INVESTIGATION OF PLASMA CONFINEMENT IN A TOROIDAL THETA-PINCH WITH $M+S$-LIKE CONFIGURATIONS

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(Received 21 November 1962)

It has been shown theoretically[1] that as a solution of the equilibrium problem for a plasma with $\beta=1$ ($\beta=8\pi p/B^2$) there exist certain toroidal closed plasma surfaces ($M+S$ surfaces) without resulting azimuthal currents. For low β, field configurations with rotational transform represent stationary state solutions (with secondary currents) of the equilibrium problem.[2] Calculations have shown that single particle containment can exist in the "bumpy torus."[3]

In a system with the rotational transform ι the normal diffusion is increased by a factor $(1+8\pi^2/\iota^2)$ due to the energy dissipation by the secondary currents.[4] $M+S$-like configurations for $\beta<1$ would have the advantage that these secondary currents are cancelled over a comparatively short range, and therefore the increase of normal diffusion may be small.

Experimentally we are investigating the behavior of a plasma in $M+S$-like configurations. The initial experiments were performed using a toroidal theta-pinch device with purely azimuthal fields.[5] The characteristics are as follows: minor and major radius $r=3$ cm and $R=25$ cm, discharge frequency 30 kHz (or crowbarred), maximum field strength $B_{\max}\approx 12$ kG. The investigations of discharges in the gases H_2, He, Ne, Ar, Kr, and with the initial particle densities 10^{15}-$10^{16}/\text{cm}^3$ showed volume compression ratios of 10 to 30, electron temperatures of several eV, and β changing from about 1 to 10^{-2} from the beginning of discharge to the time of $B_{\max}$.

In purely azimuthal fields no macroscopically visible plasma instabilities were observed, but the plasma as a whole showed an accelerated motion in the direction of the decreasing magnetic field. The time for the motion from the center to the wall $t=(3rR)^{1/2}/\bar{v}$ ($\bar{v}$ = rms thermal velocity), calculated from a simple magnetohydrodynamic model, agrees approximately with the observations.[5]

The azimuthal field then was corrugated (16 or 24 periods) by adding auxiliary windings, initially on the inner circumference of the torus. In this configuration the drift of the whole plasma could be prolonged by a small amount or could be reversed.[6]

But in order to reverse the plasma drift we had to increase the auxiliary currents J_a to such an extent that magnetic field lines from the surface of the compressed plasma crossed the inner wall of the torus and hence the plasma touched the wall at these points.

We prevent this now by arranging the paths of the auxiliary currents J_a in such a way that they pass through the torus, as indicated in Fig. 1(a). Although the configuration of the magnetic field produced by these currents is not yet known exactly, we observe that in the plane of the torus the plasma approximates an $M+S$ surface, an example of which[7] is shown in Fig. 1(b). Two series of image converter pictures taken from consecutive discharges in 40 μ of He are shown in Fig. 2, (a) without and (b) with auxiliary currents. The exposure time is 0.3 μsec and the time interval between the pictures 1 μsec.

The section of the torus shown corresponds to more than one period of the field configuration.

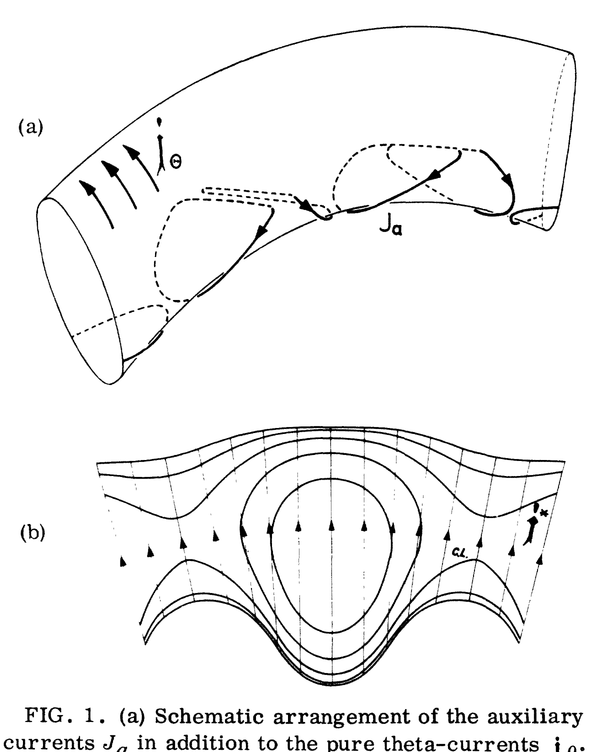

FIG. 1. (a) Schematic arrangement of the auxiliary currents J_a in addition to the pure theta-currents j_θ. (b) Example of an $M+S$ surface[7] with (equidistant) current lines j^* and contour lines C.L. Both sections show more than one of the 16 periods.

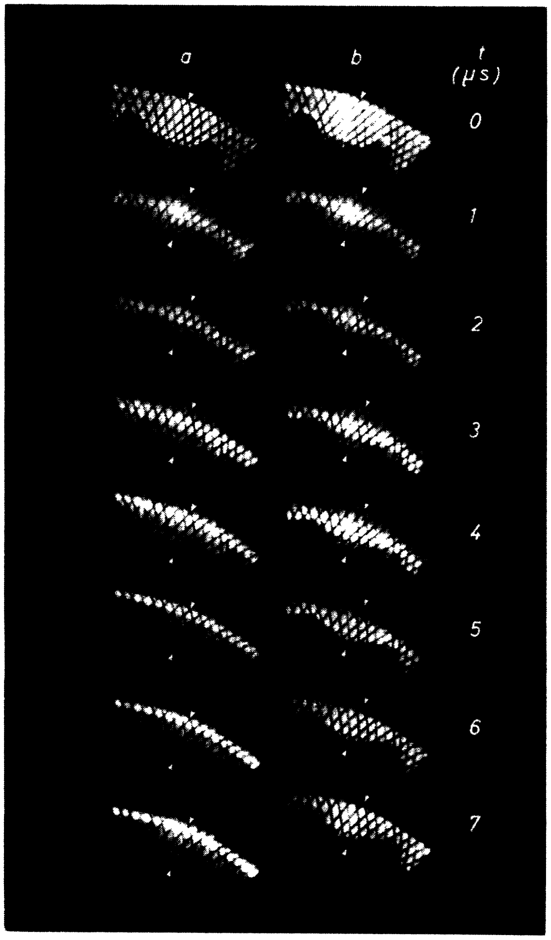

FIG. 2. Image converter pictures of consecutive discharges in 40μ of He. The time scale begins at the zero point of the discharge current and indicates the time at which each picture was taken. Series (a) is taken without and series (b) with the auxiliary currents J_a. The white triangles mark the inner walls of the vessel in the plane of the torus.

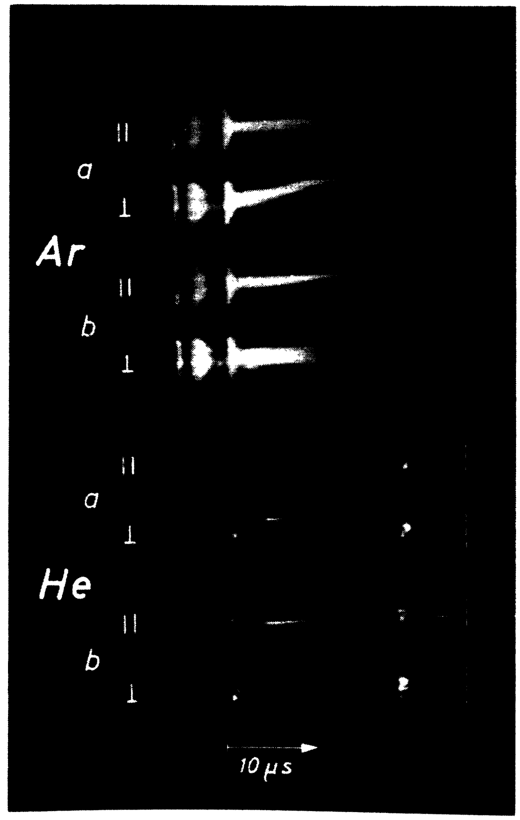

FIG. 3. Smear camera pictures. The upper half shows a crowbarred discharge in 20μ of Ar (a) without and (b) with the auxiliary currents J_a; $\perp$ view perpendicular to the plane of torus, $\parallel$ parallel. In the lower half is shown the first half-cycle and the beginning of the second one of a discharge in 40μ of He, taken in the light of the He-II line at 4686 Å.

The crossed dark lines are the windings for the main azimuthal field. From technical reasons the torus is not visible between the inner circumference and those points where the auxiliary currents J_a pass through the torus. But the pictures here shown and also more detailed observations indicate that the plasma keeps away from any surface of the vessel at these points. In case (a), the plasma reaches the outer wall within 4 μsec after the beginning of the first half-cycle of the main discharge, whereas in case (b) the center of the luminous region stays fairly unaltered for 7 μsec. Smear camera pictures from the same discharge are shown in the lower part of Fig. 3; they are taken in the light of the He-II line at 4686 Å using an interference filter. The position of the slit corresponds to the center of the image converter pictures. In case (a) the plasma drifts to the outer wall within about 4 μsec (view $\perp$) and then it shows a spreading out perpendicular to the plane of the torus (view $\parallel$) which may be caused by cooling. Instead of this spreading out we observe in case (b) (view $\parallel$) a well-defined luminous region for about 12 μsec. The luminosity decreases with the decreasing external magnetic field at the end of the first half-cycle. The upper half of Fig. 3 shows a crowbarred discharge in 20μ of Ar taken without any filter. Here the predischarge is visible. One can distinguish clearly between the accelerated motion of the plasma in the normal toroidal field [(a), $\perp$] and the fixed position of the plasma in the $M+S$-like configuration [(b), $\perp$] until the luminosity vanishes rather rapidly. This latter phenomenon has not yet been investigated, but it appears to be clear from the experiments that the confinement time for a plasma with $\beta < 1$ can be markedly increased by $M+S$-like configurations.

These investigations are being extended to higher energies ($B_{max} \approx 40$ kG), using a vessel and coils shaped to an $M+S$-like geometry.

We would like to express our gratitude to Professor A. Schlüter, who greatly advanced this work through many stimulating discussions. We are likewise indebted to Dr. G. V. Gierke for his continuous support, and to Dr. H. U. Schmidt and Dr. D. Pfirsch for many stimulating and valuable discussions.

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[7]We are indebted to Dr. H. U. Schmidt for the calculations of $M+S$ surfaces.

MEAN FREE PATH OF HOT ELECTRONS AND HOLES IN METALS*

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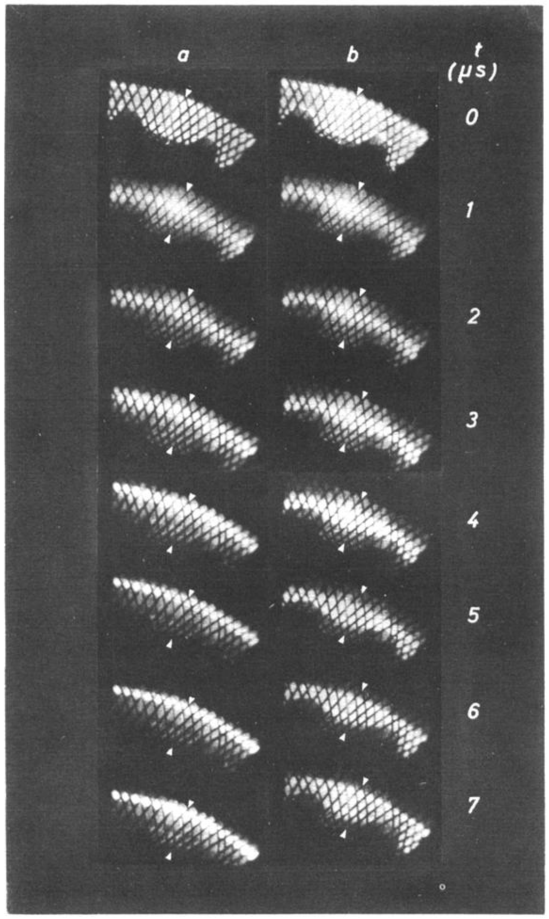
Knowledge of the mean free path of hot electrons in solids is of considerable interest and importance. Recently, Crowell, Spitzer, and their co-workers have measured the attenuation length of hot electrons[1,2] in Au, Ag, Cu, and Pd and of hot holes in Au.[3] From a fundamental point of view, the principal importance of these measurements lies in the information which may be derived from them concerning the mean-free-path lengths for electron-electron scattering. The difficulty in obtaining mean free paths from attenuation lengths is due to the fact that neither diffusion theory nor age theory is adequate for problems in which the initial source is concentrated within a few mean free paths of the surface,[4] as is the case here. However, as has been well demonstrated in the treatment of similar problems in neutron physics, the problem can be treated as accurately as necessary by the application of the Monte Carlo method.[5] It is the purpose of this paper to report on such calculations made for the systems[6] studied by Crowell, Spitzer, and their co-workers.[1-3]

Using the Monte Carlo method,[7] the photoyield was calculated as a function of film thickness for the geometry used by Crowell et al. In doing this, the exponential spatial distribution of the optical absorption was taken into account and the assumptions listed below were made. The probability of an electron being excited into a state with energy between $h\nu + E_F$ and $\phi + E_F$ was taken to be independent of the energy of the states involved. Here E_F is the energy of the Fermi level, ϕ is the height of the metal-semiconductor barrier, and $h\nu$ is the photon energy. Only scattering by phonons and other electrons was considered. Due to the large energy loss involved in electron-electron scattering, an electron was assumed to have zero escape probability after such an event. The direction of motion of the electron was taken to be isotropic following excitation and each subsequent phonon-electron scattering event. The reflection of electrons at the surface was taken to be spectral. All the electrons with sufficient momentum to escape were assumed to do so, i.e., the reflection coefficient for these electrons was taken to be zero.

Figure 1 gives the calculated photoyield as a function of the thickness of the metal film for a photon energy of 1.015 eV, a barrier height of 0.79 eV (corresponding to that of Au on Si),[1,3] and for values of 500 and 1000 Å for the phonon-electron mean free path l_p and electron-electron



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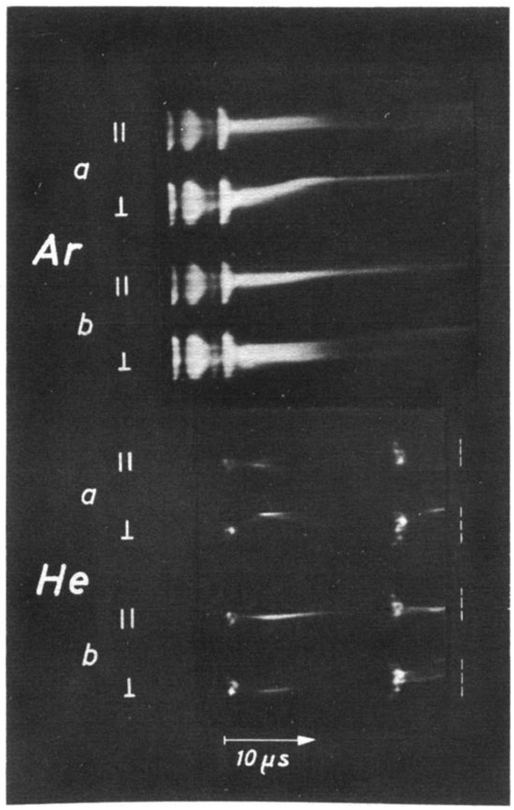

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