Operation of the Rotamak as a Spherical Tokamak: The Flinders Rotamak-ST

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By adding a current-carrying central rod to the basic rotamak apparatus, a magnetic configuration has been produced which is that of a spherical tokamak (ST) maintained in steady state by the application of a rotating magnetic field. The noteworthy reproducibility of the rotamak-ST discharges has facilitated the measurement of the time-averaged magnetic field components throughout a poloidal plane. These measurements, together with an assumption of axisymmetry, have enabled the field lines of an ST to be directly reconstructed from experimental data for the first time. [S0031-9007(98)07036-7]

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The investigation of plasma/field configurations of the compact torus variety is of current interest in the field of fusion research. Two configurations of this genre are the field reversed configuration (FRC) which does not have an externally applied toroidal magnetic field and the spherical tokamak (ST) which possesses such a field.

The rotamak [1] is a compact torus configuration having the unique and distinctive feature that the steady toroidal plasma current is driven in a steady-state, noninductive fashion by means of the application of a rotating magnetic field (RMF) [2]. The toroidal current ring is kept in horizontal and vertical equilibrium by an externally applied magnetic field and, if conditions are appropriate, it can reverse this equilibrium field thus generating a compact torus configuration of the FRC type. Some of the latest results describing the operation of the rotamak as an FRC can be found in [3].

The ST is the low aspect ratio limit of the tokamak. It has the advantages of simple construction, lower magnetic fields, and improved stability over the conventional tokamak. Interest in this particular compact torus concept is growing apace, supported in part by a favorable report [4] which highlights its potential as an economic fusion power plant.

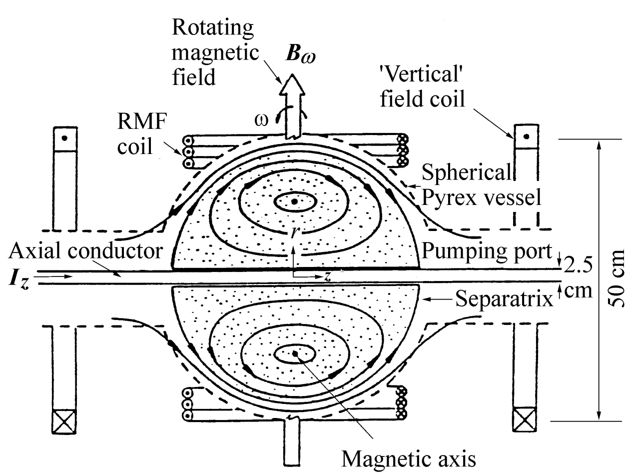

FIG. 1. The Flinders Rotamak-ST.

By means of a simple modification, a steady toroidal magnetic field can be added to the basic rotamak apparatus and the configuration then becomes that of an ST maintained in steady state by means of the application of the RMF. Such a modified rotamak apparatus was indeed the first spherical tokamak experiment [5].

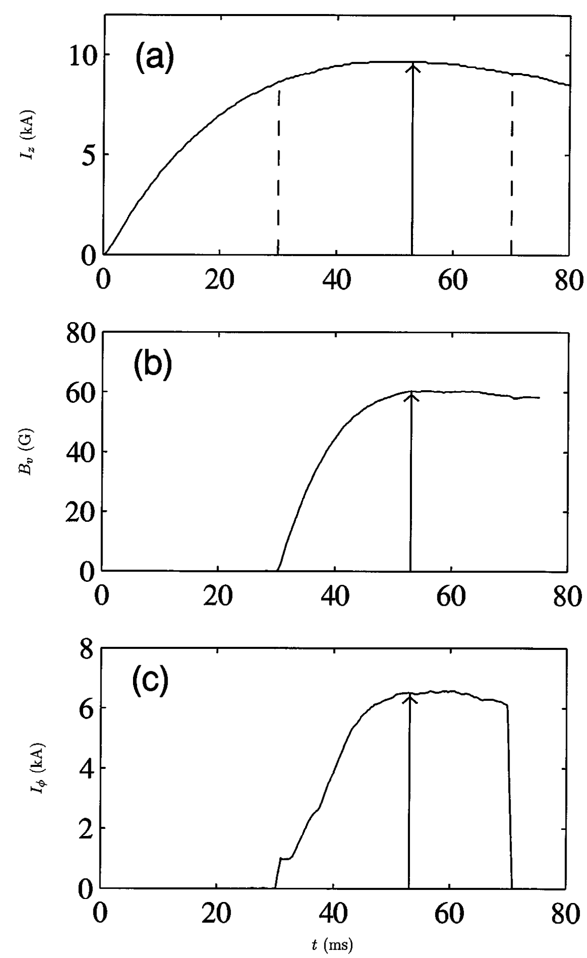

FIG. 2. Time history of (a) the rod current, (b) the vertical field, and (c) the driven toroidal plasma current. The RMF was applied during the period 30–70 ms.

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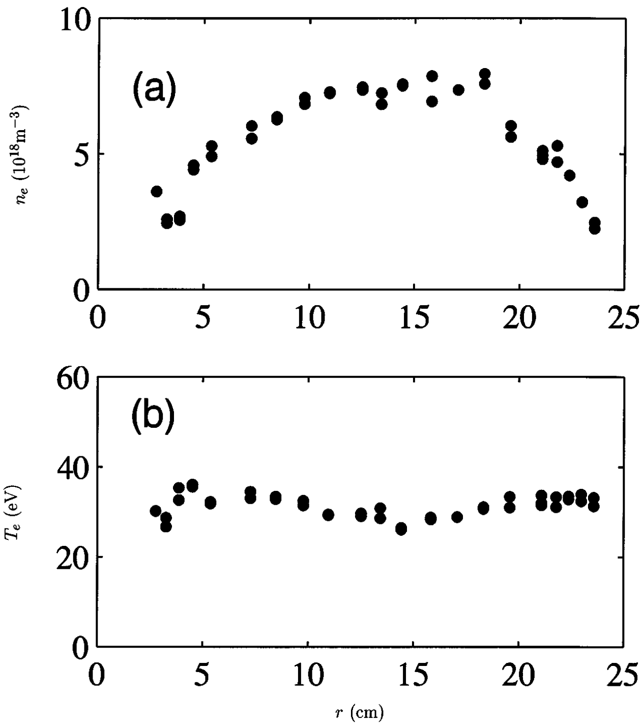

FIG. 3. Radial profiles of n_e and T_e at $z = 0$.

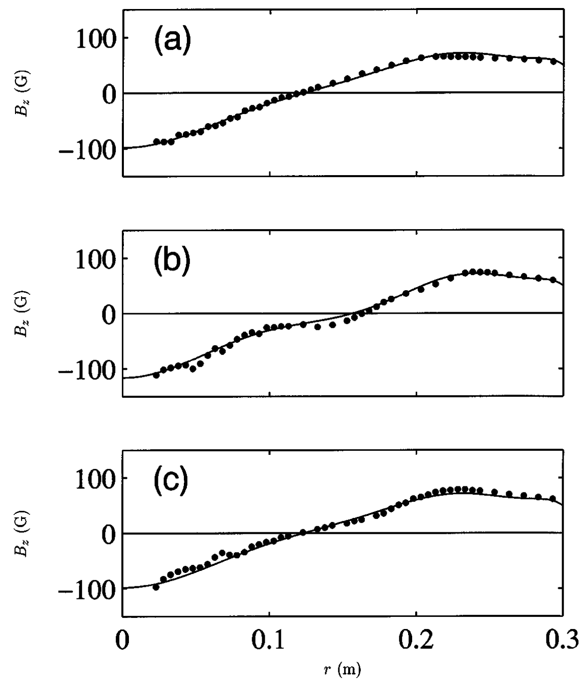

FIG. 4. Radial profile of B_z at (a) $z = -9.5$ cm, (b) $z = 0$, and (c) $z = 9.6$ cm; (•) experimental data; (—) cut in fitted surface.

After a hiatus of ten years, the operation of the rotamak as an ST has been revisited and the purpose of this Letter is to present the initial results obtained using a larger and more powerful apparatus than that employed in [5]. Although some preliminary measurements of the plasma properties are included, the main thrust of this presentation is concerned with the magnetic field structure of the ST configuration produced within the Flinders Rotamak-ST device.

Figure 1 shows the components of the Flinders Rotamak-ST apparatus. rf currents (0.5 MHz, 40-ms pulse duration), dephased by 90°, and passing through two orthogonal coils (only one phase is shown in Fig. 1) produce an RMF of amplitude, B_ω, and angular frequency, ω. Steady currents passing through the two vertical field coils generate the equilibrium field which we characterize by its value, B_v, at the center of the spherical pyrex discharge vessel (radius = 25 cm) *in the absence of plasma*. The steady toroidal magnetic field is produced by discharging an electrolytic capacitor bank through a conductor which threads the central axis of the discharge vessel six times. The stainless steel tube which contains these turns has an external diameter of 2.5 cm. Various entry ports allow the introduction of electric and magnetic probes and the placement of a Rogowski coil around a poloidal cross section of the discharge vessel yields a measurement of the driven toroidal plasma current, I_ϕ. The discharge vessel is furnished with a pumping port which connects it to a conventional vacuum system. For the results reported here, hydrogen gas was continuously flowed through the vessel at an equilibrium pressure of 1 mTorr.

A particular rotamak-ST discharge has been studied in detail. For this discharge, the toroidal field was switched on at $t = 0$; the time history of the rod current, I_z, is shown in Fig. 2(a). At $t = 30$ ms, both the vertical field,

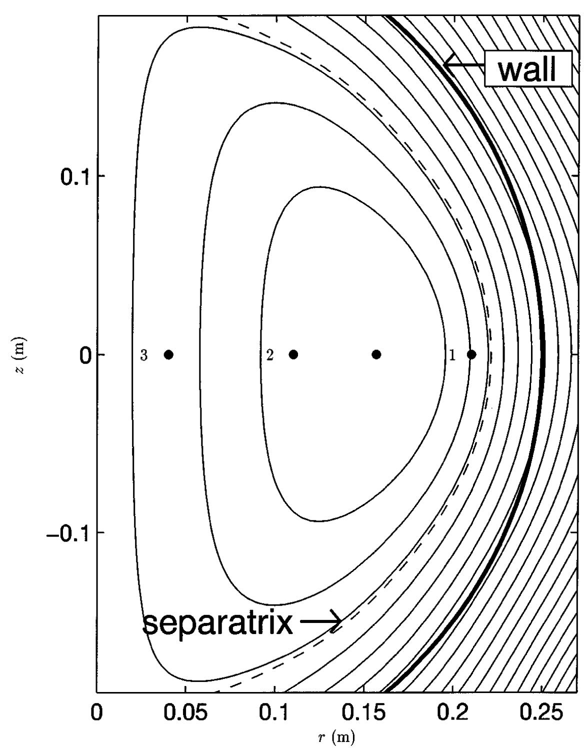

FIG. 5. Poloidal flux contours; contour spacing = 96 × 10^{-6} Wb.

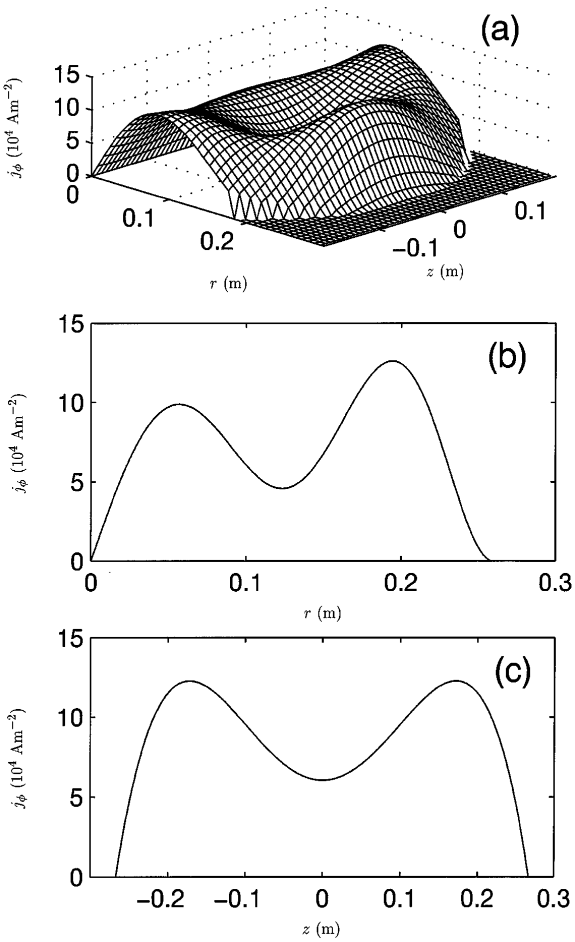

FIG. 6. The toroidal current density (a), with cuts in the fitted surface shown at (b) $z = 0$ and (c) $r = 0.1$ m.

B_v, and the 40-ms duration pulse of RMF were switched on simultaneously. Figure 2(b) shows the time history of B_v while Fig. 2(c) shows the pulse of toroidal plasma current, I_ϕ, which was driven by the RMF.

Detailed measurements of this discharge were made at the indicated time of $t = 53$ ms. At this time, $I_z = 9650$ A, $B_v = 60$ G, and $I_\phi = 6500$ A. The power delivered by both rf generators was 240 kW, of which 42 kW was dissipated in the coils and matching circuits while 198 kW was dissipated in the plasma; i.e., the overall efficiency of power transfer was 83%.

Electric probe measurements of $n_e(r, z)$ and $T_e(r, z)$ were made; the results obtained in the $z = 0$ plane at $t = 53$ ms are shown in Fig. 3. Compared to similar measurements undertaken in the smaller ST experiments of Collins *et al.* [5], the values of T_e are significantly higher (typically 30 eV compared to 12 eV) in the center of the discharge vessel. Since the electron number densities and the input rf power densities are comparable in the two experiments, this suggests that the electron energy confinement time improves with device size.

The quasisteady (dc) components of the magnetic field of the rotamak discharge were measured with Hall probes at $t = 53$ ms. The $B_z(r, z)$ data were collected, on a

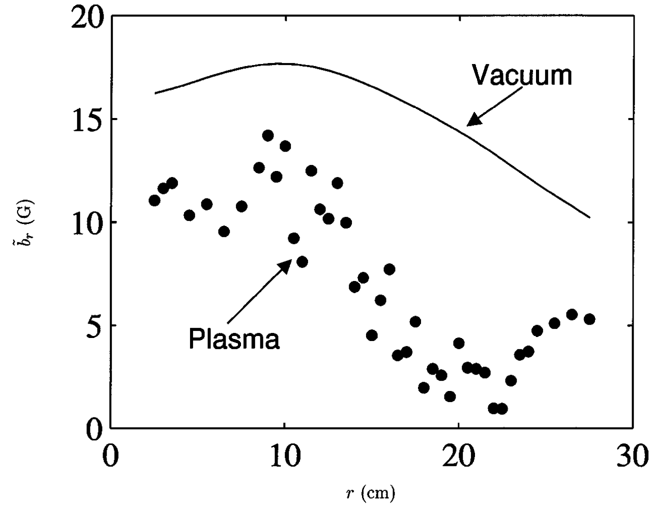

FIG. 7. Radial profile of the magnitude of the r component of the RMF at $z = 0$.

shot-to-shot basis, for a matrix of 546 points (42 r-positions, 13 z-positions). The satisfactory collation of this magnetic field data depended, in large measure, on the excellent shot-to-shot reproducibility of the rotamak discharge. The quality of the data can be gauged from an examination of Fig. 4 in which sample data from 3 z-positions are shown. The experimental $B_z(r, z)$ data were fitted to two-dimensional orthogonal polynomials [6] and appropriate cuts in this fitted surface are also shown in Fig. 4. Given this fitted surface for $B_z(r, z)$, the assumption of axisymmetry and the fact that $\nabla \cdot \boldsymbol{B} = 0$, it was possible to derive a two-dimensional surface for $B_r(r, z)$.

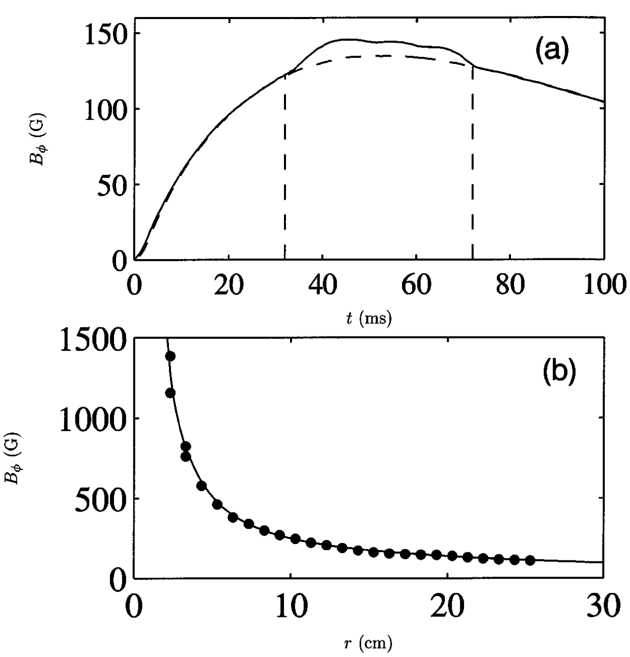

FIG. 8. The toroidal magnetic field: (a) Time history at $r = 20.3$ cm, $z = 0$ cm; (b) radial profile at $z = 0$; (•) measured data; (—) fitted surface.

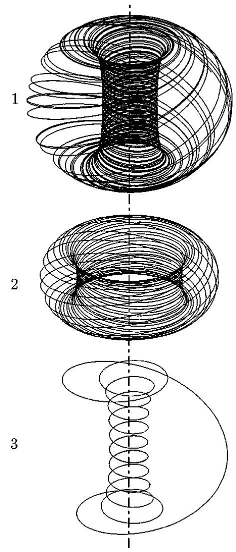

FIG. 9. Reconstructed magnetic field lines.

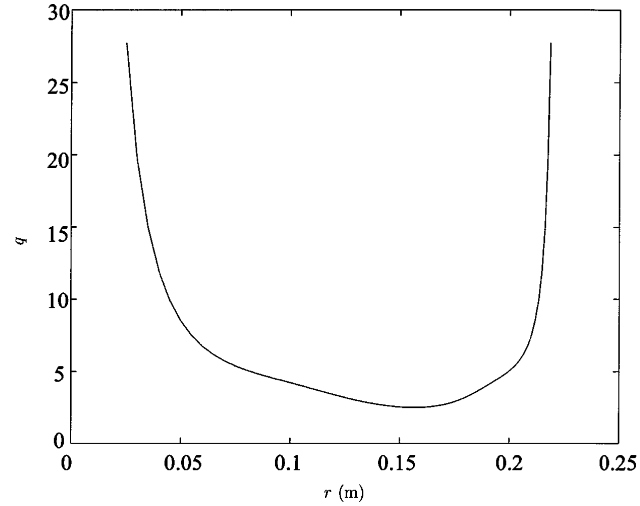

FIG. 10. Radial profile of the safety factor in the $z = 0$ plane.

Figure 5 shows the poloidal flux contours (at $t =$ 53 ms) derived from the fitted surface for $B_z(r, z)$. While investigations of rotamak-FRC discharges in the same apparatus have consistently revealed compact torus configurations having their separatricies at the vessel wall ($r = 25$ cm), here we see that the separatrix sits well inside the vessel wall at $r = 22$ cm. The magnetic axis is at $r = 15.7$ cm and the aspect ratio is 1.12.

Figure 6 shows the derived two-dimensional surface for the toroidal current density, j_ϕ, together with two representative cuts. The use of the RMF current drive technique has led to a distribution of the 6500 A in the poloidal plane which is hollow and elongated, a highly desirable circumstance from the point of view of access to the second stability region for ballooning modes. Even though the penetration of the RMF into the plasma (Fig. 7) is superior to that observed in rotamak-FRC discharges, calculations show that other current drive mechanisms must be operative in addition to the expected RMF current drive. We note that, for the first time in rotamak research, the amplitude of the RMF is a small fraction of the generated steady magnetic field; at each point in the $z = 0$ plane it is less than 5% of the steady field at that point.

The rotamak-ST discharge is slightly paramagnetic in accordance with the expectations of Peng and Strickler [7]. This can be seen from Fig. 8(a) which shows the time history of the steady toroidal magnetic field, B_ϕ, at a particular position within the discharge. Measurements of $B_\phi(r, z, t)$ were made in the poloidal plane and the experimental data for $t = 53$ ms were fitted to a two-dimensional surface. Figure 8(b) shows a sample of the measured data in the $z = 0$ plane and the appropriate cut in the fitted surface.

Given the values of B_r, B_ϕ, and B_z at each point in the poloidal plane, it was possible to reconstruct, by integration, the structure of the magnetic field lines within the rotamak-ST discharge. The magnetic field lines which pass through points 1, 2, and 3 indicated in Fig. 5 are shown in Fig. 9. Magnetic field lines 1 and 2 are irrational while line 3 is rational with $q = 12$. These field lines are representative of those which constitute a spherical tokamak configuration. The q profile of the discharge is shown in Fig. 10.

Present experimentation is focused on exploring the parameter space which is accessible to the rotamak-ST apparatus. Already driven toroidal plasma currents in excess of 12 000 A with $I_\phi / I_z = 1.1$ have been achieved.

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