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Simulation of LHC Bunches under Influence of 50-Hz-multiple Lines on the Cavity Field

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Keywords: emittance, blow-up, RF noise, 50 Hz, LHC

Summary

The effect of coherent lines at multiple of 50 Hz, with amplitudes as measured in the test stand, on the longitudinal emittance of LHC proton bunches was studied by simulation. In the absence of other effects it was found that the measured noise gives a negligible effect.

1. Introduction

RF phase and amplitude noise can blow up the longitudinal emittance of bunches. To examine for LHC the effect of the real phase noise on the cavity field the latter was measured [1] in the SM18 test stand (without beam) and it is expected that in the tunnel the situation will be very close. This phase noise measurement, as represented in Fig. 1 (copied from [1]), was used in the present paper for simulations of the bunches in LHC with the program [2]. Amplitude noise, generally less dangerous than phase noise, is also considered in a special context where it may be particularly harmful, but there simulations are based rather on estimations than measurements.

The noise-floor measured in 0-1 kHz is at –100 dBV and probably is only ‘produced’ by the measuring instrument, the true noise being even lower. With the above calibration this corresponds to an rms noise amplitude of $2.3\cdot10^{-4}$ ps/√Hz. Assuming that this noise floor is present in the whole base band 0-f_{rev} (11250 Hz) and absent above, this yields an rms noise amplitude of $2.4\cdot10^{-2}$ ps in this range.

As estimated in [3], the effect of synchrotron radiation damping in coast at 7 TeV is about compensated by a white noise of 1.15 ps rms amplitude, coherent on all cavities. Therefore synchrotron radiation damping will largely overpower the measured noise floor, i.e. one can neglect it here and only consider the much stronger 50-Hz-multiple lines.

In the simulation program for phase perturbation the change of energy encountered by particle i on turn n is expressed as

$$\Delta E_{i,n} = eV_0 \ \sin\left(-\frac{2\pi \cdot z_{i,n}}{\lambda_{RF}} + \sum_k \delta\varphi_k \cdot \cos\left(\omega_k \cdot n \cdot T_{rev} + \psi_k\right)\right) \tag{1}$$

where $z_{i.n}$ is the longitudinal position of the particle, k is the (integer) index of the 50-Hz-multiple line, ω_k and $\delta\varphi_k$ their angular frequency and phase stroke amplitude, respectively. To describe amplitude modulation we use

(2a) $$\Delta E_{i,n} = e\left(V_0 + \sum_k \delta V_k \cdot \cos\left(\omega_k \cdot n \cdot T_{rev} + \psi_k\right)\right)\ \sin\left(-\frac{2\pi \cdot z_{i,n}}{\lambda_{RF}}\right) \quad \text{or}$$

(2b) $$\Delta E_{i,n} = eV_0\left(1 + \sum_k m_k \cdot \cos\left(\omega_k \cdot n \cdot T_{rev} + \psi_k\right)\right)\ \sin\left(-\frac{2\pi \cdot z_{i,n}}{\lambda_{RF}}\right)$$

with the corresponding voltage amplitudes δV_k or the modulation index $m_k = \delta V_k / V_0$. For amplitude and phase noise we assume the worst case: all 8 cavities (in one beam) are modulated identically; for incoherent modulation the total effect on the beam is smaller. If the lines would have mutually a random phase, statistically the resulting effect on the beam would be smaller by a factor $1/\sqrt{8}$; however, the excitation is deterministic, hence a random phase assumption is not good. Since the mutual phases ψ_k of the different lines were not determined, we have simply assumed $\psi_k=0$ for all k.

Acceleration is achieved by a continuous change of (synchronous) revolution time, following the change of magnetic field. Then all particles get (averaged over a synchrotron period) the same energy increase.

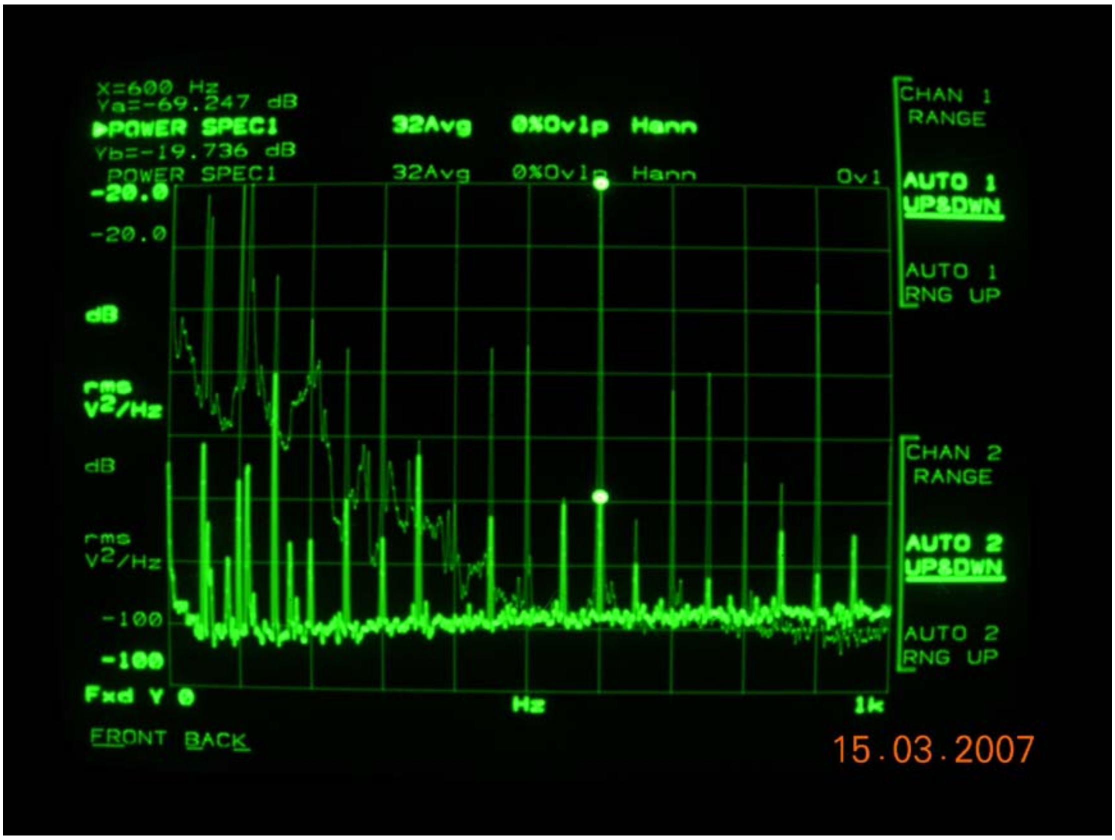

Fig. 1: Cavity field phase noise with prominent 50-Hz-multiple lines on the phase as measured [1] in the SM18 test stand on a system as used in the LHC tunnel. The measurement is displayed in dBV for rms V^2/Hz, the analyzer bandwidth being 1.25 Hz at the chosen 1 kHz range, the phase calibration 0.3 V/deg at 400 MHz. The weakly illuminated trace shows the open loop case, the well-illuminated trace the closed loop case. The present simulations are based on the latter.

Table 1

The 50-Hz-multiple lines from Fig. 1 and the corresponding ‘noise’; analyzer BW=1.25 Hz, calibration 0.3V/deg at 400 MHz.

f_{mod}[Hz]	meas[dBV^2_{rms}/Hz]	V^2_{peak}	$\delta\phi_{peak}$[deg]	δt_{peak}[ps]
50	-62	1.577e-06	4.186e-03	2.907e-02
100	-65	7.906e-07	2.964e-03	2.058e-02
150	-50	2.500e-05	1.667e-02	1.157e-01
200	-76	6.280e-08	8.353e-04	5.801e-03
250	-70	2.500e-07	1.667e-03	1.157e-02
300	-77	4.988e-08	7.445e-04	5.170e-03
350	-62	1.577e-06	4.186e-03	2.907e-02
400	-100	2.500e-10	5.270e-05	3.660e-04
450	-72	1.577e-07	1.324e-03	9.194e-03
500	-100	2.500e-10	5.270e-05	3.660e-04
550	-70	2.500e-07	1.667e-03	1.157e-02
600	-70	2.500e-07	1.667e-03	1.157e-02
noise floor	-100			

There are four essential cases of concern to be examined. The first is the long time coast at 7 TeV/c and 16 MV RF voltage with a synchrotron frequency around $f_{s,0}$=23 Hz and a longitudinal emittance of 2.5 eVs, the populated phase space area having all (incoherent) synchrotron frequencies below 25 Hz.

Furthermore, a small change of machine conditions (coast energy, momentum compaction) and/or RF voltage can shift the synchrotron frequency band around 25 Hz. For amplitude noise the worst frequency condition is an excitation at $2 \cdot f_s$, hence here amplitude noise on the 50 Hz line will be the worst case. Therefore long time coasts under these conditions have also been examined.

Since at injection – as planned – the synchrotron frequencies for a 0.7 to 1.0 eVs bunch are all above 50 Hz and in coast definitively below 50 Hz, the 50 Hz line has to be crossed by all particles on the ramp. The time for the populated area to cross is not very long (about a minute) but this happens at the worst frequency conditions for phase noise: $f_s=f_{mod}$.

Finally a 1 h ‘coast’ at 450 GeV/c with 8 MV RF (injection) voltage was examined.

The simulation assumes independent macro-particles, i.e. intra beam scattering is neglected. Also the synchrotron radiation damping with about 24 h longitudinal bunch length damping time is not taken into account here.

For a perfectly stable (simulated) bunch the projection on the longitudinal z-axis (the longitudinal bunch profile) is different at different times due to the granularity of the (pseudo-) random distribution. However, a histogram of the action angle variable J ($\sqrt{J}$ can be seen as a radial coordinate in phase-space with J=0 at the bunch centre) remains perfectly invariant[1] for an unperturbed bunch and any changes in the J-distribution indicate a true change of the bunch. Therefore we will use this histogram as the main observable. In most cases the z-projection and the phase space distribution of the bunch will also be shown.

[1] The program is designed such that for any unperturbed particle J remains *also numerically* perfectly constant even for a non-differential advance in phase space with finite step width.

2. Long run with nominal coast condition

For the 50-Hz-multiple lines between 50 and 600 Hz as measured (Table 1) – neglecting the noise-floor several orders of magnitude below the synchrotron radiation damping equivalent – we have simulated a coast of 8 h duration with 10,000 macro-particles. The J-histogram in Fig. 2 shows that there are only negligible changes to the bunch. Therefore we can conclude that – in the absence of any other effects – for a realistic coast there will be no blow-up due to 50-Hz-multiple lines but the synchrotron radiation damping with about 24 h damping time will even cause the bunch to shrink.

We have also simulated an otherwise identical run but all line amplitudes multiplied by an amplification factor a=30 (+30dB). Results in Figs. 3a-c show only negligible bunch shape changes, i.e. a coast as planned should not be perturbed by the measured 50-Hz-multiple lines.

Finally, white noise sufficient to compensate synchrotron radiation damping (1 ps rms) was simulated together with the 30 times magnified lines. No increase of bunch perturbation was observed but there were 0.05% losses instead of 0.02% losses for the pure noise case without 50-Hz-multiple lines; results are shown in Fig. 4, 5 and 6.

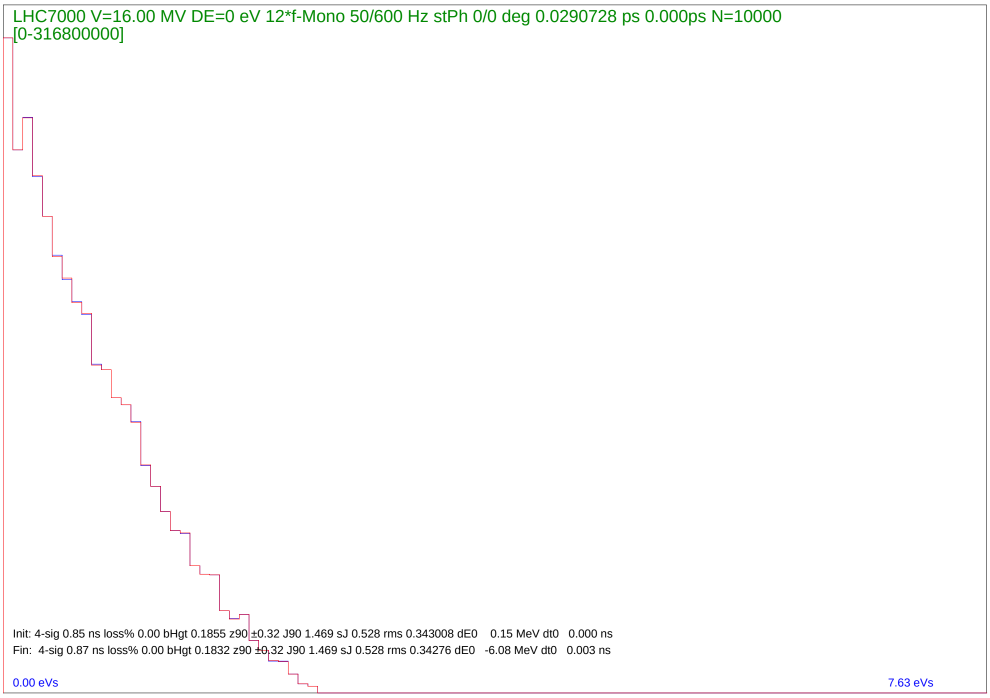

Fig. 2a: J-histogram at 7 TeV/c for initial (blue) and final (red) bunch of 2.5 eVs (initial longitudinal distribution proportional $\cos^2(\pi \cdot z/L)$, $-L/2 \leq z \leq L/2$, see Fig. 2b) during 8 hours (about $3.2 \cdot 10^8$ machine turn) at 7 TeV/c coast for 10^4 macro-particles for the 50-Hz-line multiples as measured. (The blue line, drawn first, is practically covered by the red line). The (incoherent) synchrotron frequencies were 23.84 Hz at the bunch centre and about 21 Hz at the limiting J_b=2.5 eVs line, the bucket size being 7.63 eVs.

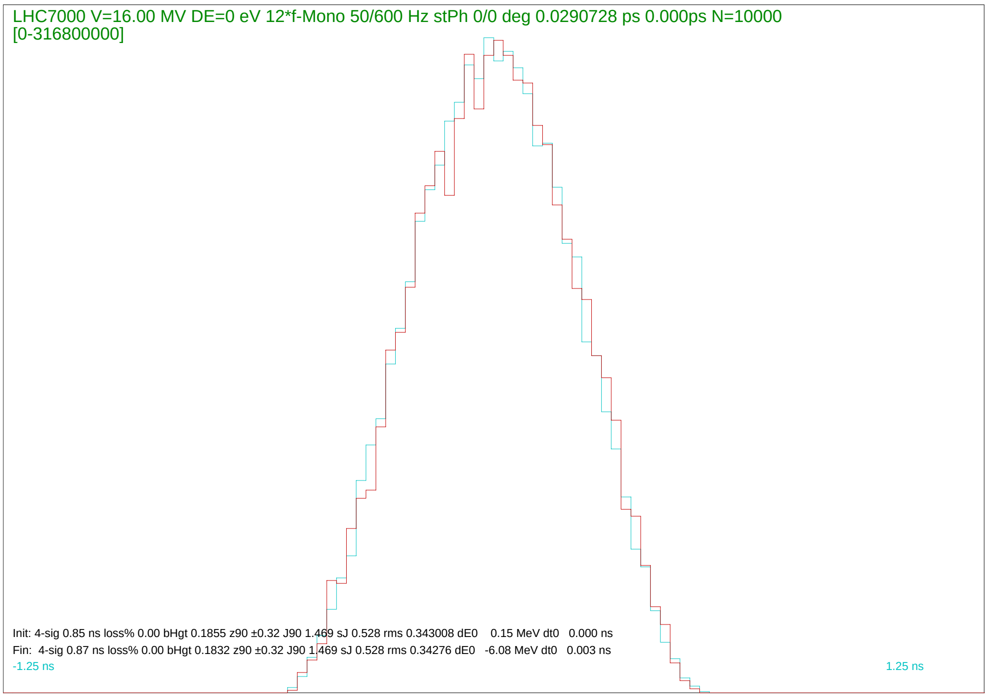

Fig 2b: z-projection for the same bunch as in Fig. 2a.

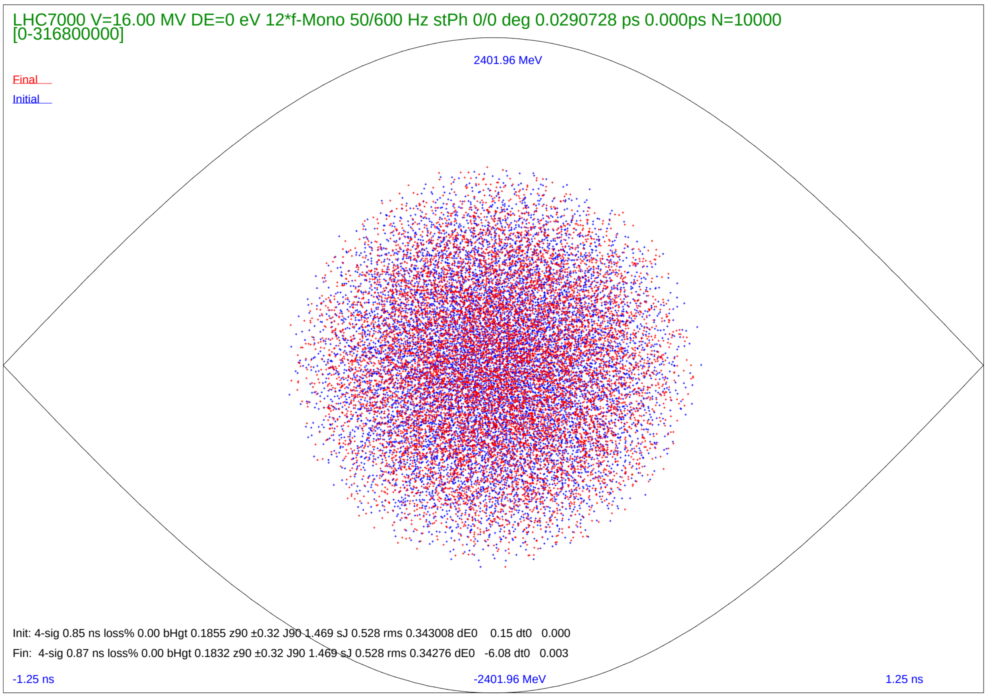

Fig 2c: phase space distribution for the same bunch as in Fig. 2a, 2b.

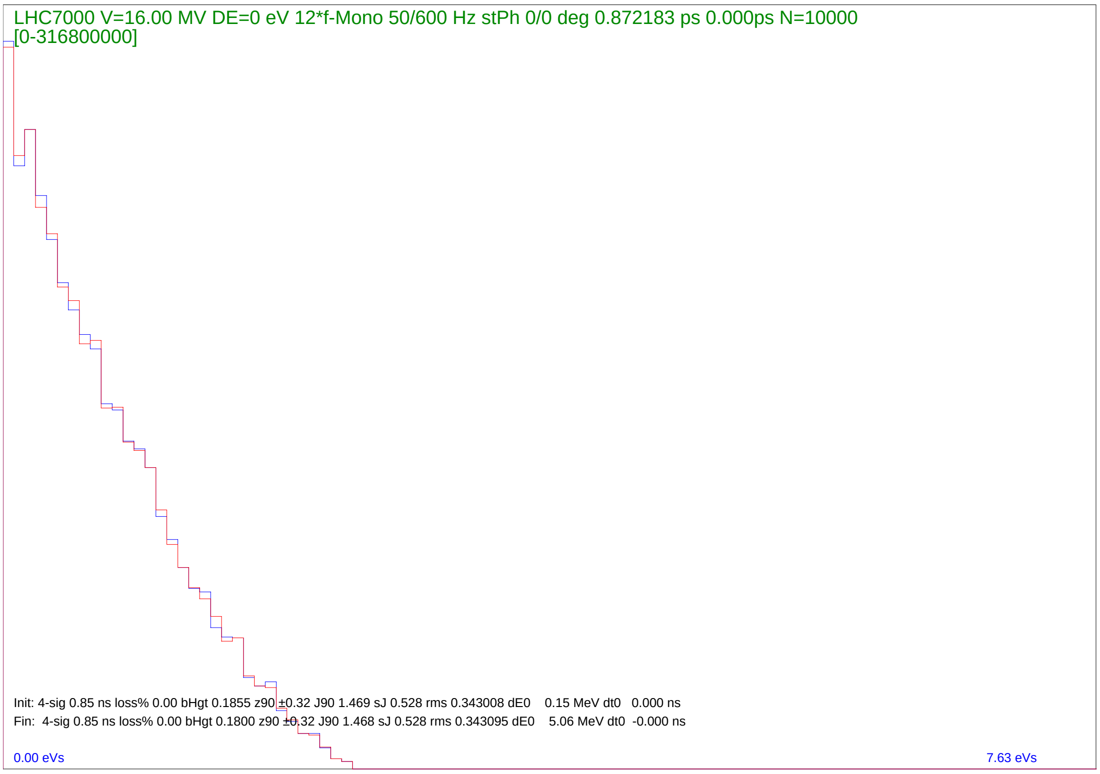

Fig. 3a: J-distributions at 7 TeV/c for initial (blue) and final (red) bunch for 8 h coast with a=30 (+30dB) magnified line amplitudes (10^4 macro particles)

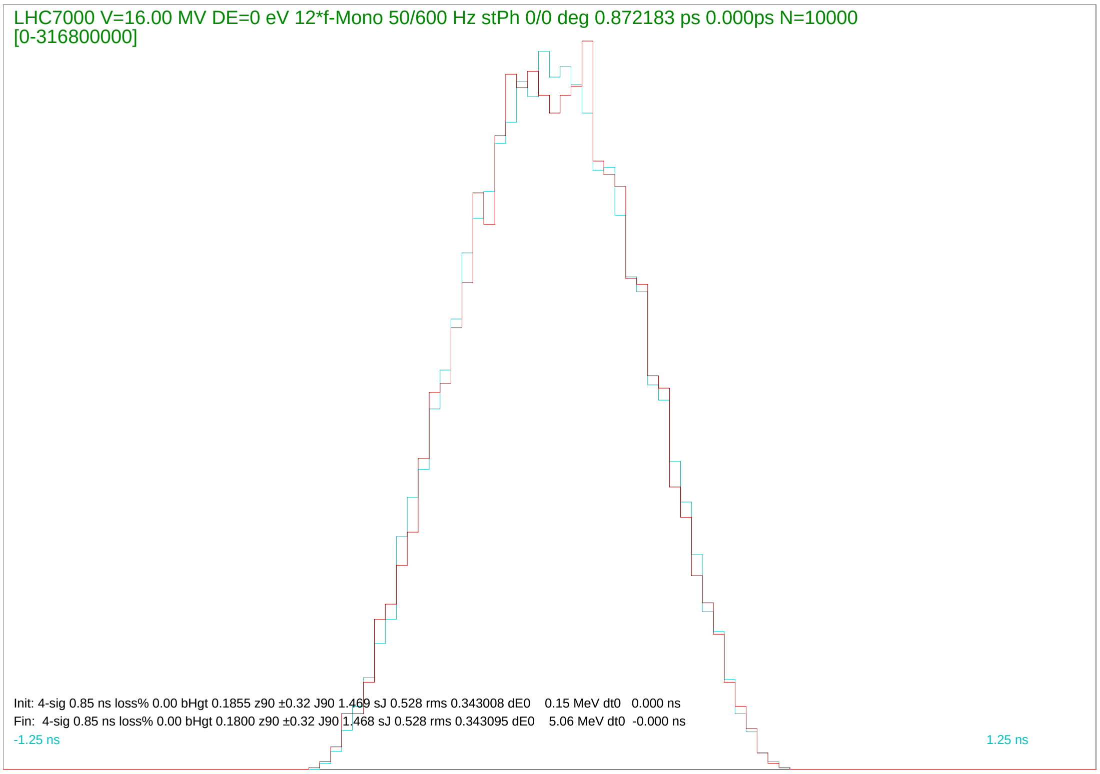

Fig. 3b: Longitudinal z-distributions at 7 TeV/c for initial (blue) and final (red) bunch for 8 h coast with a=30 (+30dB) magnified line amplitudes (10^4 macro particles).

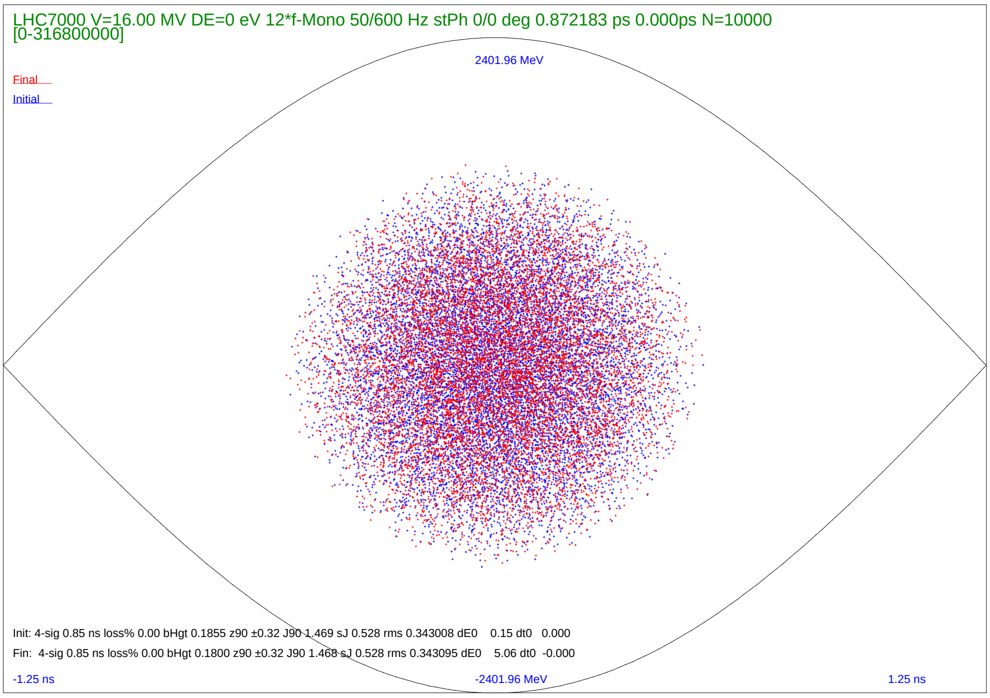

Fig. 3c: Phase space at 7 TeV/c for initial (blue) and final (red) bunch for 8 h coast with a=30 (+30dB) magnified line amplitudes (10^4 macro particles).

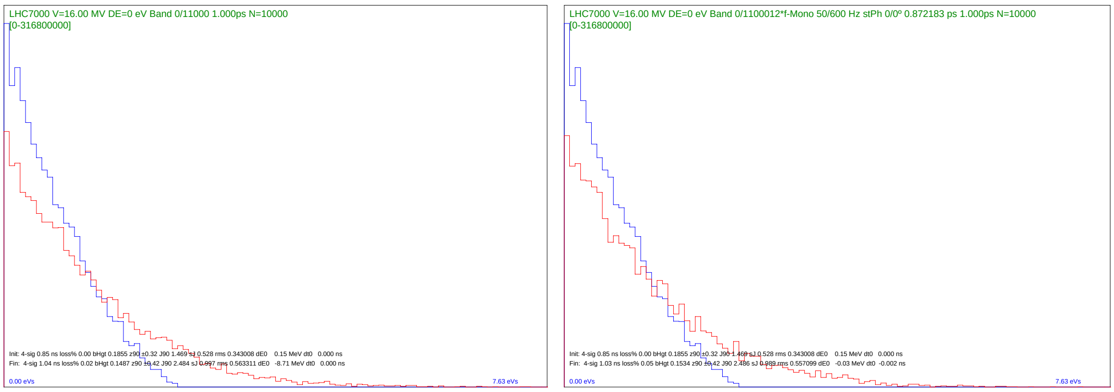

Fig. 4a,b: J-histogram at 7 TeV/c with white noise (1 ps rms): (a) pure noise and (b) with a=30 (30 dB) magnified lines (8 h coast, 10^4 macro-particles)

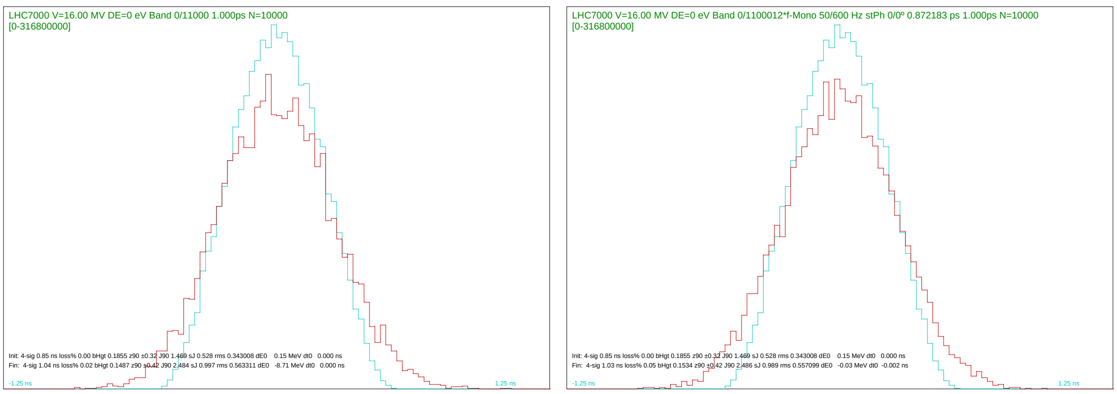

Fig. 5a,b: z-histogram at 7 TeV/c with white noise (1 ps rms): (a) pure noise and (b) with a=30 (30 dB) magnified lines (8 h coast, 10^4 macro-particles).

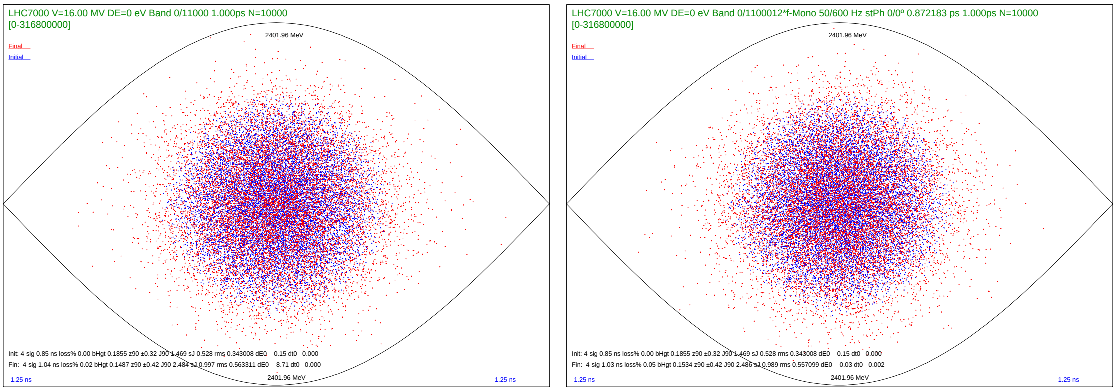

Fig. 6a,b: phase space plot at 7 TeV/c with white noise (1 ps rms): (a) pure noise and (b) with a=30 magnified lines (8 h coast, 10^4 macro-particles).

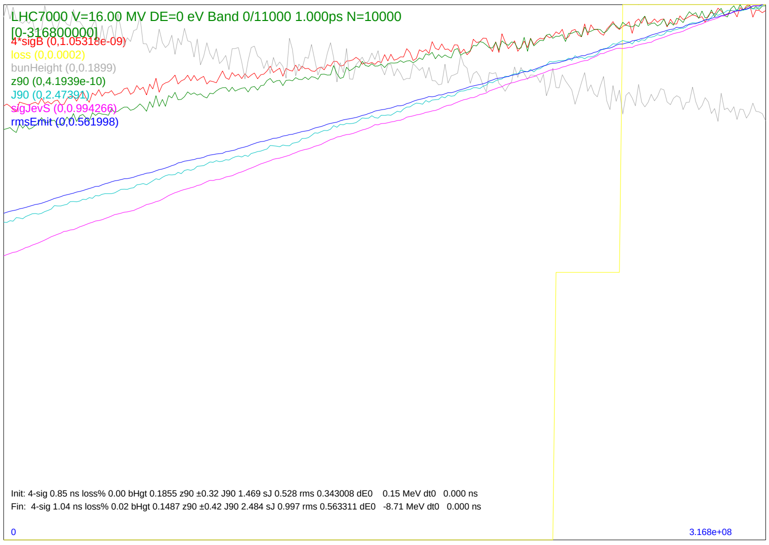

Fig. 7a: Development with respect to the turn number (i.e. time) of some quantities of the bunch at 7 TeV/c coast with only white phase noise at 1 ps rms (as Fig. 4a, 5a and 6a), all quantities behaving quite linear. The rms-emittance (dark blue) for example increases within 8h from 0.343 to 0.563 units which can be linearly extrapolated to 12.5 h for a factor 2 (i.e. to 0.686 units), matching very well the expected 12 h for this noise [3], which about compensates synchrotron radiation damping.

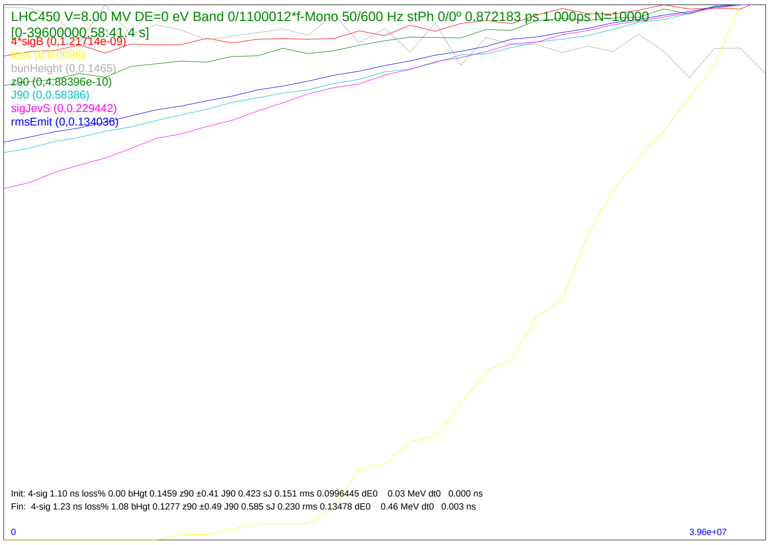

Fig. 7b: Development with respect to the turn number (i.e. time) of some quantities of the bunch at 7 TeV/c coast with <u>white phase noise</u> at 1 ps rms <u>and 50 Hz-multiple lines with a=30 (+30 dB) magnified</u> amplitude (as Fig. 4b, 5b and 6b), All quantities behaving quite the same way as in Fig. 7a without 50-Hz-multiple lines, only losses are higher

3. Coast with synchrotron frequency band covering 25 Hz and RF amplitude modulation at 50 Hz

Already small changes can shift the synchrotron frequency band corresponding to the populated bunch area around 25 Hz. The machine parameters and/or RF voltage may be changed, the details are not very important. Therefore we have left the machine parameters untouched but increased the RF voltage slightly. Already a shift from the standard 16 MV to 18 MV brings $f_{s,0}$ on 25 Hz. To probe the worst case, we want to have f_s=25 Hz in the middle of the band and use 20.5 MV RF voltage with $f_{s,0}$=27.0 Hz and $f_{s,b}$=24.4 Hz at the outer bunch limit for a 2.5 eVs bunch ($\cos^2$ distribution).

Table 2

Synchrotron frequency bands at 7 TeV/c for different V_{RF}

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21 MV: Centre 27.31 [Hz]; Outer 24.7 [Hz]

20 MV: Centre 26.65 [Hz]; Outer 24.1 [Hz]

19 MV: Centre 25.98 [Hz]; Outer 23.4 [Hz]
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We have simulated the case of a single 50 Hz line amplitude modulation (higher ones have little effect) with a rather large amplitude of □V_{50Hz} = 200 kV for an RF amplitude of V_0=20.5 MV, i.e. a modulation index m=1%. The resulting effect was observed for 10 seconds, 2 minutes and 8 hours. We see in Figs. 8, 9 and 10 that after the initial perturbation for 10 seconds there is not much more perturbation till 2 minutes and then only tiny further changes for a full coast of 8 hours.

The reason for this might be that within 10 seconds already the particles at f_s=25 Hz are redistributed and from then on the long time action of a sharp (i.e. BW=0 Hz) 50 Hz modulation makes very little further effect. The real 50 Hz line of the power grid is not absolutely stable and there might also be UPS[2] with a slightly 'different 50 Hz' that might enter over electronics supplied by it. Also the magnetic focusing and the RF voltage are not infinitely stable and may have small drifts. To take this into account, we have made a second series of simulations, also for 10 seconds, 2 minutes and 8 hours (Figs. 11, 12 and 13). But instead of a sharp 50 Hz modulation with 200 kV amplitude, we have assumed a noise band of 0.2 Hz width between 49.9 Hz and 50.1 Hz. To have the same noise-power as the delta noise of a sharp line, we need the same rms amplitude distributed over the noise band, i.e. $1/\sqrt{2}$ times the peak amplitude value, hence 141 kV_{rms} on the whole noise band or 316 $kV_{rms}/\sqrt{Hz}$ in our case. The perturbation of the bunch distribution by the band is slightly larger but not essentially different from the sharp 50 Hz line case (compare Fig. 8 and 11, 9 and 12, 10 and13).

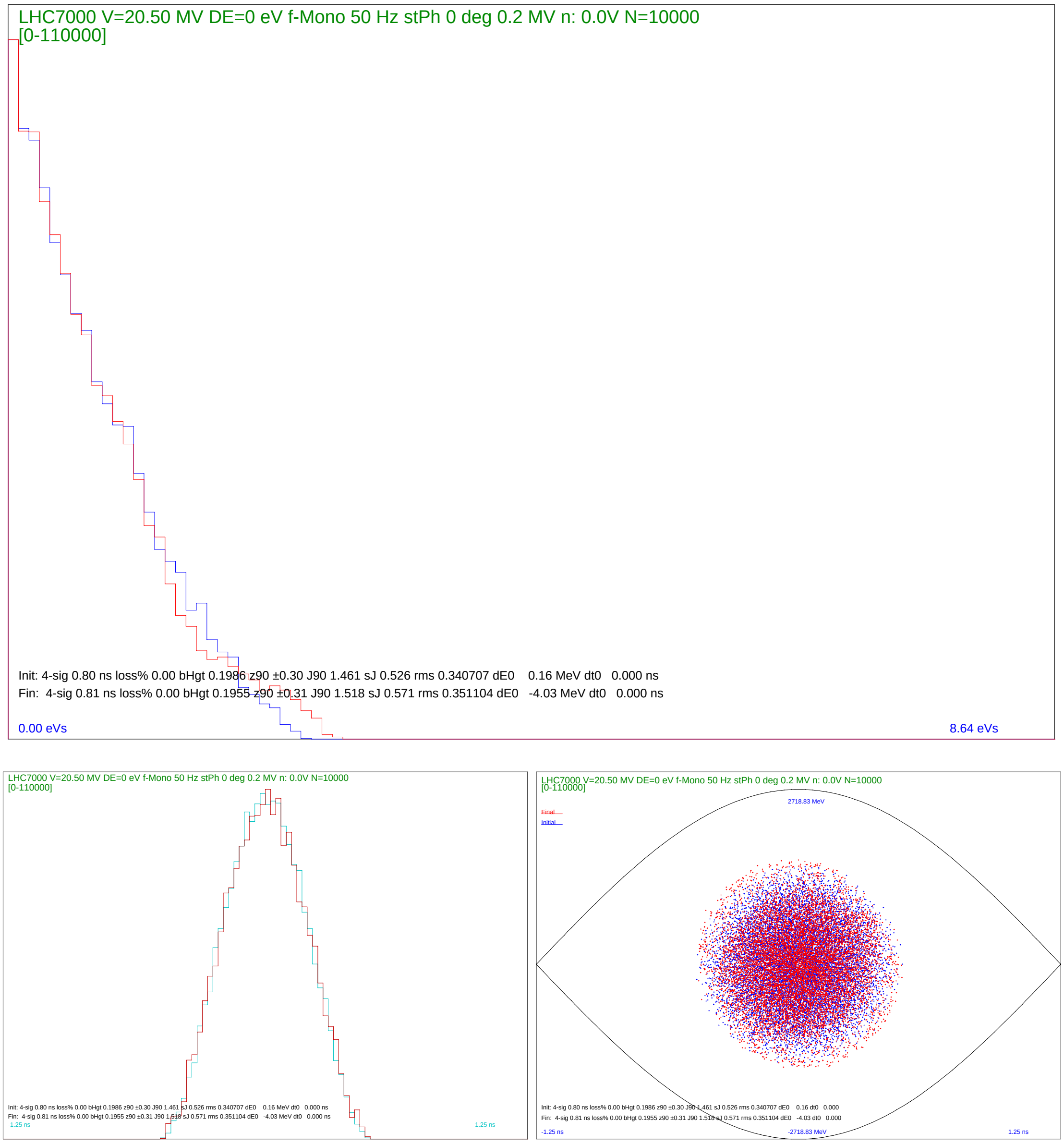

Fig. 8a (top): J-histogram, 8b (bottom left): z-histogram, 8c (bottom right): phase space distribution at 7 TeV/c for 10^4 macro-particles. 10 seconds coast with 200 kV amplitude

[2] Uninterrupted Power Supply, not necessarily locked to the 50 Hz of the power grid.

modulation at 50 Hz (sharp line) (at 20.5 MV RF voltage, i.e. m=1%). Blue: initial bunch, red: final bunch.

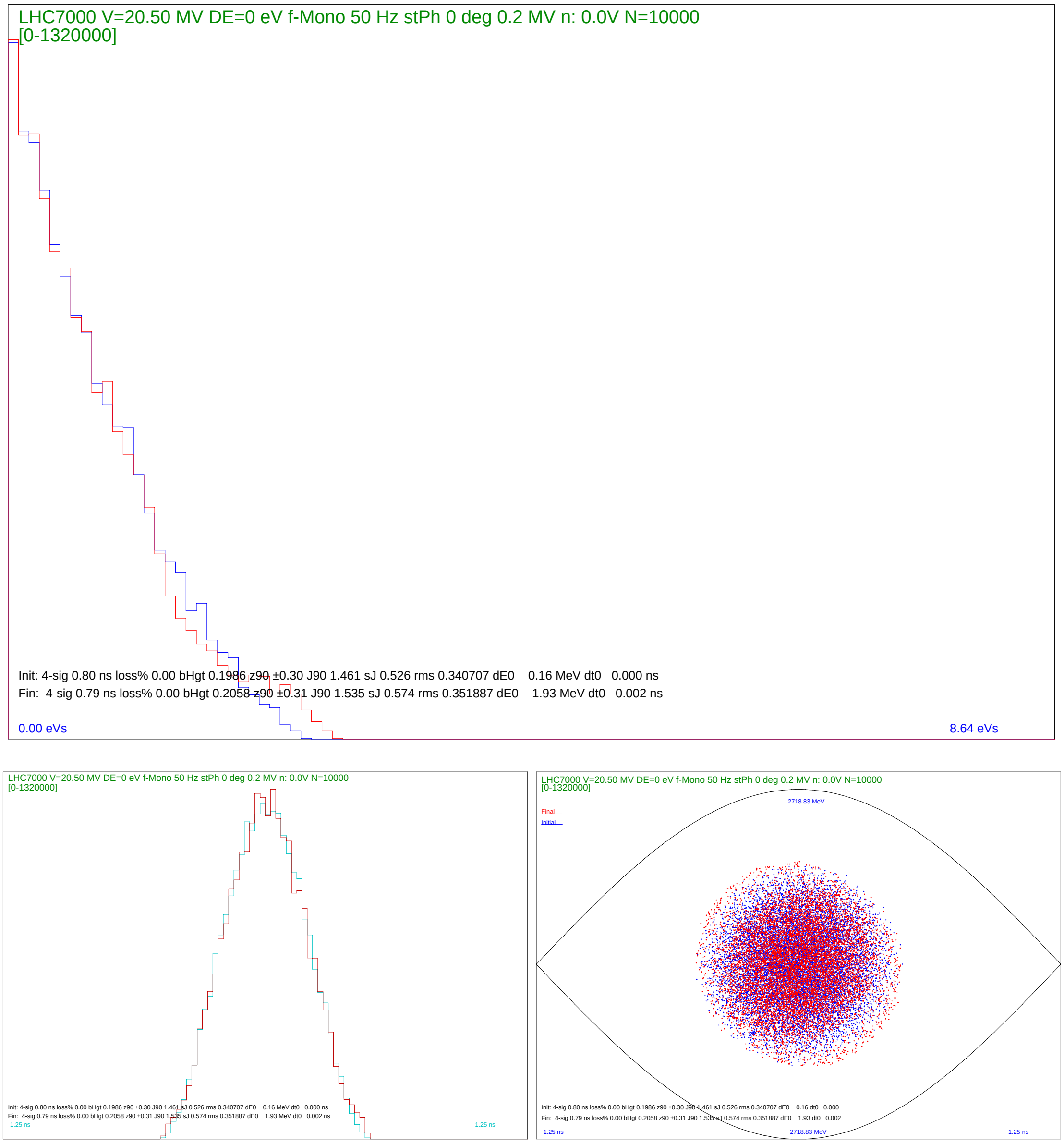

Fig. 9a (top): J-histogram, 9b (bottom left): z-histogram, 9c (bottom right): phase space distribution at 7 TeV/c for 10^4 macro-particles. 2 minutes coast with 200 kV amplitude modulation at 50 Hz (sharp line) (at 20.5 MV RF voltage, i.e. m=1%). Blue: initial bunch, red: final bunch.

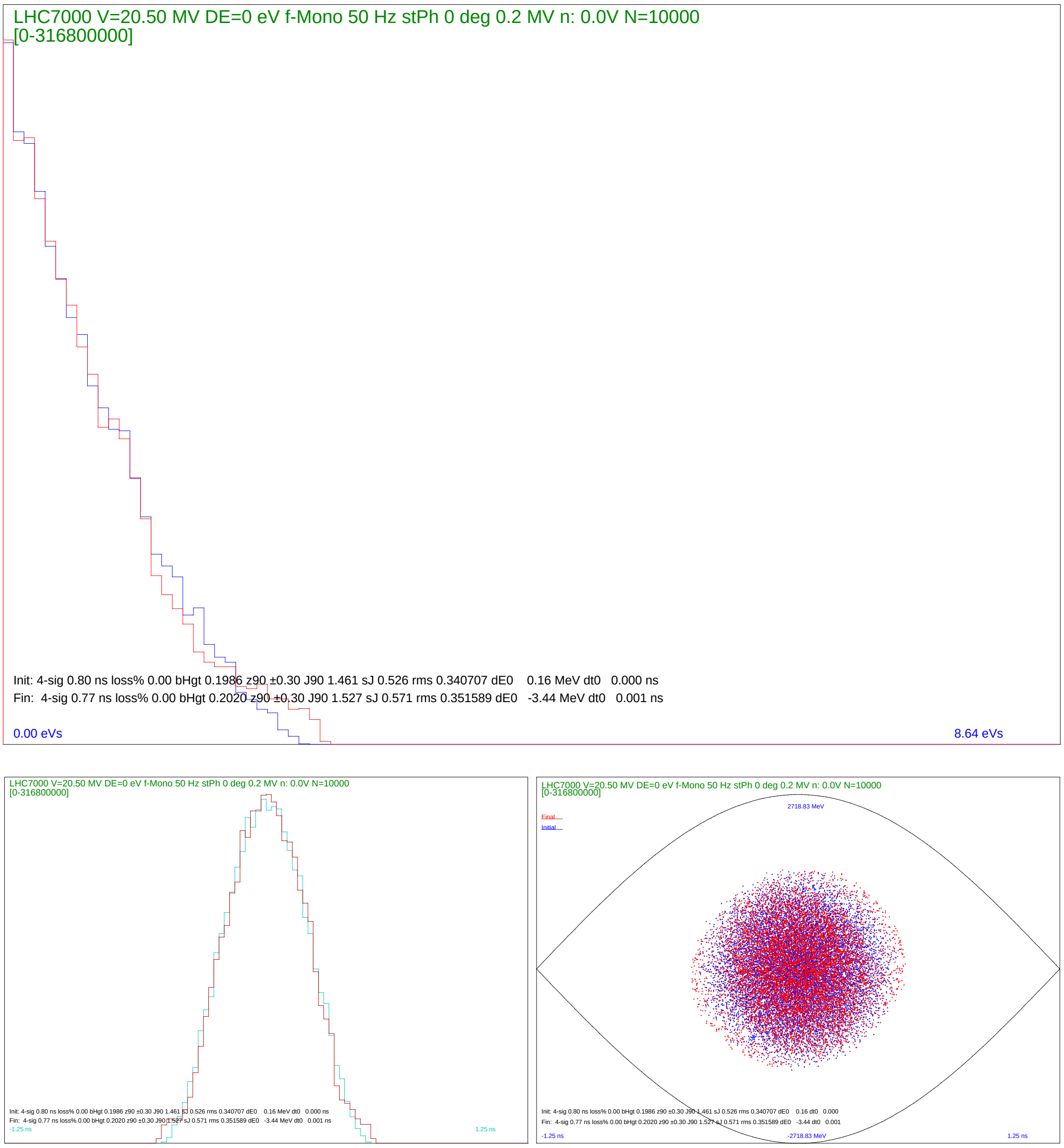

Fig. 10a (top): J-histogram, 10b (bottom left): z-histogram, 10c (bottom right): phase space distribution at 7 TeV/c for 10^4 macro-particles. 8 hours coast at 200 kV amplitude modulation at 50 Hz (sharp line) (at 20.5 MV RF voltage, i.e. m=1%). Blue: initial bunch, red: final bunch.

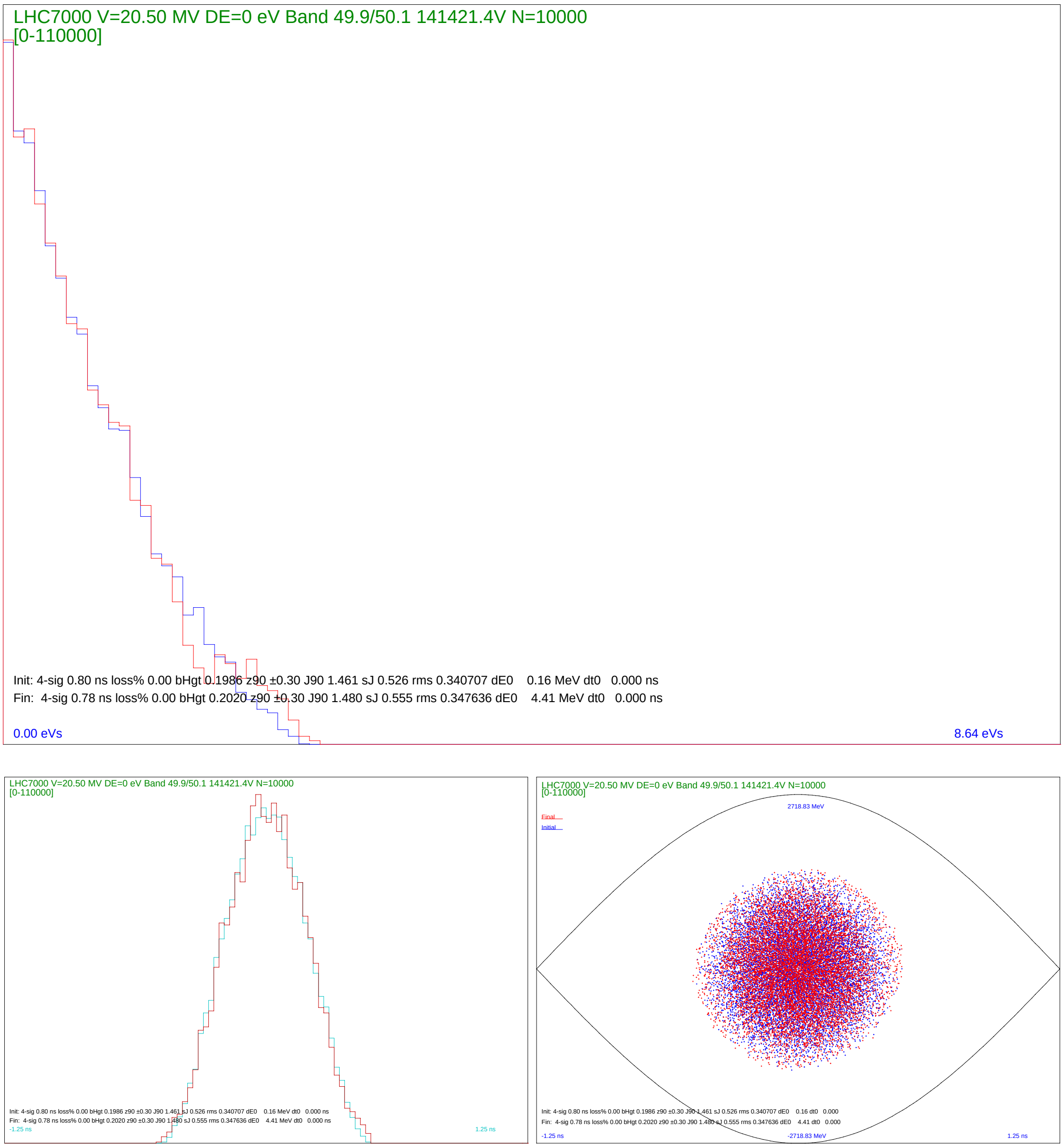

Fig. 11a (top): J-histogram, 11b (bottom left): z-histogram, 11c (bottom right): phase space distribution at 7 TeV/c for 10^4 macro-particles. <u>10 seconds</u> coast with $\sqrt{<\Delta V^2>} = 141\ \mathrm{kV_{rms}}$ in the <u>band 49.9 Hz to 50.1 Hz</u> (20.5 MV RF voltage). Blue: initial bunch, red: final bunch.

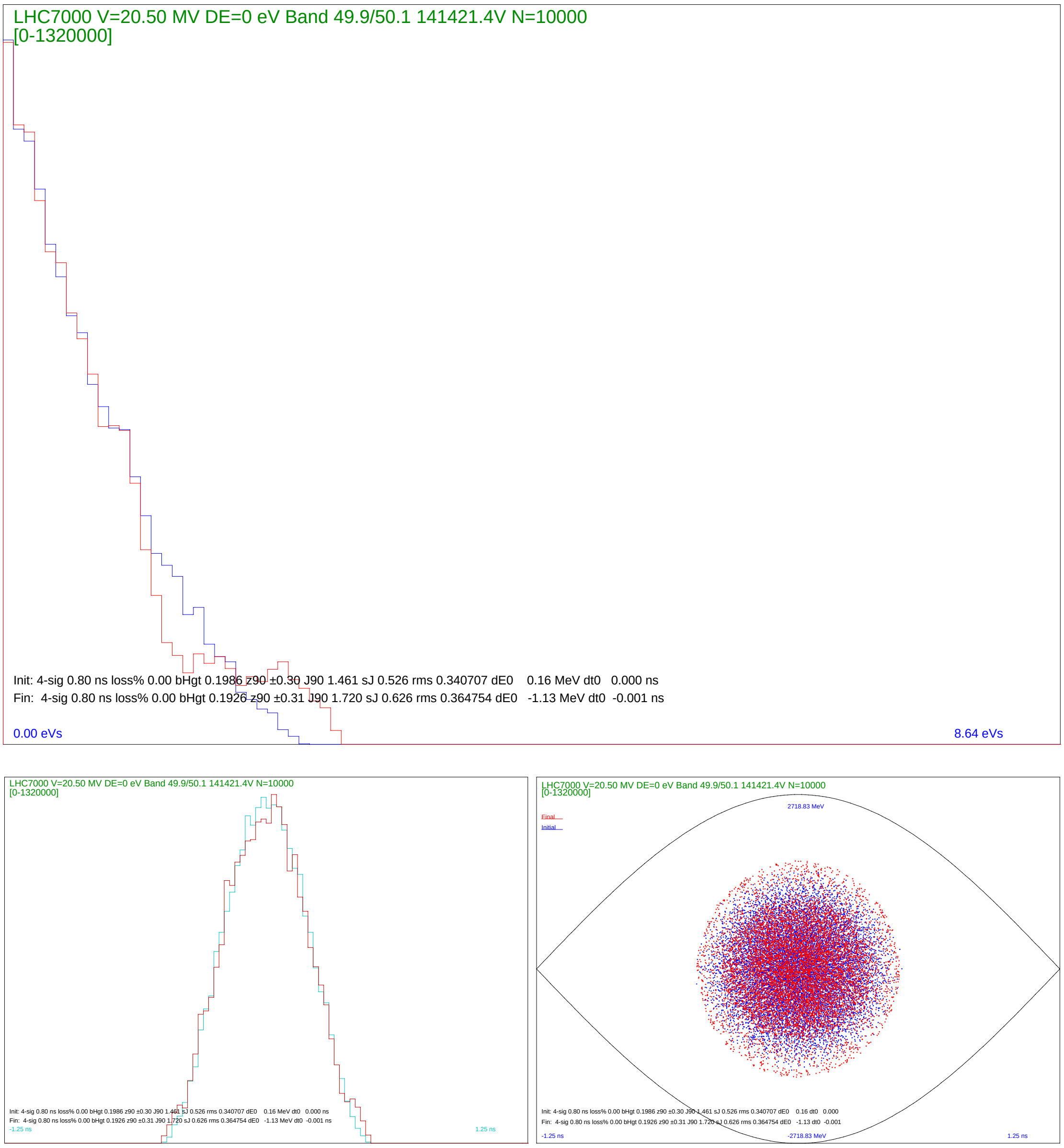

Fig. 12a (top): J-histogram, 12b (bottom left): z-histogram, 12c: (bottom right) phase space distribution at 7 TeV/c for 10^4 macro-particles. 2 minutes coast at $\sqrt{<\Delta V^2>}$ = 141 kV_{rms} in the band 49.9 Hz to 50.1 Hz (20.5 MV RF voltage). Blue: initial bunch, red: final bunch.

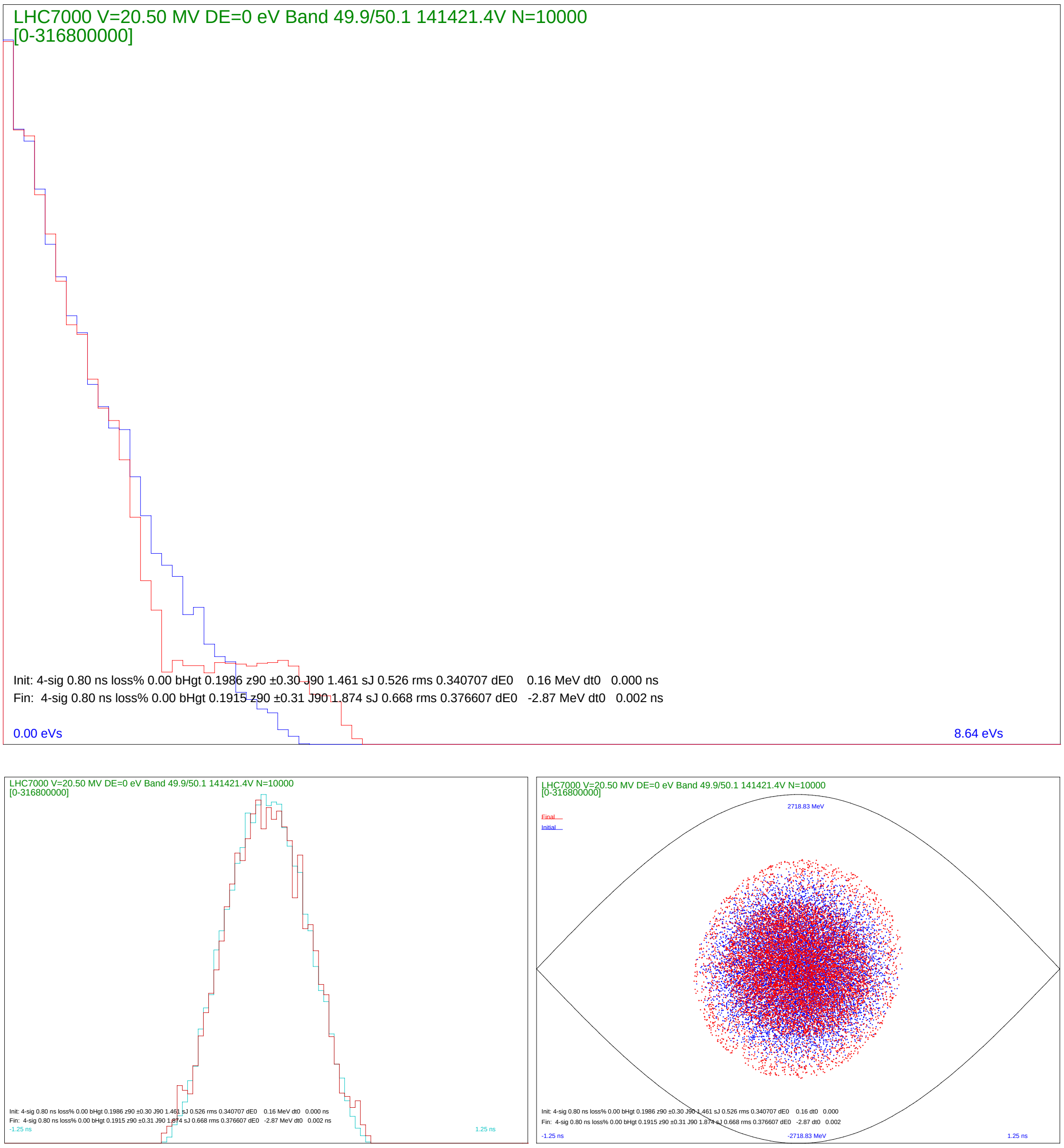

Fig. 13a (top) J-histogram, 13b (bottom left) z-histogram, 13c (bottom right) phase space distribution at 7 TeV/c for 10^4 macro-particles. <u>8 hours</u> coast at $\sqrt{<\square V^2>}$ = 141 kV_{rms} in the <u>band 49.9 Hz to 50.1 Hz</u> (20.5 MV RF voltage). Blue: initial bunch, red: final bunch.

4. 50 Hz phase noise crossing on the ramp

The program [2] used was originally designed to observe microscopic changes of any particle distribution in phase space only in coast. To do this rapidly it initially sets up – in a CPU extensive process – energy and RF voltage dependent constants for later high-precision fast evaluation of the behaviour of the particles in regular time/turn laps. Its capabilities have been enlarged now for the present (and other future) applications such that also energy and voltage ramping is possible now without losing the high numerical precision in evaluation nor speed for the initially foreseen coasting cases.

At 500 GeV/c (and 8 MV RF voltage) the synchrotron frequency spectrum for a 0.7 eVs bunch ranges from 62.7 Hz (centre) down to about 53.7 Hz (border) – all above 50 Hz while at 800 GeV/c (8 MV) it ranges from 49.7 Hz (centre) down to about 44.4 Hz – all below 50 Hz. Therefore it is sufficient to simulated the LHC energy ramp between 500 GeV/c and 800 GeV/c. The ramp is planned to last about 20 minutes, hence for about linear energy increase (appreciatively 0.5 MeV/turn) the passage over the above range lasts roughly a minute. Fig. 14 shows the J-histogram for 10^6 macro particles for this case. There is only a practically negligible change during the crossing due to the 50 Hz crossing.

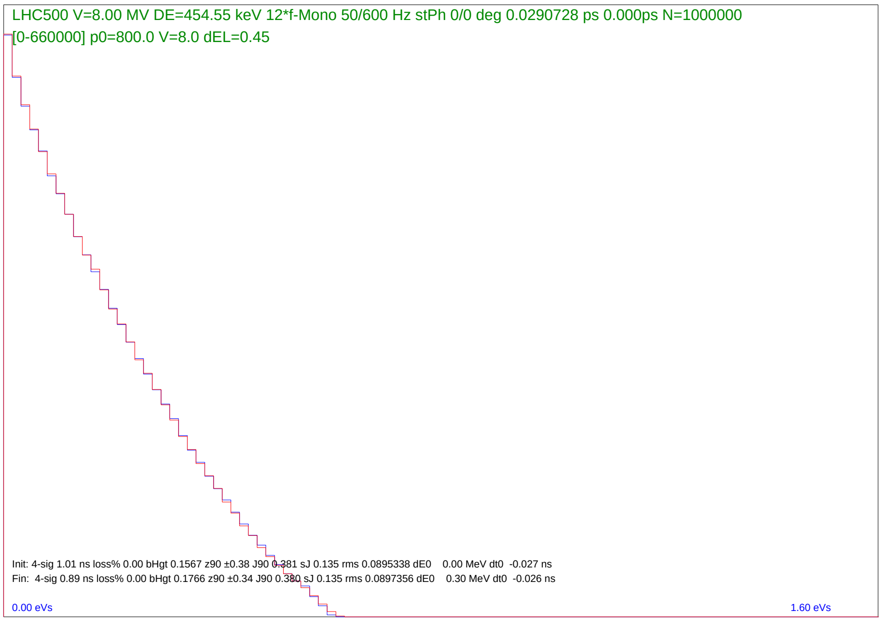

Fig. 14a: J-histogram (10^6 macro particles) for the initial 0.7 eVs bunch (blue) and the final (red) bunch after 50 Hz line crossing within 60 s; bucket size 1.52→1.60 eVs.

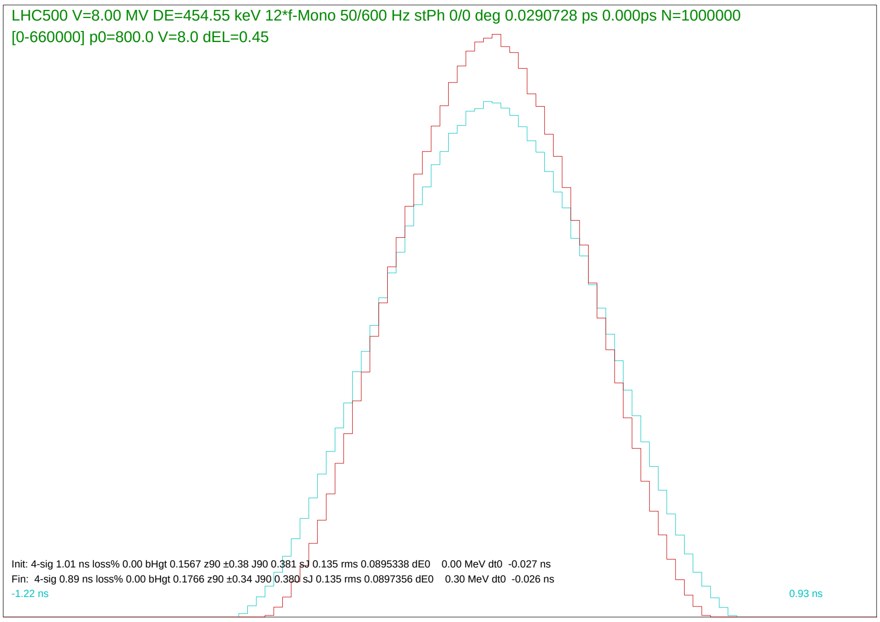

Fig. 14b: z-projection of the same bunch as in Fig. 14a. The initial case (blue) is at 500 GeV/c, the final one (red) at 800 GeV/c, hence the difference in bunch length for the same emittance (see Fig. 14a), both at 8 MV RF voltage.

The phase space distribution is not displayed here due to the large number (10^6) of macro-particles, showing graphically a nearly uniformly coloured spot. But we have calculated cases with magnified line amplitudes as displayed in Fig. 15.

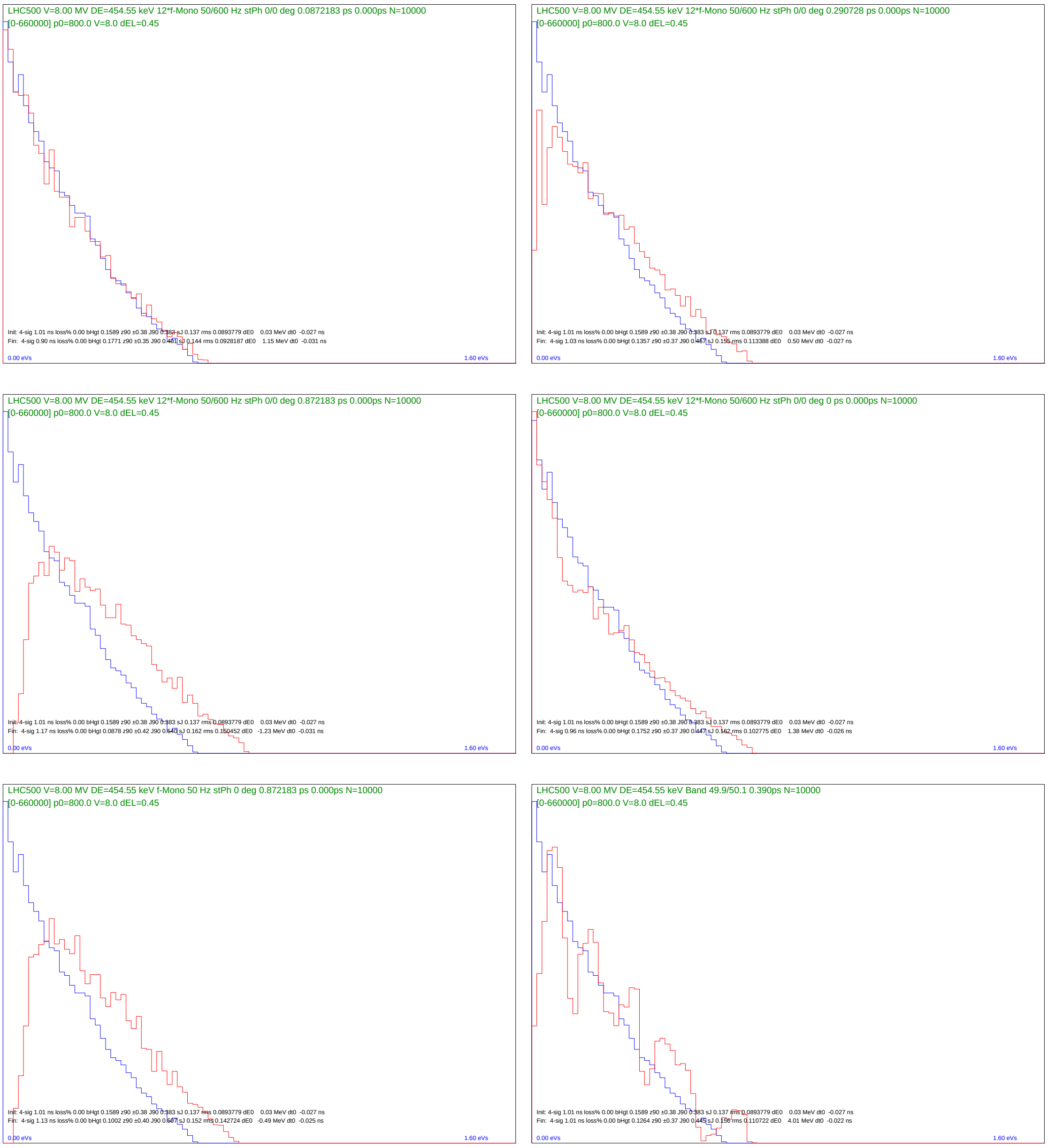

Fig. 15 a-f: J-histograms of simulations for conditions as Fig 14 but only 10^4 macro particles and line amplitudes magnified by (top left, 15a): a=3 (+10dB); (top right, 15b): a=10 (+20dB); (middle left, 15c): a=30 (+30dB); (middle right, 15d): as 15c but 50 Hz line 'switched off'; (bottom left, 15e): only 50 Hz line with a=30; (bottom right,15f): only band in 49.9-50.1 Hz with same phase noise power as for 15e, (i.e. a=30 times the measured 50 Hz amplitude). Figs. 15c-f show that the 50 Hz line alone causes most of the effect.

In fact, when increasing the amplitude of the phase noise lines, the situation changes rapidly. Fig. 15 shows the J-histogram for lines magnified by factors 3 (a), 10 (b) and 30 (c). A factor 3 appears still tolerable but a factor 10 cleans part of the bunch centre and for a factor 30 the bunch centre is 'blown away' completely. 'Switching off' the 50 Hz line only (15d) or using such a line (15e) or band around 50 Hz (15f) exclusively shows that most of the damage is done by this line alone.

Therefore the crossing of the 50 Hz line on the ramp is, despite the short time, much more damaging than an 8 h coast under standard conditions.

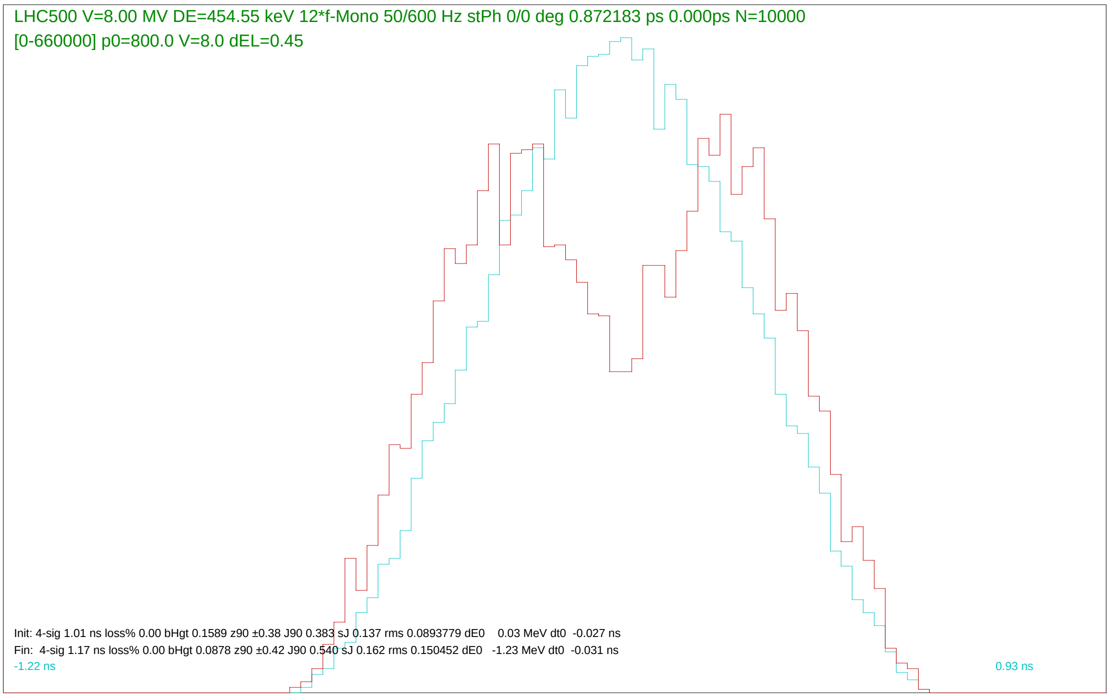

Fig. 16a: z-projection of the bunch of Fig. 15c for a=30 times (30 dB) magnified line amplitudes.

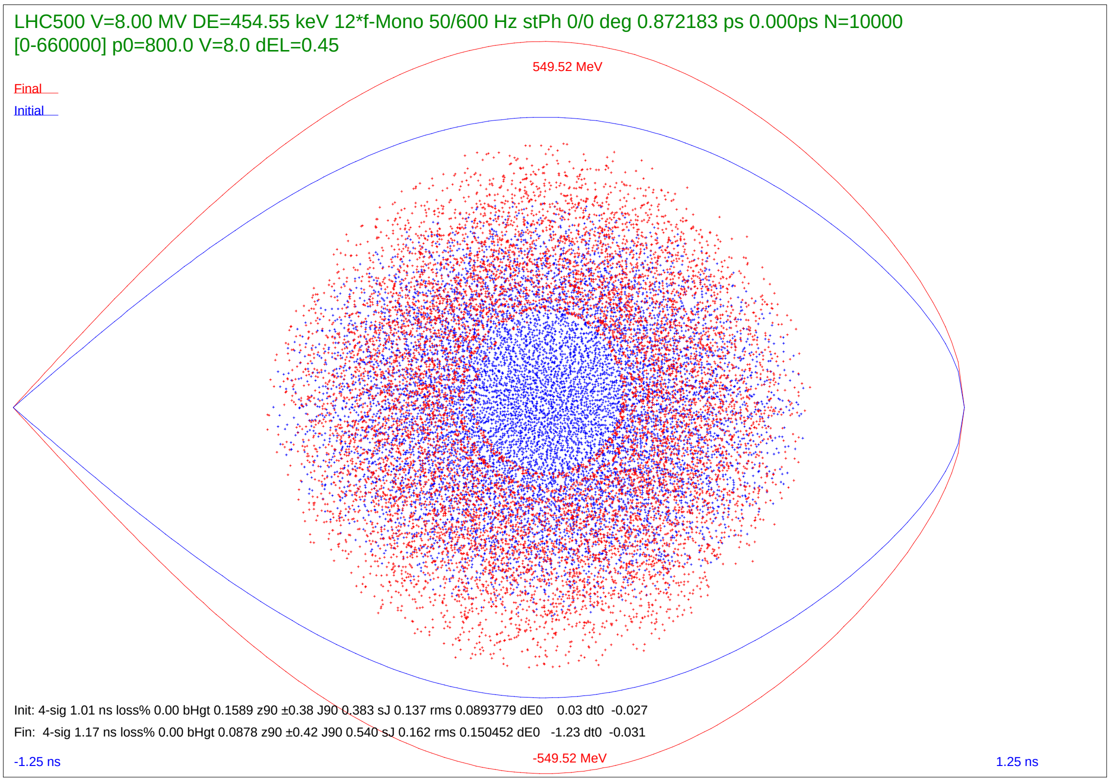

Fig. 16b: Phase space image: bunch of Fig. 15c and 16a (a=30 times magnified line amplitudes) in accelerating bucket at 500 and at 800 GeV/c with constant 8 MV RF voltage. As to be expected from Fig. 15c and 16a, the bunch centre is 'blown away'

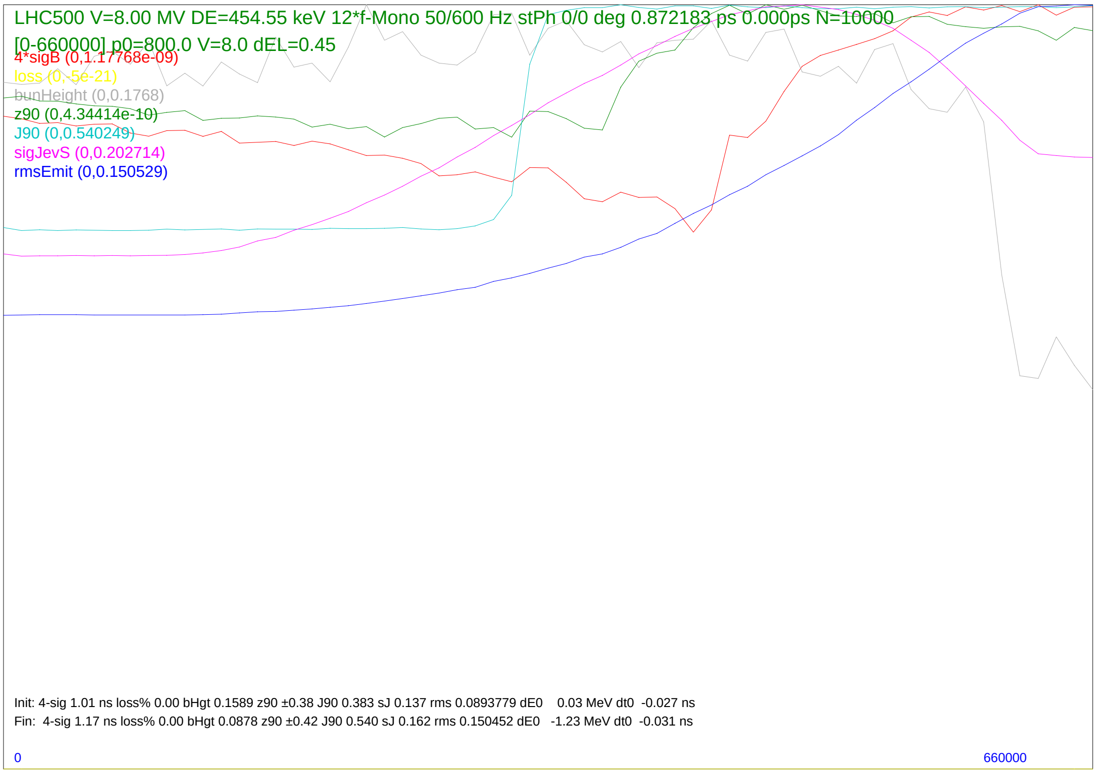

Fig. 16c: Time development of global bunch quantities (for <u>a=30 times (30 dB) magnified line amplitudes</u>) during the 50 Hz frequency crossing (60 s, 66000 turns) for the bunch of Fig. 16a,b and 15c. In the initial period no blow-up takes place – the frequencies do not yet match close to 500 GeV/c. Once blow-up starts, σ_J (magenta) grows about linearly but drops in the last part again while ε_{rms} (dark blue) rises about parabolically. J_{90} (cyan) – the emittance-area containing 90% of the bunch population, makes a sudden jump – probably particles were projected to the outer part of the bucket at that 'instant', $4\sigma_B$ (red) and z_{90} (dark green) – the bunch-length containing 90% of the bunch population – show a similar but delayed behaviour. In the very last period (close to 800 GeV/c) the blow-up has stopped again – all particles have passed the dangerous frequency region.

There is no way around the fact that during the energy ramp particles at some time have to cross the 50 Hz line. We want to examine if even for increased phase noise amplitudes with a=30 (+30dB) the crossing can be achieved without real damage to the bunch. It was tried[3] to first increase the RF voltage at the beginning of the ramp to such a value, that the synchrotron frequency band of the bunch still remains above 50 Hz at 800 GeV/c, hence during this part of the energy ramp no crossing takes place. The latter can then be done in lowering the voltage relatively rapidly – we tried within 1 s – to 8 MV again – with the entire populated synchrotron frequency band then below 50 Hz – so that during this short moment there is not too much damage of the bunch shape. In fact this is possible as shown in Figs. 17 to 21. One sees that the first voltage ramp and the energy ramp to 800 GeV/c does not change the emittance, but there is still a small tail (spiral arm in phase space) created during the 1 s of 50 Hz crossing.

[3] Proposed by Trevor Linnecar

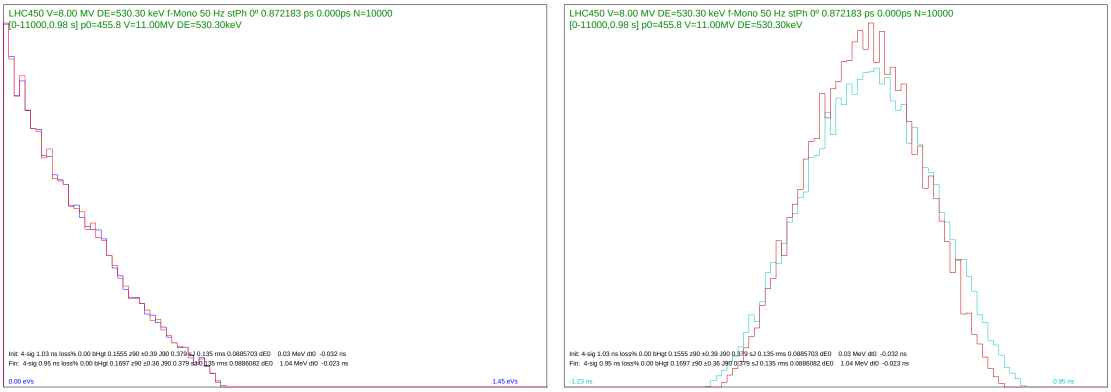

Fig. 17a,b: J-Histogram (a) and z-histogram (b) after voltage ramp-up from 8 MV to 11 MV within one second (E rises from 450 GeV/v to 455.8 GeV during this time) for 10^4 macro-particles).

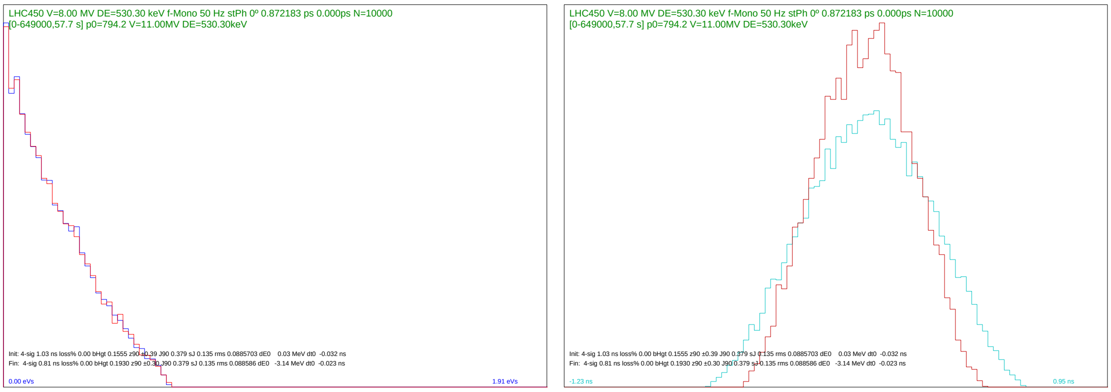

Fig. 18a,b: J-Histogram (a) and z-histogram (b) after voltage ramp-up (8 MV to 11 MV) within one second and E rise to 800 GeV/c (exactly 794.2 GeV/c) in 1+58 seconds

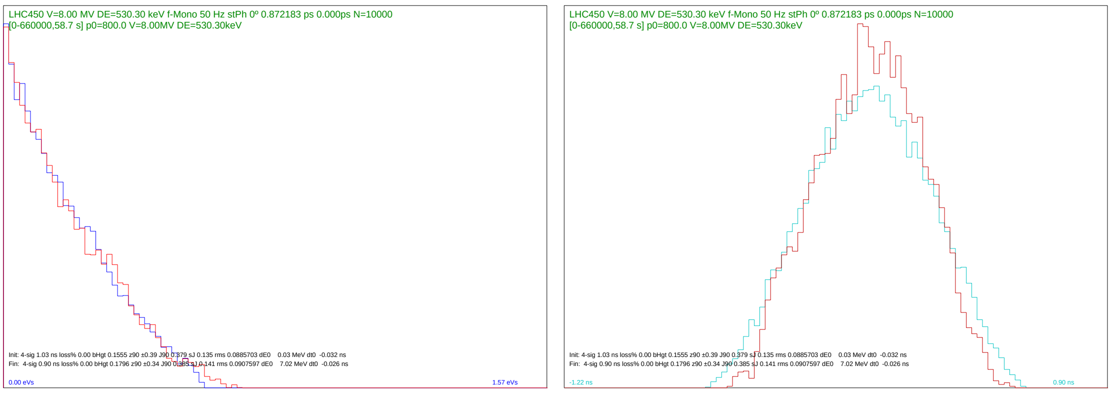

Fig. 19a,b: J-Histogram (a) and z-histogram (b) after voltage ramp-up, E rise to 800 GeV/c and voltage ramp-down (11 to 8 MV, within 1 s) while crossing the 50 Hz line. A small tail appears.

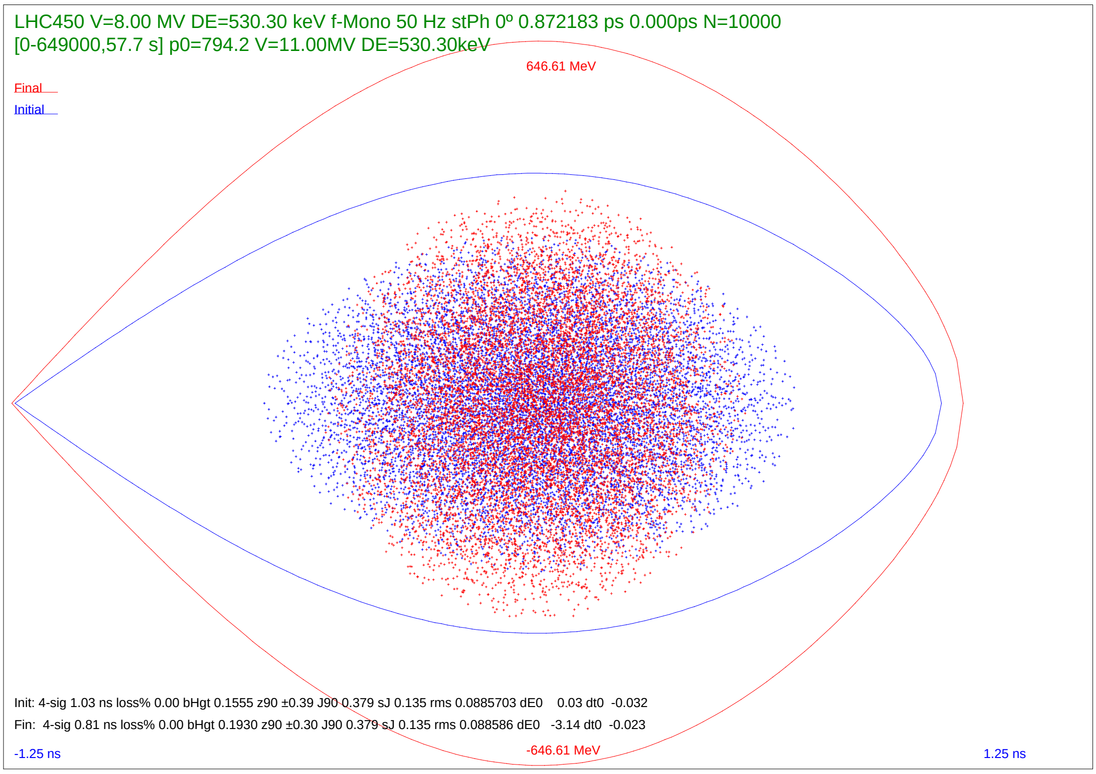

Fig. 20: phase space of the bunch at 800 GeV/c in the state as in Fig. 18, <u>just *before* voltage ramp-down</u> from 11 to 8 MV <u>causing the 50 Hz line crossing</u> (10^4 macro-particles).

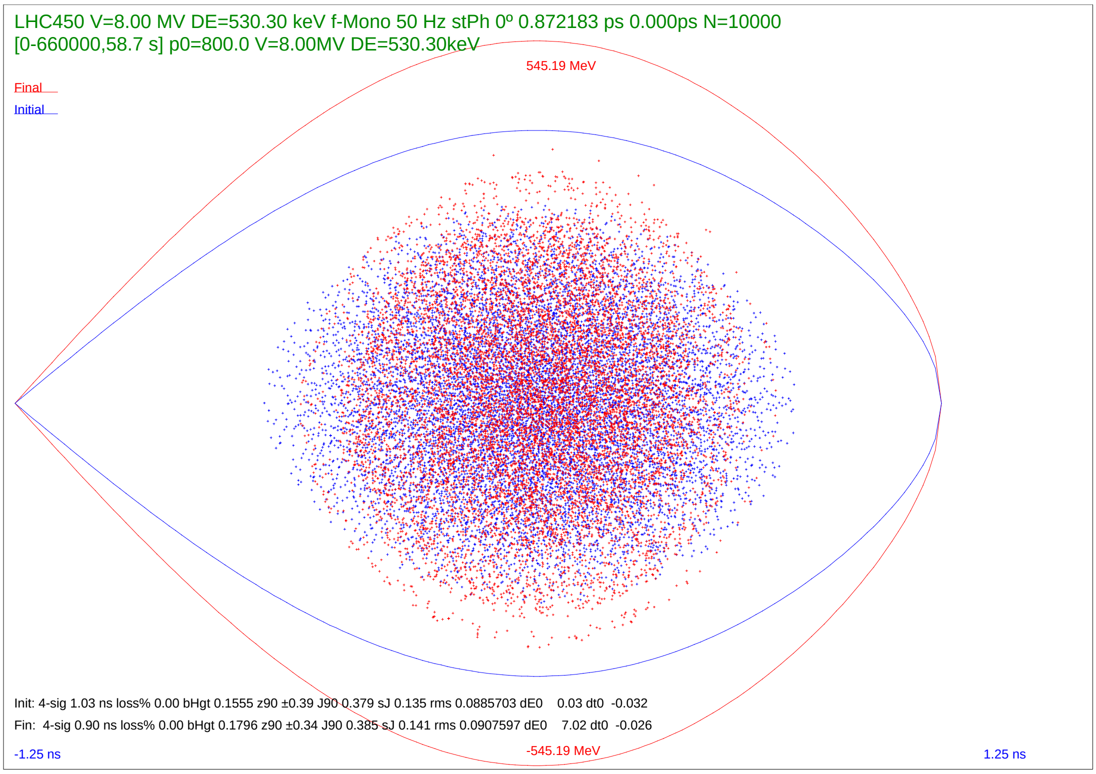

Fig. 21: phase space of the bunch in the ‘final’ state as in Fig. 19 <u>*after* 50 Hz line crossing</u>. One sees the ‘spiral arm’ that was not present before the crossing

5. Coast at 450 GeV/c

In an initial phase (non-physics) coasts at 450 GeV/c are planned with 8 MV RF voltage per beam. Therefore we have also run simulations under these conditions. As for the 7 TeV/c coast the 50-Hz-line multiples do not hit the populated synchrotron frequency band and there is no significant effect to be observed. Then we have also applied the same white phase noise as for the 7TeV/c case (1 ps rms). This noise alone blows up the bunch at 450 GeV/c so that after about 1 h coast more than negligible particle losses occur (0.1 %); this provides an estimate for the maximum tolerable phase noise at 450 GeV/c.

Adding the with a=30 magnified 50-Hz-multiple lines does not add any significant effect on the bunch either, but losses start somewhat earlier and reach about 1 % after 1 h. Fig. 22a,b to 25a,b show the both cases in parallel.

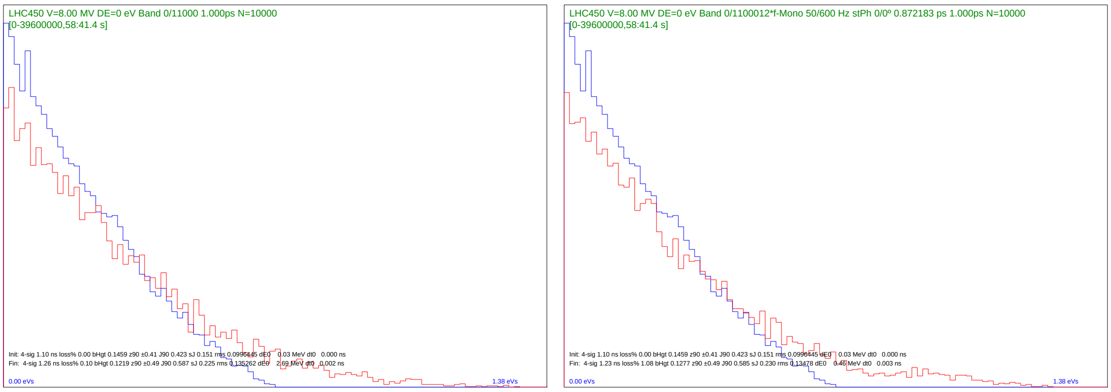

Fig. 22a,b: J distribution for a 450 GeV coast during 1 h; (a) with only 1 ps rms phase noise, (b) additional 50-Hz-multiplelines with <u>a=30 times (30 dB) magnified line amplitudes</u> (10^4 macro-particles)

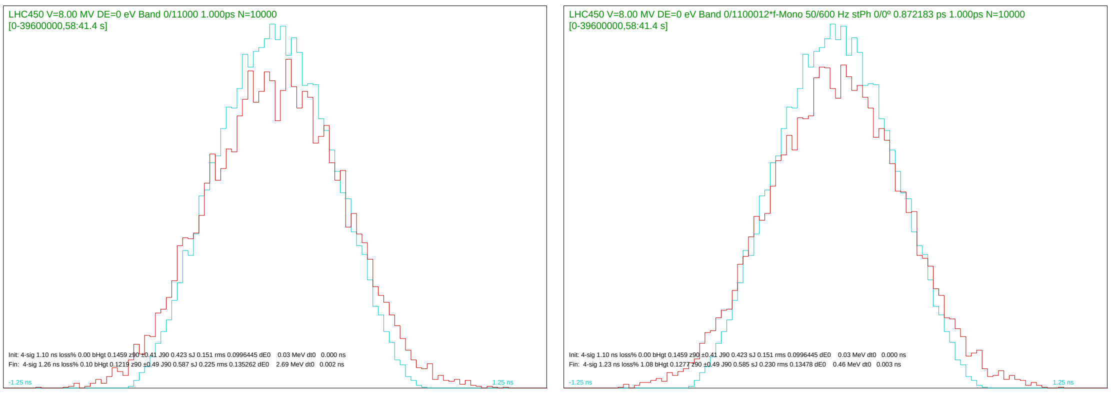

Fig. 23a,b: z distribution for a 450 GeV coast during 1 h; (a) with only 1 ps rms phase noise, (b) additional 50-Hz-multiple lines with <u>a=30 times (30 dB) magnified line amplitudes</u>

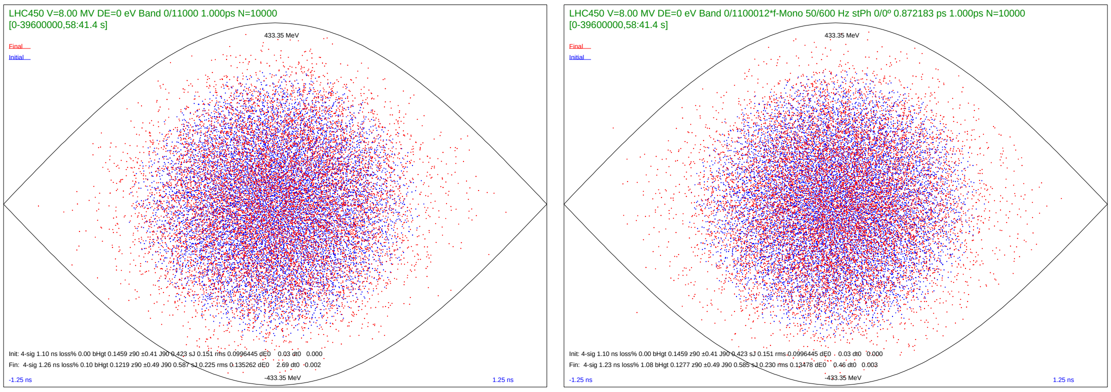

Fig. 24a,b: Phase space distribution for a 450 GeV coast during 1 h; (a) with only 1 ps rms phase noise, (b) additional 50-Hz-multiple lines with <u>a=30 times (30 dB) magnified line amplitudes</u>

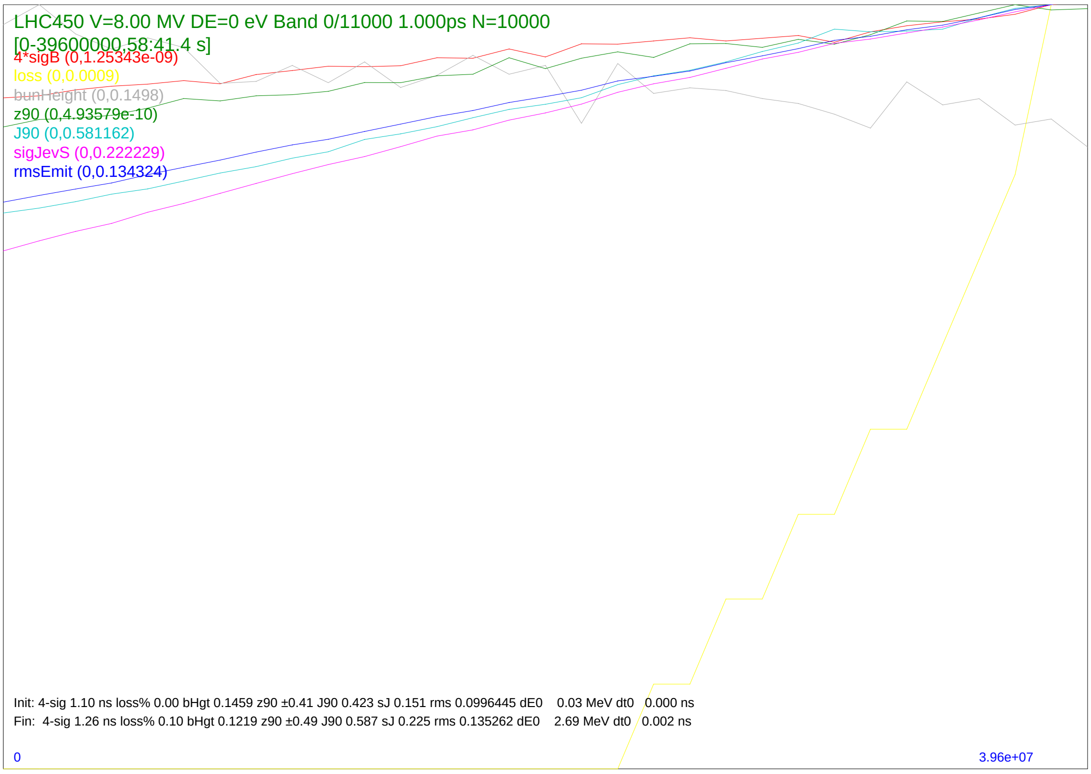

Fig. 25a: Time (turn number) development of bunch quantities for a 450 GeV coast during 1 h with only 1 ps rms phase noise (10^4 macro-particles)

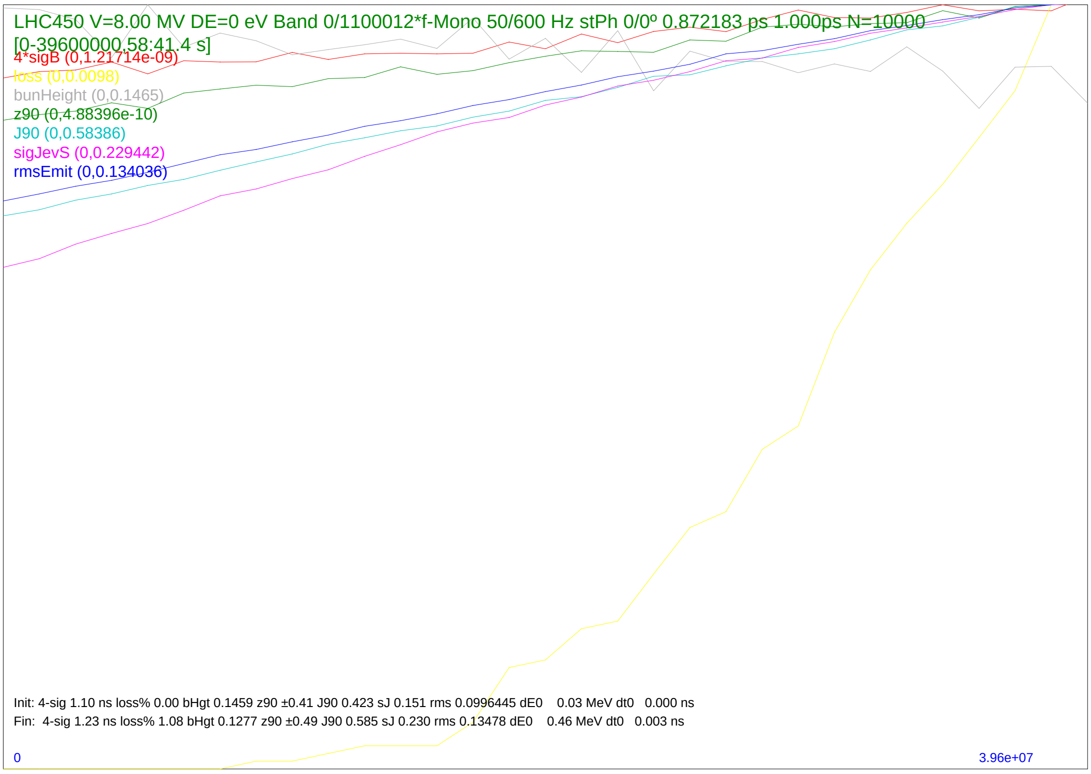

Fig. 25b: Time (turn number) development of bunch quantities for a 450 GeV coast during 1 h with 1 ps rms phase noise and 50-Hz-multiple lines with a=30 times (30 dB) magnified line amplitudes (10^4 macro-particles)

6. Conclusions

The effect of 50-Hz-multiple coherent phase noise lines – as measured in a test stand – was studied by simulation for LHC, neglecting intra beam scattering, synchrotron radiation damping and broad band noise. The latter was also measured but found so low that the effect of synchrotron radiation will overpower it at 7 TeV/c.

It could be shown that even a 30 times increased amplitude of all lines (+30dB) causes only an effect in the order of 10^{-3} for an 8 hour coast under the conditions as planned for the nominal coast.

For an assumed amplitude modulation (which was not measured) of 200 kV on 20 MV (i.e. m=1%) with a synchrotron frequency band around 50 Hz – i.e. conditions slightly modified with respect to the nominal ones – the bunch is blown up in rms emittance by about 3% by a single 50 Hz line (the higher lines do little as demonstrated above). A noise band of 0.2 Hz width (49.9 – 50.1 Hz) with the same noise power gives an 8% blow-up. Since a modulation index of 1% is huge and should never be reached, there seems to be no danger for real conditions

The most dangerous case is the crossing of the 50 Hz line during the ramp for about 1 minute. For the lines as measured, an rms emittance increase of up to 0.2% (part might be attributed to perturbation by the energy ramping) is expected, but for a=3 times magnified line amplitudes (+10 dB) already 4%, for a=10 (+20 dB) about 27% with a bunch centre reduced in population and for a=30 (+30 dB) the bunch centre is cleaned out completely. For the same case a=30 but without the 50 Hz line (‘switched off’) but leaving the other 50 Hz multiples the bunch centre is not affected at all and the bunch is blown up about homogeneously in rms emittance by only 15%. Furthermore with a=30 for the 50 Hz line exclusively or a very narrow noise band around 50 Hz exclusively the bunch centre is cleaned, i.e. the 50 Hz line alone does most of the damage. However, by a slightly more elaborate ramping scheme the 50 Hz line can be crossed by (relatively fast) voltage ramping exclusively, causing much less damage. This method is then the fallback solution in case of much more phase noise in the tunnel as compared to the measurement in the test stand.

Under injection condition (450 GeV/c and 8 MV RF voltage) the 50-Hz-multiple lines do little harm but a phase noise of 1 ps rms – which would compensate synchrotron radiation damping at 7 TeV/c – leads to blow-up and losses after about 1 h of 'coast', with or without additional 50 Hz contributions.

In general it can be said that if the 50-Hz-multiples are not an order of magnitude larger in the final installation, there should be no problem concerning bunch blow-up or deformation.

References

[1] Ph. Baudreghien and J. Molendijk, priv. comm.

[2] J. Tückmantel, "NoisySynchro, a Simulation Program for bunches in a synchrotron with RF noise", unpublished

[3] J. Tückmantel, "Synchrotron radiation damping and longitudinal bunch shape", CERN-LHC Project Note 819, 2005

Appendix: Program Checks

To demonstrate that the simulation program has a numerical 'clutter' largely below the observed effects and hence does not create the observed effects, three cases were examined and the initial and final J-histograms are displayed. We considered

• A coast of 8 hours at 450 GeV/c without any RF noise (practically a single *50 Hz line with zero-amplitude*) nor energy/voltage ramp.

• A coast of 8 hours at 7 TeV/c without any RF noise nor energy/voltage ramp.

• A ramp from 450 GeV/c and 8 MV RF voltage in an accelerating bucket to 7 TeV/c and 16 MV RF voltage without any RF noise; the only perturbation is the non-adiabaticity of the ramping of energy and voltage due to *finite* acceleration speed.

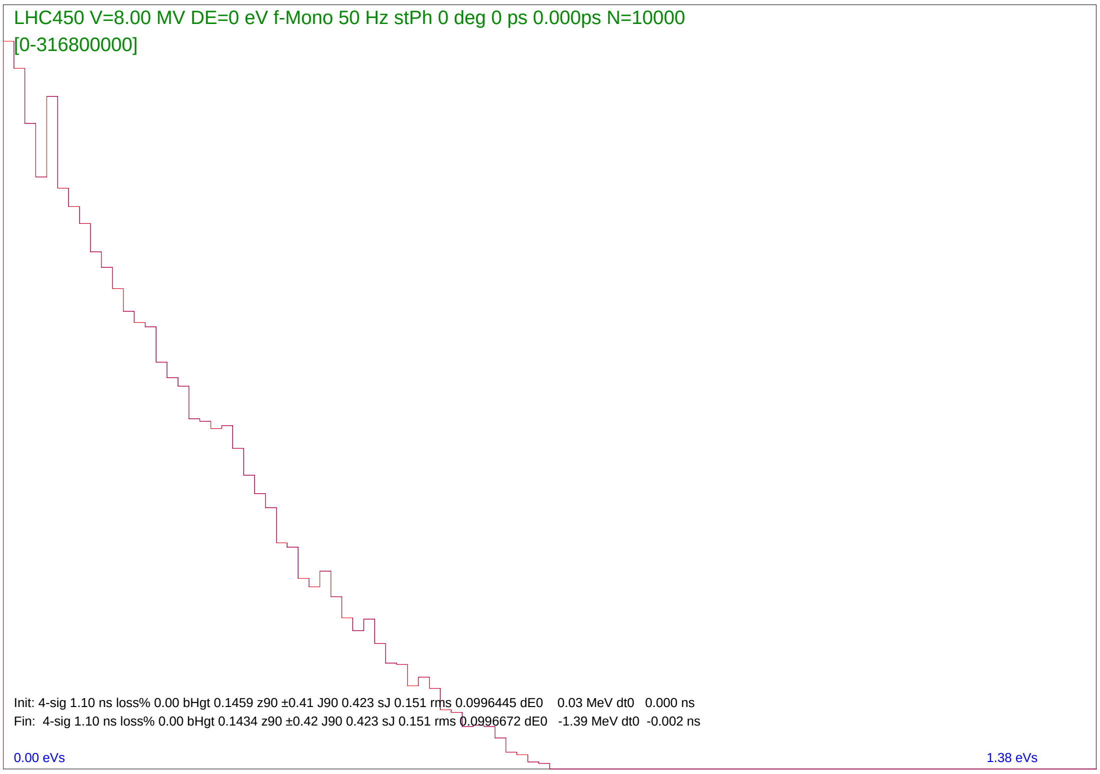

Fig A1: Initial (blue) and final (red) J-histogram (100 bins) for an 8 hours coast at 450 GeV/c (ε_0=0.7 eVs and 10^4 macro-particles) with no perturbations at all. The red line (drawn later) covers the blue one perfectly, i.e. J is conserved numerically with high precision.

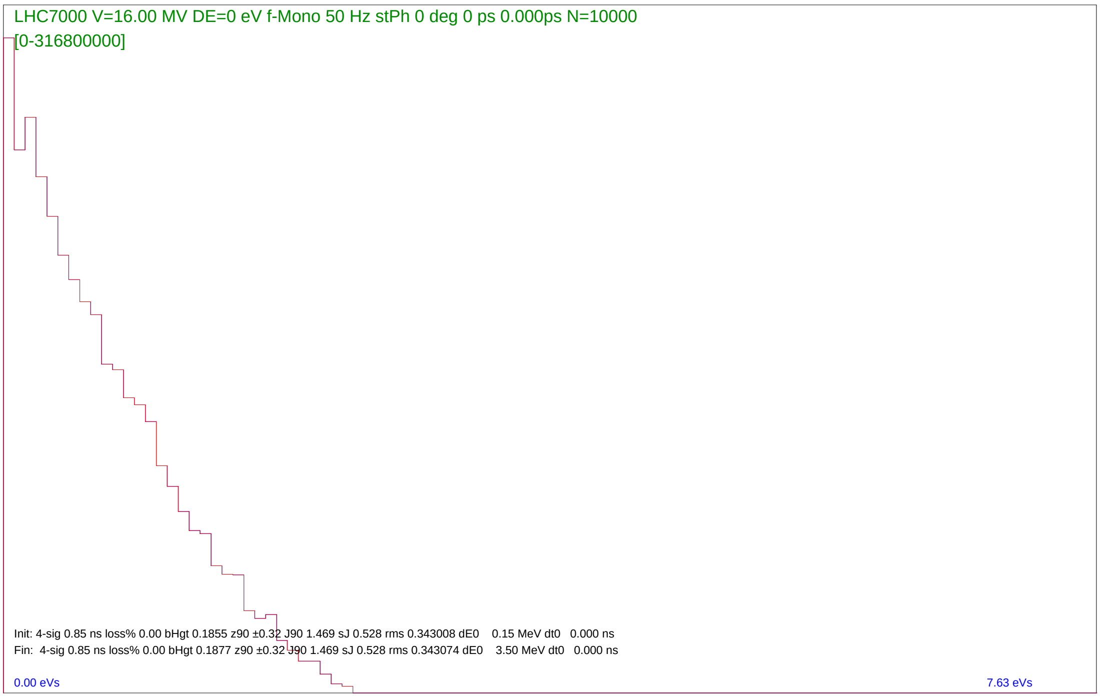

Fig. A2: Initial (blue) and final (red) J-histogram (100 bins) for an 8 hours coast at 7 TeV/c (ε_0=2.5 eVs and 10^4 macro-particles) with no perturbations at all. The blue line (drawn first) is graphically covered by the red one perfectly, i.e. J is conserved numerically with high precision.

Fig. A3a: Initial (blue) and final (red) J-histogram (1000 bins) for a 20-minute ramp from 450 GeV/c with 8 MV RF voltage to 7 TeV/c with 16 MV RF voltage (ε_0=0.7 eVs and 10^4 macro-particles) in an accelerating bucket with no RF noise. In theory only non-adiabaticity due to the finite speed of the ramp can change the bunch. The blue line (drawn first) is graphically covered by the red one perfectly, i.e. also during the energy and voltage ramp the distribution in J is conserved numerically with high precision.

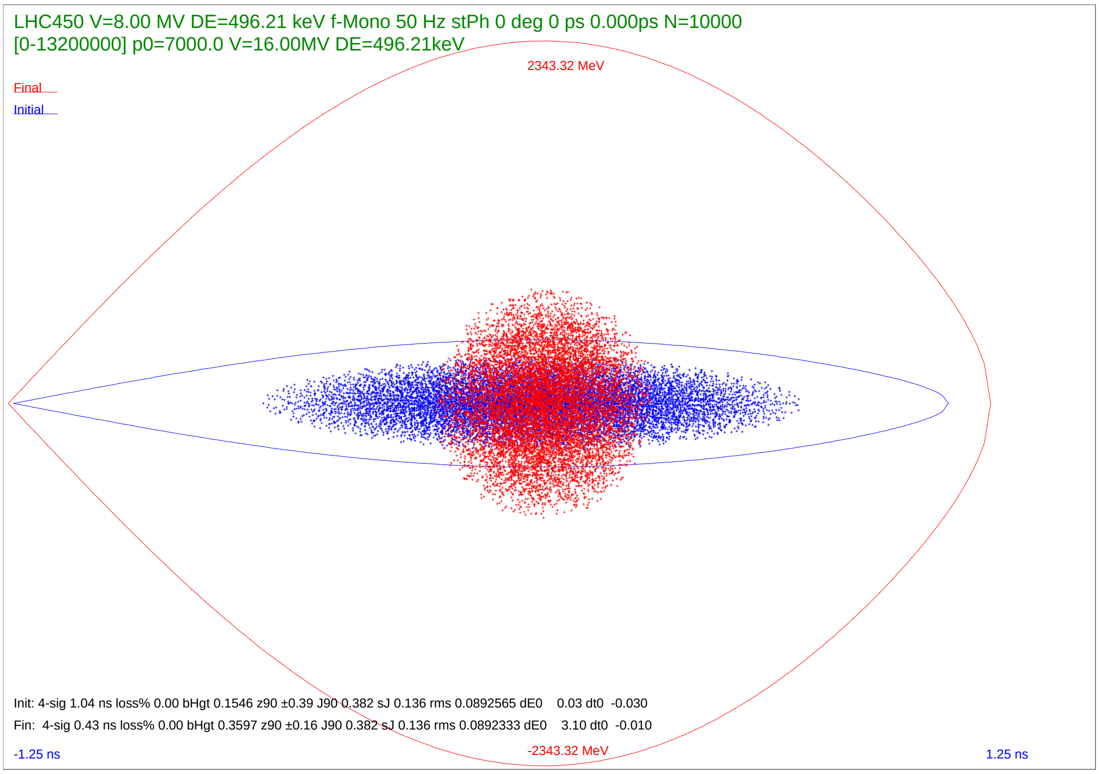

Fig. A3b: Phase space plot of the bunch of Fig. A3a (initial 450 GeV/c and final 7 TeV/c states in the same phase space scale).