BUNCH LENGTH MEASUREMENTS IN LEP

A. J. Burns, H. Schmickler, CERN, Geneva, Switzerland

Abstract

For many years a streak camera has been used for observing the longitudinal distribution of the particles in any LEP e^+ or e^- bunch (5-50 ps r.m.s. length) on a turn by turn basis, using synchrotron light. In 1996, a comparison made with the longitudinal vertex distributions of 3 LEP experiments allowed the identification and elimination of certain systematic errors in the streak camera measurements. In 1997, a new bunch length measurement technique was commissioned that uses the high frequency slope of the bunch power spectrum from a button pickup. In 1998, this new method was confronted with measurements from the streak camera and the LEP experiments. The measurements made in 1996 and 1998 are presented, with emphasis on the calibration of the two instrumental methods and their respective precision and limitations.

1. STREAK CAMERA SET-UP

Synchrotron light pulses are produced when e^+ and e^- bunches pass through small wiggler magnets on either side of intersection point 1 of LEP [1]. The visible light is extracted by two thin beryllium mirrors and focused on a double sweep streak camera [2] in an underground optical laboratory [3]. The optical set-up allows the simultaneous observation of the *top* and *side* views of any photon bunch from both LEP beams within the same fast sweep [4]. The photon bunch length and longitudinal density distribution corresponds to that of the particle bunch that emitted it. The slow sweep allows up to 100 fast sweeps to be recorded on one image, which can be used to follow successive bunch passages. Although originally requiring local manipulation, the camera can now be fully operated via the control system network [5]. Bunch dimension averages are transferred every 10 s to the LEP measurement database, and a high bandwidth video transmission allows the streak camera images and processed results to be viewed in real time (at 25 Hz) in the LEP control room (Figure 1).

2. STREAK CAMERA BUNCH LENGTH MEASUREMENTS (1995-96)

During an experiment to investigate the LEP machine impedance in August 1995, the lengths of very low current (3µA ≡ 2 10^9 e^+) bunches were measured. This was the first reliable indication of the existence of a 10 mm^2 offset in the square of the bunch length measured by the streak camera (Figure 2).

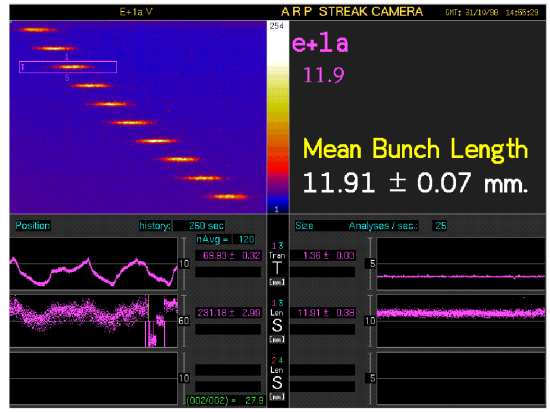

Figure 1: Control room video display updated at 25Hz.

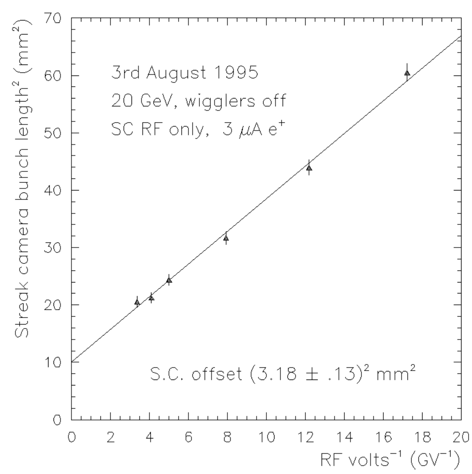

Figure 2: Streak camera bunch length^2 as a function of inverse RF total voltage at 20 GeV (August 1995), showing clearly the 10 mm^2 offset present at that time.

As the bunch current was well below the turbulent threshold at which bunch length starts to rise with current, the r.m.s. bunch length in metres, σ_s , is given by:

$$\sigma_s = \frac{\alpha_C R}{Q_S} \frac{\sigma_E}{E} \qquad (1)$$

where α_C is the momentum compaction, R the radius of LEP, Q_S the synchrotron tune, and σ_E / E the relative r.m.s. beam energy spread.

Using the relation $Q_S^2 \propto V_{RF}$ where V_{RF} is the total RF voltage per turn (which has been experimentally verified to apply up to 45 GeV) one obtains:

$$\sigma_s^2 \propto \frac{1}{V_{RF}} \qquad (2)$$

The good agreement of the data in Figure 2 with a linear fit implies that the measured bunch lengths need to be corrected according to:

$$\sigma_s^2 = \sigma_{meas}^2 - \sigma_{corr}^2 \qquad (3)$$

This is equivalent to the deconvolution of the observed longitudinal bunch profile with a Gaussian of width σ_{corr}. However, the value of σ_{corr} is much too large to be due to the finite instrumental resolution.

Bunch length measurements made in December 1994 had also indicated a substantial correction term (of at least 50 mm^2) [6]. However, in the analysis presented, an error had been made in the computation of the transverse spot size correction.[1] Once this error was rectified, the measurements of bunches below 12 mm were consistent with a correction term in the range 0-20 mm^2.

2.1 Comparison with LEP experiments' data

The measured bunch length is defined as the observed r.m.s. longitudinal deviation of the particles about the bunch centre of charge. Making the reasonable assumption that both beams have the same bunch length and shape, the bunch length defined in this way is a factor of $\sqrt{2}$ greater than the r.m.s longitudinal deviation of e^+e^- interactions about the average position in each experiment. This is true for any bunch shape, and so is insensitive to departures of the actual bunch shape from a pure Gaussian distribution.

A comparison made in 1993 between the streak camera measurements and the longitudinal vertex distributions of the LEP experiments had demonstrated agreement within 5-10% between the two sets of measurements, for bunch lengths of 9-13 mm [8]. As a 10 mm^2 correction alters a 10 mm bunch length by only 5%, in 1996 the additional RF capacity installed for running LEP above 80 GeV was used to produce bunches with σ_s below 5 mm at 45 GeV.

To ensure that the vertex distribution widths accurately reflected the corresponding bunch lengths, various cuts and checks were made on the raw data from the LEP experiments (event reconstruction quality, numbers of tracks, distribution symmetry, hour-glass effect,…) [9].

The first comparison made in August 1996 (Figure 3) confirmed a 10-12 mm^2 quadratic offset, similar to the August 1995 data. A second comparison made in October-November 1996 (Figure 4) produced a much smaller offset of 1.6 ± 0.6 mm^2, by using an interference orange-red filter (FWHM 9 nm) in front of the streak camera.

These comparisons also confirmed the correctness of the streak camera "scale factor" to a few % (slope of streak camera versus experiments correlation consistent with unity), which also corresponds to the accuracy of the calibrations using an optical delay line [9].

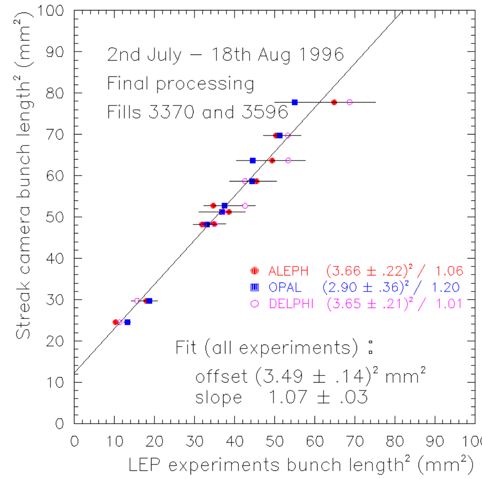

Figure 3: Streak camera bunch length² as a function of LEP experiments' bunch length² (August 1996).

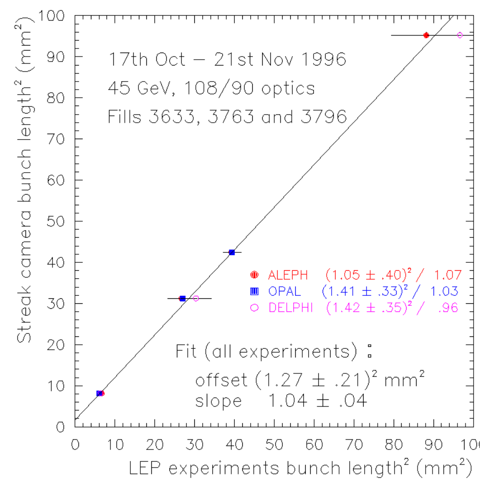

Figure 4: Streak camera bunch length² measured with orange-red monochromatic filter as a function of LEP experiments' bunch length² (Oct.-Nov. 1996).

A similar offset of 0.9 ± 0.1 mm^2 was also obtained when short bunches (1-2 mm) were measured at different RF voltages at 22 GeV with orange/red light.

2.2 White light effects

Group velocity dispersion (GVD) is a physical phenomenon that is well known in the domain of laser pulse transmission in optical fibres. The variation of the group velocity with wavelength separates in time the different wavelength components of the synchrotron radiation pulses. The white light pulses measured by the streak camera are therefore lengthened compared to the pulses generated in LEP.

The group velocity, that characterises the rate of the transmission of energy, can be derived from elementary wave packet theory as:

[1] The transverse spot size in the direction of the fast sweep, σ_T, adds quadratically to the bunch length, σ_s, to produce the observed streak length, σ_L [7]: $\sigma_L^2 = \sigma_s^2 + \sigma_T^2$

$$g(\lambda) = v(\lambda) - \frac{dv}{d\lambda} \qquad (4)$$

where $v(\lambda)$ is the phase velocity of the individual simple harmonic wave components and is related to the refractive index of the medium, $n(\lambda)$, by $v(\lambda) = \frac{c}{n(\lambda)}$.

Measurements of the chromatic separation produced by the dispersive material in the original e^+ *side* path (~25 cm of glass and quartz) are shown in Figure 5, with respect to the arrival of the 620 nm component of the pulse.

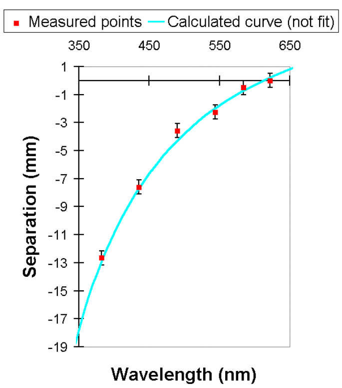

Figure 5: Measured separation of different wavelength components of synchrotron light pulses at entrance to streak camera.

The calculated curve was obtained from the thickness of quartz and BK-7 glass in the optical path and the group velocities $g(\lambda)$ calculated from the known refractive indices of the two materials.

In order to estimate the amount of pulse lengthening produced on the measured "white" light pulses, the proportion of different wavelengths contributing to the final steak image had to be measured. This produced slightly different spectra for each light path, but on average the spectra were centred at 500 nm with a FWHM of ~150 nm.

Numerically convoluting these spectra with the expected GVD produced the result that the r.m.s. length of the original white light pulses were increased quadratically by the square of 0.10-0.11 mm per cm of quartz (or 0.8 cm of BK-7 glass) in the optical path. As an example, the 28 cm of quartz-equivalent (quartz + 1.25*glass) in the e^+ *side* path should produce a lengthening term of ~ 8 mm^2 (2.8^2).

There is in addition a small reduction in measured bunch length as the wavelength of the light used is increased. Measurements with different wavelength filters showed decreases in bunch length of 0.4-0.5 mm in going from blue to red light (Figure 6).

The different slopes indicate that this effect does not produce a constant mm^2 offset for a given wavelength shift. Nevertheless, the magnitude of the difference between measuring at the average wavelength of the white light spectrum (~500 nm ≡ 2.5 eV) and with a 600 nm filter (≡ 2.0 eV) can be seen to be 1-2 mm^2.

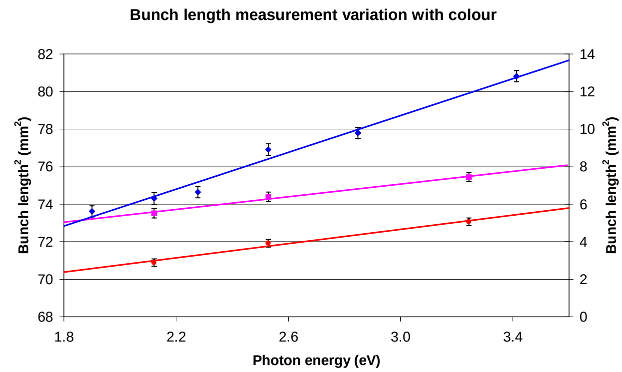

Figure 6: Measured bunch length^2 as a function of photon energy for 8.5 mm (top data), 2.2 mm (middle data) and 1.6 mm (bottom data) bunches.

Thus the total difference in quadratic offset between measuring with white light and with a orange-red filter is expected to be 9-10 mm^2, in reasonable agreement with the comparison with the LEP experiments.

3. BUTTON MONITOR BUNCH LENGTH INSTRUMENT

A new technique for measuring bunch lengths in LEP was tested in 1996 and commissioned in [10]. It is based on the spectral analysis of signals from a small (7 mm diameter) button pickup. Assuming Gaussian bunches and after correction for the calculated system transfer function, the slope of log (amplitude) versus frequency^2 gives the bunch length^2.

In practice 2 or 3 frequency zones (around 6.2, 7.6 and 8.9 GHz) are used, in which there are no dominant resonances from the BPM, cable, or feedthroughs. The highest frequency zone is excluded from the analysis when it is too close to the noise level. In 1997, bunch length measurements in the range 3-12 mm were made as a function of bunch current at different energies and led to an estimate of the longitudinal inductive impedance, Im (Z/n) ≅ 0.2 Ω [10,11]. No cross-check was made with the streak camera.

4. STREAK CAMERA-BUTTON MONITOR CROSS-CALIBRATION (1998)

4.1 Changes to streak camera set-up

The streak camera set-up used in 1998 was optimised taking into account the results of 1996. Although special measurements at 45 GeV and below could still be done with the mini-wigglers, routine monitoring at all beam energies up to 94.5 GeV used a "parasitic" light source in a quadrupole. This was done to avoid the risk of damage to other instrumentation from the very hard X-rays emitted by the mini-wigglers from high energy beams. The loss of light intensity was compensated by eliminating the *top/side* split (gaining a factor of 4) and a 50% split to a test bench. The light was focused to the smallest possible spot to minimise the importance of the spot size correction needed with "wider" streak images. Finally, the chromatic effects described in section 2.2 were made negligible by using a cut-off filter transmitting only the orange-red end of the spectrum and removing the Dove prisms used to rotate the transverse axes of the beam images. The total amount of dispersive material in the optical path was thus reduced by a factor of 2 compared to 1996. The image in figure 1 was taken in these conditions at 94.5 GeV.

4.2 Bunch length comparisons

Differences of ~1.5 mm between the button measurements using all 3 frequency bands or only the lower 2 bands led first of all to the elimination of the 8.9 GHz band from the analysis. There was then reasonable agreement between the streak camera and button measurements in the bunch length range 9-12 mm.

However, a dedicated machine experiment with short bunches (2-5 mm) at 22 and 45 GeV showed that there remained considerable disagreement in the lower range of bunch length [12]. Figure 7 shows measurements from both instruments at 45 GeV as a function of inverse Q_S, as well as the 100 µA current prediction (dashed line) from the longitudinal inductive impedance measurements of 1997 [11] and the zero current prediction (dotted line). An offset of 2 mm^2, obtained from plotting bunch length^2 against inverse square of Q_S, was removed from the streak camera data.

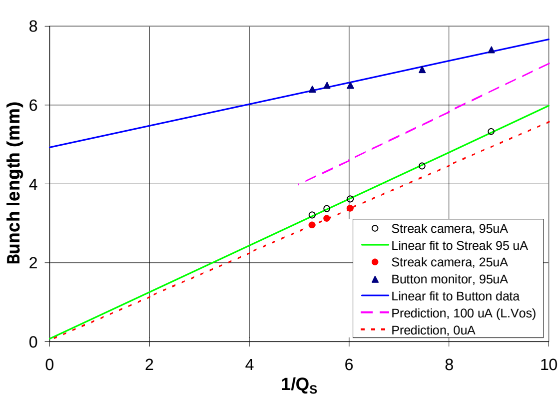

Figure 7: Streak camera and button monitor measured and predicted bunch lengths as a function of inverse Q_S at 45 GeV (July 1998).

As well as a substantial difference between the two instrumental methods, the 25-95 µA bunch length difference measured by the streak camera was much less than the prediction.

The absolute calibration of the streak camera made in 1996 required that both this prediction and the button measurements must be wrong. Advantage was therefore taken of a 45 GeV calibration period in October 1998 to repeat the comparison with the experiments' vertex distributions. As before, reducing the current in the wigglers and increasing the total RF voltage during Z^0 physics coasts enabled measurements to be made at a few distinct bunch lengths in the range 2.5–6.5 mm.

The LEP experiments confirmed the calibration of the streak camera measurements to within 5% and indicated the presence of an average offset in the square of the bunch length of 3.9 ± 0.5 mm^2. On the other hand, the button pickup measurements suffered from a very large offset of around 40 mm^2.

During the entire Z^0 runs, constant monitoring of the bunch length measurements from the streak camera and button pickup allowed numerous additional comparisons to be made between the 2 instruments over the bunch length range up to 10 mm. Measurements from subsequent 94.5 GeV fills extended this to 11.5 mm. This data is shown in Figure 8, together with data from a number of 94.5 GeV fills in July.

The measured average quadratic offset of 4 mm^2 has been subtracted from the streak camera values, whereas no correction has been applied to the button pickup data.

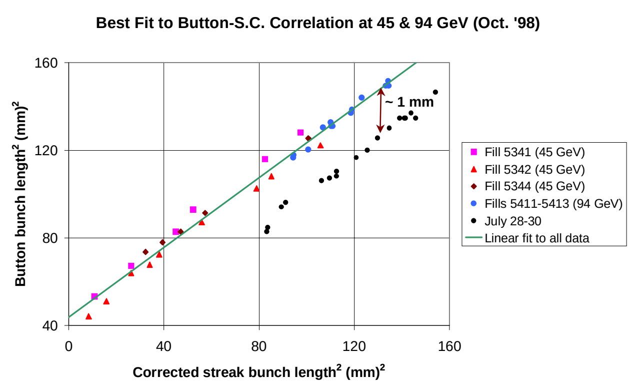

Figure 8: Correlation between streak camera and button monitor bunch length^2 at 45 and 94 GeV (October 1998).

The line represents a linear fit to the data from the Z^0 runs and subsequent high energy runs of October 1998 and corresponds to the formula:

$$\sigma_s^2 = 1.25\left(\text{Button}\,\sigma_s^2 - 44\right)\,\text{mm}^2 \qquad (5)$$

Using this as a correction formula, the button pickup values then agree with the corrected streak camera values to ± 0.5 mm over the range 5-11.5 mm. Shorter bunch lengths are not well corrected by this means; but given the large measurement offset of (6.5 mm)^2 and its poor stability (e.g. a systematic shift of 7 mm^2 between data from fills 5341 and 5342), it is not reasonable to try and measure such short bunches with the button pickup anyway.

Finally, although the July 1998 data have the same slope as the October data, they are offset by about -20 mm^2. Indeed applying the correction formula (5) produces an error of 1-2 mm with respect to the corrected streak camera values. Such an unexplained shift would imply that, without continual cross-calibration, even the "corrected" button pickup values could be wrong by typically ± 1.5 mm.

4.3 Bunch current dependence

The bunch current from which measurements are possible with the streak camera depends on the synchrotron light source used (mini-wiggler or parasitic), the bunch length, the optical attenuation (especially chromatic filtering), the camera sweep speed and image intensifier gain. In the normal operating conditions described in section 4.1 using parasitic light from 10 mm bunches, adequate measurements are possible from 30-50 µA per bunch and good quality measurements from 50-100 µA. The use of the dedicated mini-wiggler source and less chromatic filtering allows the measurement of bunches down to a few µA of current (few 10^9 particles).

The power measured by the button pickup is integrated over all bunches in LEP and therefore depends on the total beam current. During filling, the bunch length generated by the spectrum analysis algorithm was observed to rise from low values and slowly approach a stable value. In the case of 15 mm bunches, less than 4 mm was "measured" with 1 mA and a total beam current of 2.3 mA was needed before 90% of the final bunch length was reached. During the same period, the bunch length measured by the streak camera changed by less than 5%. Shorter bunches, that produce more relative power in the higher frequency band, can be measured at lower current, e.g. 1.1 mA for 10 mm and 0.8 mA for 3.5 mm bunches

These observations differ from the previously published conclusion that *"for a 10 mm long bunch at least 200 µA total beam current is required to make a proper measurement"* [11]. In addition, even using 2 beams of 8 bunches each ("bunch-train" mode), it would seem impossible to make meaningful measurements of the dependence of bunch length on current below bunch currents of around 50-70 µA, without first calibrating the instrumental beam current dependence.

5. CONCLUSIONS

Two different methods for measuring bunch lengths have been used in LEP. After correction of a large offset in the results from the spectral analysis of button monitor signals, it is found that bunch lengths in the range 5-12 mm can be measured with an absolute precision of ± 1.5 mm for sufficiently high total beam currents (typically above 1 mA, i.e. 6 10^{11} particles). The large measurement offset (that can be assimilated to an error in the transfer function) indicates that the transfer impedance is difficult to calculate in the presence of other effects in the spectra.

The image analysis of synchrotron light pulses incident on a streak camera remains the most accurate bunch length measurement technique in LEP. For precise measurements on "short" bunches (< 8 mm), the path length in dispersive media must be minimised and the spectral acceptance limited (preferably in the longest wavelength part of the spectrum). Comparisons with LEP experiments in 1996 and 1998 confirmed the correct calibration to 3-5% and indicated a small quadratic offset in the range 2-4 mm^2.

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