SPS

Beam Losses and Lifetime of the LHC Beam in the SPS

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Summary

Studies of the LHC beam loss in the SPS started in 2003 [1], [2] and continued in 2004. The flat bottom losses strongly depend on the batch intensity and the RF voltage. For beam with the 75 ns spacing at the same bunch intensity they are smaller than for the 25 ns spaced bunches. Large voltage on the flat bottom together with some optimum voltage at injection helps to reduce losses. Analysis of data from 2003 has shown that observations are compatible with a diffusion like process on the flat bottom. Therefore significant time during 2004 was devoted to studies of possible RF noise sources. However the main improvement in beam lifetime on the flat bottom was observed after a change in the working point in the transverse plane (MD on 1.09.2004). In this Note we present measurements of beam loss and lifetime done during several dedicated SPS MDs for different conditions in the ring. Analysis of beam coasts will be presented separately.

1 MD on 8.06.2004

During this MD we had the LHC beam with the 75 ns spacing. In 2004 the length of the flat bottom in the LHC cycle in the SPS was increased, in comparison to the previous years, to reduce possible effects from the B-field variation on the flat bottom (beam injected later).

We started with two batches of 16 bunches each injected from the PS (usually with the 75 ns spacing one PS batch has 24 bunches). During the ramp we used the voltage programme designed for the 0.6 eVs bunch emittance (with the filling factor in momentum of 0.95) - operational for the LHC beam at the end of 2003 year. Measurements of capture loss were done for an average total intensity at injection of 3.7×10^{12} (1.16×10^{11} p/bunch) and different constant voltages on the flat bottom. For 1, 2 and 3 MV (constant from injection) the relative capture losses (measured at 30 GeV/c) were correspondingly 8.5%, 5.3% and 5.1%.

Beam losses after injection still had an asymmetric character (as in 2003) with uncaptured beam moving mainly to the front of the batch. This asymmetry was reduced with increasing capture voltage. The flux of uncaptured particles (observed using the 200 MHz beam component) had pulses at 1.2 s intervals. The reason was not understood.

Measured bunch lengths were in the range (3.7 - 4.7) ns with average 4.2 ns. With new beam-control settings in the PS (S. Hancock) bunches became shorter, (3.4-4.4) ns, but also more unstable in the SPS so that the longitudinal damper was switched on. Bunch to bunch intensity variation was also larger than usual in 2003. Using previous settings in the PS increased beam stability in the SPS, but it was still not perfect. Further increase of longitudinal emittance in the PS led to increased capture loss in the SPS, $\sim 9\%$. In this case the decay of PD (Peak Detected) signal on the flat bottom was about 1%.

2 MD on 1.07.2004

During this MD we had LHC beam with 25 ns spacing. We studied beam losses during the cycle with one PS batch in the SPS ring.

Estimations of losses presented in this Note are based on beam intensity measured by a BCT (Beam Current Transformer) at different moments in the cycle, as shown in Table 1.

m	time ms	momentum GeV/c	intensity N_m	beam loss definition
0	0	26	N_0	
1	1086	26	N_1	$l_1 = 1 - N_1/N_0$
2	11430	30	N_2	$l_2 = 1 - N_2/N_1$
3	12330	50	N_3	$l_3 = 1 - N_3/N_2$
4	13140	80	N_4	$l_4 = 1 - N_4/N_3$

Table 1: Synchronous momentum of the beam at different times of the LHC cycle in the SPS corresponding to the standard (displayed on "Larger" video page) intensity measurements.

Results of beam loss measurements for one batch and different voltage programmes of the 200 MHz RF system are shown in Table 2.

Discussion of results presented in Table 2:

- Increasing voltage in general helps. For a constant bucket area through the cycle of 0.55 eVs ($V_{fb} = 1.3$ MV), 0.6 eVs ($V_{fb} = 1.8$ MV) and 0.7 eVs ($V_{fb} = 2.1$ MV) total losses are decreasing from 16% to 12.6% and then to 10.4%. The total loss reduction is mainly due to the decrease of loss l_2 at 30 GeV/c, while losses at the end of flat bottom stay practically unchanged (3.3-3.4%).

- With high voltage on the flat bottom ($V_{fb} = 3$ MV) there is some optimum injection voltage (probably close to 1.5 MV). There is also some danger of recapturing lost particles and creating long tails in the main bunches as well as satellite bunches.

- For the same conditions on the flat bottom ($V_{inj} = 2.0$ MV and $V_{fb} = 3.0$ MV) the increase of voltage during the ramp (from 0.55 eVs to 0.6 eVs and then to 0.7 eVs corresponding bucket area) leads to decrease in total beam loss from 10.9% to 9.9% and then to 9.1%. This gives some estimation of bunch halo population. For 3 MV on the flat bottom the bucket size is 0.8 eVs while the measured 4σ bunch length of 2.7 ns (after corrections) corresponds to an emittance of 0.4 eVs.

- We observed that some bunches were unstable on the flat bottom. They could be stabilised by using the 800 MHz RF system with 240 kV in the bunch shortening mode. However this does not seem to have any effect on the beam loss.

- Using the voltage programme for a constant bucket area through whole cycle practically eliminates the high energy losses (at 50 GeV/c and above) which are quite small anyway.

voltage programme				intensity		relative beam losses							
V_{inj} MV	V_{fb} MV	V_{800} kV	ε_a eVs	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_3 %	σ_3 %	**total** %	σ_t %
2.0	2.0	0	0.55	8.24	0.18					-	-	13.1	0.8
3.0	3.0	0	0.55	8.40	0.09	3.9	0.3	8.0	0.5	1.6	0.6	13.5	0.7
1.3	1.3	0	0.55	8.50	0.06	3.4	0.2	12.6	0.9	0	0	16.0	1.0
1.2	3.0	0	0.55	8.62	0.12	4.4	0.1	6.2	0.8	1.0	0.1	11.6	0.7
2.0	3.0	0	0.55	8.42	0.11	3.8	0.2	5.7	2.1	1.3	0.4	10.9	2.4
1.8	1.8	0	0.6	8.47	0.05	3.3	0.2	9.3	0.2	0.0	0.0	12.6	0.3
2.0	3.0	0	0.6	8.38	0.16	4.2	0.2	4.9	0.6	0.3	0.3	9.4	0.6
1.5	3.0	0	0.6	8.37	0.17	4.2	0.3	4.4	0.7	0.4	0.1	9.1	0.7
1.5	3.0	240	0.6	8.42	0.09	4.5	0.3	3.9	0.3	0.5	0.2	8.8	0.4
1.5	2.0	240	0.6	8.38	0.09	3.5	0.1	6.9	0.4	0.2	0.2	10.6	0.4
2.0	3.0	240	0.6	8.38	0.12	4.3	0.2	4.8	0.4	0.7	0.2	9.9	0.4
2.1	2.1	240	0.7	8.26	0.09	3.4	0.3	6.9	0.6	0.2	0.2	10.4	0.8
2.0	3.0	240	0.7	8.37	0.09	4.2	0.3	4.8	0.3	0.1	0.1	9.1	0.3

Table 2: MD on 1.07.2004. Comparison of particle losses for one batch in the ring measured at various energies during the cycle for capture voltage V_{inj} raised after 50 ms during 150 ms to voltage on the flat bottom V_{fb}. Voltage programme during the ramp corresponds to ε_a bucket area. Measurements were done with the 800 MHz RF system switched off or on ($V_{800} = 240$ kV, bunch shortening mode) on the flat bottom and always with the 800 MHz on during acceleration.

The losses on the flat bottom which were growing with voltage increase (seen from BCT), were slightly reduced by decreasing the chromaticity (G. Arduini).

Beam losses measured in 2003 [1] at 30 GeV/c with a single batch in the ring for the same voltage programme (2 MV constant on the flat bottom and a 0.55 eVs bucket area during the ramp) are very close to losses measured during this MD. Indeed for a batch intensity of 8.4×10^{12} they were 11.3% and 10% for 8.0×10^{12}. In this MD (see Table 2) we have 13.1% measured for 8.2×10^{12}. However these measurements also include $\sim 3\%$ losses on the flat bottom not taken into account before.

Note also that in 2004 the flat bottom in the SPS was longer (by 10 s) than before. This should have reduced the effect of decay of magnetic field at the time of beam injection. The voltage programme is also slightly different due to a different calculation method (a constant bucket area now and a constant filling factor in momentum before).

In the second part of this MD the number of the PS batches injected into the SPS ring was varied between one and four. Results of beam loss measurements for these conditions are shown in Table 3.

It seems that losses were mainly affected by the average batch intensity, see Fig. 1. With more than one batch in the ring there was no improvement in the beam loss when the voltage is decreased at each batch injection (dip).

3 MD on 1.09.2004

Here we present the results of the second part of the long MD on 1.09.2004 (after 18:00). The results obtained with coasts during the first part of the MD will be discussed separately. Nevertheless the variation of the average bunch length and peak amplitude with time for three different coasts is shown in Fig. 2. The first batch was injected into a voltage of 1.85 MV which was then changed to 3 MV, 2 MV or 1.5 MV. One can see that the beam behaviour during the first 10-20 s is very different from the

number of batches	number of dips	intensity N_{av}^{batch} 10^{12}	σ_N 10^{12}	relative losses measured at l_1 %	σ_1 %	l_2 %	σ_2 %	l_3 %	σ_3 %	**total** %	σ_t %
1	1	8.38	0.12	4.3	0.2	4.8	0.4	0.7	0.2	9.9	0.4
2	1	8.68	0.09	4.3	0.3	5.5	0.2	1.0	0.2	10.8	0.4
2	2	8.69	0.06	5.3	0.2	5.9	0.5	0.6	0.3	11.9	0.5
3	2	8.45	0.07	4.7	0.2	5.8	0.4	0.9	0.1	11.4	0.7
3	3	8.51	0.07	4.7	0.2	6.0	0.3	0.9	0.1	11.6	0.5
4	3	8.42	0.08	3.5	0.2	5.2	0.3	1.0	0.1	9.7	0.5
4	4	8.35	0.25	3.4	0.4	4.6	0.3	1.0	0.1	8.9	0.5
4	$4^{(*)}$	8.39	0.14	3.7	0.8	4.7	0.3	1.0	0.1	9.3	0.6

Table 3: MD on 1.07.2004. Comparison of particle losses for different number of batches in the ring measured during the cycle for 3 MV voltage on the flat bottom and with or without dip to 2 MV for each following batch injection. Voltage programme during the ramp corresponds to constant bucket of 0.6 eVs. $^{(*)}$All measurements except the last one were done with the 800 MHz RF system switched on (240 kV, bunch-shortening mode) on the flat bottom. The 800 MHz RF system was always on during acceleration.

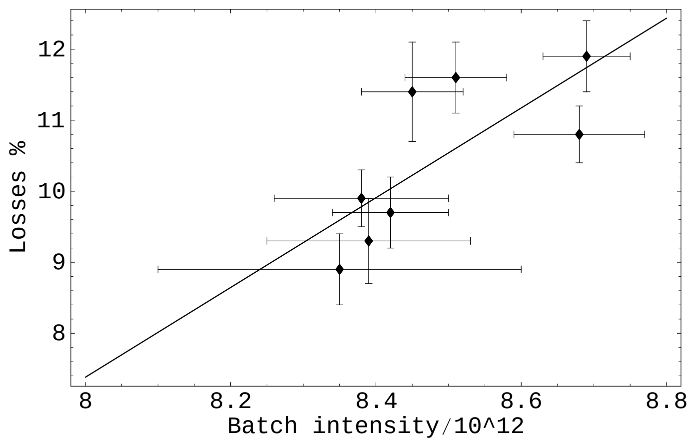

Figure 1: MD on 1.07.2004. The dependence of the relative total loss on the average batch intensity. All measurements included (Table 3).

later period (20 s to 100 s). This time scale can be probably connected to the length of the flat bottom (10.86 s) or of the cycle (21.6 s). These measurements were done with a new working point in the transverse plane (see the next section).

It seems that later, after the change of the SPS supercycle (from SC950 to SC546), the bunch length increase on the flat bottom became much less important, see Fig. 3.

3.1 Beam loss studies

We started with a new working point in the transverse plane (measured at nominal intensity Q_h=26.13 and Q_v=26.19) which is supposed to help at high vertical chromaticity, necessary to reduce vertical emittance blow-up due to e-cloud. The previous working point was (26.19, 26.13). We took measurements of beam losses for two, three and four batches in the ring. Results for the new working point, low vertical chromaticity and the 800 MHz on for the beam loss on the flat bottom are presented in Table 4.

In general during this MD we observed a more uniform batch structure (intensity) from the PS. At

number	voltage		total intensity		relative losses measured at							
of batches	V_{inj} MV	V_{fb} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_{3+4} %	σ_{3+4} %	**total** %	σ_t %
2	2.0	3.0	17.89	0.15	1.1	0.2	5.6	0.7	0.8	0.1	7.4	0.7
3	2.0	3.0	26.72	0.24	1.0	0.2	6.3	1.4	1.2	0.2	8.4	1.7
4	2.0	3.0	35.07	0.24	0.7	0.2	5.8	0.8	1.2	0.1	7.6	1.7
4	3.0	3.0	34.96	0.31	0.6	0.2	6.3	0.9	1.2	0.1	8.1	1.0
4	2.0	2.0	34.83	0.31	0.6	0.2	5.4	0.7	0.6	0.1	6.7	0.8

Table 4: MD on 1.09.2004. Relative beam losses for different number of batches (2, 3 and 4) with nominal intensity and different voltages on the flat bottom. New working point and low vertical chromaticity (0.265). Long (nominal) bunches. The change of the 200 MHz voltage from 2 MV to 3 MV is done only at the first injection. In all cases the voltage program during the ramp is 0.6 eVs and the 800 MHz voltage on the flat bottom is 240 kV (bunch shortening mode).

the beginning of the MD some additional losses (around 0.5%) were measured at 450 GeV (not shown in the Table 4). Later they were eliminated by reducing the amplitude of the excitation used for the controlled emittance blow-up at high energy.

Summary of Table 4 data:

- No significant difference in the relative loss for different number of batches in the ring.
- Contrary to results with the old working point, constant 2 MV on the flat bottom now gives lower losses than constant 3 MV.

After this series of measurements the bunch length measured on the first turn (uncorrected) was between 3.8 ns and 5.2 ns with average 4.5 ns.

Results of measurements for 4 batches in the ring, nominal vertical chromaticity (0.365) and different voltages are shown in Table 5.

voltage		intensity		relative losses							
V_{inj} MV	V_{800} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_{3+4} %	σ_{3+4} %	**total** %	σ_t %
2.0	0.	35.1	0.2	1.1	0.2	8.8	1.9	1.0	0.1	10.8	2.2
2.0	0.	35.2	0.2	0.7	0.1	5.2	0.8	0.6	0.1	6.6	0.9
3.0	0.	35.2	0.2	1.5	0.1	6.5	0.5	1.2	0.1	9.3	0.6
3.0	0.	35.2	0.2	1.6	0.2	7.2	0.5	1.4	0.1	10.2	0.6
3.0	0.	35.2	0.4	1.5	0.2	6.6	0.7	1.3	0.2	9.3	0.9
2.0	0.24	35.3	0.3	0.7	0.1	5.2	0.4	0.5	0.1	6.4	0.5
2.0	0.24	34.2	0.2	0.6	0.2	7.6	0.6	0.6	0.1	8.9	0.8
2.0	0.24	34.3	0.2	0.5	0.1	4.6	0.6	0.5	0.1	5.5	0.6

Table 5: MD on 1.09.2004. Comparison of particle losses for 4 batches and different conditions in the ring. Mainly effect of the drift of the injection phase. New working point, nominal vertical chromaticity of 0.365. Measurements from the fifth line - the coherent signal at 790 Hz was removed. Long (nominal) bunches. In all cases voltage program during the ramp is 0.6 eVs and the 800 MHz voltage on the flat bottom is applied in bunch shortening mode.

Summary of data in Table 5:

- The effect of the injection phase drift on beam loss is significant (different lines in the Table with the same other conditions - the first and the second, and three last lines).
- On the flat bottom 2 MV constant is better than 3 MV again.
- From comparison with Table 4 - no obvious effect from the change in vertical chromaticity.
- Possibly some effect of elimination of the coherent excitation at 790 Hz from the feedforward electronics (compare the second and the last line in the Table 5 and the fourth and the fifth). Was also visible on Schottky spectrum [3].

Around 1:50 we came back to the old working point to make a comparison with results obtained with the new one. The results of these measurements are presented in Table 6. The injected bunch length measured at 2:20 was on average 0.4 ns shorter than before (during this MD and the previous).

voltage		intensity		relative losses							
V_{inj} MV	V_{fb} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_{3+4} %	σ_{3+4} %	**total** %	σ_t %
2.0	2.0	33.23	0.26	2.5	0.6	6.1	0.7	0.5	0.2	9.1	0.9
3.0	3.0	33.18	0.29	3.6	1.0	5.1	1.2	0.8	0.1	9.5	1.0
2.0	3.0*	33.18	0.43	4.97	1.1	3.0	0.1	0.5	0.1	8.4	1.1
2.0	3.0*	8.55	0.11	4.6	0.4	2.8	0.2	0.4	0.2	7.8	0.6
2.0	3.0	8.67	0.09	1.6	0.3	2.4	0.2	0.4	0.2	4.4	0.5
2.0	2.0	8.69	0.10	1.5	1.1	4.8	0.8	0.2	0.2	6.5	1.2
3.0	3.0	8.66	0.07	2.2	0.5	4.5	0.4	0.2	0.6	7.3	0.6

Table 6: MD on 2.09.2004. Particle losses for different working points: old working point above the double line and new - below. First three lines - 4 batches in the ring. Nominal vertical chromaticity of 0.365. 800 MHz is on (235 kV) on the flat bottom. Comments: (*) - 4 dips to 2 MV. Shorter bunches at injection (by 0.4 ns) in all cases.

With the new working point losses are significantly reduced (mostly seen at the end of the flat bottom). For both the new and the old working point the best transmission is obtained for the scheme with a capture voltage of 2 MV increased after some time to 3 MV, compare with Table 5.

3.2 Beam lifetime studies

During this MD the beam lifetime studies under different conditions were carried out in parallel to the beam loss measurements presented in the previous subsection. The measurements of beam lifetime were done on the 10.86 s long flat bottom. The results of analysis of 12 different acquisitions (mountain ranges) are shown in Table 7.

The bunch length as a function of the bunch number along the first batch at injection is shown in Fig. 4. In practically all cases the injected bunch length increases from the head of the batch to the tail. All shown values correspond to the raw uncorrected data. They should be reduced by approximately 0.4 ns to obtain the real bunch length. Average values along the batch at injection are shown in Table 7 together with their minimum and maximum. For the first 6 acquisitions the average bunch length is 4.4 ns (this was due to a problem with the 80 MHz RF system in the PS). For the rest of data the average bunch length is 4.0 ns. For shorter bunches the scatter in the bunch length was also reduced from 35 % to 20%.

Time	mr	V_{RF} [MV]	N_{D}	ξ_{v}	N_{B}	WP	$\tau_{\mathrm{i,avg}}$ [ns]	$\tau_{\mathrm{i,min}}$ [ns]	$\tau_{\mathrm{i,max}}$ [ns]	τ_{FB} [ns]	$a_{\mathrm{pk,avg}}$ [V]	$a_{\mathrm{pk,min}}$ [V]	$a_{\mathrm{pk,max}}$ [V]	T_{pk} [s]	$\sigma_{T_{\mathrm{pk}}}$ [s]
19:37	111	3		0.265	4	new	4.4	3.7	5.2	3.25	16.2	14.0	20.0	175	8
19:47	112	2		0.265	4	new	4.4	3.7	5.3	3.40	15.6	13.2	19.2	190	7
21:30	113	2		0.365	4	new	4.4	3.7	5.2	3.35	16.1	14.0	19.2	170	6
21:40	114	3		0.365	4	new	4.4	3.7	5.5	3.15	15.9	14.0	19.7	191	11
23:23	115	2		0.365	4	new	4.5	3.7	5.2	3.40	15.8	13.6	19.9	198	11
23:40	116	2		0.365	4	new	4.3	3.8	5.1	3.35	16.5	14.9	20.2	178	17
02:22	117	3		0.365	4	old	4.0	3.7	4.2	3.00	16.1	14.4	18.6	173	16
03:01	118	2→3	4	0.365	1	old	4.0	3.7	4.5	2.80	16.1	14.5	18.4	110	7
03:57	120	2→3	1	0.365	1	new	4.0	3.7	4.2	2.80	16.4	14.5	19.2	721	99
04:07	121	2→3	1	0.365	1	new	4.0	3.7	4.2	2.75	15.7	13.5	18.2	864	157
04:12	122	2		0.365	1	new	4.0	3.7	4.4	3.25	16.2	14.1	18.4	394	42
04:29	123	3		0.365	1	new	4.1	3.7	4.6	3.10	16.0	14.4	18.9	418	43

Table 7: Parameter overview for all acquisitions for the MD on 1.09.2004 (beam life time studies). The RF voltage at injection and flat bottom, V_{RF}, is either constant or with a dip at each injection (number of dips given by N_{D}). The TWC 800 MHz was always on along the flat bottom (240 kV, bunch shortening mode). The vertical chromaticity is given by ξ_{v}, the number of batches injected by N_{B}. The working point, WP, is either new ($\mathrm{Q_H} = 26.13$, $\mathrm{Q_V} = 26.19$) or old ($\mathrm{Q_H} = 26.19$, $\mathrm{Q_V} = 26.13$). The bunch lengths at injection are characterised by the average of the 72 bunches in the batch 1, $\tau_{\mathrm{i,avg}}$, the minimum bunch length in the batch, $\tau_{\mathrm{i,min}}$, and the maximum bunch length $\tau_{\mathrm{i,max}}$. The bunch length after injection, which stayed practically constant all along the flat bottom is given by τ_{FB} within $\pm$ 0.05 ns. The lifetime of the average bunch peak amplitude along the flat bottom is given by T_{pk} and its error by $\sigma_{T_{\mathrm{pk}}}$. The average bunch peak amplitude at injection is given by $a_{\mathrm{pk,avg}}$, and the minimum and maximum values by $a_{\mathrm{pk,min}}$ and $a_{\mathrm{pk,max}}$, respectively.

After the injection transient (filamentation) followed by bunch shortening in the mismatched voltage (too high), the bunch length stayed practically constant during the following 10.86 s (see Fig. 3). The average bunch length on the flat bottom is shown in Table 7.

Bunch peak amplitude as a function of the bunch number along the first batch at injection is shown in Fig. 5. The peak amplitude averaged over 72 bunches was used to calculate the beam "lifetime" along the flat bottom. The results are presented in Table 7.

As one can see, for the same conditions in the ring the lifetime measured from the average peak amplitude decay along the flat bottom is significantly increased:

- with shorter bunches (by more than factor 2)
- with the new working point (a factor 2.5 for the constant voltage and a factor 6 for the voltage step from 2 MV to 3 MV)
- with the voltage step from 2 MV to 3 MV (only for the new working point).

Note also that for the comparable cases of short and long bunches (the same voltage and working point) the number of batches in the ring was different (four at the beginning and one at the end). The measurements were always made on the batch number one.

However there is no obvious correlation between the individual bunch length or the bunch peak amplitude at injection with the individual bunch peak amplitude lifetime along the flat bottom shown in Fig. 6 (except maybe one case, `mr118`). One can notice that the bunch lifetimes along the batch are modulated with a period close to 30 bunch spacings, this gives a frequency around 1.3 MHz.

The pattern of the bunch position modulation along the batch established after the injection transients, see Fig. 7, practically doesn't depend on conditions in the ring and is mainly due to the beam loading effect in the 200 MHz RF system. The typical frequency of modulation is also around 1.3 MHz. The modulation amplitude is clearly higher for 2 MV than for 3 MV. It seems nevertheless that the average peak amplitude lifetime is not affected (at least for the new working point). On the other hand, the standard deviation of bunch position, shown in Fig. 8 for all acquisitions, seems to be anti-correlated, at least for the first six acquisitions with longer bunches, to the individual bunch lifetime presented in Fig. 6. The period of modulation towards the end of the batch is approximately 15 bunches which corresponds to the frequency around 2.6 MHz. In cases corresponding to the maximum lifetime, (`mr120` and `mr121`) the deviation of bunch position along the batch is practically flat and is also smaller.

The vertical chromaticity was the same (0.365) for all measurements except the first two where it was 0.265. No positive effect on peak amplitude lifetime could be noticed for higher chromaticity which is supposed to cure the vertical single bunch instability due to e-cloud.

4 MD on 9.11.2004

The purpose of this MD was to define the limits for using the 800 MHz RF system for beam stabilisation (against coupled-bunch instabilities) by increasing the voltage amplitude of the 800 MHz RF system in bunch shortening mode. This could be an alternative to controlled emittance blow-up at high energies which potentially can increase particle loss at capture into the 400 MHz RF system of the LHC. The voltage available at 800 MHz is limited at the moment to 1 MV (one cavity). To have the voltage ratio of the two RF systems around 1/4 on the flat top, the voltage at 200 MHz was kept at 4 MV (without the usual increase to 7 MV). Other parameters used were similar to the previous MD (on 1.09.2004).

Due to different problems (power amplifier trip, Linac) we had time for measurements from only 4:30 till 6:30 a.m., with setting-up on the previous day.

Capture losses clearly depend on intensity: they have increased from (6-7)% for an injected intensity 3.2×10^{13} (4 batches) to 10% for an intensity of 3.56×10^{13}.

For new working point and voltage on the flat bottom of 3 MV with 4 dips to 2 MV at each injection, measurements of losses are presented in Table 8. Losses of 0.64% were measured at highest energy (l_4).

voltage		intensity		relative losses							
V_{inj} MV	V_{fb} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_3 %	σ_3 %	**total** %	σ_t %
2.0	3.0	34.51	0.98	2.4	0.3	7.0	0.8	0.9	0.1	10.3	1.0

Table 8: MD on 9.11.2004. Particle losses for the new working point, 4 batches in the ring. The 200 MHz voltage had 4 dips to 2 MV.

5 MD on 15.11.2004

5.1 The 25 ns bunch spacing

Settings were similar to the last MDs with the new working point in the transverse space. We started with the beam with 25 ns bunch spacing.

We noticed that beam was more unstable than usual on the flat top. Looking more closely at the controlled emittance blow-up at high energy we discovered that it affected only a few bunches in the batch. For nominal beam intensities and 190 Hz central frequency of noise excitation (usual settings) the beam was unstable on the flat top. For 165 Hz only the first few bunches were affected. With 145 Hz we could hit all bunches, but with particle loss. This observation can be explained by a large phase offset between the 200 MHz and 800 MHz RF systems combined with the beam loading [4].

We continued with measurements of the capture loss for different voltage programmes on the flat bottom. Results for bunches with emittance $\varepsilon = 0.31$ eVs and bunch length $\tau = 4.1$ ns (measured in the PS) are shown in Table 9.

The next part of this MD was devoted to capture loss measurements with shorter bunches from the PS, produced by using extra voltage in the 80 MHz RF system during the bunch rotation before extraction to the SPS. According to the measurements in the PS [5] the injected beam should have the same longitudinal emittance and $\tau = 3.7$ ns. However measurements in the SPS showed an average 4σ bunch length of 3.9 ns (after pick-up and cable corrections). Results for shorter bunches are presented in Table 9 in the measurement set (4). Note that before and after this set of measurements the injection phase was adjusted. This seems to have more effect on the loss reduction than a change in the bunch length which was small in any case.

Later, from set (5) in Table 9, the settings in the PS were changed back to nominal. At the same time the injection phase was corrected again. Next measurements were made with the nominal settings in the PS. First, set (5), with the longitudinal feedback in the PS off (longer bunches at the end of the batch) and then with the feedback on, set (6). Results for beam losses are presented in Table 9. The last measurement was done with four PS batches equally spaced in the SPS ring.

5.2 The 75 bunch spacing

In the second part of this MD we had beam with the 75 ns bunch spacing. As usual with this bunch spacing beam is much more stable - no need for the high energy emittance blow-up. With 1.4×10^{11}/bunch no instabilities (like transverse mode-coupling instability - TMCI) were observed at injection. Beam losses under different conditions are shown in Table 10. First we had on the flat bottom the voltage of 3 MV with 4 dips to 2 MV for each batch injection. Then, for comparison, losses were measured for a constant voltage of 2 MV and 3 MV. As can be seen from Table 10 a constant voltage leads to larger particle loss.

After these measurements we noticed that injected bunches were approximately 0.2 ns longer than before. At this moment the measurements were repeated with the same voltage programme on the flat

set	voltage		intensity		relative losses							
	V_{inj} MV	V_{fb} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_{34} %	σ_{34} %	**total** %	σ_t %
1	1.0	2.0	34.59	0.26	1.0	0.3	5.1	0.2	1.2	0.1	7.3	0.4
2	2.0	2.0	33.80	0.39	0.6	0.2	6.2	0.3	1.1	0.1	7.9	0.3
3	2.0	3.0	35.03	0.79	1.1	0.3	4.6	0.3	0.9	0.1	6.6	0.4
4	2.0	3.0	34.40	0.80	0.9	0.1	4.3	0.4	0.9	0.1	6.1	0.5
5	2.0	3.0	33.95	0.16	0.9	0.1	5.2	0.2	0.9	0.1	6.9	0.2
6	2.0	3.0	34.09	0.26	0.8	0.1	4.0	0.2	0.7	0.2	5.6	0.2
7	2.0	3.0	34.14	0.19	0.8	0.1	4.0	0.2	0.7	0.1	5.4	0.2

Table 9: MD on 15.11.2004. Particle losses for 4 batches with the 25 ns bunch spacing and different conditions in the PS and SPS. New working point in all cases. The 200 MHz voltage on the flat bottom had 4 dips (for each batch injection) except in the measurement set (2), where it was constant. Shorter bunches from PS for set (4). Back to “long” injected bunches from set (5). Injection phase drift corrected before set (5). Longitudinal FB in the PS off for set (5). Four PS batches equally spaced in the SPS ring in set (7).

set	voltage		intensity		relative losses							
	V_{inj} MV	V_{fb} MV	N_{av} 10^{12}	σ_N 10^{12}	l_1 %	σ_1 %	l_2 %	σ_2 %	l_{3+4} %	σ_{3+4} %	**total** %	σ_t %
1	2.0	3.0	12.51	0.07	0.1	0.1	1.9	0.2	0.6	0.1	2.6	0.2
2	2.0	2.0	12.39	0.06	0.0	0.1	2.7	0.3	0.7	0.2	3.4	0.4
3	3.0	3.0	12.41	0.06	0.1	0.1	3.6	0.1	1.0	0.1	4.7	0.2
4	3.0	3.0	12.43	0.04	0.1	0.1	3.9	0.2	1.1	0.1	5.0	0.3
5	2.0	3.0	12.42	0.06	0.1	0.2	2.4	0.2	0.9	0.1	3.3	0.3
6	2.0	3.0	3.08	0.03	0.1	0.1	1.9	0.4	0.5	0.4	3.0	0.6
7	2.0	3.0	3.08	0.02	0.2	0.2	2.2	0.6	0.4	0.4	2.8	0.6

Table 10: MD on 15.11.2004. Particle losses for beam with the 75 ns bunch spacing and different conditions in the PS and SPS. New working point in all cases. The 200 MHz voltage on the flat bottom had 4 dips (for each batch injection) except in sets (2) and (3), where it was constant, and set (7), where it had one dip at time of the first injection. Longer bunches from the PS were measured in the SPS from set (4). Four PS batches in the SPS in sets (1)-(5) and one PS batch in sets (6)-(7).

bottom as in sets (1) and (3). The results correspond to sets (4) and (5) in Table 10. Capture losses are slightly larger for longer bunches.

Measurements of capture loss for a single batch in the ring were done with two voltage programmes on the flat bottom - with one and four dips - sets (6) and (7) in Table 10. Relative losses are small in general and not very different from results with 4 batches in the ring, compare with sets (1) and (5).

The beam transfer functions measured on flat bottom with one batch in the ring for different voltage ratios in the 200 MHz and 800 MHz RF systems and for bunch-shortening and bunch-lengthening modes are presented in [6].

The observation of beam signals at frequencies corresponding to the known HOMs in the 200 MHz cavities was also done during this MD. The signal at 629 MHz was growing only if the longitudinal damper was off on the flat top, while the signal at 912 MHz was always growing exponentially (this HOM in 200 MHz cavities is not specially damped).

6 Summary

With the new working point in the transverse plane the beam losses have been significantly reduced (from 10% to 5.5% for the best conditions). Relative losses for the beam with 75 ns bunch spacing and the same (or higher) bunch intensity are approximately a factor 2 lower (both with the old and the new working points).

For a single batch the 3 MV voltage with the dip to 2 MV gives minimum particle loss. Less clear advantage of this RF manipulation was observed for 4 injected batches and 4 dips, since losses increase with one batch and 4 dips.

Beam losses are very sensitive to the injection phase error which needs continuous adjustment. Injection of slightly longer (than nominal) bunches increases the beam loss and decreases peak amplitude beam life time. There is no clear improvement of beam losses for the reduced bunch length since the changes in losses due to the small reduction in bunch length were in the shadow of the effect of the injection phase error.

7 Acknowledgments

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[5] S. Hancock, private communication.

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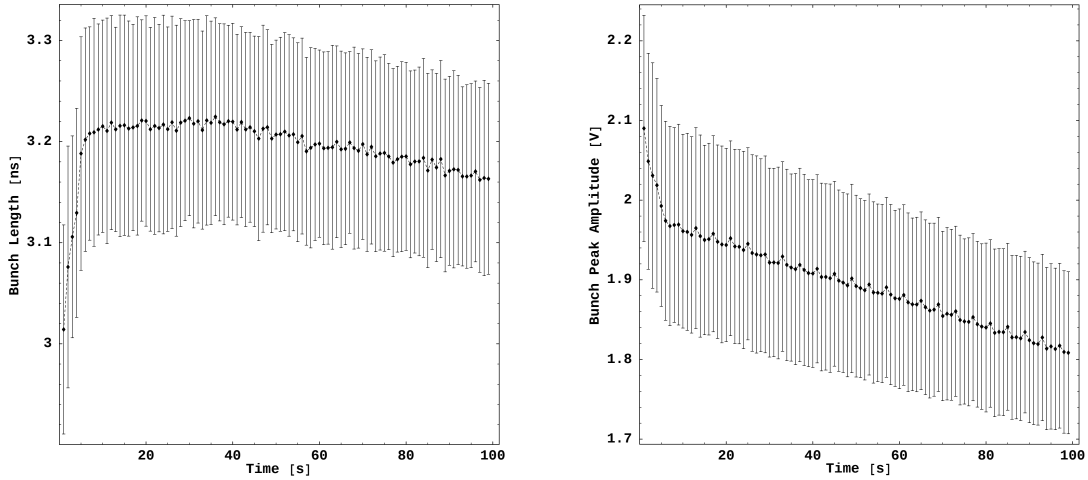
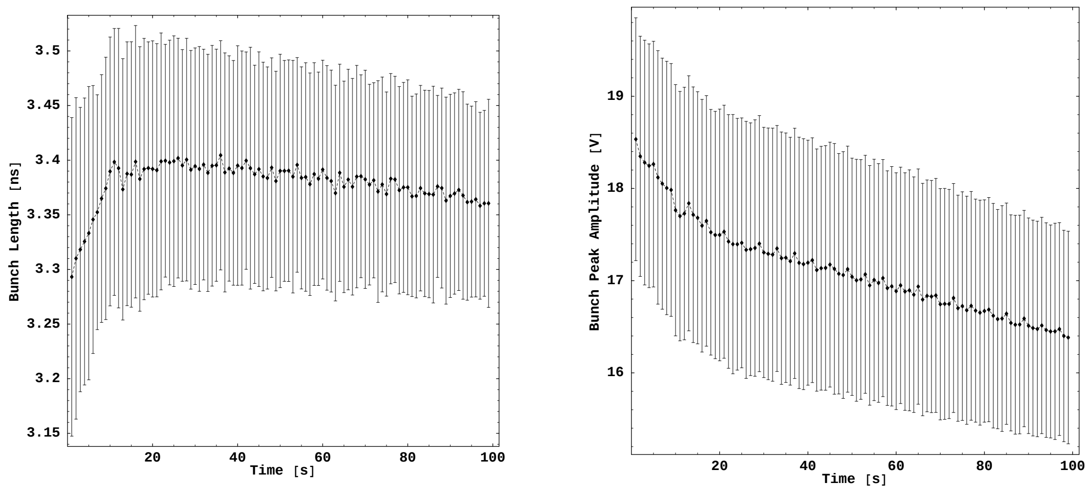
$\texttt{mr101}$, new WP, $2 \rightarrow 3$ MV



$\texttt{mr104}$, new WP, 2 MV



$\texttt{mr108}$, new WP, $2 \rightarrow 1.5$ MV

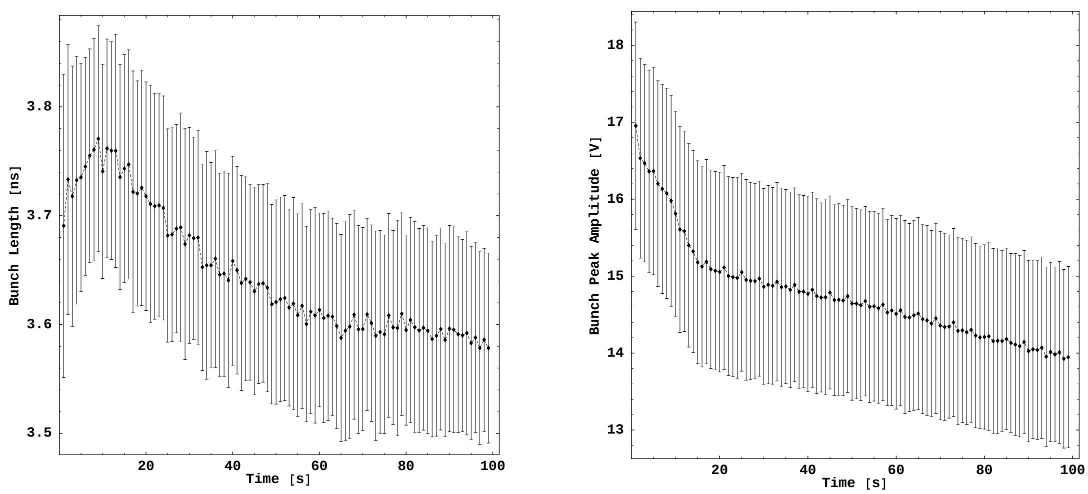


Figure 2: MD on 1.09.2004. Average bunch length (uncorrected, left figure) and peak amplitude (right) during the coast at 26 GeV/s. The 800 MHz RF system is off. Batch 1.

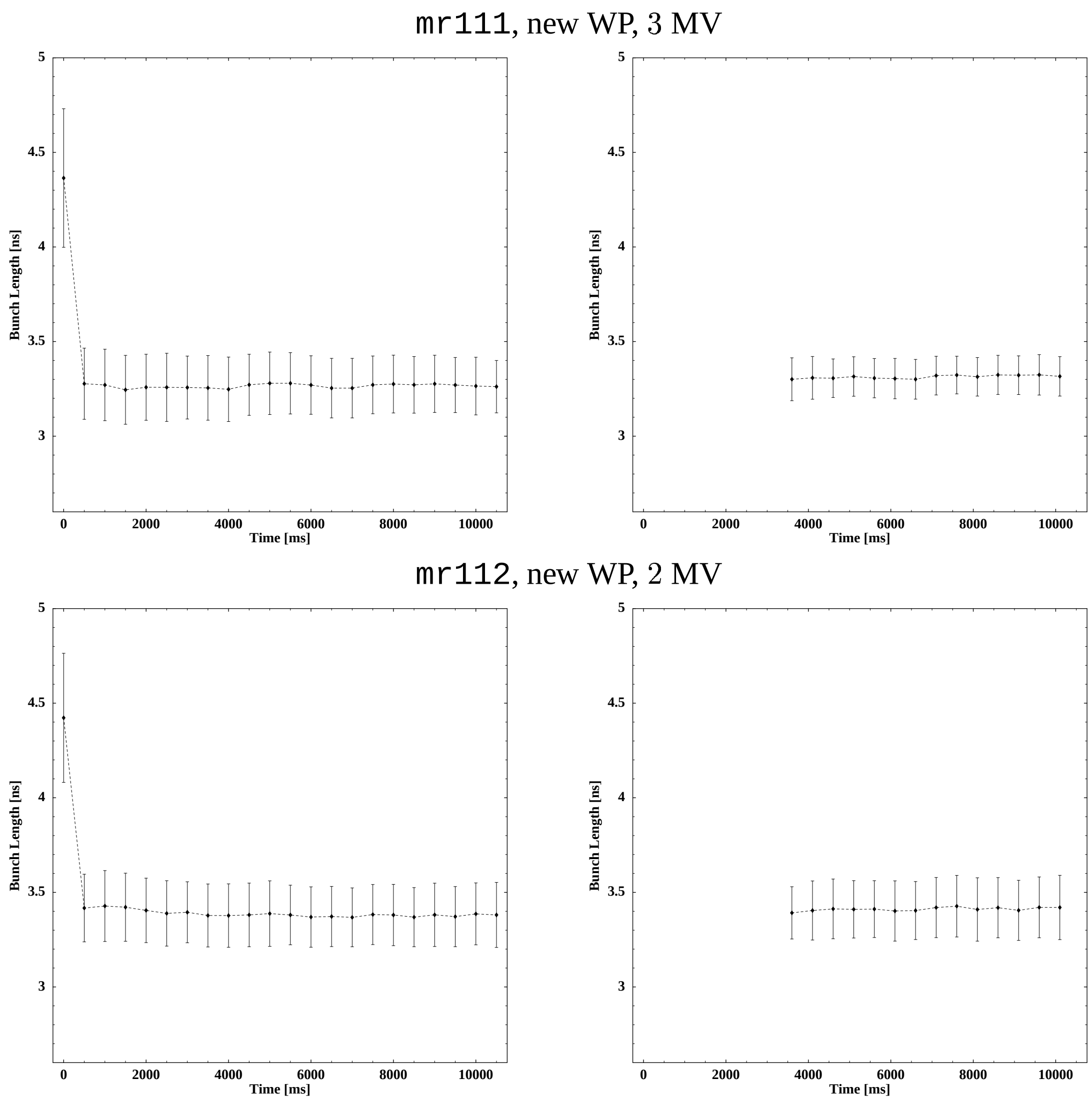


Figure 3: MD on 1.09.2004. Average bunch length (uncorrected) in the first batch (left) and the second batch (right) as a function of time on the flat bottom at 26 GeV/s. The 800 MHz RF system is off. Constant voltage of 3 MV (top) and of 2 MV (bottom).

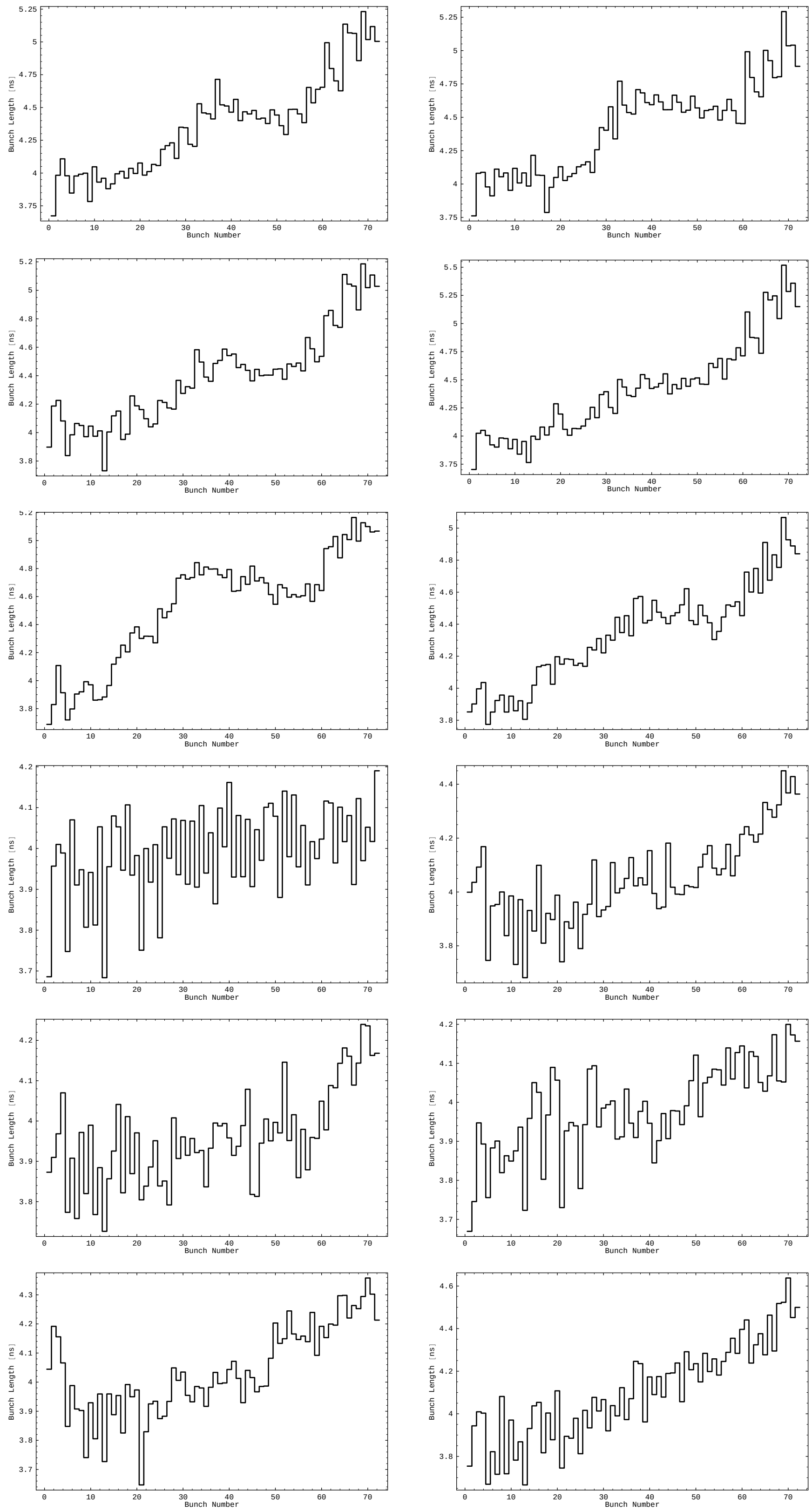


Figure 4: MD on 1.09.2004. Bunch length at injection (uncorrected) as a function of bunch number in the first batch; `mr111` to `mr118` and `mr120` to `mr123` (left to right, top to bottom).

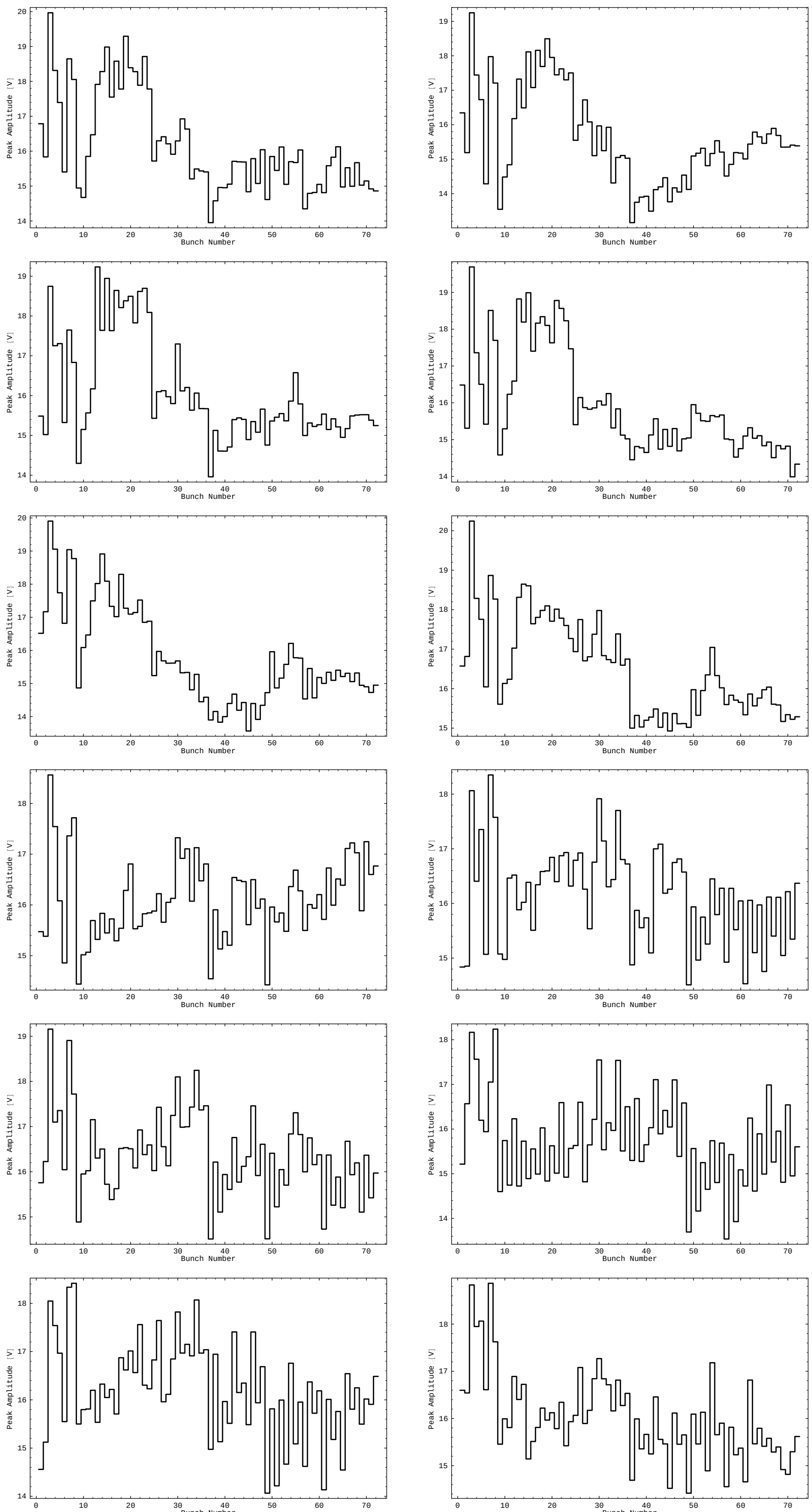


Figure 5: MD on 1.09.2004. Bunch peak amplitude at injection as a function of bunch number in the first batch; `mr111` to `mr117` and `mr119` to `mr123` (left to right, top to bottom).

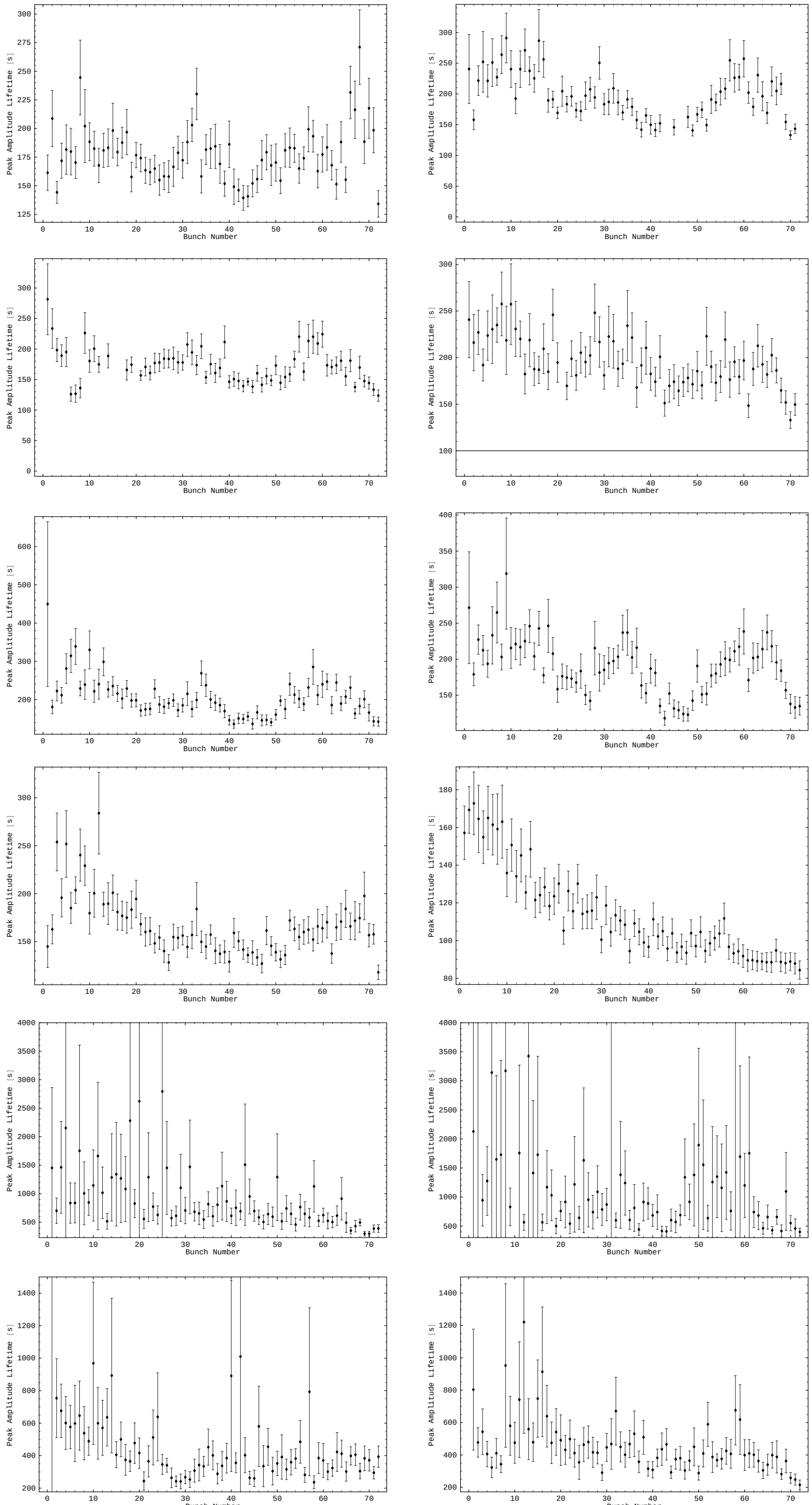


Figure 6: MD on 1.09.2004. Bunch peak amplitude lifetime along flat bottom (0.5 s to 10.5 s) as a function of bunch number in the first batch; `mr111` - `mr118` and `mr120` - `mr123` (left to right, top to bottom).

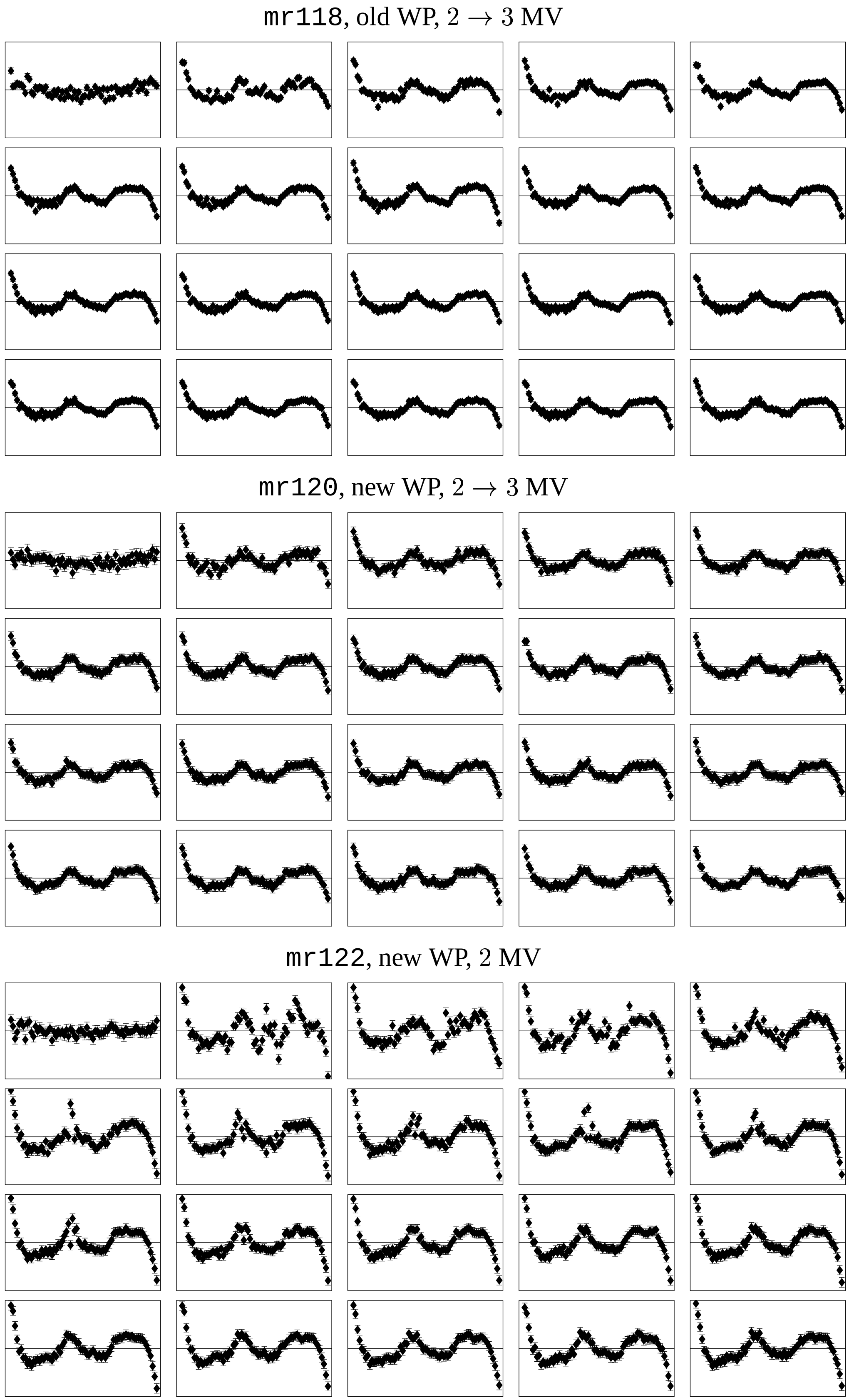


Figure 7: MD on 1.09.2004. Bunch position for 72 bunches along the first batch from injection onward every 500 ms up to 10 s; `mr118`, `mr120` and `mr122`. Vertical scale from -210 ps to 210 ps.

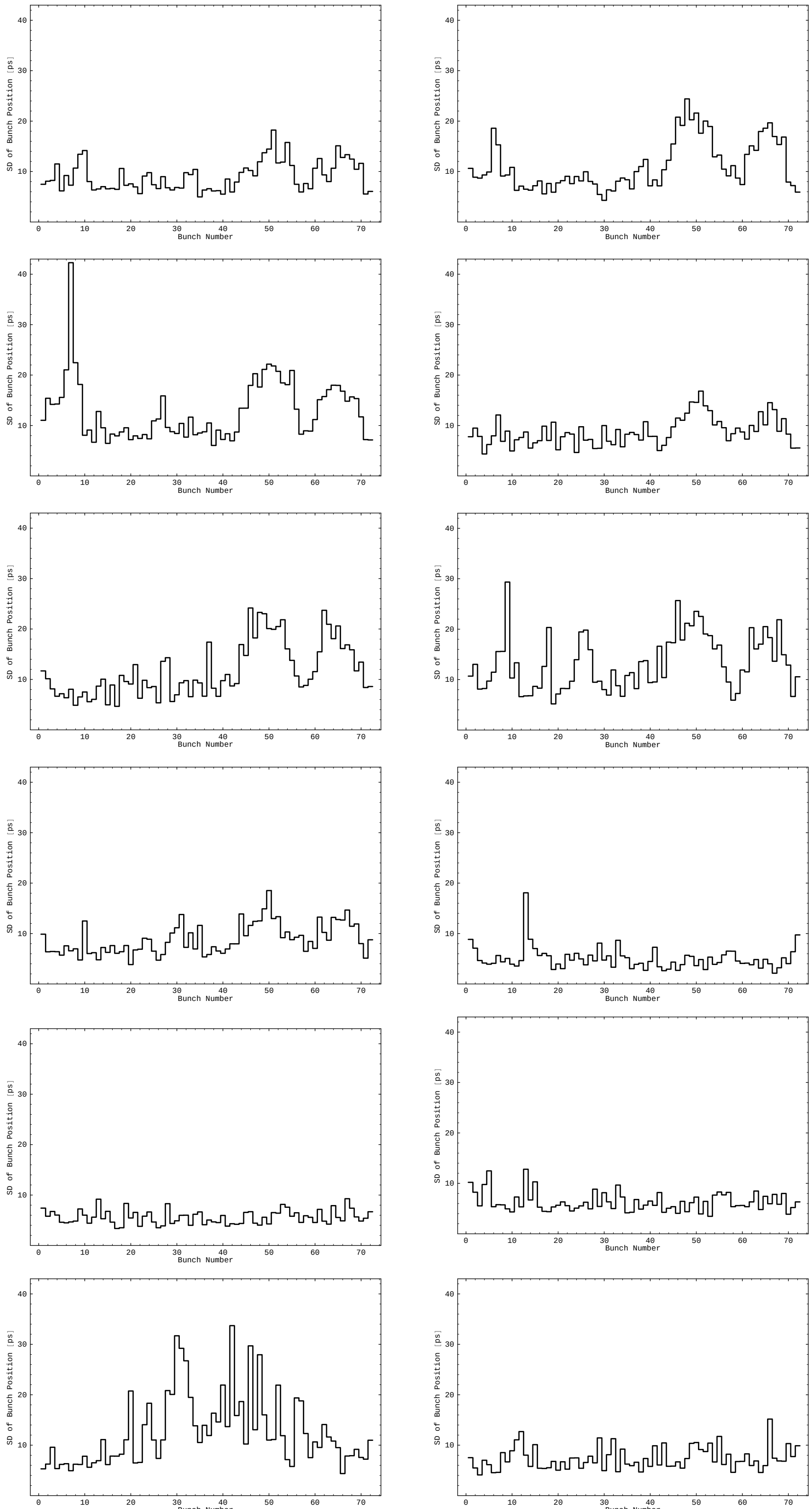


Figure 8: MD on 1.09.2004. Standard deviation of bunch position on the flat bottom (0.5 s to 10.5 s) as a function of bunch number in the first batch; `mr111` - `mr118` and `mr120` - `mr123` (left to right, top to bottom).

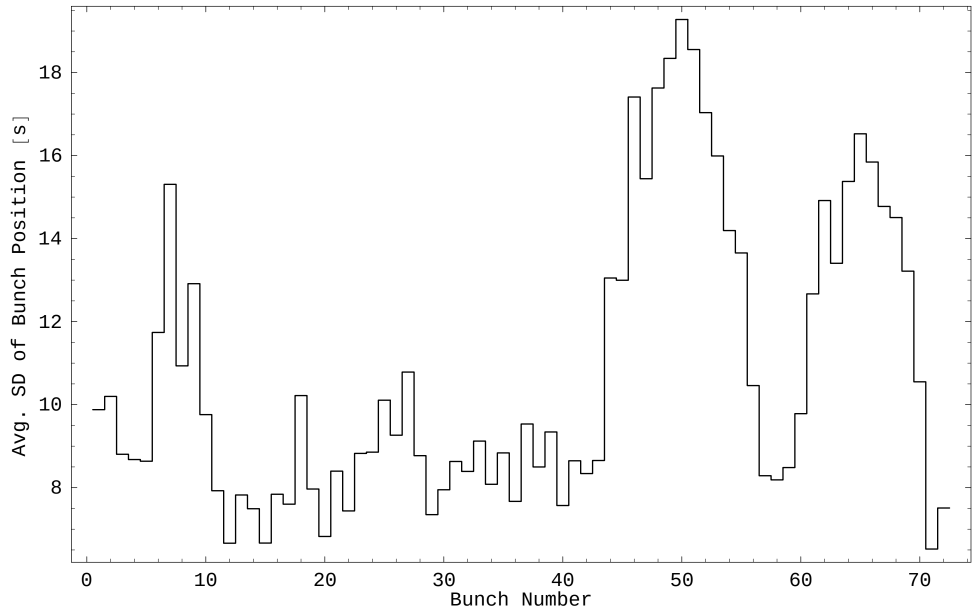


Figure 9: Average of standard deviation of bunch position versus bunch number in the first batch for `mr111` to `mr117`.

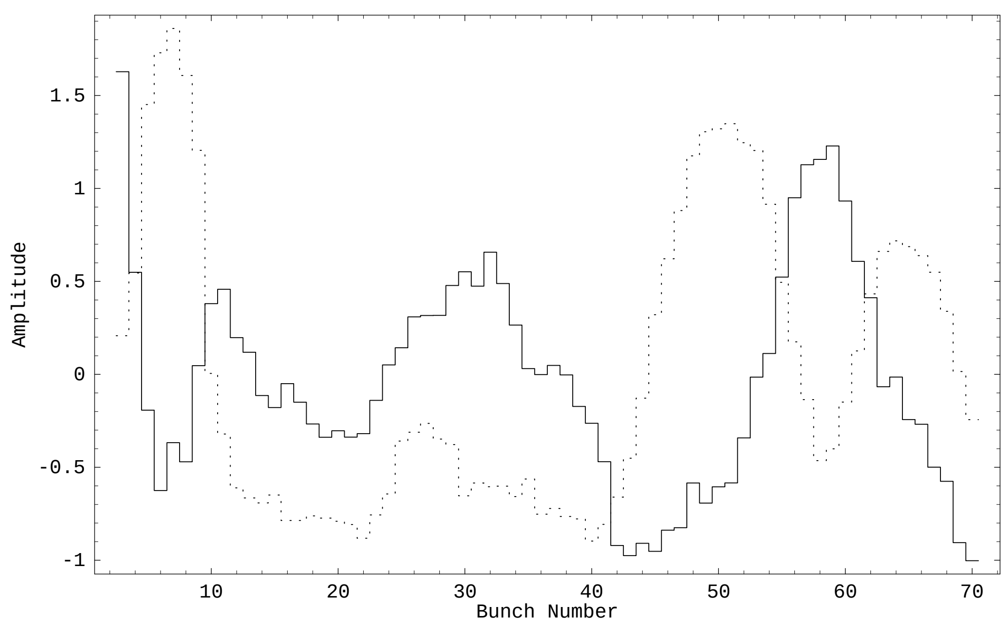


Figure 10: MD on 1.09.2004. Bunch peak amplitude lifetime (solid line) and standard deviation of bunch position (dashed line) versus bunch number in the first batch. The data was smoothed with a moving average algorithm (averaging factor 6) and the amplitudes were normalised. `mr113`.