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SNOW – A Digital Computer Program for the Simulation of Ion Beam Devices

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SNOW - A DIGITAL COMPUTER PROGRAM FOR THE SIMULATION OF ION BEAM DEVICES

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ABSTRACT

A digital computer program, SNOW, has been developed for the simulation of dense ion beams. The program simulates the plasma expansion cup (but not the plasma source itself), the acceleration region, and a drift space with neutralization if desired. The ion beam is simulated by computing representative trajectories through the device. The potentials are simulated on a large rectangular matrix array which is solved by iterative techniques. Poisson's equation is solved at each point within the configuration using space-charge densities computed from the ion trajectories combined with background electron and/or ion distributions. The simulation methods are described in some detail along with examples of both axially-symmetric and rectangular beams. A detailed description of the input data is presented.

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I. INTRODUCTION

This report will describe a digital computer program SNOW (Simulation of Neutron Operating Ware) developed for the simulation of moderate energy ion beam accelerators and tubes. The program is an extension of a program¹ (SNEER) described earlier for the simulation of beams and lenses with the addition of a plasma filled injection region. Relaxation techniques are employed to simulate the Poisson and Poisson-Vlasov equations including the plasma source expansion cup and drift space plasma if desired. Results obtained for several accelerators and tubes have been in remarkable agreement with experimental results, frequently within 10 percent of current and expected beam diameters.

Most ion accelerators consist of a plasma source, a plasma expansion cup, from the surface of which the ions are drawn, one or more acceleration stages, and frequently a drift space where the beam space charge may or may not be neutralized.

Typical configurations are shown in Fig. 1. Figure 1(a) is a typical axisymmetric tube or accelerator injector. The plasma is injected at the ion injection plane and expands into the plasma expansion cup. The plasma surface forms approximately at the point where the plasma ion current density equals the Child's law current density required by the accelerating potential. Trajectories reaching this surface are then drawn away by the extractor voltage, usually into a drift space. In the drift space the beam may be neutralized if potentials are maintained to trap electrons.

Figure 1(b) represents either a hollow beam or a two-dimensional strip beam. The plasma injection is similar to the axisymmetric case but it must be remembered that the current injected represents one meter of depth for the strip beam. It should also be noted that the beam neutralization routines will not work for this type of beam (hollow or strip).

The plasma source is usually a collision-dominated plasma which is impractical to simulate and is not included in these calculations. The plasma expansion cup is usually not collision dominated and can be simulated with the Poisson-Vlasov equation. The acceleration region(s) can be simulated with Poisson's equation since any background electrons or ions will be rapidly swept out by the strong electric fields which are present. The drift region can include a specified gas pressure and ionization cross section generating ions which drift radially to the wall, all with an equilibrium background electron distribution.

The method used for the solution of this problem is to alternately compute trajectories (of representative ions) through the device and to use relaxation techniques to determine the potentials. For the ions, the non-relativistic Lorentz force equation is solved in difference form which uses values from a matrix of the potentials within the electrode configuration. The ion space-charge density

Figure 1. Typical axisymmetric (a) and rectangular strip (or hollow axisymmetric) beam (b).

distribution is computed from the trajectories and is stored on a matrix identical in size and shape to the voltage matrix. The potentials are solved in turn by iteratively solving Poisson's equation, expressed in difference form, using the space-charge density distribution computed from the trajectories combined with appropriate background electron (or ion) distributions in plasma regions.

The program is written for the CDC6600-7600 series of computers with somewhat better speed and accuracy obtainable from the larger and faster 7600. Optimum speed is obtained using the Fortran Extended compiler. Execution time can vary from three minutes for a small-voltage matrix (40 x 80 points) and a low number of particle trajectories (20) to several hours for a larger-voltage matrix (100 x 200 points) and a large number of representative trajectories (5000).

Included in this report will be a description of the theory and the techniques employed in the solution of the problem. A detailed description of the input data will be presented to enable one with modest familiarity with ion beams, plasma sources, and computers to use the program. Sample data sets will also be presented.

II. DEVELOPMENT OF THE COMPUTER PROGRAM

The method employed in the analysis developed here is basically the same as that of earlier analysis;^{1,2,3} the advantages lie in the fundamental techniques used. Added to these programs are liberal amounts of techniques developed by others,^{4,5,6,7} the thievery being here acknowledged. The development of an elementary, iterative solution procedure for the difference equations outlined below permits the realization of a relatively compact program. This in turn permits large matrices and greater accuracy for the computations.

The general flow chart for the digital computer program is shown in Figure 2. The main divisions are seen to be:

1. The reading of data and setting of initial conditions (or restoring of earlier data).
2. The computation of the particle trajectories and space-charge densities.
3. The determination of potentials over the matrix.
4. The printing and saving of results.

Figure 2. Basic Flow Chart For SNOW.

The trajectories are computed by solving the Lorentz force equation

$$\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

in axisymmetric, cylindrical coordinates or two dimensional rectangular coordinates. Space-charge densities are computed from the trajectories by requiring zero divergence of the current density.

The solution of the voltage matrix is accomplished by the most elementary of relaxation techniques, i.e., the iterative solution of Poisson's equation,

$$\nabla^2 V = \frac{-\rho}{\epsilon_0} \quad (2)$$

expressed in difference form, at each matrix point within the electrode configuration.

The Trajectory Computations

It is possible to derive the trajectory computations from the relativistic Lagrangian;¹ but since this is primarily an ion beam simulation program and the ions, in general, do not reach relativistic velocities, the nonrelativistic Lorentz equation will be used. Expressed in terms of the three axisymmetric, cylindrical, scalar equations, this becomes

$$\ddot{z} = -n(E_z - r\dot{\theta}B_r) \quad (3)$$

$$\ddot{r} - r\dot{\theta}^2 = -n(\epsilon_r + r\dot{\theta}B_z) \quad (4)$$

$$\text{and} \quad \frac{d}{dt}(r\dot{\theta}) = nr(\dot{r}B_z - \dot{z}B_r), \quad (5)$$

where n is the charge to mass ratio (e/m).

To get these equations in a form suitable for the computer simulation, the applied magnetic fields are expressed in terms of the magnetic vector potential

$$\vec{B} = \text{curl } \vec{A}. \quad (6)$$

Expanded in axisymmetric coordinates

$$B_z = \left(\frac{1}{r}\right) \frac{\partial(rA_\theta)}{\partial r} \quad (7)$$

$$\text{and} \quad B_r = -\frac{\partial A_\theta}{\partial z}. \quad (8)$$

Substituting these expressions in Eq. (5) gives (with some rearranging)

$$\frac{d}{dt}(r^2\dot{\theta}) = r \frac{d}{dt}(rA_\theta) \quad (9)$$

which can be integrated to give

$$\dot{\theta} = \frac{n}{r} A_\theta + n \frac{r_0}{r^2} A_{\theta_0} \quad (10)$$

where r_0 is the initial radius of the particles and $A_{\theta_0} = A_\theta(r_0)$, the initial flux linking the trajectory. Equation 10 is Busch's theorem expressed in terms of the magnetic vector potential.

Substituting equations 7, 8, and 10 into equations 3 and 4 yields the following expressions for the radial and axial acceleration

$$\ddot{r} = -n \left[E_r + n \left(\frac{r_0}{r} A_{\theta_0} - A_{\theta} \right) \left(\frac{\partial A_{\theta}}{\partial r} + \frac{r_0}{r^2} A_{\theta_0} \right) \right] \quad (11)$$

$$\text{and} \quad \ddot{z} = -n \left[E_z + n \left(\frac{r_0}{r} A_{\theta_0} - A_{\theta} \right) \frac{\partial A_{\theta}}{\partial z} \right] \quad (12)$$

The electric fields E_r and E_z are expressed (to second order) in terms of voltages from the voltage matrix. A_{θ} and its derivatives can be expressed as

$$A_{\theta}(r, z) = \frac{1}{r} \int_0^r r B_z(r, z) dr, \quad (13)$$

which becomes

$$A_{\theta}(r, z) = \frac{r B_z(r, z)}{2} \quad (14)$$

if B_z is a slowly varying function of r , which is usually true near the axis of a solenoid. The derivatives are readily computed by

$$\frac{\partial A_{\theta}}{\partial r} = \frac{B_z(z_k)}{2} = \frac{1}{2} \left(B_i \left(1 - \frac{h_z}{\Delta z} \right) + B_{i+1} \frac{h_z}{\Delta z} \right) \quad (15)$$

and

$$\frac{\partial A_{\theta}}{\partial z} = \left(\frac{B_{i+1} - B_{i-1}}{2 \Delta z} + \frac{(B_{i+1} - 2B_i + B_{i-1}) h_z}{(\Delta z)^2} \right) \frac{r_k}{2} \quad (16)$$

where the magnetic field (B) is assumed known at points along the V matrix (see below) and h_z is the distance between column i and the z_k coordinate of the electron trajectory.

The electric fields can also be represented by difference formulas, employing voltages from the V matrix. Including second-order terms gives

$$\begin{aligned} E_r &= - \frac{\partial V}{\partial r} \\ &\approx - \frac{V_{i,j+1} - V_{i,j-1}}{2 \Delta r} - \frac{V_{i,j+1} - 2V_{i,j} + V_{i,j-1}}{(\Delta r)^2} h_r \end{aligned} \quad (17)$$

and

$$E_z = - \frac{\partial V}{\partial r} \cong - \frac{V_{i+1,j} - V_{i-1,j}}{2(\Delta z)} - \frac{V_{i+1,j} - 2V_{i,j} + V_{i-1,j}}{(\Delta z)^2} h_z \quad (18)$$

where h_z and h_r are the distances between i and z_k and j and r_k , respectively.

Setting $\bar{r}$ equal to a_r and $\bar{z}$ equal to a_z , Eq. 11 and 12 become in difference form

$$z_{k+1} = 2z_k - z_{k-1} - n(\Delta t)^2 a_r \quad (19)$$

$$r_{k+1} = 2r_k - r_{k-1} - n(\Delta t)^2 a_r \quad (20)$$

where Δt is the time increment between the points (r_k, z_k) and (r_{k+1}, z_{k+1}) along the trajectory.

For rectangular configurations, it is only necessary that the applied magnetic field be zero in Eq. 11 and 12.

The Potential Computations

The potentials are solved by Poisson's equation expressed in axisymmetric, cylindrical coordinates:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) + \frac{\partial^2 V}{\partial z^2} = - \frac{\rho}{\epsilon_0} \quad (21)$$

where derivatives with respect to θ are eliminated due to the symmetry.

Expanding this equation using the usual difference approximations becomes

$$\frac{V_{i,j+1} - 2V_{i,j} + V_{i,j-1}}{(\Delta r)^2} + \frac{1}{r_j} \frac{V_{i,j+1} - V_{i,j-1}}{2\Delta r} + \frac{V_{i+1,j} - 2V_{i,j} + V_{i-1,j}}{(\Delta z)^2} = \frac{-\rho}{\epsilon_0} \quad (22)$$

where i, j , r , z , and r_j are as defined in Fig. 3. Solving Eq. 22 for $V_{i,j}$ assuming $\Delta r = \Delta z$ (a matrix of squares);

$$V_{i,j} = \frac{V_{i+1,j} + V_{i-1,j} + V_{i,j+1} + V_{i,j-1}}{4} + \frac{\Delta r}{8r_j} (V_{i,j+1} - V_{i,j-1}) + c_{i,j} \quad (23)$$

where

$$c_{i,j} = \frac{(\Delta r)^2 \rho}{4\epsilon_0} \quad (24)$$

On the axis it can be shown that

$$V_{i,j} = \frac{4V_{i,j+1} + V_{i+1,j} + V_{i-1,j} + 2}{6} + \frac{2}{3} c_{i,j} \quad (j = 1) \quad (25)$$

$$V_{i,j} = \frac{V_{i-1,j} + V_{i+1,j} + V_{i,j-1} + V_{i,j+1}}{4} + c_{i,j} \quad (26)$$
$$\rho_{i,j} = \frac{(\Delta x)^2 \rho}{4\epsilon_0} \quad (27)$$

However, if one now wishes to solve this problem with the space-charge density (ρ), a function of both ion and electron densities, the problem is much more complex.

If the electrons are assumed to be in a Boltzman distribution

$$\rho_e = \rho_{e0} \exp(-eV/kT_e) \quad (28)$$

where ρ_{e0} and T_e are the electron space-charge density and temperature in the plasma, then

$$\rho = \rho_{ion} + \rho_e \quad (29)$$

becomes a function of the voltage and the solution of Eq. 23 (or Eq. 25) becomes much more difficult.

Equation 23 now takes the form

$$V_{i,j} = \frac{V_{i,j+1} + V_{i,j-1} + V_{i+1,j} + V_{i-1,j}}{4} + \frac{\Delta r}{Br_j} \left(V_{i,j+1} - V_{i,j-1} \right) + \rho_{i,j}(V_{i,j}) \quad (30)$$

where $\rho_{i,j}(V_{i,j})$ now involves ρ_e from Eq. 28. Since this is a highly non-linear function of $V_{i,j}$, it is necessary to find a suitable solution for $V_{i,j}$. The technique used here is to solve the right-hand side of Eq. 30 using the available voltages from the matrix to determine a new value for $V_{i,j}$ on the left-hand side. This new value for $V_{i,j}$ is then fed back through the right-hand side several times. However, this calculation tends to be unstable and it is necessary to damp this feedback by

$$V_{i,j}^{n+1} = \left(V_{i,j}^n - V_{i,j}^{n-1} \right) \beta_V + V_{i,j}^{n-1} \quad (31)$$

where β_V is a number less than or equal to one.

The source plasma region is calculated with β_V values generally between 0.005 and 0.2. The space-charge density in this region consists of two components, the injected ion beam and the background electrons.

$$\rho_{i,j} = \rho_{i,j}^{ion} - \rho_e \exp(-eV_{i,j}/kT_e) \quad (32)$$

The value of ρ_e is selected to be equal to ρ_{ion} at the point of highest injected ion current density. If this occurs on the axis of symmetry, ρ_e is computed automatically by the program. If the peak injected ion current density is not on the axis, CMAX (see Appendix A) must be computed from

$$CMAX = \left[\sum_{n=1}^N \left(\frac{S_n}{SP_n} \right) \right] \exp(V_i/E_T) \quad (33)$$

where V_i is the voltage at the plasma injection plane, E_T the plasma electron temperature, n the number of beams injected at the point of highest injected ion current density, S_n the relative current density at that point and SP_n the relative speed of the injected ions in the n th beam. Also, if any deviation from neutrality is desired at the injection plane, CMAX can be read in as $(1.0 \pm \text{the deviation desired})$.

In the accelerating column, only the primary ion beam is taken into account in the space charge. Any electrons or ions resulting from ionization of the background gas are ignored. All electrons would be swept out by the accelerating field at any reasonable gas pressure and at the low pressures assumed here (a few millitorr); the secondary ions are also assumed negligible. β_V is 1.0 in this region.

In the drift space, the trapped background electrons and the collision generated ions must both be taken into account. The space-charge density term now becomes

$$\rho_{i,j} = \rho_{i,j}^{\text{ion } b} - \rho_{ed} e^{\frac{-e}{kT_d} (V - V_m)} + \frac{1}{r} \int_0^r \frac{\rho_{\text{ion}} n v_b x dx}{\sqrt{2n_i [V(x) - V(r)]^2}}, \quad (34)$$

where the electrons (ρ_{ed}) are assumed to be sitting in a well (with a minimum potential V_m) created by the ion space charge. The collision generated ions are assumed to be drifting to the wall and are taken into account by the last term in the above equation (after Holmes⁷), where n is the background gas number density, σ is the ionization cross section, v_b the ion beam velocity, and n_i the charge to mass ratio of the background gas. The magnitude of ρ_{ed} is selected so that the electron current to the wall equals the secondary ion current generation rate.

Should the ion beam current density be highest at some point other than the center of the beam, a region would be generated inside this diameter which would trap the secondary ions. Should this happen, the program will automatically fill in the ion space-charge density distribution so that there will be no trapping region left. This is most likely to happen in the initial beam formation region of a high density ion beam.

The iterative procedure consists of applying the difference equations at appropriate points within the electrode configuration. The voltage matrix consists of a two-dimensional array as shown in Fig. 3. The first subscript (usually I) begins at the left edge of the matrix and increases axially in the +z direction. The second subscript (usually J) begins at the axis (or bottom edge of the matrix) and increases radially. The relaxation operations are generally carried out starting at the left side of the matrix and passing up each column in sequence across the matrix, and then in the reverse direction across the matrix from right to left.

This method of computing the potentials requires a knowledge of the locations of electrodes and dielectric interfaces relative to the radial columns. This is accomplished by supplying as input data integer matrices the same axial length as the voltage matrix which specify the J coordinates of electrodes and dielectric interfaces. Computations are carried out in each column I from the first matrix J(I,1) to the second matrix J(I,2), then from J(I,3) to J(I,4) up to seven pairs of matrices. These matrix pairs must be in order radially from the axis but do not have to be in sequence. The axis may be included in the computations by specifying appropriate values of J(I,odd) as zero with a finite, non zero upper limit. If both the lower and upper limit are zero, the matrix pair will be skipped. Any finite or infinite offset from the axis may also be specified.

Dielectric surfaces sloping at 45 degrees or less to the axis are specified by setting the upper limit of one of these matrix pairs equal to the lower limit of a succeeding pair, e.g., $J(I,2) = J(I,3)$ or $J(I,2) = J(I,5)$. Surfaces perpendicular or at angles steeper than 45 degrees to the axis are treated separately and will be described below. The techniques employed on the interfaces were derived by Dorny⁸ and are described in some detail in Reference 3. Note also that electrodes sloping at 45 degrees or less to the axis must be at least one matrix square thick or they will be treated as a dielectric surface.

The source plasma must always be between the first and second J matrices, although the ion beam itself (away from the source) may pass between any pair of matrices. The drift space neutralization region must also be between the first pair of matrices and the first matrix must be the axis.

Vlasov's equation for the ions

$$\vec{v} \cdot \nabla f + n \nabla V - \nabla_V f = 0 \quad (35)$$

where $\vec{v}$ is the velocity and f the distribution function which yields

$$n_i = \int f d\vec{v} \quad (36)$$

the ion density distribution. In practice, this problem is solved by actually injecting ions into the plasma and computing the trajectories through the plasma, either to the walls of the expansion cup or into the ion beam.

The ion space-charge density term from equation 23,

$$\rho_{1,j} = \frac{(Lr)^2 J}{4\pi\epsilon_0} \quad (37)$$

must be expressed in terms of the quantities available from the trajectory computation. Expressing the velocity in terms of ds/dt , where s is the trajectory path and the fact that current carried by each particle must remain constant

$$2\pi r_0 \Delta r J_0 = 2\pi r (\Delta r \sin \theta) J \quad (38)$$

where the zero subscripts refer to initial conditions and θ is the angle greater than 45 degrees that the trajectory makes with an axial or radial matrix row or column. Substituting Eq. 38 into Eq. 37, one obtains

$$\rho_{i,j} = \frac{\Delta r^2 \Delta t r_0 J_0}{4 \Delta s \epsilon_0 r \sin \theta} \quad (39)$$

Since the space-charge density at any given point is the sum of all the trajectories passing near the point, the actual terms used by the program are, for a radial line crossing,

$$\rho_{i,j} = \rho_{i,j} + \frac{J_0 \Delta t (1 - R_r) (\Delta r)^2 r_0}{4 \epsilon_0 r \Delta s \sin \theta} \quad (40)$$

and

$$\rho_{i,j+1} = \rho_{i,j+1} + \frac{J_0 \Delta t R_r (\Delta r)^2 r_0}{4 \epsilon_0 r \Delta s \sin \theta} \quad (41)$$

where R_r is the normalized (to Δr) distance from the r -coordinate to the line through j , with similar expressions for an axial line crossing.

The trajectories of the ions are computed with the difference Eq. 11 and Eq. 12. The time increment is varied over the path of the trajectory so that at least one and typically two time increments are needed to cross each matrix square. It is essential that at least one point be computed in each matrix square or serious errors can be generated. Should this occur, the time increment (Δt) must be reduced.

III. USING THE PROGRAM

Results obtained with the program appear to be as good as the effort put into simulating the given configuration, e.g., the accuracy of the results is proportional to the care employed in setting up the problem. Perveance [current/(voltage)^{3/2}] can usually be predicted to within 5 percent as can the beam diameter if the source plasma has a well defined ion velocity distribution and background electron temperature. The current density distribution within the beam tends to produce larger variations, 10 to 50 percent deviation from experimental data, but again better results are usually obtained with greater care in setting up the problem.

The best results (compared with experimental data) are obtained by starting the simulation from the bottom of the plasma expansion cup. The three most important parameters appear to be the total current injected, the angular distribution and the initial velocity(ies). The exact current density distribution across the injection

plane does not appear to be critical and uniform current distributions have frequently been quite adequate.

One of the more important parameters to watch is the number of representative particles employed. For fairly simple source plasmas (not very deep in the plasma) as few as 2 particle trajectories may be sufficient (although more particles would probably produce a smoother, more accurate simulation). However, as the simulation of the plasma becomes more complex (deeper in the plasma, a spread in angular or velocity distribution, more expansion cup geometry) the need for more representative particle trajectories rises rapidly to 1000 or even 10,000. A typical plasma expansion cup used with a one quarter-amp duoplasmatron or duopigatron ion source can usually be adequately simulated with 500 to 1000 trajectories. A simulation of the thermal spread in either velocity or angular distribution will quickly double or triple the required number of particles.

Probably the most sensitive area in the simulation is in the source plasma, and in the plasma the axis of symmetry must be watched most carefully. Most of the earlier axisymmetric simulations¹¹ are flawed (at least partially) by failing to treat the axis with sufficient care. The axis problem can develop when particles cross or pass near the axis. If one or several particles produce too high a space-charge density on the axis, there is a strong tendency to hollow out the beam due to the low voltages produced there. The cure for the problem is to increase the number of particles, from the region where the crossing particles are originating, so that no particle will create too large a space-charge density on the axis. Excess particles will generally be deflected out of the effected region.

Pierce Diode

Figure 4 represents approximately a "Pierce" diode except that the charged particle source is an ideal plasma ion source. A uniform ion current density is injected at the left, it passes through a short plasma (i.e., background electron region) into an approximate Pierce cylindrical diode. If indeed it is true that the plasma surface behaves like a space-charge limited emission source, the beam particles should proceed in straight parallel lines through the acceleration region. Indeed this is found to be very nearly the case when the electron temperature is low, e.g., one eV. However, with an electron temperature of 8 to 10 eV this situation changes significantly.

With a 10 eV electron temperature in the plasma the background electron distribution starts moving out beyond the Child's law surface, this changes the potential significantly in this region. Ultimately the potentials just in front of the Child's law surface rise above the Child's law curve and this in turn raises the potentials behind this surface permitting about 5 percent more current to pass thru the diode. With the higher temperature a small modification of the focusing electrode is needed at the edge of the beam to conform to the new equipotentials within the ion beam.

Figure 4. Ideal Cylindrical Pierce diode.

Target Test Facility (TTF) Accelerator

The TTF,¹⁰ as shown in Fig. 5, consists of a duopigatron ion source with a 12.7 mm diameter expansion cup 15.2 mm deep. A 45 degree focusing electrode surrounds the cup with the accelerating electrode 25.4 mm from the focusing electrode. This accelerator has been tested up to 185 mA at 200 kV. The beam from the device is fairly well focused on a target which can be placed 0.6 m or 1.5 m from the source. There is a relatively low density halo about the beam which strikes a drift tube 63.5 mm in diameter approximately 0.7 m from the source. The neutralization point can be moved from very near the entrance to the drift tube to 50 mm down the tube.

The computer simulation is broken into two parts due to the length of the drift region. The first part includes the plasma expansion cup, the acceleration region and the injection into the neutralized drift region. The second part of the simulation involves a small overlapping section and the remainder of the drift region to the target. Two slightly modified versions of SNOW were prepared to accomplish this.

The changes needed to accomplish the first part are shown by the following update cards.

```
*INJECT, 1004.00
  INUT = 50
  ISAVE = 211
*INJECT, 2004.00
  IF (IX(1).NE.(ISAVE) 50 TO 1977)
  JJ = JX(ISAVE, 0)
  WRITE (1801) N, L, UT, RHOCON, SZERO
  WRITE (1801) CMUV(IQ), RLOC(IQ), R1(IQ), R2(IQ), Z1(IQ), Z2(IQ), NOE(IQ)
  , IQ=1, NOE1
  WRITE (1801) (V(ISAVE, JJ), JJ=1, JJ)
```

Figure 5. Schematic Drawing of Target Test Facility.

The above cards save all the pertinent beam and voltage data at a plane (ISAVE = 211; near the end of the first simulation region. This is ten matrix squares from the end plane to get away from the end effects since it is held at a constant voltage.

The changes needed for the drift region are somewhat more complex and are accomplished by the UPDATE cards on the following page. The data saved from the first part are restored and some of the initial beam set up is bypassed. The variable time incrementing is turned off due to the complexity of transferring all the necessary data. The last third of these cards are the changes needed due to the different form of the input data for the beam.

The input data to the program for the first part of the above are essentially the same as for any ordinary run. However, some additional data (Tape 55) must be saved at the end. On the CDC7600 at SLA this is accomplished by cataloging the permanent file (TAPE55).

The program has the capability of extrapolating the beam data, including the current density distribution, to a target at any specified distance. This is a linear extension of the trajectories in the beam, using the exit plane slope and radius to compute the radius at the target. A comparison of extrapolated and computed drift spaces will be presented on the next two pages.

The normalized ion current densities injected at the bottom of the plasma expansion cup are shown in Fig. 6(a). The current density distribution was the first guess as to what it might look like. The angular distribution required several trials as the current distribution at the top of the cup was adjusted to Bacon's¹⁰ experimental data [Fig. 6(b)]. The deviations of less than five percent are typical and will continue to slowly vary about the experimental values if the program is run for additional cycles.

Ions are injected at an energy of 70 eV and gain about 10 eV passing thru the cup to compare with Bacon's¹⁰ data which peaks near 80 eV. The background electron temperature can be varied from 3 to 6 eV, with minor changes in other parameters, with similar results.

A comparison with experimental data of Bacon¹¹ can be made at the 0.6 m target location. With the neutralization point at 69 mm from the focus electrode, the computer program predicts a 44 mm diameter at a pervance of $2.1 \times 10^{-9} \text{ A/V}^{3/2}$ and a 38 mm diameter at $P = 1.8 \times 10^{-9} \text{ A/V}^{3/2}$, in very good agreement with Bacon's 44 mm and 37 mm diameter. The computer results are shown in Fig. 7 where the importance of computing the entire drift space can be seen compared with extrapolated data. A further comparison with experimental data is made in Fig. 8, where the measured target-current distribution overlaps the computed current density distribution. While there are significant differences in the details, the gross distributions are similar and the diameter is in excellent agreement.

```

*CONT, RUN
*DELETE, CALL, 2, 3
COMMON VC(735,41), JX(735, 8), JB(735), RHO(735,41), RMB(111)
, RI(111), RIM(111), RIP(111), RM(735), RMI(111), JE(735)
, RR1(111), RR2(111), ZZ1(111), ZZ2(111), INOE(111)
*DELETE, CALL, 5, 8
COMMON /TRAJ/ GENI(2500), CODEI(2500), CM(2500), CMSV(2500), RQ(2500)
, RLQ(2500), ZLOC(2500), R1(2500), Z1(2500), R2(2500), Z2(2500),
, INO(2500), JM(2500), ARS(2500), RSTR(2500), NO(2500), AR(2500),
, SPD(2500)
*DELETE, CALL, 1
COMMON RLOC(111), R(111), Z(111), IPT(111), INX(8), INY(8), XYM(40),
*DELETE, CALL, 2, 3
DOVR = 735+41
MONTH = 710
*DELETE, CALL, 2
DOVR = 735+41
*DELETE, CALL, 3
DOVR = 735+41
*DELETE, CALL, 4
DOVR = 735+41
*DELETE, CALL, 5
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*DELETE, CALL, 98
DOVR = 735+41
*DELETE, CALL, 99
DOVR = 735+41
*DELETE, CALL, 100
DOVR = 735+41

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Figure 6. Plasma Expansion cup current injection conditions (a), and current density output (b) compared with experimental current density distribution.

A further comparison can be made with the neutralization point 33 mm from the focusing electrode. In Fig. 9 two experimental target temperature distributions are compared with the computer simulation. If the center spike in the current density, which is caused by minor trajectory changes near the axis, is redistributed over the central 4 mm, the distributions are reasonably similar. Again, the predicted diameter is in good agreement, especially with the slightly higher perveance. The low density halo between $R = 8$ and 10 mm would not be detectable by the infrared television target monitor because the I.R. lower useful limit was over 100°C.

Figure 9. Target current (Temperature) distribution with neutralization point 33 mm from focus electrode.

The electrode configuration and the beam producing the results shown in Fig. 6 are shown in Fig. 10. The improved version of the electrodes is shown in Fig. 11. The diameter of the source plasma expansion cup has been increased by 10% (which results in a 20% area expansion at the top of the cup) reducing the required current density and flattening the plasma emission surface, in combination with a modified focusing electrode as shown in Fig. 11. The improved beam distribution is as shown in Fig. 12 where the beam diameter would now be 34 mm at a perveance of 2.1×10^{-6} A/V^{3/2}.

A Strip Beam

A two dimensional strip beam is shown in Fig. 13. The plasma source parameters are the same as those used by Cooper⁶, et, al., for the simulation of the LBL 10 Amp plasma source, except that the current density in the plasma is 2000 A/m² rather than 5000 A/m². The purpose of this design was to obtain a variable voltage, high current ion beam of about 10 keV energy at the target. Since the Berkeley group has had some problems with their rather fragile accelerating structure it was felt desirable to use more robust electrodes. Larger electrodes require larger spacings and higher voltage if a reasonable portion of the plasma is to be employed.

A double lens system similar to that employed by the Berkeley group was developed on a large scale for operation with 90 kV on the first accelerating electrode. This is followed by two asymmetrical Einzel lenses which simultaneously focus the beam and reduce its final energy to the 10 keV region. The double lens system is needed to maintain beam focusing as the final beam energy is varied. The second lens is degenerate in that the final two electrodes are at the same potential, the ion space-charge density forming an electron trap to neutralize the beam space charge.

The beam at the target has a fairly uniform current density distribution of 3300 A/m², approximately a 1.66:1 compression ratio compared to the source current density of 2000 A/m². The beam current is 16.1 A per meter of depth.

Multiple Strip Beam

A more useful form for the strip beam is shown in Fig. 14. Here three of the five strip beams that could be obtained from a 70 mm wide plasma source are shown. The intent here is to focus the separate beams into a single beam with current densities between 3000 and 15000 A/m² depending on the amount of beam overlap at the target. As shown in Fig. 14 the target current density is 3000 A/m², with the target at 110 mm the density would be 15000 A/m² with all the beams overlapping.

This simulation is done on a 161 x 101 voltage matrix before the device is built the calculations should be repeated on a 321 x 201 (or larger matrix) to smooth out and more accurately simulate the electrodes. The maximum current obtainable will be the order of 80 A per meter of depth or 8 A for a 100 mm deep by 70 mm wide plasma source.

Figure 10. TTF beam and electrodes at 170 kV, 130 ma

Figure 11. Improved Expansion cup and focusing electrode for TTF.

Figure 12. Target current distributions for linearly extrapolated trajectories (solid line) and computed drift spaced (dashed line) for a permeance $2.1 \times 10^{-9} \text{ A/V}^{3/2}$ deuterium beam.

Figure 13. A two dimensional strip beam employing a Berkeley 10 amp ion source.

Figure 14. Three of the five strip beams that could be drawn from a 70 mm wide Berkeley⁶ ion source.

This simulation is included because it effectively has three plasma-beam interfaces plus a neutralized drift space. Neither condition can be handled efficiently by the basic program. The update needed to handle this configuration is shown on the next page.

There are four sections to the update. Section 1 changes matrix sizes and shapes to that required by this data set. This section will be present on most runs if the original deck is not exactly the right shape.

The second group of cards effectively neutralize the space-charge density in the final gap between the last focusing electrode and the target. No convenient theory is available for neutralization in this configuration so the potential is set to the target potential ($0.1111 \times 90,000$ or 10 kV) wherever the beam space-charge would try to lower the potential below 10 kV. If sufficient electrons were not available in the operating device, these could be supplied externally.

The adjustment needed to efficiently handle the three emission surfaces is accomplished by the third group of cards. Two changes are needed, one is accomplished by the delete statement, permitting plasma calculations between pairs of matrices beyond the first pair. IDIV is set equal to 19 to cover the plasma interface for the uppermost beam. This unfortunately would require rather large areas of plasma calculations for the lower two beams where the plasma is not needed. The two IF

statements effectively modify IDIV for the lower two beams so that plasma calculations are minimized. IDIV becomes 10 for the first pair of matrices (L=1) and 13 for the second pair (L=3) of matrices.

The fourth update group adjusts the check printing region so that a sample of the potentials is obtained from each beam. This is useful in judging convergence of the program from one run to the next as relatively small changes in potentials near the plasma surface can cause significant changes in beam properties.

```

*IDENT, RUN
*DELETE, CDALL, 2, 3
COMMON V(161,101), JX(161,10), JB(161), RMD(161,101), RMB(101)
1, RI(1,10), RIM(1,10), RIP(1,10), RM(161), RMI(1,10), JE(161)
*DELETE, CDALL, 6, 8
COMMON /TRAJ/ SINE(1100), COSINE(1100), CM(1100), CMSV(1100), RO(1100)
1, RLDC(1100), PLDC(1100), RI(1100), ZI(1100), R2(1100), Z2(1100),
2 IMC(1100), JMC(1100), ARCC(1100), RSTR(1100), NDC(1100), APC(1100),
3 SPD(1100)
*DELETE, CDVIO, 2, 3
NVR = 1.1E14
MLV1 = 161
*DELETE, CDVIO, 5
NI = 1100
*DELETE, CDW, 457, 439
40 CONTINUE
IF (I .GT. 131) 955, 875
955 V(I,J) = AMAX1(1.111, (VNU-V(I,J))*BETA+V(I,J))
GO TO 877
875 V(I,J) = (VNU-V(I,J))*BETA+V(I,J)
879 CONTINUE
*DELETE, SNOW, 588, 598
1000 CONTINUE
IF (II .GT. 131) 1070, 1070
1070 V(II,JJ) = AMAX1(1.111, (VNU-V(II,JJ))*BETA+V(II,JJ))
GO TO 1090
1090 V(II,JJ) = (VNU-V(II,JJ))*BETA+V(II,JJ)
*INSERT, SNOW, 445
IF (L.EQ. 1 .AND. I .GE. 10) GO TO 830
IF (L.EQ. 3 .AND. I .GE. 13) GO TO 830
*INSERT, SNOW, 543
IF (L.EQ. 1 .AND. II .GE. 10) GO TO 1040
IF (L.EQ. 3 .AND. II .GE. 13) GO TO 1040
*DELETE, SNOW, 1074, 1074
DO 213 J=16,30
213 PRINT 2450, J, (V(I,J), I=1,40)
DO 2131 J=48,53
2131 PRINT 2450, J, (V(I,J), I=1,40)
DO 2132 J=73,90
2132 PRINT 2450, J, (V(I,J), I=1,40)
*DELETE, SNOW, 1061
JU = NR
*COMPILE, SNOW

```

IV. SUMMARY AND CONCLUSIONS

A digital computer program for the simulation of ion beam devices has been shown to be a powerful tool for the accurate simulation of these devices. The program permits the accurate determination of the perveance and beam size and, with somewhat less accuracy, current distributions with the beam.

Some knowledge of the plasma ion source is needed, notably the ion temperature and current distribution and the background electron temperature. The only other input data required is a description of the electrodes and their potentials.

The program is stable, given the proper under-relaxation parameters, with 10 to 100 cycles thru the program required to reach convergence. Results are not dependent on any input parameter and will always reach the same solution; an initially bad guess will either be corrected or will cause divergence of the program solution.

The ultimate aim of this work would be to obtain a general program for the design of any type of ion beam device. It would seem to be practical to obtain a rapid design procedure by employing a large digital computer with a CRT (cathode-ray tube) plotter and on-line controls. The results could be displayed on the CRT and the effects of electrode modifications viewed immediately. It would appear possible for a person knowledgeable in electrodynamics to be able to obtain an accurate design in one to two hours on a CDC7600 computer.

APPENDIX A

The Computer Program (SNOW)

A general flow chart for the program was shown in Fig. 1. A brief description of the internal construction of the program will be presented here along with a detailed description of the input data. An example of a run and a microfiche listing are described in Appendix D.

SNOW is maintained in a form acceptable to the CDC UPDATE processor. This permits quick and easy adjustment of the matrix sizes and shapes to fit the requirements of any particular analysis. All of the matrices and constants effecting the matrices are set in Update COMDECKS, so that it is only necessary to change sizes or shapes in one COMDECK rather than each subroutine.

The efficient execution of the program requires the presetting of the matrix sizes and shapes; all other parameters are specified in the input data. The matrices required fall into three basic groups, the description of the electrode configuration, the computation of trajectories and the plotting of the results. The calculations of the potentials are handled on the V (voltage) matrix using space-charge densities from the RHO matrix. The electrode configuration on the V matrix is described by the JX matrix with radial dielectric interfaces described on the ID matrix. The dimensions of the V and RHO matrices are identical with the first dimension the axial length and the second dimension the radial extent of the matrix. The first JX dimension is again the radial length of the V matrix but the second dimension is 14, or 2 greater than the actual number of matrices required to describe the configuration.

Incidental matrices possessing the same dimensions as these matrices are: the BM (magnetic field distribution), JB and JE all with the same axial length as the V matrix, and RI, RIM, RIP, RHB, and RHI matrices all with the same radial dimensions as the V matrix.

The actual data may use any portion of these matrices but if larger arrays are needed, the program must be recompiled with the larger matrices.

The second group are the matrices, shown here being 250 locations long, which are used in the trajectory computations. These are stored in "TRAJ" Common. As shown in the microfiche listing, these are 250 locations long; if 5000 particles are needed the total number of locations rises to 90,000, requiring indirect addressing on the CDC7600 and cannot be run at all on the CDC6600. Any number of trajectories may be employed up to the limit set by the length of these arrays.

The arrays needed for plotting form the next group of Common. The R and Z arrays are used to store a complete equipotential in the contouring subroutines, 2000 points should be sufficient for a V matrix up to 200 by 100 points. REC should in general be equal to 60 percent of R or Z or 1200 points for an R matrix 2000 points long. IR and IZ hold the integer values of R and Z for the plotting routines and the second dimension of these must be at least the maximum of the R array dimension or the

maximum number of trajectories. The remaining arrays are used internally and generally should not be changed.

The remaining Common statement is transmitting data to the subroutines and generally should not be changed.

The LEVEL 2 statement places most of the arrays and variables in Large Core Memory (LCM) on the CDC 7600 and should be deleted on the CDC 6600.

The constants in the CDV1J comdeck are related to the matrix sizes. MLNTH is the axial length of the voltage matrix and is employed in the plotting routines. NVR is the total number of points in the voltage matrix. NT is the maximum number of trajectories that may be used, i.e., the same length as each array in TRAJ COMMON.

The 'tapes' (real or simulated) are listed on the PROGRAM card. INPUT and OUTPUT are the standard input and output files. TAPE10 is the plotter output file with tapes 51 thru 55 used as intermediate storage for the equipotential plotting routines. If more than six frames are needed for equipotential plots, additional tapes (56, 57, etc.) should be added to this list. TAPE4 is the tape from which data, e.g., the voltage and space charge density matrices, are restored from earlier runs and TAPE5 is where the same data can be saved at the end of a run by use of the M11 parameter (see below).

The first section of the program, up to statement number 730, reads the input data and does the initialization for the main part of the program which follows. The data include the description of the electrode configuration on the voltage matrix, the description of the injected beam and the initial potentials to be set on the electrodes, dielectric interfaces (if needed), and the axis of symmetry. Careful handling of the initial conditions can save significant computing time.

The program will automatically put linear voltage distributions between electrodes and between the axis (if present) and the first radially encountered electrode. Potentials are also set at all points within electrodes to the value at the bottom edge of the electrode.

The relaxation of the potentials is then carried out by two large loops, one that goes forward through the matrix (I and J increasing) and one that goes backward through the matrix (I and J decreasing). This technique permits corrections to propagate equally well in any direction, speeding convergence of the relaxation. Within these large loops are three sections that handle the plasma, acceleration and drift space regions, performing the appropriate calculations in each region.

The particle trajectories are then traced through the device by the next section of the program. During this calculation space-charge densities are computed and stored on the RHO matrix. Also, these data may be printed and/or plotted during the last of these cycles.

After the last of the voltage relaxation-trajectory computation cycles significant exit plane and/or target data are computed and printed. Included are the angle of the trajectory with the axis, the average angle (weighted with the current), the total current out to each trajectory, the radius of the trajectory at the target in mm (at any specified distance from exit plane), radius in scaled units at exit plane, and the long term average current density distribution at the exit plane.

The long-term average current distribution at the exit plane is then printed adjacent to the current distribution on the last cycle either at the exit plane or at the specified target distance. If the target corresponds to the exit plane, the long-term average can be compared to the last cycle as a further estimate of the convergence of the program.

After each cycle thru the program, the target current, the target impedance ($1/VSCALE$) and the target perveance ($1/V^{3/2}$) are printed along with the matrix coordinates for the edge of the beam. Both the beam current and the beam edge should stabilize if the program is well converged.

The last of the data printed are sampling (every fifth column) of the current densities in the plasma expansion cup and the voltages in the rows where the beam is injected. These are printed to be sure no problems have occurred either in the trajectory computation (in the plasma) or in the voltage relaxation in the region of the beam.

On page 63 a complete compilation and execution of SNOW is presented on a microfiche card. The compilation includes a maximum listing of references ($R=3$) for the Fortran Extender compiler. The data are presented in a fairly well converged solution for the sample data set described in Appendix D. This run required 593 seconds on the CDC 7600 Computer.

APPENDIX B
Snow Input Data

The following is a card by card description of the input data needed for SNOW.
Data sheets for making up data will be shown on the following pages.

CARD 1 - FORMAT 1814

1. NM - Major cycles through the program can vary from 5 to 50; 25 would be a typical number.
2. KM - Cycles through the voltage matrix relaxation typically 15 to 50; NM + 5 would be a typical number.
3. NBMAX - Maximum number of changes allowed in the beam matrix at convergence. This should typically be 2, or, -2 to force the maximum number of cycles.
4. NVMAX - Maximum number of changes exceeding EPSV (see below) allowed on the voltage matrix at convergence, typically this value is 2.
5. NZ - Axis length of the voltage matrix to be employed.
6. NR - Radial width of the voltage matrix to be employed.
7. NRO - Radial offset from the axis. Zero if the axis is the bottom edge of the matrix, 9999 for rectangular configurations, and equal to the number of matrix squares from the axis to the bottom of the matrix for finite offsets.
8. MU - Determines whether data is to be saved or restored. One neither saves nor restores data; two restores data only; three both restores and saves data; and four saves data for restarts.
9. NMR - Number of matrices read in to describe the electrode configuration, this number will always be even.
10. ITC - The beginning point of a region along the axis wherein the time increment is divided by 5 in order to improve the accuracy in this region. If this number is not used it should be left zero.
11. ITPL - The matrix point at which the neutralization calculations start, for no beam neutralization this is NZ or 0.
12. IPLOT - This number is 0 for no plots and 1 if plots are desired.
13. ISN - Beam target plane matrix column number if it is not the right edge of the voltage matrix, otherwise 0.
14. IPD - Controls printing of voltage and space-charge density matrices; 1 deletes both, 0 prints both.
15. KDI - The number of the JX matrix describing a dielectric surface where trajectories will or may be intercepted. KDI can be left zero if it is not needed.
16. MPLT - Fore-shortens all plots produced by the factor 1/MPLT, 1 or zero produces no distortion.

17. ITP - If ITP is 0 the trajectories will be printed and if it is 1, they will be deleted.
18. IDIV - Second or third I coordinate in front of expected plasma emission surface along Z direction.

CARD 2 - FORMAT 1414

These are the number of potentials to be set on electrodes on each of the 14 possible matrices. The cards to set the potentials will be described below.

CARD 3 - FORMAT 8E9.2

1. ZZERO - The location of the plasma injection plane in scaled units.
2. VSCALE - The scaling voltage (in volts) of the accelerating column, typically the highest voltage employed. All voltages read in as data or printed out are normalized to this value.
3. ZSCALE - Tube length (in meters) that corresponds to one scaled unit. All data read in or printed out is in scaled units, and this is usually chosen such that printed data is in convenient units, e.g., if ZSCALE = 0.0254 meters, 1.0 unit = 1.0 inch.
4. DZ - The length of one matrix square in scaled units, i.e., if 20 matrix squares = one scaled unit, $DZ = 0.05$.
5. EPSV - The convergence requirement for the voltage matrix calculation; a good value is 1.0×10^{-4} . This is the largest percentage change the can take place between succeeding values of the voltage at any matrix point at convergence.
6. PP - The ratio of the particle mass simulated by the program to that of an electron, e.g. 1.0 would be an electron, 1840.0 a proton. Any value less than 1.0 will automatically be set equal to 1.0.
7. RELAX - The under-relaxation factor for the voltage relaxation. This value can vary from 0.005 to 1.0, depending on the stability of the program. Most accelerator problems require values of 0.05 to 0.2 but simulations from deep in a complicated expansion cup may require values as low as 0.005.
8. EQ - The initial energy (in eV) of the particle at the injection plane. For ions into a plasma typically this could be 10 to 80 eV.

CARD 2 - FORMAT 8E9.2

1. BMAG - The magnetic field strength (in tesla) on the axis. All applied magnetic field data read in (below) must be scaled to this number. If this number is zero, the matrix BM (below) will not be required and all magnetic fields will be zero.
2. BRHO - An under-relaxation factor for the space charge density computation. This is the fraction of the space charge density which will be new after each cycle through the program. For most plasma source calculations, this will be 0.2, but may be smaller or larger depending on the solution stability.

3. ET - The electron temperature in the ion source plasma in eV. This will vary from 1 to 10 eV depending on the type of source.
4. ETI - The electron temperature in the neutralized beam in eV. Typically this is 8 to 10 eV for 100 to 200 kV deuterium beam.
5. CMA_X - The multiplier for the electron density (ρ_e) in the source plasma. For a solid axisymmetric beam this number can be left as zero. If some deviation from neutrality at the injection plane is desired, CMA_X should be $1.0 \pm$ the desired deviation. For non-solid beams this must be computed by the equation 33.
6. DTGT - The distance in scaled units to the target from the right edge of the matrix. This permits the linear extrapolation of the trajectories to the target plane and the calculation of the current density distribution at that plane.
7. SIGMA - Total ionization cross section for the ion beam on the background gas in (cm)².
8. GASM - Mass of background gas in drift tube (M/m₀).

CARD 5. FORMAT BE9.2

1. PNG - Pressure of background gas in drift tube (Torr).
2. ESPIN - Azimuthal energy of injected particles at entrance plane (eV). $E_0 = (\text{ESPIN}) \cdot (\text{Initial radius})/(\text{Max initial radius})$, rotational energy is proportional to initial radius.
3. ZZDLT - Z position (in scaled units) before which only every DLT'th trajectory is plotted. This reduces the number of trajectories plotted to the left of this position.
4. DLT - Number of trajectories to be plotted, e.g., if DLT = 3.0, only every third trajectory will be plotted for Z less than ZZDLT.
5. CRHIT - The expected beam current (Amps) in the neutralized drift region.

CARD 6. FORMAT BA10

This is the title card for the output data and any comments can be punched anywhere on the card.

CARD 7. FORMAT 2I4, 7E9.2

This card describes the presence (or absence) of dielectrics in the simulation. The first number on the card is IEP and should be 0 if no dielectrics are employed and should be 1 if dielectrics are present. If IEP is zero, the remainder of the card may be left blank and the next two groups of data describing interfaces may be omitted. If IEP is one, IDI (the second number) gives the number of vertical dielectric interfaces to be employed, and the rest of the card consists of the relative dielectric constants for consecutive pairs of matrices and is stored in the EP array.

CARD(S) 8. FORMAT 12F6.

The relative dielectric constants (EPV) across the vertical interfaces are then listed. The first two values are to the left and right of the first interface. The second and third values are to the left and right of the second interface. The third and fourth values are to the left and right of the third interface, etc. Note that there will be one more constant listed than there are actual interfaces. It may also be necessary to have "dummy" interfaces (see below) to make the dielectric constants come out right.

CARD(S) 9. FORMAT 20I4.

The interfaces are specified in detail on the ID matrix, each interface being described by a sequence of four numbers. The first number in the sequence specifies the type of boundary at the lower and upper ends of the column. The possible boundary conditions are shown in Fig. 8. The six numbered lines at the bottom and top of the interface are the only possible directions a dielectric boundary can take. Number, (from 1 to 6) are used to tell the program the type of boundary to compute. The boundary conditions are given by a four-digit number, the first two digits specify conditions at the lower limit and the last two digits specify conditions at the upper limit. A metallic boundary is given by the value zero, and the six possible dielectric configurations are shown in Fig. 8. Examples will be given in the sample plot discussion.

Figure 15. Types of Possible Boundary Conditions at the Top and Bottom of a Vertical Dielectric Interface: a, metallic boundaries; b, dielectric boundaries.

The next three numbers give the location of the interface. The first of these numbers is the column I, and the last two are the lower and upper coordinates, respectively.

This sequence of four numbers is repeated for all such interfaces. If all four numbers are zero, the interface will be skipped, as would be the case when the dielectric constant list is not right for a particular interface.

CARD 10. FORMAT I4, F9,2

1. ICS - The number of cards that follow which describe the ions injected into the simulation.
2. CRNT - The current in amps (or amps per meter) of ions injected into the plasma in an axisymmetric (or rectangular) simulation.

CARD(S) 11. FORMAT (I4, 3E9.2, I4, F5.1)

1. JL - The lower radial position of a segment of the injection plane (no. of the matrix point along the R-axis).
2. SL - The relative current density injected at JL.
3. AL - The angle the trajectory at JL makes with the axis (in degrees). $-180 \leq AL \leq 180$
Positive angles go away from the axis and negative angles toward the axis.
4. BL - The relative axial magnetic flux density the trajectory has crossed between its emission point and its injection point into this program.
5. JH - The upper limit of this emission region (no. of the matrix point along R-axis).
6. SH - The relative current density injected at JH. The program does a linear interpolation between JL and JH.
7. BH - Relative magnetic flux linked at JH, again a linear interpolation is made between JL and JH.
8. CS - The spacing between trajectories in matrix square lengths, typically between 0.1 and 1.0.
9. I_i - The number of trajectories from a point source, nearly always zero for plasma simulation.
10. SP - The relative speed of the ions injected into the plasma 1.0 is the velocity for E0 initial energy (see above).

Relatively complex distributions of injection conditions can be simulated by overlaying several of these linear distributions. The only restrictions are that all the injected trajectories must be in one radial plane, and as the program is shown in Appendix A, only 250 trajectories may be plotted.

CARD 12. FORMAT 414.

This card gives a rough description of the expected beam boundary and consists simply of two points which describe a straight line. The two points are generally the expected outer radius of the plasma emission surface and the outer radius of the beam at the exit plane. These values are not critical, and need only be given approximately.

1. IL - The approximate matrix square along the Z - axis where the ion beam begins.
2. JL - The approximate matrix square along the R - axis for the outer edge of the ion beam at IL.
3. IH - The approximate matrix square along the Z - axis where the ion beam ends.
4. JH - The approximate matrix square along the R - axis for the outer edge of the ion beam at IH.

CARDS 13. FORMAT 2013.

These cards contain the integer matrices which describe the electrode configuration on the matrix. In general, these calculations start at the bottom left edge (or axis) of the matrix and proceed up each column, in sequence, across the matrix. Then this same calculation is repeated going down each column from right to left. This is a form of over-relaxation since it permits corrections to propagate rapidly in both directions.

The integer matrices, JX (I,N), consist of N/2 pairs each I = NZ locations long. These pairs describe the lower and upper limits of each gap between electrodes or dielectric surfaces proceeding along each radial column. These pairs need to be in order going up each column, but do not need to be in sequence.

Dielectric interfaces that slope at 45 degrees or less to the axis are simulated by making the upper limit of one pair of matrices equal to the lower limit of a succeeding pair of matrices, i.e., $JX(I,2) = JX(I,3)$. If the slope is greater than 45 degrees, the vertical interface routines described above may also be required.

The source plasma, and the drift space neutralization must be included in the first pair of matrices. The drift space neutralization will work only for a solid, axisymmetric, positive ion beam.

The following cards set potentials on electrodes, boundary points and dielectric interfaces if present. It is desirable to set potentials on the axis as reasonably as possible as this can significantly reduce the time needed to reach convergence. The setting of reasonable potentials on dielectric interfaces will also aid in convergence. In general, no section of the matrix should have all zero voltages, if some section of the configuration will be near zero it may be desirable to put a very small voltage on the electrodes describing the region.

CARD 14. FORMAT I4

LL is the number of cards that follow this one which set linear radial potentials in the voltage matrix.

CARD(S) 15. FORMAT 3I4, 2E9.2

1. I - The matrix column where the voltages are to be set.
2. L - The lower radial matrix point to be set.
3. N - The upper radial matrix point to be set.
4. VL - The normalized voltage at (I,L).
5. VN - The normalized voltage at (I,N).

A linear interpolation is carried out between the two specified voltages and points.

CARD 16. FORMAT I4.

The number of cards that follow this one which set linear axial variations in the voltage matrix.

CARD(S) 17. FORMAT 3I4, 2E9.2

1. L - The lower axial matrix point to be set.
2. N - The upper axial matrix point to be set.
3. J - The radial matrix row where the voltages are to be set.
4. VSL - The normalized voltage to be set at (L,J).
5. VSH - The normalized voltage to be set at (N,J).

Again a linear interpolation is made between L and N in row J.

CARD 18. FORMAT I4

The number of cards that follow this one which set logarithmic radial variations in the voltage matrix.

CARD 19. FORMAT 3I4, 2E9.2

1. I - The matrix column the voltages are to be set on.
2. L - The lower radial matrix point to be set.
3. N - The upper radial matrix point to be set.
4. VL - The normalized voltage to be set at (I,L).
5. VN - The normalized voltage to be set at (I,N).

A logarithmic radial variation of potentials is set between the two radial limits, taking into account any radial offset (NRD) which may be present. This should not be employed at all for a rectangular configuration.

CARD 20. FORMAT I4

The number of cards that follow this one which set voltages at points in the voltage matrix.

CARD(S) 21. FORMAT 2I4, E9.2

1. I - The axial matrix coordinate.
2. J - The radial matrix coordinate.
3. V - The normalized voltage at (I,J).

CARDS 22. FORMAT (8E9.2)

This matrix describes the normalized applied axial magnetic field (BM) and is not needed at all if BMAG (card 4) is zero. One normalized axis value must be read in at each axial position (NZ/8 cards) if BMAG is non-zero.

CARDS 23. 2I4, E9.2

The total number of cards required will be the total of all the numbers found on card 2. These cards set constant potentials along surfaces defined by the matrices describing the electrodes and/or dielectrics.

1. IL - The lower axial matrix point in an electrode matrix to be set at a constant potential.
2. IH - The higher axial matrix point in an electrode matrix to be set at this potential.
3. VS - The normalized potential to be set on the electrode.

CARDS 24. FORMAT (8E9.2)

The normalized equipotentials to be plotted (up to 24) are given (8 on each card) by these cards. Equipotentials will be plotted until a zero is encountered, if the first number is zero no equipotential plot will be made. Do not try to plot the zero equipotential (use 0.0001).

CARD(S) 25. FORMAT 4I4

These cards will be read only if an equipotential plot is called for by cards 24. Groupings of portions of the equipotential plots can be obtained by specifying the left and right, lower and upper coordinates of square regions of the voltage matrix.

1. IL - Lower axial column matrix number.
2. IH - Upper axial column matrix number.
3. JL - Lower radial row matrix number.
4. JH - Upper radial row matrix number.

This is terminated with a blank card, if no blowups are needed only the blank card is required. This terminates the data set.

The program then returns to its starting place calling for new data. If this is the end of the run, 5 blank cards are needed. If there is a second data set, it should start here.

APPENDIX C

SNOW Input Data Forms

The following pages are forms useful for making up input data for the program. Given are the names and formats for all input data in a form suitable for punching on cards.

[illegible]

LL	RADIAL LINEAR				I4
					314, 2E9
I	L	N	V(I,L)	V(I,N)	
LL	AXIAL LINEAR				I4
					314, 2E9
L	N	J	V(L,J)	V(N,J)	
LL	RADIAL LOGRITHMIC				I4
					314, 2E9
I	L	N	V(I,L)	V(I,N)	
LL	POINT SETTING				I4
					214, E9
I	J	V(I,J)			

APPENDIX D

SNOW Input Data Example

The following is a sample data set for an initial run using SNOW. The results produced are not a convergent solution. Many more cycles would be required to bring this to adequate convergence. The configuration is the same as that used for the target test facility at SLA, results from which were presented earlier. The final beam produced at convergence would be 0.160 A at 180 kV. The ion source for this device is a duopigatron¹⁰ which produces a deuterium beam with an m_i/m_e of 5067. The electron temperature is assumed to be 3 eV with an average ion energy at the injection plane of 60 eV. The drift space is filled with D_2 gas at a pressure of 10^{-3} Torr with an ionization cross section of 2×10^{-16} cm² and an electron temperature of 9 eV.

The input data for this run are shown on the following pages. Included are the control cards and update cards for this particular data set. Note that on this initial run, the file TDA does not yet exist, although the ATTACH and PURGE cards are already present. Since subsequent runs are to be expected and these control cards do not bother the control system, they may be included in the initializing run.

The UPDATE cards are the standard changes for a change of matrix sizes and shapes.

Changes are made in the under-relaxation parameters BRHO and BETA because this is an initial run. BRHO is increased from 0.05 to 0.15 to build up the space-charge density faster and to permit larger changes from cycle to cycle. BETA is increased from 0.03 to 0.06 to permit the potentials to change faster. Once the program has reached the point where the results are fluctuating (i.e., ± 3 percent current changes) the parameters should be reduced (possibly in two or three steps) to the smaller values. When the current fluctuations reach ± 1 percent and the voltages near the emission surface are fluctuating only in the third significant digit, the program should be converged. Be extremely wary if voltages are consistently rising or falling near the emission surface. As many as ten, ten-minute runs will probably be needed to reach convergence for this configuration.

Better stabilization will usually be reached if the number of trajectories is increased. The six hundred particles injected here is close to the lower limit for a reasonable simulation of this configuration.

The following pages present a summary of this initial run.

FNCTST,TAADN,EC400. J E 40EWS 2352 802/302

ACCOUNT,517130CH23,02120,60100,4061020,RT,ADMC.

ATTACH,TAP2L,TJA,CY1.

REQUEST,TAPFS,MP.

ATTACH,TAP2T,5432,CY1.

ATTACH,FASCDPS,FASCDPS.

[187377 FASCDPS]

UPDATE,P=TAP2L,L=U.

FTN,1=C0001[1E,0012,0000]2=0/PL=001L=0.

MAP,OFF.

LOSE,PIPHFSE,1=ZCHJ]

LGO,PL=00000.

PURGE,TAP2T,1=0000,CY1=134,EA=134,NO=134.

CAT&LOG,TAPFS,134,CH=134,EA=134,NO=134,CY=1.

30000000000000000000

*DELETE,21M

*DELETE,CNALL,0.3

COMMON V1(221,111), J1(221,121), J2(221), 240(221,111), 440(1111)

1, 21(1111), 21(1111), 21(1111), 21(221), 21(1111), J2(221)

*DELETE,CNALL,0.3

COMMON 71000/ 1=C(25001,CJST12(25001),CH(25001),C4501(25001),2J1(25001)

1,9LOC(25001),2L7C(16501),P1(25001),2L1(25001),2J2(25001),2L1(25001).

2,14(25001),J1(25001),2451(25001),251(25001),202(25001),2401(25001).

3 500(25001)

*DELETE,C0V1J,0.3

NVS = 221*111

WCHYH = 221

*DELETE,C0V1J,0

MT = 2500

*COMPILE,SN04

00000000000000000000

9 60 -2 2 221 1.0 0 6 4 4 1 0 1 0 0 1 32

0 3 2 0

0.0 180000. 0.0121 0.00 0.0001 5067.0 0.0001 60.0

0.0 0.15 3.0 7.1 36.2 2.0E-15 5580.0

0.1E-5 0 1.0 20.0 0.16

NEW TIF FJCOST12 1221000

0 0

2 0.458

1 1.0 0.0 0.0 1.0 14.847 0.0 0.01 0 1.0

5 1.0 14.847 3.0 7 3.7 22.0 0.0 0.01 0 1.0

3 11 221 11

0 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
11 11 11 11 11 11 11 11 11 11 11 11 11 11 11
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
101 102 103 104 105 106 107 108 109 110 111 112 113 114 115
101 102 103 104 105 106 107 108 109 110 111 112 113 114 115
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15

Figure 16. Plot obtained for results of Initial Run with SNOW.

SAMPLE PROGRAM INITIATING RUN									
1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100
101	102	103	104	105	106	107	108	109	110
111	112	113	114	115	116	117	118	119	120
121	122	123	124	125	126	127	128	129	130
131	132	133	134	135	136	137	138	139	140
141	142	143	144	145	146	147	148	149	150
151	152	153	154	155	156	157	158	159	160
161	162	163	164	165	166	167	168	169	170
171	172	173	174	175	176	177	178	179	180
181	182	183	184	185	186	187	188	189	190
191	192	193	194	195	196	197	198	199	200
201	202	203	204	205	206	207	208	209	210
211	212	213	214	215	216	217	218	219	220
221	222	223	224	225	226	227	228	229	230
231	232	233	234	235	236	237	238	239	240
241	242	243	244	245	246	247	248	249	250
251	252	253	254	255	256	257	258	259	260
261	262	263	264	265	266	267	268	269	270
271	272	273	274	275	276	277	278	279	280
281	282	283	284	285	286	287	288	289	290
291	292	293	294	295	296	297	298	299	300
301	302	303	304	305	306	307	308	309	310
311	312	313	314	315	316	317	318	319	320
321	322	323	324	325	326	327	328	329	330
331	332	333	334	335	336	337	338	339	340
341	342	343	344	345	346	347	348	349	350
351	352	353	354	355	356	357	358	359	360
361	362	363	364	365	366	367	368	369	370
371	372	373	374	375	376	377	378	379	380
381	382	383	384	385	386	387	388	389	390
391	392	393	394	395	396	397	398	399	400
401	402	403	404	405	406	407	408	409	410
411	412	413	414	415	416	417	418	419	420
421	422	423	424	425	426	427	428	429	430
431	432	433	434	435	436	437	438	439	440
441	442	443	444	445	446	447	448	449	450
451	452	453	454	455	456	457	458	459	460
461	462	463	464	465	466	467	468	469	470
471	472	473	474	475	476	477	478	479	480
481	482	483	484	485	486	487	488	489	490
491	492	493	494	495	496	497	498	499	500
501	502	503	504	505	506	507	508	509	510
511	512	513	514	515	516	517	518	519	520
521	522	523	524	525	526	527	528	529	530
531	532	533	534	535	536	537	538	539	540
541	542	543	544	545	546	547	548	549	550
551	552	553	554	555	556	557	558	559	560
561	562	563	564	565	566	567	568	569	570
571	572	573	574	575	576	577	578	579	580
581	582	583	584	585	586	587	588	589	590
591	592	593	594	595	596	597	598	599	600
601	602	603	604	605	606	607	608	609	610
611	612	613	614	615	616	617	618	619	620
621	622	623	624	625	626	627	628	629	630
631	632	633	634	635	636	637	638	639	640
641	642	643	644	645	646	647	648	649	650
651	652	653	654	655	656	657	658	659	660
661	662	663	664	665	666	667	668	669	670
671	672	673	674	675	676	677	678	679	680
681	682	683	684	685	686	687	688	689	690
691	692	693	694	695	696	697	698	699	700
701	702	703	704	705	706	707	708	709	710
711	712	713	714	715	716	717	718	719	720
721	722	723	724	725	726	727	728	729	730
731	732	733	734	735	736	737	738	739	740
741	742	743	744	745	746	747	748	749	750
751	752	753	754	755	756	757	758	759	760
761	762	763	764	765	766	767	768	769	770
771	772	773	774	775	776	777	778	779	780
781	782	783	784	785	786	787	788	789	790
791	792	793	794	795	796	797	798	799	800
801	802	803	804	805	806	807	808	809	810
811	812	813	814	815	816	817	818	819	820
821	822	823	824	825	826	827	828	829	830
831	832	833	834	835	836	837	838	839	840
841	842	843	844	845	846	847	848	849	850
851	852	853	854	855	856	857	858	859	860
861	862	863	864	865	866	867	868	869	870
871	872	873	874	875	876	877	878	879	880
881	882	883	884	885	886	887	888	889	890
891	892	893	894	895	896	897	898	899	900
901	902	903	904	905	906	907	908	909	910
911	912	913	914	915	916	917	918	919	920
921	922	923	924	925	926	927	928	929	930
931	932	933	934	935	936	937	938	939	940
941	942	943	944	945	946	947	948	949	950
951	952	953	954	955	956	957	958	959	960
961	962	963	964	965	966	967	968	969	970
971	972	973	974	975	976	977	978	979	980
981	982	983	984	985	986	987	988	989	990
991	992	993	994	995	996	997	998	999	1000

TARGET LOCATION = 117256700 TARGET IMPEDANCE = 101533E+07 TGT PERM = 2.4621E+04

AFTER 3 OF POSSIBLE 11 CYCLES, THE LAST COMPUTATION RESULTED IN 335 CHANGES IN 137 LOCATIONS

THE NEW JITTER BEAR NUMBER

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340	1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373	1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384	1385	1386	1387	1388	1389	1390	1391	1392	1393	1394	1395	1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439	1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	1454	1455	1456	1457	1458	1459	1460	1461	1462	1463	1464	1465	1466	1467	1468	1469	1470	1471	1472	14
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~~TADGEI ZUWYV 16788E'00 INGLE IMPEDIMENT = 11085F'00 UT PERV 2-12-92=00~~

AFIRM - 2 OF 4 POSSIBLE 11 CYCLES; THE LAST COMPUTATION RESULTED IN 11-50 CHANGES IN 11-50 LOCATIONS

THE NEW YORK PUBLIC LIBRARY

[illegible]

1154 P. J. V. Oort et al.

5f 8 8241

1146 = 492.544

POLYMERIZATION NOT WELL CONVERTED

WALL LUMBER = .21171470. STAIN (P) LUMBER = .33304285
FLOOR LUMBER = .19931400. FLOOR LUMBER = .19931400 (16) STAIN = 2.134347-00

AFTER= 2 OF = POSSIBLE 11 CYCLES THE LAST COMPIATION RESULTED IN 54 CHANGES IN 54 LOCATIONS

[illegible]

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86</													

1147 = 147.094

4E-5-0721

1148 • J. Neurosci., July 26, 2006 • 26(30):1142-1151

NOTES: RESEARCH NOT YET COMPLETED

WALL CURRENT = .0001500, SEAN IMPEDANCE = .0001000
IN-LET CURRENT = .0003300, TANGENT IMPEDANCE = .0001000, TANGENT IMPEDANCE = .0001000

AFTER 7 OF 22, WHILE IT EXISTED, THE LAST COMPARISON RESULTED IN NO CHANGES IN IDENTIFICATION

IM: 11-12-63 3FAG 000364

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99

THE JUDICIAL...

962

TIME = 104.593

POLYMER LETTERS 421 WELL CONVINGED

MAIL LICENSE # 247721-000, JOHN TROVATI # 330312-003
 JAMES L. GUNDMAN # 117708-000, JAMES L. GUNDMAN # 117708-000, JAMES L. GUNDMAN # 117708-000, JAMES L. GUNDMAN # 117708-000

AFIRM 10 OF 2 POSSIBLE 1) CILBERT INT LOSS COMPARATION ALBOUT 10 IN 6 CHANGES IN 8 LOCATION

PH: 1-800-275-2847

[illegible]5
11/11/11 10:11:11

POLYNOMIAL RELATIONSHIP NOT WELL CONVERGE

[illegible]

326	-1.443482E+02	3.463101E+03	1.479104E+01	4.714735E+00	1.552218E+01	0.0000
327	-1.554008E+02	3.333445E+03	1.444444E+01	5.221818E+00	1.444444E+01	0.0000

COMPUTED BY THE COMPUTER

J	ATLANTA	SEASIDE
1	12779.71E1	1651.1500
2	2537.51E1	2042.2200
3	3814.30E0	1511.4337
4	4834.10E0	1495.0713
5	5440.72E0	1422.7443
6	5737.40E0	257.1033
7	5714.00E0	501.7177
8	5611.00E0	557.1641
9	521.30E0	537.0806
10	51.60E0	1554.1814
11	20.00E0	931.5571
12	17.10E0	805.0743
13	9.50E0	37.4142
14	0.00E0	0.0000
15	0.00E0	0.0000
16	0.00E0	0.0000
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74	0.0000	0.0000
75	0.0000	0.0000
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77	0.0000	0.0000
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80	0.0000	0.0000
81	0.0000	0.0000
82	0.0000	0.0000
83	0.0000	0.0000
84	0.0000	0.0000
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108	0.0000	0.0000
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111	0.0000	0.0000

UNIT CURRENT = .30922500, J3AN TH-CUENCE = .30920100
 TARGET CURRENT = .10000000, TARGET IMPEDANCE = .12100000, TARGET PERM = .10000000

AFTER 11 OF 100 POSSIBLE 11 CHANGES THE LAST COMPUTATION RESULTED IN 23 CHANGES IN 23 LOCATIONS
 THE NEW JPPET BEAT NUMBER

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	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2023-2024

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.00820	.47190	+10000	.61000	.20000	.07900	.30000	.03000
.40000	.00000	-50000	.00000	.70000	.99000	.00000	.00000
.00000	.00000	+30000	.00000	.00000	.00000	.00000	.00000

THE NUMBER OF SUBMITTALS IN FILE	10 12	5
THE NUMBER OF SUBMITTALS TRANSFERRED TO FILE	10 12	11715

References

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