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AEC RESEARCH AND
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GA-10278
UC-20, Controlled
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Processes

CONTROLLED THERMONUCLEAR RESEARCH PROGRAM

SUMMARY PROGRESS REPORT

FOR THE PERIOD AUGUST 1, 1969 TO JULY 31, 1970

by

T. Ohkawa

Prepared under
Contract No. AT(04-3)167
Project Agreement No. 38
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

September 15, 1969

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Gulf General Atomic

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Work done by:

Fusion Staff

Report written by:

T. Ohkawa

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Contract No. AT(04-3)167
Project Agreement No. 38
U. S. Atomic Energy Commission
Washington, D. C.
Gulf General Atomic Project No. 4012

September 15, 1970

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I. INTRODUCTION

This report summarizes the program conducted under Contract AT(04-3)167, Project Agreement 38, between the Atomic Energy Commission and Gulf General Atomic during the period 1 August 1969 to 31 July 1970, as well as the work carried out under a Gulf General Atomic parallel program. The program consists of the experiments with two devices, namely, the dc octopole and the Doublet-II, and the supporting theoretical efforts.

The dc octopole was completed in the previous contract year and has now demonstrated good plasma confinement. A containment time of 500 Bohm times has been observed in the collisionless regime. If this containment time scales according to the Bohm formula up to plasma parameters of thermonuclear interest, the containment should be good enough for a reactor of a moderate output power. In the collisional regime the plasma behavior may be explained by classical theory. Except for a small discrepancy of a numerical factor, the plasma loss has the characteristics of resistive diffusion. The dc octopole has been and will be productive as a test bed for studying the plasma in toroidal geometry. The effects of field errors, background gases, properties of plasma convection cells, heating of plasma, propagation properties of waves, and trapped particle instabilities are examples. It is planned to add a toroidal field to the dc octopole device. The whole range of zero toroidal field (multipole field only) to zero multipole field (toroidal field only) becomes available for the study of plasma confinement. The main subject will be the study of the relative

importance of the symmetry of the configuration and the transform angle or the shear.

The construction of the Doublet-II device is in progress. The submarine batteries, which will be used as the power source for the toroidal magnetic field for both the Doublet-II and dc octopole, have been installed. The vacuum chamber has been delivered. The design of the coils for the toroidal magnetic field and the coils for the toroidal electric field has been completed. The order for the condenser bank for powering the electric field coils has been placed. It is expected that the device should be completed in this contract year.

The theoretical efforts are directed toward the understanding of the plasma behavior in the dc octopole and the analysis of the equilibrium and the stability of Doublet configurations.

We have found a novel method for maintaining a current in Tokamak and Doublet-like plasmas. Dual beams of ions may drive a current in the plasma and also heat the plasma in the thermonuclear regime.

II. DC MULTIPOLE

The dc multipole has been described in previous reports.^{1,2} A brief recapitulation of the machine and the plasma parameters is given in this section, followed by a description of the experimental results obtained so far.

2.1 DESCRIPTION OF THE EXPERIMENTAL DEVICE

Figure 1 shows the magnetic-field configuration and the dimensions of the system. Six current rings are used to produce the octopole field, with the two outer rings carrying return current. The rings are each held in position by three mechanical supports, one of which serves as a coaxial electrical feed. The plasma volume is approximately 10^7 cm^3 and the support area is roughly 10^2 cm^2 . The entire ring system is contained in a vacuum chamber. A background pressure is maintained below 10^{-7} Torr by oil diffusion pumps and a titanium pump. For most of the experiments the average magnetic field on the stability limits is $\bar{B} = (\oint dl) / (\oint dl/B) = 260 \text{ G}$, which corresponds to an average of 18 gyroradii between the separatrix and the stability limit for 1-eV protons. The hydrogen plasma is produced by a coaxial gun and is injected between the current rings as shown in Fig. 1. The end of the gun is located just outside the stability limit. The amount of injected plasma is varied by changing the size of the aperture at the gun output.

Microwave interferometers (3 cm and 8 mm) measure the plasma density integrated over the diagonal path through the magnetic axis shown in Fig. 1.

LC-77179

Fig. 1--Octopole flux configuration showing location of the six current rods and main flux surfaces. ψ_S is the separatrix, ψ_L is the surface with a minimum $\oint dl$, and ψ_C is the surface with minimum $\oint dl/B$. The horns for the microwave interferometer and the path of the injected plasma are also shown

Langmuir probes are used to measure the electron temperature and plasma density. Ion energies are measured using a gridded electrostatic probe. An azimuthally rotating probe holder is installed inside the vacuum chamber to measure the azimuthal dependence of plasma parameters. The probes are also movable across the flux line in an azimuthal plane by a remote controlled motor drive. Plasma losses toward the wall are measured by limiters located near the rings on the magnetic-field lines which are separated from the separatrix by the same amount of flux as the stability-limit line. Particle collectors are also mounted on all supports to measure the support losses.

2.2 PLASMA CONFINEMENT IN THE dc OCTOPOLE

The average energy of hydrogen ions produced by the coaxial gun is about 100 eV. The electron temperature is initially about 5 eV. The injected plasma propagates around the torus in a few hundred microseconds and the azimuthal density distribution becomes roughly uniform in about one millisecond. However, it takes another 20 msec before a steady state is reached. During this period the measurement of plasma loss by the limiters shows a transient plasma loss to the wall and the rings. Apparently, plasma is turbulent as a result of a violent injection process. Therefore, the measurement of the plasma confinement is made after 50 msec from the plasma injection.

The behavior of the plasma density measured by a microwave interferometer is shown in Fig. 2 as a function of time. There are two significant features in the density decay. Initially the plasma density is inversely proportional to time as shown in the plot of $1/n$ versus time. At roughly 200 msec when the density is about $5 \times 10^9 \text{ cm}^{-3}$ the time dependence becomes exponential with an e-folding time of 200 msec. This time constant varies with background gas pressure, and a time constant of up to 500 msec has been observed.

LC-77260

Fig. 2--Time dependence of the plasma density n . Plots of $1/n$ and $\log n$ indicate that the density decays as $1/t$ early in time and exponentially late in time

The rate of the $1/t$ density decay can be specified in terms of the decay constant $n_0 \tau_0 = nt$. Figure 3 shows that the decay constant $n_0 \tau_0$ is proportional to the square of the average magnetic field. The exponential decay time is also shown in Fig. 3 as a function of the average magnetic field. The dependence is approximately linear.

Figure 4 shows the ion and electron temperatures as a function of time. The ion temperature is measured by a gridded electrostatic probe and the electron temperature from the Langmuir characteristic of an electrostatic probe. The ion temperature is initially higher than the electron temperature and becomes about equal in 20 msec. This behavior is reasonable, when we consider that the energy relaxation time between electrons and ions is a few milliseconds, calculated for the plasma with density of 10^{10} cm^{-3} and electron temperature of 1 eV. The plasma temperature is independent of the magnetic field within the experimental errors.

The exponential decay time at late times decreases with an increase in the electron temperature. In a plasma with an electron temperature of 5 eV the decay time is shortened to 60 msec.

The plasma loss flux to the limiters initially varies as the inverse square of the time and later decays exponentially. The transition in the time dependence occurs at the same time as that observed in the density decay. The plasma loss flux to the supports is proportional to the plasma density. The support loss percentage of the total loss also changes after the transition. The support loss at 100 msec is 20% of the total plasma loss but after the transition it increases to 45%. The total measured loss flux agrees with the instantaneous density decay rate within the experimental error, which is about a factor of two.

LC-77261

Fig. 3--Decay constant $n_0\tau_0$ and exponential decay time τ as functions of the magnetic-field strength. The decay constant $n_0\tau_0$ is proportional to the square of the magnetic-field strength at early times. The exponential decay time is proportional to the magnetic-field strength

LC-82997

Fig. 4--Electron and ion temperatures as a function of time. The electron temperature is measured by a Langmuir probe and the ion temperature by a gridded-electrostatic probe

The magnetic-field dependence of the loss flux to the limiters is initially $1/B^2$ and becomes $1/B$ after the transition. This dependence is consistent with the dependence of the containment time on the magnetic field strength. The plasma loss flux to the supports does not depend on the magnetic field.

The density distribution across the plasma is measured by a Langmuir probe. The probe is moved radially between the No. 3 ring and the wall on the median plane. The density profile is centered on the separatrix and does not change appreciably in time.

The azimuthal distribution of the plasma is measured by Langmuir probes mounted on an azimuthally rotating probe holder. The azimuthal distribution on the separatrix is uniform within the experimental uncertainty of $\pm 2\%$. Figure 5 shows the azimuthal distribution of the plasma density near the stability limit flux line, where the plasma density is about one-fifth of the density on the separatrix.

The azimuthal variation of the density seems to be related to the inhomogeneity of the magnetic field. The magnetic-field strength is measured at the same positions where the density is measured. The positions of four maxima in the azimuthal density distribution near the edge of the plasma coincide with the positions of the maxima and minima of the magnetic-field strength.

Near the supports, the plasma density shows irregularities in addition to the inhomogeneities shown in Fig. 5. Figure 6 shows the azimuthal distribution on an expanded scale near the supports when the supports are grounded electrically. It shows a step accompanied by a peak on the higher side of the step. The step is downward in the direction of the diamagnetic current.

LC-83003

Fig. 5--Azimuthal density distribution near the stability limit where the density in average is one-fifth of the density on the separatrix. The measurement is made at late times when the density decays exponentially in time

LC-80851

Fig. 6--Azimuthal density distribution near the support measured by a Langmuir probe. The probe is near the stability limit where the density in average is one-fifth of the density on the separatrix. The supports are grounded

The plasma behavior is different in high-and low-density regimes. The high-density regime is characterized by the following properties: (1) The plasma density decays as $1/t$ while the shape of the density profile remains unchanged; (2) the loss is mainly to the limiters and the loss flux varies as $1/t^2$; and (3) both the inverse of the density decay constant $(n_0 \tau_0)^{-1}$ and the loss flux to the limiters vary as $1/B^2$. These characteristics indicate that the main loss is due to classical diffusion. On the other hand, the characteristic properties of the low-density regime are: (1) The plasma density and the loss fluxes decay exponentially; (2) the loss fluxes to the limiters and supports are comparable; and (3) the decay rate is roughly proportional to $1/B$. These observations suggest that there is a loss due to anomalous transport of the plasma in addition to the support loss.

The plasma transport equation integrated along the flux lines may be written

$$\frac{\partial n}{\partial t} \oint \frac{dl}{B} = \frac{\partial}{\partial \Psi} \left(\oint D_c R^2 B dl \frac{\partial n}{\partial \Psi} \right) + \frac{\partial}{\partial \Psi} \left(\oint D_a R^2 B dl \frac{\partial n}{\partial \Psi} \right) + L_s \quad (1)$$

where Ψ is the flux function ($2\pi\Psi = \text{magnetic flux}$), B is the magnetic field, R is the major radius, and L_s is the loss to the support. D_c is the classical diffusion coefficient given by $D_c = \eta nk(T_e + T_i)/B^2$, where η is the classical perpendicular resistivity.³ D_a is the anomalous diffusion coefficient. However, if the dominant process is not diffusive but convective, the second term will have a different form.

The separable solution of Eq. 1 is given by

$$n = n_0 \tau_0 F(\Psi) \left\{ \tau [e^{(t+t_0)/\tau} - 1] \right\}^{-1} \quad (2)$$

where $F(\Psi)$ is the normalized profile and τ is the asymptotic decay time. In the high-density regime the first term dominates the right-hand side of Eq. 1 and the solution is approximately given by

$$n = n_0 \tau_0 F(\Psi) / (t + t_0) \quad (3)$$

where

$$n_0 \tau_0 \approx \frac{(8/3\pi)(\Delta\Psi)^2 \oint B^{-1} d\ell}{\eta k(T_e + T_i) \oint R^2 B^{-1} d\ell}$$

and

$$\frac{\Psi}{\Delta\Psi} = \left(\int \frac{dx}{[F(\Psi)]^{1/2} (1-x^{3/2})^{1/2}} \right) \left(\int_0^1 \frac{dx}{(1-x^{3/2})^{1/2}} \right)^{-1}.$$

Terms containing $(\partial/\partial\Psi) \oint R^2 d\ell/B$ and the magnetic-well effects have been neglected. In the wings of the theoretical plasma profile the density gradient is very large, to the extent that the density gradient length is comparable to the ion gyroradius. Therefore, in these regions the diffusion rate may be affected by ion viscosity.⁴ The relative importance of plasma losses to the supports also increases in the wings of the profile. A convective motion in the plasma may also distort the wing of the density profile from that of the theoretical profile. The observed density gradient in the wings is much smaller than the theoretical value given by Eq. 3.

The value of the decay constant $n_0 \tau_0$, calculated by equating the theoretical half-width of the density profile to the experimental half-width, is $4.4 \times 10^9 \text{ cm}^{-3} \text{ sec}$. This agrees with the experimental decay constant, $1.2 \times 10^9 \text{ cm}^{-3} \text{ sec}$, within experimental error. Thus the diffusion process

in the high-density regime agrees with the classical diffusion theory not only in its dependence on plasma parameters, but also in the magnitude of the diffusion coefficient.

The plasma-loss process in the low-density regime is "anomalous" in the sense that the decay time is roughly proportional to the magnetic-field strength and becomes shorter at higher electron temperatures. However, the decay time is more than two orders of magnitude longer than the Bohm time. For an electron temperature of 1 eV, the observed confinement time of 200 msec corresponds to 300 times the properly averaged Bohm time.⁵ The confinement time is also 300 times longer than the time required for a sound wave to travel around the torus.

In determining the loss processes responsible for the plasma decay in the low-density regime, it would be helpful to study the dependence of the plasma confinement on various parameters. Beside the dependence on the magnetic field and the electron temperature described before, three parameters are found that are particularly effective in affecting the confinement time: (1) the error in the magnetic field; (2) the bias voltage applied to the particle collectors; and (3) the residual gases in the vacuum chamber. The dependence on these parameters is described separately in the following subsections.

2.3 THE EFFECT OF THE FIELD ERRORS ON THE PLASMA CONFINEMENT

There are three possible sources of field errors: (1) the nonuniform image current flowing in the metal skin of the rings and the vacuum chamber; (2) the effect of ferromagnetic objects outside the vacuum chamber, such as iron beams in the building structure; and (3) the imperfection of the coil winding. These three sources will be discussed separately.

1. The image currents can be eliminated simply by allowing a time long enough for them to die down before the plasma is injected. In the dc octopole the magnetic field produced by each ring reaches at least 95% for its steady-state value before the plasma is produced. Experimentally, the effect of the finite image current on the plasma confinement is insignificant, since no change in the plasma behavior is detected when the plasma injection time is varied by a few seconds. Also, no azimuthal variation in the plasma density is observed at the openings in the vacuum chamber or at the welding sections.
2. The ferromagnetic structure in the building does not seem to affect the plasma significantly since no azimuthal density variation correlated with these structures is observed.
3. In order to estimate the field error caused by the irregularity in the winding, the poloidal component of the magnetic field is measured exciting each ring separately. The measurement in the vicinity of a ring gives the effective center of the current distribution in the ring. Figure 7 shows the projection on a cross section of the effective center of the No. 1 ring. The angles shown on the figure correspond to the azimuth in reference to the position of the gun (0 deg). The displacement of the effective center is about ± 0.3 cm at maximum. In comparison, the minor diameter of the ring is 10.2 cm.

The displacement of the effective center of the current distribution should produce a toroidal component in the magnetic field. The azimuthal distribution of the toroidal component calculated from the above result is

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Fig. 7--Displacement of the effective center of the current distribution in the No. 1 ring, projected on a cross section. The angles in the figure are the azimuthal angles with respect to the position of the gun. The minor diameter of the ring is 10.2 cm

in good agreement with the measured azimuthal distribution of the toroidal component.

The field error produced by the displacement of the effective center decreases with the distance from the ring. As an average point we may take a point on the separatrix closest to each ring. The calculated azimuthal field variation at this point is $\pm 3\%$ at maximum for the No. 1 ring, $\pm 4\%$ at maximum for the No. 2 ring at the top, $\pm 4.5\%$ at maximum for the No. 2 ring at the bottom, and $\pm 3\%$ at maximum for the No. 3 ring. Another typical place is at the field minimum on the stability limit. The measured azimuthal variation of the magnetic-field strength is $\pm 1\%$ at maximum.

It has been proposed that the field errors could be a major source of plasma loss in some of the multipole devices.⁶ The correlation between the density variation and the inhomogeneity of the magnetic field has been observed. However, the direct observation of the effects of the error field on the confinement time has not been made.

An experiment has been undertaken in collaboration with D. Meade and T. Jernigan of the University of Wisconsin on the field error effects under a controlled condition.

A set of coils are placed either on the side wall or on the top of the vacuum chamber. The coils are circular and produce dipole-like magnetic fields with their axes in the radial or the vertical direction. They are equally spaced in the azimuthal direction. By choosing a right combination of the numbers of coils and the polarity of the dipole field, a field pattern of desired azimuthal mode number m may be produced. A 100-kW power supply energizes the coils. With the coils on the side wall, the

dipole field on the multipole separatrix outside the No. 3 ring is 80 G with the maximum coil current. It is about 17% of the multipole field at the location.

The plasma confinement time shortens when the error field coils are energized. The decay rate (the inverse of the confinement time) and the particle loss to the wall are shown in Fig. 8 as a function of the error field when the coils are on the side wall and $m = 5$. At larger error fields the decay rate and the particle loss are proportional to the error field. The losses to the wall and to the ring limiters are comparable, and the ratio is constant when the error field is varied.

When the polarity of the error field is reversed, the decay rate and the losses do not change. Curves similar to those in Fig. 8 are obtained with the opposite polarity.

The dependence of the confinement time on the azimuthal mode number m is tested by changing the connection of the coils. In the range of $m = 0$ to $m = 5$, the confinement time becomes shorter progressively with m for a given size of error field. Since at the maximum value of $m = 5$ the distance between the coils is still smaller than the plasma minor radius, the effectiveness of the error field to pump out the plasma should increase with m number.

The density distribution is perturbed by the addition of the error field. Figure 9 shows two azimuthal density distributions, one on the separatrix and the other near the stability limit where the density is about one-fifth of the density on the separatrix when no error field is applied. The position of the coils is shown by arrows in the figure. It shows that the plasma shifts toward the wall in front of the coils and moves

LC-83004

Fig. 8--The reciprocal of the confinement time and the wall loss at a constant plasma density as a function of the error field measured on the separatrix in the median plane between the No. 3 ring and the wall.

LC-83002

Fig. 9--Azimuthal density distribution with an error field applied on the separatrix (full circles) and near the stability limit (open circles), where the density is about one-fifth of the density on the separatrix with no error field applied. The measurement is made at late times when the density decays exponentially in time.

away from the wall between the neighboring coils. The azimuthal density variation is about $\pm 15\%$ on the separatrix and $\pm 90\%$ near the stability limit. The correlation between the density distributions on the axis and near the edge of the plasma indicates that the density profile across the plasma flattens in front of the error field coils. Also, the azimuthal density distribution has an $m = 10$ component as well as an $m = 5$ component.

The multipole configuration is susceptible to a type of field error which involves azimuthally inhomogeneous toroidal fields. If we consider two azimuthal planes and if the total toroidal fluxes across the planes are finite and opposite, there must be a net radial flux between these planes. The field produced externally by the error field coils and the field produced by the imperfection in the ring winding are of this type. On the other hand, if the multipole configuration is perturbed to make it merely noncircular, the magnetic field strength and the plasma density measured on a circular path will show the inhomogeneity. However, the two cases should differ in harmonic relations between the magnetic field distribution and the density distribution. A simple deformation without an enhanced plasma loss should have the same m number for the magnetic field and the density distribution. When the perturbation makes the flux lines leave the plasma region, the density distribution should have a mode number twice as large as that of the magnetic field distribution. Experimentally, the density distributions with and without the externally produced field errors show the second harmonics. Therefore, it is likely that the major part, if not all, of the plasma loss without the external error field is due to the imperfection of the ring winding. We are attempting to construct a theoretical model of the plasma loss due to the field errors and, hopefully, to

identify the plasma loss processes responsible for the observed confinement time. We are also looking into the possibility of minimizing the error field by winding correction coils.

2.4 PLASMA LOSS DUE TO RING SUPPORTS

The ring supports intercept the plasma particles and contribute to the plasma loss. Since the plasma must flow across the magnetic field to reach the supports, a convective motion may develop. Actually the azimuthal density distribution near a support shows a step, as shown in Fig. 6. The distribution is sensitive to a bias voltage on the supports. The step may be reversed by a negative voltage of a few volts, as shown in Fig. 10. These results are similar to the observation made in the Wisconsin octopole.⁷

The perturbed density distribution is suggestive of a convective motion, although the spatial size of the "cell" appears to be too small to affect the bulk of plasma.

Plasma confinement time and loss to the limiters are measured as a function of the support bias voltages to test whether the supports induce plasma losses to the limiters by driving a convective motion.

A bias voltage of a few volts does not affect the confinement time nor the limiter loss. The bias voltage may be either between the supports or between the supports and the limiters. Since the bias voltage of this magnitude affects the density distribution near the supports, the small-scale convective motion near the supports hardly contributes to the plasma loss.

When a large bias voltage, say 150 V, is applied, the confinement time shortens by roughly 20%. However, the limiter losses change little. Also, the effect on the confinement time is independent of the manner in

LC-80850

Fig. 10--Ratio of the densities on the upstream (along the diamagnetic current) and downstream side of the supports is shown as a function of the voltage applied to the support. The measurement is made by a Langmuir probe at 10 cm from the plasma boundary.

which the bias voltage is applied, i.e., between the supports in the same azimuthal position or between the supports at different azimuthal positions. The shortened confinement time is accounted for within the experimental errors by the increased particle fluxes to the supports.

We performed additional experiments with a pulsed bias voltage on the supports to measure the delay between the bias voltage switching and the change in the confinement time. The reasoning is that the convection cell may take a period of the order of the circulation time before it reaches the full amplitude or it decays out. The experimental results were negative; i.e., the response was instantaneous both for the rising part and for the decaying part of the pulsed voltage.

These results indicate that the loss to the support does not induce a significant amount of plasma loss to the wall.

2.5 RESIDUAL GAS EFFECTS ON PLASMA CONFINEMENT

Plasma confinement time depends upon the partial pressures of the various background gases. For example, the dependence of confinement time upon the ionization gauge reading changes during the course of the initial pumpdown. When the total pressure first reaches 2×10^{-7} Torr, the confinement time is relatively short. At a pressure of 1.0×10^{-7} or below, the decay time increases to at least 400 msec. After a few days pumping, however, the pressure may be allowed to rise again to 2×10^{-7} Torr with very little effect upon confinement time. A possible explanation is that some critical change in the gas composition has occurred during the process of outgassing.

The confinement time also changes when a gas is deliberately introduced into the vacuum chamber. The effectiveness varies from one species to another.

Hence, the analysis of the background gas and the measurements of the confinement time when a known species of gas is injected should tell us whether the observed confinement time at the best vacuum is limited by the process involving the background gas.

2.5.1 Measurement of Partial Pressures in the Vacuum Chamber

The species of gases expected in the dc octopole machine are: (1) water, (2) hydrocarbons from the pump oils and epoxy used to impregnate the current-carrying rings, and (3) other major components, such as nitrogen and oxygen from the air and hydrogen from the gun.

A mass spectrometer was installed on the system in order to analyze the residual gases in the vacuum chamber. The instrument is a Consolidated Electrodynamics type 21-615 cycloidally focused spectrometer. Table I lists the detected gases, their partial pressures, and their probable sources under typical vacuum conditions. The system had not been vented for about two weeks, had a fresh layer of titanium, and showed a base pressure of 7×10^{-8} Torr.

The dominant gases are nitrogen, argon, methane, ethane, and water. The low reading for the partial pressure of water was obtained only after baking the analyzer at 375°C for several hours under good vacuum. No special efforts were made to calibrate either the ionization gauge or the analyzer because a factor of two or three accuracy was felt to be adequate.

The partial pressure of "other hydrocarbons" listed in Table I is an educated guess. A few very small peaks in the $M = 30$ to $M = 50$ range do not fit any known pattern for diffusion pump oils or solvents.⁸ Assuming a poor sensitivity to these unknown hydrocarbons, we may nevertheless assign a probable upper limit of 5×10^{-10} Torr. Such a pressure is

TABLE I

RESIDUAL GASES FOUND IN THE dc OCTOPOLE MACHINE

The total pressure is about 7×10^{-8} Torr. Most pressures accurate to a factor of two (see text).

<u>Gas</u>	<u>Source(s)</u>	<u>Partial Pressure</u>
N ₂	Air leak, outgassing	2×10^{-8}
Ar	Air leak, not pumped by Ti surface	5×10^{-9}
CH ₄ (Methane)	Outgassing of epoxy, conversion of other hydrocarbons by Ti surface	5×10^{-9}
H ₂ O	Outgassing of Al walls	2×10^{-9}
C ₂ H ₆ (ethane)	Outgassing of epoxy, mechanical pump oil fragment	1.5×10^{-9}
Other Hydrocarbons	Outgassing of epoxy backstreaming of DC-704 diffusion pump oil, mechanical pump oil fragments, cleaning solvents	$< 5 \times 10^{-10}$
O ₂	Air leak, outgassing	2×10^{-10}
CO ₂	Air leak	$< 1 \times 10^{-10}$
CO		$< 1 \times 10^{-9}$

consistent with the use of a liquid-nitrogen-cooled diffusion pump system. It is also of interest to note that although the titanium surface does not pump hydrocarbons, it probably converts a good percentage of those present to methane.⁹

The response of the gas analyzer system is fast enough to allow measurement of the hydrogen gas pressure. When the gun is fired, the pressure rises to about 1.7×10^{-5} Torr in 150 msec and then slowly decays with an e-folding time of about 1 sec. This time dependence agrees quite well with that of the ionization gauge collector current. The ionization gauge gives a peak reading of 8×10^{-6} Torr. Such agreement is quite reasonable.

2.5.2 Measurement of the Effect of Gases on Plasma Confinement

Plasma density decay and wall loss were measured as a function of the partial pressure of injected gas species. The plasma decay time was measured with a Langmuir probe. The total loss current is taken to be the sum of the losses to the limiters and supports. Effects of Ar, N₂, H₂, CH₄, H₂O, CO₂, and O₂ were studied. Figures 11 and 12 summarize the results. The reciprocal of the plasma decay time is plotted as a function of partial pressure for several gases in Fig. 11. In Fig. 12 the ordinate is the wall loss current. The change in partial pressure of the injected species as read by the analyzer always agrees with the change in total pressure as read by the ionization gauge to within a factor of about three.

A very strong dependence of plasma confinement upon the partial pressures of O₂, CO₂, and H₂O has been observed. In the case of oxygen, a measurement was made to see if ion mass changed with increasing O₂ pressure. The ratio of electron collection current (+ 10 V bias) to ion

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Fig. 11--Reciprocal of confinement time (τ^{-1}) versus partial pressure of injected gas.
 Error in the measurement of τ is about ten percent. See text for a description
 of the absolute accuracy of pressure determinations

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Fig. 12--Total wall current versus partial pressure of injected gas. Error in the measurement of wall current is about ten percent. See text for a description of the absolute accuracy of pressure determinations

collection current (-10 V bias) of a Langmuir probe was recorded as a function of O_2 pressure. The ratio remained constant. Thus, the decrease in Langmuir current with increasing O_2 pressure is probably not associated with a gross change in plasma ion mass.

Extrapolation to zero pressure, however, shows that at their normal partial pressures O_2 , CO_2 , and H_2O contribute little to plasma losses.

The gases Ar, N_2 , and H_2 were found to have no effect upon plasma behavior in the same range of pressures. Even when the H_2 pressure was increased to 6×10^{-5} Torr (i.e. three times the peak pressure attained after firing the gun), no significant change in the plasma behavior was observed. The hydrocarbon methane showed an intermediate effect, with a slope in Figs. 11 and 12 about ten times smaller than that for the O_2 .

Since the presence of gases not only shortens the containment time but also increases the loss to the wall, more than atomic processes are likely to be involved--for example, an enhanced diffusion or an instability induced by some atomic processes. Nevertheless one must know first the cross sections for the atomic process involved (such as charge exchange, recombination, negative ion formation, etc.). Unfortunately, these cross sections are not well known in the range of 1-eV temperature, and a review of the literature is now underway.

A possible instability due to negative ion formation has been found, and this may account for the effectiveness of oxygen-containing gases in shortening the containment time. A more detailed study (for example, measurements of fluctuations) is needed before a positive identification can be made.

III. DOUBLET-II

During the past year, the main Doublet effort has been directed toward detailed design and procurement of parts for the Doublet-II experiment. No major delay has developed, and the device is expected to be completed on schedule. Also, the theoretical studies of the Doublet concept have continued. The list of physical effects that limit the operation of Doublets (and Tokamaks) has been extended. This extension has confirmed the previous conclusion that there is a certain region in a $\log T$ - $\log n$ plane where one can expect trouble-free operation.

3.1 THEORETICAL CONSIDERATIONS

A long list of physical effects and requirements of importance for Doublets (and Tokamaks) was given in the previous proposal.¹⁰ These studies showed that for a given value of the rotational transform angle ι , the toroidal magnetic field, and the physical dimensions of the device, the importance of one physical effect could be characterized by a line in the $\log T$ - $\log n$ plane (T and n are the plasma temperature and density, respectively). It was such that conditions were "good" on one side of the line and "bad" on the other. The result was that one can find circumstances where a "good" triangular region exists in the $\log T$ - $\log n$ plane.

The requirement that there be at least several banana orbit widths from the plasma center to the plasma surface has been considered. The details are given below and the result is that for a given value of ι the plasma temperature must be below a limiting temperature for the ion orbits

to be contained. This limiting temperature is close to the limiting temperature found from the previously considered processes.

The skin effect has also been considered. Because of this the current density distribution tends to become peaked at the plasma surface when the plasma current is increasing. For Tokamaks this decreases the shear and thereby possibly gives rise to plasma loss. It is found, as shown below, that under certain simplifying assumptions, the adverse effect of the skin effect disappears only when β_p is large compared to unity and, therefore, seriously limits the previous "good" regime in the $\log T$ - $\log n$ plane. This argument applies, however, only for Tokamaks where the rotational transform is supposed to decrease toward the surface. For Doublets, where outside the separatrix the rotational transform increases toward the surface, the skin effect will have little adverse effects.

These two effects, as well as most of the effects considered previously, can conveniently be considered in the $\log T/(\iota/2\pi)^2$ - $\log n$ plane. Thereby the results become independent of the rotational transform. For the operating point to stay inside the good region during the rise of the plasma current, it is important to keep $T/(\iota/2\pi)^2$ constant during the experiment. Since $\iota/2\pi$ is proportional to the plasma current, this emphasizes the importance of programming the plasma current.

3.1.1 Magnetohydrodynamic Equilibrium

The magnetohydrodynamic equilibria and stabilities have also been studied for Doublet. For the design of Doublet, the inner surface of the copper field shaper must be determined by the calculation of the magnetohydrodynamic equilibrium. One of the criteria for choosing an equilibrium is to optimize the magnetohydrodynamic stability.

The calculation of the magnetohydrodynamic equilibrium involves two quantities that cannot be predetermined: the current distribution (or the pressure distribution) in the plasma and β_p . The idea is to arrive at a boundary condition, i.e., a shape of the outermost flux surface, with which the magnetic configuration in the plasma region is reasonably insensitive to these unknown quantities.

An equilibrium is calculated for a case with $\beta_p = 1$ with the poloidal current proportional to $1/R$ (R = major radius). Then with the same boundary condition, β_p is varied. The configurations thus calculated differ only slightly from the original equilibrium. This result is expected because the sensitivity to β_p is due to the toroidal effect and the range of the major radius in the plasma region is small for the Doublet configurations. Next, the current distribution is modified with a fixed value of β_p . The equilibria thus calculated differ only slightly from the original equilibria as long as the inhomogeneity of the current distribution is not drastic.

A calculation was made for the Doublet equilibrium by R. Dory at Oak Ridge for a case where the plasma reaches an asymptotic equilibrium as a result of collisional diffusion.¹¹ The configuration looks very similar to the cases we have calculated.

The shape of the cross section of the boundary has been changed from the originally proposed "hourglass" shape to the "embryo" shape. The shape chosen is shown in Fig. 13. It has as large a shear as the previous configuration with added magnetic wells for the regions inside the separatrix. The difference between the integral $\int ds/B$ between the elliptic magnetic axes and the hyperbolic magnetic axis is about 15%. Besides this advantage, the embryo shape has constructional advantages in that the "hot vacuum liner" can be slipped over the assembled inside part of the flux shaper.

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Fig. 13--Schematic of Doublet-II

We plan to calculate the equilibria for the "embryo" boundary chosen for a number of values of β_p and various current distributions. The main purpose of these calculations is to compile a list of the magnetic field distributions outside the plasma region which are to be compared with the experimental measurements in the future. The plasma parameters, such as pressure and current distribution, should then be calculated from the data.

3.1.2 Banana Orbit Criterion

The physics argument behind this criterion is that the number N of banana orbits over the density gradient length r must be larger than one in order for an equilibrium to exist. We define

$$N \equiv \frac{r B_p e}{M v_i} \quad (4)$$

where B_p is the poloidal magnetic field strength at the plasma surface, e and M are the ion charge and mass respectively, and v_i is the ion thermal velocity. We have approximately for the transform angle ι that

$$\frac{\iota}{2\pi} = \alpha (R B_p / r B_t) \quad (5)$$

where $\alpha = 1$ for Tokamak and 0.2 for Doublet, R is the major radius, and B_t the toroidal magnetic field strength. By eliminating B_p from Eqs. 4 and 5 we obtain

$$\frac{T}{(\iota/2\pi)^2} = \frac{1}{N^2} \left(\frac{r}{R} \right)^2 \frac{r^2 e^2 B_t^2}{\alpha^2 M} \quad (6)$$

which means that if N has to be larger than a certain value, then $T/(\iota/2\pi)^2$ has to be smaller than a certain value. For the published T-3 results we have $N \sim 5$. For the comparison between Tokamaks and Doublets,

one sees that for similar values of parameters, the limiting temperature is about 25 times higher for Doublet than for Tokamak.

3.1.3 Skin Effect

When the plasma current increases in time, the skin effect tends to produce a current density distribution that is peaked at the plasma surface. For Tokamak configurations, the magnetic shear depends on the current distribution. If the current distribution is peaked near the plasma edge initially, the configuration must go through a state of uniform current distribution with little magnetic shear before it reaches the final state where the current is peaked on the plasma axis. To avoid this problem, the current should be increased slowly with a time scale longer than the skin time.

We define three characteristic times:

$$\text{Energy confinement time: } \tau_E = \frac{3nT}{P_{\text{loss}}} \quad (7)$$

where P_{loss} is the specific power loss due to incomplete confinement,

$$\text{Heating time: } \tau_H = \frac{3nT}{j^2 \eta - P_{\text{loss}}} \quad (8)$$

where j is the current density and η the plasma resistivity, and

$$\text{Skin time: } \tau_s = r^2 \mu_o (1/\eta) \quad (9)$$

By elimination of η and P_{loss} from Eqs. 7 and 9 and introducing

$$\beta_p = \frac{2nT}{(B_p^2/2\mu_o)} = \frac{16}{j^2 \mu_o r^2} nT \quad (10)$$

we obtain

$$\beta_p = \frac{16}{3} \frac{\tau_H}{\tau_s} \frac{\tau_E}{\tau_H + \tau_E} \quad . \quad (11)$$

The heating time should be longer than the skin time to avoid the transient shearless configuration. The above equation shows that β_p must be larger than unity for a long confinement time. For Tokamaks, the energy confinement time, the heating time, and the characteristic time for the current rise are of the same order of magnitude. With the experimental value for β_p , Eq. 11 is approximately satisfied.

The condition for a minimum value of β_p to obtain a long confinement time provides a lower limit for n in the $\log T/(\iota/2\pi)^2$ - $\log n$ diagram. At least for small values of $T/(\iota/2\pi)^2$ this limitation is more restrictive than the lower limit criterion from the previous analysis¹² which required $j < ne \sqrt{T/M}$.

This limitation does not apply to Doublet configurations because the shear is mainly due to the geometry, not due to the peaked current density.

3.2 DOUBLET-II DESIGN

The major components of the Doublet-II device are shown in Fig. 13. The elliptic axes are located at $R = 63$ cm and $Z = 30$ cm. The methods used in determining the actual shape of the plasma containing vessel have been described.

The plasma surface is determined by a limiter, 5 mm high, attached to the inside of the hot vacuum liner. This limiter is cut and located to coincide with a calculated flux surface where the shear is approximately 3%. The hot liner is formed from 0.02-in. stainless steel and has 0.25-in. reinforcing ribs every 15° around the outside of the surface. There are

eight 1-inch-diameter pumping and diagnostic ports located above and below the plasma magnetic axis (16 total). The complete hot liner is gold-plated on both the inside and outside surfaces. This helps prevent the formation of oxygen layers, which could contaminate the plasma, on the inside surface and acts as a radiation shield on the outside surface. The hot liner will be bakeable to 400°C by inducing a current in the liner itself. An 800-cps, 8-kVA aircraft generator connected to the E-coil will drive the heating current.

The vacuum system consists of two parts, namely, the primary vacuum, inside the "hot liner," and the secondary vacuum system, between the hot liner and the vacuum tank, as shown in Fig. 13. The secondary vacuum is necessary because the hot liner, which for electrical reasons must be thin-walled, cannot withstand any appreciable pressure difference. Furthermore, the secondary vacuum facilitates the heat insulation problem between the hot liner and the liquid-nitrogen-cooled field shaper.

The secondary vacuum system is conventional with O-rings and an oil diffusion pump. The primary vacuum system is a bakeable, all-metal vacuum system using a turbomolecular pump. The time constant for the primary system (volume divided by pumping speed) is 3 sec for hydrogen. Only two bakeable valves will be incorporated in the system, namely, a valve in front of the turbo pump and a "safety" valve which connects the primary to the secondary vacuum. In the event of a major leak in either of the vacuums the safety valve will open to prevent damage to the hot liner. For the same reason, also during pump down, when the pressure is above 10 mm Hg, the safety valve will be open.

During operation, a continuous flow of hydrogen from a palladium hydrogen purifier will be provided.

The inside surface of the copper field shaper is determined by solving Maxwell's equations in the vacuum region outside the plasma surface. A space of approximately 2 cm between the hot liner and the field shaper allows the thermal expansion of the hot liner and thermal contraction of the field shaper, which is operated at -196°C . The thickness of the copper is dictated by the requirement of at least three skin depths. At liquid nitrogen temperatures, the poloidal magnetic field penetrates approximately 1 cm; hence, a minimum thickness of 3 cm is required.

There are three electrically insulated gaps in the field shaper. The B_t gap shown in Fig. 13 lets the toroidal magnetic field enter the field shaper. There are also two radial gaps 180° apart, which are necessary for the toroidal electric field (E_t) to penetrate. Considerable attention has been paid to the problem associated with the finite E_t gap. If the field shaper were a perfect conductor and the E_t gap very narrow, the magnetic field would be parallel to the inner surface of the field shaper and would have the desired theoretical shape. Since the skin depth is approximately 1 cm, the gap widens in time and the location of the external conductors that produce the E_t field must be carefully determined so that both the secondary vacuum chamber, which is constructed from aluminum alloy, and the field shaper are approximate surfaces of constant flux. The position of the field shaper is therefore adjusted inside the vacuum chamber so that the net vertical flux in the plasma region at the gap is minimized. Later in time the flux soaks through the aluminum tank and the E-coil determines the field shape within the chamber. The E-coil, which is also designed to minimize the gap effect, is described below.

3.3 E-COIL

The E-coil may be considered the primary winding of an air core transformer where the plasma forms the secondary winding. The main aspects of the coil design are: (1) gap error fields, (2) coupling between coil and plasma, and (3) necessary mechanical strength of the coil.

During the early phase, the aluminum vacuum tank acts as a good conductor, and therefore the error field at the gaps in the field shaper is determined by the shapes of the field shaper and the aluminum tank. This error field has been minimized, as has been discussed, and it is, in principle, independent of the E-coil configuration. Later in time, the aluminum tank cannot be considered to be a good conductor and the error field at the field shaper gaps depends on the E-coil configuration. The configuration that gives the minimum field error depends on the ratio between the plasma current, which is driven by the electric field produced by the E-coil, and the current in the E-coil. It also depends on the specific plasma equilibrium, as discussed in Sec. 3.1.

Thus one has to develop a simplified model for the response of the plasma to the toroidal electric field.

For this model we assume that β_p is a constant during the experiment. This assumption is justified from the theoretical considerations set forth in Sec. 3.1. It is further assumed that the fraction, $1-\kappa$, of the energy input into the plasma is lost to the walls and that κ is independent of time, i.e.,

$$\frac{d}{dt} (3nT) = \kappa \frac{j^2}{\sigma} \quad (12)$$

where the conductivity, σ , is assumed proportional to $T^{3/2}$:

$$\sigma = \sigma_0 T^{3/2} \quad . \quad (13)$$

The time dependence of T and j and the electric field $E = j/\sigma$ can now be determined. We find that the plasma is electrically inductive with a constant "specific self-inductance":

$$\mathcal{L} \equiv E/(dj/dt) = \frac{3}{2} \mu_0 r^2 \frac{\beta_p}{k} \quad . \quad (14)$$

The "plasma self-inductance", the ratio between the one-turn voltage and the plasma current, is then given by

$$L_0 = \frac{2\pi R_0}{A} \mathcal{L} \approx 2.6 \times 10^{-7} \frac{\beta_p}{k} \text{ Hy} \quad (15)$$

where R_0 is the average radius of the plasma, A is the plasma cross section area, and the skin effect has been neglected.

The important result is that the ratio between the plasma current and the E-coil current stays constant. Another result of the model is that the currents should be proportional to $t^{1/3}$. Although these results stem from a very simplified model of the plasma, they are used as guides in the design of the E-coil as well as the E-coil energy supply system.

Once the ratio of the plasma current and the E-coil current is given, the complete solution of the magnetic field distribution may be calculated with a desired boundary condition. The error field at the gap may be calculated from the current distribution on the surface of the gap. When a large mismatch occurs between the current densities of the outer surfaces

and the inner surface of the copper field shaper, the error field at the gap is large.

A computer program has been developed to calculate the field distribution. The inputs to this program are the coil configuration, the coil current, the field shaper geometry, the plasma equilibrium, and the ratio β_p/κ which through Eq. 15 determines the plasma "self-inductance." The program calculates the ratio between the coil current and the plasma current and the apparent self-inductance seen from the terminals of the coils. The program also compares the current distribution of the inner and outer surfaces of the field shaper. When these currents match, the field errors are minimized.

It turned out to be fairly easy by trial and error to change the coil configuration to obtain a minimum of field errors. However, if the estimate of the ratio β_p/κ is changed, the optimum configuration is changed. Also if the equilibrium changes, the optimum coil configuration changes. We are presently working on a compromise coil configuration that can accommodate a reasonable range in these input parameters. The outside part of the E-coil will have relatively few turns and the forces on it are relatively small. Therefore, this outside coil can be made with taps so that the field configuration may be varied.

The design parameters are tentatively: inside coil 20 turns, outside coil, 6 turns; self-inductance with plasma 10^{-4} H, without plasma 1.2×10^{-4} H; and coil ampere-turns, 5 times plasma current. The resistance of the coil will be about 4 m Ω .

3.4 E-BANK

The E-bank is the energy storage system that will supply the current to the E-coil. As mentioned earlier, it is considered important that the

coil current can be programmed in time. There should be enough flexibility so that the programming may be adjusted according to the actual plasma impedance. For the design, this has been kept in mind while the results from the model given in Sec. 3.3 have been used as a guide.

The E-bank is designed for a maximum plasma current of 360 kA. The rotational transform angle is 1.2π at the plasma surfaces, when the toroidal magnetic field is 10,000 G and the plasma current is 360 kA. From the characteristics of the E-coil and its coupling to the plasma mentioned in the previous section, the maximum coil current is 70 kA. To initiate the discharge, a maximum electric field of 1 V/cm has been chosen. This corresponds to a maximum voltage on the coil of 10 kV. From the model described earlier it was found that the current in the coil should increase as $t^{1/3}$ after the initial breakdown stage.

According to the model there is a considerable variation in the time t_0 at which the maximum current should be reached. From the calculations of Sec. 3.3 we obtain

$$t_0 = \frac{1}{2} \sigma_0 T^{3/2} \mu_0 r^2 \beta_p / \kappa$$

$$\sim 5 \times 10^{-6} \frac{\sigma_p}{\sigma_{sp}} (T/e)^{3/2} \beta_p / \kappa \text{ sec}$$

where σ_p / σ_{sp} is the ratio between the plasma conductivity and the "Spitzer" value of the conductivity, and T is the temperature reached at the time t_0 . For reasonable choices of the parameters involved we obtain $t_0 \sim 15\text{-}20$ msec.

The circuit for the E-bank is shown in Fig. 14. Switch SW_1 is closed at $t = 0$. When the voltage on capacitor C_2 is about zero, switches SW_2 ,

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Fig. 14--Circuit diagram of E-bank

SW_3 , and SW_4 are closed. At that time a considerable part of the energy originally stored in C_2 is stored in L_2 . When C_3 is nearly discharged, most of the energy that was residing in L_2 is transferred to the load. Figure 15 shows the time dependence of the current produced by the circuit. The deviation from the desired $t^{1/3}$ dependence is small.

The transformer will have a turn ratio of 15:1 and an iron core with a cross-sectional area of about 4 ft^2 .

The E-circuit is designed so that it can be easily modified to accommodate a variation of plasma parameters.

3.5 TOROIDAL MAGNETIC FIELD SYSTEM

The toroidal magnetic field is produced by the B-coil shown in Fig. 13. This coil consists of 48 turns of copper bar stock approximately 2×3 inches in cross section. Each turn of the coil consists of four sections and can be disassembled so that other parts of the Doublet-II system are accessible. The inner sections of the coil have a pie-shaped cross section and are tightly packed with strips of insulation between each turn to form a solid center post. This center post is water-cooled, and the rest of the coil is cooled by air convection between the turns. The coil is designed to operate at 60,000 amps for three seconds every two minutes and will produce a 10,000 G toroidal field at the center of the plasma. The error in the toroidal magnetic field due to the finite number of turns has been calculated and found to correspond to the displacement of flux lines of 10^{-5} meter. Therefore, its perturbing effect on the plasma can be neglected.

The power supply for the toroidal field coil is made up of 630 cells of five Guppy II Mod B submarine batteries that were obtained from the Navy. The batteries will be connected in four parallel strings of 156 cells. The

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Fig. 15--Current through load (R_o and L_o) versus time (solid curve) compared with $t^{1/3}$ curve (dotted curve). All capacitors initially charged to 10 kV. $C_1 = 2.5 \times 10^{-3}$ F, $C_2 = 4 \times 10^{-3}$ F, $C_3 = 8 \times 10^{-3}$ F, $L_2 = 4 \times 10^{-4}$ Hy, $R_2 = 10^{-3} \Omega$, and the load: $R_o = 4 \times 10^{-3} \Omega$, $L_o = 10^{-4}$ Hy

output voltage under no load is about 325 V and about half this when connected to the load. Each parallel string has two series contactors to insure interruption of the load current and to completely isolate the batteries from ground when they are not in service. A free-wheeling diode is placed across the inductive load so that the magnetic energy will be dumped into the coil instead of the switch arc.

3.6 DIAGNOSTICS

The anticipated diagnostics include electric and magnetic probes, microwave interferometer, laser scattering equipment, optical spectrometers, and particle analyzers.

Rogowsky loops placed in the E-gaps of the field shaper will measure the total plasma current. Flux loops will be placed next to the Rogowsky loops to measure the change in toroidal flux when the plasma is present. These measurements alone will give an approximate value of the plasma pressure and of β_p .

At one azimuthal position we will place 24 coils around the inside of the field shaper. These coils will measure the details of the poloidal magnetic field. From this it is expected that details of the equilibrium can be determined, namely, β_p and the current distribution.

At the midplane, 24 coils will be placed at the inside surface of the inside part of the field shaper. These coils can measure the azimuthal dependence of the poloidal magnetic field. Thus, using the two sets of 24 coils, we can identify wave numbers of instabilities.

The 2-mm microwave interferometer measures the plasma density which, with the plasma pressure, gives a plasma temperature. The interferometer

will use two opposite vertical pumping and diagnostic ports. These ports can also be used for particle analyzers.

There will also be two ports for radial optical observations. The ports will be placed outside the two elliptical axes at the same azimuth as one of the pumping and diagnostic ports. Thus, these ports can be used for both spectroscopic measurements and laser scattering experiments.

IV. THEORY

The main effort is directed toward the understanding of the experimental results obtained in the dc octopole device and also toward predicting the plasma behavior in Doublet configurations.

We have a little better understanding of plasma convection. It was found that a steady state with a nonuniform electric field requires a mixture of electrically trapped particles and untrapped particles. The question of how plasma may reach the convecting state starting from a uniform equilibrium without an electric field is also being studied. One possible process involves the presence of cold plasma near the wall. This raised an interesting speculation that the confinement time is described by the Bohm formula with the temperature of the cold component, and therefore, the higher the plasma temperature, the better the confinement becomes in terms of Bohm formula.

Instabilities involving collisional processes and shear flows are also being studied.

For Doublet, magnetohydrodynamic equilibrium and stability, collisional processes, and possible instabilities that may lead to enhanced plasma loss are being studied in addition to the study of scaling laws. The Doublet configuration still looks attractive after these studies.

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APPENDIX A

GULF GENERAL ATOMIC PROGRAM

APPENDIX A

GULF GENERAL ATOMIC PROGRAM

This part of the research has been supported by Gulf General Atomic as a parallel program. The major part of this program is devoted to aid the Doublet-II project. In addition, the studies of the Doublestar configuration and the methods of plasma heating are continuing.

An interesting method of driving a current in a Tokamak-like plasma has been found. Beams of high energy ions may replace the inductive voltage applied in Tokamak-like devices.

A.1 METHOD OF DRIVING PLASMA CURRENT

In toroidal fusion devices of Tokamak¹ and Doublet² types, ohmic current in plasma produces an essential part of the confining magnetic field. The current is driven by an azimuthal electric field produced inductively by a transformer. Consequently these devices must operate intermittently. On the other hand, Stellarators³ may operate as a steady-state device. However, the simplicity of the configurations and the recent encouraging results seem to enhance the attractiveness of the axially symmetric devices. If a method of maintaining ohmic current other than the induced electric field is found, the axially symmetric devices may be made to operate as steady-state devices. In the following, such methods are proposed.

Ohmic current decays because of the momentum loss between electrons and ions by Coulomb collisions. If opposite forces are applied to electrons

and ions separately and their strengths are equal to the momentum loss rate, the current will be maintained. The required force F per unit volume of plasma is given by

$$F = en \eta \cdot j \quad (1)$$

where n is plasma density, η is resistivity and j is current density.

The current density determines the poloidal magnetic field B_p , i.e.,

$$B_p \approx \mu_o j r / 2 \quad (2)$$

where r is the plasma radius. The necessary poloidal magnetic field is related to plasma density and temperature through a parameter β_p defined by

$$\beta_p = 2nkT / (B_p^2 / 2\mu_o) \quad (3)$$

For plasma equilibrium and stability β_p may have a value between one and ten in a Tokamak-like device.

Then the force is given by

$$F = 4en\eta \left(\frac{nkT}{\beta_p \mu_o r^2} \right)^{\frac{1}{2}} \quad (4)$$

The power W required to exert the force F is given by

$$W = F \cdot v_g \quad (5)$$

where v_g is the ratio of energy and momentum of the energy flux doing the pushing. For radiation and relativistic beams, v_g is equal to the velocity of light. For a particle beam, v_g is a half of the particle velocity.

The required power per unit volume of plasma, W , must be much smaller than the fusion output power per unit volume for the scheme to be of interest.

The fusion power, W_f for D-T reactions is given by

$$W_f = \frac{1}{4} \langle \sigma v \rangle_{DT} n^2 \cdot 17.6 \text{ MeV} \quad (6)$$

where $\langle \sigma v \rangle_{DT}$ is the probability of D-T fusion reaction.

In a fusion reactor, the heat load H on the vacuum chamber wall limits W_f , i.e.,

$$W_f = 2H/r \quad . \quad (7)$$

If the heat load is kept constant, the required power W decreases with temperature. On the other hand, too high a temperature would increase the radiation loss. The reasonable temperature range for D-T reaction may be $10 \text{ keV} < T < 50 \text{ keV}$.⁴

With $H \approx 10^7 \text{ watt/m}^2$, the values of W are given by

for $T = 10 \text{ keV}$

$$n = 2.5 \times 10^{20} r^{-\frac{1}{2}} \text{ m}^{-3}$$

$$W = 6.6 \times 10^7 \text{ watt/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} (v_g/c)$$

(8)

for $T = 50 \text{ keV}$

$$n = 1 \times 10^{20} r^{-\frac{1}{2}} \text{ m}^{-3}$$

$$W = 3.3 \times 10^6 \text{ watt/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} (v_g/c) \quad .$$

These values should be compared to

$$W_f = 2 \times 10^7 r^{-1} \text{ watt/m}^3 \quad . \quad (9)$$

For $T = 10 \text{ keV}$, v_g/c must be substantially smaller than unity. This rules out the use of radiation or relativistic beams. For $T = 50 \text{ keV}$, the situation is better. The radiation could be microwave or laser light. Even radiation from plasma itself may be used to push electrons by installing

directionally reflective walls. However, the necessary power seems still too large for practical use.

Electrons may be pumped by using wave-particle interaction such as Landau damping or by rf synchronous acceleration around a torus. In these cases, the velocity v_g is comparable to the electron thermal velocity. The electron velocities are $c/5$ and $c/2.5$ for 10 keV and 50 keV. Therefore, the improvement over the free radiation is only slight. These velocities are three orders of magnitude larger than the drift velocity given by $\bar{v}_e = j/en$.

A more attractive method is to use a high-energy ion beam. Suppose an ion beam is injected into the plasma. The injection is facilitated by using a neutral atom beam. The resultant ion beam in the plasma will lose its energy and momentum to ions and electrons through Coulomb collisions. The rate of momentum changes are given by⁵

$$\frac{dw_{\parallel}}{dt} = - \frac{16 \sqrt{\pi} e^4 Z^2 n w_b \ln \Lambda}{(4\pi\epsilon_0)^2 3 m_b m_e v_e^3} \left\{ 1 + \left(1 + \frac{m_b}{m_i} \right) \frac{3 \sqrt{\pi}}{4} \sqrt{\frac{m_b}{m_e}} \left(\frac{T_e}{U_b} \right)^{3/2} \right\} \quad (10)$$

$$\frac{dw_{\perp}^2}{dt} = \frac{8\pi e^4 Z^2 n \ln \Lambda}{(4\pi\epsilon_0)^2 m_b^2 w_b} \left\{ \frac{4}{3 \sqrt{\pi}} \frac{w_b}{v_e} + 1 \right\} \quad (11)$$

where w_b is the velocity of ions in the beam, $w_{\parallel}$ and $w_{\perp}$ are the parallel and the perpendicular components of w_b , v_e and v_i are the thermal velocities of electrons and ions of plasma, $\ln \Lambda$ is the Coulomb collision parameter, m_b , m_i , and m_e are the masses of beam ions, plasma ions, and electrons, Z is the charge number of beam ion and U_b is the energy of beam ion. It is assumed that $v_e \gg w_b$ and $w_b \gg v_i$. The

first terms in the right-hand side of Eqs. 10 and 11 represent collisions with electrons and the second terms represent collisions with plasma ions.

If the energy of beam ions is chosen so that $(1 + m_b/m_i) \sqrt{m_b/m_e} (T_e/U_b)^{3/2} \ll 1$, the beam loses its directed momentum chiefly to electrons. When the ion energy decreases to the critical energy $U_c \approx (1 + m_b/m_i)^{3/2} (m_b/m_e)^{1/3} T_e$, then the ions lose their momenta equally to plasma ions and electrons. The gain in the perpendicular energy becomes appreciable below the critical energy and the beam will be thermalized through collisions with ions. A beam ion will have lost the momentum $\sqrt{(2m_b U_b)} - \sqrt{(2m_b U_c)}$ to electrons by then. In a steady-state situation, the distribution function f_b of beam ions is proportional to $w_{\parallel}^{-1} \delta(w_{\perp})$ above the critical velocity $w_c = \sqrt{(2U_c/m_b)}$. It is proportional to $w_{\parallel}^2 \delta(w_{\perp})$ below but near w_c and decreases faster at small velocities because of increased $w_{\perp}^2$. It may be given approximately by

$$f_b(w_{\parallel}) = \frac{n_b}{\ln(1 + w_b^3/w_c^3)^{1/3}} \frac{w_{\parallel}^2}{w_{\parallel}^3 + w_c^3} \quad (12)$$

The injection current for maintaining the steady state is given by

$$I_b = \frac{16 \sqrt{\pi} e^4 n Z^2 \ln \Lambda}{(4\pi\epsilon_0)^2 3 m_b m_e v_e^3} \frac{eZ n_b (1 + w_c^3/w_b^3)^{-1}}{\ln(1 + w_b^3/w_c^3)^{1/3}} \quad (13)$$

The average velocity $\overline{w_b}$ of the beam ions is

$$\overline{w_b} = \frac{1}{\ln(1 + w_b^3/w_c^3)^{1/3}} \left\{ w_b - w_c \left(\frac{4\pi}{3 \sqrt{3}} + \frac{1}{6} \ln \frac{(w_b + w_c)^2}{w_b^2 - w_b w_c + w_c^2} \right) \right\} \quad (14)$$

$$\approx \frac{w_b}{\ln(w_b/w_c)} \quad (\text{for } w_b \gg w_c) \quad (15)$$

To keep the total plasma momentum unchanged, a second beam is injected in the opposite direction. The beam energy is chosen to be below U_c so that the beam interacts mainly with plasma ions. The beam may be of the same kind of ions as the plasma ions, and the energy may be equal to the thermal energy of plasma ions. The total momentum is balanced if the injection current I_2 of the second beam is given by

$$I_2 = I_b \frac{m_b w_b}{Z m_i v_i} \quad . \quad (16)$$

The ions in the second beam thermalize and the final result which may be approximated is a Maxwellian distribution shifted by $\bar{v}_i$, where $\bar{v}_i$ is given by

$$\begin{aligned} \bar{v}_i &= - \frac{m_b \int_0^{w_b} f_b w dw}{m_i n_i} \\ &= - \frac{m_b \bar{w}_b n_b}{n_i m_i} \quad . \end{aligned} \quad (17)$$

If the ions of the first beam have the same ratio of charge to mass as the second beam ions, then the total ion current vanishes also. In the steady state, we have three groups of particles. They are: the ions with a Maxwellian distribution shifted by $\bar{v}_i$, the electrons with a Maxwellian distribution shifted by $\bar{v}_e$, and the first beam ions. The balance of force on electrons determines $\bar{v}_e$, hence the current density. The force on electrons is given by

$$m_e n_e \frac{d\bar{v}_e}{dt} = \frac{16 \sqrt{\pi} e^4 \ln \Lambda}{(4\pi\epsilon_0)^3 3 m_e v_e^3} \left\{ \int (w_b - \bar{v}_e) f_b dw Z^2 + (\bar{v}_i - \bar{v}_e) n_i \right\} \quad . \quad (18)$$

The expression for dynamic friction used in the above equation leads to a slightly larger value for the plasma resistivity. This is due to the fact that the electron distribution function is assumed to be Maxwellian here, while the calculation of the resistivity takes the distortion of the distribution function into account.

The forces on electrons balance each other, if

$$n_b (\bar{w}_b - \bar{v}_e) Z^2 + (\bar{v}_i - \bar{v}_e) n_i = 0 \quad . \quad (19)$$

By using Eq. 17, Eq. 19 becomes

$$n_b \bar{w}_b = n_e \bar{v}_e \frac{1 + Z(Z-1)(n_b/n_e)}{Z^2 - m_b/m_i} \quad . \quad (20)$$

If we choose

$$m_b/m_i = Z$$

and also $\bar{w}_b \gg \bar{v}_e = j/en$, we have

$$e Z n_b \bar{w}_b \approx en \bar{v}_e / (Z - 1) \quad . \quad (21)$$

The injection current required for the steady state is then given by

$$I_b \approx \frac{j}{w_b(Z-1)} \frac{16 \sqrt{\pi} e^4 n Z^2 \ln \Lambda}{3 (4\pi\epsilon_0)^2 m_b m_e v_e^3} \quad . \quad (22)$$

The required power W is

$$W = U_b I_b / eZ = \frac{U_b j}{e w_b (Z-1) Z} \frac{16 \sqrt{\pi} e^4 n Z^2 \ln \Lambda}{3 (4\pi\epsilon_0)^2 m_b m_e v_e^3}$$

or

$$\approx \frac{w_b}{2} \frac{Z}{(Z-1)} en \eta j \quad . \quad (23)$$

Except for the factor $Z/(Z - 1)$, this is identical to Eq. 5. Both the power and the current are not very sensitive to the choice of Z except near $Z = 1$. If we choose the beam velocities of 2×10^7 m/sec (4 MeV for a deuteron) and 1×10^7 m/sec for 50 keV and 10 keV plasma temperatures, respectively, the required power is given by

$$W = \frac{Z}{Z - 1} 1.1 \times 10^6 \text{ watt/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} \quad \text{for } T_e = 10 \text{ keV}$$

$$W = \frac{Z}{Z - 1} 1.1 \times 10^5 \text{ watt/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} \quad \text{for } T_e = 50 \text{ keV} \quad . \quad (24)$$

They are much smaller than the fusion output power given by Eq. 9. The corresponding injection currents per unit volume are given by

$$I = \frac{Z}{Z - 1} 1.0 \text{ amp/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} \quad \text{for } T_e = 10 \text{ keV}$$

$$I = \frac{Z}{Z - 1} 27 \text{ mA/m}^3 \beta_p^{-\frac{1}{2}} r^{-7/4} \quad \text{for } T_e = 50 \text{ keV} \quad . \quad (25)$$

The current and the power of the second beams are (w_b/v_i) and (v_i/w_b) times of the first beam. The factors for the above examples are 10 and 1/10.

Since the power and the current of the beam depend on Z only weakly, the choice of Z should be made based on the other considerations, such as the radiation loss and the beam dynamics.

The Bremsstrahlung due to the beam ions is proportional to $Z^2 n_b$. The beam density is proportional to $\{Z(Z - 1)\}^{-1}$. Therefore, the Bremsstrahlung loss is not sensitive to the value of Z . On the other hand, the energy loss due to excitation radiation may become large for a large value of Z . The cross-sections for excitation are larger than the ionization cross-sections and an atom radiates many times before it is stripped of electrons.

Although a large energy loss per beam ion may be tolerated because of its large kinetic energy, the loss due to excitation radiation will set an upper limit on Z .

In the above considerations the plasma effects have been neglected. If the plasma shows anomalous resistivity the friction between ions and electrons have to be modified. The ion distribution has double peaks and it may become unstable. However, since the separation of the peaks in the velocity space is much smaller than the electron thermal velocity, the longitudinal mode is unlikely to be unstable because of electron Landau damping. More serious problems may arise from the perpendicular modes. The current due to the beam ions is in the opposite direction of the current due to electrons. Therefore, the part of the force produced by the beam current and the poloidal magnetic field is outwards. This may cause a blow up of the beam. A more detailed analysis of the beam stability is needed.

For plasma temperature of 50 keV, the beam energy may be less than 1% of the fusion output power. Therefore, if the overall power efficiency of producing the beam is better than a few percent and the capital cost for the system is smaller than the capital cost for the inductive electric field, the method is of importance for a fusion reactor. This method becomes more attractive for fusion reactors utilizing $D-He^3$ reactions because of a high plasma temperature.

In summary, new methods of driving current in resistive plasmas are proposed. When used for a toroidal plasma device, the methods eliminate the necessity of inductive electric fields, thus making it possible for the device to operate in a steady state. The required power for the methods

may be made much smaller than the fusion output power. Further studies, especially on beam stability, are needed to show the feasibility of the methods.

APPENDIX A

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APPENDIX B

MEETINGS ATTENDED AND/OR PAPERS PRESENTED

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MEETINGS ATTENDED AND/OR PAPERS PRESENTED

NINTH INTERNATIONAL CONFERENCE ON THE PHENOMENA IN IONIZED GASES,
Bucharest, Romania - September 1-6, 1969

"Plasma Transport and Fluctuations in a Toroidal Quadrupole,"
Masaji Yoshikawa and Tihiro Ohkawa

INTERNATIONAL SYMPOSIUM ON CLOSED CONFINEMENT SYSTEMS - Dubna
September 29-October 3, 1969

"Gulf General Atomic dc Octopole Experiments,"
Tihiro Ohkawa, Masaji Yoshikawa, Robert E. Kribel, and
Arthur A. Schupp

"Plasma Current Multipole,"
Tihiro Ohkawa, Torkil H. Jensen, and H. Gordon Voorhies

DIVISION OF PLASMA PHYSICS MEETING, AMERICAN PHYSICAL SOCIETY,
Los Angeles, California - November 12-15, 1969

"Effect of Trapped Particles on the Drift-Cyclotron Instability
in a Multipole," Dilip K. Bhadra

"Plasma Confinement in a Toroidal dc Octopole
Robert E. Kribel, Masaji Yoshikawa, Tihiro Ohkawa, and
Arthur A. Schupp

"Plasma Confinement in a dc Octopole,"
Masaji Yoshikawa, Tihiro Ohkawa, and Robert E. Kribel

"Scaling Laws for Tokamaks and Doublets,"
Torkil H. Jensen and Tihiro Ohkawa

AMERICAN PHYSICAL SOCIETY - Washington, D. C. - April 27-30, 1970

"Plasma Confinement in a dc Toroidal Octopole,"
Masaji Yoshikawa and Tihiro Ohkawa

APPENDIX C

GULF GENERAL ATOMIC REPORTS

APPENDIX C

GULF GENERAL ATOMIC REPORTS

AUGUST 1, 1969 THROUGH JULY 31, 1970

- GA-9131 PLASMA CONFINEMENT IN GULF GENERAL ATOMIC TOROIDAL QUADRUPOLE
Masaji Yoshikawa, Tihiro Ohkawa, and Arthur A. Schupp -
December 9, 1968 - Phys. Fluids 12, 1926 (September 1969)
- GA-9142 PLASMA FLUCTUATIONS IN GULF GENERAL ATOMIC QUADRUPOLE DEVICE
Tihiro Ohkawa and Masaji Yoshikawa - December 13, 1968
Plasma Physics 11, 795 (October 1969)
- GA-9403 EFFECT OF TRAPPED PARTICLES ON THE DRIFT-CYCLOTRON INSTABILITY
IN A MULTIPOLE - Dilip K. Bhadra - May 15, 1969
Phys. Rev. A⁴, Vol. 1, 1201 (April 1970)
- GA-9788 PARAMETER STUDIES FOR TOKAMAKS AND DOUBLETS
Tihiro Ohkawa and Torkil H. Jensen - June 12, 1969
Plasma Physics 12, 789 (1970)
- GA-9809 PLASMA CONFINEMENT IN D.C. OCTOPOLE - T. Ohkawa, M. Yoshikawa,
R. E. Kribel, A. A. Schupp, and T. H. Jensen - October 29, 1969
Phys. Rev. Letters 24, 95 (January 1970)
- GA-9812 NEW METHODS OF DRIVING PLASMA CURRENT IN FUSION DEVICES
T. Ohkawa - November 12, 1969 - Nuclear Fusion 10, 185
(June 1970)
- GAMD-9835 MULTIPOLE CONFIGURATIONS WITH NONUNIFORM PLASMA CURRENT
Dilip K. Bhadra - November 13, 1969
- GA-9866 TWO-DIMENSIONAL EQUILIBRIUM OF LOW β PLASMAS WITH ELECTRIC
FIELDS - T. Ohkawa and R. N. Sudan - August 11, 1969
- GA-9877 PLASMA INSTABILITY DUE TO SHEAR FLOW - T. Ohkawa and D. Bhadra
September 19, 1969
- GA-9993 SUFFICIENT CONDITIONS FOR MHD INTERCHANGE INSTABILITY OF
DOUBLET CONFIGURATION - T. Ohkawa - March 6, 1970
- GAMD-10033 CYCLOTRON, SYNCHROTRON, AND BETATRON USING DRIFT ORBITS
Tihiro Ohkawa - April 2, 1970

APPENDIX C

GULF GENERAL ATOMIC REPORTS (continued)

GA-10051   STABILIZATION OF THE TRAPPED PARTICLE MODE BY A COIL PLASMA
COMPONENT - Chuan Sheng Liu - April 7, 1970

GA-10123   PLASMA INSTABILITIES DUE TO INELASTIC SCATTERING
Tihiro Ohkawa - May 8, 1970

GA-10145   CONVECTION CELL PRODUCED BY LOW FREQUENCY FLUTE INSTABILITIES
Tihiro Ohkawa - May 21, 1970

GA-10147   'UNIVERSAL' DRIFT INSTABILITY IN A COLLISIONAL PLASMA
Dilip K. Bhadra - April 14, 1970

GA-10168   PLASMA CONVECTION PRODUCED BY ION-DRIVEN DRIFT INSTABILITY
Tihiro Ohkawa - June 9, 1970

GA-10170   PLASMA SHEAR FLOW INSTABILITY WITH ION-ION COLLISIONS
Dilip K. Bhadra - February 17, 1970

GA-10184   THE EFFECTS OF FIELD ERRORS IN TOKAMAKS AND DOUBLET
Tihiro Ohkawa - June 15, 1970

GAMD-10197   PLASMA EQUILIBRIUM WITH NONUNIFORM CURRENT - Dilip K. Bhadra
June 15, 1970

GA-10222   TRAPPED PARTICLE EFFECT ON DRIFT WAVE INSTABILITY IN TOROIDAL
SYSTEMS - Chuan Sheng Liu and Dilip K. Bhadra - July 10, 1970

APPENDIX D

ABSTRACTS OF PAPERS LISTED IN APPENDIX B

Plasma Transport and Fluctuations in a
Toroidal Quadrupole

Masaji Yoshikawa and Tihiro Ohkawa

The plasma transport rate in the toroidal quadrupole at Gulf General Atomic is calculated from the properties of fluctuations. The transport rate is compared with the density decay time. The fluctuation-induced diffusion is consistent with the observed decay time, except near the separatrix. Within an ion orbit of the separatrix additional transport processes are required to account for the observed decay time.

The work reported herein was supported by the U.S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

GULF GENERAL ATOMIC dc OCTOPOLE EXPERIMENTS

T. Ohkawa, M. Yoshikawa, R. E. Kribel, and A. A. Schupp

Gulf General Atomic Incorporated

The toroidal octopole at Gulf General Atomic is a dc device with small current ring supports. The diameter of the magnetic axis is 2.6 m, the plasma volume about 10^7 cm^3 , and the support area is approximately 170 cm^2 . The plasma is produced by a coaxial gun and injected directly into the octopole field. The plasma density and confinement time measurements with Langmuir probes and microwave interferometers will be discussed. The relative magnitudes of plasma losses to the current rings, supports and limiters will also be discussed. The behavior of plasma fluctuations will be compared with theory.

The work reported herein was supported by the U. S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

Plasma Current Multipole

T. Ohkawa, T. H. Jensen, and H. G. Voorhies

Gulf General Atomic Incorporated

A small device (Doublet-I) has been built to test mhd stabilities of plasma current multipole¹ configurations. The relevant parameters are: major radius 16 cm, density gradient length 2 cm, toroidal magnetic field 800 G, minimum toroidal electric field 1 V/cm, plasma density $5 \times 10^{14} \text{ cm}^{-3}$, and electron temperature 5 eV. The magnetic probe measurements show that the distribution agrees with the theoretical prediction and a quadrupole-like configuration is maintained for the whole period of the discharge. The fluctuations on the magnetic field are several percent near the wall. A large amount of oxygen is observed coming into the plasma off the wall and the plasma temperature is limited by radiation cooling 100 μsec after the start of the discharge. The various instabilities and the heat conduction processes of plasma current multipoles have been analyzed. They include the dissipative instabilities, drift instability, and heat conduction due to banana orbits. It will be shown that it is possible to reach the stable plasma regime by ohmic heating and the β of more than 10% is possible because of a large ratio of the poloidal and the toroidal magnetic field.

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Effect of Trapped Particles on the Drift-Cyclotron
Instability in a Multipole

Dilip K. Bhadra

Gulf General Atomic Incorporated

The effect of trapped particles on the drift-cyclotron instability in a multipole configuration has been considered. Dispersion equations have been obtained for this instability in a nonuniform collisionless plasma using a simplified approach which takes into consideration the magnetic field strength and curvature variation along field lines. The results show the existence of a branch of oscillations with frequency $\omega \sim \bar{\Omega}_i - k_{\perp} \bar{v}_g - \bar{\omega}_b$, where $\bar{\Omega}_i$, $\bar{v}_g$, and $\bar{\omega}_b$ are the average gyrofrequency, drift velocity due to magnetic field gradient, and ion 'bounce' frequency, respectively, $k_{\perp}$ being the wave-vector transverse to the magnetic field. This may explain the discrepancy between the experimentally observed frequency and the theoretical value obtained previously. This branch of the oscillation also shows a larger growth rate.

The work reported herein was supported by the U.S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

Plasma Confinement in a Toroidal dc Octopole

Robert E. Kribel, Masaji Yoshikawa, Tihiro Ohkawa,
and Arthur A. Schupp

Gulf General Atomic Incorporated

A coaxial gun is used to inject a hydrogen plasma into a steady toroidal octopole field.¹ The plasma volume is approximately 10^7 cm^3 . Measurements of the plasma density profile and lifetime are made with Langmuir probes and microwave interferometers at 10 Gc and 35 Gc. Collectors on the current rod supports are used to measure the support losses. Other plasma losses are measured with limiters at the stability limit and on the current rings. The dependence of plasma properties on variations of system parameters is discussed.

The work reported herein was supported by the U. S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

¹A. A. Schupp and T. Ohkawa, Bull. Am. Phys. Soc. 13, 1527 (1968).

Plasma Confinement in dc Octopole

Masaji Yoshikawa, Tihiro Ohkawa, and Robert E. Kribel

Gulf General Atomic Incorporated

Experiments on the plasma confinement in the dc octopole is discussed. The total number of particles estimated from the plasma density distribution is compared with the number of particles lost to the plasma boundary. Possible loss processes caused by the fluctuation and convective motion in the plasma will be discussed. The plasma transport rate evaluated from the electric field and density nonuniformity in the plasma is compared with the confinement time of the plasma.

The work reported herein was supported by the U. S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

Scaling Laws for Tokamaks and Doublets

Torkil H. Jensen and Tihiro Ohkawa

Gulf General Atomic Incorporated

Tokamak and Doublet are schemes for toroidal confinement and heating of plasma. Both configurations utilize a toroidal magnetic field established by currents in coils outside the plasma and poloidal magnetic field associated with a toroidal current in the plasma. For Tokamaks the cross sections of the flux surfaces are circular while the poloidal field in Doublets is quadrupole like. A number of limitations in the choice of parameters are imposed on these schemes by instabilities, radiation, and heat conduction. These limitations are discussed. Comparison is made between Tokamaks and Doublets. It is found that the limitations are generally less restrictive for Doublets than for Tokamaks. This is because Doublets have a larger ratio between the poloidal and the toroidal circumferences of the plasma and a larger shear due to the quadrupole-like poloidal field than Tokamaks.

Plasma Confinement in a dc Toroidal Octopole

Masaji Yoshikawa and Tihiro Ohkawa

Gulf General Atomic Incorporated

It has been reported¹ that the plasma decay in the toroidal octopole is consistent with the classical diffusion for the plasma densities above 10^{10} cm^{-3} . When the density is lower, the decay is Bohm-like with a diffusion coefficient of $1/300$ of the Bohm. The field intensity is increased by a factor of two to study the field dependence for a wider range. The azimuthal distribution of the density and the potential is measured. The azimuthal dependence of the plasma loss to the wall is also measured by a movable collector probe. The convective motion in the plasma will be discussed in connection with the Bohm-like decay process at lower densities.

The work reported herein was supported by the U. S. Atomic Energy Commission under Contract No. AT(04-3)-167, Project Agreement 38.

¹T. Ohkawa, M. Yoshikawa, R. E. Kribel, A. A. Schupp, and T. H. Jensen, Phys. Rev. Letters 24, 95 (1970).