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SPS

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Longitudinal beam parameters and quality checks of the LHC beam in the SPS: further results and comparisons

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Summary

Controlled longitudinal emittance blow up is used, along with other measures, to stabilize the nominal LHC beam in the SPS. Two Machine Development studies (MDs) were carried out in 2007 to evaluate the effectiveness of different noise settings for the longitudinal blow up of the beam. The noise settings are affected by both the presence of the 800 MHz RF system and intensity effects which modify the synchrotron frequency distribution inside the bunch. The results for the first MD are reported in Note [1]. This Note reports on the results of the second MD, carried out on 2007-10-17, as well as the comparison between the two in order to analyse the differences between the two occasions. Figures of merit are used that allow rapid evaluation of the quality of the beam as for example stability and bunch length uniformity across batches.

1 Cycle description

Particle momentum, calculated synchrotron frequency and applied RF voltages (200 MHz and 800 MHz) are shown in Figure 1 for the SPS cycle used in these MDs. The synchrotron frequency is acquired from the LHC Software Analysis (LSA), where it is calculated for the 200 MHz voltage only, not taking into account the 800 MHz system.

The long flat bottom (until 10860 ms) allows the injection of up to four PS batches, spaced 3600 ms. The voltage along flat bottom is 3 MV, decreased at the injections to 2 MV to be closer to the voltage matched to the PS bucket (which would be $\sim$ 700 kV). The beam is then accelerated from 26 GeV/c to 450 GeV/c. Flat top starts at 18390 ms. Between 18590 ms and 18890 ms the voltage is raised to 7 MV to decrease the bunch length for LHC bucket compliance.

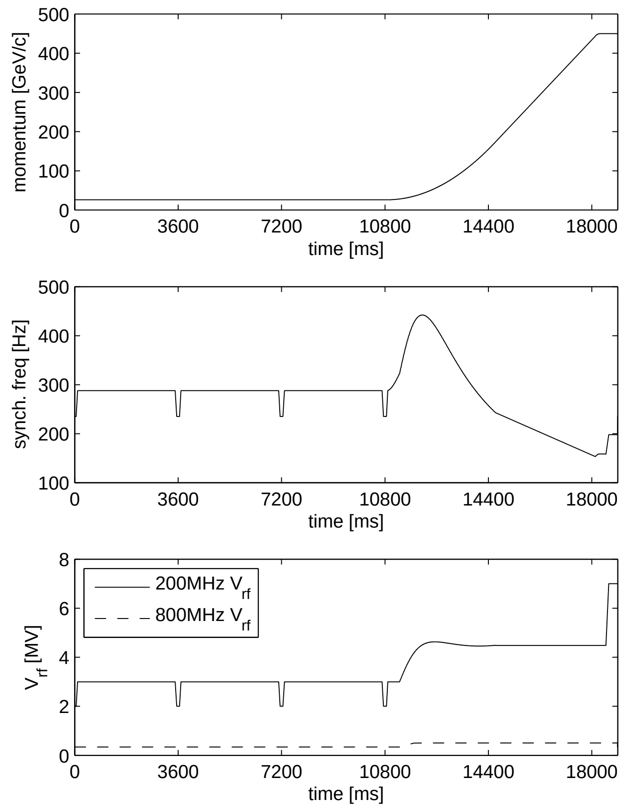


Figure 1: Particle momentum, calculated synchrotron frequency, 200 MHz voltage and 800 MHz voltage programme of the MD cycle. The 800 MHz voltage was kept constant at 450 GeV/c and did not follow the 200 MHz rise to 7 MV.

2 Measurement setup

Two different setups were used for data acquisition during the two MDs. In order to reduce the amount of data to be analyzed (to have fast online data analysis) the setup used on 2007-10-17 consists of a reduced set of bunch profiles with respect to the one used on 2007-08-22 [1]. A comparison between the two MDs is based on bunch profiles acquired at the same times in the cycle and consequently uses all the acquisitions for the 2007-10-17 MD and a subset of the acquisitions for the 2007-08-22 MD.

The bunch profiles are acquired at the following times in the 2007-10-17 MD:

- 0 ms, 3600 ms, 7200 ms and 10800 ms, the times of the four injections, in order to study the statistics of the beam as coming from the PS. Note that only 1, 2 or 3 injections were actually injected, so measurements at 10800 ms do not show newly injected beam;
- 14700 ms (i.e. 100 ms before noise is applied);
- eight frames at flat top as of 18700 ms ($V_{200\mathrm{MHz}} = 7$ MV), spaced 27 turns (as this is roughly one eighth of a synchrotron period, this spacing allows a good estimation of the amplitude of both dipole and quadruple oscillations with a minimum number of acquisitions [1]).

The overall acquisition setup adds up to only 13 frames per cycle acquisition. The main difference with the setup used in the first MD is the absence of the acquisition at 18200 ms (i.e. after the noise excitation is finished and before the beam has reached flat top).

The bunch profile data are subsequently deconvolved for pick up and cable transfer functions [2], Gaussian fits are performed and bunch length (4σ) and bunch position information extracted.

The effect of emittance blow up with the purpose of beam stabilization at flat top is studied. The emittance blow up is achieved by applying phase noise to the 200 MHz RF voltage. The characteristics of the noise are described in another Note [3]. The noise excitation is applied during the acceleration ramp, starting at 14800 ms and lasting 3000 ms.

The beam under study during the second MD consisted of 1, 2 or 3 PS batches of 72 bunches. In this report, though, mostly the first batch is analyzed for simplicity (the motivation is presented in section 3.3). The average intensity per batch at injection $\mathrm{I_{inj}}$ is $\sim 830\ 10^{10}$ p/batch ($\sim 1.15\ 10^{11}$ p/bunch) for the second MD.

Two parameters are used hereafter to define the noise setting: the amplitude $\mathrm{A_{noise}}$ [$\mathrm{mV_{pp}}$] and the noise bandwidth higher cutoff frequency $\mathrm{f_{high}}$ [Hz]. The noise bandwidth Δf is 100 Hz for all settings, the noise parameter fractRise [3] is set to 100%. This gives a spectrum rising linearly in amplitude from zero to a maximum at $\mathrm{f_{high}}$.

Along with the noise settings $\mathrm{A_{noise}}$ and $\mathrm{f_{high}}$, also the 800 MHz phase setting in the hardware (ϕ_{800}, in degrees at 200 MHz) was varied during the second MD. A setting of ϕ_{800} to $223°$ for example corresponds to a phase at 800 MHz which is very close to the value of π rad expected for a double RF system operating in bunch shortening mode [4].

In fact, the second MD was devoted to finding optimum settings in a multidimensional parameter space as it was difficult to reproduce the good results found in the previous MD. Three different parameter scans were carried out:

- scan of ϕ_{800} without noise excitation (see Table 1);
- scan of ϕ_{800} with fixed noise excitation, $\mathrm{A_{noise}} = 400$ $\mathrm{mV_{pp}}$ and $\mathrm{f_{high}} = 254$ Hz, (see Table 2);
- scan of $\mathrm{f_{high}}$ with $\phi_{800} = 223°$ and $\mathrm{A_{noise}} = 200$ $\mathrm{mV_{pp}}$ or 400 $\mathrm{mV_{pp}}$ (see Table 3).

Table 1: Conditions for the first measurement set (noise off): number of batches, 800 MHz phase (ϕ_{800}), number of acquisitions per set ($\mathrm{n_{acqs}}$) and average intensity at injection ($\mathrm{I_{inj}}$).

data set	batches	ϕ_{800} [°]	$\mathrm{n_{acqs}}$	$\mathrm{I_{inj}}$ [10^{10} p/batch]
1	1	213	2	840
2	1	218	2	850
3	2–3	223	3	820
4	1	228	1	830
5	1	233	2	850

Table 2: Conditions for the second measurement set: number of batches, 800 MHz phase (ϕ_{800}), noise parameters (A_{noise} and f_{high}, while Δf = 100 Hz), number of acquisitions per set (n_{acqs}) and average intensity at injection (I_{inj}).

data set	batches	ϕ_{800} [°]	A_{noise} [mV_{pp}]	f_{high} [Hz]	n_{acqs}	I_{inj} [10^{10} p/batch]
6	1	213	400	254	2	840
7	1	218	400	254	2	850
8	1	221	400	254	2	840
9	1	222	400	254	2	840
10	1	223	400	254	3	850
11	1	224	400	254	2	830
12	1	225	400	254	2	850
13	1	228	400	254	4	850

Table 3: Conditions for the third measurement set: number of batches, 800 MHz phase (ϕ_{800}), noise parameters (A_{noise} and f_{high}, while Δf = 100 Hz), number of acquisitions per set (n_{acqs}) and average intensity at injection (I_{inj}).

data set	batches	ϕ_{800} [°]	A_{noise} [mV_{pp}]	f_{high} [Hz]	n_{acqs}	I_{inj} [10^{10} p/batch]
14	2	223	200	234	3	830
15	2	223	200	244	1	830
16	3	223	200	254	2	820
17	1–2	223	400	254	6	840
18	2–3	223	200	264	3	820
19	1	223	400	274	3	840
20	1	223	400	294	2	840

3 Second MD results

3.1 Bunch length before controlled blow up

The bunch length distribution along the first batch at the first turn in the SPS is presented in Figure 2 (average on all acquisitions). It shows a double dependence on bunch number: a periodic pattern with periodicity of four bunches due to the imperfect bunch splittings performed in the PS (10 MHz RF system), and an overall positive slope in bunch length across the batch so that the first bunches are shorter than the last ones.

Figure 3(a) shows bunch lengths at the time of the fourth injection (10800 ms, i.e. the end of flat bottom) while Figure 3(b) shows bunch lengths just before blow up is applied (14700 ms). In both plots the bunch length variation along the batch is modified due to the effect of beam loading in the 200 MHz and 800 MHz cavities. The bunch length at 10800 ms is shorter than at injection. This can be due to a change in distribution during the capture process and along the flat bottom. The shorter bunch length observed at 14700 ms compared to 10800 ms is due to the higher momentum of the particles (~ 180 GeV/c at 14700 ms and 26 GeV/c at 10800 ms) and higher RF voltage (e.g. ~ 4.5 MV at 14700 ms and to 2 MV at 10800 ms).

It is worth noting that the bunch position at the end of flat bottom (10800 ms) for the first batch

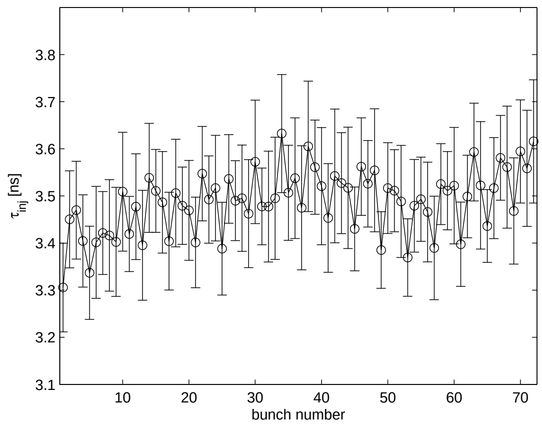


Figure 2: Bunch length at injection: mean (circle) and rms spread (error bar) across all acquisitions.

keeps a trace of whether the beam is constituted by one or more batches. In Figure 4 this is highlighted by the use of different colours.

3.2 Bunch length at flat top and Beam Quality Monitor-like analysis

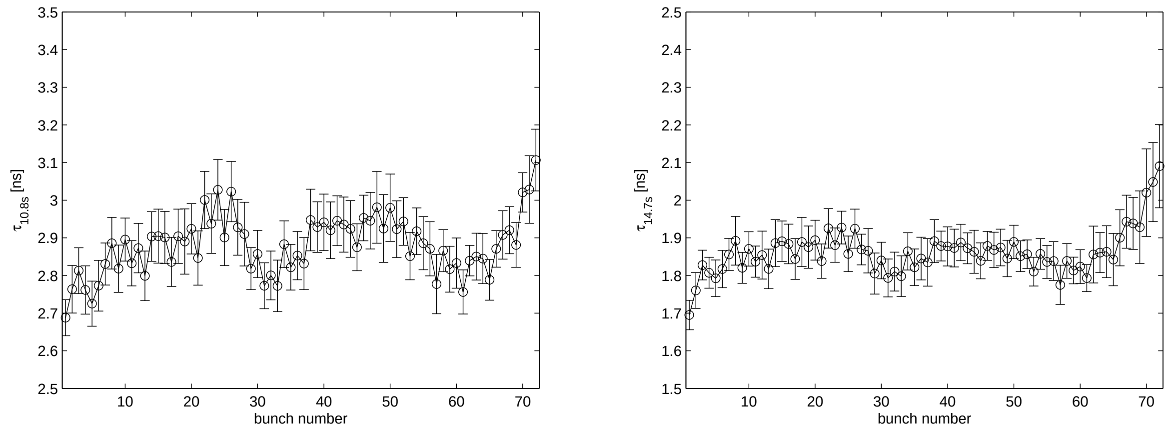
The eight beam profiles acquired at flat top are analyzed to access bunch lengths and positions. By comparing the results for the same bunch across the eight measurements, an indication of the stability of that bunch can be gained, as both mean value and minimum-to-maximum variation of the calculated parameters can be evaluated. An excessive amount of min-to-max variation on bunch position or length is an indication of instability, i.e. dipole or quadrupole oscillations.

Figure 5 summarizes a few figures of merit for each MR acquisition and can be compared to similar images in the previous Note [1]. The mean bunch length across the eight flat top acquisitions and its standard deviation are plotted in black as circle and errorbar. Min-and-max bunch lengths are the red triangles. The maximum min-to-max variation of bunch length are the blue diamonds and the maximum min-to-max variation of bunch position are the magenta diamonds. Vertical broken lines distinguish between different settings, highlighted on the x-axis.

The previous data are reorganized in Figure 6 so to highlight the effectiveness of the emittance blow up technique for a given phase setting. The controlled emittance blow up gives bunch lengths that are on average longer than in the case where the RF noise is not applied. At the same time, the amount of oscillation is much reduced when the RF noise is applied, i.e. much lower maximum min-to-max variation of both bunch length and position is achieved, suggesting a more stable beam.

The data in Figure 5 can also be reorganized to underline the dependence on the choice of ϕ_{800}, as shown in Figure 7. The best performance, lower min-to-max oscillations and lower mean bunch length, is obtained in the range $\phi_{800} = 225$–$228°$ both with and without RF noise. While during the MD the optimum setting was thought to be $\phi_{800} = 223°$, it was later found out that the setting was a few degrees off, and this is in agreement with the results shown in Figure 7.

It is worth pointing out that a setting of ϕ_{800} too far from the correct value has very negative effects on the beam. The choice of $\phi_{800} = 213°$ results in a minimum synchrotron frequency spread which is not sufficient to stabilize the beam even already early in the cycle. In Figure 8 bunch lengths at 14700 ms



(a) (b)

Figure 3: Bunch length at the end of flat bottom, at 10800 ms (a), and before blow up starts, at 14700 ms (b). Mean and rms spread across all measurements from all data sets, apart from the ones taken with $\phi_{800} = 213°$ (see section 3.2).

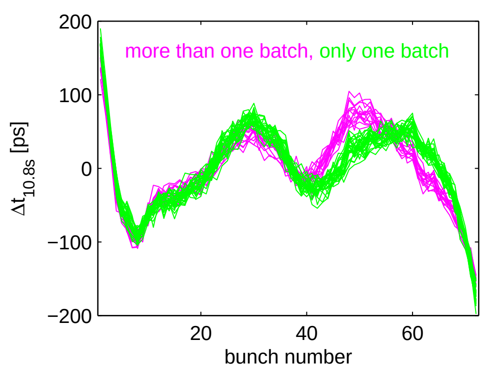


Figure 4: Bunch position at the end of flat bottom, first batch, all acquisitions. One-batch beam in green and two- or three-batch beam in magenta.

for all measurements are reported, and it is clear that the choice $\phi_{800} = 213°$ (red curves) caused the beam to be blown up even before the noise is applied. For this reason the four measurements on which this setting was applied were not included in Figure 3.

Another point of interest is underlined in Figure 9. The top graph shows the bunch length at flat top (average across eight measurements). The bottom graph shows the same quantity normalized so to have zero average across the batch. All different measurements are very coherent in showing a structure with three peaks, which was already present but not so evident in the top graph. This suggests that bunches belonging to different measurements experienced a different average blow up with an extra variation, very similar to the beam loading effect already pointed out in Figure 3, superimposed on this average.

Figure 10 highlights the dependence of the average blow up across the batch on the amplitude of the applied noise A_{noise}. A lower noise amplitude A_{noise} gives lower average blow up.

3.3 Second and third batch

Figures 11 and 12 report the comparison of bunch lengths and positions at different times in the cycle for the first, second and third batches. These figures motivate the choice of studying only the first batch in every MR acquisition as there is no significant difference between the different batches.

It is worth pointing out that the bunch position in a batch at the end of flat bottom in particular (see Figure 12, left) is influenced by the batch structure of the beam, as already introduced when referring to Figure 4. Two families of curves can be distinguished around bunch 25 highlighting whether the beam has one or more batches (see black curves versus red and green curves). Around bunch 50 in the batch, two groups of curves can also be distinguished. The higher group is formed by first batches when followed by second batches and second batches when followed by third ones. The lower group is formed by first batches in one-batch beam, second batches in a two-batch beam, third batches in a third batch beam. This comes from the influence of the one-turn feedback on the induced voltage in the cavities, the correction to each batch extending beyond the end of the batch.

3.4 Summary of results

The controlled blow up was effective in stabilizing the beam on the flat top if intensity effects are taken into account (noise frequency shift Δf $\sim$ 40 Hz from "low intensity" case calculated through simulation), a lower amplitude of dipole and quadrupole oscillations being observed; this stability is obtained at the price of increased average bunch length.

An optimum setting for the ϕ_{800} phase can be found, and for this MD it was ϕ_{800} = 225–228° (at 200 MHz).

Bunch lengths at flat top for all measurements of this MD show a strong beam loading-like variation (the three-peaked structure across the batch).

The blow up at the end of the batch (bunches 60–72) is higher than for the rest of the batch. This might come from the beam loading which tends to increase bunch lengths at the end of the batch, added to the increased bunch intensity in tail bunches.

No settings were found that could reproduce the good results of the 2007-08-22 MD, for which a uniform bunch length at flat top could be obtained.

As found out later, the phase ϕ_{800} had an offset proportional to the synchronous phase and was not optimum all along the cycle. It is likely that its setting was better at the flat bottom and at the flat top, and this presumably influences the results during ramp.

4 Comparison of the two MDs

4.1 Beam characteristics before blow up

Two different intensity ranges were studied in the two MDs; as the lower intensity beam was only present in the first MD [1], it is not taken into account in this comparison and only the case of higher intensity is studied further. In the case of "higher" intensity, the beam intensity at injection is $\sim 1.15\ 10^{11}$ p/bunch or $820-850\ 10^{10}$ p/batch (i.e. $\sim 90\%$ of the nominal LHC intensity). The intensity measured at injection for the acquisitions in the two MDs is presented in Figure 13, showing that in the later MDs the average intensity was only $\sim 2\%$ higher than in the earlier MD.

Frames acquired at injection, at the end of flat bottom (i.e. fourth injection, 10800 ms) and at 14700 ms can be compared to verify uniformity of conditions before the RF noise is applied. The beam characteristics are shown in Figure 14 for injection (of the first batch, i.e. 0 ms), Figure 15 for 10800 ms and Figure 16 for 14700 ms.

Figure 14 displays the 4σ bunch length at injection (left plots) and the product between bunch length and bunch peak amplitude (right plots). The bunch lengths for both MDs are very similar. They show a four-bunch periodicity, signature of the imperfection of the bunch splitting performed in the PS (10 MHz RF system), and an overall positive slope across the batch (bunches at the end of the batch are longer than bunches at the beginning of the batch).

The product between bunch length and bunch amplitude is a suitable indication of bunch intensity at injection as all bunches coming from the PS have similar shapes. In Figure 14 it is possible to see that the distribution is similar in the two MDs apart from the tail of the batch (bunches 60–72) where the second MD had more intense bunches ($\sim 10\%$). This is likely to be due to a different setting in the PS Booster (more precisely, the second batch of the fourth ring). The total intensity per batch is instead very similar (less than 1% difference between the averages on the two MDs).

Figure 15 shows bunch lengths (left plots) and bunch positions (right plots) at 10800 ms. While the average bunch positions between the two MDs are in good agreement, the second MD shows slightly smaller bunch lengths than the first MD at 10800 ms. The difference is 100 ps on average across the batch (standard deviation 70 ps), i.e. 3.5% of bunch length. If this is related to a voltage difference (according to the inverse fourth power law), it translates to a 15% difference in voltage, suggesting that the voltage in the second MD might have been higher by that amount than the 200 MHz voltage in the first MD.

Figure 16 reports bunch lengths (left plots) and bunch positions (right plots) at 14700 ms. The difference in bunch length pointed out at 10800 ms is not present at 14700 ms anymore. This could be simply due to the fact that the bunch length at 14700 ms is roughly half than at 10800 ms, suggesting a difference of the order of ~ 50 ps (half of the estimated ~ 100 ps at 10800 ms), which would be harder to spot on the plot and has less statistical meaning.

4.2 Data sets with equal noise settings

Only four data sets were acquired in both MDs with the same settings for ϕ_{800}, f_{high} and A_{noise} and can thus be directly compared at flat top, after the RF noise has been applied. The settings and the data set numbers as used in the previous Note [1] are shown in Table 4.

Table 4: Conditions for compared data sets: 800 MHz phase (ϕ_{800}), noise parameters (A_{noise} and f_{high}), data set number as appeared in previous notes.

set	ϕ_{800}	A_{noise} [mV_{pp}]	f_{high} [Hz]	data set on 08-22 (batches)	data set on 10-17 (batches)
1	223	400	254	12 (1)	10 (1), 17 (1–2)
2	223	200	264	10 (1)	18 (2–3)
3	223	400	274	9 (1)	19 (1)
4	223	400	294	4 (1)	20 (1)

The data are analyzed for the evaluation of 4σ bunch lengths, bunch amplitude (only at injection) and bunch positions. The parameters resulting from each set are compared in Figures 17 to 20. In each figure, nine plots are shown. For each plot, quantities are shown either as average per data set (i.e. across different measurements), or as maximum per data set in the case of min-to-max variations.

The top plots show bunch length at injection, 10800 ms and 14700 ms. The middle plots show the product between bunch length and bunch amplitude (indication of bunch intensity) and bunch positions at 10800 ms and 14700 ms. The bottom plots show average bunch length at flat top, and give an indication of quadrupole or dipole oscillation amplitude from the bunch length and bunch position variation at flat top.

Bunch lengths at injection and 14700 ms are very similar for all four sets, while bunch length at 10800 ms is less in the second MD than in the first one (see also Figure 15 and comments).

No meaningful difference in bunch position is found at 10800 ms, nor at 14700 ms.

Middle and right bottom plots are indications of oscillation amplitudes, as bunch length or position oscillation. Set four was acquired with the worst settings as bunch oscillations are very wide, while set two was acquired with better settings as the beam is found to be very stable. Sets one and three show some limited amount of oscillation.

Together with oscillation amplitudes, the uniformity of bunch length at flat top is another indication of the goodness of the noise settings. No settings led to bunch lengths at flat top on 2007-10-17 as uniform as on 2007-08-22, in particular bunches are more blown up in the tail of the batch and around bunch 15 and 45 (the "three-peak structure" already discussed in section 3.2, which is present on 2007-10-17 data regardless of noise settings or ϕ_{800}). This is particularly true for sets one and three, while set two obtained best results of all as the three-peak structure is less pronounced.

Still it has to be pointed out that for all sets (even for set two) the blow up of the batch tail is excessive. This is possibly due to the increased bunch intensity in the tail as hinted from the amplitude-tau plot at injection (note the blow up dependence on intensity, and see Figure 14 and comments), in addition to beam loading effects. Beam loading in fact makes tail bunches longer than earlier bunches in general, as can already be seen before the RF noise is applied, i.e. 10800 ms or 14700 ms. In fact, the tail bunch lengths of 2007-10-17 batches can already be seen increasing when looking from injection to 10800 ms and 14700 ms data (top plots in Figures 17 to 20), suggesting that tail blow up starts before the RF noise is applied.

It is important to remember that the second MD was carried out during the ion beam runs, which implied modifications to the 200 MHz RF system. It was found out later that the voltage amplitude applied in the later MD could be questioned, the effect coming from a difference between the programmed voltage and that actually available on the cavities. This difference is estimated to be of the order of 10% maximum. Below 2.5 MV the 200 MHz voltage is estimated to be lower than programmed, while above 2.5 MV it is estimated to be higher.

This is in contrast though with the bunch length measurement at 10800 ms ($V_{200}(10800) = 2$ MV), which suggests a higher voltage on 2007-10-17. At the same time, a lower voltage later in the cycle could have explained the three-peak structure, which is very close to the effect of beam loading. Additionally, no meaningful difference in bunch position is observed - a small shift should be present in the case of different voltages.

Hardware settings were compared. The voltage program for the 200 MHz and 800 MHz cavities, octupole settings, longitudinal damper gain were found to be the same. Horizontal chromaticity had a deviation of 0.1 at flat top, while vertical chromaticity changed of 0.1 over the whole cycle. Settings for the feedback and feedforward systems were verified and no significant difference could be pointed out. The same executable disk file was used to create the noise stimulus.

Figure 21 compares the case of phase noise off in the two MDs (named "set 5" after Table 4). Three acquisition are shown for each MD, belonging to the first set in the first MD (one batch) and to the third set in the second MD (two or three batches). In all shown acquisitions ϕ_{800} is set to 223°. The bunch lengths from the second MD are more blown up than in the first one suggesting a less stable beam in the second MD when the noise is not applied. It is also possible to see hints of the structure due to the effect of beam loading already pointed out when the noise is applied. This suggests that some hardware setting was nevertheless different in the two MDs, and contributed to the bunch length variation at flat top.

4.3 Conclusions and future plans

During the second MD the results from the first could not be reproduced when using the same beam parameters and the same known hardware settings. Scans in parameter space for the 800 MHz phase and for the noise settings were performed, but relatively uniform bunch length across the batch as in the first MD was not obtained. The noise excitation effectively increased the emittance, but this was often not sufficient to provide stability. When the noise excitation was not used, the beam was more unstable in the second MD compared to the first one. The only significant difference between the two MDs is the addition of ion cycles to the super-cycle, requiring modifications to the 200 MHz RF system.

For the next MDs, data acquisitions after the end of the noise excitation but before the flat top is reached are needed to assess the effect of the noise before instabilities on the flat top develop. At the same time, an online assessment of beam parameters is indispensable to quickly verify the goodness of the parameter settings and hence optimize the use of the MD time.

5 Acknowledgements

We would like to thank U. Wehrle for his help in the setting-up of the beam and the instrumentation in the SPS.

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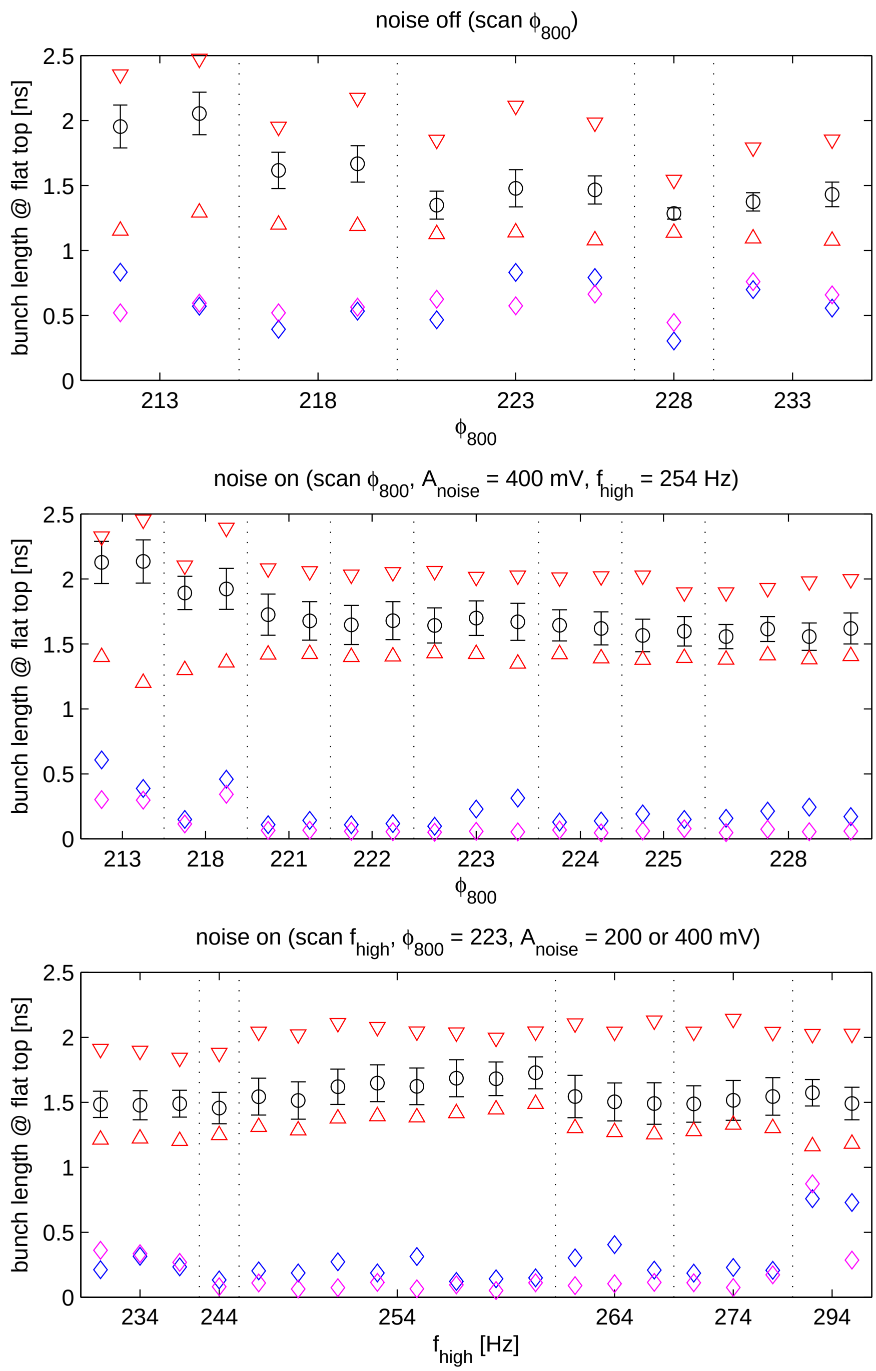

Figure 5: Figures of merit for each measurement: average bunch length at flat top (○), rms spread (errorbar), minimum (△) and maximum (▽) values, maximum min-to-max variation of bunch length (◇, blue) and position (◇, magenta). Top graph for ϕ_{800} scan with noise off, middle graph for ϕ_{800} scan with noise on, bottom graph for noise f_{high} scan.

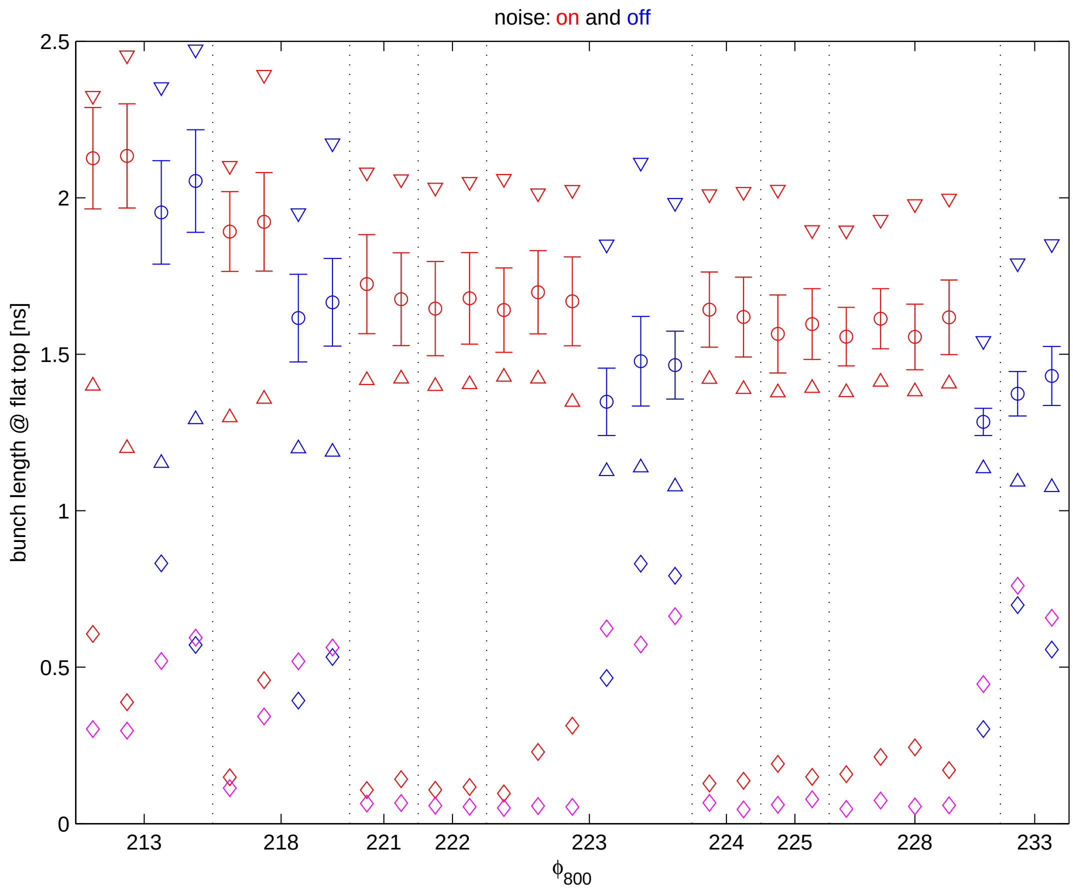

Figure 6: Comparison between ϕ_{800} scans with (red) and without (blue) noise. Average bunch length at flat top (○), rms spread (errorbar), minimum (△) and maximum (▽) values, maximum min-to-max variation of bunch length (◇, blue and red) and position (◇, magenta).

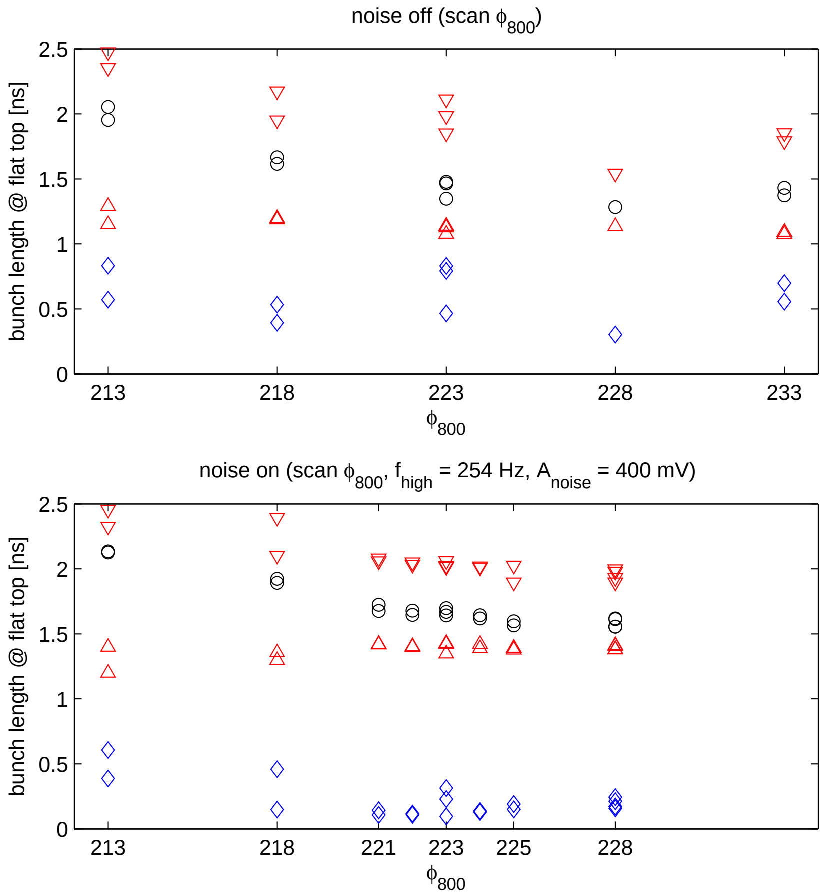

Figure 7: Figures of merit plotted versus ϕ_{800}, scans without (top graph) and with (bottom graph) noise. Average bunch length at flat top (○), minimum (△) and maximum (▽) values, maximum min-to-max variation of bunch length (◇).

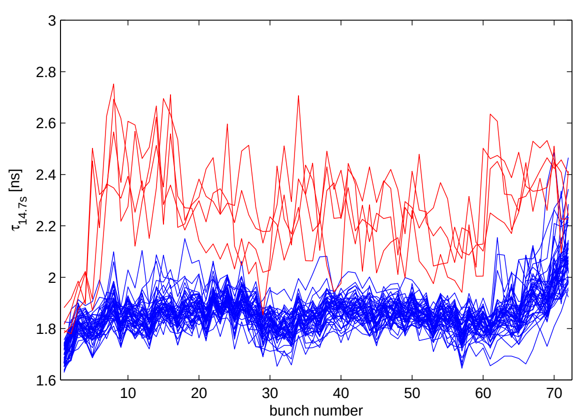

Figure 8: Bunch length at 14700 ms, all measurements in blue, apart from the ones taken while having set $\phi_{800} = 213$, which are in red.

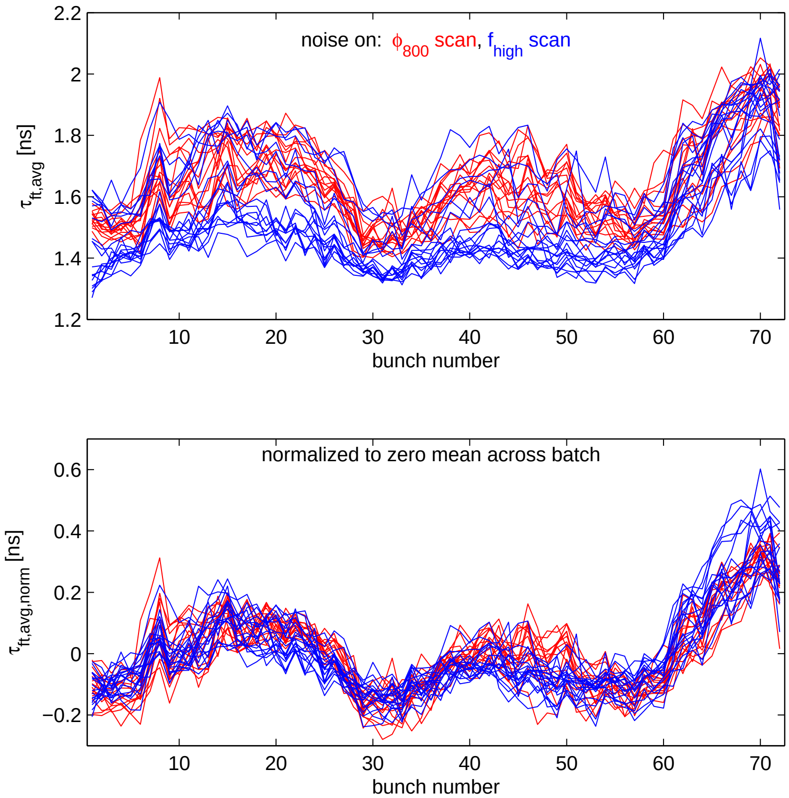

Figure 9: Bunch length at flat top, average across 8 measurements in top graph, normalized to zero mean across batch in bottom graph. All measurements are with noise, ϕ_{800} scan set in red, f_{high} scan set in blue.

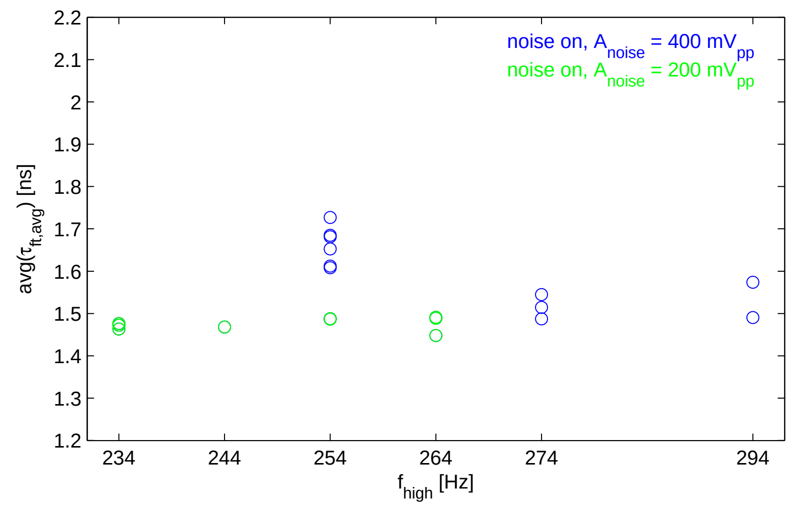

Figure 10: Bunch length at flat top, average across 8 measurements and across batch. Third scan set, through f_{high}. Different noise amplitudes A_{noise} are also highlighted.

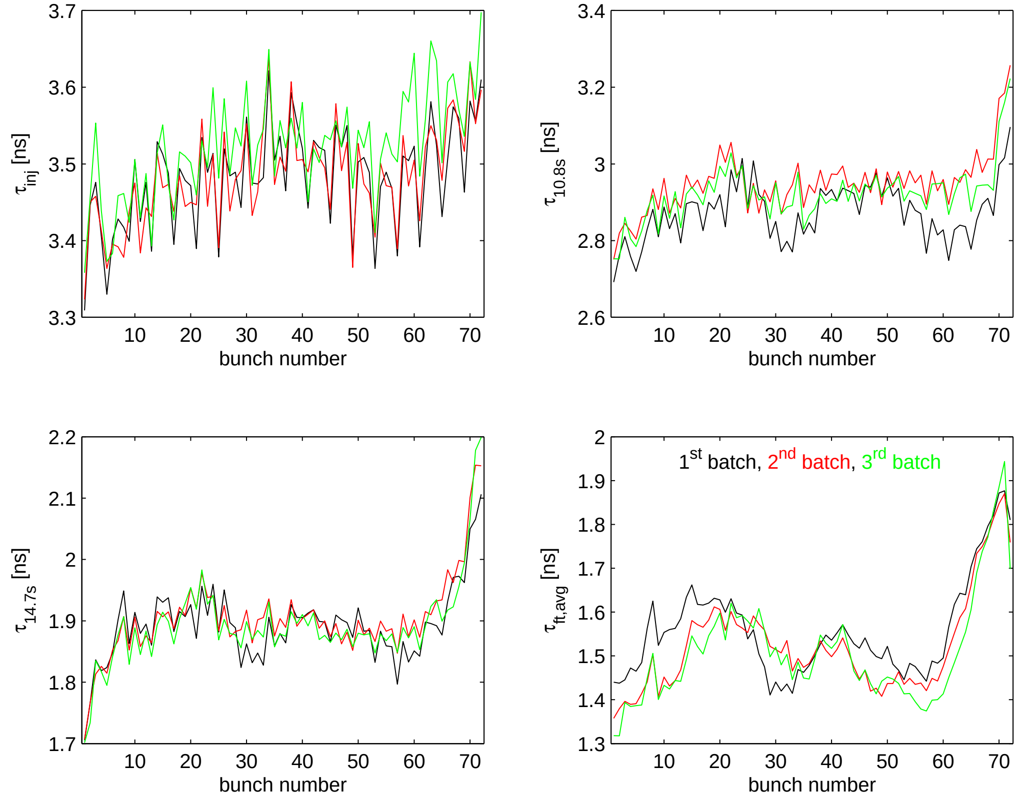

Figure 11: Bunch length at injection, end of flat bottom, before blow up and flat top (average across 8 measurements) on average across all acquired first batches (black), all acquired second batches (red), all acquired third batches (green).

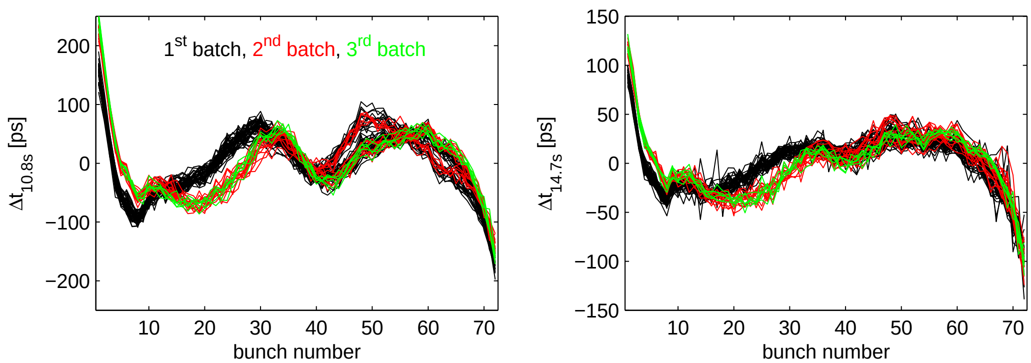

Figure 12: Bunch position at the end of flat bottom and before the noise is applied. All acquired first batches in black, all acquired second batches in red, all acquired third batches in green.

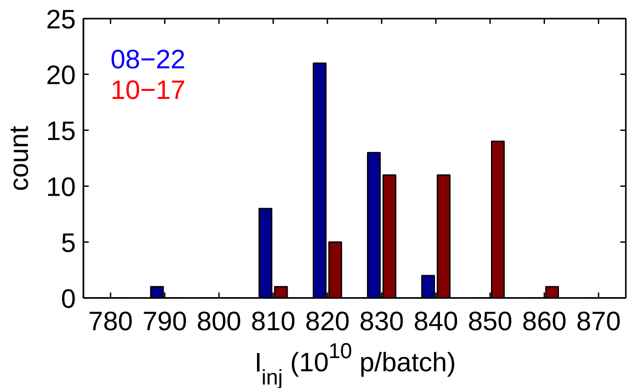

Figure 13: Beam intensity measured at injection I_{avg}. In the case of beam constituted of more than one batch, the BCT reading is divided by the number of batches after verifying that the $A\tau$ (product of bunch amplitude and length) batch profiles are similar.

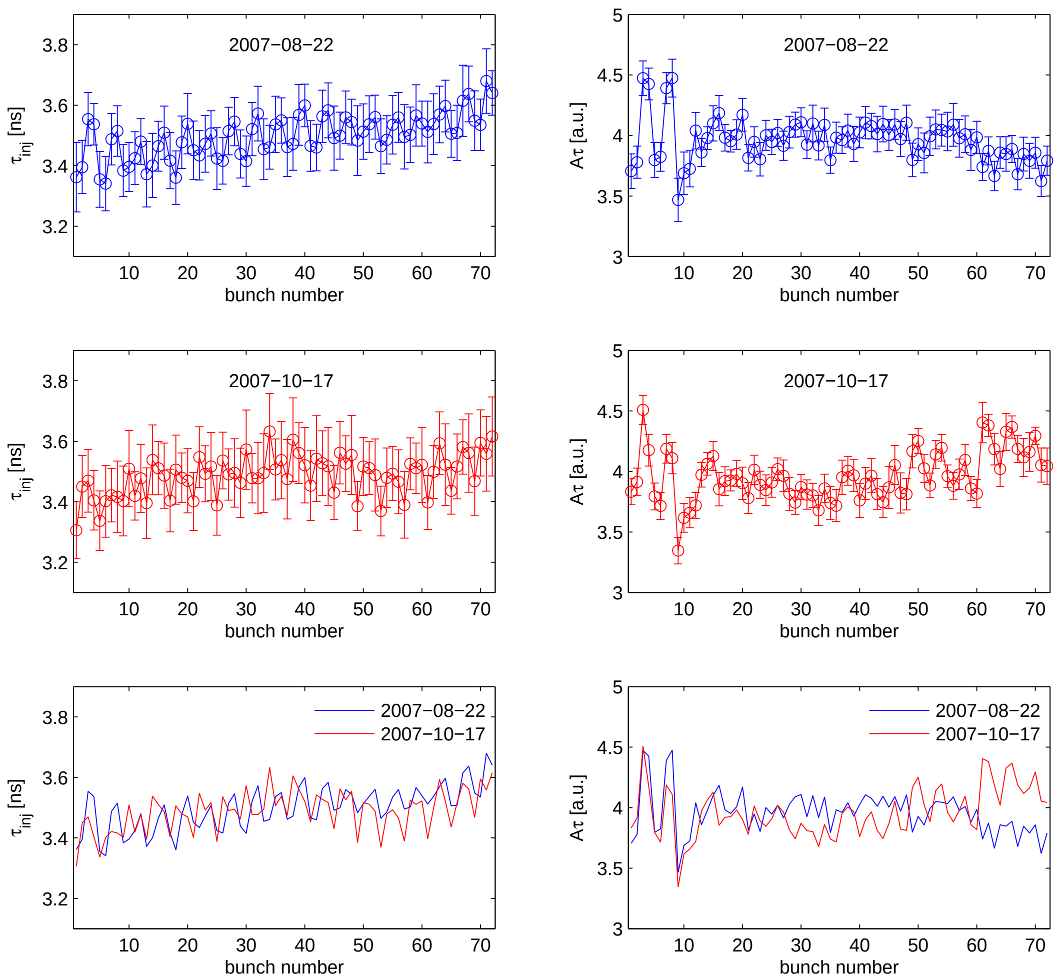

Figure 14: Bunch length (left plots) and product between bunch length and amplitude (right plots) at injection. Average and standard deviation across all measurements from 2007-08-22 (top plots) and from 2007-10-17 (middle plots), average across all measurements (bottom plots).

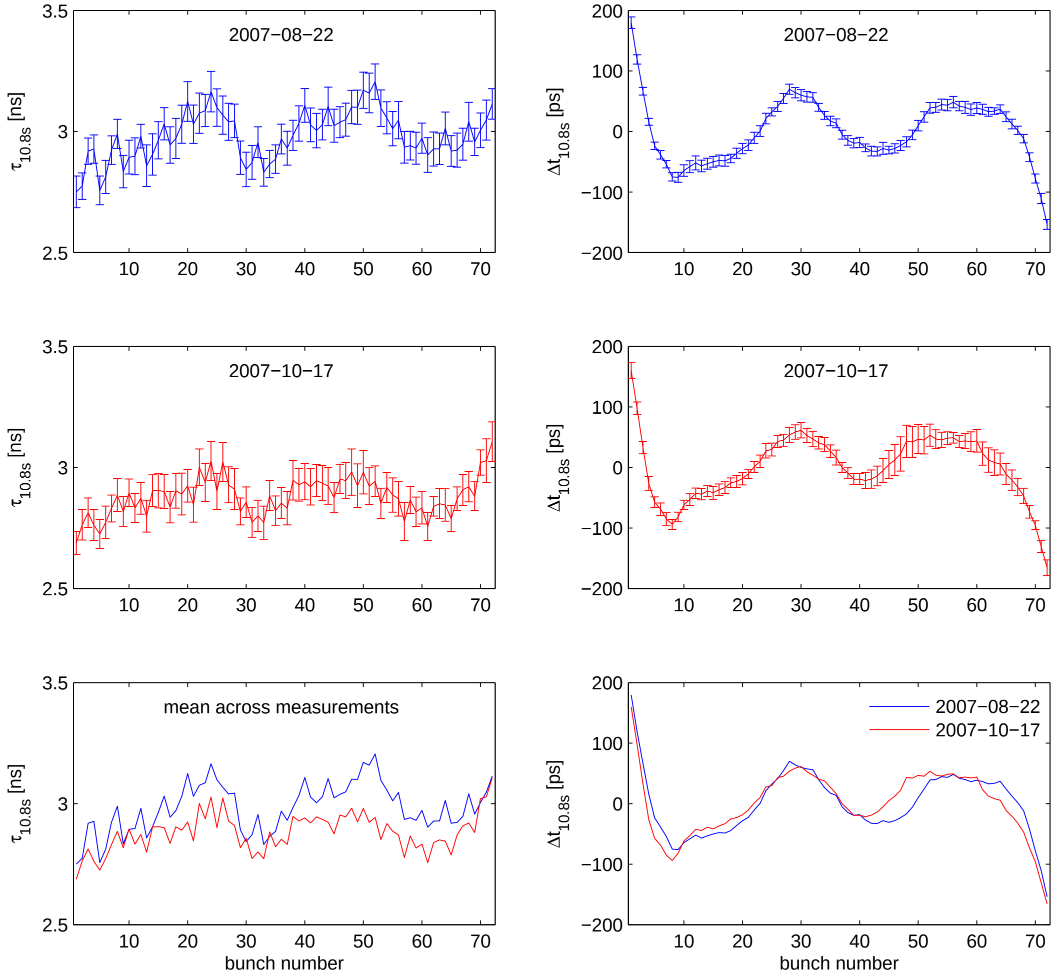

Figure 15: As Figure 14, but at 10800 ms; i.e. bunch length (plots on the left) and position (plots on the right) at 10800 ms, mean and standard deviation. On all measurements from 2007-08-22 (top plots) and from 2007-10-17 (middle plots), average across all measurements (bottom plots).

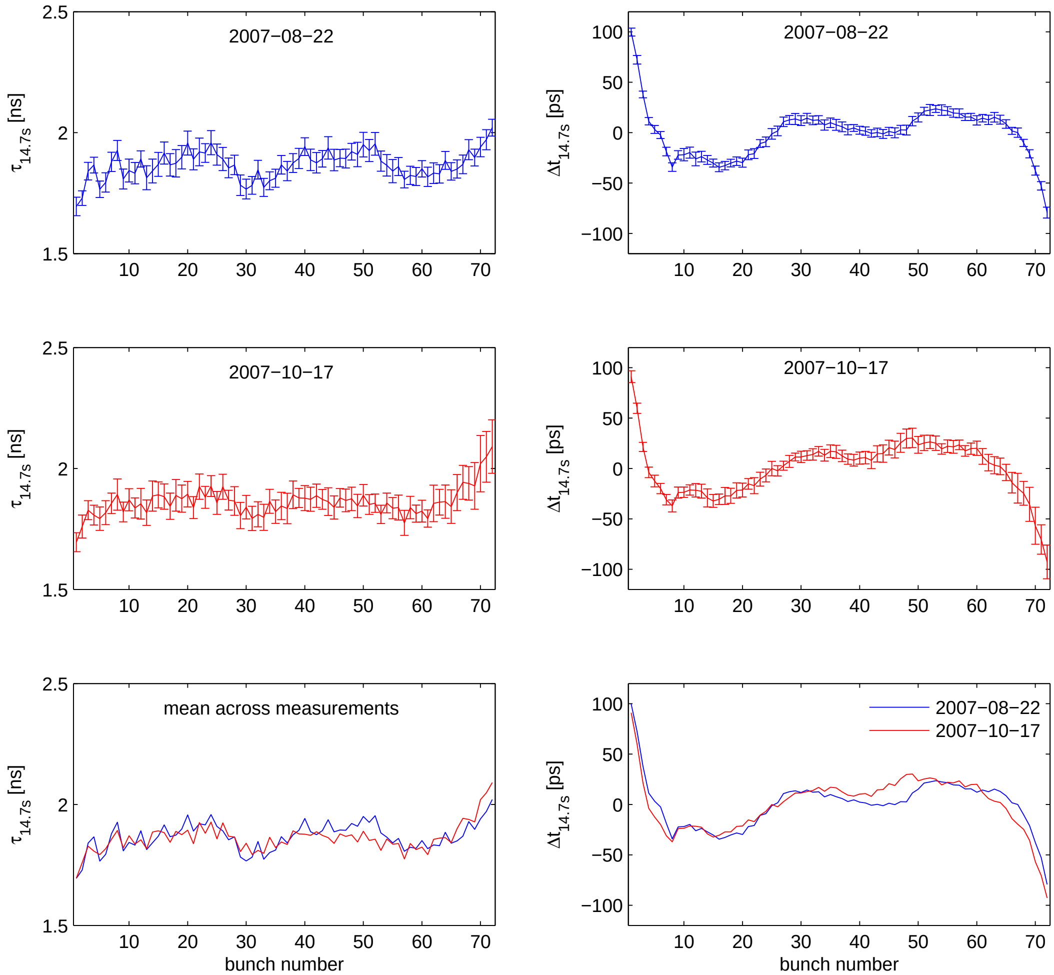

Figure 16: As Figures 14 and 15, but at 14700 ms; i.e. bunch length (plots on the left) and position (plots on the right) at 14700 ms, 100 ms before the noise is applied. Average and standard deviation on all measurements from 2007-08-22 (top plots) and from 2007-10-17 (middle plots), average across all measurements (bottom plots).

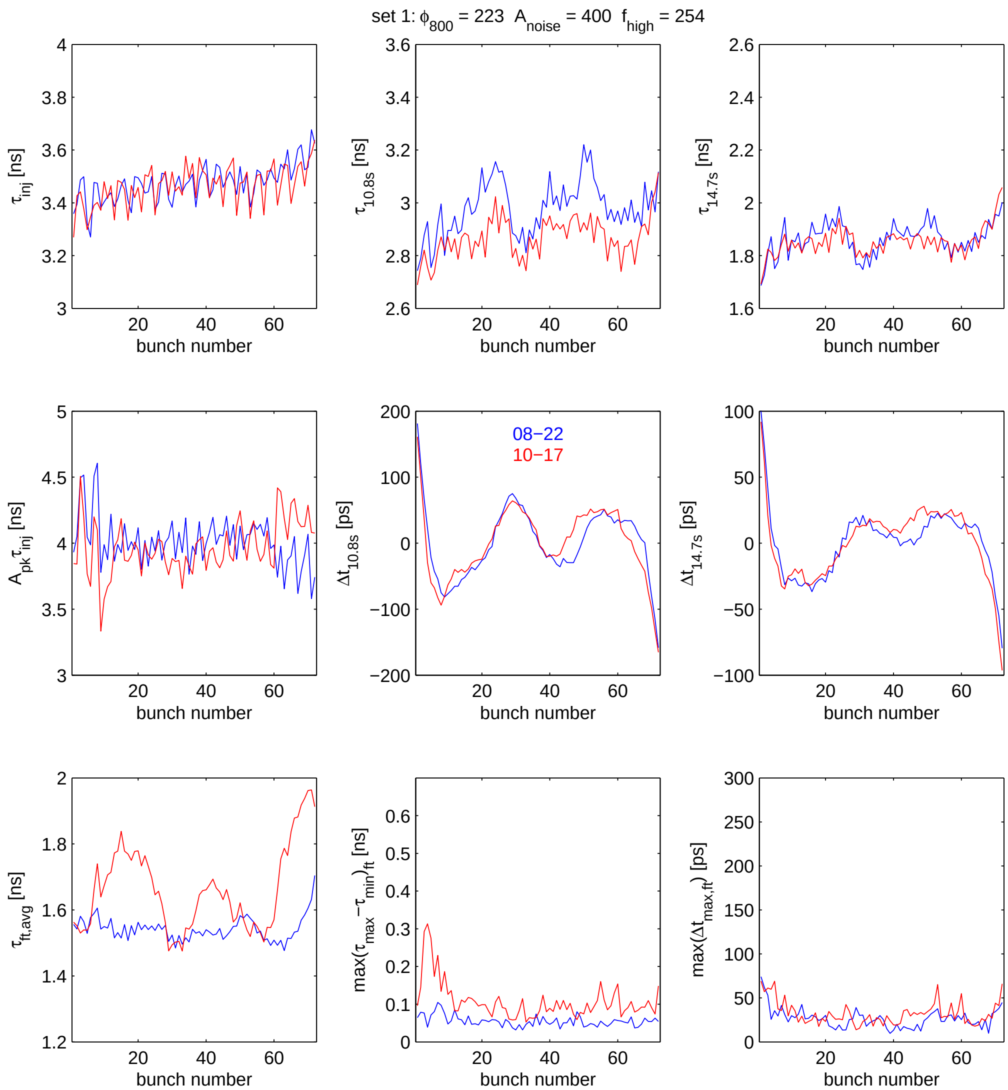

Figure 17: Bunch lengths and positions for set one ($\phi_{800} = 223°$, $A_{noise} = 400$ mV$_{pp}$, $f_{high} = 254$ Hz). Averages or maxima in measurements on 2007-08-22 in blue and 2007-10-17 in red.

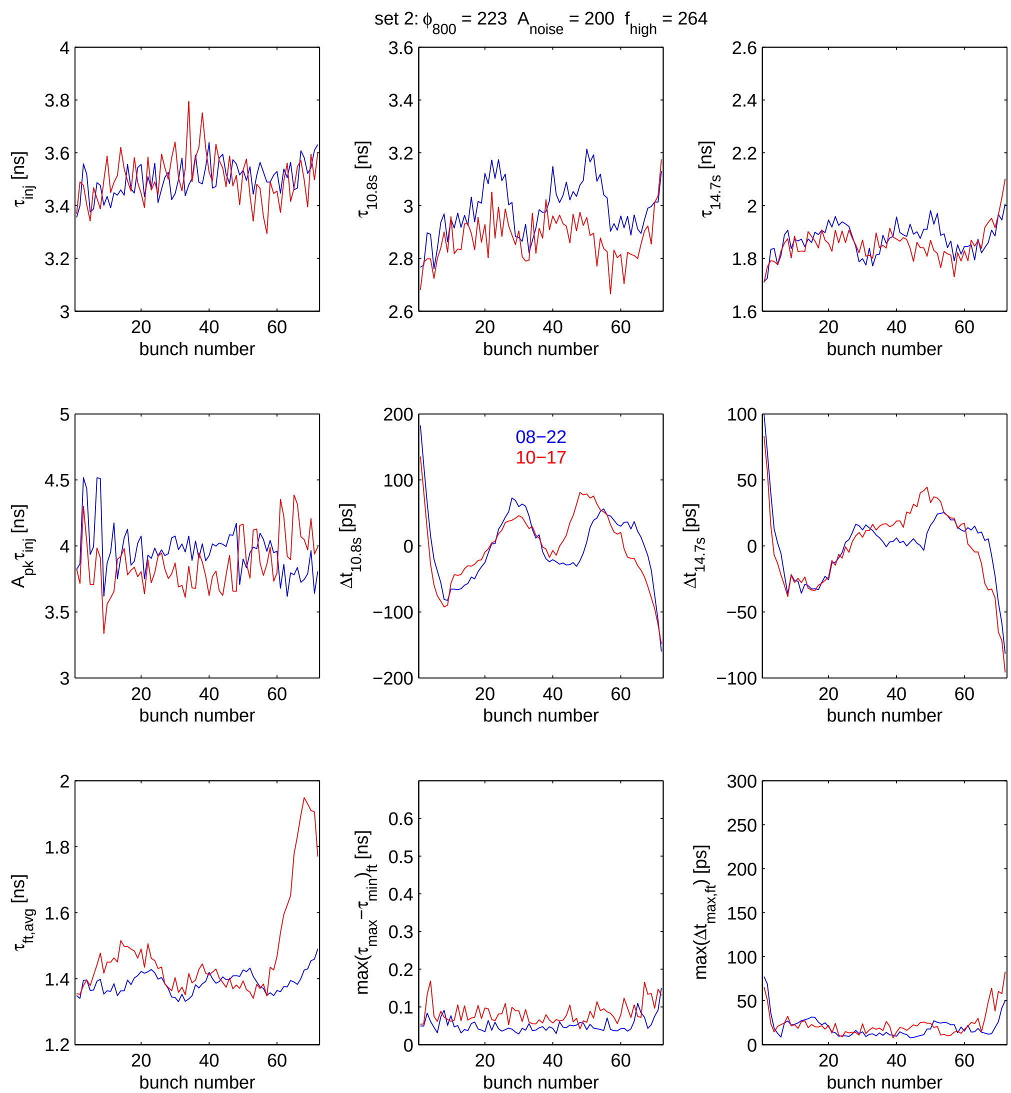

Figure 18: Bunch lengths and positions for set two ($\phi_{800} = 223°$, $A_{noise} = 200$ mV_{pp}, $f_{high} = 264$ Hz). Averages or maxima in measurements on 2007-08-22 in blue and 2007-10-17 in red. As Figure 17, but different noise settings.

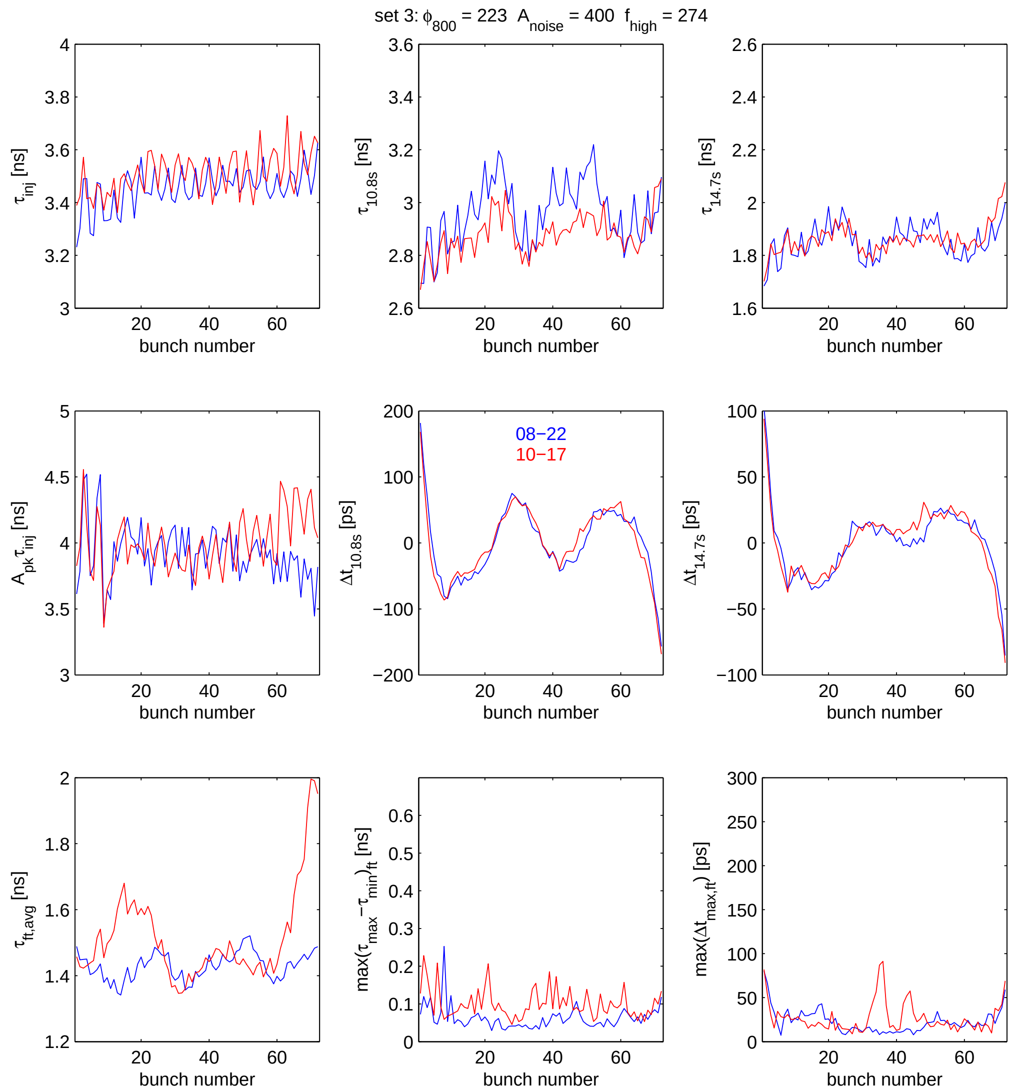

Figure 19: Bunch lengths and positions for set three ($\phi_{800} = 223°$, $\mathrm{A_{noise}} = 400\ \mathrm{mV_{pp}}$, $\mathrm{f_{high}} = 274$ Hz). Averages or maxima in measurements on 2007-08-22 in blue and 2007-10-17 in red. As Figures 17 and 18, but different noise settings.

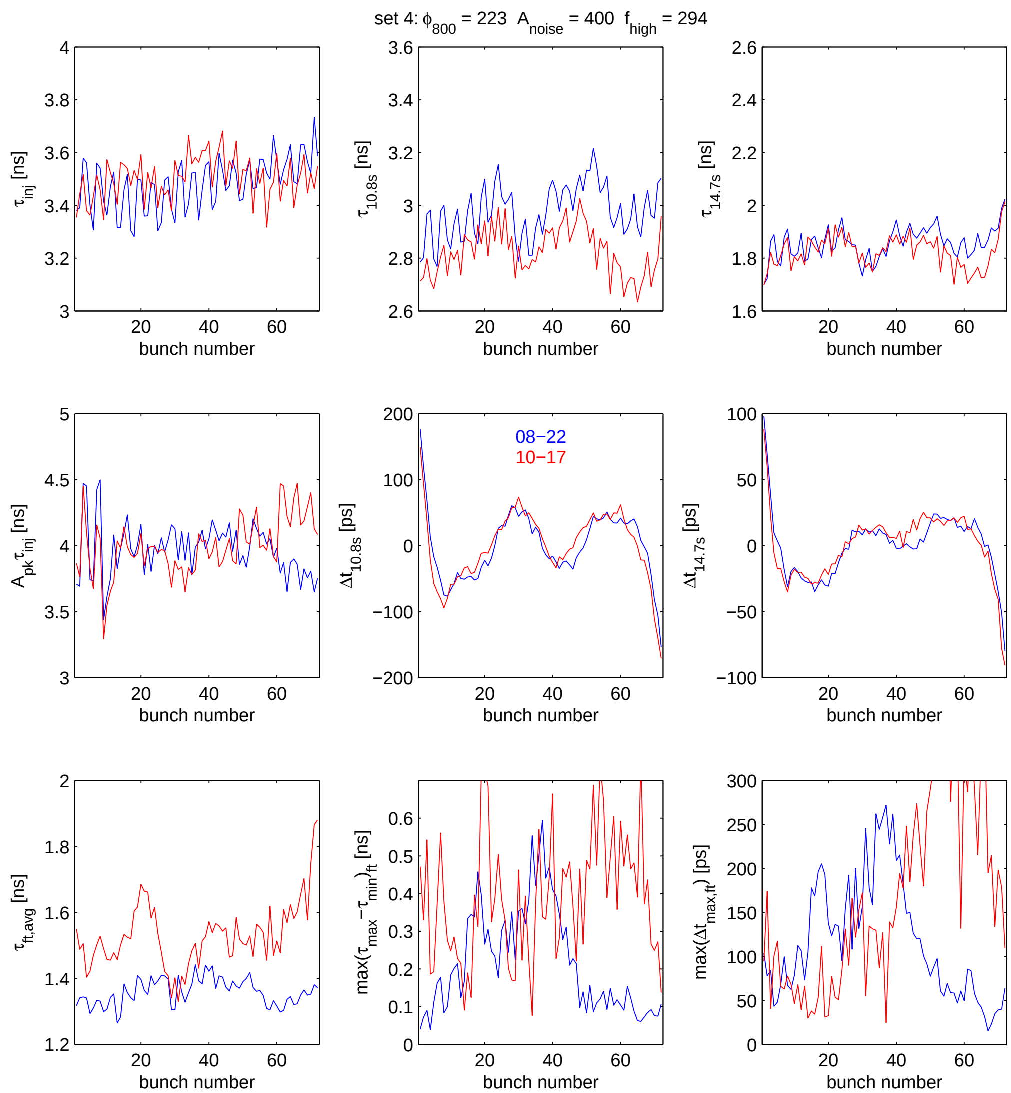

Figure 20: Bunch lengths and positions for set four ($\phi_{800} = 223°$, $A_{\text{noise}} = 400$ mV_{pp}, $f_{\text{high}} = 294$ Hz). Averages or maxima in measurements on 2007-08-22 in blue and 2007-10-17 in red. As Figures 17, 18 and 19, but different noise settings.

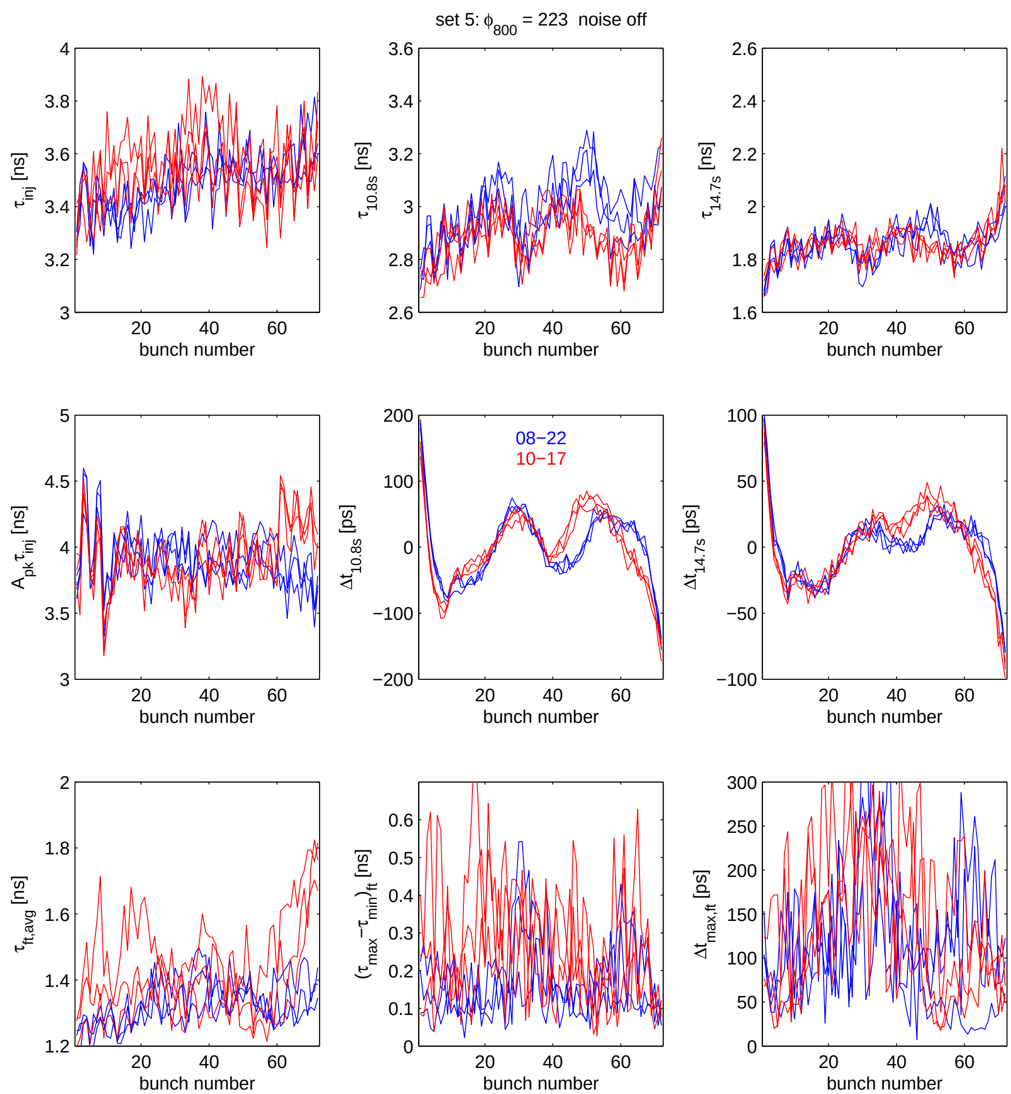

Figure 21: Bunch lengths and positions for set five ($\phi_{800} = 223°$, noise off). Three measurements per MD, 2007-08-22 in blue and 2007-10-17 in red.