(1967).

[8]In order to produce only a small modification of the particle orbit in a bouncing time, the electric field must satisfy $q\varphi/k\tau < \pi^2(k_0/k)^{1/2}$, a condition that is seen to be weaker than (15), which is required for the scattering effects described.

[9]C. R. Roberts and M. Schulz, J. Geophys. Res. 73, 7361 (1968).

[10]G. N. Watson, *A Treatise on the Theory of Bessel Functions* (Cambridge Univ. Press, Cambridge, England, 1966).

[11]Note that, in the case of a Langmuir turbulence, because of the very high frequency ($\omega \sim \omega_{pe}$) of the waves, any possible effect both on the electrons and on the ions would occur on a time scale faster than the respective bouncing periods, so that the condition (15) of our theory cannot be satisfied (unless the turbulence level is unrealistically small).

Dynamic Equilibrium of a Curved θ Pinch

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Experiments with a curved θ pinch show that the application of an oscillating axial current suppresses the usual toroidal drift of the plasma column and allows a stable, dynamic equilibrium to be established.

The linear θ pinch is a proven method for preparing a hot, dense plasma of thermonuclear interest. In order to avoid end losses, current experiments on θ pinches are concentrating on producing the high-β plasma in toroidal discharge tubes.[1-4] The curvature of the discharge tube, however, causes the field B_z to be inhomogeneous; and the plasma column experiences a net force which drives it towards the outer wall. Considerable interest now centers on finding a modification to the basic magnetic field configuration which neutralizes this toroidal drift and allows a stable, toroidal equilibrium to be achieved.

A possible method of obtaining a toroidal equilibrium is to pass a quasisteady current I_z along the pinched plasma column, that is, one produces a pinch which is confined by a helical magnetic field (the screw pinch[5,6]). After a small outward displacement of the toroidal plasma column, the plasma feels a restoring force due to the compression of the field component B_θ between the plasma and a metal shell placed around the discharge tube, and a toroidal equilibrium is established. Theoretical and experimental investigations indicate that there is a critical value of β below which the equilibrium is stable and above which the amount of I_z necessary for toroidal equilibrium exceeds the Kruskal-Shafranov limit, thus making the high-β screw pinch unstable. Typically, the critical β value is about 5%.

The above constraint on the β value, which is rooted in stability considerations, can, in principle, be circumvented by oscillating the direction of the axial current I_z. The theory of dynamic stabilization[7] suggests that if the pitch of the confining helical magnetic field is changed sufficiently rapidly, then stability should be achieved for any β value irrespective of whether or not the rms value of $\tilde{I}_z$ (the oscillating current) exceeds the Kruskal-Shafranov limit. An experiment has been made using a straight discharge tube which supports this theory.[8] No instability was seen to occur with the application of $\tilde{I}_z$ even though its amplitude would have been sufficient, under quasisteady conditions, to excite the Kruskal-Shafranov instability modes.

In a toroidal apparatus the oscillating current $\tilde{I}_z$ can also serve to maintain equilibrium. In this case the equilibrium is dynamic; the plasma column oscillates about some equilibrium position which is displaced towards the outside wall of the discharge tube. At the present time there are no exact calculations which predict the necessary amplitude and frequency of $\tilde{I}_z$. However, reasonable estimates indicate that the outward shift of the equilibrium position is determined by the rms value of $\tilde{I}_z$ and that the amplitude of the oscillation about this position will be small if $\frac{1}{4}\tau$ (where τ is the period of the oscillating current) is some small fraction of the time taken by the plasma column to drift to the wall in the absence of the axial current.

In this Letter we report on what is believed to be the first experimental observation of a dynamic, toroidal equilibrium of a high-β plasma column. Figure 1 is a schematic diagram of the experimental apparatus. The important experimental parameters are listed on the diagram. For

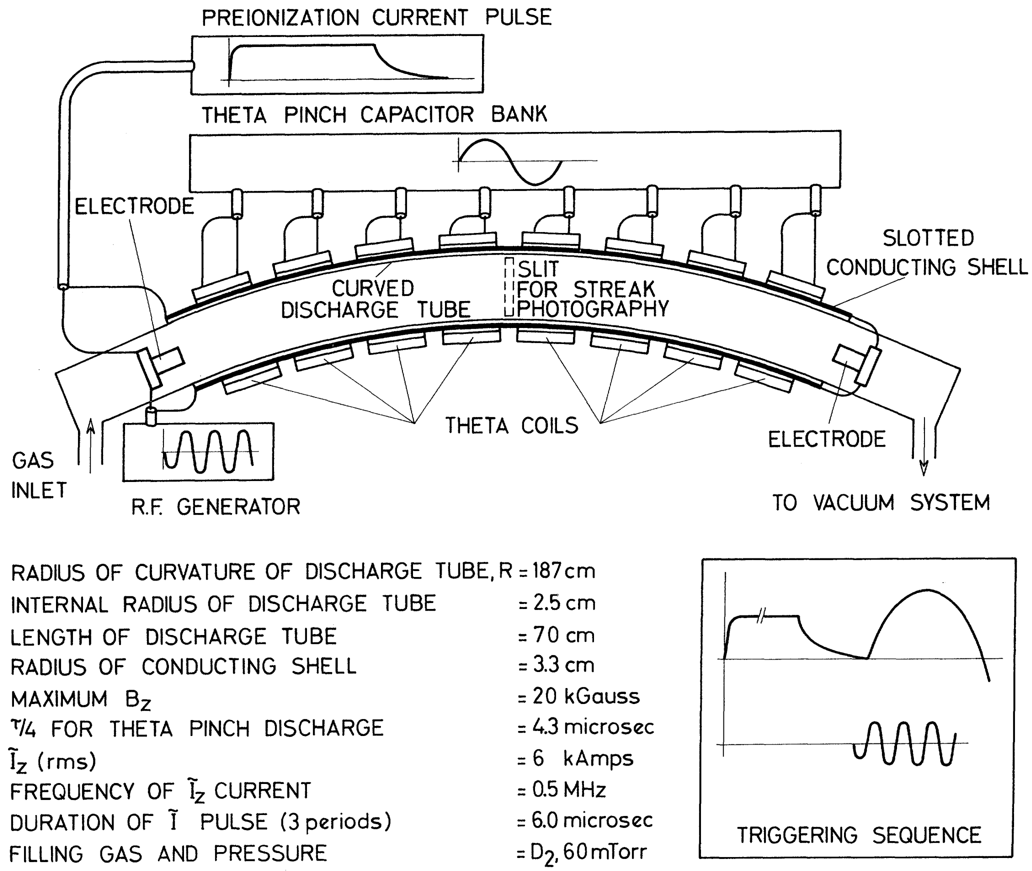

FIG. 1. Schematic diagram of the experimental apparatus.

economic reasons the experiment was conducted in a segment of a torus. It was estimated that end effects did not substantially affect the center-plane plasma during the useful duration of the experiment (which was determined by the quarter period of the uncrowbarred θ-pinch discharge, i.e., 4.3 μsec). Deuterium gas at a pressure of 60 mTorr was allowed to flow continuously through the discharge tube. Preionization of this gas was achieved by striking an arc between the electrodes situated at each end of the discharge tube. Two preionization circuits were used during the course of these experiments. The first (PRE I) generated a trapezoidally shaped current pulse which had a maximum current plateau of 8 kA lasting 15 μsec. The main θ-pinch discharge was triggered 16 μsec after the end of the 8-kA plateau. At that time the preionization current was negligible. The second preionization method (PRE II) consisted of discharging a capacitor between the two end electrodes. The discharge was damped by means of nonlinear resistors; this gave a half-sine current pulse having a maximum value of 16.5 kA. With this preionization circuit it was possible to trigger the θ-pinch discharge 7.5 μsec after the current maximum.

The generation of the main θ-pinch discharge was conventional. On the contrary, the oscillating axial current $\tilde{I}_z$ was not produced by the usual technique of discharging a high-Q capacitor but, rather, was provided by a line generator of the type developed in this laboratory in recent years.[9-11] The equivalent generator impedance and the rms open-circuit voltage were 3.0 Ω and 18.2 kV, respectively. No attempt was made to match the generator to the load. In fact, since the load impedance was at all times a small fraction of the generator impedance, the generator behaved essentially as a constant current source. If the $\tilde{I}_z$ current was being applied during an experimental shot, then the generator was triggered one half-period ahead of the main θ-pinch discharge. The effect of varying the delay between the start of the current $\tilde{I}_z$ and the start of the θ discharge was not studied in these experiments.

In Fig. 2, streak photographs taken in the mid-

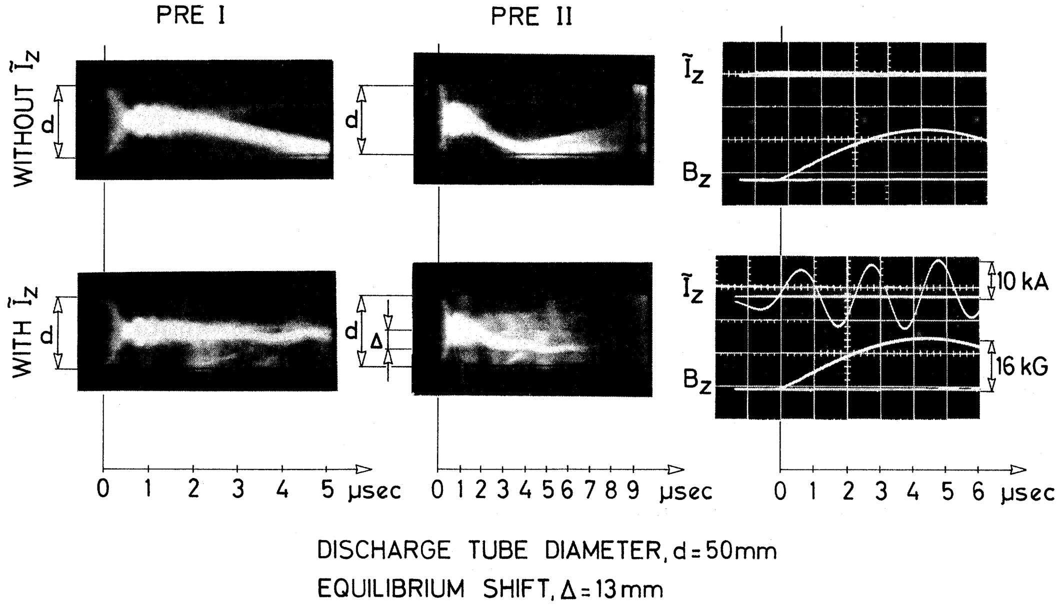

FIG. 2. Streak photographs showing the effect of the application of $\tilde{I}_z$. Note that the time scales are not identical; the origin of each scale, however, coincides with the start of the main θ-pinch discharge.

plane of the discharge tube show the effect of the application of $\tilde{I}_z$. The two sets of photographs correspond to different preionization conditions. Note that the time scales under each set of pictures and under the oscilloscope traces are not identical; the origin of each time scale, however, coincides with the start of the main θ-pinch discharge. In the streak photographs, the outer wall of the discharge tube is situated in the lower half of the picture.

The characteristics of the θ-pinch plasma were found to be dependent on the method of preionization. (In the following discussion, the different θ-pinch plasmas are identified by the name of the preionization circuit used in their preparation.) From a measurement of the drift of the plasma column to the outside wall of the discharge tube in the absence of $\tilde{I}_z$, it was possible to deduce a mean plasma temperature $\langle k(T_e+T_i)\rangle$ which was averaged over the plasma radius and over the drift time.[12] For the PRE I plasmas the average value of $\langle k(T_e+T_i)\rangle$ was 55 ± 10 eV while for the PRE II plasmas it was 84 ± 6.5 eV. It is reasonable to suppose that the plasma had at least these mean temperatures in the experiments where the $\tilde{I}_z$ current was applied.

Average densities were deduced from measurements of the mass oscillation frequencies and estimates were made of the plasma area. The average electron densities obtained in this way lay in the range $(1-5)\times 10^{16}$ cm^{-3}. For both the PRE I and II plasmas, the mass oscillation frequencies corresponded to a compression of at most 45% of the filling gas. Bodin *et al.*[13] have recently reported a similar inefficient gas collection in toroidal θ pinches of comparable strength.

Some idea of the average β values could be obtained from the average-density and mean-temperature measurements. Magnetic probe measurements of the field component B_z were also used to obtain values of β on the discharge-tube axis. While there were marked discrepancies between the β values obtained by these two methods, both were consistent in showing that the β of the PRE II plasma was generally more than twice that of the PRE I plasma. The magnetic probe measurements showed that the value of β for the PRE I plasma decreased from 0.2 to 0.1 in the time interval $1 < t < 2$ μsec.

The streak photographs show clearly that the application of the current $\tilde{I}_z$ suppresses the toroidal drift of the plasma column. They also show that a dynamic, toroidal equilibrium is established. The equilibrium shift Δ is barely measurable on the photographs obtained using PRE I. On the other hand, the photographs taken of the PRE II plasma show that the column is displaced to an equilibrium position situated about midway between the center and the outer wall of the discharge tube. The plasma column oscillates about this equilibrium position with an amplitude of about one third the plasma radius. The ratio of the drift time to the wall in the absence of $\tilde{I}_z$ to the quarter period of the $\tilde{I}_z$ current was 7 in the PRE II experiments.

The fact that Δ differs for the two plasmas can probably be ascribed to the difference in their β values. In general, the equilibrium shift in screw pinches is an increasing function of β. A comparison of the measured and calculated values of Δ (the calculation being made on the assumption that Δ is determined by the rms value of $\tilde{I}_z$) indicates that a theoretical model based on a vacuum B_θ distribution and a sharp-boundary plasma does not apply in the present experiments. Indeed, preliminary magnetic probe measurements of the oscillating field component B_θ show that after the first 1.3 μsec of the experiment, during which the distribution of B_θ outside the dense plasma column has a $1/r$ dependence, the axial current switches to the region of the discharge tube wall where it forms a layer characterized by a skin depth of 7.5 mm. It is conjectured that the switching of the current to the wall, and also the background light which is apparent in the streak photographs, is due to the ionization of the neutral filling gas which is not collected during the initial implosion of the θ pinch.

The streak photographs do not reveal the presence of any gross magnetohydrodynamic instabilities. It is interesting to note that if the parameters of this experiment are inserted into the Kruskal-Shafranov theory, then the growth rate of the most dangerous $m=1$ mode in the equivalent dc screw pinch (axial current equal to rms $\tilde{I}_z$) is 1.6×10^6 sec^{-1}.

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Ion-Molecular Reactions in Plasma Containment Devices*

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We investigate ion-molecule charge exchange followed by dissociative electron recombination with molecular ions due to the presence of common impurities in a plasma-containment device . For a He^+ plasma with N_2 impurity, the ionic constituency of plasmas is changed from He^+ to nitrogen ions with a time constant τ^* given by $\tau^* P(N_2) \simeq 24$ msec μTorr. However, those ion-molecular recombination processes are not responsible for the enhanced plasma loss in the Princeton spherator at the best vacuum condition.

Recently, plasma decay times of 200–500 msec have been obtained in toroidal multipoles.[1,2] This is 100–300 times the so-called Bohm time. However, He^+ plasma in the spherator device still decays somewhat faster than expected from classical collisional processes, which indicates that

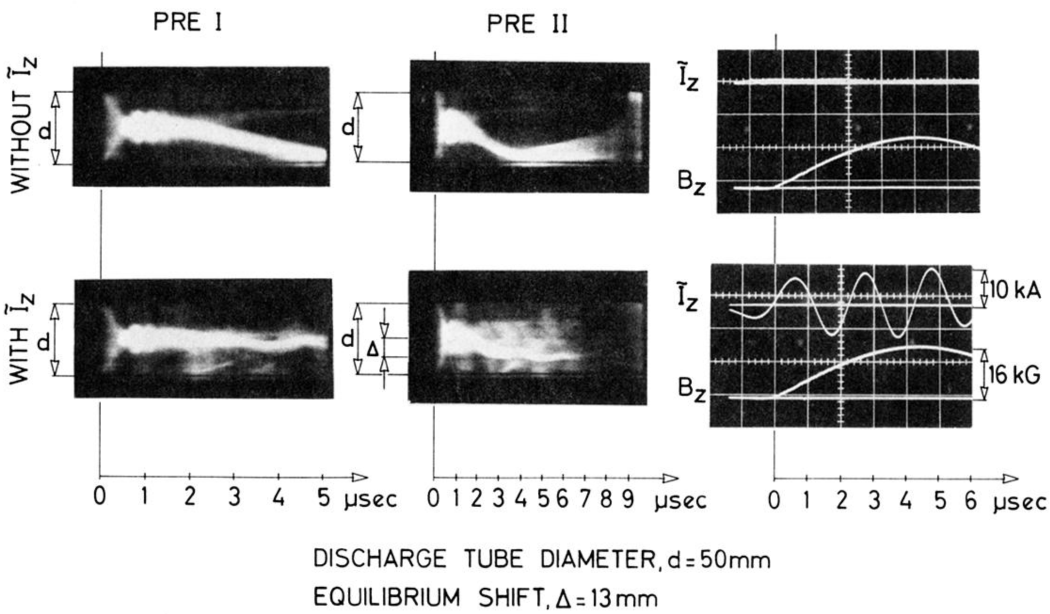

FIG. 2. Streak photographs showing the effect of the application of $\tilde{I}_z$. Note that the time scales are not identical; the origin of each scale, however, coincides with the start of the main θ-pinch discharge.