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Technical Summary Report

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on

Potential Well Formation in Electrostatic
Confinement Devices

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by

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ABSTRACT

The experimental and theoretical studies on Inertial Electrostatic Plasma Confinement that have been performed in the Gaseous Electronics Laboratory of the University of Illinois are reviewed, with particular emphasis on that portion of the work that has been supported by the U. S. Department of Energy. There has been experimental confirmation of the production of a multiple potential structure in both small and large spherical devices and the theoretical analysis has indicated the parameter range that is necessary in order to explain such results. Further experimental and theoretical approaches to testing the IEPC concept are suggested.

I. An Overview of Research on Inertial Electrostatic Plasma Confinement.

The concept of Interel electrostatic Plasma Confinement (IEPC) is based upon the idea that bipolar injection of electrons and ions in spherical geometry may lead to alternating positive and negative potential wells within the device (as predicted by a simple application of Poisson's equation) and if the potential wells can be made deep enough, energetic ions could be confined within the center for fusion purposes. Even though little credence was put in this simplistic theory, early experiments by Hirsch¹ utilizing ion injection in D-T at 150 keV showed that a significant steady state neutron production was possible in such a device and the limited diagnostics available suggested that energetic ions confined near the center of the device were responsible.

It was at this stage that the Gaseous Electronics Laboratory became involved with this project. It was our aim to determine what was actually happening inside the IEPC devices and how they could be properly described.

Our first experiments, under AFOSR sponsorship, approached the problem from two different directions. The spatial variation in electron density was investigated in a cylindrical device by using laser diagnostic techniques developed in our laboratory.^{2,3} The potential structure in spherical geometry was also studied by using a refinement of the electron beam probing technique originally used by Hirsch.^{4,5}

The experiments performed in cylindrical geometry utilized both ion and electron injection and demonstrated that a spatially oscillating electron density distribution did exist within an IEPC structure.³ This was the first evidence that substantiated the simple model for neutron production in Hirsch's high energy experiments.

Slightly after the experiments on cylindrical geometry began, our electron beam probing experiments on a fairly small, low voltage device⁵ showed that when only electrons are injected, an almost perfectly parabolic potential well is formed, and the depth depends on the injected current (or, more properly, on the perveance $I/V^{3/2}$). This is at variance with Langmuir's theory⁶ based on perfectly radially focussed electrons. A careful reconsideration of the theory of potential formation for electron injection based on the work of Lavrent'ev⁷ and Dolan², allowed us to obtain excellent correlation to the experimental results by taking into account the spread in angular momentum of the injected electrons.⁸ The theory predicts the parabolic potential well observed with excellent accuracy.

The most significant results obtained from the spherical device occurred when both electrons and ions were injected. When ions were produced within the IEPC device, by allowing low pressure deuterium gas to form the background for electron injection, a potential well for ions was observed near the center of the device.^{4,5} This lent further credence to the basic ideas of the early theory and Hirsch's experimental results. A further extension of the theoretical model showed that such an observation could be explained by the acceleration of the ions towards the center of the device under the influence of a highly symmetric electronic space charge well⁹ - in other words, the ions had to have very little angular momentum. The studies of the space charge well formed under conditions of electron injection had shown this remarkable degree of symmetry, so the resulting ion focussing is no surprise.

Progress since then has been along two fronts. The experimental apparatus has been enlarged considerably and has injection capabilities of 10 A and 20 kV maximum. Similar phenomena have been observed with the added feature that the potential well can be fully depressed by electron

injection. Similarly, probe studies have confirmed ion focussing within the device with the requisite small angular momentum. The aim of the work in the larger device is to examine the scaling of the trapped ion densities and energies as the device approaches the necessary conditions for fusion reactions. On the theoretical front, the latest efforts to simulate the conditions in an IEPC device have predicted a triple well, such as must have occurred in Hirsch's device if our explanation of what was happening is correct.⁹

II. Experimental Activities During 1978

During the last year, the primary emphasis of our work has been to extend the operating regime of our large spherical device to higher ion densities, and determine the ion focussing characteristics at these densities.

In the past, we have utilized electron impact ionization from our electron guns to generate a small number of ions. We desired to use a pre-formed plasma as our source of background ions, since it is easily created and could yield a wide range of ion densities ($10^7 - 10^{11}/\text{cm}^3$).

In order to operate our device under these conditions, several modifications were necessary. In order to flow gas through the system, our ion vacuum pumps were replaced by a closed cycle cryogenic vacuum pump, and the electron guns were re-designed to operate at higher background gas pressures. In addition, microwave diagnostics were installed to measure the background plasma density, and our electrostatic probe was re-designed as a twin element probe with radial and angular directionality.

Operating of the device at higher gas pressures has proved to be difficult. Figure 1 shows the electron densities obtained inside our anode using a DC discharge to create a target plasma. Injecting electrons to establish wells, and taking ion probe density measurements inside a discharge plasma has proved to be very challenging. Our data over the last few months of full operation has been encouraging but inconclusive due to the small signal-to-noise ratios. However, we are slowly improving our ability to extract data out of the operating noise as we come to better understand the operating characteristics of our device under these difficult conditions.

III. Areas for Future Research

There are still several critical questions regarding the IEPC concept that need to be answered to fully evaluate that scheme. The crux of the matter is the density of ions that can be "trapped" or built up within the electronic well. As Hirsch¹ and Lavrent'ev¹⁰ have both pointed out, in order for the IEPC concept to work (in other words, without requiring enormous anode currents) significant current multiplication must be possible between the alternating virtual cathodes and anodes within the device. This translates itself into trapping of larger circulating currents inside the anode. The theoretical models⁹ have always assumed that trapped particles are there in predicting multiple potential wells and in explaining the ionic space charge observed in our first experiments. The question of how those particles were injected in the first place has not been addressed although it is obviously a crucial issue for IEPC. Remember that the observation of ionic space charge in the center of our spherical device was observed under the condition that the anode potential was depressed by only 30% for electron injection. Obviously, then, a large electron current was circulating through the anode. But, we have never observed a multiple well when the interior has been fully depressed by large injected currents.

Consider the experimental fact that we have excellent ion focussing for shallow wells. This is a most encouraging result and should continue to hold for fully depressed wells. But, the fact that we have not observed a central ion peak for fully depressed wells raises some important questions. Namely, what are the conditions that allow ions to flow past a virtual cathode and build up a significant trapped density?

Fig. 1. Electron density inside the spherical anode during a DC discharge.

From a theoretical point of view, some work has already been begun by Verdeyen¹¹ and Schlein¹² on understanding the extraction of ions from a plasma when an electron beam is injected to form a virtual cathode. We also have the experimental facilities to produce a plasma in our spherical device and to completely depress the potential by electron injection. We can, therefore, experimentally study the ion current flowing past a virtual cathode.

In addition to the previous point, there are two issues which also should be examined theoretically and experimentally. The first is the necessity or nature of space charge symmetry within our systems. Under conditions of asymmetric electron injection - which is the real situation - to what extent will the space charge field be asymmetric, either spatially or in time, and how will this affect the angular momentum of the accelerated ions? [Remember, theory predicts that very little angular momentum can be tolerated if a significant ion well is to be formed within the device. The experimental device does have a large degree of control over the injection geometry, so this may be best approached experimentally. The last question (for now!) is related to time stability. The theoretical formulations so far have assumed steady state solutions. This may not be so. There is a real need to explore the temporal behavior of the ions injected or accelerated by a space charge to see if the former theoretical results - and possibly the desired results - are actually a "time average" of a complicated dynamic interaction.]

REFERENCES

- ¹R. L. Hirsch, J. Appl. Phys. 38, 4522 (1967).
- ²T. J. Dolan, J. T. Verdeyen, D. J. Meeker and B. E. Cherrington
J. Appl. Phys. 43, 1590 (1972).
- ³D. J. Meeker, J. T. Verdeyen and B. E. Cherrington, J. Appl. Phys 44,
5347 (1973).
- ⁴D. A. Swanson, B. E. Cherrington, and J. T. Verdeyen, Appl. Phys. letters
23, 125 (1973).
- ⁵D. A. Swanson, B. E. Cherrington and J. T. Verdeyen, Phys. Fluids
16, 1939 (1973).
- ⁶I. Langmuir and K. R. Blodgett, Phys. Rev. 24, 49 (1924).
- ⁷O. A. Lavrent'ev, Magnitnye Lovushki AEC report #AEC-tr-7002, 1970.
- ⁸D. A. Swanson, B. E. Cherrington and J. T. Verdeyen, Phys. Fluids 17,
1269 (1974).
- ⁹B. E. Cherrington and D. A. Swanson, Phys. Fluids 20, 2139 (1977).
- ¹⁰O. A. Lavrent'ev, Ann. NY Acad of Sci 251, 152 (1975).
- ¹¹J. T. Verdeyen, private communication.
- ¹²R. G. Schlein, "Ion Extraction Using Electronic Space Charge Fields -
A Theoretical Analysis," Ph.D. thesis, University of Illinois, 1978
(unpublished).

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Publications on Inertial Electrostatic
Plasma Confinement

"Electrostatic-Inertial Plasma Confinement"

T. J. Dolan, J. T. Verdeyen, D. J. Meeker, B. E. Cherrington, J. Appl. Phys. 43 1590 (1972) and

"Measurement of Electron Density in a Cylindrical Inertial Electrostatic Plasma Confinement Device"

D. J. Meeker, J. T. Verdeyen, B. E. Cherrington, J. Appl. Phys. 44 5347 (1973). (AFOSR Support)

These papers reported our first work on the IEPC concept and represented an investigation of the density of trapped particles. A definite structure to the charge density was observed. The beginnings of a theoretical approach was developed with the important result that a multiple potential structure could not be produced if the trapped particles had any appreciable angular momentum.

"Multiple potential-well structure created by electron injection in spherical geometry" (AFOSR)

D. A. Swanson, B. E. Cherrington, J. T. Verdeyen, Appl. Phys. Lett 23 125 (1973) and

"Potential well structure in an inertial electrostatic plasma confinement device" (AEC)

D. A. Swanson, B. E. Cherrington and J. T. Verdeyen, Phys. Fluids 16 1939 (1973).

These papers reported details investigations of the potential well structure in a spherical device. The parabolic form of the potential well with electron injection was shown. The multiple potential structure (corresponding to well focussed ions) was also shown.

"Theory of the negative electrostatic potential well in spherical geometry"

D. A. Swanson, B. E. Cherrington and J. T. Verdeyen, Phys. Fluids 17
1269 (1974) (AEC) and

"Theory of the multiple potential well structure created by bipolar
injection in spherical geometry" (ERDA)

D. A. Swanson, B. E. Cherrington, Phys. Fluids 20 2139 (1977).

These papers presented the detailed theoretical basis for
understanding and predicting the potential well created by
electron injection only and also showed that significant ion
focussing and density build up is possible when ions are
accelerated by a very uniform electronic space charge field.

"Recent Development in Electrostatic Confinement-Experimental"

J. T. Verdeyen, B. E. Cherrington, D. A. Swanson, D. J. Meeker
and

"Recent Developments in Electrostatic Confinement-Theoretical"

B. E. Cherrington, J. T. Verdeyen and D. A. Swanson, Annals NY Acad of
Sciences 251 126,139 (1975). (AEC)

These are review articles on the IEPC concept.