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THE COMPACT TORUS

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ABSTRACT

The objective of the compact torus approach is to provide toroidal magnetic-field configurations that are based primarily on plasma currents and can be freed from closely surrounding mechanical structures. Some familiar examples are the current-carrying plasma rings of reversed-field theta pinches and relativistic-electron "smoke ring" experiments. The spheromak concept adds an internal toroidal magnetic field component, in order to enhance MHD stability. In recent experiments, three different approaches have been used to generate spheromak plasmas: (1) the reversed-field theta pinch; (2) the coaxial plasma gun; (3) a new quasi-static method, based on the initial formation of a toroidal plasma sleeve around a mechanical ring that generates poloidal and toroidal fluxes, followed by field-line reconnection to form a detached spheromak plasma. The theoretical and experimental MHD stability results for the spheromak configuration are found to have common features.

I. Introduction

Plasma confinement on closed magnetic field lines facilitates the achievement of high reactor-power-multiplication factors; open-ended confinement, on the other hand, lends itself to simplified reactor geometry. The objective of compact-torus research is to develop configurations that combine these desirable features: closed toroidal confinement, including the possibility of ignition, along with simple poloidal-field-generating coils, which do not link the plasma toroid.

Two principal compact-torus options are illustrated in Fig. 1. Confinement in the field-reversed theta pinch[1,2] is based on poloidal magnetic field, the toroidal component being identically zero. Within the ideal MHD stability theory, such configurations are always unstable, particularly against kinklike modes, even in the presence of a close-fitting conducting shell. As noted in Fig. 2, however, if the plasma shape is fairly prolate (height-to-width ratio $b/a \gg 1$) the unstable modes are sufficiently weak so that they might disappear entirely in a realistic nonideal theoretical treatment.[3-5] In any case, actual experiments[1-3] on configurations like that in Fig. 1a show a remarkable degree of gross stability, lasting for many characteristic MHD times. The special advantages of case (a) are: (1) no toroidal flux needs to be generated; (2) the plasma beta-value is maximal.

The spheromak configuration of Fig. 1b has null toroidal field outside the plasma, but has $B_{tor} \sim B_{pol}$ inside the plasma.

The poloidally directed current required to generate B_{tor} flows in the plasma itself, so that no external coils are required to maintain B_{tor}, but external means are needed to create the toroidal flux in the first place. An advantage of the spheromak is that it can be made entirely stable within ideal MHD theory, at maximum beta values that were initially estimated to be at least five percent,[6] and later extended to ten percent or more.[7] Such stability can only be realized, however, in an oblate spheromak (Fig. 2) with a fairly nearby conducting shell.

A compact-torus geometry closely resembling that of Fig. 1a can also be generated in a mirror machine (Fig. 3) by injection of high-energy electron beams[8,9] (Astron) or ion beams[10] (field-reversed mirror machine). In these cases, where the gyroradius of the particles can be larger than the half-width of the plasma ($\rho_{pol} > a_{plasma}$), the applicability of the ideal MHD theory evidently breaks down completely, and a wide range of cross-sectional shapes and B_{tor}/B_{pol}-ratios may be stable. A special advantage is that such configurations may be maintainable in steady state by continuous injection — but the associated power requirement will, of course, limit the attainable energy multiplication factor. A simplified group portrait of the compact-torus family is presented in Fig. 4.

II. Field-Reversed Theta Pinch

Plasma configurations of the type shown in Fig. 1a have been produced straightforwardly in theta-pinch research since the 1950's.

As illustrated in Fig. 5, the basic procedure is to begin with a weak initial axial bias field, then rapidly apply a stronger reverse axial field. A tubular sheet pinch will then form between the regions of oppositely directed field, and the field lines will reconnect to create the desired closed configuration.

In the earlier experiments,[11] such configurations lasted only for microseconds. By careful development of special-plasma handling techniques (including the application of transverse multipole fields to prevent plasma expansion at the first instant of axial-field reversal) the authors of Ref. 1 created stable plasmas lasting for tens of microseconds, and thus drew attention to the paradoxically good stability properties of the compact-torus configuration. Recent experiments have been characterized by densities of $\sim 10^{15}$ cm^{-3}, temperatures in the 100-200 eV range for both electrons and ions, and plasma lifetimes ranging up towards 100 μsec. Typical experimental apparatus is illustrated by the new FRX-C experiment [3] at LASL, shown in Fig. 6, which is expected to reach several times higher temperatures and hopefully much longer plasma lifetimes.

The usual mode of plasma termination in field-reversed theta-pinch plasmas has been the development of a rotating elliptical deformation, which is <u>not</u> predicted to be unstable by the ideal MHD theory. The observed mode is believed to be caused by a bulk rotation of the plasma ions, which in turn arises gradually from plasma diffusion and loss processes.[3] The scaling of these mechanisms is such that the rotational mode would be expected to fade as ρ_{pol}/a_{plasma} decreases, while the predicted ideal MHD modes may then make their first appearance — if they really exist.

Figure 6 incidentally illustrates a convenient topological feature of compact toruses. Unlike most toroidally confined plasmas which are trapped in a fixed location by the field-generating coils, a compact torus can be removed magnetically into a different chamber (the CTX vacuum tank of Fig. 6), which can have features that are better suited to long-time confinement. The hot closed-field-line region simply slides along an external axial field, remaining centered within the guiding vacuum tube by the usual eddy-current repulsion effect. The colder plasma on the outer, open field lines (cf. Fig. 5) flows along the axial guide field to the ends, thus providing a kind of natural divertor action.

III. The Spheromak

The equilibrium configuration of Figs. 1b and 7, which has come to be called the "spheromak," has been studied since the mid-1950 s in an astrophysical context[12]; its relevance to controlled fusion was first pointed out in Ref. 13. A number of authors[14-16] have persistently called attention to the merits of the spheromak configuration, but an experimental program of substantial scale was initiated only during recent years. The basic obstacle has been the difficulty of generating the desired magnetic-field configurations.

A fresh impetus was given to this endeavor by the success of the tokamak and the hope that comparably good confinement might be obtainable in the superficially similar and technologically more attractive spheromak configuration. The potential advantages of the spheromak include not only the simplification of the coil and blanket topology, but also the attainability of much higher plasma pressures. In tokamaks, the plasma beta value is usually defined as $\langle\beta^*\rangle_o = 8\pi\langle P^2\rangle^{1/2}/B_o^2$, where P is the plasma pressure and B_o is the magnetic field at the plasma center. From the reactor-engineering point of view, the most relevant measure, however, is $\langle\beta^*\rangle_{coil} = 8\pi\langle P^2\rangle^{1/2}/B_{coil}^2$, where B_{coil} is the maximum magnetic field strength appearing at the field-generating coil. As illustrated in Fig. 8, MHD-stable values of $\langle\beta^*\rangle_o$ appear to be roughly comparable in spheromaks and tokamaks, but $\langle\beta^*\rangle_{coil}$ is very much greater for the spheromak. (This advantage in $\langle\beta^*\rangle_{coil}$ is shared or even exceeded by the field-reversed theta pinch — which, in addition has infinite $\langle\beta^*\rangle_o$.)

Aside from estimating the beta limit of the spheromak configuration, Ref. 6 investigated its gross stability properties and found the worst mode to be a tilting of the entire closed-field-line region. All prolate spheromaks were found to be unstable against this mode, even with a conducting shell placed right on top of the separatrix. Figure 9 illustrates that for a fixed separatrix the plasma still tends to position itself transverse to the axis of symmetry. The tilting mode is found both in the ideal-MHD and resistive-MHD treatments; the latter case is particularly damaging, since the field lines reconnect, as in Fig. 9d, and the confinement then becomes open-ended.

An oblate spheromak can be stabilized against tilting by a close-fitting external shell.[6] For sufficient oblateness, an external shell is no longer needed to arrest the tilting mode[17]; oblateness, however, implies a mirror-like applied magnetic field, causing a sideways-sliding mode, which needs to be stabilized at least by loose-fitting external conductors.

The theoretical tilting-mode prediction met with considerable skepticism at first, since it applies also to the field-reversed theta-pinch case, $B_{tor} \cong 0$, which shows no sign of tilting in spite of its extreme prolateness. The stability of prolate reversed-field theta pinches containing toroidal field had also been studied in the past,[1,18] with the assistance of axial toroidal-field-generating conductors inside the plasma; these plasma sleeves, of course, neither did nor could exhibit tilting.

The generation of prolate spheromaks by the theta-pinch approach was resumed recently at the University of Maryland in configurations without internal conductors, by passing axial currents through the plasma itself during the field-reversal process.[19] The initial experiments indicated gross stability for tens of microseconds, but more refined measurements subsequently showed the presence of tilting. Stability can be achieved experimentally[20] by reducing the prolateness of the plasma to the level shown in Fig. 10. The contrast between the appearance of tilting in the $B_{tor} \neq 0$ case and its absence in the $B_{tor} \equiv 0$ case is presumably related to non-MHD considerations, such as the relative magnitude of the parameter ρ_{pol}/a_{plasma}.

A second major line of approach to spheromak experimentation has been the revival of the coax l-gun technique (Fig. 11) originally described in Ref. 12. In this approach, toroidal magnetic field is generated by passing a current from the inner to the outer coaxial gun electrode, through a toroidal body of plasma. The plasma is then accelerated by the toroidal-field pressure, and leaves the gun, distending the (radial) poloidal fringe field placed at the muzzle, while carrying some of the toroidal flux along in its interior. The poloidal field lines then reconnect, and the resultant plasma can be guided by an external axial field to its desired equilibrium location.

The great advances that have been achieved in coaxial "Marshall gun" development since the 1950 s have allowed recent experiments[3] at LASL to achieve significant spheromak parameters: major diameters of ~50 cm, densities of ~10^{14} cm^{-3}, electron temperatures of 50-100 eV, and toroidal currents of several hundred kA. The LASL gun generator can be used to place spheromak plasmas in magnetic guide fields and within conducting shells of various geometries, including the CTX tank of Fig. 6.

Initial experiments with plasmas shot into prolate cylindrical shells[21] gave the first clear-cut evidence of the predicted tilting mode. In the absence of an externally generated field, the spheromak turned sideways, as in Fig. 9c, and then decayed stably during times of about 100 μsec. In the presence of an external field, the decay was much more rapid, presumably corresponding to the reconnection mechanism of Fig. 9d.

When the spheromak plasma was shot into an oblate cylindrical shell, it refrained from tilting and decayed smoothly during times exceeding 100 μsec. Under these conditions, the magnetic-field fluctuation level was found to drop to a low value — somewhat reminiscent of the "quiescent phase" of the reversed-field Z-pinch (RFP).[22] This similarity in experimental behavior may be related to the obvious theoretical similarity between the spheromak and the RFP; in both cases, it is possible for the plasma to settle into a "Taylor-type" minimum-energy state.[6,23,24]

Addition of a weak external field to the LASL oblate-shell experiment served to extend the decay times to ~150 μsec; still larger external fields brought back the tilting mode and the rapid plasma decay process. These plasma-gun experiments probably represent the broadest and most significant investigation of spheromak stability properties to date — and incidentally also seem to exhibit the best agreement with theory. Similar experiments are under way at LLL,[5,25] where it is hoped to use a spheromak plasma as the starting point for prolonged neutral-beam-driven field reversal, as in the approach shown in Fig. 3.

The theta-pinch and coaxial-gun approaches to the formation of compact toruses have the inherent drawback of utilizing dynamic (i.e., inertial) effects during the formation process: The scaling of dynamic phenomena is such as to imply relatively high instantaneous power levels and voltages for reactor plasma parameters. An alternate approach, pursued at PPPL, has been to form the spheromak by quasi-static means.[4] A thin-walled metal ring, with external current leads and internal poloidal and toroidal-field coils is used to set up the initial poloidal field of Fig. 12a, with the assistance of an externally generated axial field. The internal toroidal-field-generating solenoid is then pulsed on, inducing an equal and opposite toroidal flux in the plasma region on the exterior of the ring. Next, the poloidal field of the ring is reversed (Fig. 12b). Finally, the field lines reconnect and a separated spheromak configuration remains (Fig. 12c), held in equilibrium by the initial external field.

This basic formation scenario was developed in the course of extensive two-dimensional resistive MHD simulations[4] at PPPL and Columbia University. Successful plasma formation appears to be fairly insensitive to the details of the computer modeling. Recently, a small-scale experimental demonstration was carried out (Fig. 13) at the 20-kA level, which agreed well with theoretical expectation. Construction of the S-1 device, a 500-kA spheromak-generator designed on the principle of Fig. 12 is under way.[26] S-1 operation will begin in late 1982 and will hopefully lend itself to an assessment of energy-transport physics in spheromak plasmas with millisecond decay times.

While the tilting and sliding modes of the spheromak are expected to be readily controllable (if necessary, by the addition of force-free plasma on the open field lines, plus external helical windings[6] or even a central axial conductor), the "pessimistic" finite-resistivity version of the ideal MHD stability theory also predicts various surface kink modes of more localized character, which could be suppressed only by a very snugly fitting external shell. Additional "optimistic" corrections to the ideal MHD theory, such as the finite-gyroradius effects already mentioned in connection with the field-reversed theta pinch, may overcome this danger and lead to a satisfactory degree of confinement. Paradoxically, the $B_{tor} \equiv 0$ variant of the compact torus is expected to be much less sensitive to resistive kink modes — provided it can survive the ideal modes: In this sense, there is a spreading of risks, and one may hope that the experimental outcome will favor at least some part of the compact-torus family.

IV. Reactor Prospects

There are two main trends in current thinking about compact-torus reactors: (1) By means of energetic-particle injection (or possibly rf-waves) it may be possible to maintain a steady-state field configuration,[10] as in Fig. 3. If the parameter ρ_{pol}/a_{plasma} cannot be allowed to become very small, then one may wish to contemplate a whole set of reacting toroids, placed adjacent to each other within a single overall guide field. (2) In the absence of current-drive, the compact-torus field configuration decays resistively. In large, hot reactor plasmas the magnetic-field-diffusion time can, of course, be quite long (in the tokamak reactor example it is an hour or more), but the associated engineering problems, such as first-wall thermal fatigue, are sufficiently troublesome to motivate remedial strategies. The idea of placing multiple compact toruses within a single reactor then leads naturally to moving-toroid schemes,[27] such as that in Fig. 14 where each reacting-plasma entity has a finite lifetime, but the pattern of fusion power production can be held approximately steady.

A number of reactor-study groups have proposed schemes of these two types,[28] and have begun to examine the associated parameters and design trade-offs. The reactor prospects are naturally very attractive — this aspect of the compact-torus situation being the driving force behind the current interest. A serious assessment of compact-torus reactors must await the procurement of much more precise information on the requirements for plasma stability, and at least the rudiments of an empirical scaling law for thermal diffusion.

Acknowledgment

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References:

[1]A. G. Es'Kov, e' al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) Vol. II, IAEA, Vienna (1979) 187; ibid., (Proc. 5th Int. Conf., Tokyo, Japan, 1974) Vol. III, IAEA, Vienna (1975) 71 (Nuclear Fusion Supplement (1975) 155 (for English translation); in Controlled Fusion and Plasma Physics (Proc. 7th Europ. Conf., Laussane, Switzerland, 1975) Vol. I, 55.

[2]R. K. Linford, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) Vol. II, IAEA, Vienna (1979) 447.

[3]W. T. Armstrong, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf., Brussels, Belgium, 1980) paper IAEA-CN-38/R-3-1, to be published.

[4]W. Grossmann, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf., Brussels, Belgium 1980) paper IAEA-CN-38/R-1, to be published.

[5]D. V. Anderson, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf., Brussels, Belgium 1980) paper IAEA-CN-38/R-2, to be published.

[6]M. N. Bussac, *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) Vol. III, IAEA, Vienna (1979) 249; M. N. Rosenbluth and M. N. Bussac, Nuclear Fusion 19 (1979) 489; M. Okabayashi and A. M. Todd, Nuclear Fusion 20 (1980) 571.

[7]P. Gautier, *et al.*, in *Controlled Fusion and Plasma Physics* (Proc. 9th Int. Conf., Oxford, England, 1979) Contributed Papers Volume, Culham Laboratory (1979) paper EP30.

[8]N. Christofilos, N., in *Proceedings of the 2nd International Conference on Peaceful Uses of Atomic Energy* 32 (1958) 279.

[9]H. A. Davis, *et al.*, Physical Review Letters 37 (1976) 542; D. A. Phelps, *et al.*, Physics of Fluids 17 (1974) 2226.

[10]D. E. Baldwin and M. E. Rensink, Comments on Plasma Physics and Controlled Fusion IV (1978) 55.

[11]A. C. Kolb, C. B. Dobbie, and H. R. Griem, Physical Review Letters 3 (1959) 5.

[12]R. Lüst and A. Schlüter, Z. Astrophysics 34 (1954) 263.

[13]H. Alfvén, in *Proceedings of the 2nd International Conference on Peaceful Uses of Atomic Energy* 31 (1958) 3.

[14]G. K. Morikawa, *et al.*, Physics of Fluids 12 (1969) 1648; *ibid.*, 13 (1970) 497; *ibid.*, 14 (1971) 781.

[15]D. R. Wells, Physics of Fluids 7 (1964) 826; E. E. Nolting, P. E. Jindra, and D. R. Wells, J. Plasma Physics 9, Part 1 (1973) 1.

[16] P. M. Koloc, Bulletin of the American Physical Society 22 (1977) 1152; ibid., 21 (1976) 1194; P. Koloc and J. Ogden in Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 216.

[17] S. Jardin, private communication.

[18] A. C. Kolb, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 3rd Int. Conf., Novosibirsk, USSR, 1968) Vol. II, IAEA, Vienna (1969) 567.

[19] G. C. Goldenbaum, et al., Physical Review Letters 44 (1980) 393.

[20] Z. G. An, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf., Brussels, Belgium, 1980) paper IAEA-CN-38/R-3-2, to be published.

[21] T. R. Jarboe, et al., in Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 53.

[22] E. P. Butt, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 2nd Int. Conf., Culham, England, 1965) Vol. II, IAEA, Vienna (1966) 751; A. Buffa, et al., ibid., (Proc. 8th Int. Conf., Brussels, Belgium, 1980) paper IAEA-CN-38/L-1, to be published.

[23] J. B. Taylor, Physical Review Letters 33 (1974) 1139.

[24]D. R. Wells and J. Norwood, Jr., J. Plasma Physics 3, Part 1 (1969) 21.

[25]W. C. Turner, et al., in Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 16.

[26]M. Yamada, et al., in Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 171.

[27]A. C. Smith, et al., in Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 224.

[28]Proceedings of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection (Princeton Plasma Physics Laboratory, 1979) 212-236.

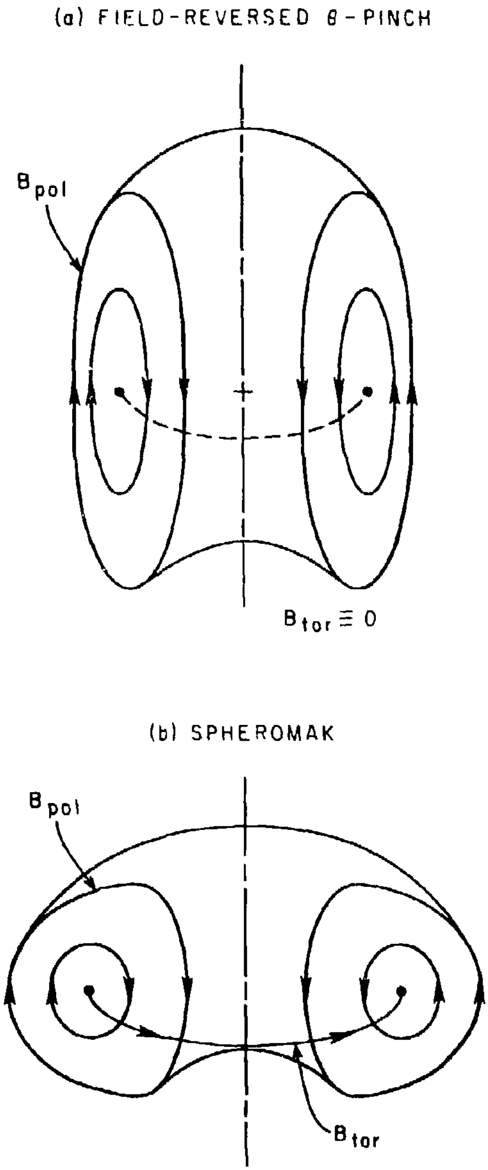

Figure 1. Two basic types of compact torus. (PPL 806487)

GROSS STABILITY ($\rho_{GYRO} < a_{PLASMA}$)

	OBLATE $b/a \lesssim 1$	PROLATE $b/a \gg 1$
$B_{POL} \gg B_{TOR}$	KINK UNSTABLE	STABLE?
$B_{POL} \sim B_{TOR}$	STABLE	TILT UNSTABLE

Figure 2.

(PPL 806477)

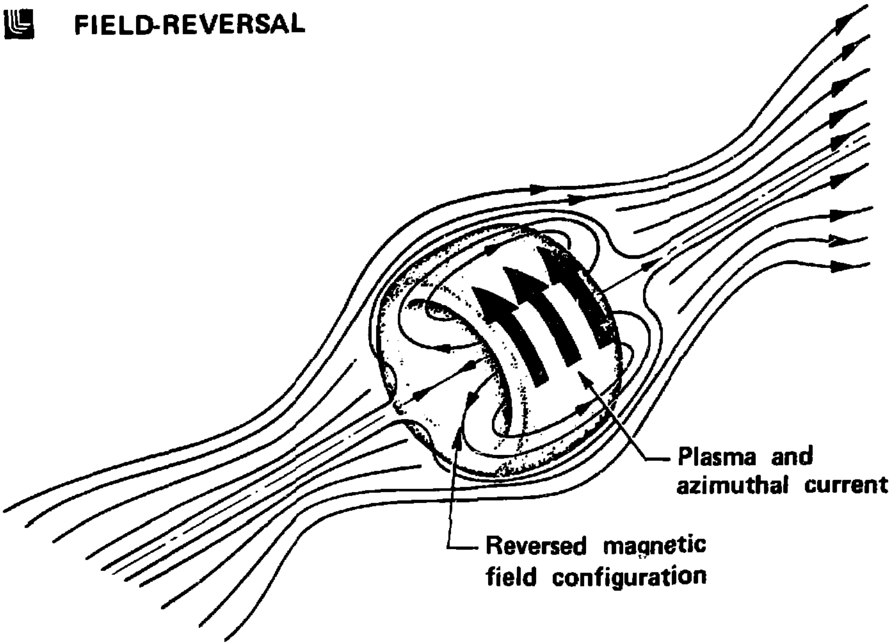

Figure 3. Mirror machine (of the minimum-B type) in which field-reversal is produced by the azimuthal (toroidal) current of neutral-beam-injected ions.[10] (PPL 806447)

Compact Toruses

<table>
<tr><th></th><th>$\rho_{POL} < a_{PLASMA}$</th><th>$\rho_{POL} > a_{PLASMA}$</th></tr>
<tr><td>$B_{POL} \gg B_{TOR}$</td><td>Field-Reversed Mirror or θ-Pinch</td><td rowspan="2">E-Layers
P-Layers
REB-Injected Toruses</td></tr>
<tr><td>$B_{POL} \sim B_{TOR}$</td><td>Spheromak or "Null-Field Z-Pinch"</td></tr>
</table>

Figure 4.

(PPL 806449)

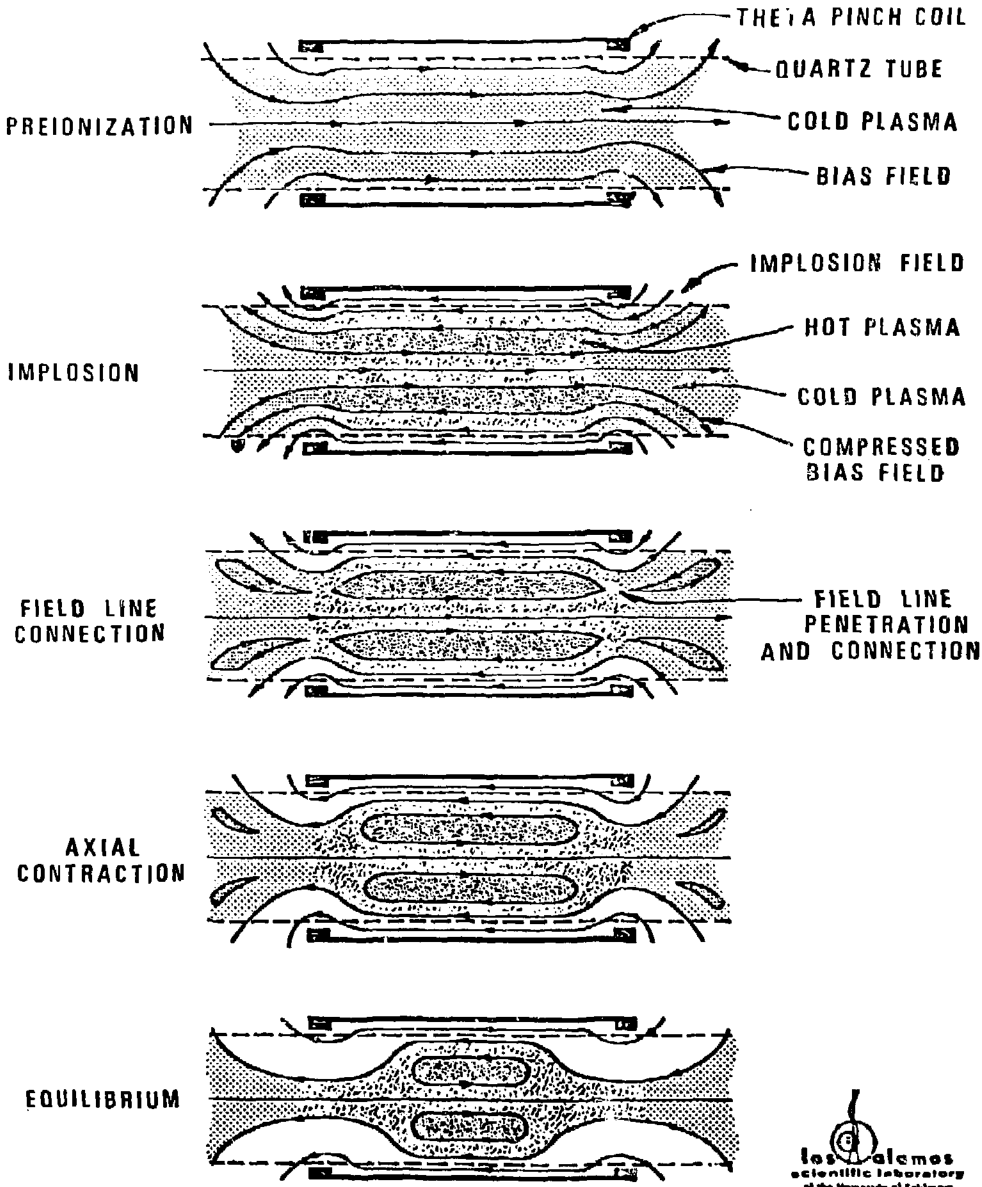

Figure 5. Formation of a reversed-field theta pinch.[2]
(PPL 806451)

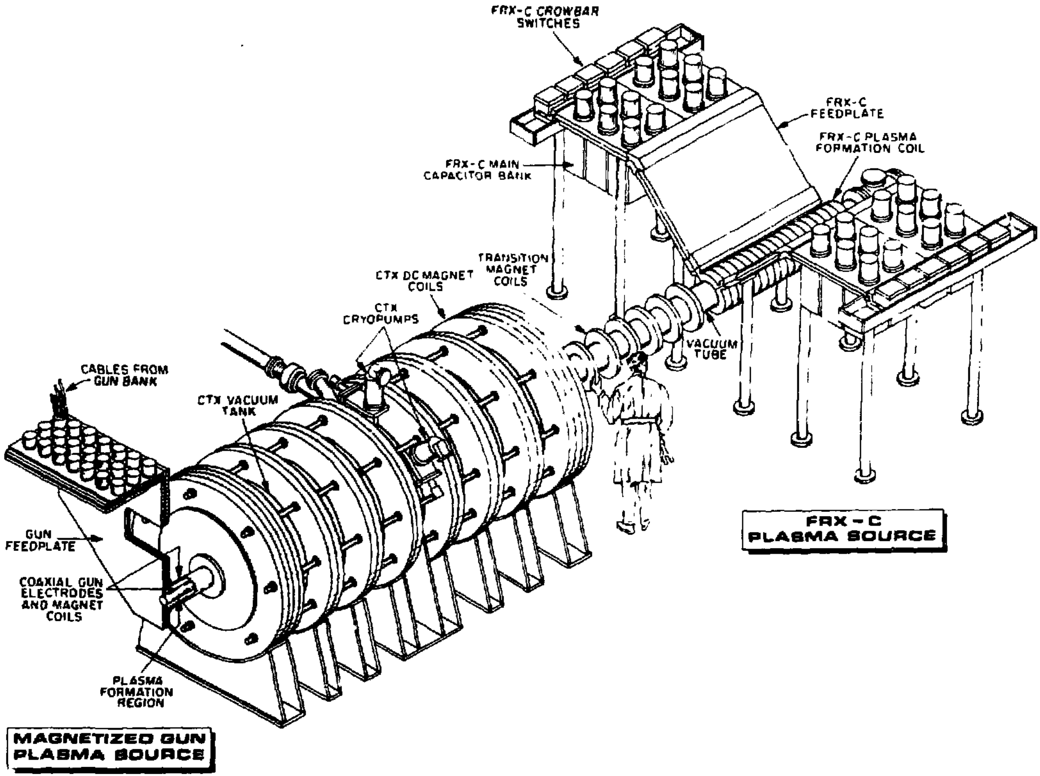

Figure. 6. The CTX facility at LASL consists of three elements: (1) The FRX-C reversed-theta-pinch generator; (2) A coaxial-gun spheromak-generator; (3) The CTX tank, for injection of compact toroids of either type (1) or (2). (PPL 806448)

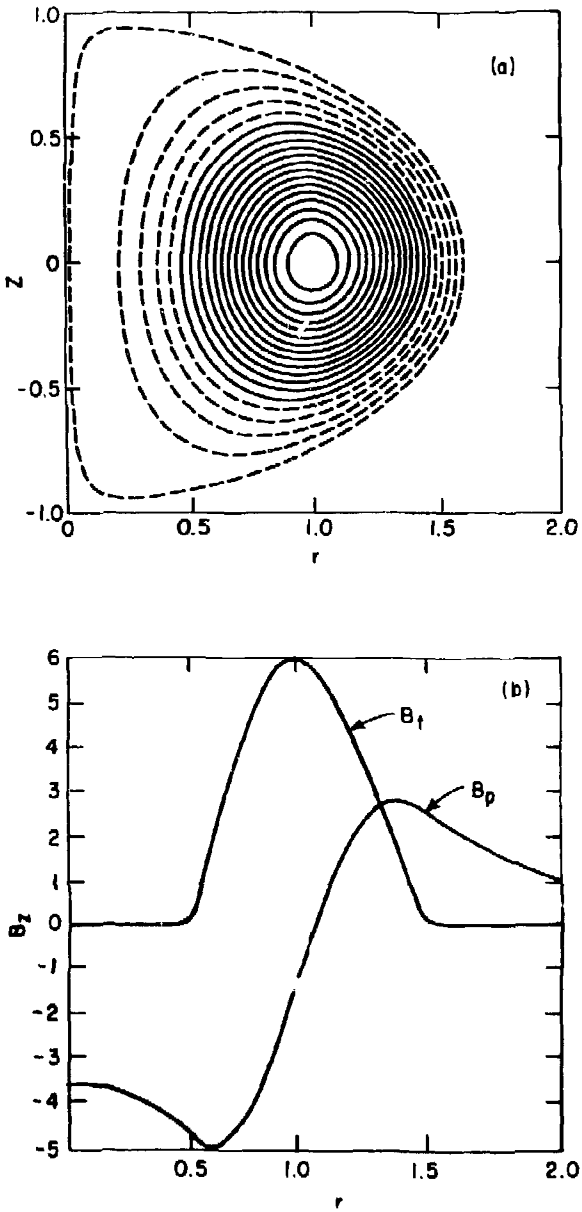

Figure 7. An oblate spheromak configuration with favorable stability properties. (PPL 786431)

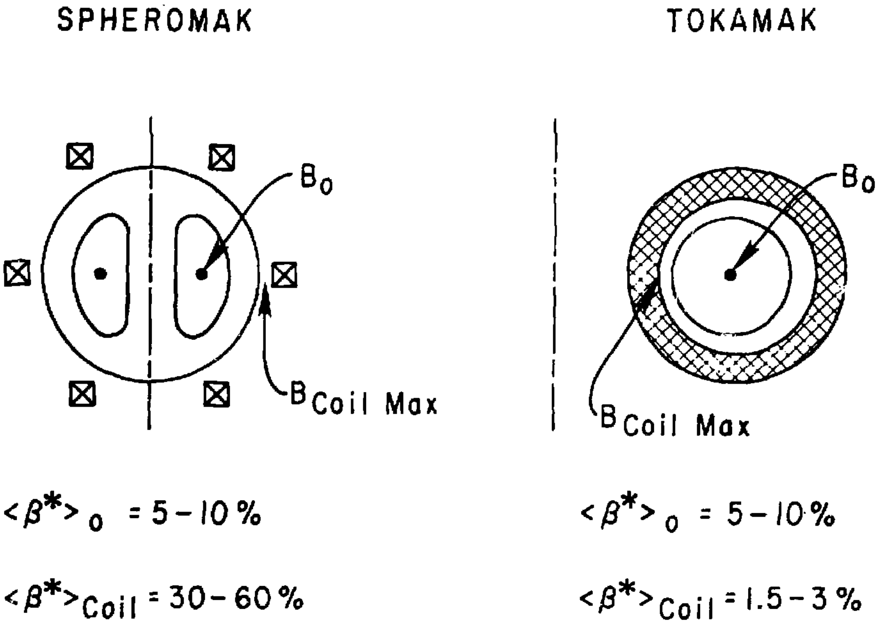

Figure 8. Comparison of beta values in spheromaks and tokamaks. (PPL 806483)

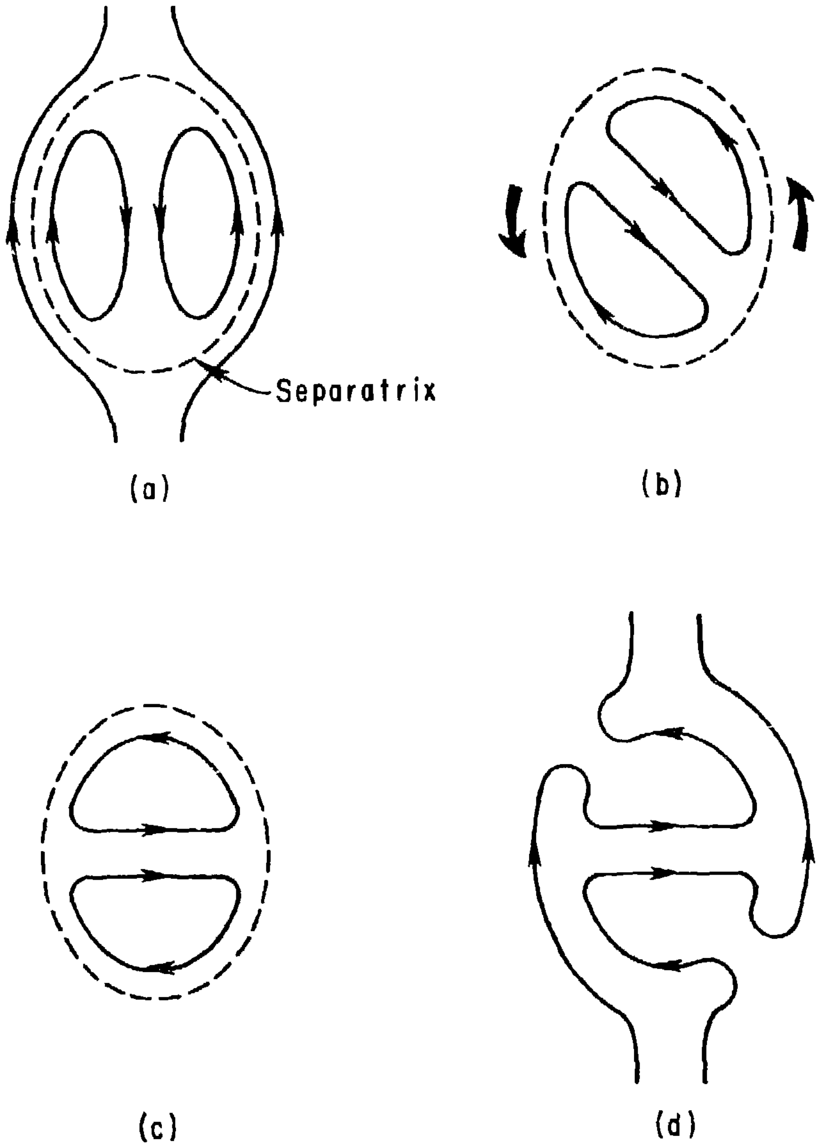

Figure 9. A prolate compact torus (a) is theoretically unstable against tilting (b). Even if the separatrix is fixed by a conducting shell, the plasma should turn sideways (c). In the finite-resistivity theory, the field lines reconnect, as in (d). (PPL 8C5484)

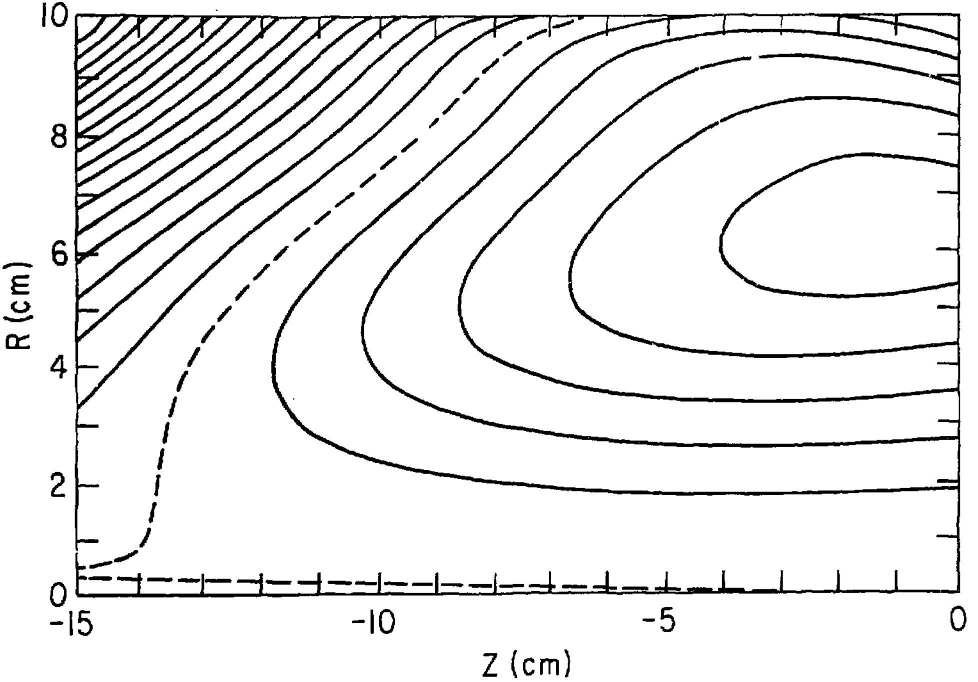

Figure 10. Experimentally measured poloidal-flux surfaces in a mildly prolate spheromak configuration generated by the field-reversed theta pinch technique.[20] The flux increment between surfaces is 20 kG cm^2. (PPL 806485)

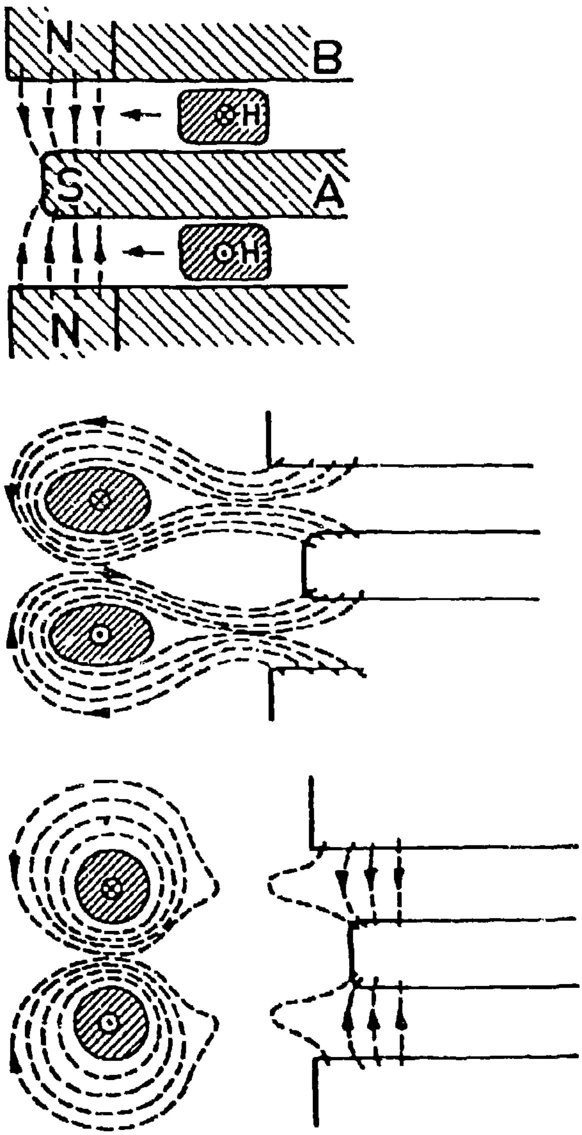

Figure. 11. Generation of a spheromak plasma by the coaxial gun technique.[13] (PPL 806446)

QUASISTATIC FORMATION USING INDUCTION

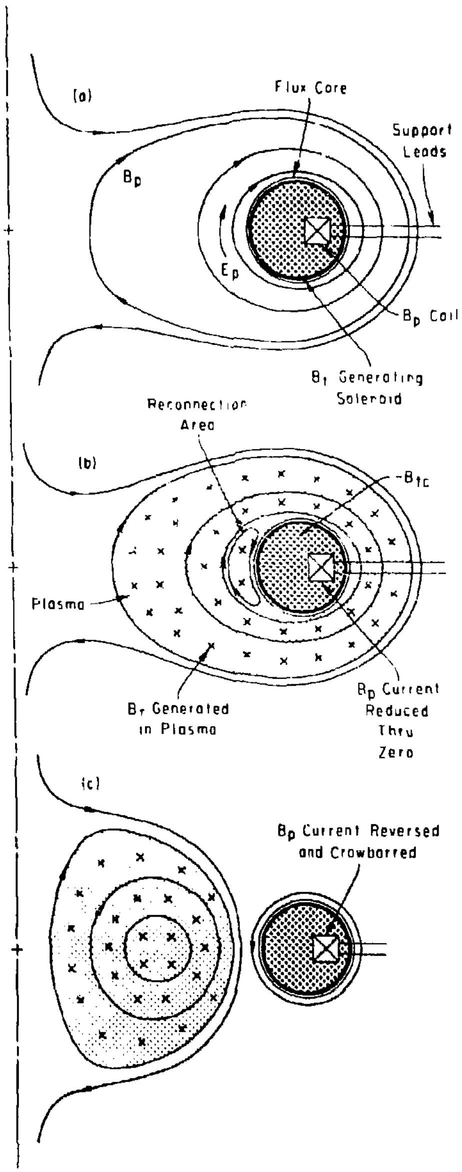

Figure 12. Quasi-static technique for spheromak formation.[4] (PPL 806488)

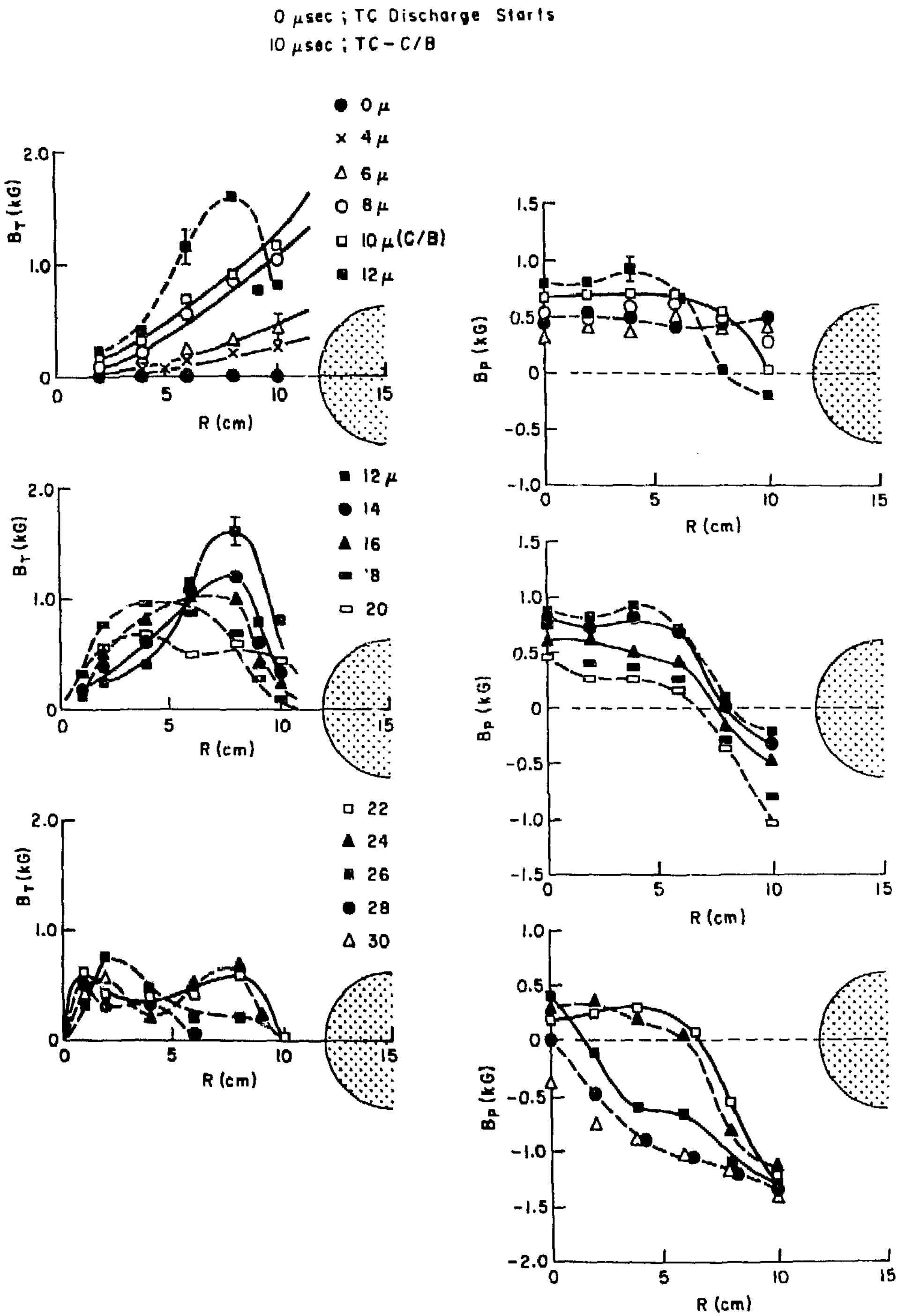

Figure 13. Magnetic probe measurements in a small spheromak-formation experiment using the method of Fig. 12. (PPL 803815)

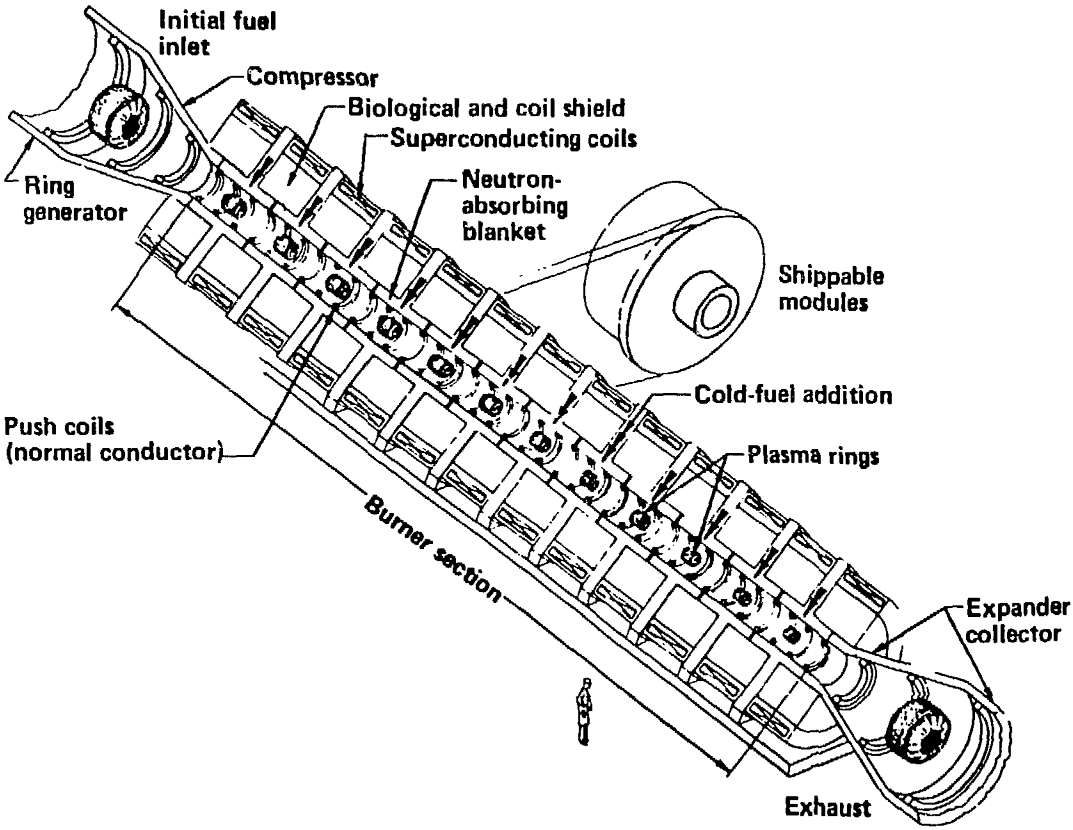

Figure 14. Conceptual design of a Moving-Ring Field-Reversed Mirror Reactor (MRFRM).[28] (PPL 806450)