Bunch Current Density Measurements in the VUV Light Source

S.L. Kramer[a)]
Brookhaven National Laboratory
National Synchrotron Light Source
Upton, New York 11973-5000, USA

Y. Wu, V.N. Litvinenko, C.B. McKee and B. Burnham
Duke Free Electron Laser Laboratory[b)]
Duke University, Durham, NC 27708-0319 USA

Abstract
Recent measurements of the bunch current density in the VUV storage ring at the National Synchrotron Light Source have been made from a stripline using a new technology of a real-time oscilloscope with bandwidth up to 5 GHz. A deconvolution technique has been developed to reconstruct the bunch current distribution in the longitudinal direction. The non-Gaussian lengthened bunch profiles at high currents and with a 4th harmonic RF system are reconstructed [See ref 4].

1. Introduction

Measurement of the bunch length in electron storage rings has typically been done using the synchrotron light emitted by the stored beam. Photodiodes can have very fast risetimes and couple to the beam over a wide frequency range, including the DC component, although the falltimes are typically much slower than the risetimes and may have one or more cycles of ringing after the pulse. Even if the coupling is optimized these diodes output small signal voltages and either require high gain amplifiers or the use of sampling techniques to measure the bunch current density. If the bunches have large, high frequency phase oscillations, sampling measurements yield a time averaged signal which may be difficult to interpret.

Single-shot techniques do not have this difficulty. These techniques require a streak camera [1] or if the bunches are long enough a high frequency transient digitizer [2], a significantly lower cost option. This latter technique was demonstrated using a borrowed unit, but a similar unit has been acquired for bunch current density measurements in the VUV ring. In fact this digitizer, the Tektronix SCD5000, is actually a slow streak camera with an electrical input, rather than optical, and a beam centroid detector system for high resolution digitization of the voltage signals. The SCD5000, although slow per measurement (1 trace per second), yields a clear measurement of the bunch distribution in a single pass with bandwidth up to 5 GHz. Shifting the trigger and switching between the 16 internal memories provides one bunch measurement per second per bunch. Since this digitizer has a fixed 5 volt window, the input signals from the beam must be large. A stripline pickup provides high coupling impedance to the beam and provides adequate signal for the digitizer down to 1 mA bunch currents. At higher currents the signal is easily attenuated using high frequency attenuators.

The bunch length can be estimated using a Gaussian fit to the leading edge of the first peak of the stripline signal. However, for a lengthened or distorted bunch the non-Gaussian bunch profile has to be restored by using deconvolution methods.

2. Bunch Length Estimation Using Leading Edge

As described in the earlier reference [2] the leading edge signal from the upstream end of a stripline for an electron bunch within a certain current range remains essentially Gaussian. The RMS bunch length can be determined by fitting the leading edge to a Gaussian RMS bunch width and subtracting in quadrature the resolution width introduced by the measurement system. This resolution width can be estimated by extrapolating the measured bunch length as a function of V_{rf}^{-1} to zero in this parameter.

In the VUV ring, we measure the stripline leading edge signal width by calculating the time difference between the minimum voltage and the leading edge point where the voltage is $\exp(-0.5)$ of the minimum. Similar values are obtained from the Gaussian fit of the leading edge. Fig. 1 shows the leading edge fit to the measured signal for a bunch with 42 mA. The RMS signal widths are 212 ± 5 and 210 ± 3 psec for the direct measurement and Gaussian fit respectively. The resolution width of 84 ± 5 psec is extrapolated from the measurements of a 1 mA bunch for a range of RF voltages. The bunch lengths of the assumed Gaussian bunches at different currents are calculated and shown in Fig. 2. A power law curve is fit to the data. If the asymptotic power law for the bunch lengthening is assumed to be from the microwave instability, it yields a broadband impedance of $|Z/n| = 1.8 \sim 3.4\Omega$ and a scaling factor [3] of $a = -0.78$ (compared to $|Z/n| = 8.8\Omega$ and $a = -0.68$ for Spear).

3. Bunch Profile Reconstruction Using Deconvolution Method

3.1 Deconvolution Method

The measured signal $V(t)$ is the convolution of the beam current $I_b(t)$ and the response function of the system $Z(t)$,

$$V(t) = \int_0^\infty Z(\tau)\, I_b(t-\tau)\, d\tau \qquad (1)$$

The response function includes the effects of coupling variations of the stripline ends, attenuation and dispersion of

---

a) Work performed under the auspices of the U.S. Department of Energy.
b) Work supported by the Office of Naval Research contract N00014-91-C-0226.

cables and attenuators, and the time response of the SCD5000 scope. In the frequency domain Eq. 1 becomes

$$V(f) = Z(f) \times I_b(f) \qquad (2)$$

where $V(f) = \hat{F}\{V(t)\}$ and $\hat{F}\{\,\}$ stands for the Fourier transformation. If $Z(f)$ is a known function, the actual beam profile can be restored using the deconvolution technique,

$$I_b(t) = \hat{F}^{-1}\{V(f) / Z(f)\} \qquad (3)$$

where $\hat{F}^{-1}\{\,\}$ is the inverse Fourier transformation.

We assume that a low current electron bunch has a natural Gaussian distribution defined by the synchrotron radiation integrals

$$I_0(t) = I_{pk} \exp(-t^2 / 2\sigma^2) \qquad (4.a)$$

and

$$I_0(f) \propto \exp(-(2\pi\sigma f)^2 / 2) \qquad (4.b)$$

The measured value of the synchrotron tune is used to determine the exact value of the bunch length. Then we compute the response function $Z(f)$ using measured signals for a low current (< 10 mA) bunch $V_0(f)$,

$$Z(f) = V_0(f) / I_0(f) \qquad (5)$$

The response function of the system is obtained from a measurement of an 8 mA bunch with RMS bunch length of 162 psec. The only difference between this measurement and measurements for higher currents is the use of appropriate broadband (18 GHz) attenuators to keep the signal within the window of the SCD5000 scope.

3.2 Deconvolution Using Incident Signal

The stripline signal is clearly separated into two peaks by the stripline length of 30 cm [2]. The negative going peak is the direct signal of the bunch passing the upstream end of the stripline and the positive going peak is the signal of the bunch passing the downstream end propagated back through the stripline. The signal from short bunches (shorter than the stripline length) has two separable peaks. To apply the deconvolution technique to the incident signal, the reflected signal is erased and zeros are padded to the tail.

The advantage of this method is that the Fourier spectrum does not have frequencies with zero coupling. The coupling impedance above 3 GHz is poorly defined due to the digitalization noise, the finite sensitivity, the frequency band limit of the system, and the zero padding in the time domain data. These high frequency noises can be filtered, although they have little effect on the bunch profile. The value of the current is normalized using the measured value of the DC beam current from a DC current transformer.

The stripline signal for a 42 mA bunch is shown in Fig. 3 and the reconstructed bunch profile is shown in Fig. 4, compared with a fitted Gaussian distribution. The fitted RMS width is roughly 45% greater than that determined by the leading edge method described in Section 2. The restored bunch is noticeably peaked forward and has a longer tail. The Fourier transform of the response function is shown in Fig. 5.

3.3 Deconvolution Using Entire Stripline Signal

For long bunches the incident signal method is not applicable. In this case the entire stripline signal is used to restore the bunch profile in the deconvolution. However, the spectrum of the total response function $Z(f)$ has nodes with zero coupling at certain frequencies, therefore the direct use of Eq. 3 will cause large fictitious peaks in $V(f) / Z(f)$ and distort the bunch profile. Nevertheless, the nodes with zero coupling are very narrow, and the bunch spectrum in the proximity of the nodes is restored using third order spline interpolation.

Fig. 3 shows the measured stripline signals for both beam currents of 42 mA and 330 mA. ,The response function using the entire stripline signal from an 8 mA bunch is shown in Fig. 6. This function has clear nodes with zero stripline coupling to the beam at multiples of about 500 MHz. High frequencies above 3 GHz can be filtered. The reconstructed bunch profiles for beam currents of 42 mA and 330 mA are shown in Fig. 4. The reconstructed bunch profile for different RF voltages and bunch configurations are found in ref [4]. The non-Gaussian bunch profiles have been observed in all cases. The non-Gaussian shapes are the results of higher order modes in the rf cavities. An analysis of these distortions is the subject of a future paper.

4. Conclusion and Future Work

One of the main reasons for developing this bunch profile reconstruction technique has been to diagnose the bunch shape created by the 4th harmonic RF system added to the VUV ring for bunch length and lifetime control [4]. This goal has been achieved by using the measurement system and the deconvolution techniques described above.

Future improvements in this system are planned using a photon detector with high gain and moderate risetime ($t_{rise} < 150$ psec) to couple to the synchrotron light and avoid the zero coupling frequencies of the stripline. This will simplify the reconstruction algorithm and remove the uncertainty of the distortions being generated by the restoration of these zero coupling signals. However, even the photon detector signal will require a deconvolution technique to obtain the real bunch current distribution.

5. Acknowledgments

This system has been made possible by the support and encouragement of S. Krinsky. We express our thanks to: R. Biscardi, G. Ramirez and the RF Group for developing the operational harmonic RF system for bunch length control in the VUV ring and for providing the incentive to develop this real-time bunch current distribution measurement system.

6. References

[1] C. Bovet, Advanced Beam Observation Methods for LEP, Proceedings of the 3rd EPAC Conference, Berlin, p.259 (1992).

[2] S. L. Kramer, Longitudinal Bunch Profile Measurements with Striplines, ibid., p.1064 (1992).

[3] P. B. Wilson, et al, Bunch Lengthening and Related Effects in Spear II, IEEE Trans. Nucl. Sci., NS-24, p.1211(1977).

[4] S. L. Kramer, et al, Bunch Length Control in the VUV Light Source, these proceedings (1994).

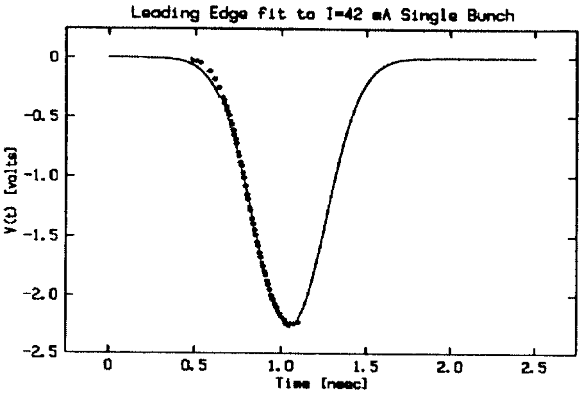

Fig. 1 Gaussian fit to the leading edge bunch signal off a stripline for a single 42 mA bunch in the VUV ring without the harmonic cavity in the ring.

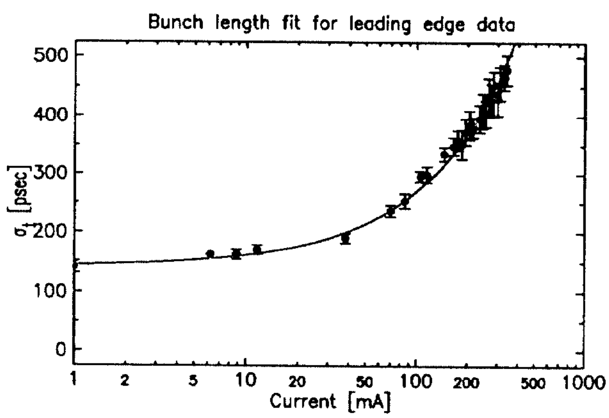

Fig. 2 The corrected data on RMS bunch lengthening as a function of current for a single bunch, obtained using the Gaussian fit to the leading edge of the stripline signal.

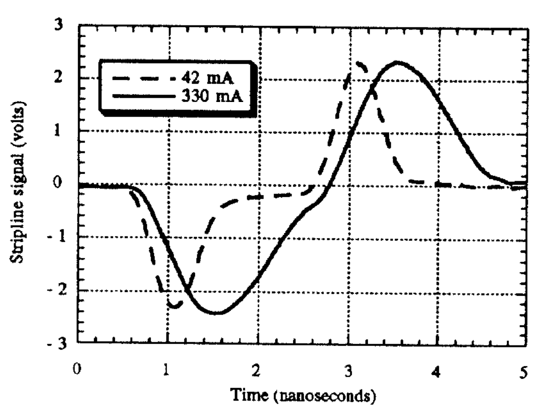

Fig. 3 The measured stripline signals for single bunch operation with currents of 42 mA and 330 mA.

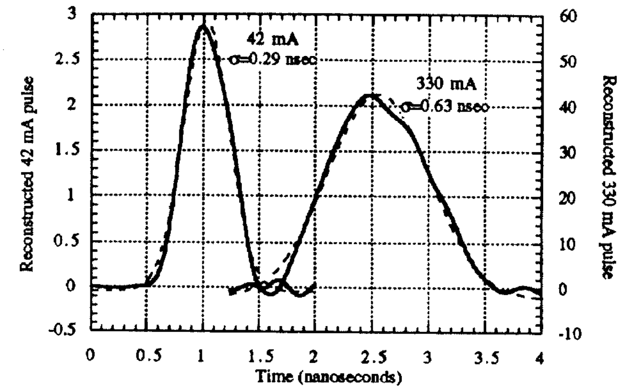

Fig. 4 The reconstructed bunch current distribution (solid line) at 42 mA and 330 mA together with Gaussian fit (dashed line).

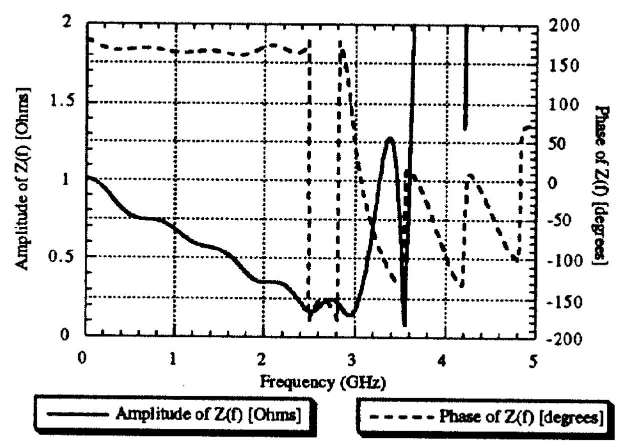

Fig. 5 The Fourier spectrum of the response function computed for the incident signal method, Section 3.2.

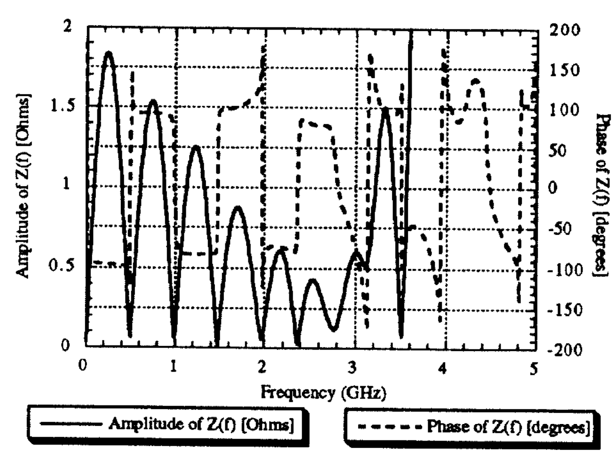

Fig. 6 The Fourier spectrum of the response function computed for the entire stripline signal method, Section 3.3.