ERRATUM

THE IONIC CENTRIFUGE AND FUSION NUCLEAR POWER

Correction to Figures 4-6: Positive voltage should have been negative.

In one of my first papers before the National Academy of Sciences\(^1\) I showed by six drawings the operation of an Ionic Centrifuge in two types of discharge. The first three are shown correctly with negatively polarized end plates and insulated cylinder. The last three are shown incorrectly with the end plates voltage marked positive. But the current shown is due to the excess of positive ions over the negative electrons. This is obviously incorrect.

In Figure 5, for example, the current flowing to the upper end plate is shown to be equivalent to a positive ion current flowing down from the upper electrode, or an electron current flowing up to the same electrode. In an actual case we would get the course of the current flow shown in Figure 5, if we make the voltages shown on the left of Figure 5 to be \(-100 \, V\), \(-90 \, V\), etc., instead of the opposite values of \(+100 \, V\), \(+90 \, V\), etc.

The voltage of the end plates should have been negative and not positive as shown. The figures would have been correct, if the voltages marked \(+100 \, V\), \(+90 \, V\), etc., as shown, had been marked \(-100 \, V\), \(-90 \, V\), etc.

With the course of the current reversed by reversing the potential on the end plates, a strong effect of the space-charge of the electrons on the nearly pure electron flow adjacent to the end plates will be introduced, and will greatly reduce the current density of pure electrons taken from the glow to the end plates. The only excuse I can offer for the bad mistake I made is that I wrote the paper while I was recovering from a stroke.

The great reduction in the current density to the end plates caused by the reversal of the end plate voltage is important\(^2\) for the opportunity of using the space charge voltage as a countereffect in determining the current density at the electrode.

\(^1\) Slepian, J., these PROCEEDINGS, 47, 313–319 (1961).
THE IONIC CENTRIFUGE AND FUSION NUCLEAR POWER

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The Ionic Centrifuge.—By Ionic Centrifuge is meant a central low-voltage arc source of ionization maintained at low voltage at the center of a rather long circular cylinder through which a longitudinal magnetic field passes. The end plates which bound the vacuum space longitudinally are maintained at one voltage; the cylinder which bounds the space circumferentially is maintained at another voltage. The anode of the arc is taken as zero voltage.1-7 (See Fig. 1.)

The Discharge in the Ionic Centrifuge Violates the Usual Rules of Magnetohydrodynamics.—Let a voltage other than zero be applied to the end plates. Then charged particles of one sign are drawn to the end plates; charged particles of the opposite sign are repelled. A space charge sheath forms adjacent to each end plate. The space charge sheaths have a high electric gradient parallel to the magnetic field, violating the principle that in a hydromagnetic discharge the electric field is everywhere perpendicular to the magnetic field.5-8

This high electrical potential gradient parallel to the magnetic field causes the induced current in the gas to have large components parallel to the magnetic field. It causes the derivative of the parallel component of the current density along the direction of the magnetic field to be large. It causes a circulating circumferential component of the magnetic field to exist. It causes a relatively large radial component of the mean velocity of the particles of the gas to exist. It makes large positive or negative radial derivatives in the mean random velocity of the electrons and ions.

Expressed in terms of the components of electric and magnetic fields, the following are no longer true. The mean motion of the gas is no longer given by \([E \times B]/B^2\), where \(E\) and \(B\) have the usual significance, and the motion of the gas is not circumferential only. Although the intrinsic conductivity of the gas is high, the lines of magnetic force do not travel in any sense with the gas.
Discharge in the Ionic Centrifuge When the End Plates Are Negatively Charged and the Cylinder Floats at Negative Voltage.—(See Figs. 1–3.) The one type of discharge actively studied experimentally for thirteen years was with negative voltage upon the end plates, and the cylinder insulated and thus floating. We discuss the properties of this discharge with assurance based on vast experience.

The ionization given off by the arc in our experiments was in most cases ions of uranium and electrons. The floating voltage of the cylinder stayed nearly equal to that of the end plates until the Larmor voltage for the ion, \( V = (-e/8\pi c^2 M)B^2r^2 \), was reached, \( M \) being the mass of the ion, \( B \) the flux density, \( r \) the radius of the cylinder, \( e \) the charge of an electron, and \( c \) the velocity of light. Larger values of voltage on the end plates gave no further increases in voltage on the cylinder (Fig. 2). When in this condition the end plates drew one-half the ions and no electrons; and the cylinder, the remaining half of the ions and an equal number of electrons (Fig. 3). By varying \( B \) and \( r \), the Larmor voltage was varied from \(-30\) volts to \(-2,000\) volts. By varying the arc current up to 100 amperes, the ion current was varied up to 10 amperes. A small amount of experience was obtained with the plates energized positively and, while differences existed, the general results were the same.

The passage of electrons from the arc to the cylinder against the opposing voltage gradient was a mystery we had to accept. This dilemma was solved in the Letter to the Physical Review, but two years were spent in vain efforts to get other physics journals to publish it. We learned then that the energies of random motion of ions and electrons per single particle when expressed in volts about equaled the voltage of the central part of the discharge.
The above characteristics of the discharge, especially the growth of the energy of random motion of the ion and electron with the radius were amply illustrated by the numerous discharges obtained with negative voltage on the end plates and the cylinder insulated and floating.

![Graph showing Volts on End Plates and Volts on Insulated Cylinder](image)

**Fig. 2.**—Volts impressed on plates.

![Diagram of Ionic Centrifuge](image)

**Fig. 3.**—Ionic centrifuge with negative voltage and cylinder floating.

*Discharge in the Ionic Centrifuge When the End Plates Are Positively Charged and the Cylinder Is at Zero Voltage.*—Although no runs were made under these conditions up to the time our work was stopped, we believe that our experience with the runs
made in the preceding section enables us to predict with some confidence what we might expect for these runs. We assume as before that the end plates and cylinder absorb all ions and electrons which reach them.

First consider the voltages and gradients produced in the Ionic Centrifuge by a positive voltage on the end plates, a zero voltage on the cylinder, and a zero arc current for the arc (Fig. 4). The problem is one of pure electrostatics. Taking the voltage on the end plates as 100, we have a voltage maximum on the mid-plane when it is surveyed radially of, say, 50 volts, and this same point has a voltage minimum of 50 volts when the survey is made axially. At the right of Figure 4 is shown the electric field. The lines of force lead away from the end plates. They bend inwards toward the arc electrodes. They bend outwards toward the cylinder.

![Figure 4](image)

**Fig. 4.**—End plates: positive voltage. Cylinder: zero voltage. Arc current: zero.

Now let the arc current be a finite value (Fig. 5). The density of ionization will be at a maximum at the central plane and will be nearly zero near the end plates. Let us assume a finite value within, and a zero value without, two boundary surfaces going from the short arc outwards, up and down, to the cylinder.

Now the mobility of the electron parallel to the magnetic field is very high. Consequently the electric field as described will first draw electrons up and down to the boundaries of the discharge, where they will produce an electric field parallel to the magnetic field. But in the discharge itself, the current of electrons forward would be limited to a small value by the space charge of the electrons, with the positive ions repelled, if the random velocity of the positive ions and electrons did not increase. If a real current limiting space charge developed, a reversed field would be produced at the place where it started, and positive ions would be brought
in to annul this effect.\textsuperscript{7, 9} We conclude that the positive ions do develop a random velocity and with them the electrons also, so that the positive ions advance against the opposing field. Thus the loss of electrons to the boundary of the discharge causes the potential of the central part of the discharge to increase, and at the same time the random energy of ions and electrons also increases, so that the mean motion of the positive ions against the electric field becomes understandable.

Now as we approach the cylinder the potential of the main discharge must drop to zero again. But now the electrons which would be retarded have random energy which they can lose with that of the positive ions as they go against the opposing electric field. They will reach the cylinder when their random energy with that of the ions is low. At the same time the electrons which had left the main discharge for the boundaries now return to the main discharge again.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{End plates: positive voltage. Cylinder: zero voltage. Arc current: finite.}
\end{figure}

Of course there will be a continuous loss to the end plates of a small space charge limited electron current.

\textit{Induced Currents in Aforesaid Discharge}.—Of course there will be currents induced in the gas as the electrons recede out of and then reassemble into the gas of the main discharge. Figure 6, left, shows these currents, but the dense currents flowing reversely at the top and bottom of the main discharge are not shown.

Figure 6, right, shows the potential in the main discharge. The voltage gradient of the central discharge which also shows the amount of circulating circumferential electric current is also shown.

\textit{Application to Nuclear Fusion Power}.—The energy of random motion of the ions proceeding from the arc to the cylinder is most remarkable. It shows first an
increase to very high values to a maximum, and then a decrease to a low value again at the cylinder where they are caught. Owing to the high positive potential on the end plates, they are not caught on any conductor while they have the high random energy. A small fraction of the electrons due to space charge are caught upon the end plates. This is ideal containment of high voltage ions for fusion nuclear power.

For fusion we take for the working gas a fuel which will undergo fusion at a high temperature, such as deuterium, \( ^1\text{H}_2 \). We will admit it to the vacuum chamber through a tiny hole in the hollow anode opposite the cathode where it is ionized by an electron stream from the cathode.

It will proceed outwards, reaching a temperature high enough for ample fusion to take place, and then reduce its temperature on discharging to the cylinder. It will pass out of the vacuum through vents in the cylinder. It may then be pumped to a high pressure again, the helium formed in it removed, and the gas readmitted to the hollow anode.

The products of the fusion reaction, the very high energy electrons, protons, and neutrons will be caught on the end plates and the cylinder, and give up their high energy. The end plates and cylinder may then be the boilers for the thermodynamic engines supplied by the nuclear fusion power.

A high-enough magnetic field should be used so that a positive voltage of 100,000 volts may be applied to the end plates. Ten thousand gauss will more than suffice for this purpose.

The electrostatic field of 100,000 volts gives the additional containment means

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**FIG. 6.—**Currents in gas. Voltage on central plane.
needed for the high-voltage ions, not provided for by the magnetic field in the schemes already being used so far without success.

Summary.—The Ionic Centrifuge is briefly described. The discharge in this device violates the usual rules of magnetohydrodynamics because of the high electric field parallel to the magnetic field in the space charge affected boundaries. The kinetic energy of random motion of the particles is proportional to the magnetic field in the space charge affected boundaries. The kinetic energy of random motion of the particles is proportional to the magnetic field in the space charge affected boundaries. The kinetic energy of random motion of the particles is proportional to the magnetic field in the space charge affected boundaries. The kinetic energy of random motion of the particles is proportional to the magnetic field in the space charge affected boundaries. The kinetic energy of random motion of the particles is proportional to the magnetic field in the space charge affected boundaries.

1. Introduction.—Let $\Sigma(t)$ be a wave surface or boundary of a disturbance which is propagated in a viscous and heat-conducting gas. Since the gas is viscous, it is commonly assumed that the velocity is continuous over the surface $\Sigma(t)$; this implies that the density is also continuous over $\Sigma(t)$ on account of the following dynamical or shock condition (3). Thus, it is natural to assume that the pressure is likewise continuous over the surface $\Sigma(t)$. But it can then be shown from the basic equations for the behavior of the gas (see section 3) that all first and higher-order derivatives of the velocity, density, and pressure must be continuous over the surface $\Sigma(t)$; in other words, the surface $\Sigma(t)$ fails to bear a discontinuity of any order and hence one is led to consider a wave of finite thickness. There is, however, no mathematical or physical necessity to require the continuity of the pressure over the surface $\Sigma(t)$. Assuming a discrete discontinuity in the pressure while imposing the recognized condition that the velocity is continuous over the surface $\Sigma(t)$, we arrive at the concept of the pressure shock which would appear to merit consideration when dealing with waves, e.g., blast waves, where pressure effects are of primary concern.

In this communication, we shall treat the problem of the propagation of pressure...