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AN IN-VACUUM WALL CURRENT MONITOR AND LOW COST SIGNAL SAMPLING SYSTEM

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ABSTRACT

The beam bunches extracted from the TRIUMF cyclotron are usually about 4 ns long, contain ~ 4×10^7 protons, and are spaced at 43 ns. A wall current monitor capable of giving the charge distribution within a bunch, on a bunch by bunch basis, has recently been installed together with a sampling system for routine display in the control room. The wall current monitor is enclosed in a vacuum vessel and no ceramic spacer is required. This enhances the response to high frequencies; ferrite rings extend the low frequency response. Bench measurements show a flat response between a few hundred kilohertz and 4.6 GHz. For a permanent display in the control room the oscilloscope will be replaced by a Stanford Research Systems fast sampler module, a scanner module, and an interface module made at TRIUMF. The time to acquire one 10 ns distribution encompassing the beam bunch is 30 ms with a sample width of 100 ps and an average sample spacing of 13 ps. The scan, sample, and retrace signals are buffered and carried on 70 m differential lines to the control room. An analog scope in XYZ mode provides a real time display. Signal averaging can be performed by using a digital oscilloscope in YT mode.

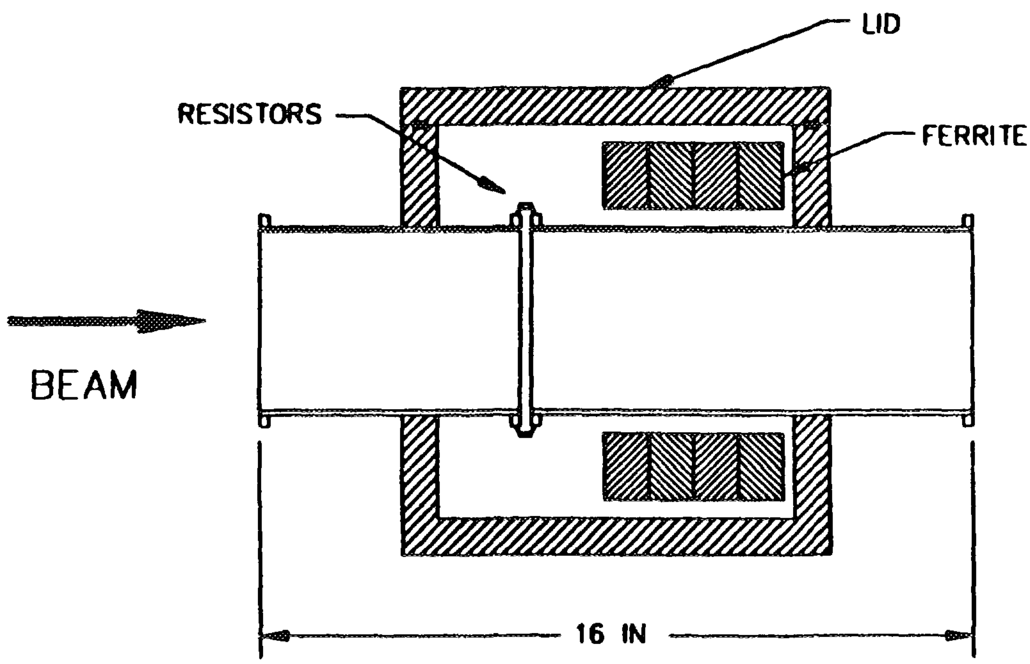

Figure 1. The wall current monitor is constructed inside a vacuum box and no ceramic is required in the gap.

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INTRODUCTION

The beam bunches from the TRIUMF cyclotron, when operating in the high current mode, are about 4 ns (FWHM) long repeated every 43 ns. Routine operation is at 140 μA, equivalent to 3.8×10^7 protons per bunch. The bunches are flat topped so that the peak current is about 1.4 mA. The charge distribution along a bunch has, in the past, been measured by introducing into the beamline a thin target which scatters protons or reaction products into a detector. Their arrival is timed with respect to a pulse train derived from either the cyclotron rf or (better) picked up from the bunches in the beam line. The instrumental resolution obtained varies from 0.1 to 0.5 ns depending on the detector and geometry. It takes some time (seconds or minutes) to acquire the data. This is inconveniently long for on line tuning; also drift or jitter in the cyclotron parameters during acquisition can broaden, or blur, the spectrum acquired, especially at high energies. In addition, insertion of a target may interfere with the experimental program. We wished, therefore, to develop a non-intercepting broadband monitor for the high current beamline which would represent the longitudinal distribution with better than 10 % accuracy at peak currents of 1 mA. A wall current, or gap, monitor was chosen [1].

ENVIRONMENT

The device would be in a low beam loss region of a high current beam line and thus the inner diameter should not be less than that of the 10 cm (4 in) beam pipe. The EMI noise level for monitors near the proposed location is ≤ 0.1 mV; the 23 MHz cyclotron rf contributing 25 μV.

The beam line vacuum in this location is only 10^{-5} torr being compromised by meson production targets and secondary particle channels a few metres downstream. This allowed us to contemplate having all material (ferrite, resistors etc.) in vacuum and avoid filling the gap with insulating material whose permittivity would increase the capacitance. We could then construct a prototype device inside a standard TRIUMF diagnostic box which is a cube with side 10 in.

BASIC PARAMETERS AND MECHANICAL CONSTRUCTION

The beam distribution at high currents has a rise and fall time of less than 1 ns. Slits have been used within the cyclotron to trim the longitudinal phase space producing a triangular distribution with FWHM 0.15 ns measured at 200 MeV [2]. A gap monitor would require a bandwidth extending to 5 GHz in order to reproduce a bunch rise time of 0.15 ns with an accuracy of 10 %.

The monitor actually measures the wall current or image charge distribution on the pipe. This imposes a limit to the resolution. The rms width of the bell-shaped image produced by a point charge at rest in the centre of a pipe of radius r is $\sigma = r/\sqrt{2}$ [3]. This is foreshortened for relativistic beams, velocity βc, to $r/\gamma\sqrt{2}$. The duration of the current pulse at the gap from a single charge would be $r\sqrt{2}/\gamma\beta c = 0.20$ ns at 500 MeV and 0.34 ns at 200 MeV.

There are few beam physics effects below the ion rotation frequency of 4.6 MHz, however a bandwidth extending to lower frequencies may enable other phenomena to be observerd, e.g. ion source plasma fluctuations.

A lumped circuit approach was used to obtain initial parameters. The resistance should be ≥ 1 Ω in order to obtain a beam related signal ten times the noise at 1 mA. A bandwidth of 5 GHz would then imply a capacitance less than 32 pF. A low frequency time constant below 1 MHz would imply an inductance greater than 0.16 μH.

The mechanical construction is shown in figure 1. The 10 cm diameter beam pipe is extended from both entrance and exit to the centre of the diagnostic box and demountable flanges installed [4]. The flanges face each other 1.6 mm apart and have a radial width (h) of 8 mm. They constitute both the capacitor and a rigid frame to which resistors may be attached. The gap when the flanges are demounted is wide enough to enable four ferrite rings to be slid over one of the beam pipe extensions (fig. 1). The box is evacuated through this gap. The pump-down time is estimated to be less than 5 minutes.

The nickel-zinc ferrite rings are each 1 in long, have an inner (r_i) and outer (r_0) diameter of 5 in and 8 in and a permeability μ = 100 at 1 MHz. If it is assumed that there is no space between the inner surface and the beam pipe and that the box walls are close to the outer surface then the total inductance of the four rings may be estimated to be 0.96 μH (eqn. 1) [5], an upper limit in our case.

$$L = \frac{1}{2\pi} \mu \mu_0 \, l \, \ln \frac{r_o}{r_i} \quad (1)$$

The capacitance of the flanges may be first approximated to be 14 pF (eqn. 2).

$$C = \frac{\epsilon_0 \, 2\pi \, r \, h}{t} \quad (2)$$

The presence of resistors and field fringing will increase this in practice.

Webber (ref. 1) points out that this gap may be considered a radial transmission line and if properly terminated by its characteristic impedance, should exhibit no frequency sensitivity. The geometry described gives an impedance of 1.9 Ω. The actual resistance is made up of eighty-four conventional 1/8 W 100 Ω carbon composition resistors distributed around the gap. With these parameters, R = 1.16 Ω, C = 14 pF, L = 0.96 μH, and assuuming a parallel RLC circuit the signal is

$$V = \frac{I}{\sqrt{\frac{1}{R^2} + (\omega C - \frac{1}{\omega L})^2}}$$

and is flat between 3 dB points of ≈ 190 kHz and 9.8 GHz.

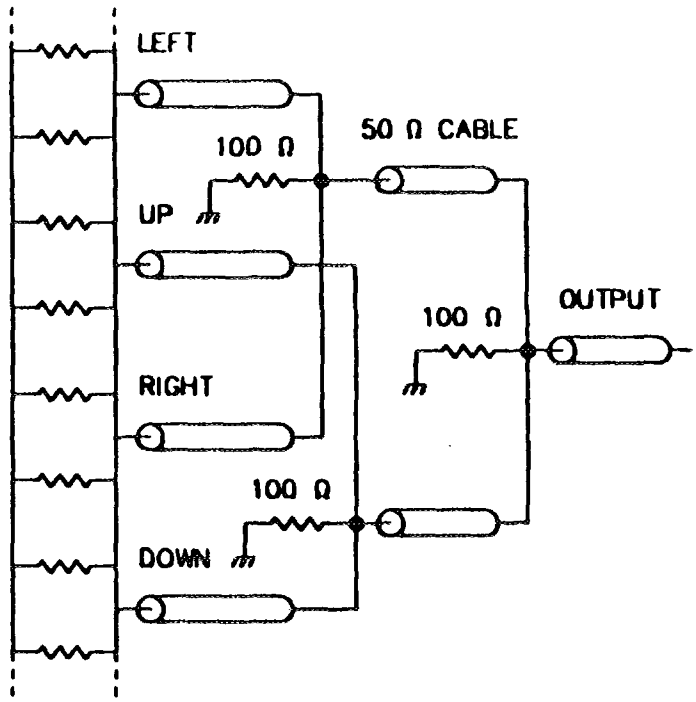

Figure 2. Eighty-four 100 Ω resistors are connected in parallel across the gap. Signals are taken from four places around the circumference and are combined twice in pairs. Shunt 100 Ω resistors at the cable junctions were sized empirically for minimum ringing.

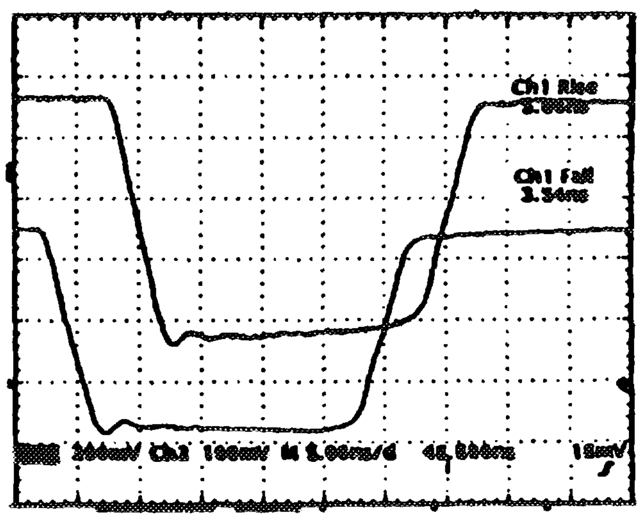

Figure 3. The response of a signal from a single pick-off point (upper trace) to a fast pulse (lower trace). The horizontal scale is 5 ns/div.

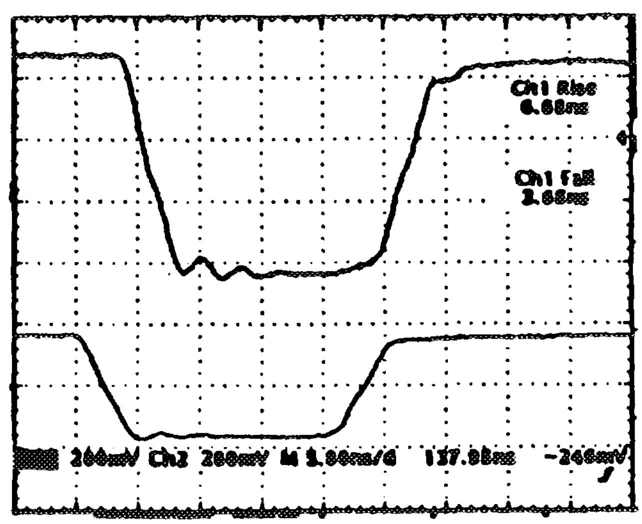

Figure 4. The response of the combined signal from all four pick-off points (upper trace) to a pulse (lower trace). The ringing is more pronounced than that from the single pick-off.

Signals are taken from four places around the circumference to reduce the position sensitivity, figure 2. Semi-rigid coaxial cable carries the signals in pairs to shunt loaded combiners and then to a final combiner. This signal emerges from the vacuum chamber via an SMA feedthrough.

BENCH TESTS

A 2" diameter pipe was passed through the centre of the monitor to form a 50 Ω coaxial structure. Tapered end sections were used to match the pipe to an upstream test signal input and a downstream termination. A network analyzer was used to measure the frequency response from the test input to the gap resistor output. The response was flat to the upper limit of the analyzer, 6 GHz, with the exception of a sharp cavity mode resonance at 4.8 GHz. The responses to fast pulses are shown in figure 3 and 4. The low frequency response was measured by injecting a long pulse and observing the output fall time. The implied low cutoff 3 dB point is 300 kHz.

SIGNAL SAMPLING SYSTEM

A block diagram of the electronics used to process and display the wall current monitor signal is shown in figure 5. The SR255 Fast Sampler module contains a Schottky diode sampling bridge which is gated by a narrow pulse formed by a step recovery diode and a shorted transmission line[6]. The Stanford design enables the gate width to be varied by changing the length of this line. Table I illustrates the trade off in bandwidth and noise for various gate widths. A 100 ps gate width was used for our tests.

Table I. The effect of the Gate Width.

Gate Width (ps)	Bandwidth (GHz)	RMS Noise (μV)
1000	0.359	200
500	0.700	350
200	1.7	600
100	3.5	800

The sampling process in the SR255 is initiated by an external trigger signal locked to the machine rf or beam pulse train. The delay from trigger to sample is controlled by an external analog voltage which is ramped to scan the sampling interval over the beam pulse. The sample is amplified, extended and fed to a gated integrator. The integrator output is held and digitized to 8 bits plus sign. This digital value, along with the gain and gate width, are used to form the address into a look-up table PROM which outputs a linearized sample value. These bits are available externally and they are also converted within the SR255 to an analog voltage output. Overall gains from 0.1 V/V to 1 V/V are available.

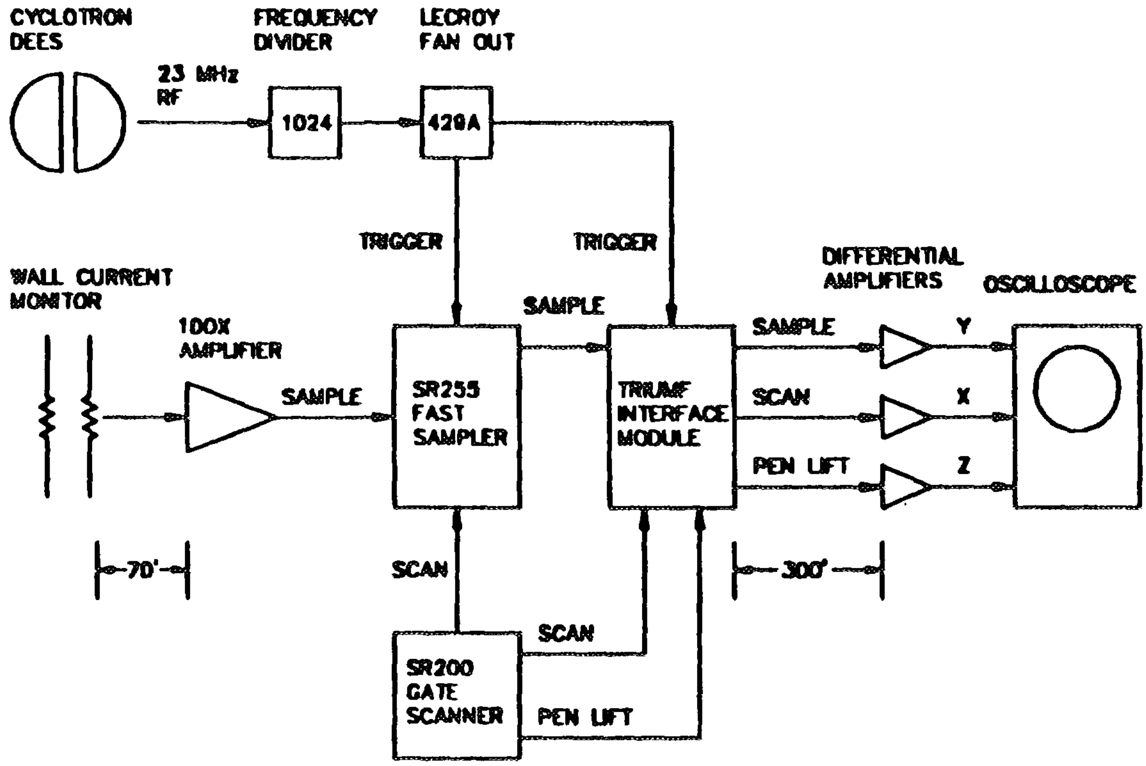

Figure 5. Block diagram of the system.

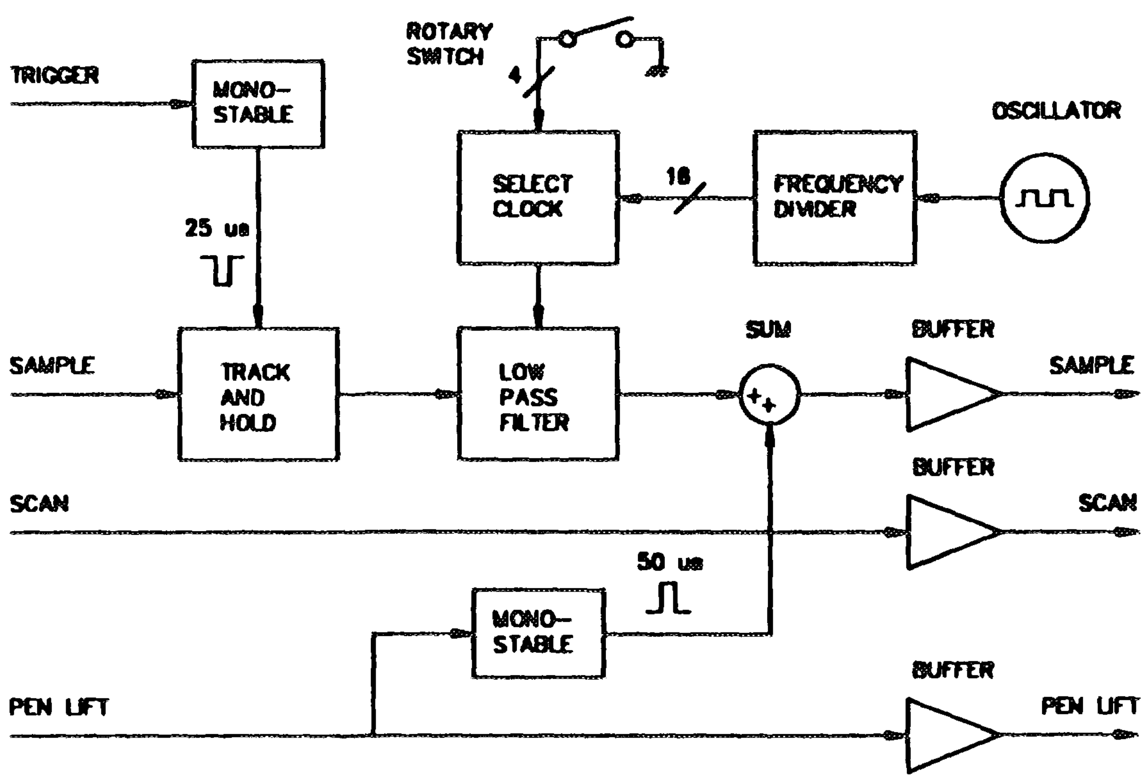

Figure 6. Block diagram of the interface module.

The range of the trigger to sample delay can be varied as shown in table II. For our bunch length, the 10 ns/V range was used.

Table II. The effect of the Delay Base Range.

Delay Base Range (ns/V)	Maximum Repetition Rate (kHz)
1	50
10	30
100	8
1000	1

The SR200 Gate Scanner Module generates a repetitive ramp voltage for scanning the sample interval across the waveform of interest. At the end of the ramp, a "pen lift" signal is generated which can be used to blank the retrace of an oscilloscope when used in XYZ mode. The module is very flexible, but for our tests we used a fixed scan duration of 30 ms to give a display with a fast update rate.

The total cost of the two modules, about $C 5k, is small compared to the cost of a dedicated sampling oscilloscope such as the Tektronix TDS 820, which is about $C 30k. The latter device has a shorter sample interval (50 ps) and dual channel capability, but the Stanford system is sufficient for this dedicated application.

The sample output from the SR255 comes from an ADC and contains glitches formed when the input to the ADC changes. The first stage of the interface module removes these glitches by holding the signal for 25 μs following each trigger, see figure 6. The signal is then filtered by a switched capacitor low pass filter with a cutoff frequency which is adjustable in octave steps from 0.76 Hz to 50 kHz. The scanning range, sample rate, and scan duration can be set so that the sample interval is moved across the bunch in steps small compared to the sample width. The filter is most useful in this case of "over sampling" as it forms a running average over a number of sequential samples, reducing the system noise. If the samples are taken further apart the filter may still be useful, though time resolution is then traded for noise reduction.

The interface module also adds a 50 μs pulse to the sample signal at the beginning of each scan so that an oscilloscope in the YT mode can display and trigger from the same signal. Output buffers are included to allow 124 Ω twinax lines to be driven. The lines are terminated in their characteristic impedance in the control room and the signals passed through differential amplifiers to avoid ground noise. The signal is normally displayed in real time on a low bandwidth analog oscilloscope using an XYZ mode. A digital scope in the YT mode may be used for signal averaging.

BEAM TESTS

The monitor has been installed in the high current beam line. The bunch shape for a 500 MeV, 140 μA tune, as measured by timing particles with respect to a pick up

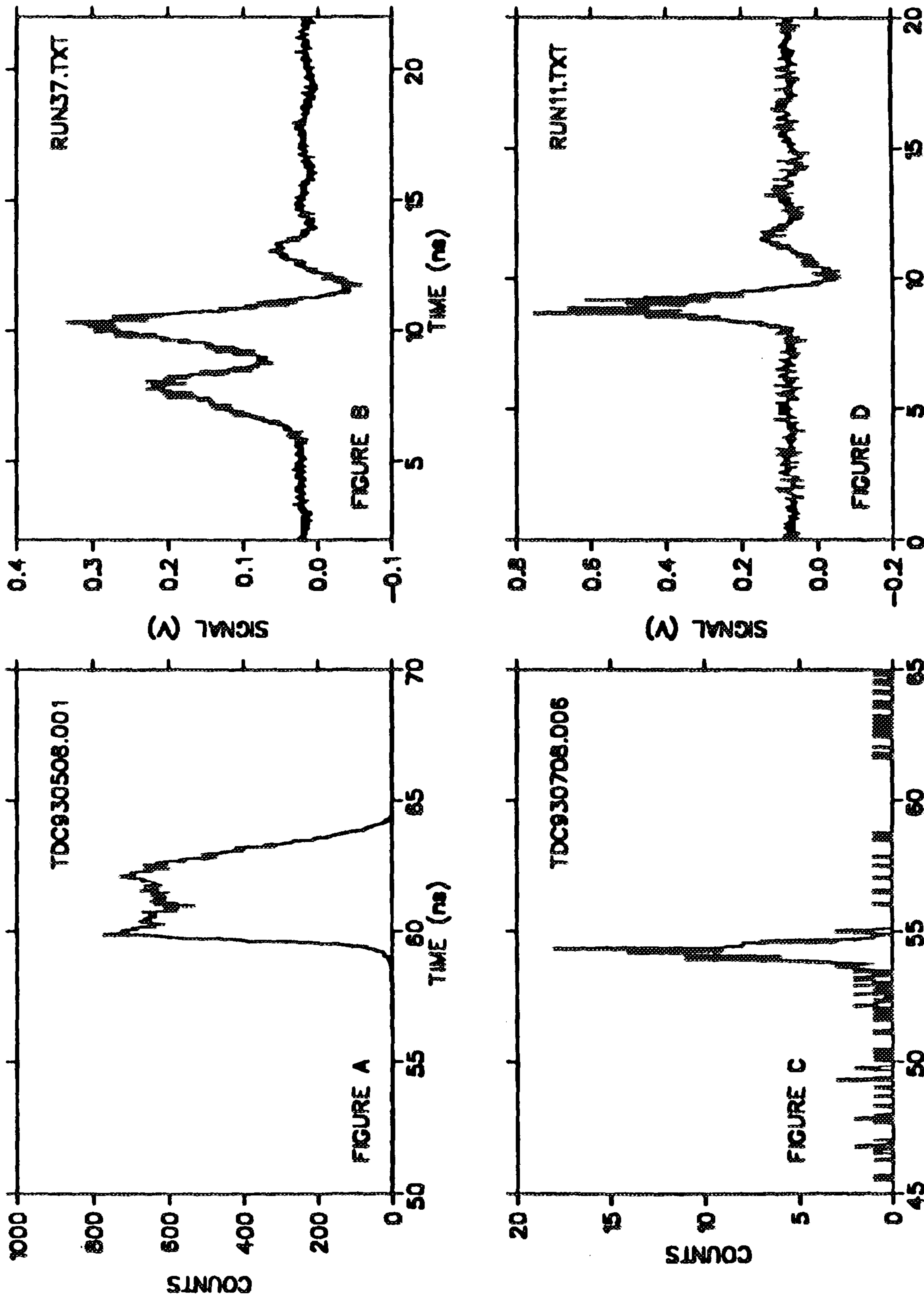

Figure 7. The longitudinal distribution measured using a particle detector system (A, C) compared with the wall current monitor (B, D) for a high current beam (A, B) and a phased trimmed beam (C, D).

with a resolution of 0.5 ns, is usually double peaked. Figure 7 compares the typical bunch shape (A) with that using the wall current monitor (B), though the two measurements were not made on the same day. The depth of the valley using the wall monitor is much deeper. This apparent discrepancy may result from movement of the peaks during the several minutes required to accumulate a particle timing histogram (A).

In our tests, the high frequency bandwidth was limited by a Phillips Scientific 774 pre-amplifier with a gain of 100 and a bandwidth of 2.2 GHz. The noise on the signal has components due to ground noise from the monitor, amplifier and sampler. Most of the monitor noise is low frequency and does not pass through the amplifier. The amplifier and sampler contribute about equally to the noise, equivalent to about 40 μV rms at the monitor.

To test the resolution of the monitor, the beam energy was first reduced to 320 MeV to reduce beam phase jitter due to rf dee vibrations. Slits and flags in the centre of the cyclotron were inserted to reduce the longitudinal acceptance. Figure 7 compares the particle timing (C) and wall monitor (D) measurements at 23 μA CW current. The 0.72 ns FWHM of the bunch in (C) is only slightly smaller than that in (D), 0.98 ns. The wall monitor signal rings for about 7 ns before settling to ground level. The origin of the undershoot and ringing is under investigation. We will also try to damp the cavity mode resonance.

ACKNOWLEDGEMENTS

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