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THE EFFECTS OF ROTATING FIELD FREQUENCY  
ON THE ROTAMAK CONFIGURATION

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ABSTRACT

Experiments have been undertaken at three rotating field frequencies, 1.0, 1.85 and 3.5 MHz, to determine the effect upon the rotamak configuration and the driven toroidal current. Toroidal current has been driven at all three rotating field frequencies for each of the gases studied. The results indicate that the 1.0 MHz frequency chosen for the rotating field in the high power AAEC rotamak experiments appears to be satisfactory.

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TOKAMAK DEVICES; COMPACT TORUS; PLASMA; MAGNETIC FIELDS; ROTATION; ELECTRIC CURRENTS; MHZ RANGE 01-100; CYCLOTRON FREQUENCY; HYDROGEN; ARGON; EXPERIMENTAL DATA

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## 1. INTRODUCTION

In the rotamak concept [Jones 1979], the driven toroidal current ( $I_\phi$ ) is generated by a rotating magnetic field. The current drive technique has been the subject of a number of theoretical studies [Blevin and Thoneman 1962; Jones and Hugrass 1981; Hugrass and Grimm 1981; Hugrass 1982], all of which have predicted that electron current can be driven provided that the following two conditions are fulfilled :

$$\omega_{ci} \ll \omega \ll \omega_{ce} , \quad (1)$$

$$\nu_{ei} \ll \omega_{ce} , \quad (2)$$

where  $\omega$  is the angular frequency of the rotating magnetic field,  $\omega_{ci}$  and  $\omega_{ce}$  are the electron and ion cyclotron frequencies (calculated with respect to the amplitude of the rotating field), and  $\nu_{ei}$  is the electron-ion collision frequency. At the lower frequency limit of condition (1), ions will tend to come into rotation leading to a bulk plasma rotation with no net driven current. At the upper frequency limit, electron inertia will prevent electron current generation. Experiments in which these conditions have been fulfilled [Hugrass *et al.* 1981; Durance 1983; Durance *et al.* 1984] have confirmed that substantial current can be driven, but it is not clear how closely  $\omega$  can approach either limit before the driven current decreases significantly.

The above conditions do not specify the optimum frequency. If it is assumed that there is a total of  $N$  electrons rotating synchronously with the magnetic field at some frequency,  $f$ , the total driven current is given by

$$I_\phi = N e f .$$

This implies that  $I_\phi$  is proportional to the frequency of the rotating field. Thus it could be concluded that the highest frequency, satisfying the current drive conditions, should be chosen to maximise the driven current.

Although near-perfect penetration of the rotating field into the plasma has been observed in certain rotating field experiments [Hugrass *et al.* 1981; Stephan 1984], all rotamak experiments so far have shown evidence of screening currents [Durance 1983; Durance *et al.* 1984]. The presence of electron-ion collisions leads to slip between the electron fluid and the rotating field, and to the generation of currents, which partially screen out the rotating field from the interior of the plasma. This screening is likely to become more significant as the frequency of the rotating field is increased, and could lead to a decrease in the driven current with increasing frequency, in contradiction to the above rigid-rotor analysis.

Experiments have been undertaken at three rotating field frequencies — 1.0, 1.85 and 3.5 MHz — to determine their effect upon the rotamak configuration and the driven current.

## 2. APPARATUS

The discharge vessel, vacuum system, Helmholtz coils, and radiofrequency (RF) power amplifiers have been described elsewhere [Durance *et al.* 1984]. To permit operation at various frequencies, a new RF source and phase shifting network have been constructed. For operation at 1.0 MHz, the output stages of the power amplifiers and the matching circuit have been modified.

The same diagnostics (miniature magnetic field probes, current transformers, voltage probes and Rogowski belt) described by Durance *et al.* [1984] have been used in the present studies. The data collection and analysis for the 1 MHz results have been performed with an LSI-11/23 based data acquisition system linked to a Tektronix model 468 digital storage oscilloscope, and the measurements at 1.85 and 3.5 MHz were recorded on Polaroid film and digitised by hand.

## 3. MEASUREMENTS

The majority of experiments were performed using hydrogen as the filling gas, although some experiments were also performed with deuterium, helium and argon. With the existing preionisation scheme, there is a lower limit to the filling pressure at which each of the gases produces reliable discharges, ranging from  $\sim 25$  mPa for argon to  $\sim 100$  mPa for hydrogen.

At each frequency, the driven current was recorded for a range of pressures and applied vertical magnetic fields. The driven current normally increases with increasing applied vertical field, although if the vertical field is too large the discharge terminates. By careful adjustment of the filling pressure and applied vertical field, the largest driven current was found for each gas at each frequency. The discharge characteristics for any one given set of conditions were highly reproducible.

A set of discharge conditions was also chosen for each gas at each frequency. The driven toroidal current, the axial component of the magnetic field  $B_z$ , and the penetration of the rotating magnetic field into the plasma were measured. The radial position of the separatrix and the axial position of the neutral points were derived from these measurements.

The radial position of the separatrix is given by the zero of the poloidal flux function

$$\psi(r, 0) = 2\pi \int_0^r r' B_z(r', 0) dr'$$

obtained by integrating the radial scan of the axial magnetic field  $B_z(r, 0)$ . The neutral points were obtained from the axial scan of the axial magnetic field  $B_z(0, z)$ . Figure 1 shows the coordinate system for the rotamak experiment. Representative results from all the measurements are given in figure 2. More details of the measurements at 1.85 MHz are given by Durance *et al.* [1984].

#### 4. DISCUSSION

The maximum toroidal current which could be driven was observed to be dependent on the type of filling gas and on the rotating field frequency (see figure 3). At the two lower rotating field frequencies, 1.0 and 1.85 MHz, the toroidal current was sufficient to reverse the externally applied vertical field on-axis. For example, in a typical experiment such as that shown in figure 2a, with hydrogen as the filling gas and a rotating field frequency of 1.0 MHz, a toroidal current of  $\sim 400$  A was driven, and the magnetic probe measurements confirmed that an oblate compact torus magnetic field structure was generated and sustained for the duration of the rotating field ( $\sim 15$  ms). The RF power input to maintain this configuration was  $\sim 3$  kW.

However, at the rotating field frequency of 3.5 MHz, the maximum driven toroidal current in hydrogen was insufficient to reverse the applied vertical field on-axis; therefore a compact torus configuration was not achieved. In the case of argon plasmas, sufficient toroidal current was driven at all three frequencies to produce reversed field compact torus configurations in each case.

The input RF power data were not measured for every case, although there were indications that less RF power was available at 3.5 MHz than at the other two frequencies. Certainly at the highest frequency the amplitude of the currents in the Helmholtz coils was observed to be less, consequently the rotating magnetic field amplitude was smaller than at the lower frequencies. Within the plasma the amplitude of the rotating field was reduced even further by screening currents. For the discharges in hydrogen at 3.5 MHz,  $\omega \sim \omega_{ce}$  prevailed throughout the bulk of the plasma rather than  $\omega \ll \omega_{ce}$ , the condition specified for current drive. This accounted for the reduction in driven current at 3.5 MHz.

From figure 4, it is apparent that the screening currents become progressively more significant as the frequency increases, as was expected on the basis of the classical skin effect. As well as the screening currents within the plasma spheroid (*i.e.* inside the separatrix), there appears to be an additional layer of screening currents just inside the discharge vessel wall (see figure 4). This layer becomes more pronounced as the rotating field frequency increases. Nevertheless, despite only partial penetration of the rotating field into the plasma, significant toroidal current is driven at all frequencies which, in itself, suggests that the penetration must be better than the classical skin depth.

Lastly, it is noted that on the basis of the Hugarss-Kirolous theory [Hugarss and Kirolous 1984], the screening currents within the plasma might be expected to generate spontaneously a toroidal magnetic field of the form observed previously by Durance [1983]. This toroidal field would have opposite directions in the two halves of the minor toroidal cross section but no net toroidal flux. There is indirect evidence to suggest that such a structure may have been present at certain times during some discharges. For example, in the axial scan of the z-component of the magnetic field shown in figure 5, a double-humped distribution is evident. This is similar to the results observed by Durance [1983] whenever the toroidal field structure

was present.

## 5. CONCLUSIONS

Driven toroidal current was observed at each of the three applied rotating field frequencies. In hydrogen, the magnitude of the driven current decreased with increasing rotating field frequency, and resulted in insufficient current at the 3.5 MHz frequency to reverse the applied vertical magnetic field. This decrease may be attributed to the fact that the condition  $\omega \ll \omega_{ce}$  required for current drive is less well satisfied with increasing frequency.

In view of these results, the 1.0 MHz frequency chosen for the rotating field in the higher power AAEC rotamak experiments appears to have been satisfactory. There is no incentive to increase the frequency.

## 6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the many useful and stimulating discussions with Professor I.R. Jones.

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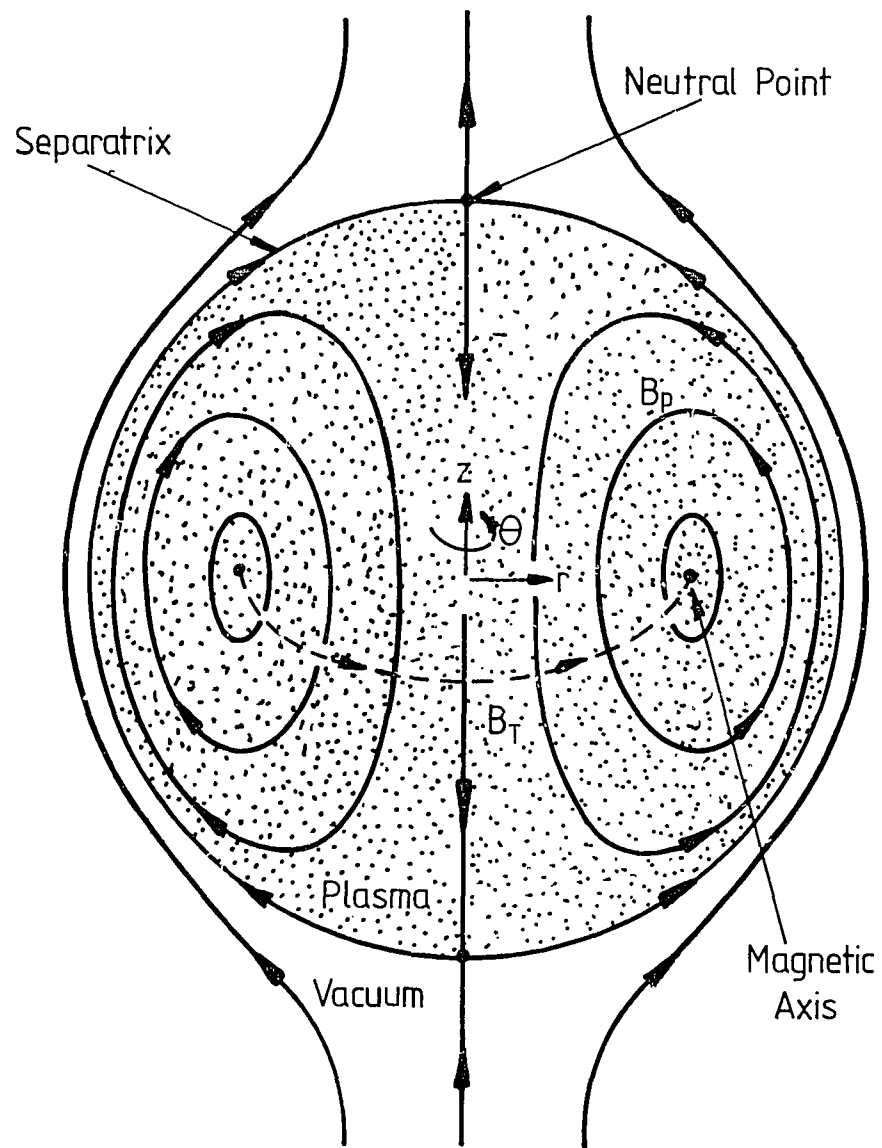


Figure 1 Magnetic field configuration of a compact torus device.  $B_p$  is the poloidal magnetic field.  $B_T$  is the possible toroidal magnetic field. The origin of the cylindrical coordinate system  $(r, \theta, z)$  used in this report is also indicated.

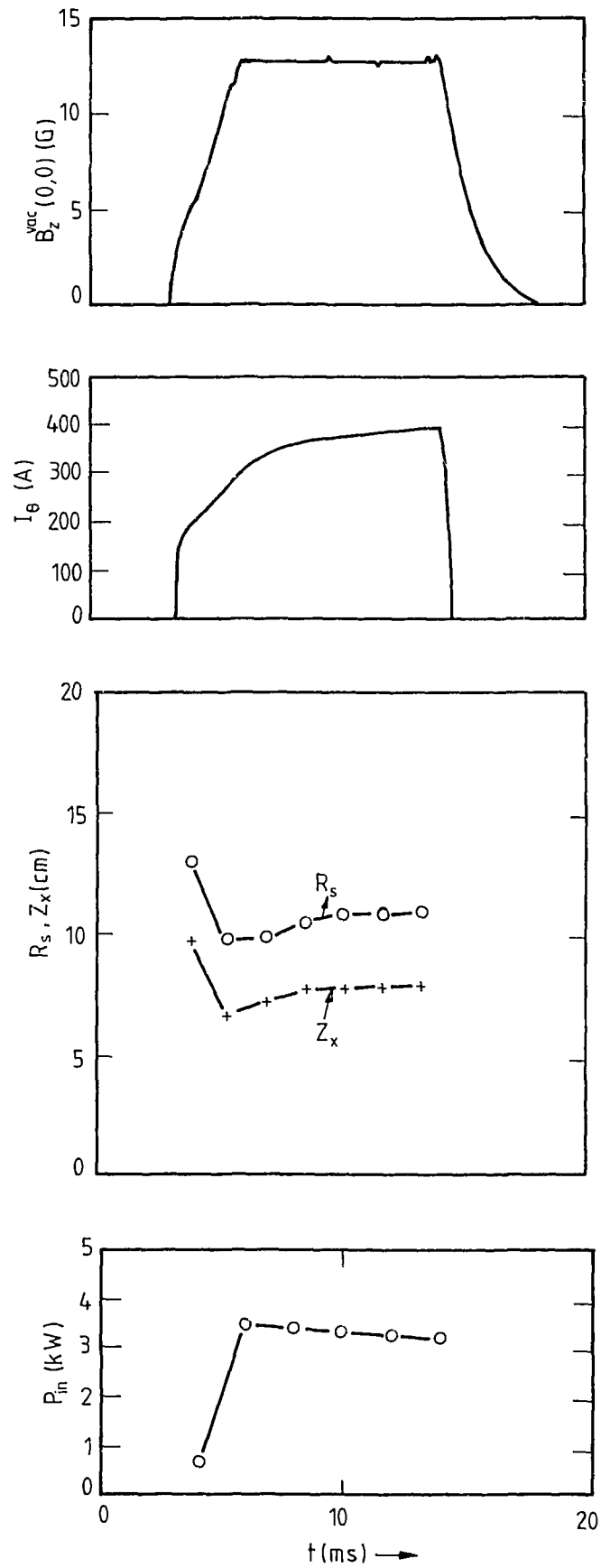


Figure 2

(a) A typical hydrogen discharge with a rotating field frequency of 1.0 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_s$ ; axial position of the neutral point,  $Z_x$ ; and the RF input power. The initial hydrogen filling pressure is 140 mPa.

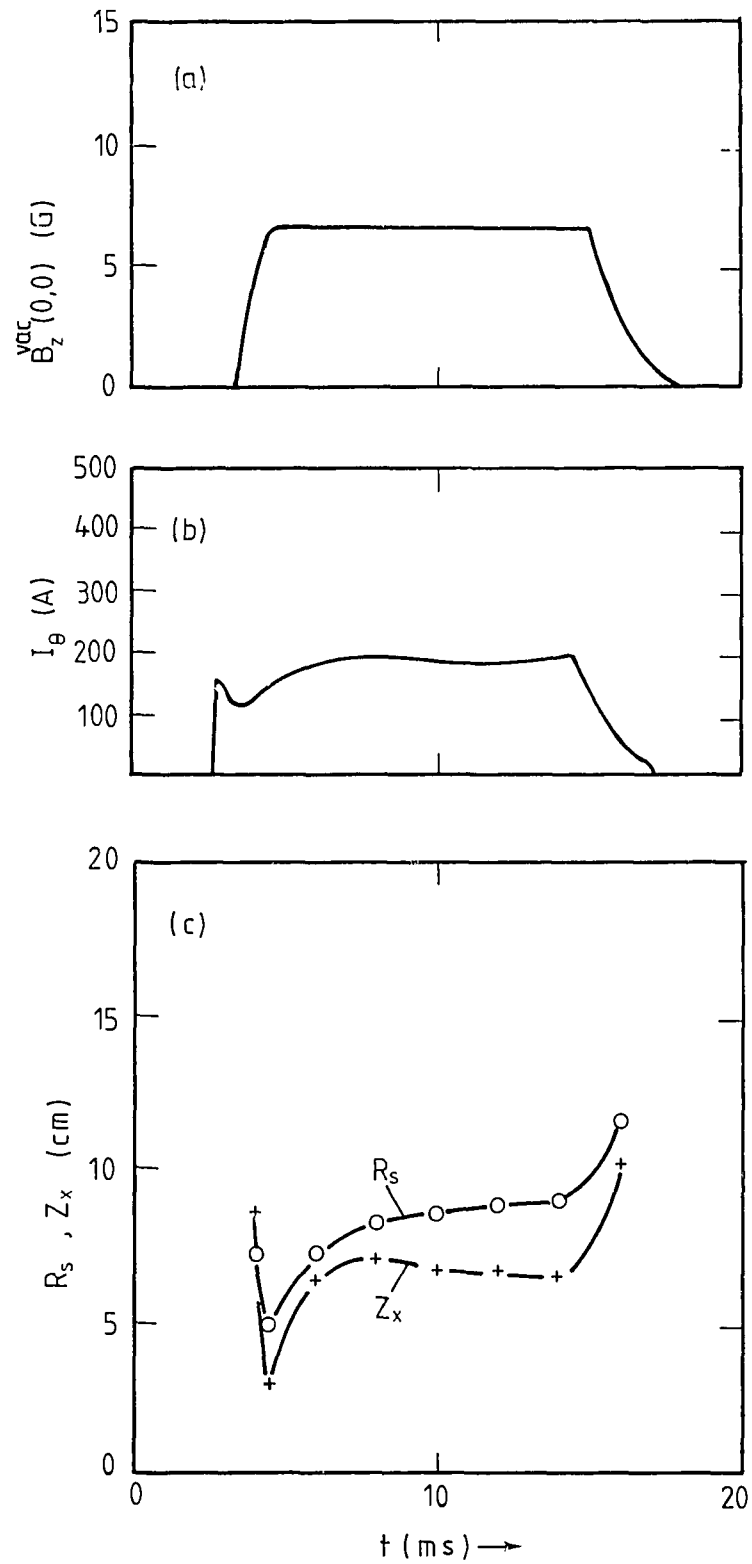


Figure 2 (b) A typical hydrogen discharge with a rotating field frequency of 1.85 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_s$ ; and the axial position of the neutral point,  $Z_x$ . The initial hydrogen filling pressure is 160 mPa.

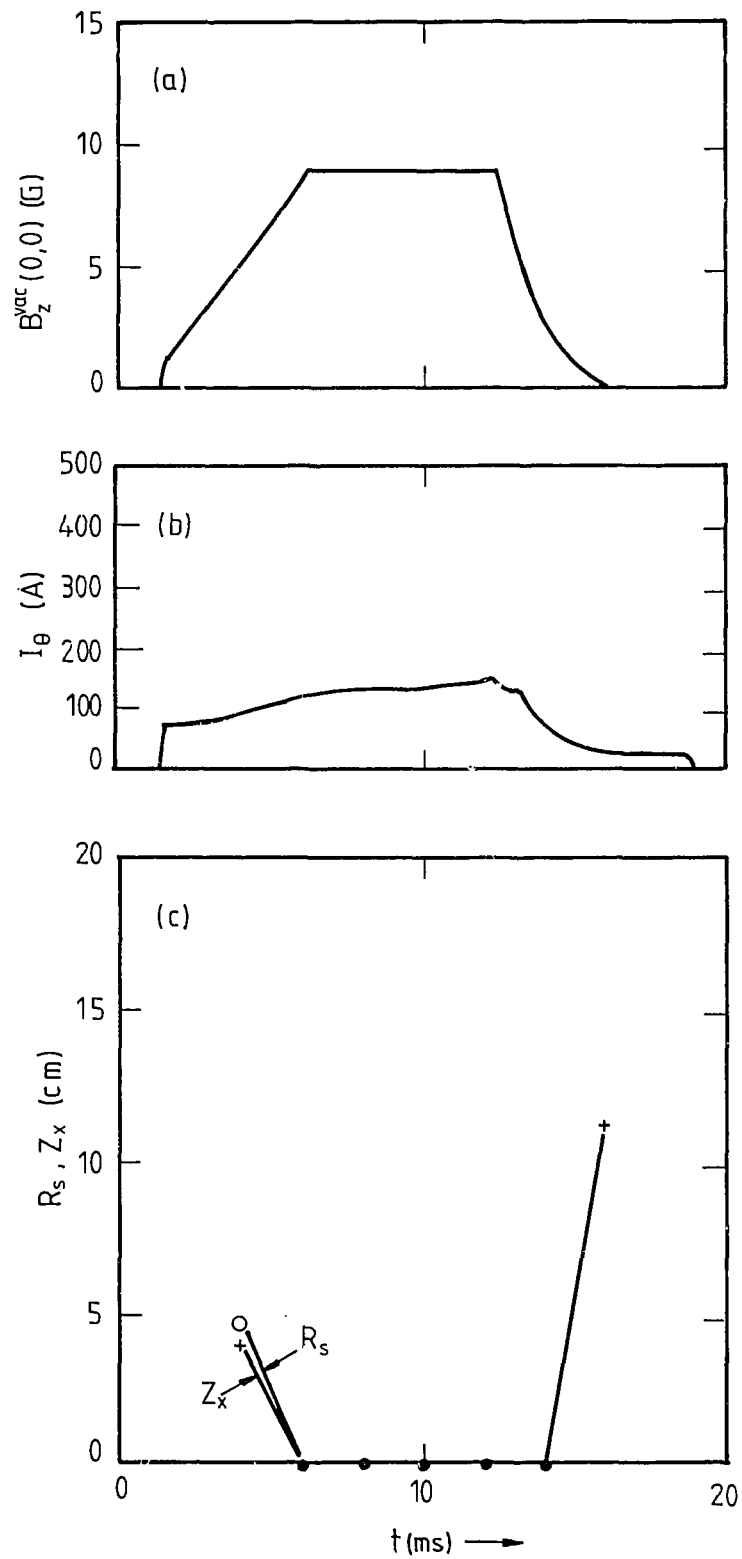


Figure 2

(c) A typical hydrogen discharge with a rotating field frequency of 3.5 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_s$ ; and the axial position of the neutral point,  $Z_x$ . The initial hydrogen filling pressure is 150 mPa.

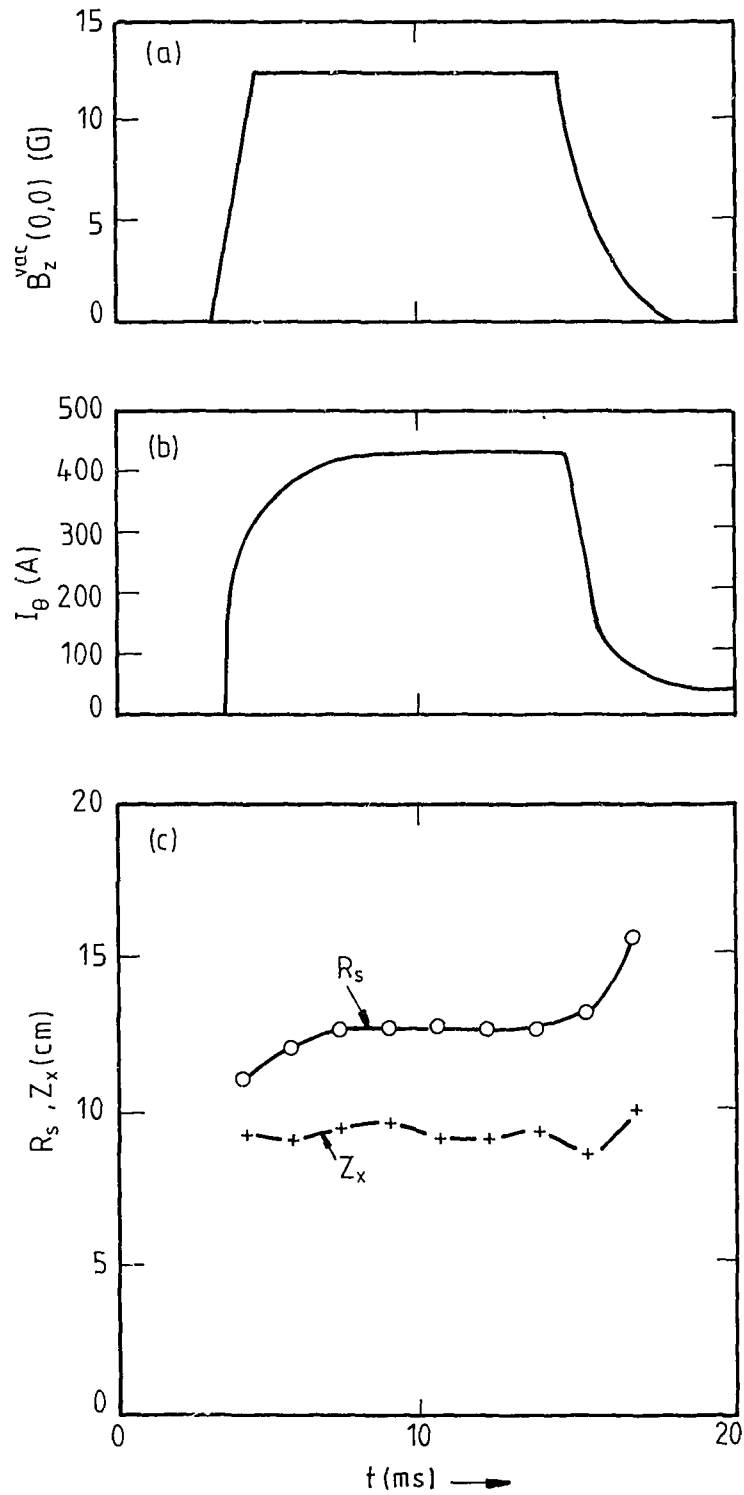


Figure 2

(d) A typical argon discharge with a rotating field frequency of 1.0 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_S$ ; and the axial position of the neutral point,  $Z_x$ . The initial argon filling pressure is 36 mPa.

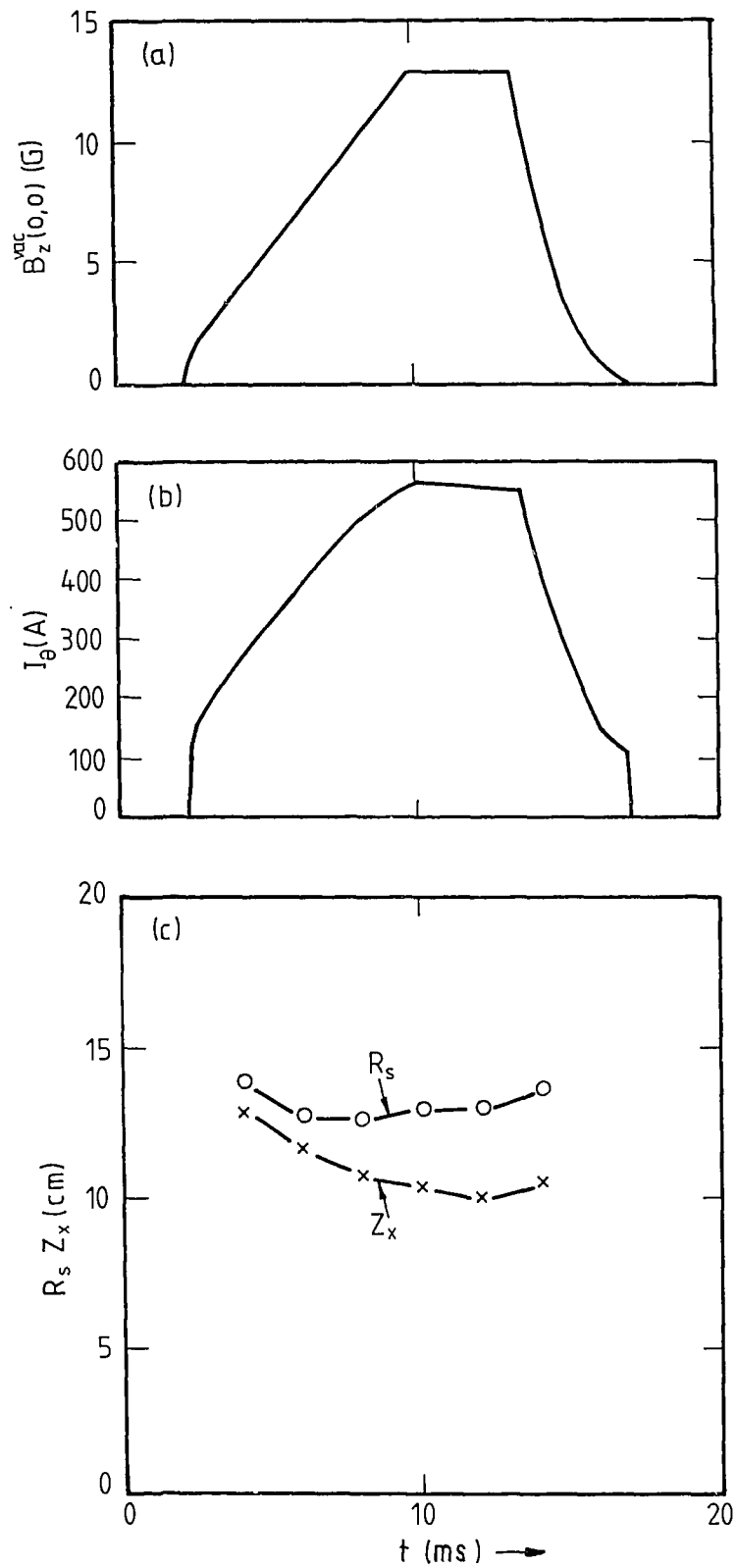


Figure 2

(e) A typical argon discharge with a rotating field frequency of 1.85 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_s$ ; and the axial position of the neutral point,  $Z_x$ . The initial argon filling pressure is 36 mPa.

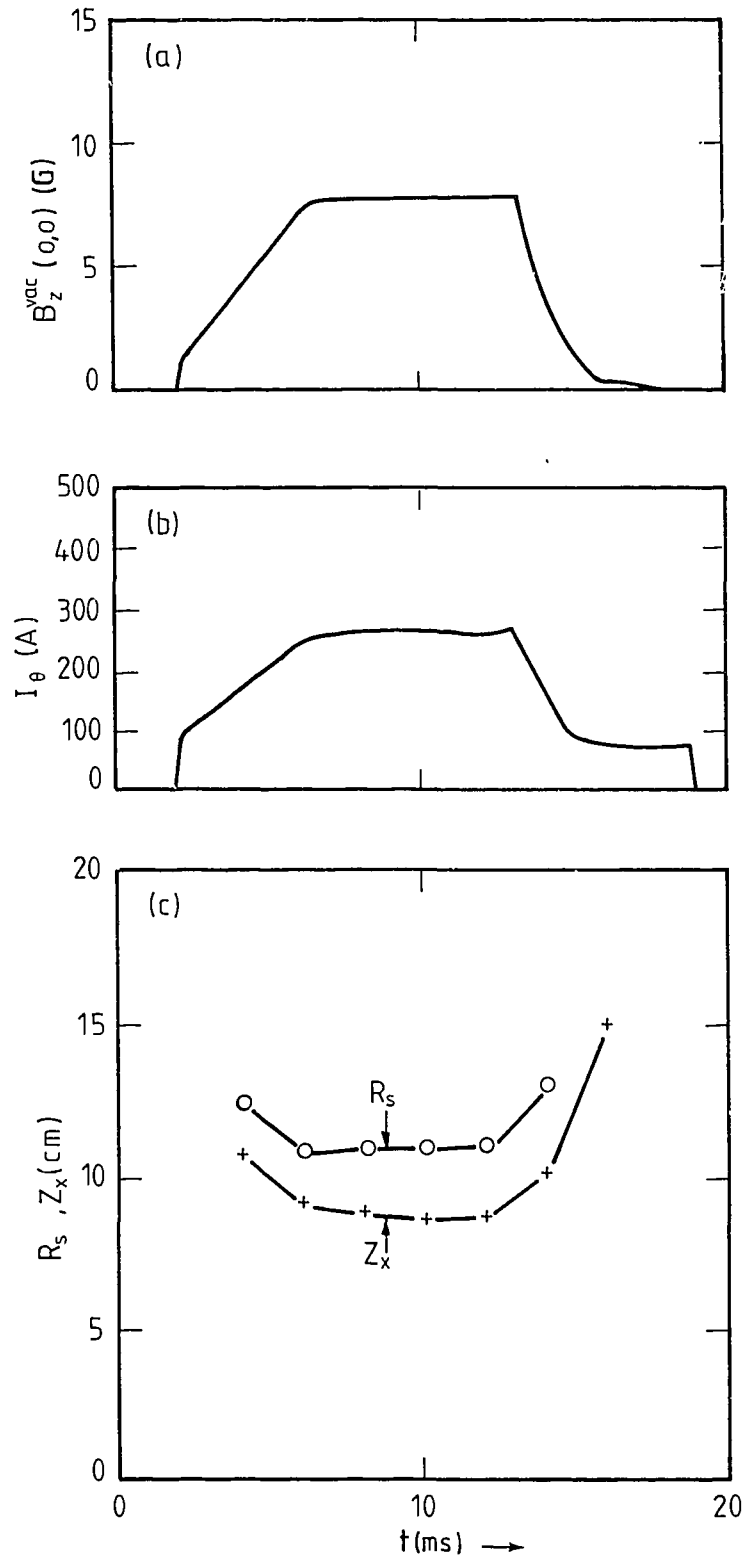


Figure 2 (f) A typical argon discharge with a rotating field frequency of 3.5 MHz showing the applied vertical magnetic field; the driven toroidal current; the radial position of the separatrix,  $R_s$ ; and the axial position of the neutral point,  $Z_x$ . The initial argon filling pressure is 40 mPa.

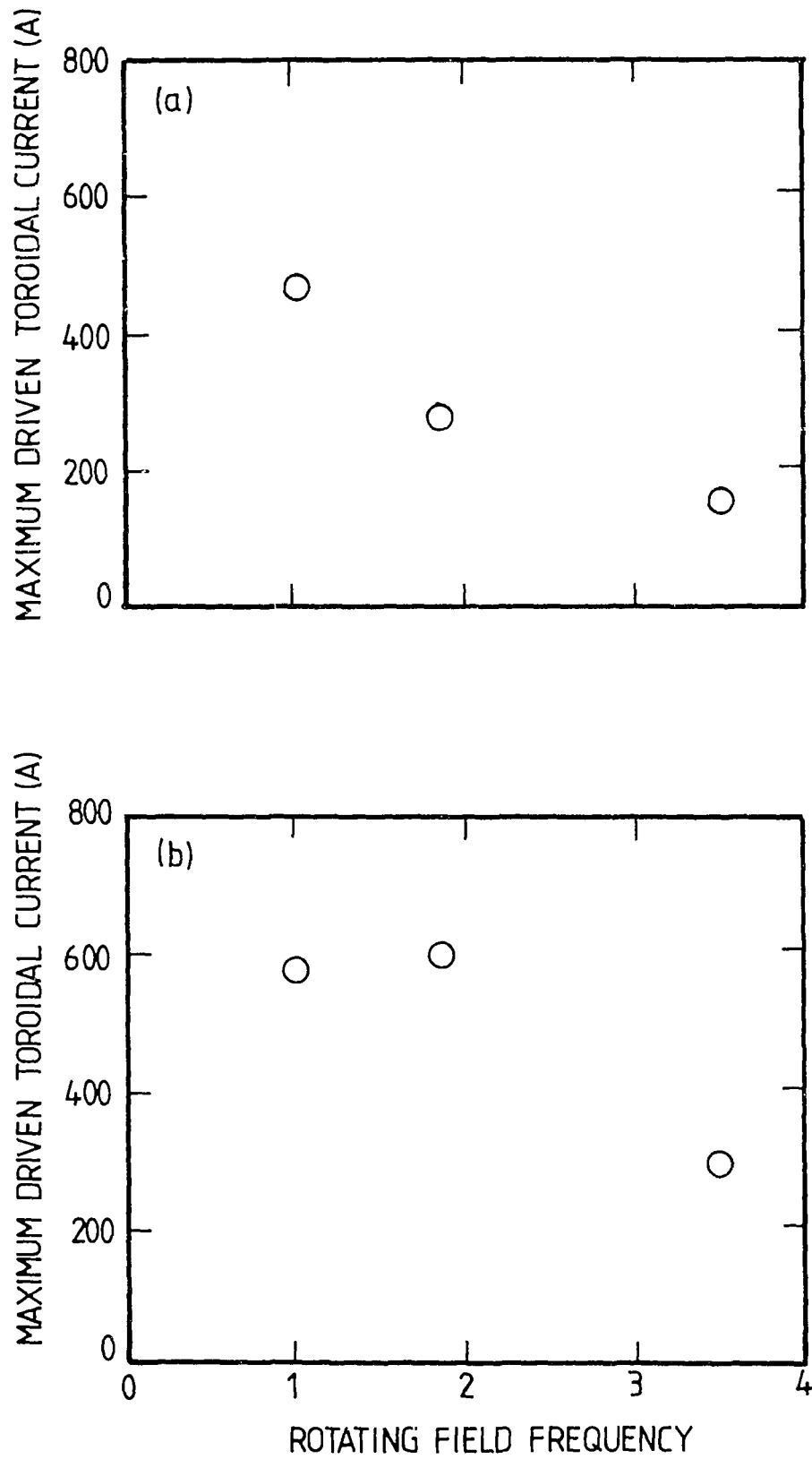


Figure 3 The maximum driven toroidal current as a function of the rotating field frequency for (a) hydrogen and (b) argon plasmas.

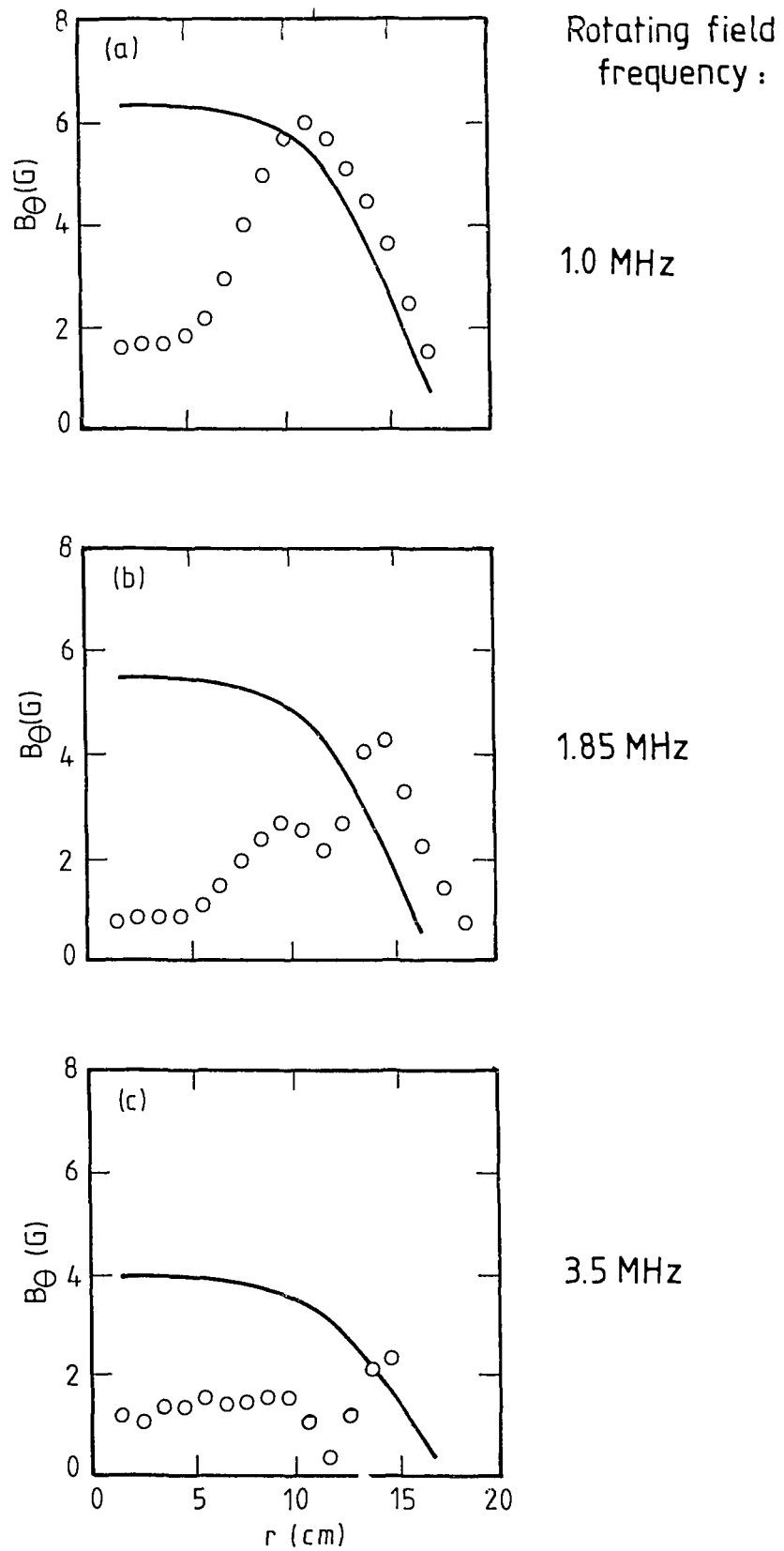


Figure 4

The variation of  $B_{\theta}(r)$  *i.e.* the penetration of the rotating magnetic field, with the rotating field frequency for a hydrogen plasma. Circles are measured data while solid lines represent vacuum distributions.

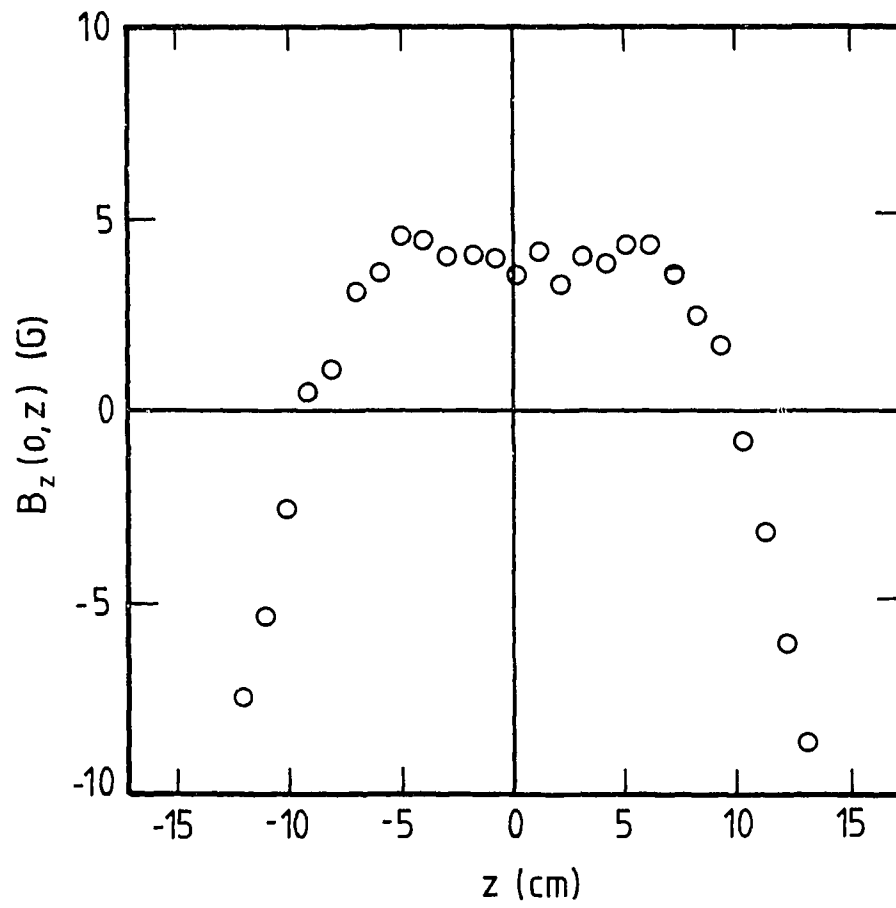


Figure 5 The axial distribution of the z-component of the magnetic field at 1 ms after the start of the discharge shown in figure 2(d).