Numerical simulations of positively-biased probes and dielectric-conductor disks in a plasma

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(Received 2 July 1984; accepted for publication 23 August 1984)

A cylindrical particle-in-cell (PIC) plasma simulation code applicable to plasma densities encountered in low earth orbit has been refined. The basic configuration simulated consists of a conductor, partially covered with dielectric material, placed upon a conducting ground plate. The plasma is Maxwellian for both ions and electrons at large distances. Current-versus-voltage curves have been computed by following in time a randomly loaded initial system in which the conductor was held at a specific voltage. The resulting time stationary state is identified as the solution of the boundary value problem. These results have been compared to experimental values showing quantitatively correct behavior. Techniques allowing the simulation of dielectric charging using PIC time scales are discussed. A method of simulating large ion-to-electron mass ratios by moving the ions once every n time steps, where n is the square root of the desired mass ratio, has been developed. Enhanced diagnostics have allowed a more detailed study of the plasma behavior near the conductor (hole) and dielectric.

INTRODUCTION

The plasma densities present in low earth orbit range from about 10^4 – 10^6 particles/cm³. These high plasma densities may be sufficient to cause spacecraft operating at high voltages in this environment to collect large plasma coupling currents.¹ In particular, large high-voltage solar-cell arrays exposed to the low earth orbit environment could collect enough parasitic current from the ambient plasma to degrade their performance. In addition, exposed dielectric material can develop large differential potentials. Punctures in insulators covering conductors have been observed to collect currents much larger than would be expected on the basis of the area of the exposed conductor.²

This paper presents the results of a continuing effort to develop a particle-in-cell (PIC), cylindrically-symmetric, 2-1/2 dimensional, self-consistent numerical simulation code. The simulation is intended to explore the interactions of an ambient plasma with a conducting disk, which may be partially covered by a dielectric material. The disk and the surrounding dielectric material represent a hole in an insulator covering a conductor. The background plasma parameters are chosen to resemble conditions of low earth orbit. Since all particles trajectories are known, any process which can be modeled statistically for a single plasma particle can be included by the simulation code. Plasma interactions currently considered include the effects of charge collection on the dielectric and secondary electron emission. The simulation region includes a ground plate on which the disk or disk and dielectric are mounted. The resulting configuration closely matches the experiments.³

This combination of geometry and plasma parameters incorporates the basic physics of the interactions which would be present between a high-voltage solar-cell array and the plasma environment. Yet, unlike the solar array, the geometry is simple enough to be handled by a particle-pushing code. Although a ratio of ion-to-electron mass of 1:1 is commonly used, mass ratios of 100:1 or higher can be used. This

allows the simulation of negative voltages applied to the central conductor. Thus, information gained from an analysis of the disk and dielectric configuration will be directly applicable to the design of large-scale, high-voltage solar-cell arrays, designed to be placed in low earth orbit.

REVIEW OF THE SIMULATION MODEL

The plasma simulation code is a further development of the 2-1/2 dimensional program described previously.⁴⁻⁷ The cylindrical simulation region is divided into a numerical grid which is used to calculate the potentials and fields of the problem. The calculational grid is shown in Fig. 1. Each cell represents a ring of space due to rotational symmetry about the Z axis (boundary region 1). Boundary regions 2 and 3 represent the outer boundaries of the calculation. The outer boundaries are assumed to be removed far enough from the

FIG. 1. Schematic view of the calculational grid showing one macroparticle and the various boundary regions.

conducting disk so that potentials imposed upon the disk do not affect the boundaries. Thus, the plasma is maxwellian at the outer boundaries and the potential is set to zero. Particles are added to the simulation along boundaries 3 and 4 according to the value of the random thermal current. Particles are lost from the simulation whenever their orbits cross one of these two boundaries. Boundary region 4 represents the ground plate. The potential on boundary region 4 is set to zero and all particles intersecting this boundary are absorbed. The surface of the dielectric covering part of the conductor is represented by boundary region 5 (may have zero length). All particles striking boundary region 5 are also absorbed. Electrons striking the dielectric may emit secondaries. The ratio of secondary electron current to primary electron current is determined by fits to experimental data presented by Haffner,⁸ and is given by the expression

$$\frac{J'_e(V)}{J_e(V)} = K(e^{-aV} - e^{-bV}). \quad (1)$$

For kapton the values of K , a , and b are 3.5, 2.0, and 15.0, respectively. The potential on the surface of the dielectric is determined by the following equation:

$$\Phi(\delta) = \frac{\delta}{\epsilon} \left[4\pi\sigma + \frac{\epsilon}{\delta} \Phi(0) \right] + \delta \Phi(\Delta z), \quad (2)$$

where δ is the thickness of the dielectric, ϵ is the dielectric constant, σ is the charge per unit area, $\Phi(0)$ is the potential of the conducting disk, and $\Phi(\Delta z)$ is the potential one grid cell above the conducting disk. This is just an infinite capacitor approximation which may not be valid near the edges of the dielectric surface. Boundary region 6 represents the exposed portion of the conducting disk which can be set at a desired potential with respect to the zero potential of the plasma exterior to the simulation region. Particles which enter boundary region 6 are absorbed and form the current drawn by the conductor from the plasma.

The simulation code is based upon standard PIC simulation techniques¹³ whenever possible. The initial particles are randomly added to the simulated space with velocities chosen from a maxwellian distribution. This represents a nonequilibrium situation unless a potential of zero is specified on the conductor. The equations of motion are integrated using a second-order leap-frog method. To avoid the singularity present in the cylindrical equations of motion as r approaches zero, cartesian coordinates are used to compute particle movement. The coordinates are converted back into the cylindrical form when the move is completed. The particle mover advances particles through the simulation in increments of the time step value. The time step value is set such that the fastest particles move less than 1 grid cell per time step (about 10^{-9} sec). Particles are added at the outer boundaries from the surrounding undisturbed plasma (assumed to have a maxwellian velocity distribution, usually of $10\,000^\circ\text{K}$, about 1 eV). All particles present which have entered any of the sink regions are discarded. The remaining particle charges are spread over the grid using volume weighting over the nearest grid cells. Successive overrelaxation with odd-even stepping is used to solve Poisson's equation—yielding a self-consistent calculation of the electrostatic potential. The electric field can then be calculated by

differentiating the potential. The simulation code has been shown to be able to simulate a free plasma for a large number of time steps without undergoing any nonphysical instabilities.

This simulation program is applicable when the plasma Debye length is of about the same order of magnitude as the disk radius. Large plasma densities would cause large fluctuations in the collected current, since this calculation makes use of a small number of particles. The PIC assumptions made also imply that the Debye length is larger than one grid cell. With these restrictions and probe sizes ranging from 1.75 to 10.0 cm in radius and with electron and ion temperatures of about 1 eV, plasma densities are then about 10 000 particles per cubic centimeter. This corresponds to environments encountered in the upper ionosphere or low earth orbit. The Debye length under these conditions is about 5 cm.

PLAIN DISK CALCULATIONS

Approach to equilibrium

The plain disk or electrostatic probe configuration is the simplest configuration simulated. The rapid approach to equilibrium is demonstrated in Fig. 2. Voltage-versus-current density curves drawn by the disk are shown for simulation runs of various durations. The value for the current can be seen to achieve an equilibrium state after 2000 time steps of the simulation have been completed. Since only two or three thousand time steps need to be taken, a large number of runs may be made for the disk only case using a relatively small amount of computer time (1 min on the CRAY I, and 36 min for the VAX 11/750 with a 4000 time step run). Thus the plain disk simulations can be used to explore a wide range of plasma parameters and establish areas of applicability for the more complex disk and dielectric simulations.

Comparison with experiment

Much of the simulation effort has been to match results from an investigation of the plasma coupling currents performed in the NASA Lewis Research Center geomagnetic substorm simulation facility.³ All tests were conducted using a nitrogen plasma in the dark with samples at room temperature. The disk-only part of this experiment consisted of a plain stainless steel disk (3.5 cm in diam by 0.1 cm thick) mounted upon an aluminum ground plate. Plasma temperature and density were measured with langmuir probes which are believed to be accurate within a factor of 2. The tempera-

FIG. 2. Rapid approach to equilibrium. Current-voltage curves at four different times are shown for the disk-only simulation.

ture was maintained at about $10\,000^\circ\text{K}$ ($\sim 1\text{ eV}$). The plasma coupling currents were then measured for positive and negative voltages for plasma densities of 2000 and 20 000 particles/cm³. During this time the plasma potential was found to be about 8 V. The calculated current density-voltage or the current-voltage curves may be directly compared to the experimental curves.

The comparison with experiment is displayed in Fig. 3. The experimental current-voltage curve is shown for a plasma density of 20 000 particles per cubic centimeter. The experimental curve has been corrected by -8 V so that voltages in both the simulation and the experiment will be referenced to the plasma potential, and not to the vacuum chamber wall. The experimental plasma densities are known only to the accuracy of a Langmuir probe (factor of 2). In spite of experimental uncertainties and statistical errors of the simulations, the experiment and calculated values of the collected current versus voltage are in good agreement. Also shown are the results of the NASCAP/LEO calculations.⁹ The agreement between the NASCAP/LEO predictions and experiment is good, although higher plasma coupling currents are predicted than those of the present simulation.

The negative voltage experimental curve can also be compared to the positive voltage simulation results. The current collected by the positive voltage simulations is scaled by the square root of the mass ratio (for a nitrogen plasma the scale factor is 160) to produce the expected results of a negative voltage run. The agreement between simulation and experiment is not as good as for the positive voltages. The simulation collects about 1/2 of the current of the experiment throughout the voltage range. This is within the experimental uncertainties and simulation statistical error. However, unlike the positive voltage case, the mean values of the collected current do not agree. This indicates that current scaling by the square root of the mass ratio for negative voltages (large ion to electron mass ratios) is only approximate.

Simulation of mass ratios greater than 1:1

For the disk-only configuration, the current collected by the positive voltage calculation can be scaled to the expected current that would be seen in a negative voltage simu-

FIG. 3. Current-voltage characteristic curve for positive voltages, compare to the experimental curve and that calculated using the NASCAP/LEO code.

lation. For the disk and dielectric configuration the current scaling to negative voltages is inappropriate due to the presence of a dielectric surface which will charge differently in the two voltage ranges. The charging of the dielectric will also depend upon the ratio between the ion and electron mass. With a 1:1 mass ratio, the dielectric surface, when exposed to the plasma, will not charge, in spite of the fact that the increased mobility of the electrons should charge the surface of the dielectric negatively. In order to be able to realistically simulate dielectric charging effects and negative voltages for the disk and dielectric configuration, it is necessary to relax the PIC requirement of 1:1 mass ratios.

The disk-only configuration provides an excellent test of the computational methods developed to handle larger mass ratios. This configuration is simple and gives simulation results with a minimum of computer time. The expected collected current for each mass ratio can be found by simply scaling the positive voltage result to the negative voltage simulation value. The diagnostics furnished are excellent.

The usual way to handle larger mass ratios is to simply give the ions a larger mass value. This method has several disadvantages. Since the simulation procedure is not affected, it takes the same CPU time per time step to simulate larger mass ratios as it would to simulate a 1:1 mass ratio. The distance each ion would move per time step decreases with the increasing value of the mass ratio. Thus, for reasonable mass ratios (hydrogen plasma, 1836:1), the simulation would have to be run many times longer (at the same relative speed) to come to equilibrium. Also the ion motion per time step might become so small as to be dominated by roundoff error. This generally limits PIC simulations to various small values of the mass ratio. From these results, speculations are made as to the effect of realistic mass ratios.

Another method to simulate large mass ratios can be developed. The relatively slow movement of the ions per time step indicates that it is a wasted effort to move them every time step. Instead, ions can be moved once every n time steps, where $n = (m_i/m_e)^{0.5}$. The combined effects of substituting $m_i = n^2 m_e$ and $\Delta t' = n \Delta t$ just cancel in the equations of motion. The particle's energy remains constant since the ion velocity is proportional to the square root of the inverse of its mass ratio. Thus, mass ratios of $n^2:1$ can be simulated simply by moving the ions only once every n time steps.

Results obtained by using the direct and indirect methods to simulate large mass ratios have no effect on the current collected by the disk for positive voltages. The collected current is dominated by electrons; any difference in the ion mass is not seen. The best test of the larger mass ratio simulation methods is the simulation of negative voltages on the conductor. In this case the ions dominate the current and the electrons are excluded from the conductor. Results of simulations using several different mass ratios by both methods are shown in Fig. 4. The expected current which would be collected by the conductor decreases with increasing mass ratios. The general shape of the current-voltage curve remains intact for both approximations down to mass ratios of 4:1. For mass ratios of 100:1, the straightforward method of computing mass ratio effects using a larger mass value begins to collect more current than the simulations which move the

FIG. 4. Current-voltage characteristic curve for negative voltages for varying ION mass ratios. Both the RATMAS and IONMOV methods are used to calculate the ION mass ratio results.

ions once per every 10 time steps. When a mass ratio of 1849:1 is attempted, by moving the ions once per 43 time steps, the current-voltage curve begins to bend over. This could be a lack of statistics (30 000 time steps result in only 700 ion movements) or possibly the assumption of constant electric fields over the 100 time step interval is beginning to break down.

THE DISK AND DIELECTRIC CONFIGURATION

The approach to equilibrium

The final equilibrium situation of the disk and dielectric is more difficult to identify than that of the plain disk. The capacitance inherent in the dielectric causes the response time for charging to be large compared with the plasma frequency. Typically the dielectric may slowly charge or discharge during the simulation run, imitating an equilibrium situation in the steadiness of the current values obtained. In practice it has been difficult to run current-voltage points long enough to arrive at an equilibrium value. Techniques have been developed to make the calculation come into an equilibrium state in a reasonable number of time steps.

The first method implemented to speed the approach to equilibrium was to charge the dielectric to an artificially low potential at the beginning of a run. A judicious choice of the initial amount of charging would speed the approach to equilibrium for low voltages (< 100 V). For higher voltages this method proved to be ineffective and a second method was developed. The second method introduced artificially high values for δ/ϵ [see Eq. (2)]. The physical effects of increasing δ/ϵ can be thought of in one of following ways:

- (1) a decrease in the capacitance associated with the dielectric;
- (2) an introduction of an artificial dielectric thickness; and
- (3) artificially increasing the charge collected by the dielectric.

This method is very effective in speeding the approach to equilibrium, as long as δ/ϵ is chosen with care. In practice, the value of δ/ϵ must be kept small enough that the change in

the potential on the dielectric surface per particle impact is only a small fraction of the potential applied to the conductor (1%).

Sheath formation

The formation of the electron sheath occurs in much the same manner as in the disk-only configuration. The average potential is shown in Fig. 5 for the 100-V run, and is displayed as a contour plot. The plasma sheath structure is identified on the contour plot as follows:

(1) Undisturbed plasma—grid cells containing plasma which are not affected by the potential present on the conductor are identified by vertical lines through the region. The plasma is considered undisturbed if the absolute value of the potential in the grid cell is less than $1/10$ of the electron thermal energy. The exact position of the boundary between undisturbed and disturbed plasma is somewhat arbitrary and subject to fluctuations. These grid cells contain plasma particles whose motions are dominated by the thermal energy.

(2) The presheath region—grid cells which have potential values less than the electron thermal energy but greater than that of an undisturbed plasma are not marked. Thus, the presheath appears as a clear area on the contour plot between the undisturbed plasma grid cells and the sheath grid cells. In this region the potential due to the conductor or space charge is about the same order of magnitude as the thermal energy.

(3) The sheath region—grid cells which have potential values greater than the electron thermal energy are marked by slanted lines through the region. In this region the potential of the conductor and space-charge effects dominate the motions of the plasma.

The contours bounding the sheath and the region of undisturbed plasma are also displayed.

Figures 5 and 6 show the average potential for the 100- and 500-V simulation runs. In both cases the presheath region shows evidence of extending past the grid boundary. This indicates that the potential boundary value of zero, par-

FIG. 5. Contour plot showing the structure of the plasma sheath for an average potential with 100 V applied to the conductor.

ticularly on the top boundary, may be forcing the potential to approach zero faster than that predicted by the self-consistent solution. However, the potential which would otherwise be present on the boundary is of less importance than the thermal energy in controlling the motions of the plasma. Previous results have shown that as long as the sheath boundary is well within the simulation grid, the current collected by the exposed conductor is not very sensitive to restrictions in the size of the presheath region.

The evolution of the sheath surface with increasing voltage is shown by comparisons of Figs. 5 and 6. The sheath region begins to include the dielectric surface next to the exposed conductor in the 100-V simulation (Fig. 5). The sheath is about 12 grid cells (11 cm) in the Z direction.

With 500 V applied to the conductor, the sheath region, in this case, covers the entire dielectric surface and some of the lower boundary as well, as shown by Fig. 6. The extent of the 500-V sheath in the Z direction is about 40 grid cells (35 cm). Comparison of the 500-V simulations, computed by the CRAY I and the VAX 11/750 machines, shows the boundary of the sheath region to be determined with an uncertainty of about 1 grid cell, indicating that this surface is well defined. The area of the sheath for the 500-V simulation is about 10 times larger than the area of the 100-V simulation. The same relationship exists between the total currents collected by the exposed conductor. When an electron crosses the sheath boundary, its orbit becomes dominated by the potential of the conductor, usually becoming part of the current drawn from the plasma. Thus the current collected by the exposed conductor is proportional to the area of the sheath.

Parametric studies: Snapover (secondary electron emission variations)

The effect of variations in σ_m , the maximum number of electrons scattered from the dielectric surface per incoming primary electron, on the current-voltage curves is shown in Fig. 7. The voltage of the onset for the increase in collected current, with reference to the plain disk, decreases with in-

FIG. 6. Contour plot showing the structure of the plasma sheath for an average potential with 500 V applied to the conductor.

FIG. 7. Current-voltage characteristic curves for positive voltages using 10×10 disk and dielectric simulations with variations in the maximum number of emitted secondary electrons for an incident primary electron (SYIELD).

creasing σ_m . The increase in σ_m lowers the energy of the first crossover for secondary emission. Also, the number of secondaries released per incoming primary particles increases. Both effects create more secondary emission than would normally be found. The sensitivity of the calculation to the secondary electron production might be sufficient to allow the measurement of the yield curve parameters for low voltages by fitting the response to experimental data.

A detailed examination of the potential present along the top of the dielectric during a simulation run which collected more current than that of the plain disk reveals what is happening. The initial condition shown in Fig. 8 is fully

FIG. 8. Snapshots taken of the potential at four different times showing the onset of the snapover phenomenon for a 100-V simulation with SYIELD set to 7.

charged dielectric; the potential on the dielectric surface is zero. This would be realistic if the voltage on the conductor were increased slowly from a value initially low enough that the dielectric surface became fully charged. As the simulation proceeds, the potential on the dielectric remains unstable, but positive for the first 6000 time steps. After the equilibrium situation is reached, the potential remains constant to the termination of the run after 20 000 time steps. The equilibrium potential over the dielectric is uniformly positive and decreasing in value from the voltage on the exposed conductor to near zero at the outside edge of the dielectric. The potentials behave as if they have snapped over from their normal zero level. This resembles the snapover phenomenon observed in experiments with solar-cell arrays.³ The potential on the cover slips of the array increased from values near zero, below 100 V, to values of about 50 V less than that of the interconnects for voltages greater than about 200 V.

Comparison with experiment and other simulations

The computed current-voltage curves for the disk and dielectric configuration are shown in Fig. 9 for a dielectric radius of 8.75 cm and an exposed conductor of 1.75 cm in radius. The simulation with a mass ratio of 1:1 collects the same amount of current as the plain disk (the size of the exposed conductor is the same) for low voltages. As the voltage on the conductor is raised, a point is reached where the current collected by the disk surrounded with dielectric material increases compared to that of the plain disk. This increase in collected current is due to the presence of the dielectric and occurs when the dielectric begins to come to an equilibrium with positive potentials near the conducting disk. The dielectric will charge to positive values when the average number of secondaries released by the impacting primary macroelectrons is greater than one. The point at which this occurs is determined by details of the energy spectrum of the primary particles. The calculated current-voltage characteristic curve shows a current enhancement be-

ginning at a lower voltage than that found in the experiment.³ The magnitude of the increase in current is also not as great as that observed by the experiment.

Also shown in Fig. 9 are calculated current-voltage curves for ion-to-electron mass ratios of 4:1 and 100:1. The larger mass ratios allow the surface of the dielectric to charge to negative potential values. The negative voltages present on the dielectric surface reduce the collection of electrons for low voltages. As the voltage on the conductor is increased, the surface of the dielectric begins to become positive, as in the 1:1 mass ratio case. From this point on, the current remains almost unaffected by the ion to electron mass ratio. These current-voltage curves show qualitatively correct behavior using the boundary conditions matching the experiment.

Figure 10 displays the equilibrium voltages in the plane of the disk for simulations of 100 and 500 V applied to the conductor. Also shown are the voltage profiles measured in the experiment. The 100-V curve indicates that the surface is beginning to charge positively at voltages lower than the experiment. The curve for 500 V applied to the conductor shows the potential on the dielectric surface to decrease more rapidly for high voltages than the experiment. These results indicate that the amount of secondary electron emission predicted by the simulation is too high for low voltages and too low for high voltages. This is thought to be the major source of the differences between the calculated and the experimental current-voltage curves.

The comparison of the current-voltage curves computed with the present simulation and other simulations is shown in Fig. 11. As in the disk-only configuration, the NASCAP/LEO code predicts slightly larger currents⁹ than the present simulation. Otherwise, the results of NASCAP/LEO and the present simulation are in good agreement. This indicates that the analytical approximations used to calculate the sheath boundaries in the NASCAP/LEO code are very good. The present simulation incorporates only the effects of secondary electron emission and charge sticking for the interactions between the dielectric surface and the plas-

FIG. 9. Current-voltage characteristic curves for the disk and dielectric configuration. Results are shown for ion to electron mass ratios of 1:1, 4:1, and 100:1. The current-voltage response curve for the plain disk simulation and that of the NASA/LEWIS disk and dielectric experiment is also displayed.

FIG. 10. Calculated voltage profiles in the plane of the disk corresponding to 100 and 500 V applied to the conductor. The experimental profiles are also shown. The radius of the dielectric in the experiment was 10 cm, for the simulation it is only 8.75 cm.

FIG. 11. Current-voltage characteristic curves for the disk and dielectric configuration compared to results of other simulations and experiment.

ma. The NASCAP/LEO code considers the effects of charge sticking, secondary emission, leakage current on the dielectric, backscattered electrons, and other effects. It's clear that the effects of secondary electron emission dominate the behavior of the disk and dielectric configuration for these voltages. Also shown is the current-voltage curve computed using the code ESP.¹² The ESP results show the collection of too much current for the voltage range shown. The ESP simulation did not include a ground plate and did not include a conductor under the dielectric. All of the above calculations did not allow the surface of the dielectric to charge negatively. Hence, agreement with experiment is poor for the lower voltages. For cases in which the dielectric is allowed to charge negatively (large mass ratios), both NASCAP/LEO and the present simulation results indicate that the current collected by the exposed conductor approaches the experimental values for low voltages.

The "pinhole" effect

The "pinhole" effect is the collection of electron current by conductors surrounded by dielectric material in excess of the current which would be collected by a similar sized conductor not surrounded by a dielectric. There are at least two possible mechanisms to explain the increase in current. The first mechanism is electron trajectory focusing as the potential of the conductor spreads onto the dielectric surface. The second mechanism is the increase in current to the conductor due to charge hopping along the dielectric surface by secondary emission. The current enhancement due to secondaries is shown in Fig. 12. The current collected by the disk-only configuration is compared to the total current collected by the disk and dielectric configuration and the current due exclusively to the collection of primary particles. The primary current for the 500-V point may be slightly lower than the actual value due to the restriction in size of the presheath area (see Fig. 6). These results show that for voltages just over the first crossover point, the effects of charge focusing and secondary electron emission are about equal. For higher voltages, the increase in current due to collection of secondary particles is the dominant mechanism.

FIG. 12. Current enhancement for the disk and dielectric configuration due to the collection of secondary-emitted particles.

SUMMARY OF SIGNIFICANT RESULTS

The purpose of the present investigation has been to develop and test a set of simulation routines which are able to closely match the tank experiments.³ The comparison of the calculated current-voltage curves with experiment has been used to upgrade the simulation model. The improved program structure has allowed the simulation of the disk-only and disk and dielectric portions of the experiment on either of the VAX 11/750 or the CRAY I computers using the same set of routines. This in turn has allowed the overall consistency of the code to be improved. The addition of enhanced diagnostic output has resulted in the extraction of more physical principles. The significant simulation results include the following:

- (1) The quantitative agreement between the calculated and experimental current-voltage curves for the disk-only configuration.
- (2) Calculations using large ion to electron mass ratios are possible by restricting both the grid size particle number and simulating the mass ratio effects by moving the ions once for every n time steps. The square root of the desired ion-to-electron mass ratio determines the value of n .
- (3) Techniques which allow the simulation of dielectric charging using the PIC time scales have been refined.
- (4) Heuristic explanations for the behavior of the disk and dielectric configuration have been put forward. The snapover, pinhole, and area effects are shown to depend primarily upon secondary electron emission occurring on the dielectric surface.
- (5) Results of the present simulation and NASCAP/LEO are in agreement for the disk and dielectric configuration. This supports the approximations adopted by the NASCAP/LEO code. The explanations of the snapover and other effects made using the NASCAP code⁹⁻¹¹ are similar to those found in the present simulation.

Further computational effort is required to extend the range of the disk and dielectric simulations to higher voltages and larger mass ratios. Adjusting the dielectric properties which govern secondary electron emission should be sufficient to obtain quantitative agreement with experiment.

CONCLUSIONS

The quantitative agreement between the computed and experimental current-voltage curves indicates that the present simulation is realistically reproducing the plasma interactions. Although much physics has been learned from the study of the disk and dielectric configuration, problems still exist in simulating the interactions of the dielectric. Changes in the simulated secondary emission yield curve are necessary to obtain quantitative results for the disk and dielectric current-voltage curves. The general behavior of the disk and dielectric configuration with positive voltages applied to the conductor can be understood using the results of either the present simulation or NASCAP/LEO. The present simulation's detailed computation of the plasma coupling currents to the 2-1/2 dimensional disk and dielectric configuration are well suited for research purposes. Production runs involving complex surfaces and large areas can be analyzed using the NASCAP/LEO code.

ACKNOWLEDGMENTS

The authors wish to thank Dr. J. H. Nonnast for his helpful suggestions and assistance, and M. Allen for important technical assistance. Invaluable run time on a CRAY-I computer was provided by United Telecom's Computer Service Group, Kansas City, Missouri. This work was supported in part by NASA Lewis Research Center, Research

Grant No. NSG-3290.

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