Longitudinal Bunch Profile Measurements with Striplines*.

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Abstract

Striplines beam position monitors are normally considered low frequency devices with at best an octave bandwidth. Some attempts to make them very high frequency and broadband have led to long and complicated tapered construction. However, conventional uniform coupling striplines can provide very high frequency and broadband response, if the downstream induced signal is gated out electronically. In this case, the leading edge beam signal can provide bunch length and even current profile information for bunch lengths shorter than the length of the stripline. Recent improvement in transient digitizers have made these measurements possible for accelerator operations. Measurements of bunch lengths down to 50 psec are results are presented. Improvements to striplines and measurement systems are discussed, that could lead to bunch length resolutions ≈ 10 psec.

1. INTRODUCTION

Constant coupling stripline pickups have been used for sometime to measure signals from accelerator beams. They have generally been considered low frequency devices due to the length of the strip (l) which contributes to a pickup impedance proportional to [1]

$$Z_{pu} \approx \sin\left(\frac{\omega\, l}{\beta\, c}\right) \tag{1}$$

Although this function has coupling up to high frequencies, they are usually attenuated and suffer phase shifts that depend critically on the care that impedance matching was achieved for the stripline. To improve the high frequency response the strips are made shorter, in order to push the first zero to higher frequencies[2]. This has led to additional problems due to microwave resonances that require considerable care in construction. Although the high frequency coupling has been increased the bunch shape is greatly distorted (differentiated).

Another approach to gaining high frequency response has been the use of tapered coupling striplines [3]. These do increase the high frequency coupling and provide large bandwidth, but the bunch shape is similarly distorted by differentiating the input bunch shape.

This paper proposes the use of long constant coupling striplines to measure the bunch length and even the current profile of the bunch. If the bunch length (σ_l) is less than the length of the stripline, the direct (upstream) signal of the bunch passage is separated in time from the reflected (downstream) signal. If a short signal transmission cable is used to avoid attenuating the high frequency signal and an oscilloscope with a bandwidth $f_{BW} > [\ 2\,\pi\,\sigma_l\ ]^{-1}$ is used, then the risetime of the direct signal yields a measurement of the bunch length, if a current profile is assumed. A measurement of the current profile can be obtained if care is taken in matching the impedance over the stripline or the impulse response is measured. A sampling scope can easily provide the bandwidth necessary for the measurement, but requires the bunch shape to be repetitive. With a recent advance in the bandwidth of transient digitizers, this repetitive pulse requirement can be eliminated, making this a useful technique for linear accelerators and storage rings with bunch instability. This technique of measuring only the direct signal from the bunch provides a signal with a "pseudo-DC" coupling[4] to the beam that has been used [5] to provide an integrable signal for beam position measurements. In our case the oscilloscope provides the electronic gating of the measurement instead of using a gated integrator or mixer.

2. EXPERIMENTAL METHOD AND RESULTS

The bunch length was measured in two storage rings at the National Synchrotron Light Source using the technique described above. The VUV Ring is a 745 MeV electron storage ring with a zero current bunch length of 170 psec at a rf voltage of 70 kV. The second ring was the 200 MeV X-ray Lithography Source (XLS) with a zero current bunch length of 40 psec for a rf voltage of 35 kV. Both machines had similar 50 Ω striplines installed with a length l=30 cm, and terminated at the downstream end with high frequency 50 Ω terminators. Although four stripline plates were available, no attempt to combine signals was made for these measurements. The beam signal from a single plate was taken to the digitizer using < 20 feet of low loss 50 Ω coaxial cable.

Although a sampling scope was tried, the expected voltages of up to 1.5 volts per mA of bunch current allowed the use of a high frequency, direct drive, real-time transient digitizer[6]. This instrument has a 4.5 GHz bandwidth response for a risetime resolution of ≤80 psec (equivalent to an rms bunch length resolution for Gaussian bunches of ≤46 psec). The digitizer is basically a direct drive oscilloscope with a fixed voltage window of 0-5 volts, with a zero offset

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of ±4 volts and a time window variable down to 5 nsec, with a time interval between data points of ≥5 psec. The trigger for the instrument was taken from splitting the beam signal using a high frequency splitter and using one signal for the trigger and the other for the input to the digitizer. Since the digitizer requires at least a 15 nsec delay between the trigger and the input signal, the storage ring rf buckets were used to provide the delay between two beam bunches. This provided the delay without attenuating the signal in extra delay cable. Phase oscillations between the bunches had no effect on this measurement as long a the signal remained in the window of the digitizer. This would not be true for a sampling scope where phase motion would contribute to a serious noise distortion.

Figure 1 shows the bunch signals obtain from these two machines using this instrument. The direct signal in both cases is clearly sharper and less distorted by phase dispersion and impedance mismatch reflections than the reflected signal. Although the striplines are similar in construction, the signal in Fig. 1a shows less ringing from impedance mismatches and variation of the coupling impedance over the length of the stripline than the signal in Fig. 1b. This is due to the addition of vacuum pumpout holes in the groundplane around the stripline used for XLS (a compact light source).

As discussed below the risetime measurement of the direct signal can then be used to measure the bunch length, assuming the bunch shape is Gaussian. In order to calibrate the bunch length resolution (σ_R) for this system the rf voltage was varied and the bunch length variation measured at low current in the XLS ring. Since the actual beam bunch length varies as

$$\sigma_l \approx [\, V_{rf} \cos(\phi)\,]^{-1/2} \frac{\sigma_E}{E} \qquad (2)$$

where $\cos(\phi) \approx 1$ for XLS and $\frac{\sigma_E}{E}$ is the rms fractional energy spread, σ_R can be estimated by extrapolating the square of the measured bunch length (σ_m^2) to $1/V_{rf} \to 0$. This extrapolation had an intercept value of $\sigma_R = 62 \pm 7$ psec. The actual bunch length can then be calculated by subtracting σ_R in quadrature from the measured bunch length. Figure 2 shows the measured bunch length for the XLS ring as a function of beam current in the two bunches, obtained with this technique. Although the minimum bunch length approaches the expected bunch length, the zero current bunch length is actually somewhat larger. A clear increase in bunch length with current is observed above 40 mA, while a bunch shortening is observed below this current.

This instrument can not only be used for bunch length measurements assuming a Gaussian bunch profile, but can also yield the profile itself. This is demonstrated in Figure 3 were a quadrupole type oscillation was measured in the XLS at low current and low rf voltage. Since the digitizer rate is < 1 Hz the time between these traces was several seconds but the oscillation between the two profiles continued for several minutes. To accurately measure the current profile it is clear that the reflection properties of this stripline will have to be measured. On the VUV ring this instrument is being considered to help optimize the bunch lengthening using a fourth harmonic cavity. Since the reflections are less for this stripline the measurement of actual bunch profile will be somewhat easier.

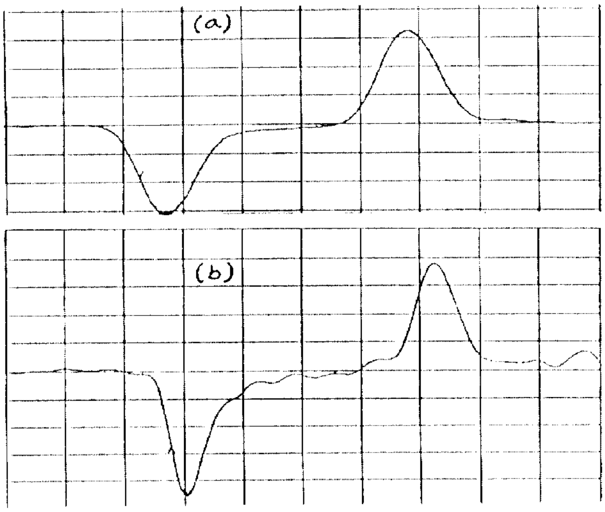

Figure 1. Measurement of bunch signals using the transient digitizer with 0.5 V/div and 500 psec/div scales for (a) a 26.7 mA bunch in the VUV and (b) a 146 mA bunch in the XLS ring. Both signals were attenuated by 20 db.

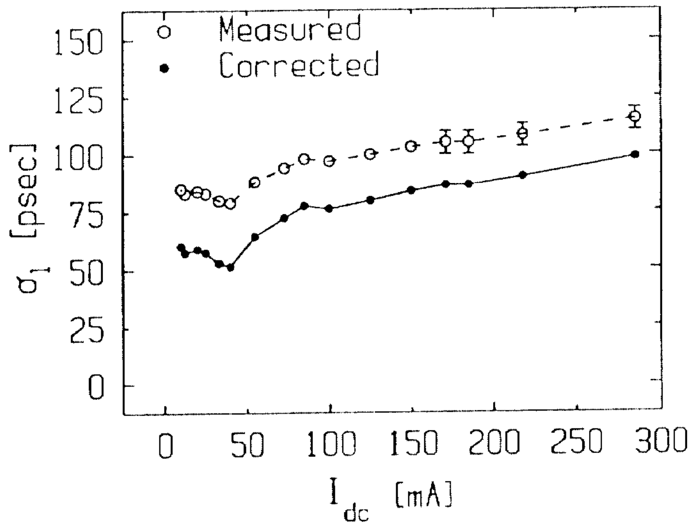

Figure 2. Measured bunch length, before and after correction for resolution, in the XLS with V_{rf}=35kV. I_{dc} is current in 2 bunches.

3. ANALYSIS OF THE STRIPLINE SIGNAL

A charge particle bunch moving in a conducting beampipe has an image charge of opposite sign moving on the inside of the pipe. The image charge density will be identical to the bunch density except for a spreading over a distance of $d \approx r/\gamma$, where r is the radius of the beampipe. For $\sigma_l > d/c$ this blurring can be ignored compared to the bunch length (for XLS $d/c \approx 0.4$psec). At a discontinuity in the beampipe (stripline) this image charge can create a potential difference between the stripline and the beampipe. If a signal cable with characteristics impedance (Z_c) equal to that of the stripline is connected at the start of the stripline a traveling wave pulse will be generated in the cable with $V(t) = I_b(t)\,F(\phi)\,\frac{Z_c}{2}$ where $I_b(t)$ is the beam current profile and $F(\phi)$ is a geometric factor related to the fraction of charge collected by the strip. After a time T= l/c the beam passes the downstream end of the strip and a similar voltage pulse is generated but of opposite sign. This reflected pulse appears at the cable at time 2T after the direct pulse causing a constructive interference at frequencies $f_c = n/(4T)$ and destructive interference at frequencies $f_d = n/(2T)$. However, the direct signal contains almost all frequency components of the beam[4] if the reflected signal is gated out. Since this time gating is not a linear process this signal doesn't lend itself to a Fourier analysis but can be most easily modeled using a transient analysis.

At the end of a signal cable of length L, the impulse response function of the cable, including the effect of skin depth variation with frequency can be parametrized by [7]

$$g(t) = \sqrt{\frac{\beta}{\pi}}\, x^{-3/2} \exp[-\frac{\beta}{x}] \quad \text{for } x \geq 0 \qquad (3)$$

$$\text{where } \beta = \frac{1.055\times10^{-3}}{f}\alpha^2 \ , \ x = t-\frac{L}{v_p} \ \text{and} \ v_p = (LC)^{-1/2}$$

for α = the cable attenuation in db at frequency f. The distortion of the voltage pulse at the scope is then given by the convolution of the bunch current with Eq.(3). This is shown in Figure 4 together with a fit to the leading edge signal by a Gaussian. Although the response function is not Gaussian, the leading edge agrees quite well with a Gaussian resolution function (σ_R = 26 psec) in quadrature with the bunch length. The difference between this and the measured resolution appears to be due to an unavoidable impedance mismatch between the stripline and the cable. This has been modeled by a reflected signal equal to 10% of the delayed by 60 psec. The leading edge analysis agrees with a resolution of 63 psec added in quadrature to σ_l.

In principle Eq.(3) could be used to deconvolve I_b from the measured V(t). However, the influence of the impedance mismatches need to be introduced into this procedure. This is possible using time domain reflectometry measurements (TDR). An additional distortion that cannot be obtained form the TDR measurements is the variations in the beam coupling impedance over the length of the stripline. These will introduce reflection like signals at times less than 2T. If these are a serious concern, the total impulse response could be measured by driving the stripline with a δ-function like pulse from wires or beams [8].

4. CONCLUSIONS AND ACKNOWLEDGEMENTS

A technique of measuring beam bunch length with conventional striplines has been demonstrated to yield resolutions to 50-60 psec using a transient digitizer. With improvements in the stripline impedance matching and expected advancements in the digitizer bandwidth, this method could yield resolutions ≤10 psec. A method for measuring the current profile of the bunch has been described and the necessary measurements discussed. Even without detailed measurements this method has been shown to provide qualitative measurements of the bunch shape.

These measurements have been made possible by the generous loan of the digitizer by Andrew Nydell (Tektronix) and Joachim Fischer (BNL).

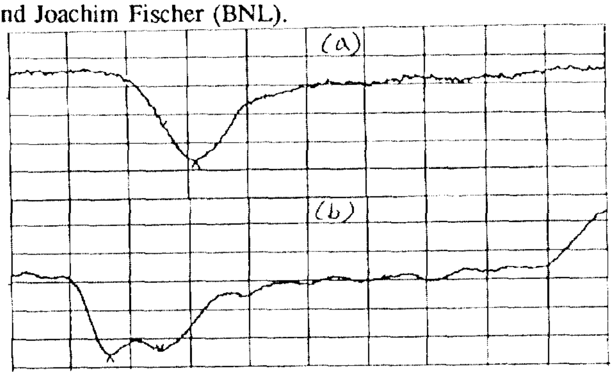

Figure 3. Measurement of the current profile in the XLS during a quadrupole bunch oscillation between trace (a) and (b). The scales have been expanded to 0.25 V/div and 250 psec/div.

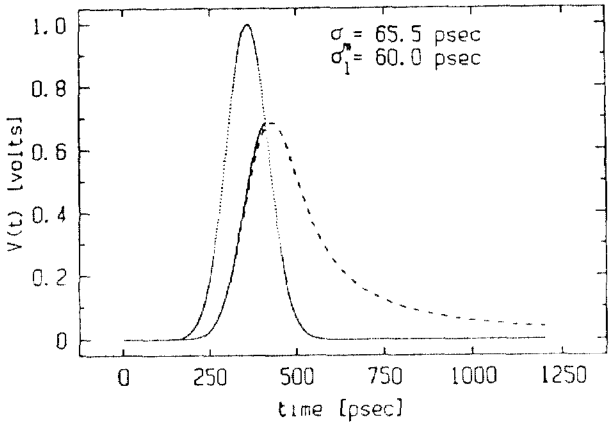

Figure 4. The dotted curve is the assumed Gaussian bunch current profile, the dashed is V(t) after a 6.5m cable and a 3 GHz bandwidth, and the solid is a Gaussian fitted to the leading edge of V(t).

5. REFERENCES

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