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A Transverse Beam Profile Monitor for p-$\bar{p}$ Studies

by

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1. Introduction

In the present program of p-$\bar{p}$ machine studies, proton beams are stored for long periods on a flat top at 270 GeV/c. The intensity varies from 2 x 10^{10} protons per bunch during single bunch storage experiments to a maximum of 10^{12} protons for continuous beam studies. Up to now, only a rough knowledge of the evolution of the transverse beam dimensions has been possible by scraping the beam periodically. In order to measure precisely the transverse density distribution in an almost non-destructive way, a simple profile monitor has been developed which is based on the 'flying wire' technique as previously proposed in 1) and 2). A fine wire is moved rapidly through the beam. The density profile can be measured either by detecting the high-energy secondary particles traversing a scintillator placed close to the beam pipe or by directly measuring the secondary emission current leaving the wire. Both of these methods give excellent results.

This device is now needed regularly during storage experiments to follow the evolution of the transverse emittance.

2. Mechanical Considerations

The upper limit of the speed of the wire is governed by the desired precision of measurement of the profile of a single bunch. To obtain a wire displacement of 0.1 mm during the revolution time of the bunch ($\sim$ 23 μsec) requires a speed of 4.34 m/sec. Since no great problems of heating of the wire exists in the intensity range of interest for storage studies, a speed of 2-4 m/sec was considered sufficient. This could most easily be achieved using existing mechanical components and electronics by modifying a rotating mechanism normally used for moving TV screens.

The wire is stretched on a fork (figure 1) which is driven by a D.C. motor and a reduction gearbox through a rotating vacuum seal. The wire rotates through an angle of 120° on a radius of 115 mm. This gives a total movement of 480 mm and allows ample space for smooth acceleration and deceleration of the fork.

A potentiometer mounted on the drive arm of the fork provides the signal for the control of the acceleration and deceleration and at the same time allows the speed to be monitored. With this simple arrangement, a transversal speed of $\sim$2.5 m/sec has been achieved. Figure 2 shows a calibration of the speeds in the clockwise and anticlockwise directions during the time of traversal of the beam. Each trace is the superposition of 15 separate traversals.

The monitor has been mounted in LSS3 2.4 metres downstream QD 317, and scans in the vertical plane.

The wire chosen for the prototype device was 120μ diameter beryllium. It is isolated from the body of the fork by ceramic insulators so that the secondary electron emission signal could be monitored.

3. Effect on the beam

3.1 Emittance blow-up

The passage of the wire across the beam produces an emittance blow-up through multiple Coulomb scattering. The emittance blow-up per scan is given approximately by

$$\frac{1}{\pi}\frac{d\varepsilon}{dn} = \frac{1}{2}\,\beta\,\langle\theta^2\rangle$$

where β is the beta value of the lattice at the wire location and $\langle\theta^2\rangle$ is the mean square scattering angle given by the Rossi formula

$$\langle\theta^2\rangle = \frac{2.25 \times 10^{-4}}{p}\,\frac{d_{eff}}{L_{rad}}$$

d_{eff} is the effective wire diameter

$$d_{eff} = \frac{d^2}{\upsilon} fr$$

where d is the wire diameter, for the revolution frequency and υ the wire speed.

Putting $d = 120\ \mu$
$fr = 44$ kHz
$\upsilon = 2.44$ m/sec
$L_{rad} = 0.347$ M
$\beta_V = 93.1$
$\beta_H = 23.2$
$p = 270$ GeV/c

then $d_{eff} = 260\ \mu$

and $<\theta^2> = 2.3 \times 10^{-12}$

Then $\frac{1}{\pi}\frac{d\varepsilon_V}{dn}$ $1.\ 1 \times 10^{-4}$ mm.mrad/scan

and $\frac{1}{\pi}\frac{d\varepsilon_H}{dn} =$ 2.7×10^{-5} mm.mrad/scan

It is convenient to compare these values with the blow-up expected due to gas scattering, given by

$$\frac{1}{}\ \frac{d\varepsilon}{dt} = 133 \frac{P_{MS}}{T} \frac{\bar{\beta}}{p^2} \text{ m.rad/sec.}$$

The measured gauge pressure is 10^{-8} torr. The effective pressure for multiple scattering P_{MS} is generally about a factor of 3 less than this. So assuming $P_{MS} \simeq 3 \times 10^{-9}$ Torr, we get

$$\boxed{\frac{1}{\pi}\frac{d\varepsilon}{dt} = 2.7 \times 10^{-3} \text{ mm.mrad/hour}}$$

Comparing this figure with the blow-up due to the wire, we see that we can make up to 25 scans/hour to have the same blow-up rate as the gas.

3.2 Particle loss

Protons are lost through nuclear interactions. The interaction probability per incident proton is given by

$$P = 6.02 \times 10^{23} \rho \theta d_{eff}$$

where ρ , the density of beryllium = 1.85 gr/cm^3
σ , the total cross section for proton nuclear interaction
= 40 millibarns/nuclei.

giving $P = 1.1 \times 10^{-3}$
i.e 0.1 % loss per scan.

Since we are only interested in making a few scans per hour, the emittance blow-up and particle loss can, for all practical purposes be neglected.

4. Heating of the wire

The upper limit of intensity at which the device may be used is governed by the heating of the wire by the beam.

The energy deposited by the interaction of the wire with N_p circulating protons is

$$E = 3.82 \times 10^{-14} \frac{\pi}{4} \frac{N_p \rho d^2 f_{rev}}{\upsilon} \cdot \frac{dE}{dx} \text{ calories}$$

Assuming that no conduction takes place during the time of traversal of the beam ($\sim$1 msec), the mass heated is

$$\text{Mass} = \frac{\pi d^2}{4} \rho h_{eff}$$

where h_{eff} is the effective beam height perpendicular to the direction of scan given by $h_{eff} = \sqrt{2\pi}\ \sigma$.

Therefore, the temperature rise during a single traversal is

$$T = 3.82 \times 10^{-14} \frac{N_p \, f_{rev}}{v \, h_{eff} \, s} \frac{dE}{dX}$$

For the machine and wire parameters given in 3.1 and assuming a vertical scan through a beam with normalised radial emittance 30π mm.mrad at 270 GeV/c, then $h_{eff} = 1.95$ mm.

$$S = 0.436 \text{ cal/gram}$$

$$\frac{dE}{dX} = 1.61 \text{ MeV.cm}^2\text{/gram}$$

$$\boxed{\Delta T = 1.3 \times 10^{-10} \; {}^{o}\text{C/proton}}$$

For single bunch storage experiments with a maximum of 10^{11} circulating protons the heating is completely negligible. However, for continuous beam studies care must be taken to limit the intensity, especially as it is not known how the wire responds to the thermal shock. The device has been successfully used on stored beams of up to 10^{12} protons.

5. The scintillator detector

The distribution of secondary particles produced by the interaction of the proton beam with the wire is strongly peaked in the forward direction. Previous calculations [2)] have shown that the flux density should be sufficiently high that a reasonably small scintillator placed close to the beam pipe should intercept a substantial number of secondaries and so reproduce the incident particle beam profile with good statistics.

After striking the wire the beam travels in an enlarged vacuum chamber of 256 mm internal diameter for about 3 metres after which the chamber profile is sharply reduced to that of an MBB chamber. Two slabs of scintillator (NE 110) each of 140 mm x 50 mm x 10 mm were placed above and below the beam pipe touching the vacuum chamber (figure 3). Light guides from each side of both upper and lower scintillator were fed into a single photomultiplier tube placed below the beam pipe. This symmetrical arrangement was used to try to make the signal independent of the beam position. The geometry allowed secondary particles to be intercepted within the angular range 9 to 25 mrads with respect to the circulating beam. The photomultiplier was shielded from direct particles by a 1.6 m steel shield built from blocks placed under the vacuum chamber.

The choice of photomultiplier was governed by the need for good linearity under the high luminous flux intensity expected. The first tube tried was a Philips XP202. The gain of the tube was $\sim 10^6$ with 2600 volts overall tube voltage. With a low intensity debunched beam this arrangement gave good profiles. Figure 4 shows some profiles obtained first with a very low intensity debunched beam (1×10^{10} protons) and also with a more intense beam (5×10^{11} protons). However, with a single bunch the tube proved to be far too sensitive. It was even possible to measure the profile of the small fraction of the beam lost from the bucket during a long period of storage in the presence of the much more dense bunch (Fig. 4c).

A much better tube for the high signal levels obtained with dense single bunches was found to be the PM 1910 . This is a 10-stage tube and was used with the dynode chain shown in figure 5. This chain was designed for good linearity at the expense of gain, the estimated gain being $\sim 2 \times 10^4$ at 1500 volts. Some typical results obtained with this tube with a single bunch are shown in figure 6.

Figure 7 shows some profiles measured at 270 GeV with the low beta simulation. The first photograph shows the profile of a bunche beam with a rather non-uniform azimuthal intensity distribution as shown on the fast beam current transformer (Fig. 7b). The profiles of individual slices of beam can quite easily be seen. Figure 7c shows the profile with RF off.

Profiles have equally been obtained at 26 GeV/c.

6. The charge collection in the wire

The charge created in the wire by the passage of a single bunch is given by

$$\frac{dQ}{dn} = \varepsilon \frac{dN_p}{dx} D$$

where ε is the charge created per traversing proton and dN_p/dx the particle density as a function of the scanning direction x. D is the wire diameter.

Usually, an efficiency for the creation of the charge of about 4.8% is expected from thin aluminium foils. Assuming the same efficiency for the beryllium wire and assuming a bunch of 10^{10} protons with an r.m.s width of 1 mm, a charge of about 3.6 p C per traversal can be expected. With the parameter of the amplifier (figure 8), this would give an output of ∿ 4.4 volts.

During the first measurements, clear beam profiles could be detected. After some modifications to reduce the noise level induced by the circulating beam, very clean profiles were obtained. Figure 9 shows a typical example for a circulating beam intensity of 10^{10} protons. The vertical r.m.s height was about 1.3 mm.

From the output signal and the known parameters of the amplifier together with the intensity of 10^{10} protons and the vertical charge distribution at the centre of

$$\frac{dN_p}{dX} = \frac{10^{10}}{\sqrt{2\pi}\,\sigma} = 3 \times 10^9 \text{ protons/mm}$$

a charge collection efficiency ε of 4.8% is obtained, which is in excellent agreement with the expected value.

Figure 9a shows the noise induced by the circulating beam when the wire is out of the beam. From this, a signal to noise ratio of 1% is obtained.

Clearing electrodes were mounted on the fork, on which a voltage of ∿ 1 kV could be applied. However, no influence of the bias voltage on the charge signal could be found at this intensity.

7. Conclusions

The fast wire scanner provides an almost completely non-destructive means of measuring a transverse profile of stored proton beams. The device has been used during storage experiments with both bunched and debunched beams at 270 GeV/c as well as at 26 GeV/c.

For operation with both protons and antiprotons, the scintillator method will easily allow measurement of both beams simultaneously even if they are debunched, due to the strong forward peaking of secondary particle production. The secondary emission detector could also be made to work for bunched beams provided the unit is placed far enough away from an intersection region to allow sufficient time between arrivals of protons and antiprotons. It is thought that ∿ 100 nsec should be sufficient for modern electronics to sort the signals from the different bunches.

References

1) L.R. Evans, R. Shafer, SPS/ABT/TR/LE/Int.Note/79-4 (1979).

2) P. Sievers, SPS/ABT/TA/PS/Int.Note/79-2 (1979).

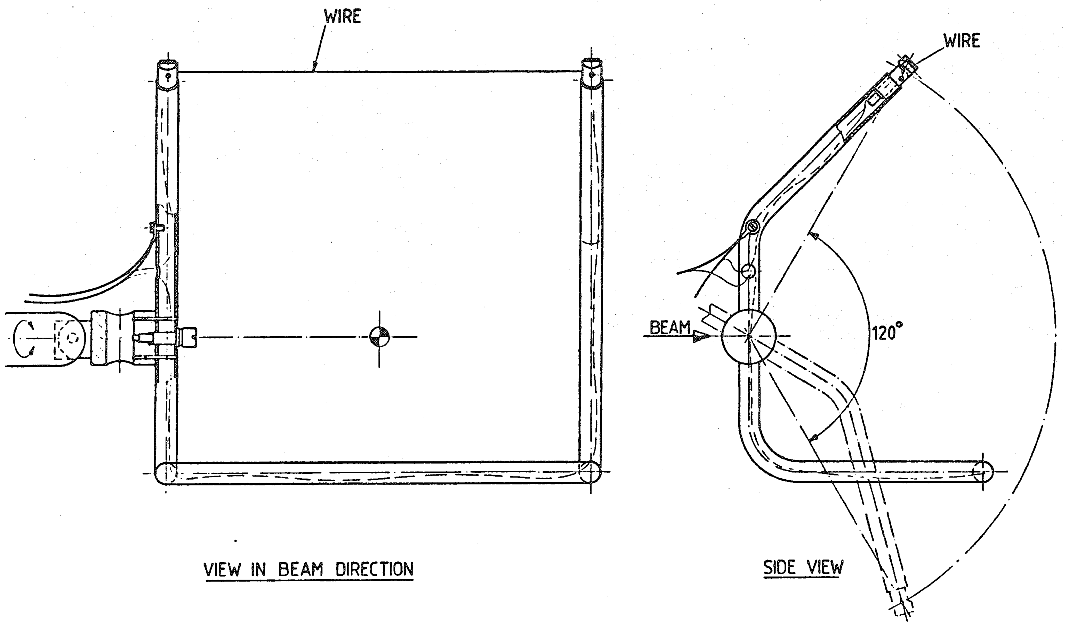
WIRE
WIRE
BEAM
120°
VIEW IN BEAM DIRECTION
SIDE VIEW
JJ Fraigat 690215

Fig. 1a)

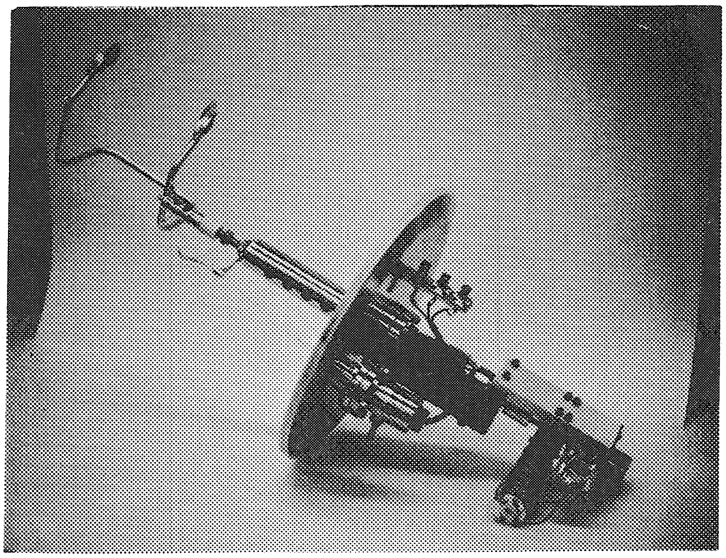
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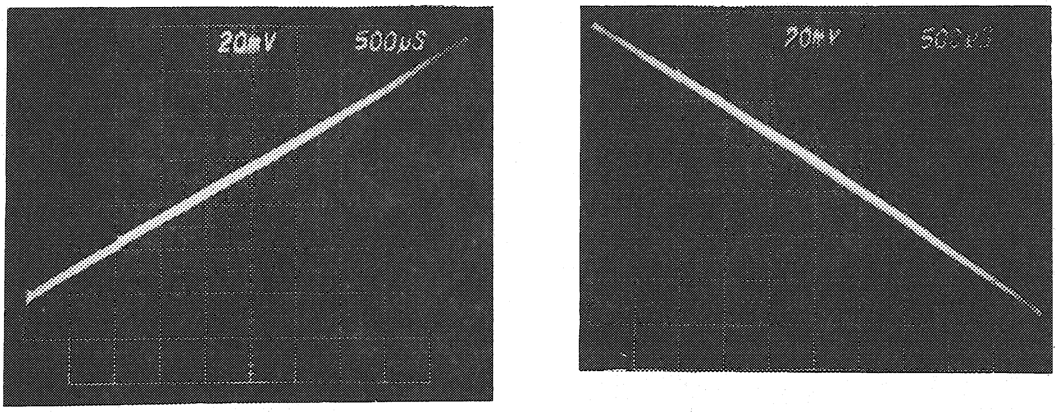
Fig. 1b)



IN

v = 2.37 m/sec

OUT

v = 2.51 m/sec

Calibration of wire speeds (10 mV/mm)

Fig. 2

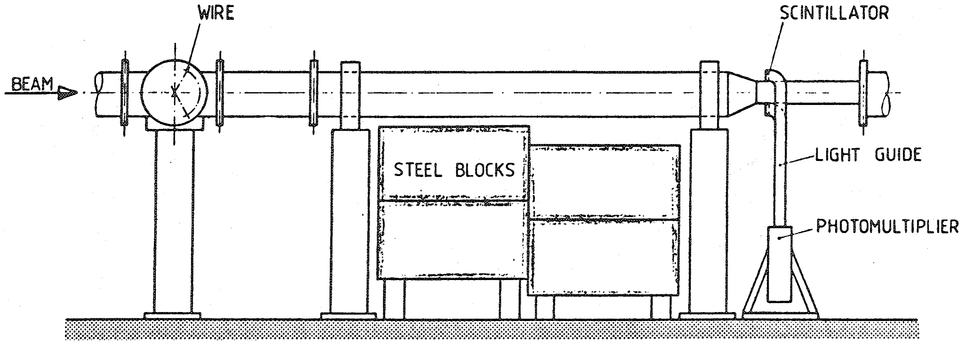


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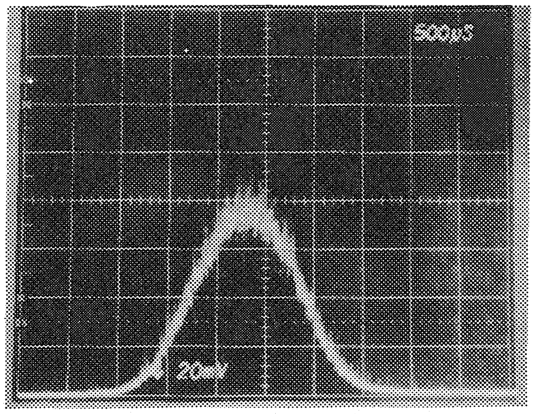
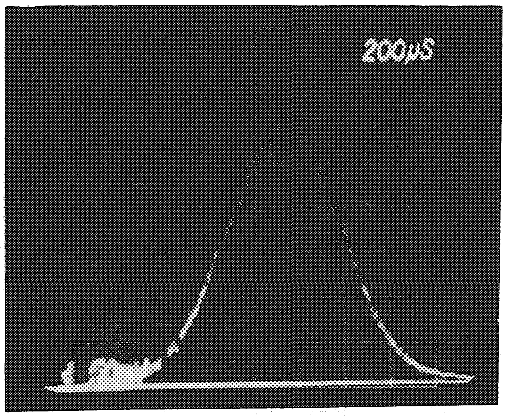
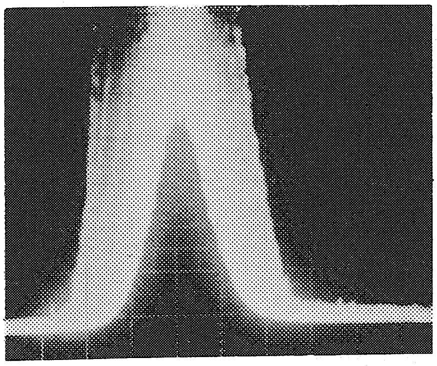
Fig. 3



a) Debunched beam of 10^{10} protons



b) 5×10^{11} protons debunched



c) Profile of untrapped beam in the presence of the bunch.

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Fig. 4

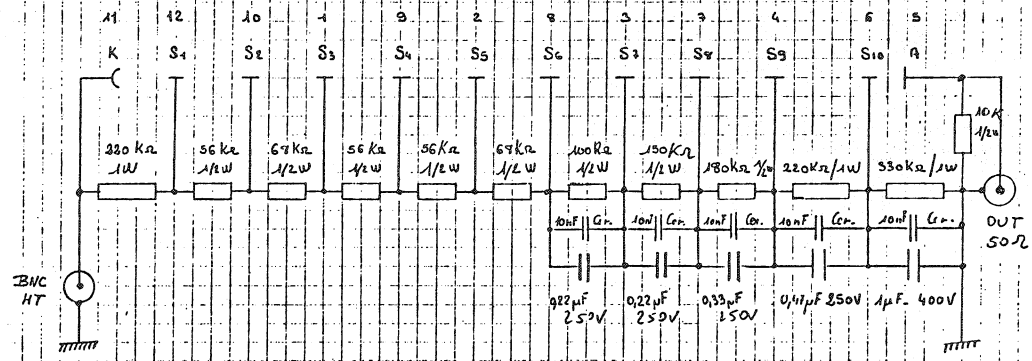

Fig. 5

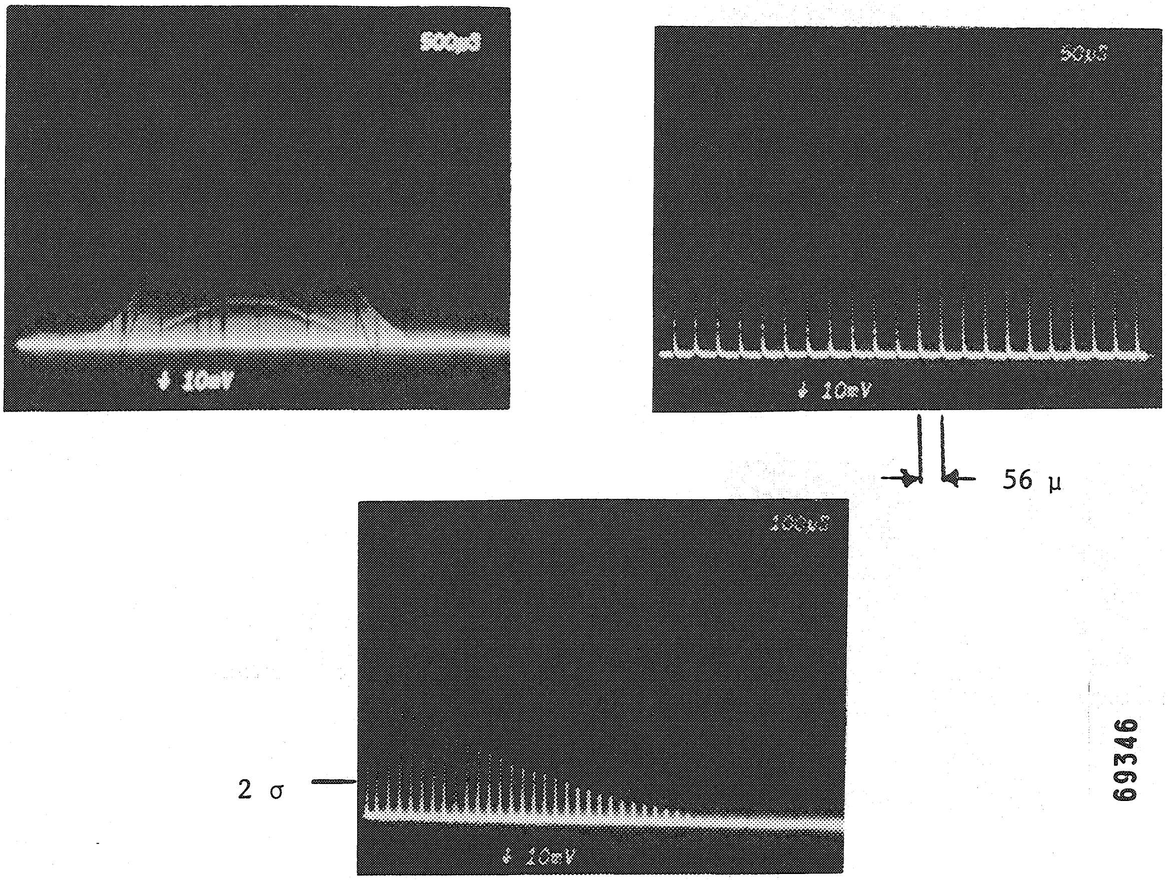

Fig. 6 Single bunch of 2 x 10^{10} protons at 270 GeV/c with scintillator.

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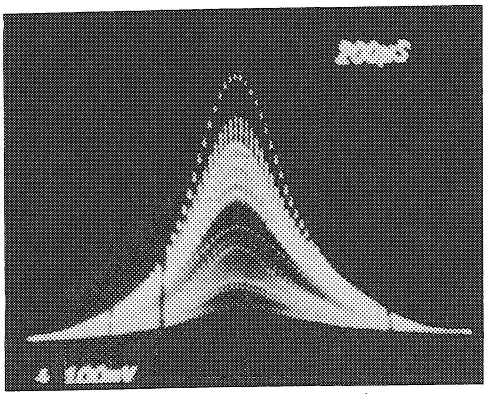
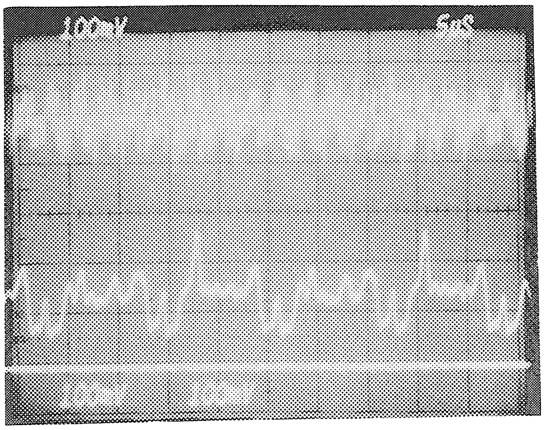
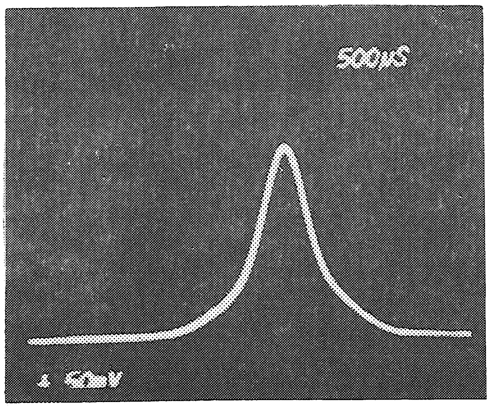


a) Profile of a continuous beam with RF on. The different profiles are due to intensity modulation around the ring shown in BCT signal below.



b) Fast BCT signal shows non-uniform density distribution.



c) RF off. Notice long tails.

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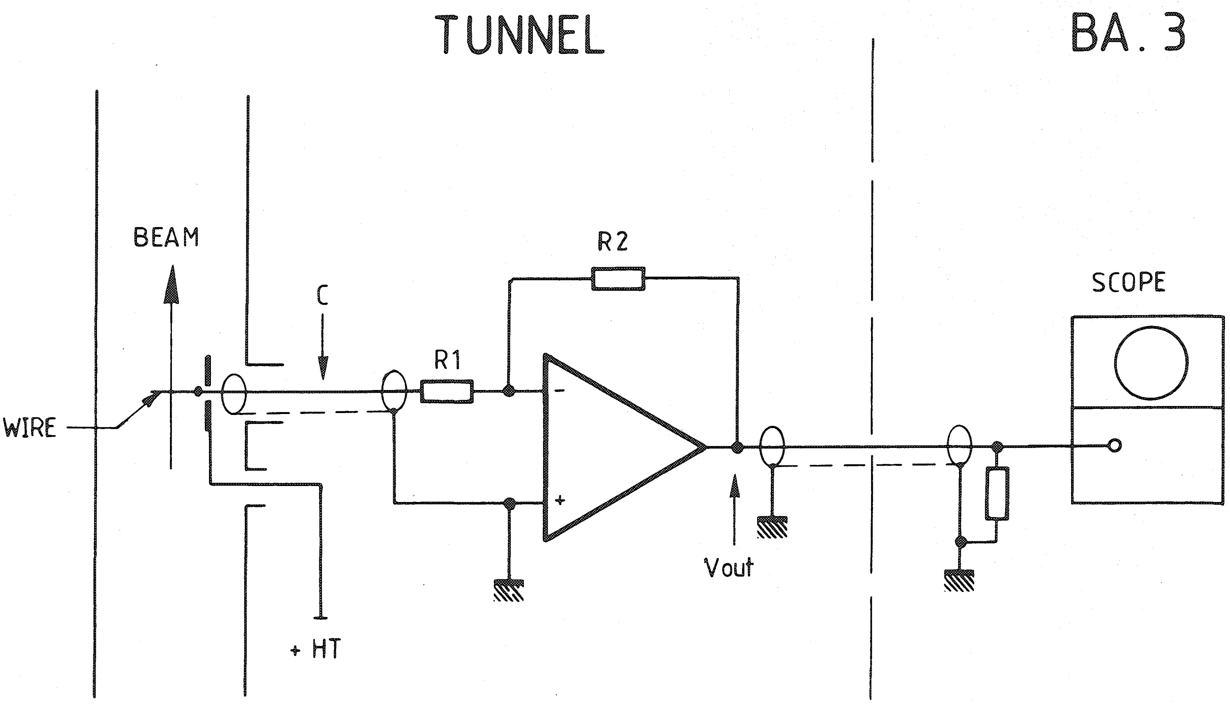
Fig. 7 Profiles with low beta simulation at 270 GeV/c with scintillator.



$$V_{\substack{\mathrm{OUT}\\ \mathrm{MAX}}} = \frac{N_p \cdot \varepsilon \cdot Q_{el}}{C} \cdot \frac{R_2}{R_1}$$

$$\tau = C \cdot R_1$$

N_p : NUMBER OF PROTONS ON THE WIRE

ε : EFFICIENCY OF SECONDARY EMISSION = 4,7 %

Q_{el} : CHARGE OF ELECTRON = $1{,}6 \cdot 10^{-19}$ C

C : INPUT CAPACITY = 250 pF

R_2/R_1 : GAIN OF AMPLIFIER = 303 , $R_2 = 10^6\,\Omega$, $R_1 = 3{,}3\ \mathrm{k}\Omega$

τ : TIME CONSTANT = 0,8 μS

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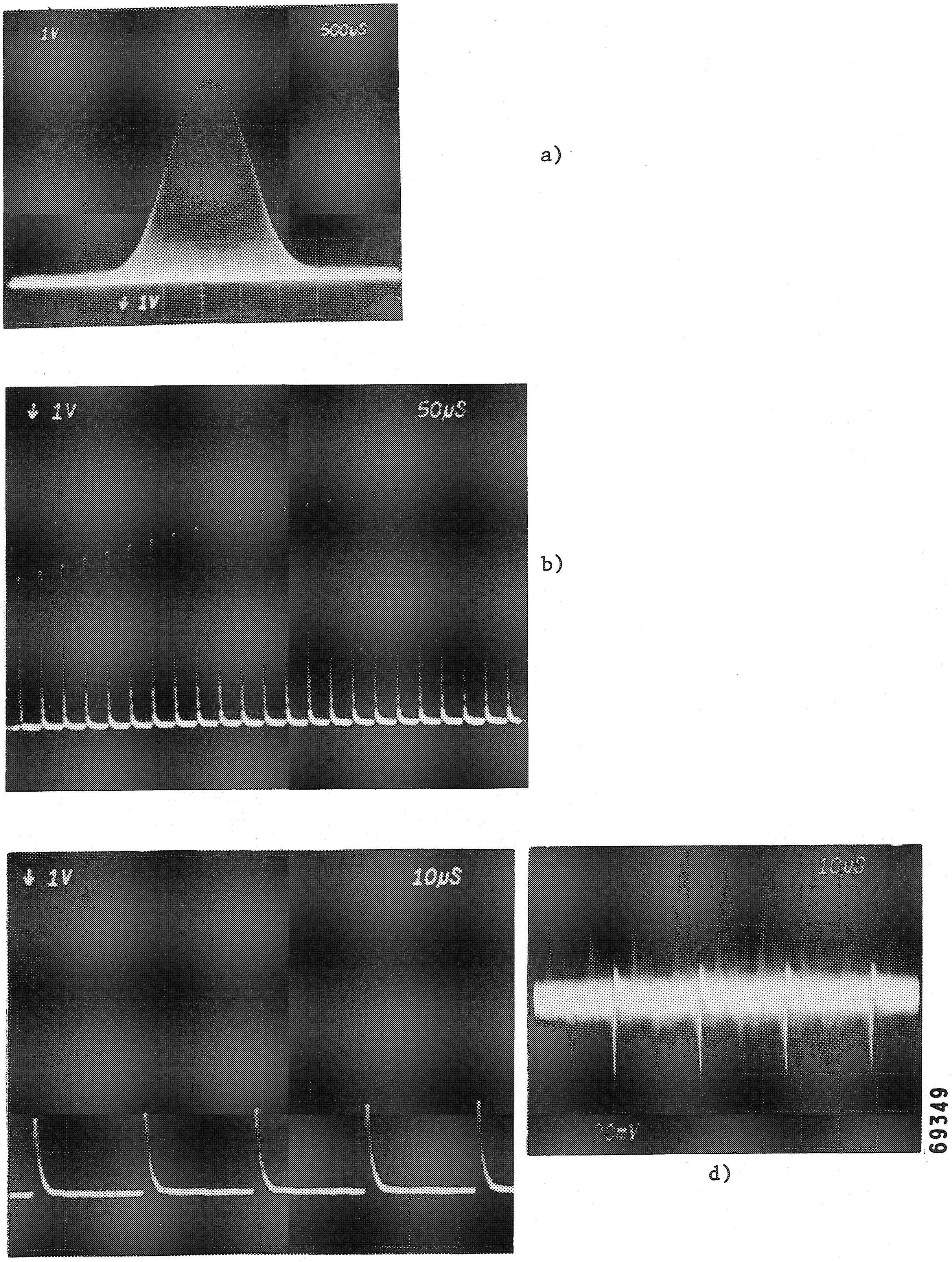
Fig. 8



a)

b)

c)

d)

Fig. 9 Profiles at 10^{10} protons/bunch with secondary emission detector.