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SUMMARY OF U. S. COMPACT TORUS EXPERIMENTS*

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ABSTRACT

During the past several years a rapid increase has occurred in compact torus (CT) research in the United States, reflecting renewed interest in this simplified reactor consequences of this configuration. This paper reviews early approaches to CT formation and results and summarizes present experimental studies. Recent experiments have demonstrated a number of macroscopic aspects of the CT, including the conditions under which a macroscopically stable CT can be formed and maintained. Scaling experiments and more detailed studies of plasma transport in progress are discussed along with experiments under construction.

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INTRODUCTION AND HISTORICAL PERSPECTIVE

Interest in the compact torus (CT) for fusion rests on forming an axisymmetric, closed, toroidal-confinement-region for plasma within a nearly uniform external field as shown in Fig. 1. The advantages of toroidal confinement are thereby obtained while retaining reactor-related simplifications in blanket and coil design and natural plasma diversion because of the open-ended external field. To achieve these dual advantages, the toroidal confinement fields must be formed by plasma currents, rather than torus-linking, external windings, which gives the CT considerable similarity to certain low-aspect-ratio, toroidal pinches.

As with many approaches to magnetic fusion, the conceptual origins of the CT approach date to the beginning of fusion research--and before in an astrophysical context. Early considerations related to the CT arose in studies of magnetized plasma guns¹ and rail-type guns² shown in Fig. 2, in studies of theta-pinches with reversed bias field³ shown in Fig. 3, and in the Astron device⁴ shown in Fig. 4. The plasma confinement possibilities were recognized and, particularly in Astron, the considerable reactor-associated advantages were given early emphasis and remained as significant considerations throughout the development of this approach.

The topological constraints inherent to the CT make production techniques particularly important. Each of the three early approaches--guns, theta-pinches, and Astron--are representative of three basic means of formation which have counterparts in present experiments. Namely, direct electrode coupling in plasma guns, inductive coupling of theta-pinches, and large orbit charged particle rings as in Astron. Further, each of the three formation possibilities produces CT's of distinctively specific characteristics. The coaxial, plasma gun tends to introduce a large, toroidal-field component, producing Spheromak-like CT's which are nearly force-free, the theta-pinch approach tends towards a $B_{\text{toroidal}} = 0$, high β CT, or Field-Reversed-Configuration (FRC) [or Field-Reversed-Mirror (FRM)], and the Astron-type CT formed with large-orbit, current-carrying particles. A summary of specific CT's is given in Fig. 5.

Early experiments have illuminated some of the macroscopic characteristics of CT's. In the magnetized coaxial plasma experiments,⁵ the possibility of formation by this approach was demonstrated and grossly stable plasma rings were obtained which lasted for many Alfvén wave transit times. CT's studied using theta-pinches⁶ were, in some cases, found to tear into separate rings, to coalesce, to contract axially towards an equilibrium state, and to develop $m = 2$ type instability associated with plasma rotation.

Fig. 1. The compact torus configuration. Poloidal field as shown is created by a current-carrying plasma ring in an external equilibrium field. No conductors link the torus and toroidal field, if present, is provided solely by plasma currents and goes to zero at the boundary of the ring.

Fig. 2. Generation of a compact torus by the coaxial gun technique.¹

Fig. 3. Formation of a reversed-field theta pinch.³

Fig. 4. The Astron Device. An induction accelerator injects tangentially, pulses of electron current which form an electron bunch. The bunch, or ring, drifts along a guide field and is trapped to form and maintain the E-layer.

Fig. 5. Diagram and classification of CT configurations, where a is the minor radius, R is the major radius, B_θ is the poloidal field, B_ϕ is the toroidal field, and l is the separatrix length.³⁹

Propagation of CT's along an axial guide field and trapping between magnetic mirrors was studied using conical theta-pinchs for formation. Propagation was observed along with efficient reflection by a static mirror field.⁷ In other experiments using a fast-gate, magnetic mirror⁸ trapping of a CT between magnetic mirrors was accomplished although the trapped lifetime was short, several reflections between mirrors.

Finally, although the Astron experiment failed to achieve field reversal, trapping of injected electron rings to build-up toward a CT configuration was observed⁹ along with a tendency towards greater stability as the electron layer current increased. Subsequent experiments¹⁰ utilizing intense relativistic electron beam sources have succeeded in achieving a completely field-reversed ring and in examining many of its properties as will be discussed later.

PRESENT U. S. EXPERIMENTS

There has been a recent increase in interest in the CT in the United States. This interest stems from the successful demonstration of toroidal confinement in Tokamaks and FRC's formed with theta-pinchs, and from a renewed desire to

investigate confinement configurations with simplified reactor consequences. In this section I will summarize experimental studies in the United States under the broad categories, CT's without B_{toroidal} (FRC), CT's with B_{toroidal} (Spheromak), and particle ring generated CT's.

FRC Experiments

FRC experiments are conducted using a theta-pinch with reverse bias field as shown in Fig. 3. Some parameters of currently operating experiments and experiments under construction are shown in Table 1. Using a theta-pinch, plasma current is inductively excited on a sufficiently short time scale so that shock heating and other dynamic effects can be important. During the formation phase, field line tearing and reconnection at the ends changes the initial open field topology to the closed, FR configuration.

The principal results of FRC experiments have been obtained at Los Alamos Scientific Laboratory in devices FRX-A and FRX-B.¹¹ A larger device FRX-C¹², under construction, is shown in Fig. 6. In FRX-A, B the initial implosion phase ($t \leq 5 \mu\text{s}$) consists of shock heating, field reconnection, and contraction of the FRC to highly prolate equilibrium state with $R = 3\text{--}5 \text{ cm}$, $a = 2 \text{ cm}$, full length $L = 30\text{--}35 \text{ cm}$, $T_e = 100\text{--}150 \text{ eV}$, $T_i = 150\text{--}1000 \text{ eV}$, and $n = 1\text{--}4 \times 10^{15} \text{ cm}^{-3}$. The equilibrium established remains macroscopically stable for times up to $50 \mu\text{sec}$, being terminated by the catastrophic growth of an $m = 2$ type deformation of the plasma column (shown in Fig. 7) which is correlated with rotation of the equilibrium at frequencies $\Omega_e > 1\text{--}2 \omega_i$, where ω_i is the ion diamagnetic drift frequency. The threshold for $m = 2$ instability is in agreement, both in magnitude and scaling, with predicted rotation-driven, MHD instability.¹³ On the other hand, the duration of the equilibrium phase corresponds to several tens to several hundreds of Alfvén-wave transits along the length of the FRC in apparent disagreement with predicted MHD instability to high m number localized kinks,¹⁴ and internal tilting,¹⁵ and possibly $m = 0$ tearing modes.¹⁶ It is quite possible that ion, finite-Larmor-radius effects play an important role in the FRC A and B experiments, both in controlling the rate at which the plasma builds up rotation, and in stabilizing MHD instabilities during the equilibrium phase. The duration of the stable phase increases rapidly with the number of gyroradii as shown in Fig. 8.

Additional experiments have been conducted using separately excited mirrors to decrease the reconnection time (FRX-A) and to investigate translation. With separately excited mirrors an increase in FRC lifetime from 20 to $35 \mu\text{sec}$ was observed. By

Table 1. FRC, Reversed-Bias Theta-Pinch Experiments

Experiment	Apparatus							Plasma				
	Coil Diam. cm	Coil Length cm	$t_{1/4}$ μ sec	Peak B , kG	Bias B , kG	R cm	a cm	l cm	T_e eV	T_i eV	n cm^{-3}	τ μ s
FRX-A ⁽¹¹⁾ (LASL)	25	100	3.2	7	-2.3	3-5	2	35-50	150-100	1000-150	10^{15} to 4×10^{15}	up to 50
FRX-B ⁽¹¹⁾ (LASL)	25	100	2.0	12	-3.0	3-5	2	35-50	150-100	1000-150	10^{15} to 4×10^{15}	up to 50
FRX-C ⁽¹²⁾ (LASL)	45	150	1.8	9		UNDER CONSTRUCTION						
HMH ⁽¹⁸⁾ (U. of Wash.) (tube)	20	300	0.55	5	-1.0	8					10^{15}	~ 10
HMH ⁽¹⁹⁾	20	100	3	10-20		UNDER CONSTRUCTION

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

Fig. 7. End-on framing photographs from FRX-B for 5 m Torr fill pressure, $t = 0$ represents main field initiation. The PI plasma structure is seen for $t < 0$. The FRC annulus is visible for $t > 0$ with the $n = 2$ rotational instability appearing at $t \sim +13$ s. (The thin, outmost halo in all the pictures originates from the vacuum tube.)¹¹

Fig. 8. Scaling of the stable period for FRX-A and FRX-B.¹¹

bringing only one mirror on before firing the pinch, it was found possible to unbalance the axial forces causing the FRC to drift out of the coil system.¹⁷ Further transport studies are planned in the FRX-C experiment.

Spheromak Experiments

Several approaches are presently being used to investigate the formation and properties of a CT with $B_{\text{toroidal}} = 0$ (Spheromak). Experiments under operation or being constructed are summarized in Table 2.

The PS-1 device²⁰ shown in Fig. 9 (Paramagnetic Spheromak, University of Maryland), uses a reverse bias theta-pinch to form the basic poloidal-field configuration. Toroidal field is introduced, after establishing the reverse bias field and before firing the main theta-pinch coil, by a Z-pinch discharge ($I_{\text{peak}} = 150$ kA, $t_{1/4} = 4$ μsec). Important implosion heating occurs during the rise of the main theta-pinch current ($t_{1/4} = 1.5$ μs) to produce a plasma with $T_i \simeq 200$ eV, $T_e \simeq 30$ -50 eV, and $n = 3 \times 10^{15}$ cm^{-3} . Reconnection occurs in the first 0.5 μsec to form a closed poloidal field structure consisting of two separate rings which merge to form a single ring by $t = 2$ μsec . The plasma $\beta_e = 2P_{\text{max}}/B_{\text{wall}}^2 \simeq 0.3$ -0.5 exceeds the ideal MHD $\beta_{\text{max}} \simeq 0.1$ ²¹ and β_e remains high at least 40 μsec into the decay. As mentioned earlier finite-larmor-radius effects may be important.

When the plasma is probed to determine the field structure tilting was found. Decreasing the separatrix length to radius aspect ratio from $L/R = 6$ to 2 stabilized the tilting mode consistent with theoretical predictions.²²

An alternate, dynamic means of forming a Spheromak using coaxial plasma guns is being investigated at LASL and LLNL (see Table 2). The approach is conceptually similar to that investigated earlier by Alfven, et al.²³ but employs high energy guns, since developed. The objective of the experiments is to develop guns for this application and to form a stable Spheromak target for subsequent heating, with neutral beams in the LLNL experiments.

A cross section of the LLNL gun experiment²⁴ is shown in Fig. 10. The plasma gun is modeled after an earlier gun developed by LASL.²⁵ For 185 kJ input energy, the gun accelerated plasma into a vacuum with roughly 90% efficiency producing roughly two equal energy components, a fast component with ion kinetic energy 1-10 keV and a slow component having about 100 eV kinetic energy. For the present application, the gun has been modified to accommodate solenoidal windings inside the inner electrode and outside the outer one to produce an initial vacuum

Table 2. Spheromak Experiments

Experiment	Apparatus	Plasma
PS-1 ⁽²⁰⁾ (U. of Maryland)	8-pinch with 2-pinch pre-discharge $D_{\text{coil}} = 20 \text{ cm}$, $B = 9 \text{ kG}$, $t_{1/4} = 1.5 \mu\text{s}$ $B_{\text{bias}} = -4 \text{ kG}$	$T_e \approx 30\text{-}50 \text{ eV}$, $n = 3 \times 10^{15} \text{ cm}^{-3}$, $\beta = 0.3\text{-}0.4$ $L/R = 2\text{-}6$ (separatrix quantities)
Beta-II ⁽²⁴⁾ (LLNL)	Magnetized, coaxial gun, $L = 100 \text{ cm}$ $R_{\text{outer}} = 15 \text{ cm}$, $R_{\text{inner}} = 10 \text{ cm}$ $U_{\text{in}} = 50\text{-}150 \text{ kJ}$	$T_e = ?$, $n = 2 \times 10^{15} \text{ cm}^{-3}$ $B = 5\text{-}8 \text{ kG}$, $I_{\text{tor}} \approx 200 \text{ kA}$ $U_{\text{ring}} \approx 5\text{-}10 \text{ kJ}$, $\tau \approx 200 \mu\text{sec}$
Coaxial Gun ⁽²⁶⁾ (LASL)	Magnetized, coaxial gun, $L = 100 \text{ cm}$ $R_{\text{outer}} = 15 \text{ cm}$, $R_{\text{inner}} = 10 \text{ cm}$ $U_{\text{in}} = 50\text{-}150 \text{ kJ}$	$T_e = 5\text{-}30 \text{ eV}$, $n = 2 \times 10^{14} \text{ cm}^{-3}$ $B = 5\text{-}8 \text{ kG}$ $U_{\text{ring}} = 5 \text{ kJ}$, $\tau \approx 200 \mu\text{sec}$
Proto S-1 ⁽³¹⁾ (PPL)	Supported ring, inductive coupling $R = 15 \text{ cm}$, $a = 3 \text{ cm}$ $B_v \leq 1 \text{ kG}$, $t_{1/4} = 10\text{-}15 \mu\text{sec}$	$T_e \approx 25 \text{ eV}$, $n = 1.2 \times 10^{15} \text{ cm}^{-3}$ $B \approx 1 \text{ kG}$, $R \approx 7 \text{ cm}$, $a \approx 2 \text{ cm}$ $I_{\text{tor}} \approx 20 \text{ kA}$, $I_{\text{pol}} \approx 50 \text{ kA}$, $\tau \approx 15\text{-}20 \text{ sec}$
S-1 ⁽³²⁾ (PPL)	Supported ring, inductive coupling $R = 100 \text{ cm}$, $a = 15 \text{ cm}$, $B_v = 2.2 \text{ kG}$ $I_{\text{ring,tor}} \leq 600 \text{ kA}$ $I_{\text{ring,pol}} \leq 15 \text{ MA}$, $U_{\text{ring}} \leq 1 \text{ MJ}$	UNDER CONSTRUCTION

Fig. 9. The PS-1 device showing the sequential formation of a Spheromak configuration.²⁰

Fig. 10. Schematic cross section of the LLNL, Beta II, gun experiment.²⁴

field similar to that shown in Fig. 2. In addition, the gun-center-electrode diameter has been increased (15 cm to 20 cm) and the guns are operated at significantly less pulsed gas input (5 vs 50 Atm-cm³). The gun is attached to an evacuated drift space (Fig. 10) in which various shaped flux-conserving "catchers" have been placed. An axial guide field ($B < 4$ kG) may also be added.

Early operation of both the LASL and LLNL experiments demonstrated very effective coupling of the accelerated gun plasma (with imbedded B_{toroidal}) and the vacuum poloidal field. At LLNL the reversed field pattern could be extended (without reconnection) several meters before axial motion would stop (Fig. 2). Reconnection to form an isolated Spheromak was presumed to be inhibited by flow of the low energy, but high momentum plasma from the gun at late times. LASL experiments, operated at low gas fill, demonstrated reconnection to form an isolated Spheromak.²⁶ Using a cylindrical flux conserver the ring was observed to tilt 90° as shown in Fig. 11. With an axial guide field a 180° flip was observed accompanied by rapid annihilation of the ring by reconnection to the open guide field.

Fig. 11. Schematic of the compact torus orientation and shape (a) with the major axis aligned with the symmetry axis and, (b) after 90° rotation.²⁶

The observed tilting is consistent with theoretical predictions²⁷ which further, predict stability for a sufficiently oblate Spheromak in a flux conserving shell. Experiments with oblate flux conservers as shown in Fig. 10, have confirmed the theoretical prediction. Isolated, oblate Spheromak rings are produced which decay stably and have parameters given in Table 2.

An interesting aspect of the above experiments, which was also observed by Alfvén, et al.,²⁸ is that the poloidal flux of the isolated ring usually exceeds, by factors of 3-5, the initial poloidal flux established inside the gun center-electrode. Amplification of the poloidal flux is similar to the spontaneous generation of reversed toroidal field in diffuse toroidal pinches. A theory,²⁹ similar to that of Taylor,³⁰ which minimizes the ring energy with the constraint of constant global helicity, $K = 1/2 \int \bar{A} \cdot \bar{B} d^3r$ gives reasonable agreement with the experiments.

At present, Spheromaks with adequate total energy, plasma density, and field intensity have been produced for subsequent heating. The decay time is, however, too short by factors of about 5. Present studies are directed towards identifying possible causes for the rapid decay.

Recently a quasistatic means of producing a Spheromak has been studied in the Proto S-1³¹ experiment at PPL, Princeton. The parameters of Proto S-1 and the S-1³² device under construction (see Fig. 12) are shown in Table 2. The objective of this approach is to inductively form a Spheromak on a timescale intermediate to a resistive diffusion time and a sound transit time. A vacuum poloidal field is established by toroidal currents in a supported ring (see Fig. 13). A toroidal solenoid inside the ring is switched off to provide a poloidal EMF while the toroidal ring current is driven down forcing reconnection. The resulting plasma currents form an isolated Spheromak as shown in Fig. 13. The process is an inductive version of the direct-coupled process employed with guns.

Experiments in Proto S-1 have produced Spheromak rings with parameters given in Table 2. Some evidence for nonsymmetric instability has been obtained.

CT Experiments Using Particle Rings

The basic approach of the Astron experiment was to build up a field-reversed E-layer by "stacking" a train of short electron rings.³³ Although saturation of buildup during stacking prevented the achievement of field reversal, long-lived rings were formed.

Fig. 12. The S-1 Spheromak device. The major radius of the ring core is $R = 100$ cm.

Fig. 13. Quasistatic technique for Spheromak formation.³²

Towards the end of the Astron experiment, it was found that efficient trapping of single pulse E-layers with 50% of the current for reversal could be achieved in a high pressure background gas with a toroidal field. Subsequent experiments have concentrated on forming a CT by a single pulse using intense, relativistic electron or ion beams. Current experiments following this approach are summarized in Table 3.

The first experiment³⁴ to be discussed here does not attempt to form a CT with trapped energetic electrons. It, instead, uses a hollow, electron beam injected through a half-cusp. The spinning beam propagates a cylindrical field reversal region within a conducting pipe as shown in Fig. 14. By choosing the right gas pressure ($p \approx 150$ m Torr) the beam is space-charge neutralized but not current neutralized initially. On departure of the beam however the gas has become sufficiently ionized to freeze in the beam-established field pattern. Conversion of up to 50% of the beam energy into trapped B-field energy has been observed. After initial transients lasting 5 μ sec, the field configuration decays uniformly ($\tau \approx 8$ μ s), consistent with classical resistivity ($T_e \approx 7$ eV). Although a closed poloidal field pattern is believed to be established (see Fig. 14), end to end current returning in the outer wall persists, making the poloidal current-flow lines open. Oppositely directed beams to remove this difficulty are planned.

The RECE-Christa, RECE-Berta, and more recently CHIP experiments³⁵ (see Table 3) provided the first successful demonstration of the formation of field-reversed rings using relativistic electron beams. A schematic of the RECE experiments is shown in Fig. 15. The REB is injected tangentially in the presence of high-pressure neutral gas ($p = 0.1$ -1 Torr) which ionizes to produce space-charge neutralization but remains highly resistive during field-line reconnection.

The RECE experiments have demonstrated many macroscopic aspects of electron-ring CT's. Compression, translation, merging of two rings, and stability have been demonstrated. In particular, no tilt or wobble instability has been seen and the precessional instability³⁶ could be stabilized by conducting walls or weak quadrupole fields. Presently, heating and confinement of plasma by the rings is under investigation.

Experiments employing high energy, pulsed ion beams from recently developed sources are less far along and no trapped, decaying rings have been formed. An ion ring experimental program at Cornell University³⁷ (see Table 3, IREX and LONG-SHOT) uses magnetically insulated ion sources (Hall accelerator) and cusp injection to produce spinning proton beams. In IREX,

Table 3. Experiments on Particle Ring CT.

Experiment	Device	Plasma
Rotating X-beam ⁽³⁸⁾	V = 900 kV, I = 80 kA	$n \approx 10^{16}$, $T_e \approx 5$ to 7 eV, $\tau \approx 8$ μ sec
HEL	Hollow RRB $\tau = 100$ μ sec Half-cusp injection	$B \approx 2$ kG
NECK-Christa ⁽³⁰⁾	REB 3 to 5 MeV, Tangential Injection	$R = 7$ to 15 cm, $I_{ring} \leq 20$ kA, $\tau_{reversal} \leq 1.1$ μ sec
Cornell U.	$B_z = 0.5 - 1$ kG $B_{tor} = 0.5-2$ kG	170% field reversal
NECK-Marta ⁽³⁰⁾	REB 0.4 MeV, Tangential Injection	$R = 8$ to 10 cm, $I_{ring} \leq 5$ kA, $\tau_{reversal} \leq$ several μ sec
Cornell U.	$B_z = 200$ G $B_{tor} = 0$	190% field reversal
CHIF ⁽³⁰⁾	REB 0.4 MeV, Cusp Injection	$R = 3$ to 4 cm, $I_{ring} \leq 3$ kA, $\tau_{reversal} \leq$ few μ sec
Cornell U.	$B_z = 600$ G $B_{tor} = 0$	120% field reversal
IREX ⁽³²⁾	Proton Beam $E \geq 430$ keV	0.5 to 1×10^{16} protons
Cornell U.	$\tau = 90$ nsec, Cusp Injection $I = 50-90$ kA $B_z = 8$ kG	~ 3 to 10% diamagnetism in propagating beam
LOWSHOT ⁽³²⁾	Proton Beam ≤ 100 keV	2×10^{16} protons
Cornell U.	$\tau = 700$ nsec, Cusp Injection $B_z = 5-7$ kG	$\sim 4\%$ diamagnetism in propagating beam
ION RING PROGRAM ⁽³³⁾	Proton Beam $E = 1-2$ MeV, Cusp Injection	10^{17} protons
HEL	$I \approx 500$ kA $B_z = 1.5$ kG	120% field reversal in propagating beam

Fig. 14. Generation of a Compact Torus configuration using two, oppositely directed electron beams. The present configuration is generated by a single beam and has $B_{wall} \neq 0$.³⁴

Fig. 15. Basic schematic of the RECE-Christa device.³⁵

rings with up to 8% diamagnetic field have been propagated along a guide field and reflected from a mirror.

A more energetic proton beam experiment is being investigated at NRL³⁸ (see Table 3). Cusp injection is used and 120% reversal of a 1.5 kG guide field has been achieved with a propagating beam.

SUMMARY

The past few years have seen a rapid growth in the number of experiments investigating various aspects of the CT. A wide variety of techniques have been successfully developed to produce a CT. Studies of the CT have increased greatly our understanding of various macroscopic properties and have shown macroscopically stable equilibria. Studies of transport and other microscopic effects are just beginning and, if successful confinement is achieved, would offer encouraging possibilities for eventual fusion reactor applications.

REFERENCES

1. H. Alfvén, in Proc. Second Int'l. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1958, vol. 31, p. 145.
2. W. Bostic, Phys. Rev., vol. 104, 292 (56).
3. Bodin, H. A. B., Newton, A. A., Phys. Fluids 6 (1963) 1338; Little, E. M., Quinn, W. E., Phys. Fluids 6 (1963) 875.
4. N. C. Christofilos, 2nd United Nat. Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 1958, Vol. 32, p. 279.
5. H. Alfvén, L. Lindberg, and P. Mitlid, J. Nucl. Energy 1, 116 (1960).
6. Bodin, H. A. B., Nucl. Fusion 3 (1963) 215.
7. R. Turner, Phys. Fluids 13, 2398 (1970).
8. W. B. Jones and R. D. Miller, Phys. Fluids 11, 1550 (1968).
9. R. J. Briggs et al., "Astron Program Final Report," UCRL-518-A (1975).
10. H. H. Fleischmann, Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 41.
11. W. T. Armstrong et al., "Field-Reversed Experiments on Compact Toroids," submitted to Phys. Fluids.
12. R. E. Siemon and R. R. Bartsch, Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1, 1980, LA-8799-C, p. 172.
13. J. Freidberg and L. D. Pearstein, "Rotational Instabilities in a Theta Pinch," Phys. Fluids 21 (7) July 1978, p. 1207.
14. M. N. Rosenbluth and M. N. Bussac, Nucl. Fusion 19, 489 (1979).

15. W. Newcomb, Phys. Fluids **23** (11), 2296 (1980).
16. H. L. Berk, J. Sayer, and D. D. Schnack, Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 122.
17. W. T. Armstrong, et al., Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 122.
18. S. O. Knox, et al., Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1980, LA-8700-C, p. 188.
19. A. L. Hoffman and G. Vlases, Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 147.
20. G. Goldembaum, et al., Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 162.
21. M. Okabayshi and A. M. M. Todd, "MHD Equilibrium and Stability of the Spheromak," submitted to Nucl. Fusion.
22. M. N. Rosenbluth and M. N. Bussac, Nucl. Fusion **19**, 489 (1979).
23. H. Alfven, L. Lindberg, and P. Mitlid, J. Nucl. Energy **1**, 116 (1960).
24. W. C. Turner, et al., Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1980, LA-8700-C, p. 113.
25. I. Henins and J. Hammel, Bull. Am. Phys. Soc. **22**, 1115 (1977).
26. T. R. Jarboe et al., Phys. Rev. Lett. **45**, 1264 (1980).
27. M. N. Rosenbluth and M. N. Bussac, Nucl. Fusion **19**, 489 (1979).
28. H. Alfven, L. Lindberg, and P. Mitlid, J. Nucl. Energy **1**, 116 (1960).
29. E. Hameiri and J. Hammer, "Turbulent Relation of Compressible Plasmas," UCRL-84977, Sept. 1980, submitted to Phys. Rev. Lett.
30. J. B. Taylor, Phys. Rev. Lett. **33**, 1139 (1974).
31. M. Yamada et al., PPPL-1723 (submitted to Phys. Rev. Lett.).
32. M. Yamada, et al., Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1980, LA-8700-C, p. 124.
33. N. C. Christofilos, 2nd United Nat. Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 1958, Vol. 32, p. 279.
34. J. D. Sethian, et al., Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 37.
35. H. H. Fleischmann, "Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1980, LA-8700-C, p. 31.
36. H. P. Furth, Phys. Fluids **8**, 2020 (1965).

37. J. B. Greenly, et al., Proc. 3'd Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, Dec. 1980, LA-8700-C, p. 36.
38. J. A. Pasour, et al., Proc. of the US-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 1979, p. 45.
39. C. Baker et al., "Trends and Developments in Magnetic Fusion Reactor Concepts," Nuc. Tech./Fusion, V 1, Jan. 1981, p. 5.

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