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THE MINIMUM LENGTH AND SHAPE OF PROTON BUNCHES AT TRANSITION AT HIGH AND LOW BEAM INTENSITY

by

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Summary

The minimum length of proton bunches at transition energy at low and high beam intensity is a source of information on longitudinal space charge forces. The observation is complicated by bandwidth limitations and by distortions. Some of the most detailed signals obtained with the wide band pick-up station and a filter are reproduced and discussed. At high beam intensity of 1.62 x 10^{12} protons a bunch length of 6 nsec has been observed as compared with 4 - 4.5 nsec at low intensity 0.30 x 10^{12} protons.

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Introduction

Four years ago E. Schulte 1) - and later Garcia-Alcaine 2) - made photos of the signal of the wide band pick-up station with the fast Tektronix 519 oscilloscope (1200 MHz) which showed that at a beam intensity of 0.80×10^{12} protons our bunches at transition are approximately triangular and have a length of 6.43 nsec. This bunch length is more than the 4.28 nsec which can be expected from adiabatic damping of phase oscillations, and it has therefore been suspected that the difference can be attributed to space charge effects 3). However, the space charge parameter depends on the third power of the bunch length $(2\Theta_0)^{-3}$. Beam loading distorts the waveform of the RF voltage 4) and contributes an additional beam loading parameter to the synchrotron equation. Therefore the author spent considerable time to answer the question: How much observed bunch lengthening is due to space charge effects and how much to the limited time resolution of the observation system? It will be shown that the bunch length at transition is still 6 nsec although the beam intensity has doubled to 1.62×10^{12} protons since the measurement in 1965. This means that space charge forces are weaker than they seemed to be.

Technical remarks

In order to answer the question of the rise time, the transmission characteristics of the wide band pick-up station (amplitude- and phase response 30 - 600 MHz) have been measured when it was removed from the PS-ring in the shut-down of April 1967, and these data have been used in a computer program to calculate and plot the observable output pulses for various bunch shapes 5) *). It was shown that the p.u. station has sufficient bandwidth to transmit a triangular bunch of 6.43 ns length with the correct length, but the signal is followed by a distortion or negative bump on the base line which should be disregarded, and a high frequency ripple is superimposed on the envelope of the bunches.

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*) MPS program list no. M1

Calculations also included the possible signal improvement by a low-pass filter 318 MHz which attenuates the ripple without too much loss of bandwidth (fig. 1). Unfortunately, the ripple (600 - 620 MHz) cannot be eliminated unless the old tank in SS 92 is redesigned. Meanwhile the low-pass filter has been made and the remaining distortions on the shortest bunches resemble the computer-plotted ones (fig. 2). (Apart from differences in cable length and sensitivity the central building and MCR receive similar signals).

More recently a better signal (fig. 3, 8) without the base line distortion has been obtained by changing the coupling condenser and resistor between the p.u. electrode and transmission line (high frequency by-pass). Since the travelling wave scope Tektronix 519 has no vertical amplifier and needs 9.6 V/cm, the small traces have been recorded on 35 mm film andenlarged photographically. With this arrangement a useful <u>system rise time of 1.3 ns</u> (no overshoot) is available rather than 2.4 ns or more with other oscilloscopes (e.g. Tek. 454).

The time base 5 ns/cm has been checked with a 200 MHz sine wave. The displays are triggered by the revolution trigger pulse which is derived from the accelerating RF 6). Thereby multiple traces of the same bunch can be observed during several revolutions and gated during 40 μs photographic exposure time.

Comments on the observed phenomena at transition

1. The series of photos fig. 3 has been taken with low beam intensity of 0.30 x 10^{12} circulating protons for comparison and for a check whether the theoretical minimum bunch length (4.28) resulting from adiabatic damping in absence of space charge forces can actually be photographed.

- Machine development session on 12. 6. 69, transition phase jump at BT = B268 + 570 μs without radial jump or perturbation, phase jump potent, setting 780 unchanged.

Since the magnetic field at transition rises at the rate of one B-pulse or 10 gauss in 780 μs, the intermediate photos between B-pulses have been triggered with 380 μs delay. When the acceleration cycle is stable, the bunch shapes at a given B-pulse or particle momentum *) are similar during many cycles or even several days, and one can photograph subsequent phases of a synchrotron oscillation in subsequent acceleration cycles (repeating accidental shots with badly injected beam). This fact which is less obvious from theory, suggests that the oscillations which we observe after the transition phase jump (figs. 4, 8), and which finally lenghen the bunches are triggered by "BT".

In fig. 3 the oscillations are small. One can see first that the bunch becomes smaller from B260 to B268.5 due to adiabatic damping the minimum length being slightly less than 5 ns. After the phase jump starts a phase oscillation of the bunch centre which is rapidly damped by beam control.

The photo fig. 3a is taken without the low-pass filter and a new cathode follower and by-pass which transmits step pulses of less than 0.5 ns rise time correctly. The bunch length is better defined and it is in fact between 4. and 4.5 ns. Thus for $\leqslant 0.3 \times 10^{12}$ protons longituninal space charge forces are negligible until transition.

2. Typical photos at high beam intensity have been taken during normal machine runs, in particular on April 24, 1969 when for the first time 1.67×10^{12} protons have been accelerated with the aid of a radial jump at transition (fig. 4) and later in June when transition has been passed with similar beam intensities without the radial jump (fig. 8).

In fig. 4 one can see that the bunches become smaller from B266 to B269.5 due to adiabatic damping but they reach only a minimum of 6.2 ns indicating weaker longitudinal focusing due to space charge forces and distortions of the accelerating waveform by beam loading before tran-

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*) In the CPS the momentum is p = 2.1009 GeV/c x B/Kilogauss.
The velocity at transition is 29.57 cm/ns.

sition (3),(4),(8). The following traces after the phase jump at BT = B269 + 600 μs are shifted by 35 ns trigger delay. The radial perturbation which had steered the beam slowly on a smaller radius now changes sign and forces the beam to jump outwards on a larger orbit radius where Q_R 9) and γ_{tr} 7) are lower such that one arrives more rapidly at $\gamma > \gamma_{tr}$.

One can see that immediately after the phase jump the bunch lags behind in phase until it is sitting almost on the crest of the accelerating RF wave and gets a maximum energy gain per turn for the radial jump *). At B272 at its leftmost position the bunch is compressed to 5 ns length and reaches its highest charge density (bunch height). Then it swings back with some overshoot to the right (B275.5) becoming longer and finally settles at a stable phase determined by radial control. However, it continues to rotate around the centre in longitudinal phase-space and a filament which is seen on the left at B276 swings to the right at B279, again to the left at B282 etc. The bunch height is peak-detected to display the variations of charge density in fig. 6.

The transition phase jump and phase oscillations can also be seen in fig. 5 which starts at B268 with subsequent horizontal sweeps shifted upwards to cover a 10 ms time interval (1 trace every 100 revolutions, Cappi-display). In fig. 7 the peak-detected bunch height is repeated for comparison with the radial control error-signal which acts on a phase shifter and shows again the phase lag of the bunch during its radial jump. The jump in radial position is shown by the ΔR - signal of p.u. station in straight section 50, which is displayed at the bottom.

3. The series in fig. 8 taken on 22.6.1969 with the same average beam intensity 1.62×10^{12} protons shows the same phenomena as fig. 4 before transition (better signal). However, the p.u. station

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*) This has been observed directly on the accelerating RF on which the bunch marks its position by a very small waveform distortion climbing from $\varphi = +63^\circ$ towards the crest $\varphi = 0^\circ$ of the cosine-waveform.

signals ΔR and Σ at the bottom of fig. 11 indicate that there is no radial jump. The beam had not been steered on a smaller radius but enters transition on a larger orbit and the transition phase jump occurs earlier at B268 + 590 µs. Consequently the bunch does not need to slip back in phase to gain additional energy per revolution but is more phase-stable from B269 onwards (see also fig. 9 and the rad. control error signal in fig. 11).

In fig. 8 the bunches at B272 are not as much compressed as in fig. 4 and the charge density displayed in fig. 10 does not reach such a high peak as in fig. 6. The rest is similar.

A more detailed picture of the bunch at B272 has been obtained two days later during a test of the pick-up station with the new cathode follower (fig. 12). Unlike "gaussian" bunches observed with small bandwidth oscilloscopes this bunch shape is triangular with a sharp top and a well-defined bunch length.

Distribution: (open)

REFERENCES

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MPS/RF/M 1. 6. 1965

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MPS/Int. RF 67-17

(3) H.G. Hereward — Estimates of bunch lengths and longitudinal space charge forces in the CPS
MPS/DL Int. 66-3 (page 12)

(4) H.H. Umstätter — On the distortion of the centre of accelerating buckets by beam loading effects
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(5) H.H. Umstätter — On the transmission of signals by the wide band pick-up station
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(8) A. Sørenssen and H. G. Hereward — Longitudinal space charge forces at transition
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(9) E. Brouzet — Mesure des dimensions transversales du faisceau interne PS à moyenne et haute énergie
MPS/Int. CO 68-21 (figs. 1-5)

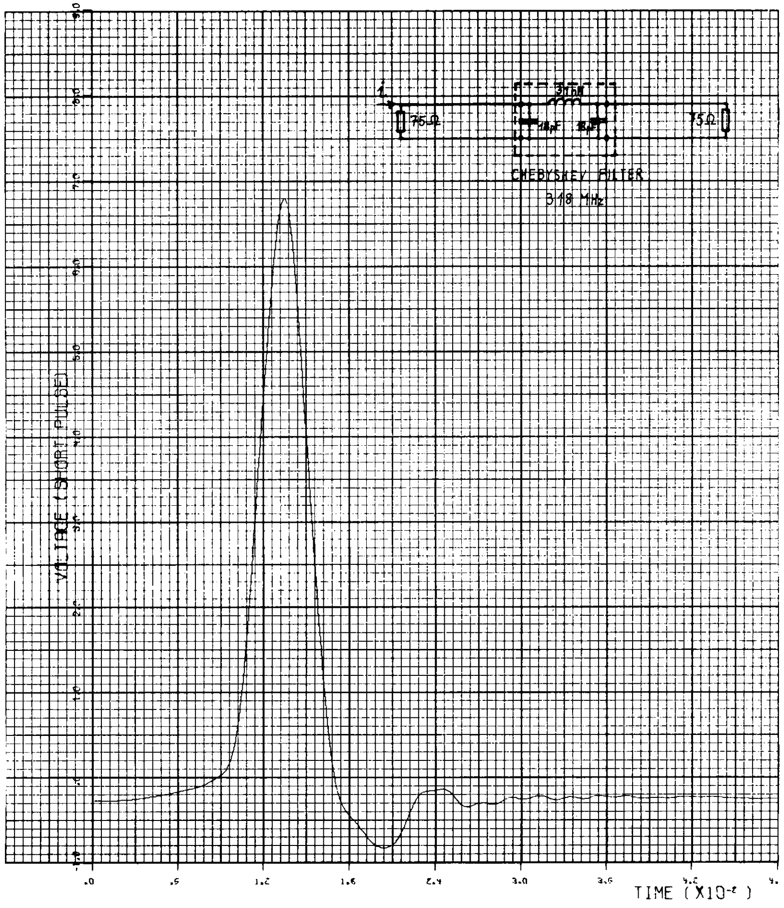


Fig. 1 Computer-plot (fig. 9 of reference 5)

6.43 ns-bunch distorted by P.U. station

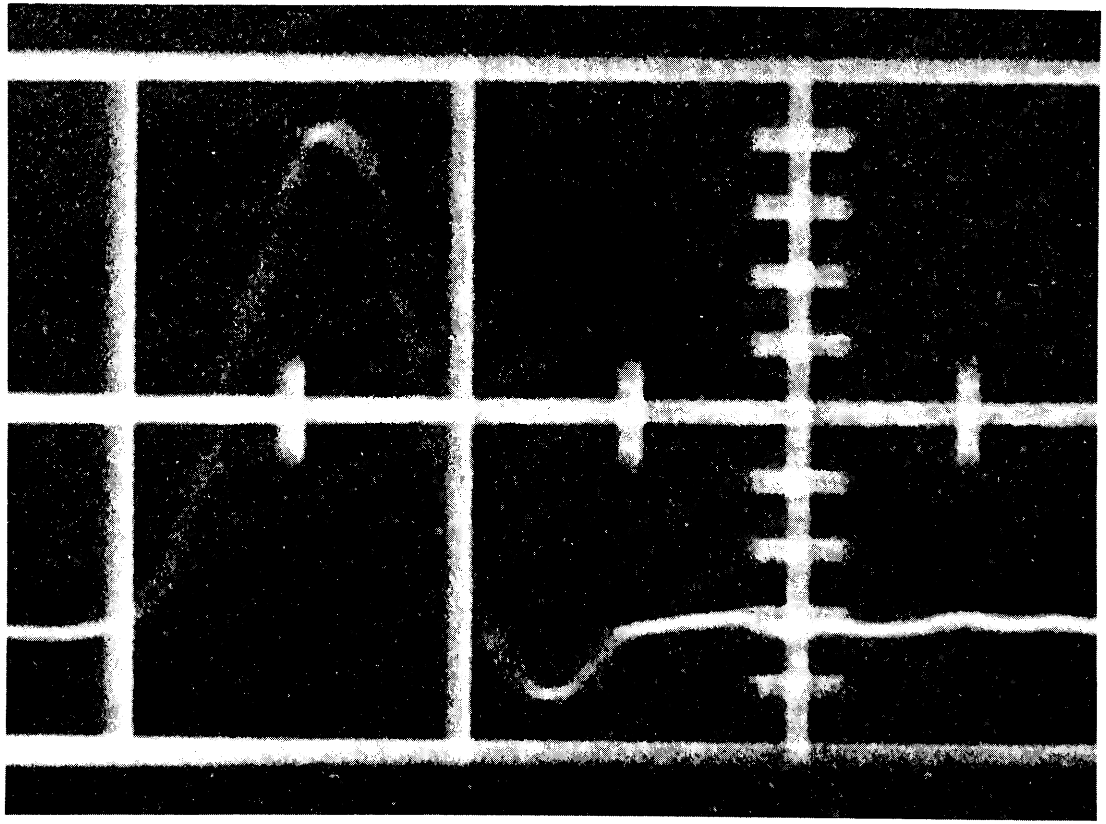


Fig. 2 Observed bunch at B272

5 ns/cm. 9.6 V/cm

1.62 x 10^{12} circul. protons

SIS/R/16379

FIG. 3

$0.30 \cdot 10^{12}$ protons

5 nsec / div 9.6 V/div

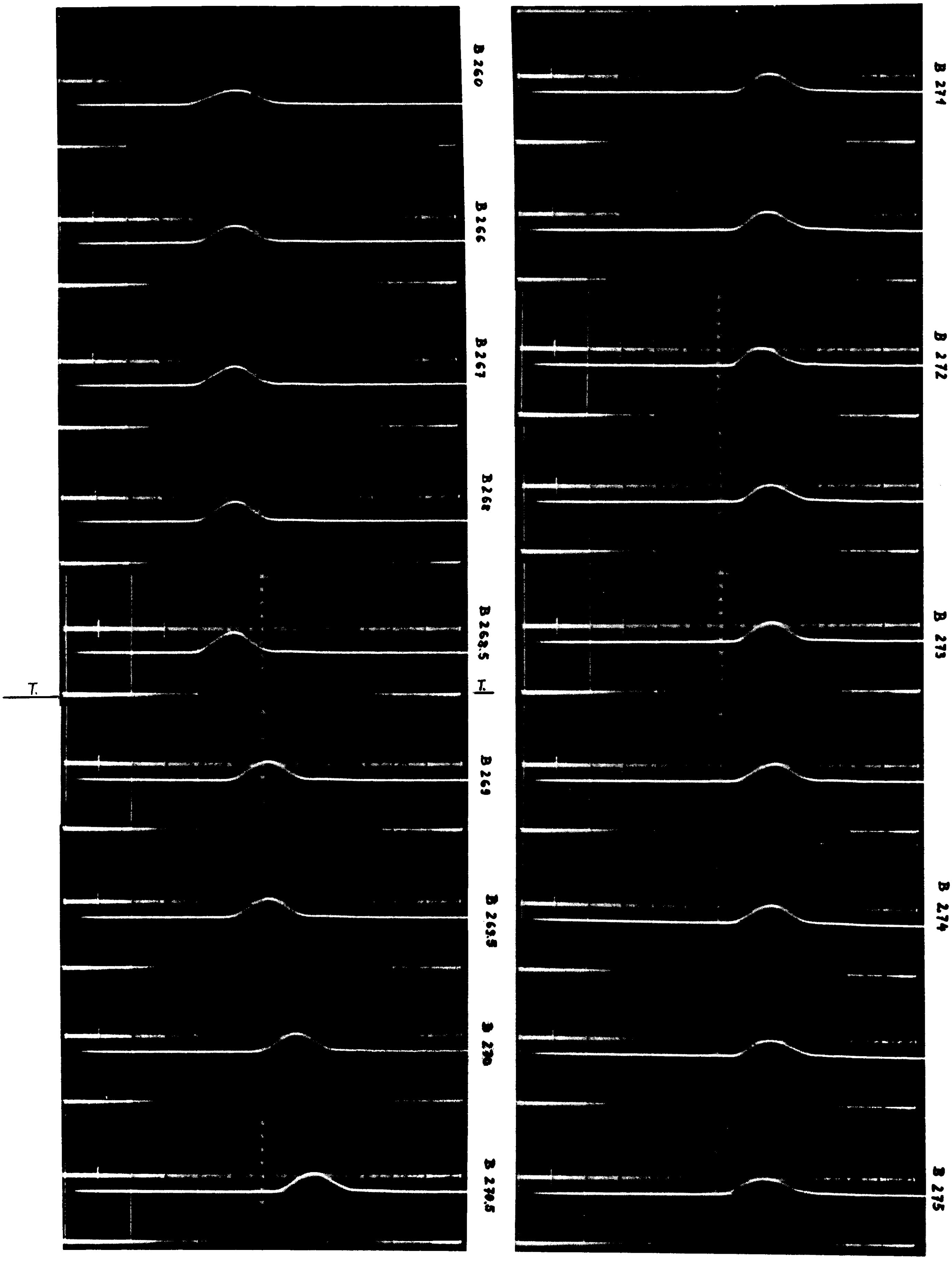
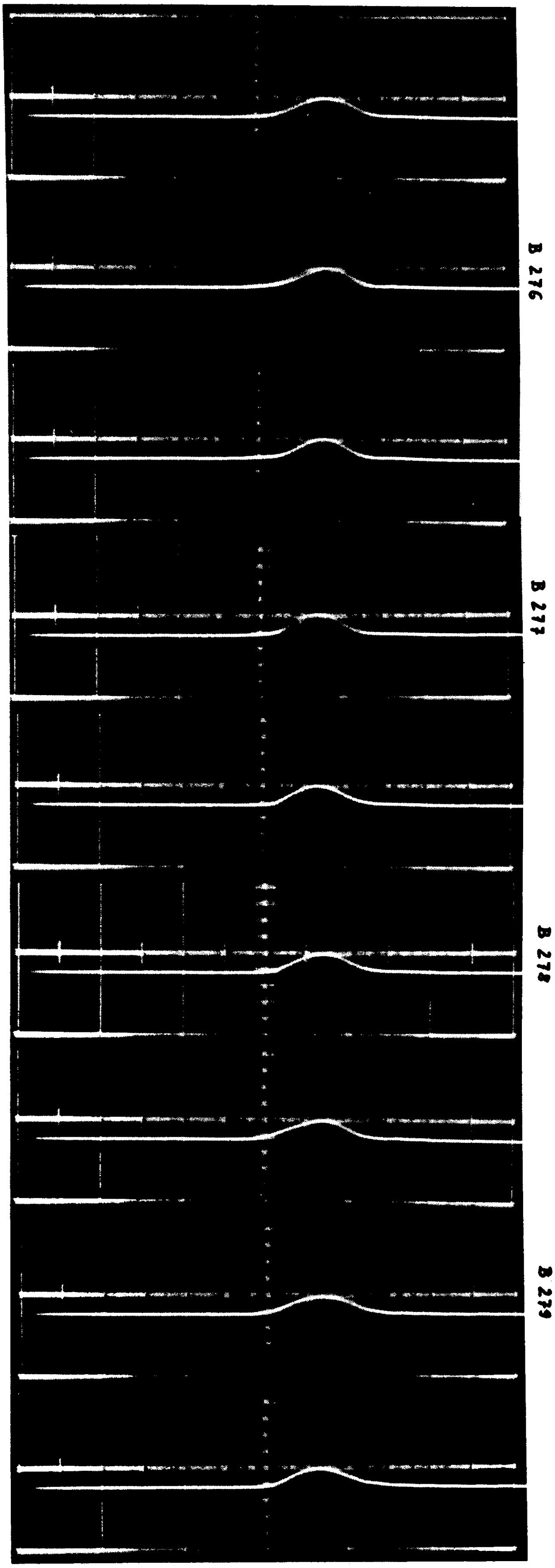


FIG.3 (contin'd)

0.30 10^{12} protons
5nsec/div 9.6V/div



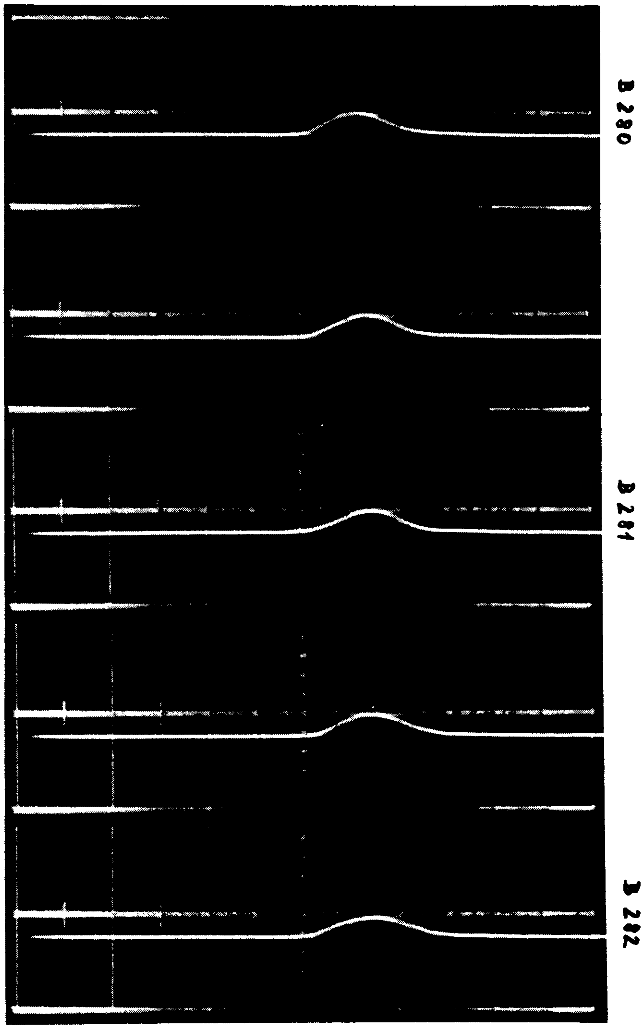


FIG. 3A
5 ns/cm at B269
(new cathode follower)

FIG. 4

$1.62 \cdot 10^{12}$ protons on 24.4.1969
5 nsec/div . 9.6V/div

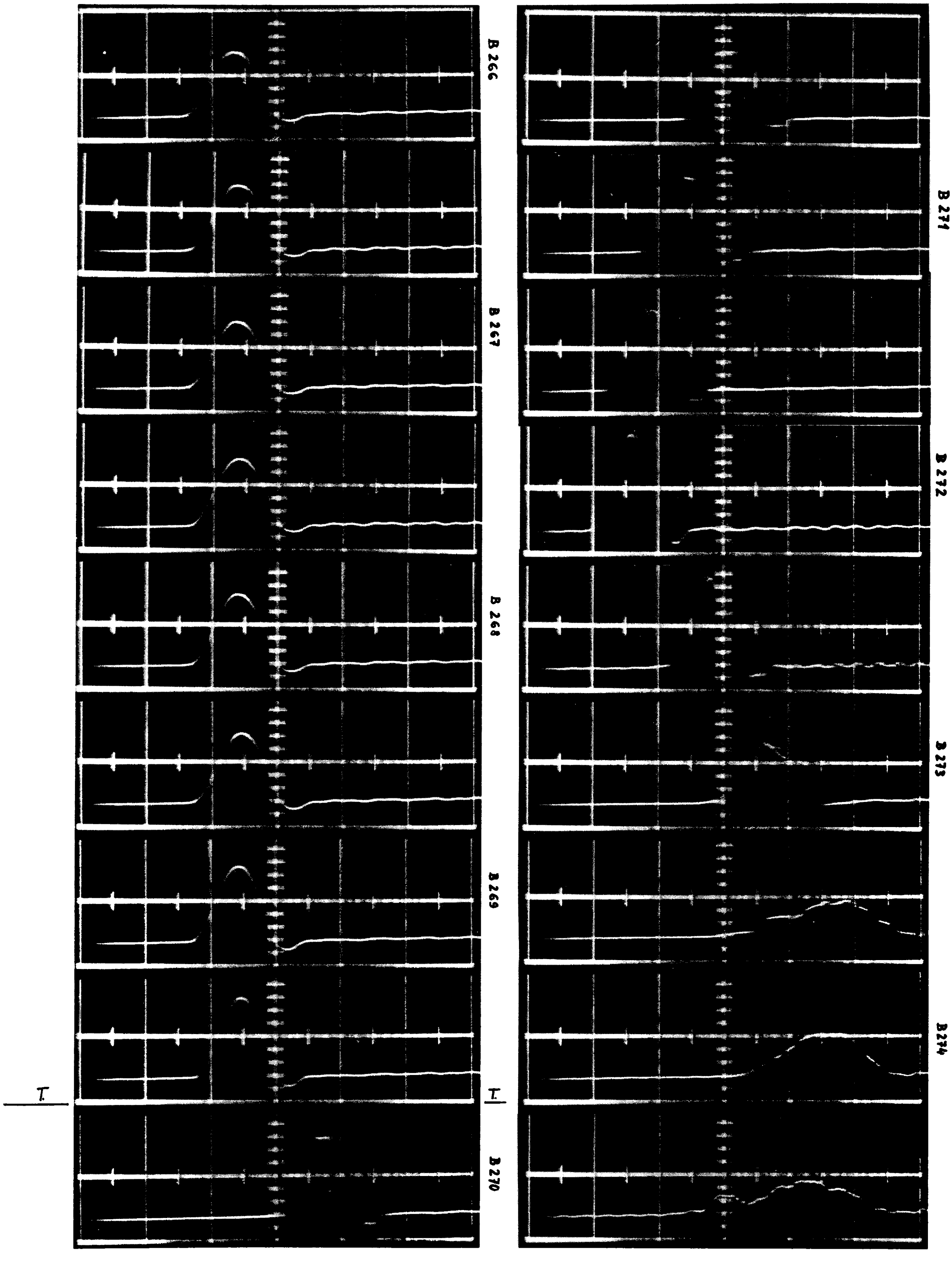


FIG. 4 (cont'd.)

$1.62 \cdot 10^{12}$ protons on 24.4.1969
5 nsec/div.

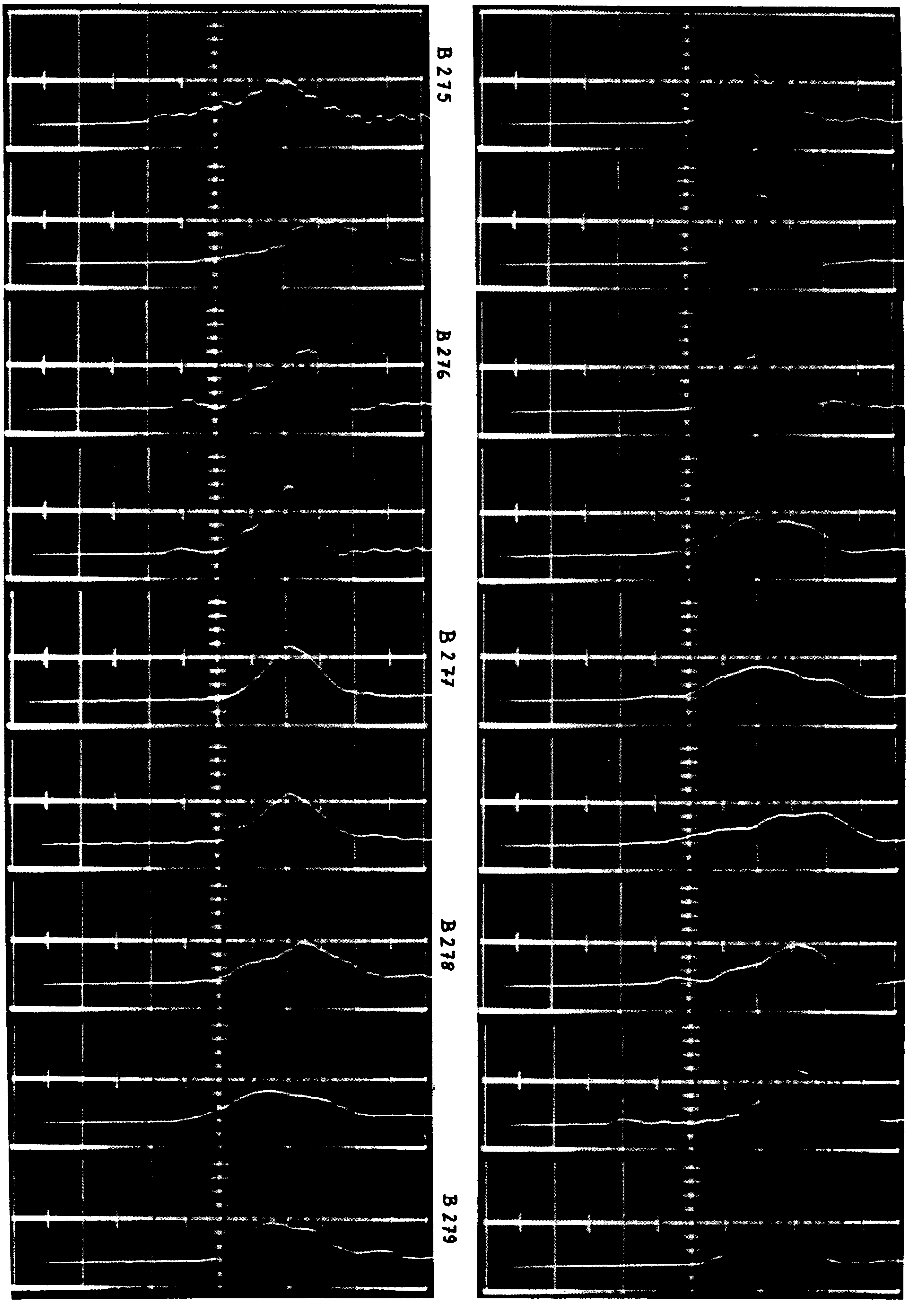


Fig. 5
10 ns/cm
one sweep every 100 turns

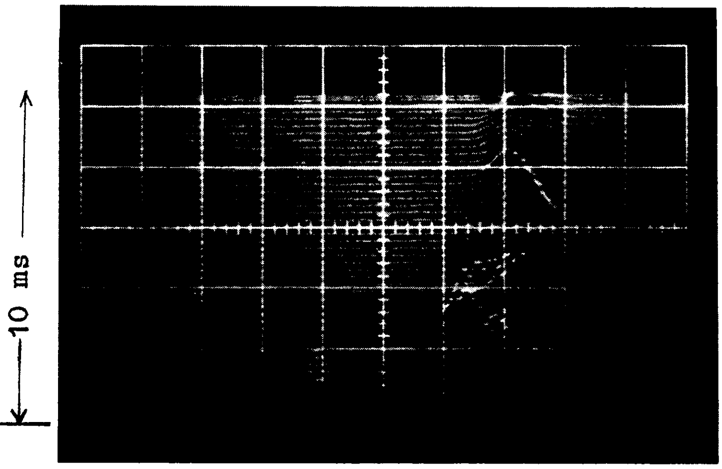


Fig. 6
peak detected bunch height
B265 and 2ms/div

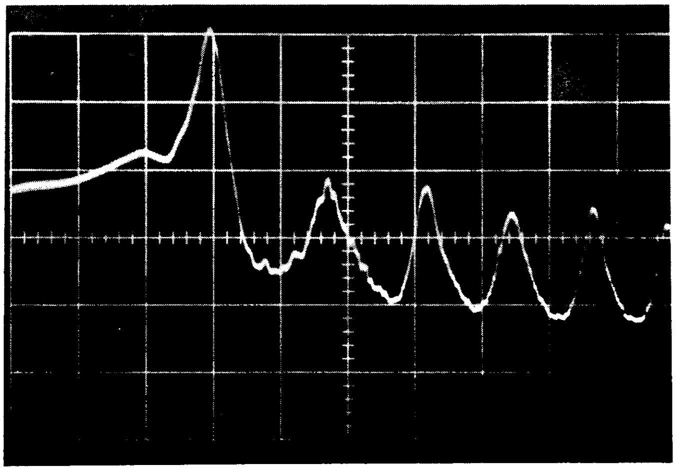


Fig. 7
B266 and 2 ms/div
bunch height 5 V/div
rad. control error 2 V/div
p.u. station ΔR .2 V/div

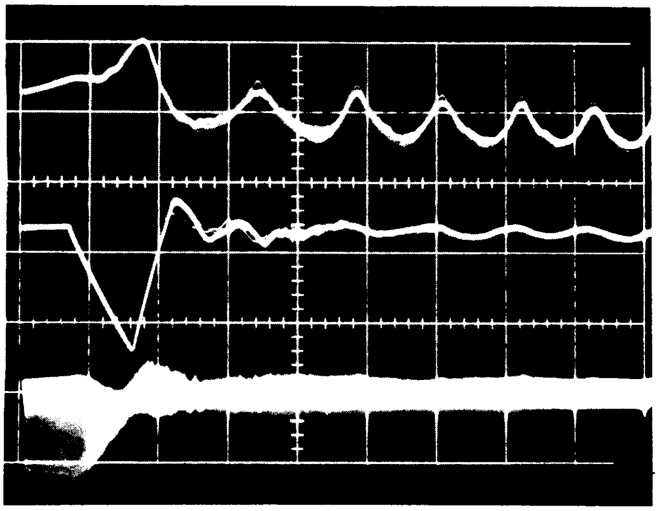


FIG. 8

$1.6 \cdot 10^{12}$ protons on 22.6.1969

5 ns/div

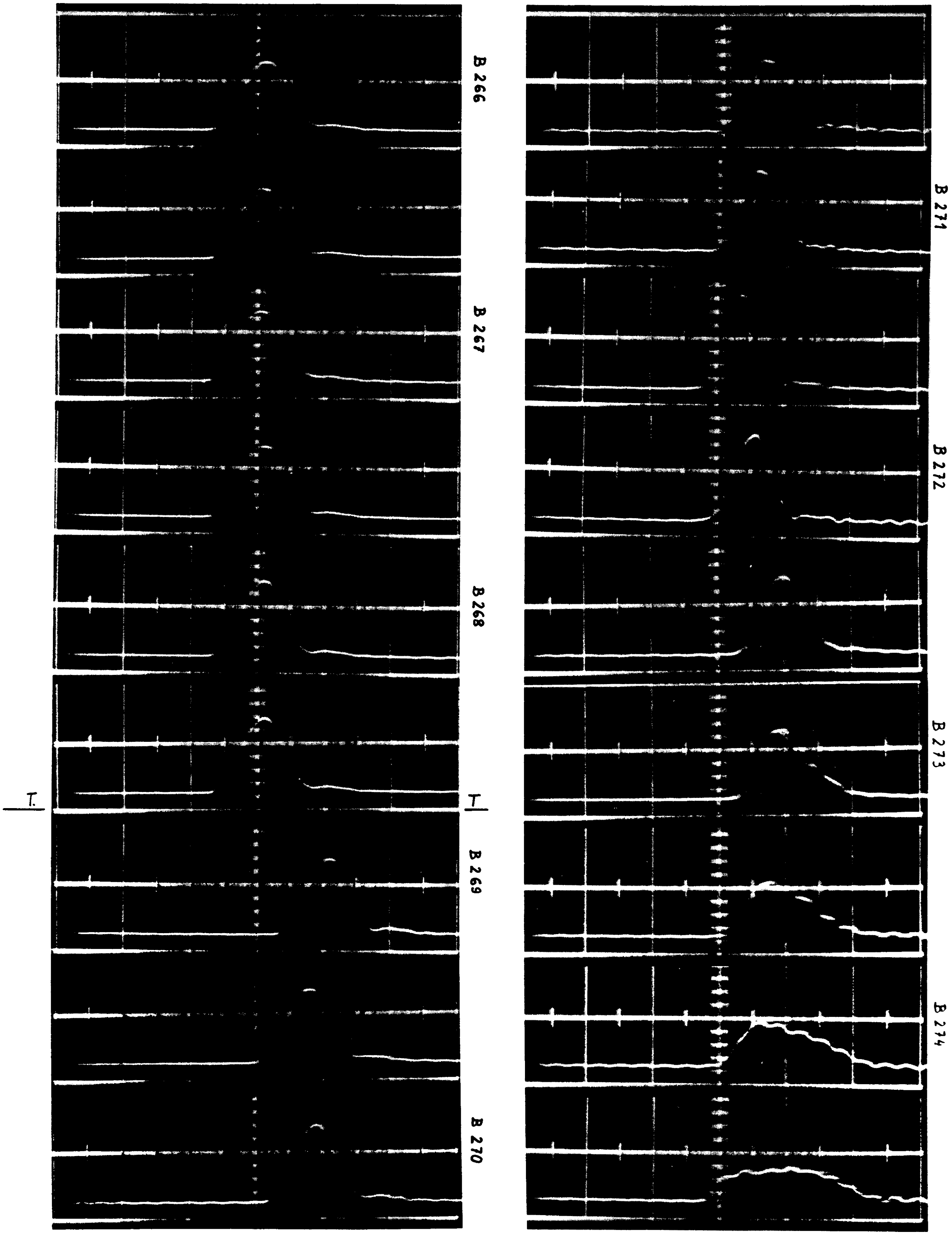
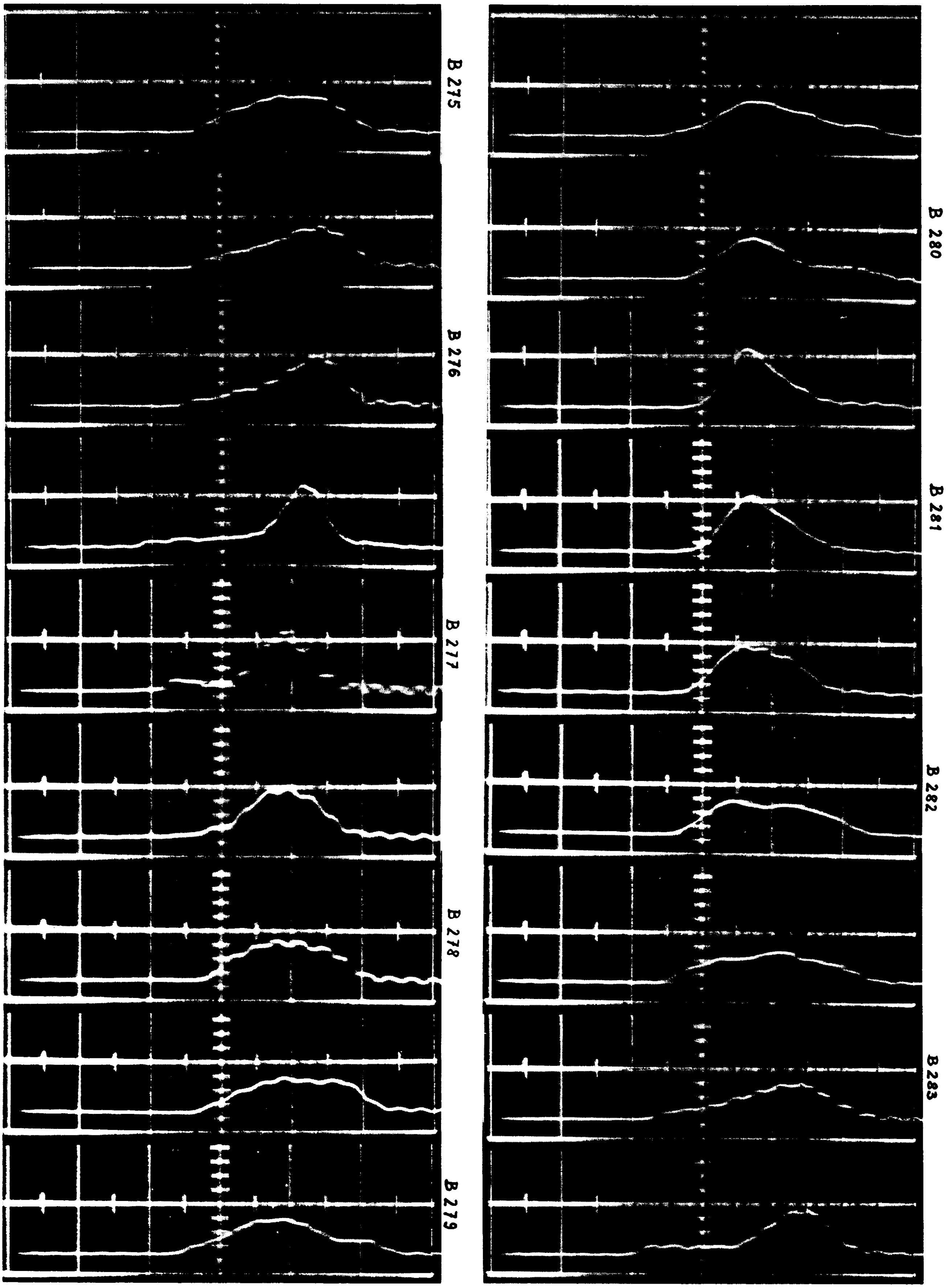


FIG. 8 (continued)

$1.6 \cdot 10^{12}$ protons on 22.6.1969

5ns/div



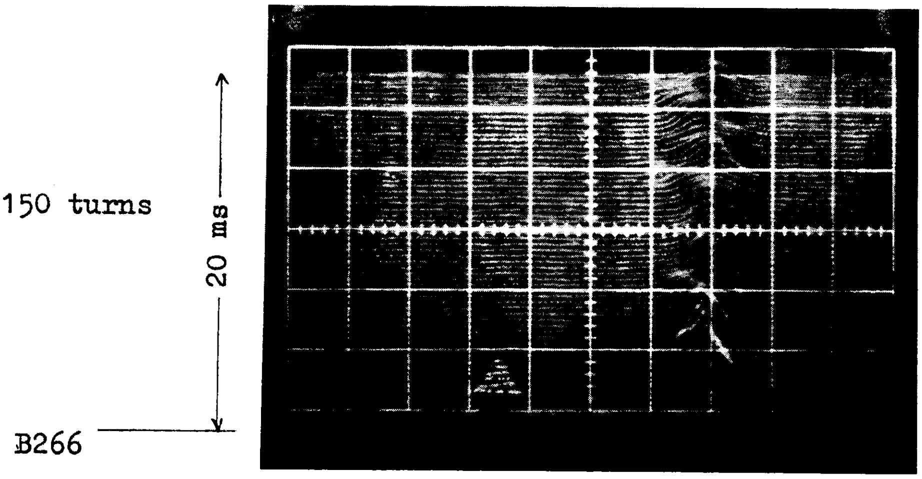


Fig. 9
10 ns/div
one sweep every 150 turns

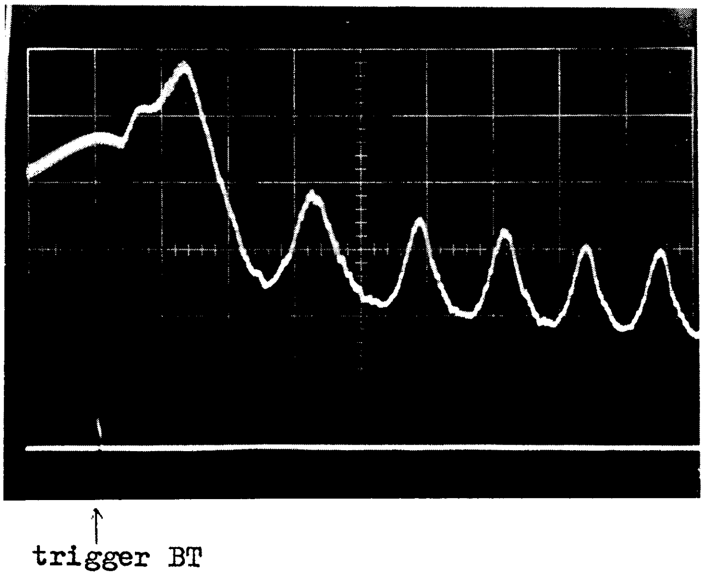


Fig. 10
bunch height (uncalibrated)
B266 and 2 ms/cm

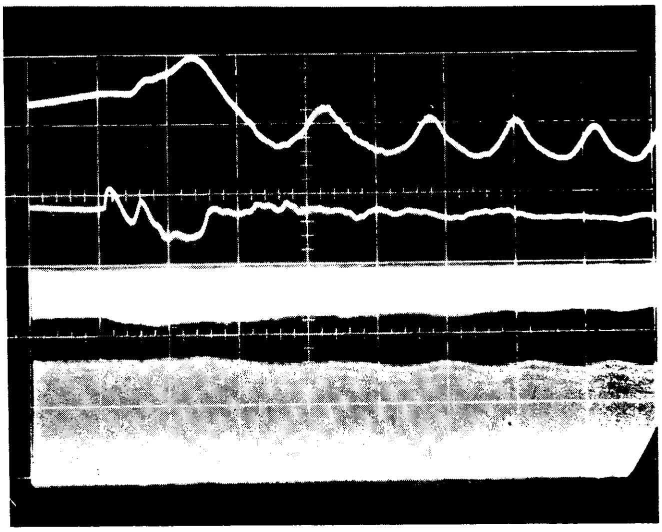


Fig. 11
B 266 and 2 ms/div
bunch height 5 V/div
rad. control error 2 V/div
p.u. ΔR & Σ .2 V/div

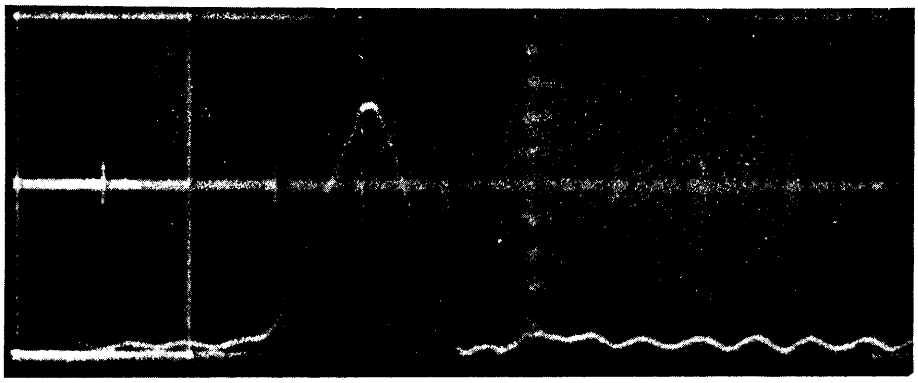


Fig. 12

1.58×10^{12} protons

5 ns/cm B272

(new cathode follower)