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New measurements of the LIL bunch length and lattice parameters

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Abstract

In addition to the studies done with the LIL machine during the MD session in March 2000 [1], some measurements have been performed in May and June 2000. At 200 MeV, the bunch length has been measured for two different charges and, in both cases, the results are consistent with a value of 7 ps. At 500 MeV, the bunch length measurements gave a similar value. Also, the energy dependence of the transfer matrix between the section 27 and the section 36 of LIL was checked experimentally at 300 MeV and a fair agreement between the predicted values of the lattice functions and our data was found.

1 Introduction

Within the framework of the CLIC Test Facility (CTF3) project, several beam studies have been performed in LIL. In March 2000, a complete week was dedicated to the measurements of the bunch length, the beam emittance and the Twiss parameters at various energies [1]. At that time, some additional measurements were proposed and we managed to do some of them during two short MD-sessions on May 24$^{\text{th}}$ and June 15$^{\text{th}}$ 2000. In particular, we measured the bunch length at two different energies (E = 200 MeV at the end of LIL-V and E = 500 MeV at the end of LIL-W) and we also checked the energy dependence of the transfer matrix between the wire-beam-scanners WL.WBS28 and HIM.WBS00, when there is no energy gain along the accelerating sections ACS31, ACS32, ACS33 and ACS34.

2 Bunch length measurements at 200 MeV and 500 MeV

2.1 Introduction

In a previous MD session on the LPI machine [1], a new technique was used in order to measure the bunch length in LIL at 200 MeV. At low charge, the main contribution to the energy spread for a given bunch length is the position of the bunch on the rf cosine wave. Thus, by varying the phase of the bunch on the rf wave and by monitoring the energy spectra in a spectrometer downstream, one can extract the properties of the longitudinal distribution of the beam. Assuming a gaussian shape for the bunches and an uncorrelated energy spread, the comparison between experimental data and simulations allows to estimate the bunch length with a good precision. During the March 2000 MD session, a good agreement between our simulations and the experimental data was found for a bunch length of about 7 $\pm$1 ps.

In this report, new results of bunch length measurements in LIL are presented. The same technique is used and detailed studies are carried out at two different energies, 200 MeV and 500 MeV :

- At 200 MeV, measurements with two different charges, 0.03 nC and 0.1 nC per bunch, are performed in order to study the possible influence of the charge on the bunch length.
- At 500 MeV, two different methods are used to vary the phase of the bunch on the rf wave. In the first one, the relative phase between the modulator MDK13 and the following modulators is changed, so that the bunch is accelerated on the crest of the rf wave from the output of the buncher up to 200 MeV, and is then accelerated from 200 MeV to 500 MeV with a constant phase shift on the accelerating wave. In the second method, the phase of the modulator MDK31 is modified, so that the bunch is accelerated on the crest from the output of the buncher up to approximately 300 MeV, and then from 300 MeV to 500 MeV with a constant phase shift.

Figure 1 shows the LIL layout, as well as the correspondence between the modulators and the accelerating sections :

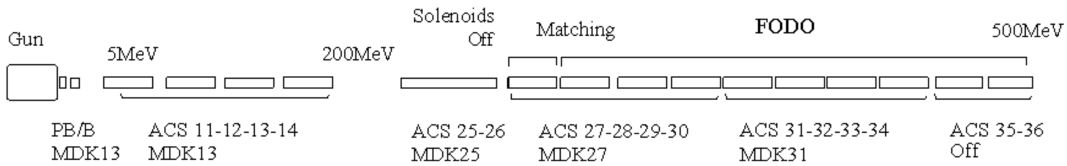

Figure 1: LIL Layout.

In addition, the deconvolution of the energy spectra with the cosine wave is computed at both energies to get the longitudinal distribution of the bunch. This allows to check the value of the bunch length directly on the distribution, and to estimate the discrepancy between the gaussian bunch model and the real distribution.

2.2 Measurements at 200 MeV

2.2.1 Measurements with a low charge per bunch

In this section, the general settings are the same as in [1]. The following data are used to cross-check the value of the bunch length found during the previous MD session, and to show the reproducibility of the method. The main parameters and some useful remarks are listed below :

- The charge is approximately 0.03 nC per bunch.
- The linear factor between the beam energy (in MeV) and the current in BSP15 (in A) is κ=0.801, as described in details in [1].
- The value of the dispersion in the bending magnet, extracted from the SEM-grid software, is D = 0.2413 m.
- The internal error of the normalization process in the SEM-grid software has been fixed and a correction matrix is no longer needed.

The experimental values of the energy spread and of the mean energy are computed from the energy spectra, as explained in [1]. The values of the phase shifts are extracted from a cosine curve fitting the mean energy points. The various contributions to the energy spread (transverse beam size in the spectrometer, beam jitter, energy spread at the output of the buncher) are taken into account in an equivalent, uncorrelated energy spread σ_0. The measured value of the energy spread σ_{meas} is then corrected into σ_{corr} :

$$\sigma_{corr}^2 = \sigma_{meas}^2 - \sigma_0^2. \quad (1)$$

The corrected data match the simulated behaviour of the energy spread as a function of the phase shift for a gaussian bunch of length 7.5 ps FWHH (3.2 ps or 0.95 mm rms), with an uncorrelated energy spread σ_0 = 1.5 MeV. Figure 2 shows a central curve for a bunch length of 7.5 ps FWHH and two other curves corresponding to the precision tolerances of ± 1 ps. For each phase, Table 1 gives the experimental values of the mean energy and of the energy spread, as well as the corrected and simulated values of the energy spread.

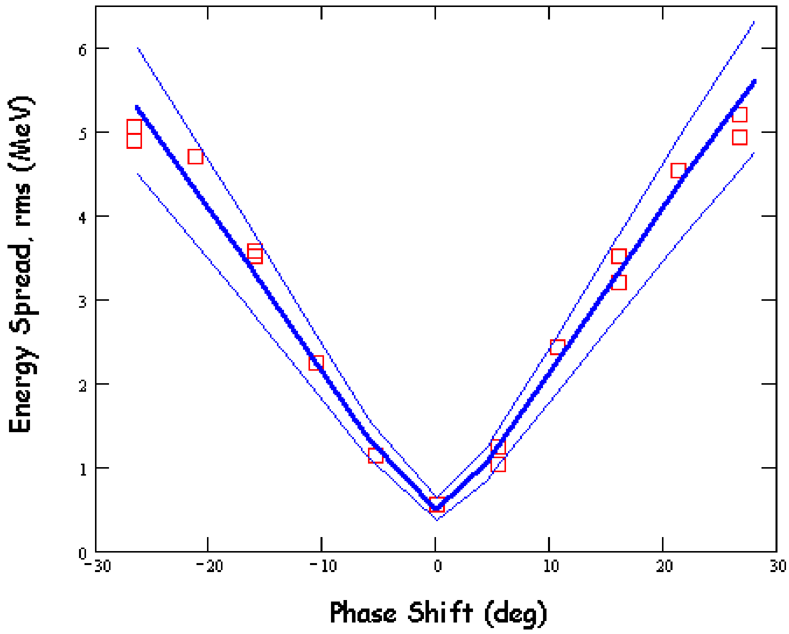

Figure 2: Corrected (empty squares) and simulated (solid lines) energy spread as a function of the phase shift, with a bunch length 7.5 ± 1 ps FWHH, at 200 MeV, and for a low charge per bunch.

Φ (°)	E_{mean}^{meas} (MeV)	σ_E^{meas} (MeV)	σ_E^{corr} (MeV)	σ_E^{sim} (MeV)
-26.4	180.0	5.1	4.9	5.3
-21.1	187.4	4.9	4.7	4.3
-16.4	192.6	3.9	3.6	3.3
-11.1	196.9	2.7	2.2	2.4
-6.0	199.4	1.8	1.1	1.3
0	200.6	1.6	0.6	0.5
+5.1	199.8	1.9	1.2	1.1
+10.5	197.3	2.8	2.4	2.2
+15.9	193.1	3.8	3.2	3.3
+21.9	186.3	4.8	4.5	4.4
+28.0	177.4	5.4	5.2	5.6

Table 1: Experimental values of the mean energy E_{mean}^{meas} and values of the measured, corrected and simulated (7.5 ps FWHH) energy spreads (respectively σ_E^{meas}, σ_E^{corr} and σ_E^{sim}) for various phase shifts.

The results presented here are in fair agreement with the values which were obtained during the previous MD session [1]. The value of the equivalent, uncorrelated energy spread is slightly lower in this case than before (1.5 MeV instead of 1.9 MeV), because the contribution of the transverse beam size in the spectrometer has been minimized by varying the current in the upstream quadrupole, in order to have a waist configuration in the spectrometer.

2.2.2 Measurements with a higher charge per bunch

The purpose of this section is to check if any change in the bunch length occurs when one increases the charge per bunch. Indeed, at higher charge, beamloading and space charge effects are expected to be more important. In the procedure used to measure the bunch length, the charge per bunch is limited in order to minimize the contribution of the beamloading to the energy spread [1]. However, the charge was increased by a factor 3, from 0.03 nC per bunch in the previous section to approximately 0.1 nC per bunch, while keeping the beamloading effects at a reasonably low level. The other settings remain unchanged, and the experimental method is the same.

Our results are summarized on Figure 3 and in Table 2.

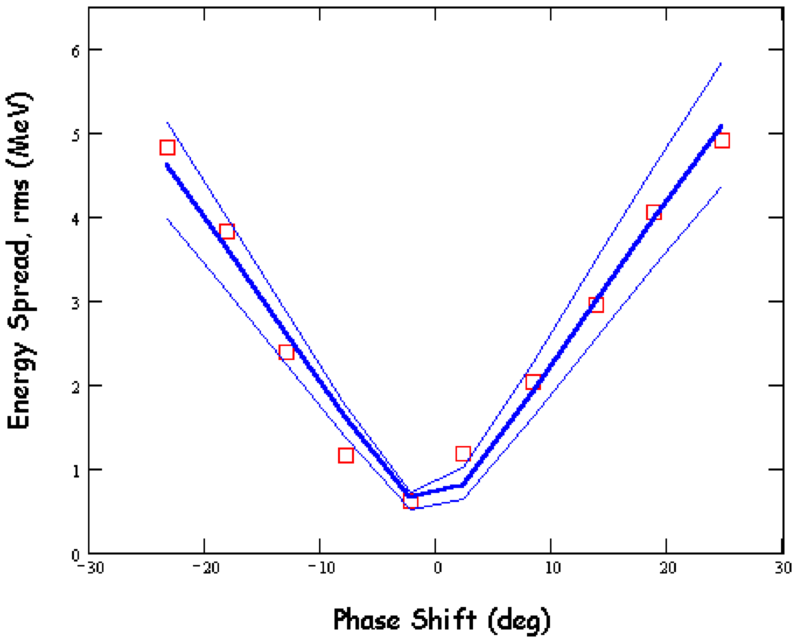

Figure 3: Corrected (empty squares) and simulated (solid lines) energy spread as a function of the phase shift, with a bunch length 7.5 ± 1 ps FWHH, at 200 MeV, and for a higher charge per bunch.

Φ (°)	E^{meas}_{mean} (MeV)	σ^{meas}_E (MeV)	σ^{corr}_E (MeV)	σ^{sim}_E (MeV)
-23.3	186.3	5.5	4.8	4.6
-18.1	192.6	4.6	3.8	3.6
-13.0	197.3	3.6	2.4	2.6
-7.9	200.5	2.9	1.1	1.6
-2.3	202.2	2.7	0.6	0.6
+2.3	202.2	2.9	1.2	0.8
+8.3	200.3	3.3	2.0	1.9
+13.7	196.7	3.9	2.9	3.0
+18.7	191.9	4.8	4.0	4.0
+24.6	184.5	5.6	4.9	5.1

Table 2: Experimental values of the mean energy E^{meas}_{mean} and values of the measured, corrected and simulated (7.5 ps FWHH) energy spreads (respectively σ^{meas}_E, σ^{corr}_E and σ^{sim}_E) for various phase shifts.

The minimum of the energy spread is not reached for the bunch accelerated on the crest, as it was previously the case, and the points are not symmetrically distributed around the point with the lowest energy spread. This effect is likely to result from the fact that the bunching system has not been optimized when switching from low charge to high charge. To increase the charge, the voltage in the extraction grid was lowered, but the downstream components (pre-buncher, buncher) were not optimized for this new voltage. This may have created some correlations in the bunch. In order to take into account this asymmetry in the simulations, a correlation in the longitudinal phase space is added before the acceleration on the cosine wave, as it is sketched on Figure 4. This brings a discrepancy between the acceleration with positive and negative phase shifts.

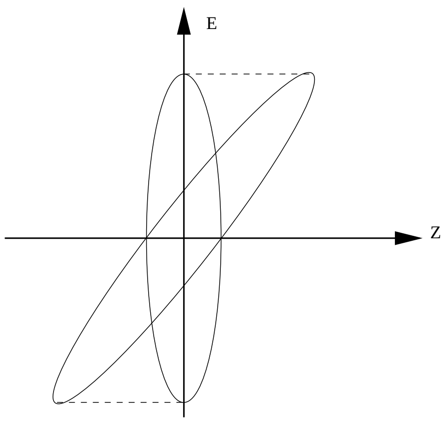

Figure 4: View of a bunch with a correlated energy spread in the longitudinal phase space.

The data are consistent with simulations for a bunch length of 7.5 ps FWHH (3.2 ps or 0.95 mm rms), with an uncorrelated energy spread $\sigma_0 = 2.6$ MeV. This value is much larger than before in order to compensate for the spread introduced by the buncher. Although the data are more difficult to analyse, no significant bunch lengthening is observed for the data with this value of the charge per bunch.

2.2.3 Longitudinal distribution

The longitudinal distribution of the bunch is extracted from the energy spectra read on the spectrometer for large phase shifts. Within the acceptance of the spectrometer, the higher the phase, the higher the precision of the spectrum and the less sensitive to the uncorrelated energy spread. The accelerating wave is assumed to be a cosine curve :

$$E(t) = E_0 \cos(2\pi\nu t) = E_0 \cos(\omega t). \tag{2}$$

Knowing the experimental energy distribution $D(E)$, the time distribution is recovered using the following transformation :

$$D(t) = D(E(t))\frac{dE}{dt}, \tag{3}$$

where $\frac{dE}{dt}$ is the normalization factor.

Figure 5 shows the longitudinal distributions computed from five different spectra with a low charge per bunch, with positive and negative phase shifts with respect to the crest. All distributions are consistent with each other and with a gaussian bunch (as used for simulations) of length 7.5 ps FWHH (3.2 ps or 0.95 mm rms).

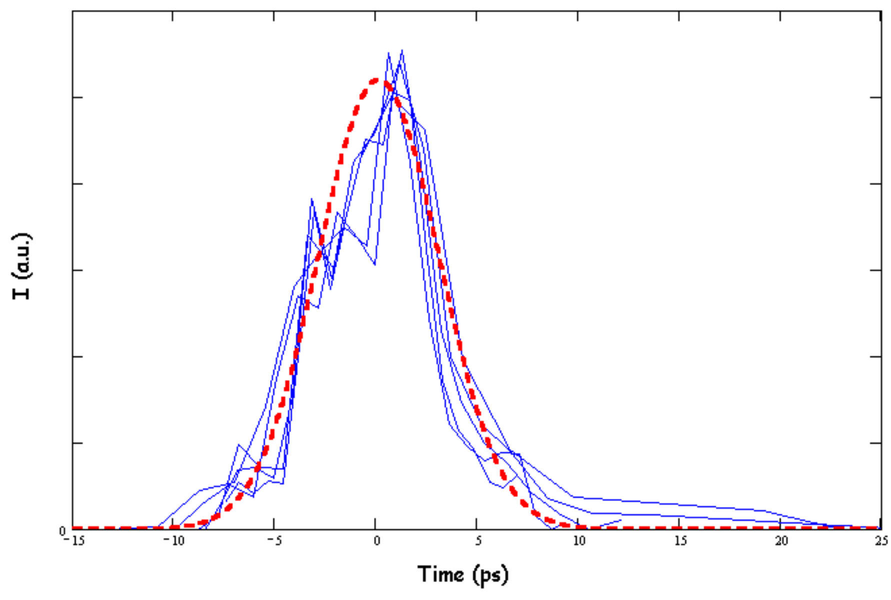

Figure 5: Experimental longitudinal distributions computed from five energy spectra (solid lines). For comparison, a gaussian distribution of length 7.5 ps FWHH is shown (dashed line).

The bunch length is also computed directly from these time distributions in order to cross-check the values previously found. The results are shown in Table 3 for the five curves which are displayed on Figure 5. For small phase shifts, the bunch is lengthened by the effects corresponding to the uncorrelated energy spread, and since the energy spectra are narrow, the precision of the time distribution gets lower.

Φ (°)	σ_L^{exp} (ps)
-26.4	7.1
-21.1	8.1
-16.4	8.7
+21.9	7.9
+28	7.2

Table 3: Experimental values of the bunch length extracted from the time distributions at 200 MeV.

2.3 Measurements at 500 MeV

The same technique is used to measure the bunch length at 500 MeV. Here, the bunch is accelerated on the crest of the accelerating wave from the output of the buncher to approximately either 200 MeV or 300 MeV. Then, the phase is shifted in the downstream modulators to accelerate the bunch with a given phase up to 500 MeV. The energy spectra are monitored in the SEM-grid HIE.MSH20, downstream the bending magnet BSH00.

2.3.1 Tuning the phase between the modulator MDK13 and the modulators MDK27 and MDK31

For the measurements at 500 MeV, the main settings are listed below :

- The charge is approximately 0.03 nC per bunch.
- The linear factor between the beam energy (in MeV) and the current in BSH00 (in A) is κ=2.890.
- The value of the dispersion in the bending magnet, extracted from the SEM-grid software, is D=0.850 m.

The simulations are done in two steps : the first step is the acceleration on the crest up to E_0=200 MeV and the second step is the acceleration with a phase on the rf wave, up to E_1=500 MeV. The equation used to describe the acceleration field is therefore :

$$E(t) = E_0 \cos(2\pi\nu t) + (E_1 - E_0) \cos(2\pi\nu t + \Phi). \tag{4}$$

Our results are summarized on Figure 6 and in Table 4.

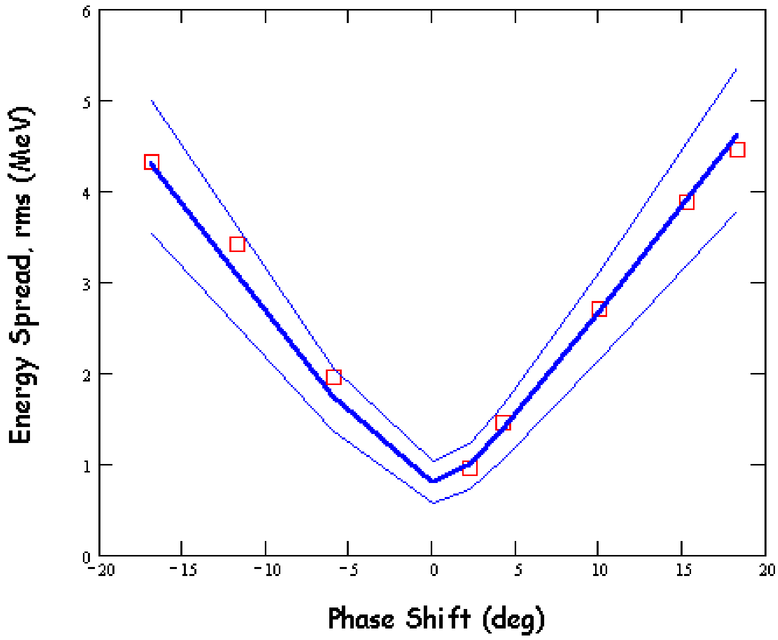

Figure 6: Corrected (empty squares) and simulated (solid lines) energy spread as a function of the phase shift, with a bunch length 6 ± 1 ps FWHH, at 500 MeV.

Φ (°)	E^{meas}_{mean} (MeV)	σ^{meas}_{E} (MeV)	σ^{corr}_{E} (MeV)	σ^{sim}_{E} (MeV)
-16.9	485.9	4.5	4.3	4.3
-11.8	492.5	3.6	3.4	3.1
-6.0	497.2	2.3	1.9	1.8
+2.2	498.6	1.6	1.0	1.0
+4.2	498.0	1.9	1.5	1.4
+10.0	494.3	3.0	2.7	2.7
+15.2	488.4	4.1	3.9	3.9
+18.2	483.8	4.6	4.4	4.6

Table 4: Experimental values of the mean energy E^{meas}_{mean} and values of the measured, corrected and simulated (6.0 ps FWHH) energy spreads (respectively σ^{meas}_{E}, σ^{corr}_{E} and σ^{sim}_{E}) for various phase shifts.

The best agreement between data and simulations is obtained for a bunch length of 6.0 ps FWHH (2.6 ps or 0.76 mm rms), with an uncorrelated energy spread $\sigma_0 = 1.2$ MeV. As expected, the equivalent, uncorrelated energy spread is lower than at 200 MeV. The contribution of the transverse size of the beam ($\sim \sqrt{\beta\epsilon}$) must be smaller since the physical emittance ϵ is smaller at 500 MeV than at 200 MeV. In addition, the contribution of the buncher is a relative contribution ($\sim D\frac{\Delta p}{p}$), and it is thus lower at 500 MeV than at 200 MeV. The bunch length is slightly shorter than at 200 MeV, but the difference (1.5 ps) remains inside the tolerance level of $\pm$ 1 ps.

2.3.2 Tuning the phase of the modulator MDK31

The settings and the experimental procedure are the same as before, except that now $E_0 = 300$ MeV. The results are summarized on Figure 7 and in Table 5.

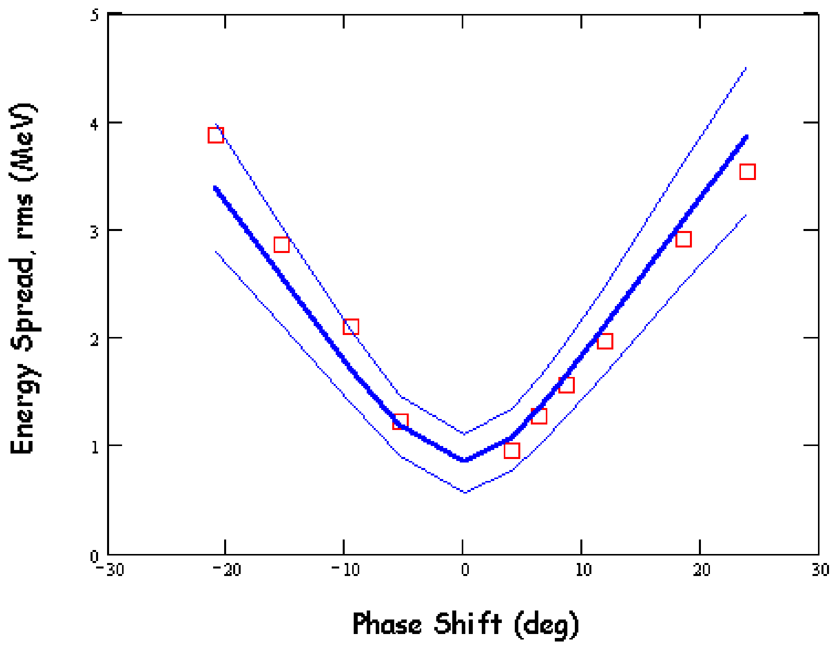

Figure 7: Corrected (empty squares) and simulated (solid lines) energy spread as a function of the phase shift, with a bunch length 6 ± 1 ps FWHH, at 500 MeV.

Φ (°)	E_{mean}^{meas} (MeV)	σ_E^{meas} (MeV)	σ_E^{corr} (MeV)	σ_E^{sim} (MeV)
-21.0	486.5	4.0	3.9	3.4
-15.5	492.3	3.1	2.9	2.6
-9.6	496.6	2.4	2.1	1.7
-5.4	498.4	1.6	1.2	1.2
+4.0	498.8	1.5	1.0	1.1
+6.3	498.1	1.7	1.3	1.4
+8.6	497.1	1.9	1.6	1.6
+11.8	495.2	2.2	2.0	2.1
+18.6	489.3	3.1	2.9	2.9
+23.9	482.9	3.7	3.5	3.9

Table 5: Experimental values of the mean energy E_{mean}^{meas} and values of the measured, corrected and simulated (6.0 ps FWHH) energy spreads (respectively σ_E^{meas}, σ_E^{corr} and σ_E^{sim}) for various phase shifts.

The best matching between data and simulations is obtained for a bunch length of 6.0 ps FWHH (2.6 ps or 0.76 mm rms), with an uncorrelated energy spread $\sigma_0 = 1.1$ MeV. This is consistent with the previous measurements. However, the data points do not match the simulation curves as well as before. Introducing the phase shift at a lower energy (as in section 2.3.1) is therefore better from the point of view of this type of measurement.

2.3.3 Longitudinal distribution

As before, the longitudinal distribution of the bunch is extracted from the energy spectra. The accelerating wave is assumed to be the sum :

$$E(t) = E_0 + (E_1 - E_0)\cos(2\pi\nu t + \Phi), \tag{5}$$

where the acceleration on the crest of the first rf wave up to 200 MeV is considered as a constant, thus making the approximation that the first acceleration does not contribute to the energy spread.

Five longitudinal distributions are displayed on Figure 8, as well as the gaussian distribution used for the simulations. A small discrepancy is observed between the distributions extracted from energy spectra with a negative phase shift and with a positive phase shift.

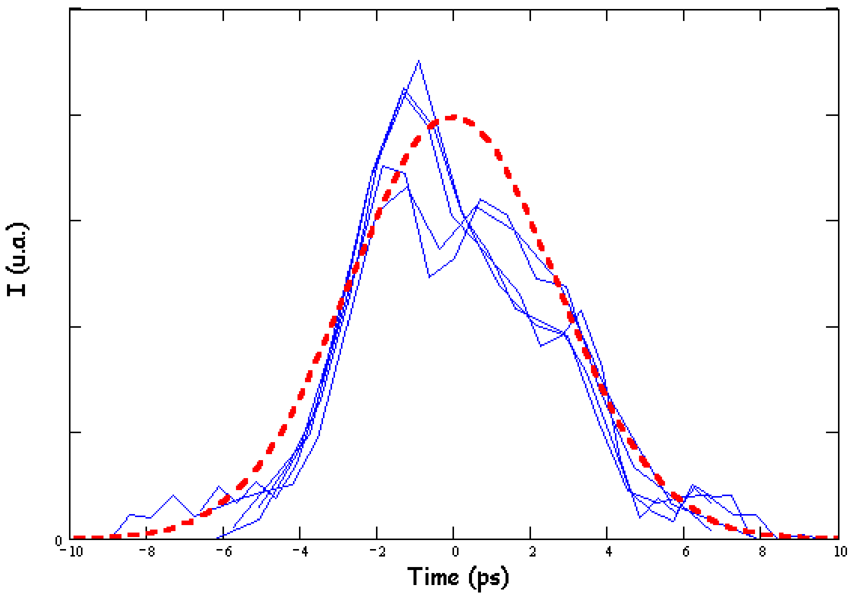

Figure 8: Experimental longitudinal distributions computed from five energy spectra (solid lines). For comparison, a gaussian distribution of length 6.0 ps FWHH is shown (dashed line).

The bunch lengths, computed from the time distributions, are given in Table 6. These values agree with our previous simulations, see section 2.3.1.

Φ (°)	σ_L^{exp} (ps)
-16.9	6.1
-11.8	6.5
+10.0	5.9
+15.2	5.8
+18.2	5.7

Table 6: Experimental values of the bunch length extracted from the time distributions at 500 MeV.

In order to prove the consistency of our method, one time distribution is computed from the energy spectrum corresponding to the phase shift +18.2° (see section 2.3.1 for details). The acceleration of this bunch is then simulated for a new phase shift (-16.9°) : one obtains an energy spectrum which is very similar to the one read directly on the spectrometer, for the same phase shift (see Figure 9).

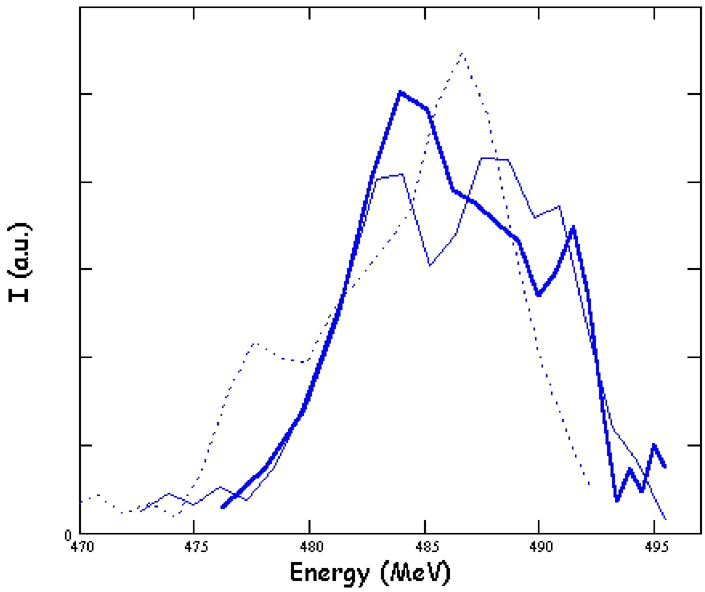

Figure 9: Energy spectrum at +18.2° (dotted line), from which a time distribution is computed (as on Figure 8). This latter time distribution is accelerated with a different phase shift -16.9°, which leads to a simulated energy spectrum (thick solid line), to be compared with the experimental spectrum for the same phase shift (thin solid line).

2.4 Conclusion

The bunch length measurements presented here confirm the results obtained during a previous session [1]. The method is valid at 200 MeV and 500 MeV, with various values of the charge per bunch, and with different experimental methods used to generate the phase shift. At 200 MeV, under the assumption of a gaussian bunch, the bunch length is found to be 7.5 ± 1 ps, for a low charge (0.03 nC/bunch) and for a higher charge (0.1 nC/bunch), although the data are more difficult to analyse in this latter case. At 500 MeV, the bunch length is 6.0 ± 1 ps, for two different methods used to generate a phase shift on the rf wave between 200 MeV and 500 MeV.

From the energy spectra at high phase shifts, it is also possible to compute the time distribution of the bunch. These distributions show a good consistency and are in agreement with the previous values of the bunch length. In addition, the time distributions can be used to simulate the energy spectra expected for any given phase shift. The comparison with the experimental spectra confirm that these time distributions are close to the real bunch longitudinal distribution.

3 Lattice functions measurements between section 27 and section 36 of LIL

During the March 2000 MD session, various measurements were performed in order to determine the beam emittance, as well as the Twiss parameters at three positions along LIL and for different energies [1]. Once the characteristics of the beam are measured at one point in LIL, some calculations performed with the TRANSPORT code [2] should allow us to predict the Twiss parameters at any other point downstream.

When one has a constant energy between the section 27 and the section 36 of LIL (MDK27 and MDK31 are switched-off), TRANSPORT simulations suggest that the transfer matrix between QNM273 and QNM363 is very sensitive to the beam energy. Also, the Twiss parameters at the entrance of QNM273 are expected to be almost independent on the energy gain in ACS25 and ACS26. All these issues need to be checked experimentally.

Therefore, during the June 2000 MD-session, six new sets of measurements were performed. They are summarized in Table 7.

PFN voltage for MDK25	32.99 kV	34.38 kV	36.04 kV
Phase for MDK25	253°	263°	263°
Mean energy in HIE.MSH20	$E_1 = 305.7$ MeV	$E_2 = 309.5$ MeV	$E_3 = 312.5$ MeV
Labels of the measurements in WL.WBS28	WBS28-x1 WBS28-y1	WBS28-x2 WBS28-y2	WBS28-x3 WBS28-y3
Labels of the measurements in HIM.WBS00	WBS00-x1 WBS00-y1	WBS00-x2 WBS00-y2	WBS00-x3 WBS00-y3

Table 7: Summary of the lattice parameters measurements on June 15$^{\mathrm{th}}$ 2000, with the corresponding settings for MDK25.

3.1 Analysis of the experimental results in WL.WBS28

In this section, we focus on the three sets of measurements performed in WL.WBS28. According to our TRANSPORT simulations [1], the dependence of the lattice functions at the entrance of QNM273 on the energy after ACS25 and ACS26 should remain small. It is now confirmed experimentally, as shown on Figure 10.

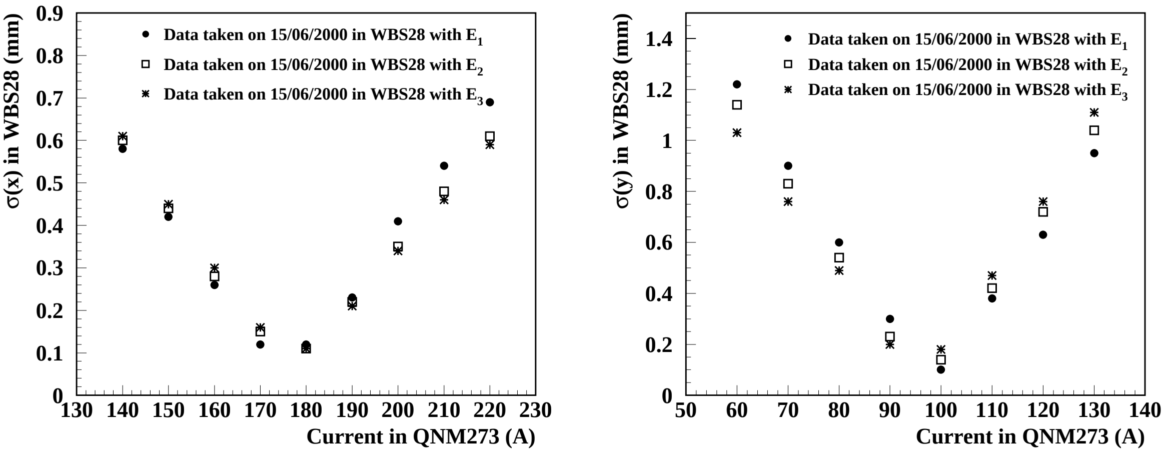

Figure 10: Variations of the horizontal and vertical rms beam size in WL.WBS28 as a function of the current in QNM273, for three different beam energies (see Table 7 for the measured values of E_1, E_2 and E_3).

The beam emittance and the Twiss parameters that one can derive from these measurements are summarized in Table 8. As it was predicted by our TRANSPORT simulations, they remain almost independent on the energy gain in the accelerating sections ACS25 and ACS26.

Measured energy	Label of the measurement	ϵ (π mm.mrad)	β (m)	α
305.7 MeV	WBS28-x1	0.057	32.4	-8.5
309.5 MeV	WBS28-x2	0.062	27.2	-7.2
312.5 MeV	WBS28-x3	0.064	25.8	-6.8
305.7 MeV	WBS28-y1	0.079	66.3	+21.2
309.5 MeV	WBS28-y2	0.079	68.6	+21.2
312.5 MeV	WBS28-y3	0.079	67.2	+20.2

Table 8: Summary of the lattice parameters measurements in WL.WBS28 on June 15$^{\text{th}}$ 2000. Here ϵ corresponds to the physical rms emittance.

3.2 Analysis of the experimental results in HIM.WBS00

In this section, we focus on the three sets of measurements performed in HIM.WBS00. We only consider the horizontal direction : the quality of the data taken in HIM.WBS00 is not good enough to allow the interpretation of the results in the vertical direction.

As predicted by our TRANSPORT simulations, a strong energy dependence of the beam characteristics on the energy can be observed : Figure 11 shows the variations of the horizontal rms beam size in HIM.WBS00 as a function of the current in QNM363, for three different energies. Despite the fact that the relative energy variations are within 2%, the three curves are very well separated.

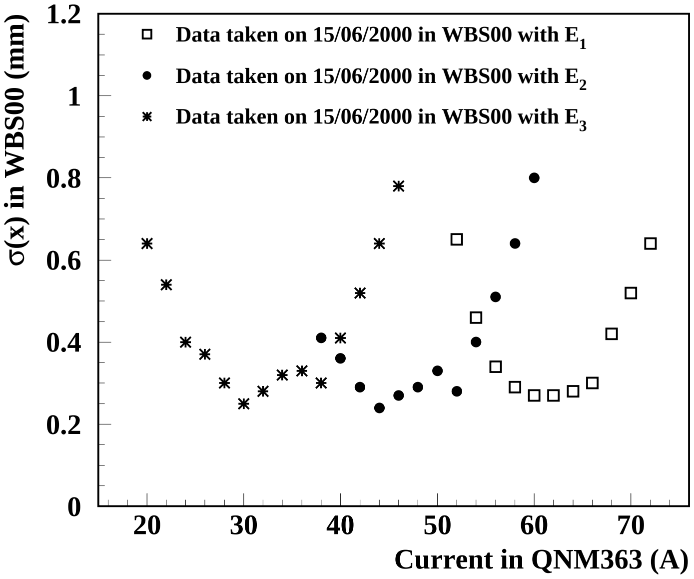

Figure 11: Variations of the horizontal rms beam size in HIM.WBS00 as a function of the current in QNM363, for three different beam energies (see Table 7 for the measured values of E_1, E_2 and E_3).

Furthermore, the data taken in HIM.WBS00 do not match the predictions made with the TRANSPORT code, unless the mean energy of the beam is brought to 310.0 MeV for WBS00-x1 (instead of 305.7 MeV), 314.0 MeV for WBS00-x2 (instead of 309.5 MeV), and 317.0 MeV for WBS00-x3 (instead of 312.5 MeV). Given the accuracy of the energy measurement at the end of LIL-W, an error of about 1% can not be excluded for the mean value of the energy. When one takes into account the possible shift of the mean energy measured in HIE.MSH20, it becomes possible to obtain a fair agreement between the TRANSPORT simulations and the data collected in HIM.WBS00 when the current in QNM363 is varied, as it is shown on Figure 12 (the measurement shown here is referred to as WBS00-x1).

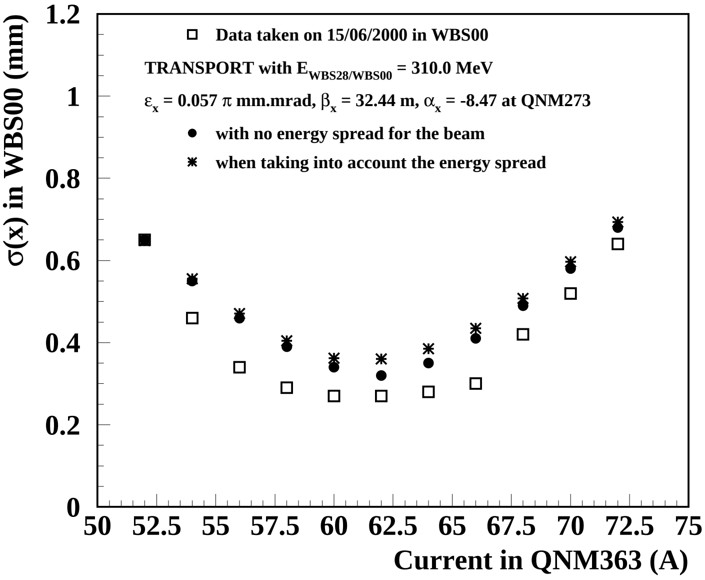

Figure 12: Variations of the horizontal rms beam size in HIM.WBS00 as a function of the current in QNM363 (TRANSPORT simulations and data).

We have thus confirmed once more that TRANSPORT allows to make good predictions for the beam behaviour in LIL, even if a high-degree of accuracy is difficult to reach. Furthermore, the normalized rms emittance measured here is consistent with the one we obtained during the previous MD session, i.e about 40 π mm.mrad [1].

4 Conclusion

This note summarizes the bunch length and lattice parameters measurements that we performed in LIL in May and June 2000.

At 200 MeV, the bunch length has been measured for two different values of the charge (0.03 nC/bunch and 0.1 nC/bunch). In both cases, our simulations and our experimental data are in good agreement when the bunch length is 7.5 $\pm$ 1 ps FWHH. At 500 MeV, the measurements gave a value of 6.0 $\pm$ 1 ps FWHH. Therefore, given the error bars, one can further consider a bunch length of 7 ps for these values of the charge, which is in agreement with what was measured in March 2000 [1].

The energy dependence of the transfer matrix between the section 27 and the section 36 of LIL has been confirmed experimentally. In addition to the various measurements done in March 2000 [1], this experiment confirms that the TRANSPORT code is relevant when one wants to simulate the transverse behaviour of the beam in the LIL machine.

References

[1] R. Corsini, A. Ferrari, L. Rinolfi, T. Risselada, P. Royer and F. Tecker, "LIL bunch length and lattice parameters measurements in March 2000", PS/LP Note 2000-01 (MD), CTF3 Tech. Note 2000-09 (MD-LPI).

[2] D.C. Carey, K.L. Brown, F. Rothacker, SLAC-R-95-462, Fermilab-Pub-95/069, UC-414, May 1995.