Bunch Length Measurements at TTF with a Streak Camera

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Abstract

We have measured bunch lengths of the TTF beam with a streak camera using synchrotron radiation from the experimental area dipole. Measurements have been made both with and without bunch compression. The minimum bunch length measured with maximum bunch compression is $\sigma_z = 0.7 \pm 0.4\,\mathrm{mm}$ ($2.3 \pm 1.3\,\mathrm{ps}$). The data are in good agreement with simulations.

1 Introduction

The electron beam of the TESLA Test Facility (TTF) is produced by an injector based on a laser driven rf gun [1]. The injector is followed by an accelerating module (ACC1), a magnetic chicane bunch compressor (BC2) [2] and a second accelerating module (ACC2). The spectrometer dipole magnet situated in the experimental area at the end of the linac is used for energy measurements. A sketch of the linac is shown in Figure 1.

The electron bunch length is one important beam parameter. In March 2000 we carried out streak camera measurements using synchrotron light from the spectrometer dipole at the experimental area. The aim was to measure the bunch length of the injector as well as the bunch length with bunch compression. Effects of the rf gun phase and the phase of the first acceleration module on the bunch length were studied. We also investigated possible substructures of the bunches.

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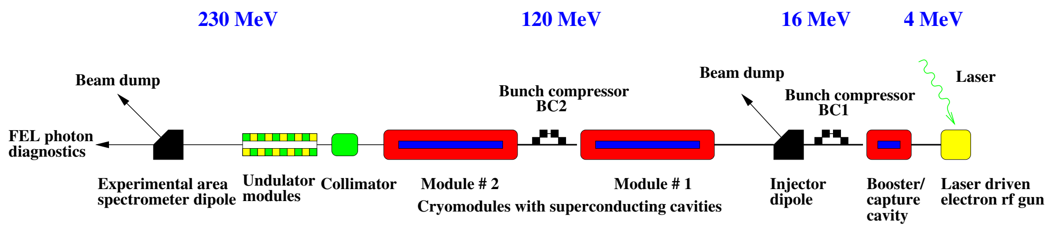

Figure 1: Layout of the TTF linac (not to scale, total length about 70 m). Approximate beam energies are indicated.

The nominal bunch length in the injector is 2 mm. The rf gun is operated with an accelerating field phase of 40°. Zero phase is defined as the phase, where the bunch center is at the zero crossing of the accelerating field. The bunch length depends on the gun phase: we expect the bunch length to vary between 1 mm and 3 mm for phases of 0° to 90°. In previous streak camera measurements at TTF, the smallest achievable bunch length was $\sigma_z = 1.95 \pm 0.08$ mm at gun phase of 25° [3]. No bunch compressor was used for this experiment. With bunch compression, we expect bunch lengths between 250 to 500 μm depending on the bunch length before compression.

2 Experimental set-up

A streak camera provides a convenient way to measure electron bunch length in the millimeter range. The streak camera used is on loan from LAL (Orsay, France) and has been manufactured by the ARP company [4].

We use synchrotron light produced by the horizontally deflecting spectrometer dipole at the experimental area. The light is reflected by an aluminum mirror through a quartz window vertically out of the vacuum chamber and guided by a set of aluminum mirrors through a 11 m long transport line into the optical diagnostics area, where it is recorded by the streak camera.

The operation principle of a streak camera is shown in Figure 2. The light pulse being measured passes through a slit in the front of the camera. In our case, the slit is horizontal, i.e. in the same plane as the dipole. The slit is imaged onto the photocathode and its function is to reduce the transverse dimension of the image. The photocathode used (S-20) is sensitive for wavelengths between 200 and 800 nm. The input optics is adapted to

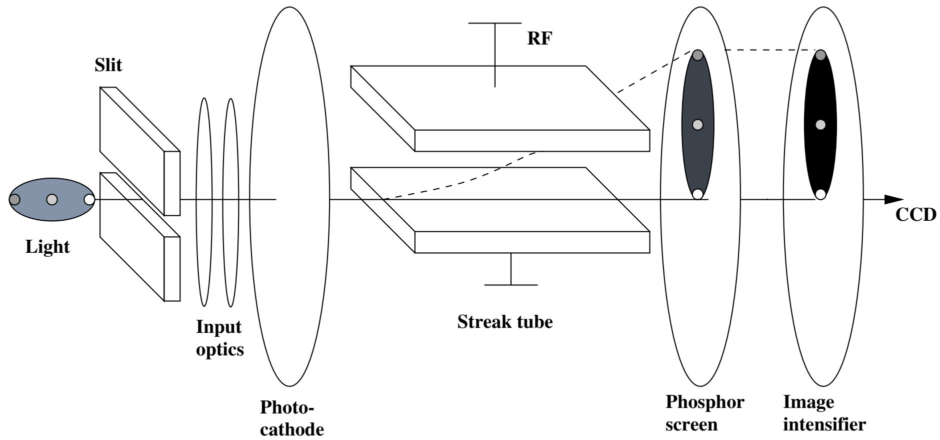

Figure 2: Operation principle of a streak camera.

this wavelength range. This allows measurements of the UV pulses (262 nm wavelength) of the photocathode drive laser. For the synchrotron radiation experiments, an additional focusing achromat lens is used, which has a cut off at 350 nm.

On the photocathode, the incident light is converted into photoelectrons, whose number is proportional to the intensity of the incoming light. These electrons are accelerated and traverse the streak tube where they are deflected transversally (streaked). The deflection is proportional to their arrival time into the tube and is a direct measure of the time structure of the incident light pulse. The streaked electrons are made visible by converting them back to photons on a phosphor screen (P-20). An image intensifier increases the light output by a factor of about $3{\cdot}10^3$. Finally, the light is registered by a CCD camera. In the direction of the streak, the image at the CCD gives the temporal profile. Perpendicular to this, the spatial profile in this direction is measured. The maximum streak speed of the camera used is 10 ps/mm providing a resolution of 0.25 ps per CCD pixel.

The intrinsic time resolution of the streak camera tube depends on the wavelength: the measured values for the maximum streak speed are $\sigma_z = 0.6 \pm 0.1$ ps for $\lambda = 760$ nm and $\sigma_z = 0.9 \pm 0.1$ ps for $\lambda = 380$ nm [5]. Due to the low intensity of the light signal, the whole wavelength range from 350 to 800 nm had to be used in this experiment. Therefore, we conservatively estimate the intrinsic tube resolution in our case to $\sigma_{\rm res} = 1.0 \pm 0.1$ ps.

3 Measurements

The electron bunch length has been measured in three series for various phase settings of the rf gun and the accelerating modules. In addition, the pulse length of the photocathode laser has been measured as well. In series 1, the electron bunch length of the injector has been measured. To do this, the beam has been transfered straight through the linac without using the bunch compressor BC2. We assume, that in this case the bunch length does not change during transport and acceleration on crest of both modules. The bunch length has been measured versus the relative phase between the rf gun and the laser (gun phase). In series 2, the beam has been transferred through the bunch compressor BC2, both accelerating modules has been run on crest. The rf gun phase has been varied. Finally, in series 3 the compression of the electron bunch with BC2 has been measured as a function of the phase of the first accelerating module. BC1 has not been used in the experiments described in this report. The parameters during the measurements are listed in Table 1. For every series, about 10 points with typically 4 measurements per point have been taken. The beam time required for one series is about eight hours.

Table 1: Machine parameters during the experiments. Series 1: Injector electron bunch length vs. gun phase, the bunch compressor BC2 was not used; Series 2: Electron bunch length vs. gun phase while passing through BC2 without compression; Series 3: Electron bunch length vs. the phase of the first accelerating module ACC1 while compressing with BC2. The bunch charge for all experiments was approximately 1 nC, and the gun gradient at the cathode was 38 MV/m.

Series	Date	Gun phase	ACC 1 phase	ACC 2 phase	BC2
1	25-Mar-00	$-3°$ to $61°$	on crest	on crest	off
2	13-Mar-00	$11°$ to $61°$	on crest	on crest	on
3	16-Mar-00	$48°$	$-20°$ to $19°$	on crest	on

4 Data analysis

In order to fully exploit the resolution of the camera, the entrance slit of the camera has to be small. For the fastest streak speed of the camera of 10 ps/mm, a slit width of 100 μm corresponds to a resolution of 1 ps. To ensure this, an image of the slit has been taken during every measurement series. For measurement series 1 the slit size is $\sigma_{\rm slit} = 107\,\mu$m, and for series 2 $\sigma_{\rm slit} = 71\,\mu$m. For series 3, the slit is larger to allow more light intensity on the camera: $\sigma_{\rm slit} = 187\,\mu$m.

In this analysis, we assume that the resolution is dominated by the streak tube resolution and the slit size. Contributions from other sources like the CCD camera pixel size and diffraction effects are small compared to that. The intrinsic tube and the slit width are subtracted from the measured value: $\sigma_z = \sqrt{\sigma^2_{\rm mes} - \sigma^2_{\rm res} - \sigma^2_{\rm slit}}$.

For every machine setting, several images are taken. An example of an image is shown in Fig. 3. The projection of the image onto the time axis is fitted by a gaussian function. The fit includes a constant background. For the fit, the measurement error of a pixel is assumed to be constant. The bunch length is then considered as the mean value of the widths (sigma) of all profiles. The error is estimated as the rms variance.

In order to calibrate the gun phase, the transmitted charge through the gun is measured as a function of the relative phase between gun and laser (phase scan). Phase zero is the phase, where half of the charge is transmitted. In addition, the laser pulse length can be estimated from the rising edge of the scan (see Fig. 4).[6]

The phase of the first accelerating module is stabilized by a feedback system. A phase value can be set with a relative accuracy of better than 1°. During the measurements, where the rf gun phase had to be changed, the gun was operated without phase feedback. The feedback system does not allow to change the phase over a wide range with closed loops. In series 1, the phase has been measured for every data point, but in series 2, only the set values for the phases are used. The uncertainty of the phases in both cases is not more than 2°.

The effect of the horizontal spread of the synchrotron radiation fan on the time resolution is negligible.

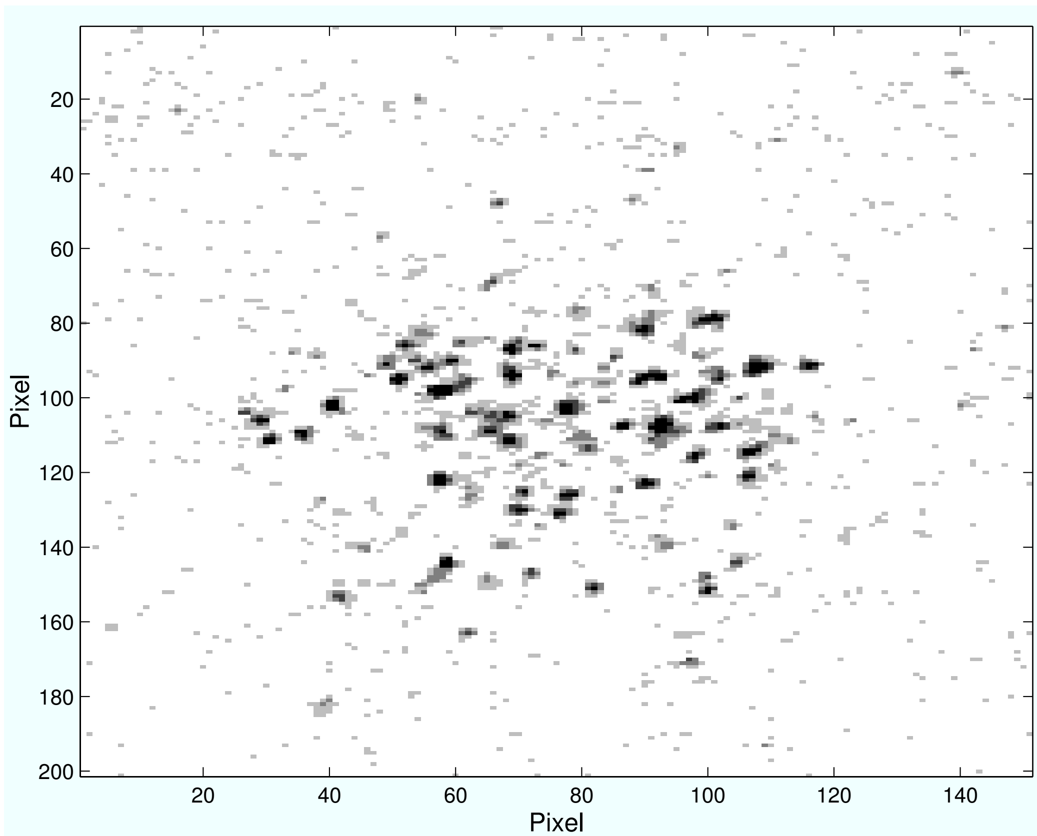

Figure 3: Example of an image taken with the streak camera. The vertical direction from top to bottom is the streak direction. One pixel corresponds to 0.25 ps. The horizontal direction is the horizontal spatial dimension. For this analysis, the image is projected onto the vertical axis.

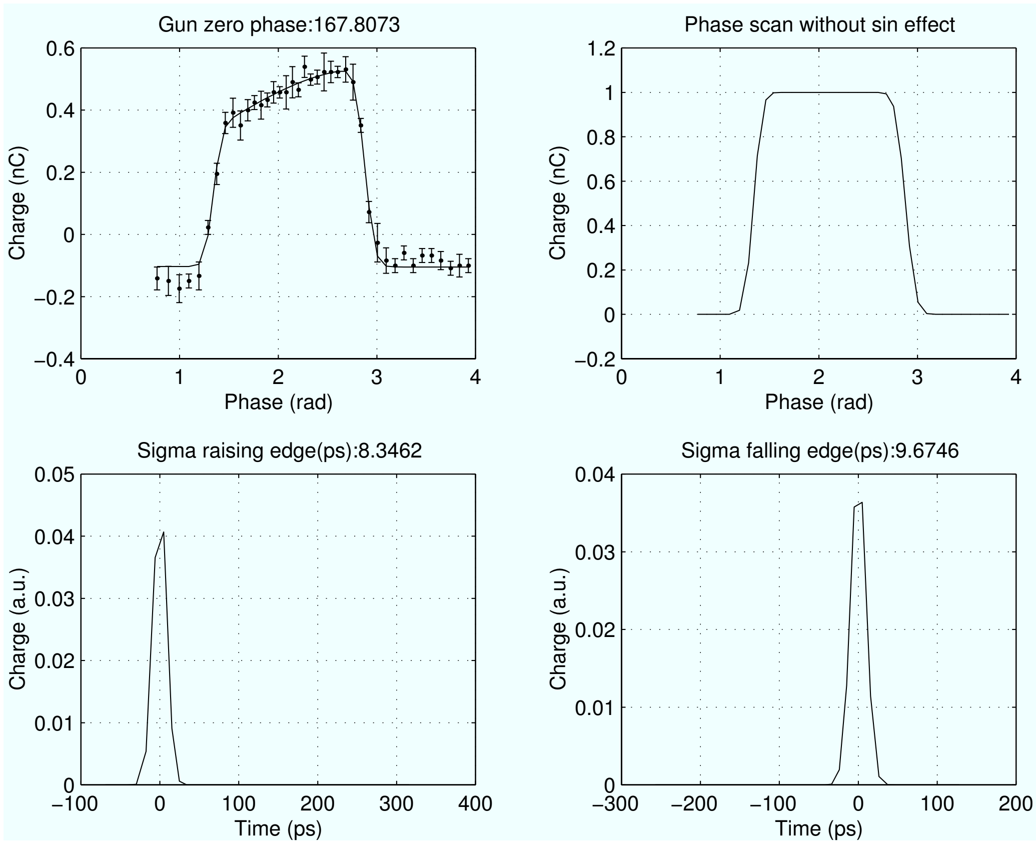

Figure 4: Example of a phase scan: the transmitted charge through the gun is measured as a function of the relative phase between gun and laser.

5 Results

Examples of longitudinal beam profiles are shown in Figures 5 and 6. In the both figures, all the four images are taken for the same machine settings. In Figure 5 the bunch compressor BC2 is off, the gun phase is 40° and both accelerating modules are on crest. For these conditions it can be assumed, that the bunch length is not changed when the beam is transfered from the injector through the linac. The average bunch length in this case is $\sigma_z = 10.1 \pm 1.1\,\mathrm{ps}$ ($3.0 \pm 0.3\,\mathrm{mm}$). Figure 6 shows examples of bunch profiles when the beam passes through the bunch compressor BC2. The gun phase has its nominal value of 40° and the phase of the first accelerating ACC1 is set for maximum compression. ACC2 is operated on crest. During this measurement, SASE FEL radiation has been achieved. The average bunch length corresponding to the profiles in Fig. 6 is $\sigma_z = 3.7 \pm 0.3\,\mathrm{ps}$ ($1.1 \pm 0.1\,\mathrm{mm}$).

Figure 7 shows the injector bunch length as a function of the gun phase (series 1). The beam has been transferred straight through the linac. For comparison, two data points with bunch compression have been included: the bunch compressor is used and the ACC1 phase set to provide two different compressions. These data have been taken during the series 1 measurements and show that the measurements in series 1 are not limited by the resolution of the camera.

As expected, the bunch length decreases with decreasing gun phase. In Figures 8 and 9 a comparison between the experimental data and simulations made by the codes ASTRA [7] and PARMELA [8] are shown. The simulations are shown for different laser pulse lengths. ASTRA favors a laser pulse length of 12 ps, while for PARMELA 14 ps fits best to the data. However, the measured laser pulse length was below 10 ps (see below). The difference between the codes is due to the fact, that ASTRA simulations are made until the entrance of the capture cavity, therefore reflecting some bunch lengthening due to longitudinal space charge force in the drift space, while PARMELA simulations are done up to the gun exit only. Despite this, the agreement between measurements and simulations is good.

Figure 10 shows the bunch length versus the gun phase when the bunch compressor BC2 is in use, but with ACC1 on crest. Although, no compression would have been expected with ACC1 on crest, the data clearly show a compression of the bunch down to about 2.5 mm. This is explained by a small correlated energy spread induced by acceleration in the gun and the capture cavity. This is nicely reproduced by the simulation: in Figure 10

ASTRA simulations for different laser pulse lengths are superimposed to the data. The data favor a small laser pulse length of $\sigma_L = 10\,\text{ps}$. The Schottky effect for the electron extraction from the photocathode is included.

Figure 11 shows the effect of bunch compression: the bunch length is plotted for different phases of ACC1 (series 3). In these measurements the gun is operated close to the nominal phase ($\phi_{\text{gun}} = 48°$) and ACC2 was on crest. Maximum compression of the bunch to 0.7 mm has been measured for a ACC1 phase of $\phi_{\text{ACC1}} = -10°$. Simulations for different laser pulse length are again included. The simulations are performed with ASTRA up to the bunch compressor entrance and then with an analytical model through the compressor. The data are well described by the simulation. Again, a laser pulse length around 10 ps is favored.

The laser pulse length has been measured with the same streak camera. The UV laser wavelength of 262 nm is within the sensitive range of the camera and its input optics. Figure 12 shows examples of laser pulse profiles. A gaussian fit on the profiles yields a laser pulse length of $\sigma_L = 8.9 \pm 0.6\,\text{ps}$.

We also tried to find substructures within an electron bunch or within a laser pulse. From our measurements, it was not possible to identify longitudinal substructures, neither in the electron bunch, nor in the laser pulse. In addition, we can exclude the presence of double pulses which are not closer than 2 ps. With the streak camera, we cover the range between 2 ps and 10 ns, the fastest and slowest streak speed resp. With a fast photodiode for the laser beam and photomultipliers detecting beam losses for the electron beam, the sensitive range is extended to 1 μs, the distance to the next pulse within the pulse train.

In some profiles, spikes are visible. However, these spikes are most likely due to statistical fluctuations of the photon signal (see Figures 5 and 6). Figure 3 shows the poor photon statistics of an image taken with the streak camera. The total number of photons arriving at the camera was $\sim 10^4$, so that the number of photons per pixel on the CCD was low.

6 Conclusions

The bunch length decreases as expected with decreasing gun phases. The smallest bunch length measured for maximum compression is $\sigma_z = 0.7 \pm 0.4\,\text{mm}$ ($2.3 \pm 1.3\,\text{ps}$). The measurements are not limited by the resolution of the camera, which is better than 2 ps. The data are in good agreement with simulations. A laser pulse length of 10 ps is favored by the simulation, which matches well with the measured value of 8.9 ± 0.6 ps.

7 Discussions

The bunch length has also been measured with the method based on longitudinal phase space rotations [9]. In a first preliminary analysis, these measurements indicate a bunch structure consisting of a spike of a size of $\sim$ 1 ps ($\sim 300\,\mu$m) and a long tail of about 6 ps (1.8 mm). The structure is not gaussian, therefore these numbers are given as FWHM values. The streak camera is not able to resolve bunch structures below ~ 2 ps (FWHM).

Other measurements of the bunch length use transition [10] and diffraction [11] radiation in the mm-wavelength range. In both cases, an autocorrelation method with a Martin-Puplett interferometer is used.

Data from the diffraction radiation experiment are in a rough agreement with the streak camera measurements. The transition radiation measurements unfortunately have not been performed under the same conditions. A very small rf gun phase has been used to achieve the shortest bunch lengths. In our measurements, we used the nominal rf gun phase which leads to the lowest transverse emittance.

It should be pointed out, that an evaluation of systematic errors on the three above mentioned methods has not been completed yet. Therefore, comparison with our data have to be done with caution and are preliminary.

It is planned to continue these measurements using in addition the first bunch compressor (BC1). We expect a factor of 2 shorter bunches. A new streak camera with better resolution has been ordered for this purpose.

Acknowledgement

We like to thank T. Garvey, M. Bernard, and B. Leblond from Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, France for making the LAL streak camera available for these measurements.

References

[1] S. Schreiber, "Performance Status of the RF-gun based injector of the TESLA Test Facility Linac", Proc. of the Europ. Particle Acc. Conf. EPAC2000, Vienna, Austria, p. 309.

[2] M. Geitz et al, "Bunch Compressor II at the TESLA Test Facility", Proc. of the Particle Acc. Conf. PAC'99, New York, p. 2507.

[3] M. Geitz et al., "Determination of the Longitudinal Phase Space Distribution produced with TTF Photo Injector", Proc. of the 21st Int. Free Electron Laser Conf., August 1999, Hamburg, Germany, p. II-83.

[4] ARP, now Photonetics, D–77694 Kehl, Germany.

[5] "Résultats de Test Caméra à Balayage de Fente aprés l'installation du tube type FSO", ARP/PSU 4/7/95.

[6] S. Schreiber et al, "Measurement of Space Charge Effects and Laser Pulse Length in the TTF RF Gun using the Phase Scan Technique", Proc. of the 21st Int. Free Electron Laser Conf., August 1999, Hamburg, Germany, p. II-69.

[7] K. Flöttmann, ASTRA user manual, `http://www.desy.de/~ mpyflo/ASTRA_dokumentation.`

[8] PARMELA, Version 5.0, B. Mouton, LAL, F–91405 Orsay, France.

[9] M. Hüning, private communication.

[10] M. Geitz, G. Schmidt, P. Schmüser, G. v. Walter, "Sub-picosecond bunch length measurement at the TESLA test facility", Nucl. Instr. Meth, A 445 (2000) 343.

[11] M. Castellano et al., "Bunch Length Measurements at TTF using Coherent Diffraction Radiation", Proc. of the Europ. Particle Acc. Conf. EPAC2000, Vienna, Austria, p. 1699.

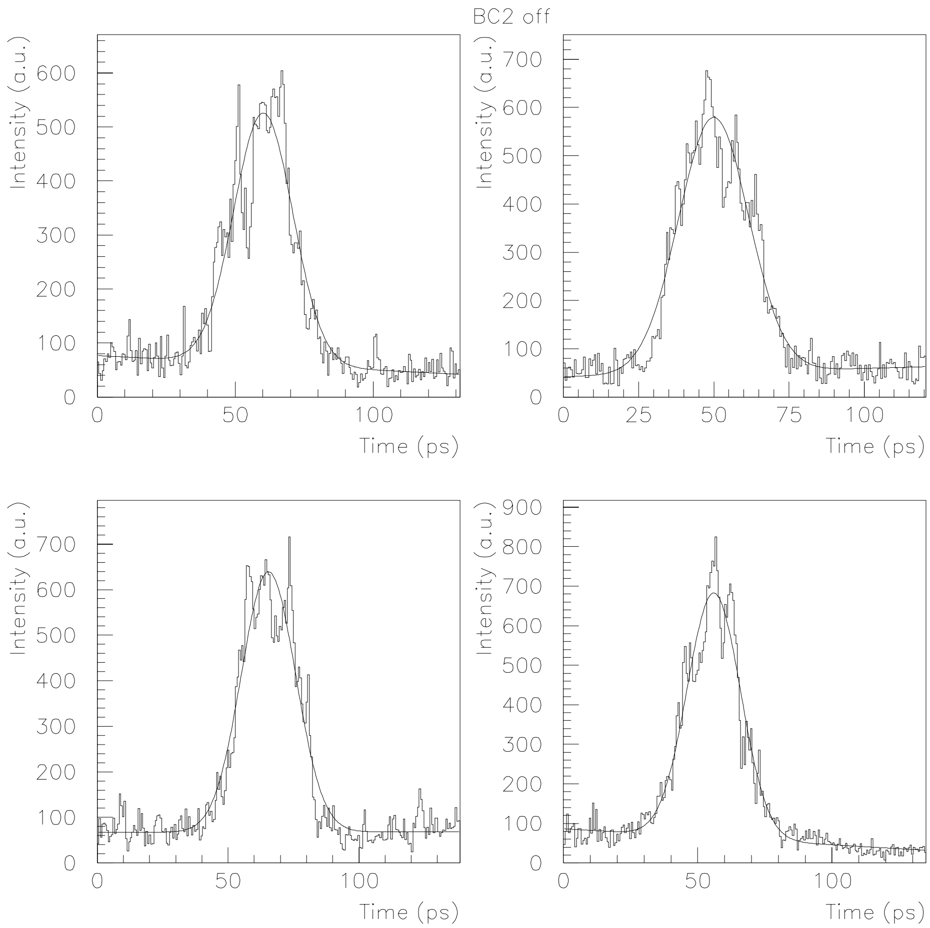

Figure 5: Examples of longitudinal injector bunch profiles.

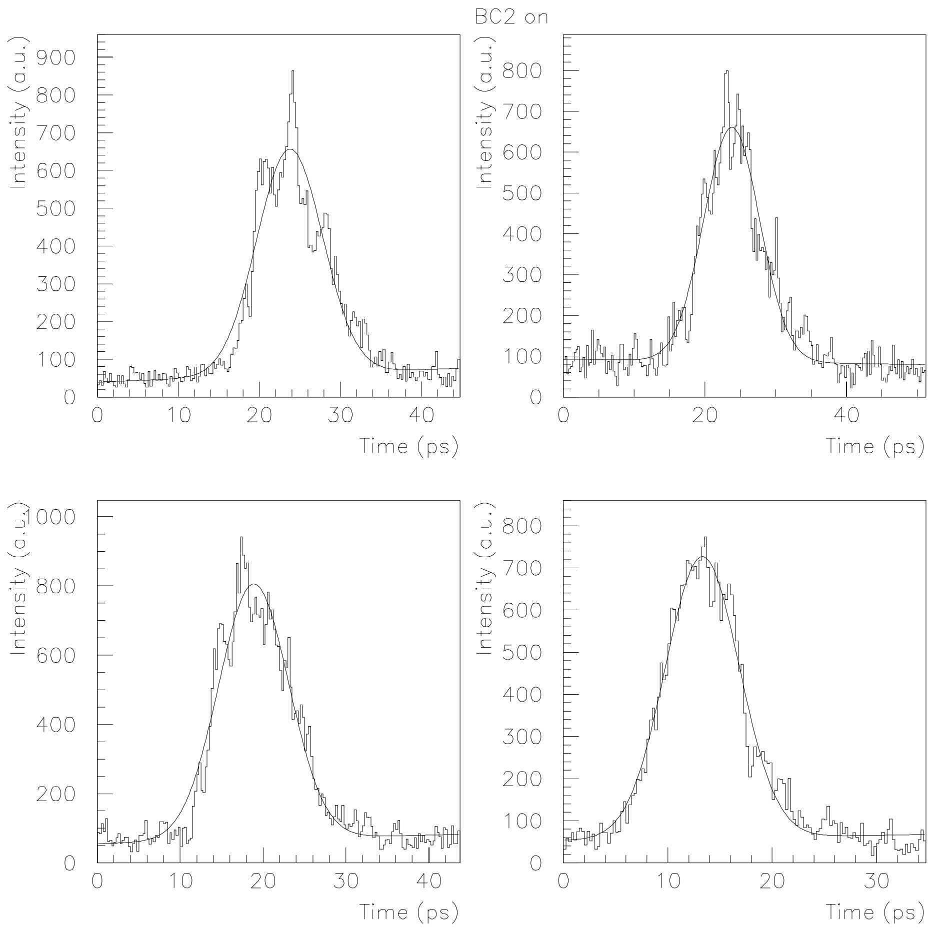

Figure 6: Examples of longitudinal bunch profiles with bunch compression.

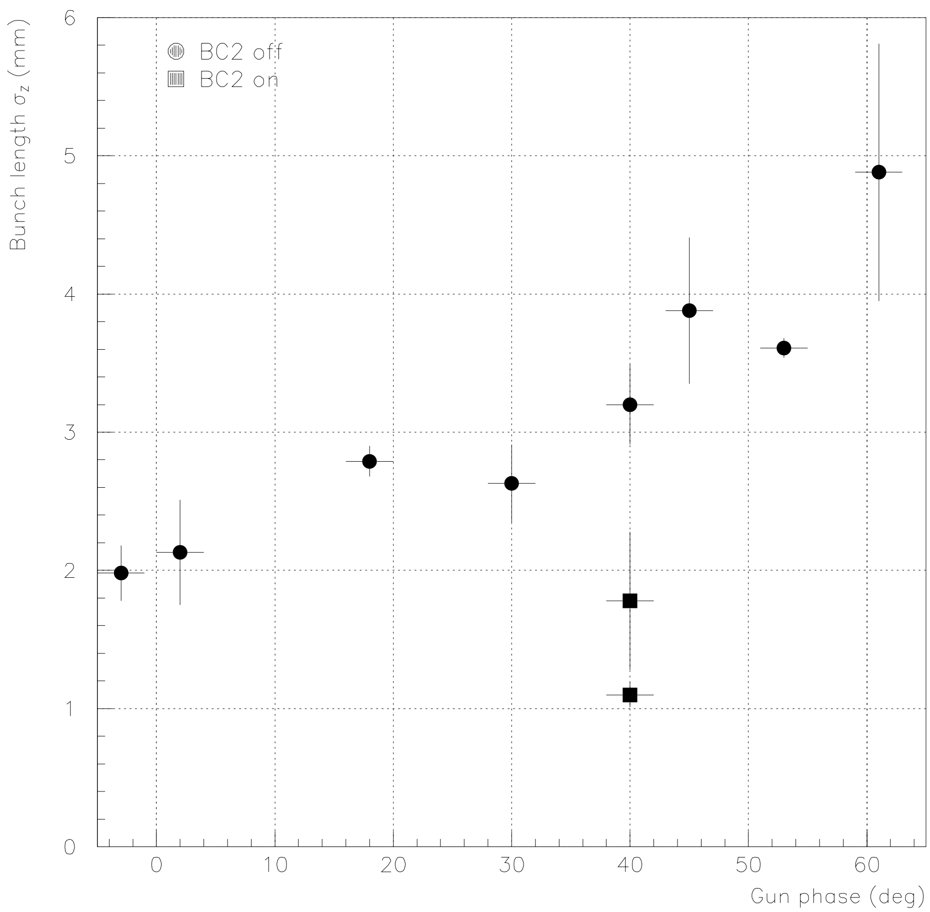

Figure 7: Injector bunch length vs. gun phase (Series 1). Two data points (squares) with bunch compression are included (bunch compressor BC2 in use and ACC1 phase set to provide two different compressions).

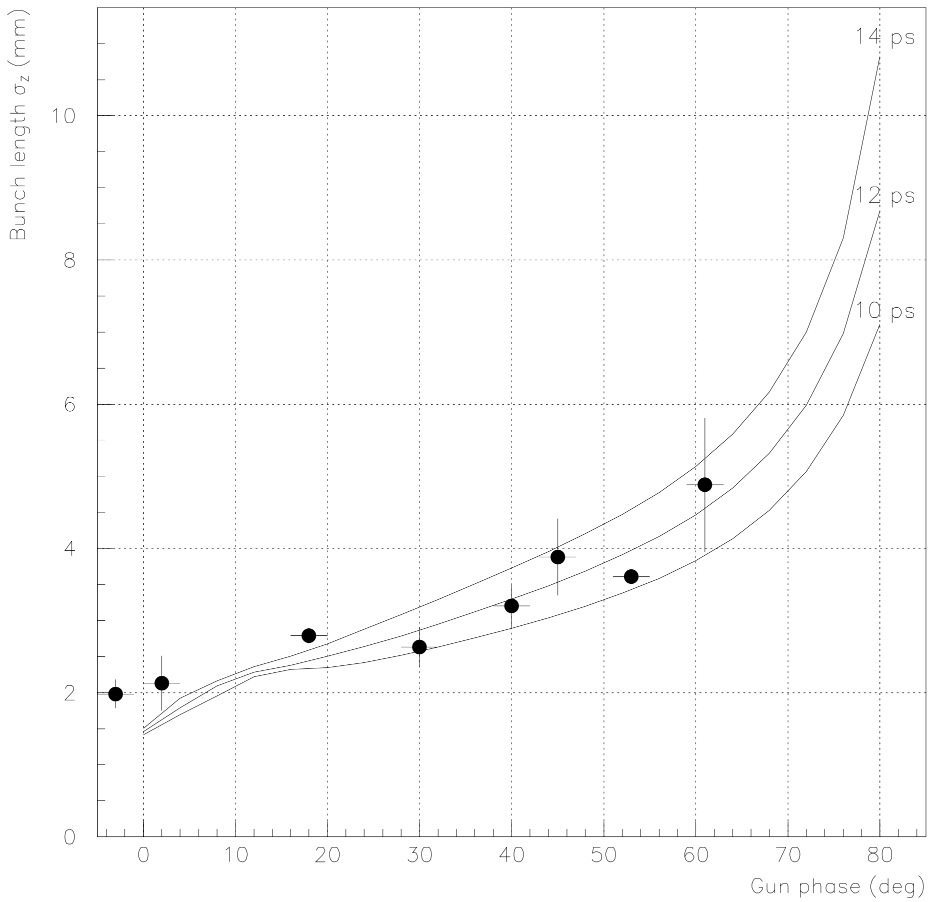

Figure 8: Injector bunch length vs. gun phase (same data as in Fig. 7); comparison between ASTRA simulations and experimental data. The simulation is shown for three different laser pulse lengths (sigma).

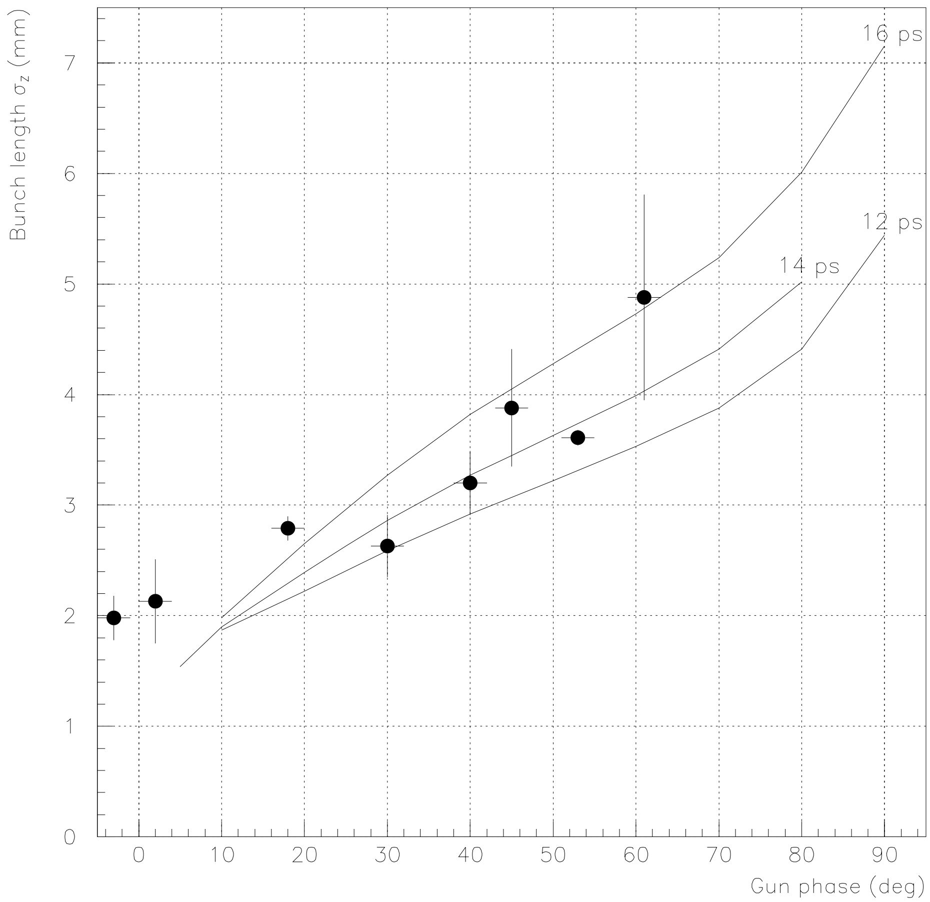

Figure 9: Injector bunch length vs. gun phase (same data as in Fig. 7); comparison between PARMELA simulations and experimental data. The simulation is shown for three different laser pulse lengths (sigma).

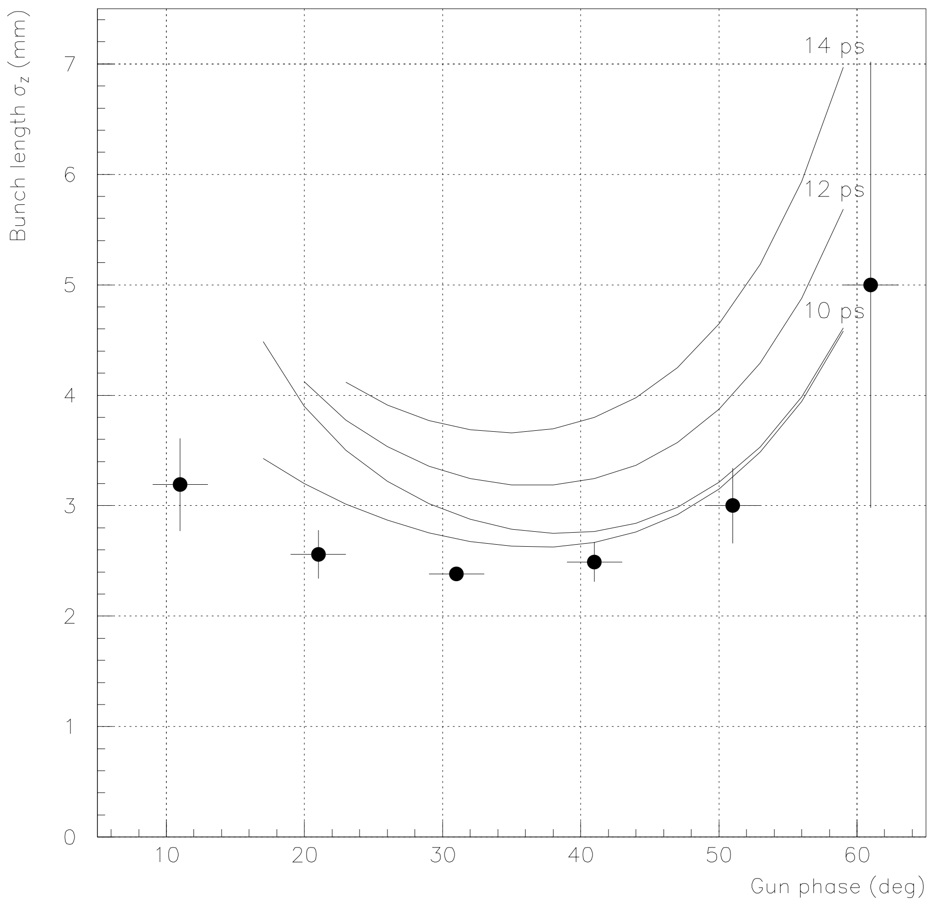

Figure 10: Bunch length vs. gun phase (Series 2); bunch compressor BC2 in use, ACC1 on crest. ASTRA simulations for three different laser bunch lengths (sigma) are shown. For 10 ps, the lower curve includes the Schottky-effect on the cathode.

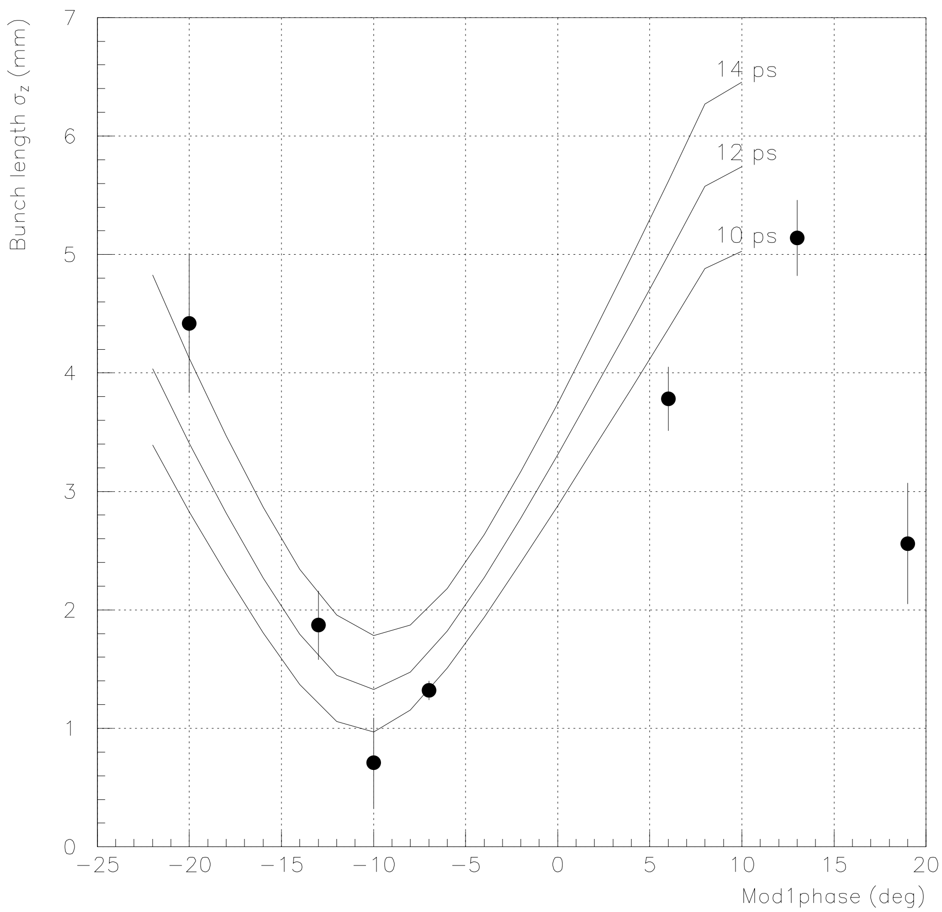

Figure 11: Bunch length vs. module 1 phase (Series 3); bunch compressor BC2 in use. ASTRA Simulations for three different laser bunch lengths (sigma) are shown.

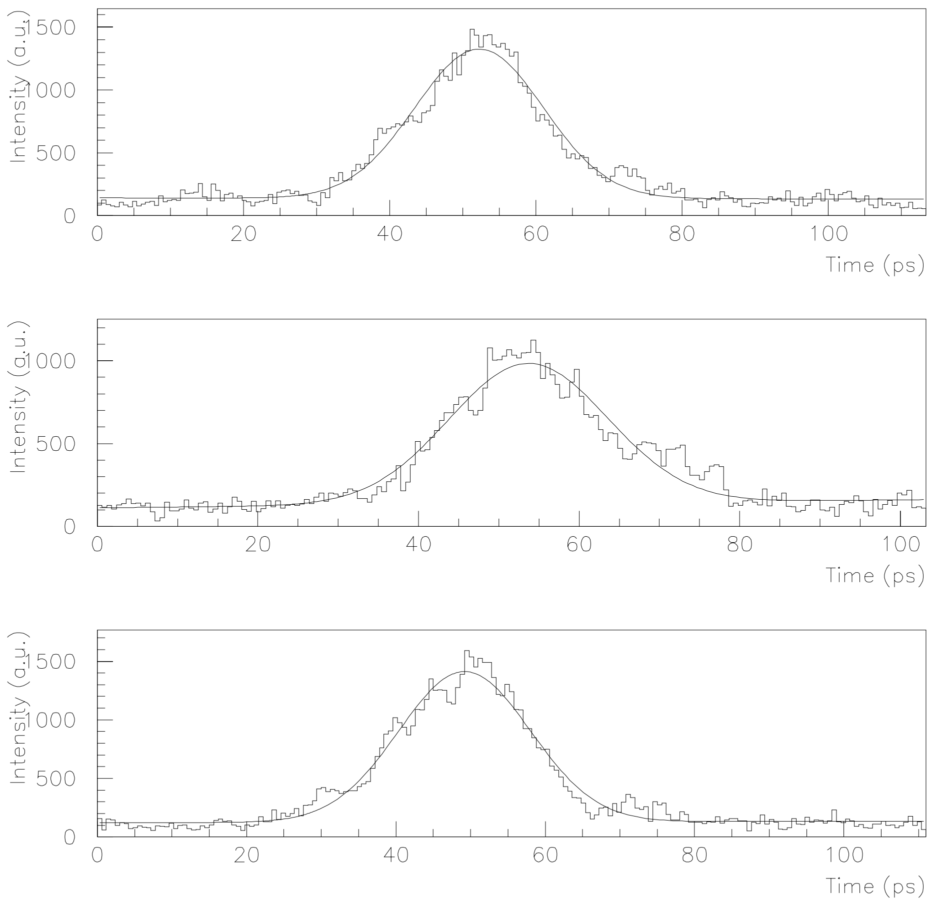

Figure 12: Three examples of measured laser pulse profiles.