COO-1726-39

TECHNICAL PROGRESS REPORT on [PLASMA PHYSICS]

For the period February 1, 1969 through January, 1970

In the past year work done on this contract included these parts:

I. Levitated Octupole Construction

II. Studies with the Original Octupole

III. Theoretical Studies

IV. Plasma Transport Toward Hoops

V. Superconducting Tests

VI. Microwave Studies and the Fabry-Perot Systems

VII. Feasibility Studies

VIII. Gun Studies and Moving Plasma Cloud Studies

PART I. LEVITATED OCTUPOLE CONSTRUCTION

As construction nears completion, many of the components are converging and being fitted together. Simultaneously, the organization of the construction and assembly job has improved greatly. A little less than a year ago the outer wall was to be assembled at Milwaukee and delivered by January 20, 1969. Apparently the pieces were not welded together concentrically. Also the bulge in the wall for levitation was allowed to shrink and to cause the height of the tank to decrease by $1^3/4$". Although much of the welding done in collaboration with the Milwaukee group was excellent, these two distortions caused immense trouble. The bulge was successfully stretched out so that most of our wall height was recovered, and this was successfully accomplished without tearing the wall. However, lack of concentricity meant that it was necessary to fill in by welding many areas with pure 1100 aluminum. Also, on the boring mill, concentricity

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was achieved on the vacuum side of the wall at the expense of wall thickness in some regions. To remedy this, 1/8" plates have been welded on the outside of the vacuum tank to build up the wall thickness to 2". We expect the outer wall to be ready very soon. Other parts have been fitted together and the last will be the outer wall. The gun drift tank and vacuum system with the gauges and controls have been running continuously for much of the past year. The complete vacuum system includes titanium gettering within the large tank and this cannot be tried until the tank is put together.

Tests of the levators have been carried out on the inside wall of the tank levitating the real load, namely the hoop. The system seems to work all right in air. While the construction was delayed, the time was used for perfecting control system details and for developing the diagnostic equipment that goes into the first experiments, for example, Fabry-Perot mirrors, Langmuir probes, plasma loss detectors, ion extraction analysis equipment and high power microwave heating equipment. All this equipment is being brought into the place for installation in the tank as it is being put together.

A resistive wall computer program has been developed and is being debugged so that we will have a better idea of the flux plot and particularly the time dependence of the flux shape. It was also quite important for knowledge of the magnetic forces on the levitated hoops.

PART II. STUDIES WITH THE ORIGINAL OCTUPOLE

Experiments with the original octupole included several topics predominantly. They were:

1. Observations of electron and ion distribution functions under the conditions where anomalous resistivity is observed. In this regime tests of anomalous resistivity have been made to determine its variation with electric field.

2. Studies of loss mechanisms which occur without fluctuations in time. Various mechanisms have been suggested which depend upon recent observations of nonuniform density and electric fields and of non-symmetric magnetic fields.

3. Electron cyclotron resonance heating has been explored under a variety of circumstances and with the ion distribution functions measuring equipment it was observed that a large density of hot ions (8 times the original ion temperature) develops.

With a special high frequency transformer connected into the magnet circuit, it has been possible to create an electric field around the toroid which drives a current parallel to the lines of force in the case where there is a toroidal field added to the multipole field. The current was measured by directional probes and it was found that anomalous resistivity developed with the electron convection current about 20% of the thermal electron speed. In this anomalous region, the current was quite closely proportional to the density. The electric fields were two orders magnitude above the run away field. The observations show greater conductivity than Buneman's and a different dependence on density. Conductivity also can exceed the mirror limited Spitzer conductivity[1]. Under these conditions of anomalous resistivity the electron distribution function was found to have no evident hump or plateau which might suggest the operation of a double electron stream instability. The electron distribution function appeared to be Maxwellian and displaced with the convection velocity. In this experiment the heating of ions has not yet been examined.

The observations of quiescent loss mechanisms have shown a potential structure and a density distribution which is fixed in space within the multipole when there is no toroidal magnetic field. The fact that it is fixed in space leads one to suspect that features of the wall or the hoop hangers are causing the pattern to develop. Several independent studies by different experimenters with our apparatus have examined different characteristics of these phenomena and a variety of theories and explanations are developing. So far, it has been difficult to demonstrate a controllable feature of the pattern which comes and goes when a perturbation is added or subtracted from the magnetic field. But the suggestion is ever-present that nearby wall features causing magnetic field errors are responsible for the variations in plasma. When the magnetic field is reversed, the stationary electric field and density distribution change in a manner which directs plasma toward the wall. Large gyroradius ions are then able to be lost.

Considerations and measurement of the effective field errors have been pursued. We know that portholes, the exciting gap, and anti-gap cause field errors noticeable particularly at the outside of the plasma near the wall where the

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[1] O. Buneman, Phys. Rev. 115, 503 (1959).

density and potential variations were discovered. There may also be troubles from the noncircularity of the hoops since the multipole has azimuthal variations of approximately 1 mm in the hoop to wall distance. Also, magnetic field errors of ≈20% have been found near the welds in the internal hoops. The effect of these magnetic perturbations on the magnetic field topology are now under study. Some of this material is in process of being published.

Most of the observations on the octupole have been made with the gun produced plasma having about 50 volt ions and with electrons which are continually cooling down during the experiment from an initial electron temperature of about 10 volts. Many of the loss experiments have been repeated with a cold ion plasma produced by electron cyclotron resonance heating. For these plasmas the ion gyroradius is expected to be extremely small; nevertheless, the flow of particles is observed to the hoops and to the wall. While the loss rate is somewhat less than with a gun produced plasma, it is nevertheless, not reduced as much as one might expect with the decreased ion temperature. A complete description of these experiments is in process of being published.

One of the interesting observations which will require more study is the appearance of ion heating as a result of electron cyclotron resonance heating. The ion distribution function apparatus shows hot ions produced after ECRH has taken place on gun plasma. The hot ion density is increased several fold in the region of 500 volts. It is highly desirable to learn more about this mechanism in hope that it may be useful to heat ions with high frequency microwaves which can penetrate the plasma and operate first on the electrons. Such indirect ion heating has been observed in other laboratories, for example, Consoli has studied this kind of heating in a mirror configuration. At Oak Ridge, however, microwave heating is known to eject the confined plasma under certain conditions.

PART III THEORETICAL STUDIES

a. The one-dimensional bit-pushing algorism has proved more successful than originally expected. The program seems to be able to reproduce the linear and non-linear behavior of various instabilities in one-dimensional plasmas with very modest demands on computer memory capacity and on computer time. A comparison theorem has been proved which provides an equivalence between a standard bit-pushing and a particle-pushing algorism in such a way that both give identical results with identical round-off and truncation errors. The choice between these then reduces to an evaluation of computer time and memory space required, for any particular problem.

Several varieties of distribution-pushing algorisms have been studied. One of them has been programmed and has given very encouraging results. It is able to reproduce the same phenomena studied with the aid of the bit-pusher, with a gain of a factor of about 3 in computer time, and with complete elimination of fluctuation noise present in bit- and particle-pushing algorisms. Theoretical studies have shown that grid-interpolation and series expansion methods are equivalent so that the choice between them in distribution-pushing algorisms in a matter of programming efficiency.

A two-dimensional particle-pushing algorism is in final stages of check-out, and a one-dimensional particle pusher is nearly completed.

b. Several results in the theory of adiabatic invariance have been obtained and are to be published. They include a method for calculating handy formulas for changes in the magnetic moment, and in the invariant for the linear oscillator. Their accuracy has been checked against numerically computed orbits. A fairly general theory of the adiabatic invariants for the linear and non-linear oscillator is in process of publication. A method for separating gyration and drift coordinates for a charged particle in a magnetic field has been discovered; it is hoped that it can be exploited to allow direct application of results for the linear and non-linear oscillator to the magnetic moment problem.

c. The effect of magnetic perturbations is studied on drift instabilities in axisymmetric tori. The dispersion relations and growth rates are calculated for the various frequency ranges of physical interest. There exists an unstable mode for which the characteristic frequency of the oscillations 'ω' is greater than the electron bounce frequency 'ω'$_{be}$. This instability can be supressed by the average favorable curvature. For the case, $\omega_{be} < \omega < \omega_{bi}$, the drift ballooning and drift universal modes are far more unstable than in the electrostatic case. The oscillations are always electrostatic for $\omega < \omega_{bi}$.

d. In the nuclear engineering department, the guiding-center method of analyzing low-frequency waves and instabilities in inhomogeneous plasmas has been investigated in detail and its equivalence to the method of integrating over particle orbits has been established for slab geometry. Present efforts are directed toward the extension of the guiding-center method with finite gyroradius correction to general low β magnetic field configurations. The dispersion relation for drift modes in the magnetic field of an infinitely long line current has been obtained as an example. This model is currently being investigated for possible modes in both monoenergetic and thermalized plasmas. The guiding-center method is also being used to investigate low frequency modes in finite β plasmas using slab geometry.

PART IV. PLASMA TRANSPORT TOWARD HOOPS

This project has been underway since May, 1969. Most of our effort thus far has been on the design and construction of the apparatus. The overall schematic is shown in figure 1. The progress to date is as follows:

1. Vacuum Vessel - The aluminum vacuum vessel is going to the final machining for diagnostic ports and is expected to be completed by the end of November, 1969.
2. Hot Plate Assembly - The hot plate design is very similar to the system used by Eastland. One hot plate assembly has been constructed and preliminary tests have been made. The ovens have been constructed and preliminary tests with neutral lithium beams have been made. In particular corrosion of thick aluminum plates (similar to our vacuum vessel) was not a problem.
3. Magnetic Field Coils - The internal coil (PF-1) was obtained from the Princeton Spherator (SP-1) with the help of Dr. S. Yoshikawa. The large external coils (EF-1) will be made of twenty, twelve turn pancakes. A prototype of the pancake has been constructed and tested under operating conditions. Coil construction whould be complete by the end of November, 1969.
4. Direct Current Power Supplies - Most of the effort has been on the design and construction of the high current D.C. power supplies. All power supplies were built using components from government surplus wherever possible. All power supplies have been tested under operating conditions.

5. Microwave Power Source - A carcinotron capable of providing 100 watts between 7 GHz and 9 GHz has been operated. The power supply is being rewired with appropriate interlocks.

The construction of all components for this experiment should be finished by the end of November with initial operation expected in December, 1969.

PART V. SUPERCONDUCTING STUDIES

In this year, tests were made of two aspects of superconducting hoops. The first of these was related to the high temperature performance of superconducting materials in a coil geometry. Coils in an isolated bomb were cooled to liquid helium temperature in a dewar, and some helium was condensed in the bomb. The coil was energized, and the bomb was lifted out of the helium in the dewar, allowing the temperature of the coil to rise. The temperature and pressure were monitored in the bomb during the rise. The temperature at which the coil went normal was measured.

The results of these tests indicated that the temperature at which the coil quenched was consistently higher than that predicted by the published short sample measurements of quench temperature for the coil current. Thus higher coil performance can be expected for a given temperature ruse, amounting in some cases to a factor of two.

These results were thought to be due to the lack of magnetic perturbations in the coil and the improved heat transfer in the high temperature, high pressure, constant magnetic field situation. It was felt that the phenomena observed could best be studied by isolating these phenomena. Thus, a program of short sample tests has been initiated in a new bomb in which the amount of condensed helium can be better controlled, and the pressure known in terms of measured temperature at fixed volume. By using short samples we can work directly on the heat transfer to a single conductor, and can control the magnetic field independently of the conductor current. When these studies are completed, we should be able to predict the required heat transfer for any coil to operate at elevated pressure and temperature, as is anticipated in an isolated superconducting hoop.

The second area of study has been the inductive charging of hoops. This is equivalent to the shielding of an external field by a superconducting coil operating in a persistent mode. Measurements of charging and shielding were made for two different types of coils, namely wound coils of RCA superconducting ribbon and Linde stabilized plasma-sprayed superconductor. The results were negative in both cases. The ribbon coil exhibited a steady penetration of flux, either for inductivity trapped internal flux or for shielded external flux. The Linde material exhibited massive flux jumps when an attempt was made to trap or shield central fields in excess of 12-15 kg. The flux jumps in both cases are felt to be due to the finite internal perturbations in the coil caused by the change in direction and strength of magnetic field in the superconductor during chargingor shielding.

PART VI. MICROWAVE STUDIES AND FABRY-PEROT SYSTEMS

On the small toroidal octupole, use has been made of the electronically stabilized microwave Fabry-Perot system developed here.[2] The electronic stabilization system operated well without low frequency drifts but there is still some high frequency distortion remaining. In the original third scale octupole, Q's of 13,000-40,000 were achieved. This is somewhat better than expected by theory and time dependent density observations were made with this apparatus. It was essential to add a large yoke to hold the two Fabry-Perot mirrors with the mounting separated from the tank. The reason is that the mechanical motion of the tank lids changes the path length. The electronics for operating this stabilized system is ready to be removed to PSL for use with the big octupole and the mirrors for use in the large levitated octupole are being made in the shop.

Work in Beyer's group of the electrical engineering department has been continued while he was on leave. He is now back. His group developed the fast response diagnostic system formed by coupling a klystron appropriately to Fabry-Perot resonator containing the plasma which has been quite successful. This system has contributed directly to the diagnostics being employed in octupole research.

The extensive work on microwave ECRH heating in the original octupole was discussed above in Part II of the Technical Progress Report.

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[2] J. B. Beyer and R. J. Chaffin, IEEE Trans. Microwave Theory Tech. 16, 37 (1968) and R. J. Chaffin, Thesis, University of Wisconsin (1968).

PART VII. FEASIBILITY STUDIES

The work over the past year has principally been to consider the question of alpha heating. Previous researchers have used the Coulomb cross section with a Debye cutoff to obtain the minimum deflection angle. This gives results which are adequate for simple binary collisions but when such details as the mean energy transfer per collision or the slowing down time are considered, the quantum mechanical results bring in differences. The magnitude of these differences is still being evaluated but preliminary results indicate that important differences are appearing. Some work has also been done on the problem of reactor start up and possible sources for ignition. This is a most serious problem and needs considerable effort.

PART VIII. GUN STUDIES AND MOVING PLASMA CLOUD STUDIES

Refinements have been made on the understanding of the effects of apertures and slits on passing plasma. Such slits are used in diagnostic equipment. Some of this material was reported last year at the Miami meeting. The same gun experimental equipment has been used with an enlarged aperture for the study of a 5 cm diameter plasma column. It has been possible to probe the passing plasma cloud with a transverse electron beam to determine the internal potential distribution of the collimated plasma cloud and to examine some details of wave effects within the cloud. Both theory and experiment are being compared in this study and we expect to be able to publish some information soon.

Gun studies have generally followed a two-fronted effort. One is the design and test of guns which are useful for injection from the inside into closed line devices. The second effort is with pulsed gas valve guns. Here the problem is in trying to insure the extremely high gas efficiency that is required for long confinement time experiments. This is an important problem because of charge exchange losses on the neutral gas from the gun.

Thus far, it has been possible to push the density in the small octupole into the 10^{12} cm^{-3} range and extensions on this are possible. Considerable time has been devoted to measuring and minimizing the impurity spectrum from occluded gas guns which produce large quantities of plasma. In the pulsed gas case it turns out the gas valve location and operation is very important as well as the current use time in the gun itself.

PUBLICATIONS

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Direct Measurement of the Ion Distribution Function in a Toroidal Octupole, C. W. Erickson, accepted for publication in the Physics of Fluids.

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Quasi Electrostatic Modes in Axisymmetric Tori, I. Kim and S. K. Malik, submitted for publication in the Physics of Fluids.

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Obstacle Induced Convection In a Toroidal Octupole, J. A. Schmidt and G. L. Schmidt, accepted for publication in The Physics of Fluids.

Plasma Convection in a Toroidal Octupole, J. A. Schmidt, to be submitted for publication to Phys. Rev. Ltrs.

ABSTRACTS

Submitted to APS Los Angeles Meeting, November 12, 1969:

Convective Structures in a Toroidal Octupole, J. A. Schmidt.

Nonadiabatic Particle Motion in Linear and Toroidal Multipole Fields, James E. Howard.

Potential Measurements in a Cylinderical Plasma with an Electron Beam Probe, Charles H. Stallings.

Drift Instabilities in Axisymmetric Configurations, I. Kim and S. K. Malik.

Ion Heating by Microwaves in a Toroidal Octupole, Glenn W. Kuswa.

Cross Field Plasma Loss in a Toroidal Octupole, A. W. Molvik.

Attempts at Ion Cyclotron Heating in a Toroidal Octupole, J. C. Sprott.

Some Features and Preliminary Tests of a Levitated Octupole, D. W. Kerst, H. K. Forsen, R. A. Breun, A. J. Cavallo and J. C. Sprott.