The quoted precisions are 1 average deviation from the mean. This result can be compared with that reported by Kaufman et al.,[5] $\Delta E_{\mathrm{H}}-\mathcal{S}_{\mathrm{H}} = 9911.38 \pm 0.03$ MHz, and with the preliminary measurements of Vorburger and Cosens.[6]

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†Alfred P. Sloan Foundation Fellow.

[1] The atomic-hydrogen fs papers are referred to as HI-HVI. The last in the series, HVI, is E. S. Dayhoff, S. Triebwasser, and W. E. Lamb, Jr., Phys. Rev. 89, 106 (1953).

[2] R. T. Robiscoe, Phys. Rev. 138, A22 (1965).

[3] R. T. Robiscoe and B. L. Cosens, Phys. Rev. Letters 17, 69 (1966). The notation is that introduced in Refs. 1 and 2.

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[5] S. L. Kaufman, W. E. Lamb, Jr., K. R. Lea, and M. Leventhal, Phys. Rev. Letters 22, 507 (1969).

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PLASMA-CURRENT MULTIPOLE EXPERIMENTS

T. Ohkawa and H. G. Voorhies
Gulf General Atomic Incorporated, San Diego, California 92112

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The magnetohydrodynamic equilibrium and stability of the plasma-current multipole configuration have been demonstrated experimentally.

The plasma confinement experiments with multipole[1] configurations with internal conductors show that the level of plasma turbulence is greatly reduced and that the containment time is much longer than the "Bohm time." These improvements are attributed to the good features of the configuration, i.e., the magnetic well and the magnetic shear with the presence of a toroidal magnetic field. On the other hand, the disadvantage of having internal conductors is obvious for a fusion reactor.

A new configuration has been suggested[2] in which a multipolelike configuration is produced by the combination of a toroidal magnetic field, a plasma current, and an external poloidal magnetic field. The calculations show that the configuration may be stable against magnetohydrodynamic instabilities. It is similar to the Tokamak[3] configuration in that the presence of the plasma current is necessary for magnetohydrodynamic equilibrium and stability, and that the configuration is axially symmetric. The advantage of the present configuration is that a larger magnetic shear allows a larger stability limit on β (ratio of plasma pressure to magnetic pressure).

A device (named Doublet-I) has been built to test magnetohydrodynamic equilibrium and stability. The time scale of the experiment is chosen to be several hundred μsec. This allows an ample time for magnetohydrodynamic instabilities to develop, since the characteristic time for the instabilities is typically 1 μsec. Thus it is simpler to use a copper wall to shape the magnetic configuration than to use an external coil.

The schematic diagram of the Doublet-I device is shown in Fig. 1. The relevant parameters are the following: major radius, 16.2 cm; cross section of chamber, ~6 cm × 25 cm; wall surface material, alumina; toroidal magnetic field, 10 000 G maximum, with half period 4 msec; toroidal electric field, 1 V/cm maximum, with half period 1 msec; hydrogen pressure, 0.1-50 μ.

The contour of the copper wall is designed in the following way. The density of the toroidal plasma current is assumed to be proportional to the reciprocal of the major radius. A quadrupole and an octopole field are superposed on the magnetic field produced by this current. Then

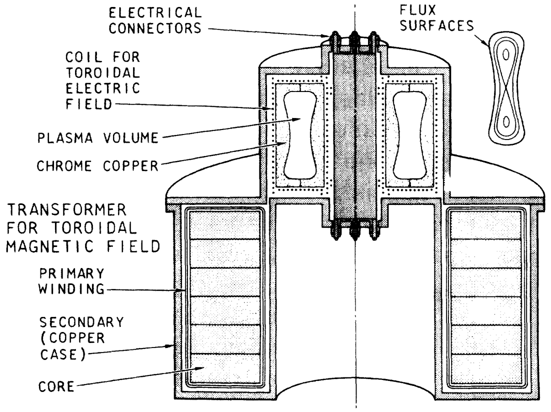

FIG. 1. Schematic drawing of Doublet-I.

the flux function ψ is given by

$$\psi=-\frac{\mu_0 J_0 R_0{}^3}{4}\left[\left(\frac{R}{R_0}\right)^2\ln\left(\frac{R}{R_0}\right)-\frac{1}{2}\left(\frac{R}{R_0}\right)^2+\frac{1}{2}+\left(\frac{z}{R_0}\right)^2\right]+\alpha_2\left[\left(\frac{R}{R_0}\right)^2\ln\left(\frac{R}{R_0}\right)-\frac{1}{2}\left(\frac{R}{R_0}\right)^2+\frac{1}{2}-\left(\frac{z}{R_0}\right)^2\right]$$
$$+\alpha_4\left[24\left\{\frac{1}{16}\left(\frac{R}{R_0}\right)^4\ln\left(\frac{R}{R_0}\right)-\frac{5}{64}\left(\frac{R}{R_0}\right)^4+\frac{1}{8}\left(\frac{R}{R_0}\right)^2\ln\left(\frac{R}{R_0}\right)+\frac{1}{16}\left(\frac{R}{R_0}\right)^2+\frac{1}{64}\right\}\right.$$
$$\left.-12\left(\frac{z}{R_0}\right)^2\left\{\frac{1}{2}\left(\frac{R}{R_0}\right)^2\ln\left(\frac{R}{R_0}\right)-\frac{1}{4}\left(\frac{R}{R_0}\right)^2+\frac{1}{4}\right\}+\left(\frac{z}{R_0}\right)^4\right],$$

where J_0 is the density of the toroidal plasma current at the major radius R_0, R is the radius measured from the major axis, and z is the distance from the median plane. The ratio of α_2 to α_4 is chosen to give about equal amounts of the poloidal magnetic flux inside the separatrix and between the separatrix and the shearless surface. A flux surface well inside the shearless surface is chosen to be the wall contour. The flux configuration is shown in Fig. 1. The rotational transform angle is largest at the elliptic magnetic axes and vanishes on the separatrix. It increases away from the separatrix until it reaches a maximum on the shearless surface.

The toroidal magnetic field is produced by the current flowing in the secondary circuit of a transformer which is energized by a 12 kV-1200 μF condenser bank. The toroidal electric field is produced by a set of coils distributed around the plasma chamber. The distribution is one which generates minimum magnetic field in the plasma volume while inducing the electric field. A 360-μF condenser bank energizes the coils.

The time sequence of the experiment is the following: (1) Fill the chamber with hydrogen, (2) energize the toroidal magnetic field, (3) energize the toroidal electric field at the time of peak toroidal magnetic field, and (4) (optional) fire a small spark discharge at the wall of the chamber. The electric field breaks down the gas and drives the plasma current. The discharge lasts about 300 μsec.

The magnetic field distribution is measured by inserting a magnetic probe in the plasma. Figure 2 shows the results of poloidal-field measurements scanned in the vertical direction 125 μsec after the start of the discharge. The toroidal magnetic field is 5500 G, the initial electric field 0.85 V/cm, and the pressure 7 μ H. It is evident that the magnetic axis is located near the predicted position. The theoretical curve is calculated for a current density of 200 A/cm^2 at the magnetic axis. Horizontal scans through the magnetic axes also give the distributions predicted by the calculation. The measurements at the top half and the bottom half are identical within shot-to-shot variations. These results show that the desired magnetic configurations are obtained and the plasma-current density has a distribution close to the predicted one. The fluctuations in the magnetic field are roughly 5% outside the separatrix and increase toward the elliptic magnetic axes to about 20%. That the configuration persists for more than 100 μsec and the fluctuation in the magnetic field is small indicate that the desired configuration is in magnetohydrodynamic equilibrium and stable against large scale magnetohydrodynamic instabilities.

The measured current gives as the value of rotational transform angle at the elliptic magnetic axis $\frac{1}{5}\times 2\pi$, which is well below the Kruskal-Shafranov limit. The value of β is also well be-

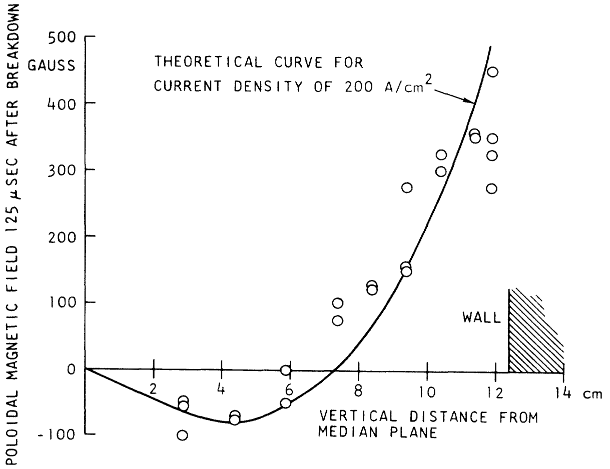

FIG. 2. Vertical distribution of the poloidal magnetic field at $R=16.2$ cm. The initial H_2 pressure = 7 μ, toroidal magnetic field 5500 G, and toroidal electric field 0.7 V/cm.

low the magnetohydrodynamic limit against interchange and the ballooning mode.

The conductivity temperature may be calculated from the measured current density and the electric field. In the present case the resistivity is 4×10^{-3} Ω cm, which corresponds to about 5-eV electron temperature. One can deduce from double-Langmuir-probe measurements that the electron temperature is several eV and that the ion density is about 3×10^{14} cm^{-3}. This value is within the experimental error of the value expected for complete ionization of the hydrogen gas.

With these values for density and temperature the following quantities may be calculated:

$$\beta\sim0.5\%,\quad v_s\sim3\times10^6\ \text{cm/sec},$$

$$\text{energy confinement time}=n(3kT+eV_i)/jE$$

$$=10\ \mu\text{sec},$$

magnetohydrodynamic characteristic times $(rR_c)^{1/2}/v_S\sim2$ μsec, or $r/v_S\sim1$ μsec, where j is the current density, E the electric field, v_S the velocity of sound, r the plasma radius, $1/R_c$ the curvature of a flux line, T the plasma temperature, and V_i is ionization potential. Thus both the duration of the configuration and the energy containment time exceed the magnetodydrodynamic characteristic times. Also the electron drift velocity (j/en) associated with Ohmic current is about equal to the velocity of sound.

The plasma current begins to decrease about 100 μsec after the start of the discharge. The following observations suggest that it is due to the radiation cooling by oxygen atoms from the wall.

When a double Langmuir probe is placed near the wall, the ion current shows a second peak. The scope trace indicates that the late increase of the density coincides with the decline of the plasma current. If the times of appearance of the late density peak are plotted against the probe position, it is apparent that the density peak is moving away from the wall at a velocity of 3×10^4 cm/sec which is equal to the sound velocity of room temperature air. The amount of gas is so large that the discharge is extinguished by the time the gas reaches the axes, although the toroidal electric field has decreased by only 20%.

Optical measurements provide additional evidence for the influx of cold gas. The intensity of the O II emission line at 4649 Å increases several orders of magnitude about 100 μsec after the start of the discharge, indicating that the decline of the plasma current is accompanied by a large increase in the oxygen content.

The measurements of the magnetic field distribution as a function of time also indicate the influx of cold gas off the wall. The current density which is proportional to the gradient of the field strength decreases near the wall first.

In summary, the desired magnetic configuration of plasma-current multipole has been established experimentally. The configuration seems to be in stable magnetohydrodynamic equilibrium. However, because of the radiation cooling by impurity ions, it is not possible to estimate the energy confinement time limited by the turbulent diffusion of plasma.

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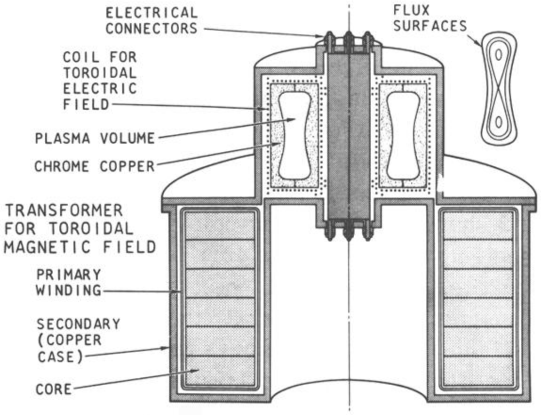

FIG. 1. Schematic drawing of Doublet-I.