# FERMILAB MAIN RING EXPERIMENT

NAL Main Ring
Accelerator Experiment : Beam Debunching at Injection Field in the Main Ring with Subsequent Recapture and Acceleration, as a Simulation of the CERN SPS Injection Scheme.

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## I. Introduction

An earlier experiment (1) simulated the CERN SPS injection conditions in the Fermilab Main Ring. It revealed a longitudinal blow up when the beam was left to debunch with no r.f. The phenomenon seemed similar to but weaker than, that which had been observed in the CERN CPS and which had prompted these studies. The experiments described here sought to :

i. Check that the blow up, like that seen in the CPS, is associated with the emission of microwave signals.

ii. simulate as closely as possible the most promising debunching-rebunching scheme on the SPS, namely debunching and rebunching in the SPS itself rather than in its injector.

iii. look at the problems associated with capture and acceleration up to top energy of a beam having a very large longitudinal emittance.

## 2. Debunching studies

### 2.1 Blow-up measurements

We repeated the measurements described in (1) to confirm the previous data. One single batch from the booster was injected, with RF OFF in the main ring and short-circuited cavities.

The emittance of the debunched beam was measured using the Schottky scan technique with the coaxial directional coupler pick-up.

The emittance of the incoming beam was checked using bunch length and time of debunching measurements.

The increase of momentum spread as a function of time, Fig. 1, looks very similar to the previous results (1).

## 2.2 Observation of microwave signals

The coaxial directional coupler detector was connected to a microwave crystal detector through various band pass filters. Photo 1 shows a typical result of this experiment. The conditions were the same as those described in 2.1. One observes (hardly visible on photo 1), just at injection, a sharp transient with a fast decay, which corresponds to the fading of the bunch structure. About 10 ms later a growing microwave signal appears again, which, we believe, corresponds to the instability responsible for the beam blow-up. This seems very plausible if one compares the growing times on photo 1 and fig. 1.

To get an idea of the frequency spectrum of the instability we used several band pass filters whose center frequencies range from 750 MHz to 2.8 GHz. Although the pick-up frequency response is not flat (directional coupler with constant cross-section) and difficult to measure, we can estimate from the experimental results a frequency spectrum of the instability which looks like the one in fig. 2.

It is very interesting to compare this result with the CPS experiments, which show the same peak frequency(2). This lends weight to the theory that the instability is driven by vacuum chamber discontinuities, because then the frequencies of interest, linked to the transverse dimensions of the vacuum chamber, would not be very different for the two machines.

We also used the spectrum analyser to observe the microwave signals, and to confirm the frequency spectrum of fig. 2 up to 1800 MHz. If one injects several batches in the machine, with RF OFF, the same picture (photo 1) repeats after each injection clearly indicating that it is a local current effect. When one tries to debunch in the main ring by RF reduction (see 2.3), the microwave signals again appear, about 30 ms after the RF is off. The fact that the instability appeared so late after injection (with RF OFF) or after the RF voltage has decayed down to zero was unexpected. The CPS conditions are such that the instability always appears before the bunches overlap, and it had been thought initially (2) that overlap would make a large local momentum spread and stabilize the process. On the contrary, we observed that the instability develops after the bunches have overlapped (debunching time is a few ms), and the simple theoretical model of a single stream instability used in (2), must now be modified. In addition, it is a very important result for the SPS because it shows that recapture is possible before the instability blows-up the beam emittance.

## 2.3 Debunching by RF voltage reduction

In an attempt to reduce the momentum spread of the beam prior to debunching, we injected the beam with RF ON, and then reduced the RF voltage down to zero. This RF voltage reduction was controlled by a pulse generator acting on both the RF drive and the parameters of the RF power amplifiers. It was not possible to short-circuit the cavities during the short period when the RF was cut off. After about 300 ms the RF voltage was brought back to its initial value (photo 2) allowing recapture and acceleration of the beam.

A single booster batch ($\simeq 10^{12}$ protons) injected in the main ring was debunched, recaptured and accelerated without significant beam losses (fig. 3). However if one tried to inject more and more booster batches the situation became worse and worse. Beam losses started to appear first during the magnetic field parabola, then at the RF capture, and even during debunching (fig. 4).

This effect was shown to be dependent on the average beam intensity, by comparing beam losses with 6 batches at full intensity and 12 batches at half intensity : they were the same. Therefore high Q resonators have to be suspected, in particular the 14 non short-circuited RF cavities. Their equivalent impedance is about : 600 k$\Omega$ x 14 = 8,4 M$\Omega$ and this can very well explain the observed losses.

We measured the evolution of $\Delta p/p$ during the RF voltage reduction, using the Schottky scan technique. Fig. 5 shows the result for 12 injected batches. The blow-up due to the RF cavities is much larger than the one which results from the microwave instability.

Fortunately reducing $\Delta p/p$ by voltage reduction is not an essential feature of the SPS injection scheme and this observation is of merely academic interest.

## 3. Adiabatic capture experiments

To simulate the SPS conditions for adiabatic capture, the ring must be more or less filled with protons. As shown above, injection of 13 batches with RF ON and subsequent debunching gave rise to cavity beam loading phenomena which are irrelevant for the SPS, therefore, we have injected 13 batches from the booster, with RF OFF in the main ring at the expense of a large beam loss at injection (8 to $9 \times 10^{12}$ instead of $1,3 \times 10^{13}$ protons injected).

The emittance just before capture was measured by Schottky scan (photo 3). We found A = 147 mrad ($\Delta p/p$ total = $\pm$ 1,27 $10^{-3}$)

The RF voltage, calibrated by a synchrotron frequency measurement was 1,4 MV at the end of the capture, before the start of the magnetic field parabola. This corresponds to a bucket area of 250 mrad.

Various capture parameters were varied without improving significantly the initial results :

- shape of the RF envelope (linear slope or smoother curve)
- time of capture after debunching
- magnetic field of booster at injection
- magnetic field of main ring at injection (the RF frequency was set by a crystal oscillator and difficult to change).

In all cases, relatively large bunch oscillations were observed at $f_s$ and $2f_s$ (photo 4) just after capture, as well as a significant beam loss. (fig. 6) The latter may be explained by an increase of momentum spread which happens when the beam becomes bunched, leading to transverse beam losses.

We measured the beam emittance just before the start of the magnetic field rise from bunch lengths estimates (photo 5). Taking a bunch length of 15 ns at the base, we obtain A = 200 mrad. Although this is rather imprecise, it shows that the capture results in a blow up of more than 30% in beam emittance. (Remember that the beam intensity has decayed by about 25% between the two emittance measurements.)

## 4. Acceleration of a beam having a large longitudinal emittance

From the RF voltage and dB/dt curves (fig. 6), one can calculate the longitudinal acceptance of the machine as a function of time (fig. 7). One sees that there is almost no reduction in acceptance at the start of the parabola (about 250 mrad).

To measure the emittance of the beam, we produced a dip in the RF voltage at about 1,5ls, large enough to just produce beam losses (fig. 6 and 8). From the parameters at this time, we calculate an emittance of 240 mrad. This shows that, at least at the start of the parabola, the buckets were full, and that there is a relatively large blow up (150 to 240 mrad) in the capture process. This is not surprising looking at the very large oscillations at capture (photo 4).

By comparing the beam intensities just before trapping and after acceleration, we measure a capture efficiency of about 80%. The 20% particles are either lost rapidly at the beginning of acceleration, because they sit outside the bucket (fig. 8), or slowly before acceleration, because their momentum deviation is too large and gives rise to transverse losses (fig. 6).

At transition, we observe a 7-8% beam loss, presumably a transverse loss caused by a too large momentum spread.

Photo 6 shows bunches after transition. From bunch length measurement (4 ns) we estimate an emittance of 220 mrad.

## 5. Conclusions

A microwave instability, very similar in nature to the one analysed in the CPS, has been observed in the main ring. The actual impedance figures (Z/n) one has to put in the formulas are of the same order of magnitude (although somewhat smaller for the NAL main ring : 70 Ω instead of 180 Ω); we believe that this is a confirmation of the vacuum chamber discontinuities model.

This is the figure obtained using the overshoot theory (no longer accepted)

A large emittance (250 mrad) beam has been accelerated without major difficulties. The capture was characterized by a reasonable efficiency (80%), but a large blow-up (150 mrad to 250 mrad). For the SPS, the situation may well be worse : the expected debunched beam emittance is 140 mrad, but the acceptance is only 180 mrad, and one could expect beam losses larger than 20%.

On the other hand retrapping in the SPS can be done earlier, hopefully, as the main ring experiment has shown, before the instability has made the emittance to grow significantly. In this latter case, the initial emittance would be only about 60 mrad, and one can contemplate an even higher capture efficiency. It remains to be seen whether some 9,5 MHz structure remains with this early trapping at the SPS.

The overall result of these accelerator experiments is of prime importance for the SPS people looking for the running-in of the machine, and it is a pleasure to acknowledge the Fermilab staff who have made it successful.

D. Boussard

References:

1. Accelerator experiment EXP-74 June 6, 1975
2. D. Boussard - Observation of Microwave Longitudinal Instabilities in the CPS.

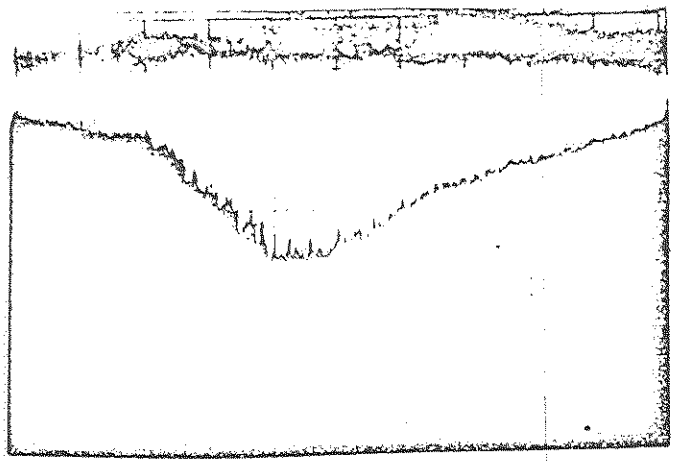

Photo 1.

Output of the microwave detector (negative) and 1,6 GHz center frequency filter.

trigger : injection
10 mV/div  5 ms/div

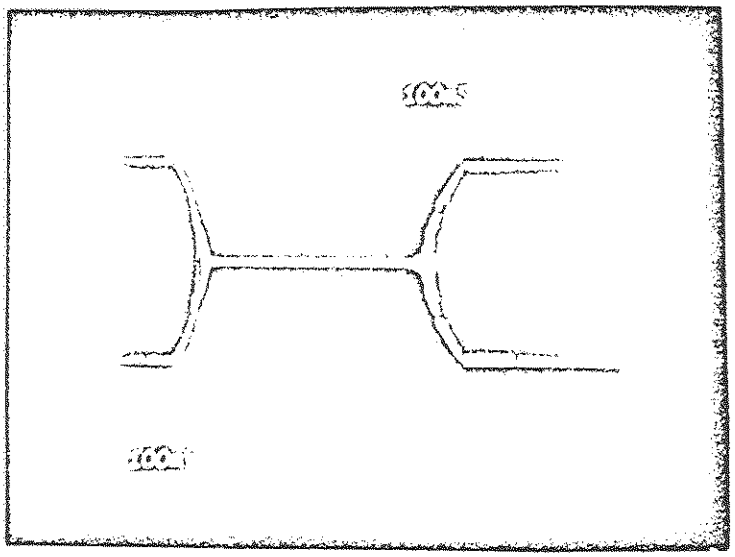

Photo 2.

Debunching by RF voltage reduction.

RF envelope.

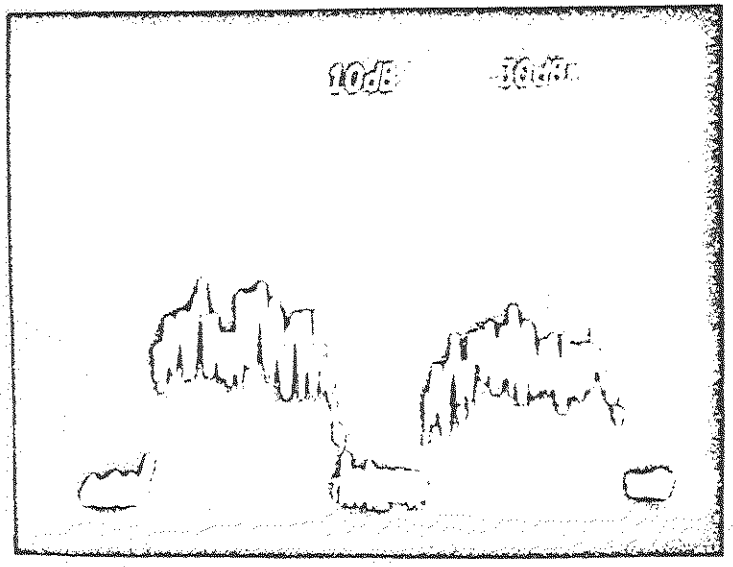

Photo 3.

Schottky scan of debunched beam with RF OFF (13 batches)
10 dB/div Center freq. 1710 MHz
10 kHz/div

$\Delta p/p = \pm 1{,}27\ 10^{-3}$

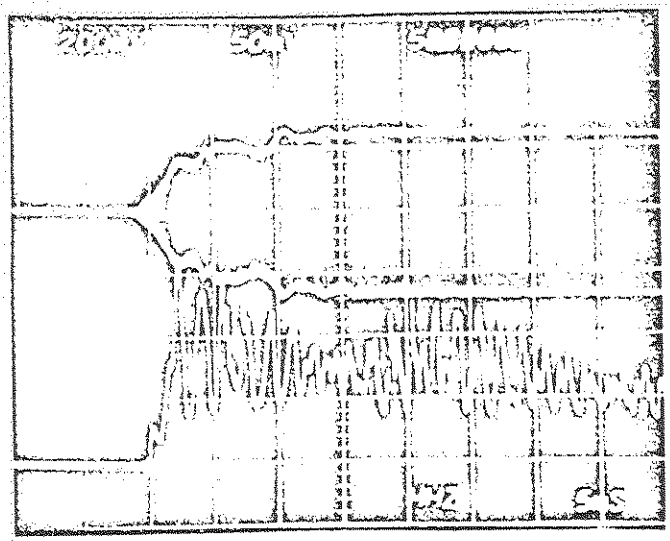

Photo 4.

"Adiabatic" Capture

Top: RF envelope Vmax = 1,4 MV

Bottom: peak detected PU signal (directional coupler PU).

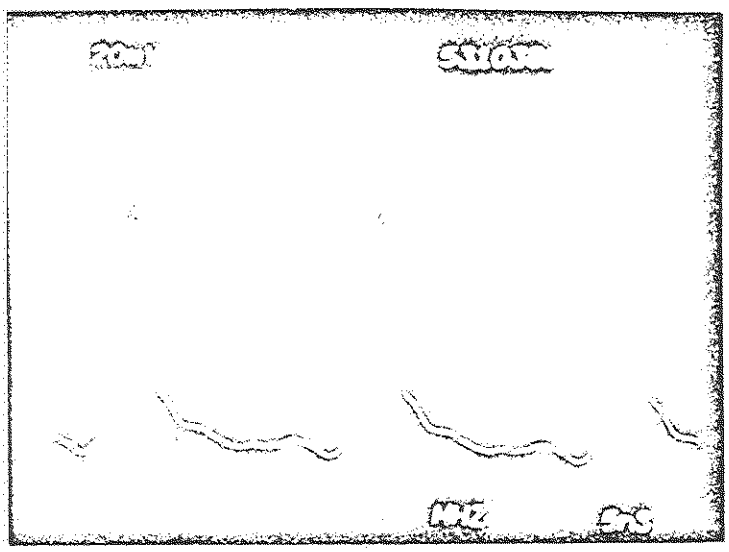

Photo 6.

Bunches after transition (resistive wall PU)

VRF = 3,45 MV

5 ns/div

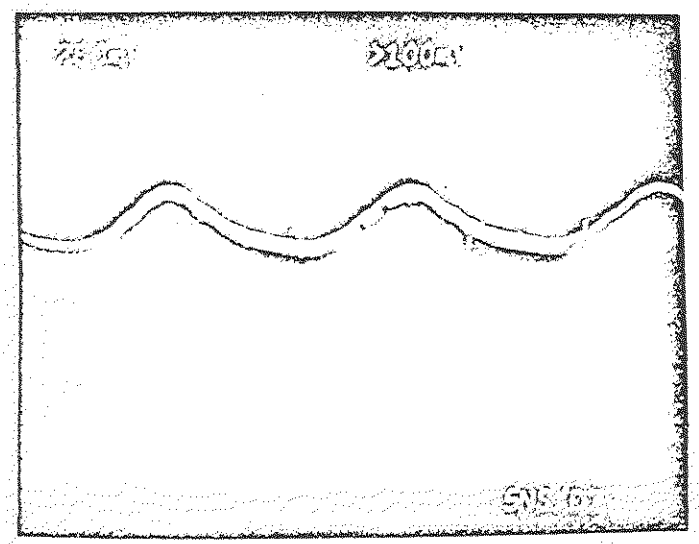

Photo 5.

Bunches at injection field (resistive wall PU)

VRF = 1,4 MV
5 ns/div

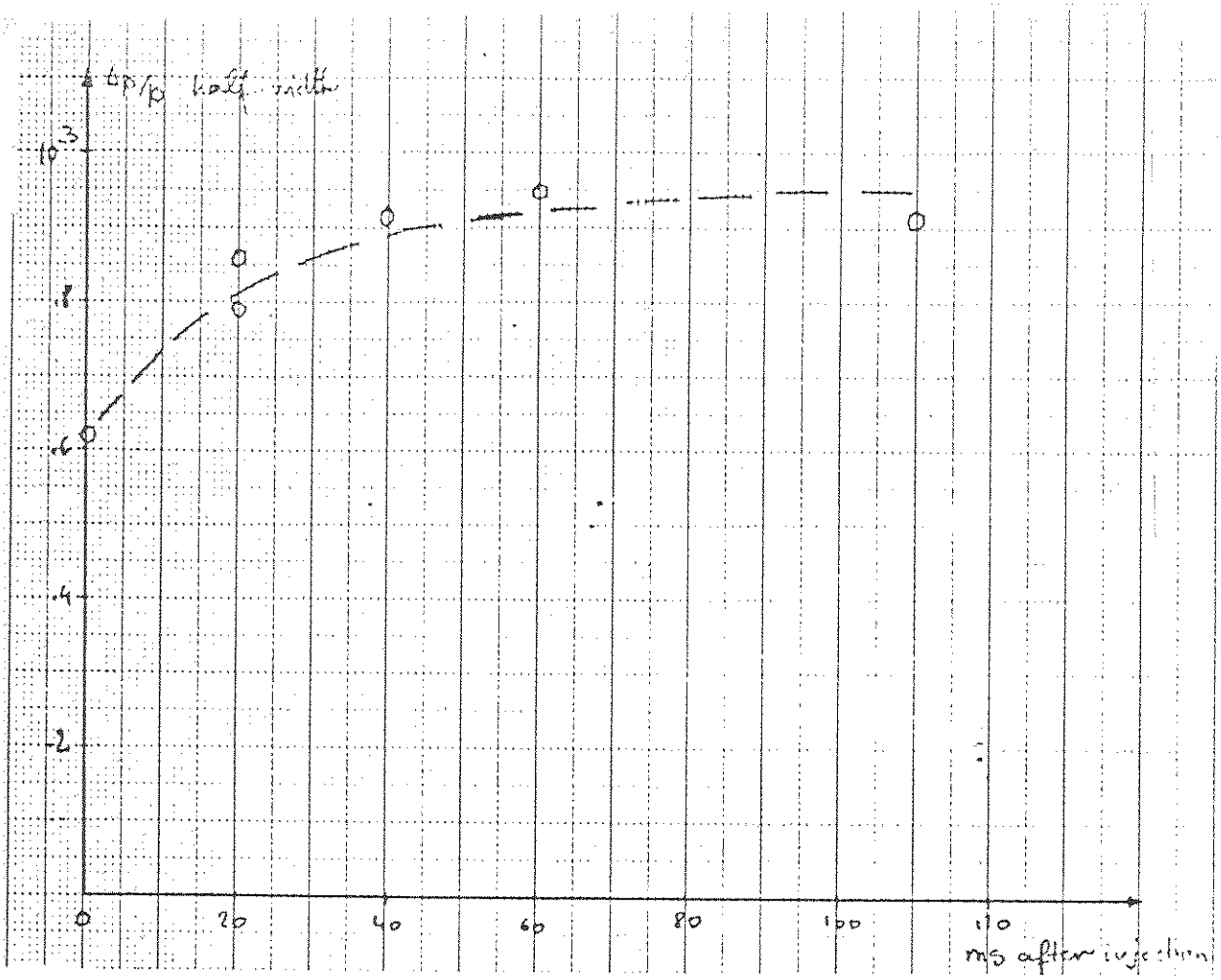


Fig. 1 Increase of momentum spread after debunching

Short-circuited cavities
$10^{12}$ protons (1 batch)

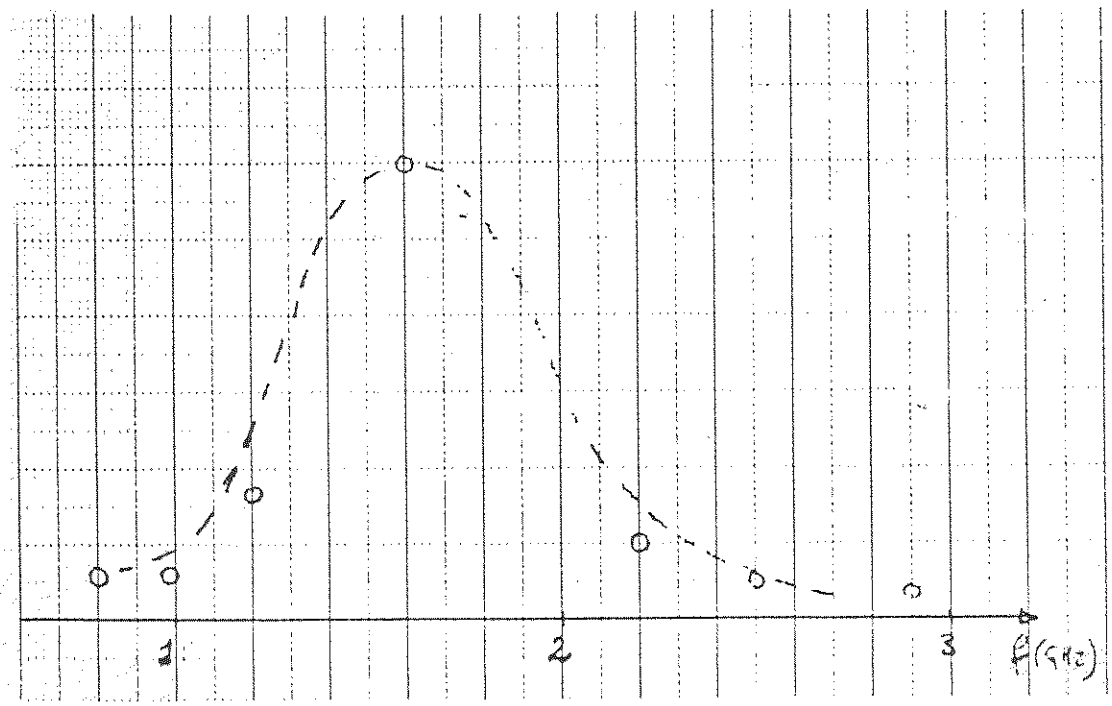


Fig. 2 Frequency spectrum of the instability
(uncorrected for SU sensitivity)

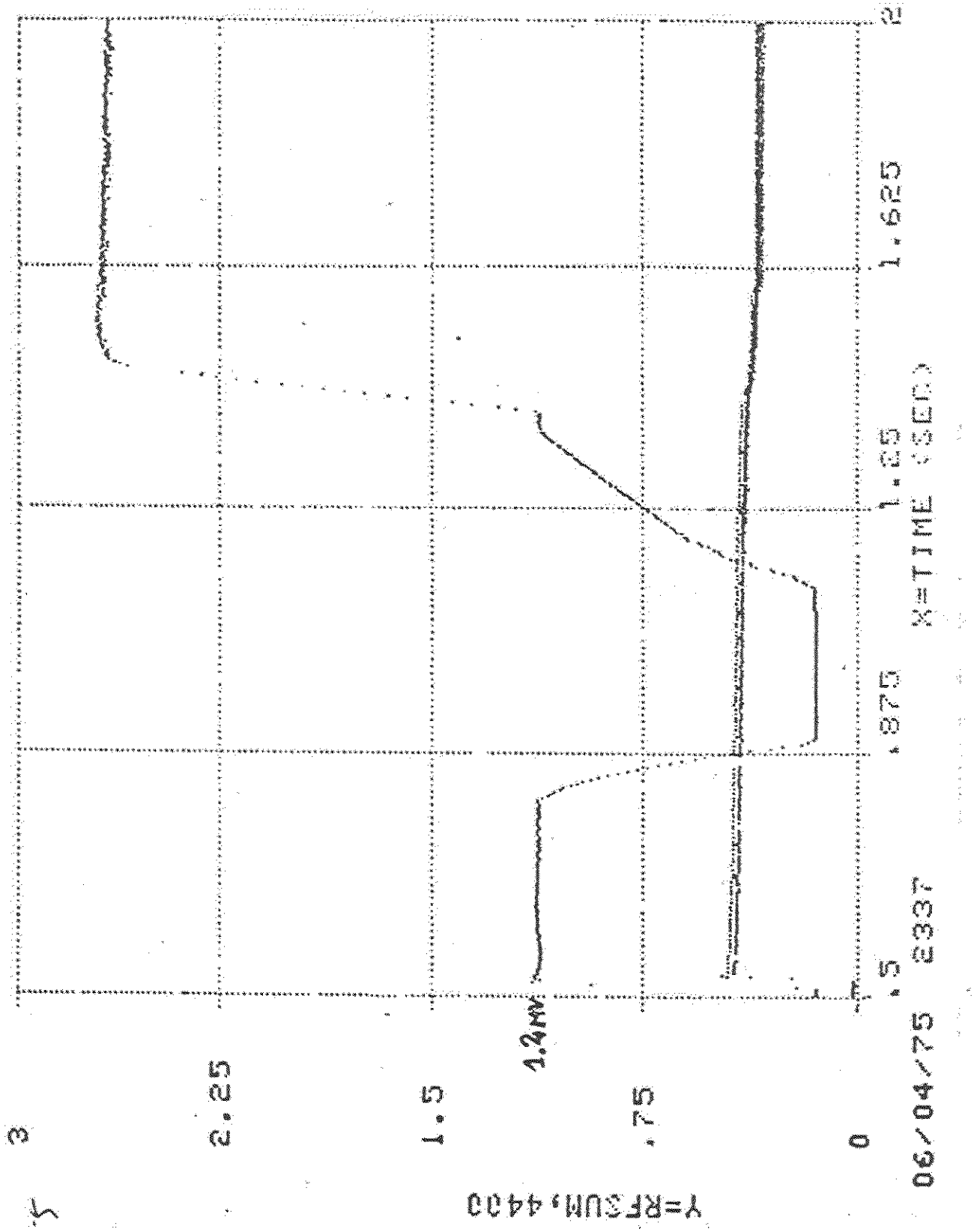


Fig. 3 Debunching and recapture of a single batch RF voltage. Beam current.

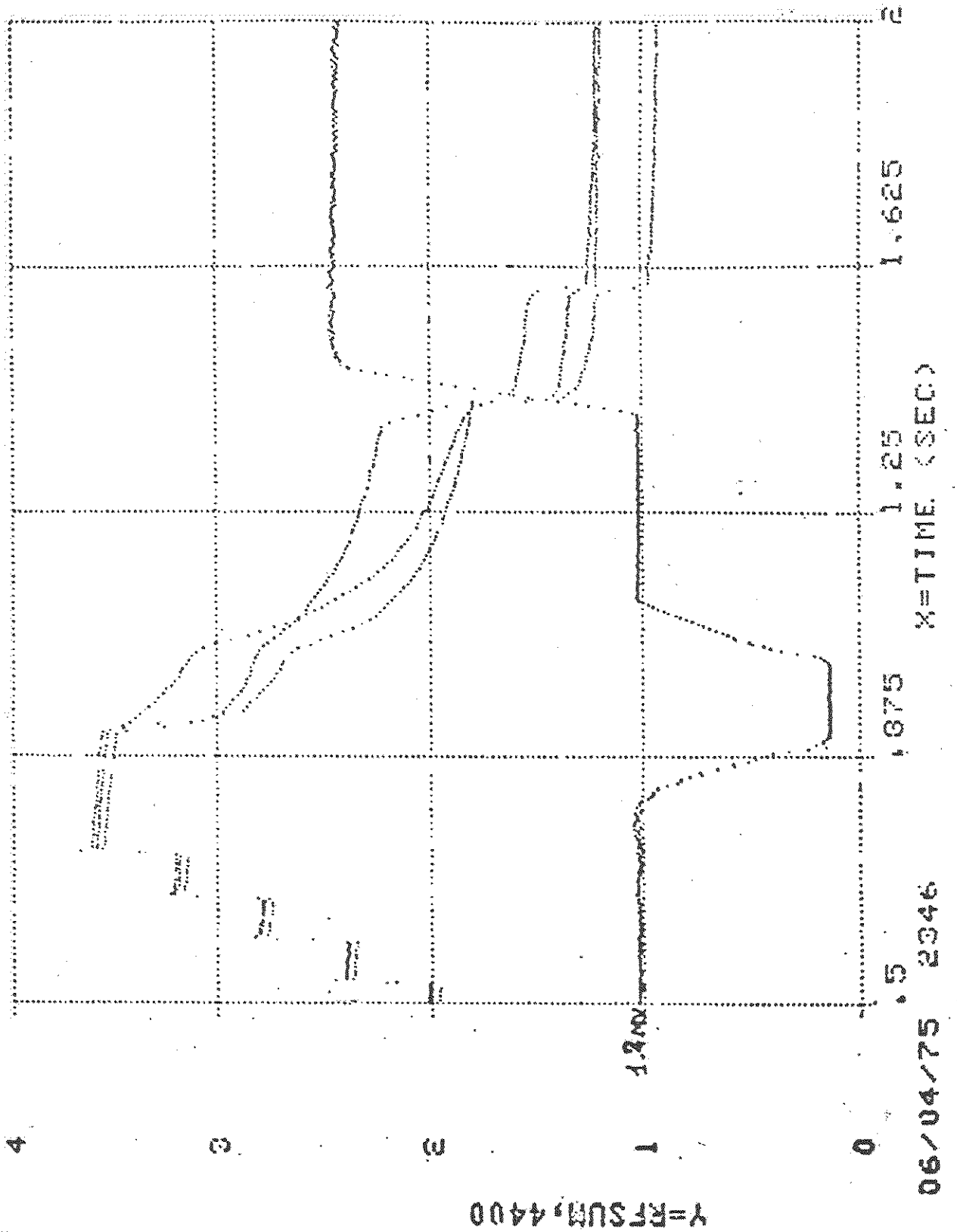


Fig. 4 Debunching and recapture of 9 batches
RF voltage. Beam current.

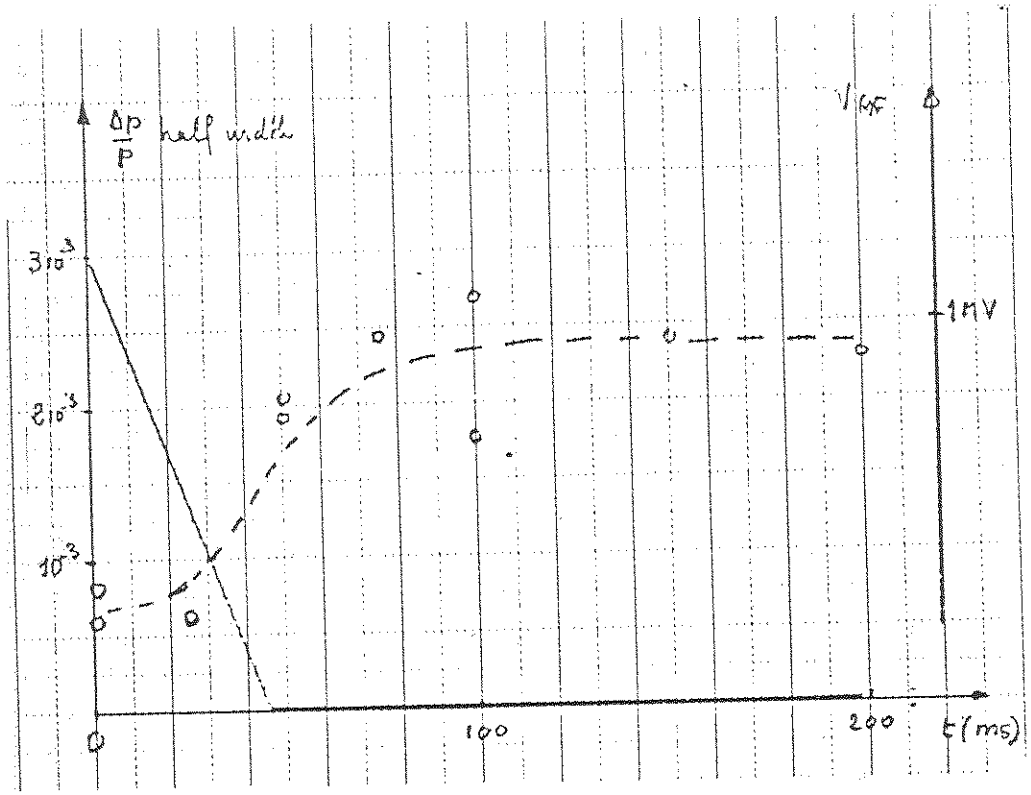


Fig. 5 Evolution of $\Delta p/p$ during RF voltage reduction (Schottky scan) (12 injected batches).

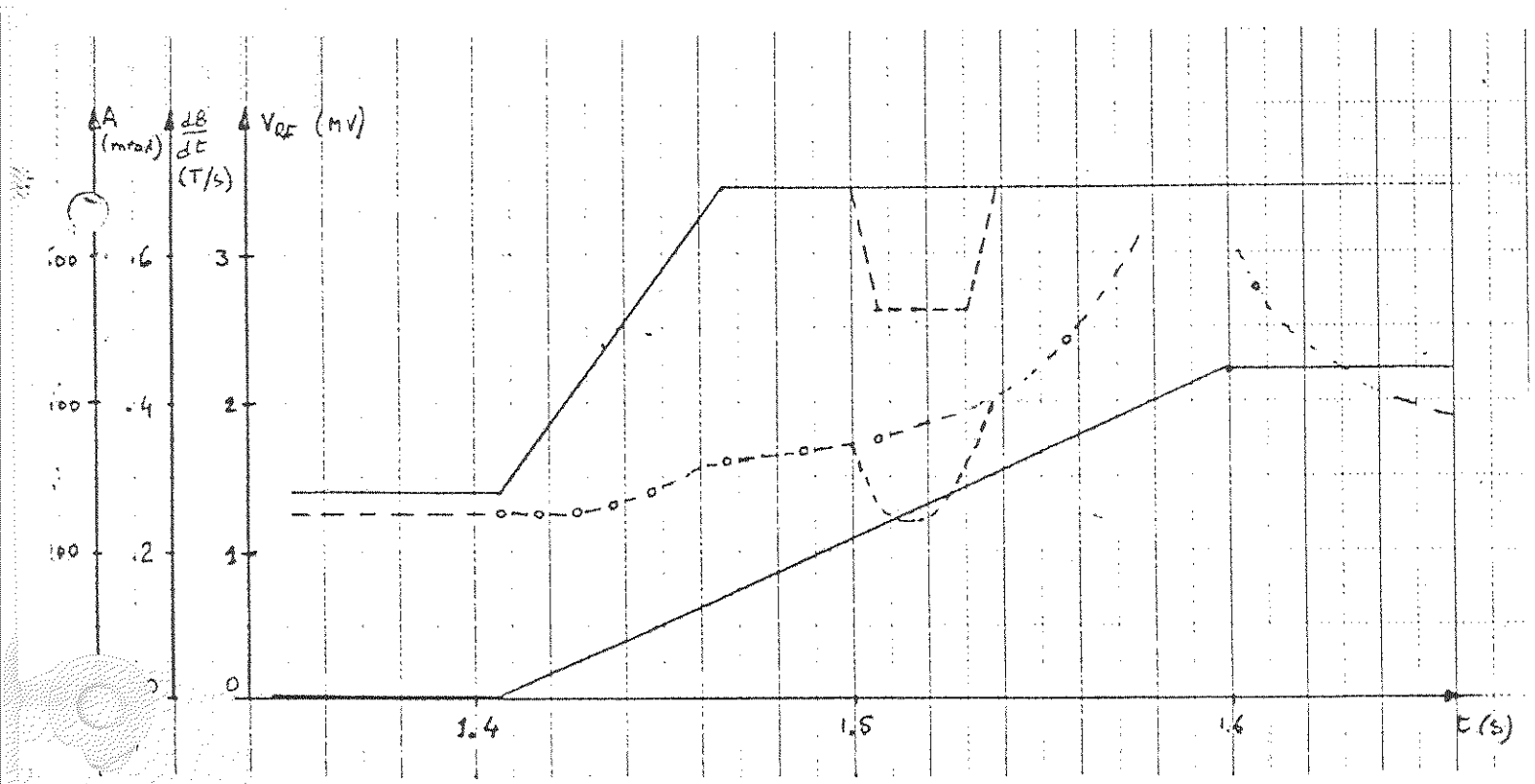


Fig. 7 Evolution of main ring longitudinal acceptance.

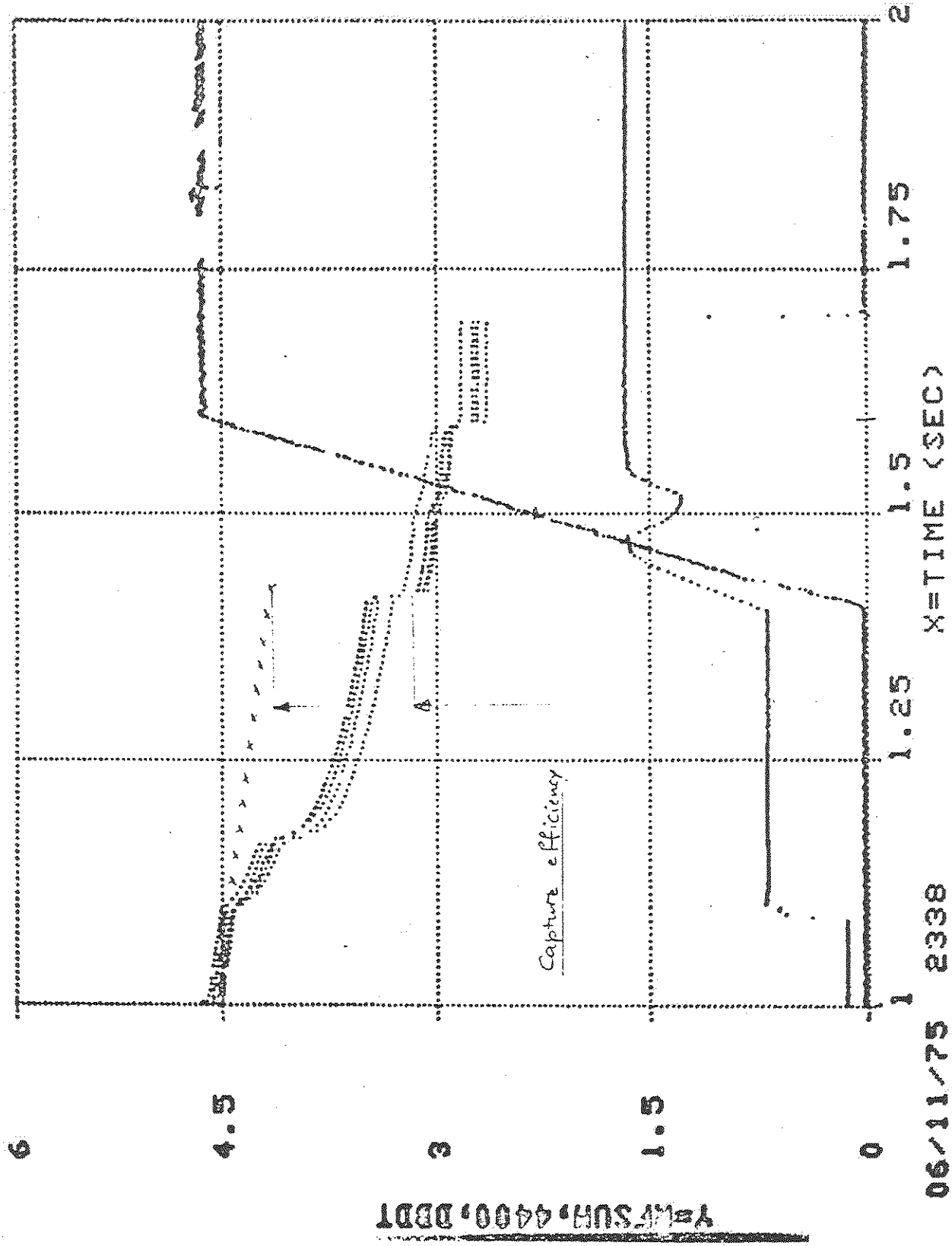


Fig. 6 Capture and acceleration after debunching
Beam current (13 batches)
RF voltage (capture = 1,4 MV)
dB/dt
Capture efficiency is about 75%

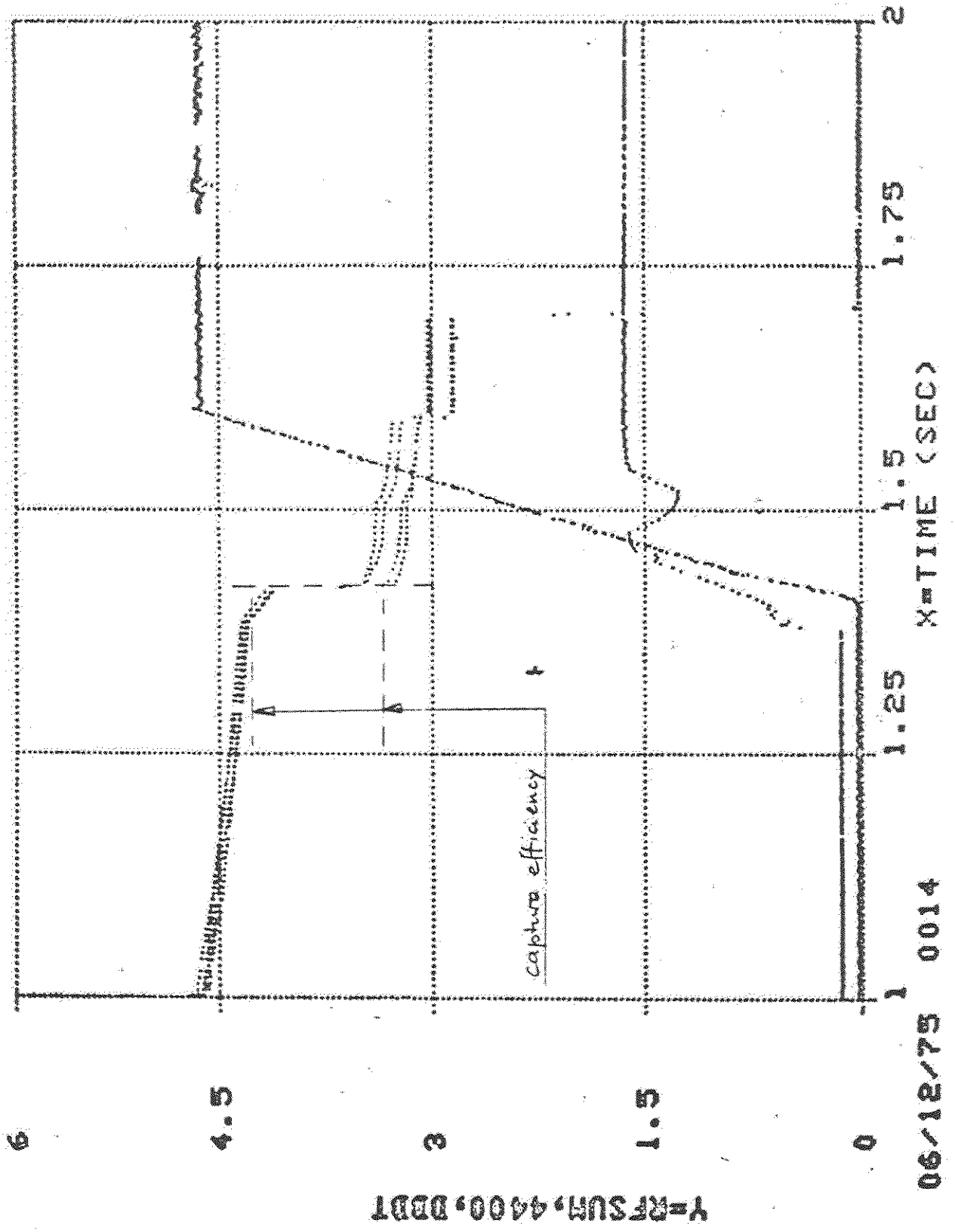


Fig. 8 Capture and acceleration after debunching
Beam current (13 batches)
RF voltage (RF capture is just before acceleration)
dB/dt
Capture efficiency is about 80%