Theoretical Notes
Note 161
23 February 1972

The Effect of Nuclear-Coulomb Electron Scattering on High Altitude EMP Sources

Capt Gary R. Knutson
Air Force Weapons Laboratory

Abstract

A Monte Carlo transport code was used to calculate the ionization rate and three components of the electron current created by monoenergetic primary electrons. The effects included in the calculation were nuclear coulomb electron scattering, continuous slowing down method of electron energy loss, and electron turning in the B field of the earth. Results are presented for 16 sets of initial conditions of electron energy, altitude, and angle between the radial direction and the B field direction. This set of calculations is intended as a benchmark set of calculations which may be used to test the accuracy of the approximations used in EMP source calculations.

I. Introduction

The problem of calculating the EMP sources (ionization rate and electron currents) created by a high altitude nuclear weapon burst is indeed a complex one. Consider, for example, all of the many interactions which must be accounted for in order to accurately calculate the EMP sources. First of all, the weapon produces a particular energy distribution of gammas and X rays. This distribution of gammas and X rays scatters in the atmosphere, the density of which varies with altitude. When the gammas and X rays scatter, they create an energy distribution of primary electrons, both by Compton scattering and by the photoelectric effect. As the primary electrons scatter in the atmosphere, they create secondary electrons, which in turn can create additional secondary electrons. And finally, the trajectories of all these primary and secondary electrons are affected both by the B field of the earth and by the E and B fields created by the electrons themselves.

Considering the complexity of the problem, one can easily see that it is necessary to include many approximations in order to attempt a solution. Consider, for example, some of the approximations that are used for a typical calculation of the EMP sources at any particular point in the atmosphere. If the weapon X-ray output is included in the calculation (not always the case), then many people use one gamma energy to represent the weapon gamma spectrum and one X-ray energy to represent the weapon X-ray spectrum. Only the primary electrons produced on the first gamma or X-ray scatter in the atmosphere are included in the calculation. Multiple gamma and X-ray scattering is not considered. The trajectories of all the primary electrons created by the gammas and X rays are represented by the trajectories of two electrons, the average energy electron created by all gamma interactions and the average energy electron created by all X-ray interactions. As these two electrons are followed on their trajectories, the electrons turn in the earth's B field and slow down while creating thermal energy secondary electrons. The electrons are not deflected from their trajectories by electron scattering in the atmosphere. Self consistent field calculations are usually not attempted.

When such a large number of approximations are used in the calculation of high altitude EMP sources, one must question the accuracy of the EMP sources and subsequently, the accuracy of the EMP fields which result from their use.

Recently more sophisticated approximations have been included in some EMP source codes. For example, Longmire and Longley (Ref. 1) have included approximations which attempt to account for the effect of having a Compton distribution of electrons instead of one representative monoenergetic electron, and for the effect of multiple electron scattering in the atmosphere. Even though it is logical to assume that these more sophisticated approximations should produce more accurate EMP sources, it is impossible to determine the accuracy of the sources unless they can be compared to experimentally obtained data or to more exact theoretical calculations which include all of the physics of the problem.

Presented in this report is the first such set of benchmark calculations which can be used to test the accuracy of approximations used in EMP source calculations. The Monte Carlo method was used to determine the electron currents and ionization rate produced by monoenergetic electrons at various altitudes and with various angles between the initial direction of the electron and the B field of the earth. Included in the calculation were nuclear coulomb electron scattering in the atmosphere, the continuous slowing down method of electron energy loss, and electron turning in the B field of the earth.

The author plans to continue work in the area of high altitude electron transport by studying the effect of electron-electron scattering in the atmosphere and by determining a practical method of including the effect in a Monte Carlo calculation. Then, another set of benchmark calculations will be made to determine the EMP sources produced by the complete distribution of electrons created by monoenergetic gammas and X rays. Included in these Monte Carlo calculations will be the effects of nuclear coulomb scattering, electron-electron scattering, and electron turning in the B field of the earth.

II. Electron Scattering and Energy Loss

The two interactions which must be included in electron transport calculations in air are nuclear coulomb scattering and electron-electron scattering. Electron energy losses by bremsstrahlung interactions are negligible in air for the energy range of the electrons included in these calculations. For example, for a 1 Mev electron in air the bremsstrahlung radiation electron energy loss is only 1.03% of the energy loss due to electron-electron scattering.

A. Nuclear Coulomb Scattering

Electrons are scattered elastically by the coulomb potential of the nuclei of the atmosphere. Since the mass of each nucleus is so much greater than the mass of the electron, the energy loss of the electron is negligible.

The nuclear coulomb scattering cross section is very large and the scattering distribution is peaked in the foreward direction. Thus, an electron undergoes many small angle scatters and a few large angle scatters before the electron loses its energy by electron-electron collisions. For example, in the Monte Carlo calculation of the EMP sources produced by a 0.742 Mev electron, the electron undergoes approximately 4,400 nuclear coulomb scatters while slowing down from 0.742 Mev to 0.001 Mev.

The Rutherford differential cross section for scattering from a coulomb potential into the solid angle $2\pi\ d\mu$ is given by

$$d\sigma_R = 2\pi\rho r_o^2\ z^2 \left(\frac{1-\beta^2}{\beta^4}\right) \frac{d\mu}{(1-\mu)^2} \qquad (1)$$

where σ_R = Rutherford cross section
ρ = atom density of scatterer
r_o = classical electron radius
z = atomic number of scatterer
β = v/c
v = velocity of electron
c = velocity of light
μ = cosine of the scattering angle

To account for the screening effect of the atomic electrons of the scatterer, Moliere (Ref. 2) used the WKB approximation and a Fermi-Thomas potential to derive a screening angle η. The effect of introducing the screening angle is to greatly reduce the Rutherford cross section when the scattering angle is less than η. The screened form of the Rutherford cross section is given by

$$d\sigma_{sc} = 2\pi\rho r_o^2\, z^2 \left(\frac{1-\beta^2}{\beta^4}\right) \frac{d\mu}{(1-\mu+\eta)^2} \qquad (2)$$

where σ_{sc} = screened nuclear coulomb cross section

$$\eta = \frac{1-\beta^2}{2\beta^2}\left[\frac{z^{1/3}}{(0.885)\ (137)}\right]^2 \left[1.13 + 3.76\left(\frac{z}{137\beta}\right)^2\right] \qquad (3)$$

Mott (Ref. 3) started with the Dirac equation and derived a complicated expression for the nuclear coulomb scattering cross section in the form of an infinite series. Mckinley and Feshback (Ref. 4) evaluated Mott's expression by expanding in a power series in α and α/β, where $\alpha = z/137$. By neglecting terms of order α^3 and higher, they derived an expression which is valid for $\alpha < 0.2$. They expressed their result as the ratio R of Mott to Rutherford cross section.

$$R = 1 - \frac{\beta^2}{2}(1-\mu) + \frac{\pi z \beta}{137}\left[\left(\frac{1-\mu}{2}\right)^{1/2} - \frac{1-\mu}{2}\right] \qquad (4)$$

The value of R becomes significant only for large scattering angles. Doggett and Spencer (Ref. 5) used a computer to accurately calculate the ratio of Mott to Rutherford cross section for various values of z and electron energy. Their tabulated values for z=6 (closest to air) agree within 1% to values obtained using equation (4).

Rester and Rainwater (Ref. 6) experimentally measured the differential cross section for coulomb scattering of electrons by aluminum for scattering angles between 30 and 150 degrees and for electron energies between 0.1 and 3.0 Mev. They found that all of their measured values of cross section agreed within the experimental error with the theoretical Mott cross sections.

The nuclear coulomb differential cross sections used for the Monte Carlo calculations presented in this report include both the screened form of the Rutherford cross section given in equation (2) and the ratio of Mott to Rutherford cross section given in equation (4).

$$d\sigma = R \, d\sigma_{sc} \qquad (5)$$

B. Electron-Electron Scattering

When electrons scatter inelastically from the atomic electrons of air, the incident electrons lose energy and can free the atomic electrons from the atom. Most of the secondary or knock-on electrons thus created have so little kinetic energy that they do not create additional ionization But the secondary electrons created by large angle scattering can have sufficient energy to create additional ionization. In order to do an "exact" Monte Carlo calculation of timedependent EMP sources, one must include electron-electron scattering collisions and must include the histories of the primary electrons and of all secondary electrons which can create additional ionization.

A method of calculation which would probably yield fairly accurate results would be to use the Moller (Ref. 7) electron-electron scattering cross sections for electron energy losses (or scattering angles) above some minimum value and to use the restricted stopping power given by Berger and Seltzer (Ref. 8) to account for electron energy losses for small angle scattering. This method was not used for the set of calculations performed for this report because the inclusion of electron-electron scattering cross sections and of a system for storing and following the secondary electrons created would complicate the Monte Carlo code and would necessitate a much longer computer run time for each solution. Also, a comparison of nuclear coulomb cross sections with electron-electron cross sections showed that at most electron energies and scattering angles the nuclear coulomb cross section is approximately a factor of six to eight larger than the electron-electron cross section. Therefore, most of the effects of electron scattering on the EMP sources can be determined by using only nuclear coulomb scattering cross sections and by using the electron stopping power to calculate the energy loss rate of the primary electrons. However, as was stated in the introduction, the author plans to include electron-electron scattering effects in a later set of benchmark calculations.

Berger and Seltzer (Ref. 8) have used the most recent theories of electron stopping power to publish tables of stopping power for electrons in many materials. They use Bethe's (Ref. 9) stopping power theory as formulated by

Rohrlich and Carlson (Ref. 10). They also include a density correction factor developed by Sternheimer (Ref. 11). The stopping power or average electron energy loss per unit path length due to electron-electron collisions is given by

$$\left(\frac{dE}{ds}\right)_{coll} = 2\pi\rho r_o^2 \; mc^2 \; \frac{z}{\beta^2} \left\{ \ln\left[\frac{T^2(T+2)}{2(I/mc^2)^2}\right] + F(T) - \delta \right\} \qquad (6)$$

where

mc^2 = rest mass energy of the electron

T = kinetic energy of electron in mc^2 units

I = mean excitation energy

δ = density correction factor

$$F(T) = 1-\beta^2 + \left[T^2/8-(2T+1)\ln 2\right]/(T+1)^2 \qquad (7)$$

and all other variables have been previously defined. Berger and Seltzer list a value of 86.8 ev for the mean excitation energy of air. The density correction factor is negligible for the electron energies considered in this report.

III. Monte Carlo EMP Source Calculations

A. Geometry

The geometry used in the one-dimensional high altitude EMP field code at the Air Force Weapons Laboratory is an r, θ, ϕ, τ coordinate system. At any point in the atmosphere where the EMP sources are calculated for the field code, the coordinate system is defined by

$\hat{e}_r$ = unit vector directed radially away from the weapon burst

$\hat{e}_\phi$ = unit vector in the direction $\bar{B} \times \hat{e}_r$ where $\bar{B}$ is the geomagnetic field of the earth

$\hat{e}_\theta = \hat{e}_\phi \times \hat{e}_r$

τ = retarded time

$= t - r/c$

t = real time

r = radial distance from the weapon

The ionization rate and the three components of the electron current will be presented in this coordinate system. However, it is easier to follow an electron throughout its history in an x, y, z, t coordinate system, where

$\hat{e}_x$ = unit vector in direction of $\bar{B}$

$\hat{e}_z$ = unit vector in direction $\hat{e}_x \times \hat{e}_r$

$\hat{e}_y$ = unit vector in direction $\hat{e}_z \times \hat{e}_x$

t = real time

and then to transform to the r, θ, ϕ, τ coordinate system before scoring the results.

B. Electron History

Starting the Monte Carlo history, the initial electron parameters are $x, y, z, c_x, c_y, c_z, E, t$ where

x, y, z = position coordinates of the electron

c_x, c_y, c_z = direction cosines of the electron direction with respect to x, y, z

E = energy of the electron

t = real time

The electron travels a distance ℓ before undergoing a nuclear coulomb scatter. As the electron travels this distance ℓ, it loses energy by the continuous slowing down process and changes direction by turning in the B field of the earth. Since the energy loss between collisions is very small, little error results by assuming that the speed and stopping power of the electron are constant between collisions. The new electron parameters after traveling a distance ℓ are $x', y', z', c_x', c_y', c_z', E', t'$ where

$$t' = t + \ell/v \qquad (8)$$

v = velocity of the electron

$$E' = E - \ell S \qquad (9)$$

S = stopping power of the electron

$$c_x' = c_x \qquad (10)$$

$$c_y' = c_y \cos\phi - c_z \sin\phi \qquad (11)$$

$$c_z' = c_z \cos\phi + c_y \sin\phi \qquad (12)$$

ϕ = angle through which the electron turns in distance ℓ

$$= f\ell/v \qquad (13)$$

$$f = \frac{qB}{m}(1-\beta^2)^{1/2} \qquad (14)$$

q = electron charge

B = earth's B field strength

m = rest mass of electron

$$x' = x + c_x \ell \qquad (15)$$

$$y' = y + \frac{v}{f}(c_z' - c_z) \qquad (16)$$

$$z' = z + \frac{v}{f}(c_y - c_y') \qquad (17)$$

After traveling the distance ℓ, the electron undergoes a nuclear coulomb scatter. The electron changes direction without loss of energy. The parameters of the electron after scattering are $x', y', z', c''_x, c''_y, c''_z, E', t'$ where

$$c''_x = c'_x \mu - c'_y \frac{b}{a} \cos\phi - c'_x c'_z \frac{b}{a} \sin\phi \tag{18}$$

$$c''_y = c'_y \mu + c'_x \frac{b}{a} \cos\phi - c'_y c'_z \frac{b}{a} \sin\phi \tag{19}$$

$$c''_z = c'_z \mu + ab \sin\phi \tag{20}$$

$$a = (c'^2_x + c'^2_y)^{1/2} \tag{21}$$

$$b = (1-\mu^2)^{1/2} \tag{22}$$

μ = cosine of the scattering angle

ϕ = azimuthal scattering angle

Starting with the electron parameters after the collision one continues the Monte Carlo history by choosing a new distance ℓ and by repeating the above set of calculations until the electron energy is reduced to some specified minimum value.

C. Use of Random Numbers to Choose ℓ, μ, and ϕ

The distance the electron travels between collisions ℓ and the scattering parameters at each collision μ and ϕ are chosen in the Monte Carlo calculation by using randomly chosen numbers with values between zero and one. The random number generator used for the set of Monte Carlo calculations in this report is a systems function subroutine available on the CDC 6600 computer at the Air Force Weapons Laboratory.

If p(x)dx is the probability of an event occurring between x and x + dx, then the integral of p(x)dx over all x is unity.

$$\int_0^\infty p(x)dx = 1 \qquad (23)$$

If g is a random number between 0 and 1, then by setting

$$g = \int_0^x p(x)dx \qquad (24)$$

it is obvious that for every value of g, equation (24) produces a corresponding value of x. This is the method used to choose the values of ℓ, μ, and ϕ in the Monte Carlo calculation.

To choose the distance between scatters, let $p(\ell)d\ell = \sigma e^{-\sigma\ell}d\ell$, where σ is the nuclear coulomb scattering cross section. Then use equation (24) to solve for the value of ℓ corresponding to the random number g.

$$\ell = -\frac{1}{\sigma}\ n(1-g) \qquad (25)$$

or use the equivalent equation

$$\ell = -\frac{1}{\sigma}\ n(g) \qquad (26)$$

Scattering is symmetric about the direction of the electron before scattering, so that $p(\phi)d\phi = \frac{1}{2\pi}\ d\phi$.

Again use equation (24) to solve for ϕ.

$$\phi = 2\pi g \qquad (27)$$

To choose the cosine of the scattering angle μ, one would use $p(\mu)d\mu = \frac{1}{\sigma}\ d\sigma$, where $d\sigma$ is defined by equation (5). The correct form of equation (24) would now be

$$g = \int_{-1}^{\mu} \frac{d\sigma}{\sigma} \qquad (28)$$

However, equation (28) cannot be solved analytically for the value of μ corresponding to the random number g.

It is possible to perform the integration and set up tables of μ versus g. But an easier method is to choose μ from an approximate scattering probability density function which can be used to analytically solve for the value of μ, and then to correct the weight of the electron to account for the difference between the approximate scattering function and the real scattering function. The equation used to choose μ in this set of calculations was

$$g = \int_{-1}^{\mu} \frac{d\sigma_{sc}}{\sigma_{sc}} \tag{29}$$

where $d\sigma_{sc}$ is defined by equation (2). Now equation (29) can be solved for μ in terms of g.

$$\mu = \frac{2g(1+\eta)-\eta}{2g+\eta} \tag{30}$$

The weight factor of the electron after the collision is corrected by multiplying the weight of the electron before the collision by the ratio of the real scatter probability to the approximate scatter probability both evaluated at the value of μ chosen for the collision.

$$N_a = N_b \frac{\sigma_{sc} d\sigma(\mu)}{\sigma d\sigma_{sc}(\mu)} \tag{31}$$

where N_a = weight after collision

N_b = weight before collision

and $d\sigma_{sc}$ and $d\sigma$ are defined by equations (2) and (5).

D. Scoring the Monte Carlo Results

Although the purpose of this set of calculations was to provide a benchmark set of calculations which is as accurate as possible, two approximations were used to simplify the calculation and reduce the amount of computer run time.

The approximations used were that the air density encountered by an electron remained constant over the entire electron history and was equal to the air density at the altitude at which the electron was created; and that the source of primary electrons was a delta function in retarded time and was constant over the range of an electron at any altitude. These are normal approximations used by every EMP source code. These are excellent approximations at most altitudes and generally should produce errors no larger than 25%.

The advantage of using these assumptions is that over the entire range of the electron at any altitude, the density of electrons is constant in retarded time. In other words in retarded time the divergence of the electron density is zero. Therefore, to calculate the EMP sources created by an electron at a given altitude, it is only necessary to start the electron history at that altitude, to follow the electron over its entire history, and to score the EMP sources created in retarded time at the retarded time corresponding to the position of the electron. It is not necessary to score the sources as a function of position because the electron density is constant in retarded time everywhere in the space determined by the electron range.

Before the results are scored, the position and time of each electron collision is transformed from the x,y,z,t coordinate system to the r,θ,ϕ,τ coordinate system. Since the weight factor of the electron changes at every collision, it is necessary to score the electron currents and ionization rate at every collision. Between any two successive collisions, if N is the electron weight, $\Delta r, \Delta\theta$, and $\Delta\phi$ are the changes in the three position coordinates, and $\Delta\tau$ is the change in retarded time, then the three components of the electron current are simply

$$J_r = \frac{Ne\Delta r}{\Delta\tau} \quad (32)$$

$$J_\theta = \frac{Ne\Delta\theta}{\Delta\tau} \quad (33)$$

$$J_\phi = \frac{Ne\Delta\phi}{\Delta\tau} \quad (34)$$

where e is the electron charge.

To calculate the ionization rate in this set of calculations, the energy loss of the primary electron was converted directly to ion pairs at the rate of 34 ev per ion pair. This method assumes that all secondary electrons are instantly thermalized. Better methods of electron ionization and thermalization will be included when electron-electron scattering effects are included in the Monte Carlo code. With the present method if ΔE represent the energy loss of the primary electron between collisions, the ionization rate is

$$I = \frac{N\Delta E}{(3.4\times10^{-5})\Delta\tau} \quad (35)$$

E. Monte Carlo Statistics

The Monte Carlo calculation was run in sets of 100 electron histories. The average value of electron current or ionization rate in each time bin for each set of 100 histories was used as a sample. If K is the number of samples and Q_i is the ith value of either electron current or ionization rate, then an estimate of the mean and variance of Q'is

$$\overline{Q} = \frac{1}{K}\sum_{i=1}^{K} Q_i \quad (36)$$

$$\gamma^2 = \frac{1}{K(K-1)}\left[\sum_{i=1}^{K} Q_i^2 - \frac{\left(\sum_{i=1}^{K} Q_i\right)^2}{K}\right] \qquad (37)$$

The square root of the variance γ is the standard deviation from the mean.

IV. Results and Discussion

Monte Carlo calculations of the EMP sources created by monoenergetic electrons including the effects of nuclear coulomb scattering, continuous slowing down energy loss, and turning in the B field of the earth were performed for 16 different sets of initial conditions. Sources were calculated for a 0.742 Mev electron at 20 kilometers altitude, a 0.742 Mev electron at 40 kilometers altitude, a 0.1 Mev electron at 40 kilometers altitude, and a 0.05 Mev electron at 60 kilometers altitude. The initial direction of the electron was assumed to be radially away from the weapon burst. For each of the four sets of initial electron energies and altitudes given above, the sources were calculated for each of the four conditions that the angle between the radial direction and the B field of the earth was 0°, 30°, 60° and 90°.

The 0.742 Mev electron is the average energy Compton electron produced by a 1.5 Mev gamma scatter in air. The 0.1 and 0.05 Mev electrons were used to represent the lower energy electrons which might be produced by X rays. The different altitudes and initial angles between the direction of the electron (radial direction) and the B field of the earth were chosen to provide an interesting cross section of initial conditions to show the effects of nuclear coulomb electron scattering on the calculation of high-altitude EMP sources.

Included in the appendix are graphs of the electron currents and ionization rates calculated for each of the 16 sets of initial conditions. The three initial conditions of electron energy, altitude, and angle between the radial direction and the B field of the earth are given in the upper right hand corner of each graph. All values of current and ionization rate were calculated using a source of primary electrons of one electron/m^3 and an earth's B field strength of 5.6×10^{-5} webers/m^2 (0.56 gauss). Air densities were taken from <u>U.S. Standard Atmosphere, 1962</u> (Ref. 12). The air density at 20 kilometers altitude is 3.6974×10^{24} atoms/m^3, at 40 kilometers 1.6616×10^{23} atoms/m^3, and at 60 kilometers 1.2722×10^{22} atoms/m^3.

The histogram on each plot is the Monte Carlo results including nuclear coulomb scattering. The error bars on the histogram represent values of $\overline{Q} \pm \gamma$ as explained in Monte Carlo Statistics (section III E.). The error bars were not plotted for the few cases where $\gamma > \overline{Q}$. The zeros on any solid histogram mean that all values on that part of the histogram are negative. Any break or discontinuity in a histogram indicates a change of sign.

Because of various symmetries set up by the initial conditions, it is obvious that some of the EMP sources are always zero. When the angle between the radial direction and the direction of the B field of the earth is 0°, both transverse currents (J_θ and J_ϕ) are zero. When the angle is 90°, J_θ is zero. For these cases where it is known that the sources are always zero, plots of Monte Carlo results are not given in the appendix.

The smooth curve on each graph is a plot of the EMP sources for the same initial conditions but <u>without</u> nuclear coulomb scattering. The same Monte Carlo code was used to calculate the sources without scatter as was used to calculate the sources with scatter. In the calculation of sources without scattering, at each nuclear coulomb collision the cosine of the scattering angle was always set equal to one. Since the trajectory of each electron is the same throughout its entire history when there is no electron scattering, the standard deviation from the mean is zero in every time bin, and no error bars appear on the plots of sources without scattering.

The overlay plots of sources with and without nuclear coulomb scattering allows one to immediately see the effect of electron scattering on the high altitude EMP sources. A brief discussion of some of these effects will follow. But since the magnitude of the effect can depend strongly on the given initial conditions, the reader can best observe the various effects by examining each individual overlay.

The general effect of nuclear coulomb electron scattering on the ionization rate in retarded time is to reduce the rate and extend it to later retarded times. At 20 kilometers altitude (for example, page 25) electron scattering can reduce the ionization rate by almost a factor of two over the normal lifetime of the electron without scattering and can extend the ionization rate or electron lifetime in retarded time by as much as a factor of six. At higher altitudes such as 40 kilometers for a 0.742 Mev electron (example, page 40) where the electron lifetime is long enough so that the electron completes more than one revolution in the earth's B field, electron scattering not only reduces the ionization rate and extends it to later times, it also eliminates most of the peaking seen in the ionization rate without scattering at the times when the electron completes a revolution in the B field.

The effect of electron scattering on the electron currents is in part similar to the effect on the ionization rate, i.e., the currents are reduced and extended to later times. But there are a few more complicated effects on the currents which should be discussed. One effect is important in that it is an effect that definitely does not appear when using any of the approximate methods of electron transport presently being used in any of the EMP source codes known to this author.

That effect is the change of sign in the late time currents (example, page 26). The change can easily be explained by the fact that the electron lifetime <u>in retarded time</u> depends on the angle between the electron direction and the radial direction. The electron lifetime increases with increasing angle. Therefore, the majority of electrons which last long enough to create currents at the late times where the change of sign occurs are electrons which have backscattered so that the angle between the electron direction and the radial direction is larger than 90°. Thus, the current must reverse in sign when the backscattered electrons are the major contributors to the electron current.

For initial condition such that the electron completes more than one revolution in the B field in its lifetime, and such that the angle between the radial direction and the B field direction is large enough so that the current changes sign many times, the effect of electron scattering on the calculation of currents is very complicated (examples, pages 43,45,49). Electron scattering not only reduces peak values, but it also changes the time histories enough so that the changes of sign in the current occur at different times. It is doubtful that any of the presently used transport approximations is capable of accurately handling this complicated effect.

The time and altitude at which electron scattering effects become important in the calculation of EMP sources naturally depends on the electron collision rate at the given altitude. It is obvious from a brief survey of the results in the appendix that for accurate calculation of late-time EMP sources, electron scattering is important at all altitudes. For altitudes as low as 20 kilometers, electron scattering effects may be important at times which could affect peak field calculations.

References

1. C.L. Longmire and H.J. Longley, Improvements in the Treatment of Compton Current and Air Conductivity in EMP Problems, Theoretical Note 128, 22 October 1971 (also MRC-N-2)
2. G. Moliere, Z. Naturforsch. 2a, 133 (1947)
3. N.F. Mott, Proc. Roy. Soc. London, Ser A124, 426 (1929)
4. W.A. McKinley and H. Feshback, Phys Rev 74, 1759 (1948)
5. J.A. Doggett and L.V. Spencer, Phys Rev 103, 1597 (1956)
6. D.H. Rester and W.J. Rainwater, Jr., Phys Rev 140, A165 (1965)
7. C. Moller, Ann. Physik 14, 531 (1932)
8. M.J. Berger and S.M. Seltzer, Tables of Energy Losses and Ranges of Electrons and Positrons, NASA SP-3012, 1964.
9. H.A. Bethe, Ann. Physik, 5, 325 (1930)
10. F. Rohrlich and B.C. Carlson, Phys Rev 93, 38 (1954)
11. R.M. Sternheimer, Phys Rev 88, 851 (1952); 91, 256 (1953); 103, 511 (1956)
12. U.S. Standard Atmosphere, 1962. National Aeronautics and Space Administration, December 1962.

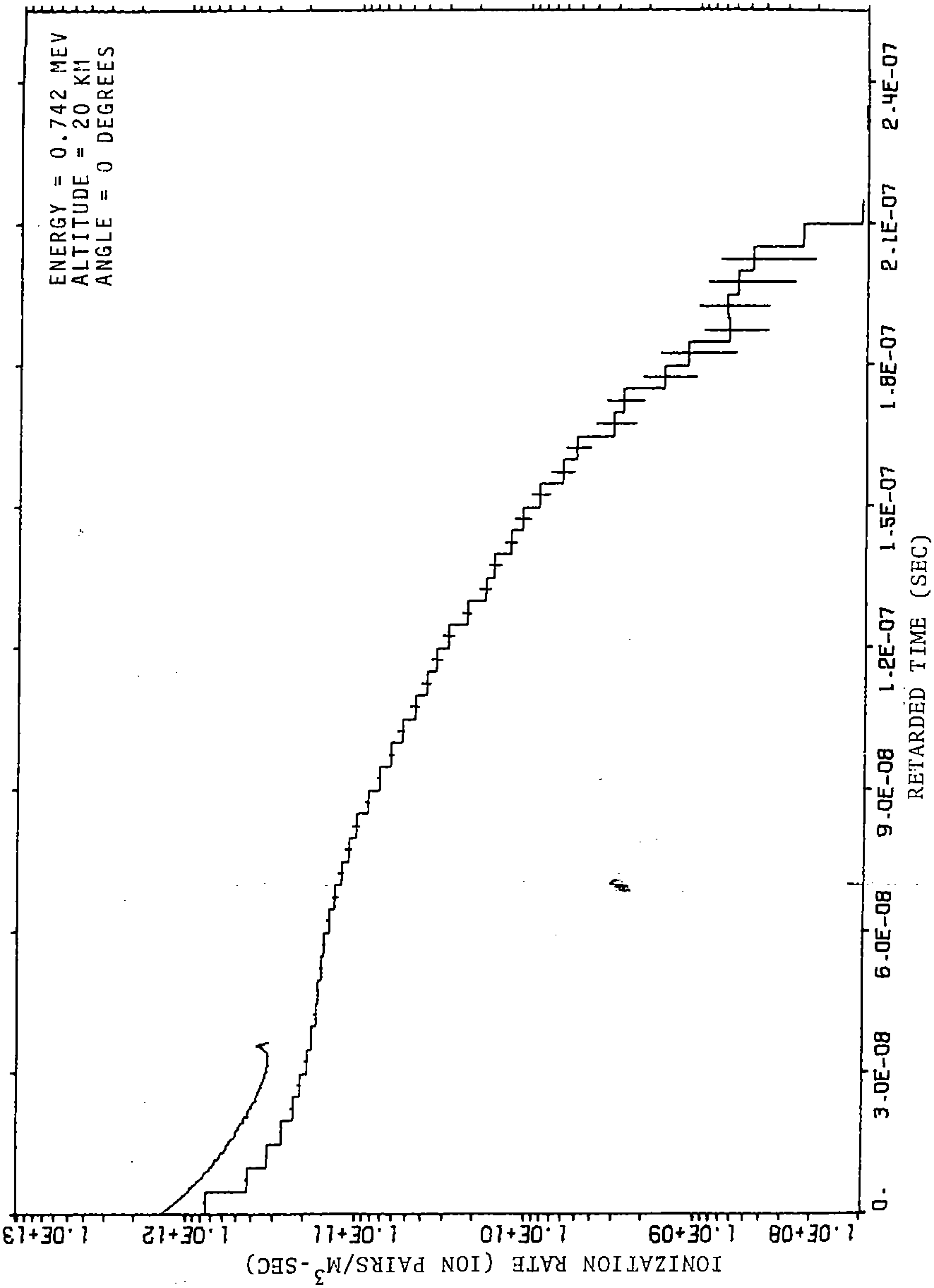
Appendix

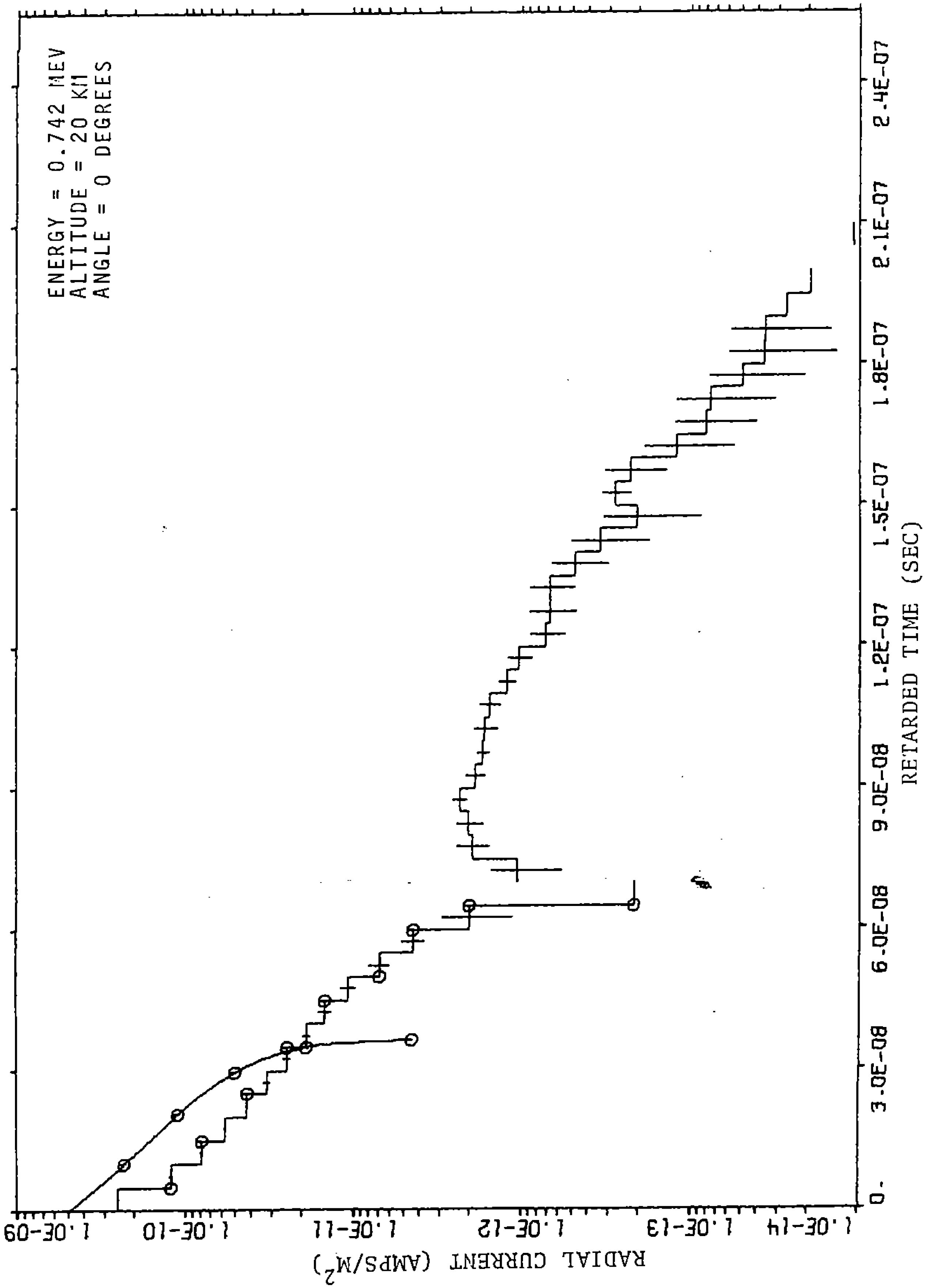
Graphs of EMP Sources With and Without The Effects of Nuclear Coulomb Scattering

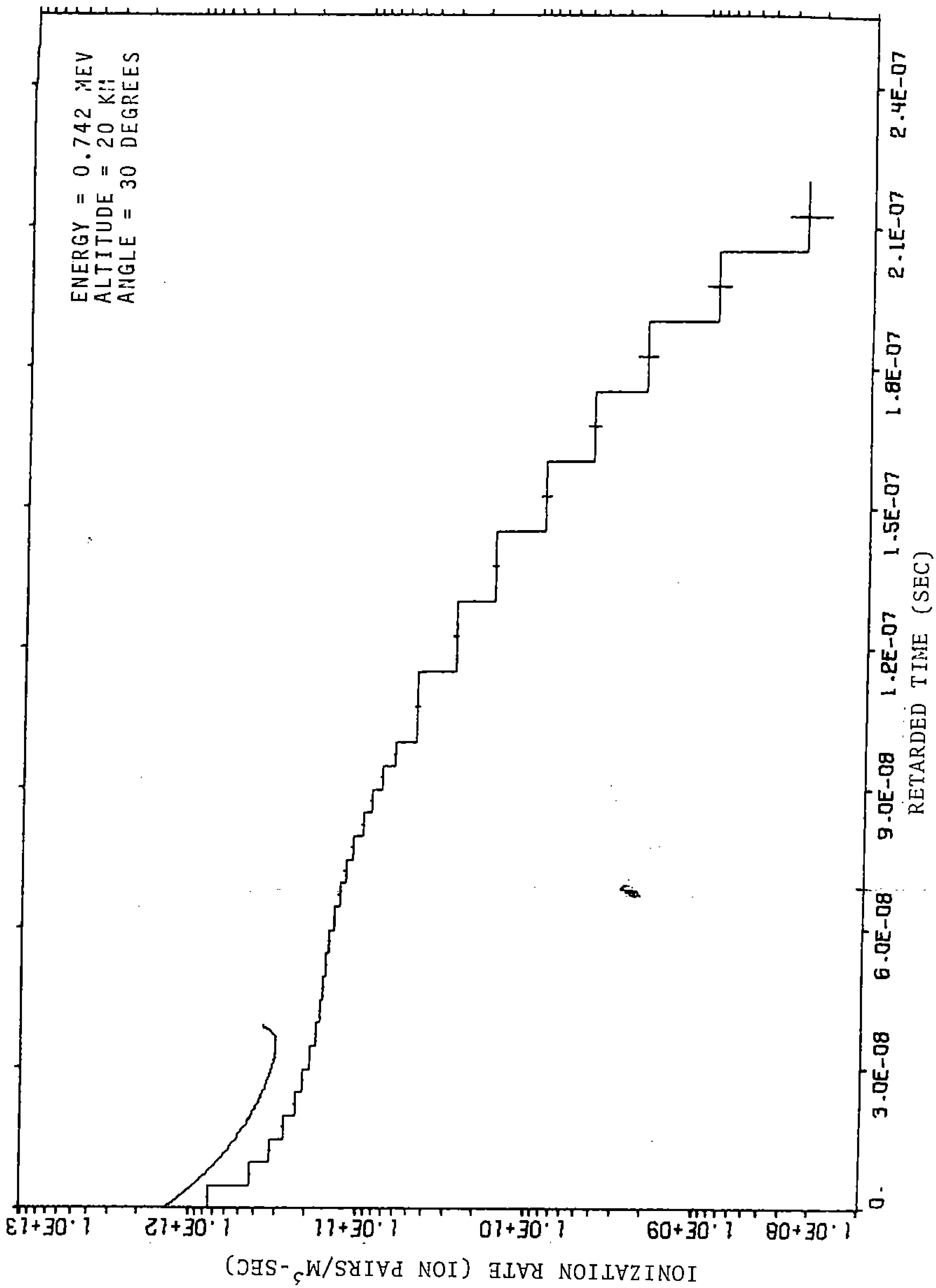
Plot Reference Guide

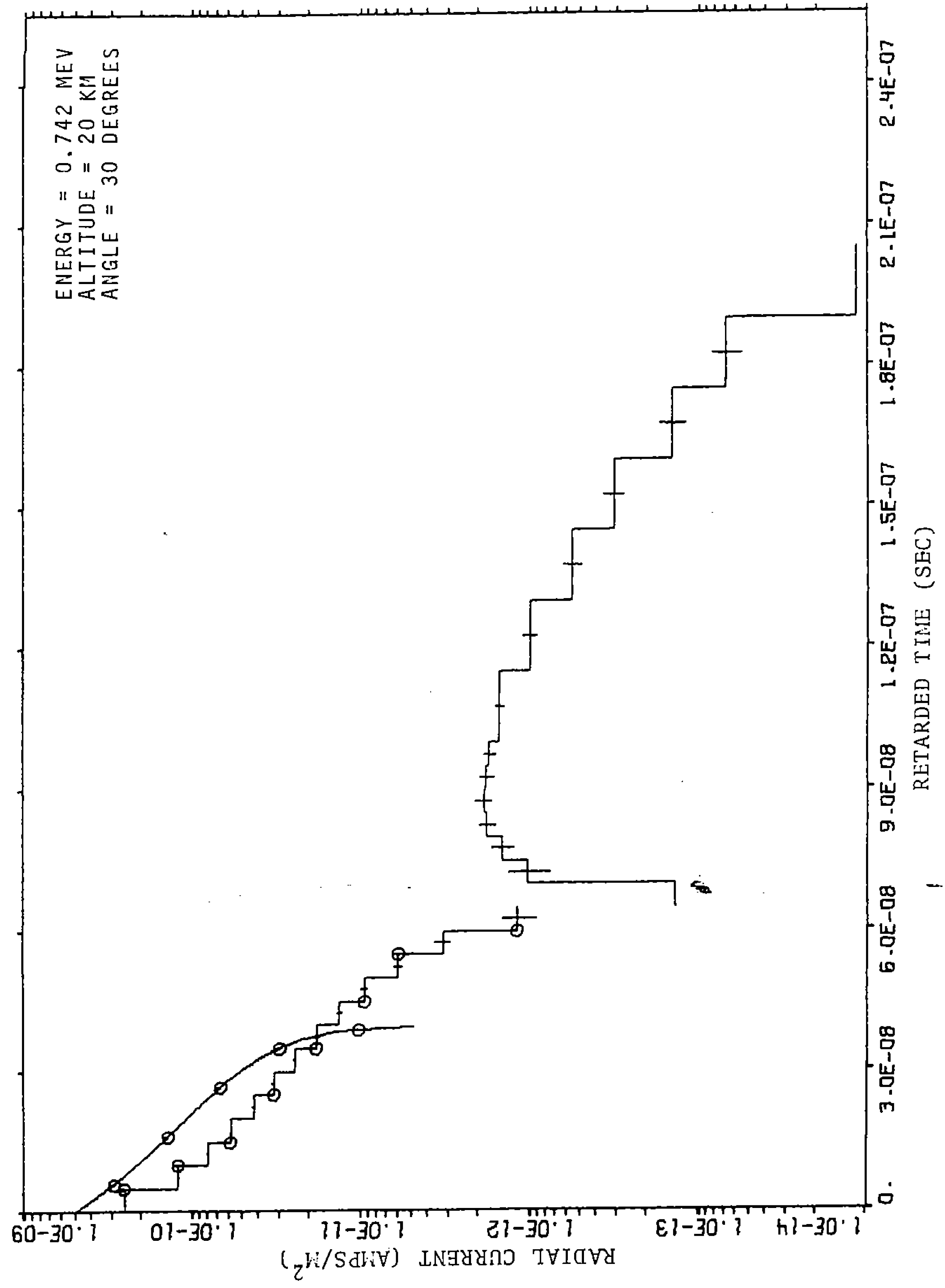
Initial Conditions

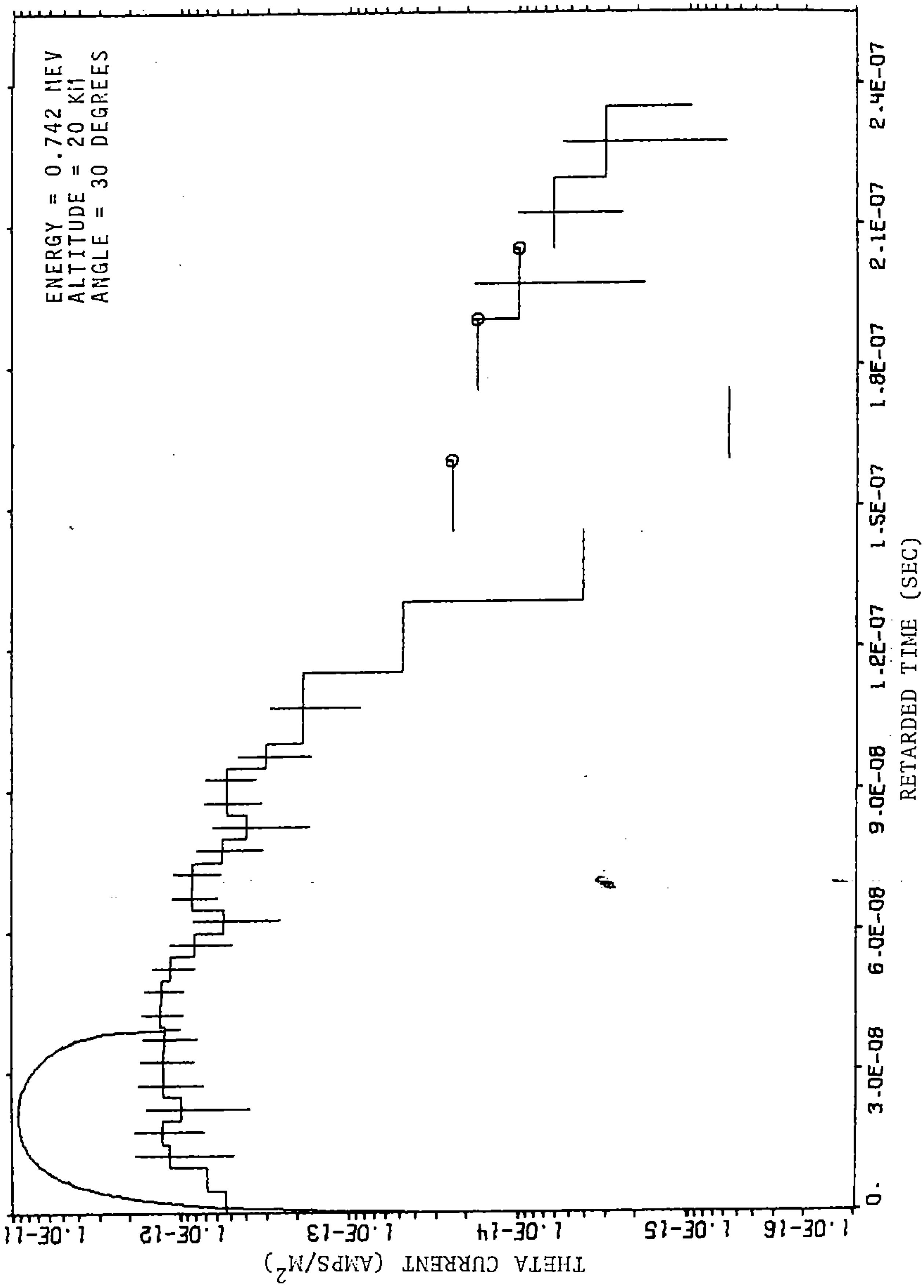
Energy (Mev)	Altitude (Km)	Angle (Degrees)	Plots of EMP Sources Page Numbers
0.742	20	0	25-26
0.742	20	30	27-30
0.742	20	60	31-34
0.742	20	90	35-37
0.742	40	0	38-39
0.742	40	30	40-43
0.742	40	60	44-47
0.742	40	90	48-50
0.1	40	0	51-52
0.1	40	30	53-56
0.1	40	60	57-60
0.1	40	90	61-63
0.05	60	0	64-65
0.05	60	30	66-69
0.05	60	60	70-73
0.05	60	90	74-76

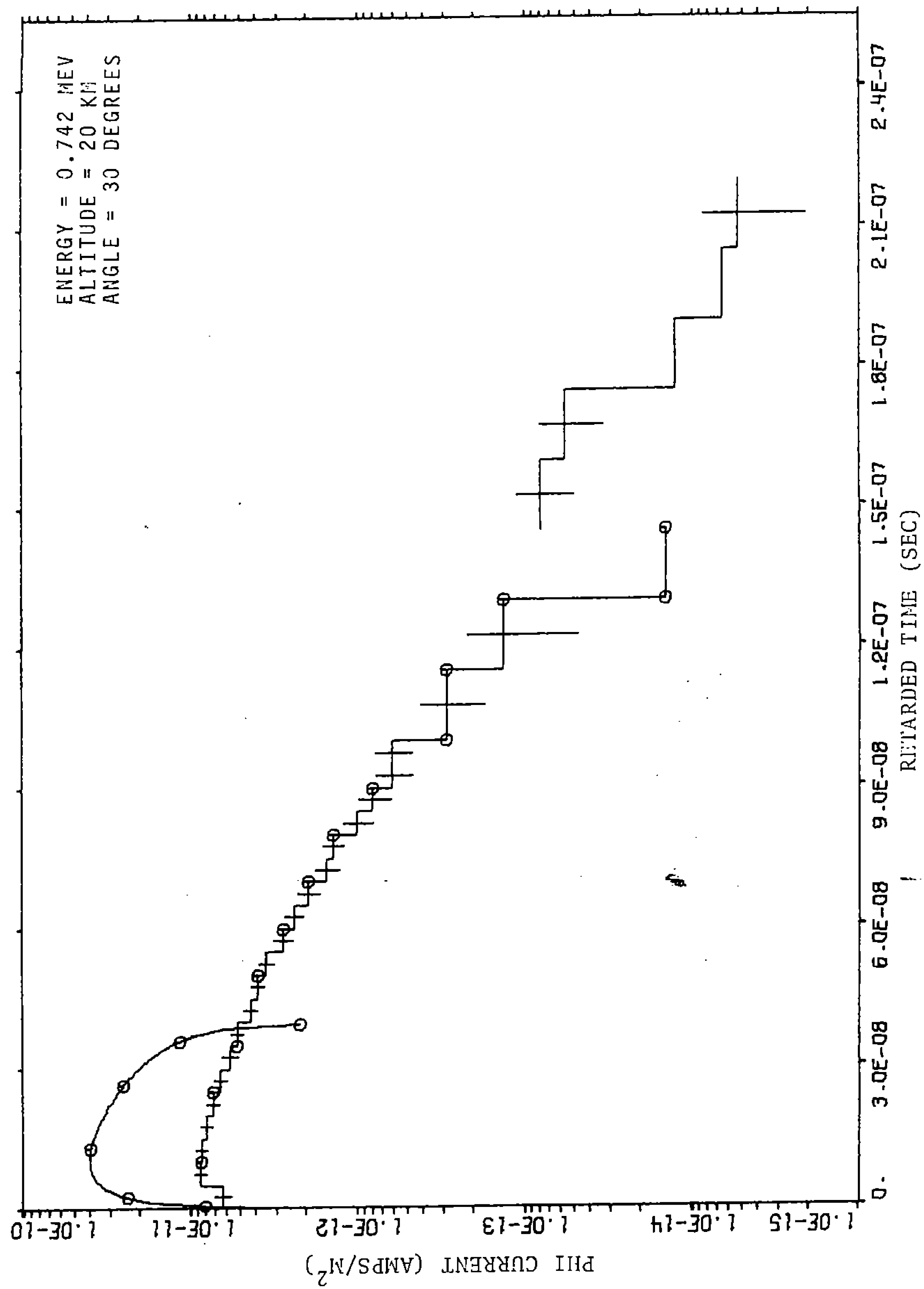

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 0 DEGREES
RETARDED TIME (SEC)
IONIZATION RATE (ION PAIRS/M^3-SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13

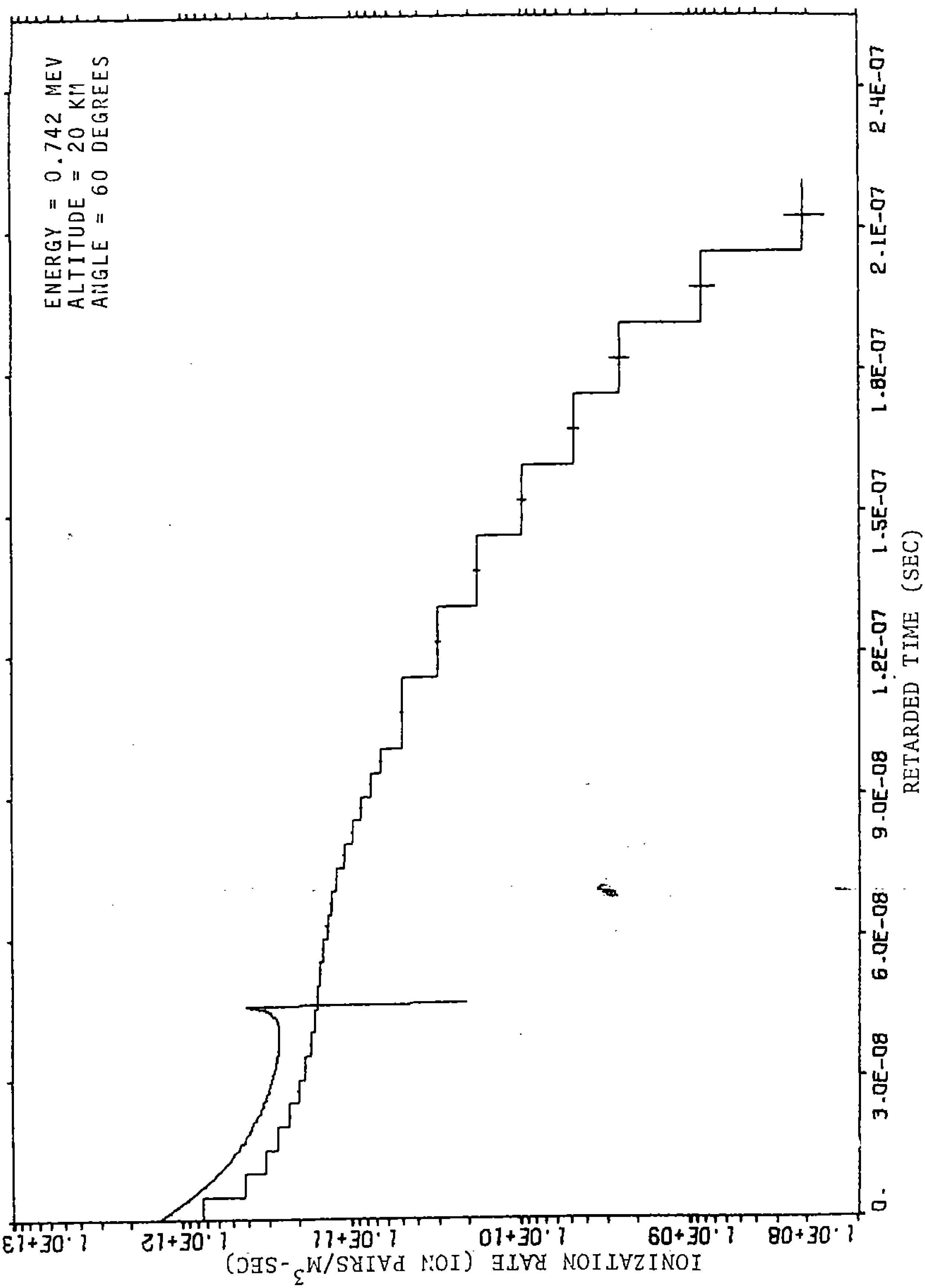

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 0 DEGREES
RADIAL CURRENT (AMPS/M^2)
RETARDED TIME (SEC)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07

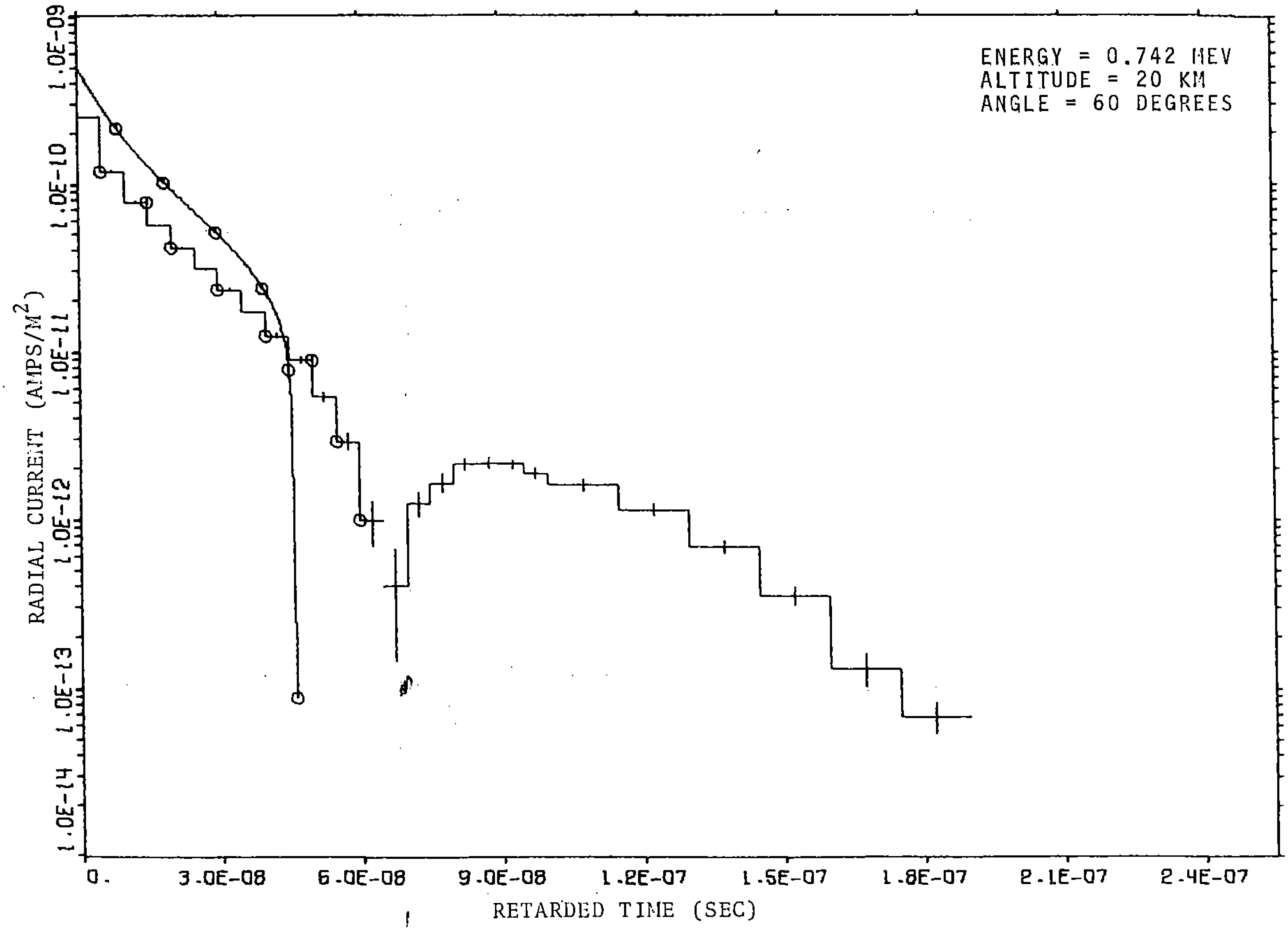

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 30 DEGREES
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
RETARDED TIME (SEC)
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13
IONIZATION RATE (ION PAIRS/M3-SEC)

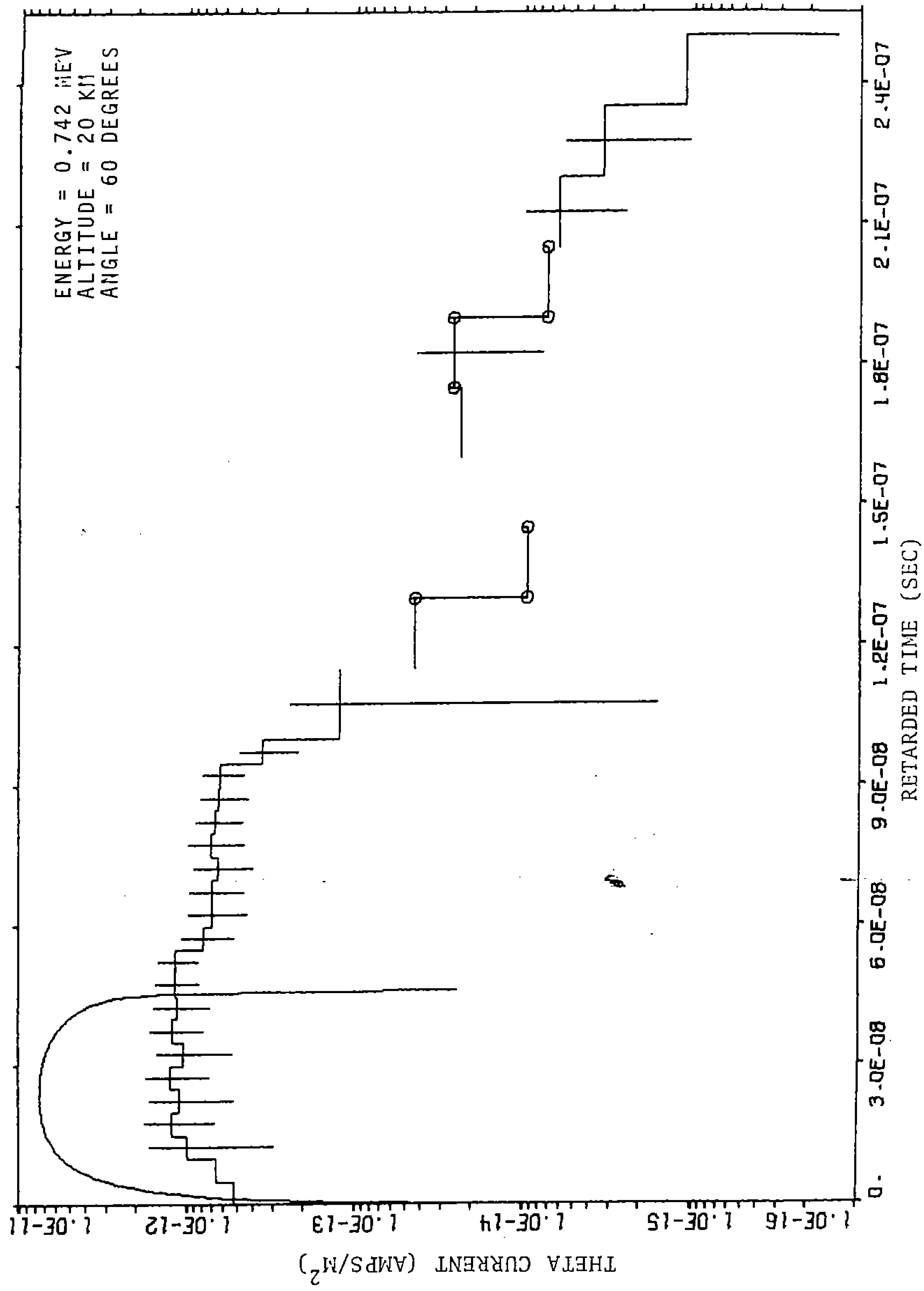

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 30 DEGREES
RADIAL CURRENT (AMPS/M2)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
RETARDED TIME (SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07

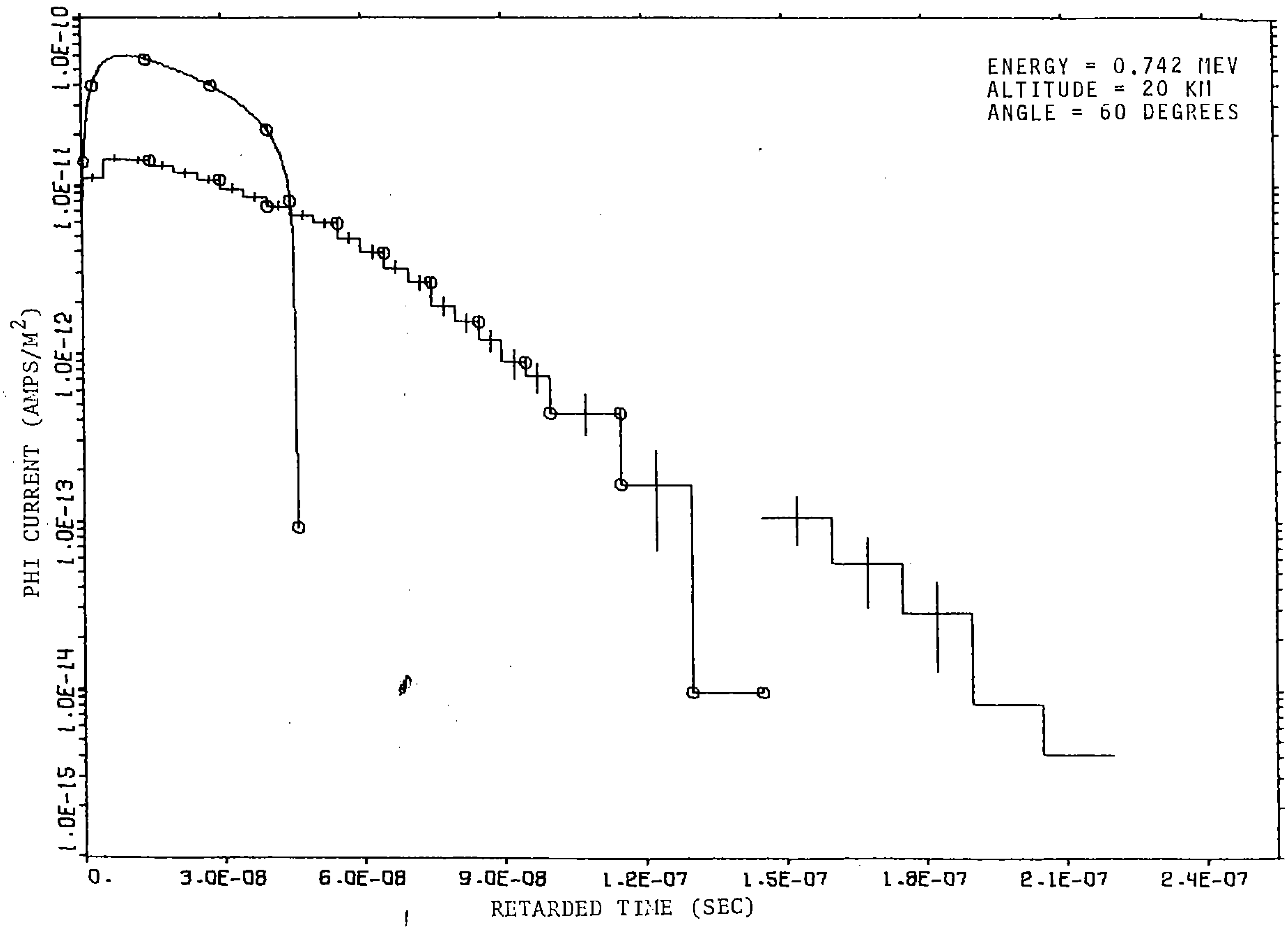

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 30 DEGREES
RETARDED TIME (SEC)
THETA CURRENT (AMPS/M^2)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16

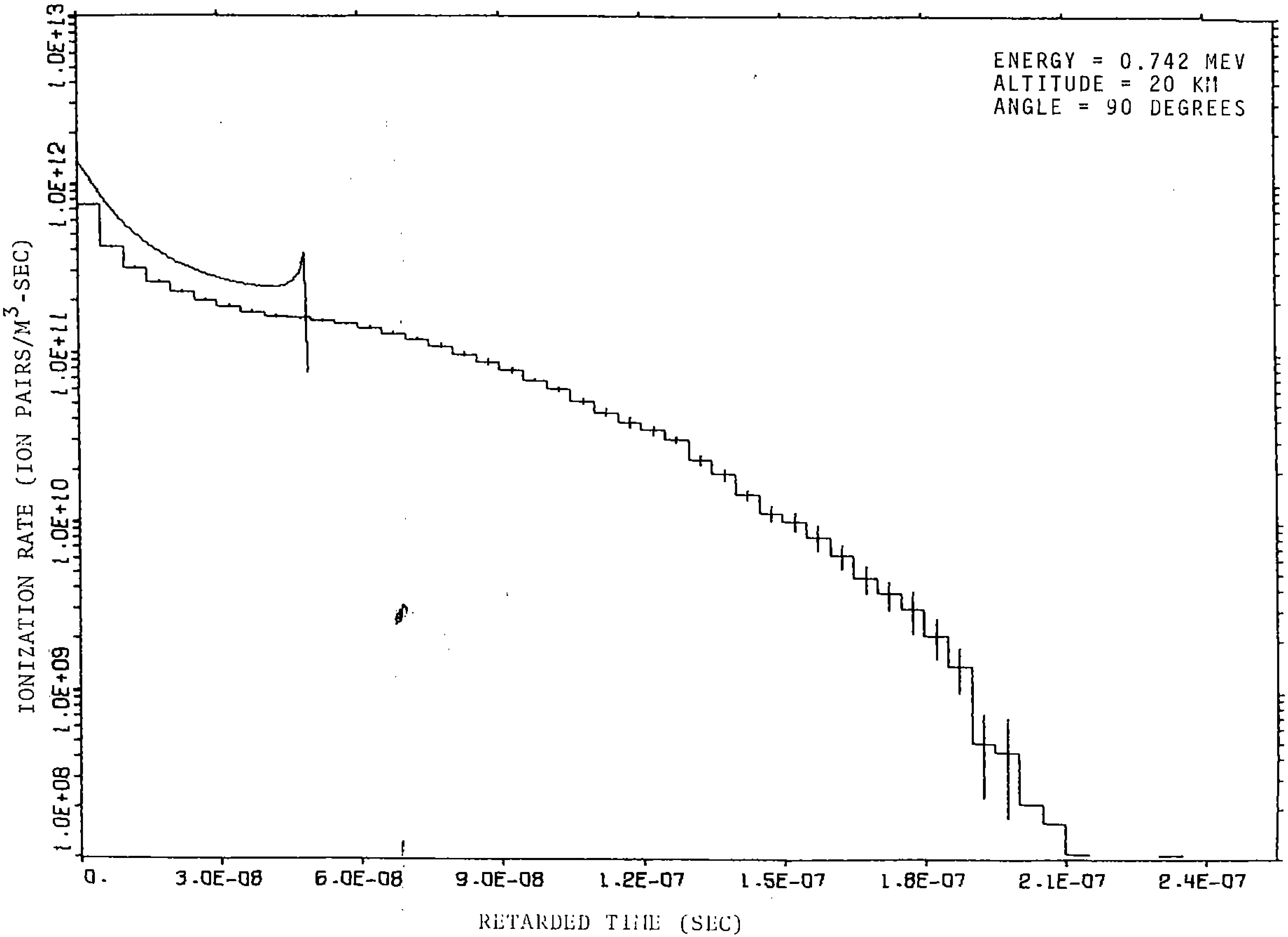

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 30 DEGREES
RETARDED TIME (SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
PHI CURRENT (AMPS/M^2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

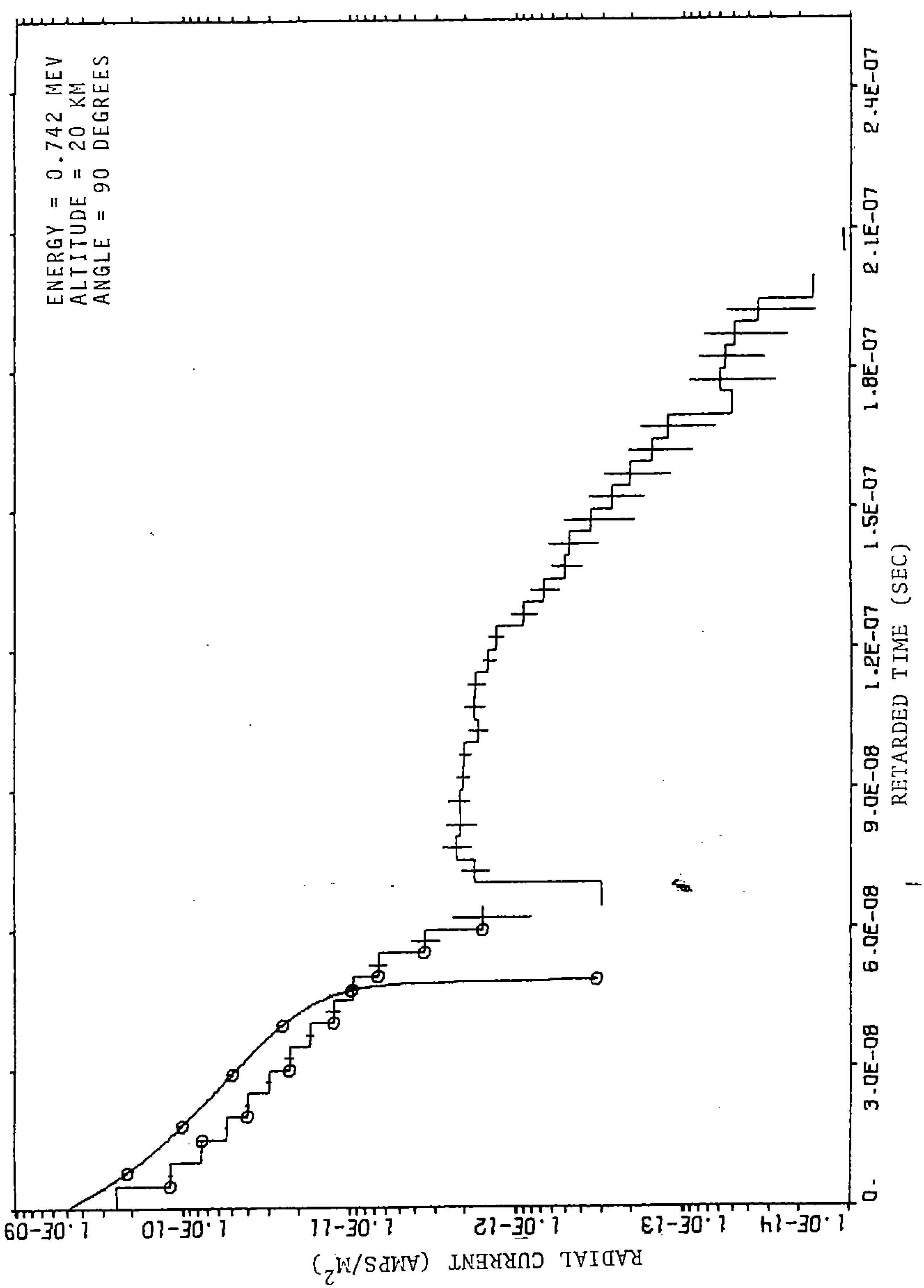

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
IONIZATION RATE (ION PAIRS/M³-SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13

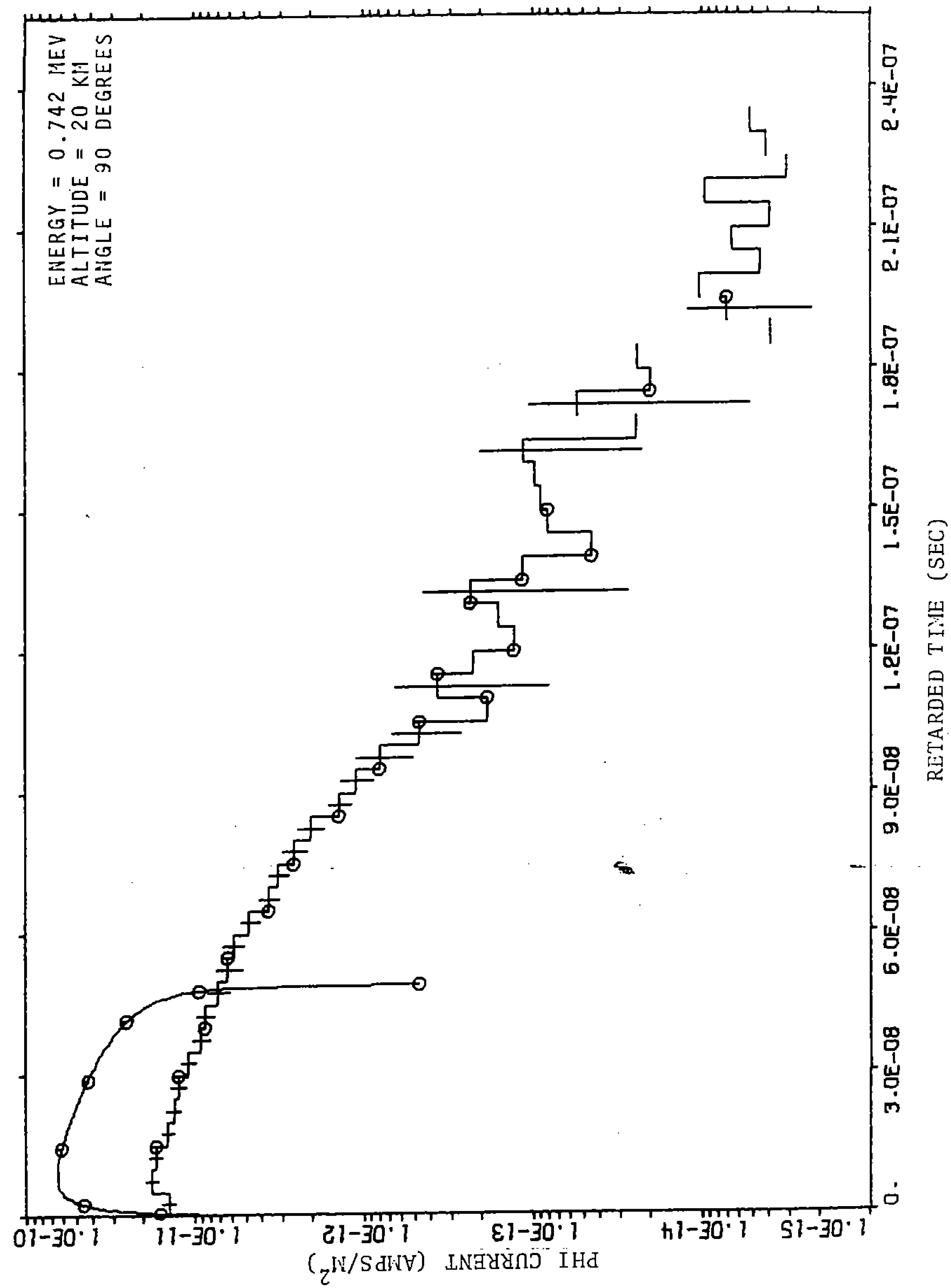

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 60 DEGREES
RADIAL CURRENT (AMPS/M²)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
RETARDED TIME (SEC)

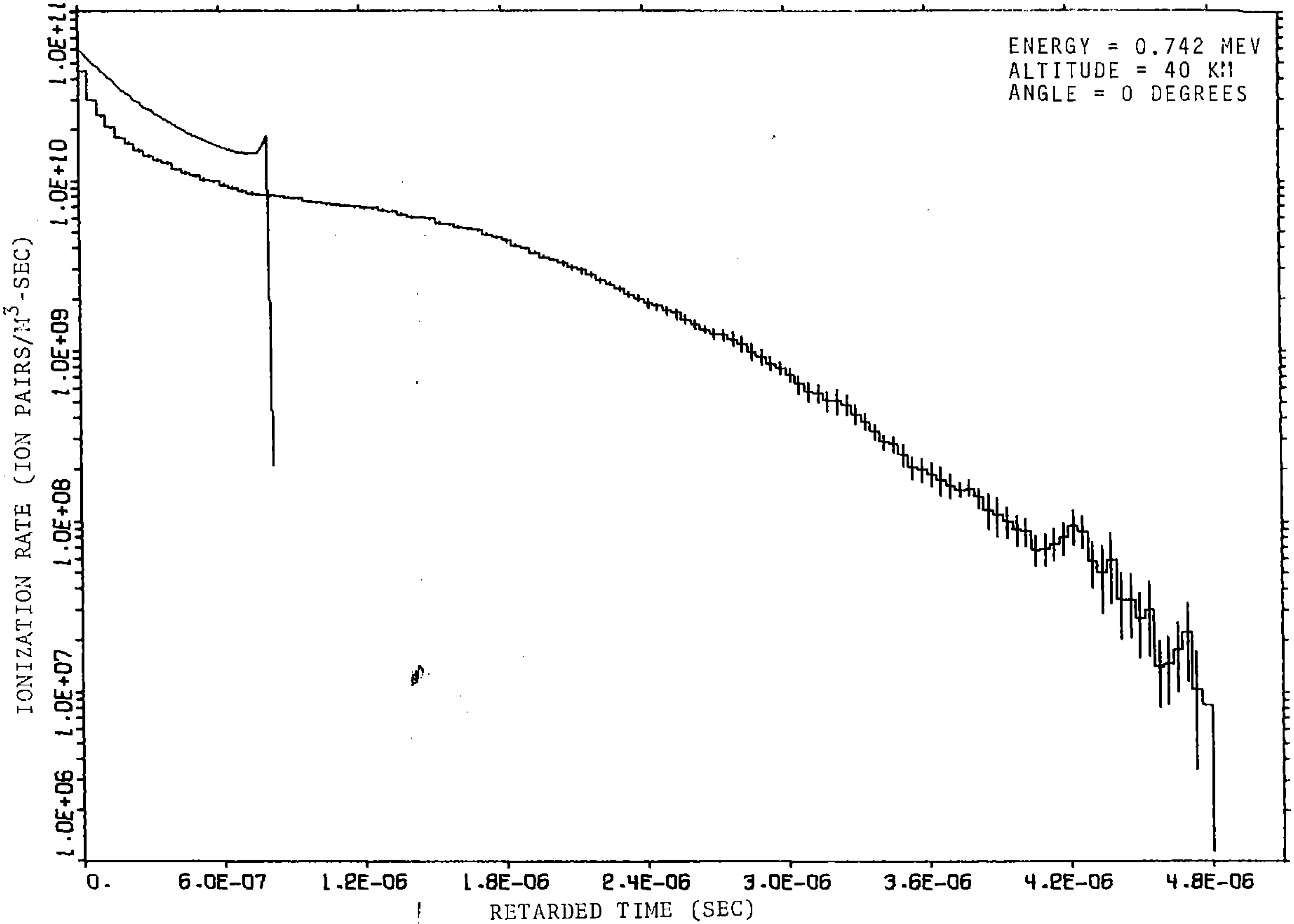

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
THETA CURRENT (AMPS/M²)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16

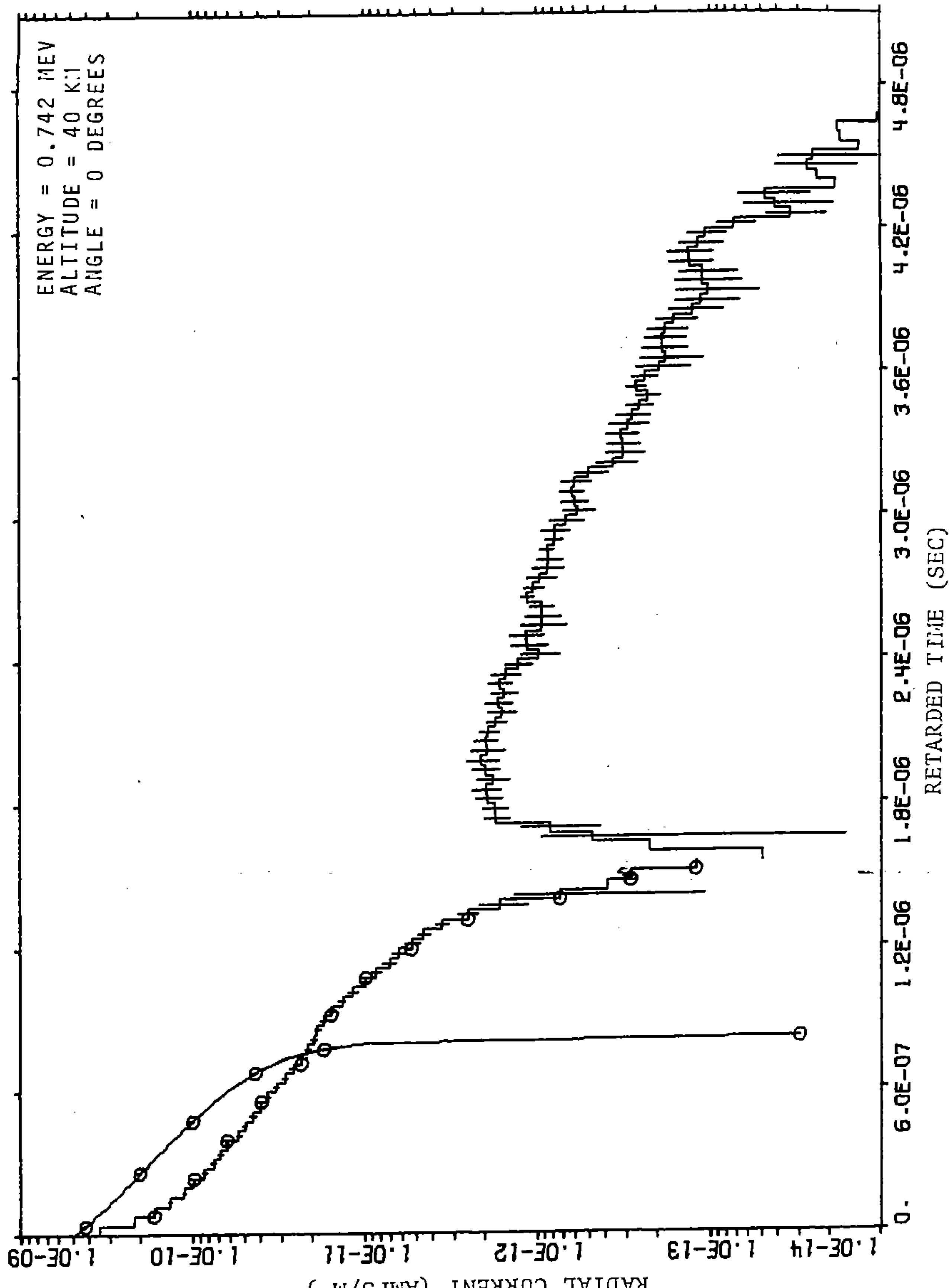

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 60 DEGREES
PHI CURRENT (AMPS/M^2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
RETARDED TIME (SEC)

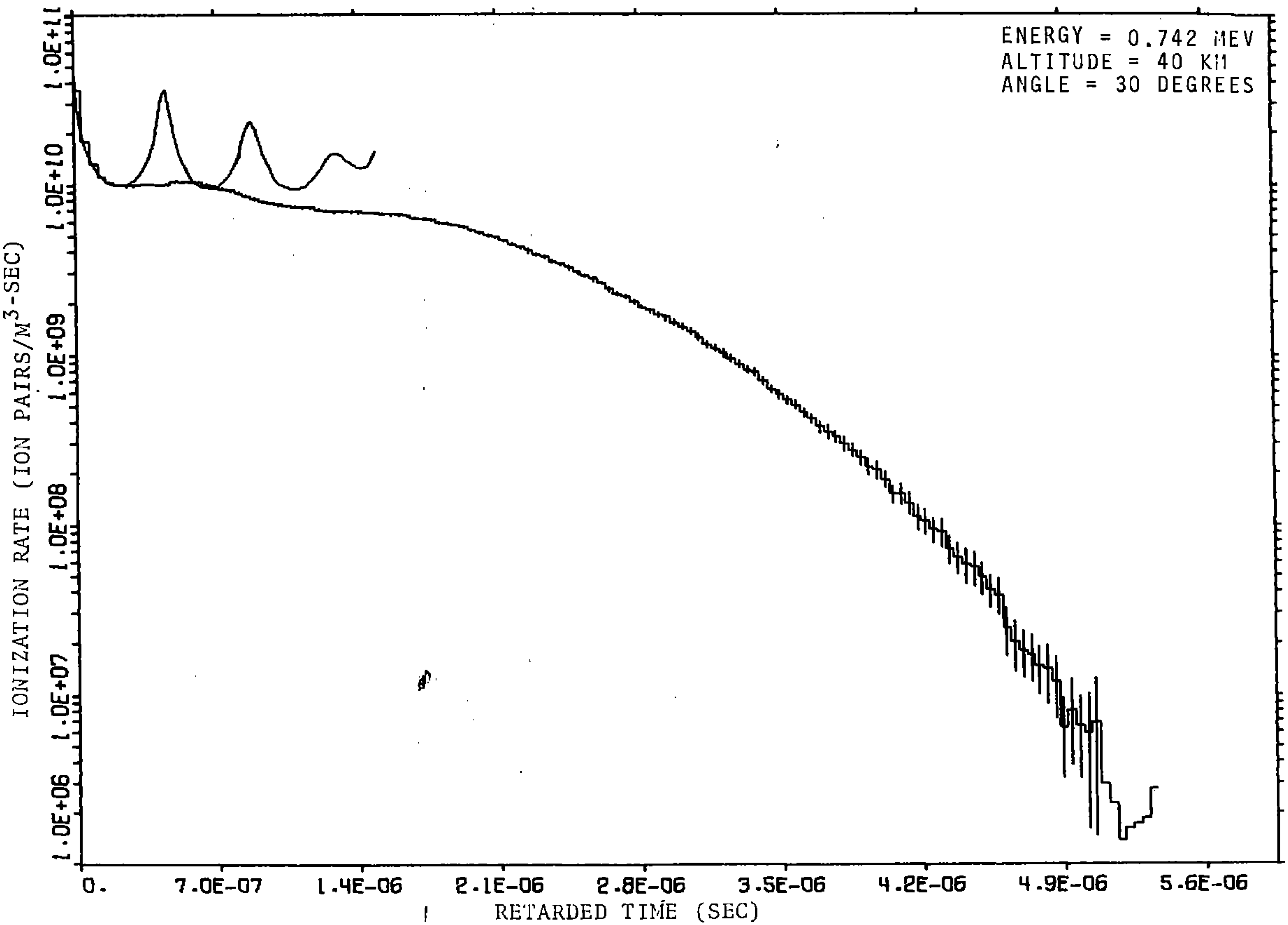

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 90 DEGREES
1.0E+13
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
IONIZATION RATE (ION PAIRS/M3-SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
RETARDED TIME (SEC)

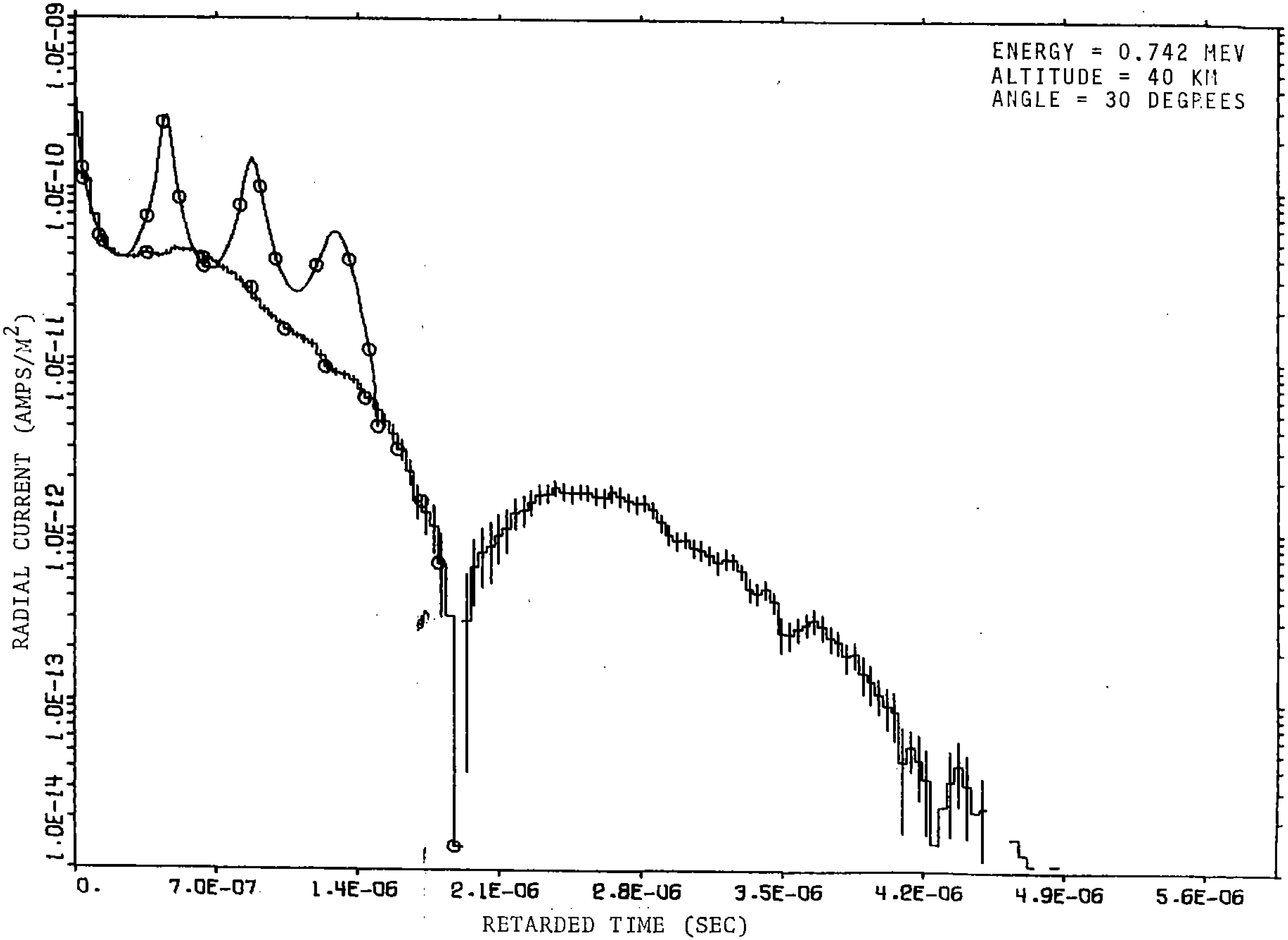

ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
RADIAL CURRENT (AMPS/M^2)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14


ENERGY = 0.742 MEV
ALTITUDE = 20 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
0.
3.0E-08
6.0E-08
9.0E-08
1.2E-07
1.5E-07
1.8E-07
2.1E-07
2.4E-07
PHI CURRENT (AMPS/M2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

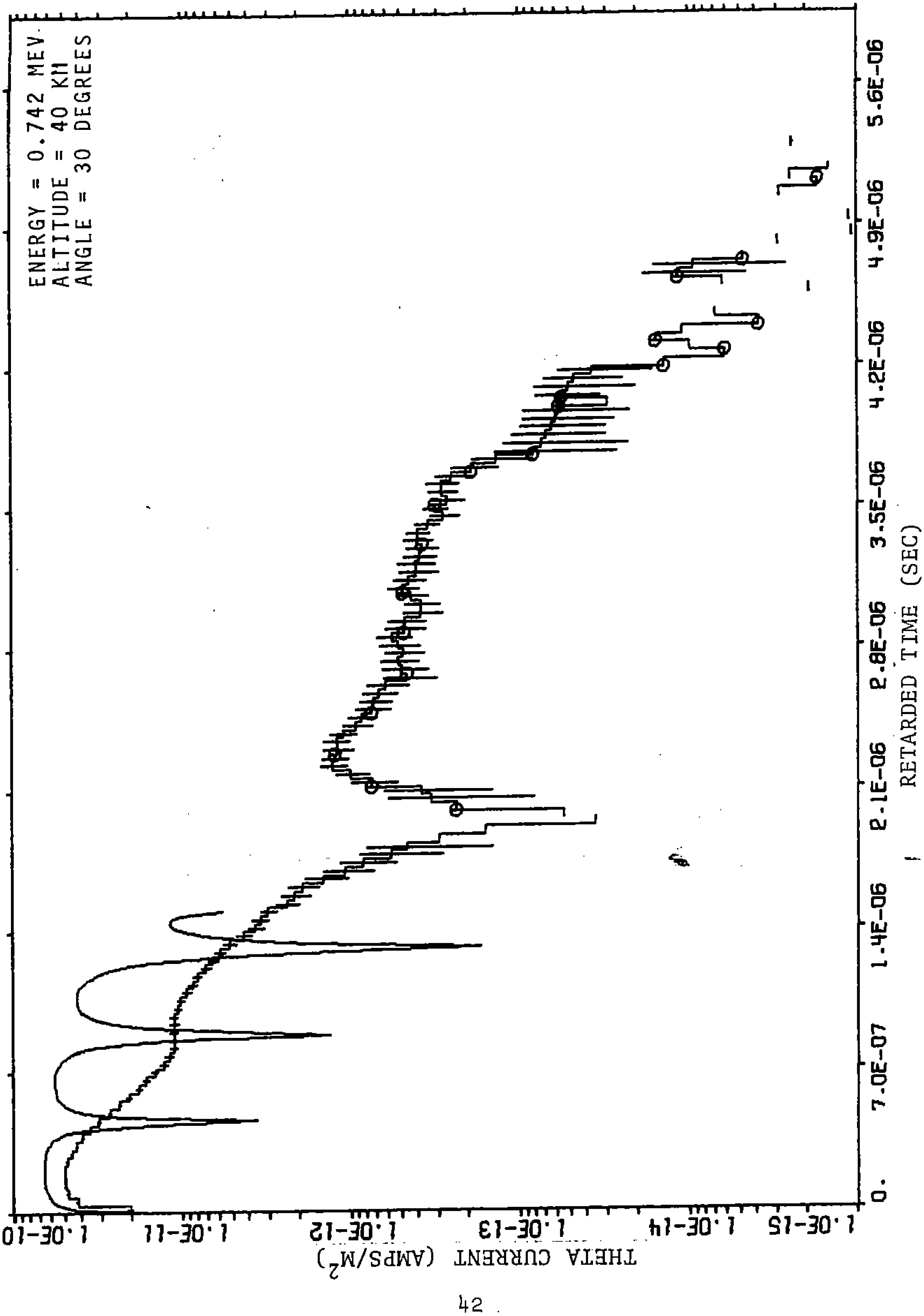

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 0 DEGREES
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
RETARDED TIME (SEC)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06


ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 0 DEGREES
RETARDED TIME (SEC)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
RADIAL CURRENT (AMPS/M2)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14

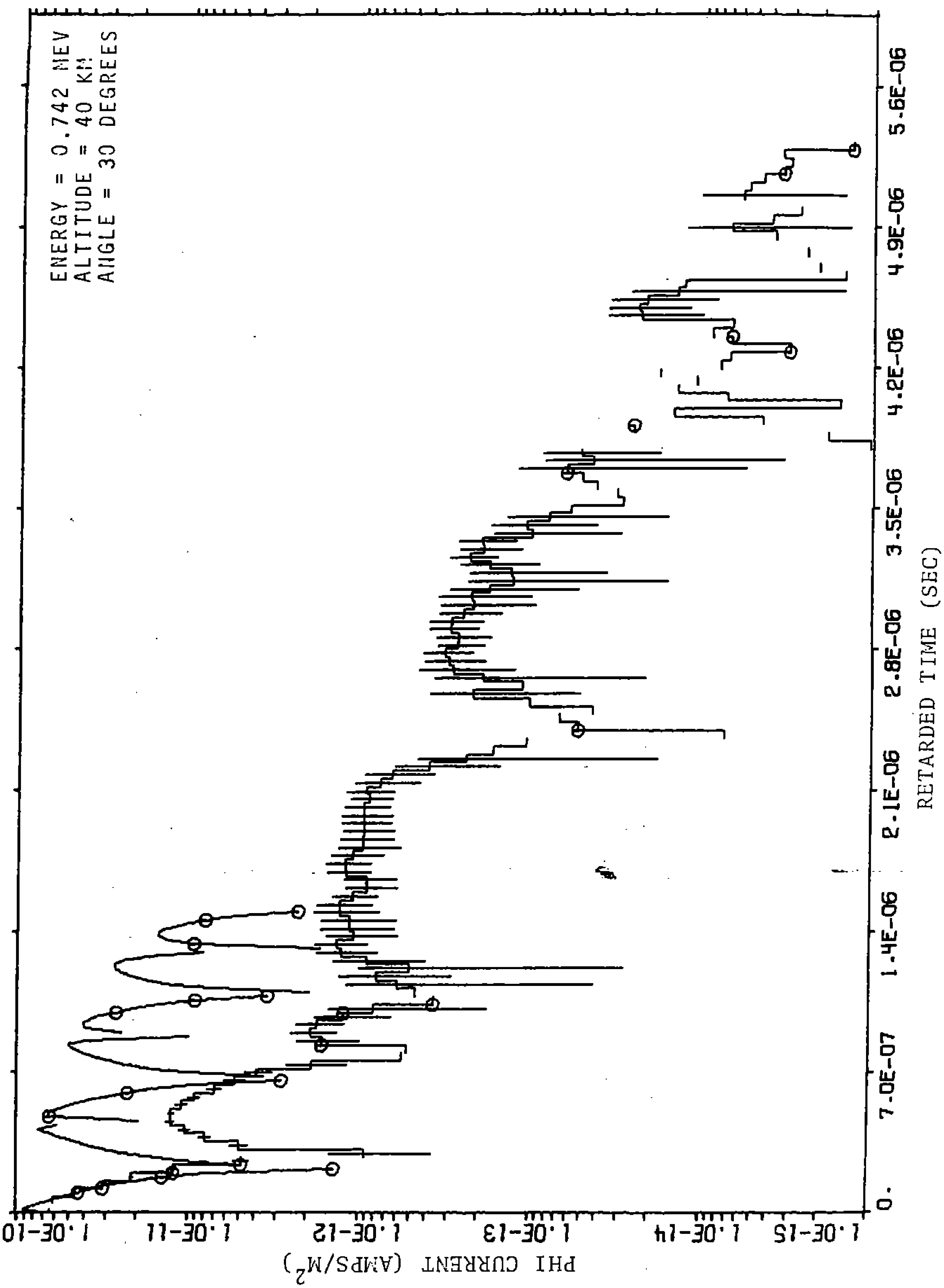

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
IONIZATION RATE (ION PAIRS/M3-SEC)
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
RETARDED TIME (SEC)
0.
7.0E-07
1.4E-06
2.1E-06
2.8E-06
3.5E-06
4.2E-06
4.9E-06
5.6E-06

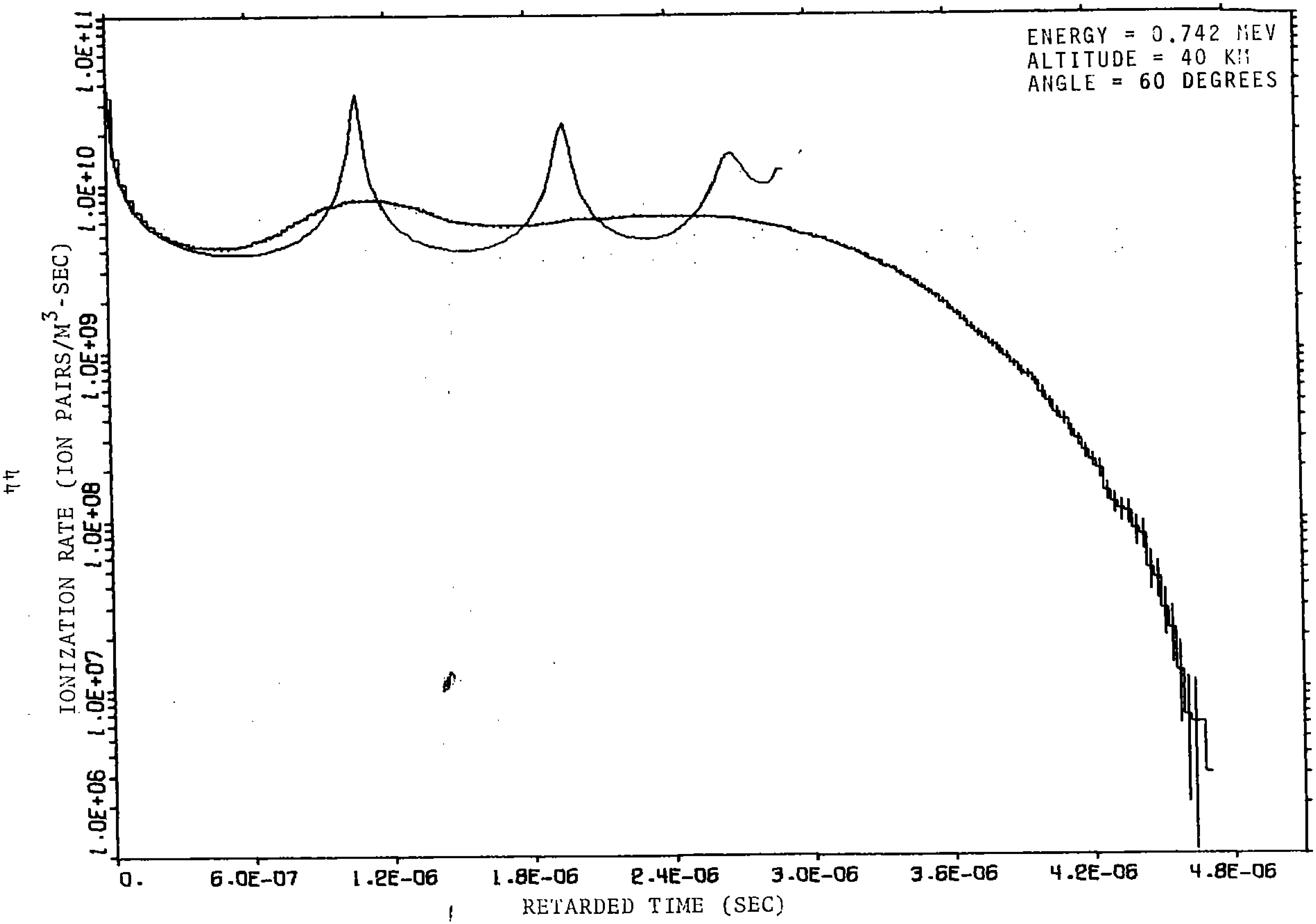


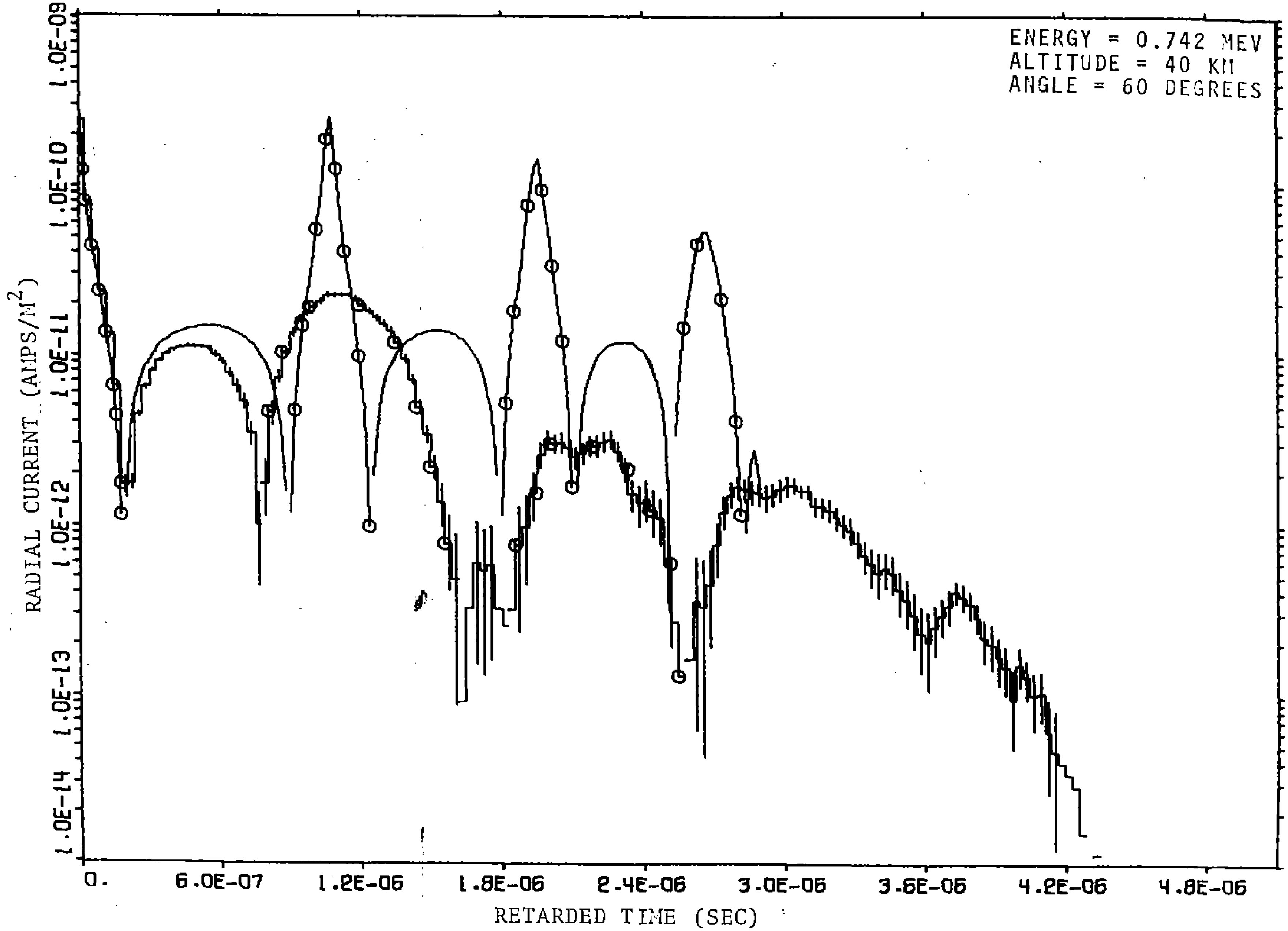
ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
RADIAL CURRENT (AMPS/M²)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
0.
7.0E-07
1.4E-06
2.1E-06
2.8E-06
3.5E-06
4.2E-06
4.9E-06
5.6E-06
RETARDED TIME (SEC)

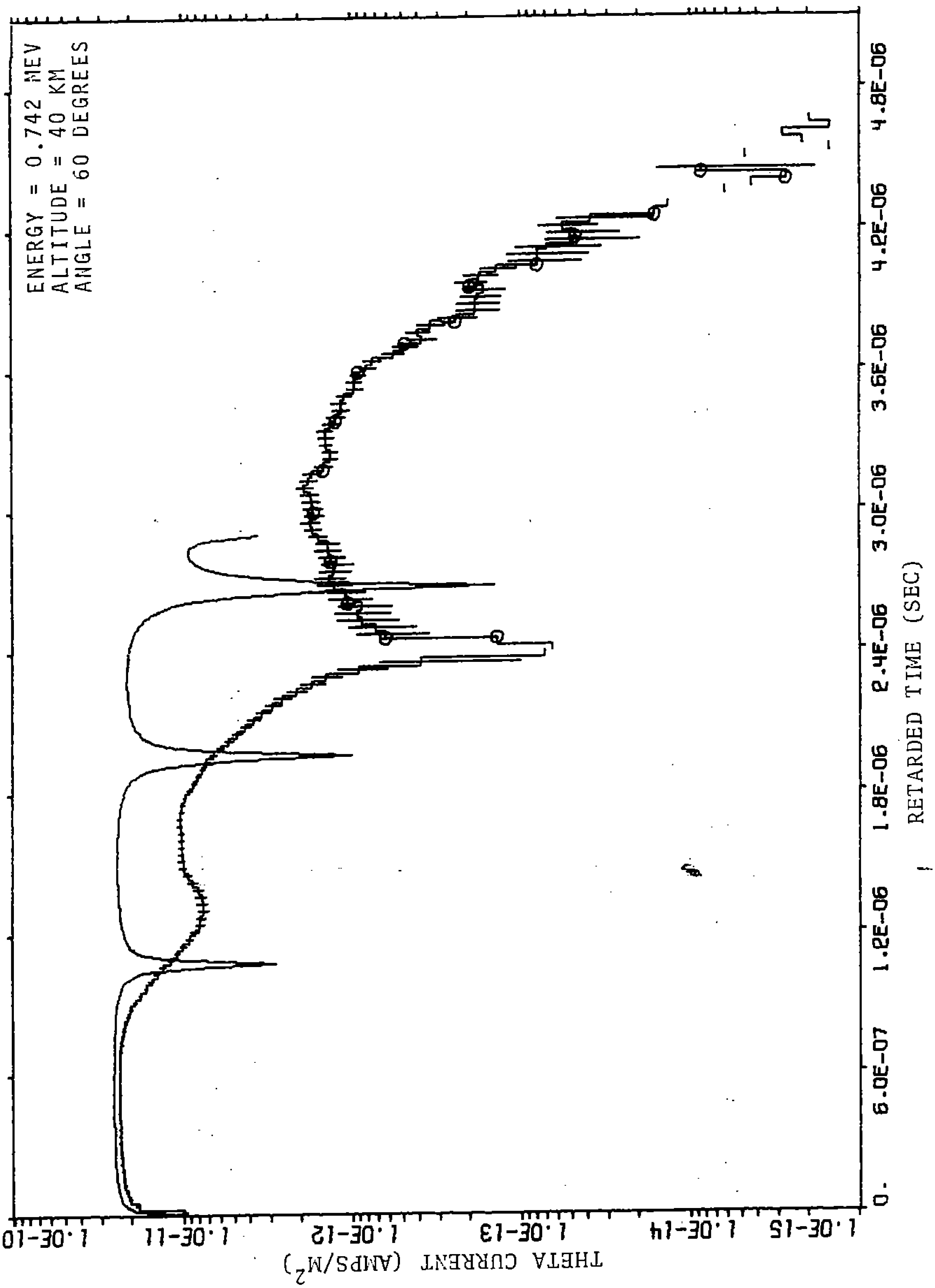


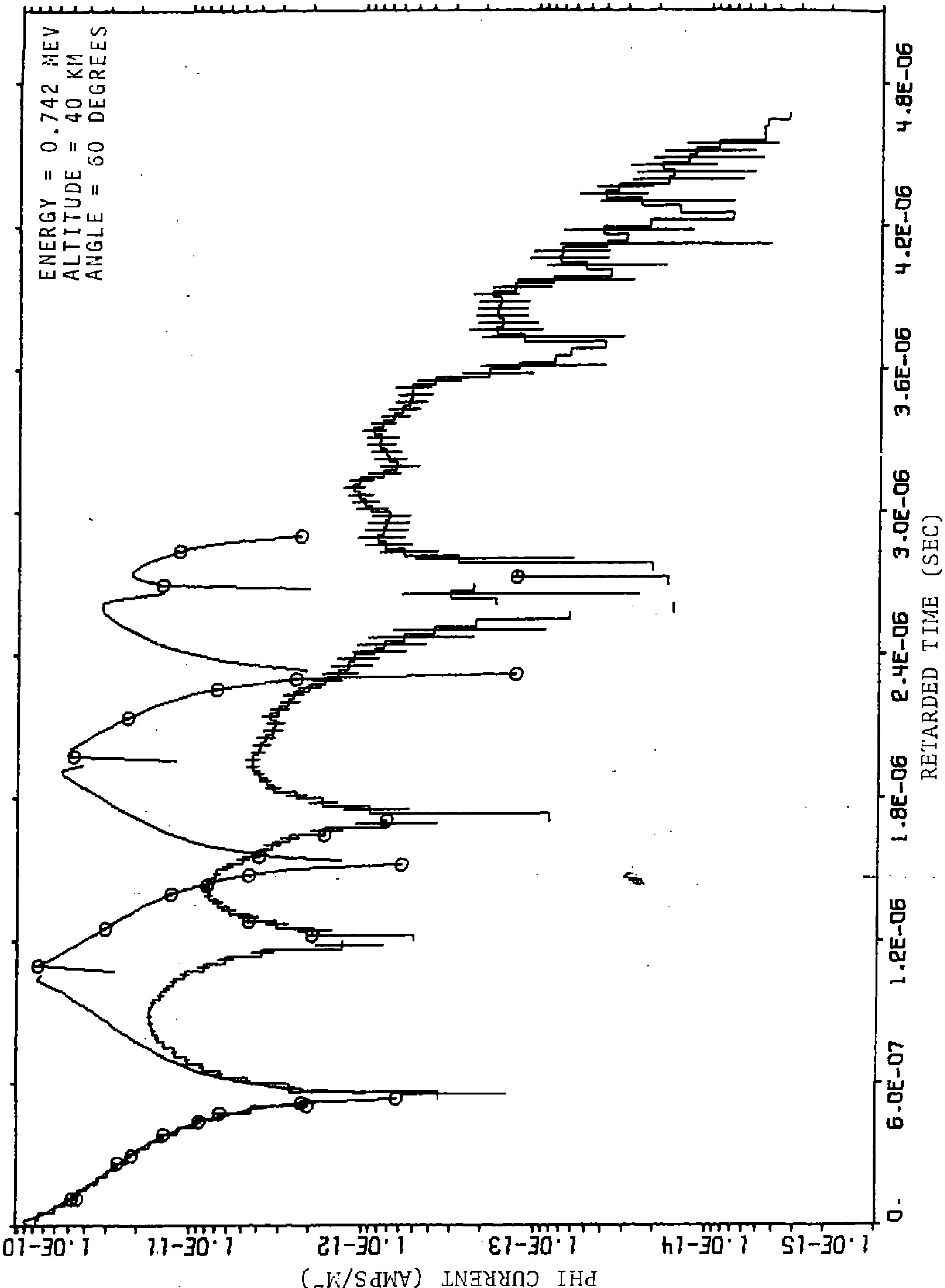
ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
0.
7.0E-07
1.4E-06
2.1E-06
2.8E-06
3.5E-06
4.2E-06
4.9E-06
5.6E-06
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
THETA CURRENT (AMPS/M2)

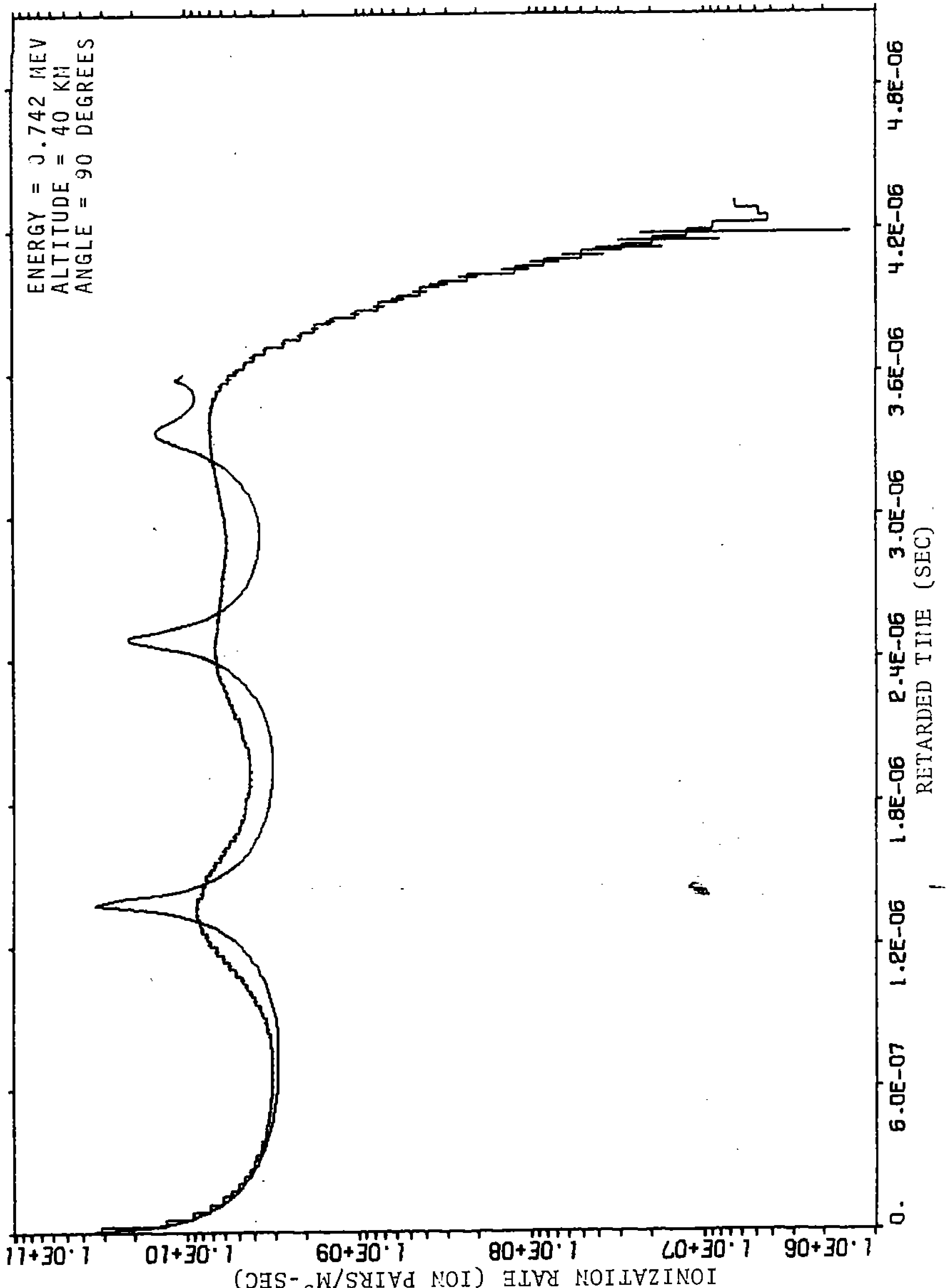

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
RETARDED TIME (SEC)
PHI CURRENT (AMPS/M2)
0.
7.0E-07
1.4E-06
2.1E-06
2.8E-06
3.5E-06
4.2E-06
4.9E-06
5.6E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

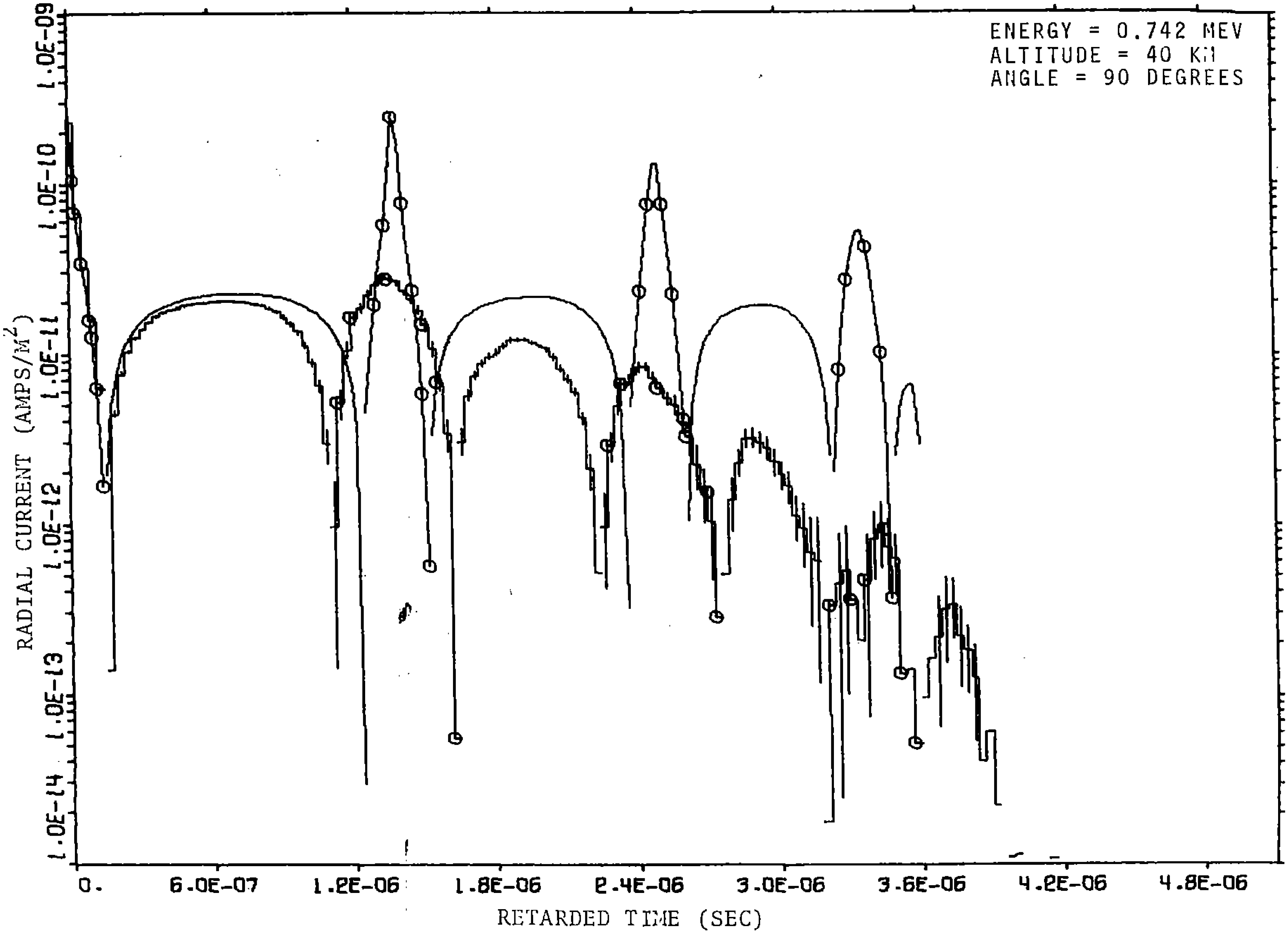

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
RETARDED TIME (SEC)

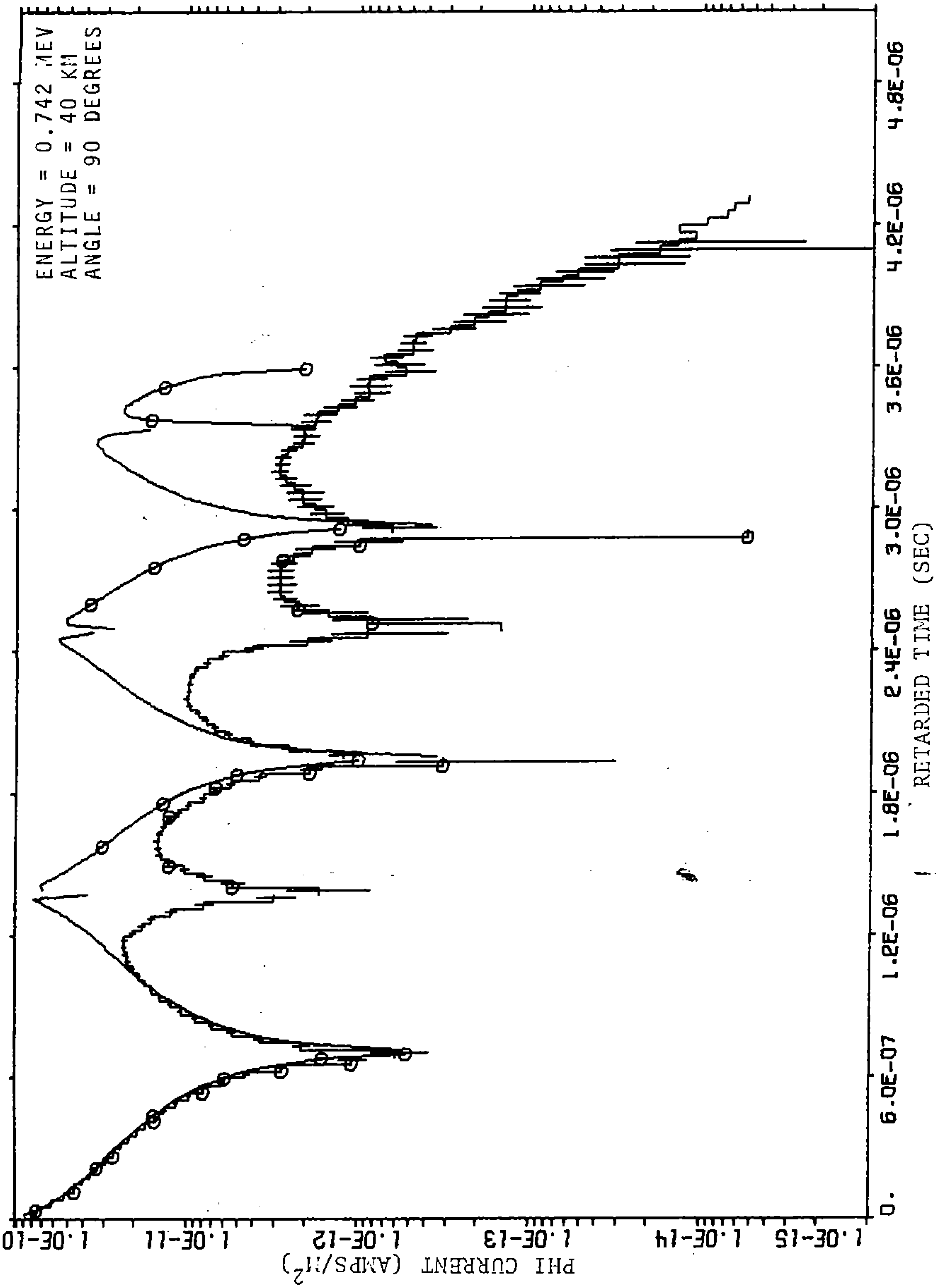

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
RADIAL CURRENT (AMPS/M^2)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
RETARDED TIME (SEC)

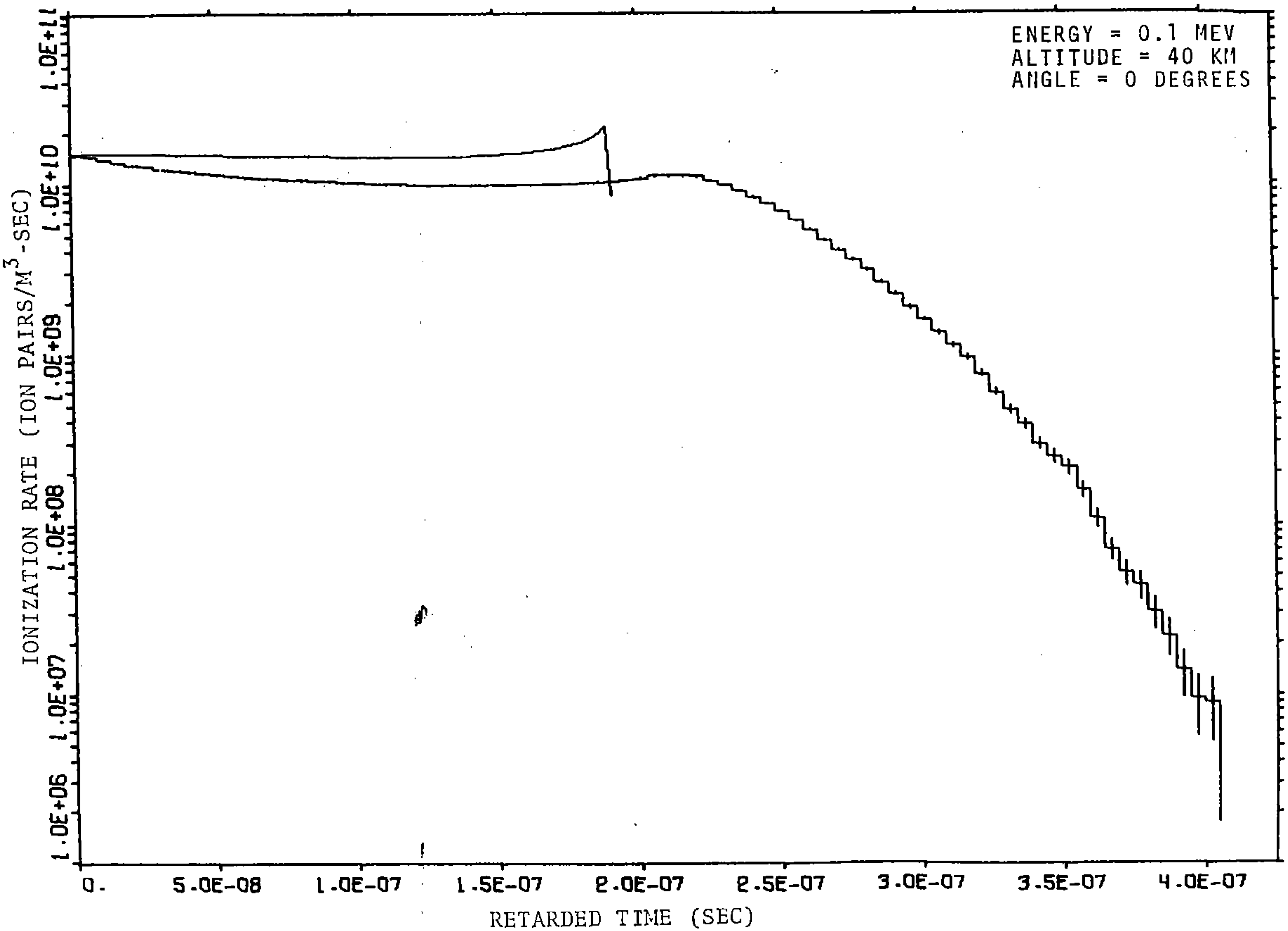

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
THETA CURRENT (AMPS/M2)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

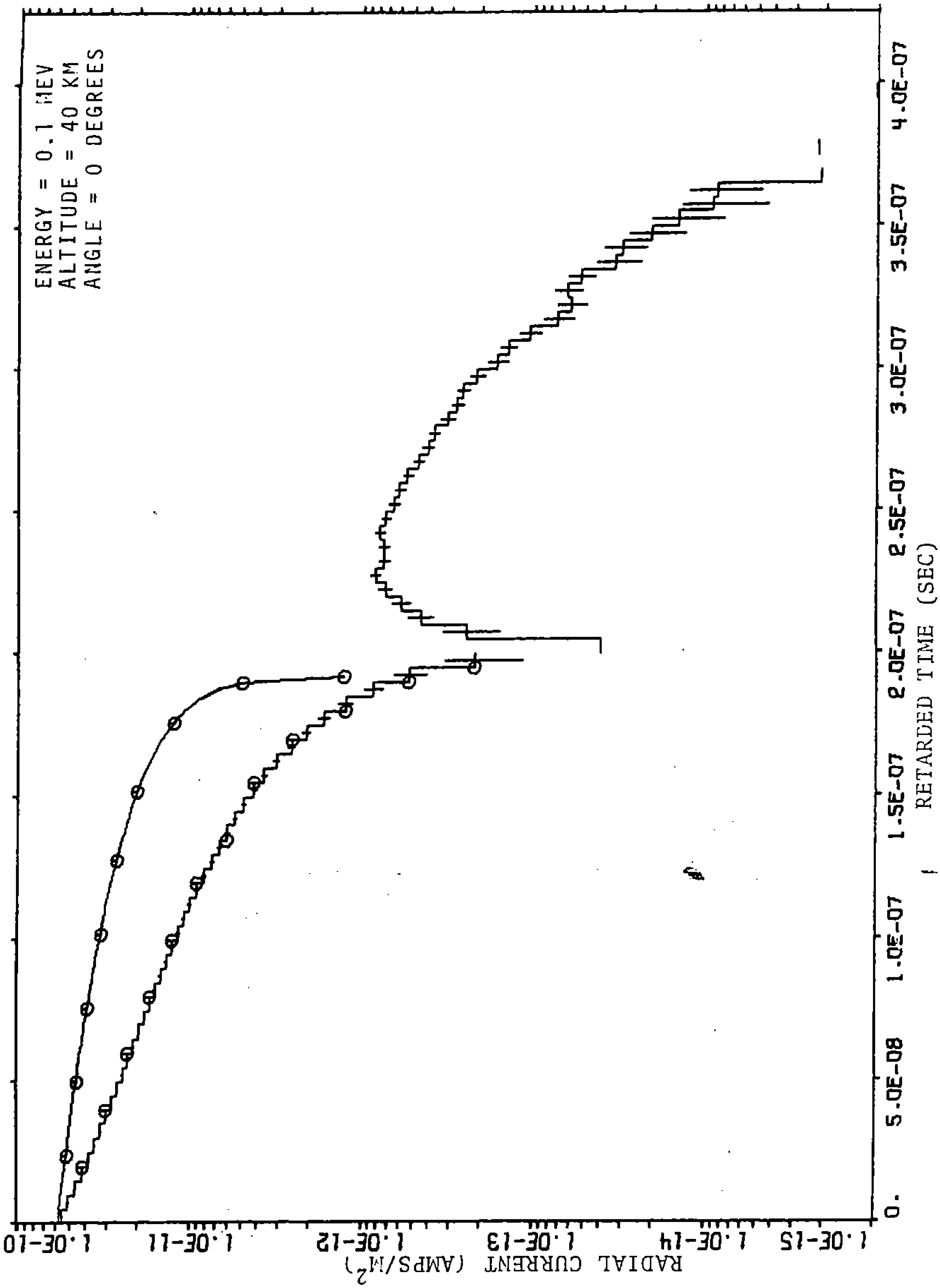

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
PHI CURRENT (AMPS/M2)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15


ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
IONIZATION RATE (ION PAIRS/M^3-SEC)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
1.0E+11

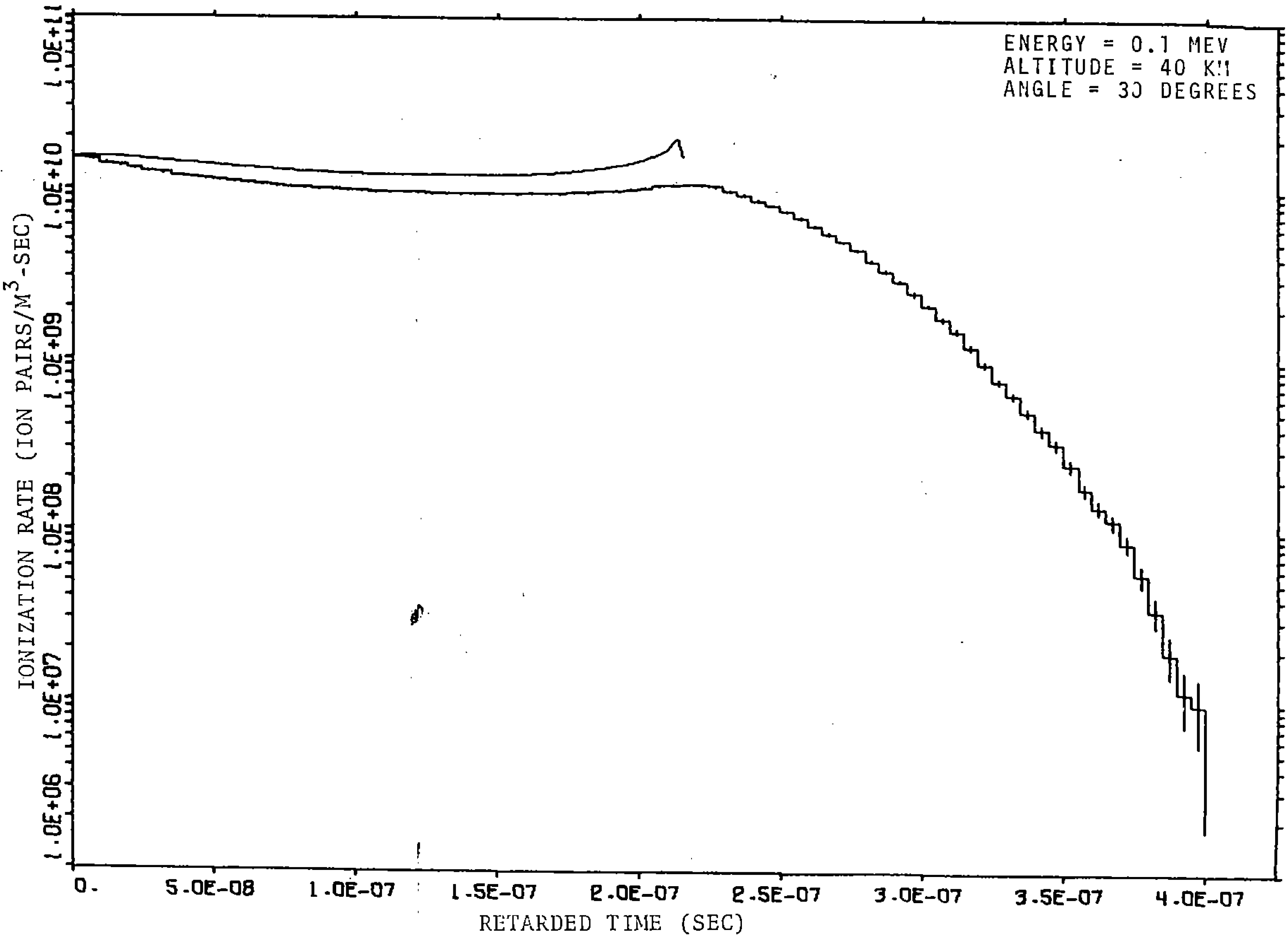

ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
RADIAL CURRENT (AMPS/M²)
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
RETARDED TIME (SEC)


ENERGY = 0.742 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
PHI CURRENT (AMPS/M²)
0.
6.0E-07
1.2E-06
1.8E-06
2.4E-06
3.0E-06
3.6E-06
4.2E-06
4.8E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

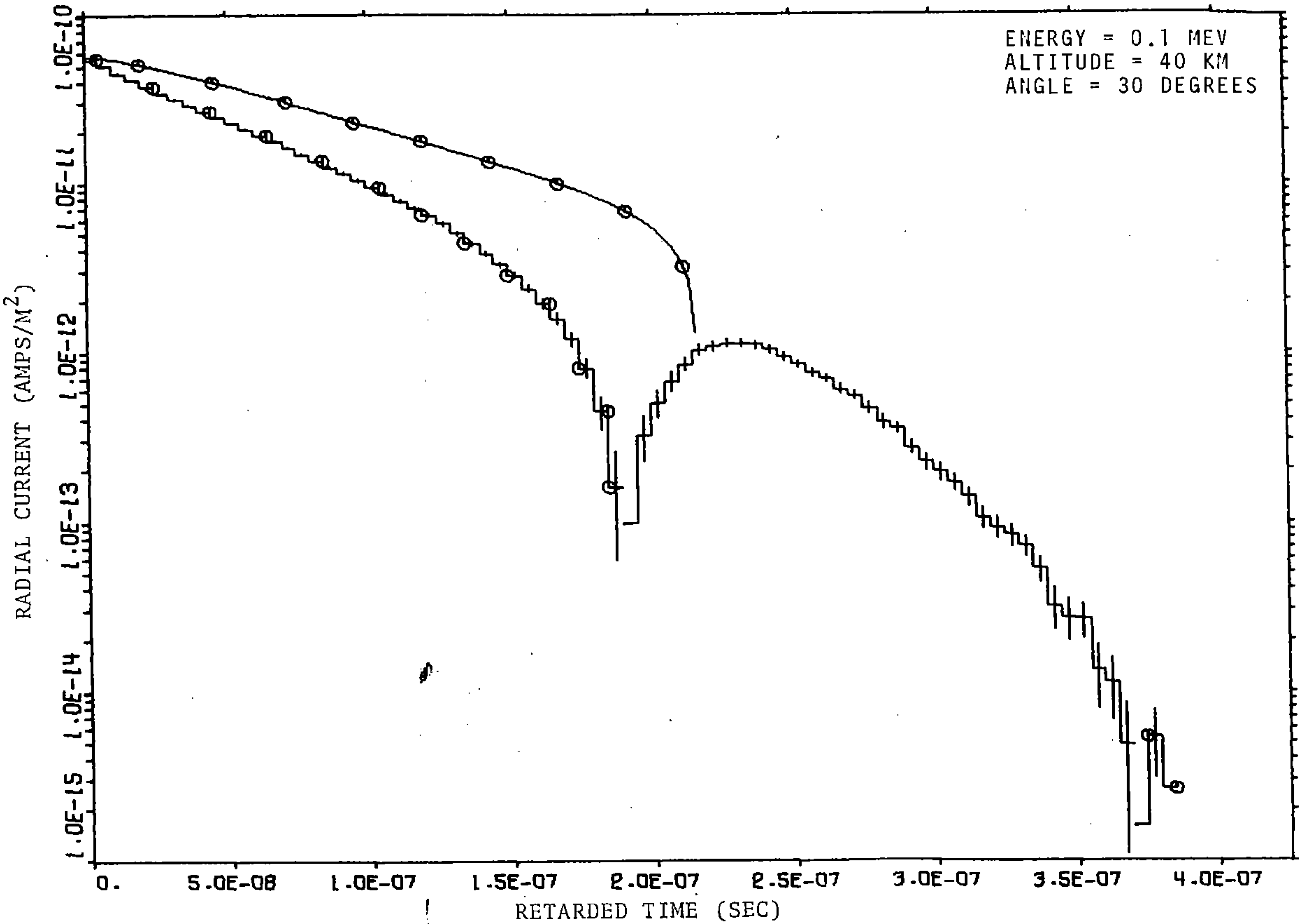

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 0 DEGREES
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)



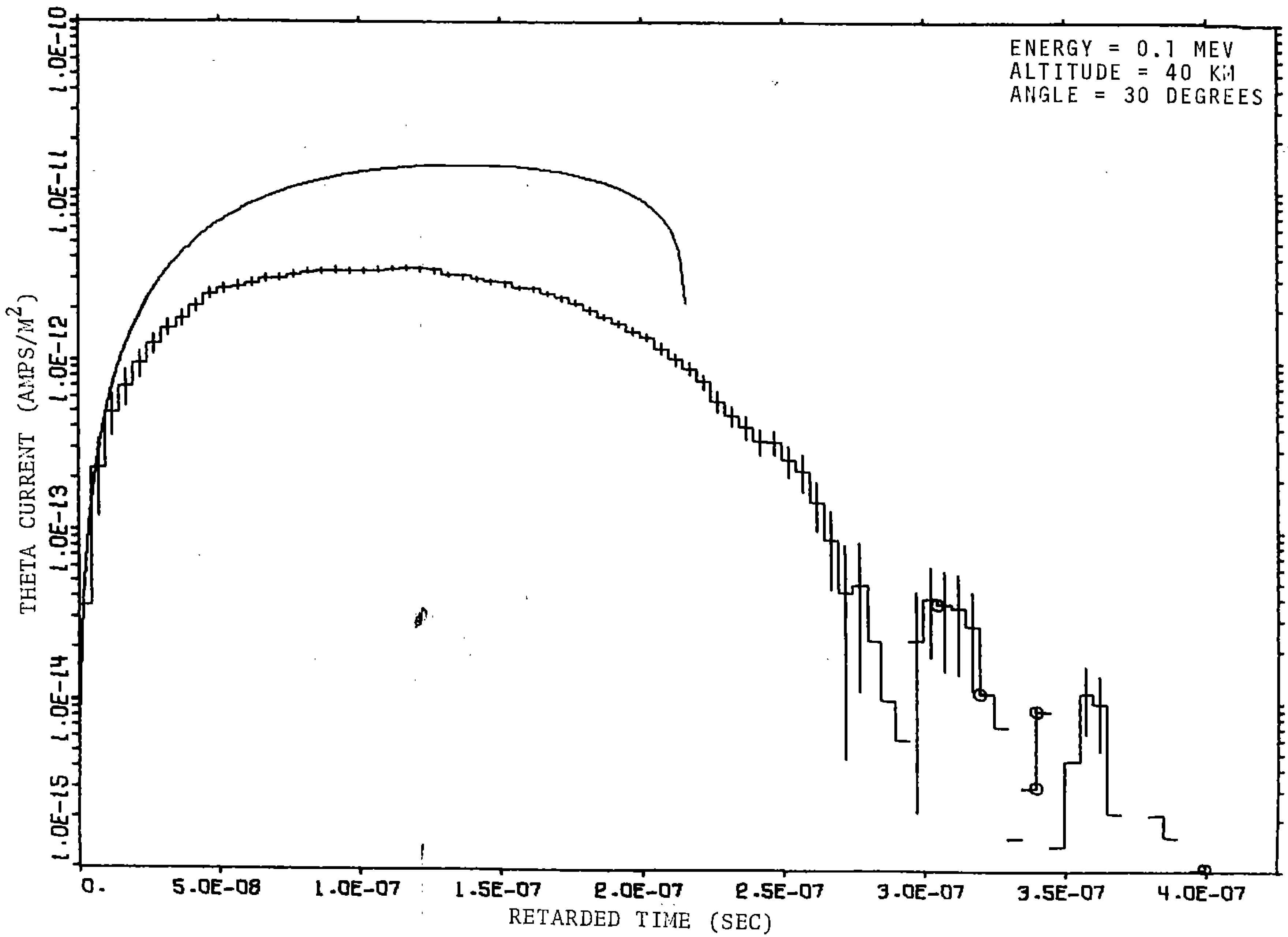
ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 0 DEGREES
RETARDED TIME (SEC)
RADIAL CURRENT (AMPS/M2)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

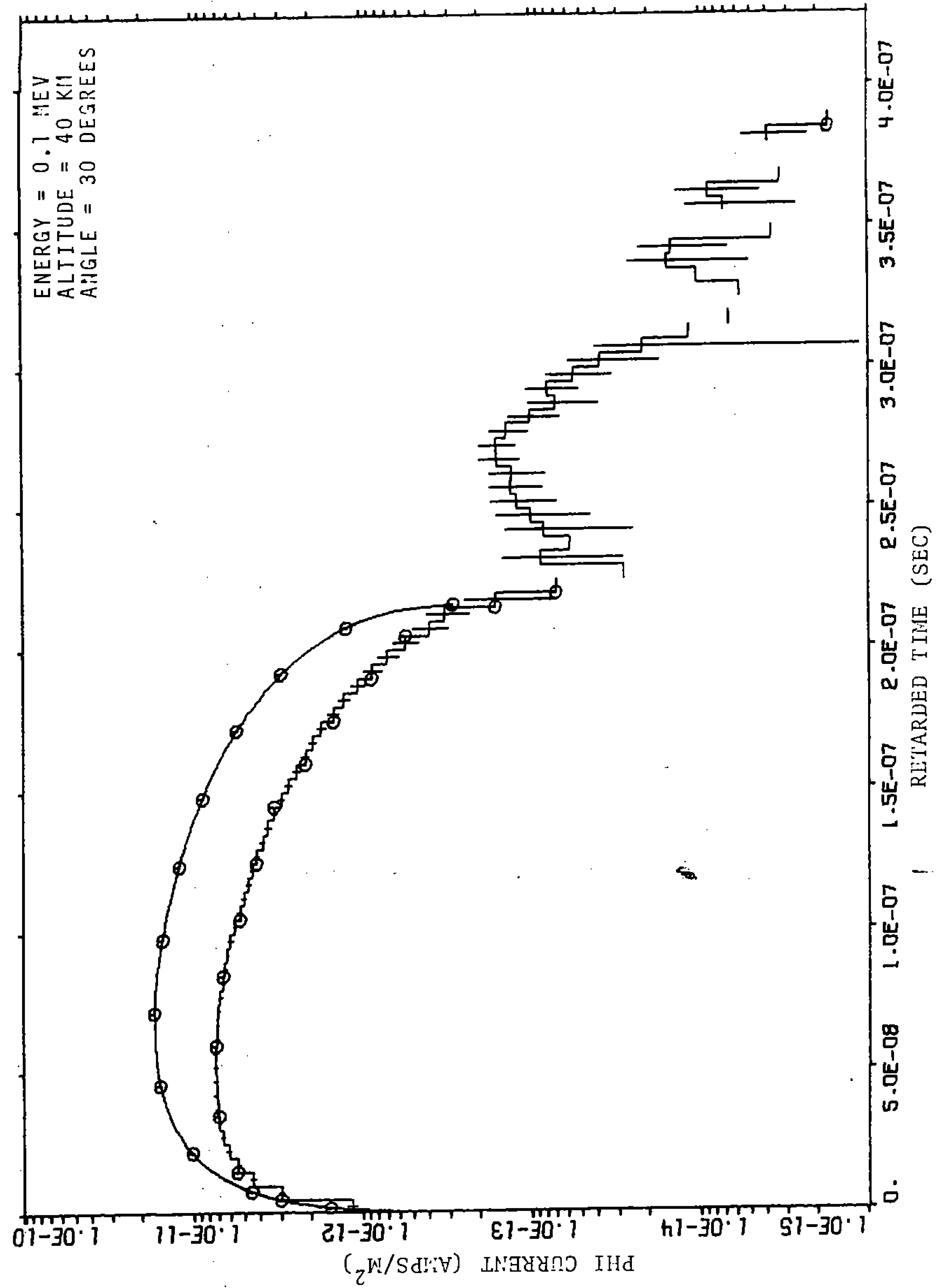


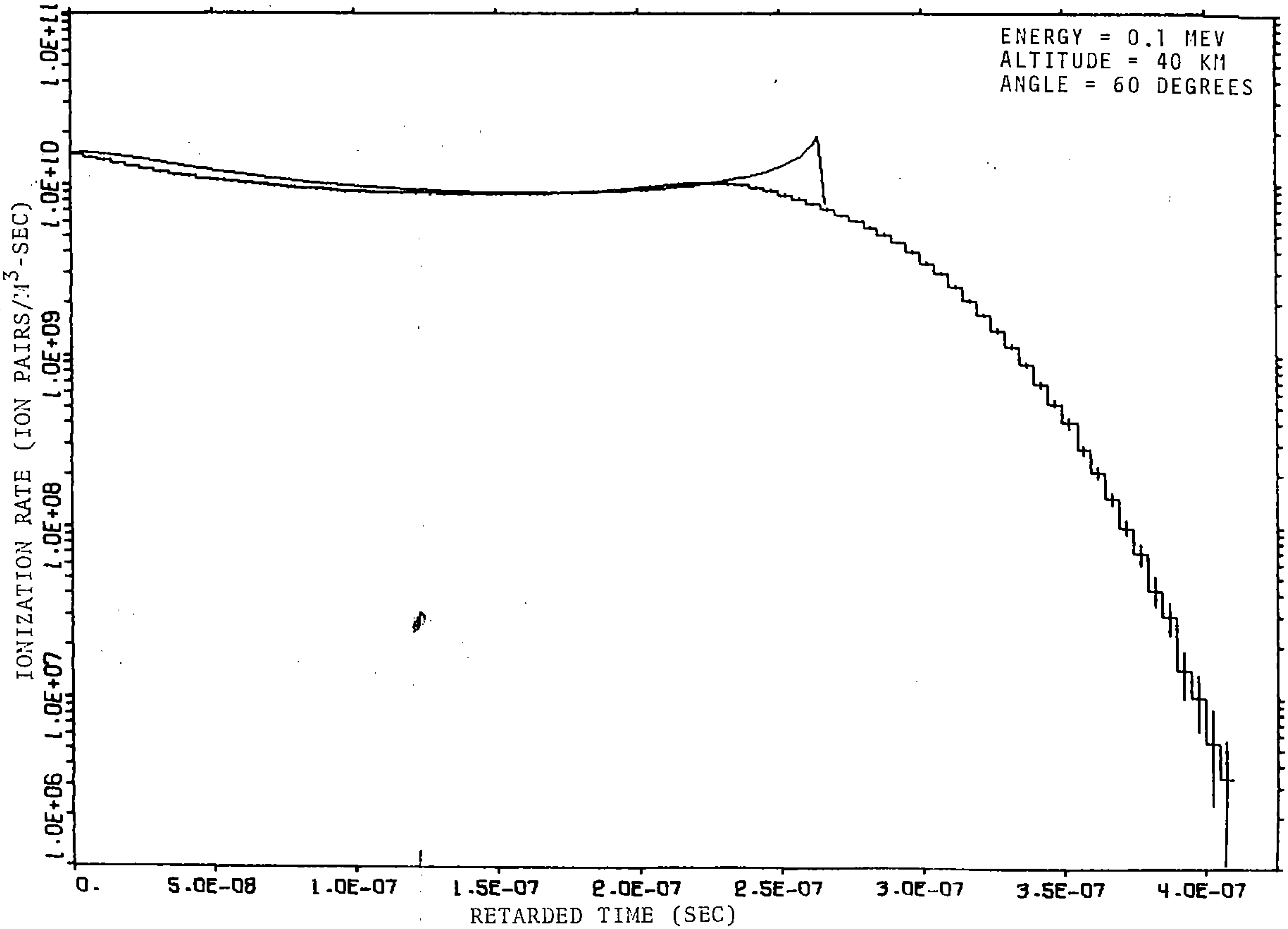
ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
IONIZATION RATE (ION PAIRS/M^3-SEC)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)



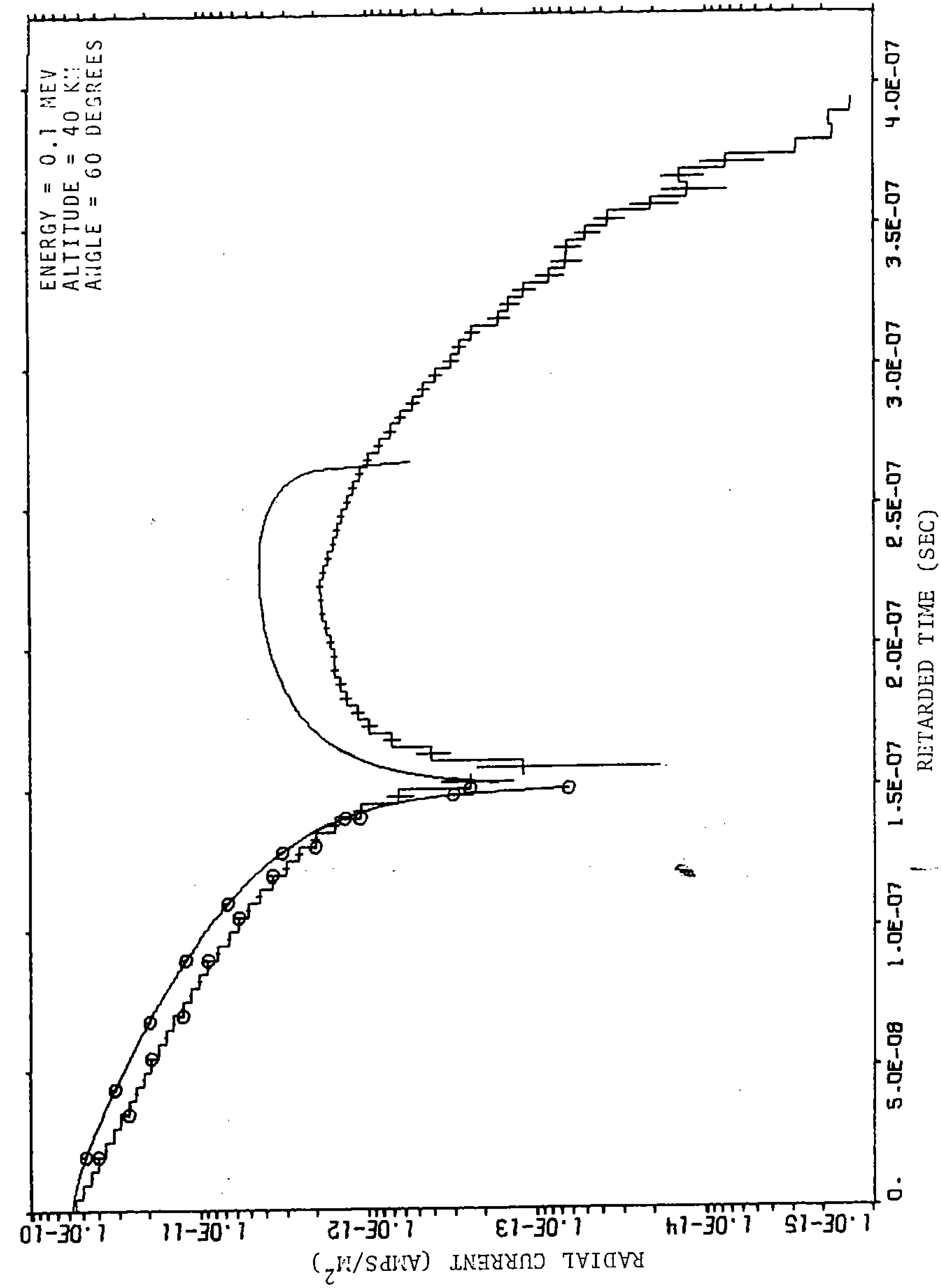
ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
RADIAL CURRENT (AMPS/M2)
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07

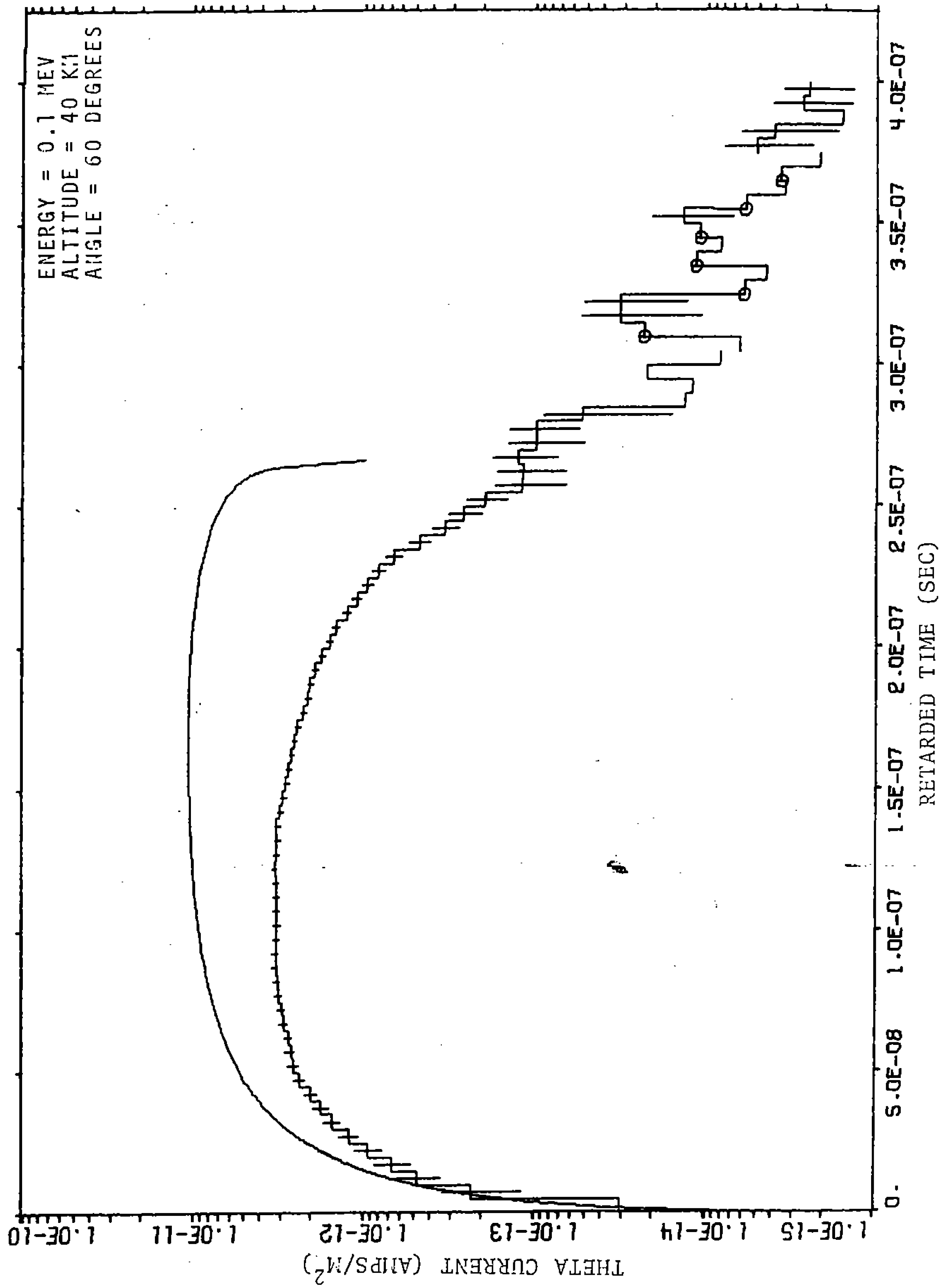

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
THETA CURRENT (AMPS/M^2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)

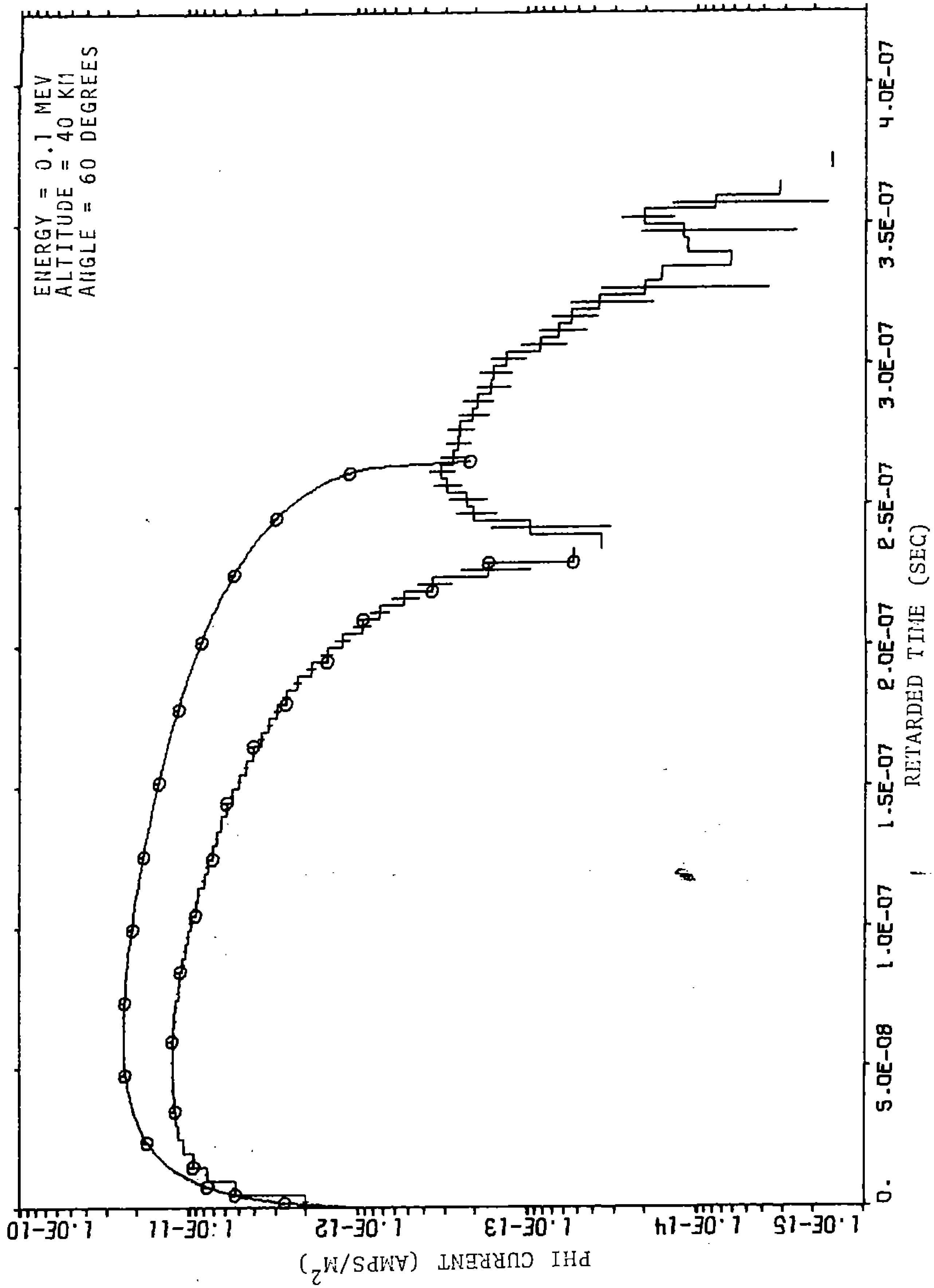

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 30 DEGREES
RETARDED TIME (SEC)
PHI CURRENT (AMPS/M2)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

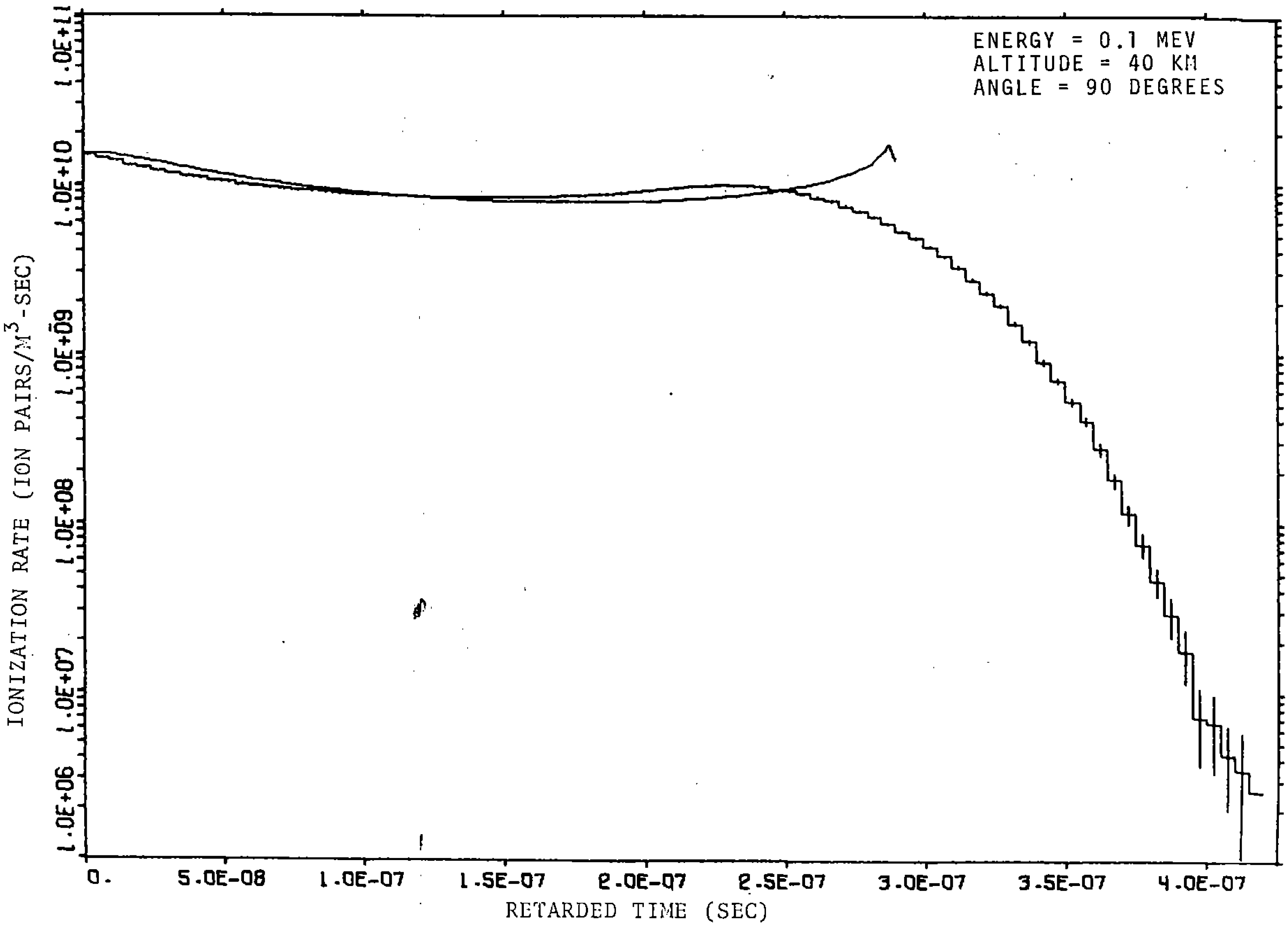


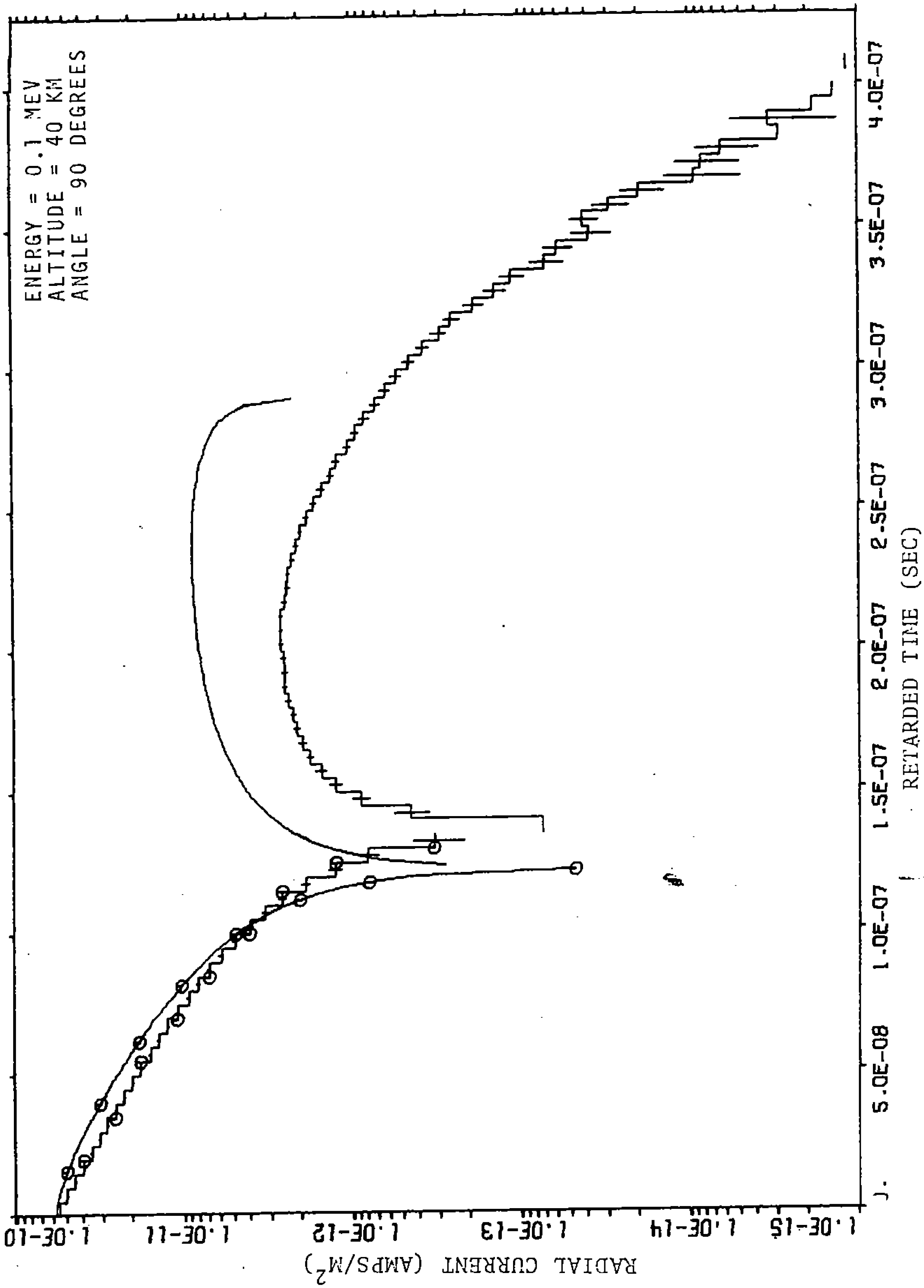
ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)

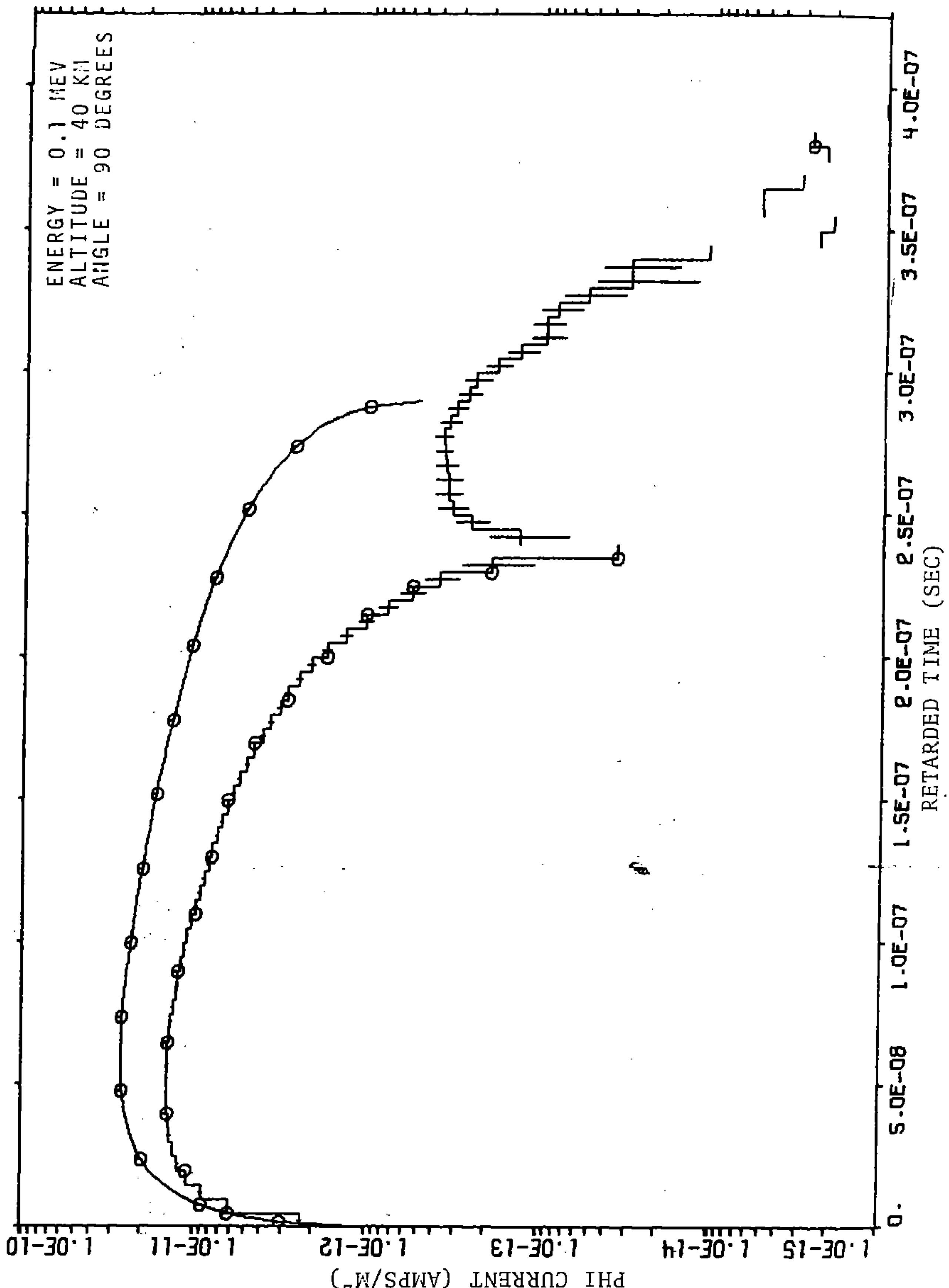

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
RADIAL CURRENT (AMPS/M^2)


ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
THETA CURRENT (AMPS/M2)

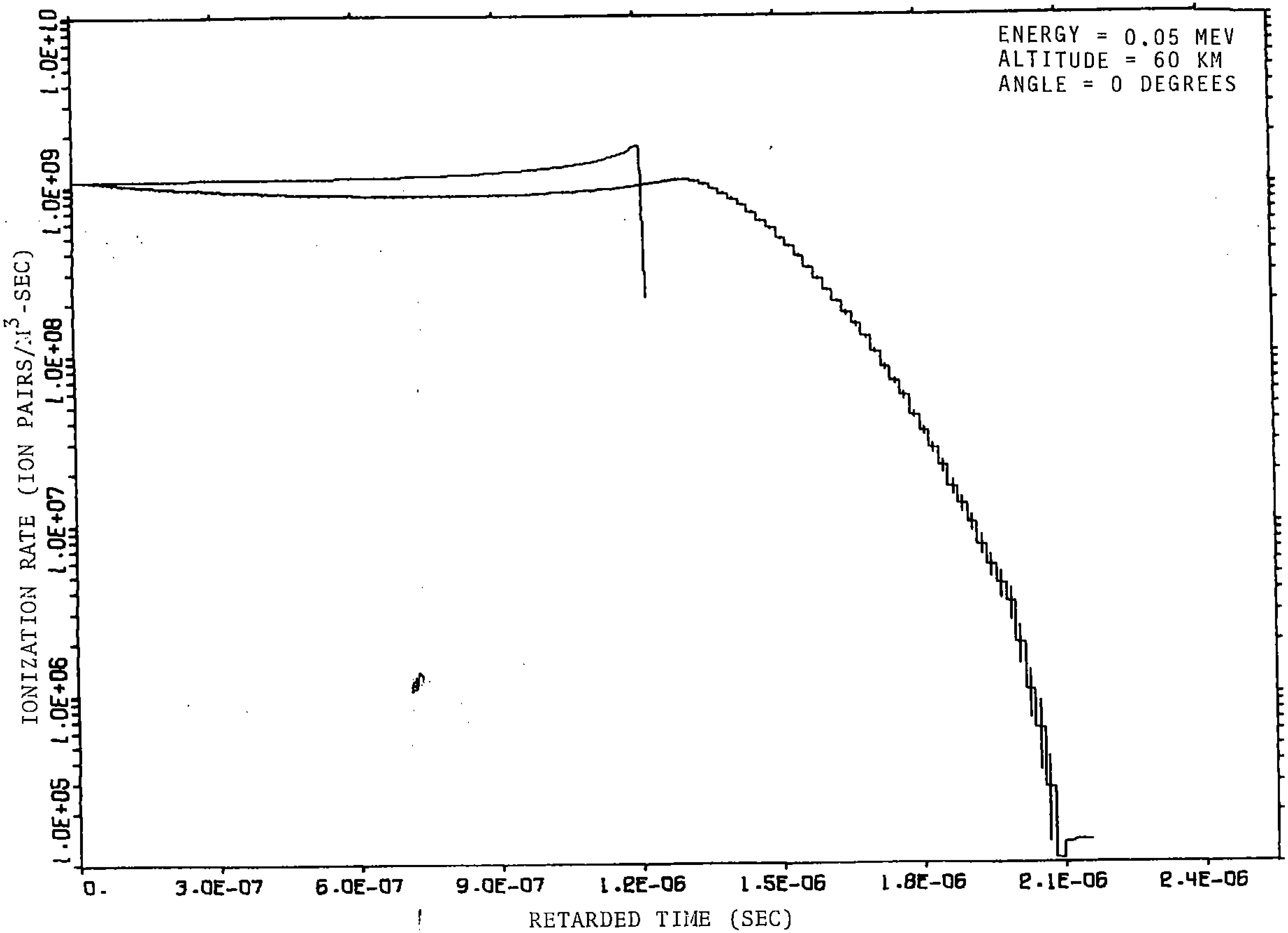

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 60 DEGREES
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
PHI CURRENT (AMPS/M^2)

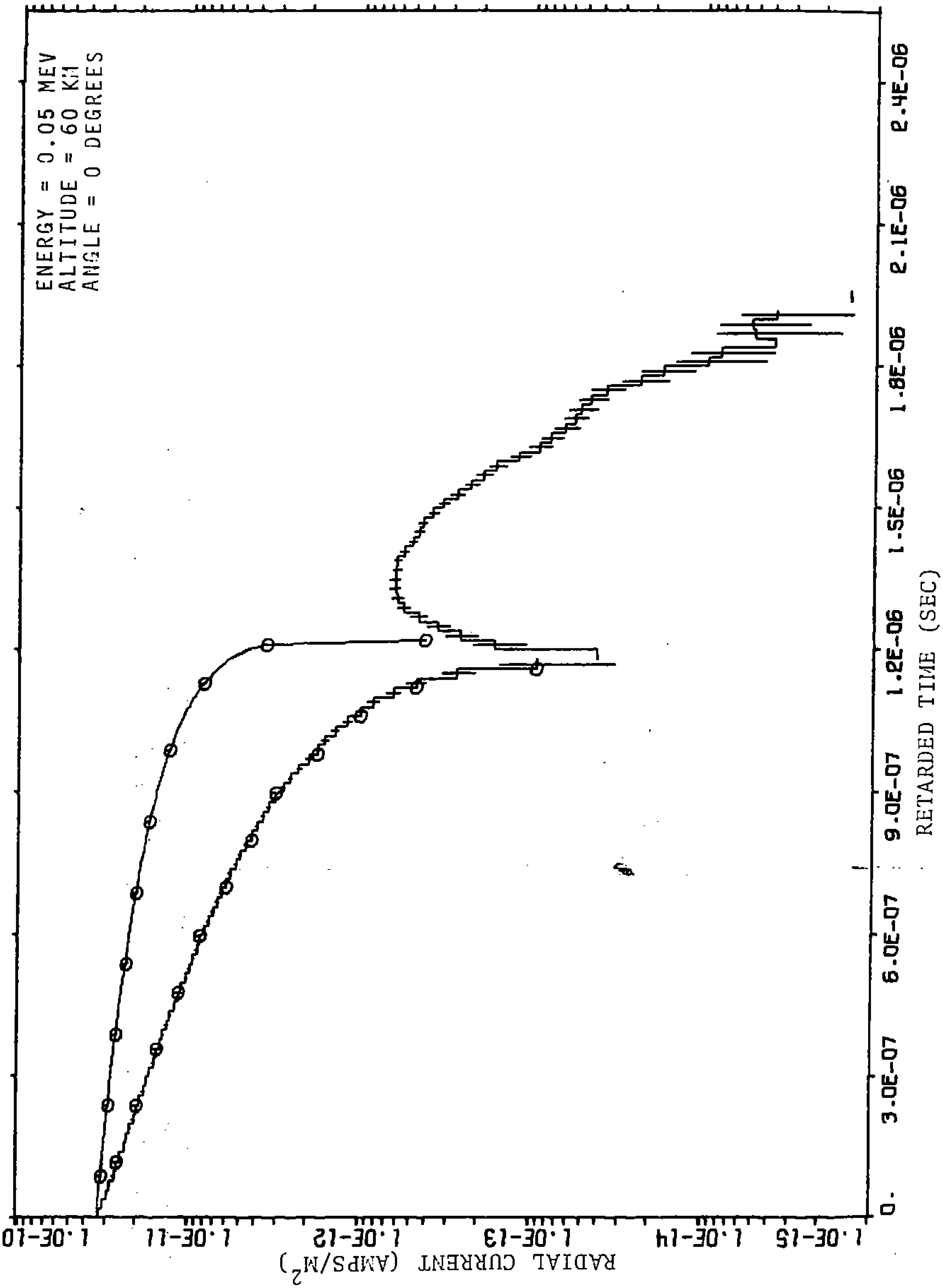

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
IONIZATION RATE (ION PAIRS/M^3-SEC)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RETARDED TIME (SEC)

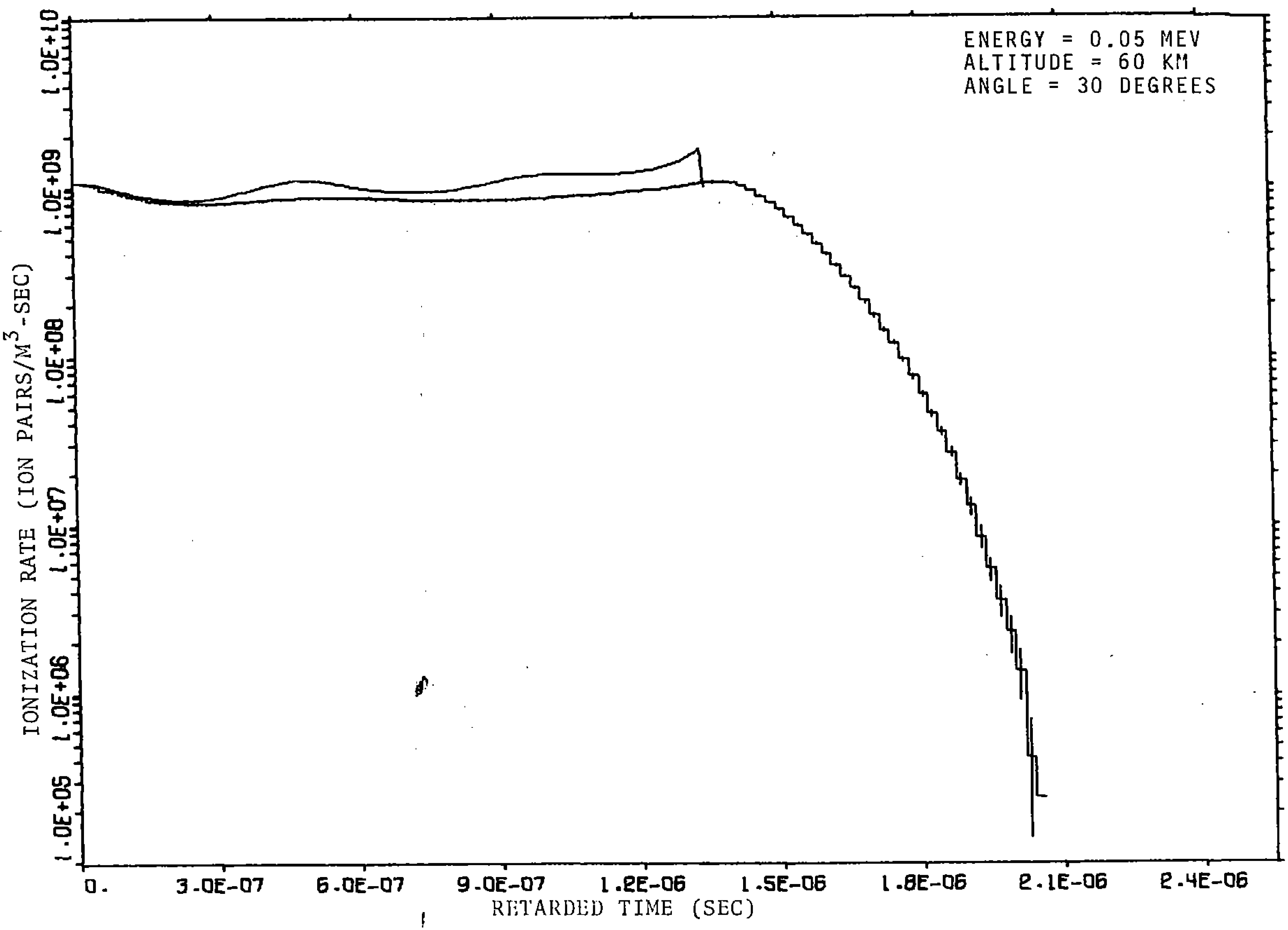

ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07
RADIAL CURRENT (AMPS/M2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

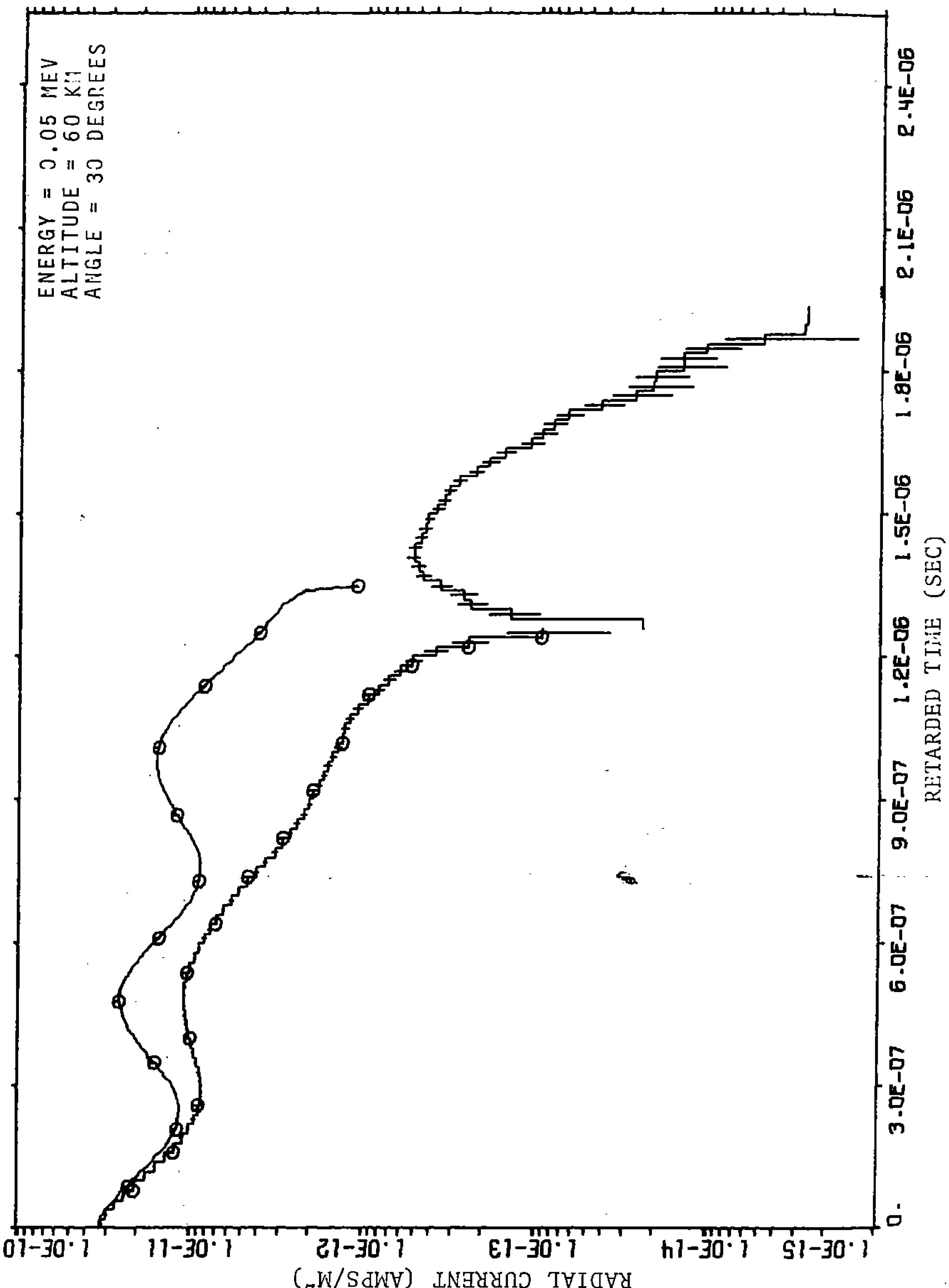


ENERGY = 0.1 MEV
ALTITUDE = 40 KM
ANGLE = 90 DEGREES
PHI CURRENT (AMPS/M2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
RETARDED TIME (SEC)
0.
5.0E-08
1.0E-07
1.5E-07
2.0E-07
2.5E-07
3.0E-07
3.5E-07
4.0E-07

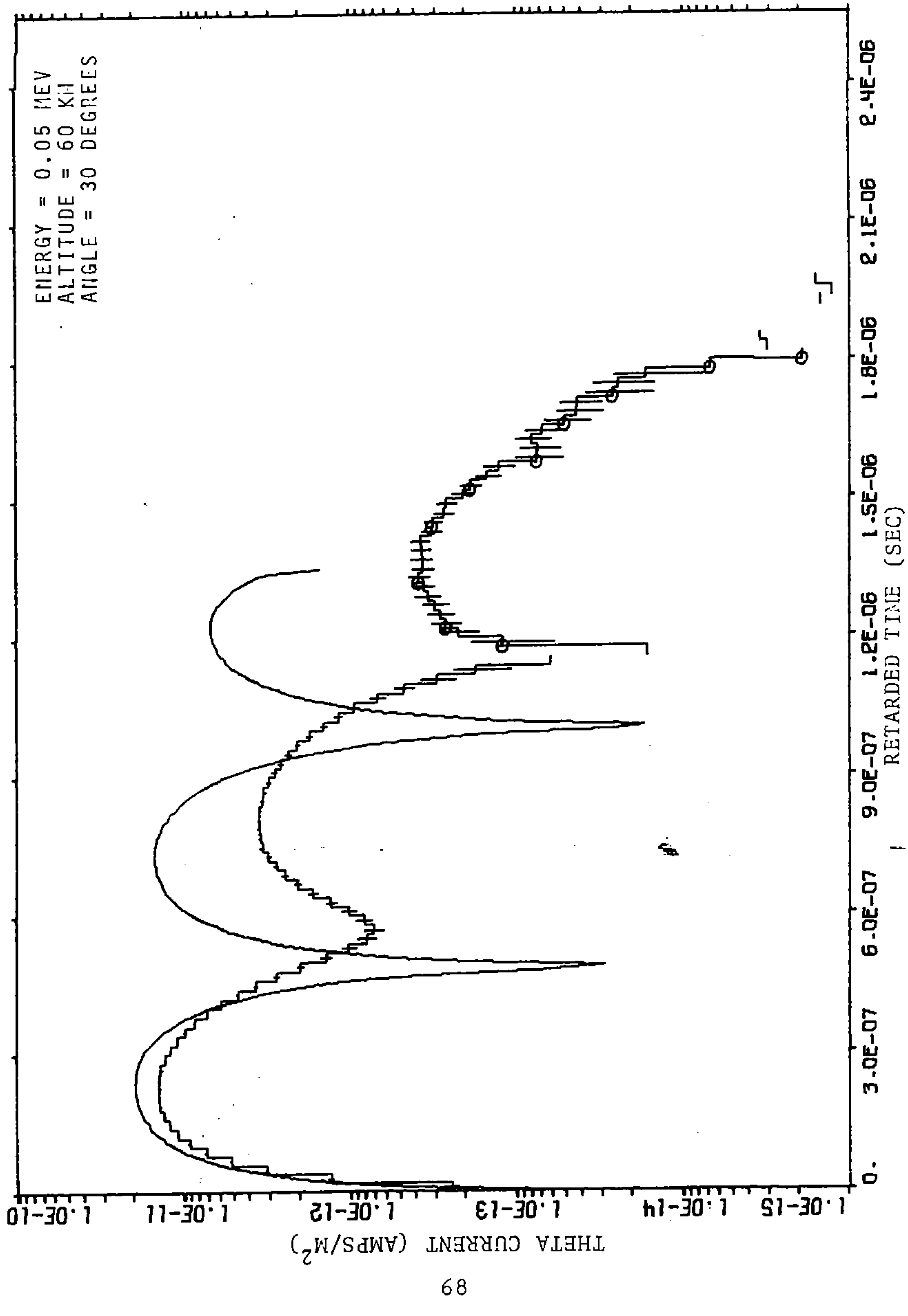

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 0 DEGREES
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RETARDED TIME (SEC)

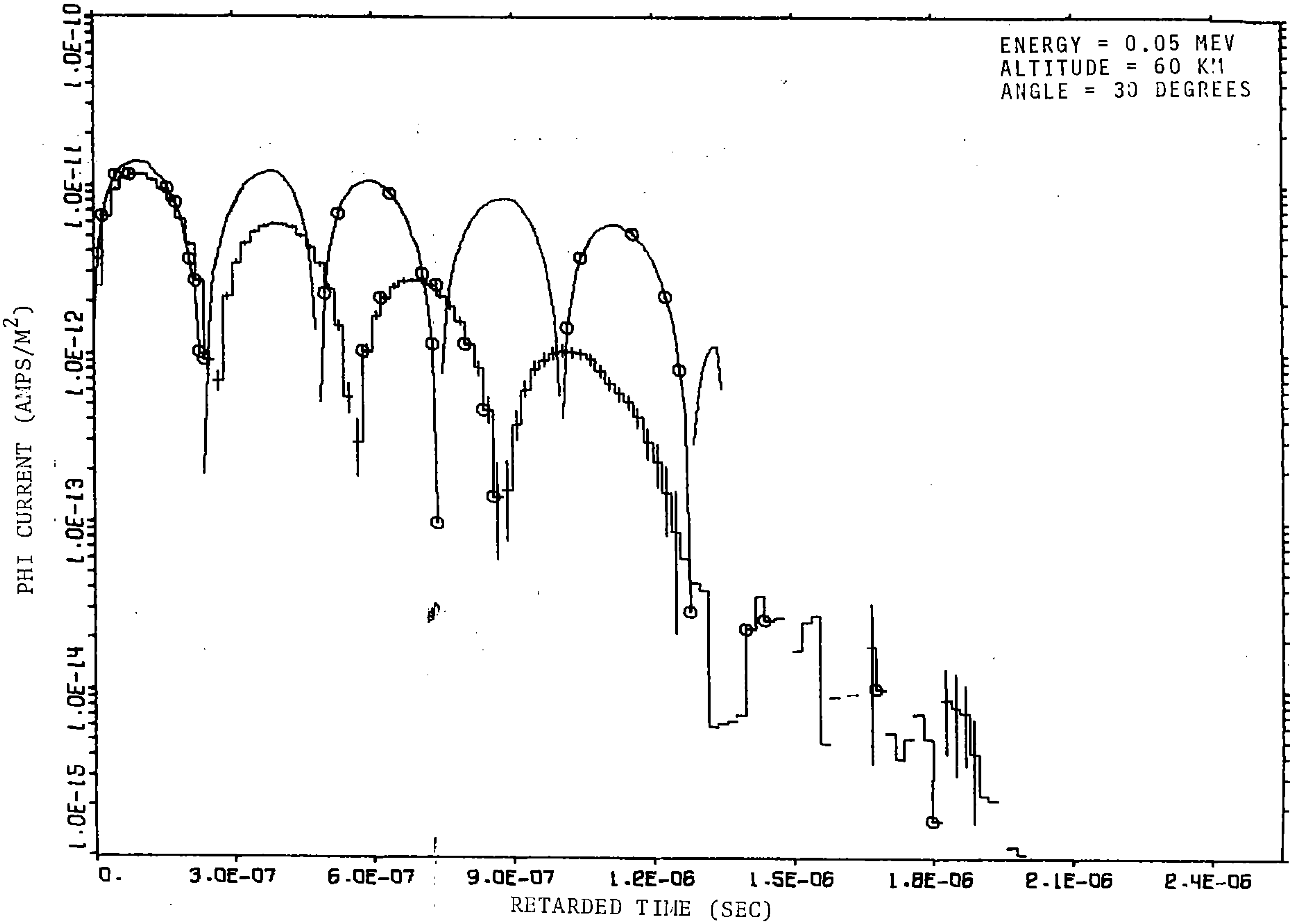

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 0 DEGREES
RETARDED TIME (SEC)
RADIAL CURRENT (AMPS/M²)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

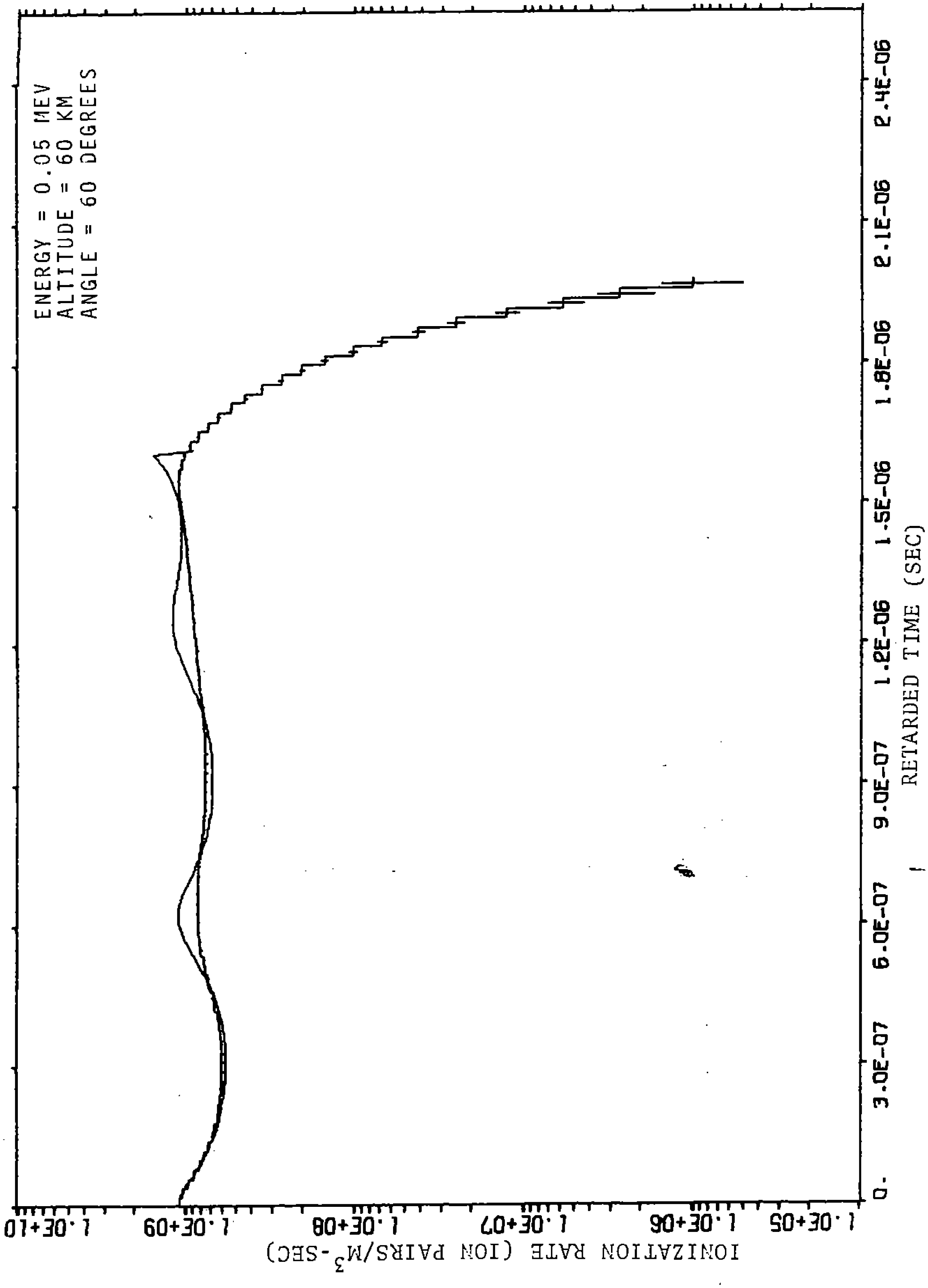

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 30 DEGREES
IONIZATION RATE (ION PAIRS/M3-SEC)
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RETARDED TIME (SEC)

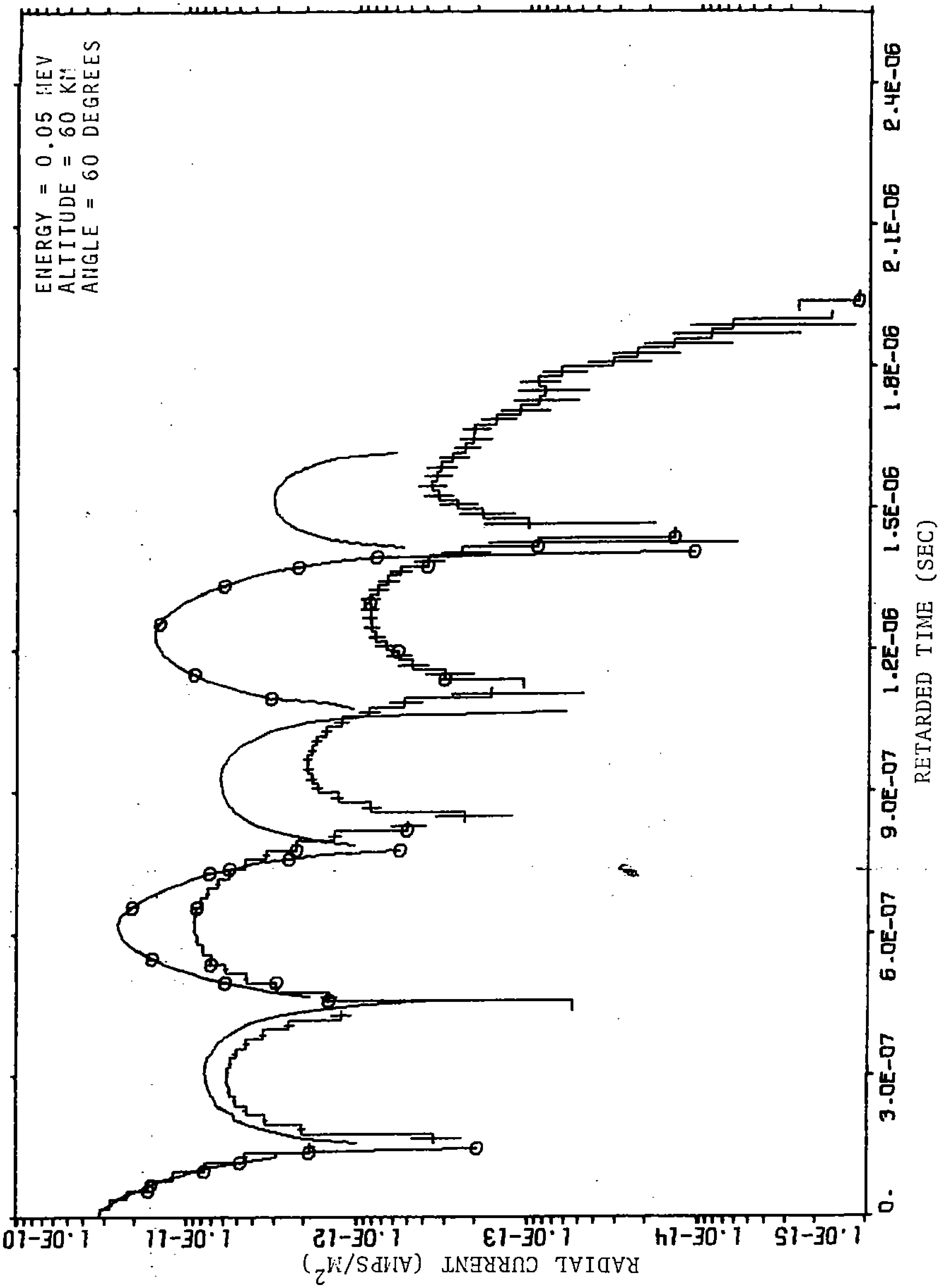


ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 30 DEGREES
RADIAL CURRENT (AMPS/M²)
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06

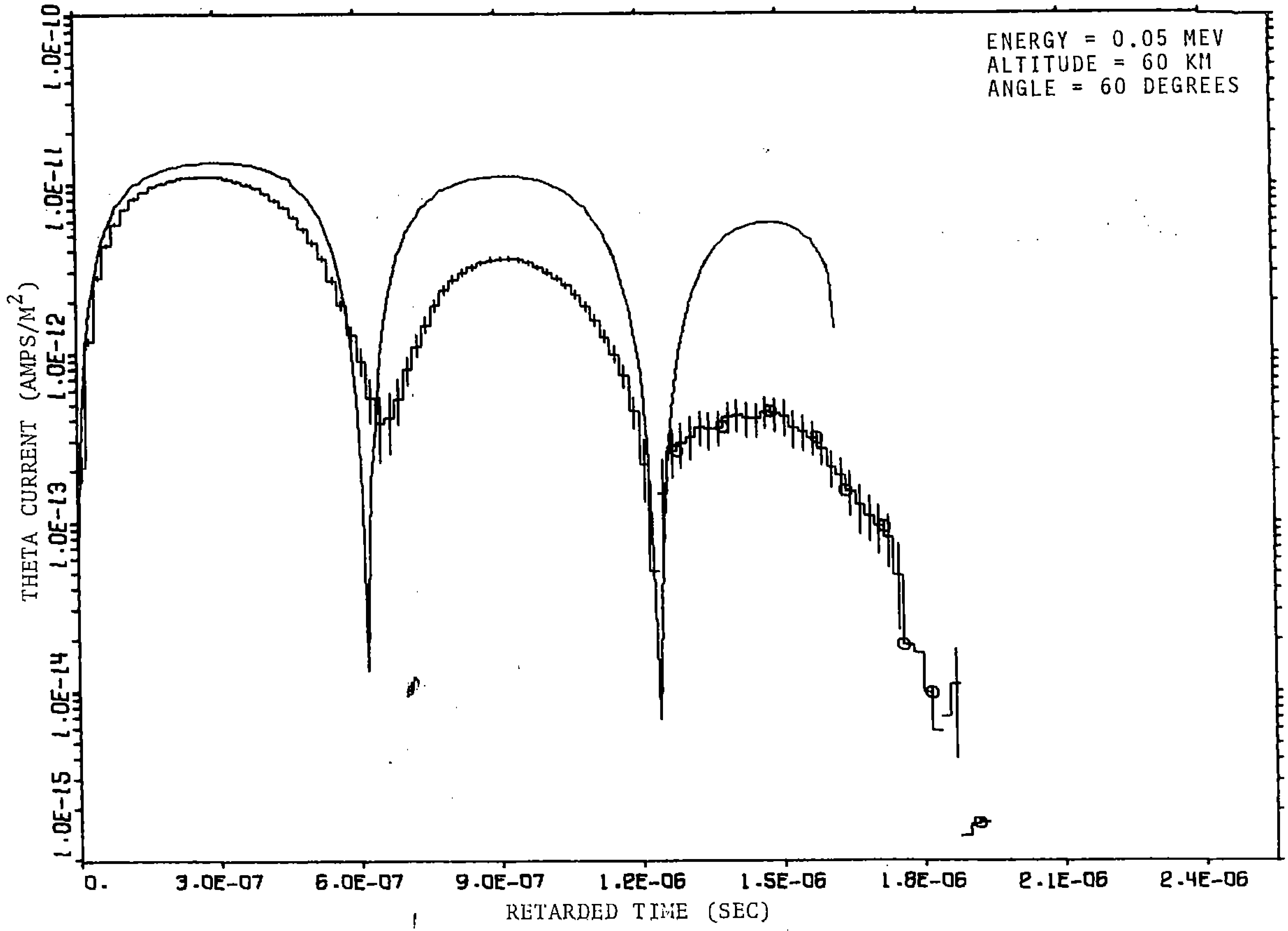

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 30 DEGREES
RETARDED TIME (SEC)
THETA CURRENT (AMPS/M2)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

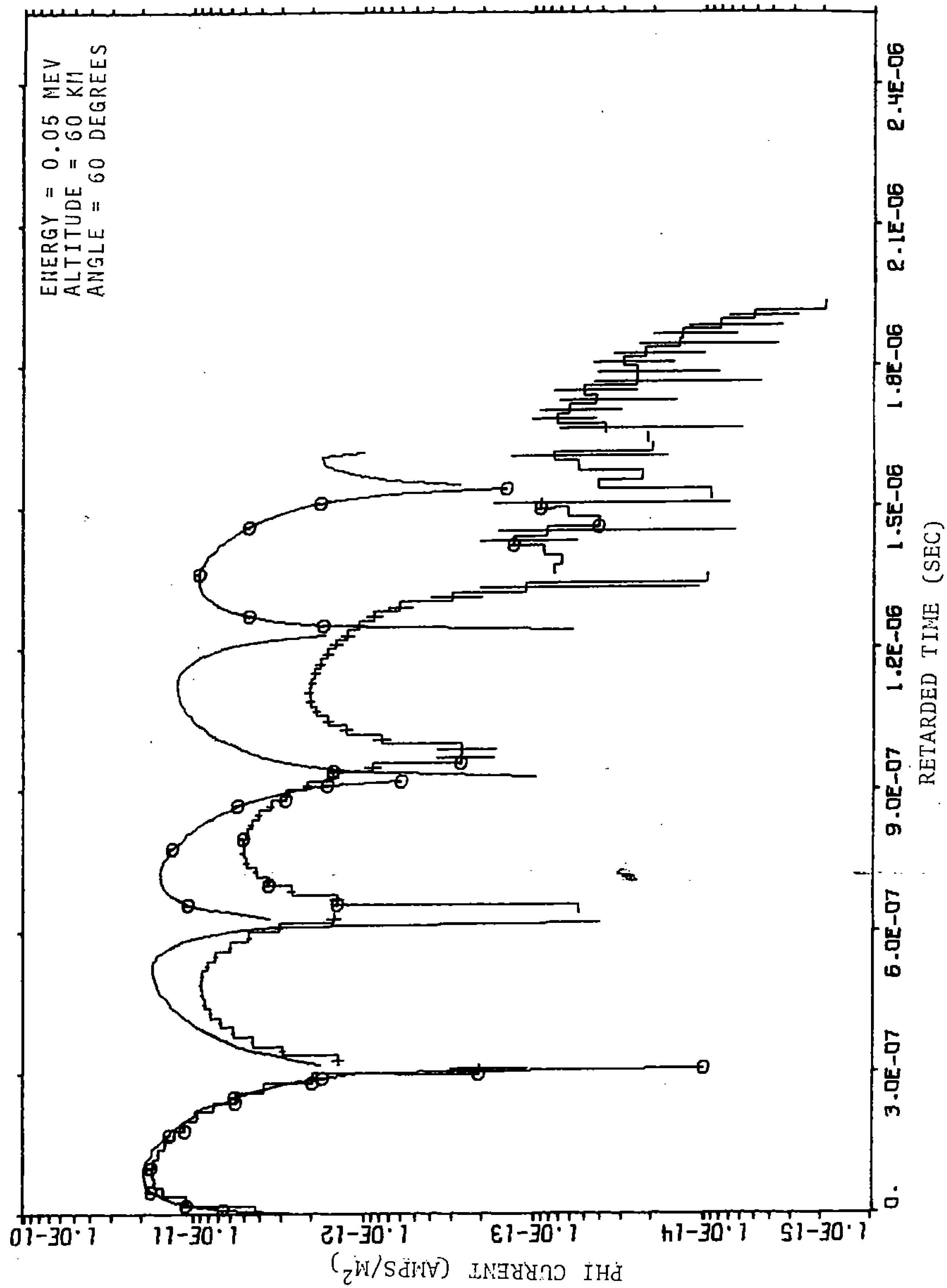

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 30 DEGREES
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
PHI CURRENT (AMPS/M2)
RETARDED TIME (SEC)

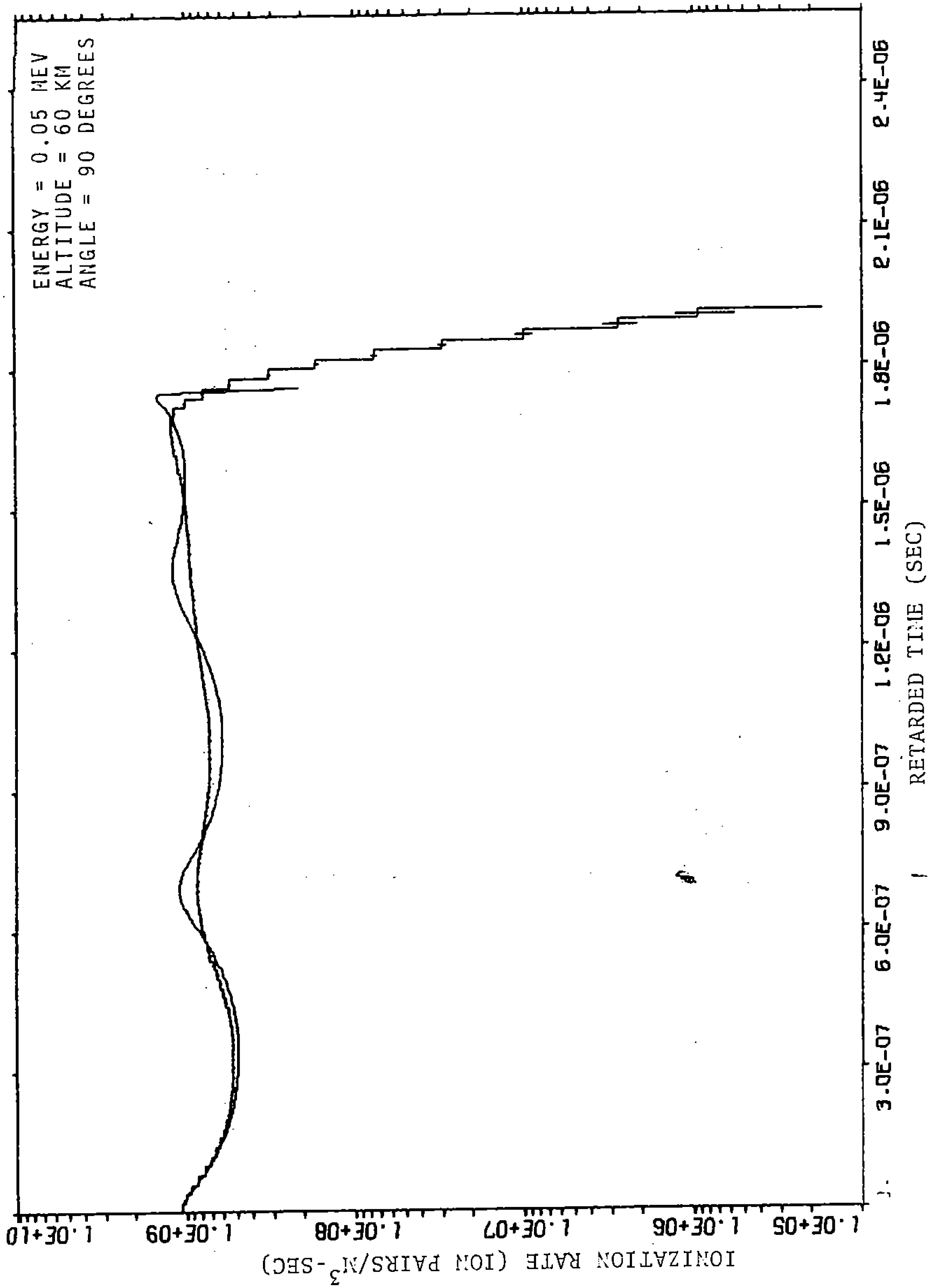

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
IONIZATION RATE (ION PAIRS/M^3-SEC)
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10



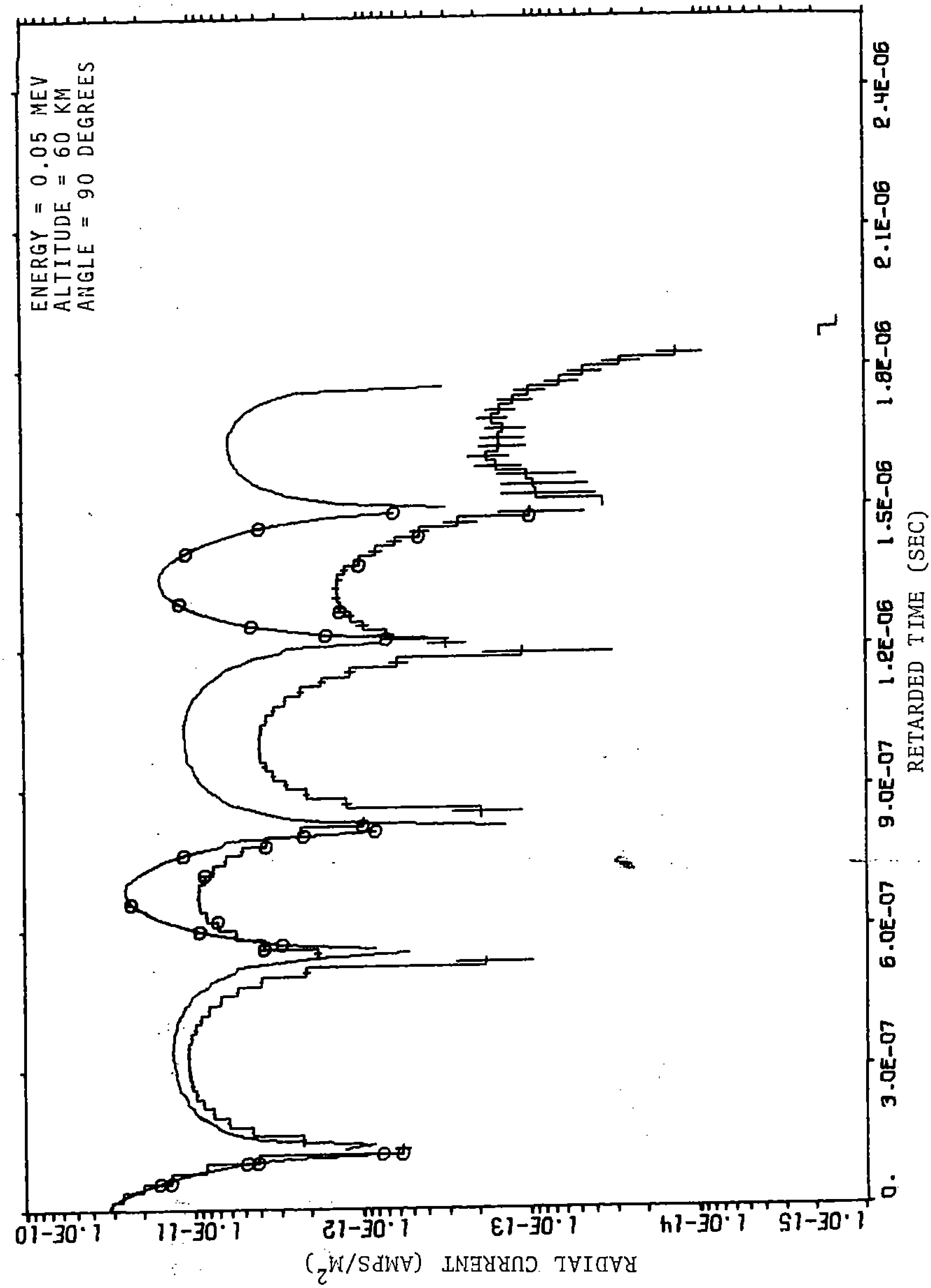
ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 60 DEGREES
RETARDED TIME (SEC)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RADIAL CURRENT (AMPS/M2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15

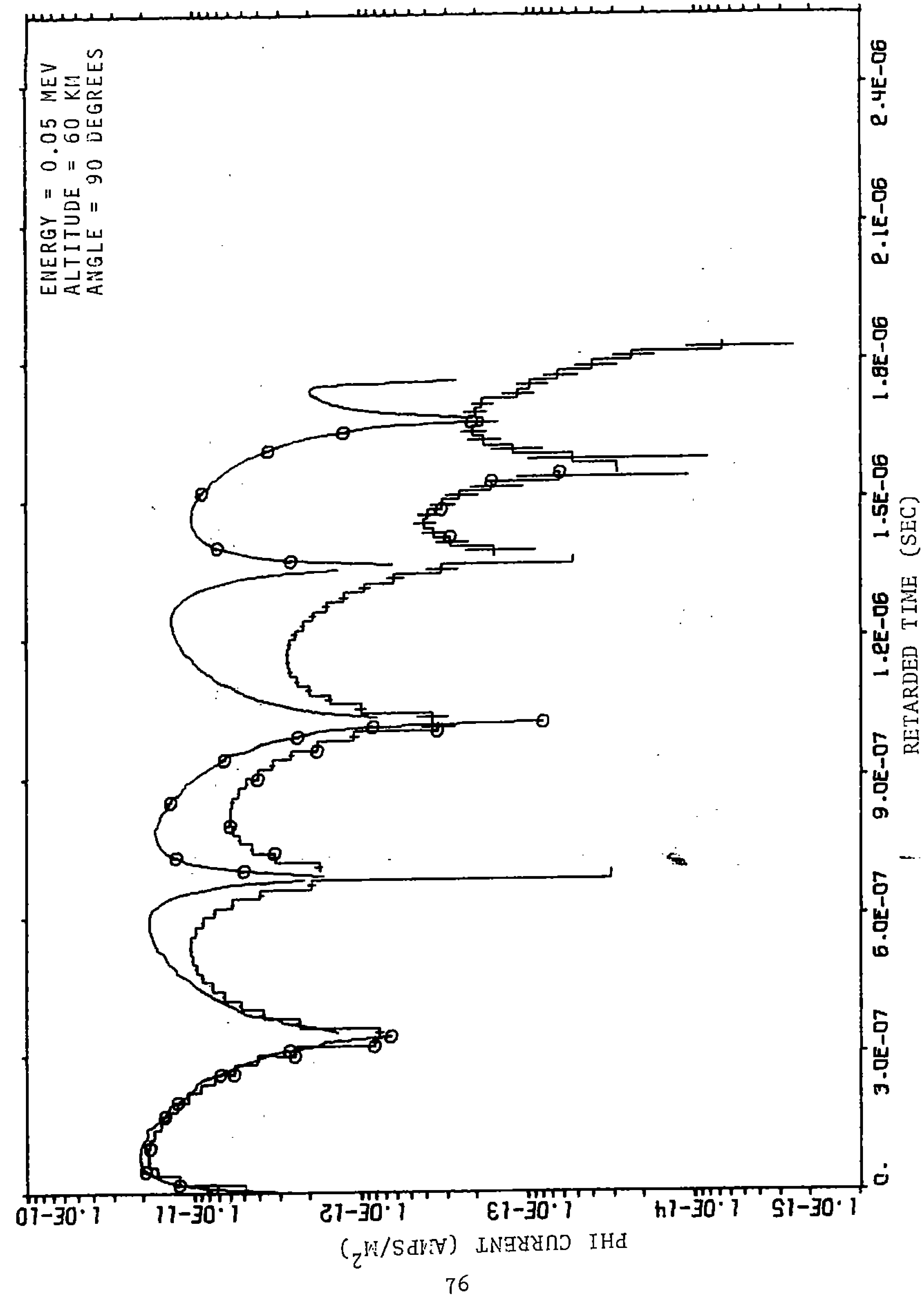

ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 60 DEGREES
THETA CURRENT (AMPS/M^2)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RETARDED TIME (SEC)


ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 60 DEGREES
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RETARDED TIME (SEC)
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
PHI CURRENT (AMPS/M²)



ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 90 DEGREES
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
RETARDED TIME (SEC)
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
IONIZATION RATE (ION PAIRS/M3-SEC)


ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
RADIAL CURRENT (AMPS/M2)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15


ENERGY = 0.05 MEV
ALTITUDE = 60 KM
ANGLE = 90 DEGREES
RETARDED TIME (SEC)
PHI CURRENT (AMPS/M^2)
0.
3.0E-07
6.0E-07
9.0E-07
1.2E-06
1.5E-06
1.8E-06
2.1E-06
2.4E-06
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15