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Low Frequency Processing for PSR Beam Position Monitors

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Introduction

The beam is injected into the Proton Storage Ring (PSR) as a train of sub-nanosecond pulses at the linac frequency of 201.25 MHz. This frequency component is sensed by 20 pairs of 200 MHz stripline beam position monitors and multiplexed to an autocorrelation position processor. The analog position information is sampled, digitized and stored under the control of timing circuits. Beam position histograms from sets of monitors are displayed in the control room. Measurements show that the amplitude of the 200 MHz component is constant during the fill indicating that the strength of the most recently injected beam does not drift during the fill. This structure begins to disappear 20 to 30 turns after a particular batch of beam has been injected. The low frequency components, however, persist and might be used to measure the position of the accumulated beam. We report calculations and experimental results for some low frequency processing systems.

Beam Dynamics and Computer Simulation

The PSR was designed to fill vertical phase space by slowly lowering the position of the synchronous closed orbit during the beam accumulation with sweep magnets. These were not operational at the time of the experiment, consequently the ring accumulated a beam which was hollow in vertical phase space and the beam pick ups saw a charge distribution that, if projected into a vertical plane through the beam pipe center, consists of two bands of relatively high charge density above and below the beam axis separated by a region of relatively low density on the axis. Fig. 1 shows an ACCSIM [1] simulation of the injection distribution.

The period of a synchrotron oscillation is comparable to the accumulation time; $Q_s = \sim 10^{-3}$. Extraction normally occurs immediately after completion of a fill, however, for diagnostics purposes beam may be injected for a short time, eg. 0.1 ms, and stored for times on the order of 1 ms. At any given time the longitudinal phase space is populated by a horizontal band of the most recently injected beam together with the previous bands rotated through a continuous distribution of angles depending on their time of injection, fig. 2. The ring has a dispersion of around 2 m in the vicinity of the beam pick ups. Consequently the mean horizontal position of the beam within the bucket has a strong dependence on phase angle (head to tail displacement). The dependence of mean position on phase within the bucket is strongest for the stored beam example, fig. 3.

We would like an eventual precision of less than 1/2 mm for the position of the projected mean of the particle distribution. The particle ensemble has a mean position, $\hat{x}(\phi)$, with an anti-symmetric or sinusoidal first harmonic component whose amplitude is much larger than the required precision. One is concerned that this large sine like signal, which should average to zero, should not affect the validity of inferring the average beam position from only a low frequency component. While the beam bunch occupies most (250/350) of the circumference in the operational mode, it may be easily shortened for beam dynamics experiments.

P.S.R. Beam Pick Ups Used for the Experiment

SRPM 4.3 The left, right, down and up signals of this 400 MHz stripline lead directly to the control room without intermediate conditioning.

CERN Capacitive Pick Up This monitor [2] consists of a ceramic cylinder with copper and gold plated electrodes on the inner and outer surfaces. The dielectric gives the device a high capacitance per unit length and this lowers the cut off frequency and avoids producing signals of very high voltage. The high capacitance is acceptable in the proton storage ring because of the very intense circulating beams. The pick-up electrodes have a capacitance of 530 picofarads and cables add 120 pF. One megohm input impedance amplifiers situated below the PSR ring take the signals from the left, right, up and down plates and form three signals corresponding to the sum of all the plates and the difference left-right and up-down. Each amplifier produces a positive and negative signal of equal amplitude, both of which are carried individually to the control room where the difference between positive and negative are formed for common mode rejection.

NIM Modules Constructed at TRIUMF (see appendix 2 for block diagrams)

AM/PM Converters

- diplexer bandpass filters select the first harmonic at 2.8 MHz
- a 90 degree phase shift is created in one channel by a bridged "T" all pass filter
- Mini-Circuit splitters and combiners add and subtract the signals vectorially to convert the amplitude information to phase information
- phase = 2 * arctan (A/B)

Limiters and Detector Module

- dual channel limiter amplifiers with a gain of about 400 are used
- allows processing of signals from a few millivolts to hundreds of millivolts as the beam accumulates
- each channel uses three emitter coupled logic chips connected as differential amplifiers
- a linear double balanced phase detector IC consisting of transistor switches is used
- the detector output is low pass filtered to remove the 2.8 MHz and its harmonics
- a DC amplifier boosts the output level

Synchronous Detector Module

- diplexer bandpass filters select the first harmonic at 2.8 MHz
- a reference signal is required to be provided externally to the module
- the reference signal required is 2.8 MHz at +10 dBm
- the phase must be locked to the machine phase and must be adjusted for each monitor position in the ring
- the inputs signals and reference signal are combined in Mini-Circuit high efficiency hot carrier mixers
- the mixer outputs are filtered to remove the 2.8 MHz and its harmonics
- DC coupled amplifiers boost the output signals

Beam Position Circuit

- performs the function 5*(A-E)/(A+B)
- converts the output of the synchronous detector to position
- the amplitude information is normalized out
- the denominator is clamped at low level to prevent the output from saturating before and after beam accumulation
- the DC accuracy is about 2% and the bandwidth about 400 KHz

Experimental Program

The experimental program had two aims. The first was to commission the electronic modules in situ and to confirm their design characteristics. The second was to compare different modes of operation of the PSR and its equipment to see whether processing only the low frequency component of the beam pick up signals gives a reliable measure of beam behaviour during accumulation of the entire ensemble of particles.

Experimental Results

Sensitivity

Sensitivity was measured by displacing the closed orbit at the pick ups and assuming that the displacement of the accumulated beam was the same as that measured by the 200 MHz striplines, ie. that of the most recently injected beam. The following table shows the sensitivities at the end of a 30 uA fill. Details of the calculations are given in appendix 1.

Pick Up	Processor	Sensitivity	
		Measured	Expected
SRPM 4.3 stripline	AM/PM	3.45	2.53
SRPM 4.3 stripline	Synchronous	6.45	4.93
CERN capacitive	Synchronous	11.5	11.6

Stripline Data

Raw data from the SRPM 4.3 stripline was digitized to 10 bits resolution with 5 ns between samples [3]. A complete set of data was taken for one of the four electrodes and then the digitizer was assigned to another electrode. Consequently, we do not have data for all the electrodes at the same instant of time, although the machine's condition was fairly stable, being regular operation at 30 microamps. The 64 K digitizer did not permit accumulation right to the end of the fill time with this 5 nanosecond resolution. The 5 nanosecond data acquisition interval means that reliable information was obtained only at frequencies of less than or equal to 100 MHz (Nyquist Theorem). The digitized data for the right plate is shown in figure 4.

The output of the 400 MHz stripline is the difference between the beam signal at some point in time minus that signal 1.25 nanoseconds earlier: in other words, a strongly differentiated output. The original beam intensity I(t) or line density was restored by integrating this signal digitally. The intensity, in absence of significant loss, would be expected to increase by 358 ns/t_{acc} each turn during the fill. Over a short period of time it will be relatively constant. One may notice, however, that the integrated shape varies on alternate turns. There is also some long-term, with respect to the revolution time, base line drift. These effects were removed by a manual straight line subtraction over the period of a few turns. A second digital integration gives the total charge induced on the plate. This rises stepwise between turns as the beam accumulates. The jitter in the difference between steps of the doubly integrated signal gives a measure of the precision of this process. An example of the stages of this integration procedure is shown in figure 5.

This offline procedure to find the total charge induced on the electrode per turn is a wideband technique, utilizing all frequency components of the beam from about 1 MHz to 100 MHz. In order to obtain beam position, the difference over sum of charge per turn was calculated and is shown in figure 6. The results are consistent with no stored beam position drift during the accumulation.

Next, the amplitude of the 2.8 MHz component only was used to calculate the difference over sum, in fig. 7. This is a narrowband technique and the results agree with the wideband technique to within about 1/2 mm.

A Fourier analysis of the raw data, fig. 8, revealed unexpected frequency components at less than 2.8 MHz. The data was integrated and a running average over 288 samples subtracted. The time between peaks was plotted in figure 9 and shows beating with the subharmonics, greatest early in the accumulation. The running mean width of 288 channels was chosen to average two cycles of the odd-turn, even-turn effect.

The AM/PM electronic processor system was used with SRPM 4.3 to yield real-time position measurement. The horizontal position and intensity signals from the electronic modules with the buncher on are shown in figure 10. The intensity signal does not rise linearily during the accumulation as it has been filtered to pass only the 2.8 MHz component. The 400 KHz bandwidth of the electronic modules is equivalent to a response time of constant of 1 microsecond, i.e. several turns. Some 5.6 MHz generated by the phase detector remains in the position signal due to incomplete filtering. The position signal does not become accurate until about 50 us into the accumulation due to lack of signal. This may be improved substantially by the use of preamps or by using more modern limiter amplifiers. The horizontal position signal indicates less than 0.25 mm drift during accumulation. Appendix 3 is an analysis of the error caused by the head to tail displacemnt.

CERN Capacitive Pick-up

The difference and sum signals were recorded simultaneously using a LeCroy 9400 digital oscilloscope and screen dumps were made to a plotter. The plots were redigitized at TRIUMF using a Hewlett Packard optical page scanner, fig. 11. Off-line wideband processing was accomplished by dividing the difference signal by the sum signal on a sample by sample basis, i.e. as a function of longitudinal phase. An arbitrary threshold of 10 mV was set on the sum below which the dividend was set to zero. Off-line narrowband processing utilized a Fourier analysis to obtain the amplitude of the 2.8 MHz component.

Data were taken 5 times during the accumulation of a centered beam with the buncher off. The off-line processing was repeated with the wideband result shown in figure 12 and the narrowband result shown in figure 13. The two techniques agree in absolute position and indicate no stored beam position drift during accumulation. Data taken with buncher on were digitized [4] and the two off-line procedures applied, figs. 14 and 15 .

The off-line wideband processing technique used on the CERN monitor data gave equal emphasis to the position of the beam at the low intensity phases of the bunch as well as the peak of the bunch intensity. The mean of the difference signal should be the projected mean of the entire ensemble of particles. An improved off-line technique might divide the mean of the difference signal over several turns by that of the sum.

The synchronous detector system was used with the CERN monitor to obtain <u>real-time</u> position measurement. The BPU signal is mixed with a cosine wave phase locked to the buncher frequency of 2.795 MHz. This produces a quasi dc output. The phase of the reference signal was adjusted to maximize the strength of the output from the sum channel at the same point during accumulation, usually the end of accumulation. Note that the prior conditioning of the CERN signals within the PSR tunnel prevented the use of the AM/PM processor as implemented and only the synchronous processor was used with this monitor.

The vertical position signal and an intensity signal are shown in figures 16 and 17 for buncher off and on. The position drift from 100 to 370 us is equivalent to less than 1 mm and may be due to electronic processing errors. Figure 18 shows the horizontal position signal from the synchronous detector system (divided by 5) for 3 values of beam bump. The position drift from 100 us to 370 us is equivalent to about 2.5 mm. The apparent position drift during accumulation may have been due to electronic processing errors. The synchronous detector system was designed to use a pair of signals of similar amplitude and phase. The CERN monitor signals, however, were available only as a difference and sum. Figure 19 shows that for a well centered beam the sum signal may be 30 times greater than the difference signal. In this case, electronic errors due to dc offsets and compression do not cancel out as they would for more balanced signals. Figure 20 shows a phase difference between the diffence and sum signals which varies through the accumulation. A small phase difference between two signals of similar amplitude results in a large phase angle when they are subtracted. Systems using the plate signals directly may be less sensitive to this type of error. The off-line narrowband processing of the horizontal signals (figure 13) did not show any position drift.

<u>Conclusions</u>

<u>Principles</u>

- The existing striplines, though designed for maximum signal pick up at 200 MHz, provide sufficient signal at 2.8 MHz for processing at 50 us (150 turns) or earlier from the start of accumulation.
- The off-line wideband and narrowband processing techniques gave no indication of stored beam position drift during accumulation. The small drifts in horizontal position seen in the module outputs can be explained by imperfect processing schemes and electronic error.
- Off-line wideband and first harmonic processing techniques gave the same absolute beam position within 1/2 mm.
- Wideband processing of the stripline signals is possible, but difficult due to sensitivity to baseline error. The restored baseline zero alternates from turn to turn and has long term drift.
- The striplines, or other high frequency devices, may not be the ideal general purpose position detector for a low frequency machine such as the PSR. The output signal has extended portions close to zero at the time when the intensity is at a peak. The maximum output occurs at the end of the bunch where the line density is falling or rising. They may be very useful devices for beam dynamics studies.
- There may be an artifact or a real beam phenomenon which alters the position distribution of a portion of the beam at a sub-harmonic of the rotation frequency.
- Operational requirements may differ from beam dynamics. The former are probably more concerned with beam loss and may prefer an indicator proportional to the mean difference signal over a bunch. This is automatically weighted by beam intensity. Beam dynamics may prefer a signal normalized by $I(\phi)$ which gives equal weight to all phase intervals in a bunch, no matter what their charge population. Processing at the first harmonic gives a signal proportional to the former.

Technical

- It was possible to calibrate both narrowband electronic systems against the 200 MHz BPM system by using programmed beam bumps.
- The AM/PM system seems to have an accuracy of better than 1 mm, though the tests done were insufficient to have confidence in this figure.
- The synchronous detector system was accurate to only 2 mm in the horizontal plane. The system was designed to operate with input signals of similar amplitude and phase. While the quasi dc Beam Position Circuit has good resolution, the rf (mixer) section does not. Hence any further work with difference signals pre-formed in the PSR tunnel should at least use an rf amplifier to boost their amplitude to a value similar to the sum signal. Preferably, the raw signals could be brought out.
- A capacitor should be provided at the input to block the approximately 500 microamp dc current from the CERN monitor. This is thought to arise from stray charge in the beam pipe.
- There is some evidence that the broadband CERN monitor system still differentiates fast signals.
- The electrical center of some of the devices (SRPM 4.3 and CERN monitor) may be off center by 1 or 2 mm. The center being defined by the usual machine tune and the 200 MHz striplines.
- A button should be provided in the control room to momentarily reverse left and right or up and down input signals in order to check display zero.

Future Experiments

- Repeat an abortive experiment which compared the position of coasting beams and bunched beams of various phase widths.
- Amplify pre-formed difference signals to improve signal to noise or use raw signals.
- Endeavor to observe the loss (beam intercepted) signal from the adjustable scrapers as a function of phase. A Cerenkov monitor should give the required resolution and be less affected by background particles.
- Digitize the SRPM 4.3 signals again, using interleaved sampling of each pair of striplines so that phase dependent effects can be studied further.
- Investigate the 2.8 MHz signals early in the accumulation process in order to determine the point in the accumulation at which signal/noise yields an accurate position measurement.

References

[1] ACCSIM: A Synchrotron Tracking Program for Simulating Injected and Accumulated Beams, TRI-DN-87-20, Fred Jones, TRIUMF
[2] Private communication, G. Gelato, CERN
[3] Data acquired by George Swain, LAMPF
[4] Data acquired by Mike Plum, LAMPF

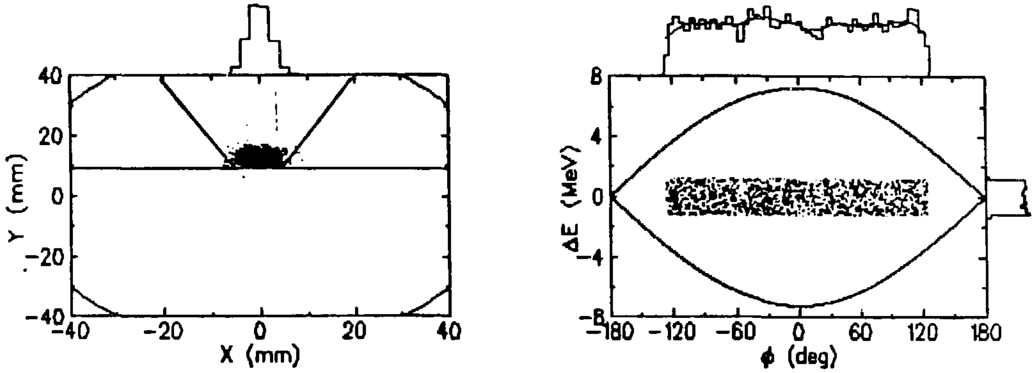


Fig. 1. The injection distribution assumed for the ACCSIM simulation.

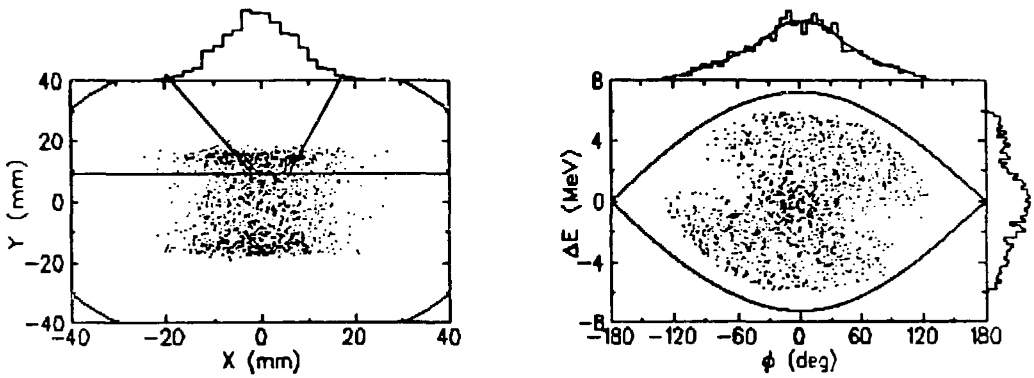


Fig. 2. The beam distribution in the PSR 300 us after the start of accumulation. Note the two bands in the projected X-Y real space and that, while the projected intensity distribution is symmetric about ø=0, the distribution in energy is not.

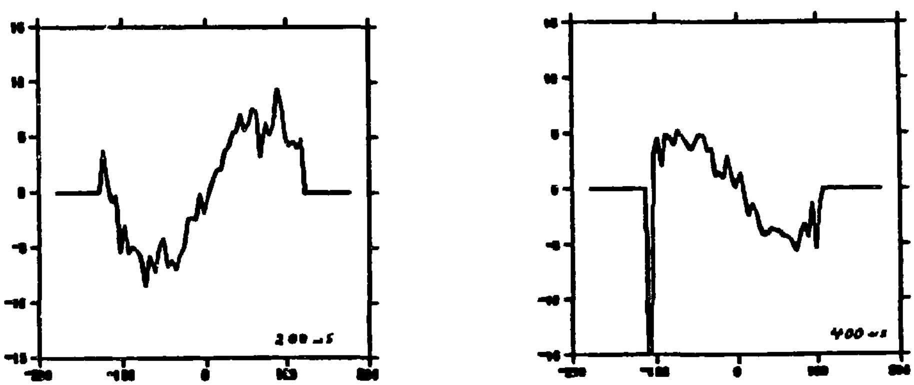


Fig. 3. The mean horizontal position of the beam (mm) as a function of ø (deg.) at 200 us and 400 us after the start of accumulation for a beam accumulated between 0 and 100 us, (ACCSIM simulation).

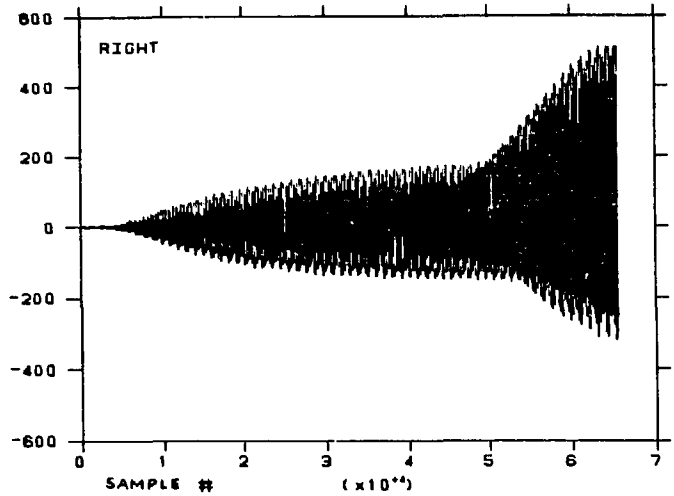


Fig 4. The raw signal from the right stripline of SRPM 4.3 digitized as 64K samples 5 ns apart with 10 bit resolution.

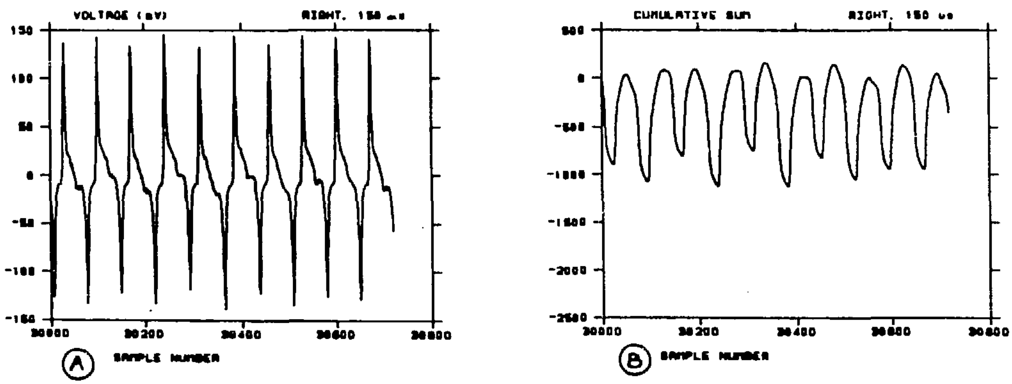
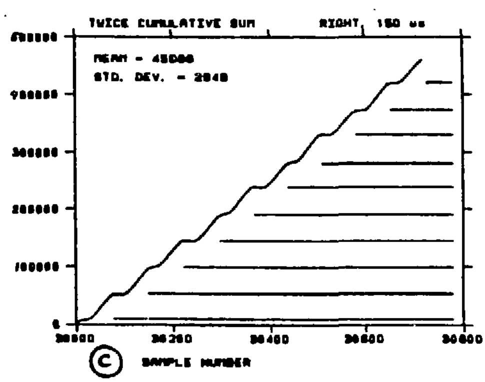


Fig. 5. Three stages in the off-line wideband processing method.

a) The digitized signal from the stripline at 150 us into the accumulation. Data is shown for ten turns.

b) The integral of a). The "baseline" is at ~ -1000, the bunch length is 3 times wider than the kicker gap.

c) The integral of b). The steps correspond to the total charge induced on the stripline each turn.



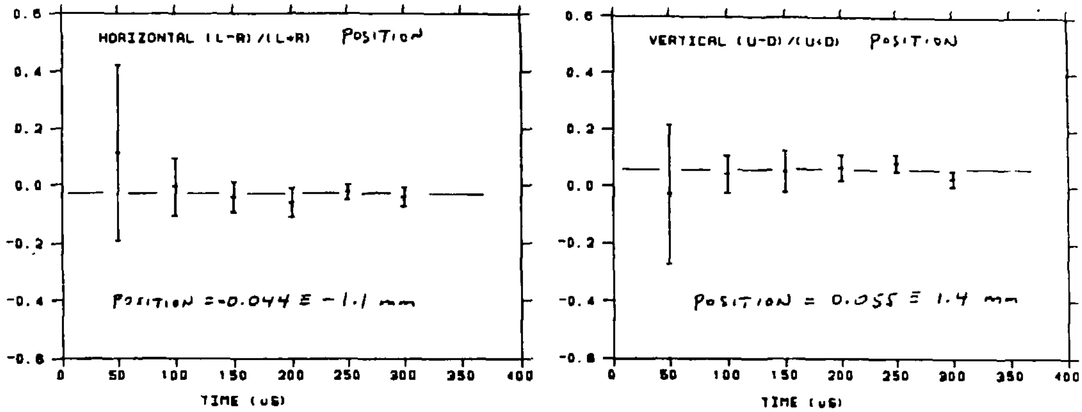


Fig. 6. The results of applying the off-line wideband processing of the stripline data at 6 times during the accumulation, where beam displacement = 49.3 / 2 mm * diff / sum. The technique is subject to large errors due to the variation in the computed beam off voltage from cycle to cycle.

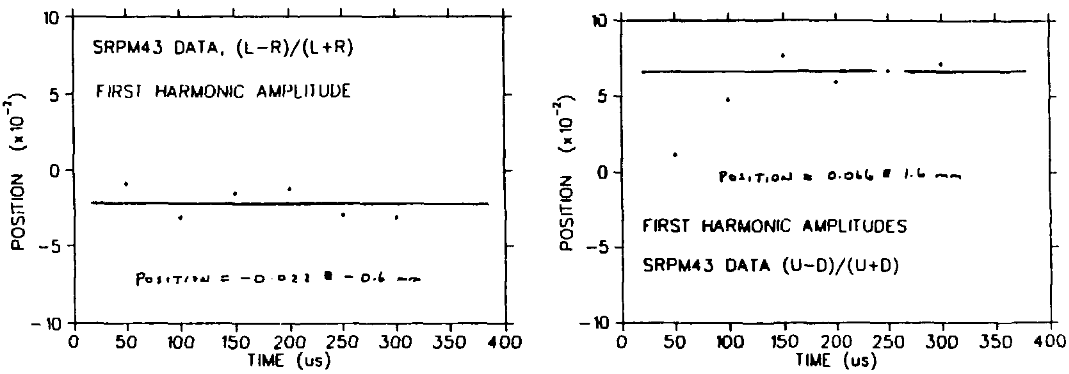


Fig. 7. The stripline signals were Fourier analyzed at 6 times during the accumulation and the diff / sum of the amplitudes of the 2.8 MHz component formed (narrow band processing). Since the four stripline signals were digitized several minutes apart, intensity drift may have affected the measurements.

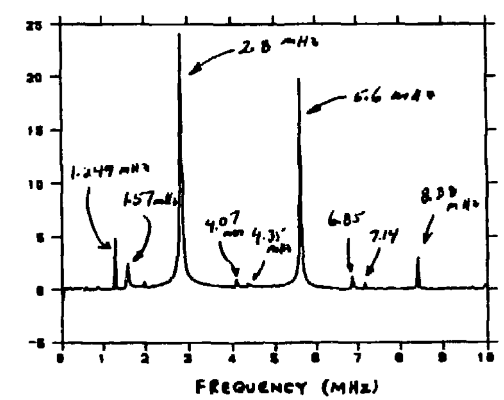


Fig. 8. Fourier analysis of the raw signal from the SRPM 4.3 left stripline at 100 us into the accumulation (7200 samples 5 ns apart beginning at sample 20,000). The subharmonics imply Q_X = integer + 0.46 or integer + 0.56 beating with the rotation frequency.

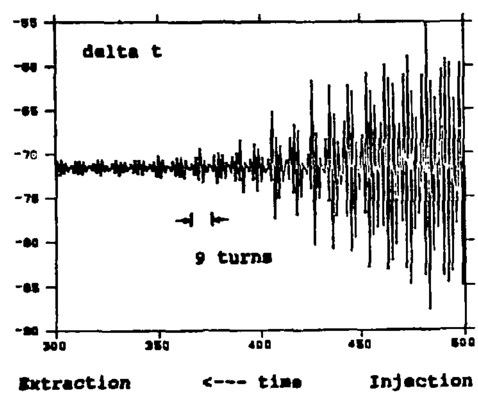


Fig. 9. The position of a portion of beam varies as a subharmonic of the rotation frequency. Delta t is the time difference (in 5 ns bins) between succesive peaks.

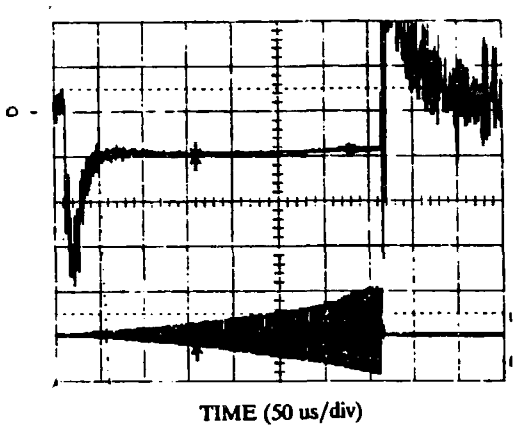


Fig. 10. The SRPM 4.3 stripline horizontal signals processed by the AM/PM electronic system. The upper trace is the position output (0.5 V/div) with a sensitivity of 3.45 mm/V. The baseline of the upper trace is two divisions from the top of the screen. The processor does not measure accurately until 50 us into the accumulation. The lower trace (50 mV/div) is the filtered 2.8 MHz component of the right stripline signal from a test point (-5 dB). The machine tune was for normal operation (buncher on) at ~ 9.5 uA.

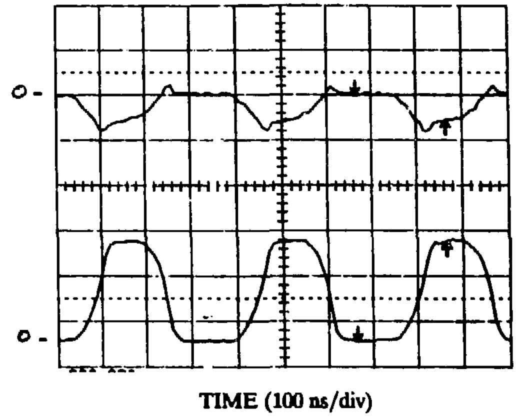


Fig. 11. The CERN monitor signals at 300 us after the start of continuous injection, with buncher off. The upper trace is the horizontal difference signal (5 mV/div) over three turns. The baseline of the difference signal is two divisions from the top of the screen. The lower trace is the sum signal (50 mV/div) with a baseline about 1/2 division from the bottom of the screen. The unnormalized position signal drifts about 1.5 mV along the bunch.

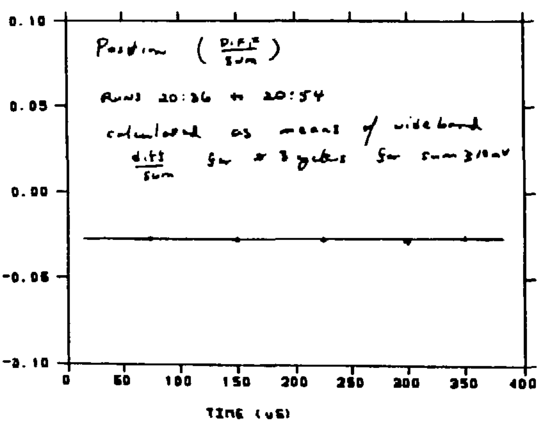


Fig. 12. The off-line wideband processing method applied to the CERN monitor horizontal signals with buncher off. No horizontal beam position drift is indicated.

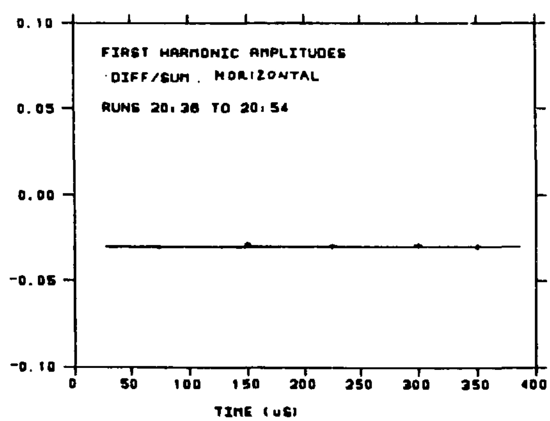


Fig.13. The off-line narrowband processing method applied to the same signals used for the previous figure.

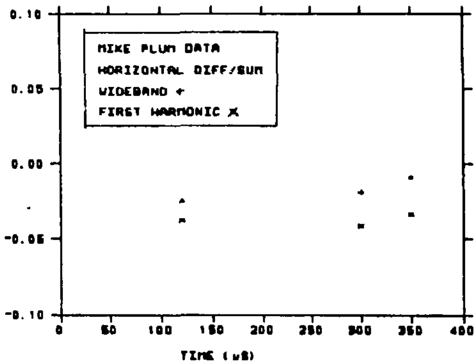


Fig. 14. The two off-line processing methods applied to the CERN monitor horizontal signals with buncher on. The two methods yield positions which differ by about 0.5 mm.

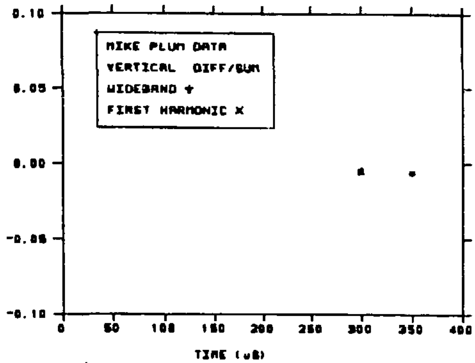
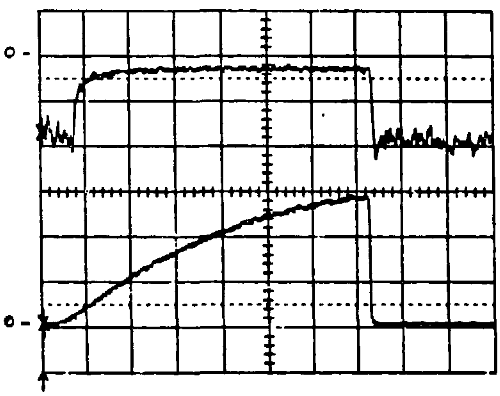
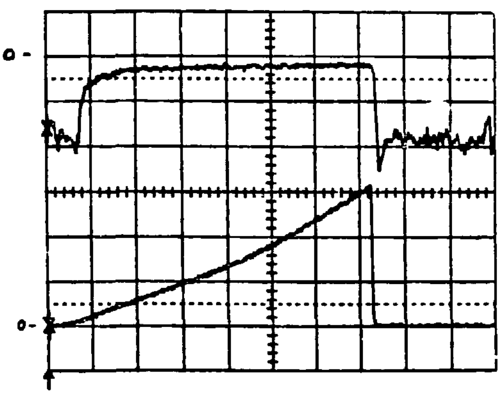


Fig. 15. Same as the previous figure, but applied to the vertical signals. The two methods yield the same results.



TIME (50 us/div)

Fig. 16. The synchronous detection electronic processor with the CERN monitor vertical signals, buncher off. The upper trace is the position output (0.5 V/div) with a sensitivity of 11.5 mm/V. The baseline is one division from the top of the screen. The lower trace is the intensity output from the processor (0.1 V/div) and is proportional to the amplitude of the 2.8 MHz component. The baseline is about 1.1 divisions from the bottom of the screen.



TIME (50 us/div)

Fig. 17. Same as the previous figure, except for buncher on (long bunch mode ~ 150 ns).

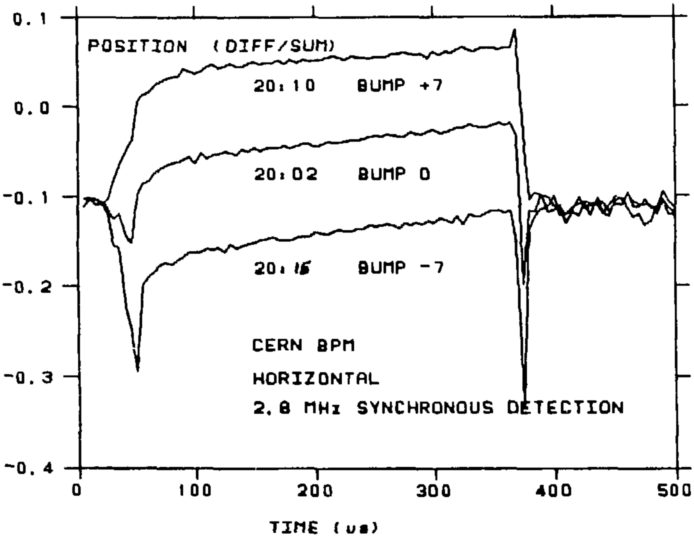


Fig. 18. The horizontal position output of the synchronous detector sytem using the CERN montor, buncher off. The vertical scale is the output voltage divided by 5 giving a sensitivity of 57.5 mm/ V. Three runs are shown superimposed. The beam position was shifted between runs by using a set of 4 steering magnets to create a beam "bump".

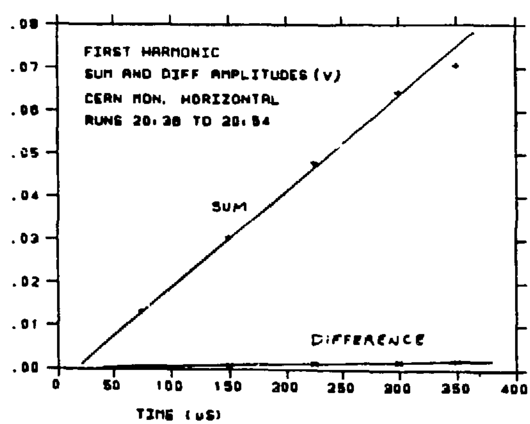


Fig. 19. The amplitude of the 2.8 MHz component is much greater than that of the difference for a well centered beam. Preamplification of the diffference signal would allow more accurate processing.

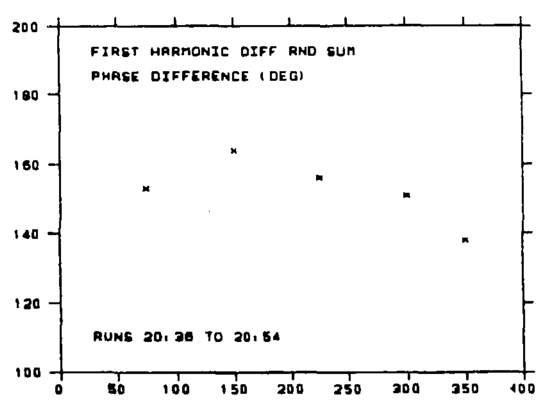


Fig. 20. The phase relation between the 2.8 MHz component difference and sum signals varies during the accumulation.

Appendix 1 Sensitivity Calculations

1) Synchronous Detector System with Stripline Monitor

```
                                          A,B
beam --> monitor --> mixers --------> 5 * divider --> V
```

x = beam position
r = electrode radius = 49.3 mm
A,B,V are voltages

$$V = 5\,\frac{A-B}{A+B} = 5\,\frac{(1+2\,x/r) - (1-2\,x/r)}{(1+2\,x/r) + (1-2\,x/r)} = 10\,\frac{X}{r}$$

$$\frac{X}{V} = 4.93 \text{ mm/volt}$$

2) Synchronous Detector System with CERN Monitor

The CERN monitor split plates are shaped for a linear position response of 0.28 dB/mm whereas the stripline response is 0.66 dB/mm.

$$0.66 / 0.28 * 4.93 = 11.6 \text{ mm/volt}$$

3) AM/PM System Sensitivity

```
                          R                P
beam --> monitor ------> AM/PM ------> phase detector --> V
```

R = left signal amplitude / right signal amplitude
P = phase difference

$$R = \frac{1+2\,x/r}{1-2\,x/r} \sim 1+4\,\frac{x}{r} \quad \text{for } \frac{x}{r} << 1$$

$$\frac{dR}{dx} = \frac{4}{r} = 0.08114 \text{ /mm}$$

$$P = 2 \arctan R$$

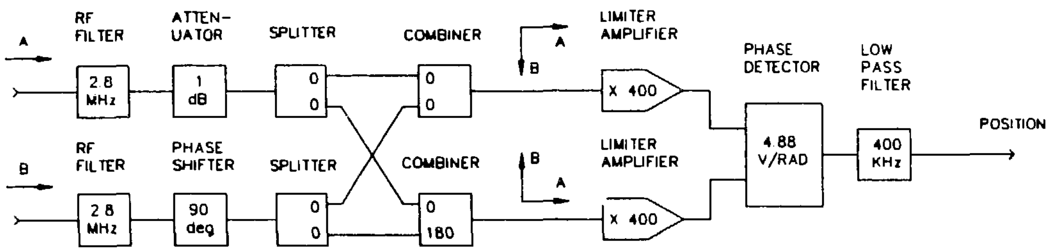
$$\frac{dP}{dR} = \frac{2}{1+R^2} = 1 \text{ rad} \quad \text{for } R = 1$$

$$\frac{dV}{dP} = \frac{2 \text{ mA} * 3830 \text{ ohms} - (-2 \text{ mA} * 3830 \text{ ohms})}{\text{pi radians}} = 4.88 \text{ volts/rad}$$

$$\frac{dV}{dx} = \frac{dV}{dP} * \frac{dP}{dR} * \frac{dR}{dx} = 0.395 \text{ volts/mm}$$

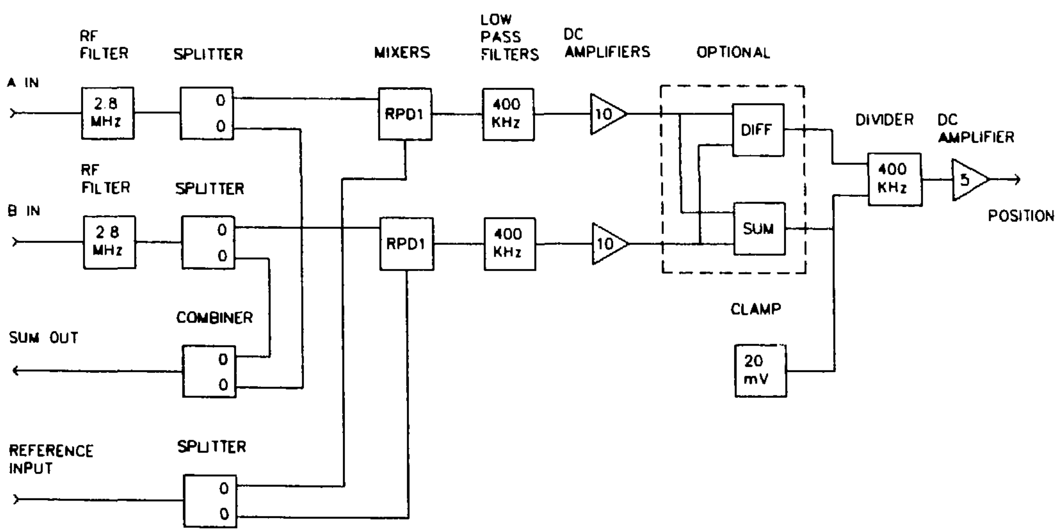
$$\frac{dx}{dV} = 2.53 \text{ mm/volt}$$

APPENDIX 2 ELECTRONICS BLOCK DIAGRAMS



AM/PM CONVERTER MODULE

LIMITER AND DETECTOR MODULE



SYNCHRONOUS DETECTOR MODULE

BEAM POSITION CIRCUIT

Appendix 3 - AM/PM Processor Error Due to Beam Head to Tail Displacement

Assume that the beam has a cosine-like line intensity and a sine-like head to tail displacement (mean horizontal position variation), fig. 1.

$Q(\phi) = 1 + \cos\phi$ where ϕ = longitudinal phase

$x(\phi) = d + b \sin\phi$ $\quad Q(\phi)$ = beam charge

$\hat{x}(\phi)$ = beam mean horizontal displacement

d = average beam displacement

b = head to tail displacement amplitude

The charge induced on the left stripline electrode is

$$Q_L(\phi) = Q(\phi)\left[1 + \frac{2}{r}\hat{x}(\phi)\right]$$

where $Q_L(\phi)$ = charge on left plate

$Q_R(\phi)$ = charge on right plate

r = radius of striplines

$$\simeq \frac{2b}{r}\sin\phi + \left(1 + \frac{2d}{r}\right)\cos\phi$$

and the dc and 2nd harmonic terms $\left(1 + \frac{2d}{r} + \frac{b}{r}\sin 2\phi\right)$ have been dropped.

Similarily $\quad Q_R(\phi) = Q(\phi)\left[1 - \frac{2}{r}\hat{x}(\phi)\right] \simeq -\frac{2b}{r}\sin\phi + \left(1 - \frac{2d}{r}\right)\cos\phi$

These signals are applied to the AM/PM processor (see diagram in appendix 2). The two resulting signals, u and v, which are fed to the phase detector are

$u = C\cos(\phi - \alpha)$ where $\quad \alpha = \arcsin \dfrac{r + 2b - 2d}{(2)^{1/2}[(r + 2b)^2 + 4d^2]^{1/2}}$

$v = D\cos(\phi - \beta)$

and $\quad \beta = \arcsin \dfrac{-r + 2b + 2d}{(2)^{1/2}[(r - 2b)^2 + 4d^2]^{1/2}}$

The phase detector output can be converted to a position signal p, where

$$p = \frac{r}{2} \cdot \frac{1 - \tan[(\alpha - \beta)/2]}{1 + \tan[(\alpha - \beta)/2]}$$

would be the measured average beam displacement.

This yields the corrrect average position d only when b = 0. Figure 2 shows p versus b for d = -10, -5, 0, 5 and 10 mm. The error (p - d) corresponds to an increase in sensitivity as the head to tail displacement amplitude increases. For b = 5 mm the increase in sensitivity is about 4 %.

Fig. 1

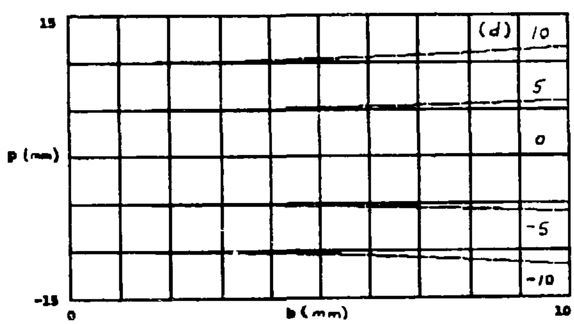


Fig. 2