Technical Progress Report

C000 - 2323 - 5

on

Potential Well Formation in Electrostatic
Confinement Devices

MASTER

Prepared for

U.S. Energy Research and Development Administration
Division of
Controlled Thermonuclear Research

by

B.E. Cherrington, J.T. Verdeyen

Gaseous Electronics Laboratory
Department of Electrical Engineering

University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

A large (2' diameter) spherical electrostatic confinement device has been constructed to test the feasibility of using inertial electrostatic forces to confine energetic plasmas capable of sustaining fusion reactions. Electron injection under high vacuum has produced negative wells that completely depress the potential in the center and approach the classical Langmuir virtual cathode. Electron injection into low pressure deuterium reproduces our previous results of an ion rich region within the negative well. Additional theoretical studies incorporating electrons with very narrow angular momentum (corresponding to trapped electrons in the center) has shown that an additional electron rich region (or ion rich if the polarities are reversed) can be produced within the ion rich region for presumably realistic ranges of parameters.

I. INTRODUCTION

Within the last year, our new experimental apparatus has been completed, tested, and initial experiments have been successfully performed. In spite of the approximately four month cumulative delay due to the late arrival of the vacuum chamber and the time taken to repair the leaks discovered in the chamber, we have completed the two major milestones scheduled for this year - production of a deep electron well under high vacuum conditions (in fact considerably deeper than we expected) and the production of a multiple potential structure with an ion rich inner region when electrons are injected into a low pressure gas background. The initial experimental results will be presented in the next section. We expect to have the complete analysis of the negative well and ion rich well completed by the end of the present contract period.

We have continued our theoretical analysis in an attempt to obtain more realistic models to compare with our experiments. We have found that the inclusion of an additional group of low angular momentum electrons in our theory, corresponding to electrons produced by electron impact ionization within the anode, indicates that a third electron rich region could be created within the center of the ion rich region. This would be extremely important if ion injection were to be used in a manner similar to Hirsch's original experiments.

II. THEORETICAL ANALYSIS OF MULTIPLE POTENTIAL WELL STRUCTURES

Our early studies of the solution of Poisson's equation for electron injection into a spherical anode, taking into account spreads in the total and angular energies, showed that excellent agreement between theory and experiment could be found for negative well formation.¹ The dominant factor determining the depth and shape of the well was found to be the angular momentum of the injected electrons.

A further analysis of the potential structures formed when both ions and electrons are injected was presented in the last progress report. Again, very good agreement was found between theory and experiment if it was assumed that the ions had a very narrow angular momentum spread and a broad spread in total energy. This distribution was not experimentally verified, but it is consistent with the physical picture of the ions being formed within the anode by electron collisional ionization of the background gas and then oscillating through the center without being scattered by the anode structure. This analysis was then extended to the conditions achievable in our new apparatus and indicated that deep negative wells could be formed and energetic ions could be contained within such a structure.

In the last year, our analysis has concentrated on two aspects. The first aspect has considered the dependence of the ion well formation on the spreads in angular and total energies of the ions and electrons. The second aspect has dealt with the conditions under which an additional electron rich region might be formed within the ion well.

A. Ion Well Structure For Varying Ion and Electron Angular and Total Energies

Referring to our previous technical report, good agreement was found between our theoretically predicted and experimentally observed multiple potential structures when the electrons were assumed to have a relatively narrow total energy spread $\Delta E_e = .05$ and a relatively wide angular energy spread $\Delta \phi_e = .15$ (which gives excellent agreement for the electron injection only case) and the ions were assumed to have a wide total energy spread $\Delta E_i = 0.3$ and a very narrow angular energy spread $\Delta \phi_i = .001$. The ratio of ion circulating current to electron circulating current was taken to be $\beta = 0.003$ and the solutions were obtained for an anode voltage $V_a = 1000$ V and an anode current $I_a = 100$ mA. Actually these last two parameters are somewhat incidental. It is the perveance ($\sim I_a/V_a^{3/2}$) that determines the well depth if all other parameters are constant.

Which of the above parameters are critical for the establishment of an ion rich region? Numerous potentials were computed as the above parameters were varied about the original solution. First of all, variations in the total energy of the injected electrons (ΔE_e) had a negligible effect on the shape of the potentials. A similar result was noticed for electron injection only, so this result is consistent.

Secondly, variations in the total ion energy (ΔE_i) were found to have a similar negligible effect. This has an interesting implication since it says that the ions could all originate close to the anode or even be beam ions and still create the desired ion rich region.

The variation in the potential well structure as the electron angular momentum, $\Delta\phi_e$, is varied as shown in figure 1. The results are very much as would be expected from the negative well theory alone. Narrowing the electron angular momentum increases the depth of the negative well as expected. There is no particularly unexpected variation in the central positive (ion rich) peak, however more energetic ions could obviously be contained in such a well. The electron angular momentum is determined primarily by the scattering of the injected electrons by the anode basket, however, the narrower the electron angular momentum, the better.

Figure 2 shows the variation in the potential structure as the ratio of ion circulating current to electron circulating current (β) is varied. $\beta = 0$ is the electron well case alone. Obviously, the multiple potential structure is evident for basically all ratios up to the point where the ions pretty well wash out the electron well. The larger the number of ions, the smaller the potential well to confine them, so it would be desirable to start with a deep electron well first. We are not able to tie a good number to β at this point since it depends upon evaluating the production and loss processes in detail. We have qualitative information but insufficient quantitative information at present to evaluate β .

As might be expected, increasing the injected current has a desirable effect as can be seen in figure 3. Increasing the injected electron current deepens the negative well in the same manner as for electron injection alone. Since we are assuming a fixed ratio of ion circulating current to electron circulating current, increasing I_a also increases the ion current, resulting in a higher potential increase at the center. Of course, the injected current

Figure 1. Variation in Multiple Potential Structure as the Electron Angular Momentum is varied.

Figure 2. Variation in Multiple Potential Structure as Ratio of Ion to Electron Current is Varied.

Figure 3. Variation in Multiple Potential Structure as the Injected Electron Current is Varied.

is dictated, or limited, by the space charge limit and so depends on V_a and the anode to cathode distance. Larger anode voltages and smaller gaps will lead to larger currents and deeper wells.

The most critical factor in determining the nature of the ion rich region is the ion angular momentum, $\Delta\phi_i$, as is demonstrated in figure 4. Clearly, the ions must have very little angular momentum in order to form an ion rich region in the center. Experimental evidence shows that this condition is obviously satisfied, however no experimental measurements on angular momentum of the ions have been performed, so it is difficult to assess how actual conditions would affect this very critical factor. Obviously, this is an area in which experimental studies should concentrate in the future.

B. Existence Conditions for "Triple-Well" Within the Anode

The original theoretical model for Inertial Electrostatic Plasma Confinement was based on electron and ion injection by beams with zero angular momentum. This model predicted an infinite set of alternating virtual anodes and cathodes as the center of the device was approached.² Our experiments have shown that at least one alternation can be seen under real experimental conditions and a reasonably realistic theoretical model indicated the electron and ion parameters that were responsible for producing such a structure. An important question, however, is whether a "triple-well" consisting of an electron rich region surrounded by an ion rich region surrounded by another electron rich region (or, especially, vice versa) can be created within an IEPC device. It would appear that a structure of at least this complexity was created within Hirsch's original experimental apparatus,² and this deduction led to all further work on such devices.

Figure 4. Variation in Multiple Potential Structure as Ion Angular Momentum is Varied.

It was important, therefore, to determine whether the theory at its present level of sophistication and with our present derived knowledge of the reasonable range of the parameters of injected electrons and ions could predict such a structure. Indeed it can. The additional factor to be taken into account is the possibility of a group of "trapped" electrons within the potential well created by the ions. This possibility was not permitted in our previous model which assumed only one group of (injected) electrons. The addition of this second group consisting of electrons with a broad total energy distribution (since they are produced along with the ions by electron neutral collisions with the background gas) and a narrow angular energy (since they suffer no scattering by the anode) indicated that the triple-well can indeed be predicted under realistic conditions as was found by Hirsch. Figure 5 shows the triple wells predicted under essentially the same conditions under which the ion rich regions were predicted except that a background electron term with $\Delta E_e = 1.0$ (totally broad) and $\Delta \phi_e = .0001$ (very narrow) was added and the trapped electron current was taken to be 20% of the injected circulating electron current. Under these circumstances, the net electron density was in reasonable balance with the net ion density, as might be expected physically.

For all values of β shown, a triple well existed, although increasing β made the effect more pronounced. The very narrow value of the trapped electron angular momentum ($\Delta \phi_e = .0001$) was used to emphasize the effect, however, broader distributions gave the same

Figure 5. Triple Wells Predicted when Background Electrons are Included.

result. Figure 6 shows that broadening $\Delta\psi_e$ (trapped) to .001 (the same as the ions) still resulted in the prediction of a triple well.

The use of the extended solution of Poisson's equation has successfully predicted the observed experimental potentials for realistically assumed distributions of electron and ion energies. The inclusion of trapped particles also predicts the form of the potential much as was assumed to occur in early experiments. The difficulty now is to determine physically improved parameters to use in the analysis. In particular, measurements of the ion angular momentum and trapped electron angular momentum would be invaluable in allowing the present theory to make realistic predictions of possible future operating conditions in an IEPC fusion reactor.

Figure 6. Variation in Triple Well Structure of Figure 5 as $\Delta\phi_e$ of Background Electrons is Varied.

III. Experimental Observations of the Negative Well and the Multiple Potential Well

Within the last year we have achieved our two major milestones - production of a deep negative well and production of a multiple potential well with an ion rich inner region. We are still at a somewhat preliminary stage in that we have worked at anode currents of up to 1.6 amps and anode voltages of up to 6 kV, whereas we hope to operate at currents of up to 10 amps and voltages of up to 20 kV (or whatever our system can sustain). Our initial theoretical modeling is also preliminary in that we have used simple scattering theory and have not so far incorporated corrections for fringing fields. From previous experience, this results in predicted deflections that have the right general variation with V_a/V_g (ratio of anode voltage to probing beam gun voltage) but tend to focus (or de-focus for a negative well) more rapidly. Our preliminary experiments do, however, allow us to make some general characterizations of the potential structures formed.

A. Negative Well Formation

In our first set of experiments, we measured the deflection of the probing electron beam normalized to the initial deflection as a function of V_a/V_g for electron injection into a vacuum. Figure 7 shows the experimental results for different V_a and I_a combinations. Superimposed on Fig. 7 is the theoretically predicted deflection for parabolic electron wells which depress the potential within the anode by 70%, 80% and 100% of the anode voltage. Since the previously mentioned corrections to the theory are expected to compress the theoretical curves to the left, we see good agreement between the

Figure 7. Experimental (Solid Lines) and Theoretical (dotted lines) Plots of Normalized Probe Beam Deflections vs V_a/V_g for Electron Injection into a Vacuum

theoretical predictions and experimental results. We notice two important pieces of information. First, as the perveance ($I_a/V_a^{3/2}$) increases, the depth of the negative well increases, as expected. Secondly, we notice that we can essentially fully depress the potential within the anode. In fact, for larger currents than those shown, we obtain deflections that seem to indicate the formation of a virtual cathode within the sphere, much as predicted by the classical Langmuir space charge limited potential solutions.

Figure 8 shows the normalized beam deflection as a function of anode current for various sets of V_a , V_g values. As expected, the deflection increases (greater scattering of the probe beam) as the current increases and the injected electron density within the anode increases. The 6000 volt data on Fig. 8 can be re-interpreted in terms of the negative well depth vs anode current for a fixed V_a . This interpretation is shown in Fig. 9. This curve follows the same general trend as previously found by Swanson et al,³ and shows that essentially full depression can take place with modest current inputs.

Since our apparatus has considerably higher overall current capabilities (a maximum of 9 amps from seven guns when fresh, about 4 amps maximum at present), we can confidently expect essentially complete depression of the potential within the anode for electron injection up to the full 20 Kilovolts (or higher) that we expect to apply.

B. Observations of Multiple Potential Well Structure

When low pressure deuterium gas is introduced into the system at around 10^{-5} Torr pressure, multiple potential structures with an ion

Figure 8. Normalized Probing Beam Deflection vs Anode Current for Electron Injection in Vacuum.

Figure 9. Negative Well Depth vs Anode Current for Electron Injection in a Vacuum.

rich inner region are produced just as in the smaller apparatus we used for prior experiments. The most obvious result of such a structure is the focussing of the probing electron beam by the ion rich region rather than the defocussing due to the electron rich region under vacuum conditions. Figure 10 demonstrates this focussing effect as gas pressure is increased and all other factors are held constant. A normalized deflection < 1.0 shows the focussing effect of the ion rich region, whereas mere neutralization of the electronic charge would cause the curve to asymptotically approach a normalized deflection of 1.0 but never become less.

Figure 11 shows the normalized electron beam deflection as a function of $U = V_a/V_g$ for various gas pressures and fixed values of V_a , I_a and initial probing beam deflection. These results show the same behavior as our previous results on the smaller device³ and are consistent with the theoretically predicted deflections by a multiple potential structure consisting of an ion rich region within a negative well.

Our experimental results have also shown the quite nonlinear variation of relative focussing of the probing electron beam as the initial deflection (or attack angle) of the probing beam is changed. This is also convincing evidence of the existence of a multiple potential structure. This particular set of experiments has also shown that over the experimental limits of the attack angle (approximately 7°) the probing beam was still interacting with an ion rich region. From this we estimate that the ion rich region has a diameter of around 3" at the center of our device, or a volume

Figure 10. Normalized Probing Beam Deflection vs Pressure for Electron Injection into a Soft Vacuum

Figure 11. Normalized Probing Beam Deflection vs U for Various Pressures for Electron Injection into a Soft Vacuum.

of around 250 cm^3 . From our previous experiments, we expect that the ion potential increases until the dominant loss mechanism is ion flow through the diagnostic holes. This would clamp the ion potential at around 70-80% of the anode potential.

One further interesting observation is shown in Fig. 12. This shows the dynamic deflection of the probing electron beam for a situation in which we primarily have a negative well as the injected electron beam is crowbarred off. The outer circle shows the outward deflection of the probing beam due to the negative well and the inner circle shows the probing beam deflection for the electrostatic case only. The interesting point is that the probing beam is initially deflected within the electrostatic circle. This is due to the effect of the ions that are within the system and are present after the electrons have already left. Thereafter, of course, the ion density decays and the beam returns to its initial deflection. Observations of the ion decay rate should be most valuable in interpreting the nature of the ion rich region.

$I_a = 1.25 \text{ A}$
 $p \sim 10^{-6} \text{ Torr}$

$V_a = 4000 \text{ v}$

6 μsec per beam revolution

$I_a = .75 \text{ A}$
 $p \sim 2.5 \times 10^{-7} \text{ Torr}$

$V_a = 4000 \text{ v}$

Figure 12. Dynamic Deflection of the Probing Beam
 for a Primarily Negative Well Structure.

References

- [1] D.A. Swanson, B.E. Cherrington and J.T. Verdeyen, Phys. Fluids 17, 1269 (1974).
- [2] R.L. Hirsch, J. Appl. Phys. 43, 1590 (1972).
- [3] D.A. Swanson, B.E. Cherrington, and J.T. Verdeyen, Phys. Fluids 16, 1939 (1973).

Professional Personnel

<u>Name and Title</u>	<u>Percent of Salary</u> <u>Support Budgeted</u>
J. T. Verdeyen, Professor Co-Principal Investigator	10%
B. E. Cherrington, Professor Co-Principal Investigator	10%
D. A. Swanson, Research Associate	100% (up to November 1975)
H. Honickman, Research Assistant	50%

Publications

1. J. T. Verdeyen, D. A. Swanson, B. E. Cherrington, and W. L. Johnson, "The use of electronic space charge to accelerate, focus, and bunch ions for pellet fusion," Appl. Phys. letters 27 380 (1975).
2. B. E. Cherrington, D. A. Swanson, and J. T. Verdeyen, "Potential Distributions due to Electron and Ion Injection in a Spherical Inertial Electrostatic Plasma Confinement Device," Bull. Am. Phys. Soc. 20 1302 (1975).
3. H. Honickman, B. E. Cherrington, and J. T. Verdeyen, "Dynamics of Potential Well Formation in an Inertial Electrostatic Plasma Confinement Device," Bull. Am. Phys. Soc. 20 1302 (1975).