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Technique for Driving Steady Plasma Currents in
Compact Toroid Devices**

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THE RMF CONCEPT: A ROTATING-MAGNETIC-FIELD TECHNIQUE FOR DRIVING STEADY PLASMA CURRENTS IN COMPACT TOROID DEVICES

by

Kenneth F. McKenna

ABSTRACT

The generation and/or sustaining of a Compact Toroid (CT) configuration using the RMF technique is a relatively new and unknown concept. In this report the basic principles, historical development, and current theoretical understanding of this concept are reviewed. Significant experimental and theoretical results, potential problem areas, and recommendations for the direction of future work are discussed. An illustrative analysis of the application of the RMF technique to a CT reactor is presented. The results of a recent experiment, the Rotamak, in which a Spheromak-like CT plasma was produced using the RMF technique, are presented.

I. Introduction

In several fusion devices such as Tokamaks, Reversed Field Pinches (RFP), and Compact Tori (CT), plasma confinement is partially maintained by a poloidal magnetic field generated by a toroidal current. In these machines the toroidal current is driven by an inductively produced electric field. Since inductive coupling cannot be utilized to sustain steady-state operation, these devices only operate in a pulsed mode. In order to obtain steady-state conditions, techniques must be developed for continuously driving the toroidal plasma current. The plasma research group at the Flinders University of South Australia, under the direction of Dr. I.R. Jones, is currently investigating an rf, Rotating-Magnetic-Field (RMF) method of producing steady-state currents, which presents an alternative to induction methods.

This report is the result of the author's recent (July 1979-February 1980) six-month change-of-station from Los Alamos to Flinders University. The purpose of this trip was to obtain an understanding of the RMF current-drive technique. This involved a study of previous experimental and theoretical investigations, the participation in the present experimental effort, the identification of significant results and problem areas, and an evaluation of the applicability of this technique to the Los Alamos CTR program. The results of this effort comprise the main body of this report.

II. Basic Principles of the RMF Current-Drive Technique

The rotating-magnetic-field, current-drive technique is based upon the response of a high conductivity plasma to an externally applied, periodically varying magnetic field. When the plasma electron and ion cyclotron frequencies, ω_{ce} and ω_{ci} , are much greater than the frequency, ω , at which the applied magnetic field changes, then the plasma particles appear "tied" to the magnetic field lines and follow the "motion" of the periodically varying field. When ω is less than ω_{ce} but greater than ω_{ci} , then the electrons are tied to the field lines but the ions are not. In this situation, differential motion between electrons and ions is usually prevented by the development of space-charge electric fields. However, if the magnetic field lines move in a direction parallel to surfaces of constant number density, a space-charge electric field does not develop and the moving magnetic field carries only the electrons along with it. Thus it is possible to generate steady electron plasma currents using periodically varying magnetic fields.

Figure 1 schematically illustrates the application of the RMF technique to the case of a cylindrical plasma column. The transverse magnetic field, of magnitude B_0 , which rotates about the z-axis of the cylinder, can be simply produced by two dipole coils which carry currents of the same frequency and amplitude but differing in phase by 90° . When the angular frequency, ω , of the rotating field lines lies between ω_{ce} and ω_{ci} , calculated with respect to B_0 , then the electrons follow the motion of the rotating field, resulting in the generation of an azimuthal current, while the ions lag behind. The amplitude of the azimuthal electron current is affected by the rate at which electrons are detached from field lines by collisions with the background ions. When the

electron-ion collision frequency, ν_{ei} , is much less than the electron cyclotron frequency, the electrons are tightly tied to the field lines and the azimuthal electron velocity approaches its maximum value, the phase velocity ($r\omega$) of the rotating field. If the plasma were completely isolated, electron-ion collisions would ultimately bring the ions into synchronous rotation with the electrons and the current would subsequently vanish. This problem, and proposed solutions, will be discussed in a later section.

Plasma equilibrium is obtained in the presence of an externally applied, steady axial magnetic field, B_a . The radial profile of the equilibrium magnetic field is the resultant of a linear combination of the steady axial field, B_a , and the axial field produced by the azimuthal current; the sense of ω is selected such that these two axial fields are of opposite direction. It can be shown that, for small ν_{ei}/ω_{ce} , the magnitude of the resultant magnetic field on the cylinder axis is $B_z(0) = B_a - 2N_0 e \omega / c$ where N_0 is the electron line density and $2N_0 e \omega / c$ is the axial field component generated by the rotating electrons. If N_0 and ω are adjusted such that $B_z(0) = 0$, then the $\beta=1$ theta-pinch profile is obtained. CT (essentially field-reversed theta pinch) configurations can be generated by selecting N_0 and ω such that $B_z(0) < 0$, with the limiting value at $B_z(0) = -B_a$. RFP and Spheromak-like configurations can be generated through the superposition of an azimuthal magnetic field, produced by the introduction of an axial current.

In the above discussion, which illustrates the basic concept of the RMF current-drive technique, it has been assumed that the rotating field, B_0 , completely permeates the cylindrical plasma column. The mechanism that enables the rf field to penetrate the plasma will be discussed in a later section.

It should be noted that several major laboratories within the United States (General Atomic Co., MIT, and PPPL) are pursuing programs on rf current drive. The object of these efforts is the attainment of steady-state Tokamak operation; since the toroidal current is driven by an inductively induced electric field, present Tokamaks operate only in a pulsed mode. A typical scheme of producing steady-state current in Tokamaks relies upon Landau damping of lower hybrid rf waves traveling in the toroidal direction. The high-phase-velocity waves have net toroidal momentum which is absorbed by resonant, high-velocity electrons traveling near the wave phase velocity, thus causing the electrons to drift toroidally creating a current. Both low- and high-phase velocity traveling waves have been studied for use in steady-state

reactors. This traveling-wave, current-drive technique differs from the rotating-magnetic-field technique. In the former scheme current is generated by a fast beam of resonant electrons contained within the high-velocity tail of the electron velocity distribution, while the RMF scheme requires the synchronous rotation of the bulk of the electrons with the rotating field. Although both these methods of steady-state current drive could impact significantly on the Los Alamos CT and RFP programs, only the RMF technique will be considered in the remainder of this report.

III. Historical Overview

The concept of driving plasma current with rf magnetic fields was proposed and experimentally demonstrated by Thonemann¹ in 1952. In his experiment, Thonemann observed 10^2 amps of toroidal current using a 1.7 MHz traveling wave in a 9-cm-major-radius, 2-cm-minor-radius torus.

At Thonemann's suggestion, the first effort at producing an azimuthal electron current in a cylindrical geometry, using a transverse, rotating magnetic field, was carried out in 1961 by Blevin and Thonemann.² In their theoretical work, they obtained the steady-state solution for the radial distribution of magnetic field and particle density in a long plasma cylinder of uniform temperature and resistivity containing a constant axial magnetic field, and a uniform transverse magnetic field which rotates about the cylinder axis. They showed that the condition $v_{ei}/\omega_{ce} < 1$ must be satisfied for penetration of the rotating field into the plasma column. Their solution yields a rigid-rotor equilibrium which, for small v_{ei}/ω_{ce} , gives the azimuthal current density distribution $j_\theta = ne\omega r$. (In 1965 Blevin and Miller³ obtained analytical expressions for the plasma equilibria when a uniform current is imposed along the cylinder axis.) Blevin and Thonemann's apparatus was similar to that shown diagrammatically in Fig. 1. Using 3- and 5-cm-diameter discharge tubes, 20 cm long, and a 1 MHz rotating magnetic field, they produced both theta-pinch and CT plasma equilibrium configurations. The rf generation of a steady azimuthal current was verified by internal measurements of the resultant axial magnetic field.

As previously noted, the maximum value of the resultant magnetic field on axis, for the cylindrical plasma column shown in Fig. 1, is $B_z(0) = -B_a$. For values of $B_z(0) > -B_a$, the internal field pressure exceeds the external field pressure and the plasma cannot be confined. Since $B_z(0) = B_a - 2N_0e\omega/c$, this limit restricts the possible values of $N_0\omega$. Davenport⁴ et al. in 1966 showed that this restriction can be removed by making the outer surface of the discharge tube wall electrically conducting in the azimuthal direction, thus

Fig. 1.
Rotating magnetic field applied to a cylindrical plasma column.

conserving the net axial magnetic flux enclosed by the wall. Prior to initiation of the rotating field, the total flux within the discharge tube is $\pi R^2 B_a$ where R is the tube radius. When the rotating field penetrates the plasma the resulting azimuthal electron current produces a magnetic flux which is opposed by an equal flux generated by the conducting wall current. The net result is an unbounded increase in the effective axial magnetic field at the tube wall, allowing unlimited values of $B_z(0)$ (i.e., $N_0 \omega$).

In Davenport et al.'s experiments the conducting wall was comprised of a series of close-fitting and insulated conducting rings which were spaced along the discharge tube outer diameter. In this manner the axial flux was conserved while still allowing the transverse rotating field to penetrate the plasma. (The dipole coils which generated the 1.5-MHz rotating field were located outside the flux conserving rings.) The discharge tube was 14 cm in diameter and 100-cm long, significantly larger than that used by Blevin and Thonemann. The measured radial profiles of magnetic field and plasma density, determined from internal magnetic probes and laser interferometry, were in excellent agreement with the theoretically predicted CT rigid-rotor equilibria profiles and demonstrated the effectiveness of the flux conserving rings.

Recently (1979) I.R. Jones and co-workers at the Flinders University of South Australia have re-examined and extended the earlier RMF current-drive studies discussed above. Experimentally, they have demonstrated that the RMF technique can be used to generate the steady equilibrium currents appropriate to a wide variety of plasma-field configurations. Specifically, RFP,⁵ theta-pinch,⁶ and screw-pinch/high-beta Tokamak⁶ radial equilibria configurations have been produced and studied in a cylindrical, 5-cm-diameter, 70-cm-long discharge tube using a 0.7-MHz rotating magnetic field. In these experiments, argon gas was used in order to easily satisfy the criteria $\omega_{ci} < \omega < \omega_{ce}$.

In their theoretical work, Hugrass et al.^{7,8} (1979-80) at Flinders have obtained numerical solutions of the nonlinear, initial-value problem where a transverse rotating magnetic field is suddenly applied to a collisional ($\omega < \nu_{ei}$) plasma column of uniform temperature and density. They find that the rotating field penetrates into the plasma a distance which is many times greater than the classical skin depth, provided that the electron-ion collision frequency is much smaller than the electron cyclotron frequency calculated with respect to the rotating field. These results show that substantial azimuthal

current can be produced in a plasma cylinder of radius R when $(v_{ei}/\omega_{ce})(R/\epsilon) < 1$. A similar theoretical treatment for collisionless plasma ($\omega > v_{ei}$) has not been carried out.

The Rotamak concept,⁹ proposed in 1979 by I.R. Jones at Flinders University, evolved from the recognized advantages of low-aspect ratio, toroidal Spheromak geometries and the demonstration, at Flinders, of the production of field-reversed configurations using the RMF technique. In the Rotamak, shown schematically in Fig. 2, a rotating magnetic field is used to drive the steady toroidal current in a Spheromak-like device. An externally applied, steady mirror field couples with the toroidal current to produce the required plasma equilibria. Recent experiments¹⁰ with a small-scale (6.4-cm-radius, spherical discharge vessel) Rotamak device, in which the author of this report participated, have demonstrated the production of a Spheromak-like CT plasma with a toroidal current of approximately 10 kA

Fig. 2.
Magnetic field distribution in the Rotamak.

generated by a 0.7-MHz rotating magnetic field. This continuing work is supported by grants from the Australian National Energy Research, Development, and Demonstration Council, the Australian Institute of Nuclear Science, and the Australian Research Grants Committee.

IV. Review of RMF, Current-Drive Theory

In RMF current-drive experiments carried out to date, the rotating magnetic field is applied to either a preionized plasma or to a neutral gas in which the induced electric fields associated with the rotating field do the ionizing. Rotating fields could also be applied to a hot, preformed CT plasma configuration to sustain steady-state equilibrium currents. In either case, the rotating field must penetrate the plasma in order to drive the required electron current. The field penetration problem is approached by first considering the appropriate Ohm's law. Assuming that the ions form a background of stationary positive charge, and neglecting the electron pressure gradient, the electron equation of motion becomes

$$\vec{E} = \frac{m_e}{ne^2} \left\{ \omega \vec{j} + \omega_{ce} \frac{\vec{j} \times \vec{B}}{B} + v_{ei} \vec{j} \right\} \quad , \quad (1)$$

where n is the electron density.

For the case where ω and ω_{ce} are both less than the collision frequency v_{ei} , Ohm's law can be approximated as $\vec{E} = \eta \vec{j}$ where the resistivity $\eta = m_e v_{ei} / ne^2$. This equation can be easily solved using Maxwell's equations and yields the classical skin depth, $\delta = (\omega/2\eta)^{1/2}$. Accordingly, under these conditions the rotating field would be expected to penetrate only a thin outer plasma layer of thickness δ . Conversely, when ω is less than both v_{ei} and ω_{ce} , Ohm's law reduces to

$$\vec{E} = - \frac{1}{nc} \vec{j} \times \vec{B} + \eta \vec{j} \quad . \quad (2)$$

The effect of the nonlinear Hall term in this expression, which becomes dominant at small values of v_{ei}/ω_{ce} , is to enable the rotating magnetic field to penetrate the plasma.

Before discussing the solution to the initial-value field-penetration problem, it is instructive to review first the results of the steady-state analysis.² Consider a long, uniform temperature and resistivity plasma column containing a constant axial magnetic field, B_a , and a transverse rotating magnetic field of amplitude, B_o . Let $\omega_{ci} < \omega < \omega_{ce}$, with respect to B_o . Then, assuming that the ions are stationary and that no radial currents exist, the system is completely described by Maxwell's equations, the appropriate Ohm's law,

$$\vec{E} = \frac{1}{nc} \vec{j} \times \vec{B} + \eta \vec{j} + \frac{1}{ne} \nabla P_e, \quad (3)$$

which is simply Eq. (2) with the electron pressure gradient included, and the externally applied fields,

$$\begin{aligned} B_r &= B_o \cos(\omega t - \theta) \\ B_\theta &= B_o \sin(\omega t - \theta) \\ B_{z_o} &= B_a \end{aligned} \quad (4)$$

The solution of this system of equations for the azimuthal current density is

$$j_\theta = \frac{ner\omega}{1 + 2\left(\frac{v_{ei}}{\omega_{ce}}\right)^2} \quad (5)$$

For v_{ei}/ω_{ce} much less than unity, the "slip" between the electron gas and the rotating field is small. In this event, rigid-rotor equilibria result,

$j_\theta = ner\omega$, and the electrons are perfectly "tied" to the rotating magnetic field lines.

The axial current density is given by

$$j_z = \frac{E_z}{\eta \left[1 + \frac{1}{2} \left(\frac{\omega_{ce}}{v_{ei}} \right)^2 \right]}, \quad (6)$$

where, from Faraday's law, $E_z = r\omega B_0 \cos(\omega t - \theta)$. The presence of a j_z current density results in a B_θ magnetic field component which is superimposed on the transverse rotating magnetic field. When the slip is small ($v_{ei}/\omega_{ce} < 1$), $j_z \approx 0$ from Eq. (6) and the rotating magnetic field is neither attenuated nor distorted within the plasma. An effective resistivity, η^* , can be defined such that

$$\eta^* = \eta \left[1 + \frac{1}{2} \left(\frac{\omega_{ce}}{v_{ei}} \right)^2 \right]. \quad (7)$$

Equation (6) can then be written as $E_z = \eta^* j_z$ which yields an effective skin depth, $\delta^* = (2\eta^*/\omega)^{1/2}$. Recalling that the classical skin depth $\delta = (2\eta/\omega)^{1/2}$, it can be readily shown that for small v_{ei}/ω_{ce} ,

$$\delta^* \approx \frac{\delta}{(v_{ei}/\omega_{ce})}. \quad (8)$$

Accordingly, for plasmas with small v_{ei}/ω_{ce} the rotating magnetic field skin depth, δ^* , is significantly larger than the classical skin depth, δ .

The total axial magnetic field, $B_z(r)$, is the sum of a linear combination of the steady axial magnetic field, B_a , and the axial field produced by the azimuthal current. From Ampere's law, $B_z(r)$ can be written as,

$$B_z(r) = B_a - \frac{4\pi}{c} \int_0^R \frac{n_e \omega r dr}{\left[1 + 2\left(\frac{v_{ei}}{\omega_{ce}}\right)^2\right]} \quad (9)$$

$$\text{or, } B_z(r) = B_a - \Delta B_z \quad . \quad (10)$$

The term ΔB_z is a maximum on axis ($r = 0$) and represents the "depth" of the magnetic well produced by the azimuthal electron current. The well depth attains its maximum possible value, ΔB_z^M , when v_{ei}/ω_{ce} is small compared to unity (electrons circulating synchronously with the rotating field). This maximum is given by,

$$\Delta B_z^M = \frac{2N_0 e \omega}{c} \quad . \quad (11)$$

Figure 3 illustrates the rigid-rotor equilibria profiles of the axial magnetic field and electron density obtained for different values of ΔB_z . The density profiles are derived from the radial pressure balance condition, $\nabla p = \vec{j} \times \vec{B}/c$, assuming the plasma temperature to be independent of radius. For $\Delta B_z < B_a$, theta-pinch profiles are generated. For $\Delta B_z > B_a$ but less than $2B_a$, a CT configuration (reversed-field theta pinch) results. Unless flux conserving rings are used, equilibria cannot be produced when $\Delta B_z > 2B_a$.

Numerical solutions^{7,8} to the initial-value problem, in which a transverse rotating magnetic field is suddenly applied to a collisional ($\omega < v_{ei}$) plasma column of uniform temperature and density, have been obtained using a finite difference method. As in the steady-state analysis, the nonlinear Ohm's law (Eq. (2)) was used, ion motion was neglected, and the condition $\omega_{ci} < \omega < \omega_{ce}$ was applied. The numerical analysis results show that, for $v_{ei}/\omega_{ce} < 1$, the rotating field fully penetrates the plasma if,

$$\frac{v_{ei}}{\omega_{ce}} \frac{R}{\delta} < 1 \quad . \quad (12)$$

Fig. 3.

Rigid-rotor equilibrium profiles of the axial magnetic field and electron density obtained for different values of ΔB_z .

In this nonlinear limit, the field penetration depth is ω_{ce}/ν_{ei} times greater than the classical skin depth, δ . This result was also indicated from the steady-state analysis (Eq. (3)), and is caused by the downward Doppler shift in the rf field frequency in a frame of reference moving with the electrons.⁸

Figures 4 and 5, taken from Ref. 7, show the time development of the penetration of the rotating magnetic field into a cylindrical plasma column, at two different values of the penetration factor, $(\nu_{ei}/\omega_{ce})(R/\delta)$. The fixed plasma parameters are, $R = 2.5$ cm, $T_e = 7$ eV, $n_e = 1 \times 10^{14}$ cm $^{-3}$ and $\omega = 5 \times 10^6$ sec $^{-1}$. The penetration requirement (Eq. (12)) can be expressed as,

Fig. 4.

Time development of the rotating-magnetic-field penetration into a cylindrical plasma column with $(\nu_{ei}/\omega_{ce})(R/\delta) > 1$.

$$1.2 \times 10^{-16} \sqrt{\omega \ell n \Lambda} \frac{n}{B_0} \frac{R}{T_e^{3/4}} < 1 \quad . \quad (13)$$

In order to illustrate the effect of this inequality, two different values of B_0 were selected; it should be noted that the inequality could also be altered by changing any of the other variables. In Fig. 4, $B_0 = 30$ gauss so that $(v_{ei}/\omega_{ce})(R/\delta) \approx 1.7$ and the penetration requirement is violated. Only partial penetration of the rotating field is observed and the depth of the magnetic well produced after steady-state conditions are obtained, ΔB_z^S , is less than the maximum, ΔB_z^M . For $B_0 = 160$ gauss, Fig. 5, $(v_{ei}/\omega_{ce})(R/\delta) = 0.3$ and the rotating field completely penetrates the plasma. In this case, all the electrons are set into synchronous rotation with the rotating field and the maximum magnetic well depth is obtained in the steady state.

As can be seen from Fig. 5, the rotating magnetic field does not instantaneously penetrate the plasma but rather gradually diffuses into the plasma until the steady state is obtained. The numerical solution to the initial-value problem discussed above indicates a characteristic field diffusion time given by,⁸

$$\tau_d = \frac{\pi R^2}{2c^2 \eta} \quad . \quad (14)$$

The RMF driven, electron current will continuously transfer momentum to the ions through electron-ion collisions. Ultimately the ions will attain an azimuthal drift velocity comparable to that of the electrons and there will be no net current flow. The characteristic time for the ions to come into rotation with the electrons is $(m_i/m_e)\tau_{ei}$, where $\tau_{ei} = 1/v_{ei}$. In past experiments this time has been on the order of several hundred microseconds and thus ion motion was negligible. However, at reactor parameters the ion spin-up time will be comparable to the burn time, about one second. To counteract the gradual decrease in net current due to the ion motion, it would be possible to gradually increase the rotating field frequency, thus increasing the electron

$B_0 = 160 \text{ G}$ $\frac{\nu_{ei}}{\omega_{ce}} \frac{R}{\delta} = 0.3$

Fig. 5.

Time development of the rotating-magnetic-field penetration into cylindrical plasma column with $(\nu_{ei}/\omega_{ce})(R/\delta) < 1$.

drift velocity while maintaining a constant net current. Another possible technique of cancelling the ion drift would be the use of counter-directed neutral beams. A third method, suggested by Wort¹¹ for a "peristaltic Tokamak," would involve the application of a low frequency traveling wave propagating in a direction opposite to that of the electron drift motion. The frequency of the wave would be selected to cancel the incremental velocity imparted to an ion during an electron-ion collision.

V. Fusion Reactor Application of the RMF, Current-Drive Technique

In order for the RMF method of sustaining plasma currents to be of interest to the US fusion effort, it must be shown that this technique is applicable in the reactor regime. Using the experimental and theoretical results discussed in the previous sections, the requirements and characteristics of the rotating magnetic field necessary to drive a possible CT reactor are presented below. It should be understood that the previously discussed theory treated the collisional plasma case where $\omega < \nu_{ei}$. In the reactor regime, $\nu_{ei} < \omega$ since the plasma will be collisionless.

Consider a prolate CT plasma configuration, such as generated in field-reversed theta pinches, with a separatrix radius, r_s , of 50 cm and a length, ℓ , of 200 cm. Total reversal, on axis, of the external field is assumed so that $\Delta B_z^M = 2B_a$ and the separatrix radius is taken to be about equal to the wall radius, R , of the containment vessel. Taking a uniform plasma temperature of $T_e = T_i = 20$ keV and an $n\tau$ of $2 \times 10^{14} \text{ cm}^{-3} \text{ sec}$, where τ is the burn time, requires an external confining magnetic field of 20 kG for a maximum density at the $\beta = 1$ magnetic axis, n_m , of $2.5 \times 10^{14} \text{ cm}^{-3}$ and a τ of 0.8 sec. A rigid-rotor equilibrium is assumed. Under these conditions, $n_m \approx 2n_0$, where n_0 is the fill density.

The initial CT plasma configuration can be generated by a number of methods, e.g., a gun, field-reversed theta pinch, or by the RMF itself. It is assumed here that the CT plasma has been established and that the rotating magnetic field is applied in order to sustain the azimuthal electron current necessary for confinement. The rotating field frequency required to sustain the configuration at the reactor parameters given above is, from Eq. (11),

$$\omega = \frac{2B_a c}{\pi R^2 e n_m} = 1.3 \times 10^6 \text{ sec}^{-1},$$

or, $f = \omega/2\pi \approx 0.2$ MHz. The requirement that electrons, but not ions, be tied to the rotating field lines, $\omega_{ci} < \omega < \omega_{ce}$, efficiently places an upper limit on the magnitude, B_0 , of the rotating field. In the absence of quantitative

theoretical guidance, the condition $\omega_{ci} = \frac{1}{10}\omega$ is assumed. This yields a maximum value for B_0 of 26 gauss.

In order for the rotating field to penetrate and remain undistorted within the reactor plasma, the condition $(v_{ei}/\omega_{ce})(R/\delta) < 1$ must be satisfied. From Eq. (13) using the plasma and rotating magnetic field parameters given here, $(v_{ei}/\omega_{ce})(R/\delta) \approx 0.2$, indicating complete penetration of the rotating field. In addition, $v_{ei}/\omega_{ce} \approx 10^{-5}$ so that the electrons are strongly tied to the rotating field lines.

The total azimuthal current sustained by the rotating field is given by,

$$I_\theta = \ell \int_0^R j_\theta dr = \frac{1}{2} e \omega R^2 n_0 \ell, \quad (15)$$

where, with v_{ei}/ω_{ce} small, $j_\theta = nev$ for the rigid-rotor equilibria. Thus for the 200-cm long CT, the total current $I_\theta = 6.4$ MA. The total resistive power dissipation within the plasma, which must be supplied by the rotating field, is

$$P = \ell \int_0^R \int_0^{2\pi} \eta j_\theta^2 r dr d\theta = 4\pi \eta \frac{I_\theta^2}{\ell}, \quad (16)$$

where η is the plasma resistivity. For the 20 keV reactor plasma, the total power input, P , required to maintain the azimuthal current is 0.01 MW.

Thus, based on these calculations, a reactor-grade plasma could be maintained by a rotating magnetic field whose magnitude is about 26 gauss, frequency is 0.2 MHz, and power input is 0.01 MW. A rotating field with these modest parameters could be used to drive the required CT azimuthal current indefinitely.

In addition to the basic parameters of the rotating magnetic field, ion motion and the diffusion of the rf field into the CT plasma must also be considered. The characteristic time for the ions to attain an azimuthal velocity equal to that of the electrons, as a result of the electron-ion collisions, is about $(m_i/m_e)\tau_{ei}$. For the selected reactor parameters, this time is approximately 0.7 sec which is nearly equal to the burn time of 0.8 sec. Accordingly, at the end of the burn time the ions would have a directed

velocity of nearly seven-tenths of the electron velocity, and the containment would fail prior to completion of the burn. Considering the relatively low value of rotating field frequency, 0.2 MHz, a reasonable method of overcoming this problem would be to gradually increase this frequency during the burn, thus maintaining the required net current. Alternative methods have previously been discussed.

It is not possible to estimate the characteristic time for the rotating field to penetrate the reactor plasma since the theoretical solution for penetration into a collisionless plasma which contains an existing azimuthal electron current (preformed CT) has not yet been determined. The classical diffusion time, τ_d , for rotating-field penetration into an initially current-free, collisional plasma, given by Eq. (14), yields $\tau_d \approx 60$ sec. This time is about two orders of magnitude greater than the reactor burn time. If a proper theoretical and experimental study of the diffusion of the rotating field into a collisionless preformed CT plasma does not indicate significantly faster diffusion times, then the successful application of the RMF technique to CT reactor plasma would be doubtful. However, it should be noted that anomalous processes alone, which all fusion plasmas exhibit, would be expected to enhance diffusion of the rotating magnetic field.

VI. Evaluation of the RMF Current-Drive Technique: Significant Results, Problem Areas, and Recommendations for Future Work

The RMF technique of driving equilibrium plasma currents in CT devices appears to be an attractive alternative to conventional induction methods. It has been demonstrated in low temperature ($T_e < 50$ eV) collisional plasma experiments that this technique can be used to generate a variety of plasma-field geometries such as the RFP, screw-pinch, and CT. The existing solution to the steady-state and time-dependent theories, which describe the rotating field interaction and subsequent electron current generation in collisional plasma of cylindrical geometry, are in excellent agreement with experimental results. The extrapolation to CT reactor-grade plasmas indicates that a rotating magnetic field of modest frequency and magnitude could be used to sustain the required equilibrium plasma current, provided that the rotating field penetrates the plasma on a time scale which is short compared to the burn

time. Accordingly, with these positive results, further theoretical and experimental studies of the RMF, current-drive technique appear to be justified.

1. Significant results

In several experiments^{2,4,6} transverse rotating magnetic fields have been used to generate azimuthal currents necessary for plasma confinement in cylindrical geometries. Internal magnetic field probe measurements, and in Ref. 4 laser interferometer data, demonstrate that the axial field produced by the driven azimuthal current combines linearly with an externally applied, steady axial field to produce the plasma equilibria appropriate to several confinement systems. The equilibria configurations generated experimentally are in excellent agreement with steady-state theory predictions.

In the Rotamak experiment,¹⁰ to be discussed in the next section, a rotating magnetic field was used to produce the toroidal current in a low-aspect-ratio, spheromak-like, plasma. Magnetic field probe measurements of the poloidal field distribution showed that the combination of the driven poloidal field with an applied steady mirror field generated a toroidal CT configuration. CTs with and without an applied toroidal magnetic field were produced.

The solution of the initial-value problem,^{7,8} which describes the penetration of the rotating magnetic field into an initially current-free, uniform collisional plasma has been obtained numerically. A result of this analysis has been the identification of a rotating-magnetic-field, penetration parameter, $(v_{ei}/\omega_{ce})(R/\delta) < 1$, which must be satisfied for complete penetration of the rf field. Qualitative verification of this threshold parameter has been obtained experimentally.⁷

2. Problem areas

The extrapolation of the RMF technique to reactor-like plasmas is based on the results from collisional plasma experiments and collisional plasma theory ($\omega < v_{ei}$). These results may not adequately describe the rotating field-plasma interaction in collisionless plasmas ($\omega > v_{ei}$). In addition, a theoretical treatment of the application of a rotating magnetic field to a preformed CT plasma has not been carried out. The absence of an appropriate theory presents a problem in designing large-scale, high-temperature CT experiments.

A major concern in the consideration of the rotating-magnetic-field technique for driving plasma currents in reactor-size devices is the prediction, from collisional plasma theory, that the rf field penetrates the plasma on classical diffusion time scales, which would be much longer than reactor burn times. Even in moderate-size, and plasma-temperature ($R \sim 20$ cm $T_e \sim 200$ eV) FRX-C-type experiments,¹² the classical diffusion time of about 20 msec is much greater than the anticipated plasma lifetime.

It would be expected that directed ion motion, resulting from momentum transfer by electron-ion collisions could ultimately cancel the driven electron current and thus confinement could not be maintained. Although this effect would represent a problem for steady-state rf current drive, solutions to this problem have been suggested.

Both the steady- and unsteady-state theories which have been used in the treatment of the RMF technique assume that the plasma ions are unaffected by the rotating field, and thus ion motion is completely neglected in the analysis. This assumption requires that $\omega_{ci} \ll \omega$; in past experiments heavy gases such as argon and xenon have been used so that the ion cyclotron frequency was much less than the rotating field frequency. The lack of a quantitative measure of the required relative magnitudes of ω_{ci} and ω presents a problem in the design of RMF driven fusion experiments which use deuterium or hydrogen gas.

In previous low temperature ($T_e < 50$ eV) collisional experiments the magnitude of the rotating field, B_o , was on the order of the applied steady field, B_a . In these experiments large values of B_o were required in order to maintain $v_{ei}/\omega_{ce} < 1$. Since $B_o \sim B_a$, the combination of these two fields results in "open" magnetic field lines which ultimately pass through the discharge vessel wall. Although it is not clear that the problems usually associated with static, open field lines arise in a time-varying situation where associated electric fields are present, the possibility of parallel electron thermal conduction losses is a problem in these experiments. As indicated in the reactor calculations, presented in Section V, the required magnitude of B_o compared with B_a is very small in high temperature plasmas, and thus this effect would not be important. In moderate size experiments where B_o is small but may not be negligible compared to B_a , the effects of open field lines should be considered.

3. Recommendations for future work

Of primary importance in the future development and application of the RMF technique to CT plasmas of fusion interest is the extension of the existing collisional plasma theory ($\omega < \nu_{ei}$) to the collisionless plasma regime ($\omega > \nu_{ei}$). An appropriate theoretical model for the penetration of the rotating field into a preformed CT plasma is required. This model should include the effects of ion motion, a nonuniform plasma density distribution, and treat the case where ω_{ci} is not negligible compared to ω .

Experimentally, a moderate scale (FRX-C-like) experiment using a preformed deuterium CT plasma should be carried out with particular emphasis placed on the identification of the rotating-magnetic-field penetration time, directed ion motion, and the plasma equilibria and stability properties. The formation of a CT plasma by the rotating magnetic field alone should also be investigated in this device.

Upon completion of the theoretical and experimental work suggested here, an accurate evaluation of the applicability of the RMF technique to the CT program could be made.

VII. The Rotamak Experiment

The Rotamak concept was proposed by I.R. Jones.⁹ This concept is a natural consequence of the recent interest in Spheromak-like plasma configurations and the continuing work on the RMF, current-drive technique directed by Jones at Flinders University. While previous rotating field experiments have generally been conducted in cylindrical devices, the Rotamak plasma is formed in a spherical containment vessel. The magnetic field configuration in the Rotamak is illustrated in Fig. 2. The steady, open poloidal magnetic field lines are produced by external mirror coils. The closed poloidal field lines, B_p , are the resultant of a linear combination of the steady mirror field, and the poloidal field generated by the toroidal electron current, j_ϕ . The toroidal current is produced and driven by the rotating magnetic field, B_θ . A toroidal magnetic field component, B_ϕ , can be generated by passing an axial current, I_z , through an insulated metal rod which is positioned along the z-axis (not shown in Fig. 2). The object of the Rotamak experiment is to determine if a toroidal, spheromak-like CT plasma can be produced using the RMF technique.

The initial results of the Rotamak experiment have been published.¹⁰ A brief description of the Rotamak experiment and the main experimental results are given below.

The Rotamak device is shown diagrammatically in Fig. 6 (see also Fig. 2). The spherical pyrex discharge vessel has an inner radius, R , of 6.4 cm, and contains ports for magnetic-field-probe and Rogowski-belt diagnostics. A pair of orthogonally-orientated Helmholtz coils, closely fitted around the discharge vessel, are positioned symmetrically about the z -axis. The Helmholtz coils carry rf currents of the same frequency, 0.7 MHz, and peak amplitude 2.7 kA, but differing in phase by 90° . These currents, generated by means of two Weibel-type line generators, produce a magnetic field which rotates about the z -axis in the r - ϕ plane (Fig. 2) with an on-axis peak amplitude of about 800

Fig. 6.

Diagram of Rotamak device.

Fig. 7.

Line generator rf current waveforms.

gauss. The rf current waveforms used to generate the rotating field are shown in Fig. 7. A pair of mirror, or "vertical," field coils positioned on the z-axis equidistant from the center ($z=0$, $r=0$) of the sphere, produce the steady mirror field, B_M , required for plasma equilibrium. $B_M \sim 400$ gauss at the sphere center, $r=0$, $z=0$. A slight modification of the discharge vessel allows the placement of a thin metal rod along the z-axis. A steady current of approximately 7 kA is passed through the rod which produces a toroidal magnetic field, B_ϕ , (Fig. 2) of about 200 gauss at the discharge vessel wall, R . The toroidal field increases, as $1/r$, as r decreases. The static argon fill gas is preionized by a combination of high-frequency-rf (~ 15 MHz) and θ -pinch discharges which occur within the tube located between the sphere and the vacuum system (Fig. 6). This arrangement generates a small degree of ionization of the gas contained within the sphere. Argon fill gas was used both to insure that the required inequality $\omega_{ci}/\omega < 1$ was well satisfied and to take advantage of the relative ease of ionization of argon gas at the low, 1.7 mTorr, fill pressure.

Figure 8 shows the total toroidal current I_ϕ , measured by the Rogowski belt, under different applied field (B_M and B_ϕ) conditions. I_ϕ is the plasma current which is initiated and driven by the rotating magnetic field. For once ionized argon, the maximum magnitude of I_ϕ , predicted from the rotating-field theory $I_\phi = (2/3)n_0 R^3 e \omega$, is about 7 kA. Figure 8a presents the toroidal current waveform, obtained for $B_M = 0$; B_ϕ is also zero for this case. In the absence of the mirror field the toroidal plasma ring is not confined and I_ϕ rapidly decays as the plasma expands to the discharge vessel wall.

Fig. 8.

Total toroidal current obtained under different applied field conditions.

Figure 8b shows I_ϕ obtained when the steady mirror field is applied. In the "formation phase" I_ϕ initially increases to a peak value of about 10 kA and then decreases to approximately 7 kA at $t \approx 8 \mu\text{sec}$. During the time interval 8-16 μsec , I_ϕ maintains a relatively "steady-phase" value of about 7 kA. The decrease of I_ϕ at $t = 16 \mu\text{sec}$ coincides with the termination of the rf pulse.

The magnetic field configuration corresponding to the toroidal current waveform of Fig. 8b was investigated by measuring the magnitude of the total poloidal field, B_p (i.e., the sum of the poloidal field generated by I_ϕ and the applied mirror field), along both the r - and z -axes. Figure 9 shows the B_p radial profiles ($z=0$) at different times during the discharge and Fig. 10 shows the corresponding axial profiles ($r=0$). In Fig. 9, the radial location at which the total poloidal field is zero approximately identifies the magnetic axis, r_m ; at r_m the plasma beta is unity in the absence of toroidal magnetic field and the plasma density is a maximum. For a given time during the discharge, the radial distribution of total poloidal magnetic flux is

TOTAL POLOIDAL FIELD RADIAL PROFILES
 ($Z = 0, B_{\phi} = 0$)

Fig. 9.

Total poloidal field radial profiles at different times during the discharge.

calculated from an area integration over the appropriate B_p radial profile. From the flux profiles the time history of the separatrix radius, r_s , which separates the regions of open and closed field lines is determined. Thus, r_s identifies the radial extent of the closed-field-line CT configuration. In Fig. 10, the axial point at which B_p is zero locates the "x"-point, z_x . At z_x , the separatrix surface meets the z -axis. Thus, z_x identifies the axial extent of the CT configuration.

The time evolution of the separatrix radius, r_s , the x-point, z_x , and the magnetic axis r_m is shown in Fig. 11. During the Rotamak formation phase, $t < 8 \mu\text{sec}$, the separatrix radius is located outside the discharge vessel inner wall. The steady phase of the discharge is characterized by a well-defined compact torus configuration lying entirely within the discharge vessel. Since

Fig. 10.

Total poloidal field axial profiles at different times during the discharge.

r_s exceeds z_x , the CT is oblate, more closely resembling an ideal Spheromak¹³ than a prolate FRX¹² configuration.

Power measurements indicate that during the steady phase of the discharge energy is fed into the Rotamak plasma at a constant rate of about 1.1 MW. Using a zero-dimensional model which calculates the temporal temperature behavior of an ohmically heated, uniform plasma, Ortolani¹⁴ has estimated that, in the steady phase of the Rotamak discharge, the energy loss rate from argon

Fig. 11.
Time history of the separatrix radius r_s , the magnetic axis r_m , and the x-point z_x .

line radiation is 1.4 MW and that the electron temperature attains a steady state value of about 7 eV. Given the approximate nature of these calculations it is concluded that the ohmic power input is balanced by line radiation in the Rotamak.

Using the calculated value of T_e , the peak electron density is $\sim 3 \times 10^{14} \text{ cm}^{-3}$, estimated to within about a factor of 2 from pressure balance. For the conditions of the Rotamak experiment, the penetration parameter is then

ROTATING FIELD RADIAL PENETRATION
($B_\phi = 0$)

Fig. 12.

Radial profile of the ϕ -component of the rotating field measured with plasma, $B_{0\phi}$, normalized to the same component measured under vacuum conditions, $B_{0\phi_v}$.

$(v_{ei}/\omega_{ce})(R/\delta) \approx 1$. Accordingly, complete penetration of the rotating field into the Rotamak plasma cannot be assured. Figure 12 shows the radial profile of the ϕ -component of the rotating field measured with plasma, $B_{0\phi}$, normalized to the same component measured under vacuum conditions $B_{0\phi_v}$. Although nearly 70% of the rf field is observed at the magnetic axis ($r_m \approx 4.8$ cm) during the steady phase, complete penetration is not obtained. Operating the existing Rotamak device at a somewhat higher value of B_0 , or a lower fill density would, according to Eq. (13), allow complete field penetration.

The total poloidal current waveform, I_ϕ , measured with both an applied mirror field, B_M , and applied toroidal field, B_ϕ , is shown in Fig. 8c. In this case, I_ϕ remains substantially constant for the duration of the rf pulse. The radial profiles of the total poloidal field obtained in this case are presented

TOTAL POLOIDAL FIELD RADIAL PROFILES
($Z = 0$, WITH B_ϕ)

Fig. 13.

Total poloidal field radial profiles obtained in the presence of an applied toroidal magnetic field.

in Fig. 13. Comparing Figs. 9 and 13, it can be seen that the presence of the applied toroidal field has a significant effect on the radial structure of the poloidal field profiles. With the applied toroidal field the separatrix radius is greater, and the magnetic axis is closer to the z -axis, than observed without the toroidal field. This indicates that the application of the B_ϕ field produces a "fatter" toroidal CT plasma. This result is supported by the relatively constant slope of the B_p profiles of Fig. 13, which suggest a broader toroidal current distribution.

In summary, it has been demonstrated experimentally that a Spheromak-like plasma configuration can be produced using the RMF current-drive technique. The Rotamak has also given some of the first data on the phenomenology of toroidal CT plasmas with and without applied toroidal magnetic field.

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