Energy- z correlation measurements of electron bunches

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Bunch length and energy- z correlation measurements were performed on the high energy (28.5 GeV) electron test beam of the A-line and End Station A (ESA) facilities at the SLAC National Accelerator Laboratory. The longitudinal profile of each bunch was measured by imaging the synchrotron light emitted as the electrons traversed a highly dispersive bend after being streaked by a transverse rf deflecting cavity. In addition, high frequency diodes and pyroelectric detectors placed at a ceramic gap in the beam line were used to measure the length of the bunch in ESA.

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I. INTRODUCTION

While it is normally quite simple to image the transverse profile of a beam (e.g. by having the beam impact a phosphorescent screen), measuring the longitudinal profile is considerably more difficult. Despite this, it is of critical importance for most modern accelerators that the longitudinal degrees of freedom (bunch length and momentum spread) be well understood and controlled.

This paper presents two methods for the measurement of the length of a bunch, including one that also provides the momentum- z correlation that exists within the bunch (where z is the longitudinal position coordinate). Of these two methods, one provides an absolute measurement of the bunch length and momentum spread, but requires a relatively special setup of the machine optics that may make it unsuitable in a lot of situations, while the second method provides a relative measure of changes in the length of the bunch, but has fewer limitations on the locations in which it can be used.

II. BEAM SETUP

The beam tests described in this paper ran parasitically with PEP-II [1] operation, and used beams accelerated in the SLAC linac in the periods between fills of the PEP-II rings. The linac operated with electron bunches at 30 Hz, with 10 Hz available for the beam tests.

The linac accelerated bunches of 1.6×10^{10} electrons extracted from the SLAC damping rings at an energy of 1.2 GeV to an energy of 28.5 GeV at the end of the linac. After the linac, the beam is transported through a 24.5-

degree “A-line bend” into the End Station A (ESA) test facility [2]. A cartoon of the SLAC ESA facility is shown in Fig. 1.

After exiting the damping ring, the bunch length is 5 mm rms with an energy spread of 0.07% rms. A compressor accelerating cavity and the ring-to-main-linac (RTML) transfer line compress the bunch length to about 300 μ m rms in the linac. The beam’s longitudinal phase space at the end of the linac and in ESA is determined by the compressor voltage, the phase of the accelerating rf compared to the beam, and the $R(5,6)$ transport matrix elements for the RTML and the A-line bend. In this study, the rms bunch length in ESA was varied between 300 μ m and 1 mm by adjusting the compressor voltage or the accelerating rf phase.

FIG. 1. (Color) A cartoon showing the SLAC linac, and the ESA facility.

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III. ABSOLUTE MEASUREMENT

The absolute measurement of the bunch length and energy spread at the end of the linac was accomplished by imaging the synchrotron light emitted from the beam as it moved around the A-line bend. It was arranged that the imaging screen was located so as to intercept the light emitted at a highly dispersive point in the beam line. At this point, since particles of different momenta will be traveling along different trajectories, the energy distribution in the bunch will be converted into a horizontal position distribution. Thus, the horizontal distribution of the image on the screen strongly correlates with the momentum distribution within the bunch.

In order to measure the longitudinal distribution of the particles, a transversely deflecting rf cavity [3] just upstream of the bend was activated. The TE mode present in this cavity imparts a transverse vertical kick to each of the particles, with an amplitude that has a sinusoidal dependence on the longitudinal position of that particle within the bunch. In this case, where the wavelength of the rf is significantly larger than the length of the bunch, and when the zero crossing of the rf corresponds to the mean longitudinal position of the bunch, the dependence of the kick on the particle position may be approximated as linear.

Since the cavity is kicking transversely, and since the strength of the kick depends on the longitudinal position within the bunch, the particles will be “streaked” in such a way that the longitudinal location of each particle within the bunch is rotated into the vertical plane.

Thus, the screen images are effectively a snapshot of the longitudinal phase space of the bunch—horizontal corresponding to the particle momentum, and vertical to the longitudinal location.

The measurement consisted of activating the transverse deflecting cavity, and recording images of the synchrotron

light on the screen for a range of compressor and linac rf settings.

A typical digitizer image is shown in Fig. 2.

A. Calibration

The horizontal (energy) axis of the synchrotron light screen was calibrated by moving the set point of the linac energy feedback, and observing the horizontal centroid of the synchrotron image. This provided the distance moved by the image due to a known energy change, thus allowing a conversion of the distance scale on the screen to an energy scale.

The vertical (longitudinal position) axis of the synchrotron light screen was calibrated by making small changes in the phase of the transverse cavity rf signal and observing the vertical centroid motion of the synchrotron image. The size of the motion on the screen can be compared to the distance through which the crossing point of the rf was moved (obtained from the value of the phase change, and the speed of light), thus giving a direct calibration of the vertical axis in terms of the longitudinal distance with the bunch.

It should be noted that the vertical calibration is valid only for known, repeatable, values of the rf amplitude. In addition, it is important that the phase change be kept small enough that the amplitude change can be considered to be linear with respect to time.

A correction to the calibration

The apparent length of the bunch as extracted from the height of the screen image will contain contributions from the vertical spread of the bunch, as well as any initial correlation between vertical and longitudinal position (i.e. bunch tilt), so it is necessary to account for these effects.

In order to remove these contributions from the vertical beam size and bunch tilt, data was taken at both zero crossings of the transverse cavity (i.e. with a phase difference of 180°), as well as with a field amplitude of zero (i.e. the rf in the transverse cavity was deactivated for one data point). The projected vertical size of the bunch, σ_p , at the synchrotron light screen can be expressed as a function of the vertical bunch size σ_y , the bunch length σ_z , the cavity voltage V , a voltage offset V_0 , and a constant K , corresponding to the scaling between the magnitude of the kicker voltage and the transverse deflection felt by the particles:

$$\sigma_p^2 = \sigma_y^2 + [K(V - V_0)\sigma_z]^2. \quad (1)$$

It will have a parabolic dependence on the transverse cavity voltage, with any incoming tilt (i.e. dy/dz) manifested by V_0 being nonzero. A parabolic fit to the data will, therefore, yield the transverse beam size, incoming tilt, and the bunch length.

FIG. 2. (Color) Digitized image from the synchrotron light screen.

The bunch length information obtained from this fit can then be used to provide a correction to the vertical calibration, allowing the image from the bunch length monitor to be correctly interpreted as a portrait of the longitudinal phase space.

B. Longitudinal transport

The longitudinal phase space measured at the end of the linac with the synchrotron light monitor can be used to calculate the longitudinal beam distribution in ESA.

Since there exists no more acceleration beyond this point, and since there were no significant sources of coupling between the transverse and longitudinal planes, it was only necessary to consider the $R(5,6)$ term of the transfer matrix; i.e., the term quantifying the correlation between the input momentum deviation of each particle, and the subsequent change in its longitudinal position.

This assumes that the energy distribution remains unchanged during passage around the bend, despite the fact that synchrotron emission is occurring, however the scale of this emission is insignificant when compared to the total energy of the beam, and may be neglected.

The longitudinal particle position in ESA, z_2 , can be calculated from the longitudinal position at the end of the linac, z_1 , and the particle's fractional energy deviation, $\frac{dE}{E}$, as follows:

$$z_2 = z_1 + R(5,6) \frac{dE}{E}. \quad (2)$$

Once the beam's longitudinal distribution at the end of the linac was determined by the synchrotron light measurements, Eq. (2) was used [with the known value of 0.465 for the $R(5,6)$] to determine the expected phase space, and therefore the bunch length, in ESA.

C. Results

A typical image from the synchrotron light monitor has already been shown in Fig. 2, where the longitudinal phase space shows the typical nonlinear behavior expected after acceleration by sinusoidally varying fields in a linac.

Figure 3 shows an image recorded under different conditions, and also includes the phase-space portrait after the calibration and correction steps mentioned in Secs. III A and .

Figure 4 shows how the bunch length varies with the rf phase ("phase ramp") in the linac. The calculated bunch length in ESA is also shown on this plot, and it can be seen that, despite the lack of variation in the bunch length measured at the end of the linac, the change in the longitudinal profile induced by the differing phases results in a significant length change in ESA.

The following sections contain details on the direct measurement of the bunch length in ESA, and it will be

FIG. 3. (Color) Another digitized image, alongside a reconstruction of the phase space for that bunch, including the correction mentioned in Sec. III A. The apparent sign change of the horizontal axis is due to a minus sign in the measured calibration constant.

FIG. 4. (Color) RMS bunch length variation with linac phase [length measured at end of linac shown in blue, and the value extrapolated from the measured phase space using $R(5,6)$ shown in red].

shown that the results presented in Fig. 4 are consistent with direct measurements in ESA.

IV. RELATIVE MEASUREMENT

While the measurements described in Sec. III are powerful enough to provide a direct measure of the bunch length, the technique is destructive to the quality of the beam, thus

not appropriate for use during regular machine operation, and impossible to integrate with, for example, a bunch-by-bunch phase feedback.

To provide an input to the linac low-level rf system, a bunch length monitor based on sampling energy radiated from the electrons was developed.

As the bunch moves through the cylindrical beam pipe, the field lines it generates terminate on the conductive boundary of this pipe, and move alongside it at the same speed (assuming a zero impedance boundary). This represents a current of the opposite charge, and with the same longitudinal charge distribution as the bunch, and is known as the “image current.”

If a material with a high resistivity (such as a ceramic) is placed in a gap in the conductive beam-pipe wall, then this will present a strong discontinuity in the electrical properties experienced by the image current. Since the magnitude of this current is determined only by the population within the bunch, it is not affected by the presence of the large resistivity, and so the apparent voltage required to generate this current must increase strongly.

This rapid increase in voltage across the ceramic gap will be observed as a strong emission of electromagnetic radiation from the beam whose spectrum depends on the Fourier transform of the longitudinal structure of the bunch.

Thus a measurement of the spectrum of this radiation will yield the longitudinal structure of the bunch.

Similarly, if the range in which the bunch lengths will fall is known *a priori*, this radiation may be monitored at a frequency calculated to respond strongly over this range.

The frequency spectrum, $I(\omega)$ of the radiation emitted from a Gaussian charge distribution with rms length, σ_z , and total charge, Q , moving at the speed of light, c , is

$$I(\omega) = \frac{Q}{\sqrt{2\pi}} \exp\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right). \quad (3)$$

The spectra expected from bunches of various lengths are shown in Fig. 5, and it can be seen that relatively high frequency measurements of ~ 100 GHz are necessary in order to distinguish the range of bunch lengths expected in ESA.

In this experiment, the radiation emerging from the ceramic gap was monitored at 16, 23, and 100 GHz, using appropriate diodes and filters (two 100 GHz diodes were installed, so four diodes were tested in total). Figure 6 shows a photograph of the beam line with two waveguides directed at a ceramic gap in order to direct the frequencies of interest at the diodes.

It can be seen from Fig. 5 that the intensity of the emitted radiation at 16 and 23 GHz is not expected to have a strong dependence on these bunch lengths. This is shown explicitly in Fig. 7, where the expected output at each of these frequencies has been plotted against the range of possible bunch lengths. Figure 7 shows that, while the amplitude at 100 GHz can be expected to change by almost 1 order of

FIG. 5. (Color) Radiation spectra calculated for Gaussian bunches of various lengths (indicated in the legend).

FIG. 6. (Color) Photograph of the waveguide installation at a ceramic gap in the beam line. Two waveguides can be seen in this picture: the upper one for transporting the lower frequency signals, and the lower, including a small horn, for coupling to the high frequency radiation.

FIG. 7. (Color) The expected amplitude of the rf emitted from the ceramic gap for the range of bunch lengths possible in ESA.

magnitude over the bunch length scan, the output of the lower frequencies will change by 10% or less.

Given that the diode's response is proportional to the power of the incident rf, the expected output goes as the square of Eq. (3) (and, therefore, the square of the values plotted in Fig. 7), thus the signal from the lower frequency diodes can be expected to change by $\sim 20\%$ over the course of a scan, while that from the 100 GHz diodes will be approximately 2 orders of magnitude.

In addition to the four diode measurements already mentioned, a pyroelectric detector (Infratec LME-301) was installed at an alternative ceramic gap ~ 3 m downstream. It has a wideband response, and the response to higher frequencies (up to infrared), means that this detector is sensitive to shorter bunch lengths.

Results

Figure 8 shows the output of the 100 GHz diode and the pyroelectric detector as a function of the linac rf phase, where it can be seen that the dependence of the signal strength in each case is approximately the same. This implies that the increased bandwidth of the pyroelectric detectors is of no benefit to the measurement of the range of bunch lengths generated here.

Figure 8 also shows that increasing linac phase corresponds to decreasing bunch length in ESA, to a limit of $\sim 49^\circ$ where the dependence appears to reverse. This reversal may be due to maximum compression having been reached (i.e. the bunch is now being overcompressed during its passage around the A-line bend). It is important to note, however, that it is possible that the bunch length is still decreasing at this point; however, the rf generated at the gap is no longer radiating strongly in the sensitive region of the pyroelectric detector and 100 GHz diode.

FIG. 8. (Color) Normalized output of (a) the 100 GHz diode and (b) the pyroelectric detector for a range of linac phase settings. Note that the phase ramp figures are quite different from those shown in Fig. 4 due to changes in the calibration of the linac phase measurement system.

Figure 9 shows the bunch length as predicted from the transverse cavity measurements plotted on the same axis as the 100 GHz diode data. Note that this data was gathered on a different occasion to that shown in Fig. 8, where the many differences in linac rf settings mean that the absolute values of the phase are not comparable. This figure clearly shows a strong anticorrelation between the diode output

FIG. 9. (Color) Output of the 100 GHz diode during a phase ramp scan, plotted alongside the predicted bunch length from the transverse cavity measurements (“LOLA” refers to the name given to the transverse deflecting cavity technique in the original paper [3]).

and the calculated length of the bunch, just as expected from Fig. 7.

V. CONCLUSIONS

Two methods for determining the length of an accelerated bunch of electrons have been demonstrated.

One method used a synchrotron light screen in a dispersive area, combined with a time dependent transverse kick of the beam, to “streak” the bunch in the longitudinal degrees of freedom (momentum p and longitudinal position z). This method provided a complete longitudinal phase-space portrait of the bunch at the end of the linac. It was then shown how this data could be used with the known $R(5, 6)$ transfer matrix element for the A-line bend to predict the bunch’s longitudinal distribution in ESA.

Despite allowing for a full phase-space measurement, a major drawback of this technique is that it is destructive, and, therefore, could not be used during periods when users require a certain quality and stability.

The second technique demonstrated relies on sampling the high frequency rf generated when the bunch passes a resistive discontinuity in the beam line. It was shown that this method is capable of measuring a large range of bunch lengths, and that its results compare well with predictions made using the first method.

This method does not measure the bunch length directly, but makes a measurement of the power contained in a certain window of the emission spectrum, where this spectrum is the Fourier transform of the longitudinal distribution of the bunch. In the case of a Gaussian bunch, this

spectrum will also be Gaussian, and a measure of the power inside a certain bandwidth will depend on the RMS bunch length. It can be seen in Fig. 7 that this dependence is, quite approximately, linear.

Although this method only measures the bunch length, and gives no information on the momentum coordinate, it has a minimal effect on the beam, and, therefore, could be included as part of an rf feedback.

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