Bunch Length Measurements at the Advanced Photon Source (APS) Linear Accelerator *

N. S. Sereno, R. Fuja, C. Gold, A. E. Grelick, A. Nassiri, J. J. Song, M. White

Advanced Photon Source, Argonne National Laboratory

9700 South Cass Avenue, Argonne, Illinois 60439 USA

Abstract

Measurements of the APS linac micro-bunch length are performed by backphasing a single 2856-MHz, S-band linac waveguide and using a downstream spectrometer to observe the beam. By measuring the beam width in the dispersive plane as a function of rf power into the linac waveguide, the bunch length can be determined absolutely provided the beam energy and dispersion at the spectrometer are known. The bunch length determined in this fashion is used to calibrate a fifth-harmonic bunch length cavity which is used for real-time bunch length monitoring.

I. INTRODUCTION

Bunch length measurements of the APS linac electron beam are required in order to evaluate the performance of the low energy bunching process of the beam emitted by the thermionic gun. Bunching of the 100-keV beam is performed by a standing wave cavity and drift (the prebuncher) followed by a 5-cell traveling wave cavity (the buncher) where each cavity operates at a frequency of 2856 MHz. After the buncher, the beam is accelerated from an energy of 1.4 MeV to 50 MeV by the first 3-m, 86-cell accelerating waveguide operating at 2856 MHz. Four downstream accelerating waveguides further accelerate the beam to 220 MeV at the positron target. After the target, nine accelerating waveguides are used to accelerate the positrons to 450 MeV.

The electron beam consists of 30-ns macropulses repeated at a 2-Hz rate. Each 30-ns macropulse consists of 86 micro-bunches after the bunching process is completed (essentially after the beam passes the buncher). The micro-bunch length of the APS linac electron beam (from now on referred to as the bunch length) has been measured by backphasing a single accelerating waveguide and observing the beam after a downstream spectrometer. The accelerating waveguide is phased so that the centroid of each micro-bunch passes through it when the electric field is zero (zero crossing). Energy spread is induced in the micro-bunch because at zero crossing, depending on the slope of the rf waveform, particles obtain more or less energy depending on their location within the micro-bunch. The induced energy spread is linearly related to the bunch length for bunches that are short compared to the rf period (350 ps at 2856 MHz).

A standing wave cavity operating at the fifth harmonic of the bunching frequency (14.28 GHz) is used for real time monitoring of the bunch length in the linac [1]. The peak output power of the cavity depends on the bunch length. The fifth harmonic frequency was chosen to maximize the output power for small ($\sim$ 5 ps rms) micro-bunches consistent with mechanical and

electrical constraints. Calibration of the cavity is accomplished by first measuring the bunch length by the backphasing technique and using the result to determine the effective cavity shunt impedance.

II. THEORY

The basic apparatus for the bunch length measurement consists of an accelerating waveguide through which a relativistic bunched electron beam passes on zero crossing. The beam is subsequently observed downstream of the accelerating waveguide at a spectrometer consisting of a dipole magnet, a drift, and a screen. The transverse position of a given beam particle in the dispersive plane on the screen is given by

$$x = x_\beta + \eta \, \frac{\delta p + (E_g/c)\sin\phi}{p}, \qquad (1)$$

where x_β is the usual betatron oscillation of the particle, η is the dispersion at the viewscreen in meters, δp is the intrinsic momentum offset of the particle, p is the central momentum of the beam, E_g is the maximum energy gain in MeV of a particle that traverses the accelerating waveguide on crest, and ϕ is the phase of the particle in radians relative to the particle that goes through the accelerating waveguide on zero crossing. Equation (1) shows that the transverse position of the particle is linearly related to the phase offset from zero crossing for $\phi << 1$ radian.

For a given particle distribution for each micro-bunch, Eq. (1) can be used to write the rms beam size in terms of parameters of the backphased waveguide and spectrometer. The rms size is defined by

$$\sigma^2 \equiv \langle (x - \langle x \rangle)^2 \rangle, \qquad (2)$$

where $\langle \rangle$ denotes integration of the particle coordinates over the particle distribution. Inserting Eq. (1) into Eq. (2) results in

$$\begin{aligned} \sigma^2 &= \sigma^2_{\left(x_\beta + D\frac{\delta p}{p}\right)} + \{ \langle x_\beta \sin\phi \rangle - \langle x_\beta \rangle \langle \sin\phi \rangle + \\ & \frac{\eta}{p}\left(\langle \delta p \, \sin\phi \rangle - \langle \delta p \rangle \langle \sin\phi \rangle \right) \} \frac{2\eta}{pc} E_g + \\ & \frac{\eta^2 \sigma^2_{\sin\phi}}{(pc)^2} E_g^2 \qquad (3) \end{aligned}$$

$$\sigma^2_{\sin\phi} \equiv \langle (\sin\phi - \langle \sin\phi \rangle)^2 \rangle. \qquad (4)$$

In Eq. (3), the first term is due to the natural emittance and energy spread of the beam. The second term results from correlations between the particle betatron oscillation, phase relative to zero crossing and natural momentum spread. The third term contains the rms bunch length when

$$\sigma_{\sin\phi} \simeq \sigma_\phi, \qquad (5)$$

which is an excellent approximation for short bunches where $\sin\phi \simeq \phi$. Typical rms bunch lengths for the APS linac are $\sim 5°$ and therefore meet the approximation given by Eq. 5 (for comparison $1° = 1.03$ ps for 2856 MHz).

III. MEASUREMENT RESULTS

Equation (3) indicates that the rms bunch length can be obtained by fitting a quadratic curve to a measurement of σ^2 vs E_g. The form the fitting function therefore takes is

$$\sigma^2 = a_\circ + a_1 E_g + a_2 E_g^2, \qquad (6)$$

where the above terms are readily identified with those of Eq. (3). The second-order term yields the micro-bunch length provided the central momentum (energy) and dispersion at the viewscreen are known. It is desireable to go to a large waveguide energy gain so that the quadratic term dominates the other two. The relative error in the quadratic term will therefore be minimized.

Figure 1 shows the data taken using a single accelerating waveguide driven by a single klystron. The beam energy at the entrance to the accelerating waveguide was 220 MeV. The data were taken at a beam current of 150 mA average current per macropulse (52 pC per micro-bunch) due to the fact that camera and viewscreen saturation effects limit resolution at higher beam currents. The micro-bunch length backphase measurement was performed using the beam resulting from a "standard" setup for the buncher and prebuncher. The resulting beam spot distribution on the spectrometer viewscreen was symmetric and easily analyzed. The beam image analysis software computes σ directly from the measured beam intensity distribution according to Eq. (2). No assumptions about the exact microbunch structure need be made. At each accelerating waveguide energy gain, the rms size was taken to be the average of the rms size of five beam snapshots taken. The error bars are taken to be the standard error for the mean [2]. This averaged out shot-to-shot fluctuations of the rms size due to rf and other noise sources. The quadratic fit to the data is shown as the solid line. The fit is acceptable with most data points lying within a distance of twice their error bar of the fit. Table I summarizes the measurement parameters, the results of the fit, and gives the inferred bunch length. The dominant errors contributing to the bunch length error are the error in the second term a_2 and the dispersion. The last entry in Table I is an estimate of the FWTM (full width at 10% of the maximum height of the distribution) bunch length. The FWTM bunch length was estimated by comparing the ratio of the FWTM beam size to σ for each data point and taking the average of this ratio for all the data points. The average ratio was found to be 4.53 (for comparison, the ratio of the FWTM size and the rms size σ for a Gaussian distribution is 4.3).

IV. FIFTH HARMONIC CAVITY CALIBRATION

The measurement procedure just described, though automated using the SDDS tools [3], is time consuming. A bunch monitor previously described [1] is used for real-time (shot-to-shot) bunch length monitoring. The peak cavity output power for a given beam current is given by

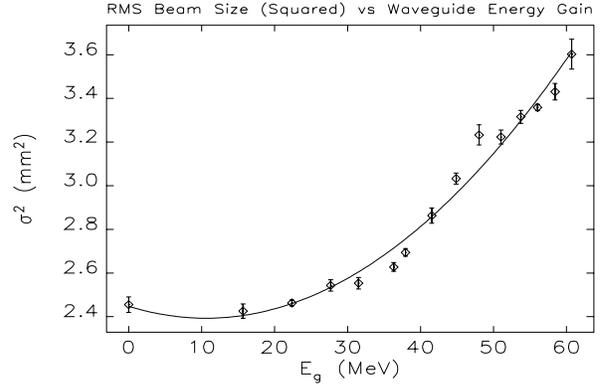$$P = \frac{RI_\circ^2}{2}\, e^{-m^2\sigma_\phi^2}, \qquad (7)$$

Figure 1. Bunch length measurement data consisting of σ^2 vs E_g. The solid line shows the best fit quadratic curve to the data.

Table I
Bunch length measurement parameters.

Parameter	Value
p	334.8 ± 3.3 MeV
η	194 ± 5 mm
$a_\circ$	$2.45 \pm .05$ mm^2
a_1	$(-1.0 \pm .3) \times 10^{-2}$ mm^2/MeV
a_2	$(4.9 \pm .5) \times 10^{-5}$ (mm/MeV)^2
σ_ϕ	$(2.2 \pm .1)°$
FWTM_ϕ	$(9.9 \pm .6)°$

where $I_\circ$ is the average beam current and the notation for the effective shunt impedance R from reference [1] is kept. The power given by Eq. (7) is seen to depend on the bunch form factor $e^{-m^2\sigma_\phi^2}$. This form factor arises specifically because a Gaussian shape for the microbunch was assumed. For short bunches, the precise functional form of the form factor matters little because the second order Taylor expansion to second order for different form factors is identical for frequencies that are small relative to the rolloff frequency given by the inverse temporal bunch length. The factor multiplying the rms bunch length m, is the harmonic number of the bunched beam signal. Since the fundamental cavity mode operates at the fifth harmonic of the bunching frequency $m = 5$ for the cavity considered here.

The reason for going to as large a harmonic number as possible is to increase measurement sensitivity to short bunches. Equation (7) is now used to estimate the smallest bunch length measurable for a cavity (or any detector) operating at some harmonic of the bunching frequency. Assuming that 0.1-dB power changes are the minimum detectable in the presence of typical noise sources, the minimum rms bunch length is given by

$$\sigma_\phi^{\min} = \frac{1}{10\,\sqrt{\log(e)}}\, \frac{1}{m}, \qquad (8)$$

which for our cavity turns out to be $1.74°$ ($7.48°$ FWTM assuming a Gaussian distribution). Inspection of Table I reveals that the bunch length determined in the backphase measurement is nearly at the theoretical lower limit defined by Eq. (8).

Calibration of the cavity consists of determining the effective shunt impedance in Eq. (7). The peak cavity output power was measured using a calibrated fast diode. Corrected for cable losses, the peak cavity output power was measured to be 45.9 mW for a beam current of 150 mA. Using the measured bunch length listed in Table I and Eq. (7), the shunt impedance turns out to be 4.2 Ω. The calculated shunt impedance from SUPERFISH is 33 Ω. The order of magnitude difference stems from two primary effects. The first is that for a 30-ns pulse, the cavity is not completely filled, and second, the loaded and unloaded Q results in a mismatch which reduces the peak output power [4]. Both these effects increase the shunt impedance by a factor of two to three.

Further studies are being conducted by varying the beam current to get a more precise value for the shunt impedance and to evaluate the measurement uncertainties involved. A measurement uncertainty of 10 % for the shunt impedance should be adequate and achievable. One way of determining the shunt impedance would be to produce a bunch length smaller than the minimum detectable as given by Eq. (8) and measure the peak power as a function of beam current squared. The slope of this curve from Eq. (7) is simply $R/2$. Bunch lengths greater than that given by Eq. (8) would manifest themselves as a reduction in the slope given by the form factor in Eq. (7). Of course, this measurement of R assumes that the bunch length does not vary appreciably as the beam current is varied. This is a good assumption at the very low beam currents used here, where space charge is negligible. Extention of this idea would require a separate bunch length measurement using the backphase technique at each beam current.

V. CONCLUSION

The bunch length has been measured by backphasing a single accelerating waveguide and observing the beam at a downstream spectrometer. Improvements to the measurement include going to higher values of E_g by using four backphased waveguides driven by a single klystron and SLED [5]. Compared to a single accelerating waveguide, four accelerating waveguides would allow four times the energy spread to to be induced in the beam for a given bunch length. Another approach would be to increase the dispersion of the spectrometer which would require hardware modification.

The fifth-harmonic cavity calibration was done at a single beam current and bunch length. Additional measurements will be made at multiple beam currents and bunch lengths to check the calibration over a broad range of beam parameters. The measured cavity shunt impedance agrees with the calculation when the effects of cavity filling during the beam macropulse and mismatch are taken into account.

VI. ACKNOWLEDGEMENTS

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