Comparison of the Radial Potential Profile Measured in a Tokamak to Predictions of Stochastic Magnetic Field Theory

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A space potential distribution which is positive at all radii has been measured in the research tokamak RENTOR. This is in sharp contrast to negative potential wells observed in other devices. The positive potential distribution is in qualitative agreement with the predictions of stochastic magnetic field theory.

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The radial electric field in tokamaks has received renewed attention on the basis that it might provide some insight as to the cause of the anomalously high electron thermal transport and as to the degradation of confinement at high levels of neutral-beam injection.[1-3] Particle diffusion in axisymmetric toroidal geometry is automatically ambipolar[4] and the radial electric field is related to the pressure gradient and plasma rotation by the radial component of the flux-surface-averaged ion-momentum equation

$$\frac{-\partial\phi}{\partial r}=E_r=\frac{1}{n_i e_i}\frac{\partial P_i}{\partial r}+\langle v_{\phi i}B_\theta\rangle-\langle v_{\theta i}B_\phi\rangle. \quad (1)$$

For Ohmic plasmas or beam-heated plasmas with balanced beam injection the ion pressure gradient should be the dominant term and it should drive a negative potential well. Unbalanced neutral-beam injection imparts a large toroidal velocity to the ions and $v_{\phi i}B_\theta$ is the dominant mechanism determining the radial electric field.[2,3] Tokamaks, however, are subject to some nonambipolar losses such as dumping of runaway electrons, charge exchange,[5] ripple diffusion,[6] and possible stochastic magnetic field fluctuations.[7-9] For some operating regimes these nonambipolar losses may be the dominant mechanism determining the radial electric field. Equation (1) must still be obeyed but now the toroidal velocity must adjust to compensate for the ambipolar field.

Measurements on ST[10] and more recently on ISX-B[2,3] showed a negative potential well for Ohmic-heated pulses in qualitative agreement with the ion pressure gradient. On beam-heated ISX-B discharges the $v_\phi B_\theta$ term dominated and the measured potential and toroidal rotational velocity profiles were in qualitative agreement with Eq. (1). Measurements on Ohmic-heated discharges on TM-4[11] also showed a negative potential well when the central plasma density was $5\times10^{13}/\text{cm}^3$. The well depth decreased as the density was decreased and a region of positive potential built up at large radii. At a density of $5\times10^{12}/\text{cm}^3$ the potential was positive over about two thirds of the plasma.

In this paper we report potential profile measurements on the small research tokamak, RENTOR. The potential is positive at all radii, is of the order of kT_e/e, and is only a weak function of radius. We have also measured the n and T_e profiles, and the relationship between the measured ϕ, n, and T_e profiles is in qualitative agreement with the predictions of Harvey *et al.*,[7] which are based on stochastic field fluctuations. It should be noted, however, that Waltz[9] argues that for stochastic field fluctuations due to internal modes, the plasma flow is automatically ambipolar and, consequently, the fluctuations do not drive a radial electric field.

RENTOR is a small, Ohmically heated tokamak[12] characterized by $R=45$ cm, $a=15$ cm, $B_T=0.4$ T, $I=20$ kA, $n_e(0)=2\times10^{12}$ cm^{-3}, $T_e(0)=125$ eV, and a pulse length of 14 msec. Typical current-voltage characteristics are shown in Fig. 1. The heavy-ion

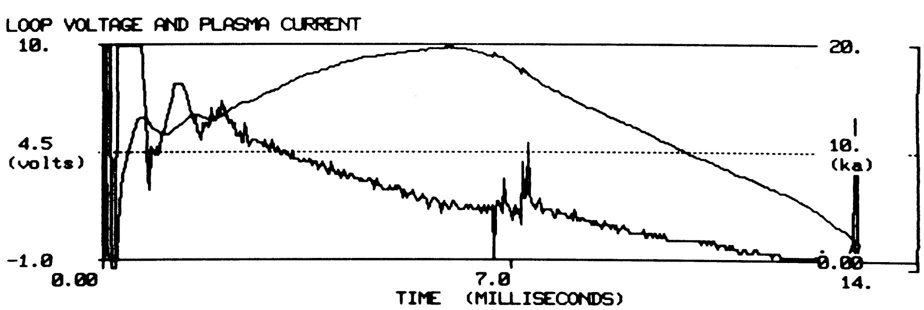

FIG. 1. Typical plasma current and loop voltage for RENTOR.

beam probe consists of a 10–25-keV Cs^+ beam injected vertically into the plasma. Either Cs^{++} or Cs^{+++} secondary ions formed by electron impact are detected outside the magnetic field region with use of an electrostatic energy analyzer. The injected primary beam is swept radially through the plasma in approximately 1 msec to produce a series of radial profiles. The space potential distribution is obtained in the conventional manner[13,14] by measurement of the energy difference between primary and secondary ions for either Cs^{++} or Cs^{+++}.

The density and electron temperature profiles can be determined from the total current of Cs^{++} and Cs^{+++}. The effective cross sections for electron-impact ionization leading to Cs^{++} and Cs^{+++} have different temperature dependences. The ratio of the two secondary ion currents is a very sensitive function of T_e in the range appropriate for RENTOR. Once T_e is determined, the density is obtained from the total current of either ion. In the present experiment Cs^{++} and Cs^{+++} could not be measured simultaneously since the system has only one electrostatic energy analyzer.

Figure 2 shows a composite of the radial profiles obtained for space potential and total ion current for both Cs^{++} and Cs^{+++}. The profiles were evaluated approximately 5 msec after the formation of the plasma when the Ohmic heating current is maximum. Three separate profiles are shown for each species, each corresponding to a different shot and a slightly different angular position of the energy analyzer. The different angular settings were used to minimize angular corrections in the space potential data.[15] The space potential was evaluated only when the correction due to the entrance angle of secondary ions into the analyzer was less than 10 V. The shot-to-shot reproducibility is quite good, and most of the scatter in the data is due to actual fluctuations in both space potential and total current.

The space potential determined from either Cs^{++} or Cs^{+++} should be the same. Figure 2 shows that the space potential is clearly positive and of the order of $\cong 140$ V, but the potential determined from Cs^{++} is consistently lower by $\cong 20$ V than that determined from Cs^{+++}. This may be due to a systematic error in our calibration procedures, or to a real change in the space potential. Approximately 30 min elapsed between the completion of the Cs^{+++} data and the initiation of the Cs^{++} sequence because of the required changes in the beam energy and the necessity for refocusing the primary beam. The important point, however, is that the space potential is definitely positive, in sharp contrast to the results from other tokamaks. We also note that the potential gradients are not strong in the central region of the plasma, indicating a relatively weak electric field.

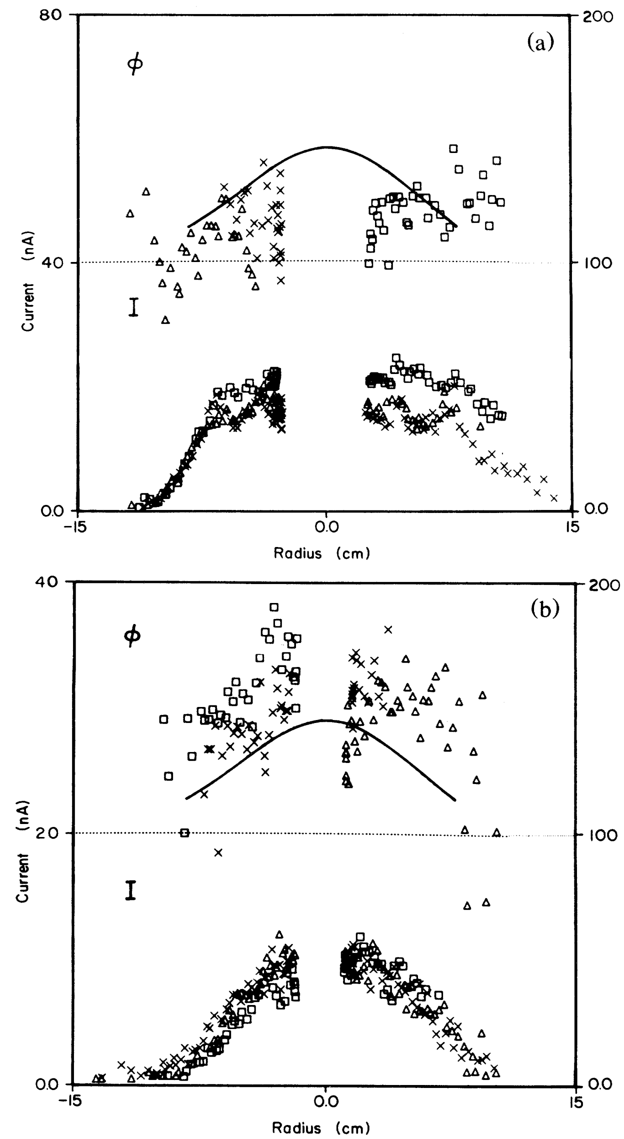

FIG. 2. (a) Space potential (upper set of data points) and total-ion-current profiles with use of CS^{++}. Solid curve is from Eq. (2). (b) Space potential (upper set of data points) and total-ion-current profiles with use of Cs^{+++}. Solid curve is from Eq. (2).

The n and T_e profiles derived from the data in Fig. 2 are shown in Fig. 3. The electron temperature profile is fairly symmetric about the center of the vacuum chamber, and can be reasonably approximated by the Gaussian distribution shown. There is some evidence that the density profile is slightly hollow, but there are larger errors involved with the density determination than with the electron temperature. The major source of error is the size of the sample volume from which secondaries are collected, which varies along a detector line. Since the T_e measurement involves the ratio of

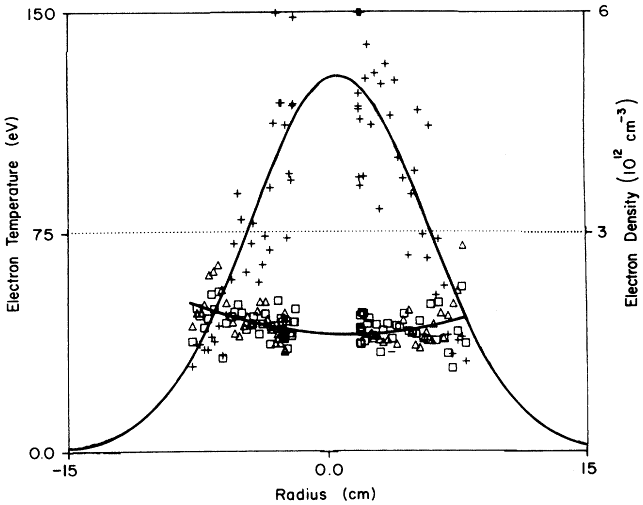

FIG. 3. Electron temperature (Gaussian shaped curve) and density profiles evaluated from the data in Fig. 2.

Cs^{++}/Cs^{+++}, the errors in sample volume cancel to first order. The density measurement, however, depends on the absolute value of the sample volume at any point.

The positive space potential in RENTOR is clearly different from the measured potentials in ST, ISX-B, and TM-4. RENTOR operates at a lower density than these other devices, and there is reasonable consistency with the TM-4 scaling of potential with density. It is clear that the ion-pressure gradient is not the major term in determining the radial electric field and that some nonambipolar process must be playing a dominant role. One possible process is stochastic fluctuations in the magnetic field. Stochastic fluctuations can cause the field lines to wander out to the wall or limiter, thereby providing a preferential loss channel for electrons with high parallel velocity. This could also explain the anomalously high electron thermal loss.

At the present time, there is no technique for obtaining direct, spatially resolved measurements of magnetic field fluctuations inside the plasma. Harvey *et al.*[7] have derived an approximate relation between potential, density, and electron temperature profiles based on stochastic field fluctuations. This relation is obtained by addition of a term of the form $\mathscr{L}(rD)\mathscr{L}\langle f\rangle$ to the kinetic equation,[16] where $\mathscr{L}$ is the operator

$$\left(\frac{\partial}{\partial r}\right)\bigg|_{v_{\parallel},v_{\perp}} - \left(\frac{eE_A}{mv_{\parallel}}\right)\left(\frac{\partial}{\partial v_{\parallel}}\right)\bigg|_{v_{\perp},r}.$$

D is the stochastic field diffusion coefficient and E_A is the ambipolar radial electric field. The kinetic equation is integrated to obtain the particle flux in terms of the density and temperature gradients and the radial electric field. Neglect of the ion particle flux leads to the relation

$$E_r = \frac{-\partial\phi}{\partial r} = -\frac{kT_e}{e}\left(\frac{1}{n}\frac{\partial n}{\partial r} + \frac{1}{2T_e}\frac{\partial T_e}{\partial r}\right), \qquad (2)$$

which is valid in a coordinate system where the field fluctuations are stationary. Equation (2) has been used to predict the potential distribution from the measured n and T_e profiles, which can then be compared to the experimentally measured potential. The predicted potential profiles are shown as the solid curve in Fig. 2.

The magnitude of the predicted potential is a sensitive function of the gradients in the edge plasma. It is possible to find reasonable extensions of the measured radial profiles such that the magnitude of the predicted potential at $r=0$ agrees with the measured potential, but there are also reasonable extensions that give different results. In addition, sheath potentials at the vacuum chamber wall could also affect the magnitude of the central potential. Since no measurements are available in the edge region and since the physics is determined by the electric field, we elected to normalize the predicted potential to 145 V at $r=0$. This provides the best fit to the experimentally measured potential profiles. There is qualitative agreement between the predicted and measured curves, but the predicted electric field is somewhat higher than one calculated from the measured potential profile.

If the predicted radial electric field is substituted into Eq. (1) and it is assumed that force balance is maintained by an induced toroidal velocity, the required velocity is 2.5×10^5 cm/sec. No attempt has been made to measure the velocity on RENTOR but this value is well below the sensitivity of most plasma-velocity measurements.

In summary, RENTOR displays a positive space potential which is in contrast to the negative potential wells that have been measured on ST, ISX-B, and TM-4. It should be emphasized that RENTOR operates in a very-low-density regime compared to these other devices, and as noted previously, the positive potential is consistent with density extrapolation of the TM-4 results. The positive potential distribution may be due to stochastic magnetic field fluctuations providing the dominant electron-loss channel on RENTOR. The results are in qualitative agreement with theory on the assumption that the fluctuations are externally bounded or induced. We speculate that on higher-density devices, particle pressure gradients play the dominant role in establishing the potential profile in the central region, but in the edge region, where the plasma parameters are similar to those in RENTOR, stochastic field fluctuations may modify the potential distribution.

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