BUNCH LENGTH MEASUREMENTS USING A TRANSVERSE RF DEFLECTING STRUCTURE IN THE SLAC LINAC*

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Abstract

The development of future free electron lasers (FEL) and linear colliders requires high brightness electron beams with bunch lengths on the order of 100-fsec. Reliable measurement of such a short bunch is not a trivial problem. Furthermore, x-ray FELs will require the ability to observe variable electron beam characteristics, such as emittance and peak current, within the length of the bunch. A simple way to measure bunch length and possibly unfold beam quality variations over the bunch length is to 'streak' the bunch using a transverse RF deflecting structure at its zero-crossing phase. Several S-band deflecting structures were constructed and tested at SLAC in the 1960's. One of these 2.4-m long structures has been installed in the SLAC linac for beam testing. We report on bunch length measurements performed using this structure and comment on future methods and applications.

1 INTRODUCTION

Several accelerator applications now require measurement of bunch length distributions on a time scale well below a picosecond. Ultra-short electron bunches can have an extremely high peak current as well as being useful as a probe for phenomena on a femtosecond time scale. Future x-ray FEL's such as the LCLS [1] at SLAC will use electron bunches compressed down to 80 fs and the Short Pulse Photon Source (SPPS) at SLAC will use bunches as short as 30 fs rms [2]. This is well beyond the reach of conventional streak camera technology. We have taken up an idea dating back to the early commissioning days at SLAC in which the beam in the accelerator is "streaked" in order to measure its bunch length distribution [3]. An RF transverse deflecting cavity operating at the same 2856 MHz frequency as the main linac is used to sweep the beam transverse to the direction of propagation, as shown in Fig. 1. The cavity is operated at the zero-crossing phase of the field, where the time derivative is maximum, so that the bunch is "crabbed", or in other words, is given a strong correlation between longitudinal *z*-coordinate and transverse position. Measurement of the beam size downstream on a profile monitor is used to measure the bunch length. It is possible to deliver a large amount of power to such a device to give the beam an extremely strong kick and thereby obtain good bunch length resolution.

Several S-band deflecting cavities were built at SLAC in the 1960's, not as bunch length measuring instruments, but as charge separation devices for use in the high-energy physics, secondary-particle beam lines [4]. We have recovered one of the 2.44-m long deflecting structures and installed it in the main linac to test its ability to reliably measure bunch length distributions in preparation for the future, short-bunch accelerator operations at SLAC. This paper reports on the first measurements of the bunch length properties of the high-energy beam with this structure.

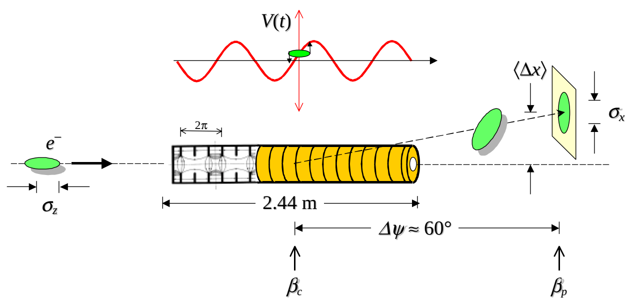

Figure 1: Principal of operation of the TM_{11} transverse deflecting RF cavity to crab the electron beam and measure its bunch length on a profile monitor.

2 INSTALLATION AND OPERATION

The structure has been installed in sector 29, close to the end of the 3-km long SLAC linac. The 2.44-m long, traveling wave cavity replaces one of the standard 3-m accelerator sections. Normally, one klystron drives four adjacent accelerator sections, but in sector 29 some of the fourth, or D-sections, have been removed to make room for transverse collimators in SLC operation. We took one of these empty locations, 29-4, to install the transverse cavity. The three neighboring accelerating structures are powered by one klystron so a second klystron was installed above the penetration leading to the transverse cavity. This permits the amplitude and phase of the transverse cavity to be varied without altering the acceleration of the beam. Spare klystron power supply modulators are not readily available so the present configuration allows power to be supplied either to the deflecting structure or to the accelerating klystron by switching cables between the klystrons.

The beam observation system also makes use of existing hardware and controls in the linac. A profile monitor is located approximately 60° in betatron phase, ψ_y, downstream of the structure, close to local minimum in the beta function, β_p. With the beta function close to a local maximum at the deflecting structure, β_c, this arrangement is optimal for best resolution of bunch length (see Eq. 3). The deflecting structure is oriented to kick the beam in the vertical plane but the profile monitor is

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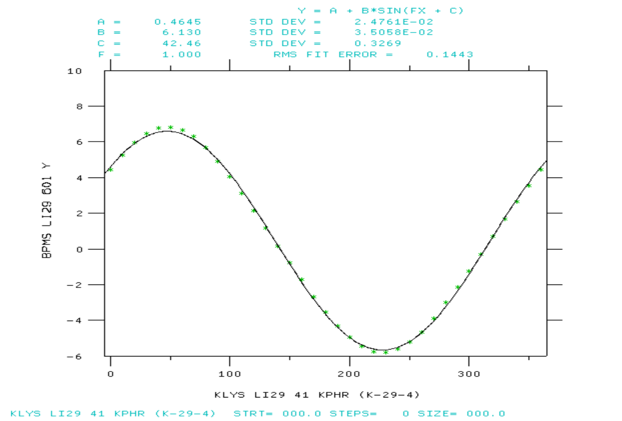

Figure 2: Beam deflection as measured on a BPM as a function of RF phase of the deflecting structure.

located off the accelerator axis in the horizontal plane. However, a pulsed horizontal deflecting magnet can be triggered to deflect individual beam pulses onto the screen. This method is used routinely to continuously monitor the transverse beam sizes and emittance by “stealing” at 1 Hz from the 120 Hz rate of operation, without having to propel the screen in and out of the beam. The image of the beam on the chrom-ox screen is digitized with a remote camera allowing the intensity profile along the bunch to be recorded.

In anticipation of future use in short-bunch programs at SLAC we have tested the system with various beams. Between PEP-II injection cycles a 28-GeV ‘scavenger’ electron bunch from the damping rings is normally used to produce positrons. This ‘scavenger’ bunch can also be diverted to the end of the linac, and the upstream bunch compressor can be varied to change its bunch length.

3 CALIBRATION

The shunt impedance of the structure gives a deflecting voltage of

$$V_0 \approx \left(1.6\ \text{MV/m/MW}^{1/2}\right) L\sqrt{P_0} \qquad (1)$$

so that a structure with L = 2.44 m we get about 17.5 MV with an input power, $P_0 \approx 20$ MW.

The most direct way to calibrate the deflection strength is to observe the beam position, y, on a downstream BPM as the RF phase is varied, as shown in Fig. 2. The position amplitude, B, of the fitted curve, $y = B \sin\phi_{rf}$, leads to the

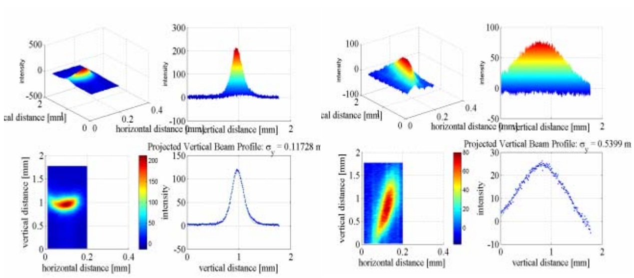

Figure 3: Digitized images of a damped 28-GeV beam when the deflector is off (left) and at 17.5 MV (right).

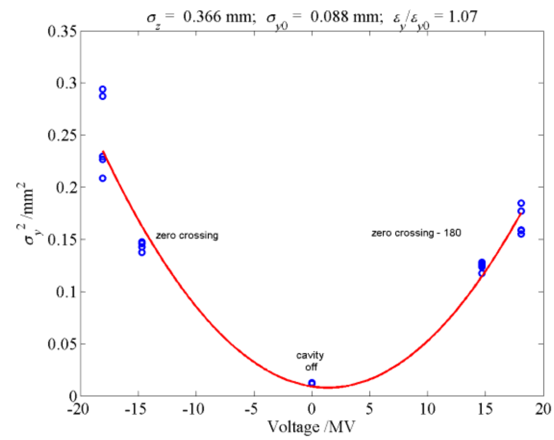

Figure 4: Vertical beam size squared measured as a function of deflector voltage, yielding σ_z=1.2 ps.

expression for the RF amplitude

$$eV_{RF} = B\frac{E_0}{R_{34}}, \qquad (2)$$

for particles of energy E_0, where R_{34} is the transfer matrix element from the structure to the BPM.

4 BUNCH LENGTH MEASUREMENT

The vertical beam size at the profile monitor is a function of bunch length and deflector parameters [5].

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda_{rf} E_0} \sin\Delta\psi_y \cos\varphi_{rf}\right)^2} \qquad (3)$$

The bunch length is determined from the quadratic relation between the square of the measured vertical beam size and the RF deflecting voltage.

$$\sigma_y^2 = A\left(V_{rf} - V_{rf_{\min}}\right)^2 + \sigma_{y_0}^2 \qquad (4)$$

where A is determined from the fit to the measured data in figure 4, giving a bunch length

$$\sigma_z = A^{1/2}\frac{E_0 \lambda_{rf}}{R_{34} 2\pi}. \qquad (5)$$

The data points in Fig. 4 at negative deflection voltage correspond to measurements at 180° in RF phase from the other zero crossing. The measured beam size can be symmetric around zero voltage, as in Fig. 4, in which case $V_{rf\,min}$ = 0. However, if the bunch is already ‘crabbed’ as it enters the deflecting structure, due to transverse wakefields in the linac, the measured bunch length will be asymmetric with voltage, as in the example in Fig. 5. The RF voltage where the beam size is minimum indicates how much external crabbing must be applied to cancel the wakefield-induced y-z correlation (‘crab’) in the bunch. For the example shown in Fig. 5 a small vertical orbit oscillation was intentionally introduced to generate transverse wakefields. This demonstrates the usefulness of

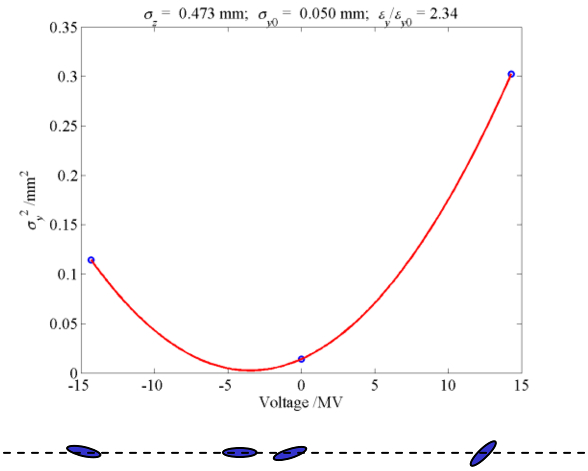

Figure 5: An asymmetric beam size scan with RF voltage indicates an incoming transverse-longitudinal correlation in the bunch, shown in the lower illustration, which is cancelled by the cavity at $V\left(\sigma^2_{y\,\min}\right)$.

the transverse cavity, not only as a bunch length diagnostic, but also as a tool for measuring transverse wakefield effects and possibly correcting them with orbit bumps. This is particularly important for linear colliders.

5 BUNCH LENGTH TUNING

The efficacy of tuning the bunch compressors based on the bunch length measured with the transverse cavity is demonstrated in Fig. 6. Here, the RF voltage in the damping Ring-To-Linac (RTL) compressor beamline is varied to change the bunch length. Bunch length measurements around the minimum have smaller error bars since the beam is more gaussian.

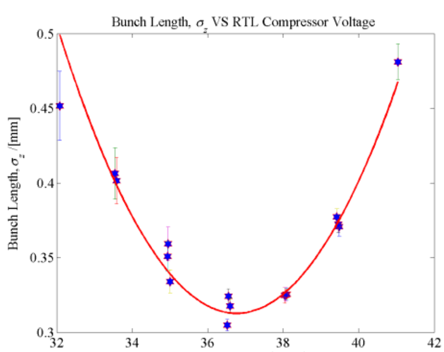

Figure 6: Bunch length measured as a function of RTL compressor voltage.

The beam is often tuned for over compression to give the head of the bunch a steeper charge distribution, which is more favorable for wakefields in the linac. The non-gaussian profile is evident in Fig. 7 where an individual bunch profile is shown for the over-compressed case. The measured profiles and bunch lengths agree favorably with particle tracking simulations shown in Fig. 8.

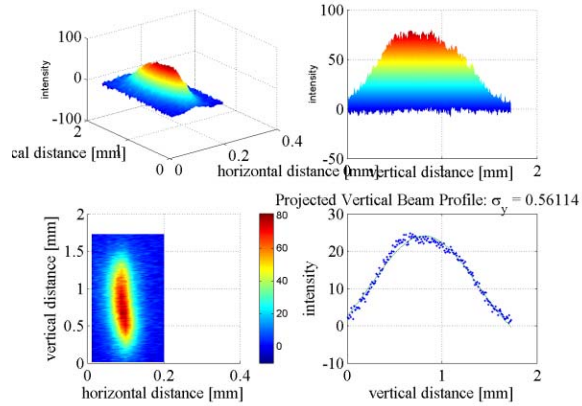

Figure 7: A non-gaussian profile is measured for an over-compressed bunch with RTL compressor voltage at 42 MV.

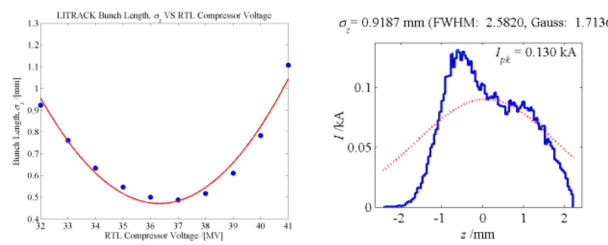

Figure 8: Tracking simulation of bunch length vs. compressor amplitude (left), and bunch length distribution for over-compressed beam at 42 MV.

6 CONCLUSION

The transverse deflecting cavity is a fast and effective means of measuring bunch length distribution. Tuning of the bunch compressor with this diagnostic clearly shows both the variation in bunch length and the shift to a non-gaussian beam distribution as the bunch is over-compressed. Head to tail tilt in the bunch due to wakefields can also be measured and compensated with this diagnostic. In addition, it is possible to measure the transverse emittance variation along the bunch length, which may be very useful for future x-ray FELs.

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