# Observation of a magnetic field line in the T-10 tokamak

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High-speed photography of the evaporation of a graphite pellet injected into a tokamak has made it possible to measure the direction of the magnetic field in the plasma and to calculate the profile of the safety factor, $q(r)$.

Graphite pellets with a size $d_p = 300$–$400\ \mu$m were injected into the T-10 tokamak, toward the center of the discharge chamber, at an angle $\alpha = 30°$ with respect to the equatorial plane, at a velocity of 140 m/s. The photography was carried out with a VSK-5 camera in the spectral interval 390–660 nm at a point 3.5 m from the center of the plasma. The optical axis of the system ran 15 cm above the equatorial plane and parallel to it. The time between frames was $\sim 30\ \mu$s. The operating regime of the device can be characterized by the following parameter values: a plasma current $I_p = 230$ kA, a magnetic field $B_\varphi = 20$ kG, a chord-mean density $\bar{n}_e = 1 \times 10^{13}\ \text{cm}^{-3}$, a limiter radius $a_L = 34$ cm, and a cylindrical safety factor $q(a_L) = 5a_L^2 B_\varphi / RI_p \approx 3.4$ at the limiter.

Figure 1 shows photographs of the cloud at three times, shown by the arrows in Fig. 2a, on a plot of the evaporation rate, $\dot{N}(r)$. In the initial stage of the evaporation, the dimensions of the cloud are on the order of 1 cm. The brightest region, which is the position of the pellet, may have either a simple point shape or a more complex shape (Fig. 1a). Although there is a noticeable elongation along the magnetic field direction, the small dimensions of the region make it difficult to determine the inclination of the magnetic field line. With increasing $\dot{N}$, the dimensions of the cloud increase (Fig. 1b), and when the evaporation rate peaks (Fig. 1c), the cloud has its maximum dimensions both along the magnetic field (10–12 cm) and across it ($\sim 2$ cm). In some cases (Fig. 1b) we observe two regions of elevated brightness, which are in the central part of the cloud and separated from each other by about 1 cm along the transverse direction. The bright spot at the left in Fig. 1c is a highlight resulting from reflection of the light from the side wall of a port.

During the middle and late stages of the evaporation, when the measurements of $\theta_i$ were carried out, the cloud was essentially symmetric in the poloidal direction, and its characteristic dimensions were smaller than those of the definitely asymmetric clouds in the CII and CIII ion lines.[1] These results indicate that the emission is due primarily to neutral atoms and is affected only slightly by drift motions of the plasma near the pellet. The cloud is elongated along the magnetic field because of the distribution of the low-temperature secondary plasma, which provides an additional source of neutrals through recombination and which participates in the excitation of the emission. The effect of drift motions in the radial electric fields should have been manifested as an increase in the drift of the cloud with increasing distance from the pellet, and this drift should have been in the same direction to the right and left of the pellet. Drift

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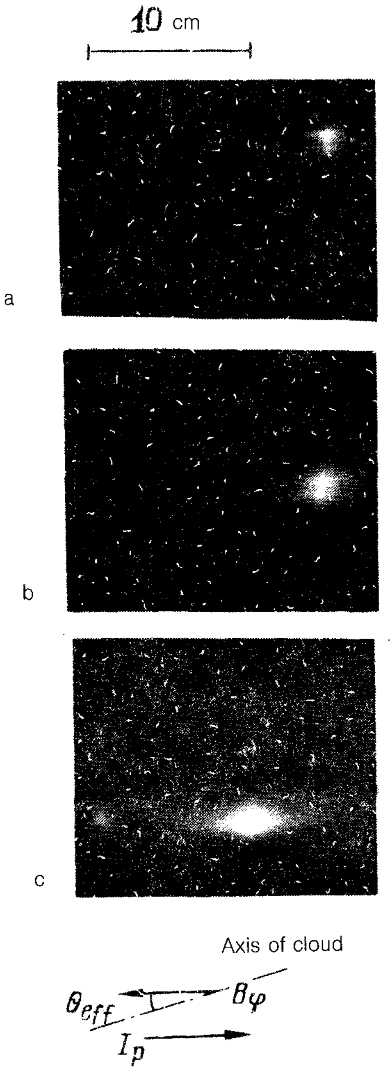


FIG. 1.

motions which might have deflected the predominant spreading of the cloud away from the direction of the magnetic field must result from some mechanism (whose physics is unclear) which changes the sign of the radial for on opposite sides of the pellet. Electric fields could not be the source of such drift motions because of the high longitudinal electrical conductivity.

In a determination of the inclination of the field line, $\theta_i(r) = B_\vartheta / B_\varphi$ ($B_\vartheta, B_\varphi$ are the poloidal and toroidal components of the magnetic field **B**), the direction of the longitudinal axis of the cloud was therefore identified with the direction of **B** in the plasma. We also allowed for the fact that the observed angle $\theta_{\rm eff}$ is smaller than $\theta_i$ by a factor of $1/\cos\alpha'$, where $\alpha'$ is the angle between the injection direction and the obser-

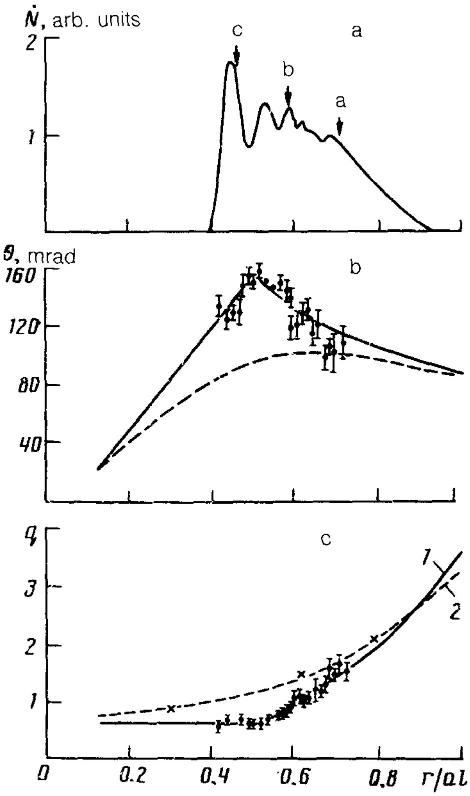


FIG. 2.

vation direction. Under these experimental conditions, the angle $\alpha'$ lay in the interval 30.4°–28.6°, corresponding to corrections no greater than 1.5% to $\theta_i$. We accordingly adopted $\alpha' = \alpha = 30°$ in the calculations. From the photographs we found the change in the angle $\theta_i$; absolute values were found from the calculated values of the angle at the periphery.

Figure 2b compares the functional dependence $\theta_i(r)$ with calculations for two distributions of the current density, $j(\rho)$, where $\rho$ is the radius of the magnetic surface. The solid line corresponds to a step profile of the current,

$$j(\rho) = \begin{cases} j_0 & \text{for } 0 \leqslant \rho/a_L \leqslant 0.45 \\ 0 & \text{for } 0.45 < \rho/a_L \leqslant 1 \end{cases}, \qquad (1)$$

while the dashed line corresponds to a smooth profile

$$j(\rho) = j_0 \, [\, 1 - (\rho/a_L)^2 \,]^3 \, . \qquad (2)$$

In the calculations the profiles of the electron density, $n_e(r)$, and of the temperature, $T_e(r)$, were taken in forms close to the experimental profiles:

$$n_e(\rho) = n_{e0} \, (1 - (\rho/a_L)^2\,), \quad T_e(\rho) = T_{e0} \, (1 - (\rho/a_L)^2\,)^2 \, . \qquad (3)$$

The data found on $\theta_i(r)$ are evidence for a sharp decrease in the current density at $r \approx 0.5a_L$.

Figure 2c shows a profile of the toroidal safety factor, $q_i^{tor}(r)^2$, found on the basis of the results on $\theta_i(r)$. The errors in the determination of $q_i^{tor}(r)$ in our measurements were determined by the errors in coordinating the evaporation rate $\dot{N}$ with the spatial coordinate ($\pm 1$ cm) and by the statistical errors in the reading of the angle $\theta_{eff}$. Among the uncontrolled sources of errors we should mention the displacement of the plasma column with respect to the chamber and the deviation of the pellet trajectory from the direction toward the center of the tokamak chamber. The curve in Fig. 2c corresponds to the profile $q_c^{tor}(r)$ calculated from the distributions $j(\rho), n_e(\rho), T_e(\rho)$ in accordance with (1) and (3). All the calculations of the profiles $\theta(r)$ and $q(r)$ incorporated toroidal corrections for conditions corresponding to an equilibrium of the plasma column.[2] It was assumed that the magnetic surfaces are nonconcentric tori of circular cross section. In regimes with $q(a_L) \approx 3$, the $x$-ray measurements of the electron temperature profile and of the profile of the effective charge[3] point to a distribution of the cylindrical safety factor $q(r)$ described approximately by

$$q(r) = \frac{q(a_L)\,(r/a_L)^2}{1-[1-(r/a_L)^2]^4}. \qquad (4)$$

This distribution is shown by curve 2 in Fig. 2c. The crosses are experimental points for $q = 1$, 3/2, and 2. The profiles $q_i^{tor}(r)$ are quite different from that described by (4). In particular, the zone with $q \lesssim 1$ is wider by a factor of about 1.5, according to our data, and the profile $q_i^{tor}(r)$ is steeper than $q(r)$ at $r > 0.5a_L$. At the center of the tokamak, $q_i^{tor}(r)$ is close to unity and approximately constant. The behavior of the inclination of the field line for the current profile corresponding to (4) [profile (2)] does not agree as well with the experimental data in Fig. 2b as the behavior corresponding to profile (1) does. A current profile slightly steeper than that calculated from the Spitzer conductivity was also found in experiments on the injection of deuterium pellets in the TFR tokamak.[4] At the same time, several other methods, which perturbed the plasma to a lesser extent—a lithium beam[5] and Faraday rotation[6]—lead to a good agreement between the measured current profile and that calculated from the conductivity. Identifying the reasons for the discrepancies between the experimental data and the theoretical predictions requires more comprehensive experiments. Some possible causes which should be noted are elevated values of the effective charge at the periphery. (This quantity has not been monitored in the experiments that have been reported.) Another possibility is a perturbation of the current profile by the pellet, although data from MHD observations indicate that graphite pellets have essentially no effect on MHD modes during the evaporation, implying that there are no pronounced perturbations of $j(r)$.

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