Bunch Current Density Measurements in the VUV Light Source

S.L. Kramer
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
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 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 rise times and couple to the beam over a wide frequency range, including the DC component, although the fall times are typically much slower than the rise times and may have one or more cycles of ringing after the pulse. 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. 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 optical 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 $V_i^{-1}$ 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 310 ± 3 ps for the digit measurement and Gaussian fit respectively. The resolution width of 84 ± 5 ps 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 $|Z/l|=1.8 - 3.4 \Omega$ and a scaling factor $a$ of $a=-0.78$ (compared to $|Z/l|=8.8 \Omega$ 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 $Z(t)$.

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

The response function includes the effects of coupling variations of the stripline ends, attenuation and dispersion of...
digitalization noise, the finite sensitivity, the frequency band
integrals
Gaussian distribution defined by the synchrotron radiation
measurements for higher currents is the use of appropriate
cables and attenuators, and the time response of the SCD5000
scope. In the frequency domain Eq. 1 becomes
\[ V(f) = Z(f) \times I_b(f) \]  
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,
\[ I_b(t) = \hat{F}^{-1} \{ V(f) / Z(f) \} \]  
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

\[ I_0(t) = I_{pk} \exp(-t^2 / 2\sigma^2) \]  
and \[ I_0(f) = \exp(-(2\pi\sigma f)^2 / 2) \]  

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 \( V_0(f) \),
\[ Z(f) = V_0(f) / I_0(f) \]  
The response function of the system is obtained from a
measurement of an 8 mA bunch with RMS bunch length of
162 pscc. 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 pscc) 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.

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the VUV ring and for providing the incentive to develop this
real-time bunch current distribution measurement system.

6. References

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.