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TRANSVERSE EMITTANCE MEASUREMENT WITH A RAPID WIRE SCANNER AT THE CERN SPS

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A simple almost non-destructive device has been built to accurately measure the transverse emittances of the proton and antiproton beams in the CERN SPS collider. A fine wire passing rapidly through the beams acts as a target for the production of high energy secondary particles. Use is made of the strong directivity of the particle production to separately record the profiles of the two beams using scintillators and photomultipliers placed close to the beam pipe in the downstream proton and antiproton directions. The wire scanners are also used to measure the emittance of high-intensity proton beams during normal fixed-target operation using the secondary emission (depletion) current leaving the wire since in this case the directivity is not required.

1. Introduction

The rapid wire scanners have been developed specifically for the measurement of beam emittance in the CERN super proton synchrotron (SPS) proton–antiproton collider. In this mode of operation, counter-rotating beams of protons and antiprotons are stored for many hours at 270 GeV/c. Each beam contains up to 6 bunches varying in intensity from 1.4×10^{11} protons per bunch to as little as 2×10^9 antiprotons per bunch. The wire scanners allow measurement of the emittance of each individual bunch of protons and antiprotons with negligible perturbation to the circulating beams. A fine wire is passed through the beams at a speed of up to 6 m s^{-1}. The transverse profiles at the wire location are measured by intercepting high energy secondary particles produced by the interaction of the beam with the wire using scintillators placed close to the beam pipe in the downstream proton and antiproton directions respectively. Use is made of the strong directivity of secondary particle production to separately record the profiles of the two beams [1,2]. These devices are now used routinely to follow the emittance evolution during storage.

The SPS also operates in its traditional rôle as a high intensity proton synchrotron where it accelerates beams of up to 3×10^{13} protons per pulse between 14 GeV/c and 450 GeV/c for fixed target experiments. In this mode the wire scanners are also used to measure beam emittance in the low energy range of the machine (< 100 GeV/c). The beam energy is limited by the heating of the wire by the beam, which increases with energy due to the γ^{-1} dependence of the emittance. The profile is measured using the charge depletion current leaving the wire since no directivity is required. This method has previously been used with good results both in the CERN proton synchrotron (CPS) [3] as well as in the SPS [4].

2. Mechanical considerations

The upper limit of the required traversal speed is governed by the 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 requires a speed of 4.3 m s^{-1}. Consequently, the wire scanners have been built to work in the range 1–6 m s^{-1}.

The wires are either 50 μm diameter beryllium or 25 μm diameter carbon filaments stretched on a fork 170 mm long (fig. 1). The fork is driven by a dc motor and a 4:1 reduction gearbox through a rotating "wobbling bellows" vacuum seal. The wire moves on a radius of 200 mm and through an angle of 210°, giving ample space for smooth acceleration and deceleration. The axis of the fork is displaced by 92.5 mm with respect to the machine centre line.

The wire is isolated from the body of the fork using ceramic insulators. Both ends are connected to the outside of the vacuum tank with coaxial feedthroughs, allowing the integrity of the wire to be tested in operation as well as providing a means of measuring the charge depletion current. This arrangement has also proved to be useful for checking the wire speed in the laboratory by measuring the induced voltage across the ends due to movement in a uniform magnetic field.

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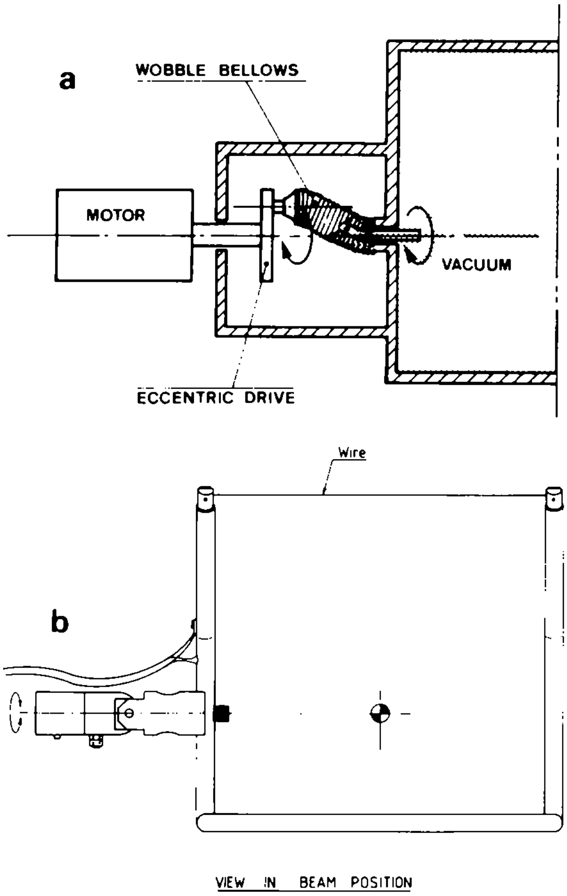


Fig. 1. Schematic diagram of rotating vacuum feedthrough (a) and wire suspension (b).

3. Speed control

The dc motor is driven by a programmable function generator. Closed loop servo control of the position is provided using the signal form a one-turn ceramic potentiometer mounted on the shaft of the fork.

The reference is programmed to give uniform acceleration and deceleration with constant angular velocity over a range of ±28° with respect to the beam centre line. The speed of the fork can be measured either from the potentiometer voltage as a function of time or more precisely using a simple disk encoder mounted on the shaft of the fork. The narrow slits in the disc in conjunction with a fixed light-emitting diode and detector provide start/stop pulses for a 44 kHz clock so that the time taken for the wire to traverse a known distance can be measured with high precision.

In the laboratory the speed has also been measured by passing the wire through a uniform magnetic field and measuring the induced voltage using a differential amplifier and oscilloscope. This measurement revealed some problems with the prototype, in which the speed was found to be varying by as much as ±10% due to the vibration of the arm of the fork (fig. 2a). This vibration was not visible with the other methods of speed measurement. Stiffening the arms resulted in considerable improvement, the modulation of the speed now being generally less than 1% at 4 m s^{-1} (fig. 2b).

A final check on the synchronism between the disc encoder and the wire was made by mounting a light-emitting diode on the end of the fork and comparing the time of crossing of a fixed slit with that of the disc under static and dynamic conditions. Within the precision of the measurement (~ 1 mm) no difference could be detected.

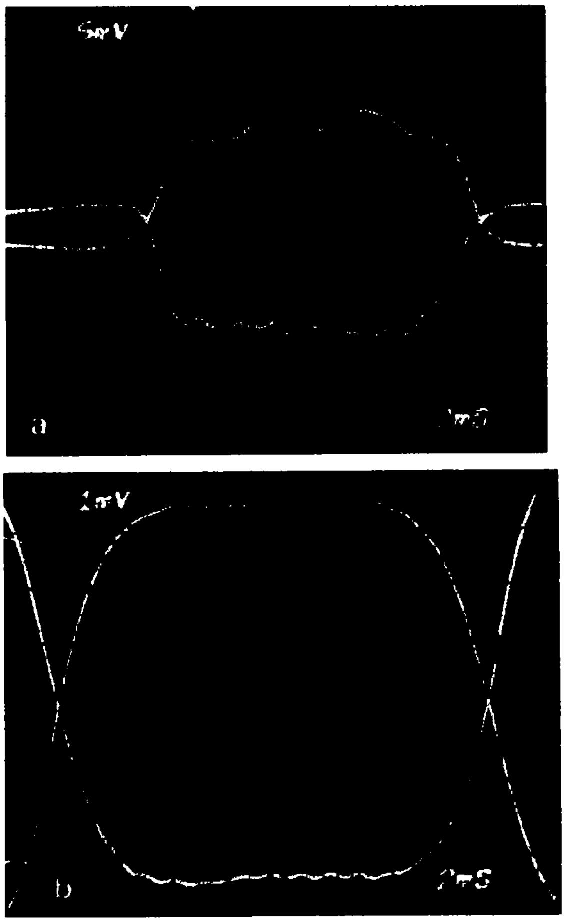


Fig. 2. Speed measurement through the voltage induced across the wire moving in a constant magnetic field.

4. Beam–wire interaction

The wire causes transverse emittance growth due to multiple Coulomb scattering as well as particle loss due to nuclear interactions.

The emittance growth per scan $d\epsilon/dn$ due to Coulomb scattering is given approximately by

$$\frac{1}{\pi}\frac{d\epsilon_{H,V}}{dn} = \frac{2.53\times10^{-4}\beta_{H,V}d^2 f}{P^2 \nu L_{rad}} \text{ rad m/scan},$$

where P is the beam momentum in GeV/c, d is the wire diameter, ν the speed, f the revolution frequency of the beam, $\beta_{H,V}$ the beta value (horizontal or vertical) at the wire location and L_{rad} the radiation length.

During beam storage, $P = 270$ GeV/c, $\beta_{H,V} \simeq 50$ m, $d = 50\times10^{-6}$ m, $f = 44$ kHz, $\nu = 4$ m s^{-1}, $L_{rad} = 0.347$ m (beryllium), then

$$\frac{1}{\pi}\frac{d\epsilon}{dn} = 1.4\times10^{-5} \text{ mm mrad/scan}.$$

This is to be compared with the natural emittance growth due to multiple scattering with the residual gas. With the measured nitrogen equivalent pressure of 2×10^{-10} Torr this is estimated to be of the order of $1.3\times10^{-4}\pi$ mm mrad/h. In fact the measured growth rate in the SPS is an order of magnitude faster than this due to intrabeam scattering [5].

The particle loss per traversal is given by

$$\frac{1}{N}\frac{dN}{dn} = \left(\frac{\pi d}{4}\right)^2 \frac{f}{\nu L_N},$$

Where L_N is the nuclear scattering length. Putting $L_N = 0.3$ m for beryllium gives a loss of about 6×10^{-5} per scan, compared with the measured normal loss rate due to other processes of about 1% per hour. Therefore for a reasonable scan frequency (a few scans per hour) the effect on the beam is small.

For high intensity operation the heating of the wire by the beam becomes important. The temperature rise per scan is given by

$$\Delta T = 3.8\times10^{-18} N \frac{dE}{dx}\frac{f}{\nu h_{eff} S},$$

where N is the number of protons, dE/dx is the energy loss in MeV cm^{-2} g^{-1}, S is the specific heat in cal g^{-1} °C^{-1} and h_{eff} is the effective height of the beam; $h_{eff} = \sqrt{2\pi}\,\sigma$ for a Gaussian beam.

The wire scanner used at high intensity is made from 25 μm carbon filament for which $dE/dx = 1.78$ MeV cm^{-2} g^{-1}, $S = 0.25$ cal g^{-1} °C^{-1} and, at 14 GeV/c, $h_{eff} = 0.015$ m. Then for 3×10^{13} protons and a scan speed of 4 m s^{-1}, $\Delta T = 580$°C. Due to the adiabatic damping of emittance, h_{eff} scales as $\gamma^{-1/2}$, so the use of the wire at such a low speed above about 100 GeV/c is excluded.

5. The scintillator detector

The distribution of high energy secondary particles produced by the interaction of the beam with the wire is strongly peaked in the forward direction. This directivity allows independent measurement of the emittance of proton and antiproton bunches in the collider. After striking the wire the secondaries travel in an enlarged vacuum chamber (fig. 3) for about 3 m after which the chamber profile is sharply reduced to that of the normal magnet chamber (56 mm × 132 mm). In the proton downstream direction, two slabs of scintillator (NE110), each of 140 × 50 × 10 mm^3 are placed above and below the beam pipe, touching the vacuum chamber and allowing secondaries in the angular range 9–25 mrad to be intercepted. Plexiglass light guides from both scintillators feed into a single photomultiplier placed below the beam pipe. The arrangement in the antiproton downstream direction is identical except that the scintillator slabs are larger (400 × 200 × 10 mm^3) to compensate for the lower intensity in the antiproton bunches.

The photomultiplier is a Philips PM 2243/B. This is a 6-stage tube with a trialkali photocathode. The dynode chain was designed for good linearity and high peak current output at the expense of gain. The gain is of the order of 10^4 at 2 kV overall voltage.

In order to keep the system linear over a wide intensity range the tube is always run at maximum voltage (2.5 kV) and if necessary the incoming light is attenuated with neutral density filters placed between the tube and the light guide. The attenuators are mounted on a rotating disc driven by a stepping motor and can be changed remotely.

Fig. 4 shows the raw signal from a single 2 ns long proton bunch of 2×10^{10} particles. An electronic interface allows computer acquisition of the data. A block diagram is shown in fig. 5. It consists basically of a peak-detector circuit followed by an ADC and memory. A clock derived from the revolution frequency train allows successive acquisition from each individual bunch up to a maximum of 6 per beam, with a maximum of 512 acquisitions per bunch. A trigger to start acquisition is derived from a discriminator linked to the potentiometer position. By changing the discriminator voltage the position of the first acquisition with respect to the machine centre line can be fixed. Successive acquisition from each bunch are made each revolution of the machine. Since the wire moves through the beam with constant angular velocity this means that successive distance steps across the beam are not constant. This effect is corrected by software, knowing the angular velocity and the position of the first acquisition with respect to the machine centre line.

The ADC itself has a 10-bit resolution. The attenuator setting is adjusted to give a signal of at least half of full scale in the peak of the profile. This then corre-

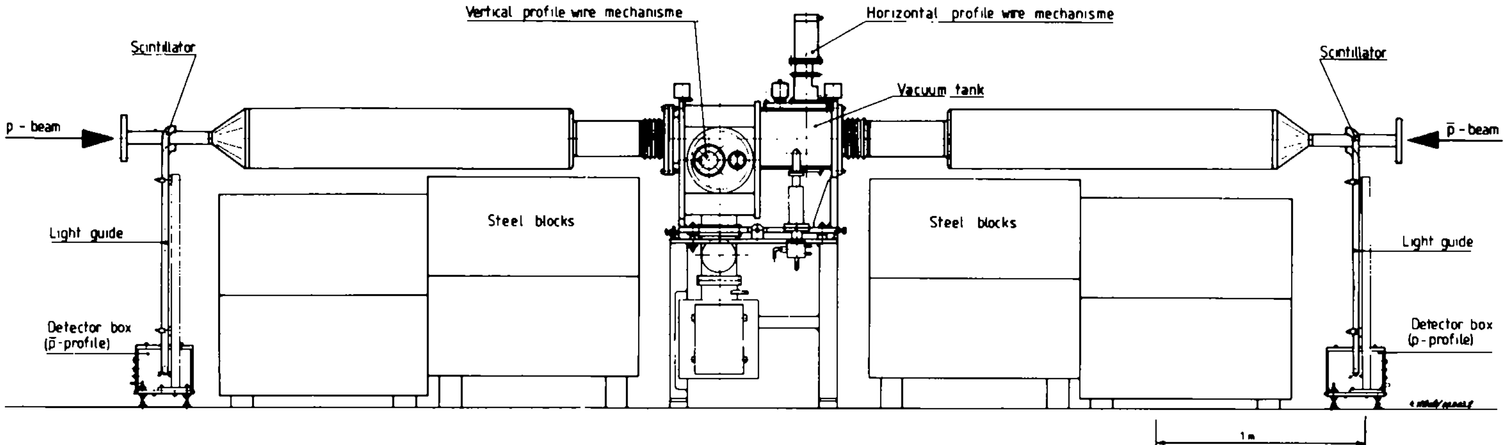
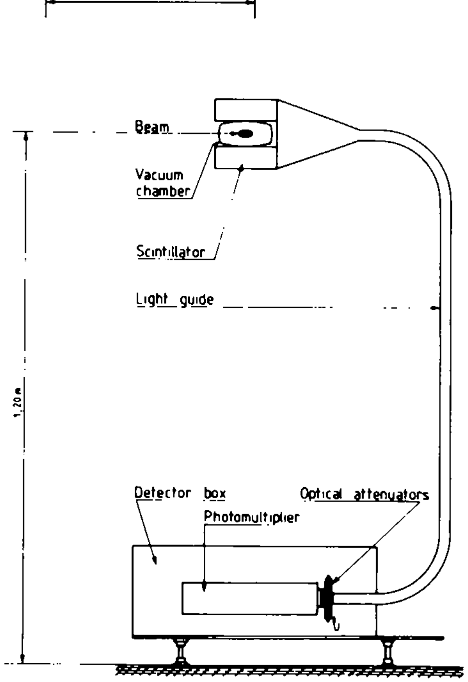


Fig. 3. Schematic layout of scintillators in proton and antiproton directions.



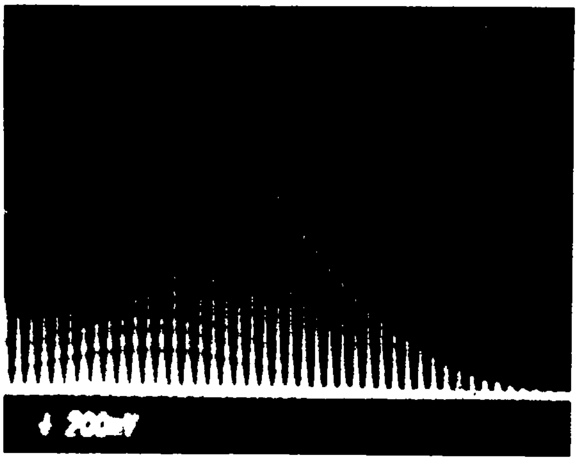


Fig. 4. Raw profile from a single bunch of 2×10^{10} protons.

sponds to about 50 bits at 2σ and allows sufficient precision ($< 1\%$) of profile measurement.

Fig. 6 shows an example of the simultaneous measurement of 3 proton and 3 antiproton bunches. The intensity of each bunch (IP in units of 10^{10}) is displayed together with the measured emittance at 2σ (EM in mm · mrad/π) as well as the normalised emittance (NE $= \epsilon\beta\gamma/\pi$).

6. Charge depletion detector

When the SPS operates as a high intensity proton synchrotron the whole ring is filled and directivity is not required. In this case it is more convenient to measure the transverse profile using the charge depletion current leaving the wire.

The ratio ξ of secondary electrons to incident protons is of the order of 5%. For a Gaussian proton beam with average current I_0 the depletion current I in a wire of diameter d at the centre of the beam distribution is then

$$I = I_0 \frac{d}{\sigma} \xi.$$

For a beam current of 100 mA, corresponding to 1.4×10^{13} protons and a low energy where σ is of the order of 1 cm then the depletion current is of the order of 10 μA for a wire of 20 μm diameter.

The signal is amplified with a preamplifier of 10 kHz bandwidth located in the ring tunnel near to the detector. After transmission to the surface through a long cable it is processed by the same electronics as the photomultiplier signal (fig. 5). However, in this mode the peak detector is used as a track and hold. In addition, the electronics had been modified to allow two scans per machine cycle. This is particularly useful for

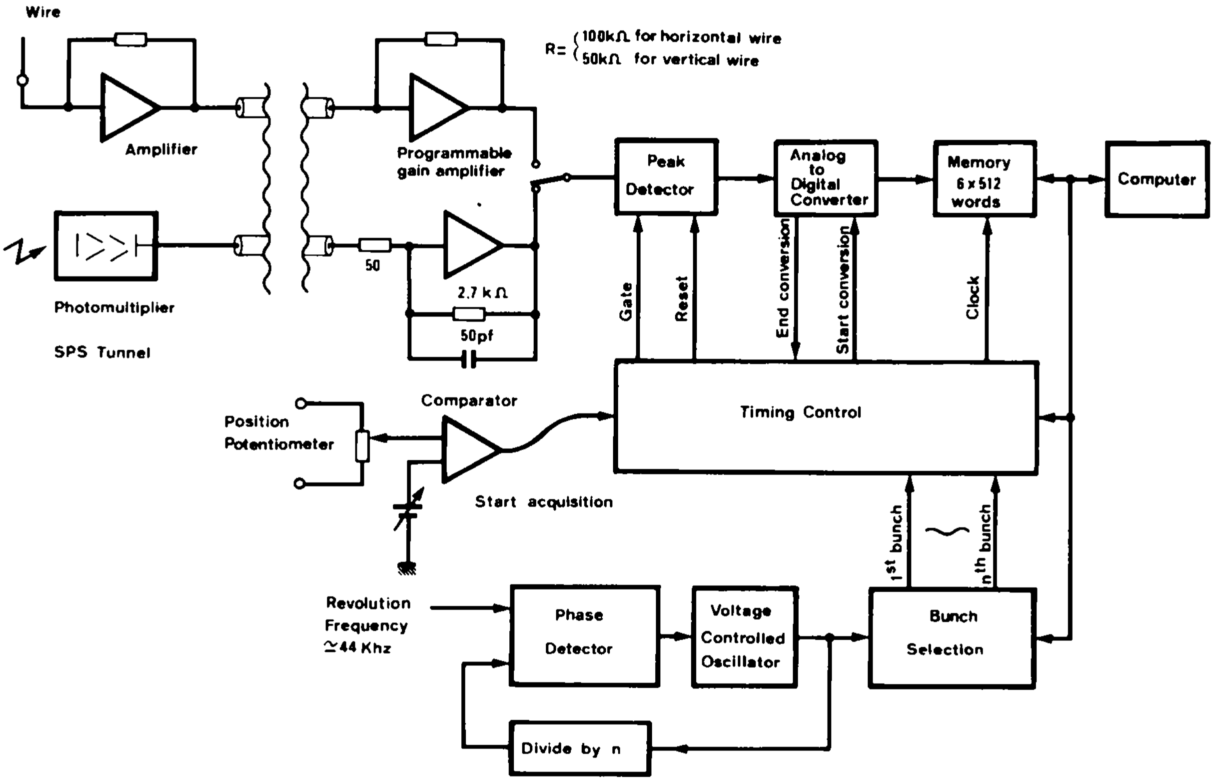


Fig. 5. Block diagram of interface electronics.

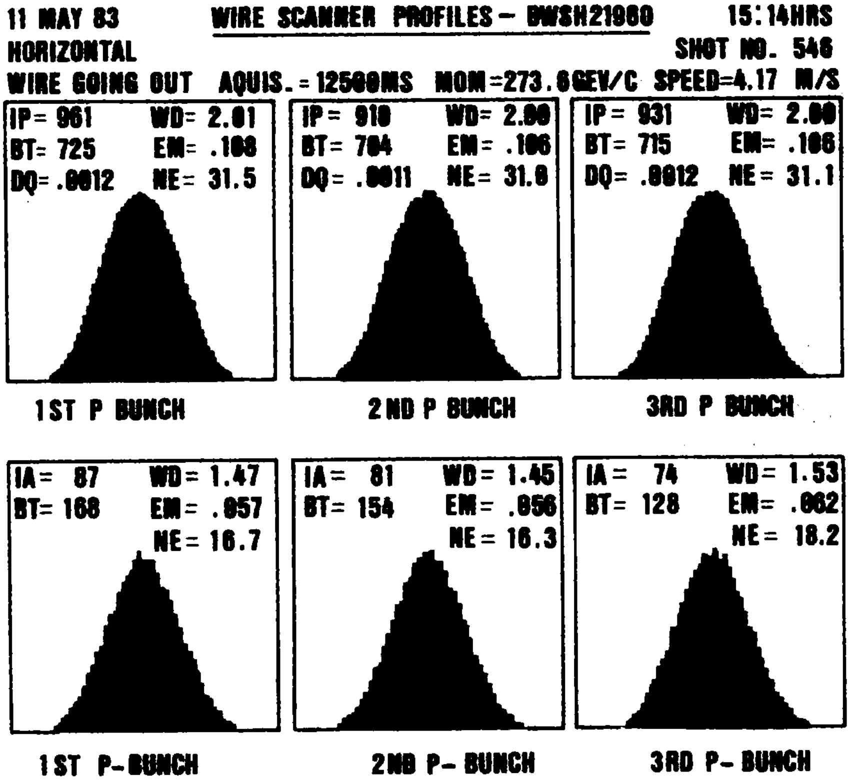


Fig. 6. Simultaneous measurement of 3 proton (upper) and 3 antiprotons (lower) bunch profiles.

investigating sources of emittance blowup due to instabilities or nonlinear resonances. Fig. 7 shows a typical emittance measurement at 14 GeV/c using this method.

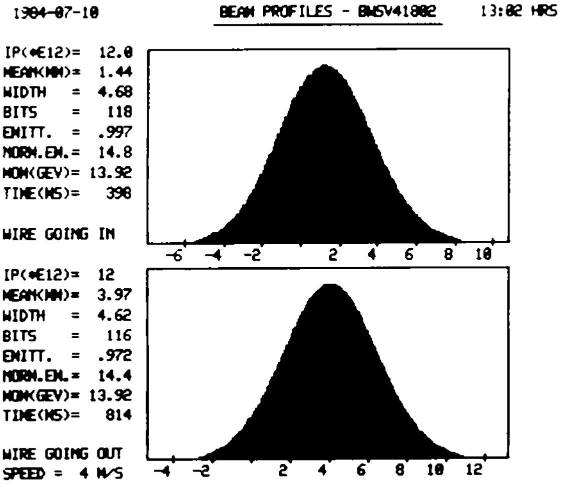


Fig. 7. Vertical profile measurement of a high intensity beam (1.2×10^{13}) at 13.92 GeV/c using the charge depletion current. The two profiles were taken at separate times (398 and 814 ms) after injection with the wire sweeping across the beam in different directions.

7. Conclusion

The rapid beam wire scanner is a useful tool for precise, almost non-interacting transverse emittance measurements. In the case of ppbar collider mode, the "photomultiplier" method, owing to the high directivity is almost always used. In the case of intense continuous proton beam the "depletion current" method is commonly used. Due to the heating of the wire by the beam, its use is limited to the low energy region (<100 GeV/c).

Presently, at the SPS, four of these detectors are used at different locations for different purposes such as luminosity or low-β measurements.

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