MASTER

Report No. COO-2180-7

STUDIES OF CHARGED-PARTICLE DISTRIBUTIONS IN AN ELECTROSTATIC CONFINEMENT SYSTEM

Final Report

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November 1, 1971 - January 31, 1976

PREPARED FOR THE U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION UNDER CONTRACT NO. AT(11-1)-2180

427 attached

DISCLAIMER

TABLE OF CONTENTS

I. TITLE

Studies of Charged-Particle Distributions in an Electrostatic Confimement System.

II. ABSTRACT

Microwave cavity techniques were used to measure electron density in a spherical, inertial-electrostatic confinement device using six ion guns. The density was roughly proportional to ion current (1 to 17 mA) and decreased somewhat with increasing ion energy (10 to 37 keV). With D_2 pressure decrease from 10 to 3 mTorr, n_e decreased faster than linearly and below $\sim$3 mTorr decreased linearly with pressure down to the lowest pressure of 0.4 mTorr. At 1 mTorr and 10 mA, measurements (with poor spatial resolution) were consistent with 10^{10} total electrons and a central n_e of 10^9 electrons/cm^3. Neutron flux (at 50 keV) was about one sixth that of Hirsch (J. Appl. Phys. 38, 4522 (1967). Six- vs. three-gun operation showed a small enhancement of both n_e and neutron flux that may indicate some particle trapping. Technical reports COO-2180-5 and COO-2180-6 describe the measurements.

III. LEGAL NOTICE

IV. INTRODUCTION

A research program to explore the fusion possibilities of inertial-electrostatic confinement of ions was initiated by Philo T. Farnsworth at I.T.T. in the mid-1950's. Subsequently Robert L. Hirsch,[1] working at I.T.T., discussed this confinement approach and described a series of experiments he had performed with a spherical device employing six ion guns.

The tests at Brigham Young University were undertaken primarily to study the electron density in the interior of such a device by means of microwave cavity techniques. In the later portion of the work the neutron flux from the device was also studied. Inasmuch as comprehensive technical reports have recently been issued (COO-2180-5 and COO-2180-6) which describe these measurements, this report will be devoted primarily to summarizing the activities and results.

V. THE RESEARCH PROGRAM

The Confinement Device

The system employs a 6.75 - in. I.D. vacuum envelope (originally used by Hirsch) with six symmetrically positioned ion guns mounted on it which direct their beams radially inward. The beams pass through 3/16 - in. dia. apertures in the 4-1/2 in. dia. spherical inner stainless-stell shell which is mounted concentrically within the grounded envelope and maintained at high negative potentials.

The Microwave Method

The spherical inner cavity into which the ions are injected can serve

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[1] Hirsch, R. L., J. Appl Phys. 38, 4522 (1967).

also as a microwave resonator and the electron density inside it can be studied indirectly by the effect the electrons have on the microwave cavity resonances. Some of the principal difficulties in applying the technique are:

1. Thermal expansion during operation causes resonant frequency shifts much larger than those caused by the presence of the electrons.
2. Since the inner sphere is operated at a high negative potential (usually greater than 20 KV) the problem of coupling to the resonator is not a simple one.
3. High sensitivity to the presence of electrons and high capability for spatial resolution of the electron density are mutually incompatible. Information regarding the spatial distribution of the electrons would be improved if shorter wavelengths could be used, but the sensitivity to the presence of electrons is greater for the longer wavelengths.
4. All spherical modes are degenerate and cavity asymmetries enhance the difficulty of identifying and studying the desired modes, particularly with high-order modes.

<u>Initial Tests</u> (Report No. COO-2180-1)

The device was assembled and initially operated by Gene A.Meeks who had previsouly assisted Farnsworth and Hirsch in the research at I.T.T.. In the initial tests the background pressure was rather high (a few milliTorr) because differential pumping had not yet been provided and the ion guns received their gas supply from the ambient pressure in the device.

Frequency shifts of the $TE_{1,8}$ and $TM_{4,1}$ microwave mode resonances (at 10.9 and 10.7 GHz) were observed at the time of manual turn-off of the high voltage. The modes were repeatedly scanned in synchronism with the line voltage and tests showed that the decay time of the electron density was substantially less than 1/60 sec. TM mode shifts of up to about 10 MHz were observed with the TE mode shift being about 1/3 as large (because the TE mode is insensitive to electrons at the center.) If the electron density were uniform throughout the cavity (which it is not) a mode shift of 3.8 MHz would correspond to a density of 10^9 electrons/cm^3.

Results with Switched Operation and Differential Pumping

In order to effect "continuous" observation of the frequency shift, provision was made to interrupt the high voltage at a rate of 5 or 10 Hz in synchronisn with the line voltage and thus to permit repeated comparison of the "plasma" and "no plasma" states. The instrumentation (described in Report No. COO-2180-3) permitted continuous recording of the frequency shifts of two modes and also of the ratio of their shifts.

During this modification the vacuum system was improved by routing a gas feed to each ion gun so that differential pumping could be effected and thus the ambient pressure could be lowered. Even with this provision, however, the attainable lowest background pressure was about 0.4 milliTorr of deuterium.

The most significant feature of the measurements was the decrease in frequency shift as the ambient pressure was lowered. For example, with 6mA total current of 20.5 keV ions, the frequency shift of the $TM_{4,1}$ mode was 2.7 MHz at 5 millitorr but only 100 kHz at 0.5 millitorr. Furthermore, even at the lowest pressure there was no evidence that this trend was not continuing (although perhaps at a more linear rate). This result suggests that even at the lowest attainable pressures the electron density is determined largely by ionization of the background gas. Unfortunately, the density is so low that the use of shorter wavelengths in order to obtain significantly better spatial resolution is not feasible.

As ion current or ion energy was varied no significant change was observed in the ratio of the frequency shifts of the TM and TE modes. Thus no evidence of electron shell structure was seen although at these wavelengths (about 3 cm) only a coarse radial structure would have been detectable.

In view of the low and decreasing electron density with reduction in ambient pressure, the decision was made to abandon further effort to obtain spatial resolution of the radial profile with high order modes and to look instead for evidence of particle trapping by observing the effect of simultaniety of injection from the six ion guns. This effect was studied with both microwave and neutron flux measurements and later, using steady state operation at voltages up to 65 kV, with measurements of only the neutron flux.

The procedure was basically to operate the device with single ion guns or with up to three unopposing guns and to measure the "normalized" frequency shift or neutron flux (i.e., the frequency shift or neutron flux per mA of total ion input current) and then to operate the device with all six ion guns (3 opposing pairs) and to again measure the normalized frequency shift or neutron flux. An increase in the normalized response with 6-gun operation, over that measured with non-opposing gun operation was called "cooperative enhancement" and the fractional increase was defined as the "cooperative enhancement coefficient" ("CEC").

If only one ion beam is injected into the device, most of the ions entering the aperture in the cathode shell would be expected to strike the inner wall in the vicinity of the opposite aperture (because of imperfect focussing and alignment and also because of beam blow-up and interaction with background particles) although some would escape through that aperture. However, it is felt that the fraction that would pass through both apertures and then return for a second entrance would be small--probably less than 10%. If all guns are operating and the ion kinetic energies within the shell are significantly altered by the resulting interior potentials that develop, the beam blow-up may be expected to increase (i.e. non-radial motions will increase) and the fraction re-circulated through the apertures would be even smaller.

If one concludes that the recirculated primary ions do not play a significant role in the behavior of the device then the presence of opposing input beams appears to be an essential operating condition if any appreciably trapping of charged particles is to be effected in the interior. If this assumption is valid then the presence of trapping would likely be accompanied by a positive "CEC" of any quantity (e,g, electron density or neutron flux) that increases with the degree of trapping of the ions or the electrons.

Observed "CEC" values were small but rather definite and were apparently more pronounced at low pressures and high ion energy. Some overall values at particular pressures were as follows:

Measured Quantity	Pressure (mTorr)	Number of Measurements (at various voltages)	Ave. CEC	σ
Frequency Shift	10	10	Negligible	.14
" "	2.5	11	.19	.10
Neutron Flux	10	7	.13	.15
" "	1.25	12	.142	.067
" "	.75	10	.332	.255

A positive "CEC value might possibly be explainable by other mechanisns than ion trapping although none are proposed here. However it should be noted that the neutron flux arising from ion collisions with the walls or with the neutral gas background would make the measured CEC lower than it would otherwise be. (The fusion interaction of opposing beams would tend to make a higher CEC but this effect is entirely negligible.)

Total Neutron Flux

Only relative measurements (with high sensitivity) were needed for the foregoing neutron flux CEC determinations. Two plastic scintillators (5-in. dia. x 5-in. long) were used for this purpose and these were symmetrically positioned so that the total counts from the pair would not "favor" any of the six ion guns. In order to compare the neutron flux with that reported by Hirsch(1), an absolute calibration (described in Technical Report No. COO-2180-6) was made from which the following comparison can be made for D_2 operation at 50 kV:

	Pressure (M Torr)	Neutron Output (n/sec)
B.Y.U. Tests (Report COO-2180-6)	1.25	2.7×10^5
Hirsch (From Fig. 11 of Ref. 1)	7.8	8.4×10^5
"	1.1	1.6×10^6
"	0.1	2.4×10^6

The measured neutron flux at B.Y.U. was thus almost a factor of six lower than that measured by Hirsch. Minor changes in the device and such factors as alignment and focussing of the ion beams might well account for the difference.

VI. CONCLUSIONS

1. Throughout the pressure range studied (0.4 to 10 millitorr of D_2) the electron density depended markedly on the pressure: below 3 mTorr being approximately proportional to the pressure and above 3 mTorr increasing more than linearly with increasing pressure. Thus interactions with the background gas may prevent or obscure effects predicted by the simple theory which neglects collisions with neutral particles.
2. The observed electron density is approximately proportional to total ion current and rather independent of ion energy in the range of 10-40 keV (decreasing somewhat with increasing energy in this range).
3. All the microwave measurements were consistent with a radial distribution of electron density that was largest at the center and decreased monotonically with radius (but the spatial resolution of the measurement was poor because the electron density was too low to permit the use of much shorter wavelengths).
4. With 1 mTorr (D_2) pressure, 10 mA (total) ion current at 20 to 40 keV produces a total electron population of approximately 10^{10} electrons and a central density of the order of 10^9 electrons/cm^3.
5. Comparison of the results of operation with three (unopposed) ion guns and operation with all six ion guns showed a small but definite "cooperative enhancement" that may be an indirect indication of particle trapping.
6. The measured flux was about a factor of 6 (lower) than that reported by Hirsch under similar conditions.
7. A modification of the geometry of the device (discussed in the next section) could eliminate many of the alignment problems and diagnostic difficulties.

VII. Suggestions for Further Work

Further tests will be considerably more meaningful if means are provided to:

1. Improve the vacuum inside the cathode.
2. Improve the ion-gun alignment.
3. Avoid the problem of traversing a high-field region to reach the cathode with diagnostic "probes".
4. Improve the symmetry with additional ion guns.

These features can all be provided by eliminating the hollow cathode shell and operating the ion guns at a high positive potential. The envelope would thus become a grounded, accurately machined, hollow cathode which could be scaled up in size and in the number of ion beams without serious structural or alignment complications. Each ion gun could have its own grounded output aperture (an inlet aperture of the cathode) as an integral part of the ion gun and each gun unit could be tested prior to its installation. A machined mounting flange would accurately position each gun. Intermediate differential pumping could be provided in each gun unit and wall cooling of the cathode would be feasible.

Such an arrangement would be more costly, because of the provisions needed to operate each gun at a high potential, but nevertheless it is technically feasible. A possible objection is that ions would not recirculate; however, the recirculation in the present device is felt to be so low that its complete elimination would not significantly alter the operation of the device.

VIII. Papers Published or Presented

American Physical Society Meeting, Philadephia, Pennsylvania, Oct. 31 - Nov. 3, 1973. Bull. Am. Phys. Soc., Series 2, 18, 1344 (1973)

Gardner, A.L.	"Continuous" Measurement of the Frequency
Evans, R.P.	Shifts of Two Microwave Cavity Modes.

New York Academy of Sciences Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams, New York, N.Y., March 4-7, 1974 (Also issued as U.S. A.E.C. Report No. COO-2180-2.)

Gardner, A.L.	Measurements on a Spherical Electrostatic
Hatch, D.M.	Confinement System Employing Six Ion Guns.
Chan, A.I.Y.	
Evans, R.P.	

(This paper was published in: Annals of the New York Academy of Sciences, Vol. 251, pages 179-189, May 8, 1975.)

Utah Academy of Sciences Arts and Letters, Spring Meeting, Provo, Utah, March 29, 1974.

Chan, A.I.Y.	Electron Density Measurements in a Spherical Electrostatic Confinement Device Using Microwave Cavity Techniques. (Published by title only)
Evans, R.P.	Instrumentation for Continuously Recording Plasma-Induced Frequently Shifts of Two Microwave Cavity Resonances. (unpublished)

Masters, Thesis, Dept. of Physics and Astronomy, Brigham Young University, April, 1974. (Also issued as U.S. A.E.C. Technical Report No. COO-2180-3.)

Evans. R.P. Instrumentation for Continuously Recording Plasma-Induced Frequency Shifts of Two Microwave Cavity Resonances.

American Physical Society Meeting, Albuquerque, New Mexico, Oct. 28-31, 1974. Bull. Am. Phys. Soc. Series 2, 19, 927 (1974)

Chan, A.I.Y.
Gardner, A.L.
Hatch, D.M. Electron Density Measurements in a Beam-Driven Electrostatic Confinement Device.

Doctoral Dissertation, Dept. of Physics and Astronomy, Brigham Young University, August, 1975 (Also issued as U.S. A.E.C. Technical Report No. COO-2180-5)

Chan, A.I.Y. Microwave Measurements of Electron Density in a Spherical Inertial-Electrostatic Confinement System using Six Ion Guns.

Masters Thesis, Dept. of Physics and Astronomy, Brigham Young University August, 1975 (Also issued as U.S.A. A.E.C. Technical Report No. COO-2180-6)

Westenskow, G.A. Measurements of Neutron Flux from an Inertial-Electrostatic Confinement Device.

American Physical Society Meeting, St. Petersburg, Florida, Nov. 10-14, 1975. Bull. Am. Phys. Soc. Series 2, Vol. 20.

Chan, A.I.Y.	Studies of the Effect of Simultaniety of
Gardner, A.L.	Injection of the Six Ion Beams in a Spherical
Westenskow, G.A.	Inertial-Electrostatic Confinement System.

IV. Graduate Student Participants

The following participated, as graduate students, in the research:

Dr. Austin I.Y. Chan	- at present an instructor in the Physics Department at Utah State University
Mr. Robert P. Evans	- now working at the Idaho National Laboratory Twin Falls, Idaho.
Mr. Glen A. Westenskow	- now in a Ph.D. program at Stanford University.
Mr. Kenneth W. Struve	- is working in the CTR program at the Lawrence Livermore Laboratory and is engaged in a PhD. program.

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In Reply Refer To:

February 11, 1976

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FINAL REPORT, EXPIRED CONTRACT NO. E(11-1)-2180, MODIFICATION NO. 2

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Harold N. Miller, Director
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Enclosure:
Final Report No. COO-2180-7 (4 cys.)

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