Compact Torus Configuration Generated by a Rotating Magnetic Field: The Rotamak

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(Received 5 March 1980)

In the rotamak concept, a rotating magnetic field is used to drive the toroidal current in a compact torus device. A rotamak device is described and initial experimental results are presented. Toroidal currents in the range 6–10 kA have been produced. Magnetic probe and power measurements, together with zero-dimensional, time-dependent plasma model calculations, indicate that a compact torus configuration has been generated for which the Ohmic power input is balanced by line radiation.

PACS numbers: 52.55.Gb

The term compact torus refers to a set of devices which contain toroidal plasmas of low aspect ratio. The magnetic field configuration consists of internal and external poloidal fields (Fig. 1); in addition, there may be a toroidal field. These magnetic fields are usually generated by a combination of external coils with either beams of high-energy particles or thermal plasma currents. The reversed-field θ pinch,[1] the reversed-field mirror,[2] and the spheromak[3] are typical examples of these compact torus devices.

The technique of generating electron currents by means of transverse rotating magnetic fields was first investigated by Blevin and Thonemann[4] and Davenport *et al.*[5] Recently, a number of significant theoretical and experimental extensions to these early studies have been made.[6-8] The technique involves applying a rotating magnetic field in a direction transverse to the axis of a cylindrical plasma column. Provided that the angular frequency, ω, of the rotating field lies between the ion and electron cyclotron frequencies, calculated with reference to the amplitude of the rotating field, B_0, and provided the electron collision frequency is less than the electron cyclotron frequency, the electrons can be considered as "tied" to the lines of force of the rotating field. They rotate synchronously with angular frequency ω, whereas the ions (at least in the short term) have no net azimuthal motion. As long as the system remains azimuthally symmetric, no charge separation occurs and the electrons are not prevented from moving by space-charge fields.

In the rotamak concept,[9] a rotating magnetic field (rotating in planes normal to the z axis; see Fig. 1) is used to drive the steady toroidal current in a steady-state compact torus device. A z-directed external "vertical" field, produced by means of external coils, couples with this toroidal plasma current to provide the inwardly directed force necessary for the equilibrium of the plasma ring. The resulting magnetic field configuration consists of the linear combination of steady external and internal poloidal fields (see Fig. 1) with the applied rotating field which, in a sense, represents a time-varying toroidal field. To clarify this point, Fig. 2 shows a computed stereoscopic pair of two total field lines, at one instant of time, due to a steady ring current of 6 kA and a transverse rotating field of 70 G. It is seen that the toroidal magnetic configuration is cut by two, diametrically opposed cusps. The magnetic helix has a different sense on each

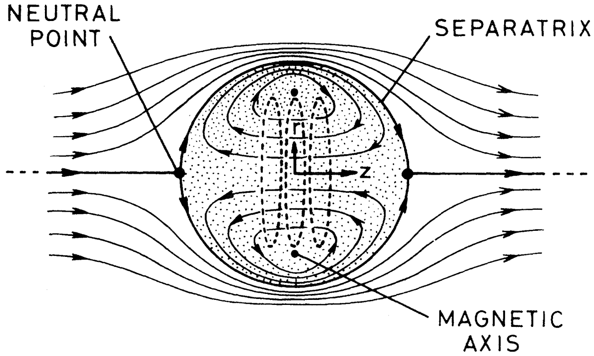

FIG. 1. Magnetic field configuration of a compact torus device. Dashed curves, possible toroidal magnetic field.

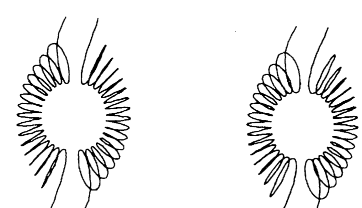

FIG. 2. A stereoscopic pair of diagrams of two total field lines of the rotamak configuration.

semicircular section. As time progresses the field pattern shown in Fig. 2 spins about the major toroidal axis (the z axis in the present context) with the frequency of the rotating field. Open field lines enter one cusp region and leave the other. It is not clear, however, that the difficulties usually encountered with static open lines arise in a time-varying situation where associated electric fields exist. These aspects remain to be examined in detail.

The purpose of this Letter is to present first results obtained in an experimental investigation of the rotamak configuration. A diagram of the apparatus is shown in Fig. 3. The Pyrex discharge vessel is spherical in shape (inner radius of 64 mm) and is equipped on the outside with a pair of orthogonally oriented Helmholtz coils. rf currents of the same frequency (0.67 MHz) and amplitude (~ 2 kA), but dephased by 90°, are passed through these coils to produce a magnetic field (~ 600 G on axis) which rotates about the z axis. The rf currents are generated by means of Weibel-type rf line generators which are modified in such a manner as to reduce substantially the necessary number of spark gaps.[10] The vertical field needed for equilibrium is produced by a pair of coils located on the z axis as shown in Fig. 3. Coils wrapped around the tube leading to the vacuum system are used to preionize the filling gas by means of separate rf and θ-pinch discharges. Argon was used as the filling gas both to ensure that the necessary inequality $\omega > eB_0/m_i$ was well satisfied and to take advantage of its relative ease of ionization at the low filling pressure which was used (1.70 mTorr). Experience showed that it was possible to achieve acceptable shot-to-shot reproducibility (± 5% variation in measured quantities) provided that the filling pressure was kept constant to within ± 0.05 mTorr. The quantities measured were the total toroidal current, I_φ, driven by the rotating field (measured by means of a Rogowski belt); the distribution of the z component of the magnetic field both along the r axis and the z axis (measured by means of a movable magnetic probe); and the power transferred between the rf line generators and the load.

Figures 4(a) and 4(b) show the $I_\varphi(t)$ oscillograms obtained without and with vertical field, respectively. For reference, Fig. 4(d) shows the characteristics of the rf pulses (shape, frequency, and duration) used in these experiments. In the absence of vertical field, the plasma ring is not magnetically confined and a comparison of Figs. 4(a) and 4(b) shows that the total toroidal current is substantially reduced under these conditions.

For the conditions under which Fig. 4(b) was obtained, I_φ initially increases to a peak value of

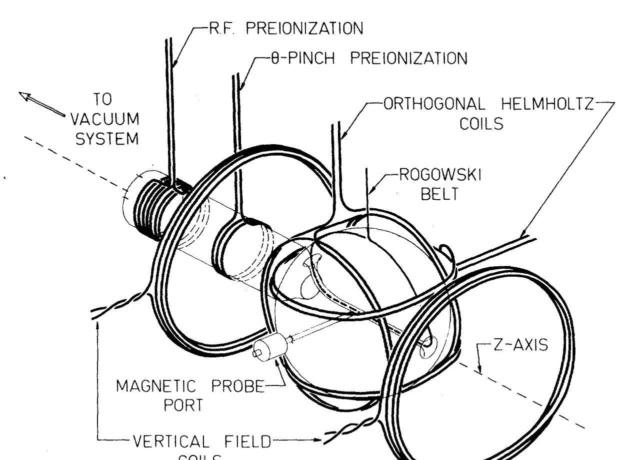

FIG. 3. Diagram of the rotamak apparatus.

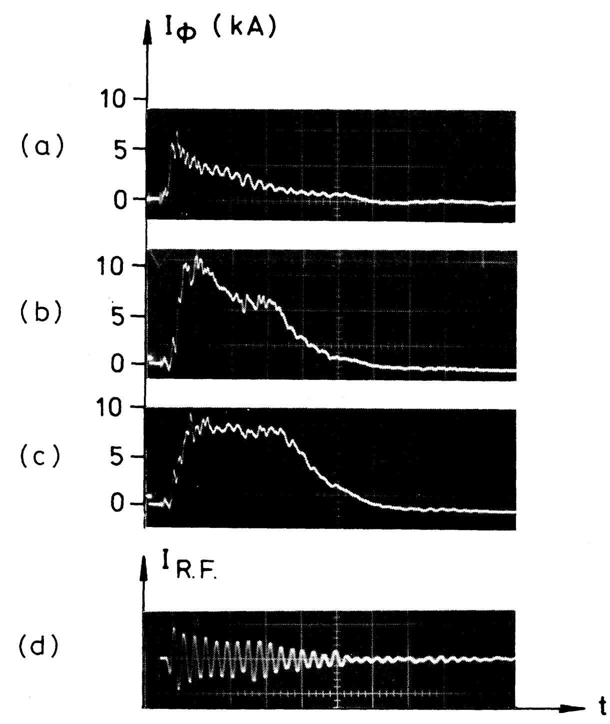

FIG. 4. $I_\phi(t)$ for (a) no vertical field, no toroidal field; (b) vertical field, no toroidal field; and (c) both vertical and toroidal fields. (d) Characteristics of the rf pulses used to generate the rotating field.

10.3 kA and subsequently decreases to a value of 6.7 kA at $t = 10$ μs. Thereafter, during the time interval 10–16 μs, I_φ remains at the substantially constant value of 6.7 kA. The eventual final decrease in I_φ coincides with the termination of the rf pulse. We refer to the initial period 0–10 μs as the "formation" phase and to the interval 10–16 μs as the "steady" phase. Experience showed that I_φ exhibited a steady phase only if the amplitude of the initially imposed vertical field was chosen to lie within a narrow range of values for a given filling pressure. For the 1.7 mTorr experiments reported here, the steady phase was obtained for vertical fields (at $r = 0$, $z = 0$) lying in the range 340–380 G.

The magnetic configuration corresponding to the conditions of Fig. 4(b) was investigated by measuring the z component of the *total* poloidal field (i.e., the sum of the vertical field and the field due to I_φ) along both the r and z axes. The distributions of this component along these axes are shown for three instants of time in Figs. 5(a) and 5(b). The interpretation of these data is facilitated by reference to Fig. 1. Appropriate integration of the profiles shown in Fig. 5(a) enables one to determine the poloidal flux and hence the position of the separatrix. For the first 10 μs of the discharge, the separatrix remains outside the position of the inner wall of the discharge vessel. However, for the interval 10–16 μs, corresponding to the observed steady phase of the discharge, the separatrix lies just outside the vessel. Further evidence for the association of the steady phase with the generation of a well-defined compact torus configuration lying entirely within the discharge vessel comes from Fig. 5(b) where it is seen that the neutral point on the z axis lies well witihin the vessel during this period.

To data, no direct measurements of the plasma parameters have been made in these experiments. However, calculations made with a zero-dimensional plasma model[11] which calculates the temporal temperature behavior of an Ohmically heated, uniform plasma suggest that, for the experimental conditions considered here, the electron temperature reaches a steady-state value of about 7 eV. These model calculations also predict that, in the steady state, energy is lost from the argon plasma by line radiation at a rate of 1.8 MW. Direct measurements show that in the 10–16 μs interval of the rotamak discharge, the two rf generators feed energy into the plasma at a total constant rate of 1.1 MW. Given the approximate nature of the calculations, we conclude that

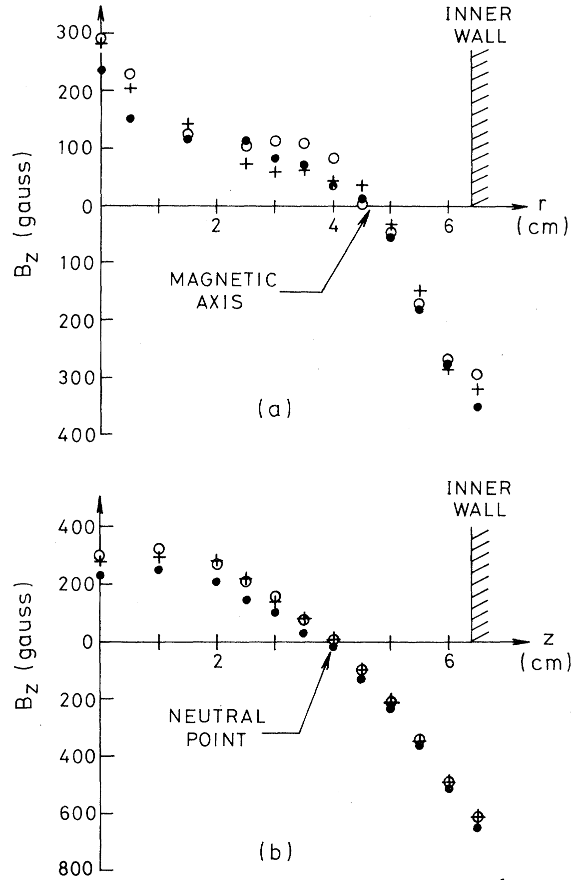

FIG. 5. Distribution of the z component of the total poloidal field along the r and z axes for the configuration corresponding to Fig. 4(b) (open circles, 10 μs; plusses, 14 μs; and closed circles, 16 μs).

the steady phase of the discharge under investigation corresponds to a compact torus configuration, lying entirely within the discharge vessel, for which the Ohmic power input is balanced by line radiation.

Preliminary measurements have been made in a rotamak device which has been modified to allow the generation of an additional steady toroidal field by means of a current flowing along the z axis. For this case, the total magnetic field lines have a more complicated structure than that shown in Fig. 2. An oscillogram of the toroidal current obtained with both an initially imposed vertical field of 360 G (at $r = 0$, $z = 0$) and a toroidal field generated by 6.7 kA flowing along the z axis is shown in Fig. 4(c). It is seen that I_φ remains at a substantially constant value for the duration of the rf pulse. The investigation of this particular configuration continues.

This Letter reports on the *generation* of a compact torus configuration by means of the rotating-field technique. This technique may also be potentially useful in *sustaining* currents in hotter plasmas generated by more conventional means.

We are grateful to Dr. Sergio Ortolani of the University of Padova for adapting his zero-dimensional plasma model to cover the case of argon plasmas. We also thank Ken Duldig for his competent technical assistance. This work was supported by grants from the National Energy Research, Development and Demonstration Council, the Australian Institute of Nuclear Science and Engineering, and the Australian Research Grants Committee.

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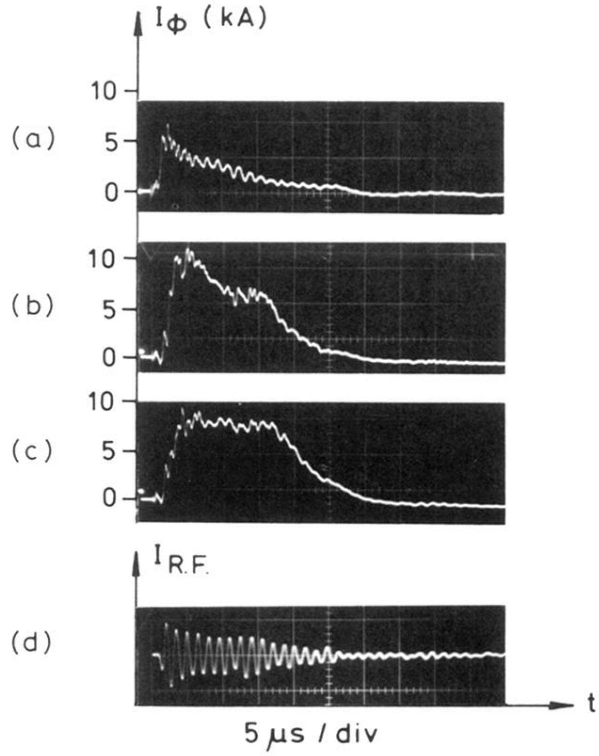

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