Local measurements of poloidal magnetic field and safety factor *q* near discharge axis by active particle diagnostic method in the Tuman-3 tokamak

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The poloidal magnetic field and the safety factor q have been determined experimentally for the first time from the angular distribution of the hydrogen atoms produced in the dissociation of molecules by the diagnostic beam. In the Tuman-3 tokamak, the safety factor 5 cm from the discharge axis is $q = 2.6$ at a current $I_d = 40$ kA.

Information on the current distribution and the associated distribution of the poloidal magnetic field is exceedingly important for reaching an understanding of the stability of the plasma column in tokamaks and of the particle and energy transport processes. A possible method for local measurements of the poloidal field was proposed in Ref. 1 (see also the monograph in Ref. 2). That method is based on the injection of a molecular hydrogen beam with an energy on the order of 10 keV into the plasma and the subsequent measurement of the angular distribution of the hydrogen atoms emitted from the plasma. These atoms are formed during the successive ionization of the molecules and dissociation of the molecular ions. The possibilities of this method have recently been analyzed for the case of the ASDEX tokamak.[3]

Let us examine an experimental layout for implementing this method of measuring the poloidal field. We assume that a neutral beam of hydrogen molecules with an energy ~10 keV is injected along a vertical chord in a tokamak at a certain distance r_b from the discharge axis [Fig. 1(a)]. The transverse dimensions of the beam along the direction of the major radius of the tokamak are small in comparison with the radius of the plasma column, a. We also assume that the Larmor radius of molecular ions with an energy equal to the energy of the molecules in the beam is small in comparison with a. This beam serves as a source of atoms which appear as a result of two successive processes: the ionization of molecules (the predominant process is the ionization which results from charge exchange with protons, $H_2 + p \rightarrow H_2^+ + H^0$) and the dissociation of molecular ions (primarily through collisions with electrons, $H_2^+ + e \rightarrow H^0 + H^+ + e$).

Let us consider the flux of atoms which are emitted in the median plane of the torus. Because of the inclination $\varphi = B_\varphi / B_\theta$ of the magnetic field lines with respect to the principal plane of the torus (this inclination stems from the current flow), the velocity of the molecular ions at the time at which they are formed near the principal plane can be thought of as consisting of two components, one transverse with respect to the longitudinal field, $V_\perp = V_0 \cos\varphi$, and one longitudinal with respect to this field, $V_\parallel = V_0 \sin\varphi$. If the subsequent dissociation occurs sufficiently rapidly (over the time

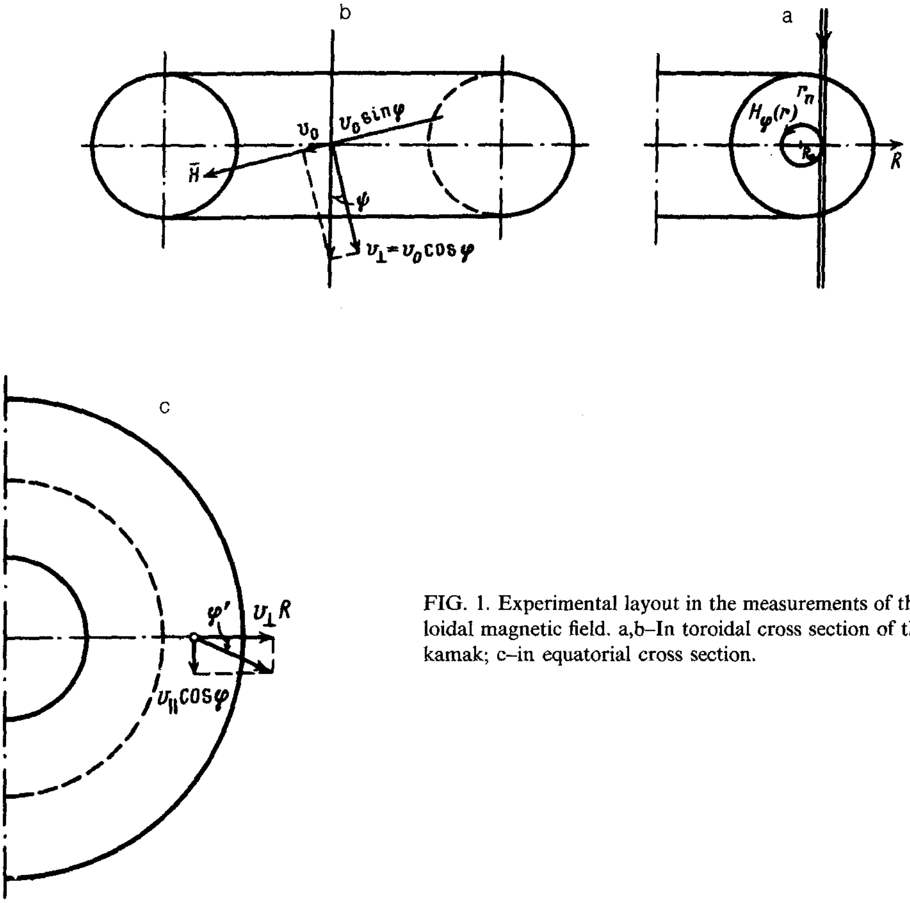

FIG. 1. Experimental layout in the measurements of the poloidal magnetic field. a,b–In toroidal cross section of the tokamak; c–in equatorial cross section.

required for one or a few orbits of a Larmor circle), it can be assumed that the relation between these velocities remains constant and that the atoms which appear as a result of the dissociation and which are emitted in the median plane of the torus escape in the direction which makes the following angle with respect to the direction of the major radius [Fig. 1(c)]:

$$\varphi' = \tan^{-1}\frac{V_\parallel \cos\varphi}{V_\perp} = \tan^{-1}\frac{V_0 \sin\varphi \cos\varphi}{V_0 \cos\varphi} = \tan^{-1}\sin\varphi \approx \varphi. \qquad (1)$$

The relationship between φ and φ' was found in Ref. 3 for the case of nonvertical injection.

A displacement of the injected beam from the poloidal plane, on the other hand, has the consequence that even if there is no current in the plasma, e.g., in the case in which a beam is injected into a gas-filled chamber with a toroidal magnetic field, the direction in which the flux of secondary atoms escapes deviates from the direction of the major radius. In an actual experiment, the toroidal angle φ' is therefore the difference between the emission directions of the secondary atoms in the cases in which there is and is not a current in the discharge chamber.

For measurements of the angle φ' in the experiments at the Tuman-3, part of the complex particle and particle-spectroscopy diagnostic apparatus of Ref. 4 was used. Specifically, the DINA-4a injector, mounted in a vertical port, and the five-channel hydrogen-atom analyzer, which made it possible to scan the plasma and the probing beam in the toroidal direction in the median plane of the torus, were used.

The beam produced by the DINA-4a injector consisted mostly (95%) of hydrogen atoms.[5] The analysis in Ref. 3 showed, however, that the use of the atomic fraction for measurements of the angle φ' is very inefficient, because of the low probability for the inverse charge exchange, itself a consequence of the small value of the density of neutral atoms in the plasma. The small molecular fraction (~3%) was accordingly used for the Tuman-3 measurements.

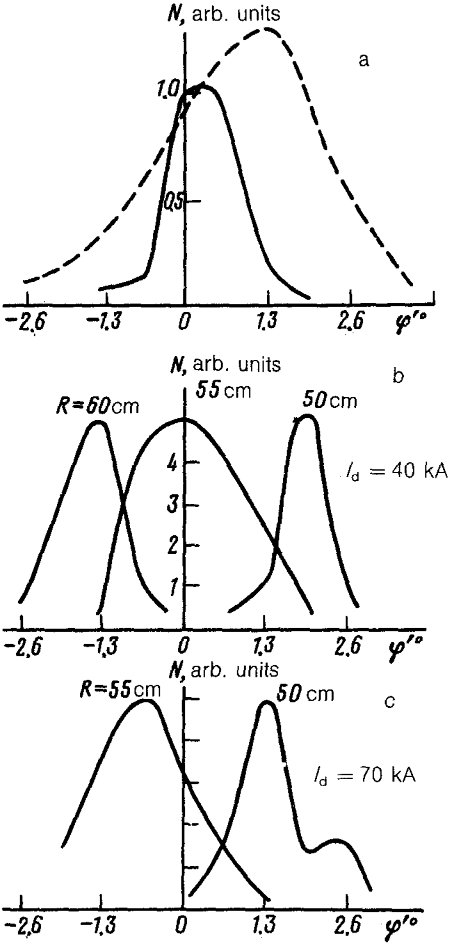

FIG. 2. a–Profile of the emission from the beam in the gas (dashed line) and profile of the flux density of secondary atoms in the gas with a longitudinal magnetic field (solid line); b,c–profiles of the flux density of secondary atoms from the plasma during the injection of the beam along various chords for discharges with currents $I_d = 40$ kA and $I_d = 70$ kA.

The angle φ' was measured under the following conditions in the Tuman-3: The longitudinal field was $B_0 = 5.2$ kG, the discharge current was $I_d = 40$–70 kA, and the average density was $\bar{n}e = 1\times10^{13}\,\mathrm{cm}^{-3}$. The major radius of the device is $R_k = 55$ cm, and the minor radius $a = 24$ cm. The low values of I_d were a consequence of geometric restrictions resulting from the dimensions of the diagnostic beam. The energy of the particles in the diagnostic beam was ~ 10 keV; the size of the beam in the poloidal direction was 2 cm; and the duration of the beam and the measurement time were 10^{-4} s. The results are shown in Fig. 2. In part a at the top, the dashed line is the profile of the emission from the beam in the gas filling the discharge chamber. This profile was measured in the Hα line with the help of a photomultiplier and the collimator of the five-channel atomic analyzer. Below we assume that the beam density profile is the same as the profile of the emission of the beam in the gas, and we have normalized all the results to the change in the beam density as a function of φ'. The solid line in this part of the figure is the profile of the flux density of secondary atoms with energies $E_{H_1^0} = 0.5\ E_{H_2^0} = 4.6$ keV emitted from the tokamak chamber with a longitudinal field and a gas (no plasma). The half-width of this curve, 1.3°, is determined by the angular resolution of the analyzer, the angular spread of the particles in the beam, and the broadening associated with the energy of Franck-Condon transitions with dissociation. The latter factor appears to be predominant.

The next part of the figure (part b) shows the profiles of the flux density of secondary atoms from the plasma with a discharge current $I_d = 40$ kA during the injection of the beam along various chords near the axis of the discharge chamber ($R_k = 55$ cm). Part c of the figure shows the corresponding results for $I_d = 70$ kA. The number of counts at the peaks ranged from 600 to 70 counts over 10^{-4} s, depending on the discharge current and the position of the injector. We see that the peaks shift as the injection direction is changed; the slope of the injector with respect to the

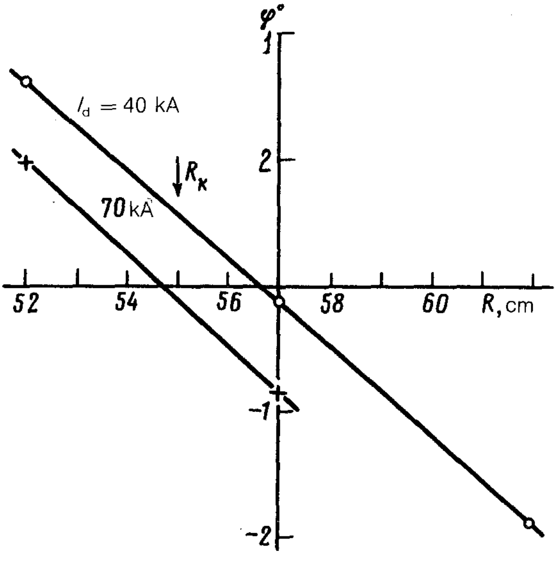

FIG. 3. Inclination of the magnetic field lines with respect to the direction in which the atomic beam was injected for discharges with currents $I_d = 40$ kA and $I_d = 70$ kA.

vertical was + 4.5° (R = 50 cm and 60 cm, respectively). The small linewidth corresponding to $R = 50$ cm at $I_d = 40$ kA, like the fluctuations in the intensity in the profile of this line at $I_d = 70$ kA, may have occurred because it was too close to the edge of the beam. An insufficient beam width could also explain the disappearance of the line corresponding to $R = 60$ cm as I_d was increased to 70 kA.

Figure 3 shows the results of measurements of the inclination of the magnetic field lines with respect to the median plane of the torus (φ) for various values of R and I_d. These results are of course averages over the beam width in the poloidal direction and over the path traced out by the H_2^+ ion along a 90° arc of a Larmor circle ($\sim\rho_L = 4$ cm). Because of the latter factor, the results of the measurements should be referred to coordinates shifted $\sim 0.5\rho_L$ from the axis of the probing beam, outward in our experiments. This shift was taken into account in the plotting of Fig. 3. It can be seen from this figure that in the case $I_d = 40$ kA the discharge axis shifted outward 1.7 cm from the chamber axis, and when I_d was increased to 70 kA the discharge axis moved 2 cm inward. This effect may be due to a decrease in the internal inductance of the plasma column.

Knowing the inclination of the magnetic field lines with respect to the median plane of the torus, φ, we can calculate the poloidal magnetic field B_φ, using the relation $B_\varphi(r) = B_\theta(R)\tan\varphi$. Knowing the position of the current axis, we can find the current density within a surface of radius r and the value of the safety factor $q(r)$. For this purpose we use the expressions

$$j(r) = \frac{1{,}6}{r} B_\theta(R_0) \frac{R_0}{R_0 + r} \tan\varphi; \quad q(r) = \frac{|r|R}{R_0^2} \frac{1}{\tan\varphi}, \tag{2}$$

where $j(r)$ is in amperes per square centimeter; r, R_0, and R are in centimeters; and B_θ is in gauss.

The results found by this procedure are given in Table I.

It can be seen from this table that the current density near the center of the plasma column remains essentially constant as the current is raised. This result might

TABLE I.

I_d kA	$q(a)$	R_0 cm	$r = R - R_0$ cm	$B_\varphi(r)$ G	$j(r)$ A/cm^2	$q(r)$
40	9.3	56.7	− 4.7	162	54.5	2.8
			+ 0.3	12	62.6	2.4
			+ 5.3	154	45.9	3.3
70	5.3	54.7	− 2.7	97	52.7	2.9
			2.3	76	53.0	3.1

be attributed to, for example, a broadening of the current density profile. The internal inductance decreases in the process; i.e., the displacement of the plasma column also decreases, in agreement with the experimental data (Table I).

In summary, these experiments demonstrate that it is possible to carry out local measurements of the poloidal magnetic field and of the safety factor near the discharge axis in tokamaks.

[1] F. C. Jobes, *Second Topical Conference on High-Temperature Plasma Diagnostics,* Report LA-7160-C, Santa Fe, 1978, p. 101.

[2] É. I. Kuznetsov and D. A. Shcheglov, *Diagnostic Methods for Hot Plasmas,* Atomizdat, Moscow, 1980, p. 73.

[3] W. Herrmann, *Sixteenth European Conference on Controlled Fusion and Plasma Physics,* Vol. 13B, Part IV, Venice, p. 1541.

[4] A. I. Abramov *et al.,* Preprint No. 1205, A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad, 1983.

[5] V. I. Davydenko *et al.,* Fiz. Plazmy 7, 464 (1981) [Sov. J. Plasma Phys. 7, 253 (1981)].

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