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M. J.B. ADAMS

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First storage experiment at 270 GeV and observations of single bunch storage (9 June 1978)

J. Gareyte, H.K. Kuhn, T. Linnecar,
W. Mills, J.D. Pahud, D. Thomas, E. Wilson

1. INTRODUCTION

The aim of this experiment was to store a continuous beam of protons at 270 GeV, the nominal maximum D.C. excitation level of the SPS. In previous experiments during the summer of 1977 we had succeeded in storing protons at 200 GeV and logarithmic decay times in excess of 15 hours had been recorded. There was some interest in seeing if, at these higher energies this lifetime would be 80 % longer as theory predicts.

There was also a chance that if all went well we might be able to inject and store single intense bunches since recently procedures for single bunch acceleration have become more streamlined. A previous storage trial with rather weak (6 x 10^9) single bunches had been carried out in October and lifetimes of several hours recorded in two brief stores. But there were some theoretical indications that at intensities approaching those required in the antiproton project single bunches might become unstable. It seems these fears were not unjustified.

2. RUNNING THE SPS D.C. at 270 GeV

After a few teething problems connected with r.m.s. current limits and with cooling circuits had been overcome, the SPS sustained 270 GeV D.C. excitation for as long as the experiment demanded. Many transitions from accelerating to storage mode were executed without incident and an uninterrupted store of 90 minutes was achieved, culminating quite normally at the request of the experimenters.

3. SPS TUNING

As far as possible, conditions identical to the best previous storage experiments were established. The Q value was set to $Q_h = 26.623$, $Q_v = 26.554$ on the 270 GeV flat top and chromaticity adjusted to be very close to zero. Octupoles, skew quadrupoles, beam damper and bunch spreader were all disabled.

An improved procedure for changing the LSF and LSD sextupoles into D.C. mode was used which is compatible with operational software and requires no hardware reconnections. In this new procedure the start and stop of the function generators are displaced to mid flat top and, once in storage mode, start pulses are interrupted with a timing unit used as a gate.

It was possible in this run to establish the delay between pushing the store button and the execution of various commands in the sattelite computers which prevent equipment pulsing again. In each case this delay is less than 250 milliseconds.

The intensity requested from the CPS was 4×10^{12}, the maximum one expects to be stable without octupoles and damper.

4. LIFETIME AT 270 GeV

Figure 1 shows the history of a continuous beam stored with r.f. on at 270 GeV for 90 minutes. The vertical scale is the logarithm of intensity measured with a BCT. After an initial drop, the loss rate remains stable. By analysing the BCT signal which is digitised and recorded every 8.4 seconds one can deduce the intensity lifetime

$$\tau = - \frac{t_2 - t_1}{\ln(I_2/I_1)}$$

In this expression t_1 and t_2 are the times at which the BCT signal drops by 10^{10} protons i.e. from I_1 to I_2. Noise in the BCT signal occasionally causes such a fluctuation and so we filter out unsustained fluctuations in treating the data. There are still considerable changes in the lifetime analysed in this way but we are confident that these average out over 30 minutes or so.

Figure 2 shows the result of this data analysis. The average lifetime is of the order of 28 hours once stable conditions are established and is longer than that previously achieved at 200 GeV approximately in the ratio 1:1.8 predicted by Coulomb scattering theory.

Of course this is merely the loss lifetime. The luminosity lifetime should in theory be about half this value. One may in principle measure the beam growth which gives rise to degradation of the luminosity with the IBS but to do so would require an experiment lasting many hours. This was the season of thunderstorms and as we shall see there are more pressing problems to study.

5. SINGLE BUNCH ACCELERATION AND STORAGE

Encouraged by this lifetime measurement and still having some hours to spare we set up the SPS for single bunch transfer, raising the Q over the whole cycle by ~ 0.08 in each plane to offset Laslett Q shift and applying a chromaticity jump at transition. In the short time available we were only able to accelerate 2×10^{10} protons in the single bunch to 270 GeV but this intensity though one fifth of that needed for the full luminosity of the $\bar{p}$ project, was sufficient to reveal a very different picture from that seen with a continuous beam.

At first the single bunch would disappear catastrophically within a few seconds accompanied by the strong transverse signals symptomatic of head tail instability (Fig. 3). Although the chromaticity was close to zero it must have been slightly negative for a positive increment of 0.1 in each plane was sufficient to remove this instability but then another loss mechanism was revealed.

The next instability mechanism develops over a minute or two. The beam disappears out of the bunch as the bunch performs a slow motion of rare beauty but alarming consequence. Some of us have watched similar behaviour at Fermilab when single bunches are stored which contain more than 10^{10} protons and in electron storage rings where the phenomenon, arrested by radiation damping, leads to bunch lengthening.

The two rapidly falling intensity records (A, B in Fig. 4) show the beam lost in two steps due to this phenomenon. By observing the wide band longitudinal pick-up with a spectrum analyser tuned to a harmonic of the revolution frequency near 500 MHz we were able to see the characteristic "ears" associated with the phenomenon as the loss occured (Fig. 5).

In one of the loss steps the ears were sidebands at the synchrotron frequency (dipole mode) and in the other step at twice this spacing (quadrupole mode). The order in which these modes appeared was not always the same. Once only the quadrupole mode was seen.

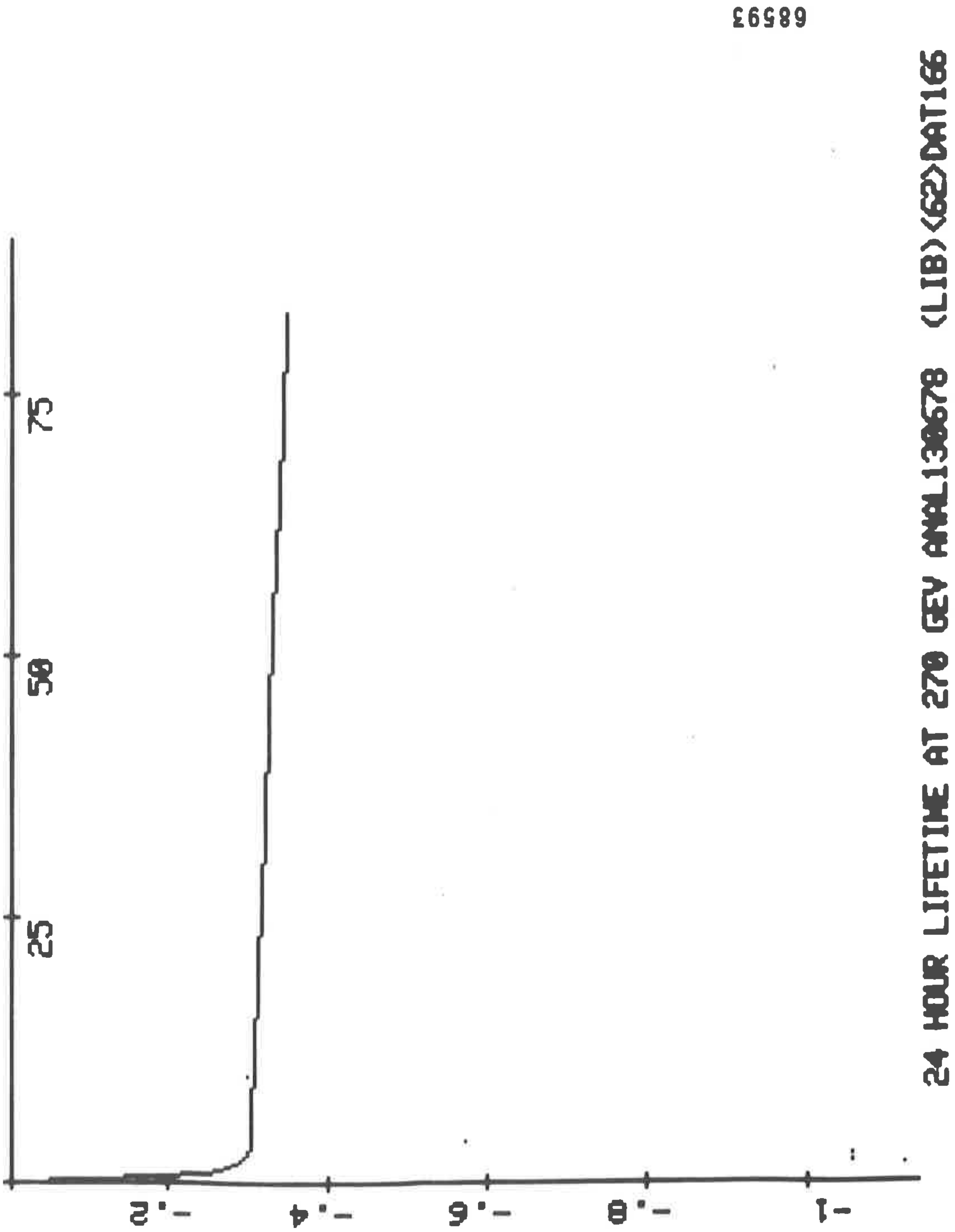
In an attempt to raise the threshold of this instability we tried inflating the bunch by firing the bunch spreader once. The lifetime improved to 32 minutes (C in Fig. 4). A more effective means to stabilise the bunch is to raise the r.f. voltage to 3.2 MV from the normal 1.6 MV used for storage. This increased the lifetime of a somewhat weaker bunch to several hours (D in Fig. 4) which may have been as much as might be achieved at this elevated Q value.

6. CONCLUSIONS

It remains to be seen whether bunches with a larger longitudinal emittance simulating more closely the $\bar{p}$ parameters will suffer this instability and whether the combined effect of higher r.f. voltage and full buckets can stabilise more intense bunches to the point that life-times realised for continuous beams can be sustained for single bunches. It would be wrong to be too pessimistic at this early stage. The resemblance of these phenomena to the bunch lengthening observed in electron storage rings is striking. At SPEAR (Stanford) for instance, a strong quadrupole mode is associated with the threshold for bunch lengthening. At intensities somewhat higher than the threshold, higher order (octupole, etc.,) modes are observed, and it does not pay to stabilize the quadrupole motion by active feedback.

Theories which predict longitudinal instability of a single bunch in a machine are hard to find and no one can fit satisfactorily the extensive SPEAR experimental data. Nevertheless, it has been shown that threshold for bunch-lenghtening coincides with the loss of Landau-damping for the quadrupole mode, when the coherent frequency emerges out of the band of incoherent frequencies. At this point, any instability, even an extremely slow one, is capable of driving the bunch modes to large amplitudes.

Clearly, there is a rich field here for both experimeter and theorist.


68593
24 HOUR LIFETIME AT 270 GEV ANAL130678 (LIB)<62>DAT166
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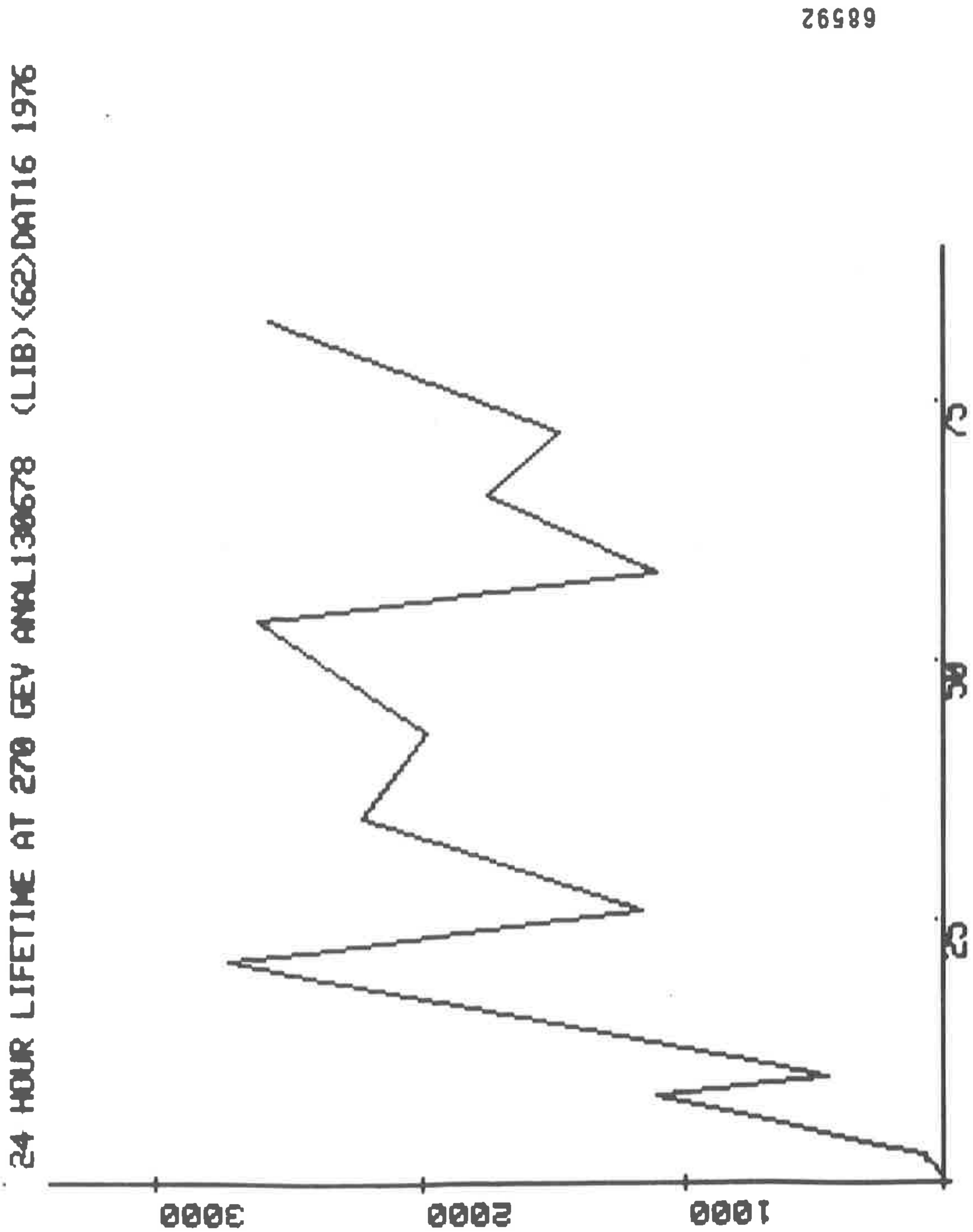
50
75
-.2
-.4
-.6
-.8
-1

Figure 1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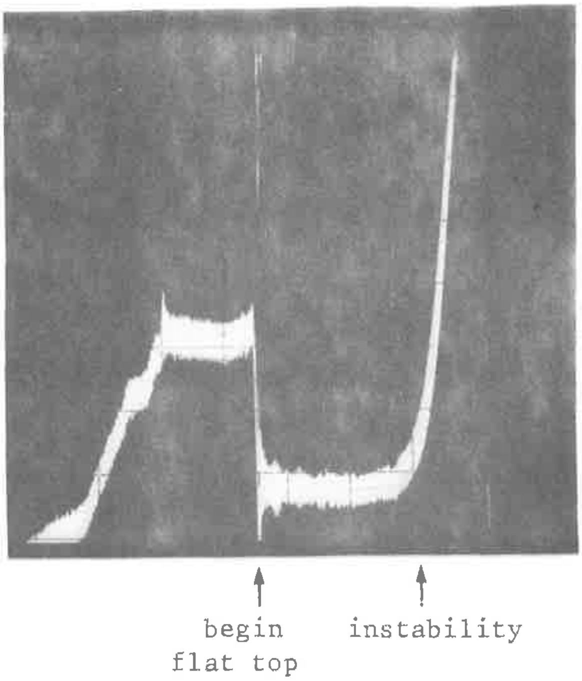
25
50
75

Figure 2



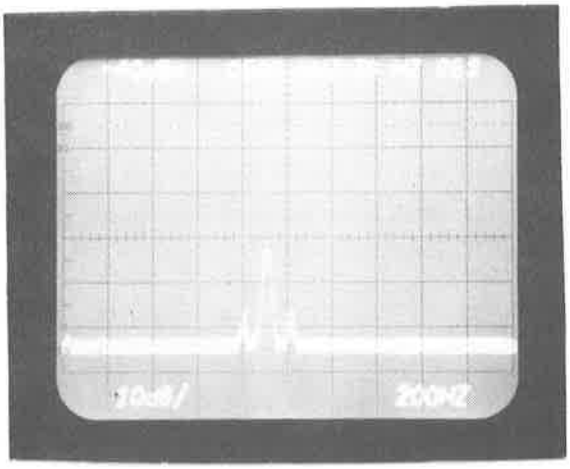
<u>Figure 3</u>

Head-tail instability destroys the beam after 6 s if $\xi < 0$.

Vertical P.U. signal (peak detected)
2 s/div
10 mV/div

e-folding time ≈ · 5 s.

a)

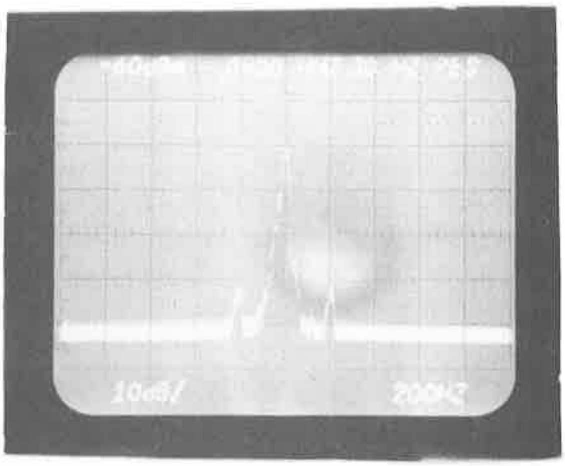


<u>Figure 5</u>

Dipole (a) and quadrupole (b) synchrotron sidebands appearing before losses A and B in Fig. 4.

Center frequency around 500 MHz
Resolution : 30 Hz
200 Hz/div
10db/div

b)



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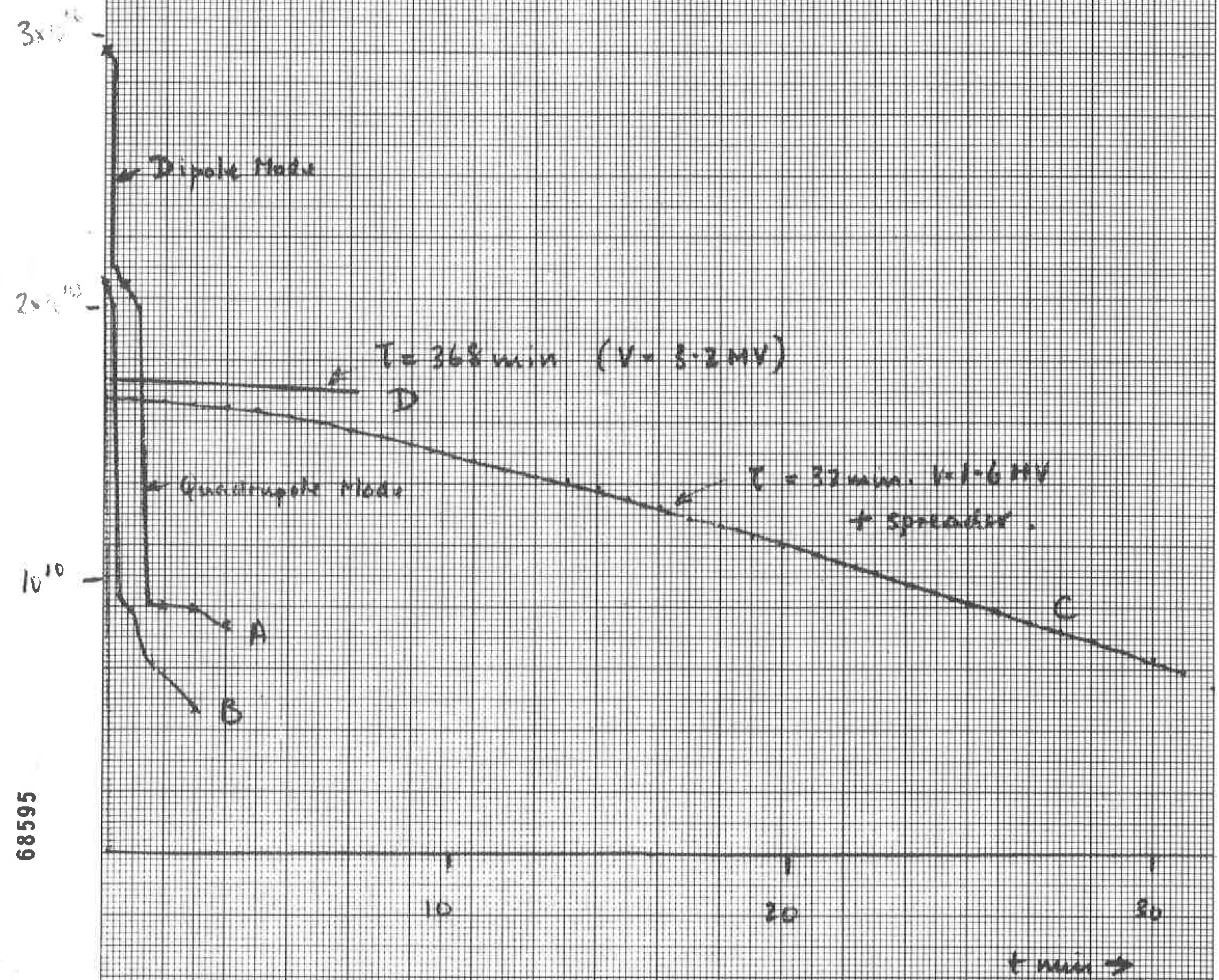
Dipole Mode
τ = 368 min (V = 3·2 MV)
D
Quadrupole Mode
τ = 32 min. V=1·6 MV
+ spreader.
C
A
B
10^{10}
10
20
30
t min →

Figure 4