

EXPERIMENTS ON MAGNETICALLY PRODUCED AND CONFINED ELECTRON CLOUDS

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This Letter presents experimental evidence indicating that a stable dense "cloud" of electrons with an associated negative electrostatic potential well can be produced inductively in cylindrical geometries. In these experiments, the electron "cloud" is produced by injecting electrons near the outer cylindrical wall while an axial magnetic field is rising. The electrons remain attached to the field lines on which they were injected and are therefore moved towards the center as the magnetic-field lines converge.

We discuss here the equilibrium configuration, some empirical evidence regarding stability limits on the electron density, and the experimental verification of the basic inductive-charging concept.

Figure 1 illustrates the basic equilibrium configuration in a long cylinder with conducting walls, and a magnetic field parallel to its axis. If this cylinder is filled with electrons to a density n_e, a potential well of depth $\varphi \approx e n_e a^2/4\epsilon_0$ will be formed around the axis,

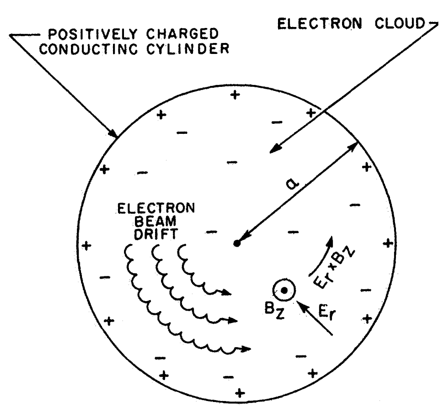


FIG. 1. Schematic diagram of the basic cylindrical equilibrium configuration described in the text.

and the inward radial electric-field strength will increase from zero at the axis to $E \approx e n_e a/2\epsilon_0$ at the wall. In the presence of the crossed fields, the electrons drift circumferentially within the cylinder as shown at a velocity such that $\vec{E} + \vec{v} \times \vec{B} = 0$, providing two conditions are met. These conditions are that the E_r/B_z drift velocity must be less than the velocity of light, and that the characteristic electron gyro radius, r_e, based on this drift velocity must be smaller than the radius of the device, a.

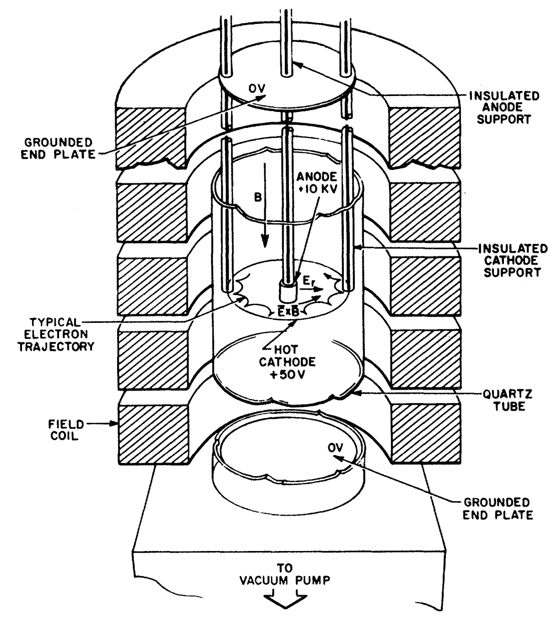
The latter assumption is equivalent to neglect of the electron inertial terms and may also be expressed as a limitation on the ratio of both the circulating frequency, ω_0, and the plasma frequency, ω_p, to the cyclotron frequency, ω_c. Since the electric field is due essentially to the trapped charge,

$$\frac{r_e}{a}=\frac{E/B}{a\omega_c}=\left(\frac{\omega_0}{\omega_c}\right)=\frac{mn_e}{\epsilon_0 B^2}=\left(\frac{\omega_p}{\omega_c}\right)^2 \ll 1. \qquad (1)$$

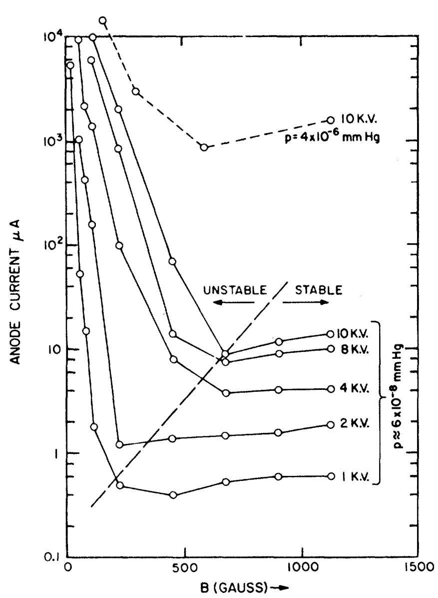
Note that the assumption that $r_e/a \ll 1$ is also an assumption regarding both the limiting electron density and the adiabaticity of the electron orbits.

The stability of this configuration is poorly understood. It is well known, however, that smooth bore magnetrons will oscillate and thereby transport electrons across magnetic-field lines at potentials considerably below the theoretical single-particle "cut-off" potential at which $r_e \approx a$. On the other hand, cold-cathode Phillips-type high-vacuum ionization gauges, which operate much farther beyond this cutoff, appear to be stable, suggesting that there may be a value of $(\omega_p/\omega_c)^2$ sufficiently less than unity corresponding to a stability limit. Figure 2(a) illustrates the basic geometry of a hot-cathode inverted magnetron (or PIG) type experiment designed to study this question. Typical experimental results are presented in Fig. 2(b). Because of the heated filament, the negative end of essentially every field line ends on a free electron. Given the apparatus size and the radial potential, it was therefore possible to estimate not only the mean electric field but also the total number of charges in the system and the average circumferential circulating current density. The measurements of the anode current indicated the existence of an effective radial transit time for an electron of about 10^{-3} sec, a result which was apparently due to ionizing collisions with residual gas molecules. At low magnetic fields the electron cloud became unstable as evidenced by rf noise and a field dependence of the current much steeper than $1/B^2$. The break in the curves in Fig. 2(b) indicates that the stable region appears to be limited to $(\omega_p/\omega_c)^2 < 1/20$-$1/30$. Similar results were obtained by Knauer and Stack[1] in a magnetron geometry with a center cathode.

The experimental arrangement indicated sche-



(a)

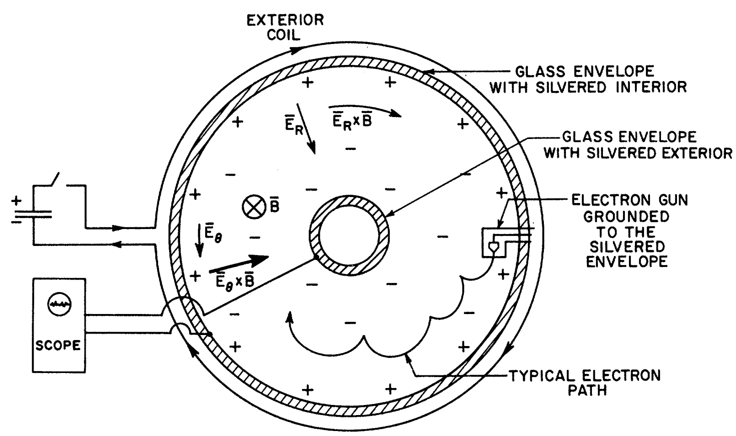


(b)

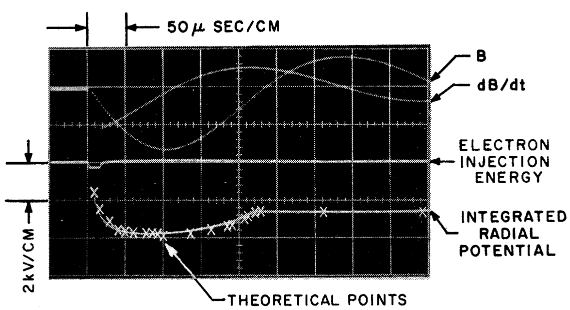
FIG. 2. (a) Schematic diagram of the dc hot-cathode inverted magnetron apparatus used for study of the $(\omega_p/\omega_c)^2$ stability limit. (b) Typical experimental results from the above experiment. The limiting anode current can be seen to scale inversely with residual gas pressure.

matically in Fig. 3(a) was set up to study the inductive-charging concept and to investigate its stability. This is a straight annular geometry with insulating end plates (not shown), an outer conducting cylindrical wall, an inner conducting cylindrical wall, an electron gun whose accelerating grid is grounded to the outside wall, and a rising axial magnetic field produced by a surrounding solenoidal field coil. The conducting silvered coatings on the inner and outer cylinders were of a thickness such that eddy currents in them did not effect the magnetic-field distribution. The potential between the two cylinders was measured with a multibeam oscilloscope and a suitable high-impedance attenuator. The oscilloscope data shown in Fig. 3(b) are typical of the preliminary results obtained with this inductive-charging experiment. In order to show the base lines, the oscilloscope traces were deliberately initiated 50 μsec in advance of the experiment. The upper pair of traces illustrates the time history of B and $\dot{B}$, respectively. The peak magnetic field of about 4 kG occurs after 110 μsec. The lower set of traces, both with the same base line, and both at a sensitivity of 2 kV/cm, illustrates the cathode voltage of the electron injection gun and the integrated radial potential, respectively. The 400-eV electron injection energy is required to overcome space-charge limitations on gun current; the electron drift energies are only a few eV. Our results are relatively independent of electron injection energy. No significant radial potential was produced unless electron injection, a rising magnetic field, and a good vacuum were present. Figure 3(b) shows potentials an order of magnitude larger than the electron injection energy. This would appear to verify the basic inductive-charging concept. The potential starts to decrease very slightly before the peak magnetic field; however, some leakage of about this magnitude would be expected due to the end plates, and due to the ionization of the residual background gas ($\approx 10^{-7}$ mm Hg).

The theoretical points drawn near the trace



(a)



(b)

FIG. 3. (a) This schematic diagram shows the apparatus used to test the inductive-charging scheme described in the text. (b) Oscilloscope photo showing typical data obtained with the above apparatus. "Theoretical points" are based on a semiempirical model explained in the text.

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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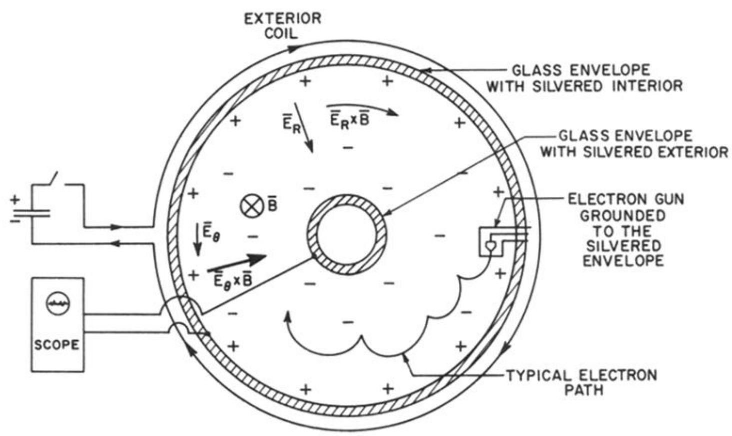
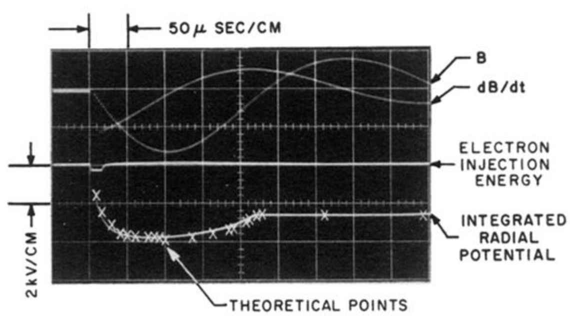
It may be possible to produce large electrostatic potential wells by a method which avoids the usual breakdown limitations. The well would be produced by a cloud of electrons suspended in a magnetic field. Experimental and theoretical evidence bearing on the stability of such clouds are discussed by 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,



(a)



(b)

FIG. 3. (a) This schematic diagram shows the apparatus used to test the inductive-charging scheme described in the text. (b) Oscilloscope photo showing typical data obtained with the above apparatus. "Theoretical points" are based on a semiempirical model explained in the text.