

**EMC2**

**AD-A257 941**

<EKXL.T3; vers 1; 07/24/91>



2

**EKXL: A Dynamic Poisson-Solver  
for Polywell<sup>tm</sup>/HEPS Spherical Converging Flow Systems<sup>†</sup>**

Katherine E. King and Robert W. Bussard

EMC2-0791-03

**DTIC  
ELECTE  
NOV 23 1992  
S A D**

APPROVED FOR PUBLIC RELEASE  
DISTRIBUTION UNLIMITED

This document has been approved  
for public release and sale; its  
distribution is unlimited.

CLEARED

OCT 22 1992

RECEIVED FOR FREEDOM OF INFORMATION  
AND SECURITY REVIEW (OASB-PA)  
DEPARTMENT OF DEFENSE

† This work performed under Contract No. MDA-972-90-C-0006 for  
the Defense Advanced Research Projects Agency, Defense Sciences Office.

92-29994



29ff

REVIEW OF THIS MATERIAL DOES NOT IMPLY  
DEPARTMENT OF DEFENSE INDORSEMENT OF  
FACTUAL ACCURACY OR OPINION.

**EMC2** ENERGY/MATTER CONVERSION CORPORATION  
9100 A Center Street, Manassas, VA 22110, (703) 330-7990

1

92-5-4578

## I. HISTORY AND BACKGROUND OF THE EKXL CODE

The EKXL code, and each of its predecessors, is a 1-D radially-dependent Poisson-solver. It gives static solutions for potential and density distributions, given edge density specifications for these parameters. It is a "point" model in that spatial variation of externally-imposed fields is possible, but spatial dependence of inter-particle interaction phenomena can not be accommodated as an integral part of code operations.

The original code, IACCEL2/EACCEL2, was developed by Ensley<sup>1, 2</sup> and provided closed analytic solutions in integral form using Struve and Bessel functions. This code employed Gaussian distributions for transverse energy and momentum. Solutions were limited, however, to electron currents of 1-10 A and core densities of  $1 \times 10^9 - 1 \times 10^{10}$   $1/\text{cm}^3$ , as indicated in Figure 1.

The first modification to Ensley's work was ACCEL, developed by Mission Research Corporation<sup>3</sup> (MRC). This version of the code utilized a more efficient algorithm for converging a solution to Poisson's equation, resulting in significant run-time savings. New physics elements were also added in order to include tangential current densities where previously only radial current was used. As shown in Figure 1, with the ACCEL improvements solutions were achieved with electron currents of 100-500 A and core densities of  $1 \times 10^{11} - 1 \times 10^{12}$   $1/\text{cm}^3$ .

What followed was a new code, XL, also developed by MRC<sup>4</sup>, that was utilized to its capacity by EMC<sup>2</sup> to study the Polywell<sup>tm</sup>/HEPS system<sup>5</sup>. This code employed a differential numerical analysis procedure and matrix inversion solution method. The distribution functions for transverse energy and momentum were changed to square functions to simplify the calculation. Features added at this time were adjustable precision

Codes	
/ or	
Special	
A-1	

and an adaptive grid. This code achieved much higher electron recirculating currents,  $1 \times 10^9$  A, and core densities,  $1 \times 10^{13}$ – $1 \times 10^{14}$   $1/\text{cm}^3$ . However, the core density barrier at  $1 \times 10^{14}$   $1/\text{cm}^3$  could not be surpassed, making any studies of Polywell<sup>tm</sup> reactor densities impossible. Work was then underway at MRC on the next revision, KXL.

## II. THE ADIABATIC KXL CODE

EMC<sup>2</sup> began working with the adiabatic code KXL in July, 1990. KXL uses the same mathematical engine developed in the XL code and a series of intermediate "steady-state" solutions over time to reach the final steady-state condition for the given input parameters. Selected parameters, such as input current and the length of the time step, can be adjusted as the calculation proceeds. As indicated in Figure 1, this method and some of the improvements discussed below allow the code to reach much higher core densities than were possible with XL.

The original MRC version of KXL used an explicit input of confinement time. This was replaced with input of the recirculation,  $G_{i,j}$ , and the confinement time is calculated in the code by  $G_{i,j} t_{\text{trans}}$ . This allowed for more consistency since the transit time is also used elsewhere in the code.

The "trapping" formula,  $F_{\text{trap}}$ , that allows feedback on the current density was first changed by David Smithe of MRC and then later by EMC2 (see below). The original form was a generic adjustment that reduced the input current by an input reduction factor. This was changed to an algorithm that adjusts the current based on the core potential to prevent the anode from maximizing, due to too many ions in the core, causing the calculation to be unsuccessful. A target anode potential and maximum beam current are input and the code adjusts the beam current up to that maximum in an attempt to obtain

the target anode height. The input variable is  $V_0$  and it represents the target well depth.  $V_0$  can be different for each species, allowing separate control over each beam. For example, a  $V_0$  for the electron beam greater than the maximum well depth would set  $F_{\text{trap}}$  equal to one and allow the electron beam to remain on at maximum current for the entire run while the code adjusted the ion current within the indicated range. The anode control formula is as follows:

$$F_{\text{trap}} = \frac{1}{1+e^{\alpha}} \quad \text{where} \quad \alpha = \frac{\varphi_0 - V_0}{\pm .03 \varphi_{\text{max}}}, \quad (1)$$

$\varphi_0$  = Current Core Potential,  $\varphi_{\text{max}}$  = Maximum Core Potential, and the  $\pm$  is determined by the charge on the beam.

If the maximum available ion current is too high, however, the  $F_{\text{trap}}$  formula cannot turn the current down enough. In effect, there is gun "leakage" and the ions build up (due to their recirculation) and overwhelm the core. When using a large ion current, it still needs to be within a reasonable range of the final gun current for the code to run successfully.

The auxiliary potential was introduced in KXL to model mirror reflection of the electrons in the cusp region,  $\mu \nabla B = \frac{1}{2} m v_{\perp}^2$ . The input to the code is the magnitude of  $\mu \nabla B$ ; therefore, it is not evident what is the magnitude of  $B$  since  $\mu$  is defined as a function of both  $B$  and  $v_{\perp}$ . Much analysis went into the auxiliary potential in an attempt to determine the magnitude of  $B$  to use in the calculation  $G_j$  based on either the wiffle ball or mirror reflection models, switching between the two where appropriate. Since the magnitude of  $B$  is indeterminate from the auxiliary potential, this linkage was not possible.

In previous work with the XL code a gridding problem had been identified. From extensive code runs, many of which did not succeed, it was found that as the system density

increased the adaptive grid was not correctly repositioning the grid points to allow proper resolution of areas of high particle density. A radial weighting factor ("R" factor) was then used to ensure an adequate number of grid points near the outer radius, the region where the density changes rapidly. This weighting of the outer regions did not allow sufficient grid points in the core region to resolve high density cases. After EMC<sup>2</sup> and MRC had worked out a solution for the XL code, the "R" factor was reintroduced when the KXL code was written. Once this factor was removed from KXL the cases began to run more consistently and the core resolution was greatly improved. Figure 2 a shows a KXL run with the "R" factor and Figure 2 b shows the same case after the "R" factor was removed. Note the improved resolution of the core region in Figure 2 b.

MRC compiled the KXL code on the Cray computer, and previous PC cases were run to verify that both codes were consistent. Once the running parameters for ion current were worked out, Cray cases were run to reach the high densities that appeared unattainable on the PC, in an attempt to fill in high density points in a study of core density vs. electron current. Examining this data, however, it became apparent that the core densities were much lower than expected from earlier calculations. Numerous variations of input variables were tried in an attempt to increase the densities. In the mean time, an explanation was sought as to why the densities were lower than predicted, and attempts were made to model this behavior. Also, the slope of core density vs. electron current was expected to be linear for constant electron confinement. As Figure 3 indicates, it was not linear until the electron current reaches 1000 A. This problem was discussed at some length by EMC<sup>2</sup>, MRC and Krall Associates.

The explanation for the change in slope at 1000 A was found, but without illuminating the too-low density problem. The electron density is increasing linearly the entire time, as expected. It is only the ion density that changes, due to the anode height. The  $\delta n$  required

to form an anode is approximately  $\delta n = (n_i - n_e) = 3.32 \times 10^9 (E_{\text{anode}}/r_o^2)$ . The electron currents below the linear slope corresponded to densities where  $\delta n$  was a significant portion of the core density. As core density moves above this density,  $\delta n$  becomes less significant, the effect disappears, and the slope finally becomes linear. By plotting this data for varying anode heights it is apparent that the curve approaches the linear condition as the anode height approaches zero (Figure 4).

In an effort to understand the too-low core densities, attention turned to the transit times. The code was modified to print the transit time at each step and this information was plotted, revealing that the code-calculated transit times were much too small to correspond to reality (Figure 5). Several changes were suggested and tried to improve the transit times, however it was then found that altering the transit time calculation had no effect on the final solution. This led to a suspicion that the  $dn/dt$  equation that was used to link the intermediate steady-state ("snapshot") solutions might be incorrect. In the KXL code this equation (for electrons) had the form:

$$\frac{dn_e}{dt} = \frac{n_{inj}}{\tau_t} - \frac{n_e}{\tau_{conf}}, \quad (2a)$$

which gives the final steady-state relation  $n_{inj} G_j = n_e$ . The basic premise of this time-dependent coupling equation (2a) is, in fact, false. The correct formulation is one that connects time-dependence of total electron populations in the system between successive static solutions from the KXL code. This equation is:

$$\frac{d\bar{n}}{dt} = \frac{4\pi R^2 n_{inj} v_{inj}}{4/3 \pi R^3} - \frac{\bar{n}}{t_c} \quad (2b)$$

However, since the codes are all written to solve only one-dimensional boundary-value problems, it was necessary to recast this equation (2b) in terms of edge (boundary) densities. Thus major modifications to this portion of the code were required. And, other physics phenomena of importance to system operation also needed to be added to the code to improve the realism of its output results.

Taking all of these factors together, at this point it was apparent that the KXL code needed considerable modification in order to be useful in analyses of Polywell<sup>tm</sup> machines in this (HEPS) program. Leaving the original generic code intact, EMC<sup>2</sup> then began development of the EKXL code, using the mathematical engine of KXL as developed by MRC (and EMC<sup>2</sup>) but now including all of the appropriate ion/electron/plasma physics analytic forms appropriate to and required for correct numerical results from EKXL code computations.

### III. THE EKXL CODE

#### Change in Edge Density with Respect to Time

The first step in customizing EKXL to the Polywell<sup>tm</sup> system was to derive a new, correct  $dn/dt$  equation. This equation is the key to the linkage of intermediate steady-state solutions over time, and numerical tests have shown solutions to be very sensitive to errors in this equation. The change in the total number of particles in the system is simply the input less the losses over a given period of time. Therefore, the change in the average number of particles with respect to time is given by:

$$\frac{d\bar{n}}{dt} = \frac{4\pi R^2 n_{inj} v_{inj}}{4/3 \pi R^3} - \frac{\bar{n}}{t_c} = \frac{3n_{inj}}{R/v_{inj}} - \frac{\bar{n}}{t_c} \quad (3)$$

where  $t_c$  is the confinement time,  $G_{i,j} t_{trans}$ . The code is only a differencing solution of a one-dimensional boundary-value problem. Thus  $dn/dt$  can only be tied to the change in edge (boundary) density, as opposed to average density, so a parameter,  $F_n = \bar{n}/n_e$ , was introduced to relate edge density to average density. Since this ratio is not fixed,  $F_n$  is calculated in the code each time the  $dn/dt$  equation is solved (see below). A second parameter, the ratio of free-stream half-transit time with no potential well to the actual transit time,

$$F_t = \frac{R/v_{inj}}{t_{trans}}, \quad (4)$$

was introduced to allow the transit time to be factored out of the  $dn/dt$  equation. The final form of the  $dn/dt$  equation is then:

$$\frac{dn_e}{dt} = \left[ \frac{3n_{inj}}{F_n F_t} - \frac{n_e}{G_{i,j}} \right] \frac{1}{t_{trans}} \quad (5)$$

### Calculation of $F_n$

The average number of particles between each pair of grid points is used to calculate the number of particles in that shell. This is summed over the entire grid and divided by the total volume to arrive at  $\bar{n}$ . A modification was necessary, however, for the electron calculation in the outer shell. In high density cases, the electron density change across the last grid space can be very large (ca.  $10^3$ – $10^4 \times$ ) and an algebraic average is not accurate. An exponential mean form was derived based on the assumption that the logarithmic gradient of the edge electron density varies inversely with the Debye length,  $\lambda_D$ , at the outer radius,  $R$ ,  $d/dr (\ln n_r) = -n_r/\lambda_R$ , and with a parameter,  $\beta$ , (typically  $\beta$  similar to



0.7), that characterizes the drop in  $E$  between the outer radius and the first grid point,  $\langle r_1 \rangle$ . When the electron density begins to increase rapidly in this region, EKXL will switch from an algebraic average to the following:

$$\bar{n} = n_R \frac{2\sqrt{\beta}}{(1-\langle r_1 \rangle)} \frac{\lambda_D}{R} \quad (6)$$

### Electron and Ion Recirculation

Although analytic forms have been derived for ion loss due to core upscattering<sup>6, 7</sup> and from fusion reactions<sup>8</sup>, it has been found convenient to choose a constant ion recirculation,  $G_i$ , as an independent input to the code. Variation in  $G_i$  affects only the ion injection current,  $I_i$ , as the circulating ion current,  $I_c = I_i G_i$ , is fixed by the parameters of a given case. The code has the ability to adjust  $I_i$  as needed (see below).

The electron recirculation,  $G_e$ , may be input at a constant value or it may be calculated in the code using the physics of electron confinement under mirror reflection (MR) and wiffle ball (WB) modes. This model is discussed in detail in other EMC2 technical notes<sup>9, 10</sup> and its pertinent algorithms and defining equations are given in Figure 6. As discussed earlier, the magnitude of  $B$  cannot be tied to the auxiliary potential and is, therefore, a separate input parameter for the mirror/wiffle model.

### Ion Losses Due to Fusion Reactions

Fusion reactions of ions in the core and surrounding region will consume ions. This source of loss is important only at conditions of high core density and large ion energy. The total fusion rate is calculated in the code as part of the fusion and gain calculations (see below).

This allows for easy inclusion of the ion losses due to fusion in the ion  $dn/dt$  equation. If the total fusion rate is  $DD_{fus}$  fusions/sec, then the number of ions lost to fusion is  $2DD_{fus}$  ions/sec. This loss term would go in to the original  $dN/dt$  equation and the resulting  $dn_e/dt$  equation would be:

$$\frac{dn_e}{dt} = \left[ \frac{3n_{inj}}{F_n F_t} - \left[ \frac{n_e}{G_i} + \frac{DD_{fus}}{F_n F_{DD}} \right] \right] \frac{1}{t_{trans}} \quad (7)$$

where  $F_{DD} = 4/3 \pi r^3 / t_{trans}$  is introduced to allow the transit time to be factored out.

### Ion Losses Due to Core Upscattering

Ion losses due to core collisional upscattering can be accounted for by adding a loss term to the  $dn/dt$  equation for ions. Based on the work of Rosenberg and Krall<sup>6</sup>, as modified by Bussard<sup>7</sup>, the upscattering time for ions,  $t_{up}$ , is calculated each time the  $dn/dt$  equation is solved, from

$$\frac{1}{t_{up}} = \frac{Z^4}{1.892 \times 10^{13} f^2 (1+f)^2 A^{1/2}} \frac{1}{R} \int \frac{n(r)}{E(r)^{3/2}} dr \quad (8)$$

A factoring parameter,  $F_u = t_{up}/t_{trans}$ , was introduced into the  $dn/dt$  equation so that the ion losses due to upscattering are given by  $n_e/(F_u t_{trans})$ . This form is easily incorporated into the ion  $dn/dt$  equation which becomes

$$\frac{dn_e}{dt} = \left[ \frac{3n_{inj}}{F_n F_t} - n_e \left[ \frac{1}{G_i} + \frac{1}{F_u} \right] - \frac{DD_{fus}}{F_n F_{DD}} \right] \frac{1}{t_{trans}} \quad (9)$$

The fractional velocity spread,  $f$ , is a specified input parameter. If  $f = 0$ , no ion upscattering is calculated. This parameter can be estimated by comparison of scattering collision rates in the core, edge, and mantle regions<sup>11, 12, 13</sup> of the system, comparing transverse momentum vs. radial momentum exchange processes. Such estimates are not yet complete; when available the analytic forms that describe them can be added to the  $dn/dt$  equation, as above.

### Average Transit Time Calculations

The data in the code is quite sufficient to calculate the ion transit time directly. Using the potential at each grid point and the input parameters  $E_{inj}$ ,  $dE$  and  $dE_{perp}$ , the average transit time across each grid point can be calculated and summed across the entire grid to arrive at the average ion transit time through the system.

The calculation of transit time for electrons, however, presents an interesting problem. The direct method used for ion transit time does not lend itself to an accurate calculation of the average electron transit time as the individual times vary greatly with the energy spread of the electrons. Electrons with a maximum  $dE_{perp}$  will be turned early and have short transit times while the electrons with maximum energy,  $E_{inj} + dE$ , and no  $dE_{perp}$  will pass through the bottom of the well and reach the core yielding much longer transit times.

Several attempts were made to calculate and average the electron transit times within the code, consuming significant computational time. Due to the dependence of  $F_n$  on transit time, however, a small deviation in average transit time could continue to feed back into a large error in  $dn/dt$ . In short, the detailed computational capability of the code would lead to amplification of numerical errors in original data. In this circumstance, the internal

data calculation was abandoned in favor of an analytic form based upon system parameters, which yields a more accurate and consistent averaged result and utilizes less computational time. As derived and discussed in another EMC2 note<sup>14</sup> (see for definitions of terms) the electron transit time is:

$$t_{\text{tot}} = \frac{2R}{v_{in}} \left[ \frac{\langle r_0 \rangle + \left[ \frac{\langle r_w \rangle^2 - \langle r_0 \rangle^2}{2\langle r_0 \rangle} \right]}{\left[ \eta' + \frac{1}{2}(1-\alpha_q) \right]^{1/2}} + \frac{2}{\left[ 1 + \frac{1}{2}(1-\alpha_q) \right]^{1/2}} \left[ \frac{1}{\langle r_w \rangle^{1/2}} - 1 \right] \right] \quad (10)$$

where  $\alpha_q = \varphi_o / \varphi_{\min}$ ,  $\eta' = 1 - \alpha_q(1 - \eta_o)$ ,  $\eta_o = E_{so} / E_o$ ,

$\langle r_w \rangle = \langle r_0 \rangle + \left[ \frac{2}{m} \langle r_0 \rangle^2 \eta' \right]^{1/(m+2)}$  and  $\langle r_0 \rangle$  is the core radius.

This is a calculation of the maximum transit time. But the electrons occupy a spread in total and transverse energy. Across this energy distribution the individual transit times can vary markedly. Analysis of this variation suggests an exponential distribution of transit times across the band. Integrated averaging over this variation yields a correction factor to give average transit times of the average electron in terms of the total maximum transit time of equation (10). This factor is found to be:

$$\bar{t}_{\text{trans}} = \frac{\ln \left[ \frac{t_{\text{trans}}}{2R/v_{in}} \right]}{\left[ \frac{t_{\text{trans}}}{2R/v_{in}} - 1 \right]} t_{\text{tot}} \quad (11)$$

## Fusion Rates and Power Gain

The KXL code contained a subroutine to calculate the approximate neutron rate (1/2 the fusion rate) for DD fusion. This subroutine was modified in EKXL to include fusion rate calculations for DT, D<sup>3</sup>He and p<sup>11</sup>B based upon the deuteron density (as the code does not currently accommodate different electron and ion injection radii, necessary for center-of-momentum, center-of-geometry placement of these ions). Calculation of system gross gain for all four fuel combinations was also added to the EKXL code, where gross gain is defined as

$$\text{GGAIN} = \frac{P_{\text{fus}}}{P_{\text{inj}}} = \frac{E_{\text{fus}} \int_0^R n_i^2(r) \sigma(E) v_i(r) 4\pi^2 dr}{P_{e_{\text{inj}}} + P_{i_{\text{inj}}}} \quad (12)$$

The densities used for each fuel combination were:

**DT** For DT fusion rates, the existing deuteron density, D, is divided in half and treated as 50:50 D:T

**D<sup>3</sup>He** For a 50:50 D:<sup>3</sup>He distribution the total D + <sup>3</sup>He density will be 2/3 the existing D density for the same potential distribution.

**p<sup>11</sup>B** For 50:50 p:<sup>11</sup>B the total density of p + <sup>11</sup>B is 1/3 the existing D density.

## Bremmstrahlung Losses

Bremmstrahlung will be an important energy loss mechanism from the system at high density conditions. This was estimated from standard formulae<sup>15</sup> for bremmstrahlung

radiation density, integrated over the system volume to give total bremsstrahlung output, ignoring self-absorption by the plasma and any internal reflection from the boundary walls. This is discussed in a separate EMC2 technical note, forthcoming. The resulting expression is used in the EKXL code to calculate bremsstrahlung gross output as

$$P_{\text{bremm}} = 1.69 \times 10^{-32} \int_0^R n_i(r) n_e(r) Z^2 \sqrt{E_e(r)} 4\pi r^2 dr \quad (13)$$

This is added to the injection power to determine net power input and system net gain.

$$\text{NGAIN} = \frac{P_{\text{fus}}}{P_{\text{inj}} + P_{\text{bremm}}} \quad (14)$$

### Ion Current Adjustment

The problem with the anode control, discussed previously – allowing too many ions to build up in the system and thus requiring the maximum ion current to be within range of the final ion current – was addressed in EKXL with a different form of anode control that calculates the ion current density based on the core densities, the electron current density and  $G_{i,j}$ . The difference in core densities is given by<sup>16</sup>

$$n_i - n_e = 3.32 \times 10^8 \frac{(\varphi_o - \varphi_{\min})^2}{r_o} \quad (15)$$

where  $\varphi_o$  is the core potential and  $\varphi_{\min}$  is the potential at the bottom of the well (both in eV),  $r_o$  is the core radius in meters and density is in  $1/\text{m}^3$ . The difference in densities at the target anode potential,  $\varphi_a$ , is then

$$n'_i - n'_e = 3.32 \times 10^8 \frac{(\varphi_a - \varphi_{\min})}{r_0^2} \quad (16)$$

The change in density from  $n_i$  to  $n'_i$  is then

$$\Delta n_i = n'_i - n_i = 3.32 \times 10^8 \frac{(\varphi_a - \varphi_{\min})}{r_0^2} + (\Delta n_e + n_e) - n_i$$

or

$$\Delta n_i = 3.32 \times 10^8 \frac{(\varphi_a - \varphi_{\min})}{r_0^2} - (n_i - n_e) + \Delta n_e \quad (17)$$

Substituting equation (15) into equation (17) gives

$$\Delta n_i = 3.32 \times 10^8 \frac{(\varphi_a - \varphi_o)}{r_0^2} + \Delta n_e \quad (18)$$

and

$$J_i = \frac{3.32 \times 10^8}{G_i r_0^2 \Delta t} (\varphi_a - \varphi_o) + J_e \frac{G_j}{G_i} \quad (19)$$

where  $J_{i,e}$  are the circulating current densities.

### Automatic Operating Mode

In the XL code a case achieved a steady-state solution or none at all. The KXL code has the ability to stop at any "snapshot" point by specifying the time duration in the input file. This allows a succeeding run to be started at the end of a previous calculation, using a special data file created when that calculation was completed, and to continue for the time duration specified in the new input file. This allows for the adjustment of time steps and

ion current necessary to achieve the final steady-state solutions previously unattainable with the XL code. The drawback is that the manual adjustment of duration time and ion currents require continuing operator input. In the EKXL code an "automatic" mode was introduced that eliminates the need for most manual restarts. In automatic mode, the code will run to the end of the specified time duration or a steady-state solution, whichever comes first, using a series of intermediate time steps (simulating the manual restarts required in KXL) automatically adjusting the length of each intermediate time step based upon whether or not the previous time step was successful. This is facilitated by the ion current control and allows the code to run unattended as far as is possible without requiring operator intervention.

#### **IV. SAMPLE CODE RUN FOR EKXL V4.1**

Figure 7 shows a sample input file for EKXL version 4.1 as it is described above. This calculation ran in automatic mode with fixed ion current for a 15 keV well in a 92 cm device. The name of the log file, a sample of which is shown in Figures 8 a-b, and the dataset file, a sample of which is shown in Figure 9, are taken from the name of the input file, with the extension indicating the nature of the data. For example, the input file in Figure 7 is named BREM2b.INP. The log file in Figure 8 is named BREM2b.LOG and the dataset file in Figure 9 is named BREM2b.OUT. The last character of the file name is used to indicate the number of the run. In this example, the "b" indicates that it is the second run and the "Initialization file" is set to "YES" in the input file. This calculation started where BREM2a.INP ended, and this is verified in the beginning of the log file (Figure 8 a) where it states that initialization file BREM2.TMP was read.

The log file prints run diagnostics of the numerical calculation<sup>4</sup> to help the user in determining if and when problems occurred in the calculation. Figure 7 a shows the



beginning of the log file, while Figure 7 b shows the end. As seen in the figures, the log file also contains the transit times ( $\tau$ ), the electron confinement time, the ion upscattering time (if this calculation is being used), the radius of the wiffle ball,  $\langle r_b \rangle$ , the actual ion and electron currents being used in the code, the fusion rates for DT,  $D^3\text{He}$  and  $p^{11}\text{B}$ , the plasma gain for all four fuels and the bremsstrahlung power as calculated from the DD density. The end of the file indicates that the snapshot was saved and lists the files to which output was written.

Figure 9 shows only the first portion of an output dataset file. This file contains the potential and ion and electron densities at each grid point for every successful snapshot in the run. The output is formatted and comma-separated which allows for easy import into spreadsheet or graphics software. A sample plot of this output data is shown in Figure 10. The beam profiles from the input file have been printed across the top of this chart and the fusion rates have been imported from the log file.

Hundreds of cases have been run with the EKXL code modelling many areas of interest from basic experiments, to current SCIF parameters, to reactor regimes. Results of these code runs have been used extensively to better understand the physics involved in Polywell<sup>tm</sup> devices and also to improve the modelling, especially as it is applied in the code. A compilation of results of specific interest to the SCIF experiment are presented in some detail in another EMC2 technical report on these computer simulations<sup>17</sup>. The potential of this code, however, has not been fully realized and there still remain many areas of interest that have not been explored.

## LIST OF FIGURES

- Figure 1.** Maximum operational levels for successful Vlasov—Poisson "1-D" code runs.
- Figure 2.** a. KXL case with R weighting factor.  
b. Same case with R weighting removed. Note improved core resolution and density.
- Figure 3.** Core density vs. electron current for a fixed electron confinement. Slope is linear for currents greater 1000 A.
- Figure 4.** Core density vs. electron current for varying anode heights. Slope approaches linear as anode approaches zero.
- Figure 5.** Electron transit time as calculated in KXL. For all currents, electron energy is 100 keV.
- Figure 6.** Formulas used in the mirror/wiffle model for  $G_j$  calculation.
- Figure 7.** Sample input file for an EKXL v4.1 code run.
- Figure 8.** a. Beginning of the log file created by EKXL for the run in Figure 7.  
b. End of the log file created by EKXL for the run in Figure 7.
- Figure 9.** Beginning of the output dataset file generated by the EKXL run in Figure 7.
- Figure 10** Sample plot of the data in the EKXL output file, as shown in Figure 9. This graph was generated in SuperCalc v5.0.

## REFERENCES

- <sup>1</sup> Ensley, D.L., "Physics Modeling Project", internal memorandum to Pacific-Sierra Research Corporation, October, 1986
- <sup>2</sup> Ensley, D.L., "IACCEL2/EACCEL2 User Guide", internal memorandum to Pacific-Sierra Research Corporation, April 1987
- <sup>3</sup> McDonald, J., B. Goplen, "ACCEL User's Manual", Mission Research Corporation Report MRC/WDC-R-180, November 1988
- <sup>4</sup> Smithe, D., "XL Reference Manual", Mission Research Corporation Report MRC/WDC-R-226, January 1990
- <sup>5</sup> King, K.E., R.W. Bussard, "Examination of Electrostatic Well Formation for Spherically Convergent Electron and Deuteron Beams", Energy/Matter Conversion Corporation Report EMC2 0990 02, September 1990
- <sup>6</sup> Rosenberg, M.(EMC2), N.A. Krall, "Ion Loss by Collisional Upscattering", Krall Associates Report KA 90 39, October 1990
- <sup>7</sup> Bussard, R.W., "Core Collisional Ion Upscattering and Loss Time", Energy/Matter Conversion Corporation Report EMC2 1090 03, October 1990
- <sup>8</sup> Bussard, R.W., "Fusion Lifetime Limits on Ion Upscattering", Energy/Matter Conversion Corporation Report EMC2 0291 04, February 1991
- <sup>9</sup> Bussard, R.W., K.E. King, "Electron Recirculation in Electrostatic Multicusp Systems: I — Confinement and Losses in Simple Power Law Wells", Energy/Matter Conversion Corporation Report EMC2-0491-03, April 1991
- <sup>10</sup> Bussard, R.W., K.E. King, "Electron Recirculation in Electrostatic Multicusp Systems: II — System Performance Scaling of One-Dimensional 'Rollover' Wells", Energy/Matter Conversion Corporation Report EMC2-0791-04, July 1991
- <sup>11</sup> Rosenberg, M.(EMC2), N.A. Krall, "Ion Loss by Collisions Outside the Core", Krall Associates Report KA 91 02, January 1991
- <sup>12</sup> Krall, N.A., "Anisotropy Profiles for the Ion and Electron Plasma in the Polywell<sup>tm</sup>/SCIF", Krall Associates Report KA 91 09, April 1991
- <sup>13</sup> Krall, N.A., "Core and Mantle Properties of Weibel Instability in the Polywell<sup>tm</sup>/SCIF", Krall Associates Report KA 91 10, May 1991
- <sup>14</sup> Bussard, R.W., K.E. King, "Electron Transit Time in Central Virtual Anode Wells", Energy/Matter Conversion Corporation Report EMC2 0291-03, February 1991
- <sup>15</sup> Book, D.L., "NRL Plasma Formulary", 1987 revised, Naval Research Laboratory, Washington, D.C.
- <sup>16</sup> Bussard, R.W., G.P. Jellison, G.E. McClellan, "Preliminary Research Studies of a New Method for Control of Charged Particle Interactions", Pacific-Sierra Research Corp. Report PSR 1899, 30 November 1988, Final Report under Contract DNA001-87-C-0052, Appendix A, Sect. on Negative Potential Well Formation
- <sup>17</sup> Bussard, R.W., K.E. King, "Computer Modelling of SIF Experiment Performance", Energy/Matter Conversion Corporation Report EMC2-0691-02, June 1991

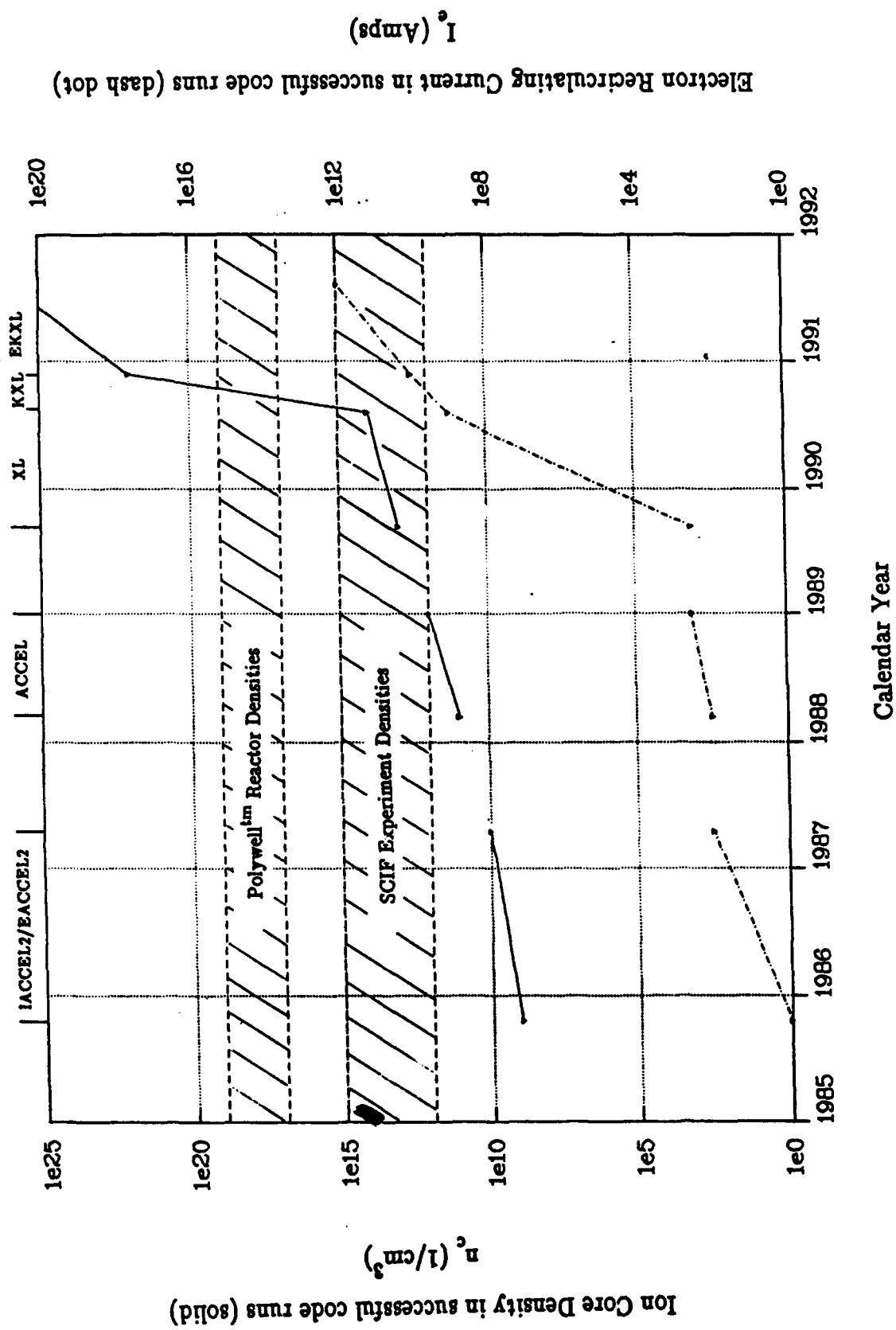


Figure 1. Maximum Operational Levels for Successful Vlasov-Poisson "1-D" Code Runs

Figure 2. a

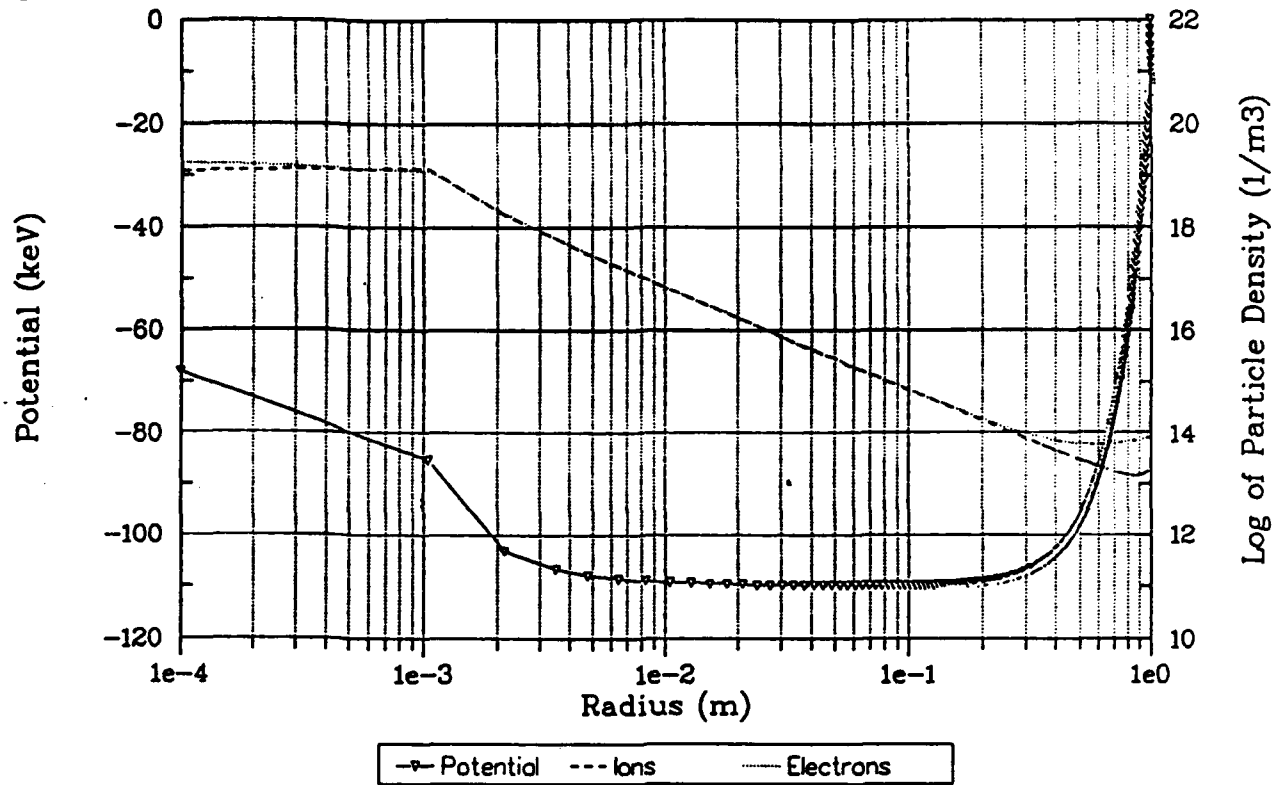


Figure 2. b

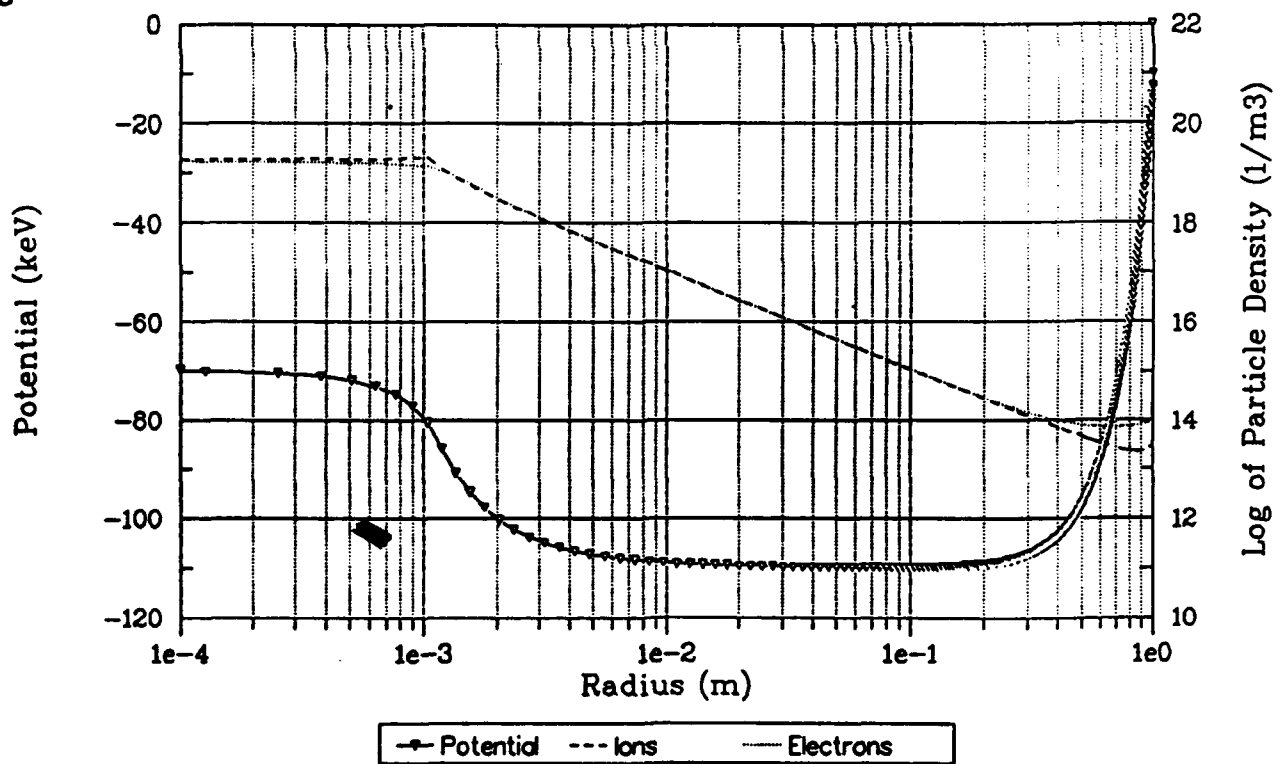
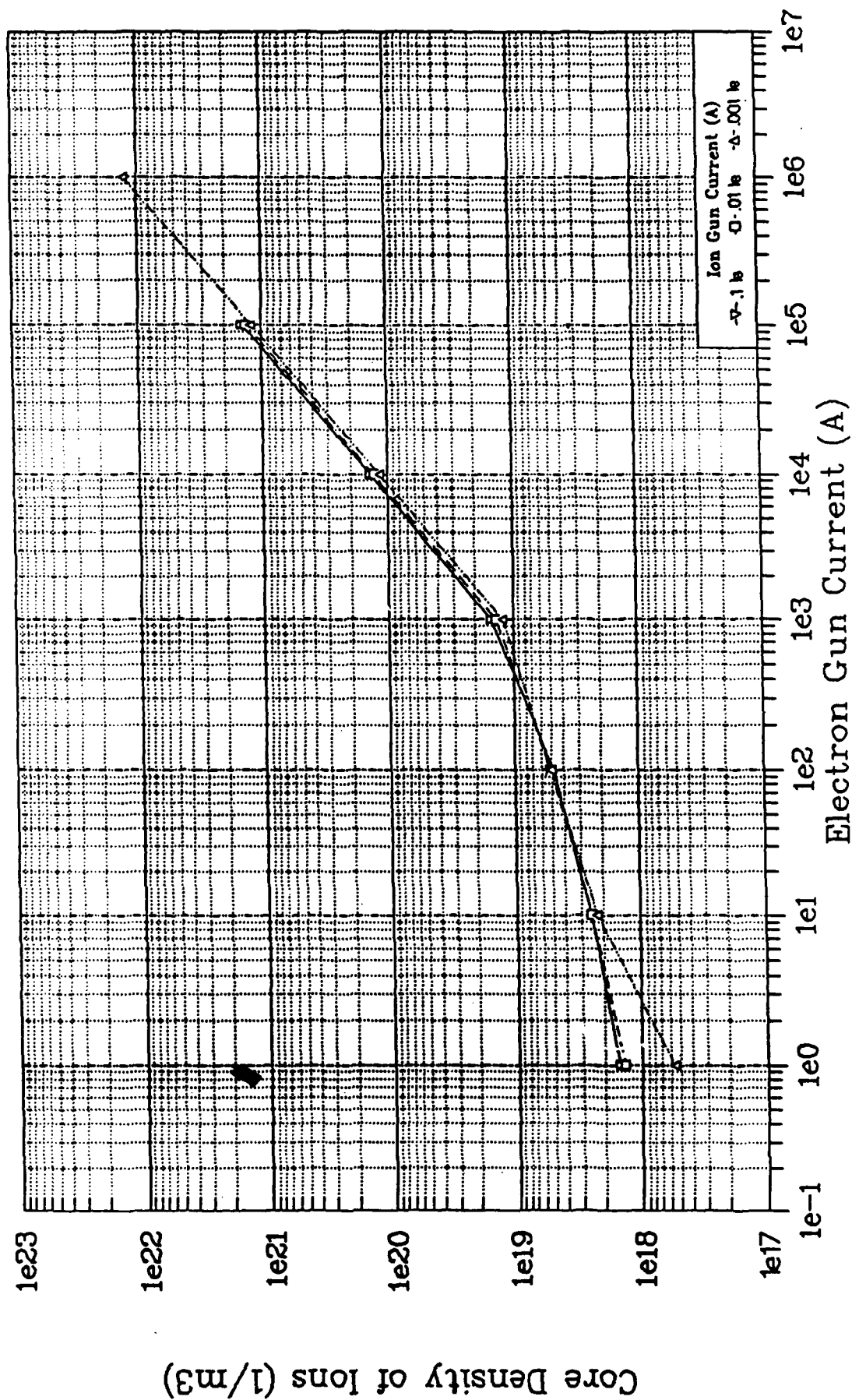
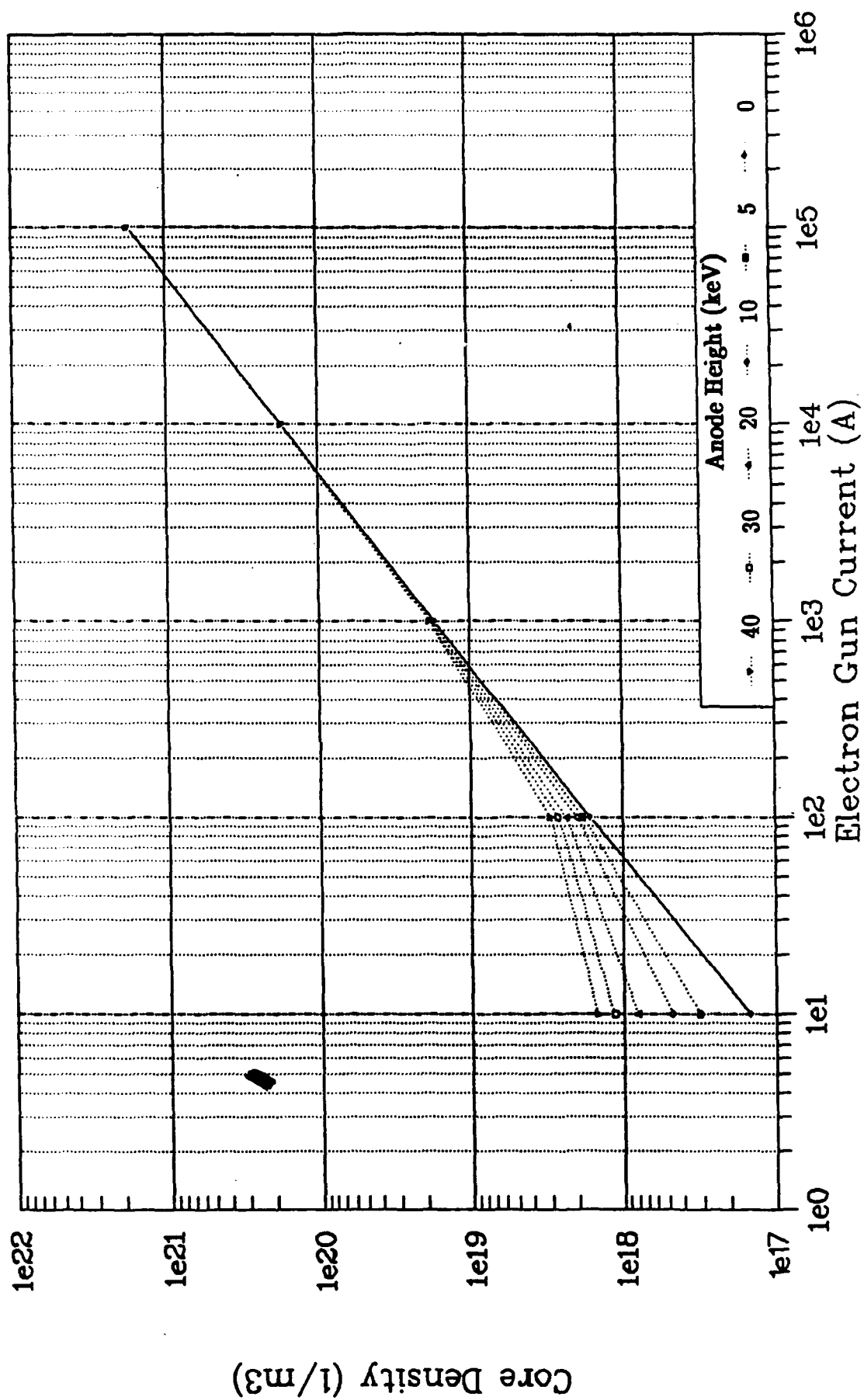


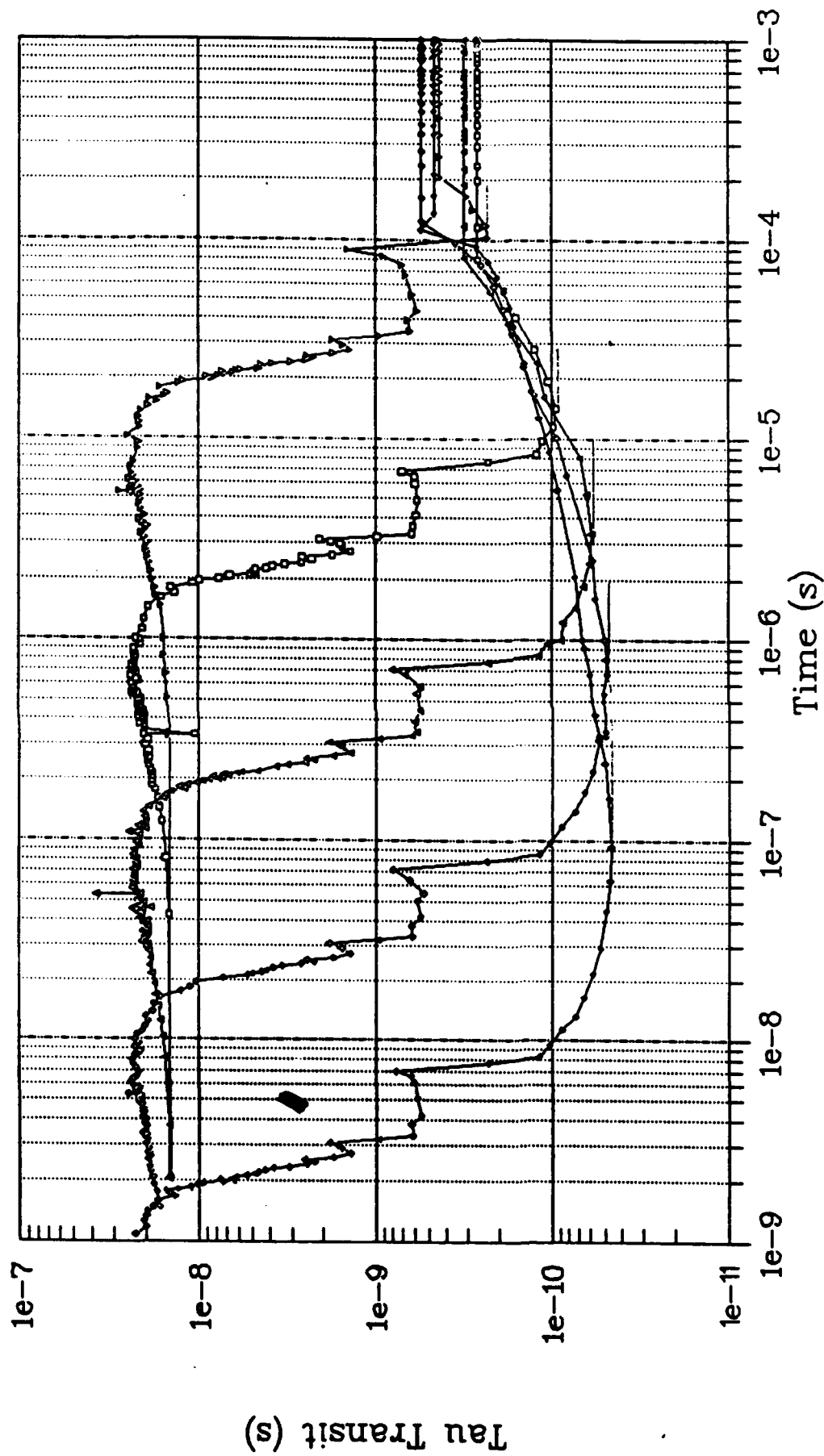
Figure 2. a. KXL case with R weighting factor.  
b. Same case with R weighting removed. Note improved core resolution and density.



**Figure 3.** Core density vs. electron current for a fixed electron confinement. Slope is linear for currents greater 1000 A.



**Figure 4.** Core density vs. electron current for varying anode heights. Slope approaches linear as anode approaches zero.



**Figure 5.** Electron transit time as calculated in KXL. For all currents, electron energy is 100 keV.



# Mirror/Wiffle Model for $G_{jo}$

$$G_{jo} = G_{jMRo} \left[ \frac{4}{N} \frac{(1-\langle r_b \rangle)}{(1-\alpha_r)} t_{MR} + \langle r_b \rangle t_{WB} \right] \frac{1}{t_{tot}} \quad r_b < r_x$$

$$G_{jo} = G_{jMRo} \left[ \frac{4}{N} \frac{(1-\langle r_b \rangle)}{(1-\alpha_r)} t_{MR} + G_{jWB} \langle r_b \rangle t_{WB} \right] \frac{1}{t_{tot}} \quad r_b > r_x$$

where:

$$G_{jMRo} = \frac{1}{\langle r_{ad} \rangle^m} [1 - \alpha_q (1 - \langle r_{ad} \rangle^m)] \quad r_b < r_{ad}$$

$$G_{jMRo} = \frac{1}{\langle r_b \rangle^m} [1 - \alpha_q (1 - \langle r_b \rangle^m)] \quad r_b > r_{ad}$$

$$G_{jWB} = \frac{2r_e Z}{Nk_L^2 S^2} \quad Z = 8\pi n_c r_c^2 \quad \text{and} \quad W = \frac{E_0}{B_0^2 R^2}$$

$$\langle r_b \rangle^{(2m+2)} = (ZW) \frac{[1 - \alpha_q (1 - \langle r_b \rangle^m)]}{[f_0(\langle r_b \rangle)]^2} \quad \langle r_b \rangle^2 = \left[ \frac{2WS^2}{r_e \langle r \rangle^{2m}} \right] \frac{[1 - \alpha_q (1 - \langle r \rangle^m)]}{[f_0(\langle r \rangle)]^2}$$

$$\langle r_x \rangle^{(2m+2)} = \left[ \frac{NWk_L^2 S^2}{2r_e} \right] \frac{[1 - \alpha_q (1 - \langle r_x \rangle^m)]}{[f_0(\langle r_x \rangle)]^2} \quad S^2 = \overline{\sin^2 \varphi}$$

$$\langle r_{ad} \rangle = \langle r_{ad0} \rangle + k_a (\langle r_b \rangle - \langle r_x \rangle) \quad k_a = \frac{\langle r_k \rangle - \langle r_{ad0} \rangle}{\langle r_k \rangle - \langle r_x \rangle}$$

$$\langle r_{ad0} \rangle^{(2m+2)} = \left[ \frac{2m^2}{\Gamma_e^2} \frac{WS^2}{r_e} \right] [1 - \alpha_q (1 - \langle r_{ad0} \rangle^m)] \left[ 1 + \frac{\langle r_{ad0} \rangle}{m} \frac{f'_0(\langle r_{ad0} \rangle)}{f_0(\langle r_{ad0} \rangle)} \right]$$

$$f_0(\langle r \rangle) = \left[ \frac{2}{1 + \langle r \rangle^{(m+2)}} \right] \quad f'_0(\langle r \rangle) = - \frac{2(m+2)\langle r \rangle^{(m+1)}}{[1 + \langle r \rangle^{(m+2)}]^2}$$

Figure 6. Formulas used in the mirror/wiffle model for  $G_j$  calculation.

```

Log Filename:  (program uses INP filename)
-----+-----+
Dataset Name:  (program uses INP filename), Initialization file: YES,
-----+-----+-----[=]-
Operating mode:  AUTOMATIC  , end time=1.000e-03 sec, with 3 snapshots/dt,
-----+-----+-----[=====]-----[==]-----
Fixed Outer Potential:      0.e3 Volts at r=0.92  m, Ncusps= 8MR, 8WB,
-----+-----+-----+-----[==]---[==]---
Number of Beam Populations:  2, with repeller effic. : 0.9000,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Name      Ig [A]      Einj[eV]      dE[eV] dEperp[eV]  B[G],Gi      V0trap[eV]
1) Elec   18.0e03     14.5e03     0.50e03  4.35e03     3.00e03     -20.0e03
2) Deut   18.0e03     10.00e00     1.00e00  1.71e00      1e00      -11.0e03
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Number of Thermal Populations:  0,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Name      [# /m**3]      @[Volts]      Temp[eV]
0) Elec    1.e16      100.e3      20.e3
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Deuterium Neutral Density:      0.e18 /m**3,  aij:      1 ICC mass ratio,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Auxiliary Potential:      14.9e3 Volts for e's, with exponent=3.  ,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Fractional velocity spread:      0, kl Radius Factor:      2.0,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Grid:  200 points with adaptive fraction of 0.8  and tolerance 1.e-5  ,
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Transit Time Correction Factor (Y/N): Y,  ka <radius>:      0.83.
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Modified B Field Shape: Y, Modified Gj: Y, Adjust Ion Current: N.
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
Bremmstrahlung <radius>:      1.00,  Ion Fusion Losses:  N
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+

```

Figure 7. Sample input file for an EKXL v4.1 code run.

Figure 8. a

Operating mode is AUTOMATIC

Auxiliary potential option is on.

Initialization file read: brem2.tmp

iter = 1, dumax = 3.21E-07, step = 1.00E+00

Electron confinement time: 6.389E-07

Wiffle radius rb: 1.936E-01

1) time = 1.000E-06, determ = 1.000E+20 Tau = 6.100E-08 3.019E-06  
2) time = 1.263E-06, determ = 1.000E+20 Tau = 6.100E-08 3.027E-06  
3) time = 1.395E-06, determ = 1.000E+20 Tau = 6.100E-08 3.019E-06  
4) time = 1.972E-06, determ = 1.000E+20 Tau = 6.100E-08 3.022E-06  
5) time = 2.053E-06, determ = 1.000E+20 Tau = 6.100E-08 3.021E-06  
6) time = 1.527E-06, determ = 1.000E+20 Tau = 6.100E-08 3.021E-06

Figure 8. b

iter = 1, dumax = 6.82E-07, step = 1.00E+00

Electron confinement time: 6.996E-06

Wiffle radius rb: 2.692E-01

787) time = 1.636E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06  
788) time = 1.663E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06  
789) time = 1.676E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06  
790) time = 1.736E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06  
791) time = 1.744E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06  
792) time = 1.690E-04, determ = 1.000E+20 Tau = 6.113E-08 2.911E-06

iter = 1, dumax = 4.24E-07, step = 1.00E+00

Electron confinement time: 6.995E-06

Wiffle radius rb: 2.692E-01

t(upscatter) = 0.000E+00 0.000E+00

Gun current 1 is: 1.800E+04

Gun current 2 is: 1.800E+04

Gun current 1 is: 1.800E+04

Gun current 2 is: 1.800E+04

Fusion Rate: DT=1.313E+14 DHe3=1.951E+10 DHe3 n=1.643E+11 pB11=5.434E+02

Gplasma: DD=6.624E-09 DT=1.417E-06 DHe3=9.550E-10 pB11=2.900E-18

Pbrem: 1.059E+01

Gicc= 9.130E-06 No/Nc = 9.523E+01 (<No>/Nc)^2= 1.378E+03

### SNAPSHOT SAVED ###

Restart file written: brem2.tmp

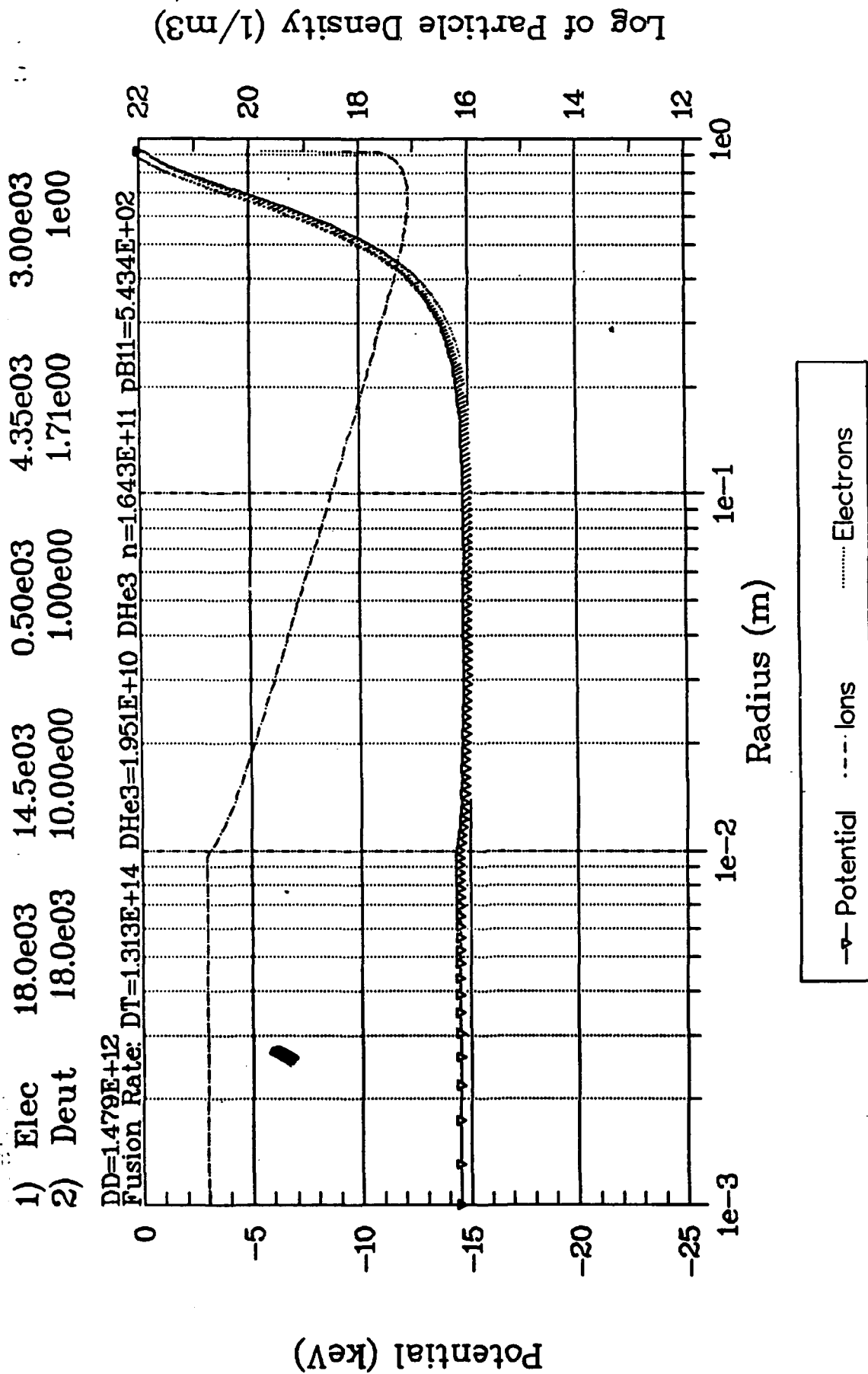
Print files written: brem2b.out  
brem2b.tim

Figure 8. a. Beginning of the log file created by EKXL for the run in Figure 7.  
b. End of the log file created by EKXL for the run in Figure 7.

Start date: 07/16/91      Start time: 17:29:20.81  
 Dataset: brem2b  
 Time: 1.74E-04 sec  
 Number of Grid Points: 200  
 Deut Beam Neutron Count rate (#/sec): DD=1.479E+12, DN=0.000E+00

R (m)	Pot (V)	DD (n/scm3)	Lambda (m)	Nb (#/m**3)	Elec	Deut
0.000000,	-1.453E+04,	1.718E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.000434,	-1.453E+04,	1.718E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.000868,	-1.453E+04,	1.718E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.001302,	-1.453E+04,	1.719E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.001737,	-1.453E+04,	1.720E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.002171,	-1.453E+04,	1.722E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.002605,	-1.453E+04,	1.724E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.003039,	-1.453E+04,	1.727E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.003473,	-1.453E+04,	1.731E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.003907,	-1.453E+04,	1.736E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.004341,	-1.453E+04,	1.744E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.004776,	-1.453E+04,	1.753E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.005210,	-1.453E+04,	1.765E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.005644,	-1.453E+04,	1.780E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.006078,	-1.453E+04,	1.799E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.006512,	-1.453E+04,	1.821E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.006946,	-1.453E+04,	1.845E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.007380,	-1.453E+04,	1.870E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.007815,	-1.453E+04,	1.893E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.008249,	-1.453E+04,	1.908E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.008683,	-1.453E+04,	1.909E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.009122,	-1.453E+04,	1.885E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.009574,	-1.453E+04,	1.820E+17,	0.000E+00,	6.601E+20,	6.601E+20,	6.601E+20
0.010045,	-1.457E+04,	1.313E+17,	0.000E+00,	5.760E+20,	5.760E+20,	5.760E+20
0.010543,	-1.464E+04,	7.805E+16,	0.000E+00,	4.414E+20,	4.414E+20,	4.414E+20
0.011077,	-1.468E+04,	5.492E+16,	0.000E+00,	3.689E+20,	3.689E+20,	3.689E+20
0.011655,	-1.472E+04,	4.027E+16,	0.000E+00,	3.150E+20,	3.150E+20,	3.150E+20

Figure 9. Beginning of the output dataset file generated by the EKXL run in Figure 7.



**Figure 10** Sample plot of the data in the EKXL output file, as shown in Figure 9. This graph was generated in SuperCalc v5.0.