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AD/RHIC-38

RHIC Technical Note No. 38

Accelerating Uranium in RHIC - II

Surviving the AGS Vacuum

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Section I - Introduction

In an earlier report,[1] the problems of accelerating fully stripped uranium ions in the AGS was investigated. Making the reasonable assumption that an adequate source of uranium ions will eventually be available at the Tandem,[2] the earlier report[1] showed that a modest intermediate Linac (~ 10 MV) would be sufficient for injecting fully stripped uranium ions into the AGS.

In this report we take a different strategy (suggested in discussions with A.G. Ruggiero). Rather than accelerating fully stripped uranium ions in the AGS, we take advantage of proposed improvements in the AGS vacuum, and investigate the survival rate of charge 90^{+} uranium ions in the AGS. In this way, the intermediate Linac would not be necessary, and the present injection scheme (Arrangement A of reference 1) would be adequate to accelerate uranium ions.

The choice of accelerating charge 90^{+} uranium has many origins. If we assume the charge state for uranium during acceleration in the Booster is 33^{+} (the same as ^{197}Au), then the top kinetic energy after the Booster is[1] 229.8 MeV/A. At this energy, experimental measurements of Anholt et al.[3] show that fully 50% of the uranium ions will be in a charge 90^{+} state after passing through foil S_B (Arrangement A of reference 1). Only 1% will be fully stripped at these energies.[3]

A straightforward calculation shows that for magnetic rigidities available in the AGS,[4] the top kinetic energy of charge 90^{+} uranium is 10.6 GeV/A. This is almost identical to fully stripped ^{197}Au ions (10.7 GeV/A), and hence clearly shows this kinetic energy can be accommodated in RHIC.[4]

The critical question to be addressed in forthcoming sections is "Can charge 90^{+} uranium ions survive the AGS vacuum?"

Section II - Acceleration Cycle for Uranium in AGS

In figures 1-5 a proposed acceleration cycle for charge 90^{+} uranium is shown. An acceleration time of 0.6 seconds was assumed, and the deduced rf voltage and phase fall well within acceptable limits.[4] These values were deduced assuming a constant bucket area X of 0.3 eV sec/A/bunch[4], and solving the usual pair of equations;[5]

$$\rho R\dot{B} = \frac{V}{2\pi} \operatorname{Sin} \phi_s \tag{1}$$

$$X = \frac{16R}{c} \sqrt{\frac{Q_e V E_s}{2\pi h|\eta|}}\ \alpha\ (\operatorname{Sin} \phi_s) \tag{2}$$

where ρ is the magnet radius, R the accelerator radius, E_s the total energy, $|\eta| = |\gamma^{-2}-\gamma_{TR}^{2}|$, and V, ϕ_s the required voltage and phase. The harmonic number h, was taken to be twelve[4] in this case.

At the present time, the exact method by which bunches will be stacked in RHIC is not finalized. For this reason, two complete acceleration cycles will be used for depletion studies. The first one will assume buckets are filled one at a time from the Booster (h=1), until all twelve in the AGS are full. Taking the worst possible case, this means with a 0.6 second acceleration time the first bunch must survive 11.6 seconds in the AGS. For the second case we simply assume one bucket at a time is transferred from the Booster and accelerated in the AGS.

Section III - Depletion Rate of Uranium Ions in AGS

The depletion rate of heavy ions in the AGS is defined as

$$\lambda(t) = \beta(t)c \sum_i n_i \sigma_{ig} \tag{3}$$

where $\beta(t)$ is the velocity of the 90^+ uranium ions, n_i is the density of gas ions in the AGS, and σ_{ig} is the interaction cross section for uranium on individual gas species.

n_i is given by, $n_i = kP$, where k is Boltzmanns constant, P is the pressure in Torr and k = 3.22 x 10^{16} molecules/cm^3 Torr. For air we assume 75.5% ^{15}N, 23.2% ^{16}O, and 1.3% ^{40}Ar.

σ_{ig} is the sum of the stripping cross section σ^k_{ig}, and the capture cross section σ^c_{ig}. For the stripping cross section we assume the theory of Bethe,[6] which has been tested for uranium by Gould[7] et al. In this theory σ^k_{ig} is given by:

$$\sigma^k_{ig} = 4\pi a_o^2 \left(\frac{\alpha}{\beta}\right)^2 \frac{1}{B_k} Z_i (1 + Z_i) f_k \left\{ \frac{\ell n(2\beta\gamma/\alpha)^2}{0.048 B_k} \right\} \tag{4}$$

where α is the fine structure constant, a_o the Bohr radius of Hydrogen, Z_i the atomic number of the gas molecule and B_k the binding energy of the k-shell electrons in uranium, in units of Rydbergs. f_k is an oscillator constant that takes the value .58 for 90^+ uranium. The kinetic factors β,γ are given by the acceleration cycle.

Neglecting finite nuclear size effects and Q.E.D. the binding energy of an electron in uranium is given by Diracs theory[8] as:

$$E = \frac{mc^2}{\sqrt{1 + \frac{Z^2\alpha^2}{\left(n' + \sqrt{(j + \frac{1}{2})^2 - Z^2\alpha^2}\right)^2}}} \tag{5}$$

For uranium atoms:			
	K Shell	Degeneracy = 2	Binding Energy = 132.36 KeV
	L Shell	" = 8	" " = 34.24 KeV
	M Shell	" = 18	" " = 6.4 KeV

The capture cross section (Radioactive Electron Capture) into the n'th shell is given by[7]

$$\sigma_{REC} = Z_i \left((\gamma-1) + B_n/mc^2\right)^2 \sigma(\epsilon)/(\gamma^2-1) \tag{6}$$

where m is the mass of an electron and B_n is the binding energy in the nth shell. $\sigma(\epsilon)$ is the photoionization cross section, which is tabulated for various shells in uranium.[9] ϵ is the photon energy, given by

$$\epsilon = 511(\gamma-1) + B_n \quad \text{(KeV)} \tag{7}$$

In figures 6 and 7, the photoionization cross section $\sigma(\epsilon)$ is shown for capture to all shells and capture to all shells minus the k-shell. It can be seen that the contribution from the k-shell is significant at these energies, and hence accelerating 90^+ uranium has definite advantages regarding capture. The photon energy in figures 6 and 7 were deduced from equation (7), where γ is the Lorentz factor for the accelerating uranium atom.

Figures 8 and 9 show the knock-out and capture cross sections for ^{90+}U + N as a function of both the uranium kinetic energy and the acceleration time. It can be seen that stripping dominates over capture at these energies, and indeed at energies greater than 3 GeV/A, capture processes can be safely ignored. The stripping cross section increases as a logarithm of γ (see equation 4). Of course, the decrease of the capture cross section at these energies is precisely the reason why accelerating fully stripped ions in the AGS is preferred. For fully stripped ions the stripping cross section does not exist of course, and for energies greater than a few GeV/A, capture is negligible.

Figure 10 shows the quantity $\lambda(t)$ defined in equation (3) for 90^+ uranium ^{15}N as a function of the acceleration time. It can be seen that the shape of $\lambda(t)$ is dominated by the stripping cross section. The small discontinuity in $\lambda(t)$ at ~ .2 sec represents the effect of neglecting capture cross sections at energies in excess of 3 GeV/A. This effect is seen to be negligible.

Section IV - Survival Ratio in the AGS

Assuming uranium intensities that are normalized to unity at time t=0, figures 11-15 show the total depletion as a function of time in the AGS for various pressures. Figures 11 and 14 correspond to the full cycle of 11 second plus .6 seconds acceleration, whereas figure 15 corresponds to the .6 second acceleration cycle only. The depletion D is defined by:

$$D(t) \sim e^{-\int_0^t \lambda(t')dt'} \qquad (8)$$

where $\lambda(t')$ is given in equation (3).

It is very encouraging to see that for a pressure of 10^{-8} torr, up to 91% of the beam can be expected to survive the full 11.6 second acceleration cycle. For a pressure of 10^{-9} torr, 99% can be expected to survive. For the present day pressure[4] of 10^{-7} torr, the beam will be depleted by a factor ~ 2.5.

If the bunch of uranium ions is transferred from the Booster one at a time and accelerated in the AGS singularly (Figure 15), then at 10^{-7} torr 95% of the beam will survive. At 10^{-8} torr 98% will survive the short acceleration cycle.

All of these results are extremely encouraging and positive for they clearly show that accelerating uranium in the AGS is feasible, even with a vacuum of 10^{-7} torr. Indeed, if as expected a vacuum of 10^{-8} torr can be achieved, then the full 12 bucket cycle, injected from the Booster, may be easily accommodated.

Of course, all this analysis assumes an adequate source of uranium ions is available at the Tandem.

Section V - Conclusions and Suggestions for the Future

1) The analysis presented in this paper shows very clearly that it is possible to accelerate uranium ions in a 90^+ charge state in the AGS, even under current vacuum specifications, and have sufficient numbers of ions survive the acceleration cycle for experimental purposes. Indeed if the AGS vacuum can reach 10^{-8} torr, as is expected in the very near future, then a full 12 bucket acceleration cycle will only result in a loss of 8% of the uranium ions. For less severe acceleration cycles, the depletion of uranium ions will be less and may be readily extracted from figures 10 and 15, because of the exponential nature of the depletion rate.

2) The energy, after acceleration in the AGS, of charge 90^+ uranium ions is 10.6 GeV/A. After acceleration in the AGS these ions would be passed

through a stripping foil and the fully stripped uranium ions could be easily accommodated in RHIC.

3) The survival rate of charge 90 uranium ions in the AGS at 10^{-7} and 10^{-8} torr, strongly indicates that there is relatively little to be gained by going to 10^{-9} torr pressure in the AGS.

4) Adding uranium ions to the available list of heavy ions would increase the interest of the experimental community at both fixed target AGS experiments and future RHIC experiments. The extra nuclear charge available would open up the experimental study of strong field Quantum Electrodynamics, and the possible exotic modes these fields can excite in nuclei.

5) The recent, extremely encouraging results in ion source development strongly suggests that funding be made available to develop negative ion sources for uranium at the Tandem.

References

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Erratum Phys. Rev. Lett. 52 (1984) 1654.
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Figure Captions

Figure 1. Time variation of the dipole magnetic field for the 0.6 second acceleration cycle.

Figure 2. Rate of charge of dipole magnetic field for acceleration cycle.

Figure 3. Time variation of rf voltage during acceleration cycle to maintain bucket area of .3 eV sec/A/bunch.

Figure 4. Graph of rf phase during acceleration cycle, showing jump across transition energy at .44 seconds.

Figure 5. Kinetic energy of charge 90 uranium ion during acceleration cycle.

Figure 6. Photoionization cross section for uranium, showing capture to all major shells.

Figure 7. As figure 5, except the k-shell capture has been removed.

Figure 8. The knock-out and capture cross sections for uranium ions as a function of kinetic energy during the acceleration cycle. The cross sections are for charge 90 uranium on nitrogen.

Figure 9. As figure 8, but plotted against acceleration time.

Figures 10-14. Depletion of charge 90 uranium ions as function of AGS acceleration cycle. The depletion is shown for various AGS pressures.

Figure 15. Depletion of charge 90 uranium ions for short 0.6 second acceleration cycle in AGS only.

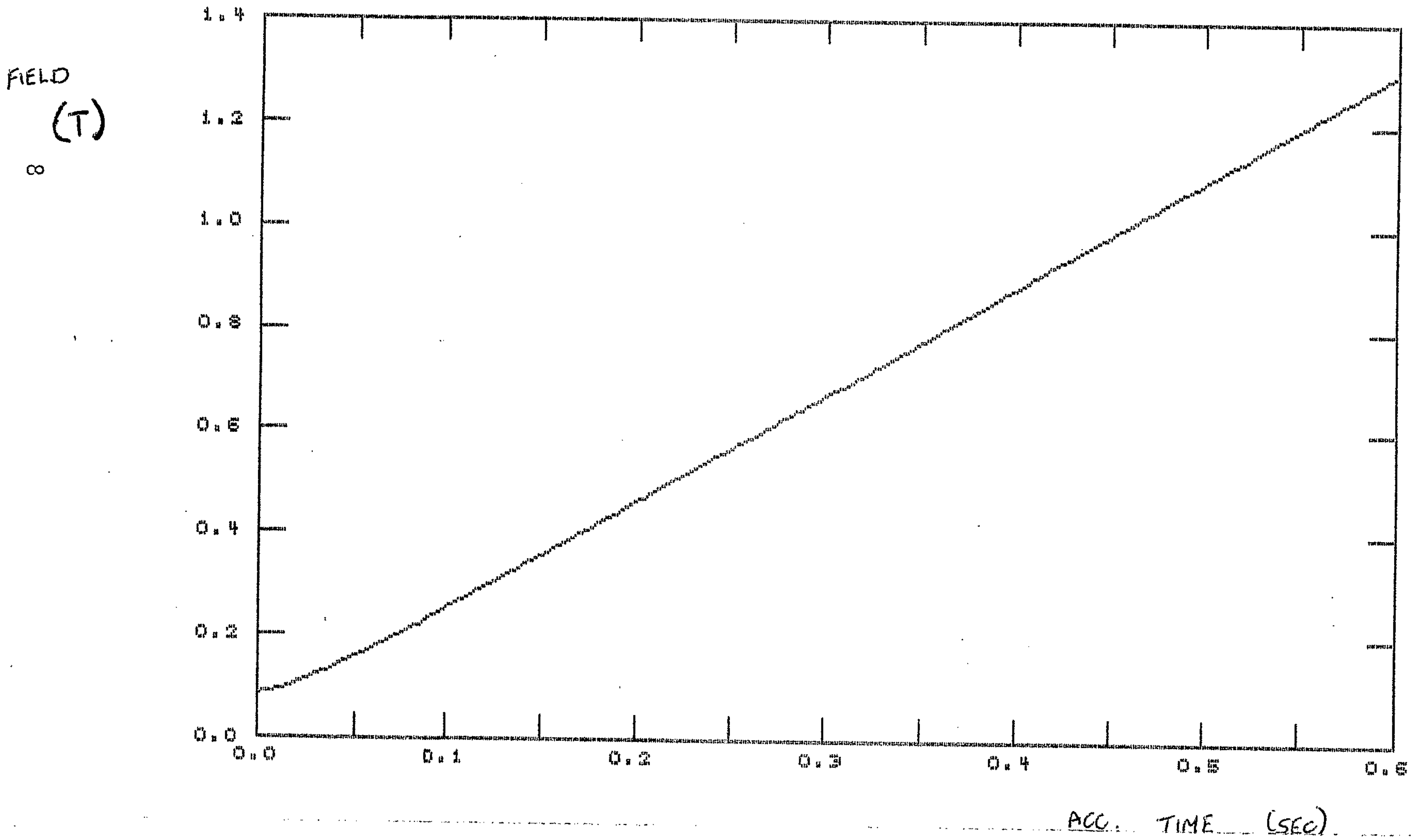


Figure 1. Time variation of the dipole magnetic field for the 0.6 second acceleration cycle.

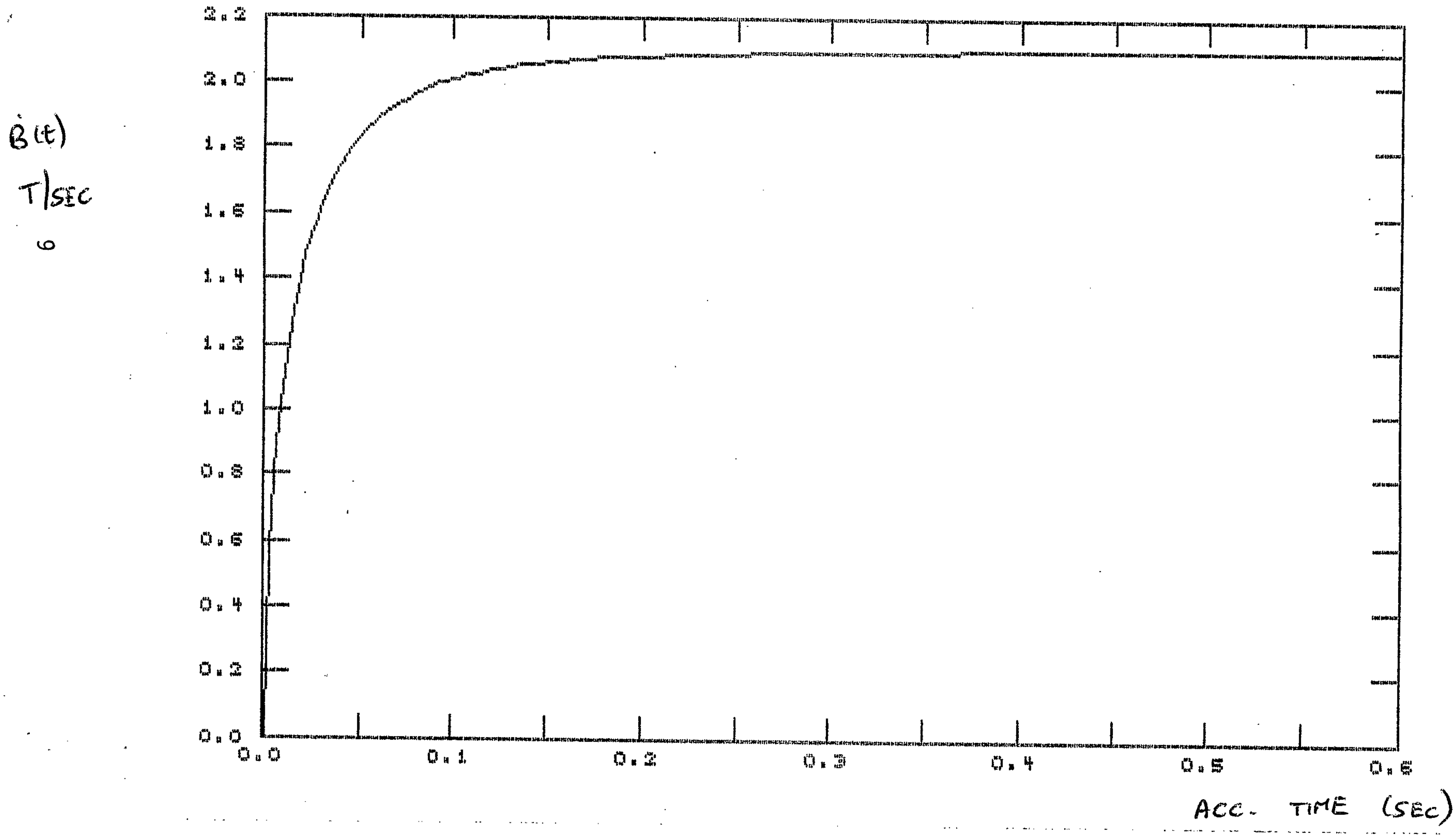


Figure 2. Rate of charge of dipole magnetic field for acceleration cycle.

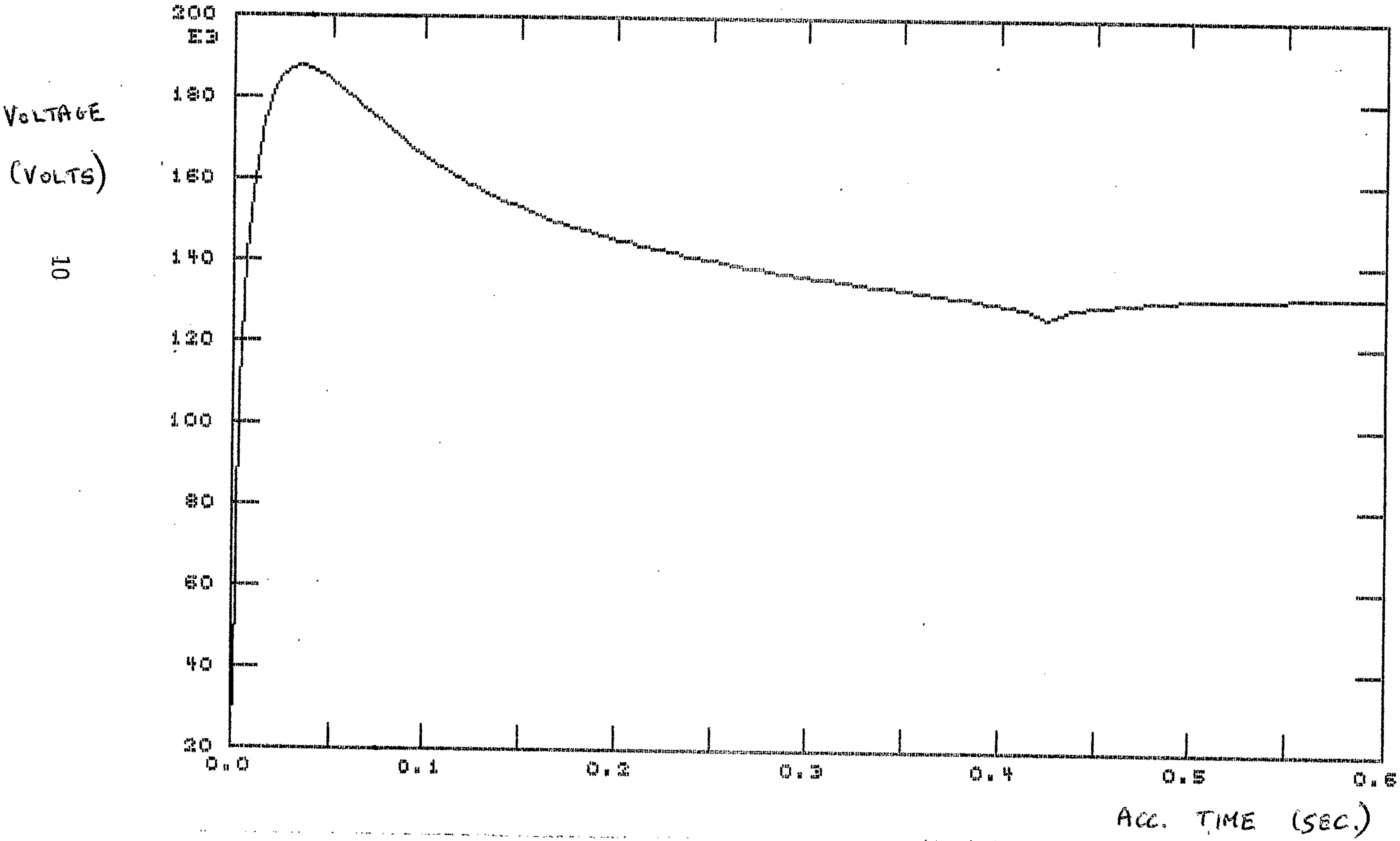


Figure 3. Time variation of rf voltage during acceleration cycle to maintain bucket area of .3 eV sec/A/bunch.

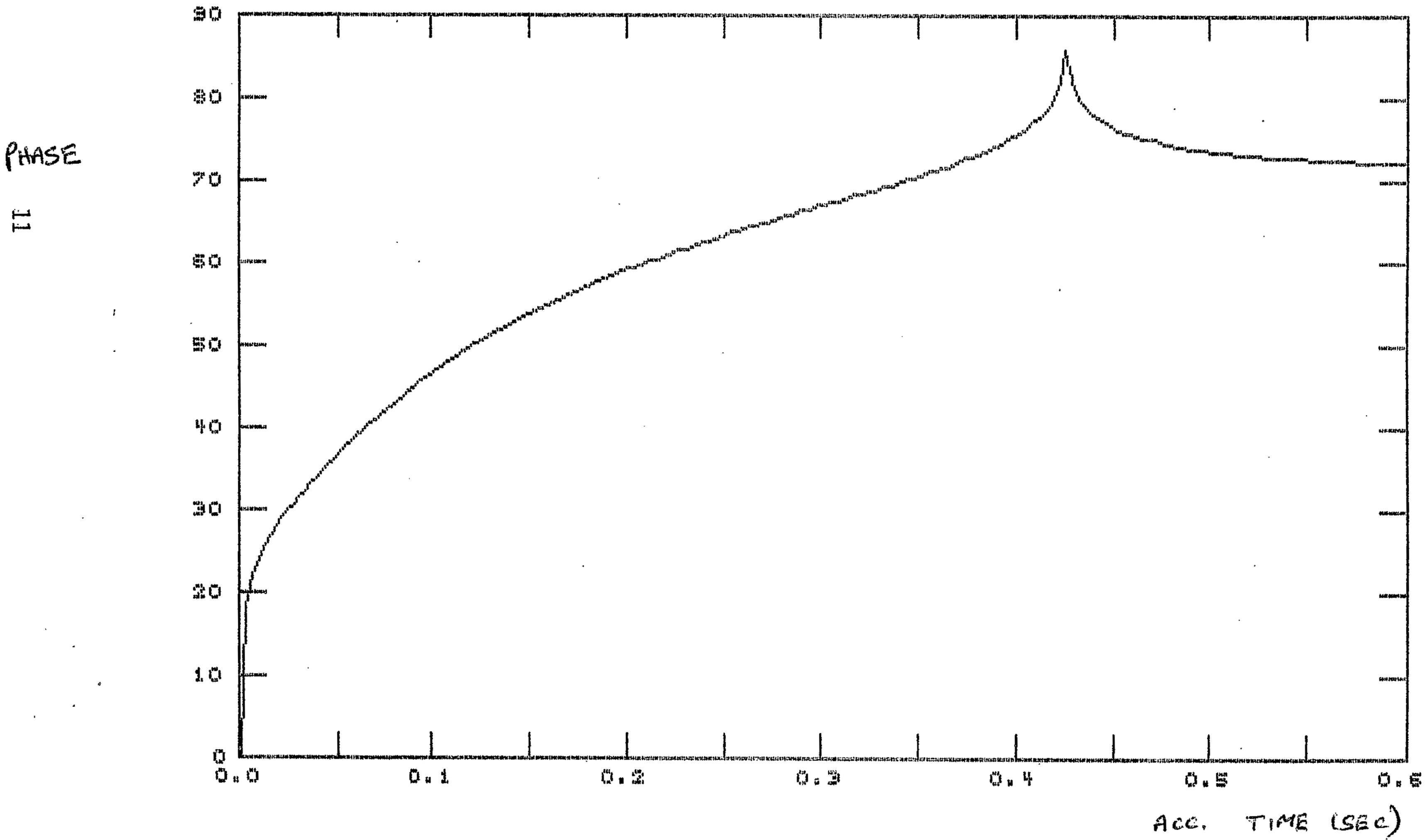


Figure 4. Graph of rf phase during acceleration cycle, showing jump across transition energy at .44 seconds.

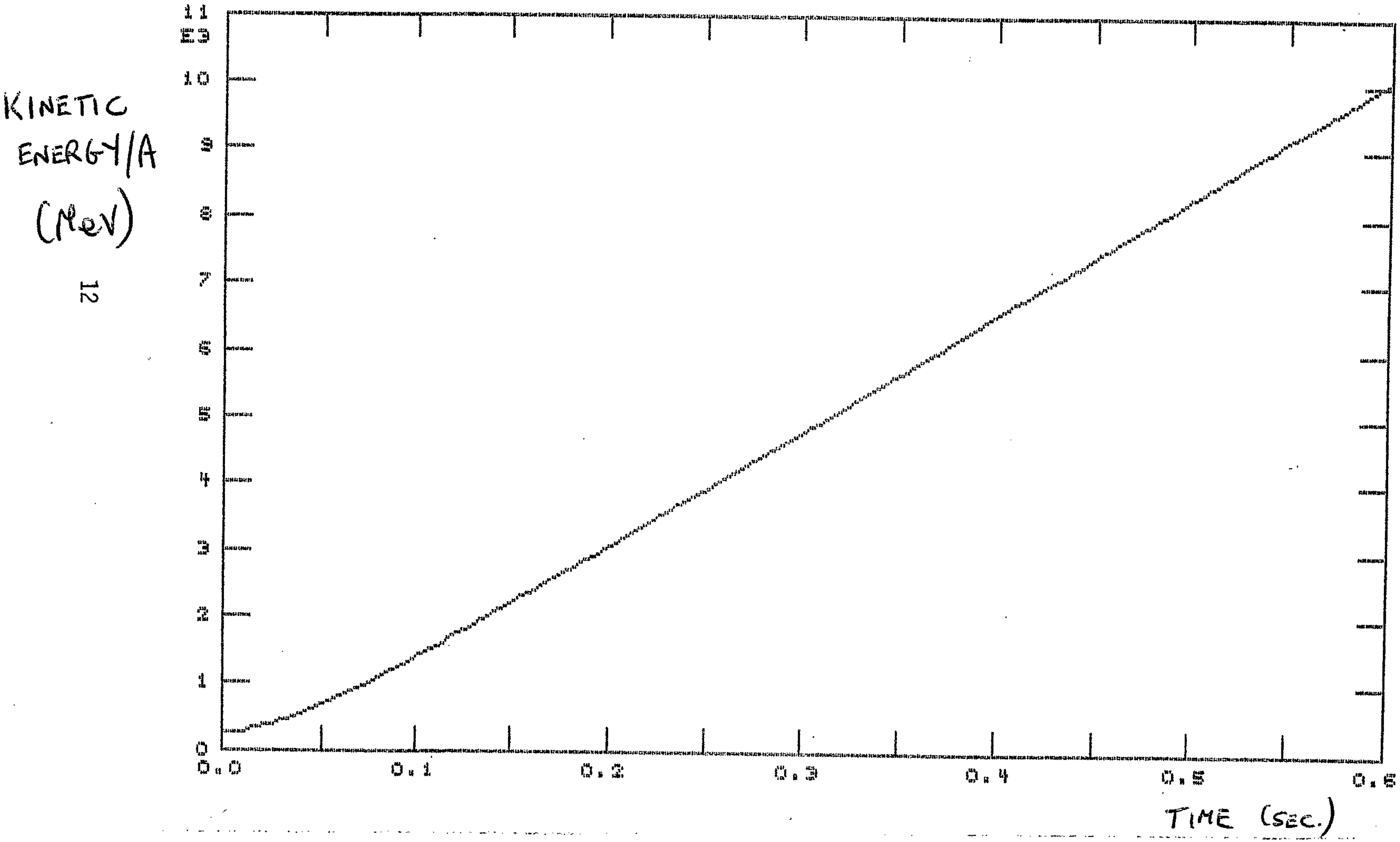


Figure 5. Kinetic energy of charge 90 uranium ion during acceleration cycle.

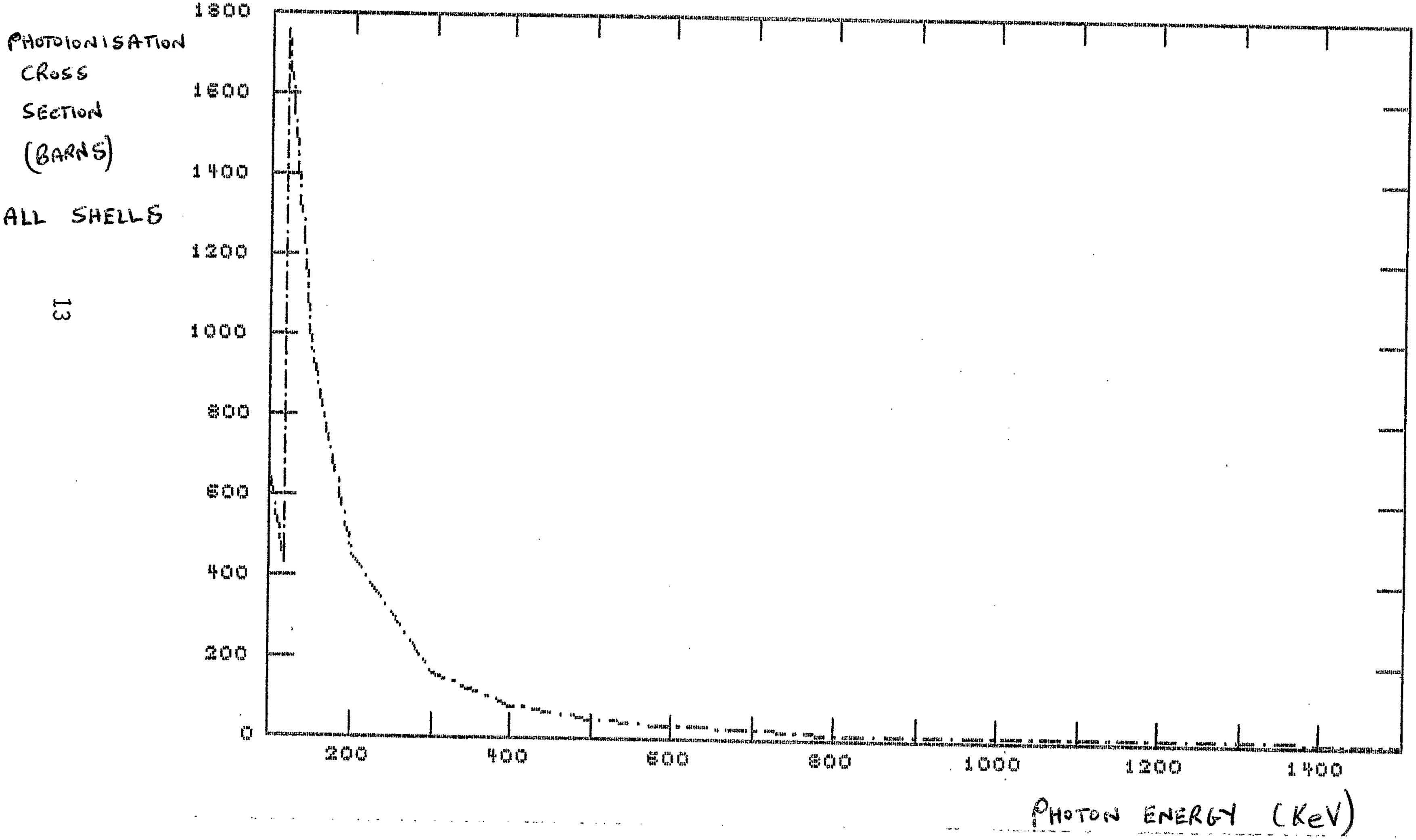


Figure 6. Photoionization cross section for uranium, showing capture to all major shells.

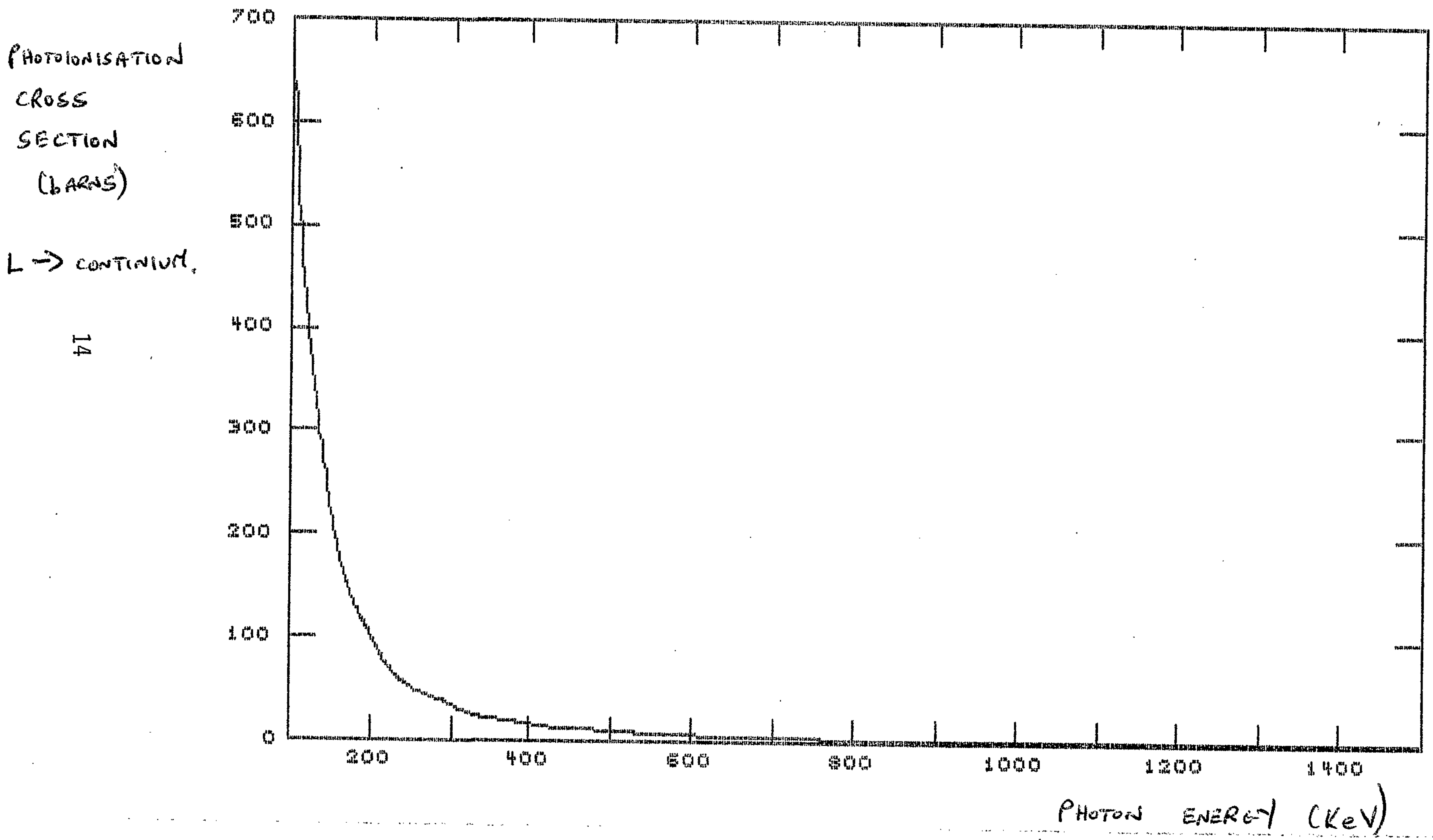
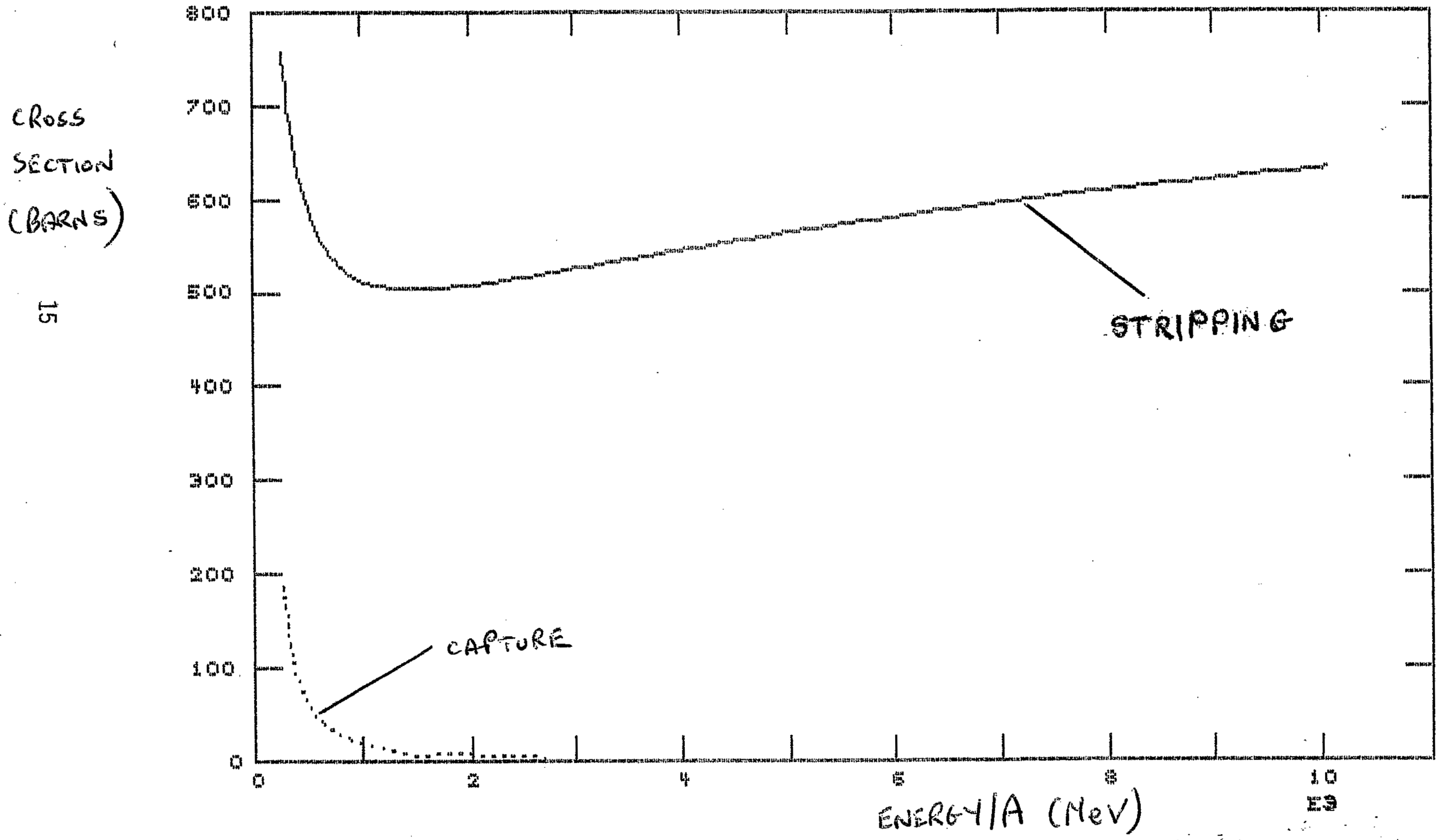


Figure 7. As figure 5, except the k-shell capture has been removed.



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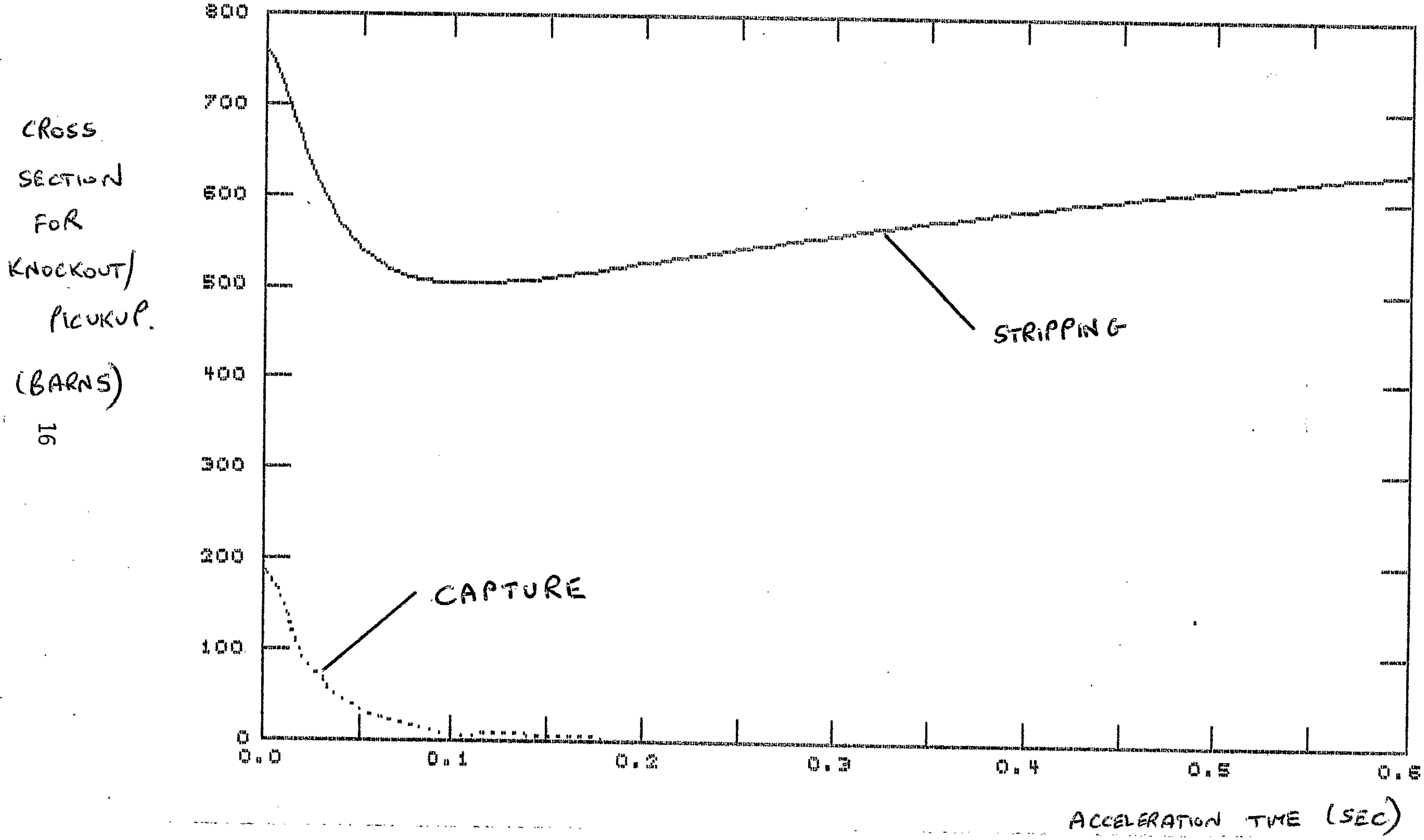

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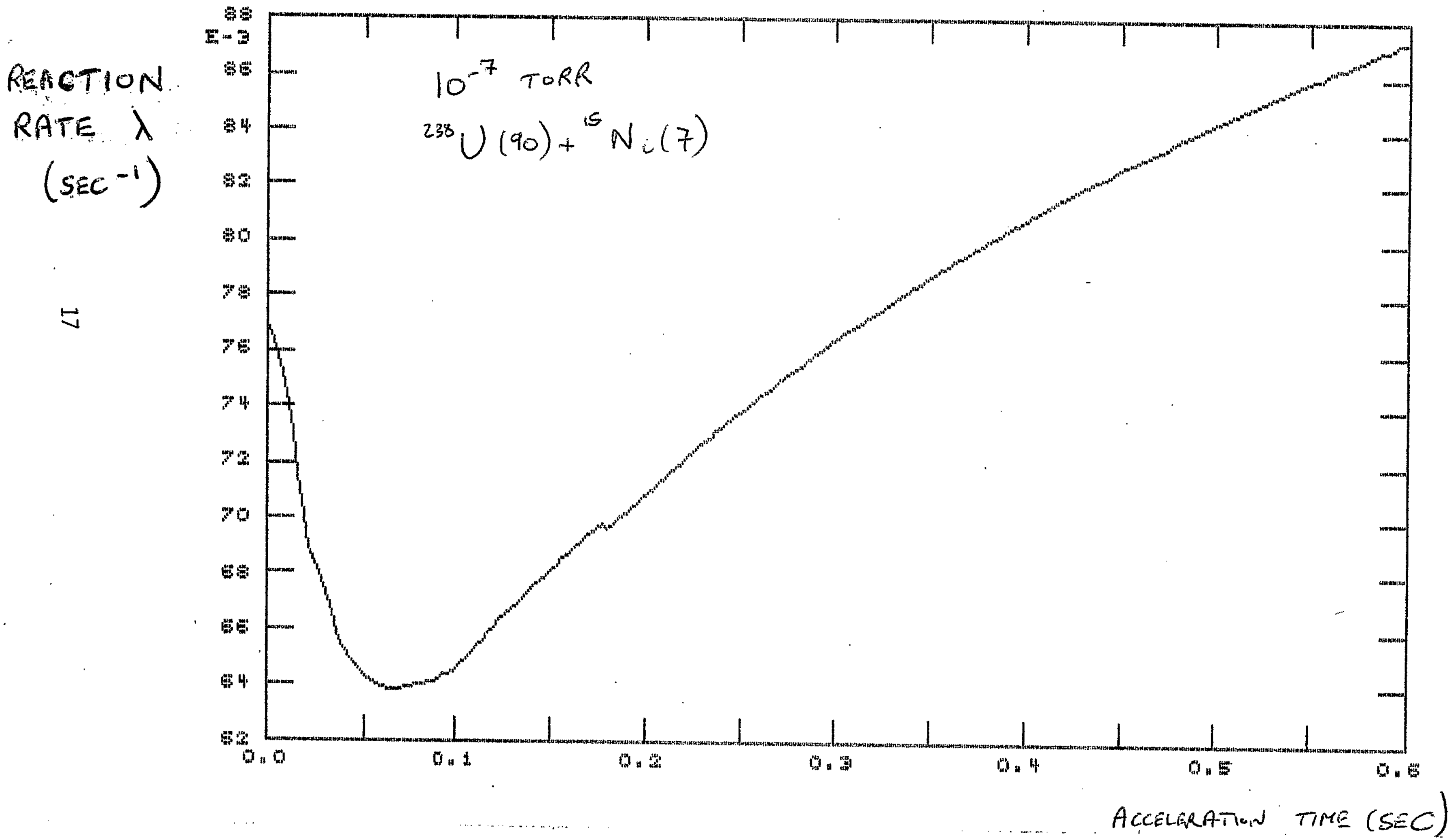

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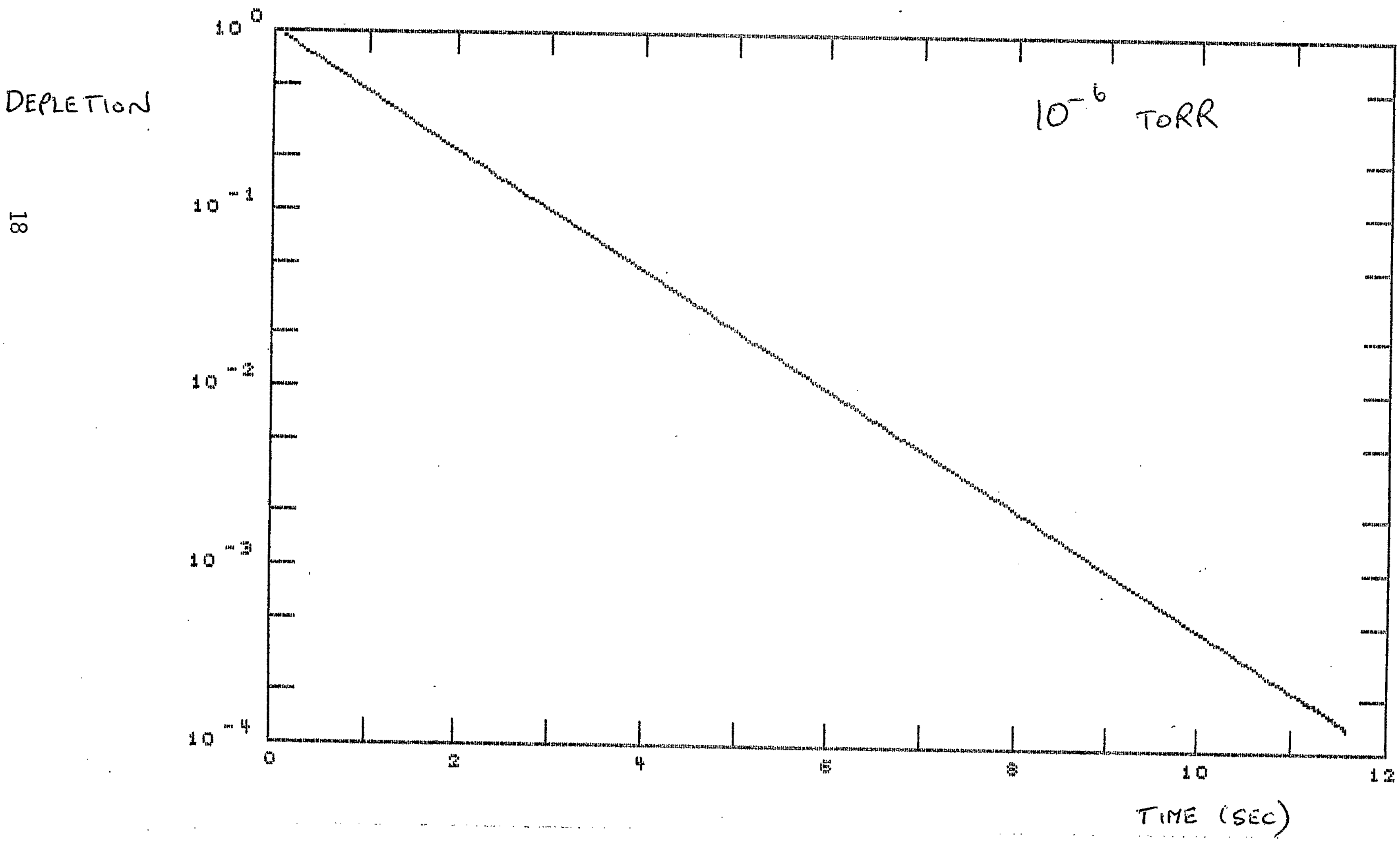

Figure 11.

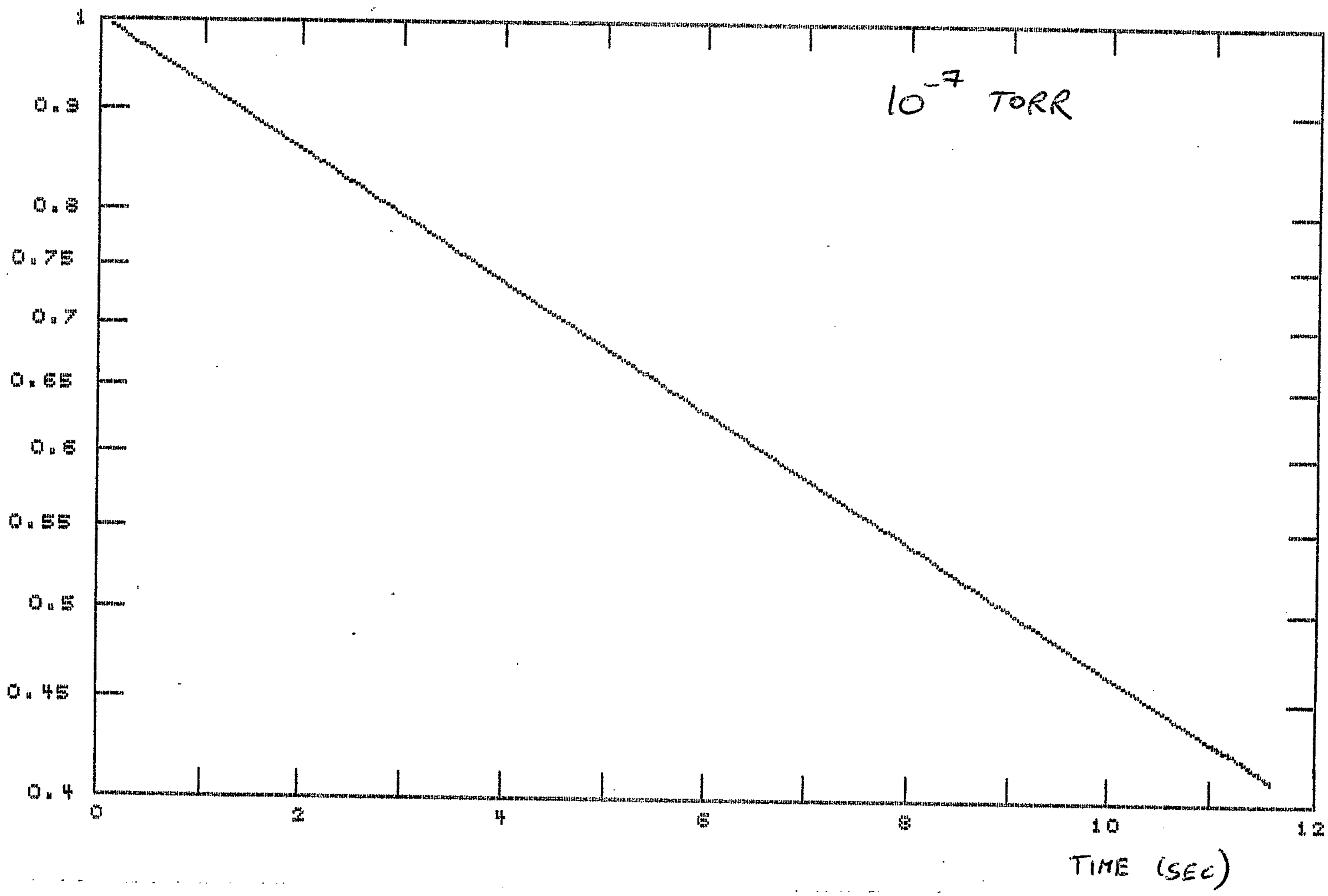
DEPLETION
1
0.9
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0
2
4
6
8
10
12
TIME (SEC)
10^{-7} TORR

Figure 12.

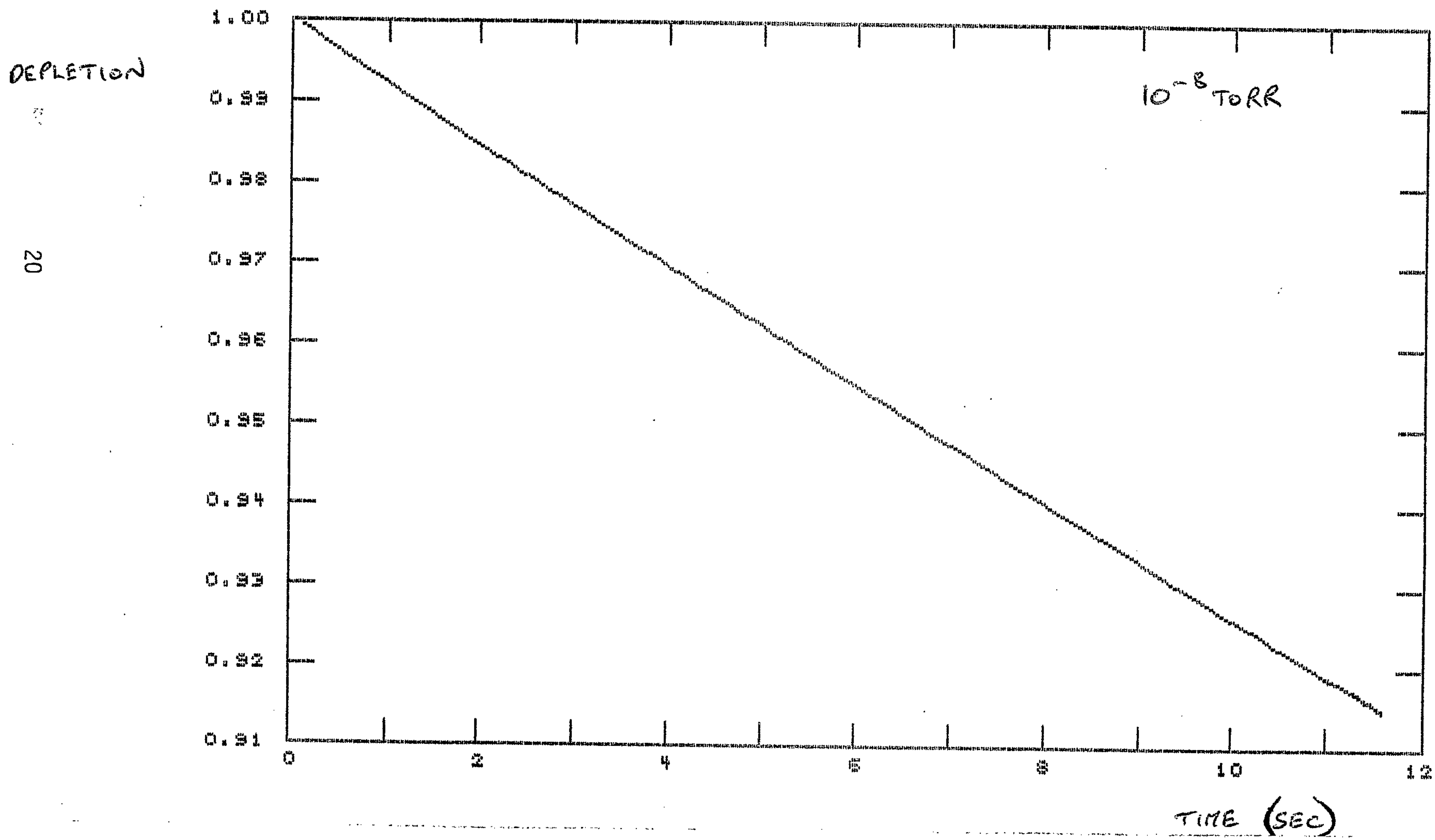
DEPLETION
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
10^{-8} TORR
0
2
4
6
8
10
12
TIME (SEC)

Figure 13,

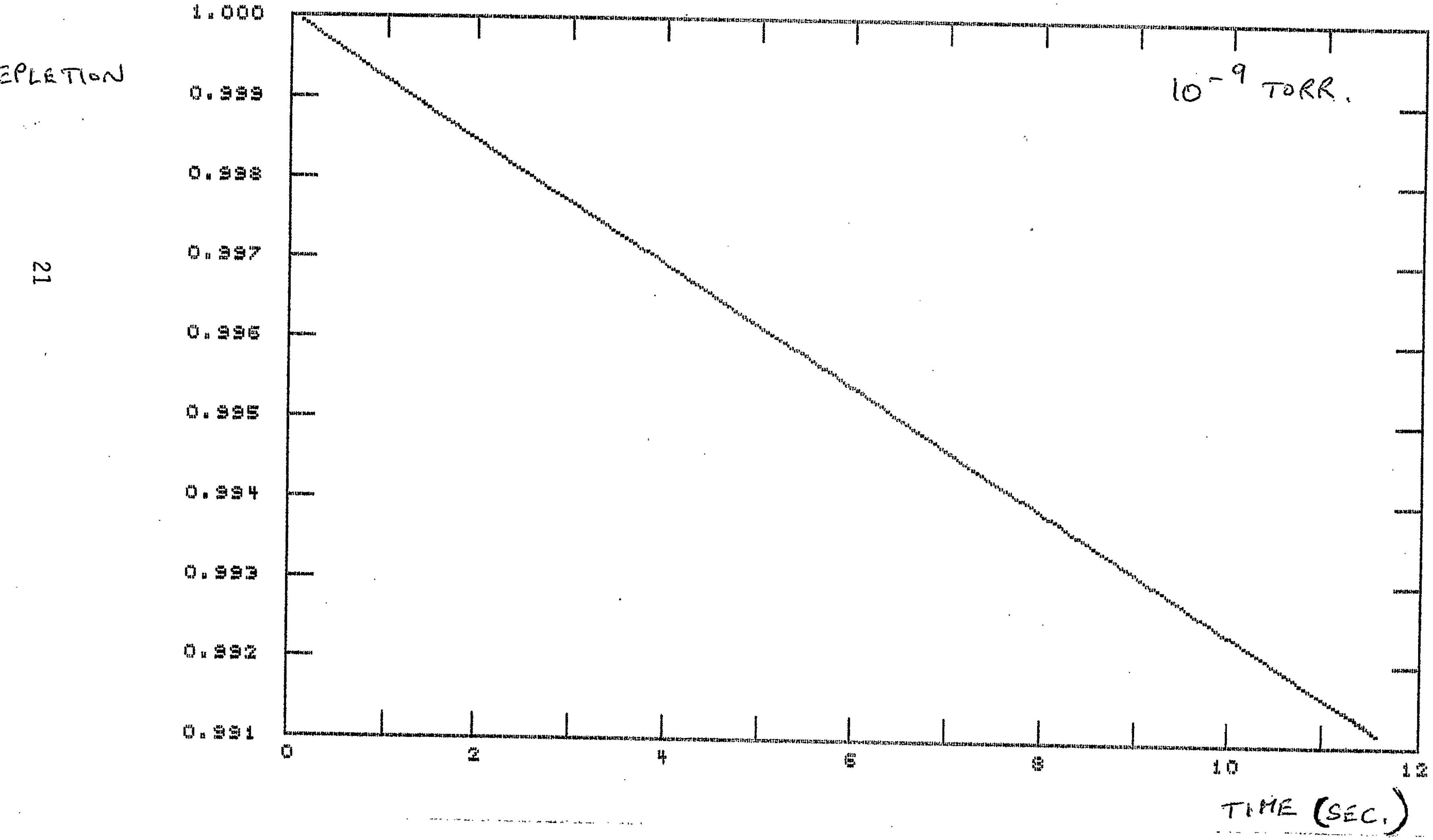
EPLETION
1.000
0.999
0.998
0.997
0.996
0.995
0.994
0.993
0.992
0.991
0
2
4
6
8
10
12
TIME (SEC.)
10^-9 TORR.

Figure 14.

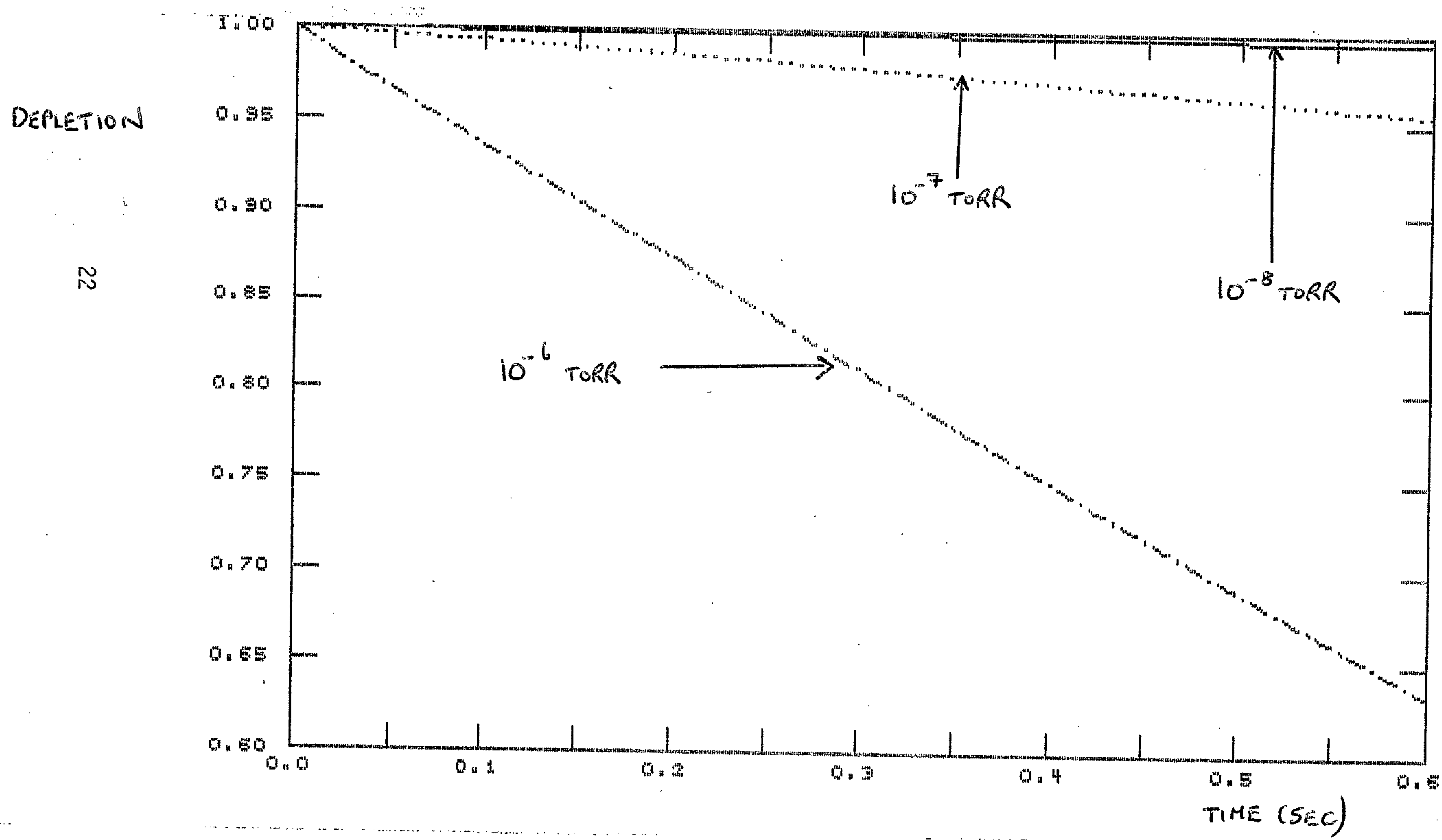

Figure 15. Depletion of charge 90 uranium ions for short 0.6 second acceleration cycle in AGS only.