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Longitudinal emittance blow-up and hollow bunches with arbitrarily shaped noise in the SPS as LHC test-bed

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Summary

In the SPS the LHC type high intensity beam can be kept stable longitudinally during acceleration to 450 GeV/c by using the 800 MHz higher harmonic system and, in addition, by making a longitudinal controlled emittance increase by a factor of about 1.5. This latter is obtained by applying band-limited RF phase noise via the main RF system. In LHC itself, which does not have a higher harmonic system, an emittance increase by a factor 2.5 is required. This was attempted in the SPS, as a test-bed for LHC, with *shaped* RF phase noise and with the 800 MHz system switched off - limiting the maximum stable beam intensity. The emittance of a single (LHC-) pilot bunch has been blown up to a factor 2.5 in coast at 270 GeV/c with a final ‘good’ bunch shape. It remains to be demonstrated that this technique can also be applied successfully for many high intensity bunches with differing synchrotron frequency profiles along the batches. Also a first very quick test to create hollow bunches was done.

1. Introduction

The longitudinal emittance of the beam to be injected from the SPS into the LHC is limited to about 1 eVs to minimise losses during the capture process at 450 GeV/c in the LHC; the available RF voltage is 8 MV at 400 MHz. On the other hand intra-beam scattering during the LHC coast at 7 TeV/c imposes, for nominal intensity, a longitudinal emittance of about 2.5 eVs. Therefore the longitudinal emittance has to be blown up in the LHC itself between injection and coast. Since there is – at least in the present stage – no higher harmonic system in LHC, the blow-up has to be done using only the main RF system.

In numerical simulations a method to do this by particle phase space diffusion created by shaped RF phase noise was found [1] and needed to be verified in the SPS as LHC test-bed. During an SPS coast at 270 GeV/c it was possible to increase the emittance by the desired ratio for a single low intensity (pilot) bunch with, finally, an acceptable parabolic longitudinal bunch shape. Higher beam currents were not possible for this test since without the 800 MHz system the beam is unstable in the SPS.

A second subject was the creation of ‘hollow’ bunches, an option for the future LHC upgrade. It can be theoretically shown that these cannot be produced from ‘standard’ bunches by slow diffusion with any shape of RF noise. However in simulations this could be achieved with a ‘rapid’ excitation using monochromatic phase modulation with a smoothly sliding modulation frequency. During the MD this smooth sliding was approximated by a sequence of frequency steps of 1 Hz. On the sampling scope the (pilot) bunch then appeared somewhat depopulated in the centre of the bunch but due to lack of MD time in coast only one cycle could be recorded. Therefore this test has to be repeated with modified hardware with parameters optimized first for a single low intensity bunch and then for a batch of high intensity bunches.

2. Special hardware

2.1 Shaped noise production and application

In previous MDs [2] we used as the basic noise source the output of one of the low-frequency signal analyzers (HP 3582A, 0-25 kHz); this produces (nominally) band-limited noise designed for transfer function measurements over a given frequency range. We used this analyser to produce noise starting at

0 Hz and with upper frequency given by the available coarse 'bandwidth' settings of 2.5, 5 and 10 Hz. The noise spectrum showed relatively large tails above this upper frequency limit. This noise signal was fed into one input of a fast analogue multiplier, the second entry being driven by a monochromatic 'carrier' frequency. The multiplier output was then a signal with a noise spectrum centred around the carrier frequency with the initial noise spectrum above and its mirror image below. The output spectrum therefore had twice the initial nominal width with tails now appearing beyond both nominal frequency limits.

Meanwhile in the framework of a longitudinal beam dynamics simulation program [3] a special numerical noise generator had been developed simulating either RF noise of natural origin or noise to be injected intentionally into the RF system for controlled blow-up in synchrotrons or colliders. This generator allows the production of time domain data strings of (practically) infinite non-periodic length having any arbitrary (but constant) noise spectrum. Evidently, the data have to be played back at a rate much faster than the typical noise frequencies to 'hide' the granularity; in the simulation intrinsically one data point per machine turn is used (i.e. about 43 kHz for the SPS, 11 kHz for the LHC). In our application in the SPS the playback clock rate was chosen to be 10 kHz for noise within 100 Hz to 300 Hz, allowing a playback period of 6 s for 64,000 data values (see below).

The noise generator *in the simulation program* does not use the built-in normalized – i.e. equal distribution in [0,1] – random generator[1] but relies on a specially designed generator having excellent long-term statistical properties [4]. Such a special design does not seem to be necessary for the relatively few data points needed here and so for simplicity we used the built-in generator coming with the PC operating system.

Once the noise data string is produced it is reformatted as required and uploaded into an arbitrary waveform generator (AWG). We used an 'Agilent 33250A' waveform generator with a capacity of 64'000 data points. The AWG then plays the noise back either as a (triggered) single burst or with infinite repetition. With respect to other noise creation methods there is the advantage that the (triggered) noise output is always identical from shot to shot (as stored in the AWG) and measurements have statistically one scattering parameter less. This is also roughly the case for a free-running cyclic operation with a large number of repetitions of the same data string – as we have applied.

The same random seed is always used on purpose for this application[2]. Then noise spectra with the same parameters created at different times are absolutely identical and a 'good case' can easily be reconstructed later.

Based on the development for the simulation program a stand-alone noise generator (written in C++) was realized[3] running on any standard PC. The program kernel can produce any arbitrary noise spectrum but, for practical reasons, the spectra to be produced were restricted to a trapezoidal shape, allowing enough freedom of (reasonable) choice together with an easy way to define the spectrum using four parameters: the lower and upper frequency limit and the lower and upper linear slope in % of the total range (Fig. 1a). To create a smooth noise switch-on and switch-off, a trapezoidal amplitude envelope function is also applied, defined by the total noise excitation time – limited to 6 s for this AWG with the chosen clock rate of 10 kHz – and the (linear) rise and fall times (Fig. 1b). The absolute noise output amplitude was set manually on the AWG as required.

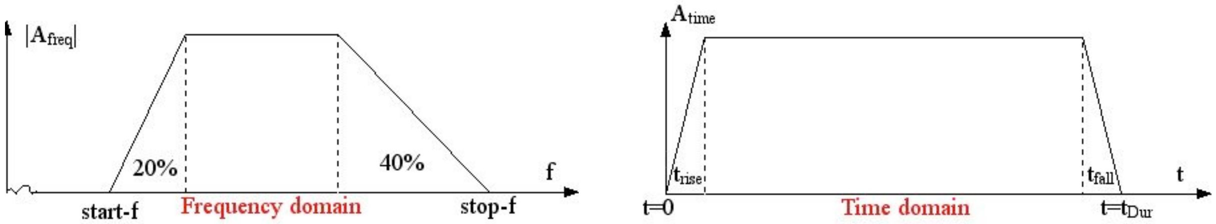

Fig. 1a, b: Trapezoidal definition of (a) the spectral (amplitude, not power) distribution in frequency domain and (b) the time-domain envelope, ramping up and down at start and end of the burst.

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[1] The random generators delivered with PC operating systems are good for 'small' data samples as for programming games but details are generally not published and one is not sure about their statistical long-term behavior - e.g. the LHC bunches do about 10^9 turns per 24h coast.

[2] In the simulation the random seed can be chosen either fixed (necessary e.g. for debugging) or provided by the internal clock, hence different even for otherwise identical parameters, to allow an estimation of the statistical scatter.

[3] Meanwhile this package has been upgraded [5], delivering also noise with time-variable spectra, capable of following synchrotron frequency shifts and changing frequency spreads. This option did not yet exist at the time of the MD described here.

A user-friendly interface was written in LabView™ to input all the above-mentioned parameters via a graphical user interface. On 'run' it executes the stand-alone noise generator program and loads up the created noise data string into the AWG over a GPIB (a standard data bus mainly for instruments). For a cycling SPS an external beam-related trigger could then launch the playback; for the present MD with coasting beam we used the periodic free running mode, set manually on the AWG. A change of spectrum took about 2 minutes in total, main contributors being the operator's working time and the GPIB loading. It is thought – also for LHC – to use a unique platform (e.g. VME with **D**igital-**A**nalogue **C**onverter) on which data are calculated and played-back in time-sharing, avoiding slow data transfer over an external bus and the need for an (expensive) AWG.

The periodicity of 6 s for the periodic free running case is not harmful in the present application. For our test, following simulations, we needed a triangular noise spectrum with the peak intensity at the high frequency end (targeting the bunch centre's synchrotron frequency), zero at low frequency (outer parts of the bunch). Such a triangular spectrum can be created as a degenerate trapezium with 100% lower end rise length and 0% upper end fall length – hence with a zero flattop. A typical triangular spectrum for a range from 195 Hz–225 Hz is shown in Fig. 3 as it was received from the analogue output of the AWG and measured on the low frequency signal analyzer (HP 3562A).

To avoid discontinuous transitions, the amplitude was ramped up and down during 0.1 s at each start and end of the AWG playback period of 6 s, leaving 5.8 s with full amplitude. This cycle was automatically (programmed into the AWG) repeated periodically every 6.1 s leaving the AWG 0.1 s for its internal functioning. The output is then very close to a continuous noise excitation with triangular spectrum.

The AWG output was fed into a linear gate (SPS 6000) to switch the noise on and off at precise times during the cycle (when in coast this was done manually). The linear gate output was connected via a 12 dB attenuator to the 'aux' entry of the RF phase loop amplifier (SPS 10289) producing the desired phase modulation of the 200 MHz main RF system.

During the MD the only parameters adjusted were the noise amplitude and the lower and upper frequencies, the other parameters were kept constant.

2.2 'Smoothly' moving monochromatic line

A monochromatic line was used to create hollow bunches, this seeming to be from simulations a possible method. We have approximated the required linear frequency sweep by using the SPS frequency synthesizer with the minimum available frequency step size of 1 Hz (SPS 6111) in local (manual) mode. A shift range of 6 Hz to 8 Hz was covered with a (manual) change of 1 Hz every 3 s, which approximately corresponds to the slope found most efficient in the simulations.

As with the previous tests, the signal passed via a linear gate and a 12 dB attenuator into the 'aux' entry of the phase loop amplifier. The noise was switched on manually during the coast, its frequencies decreased by 1 Hz about every 3 s and switched off again having completed the intended frequency sweep.

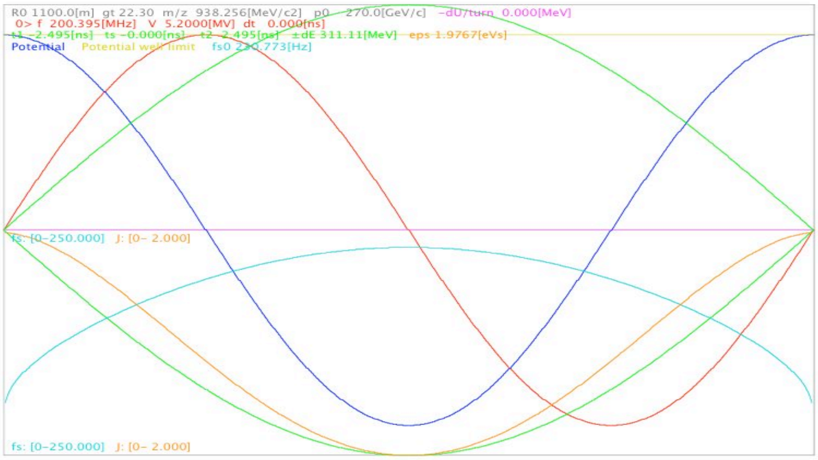


Fig. 2: Synchrotron frequencies in the SPS bucket at 270 GeV/c coast (cyan 0-250 Hz) with 5.2 MV RF voltage (red) at 200 MHz (800 MHz off). Bucket limit (green), J (orange 0 – 2 eVs), 'potential well' (blue)

3. Machine and Beam Conditions

A special cycle (LHCMD25.92-55-270_PDOT_V2) was used with injection at 26 GeV/c, a first ramp to an intermediate plateau at 37 GeV/c followed by a ramp to 270 GeV/c. During preparation the beam was dumped on a plateau at 270 GeV/c before the magnets cycled up to 450 GeV/c and then down to injection energy again. When required, the plateau at 270 GeV/c was kept for coast as long as desired.

The main RF voltage at 200 MHz was programmed to 5.2 MV during the coast; the 800 MHz higher harmonic system was switched off during the RF noise tests.

To be independent of intensity effects, only a single low intensity (LHC pilot) bunch with about $5\cdot10^9$ p was injected and coasted.

4. The measurements

Two types of measurements were done for the RF noise part of the MD using the wall current monitor AEW.317. The first, not recorded but observed in real time, was with the fast sampling scope which shows the longitudinal bunch profile during the blow-up in real-time, hence rapidly guiding the definition of the sequence of operations. The second was acquisition of the bunch profiles by a mountain range scope (Tektronix TDS 7254B), the (immediate) results being stored on disk. About 1500 traces were taken spaced at 0.1 s intervals (files MR112-MR116) and for the long-time blow-up (files MR117-MR118) 6000 traces with 0.2 s spacing, corresponding to 20 minutes acquisition, equivalent to the probable LHC ramp duration.

Since the higher priority was on the study of emittance blow-up for LHC, this was tried first. The results are summarized in Table 1.

The noise was set up with a range from 195 Hz to 220 Hz, this being the estimated optimum for 5 MV RF voltage on the 200 MHz system at 270 GeV/c. After data-loading, with the AWG showing an amplitude of 195 mV_{pp}, the bunch was blown up significantly but its longitudinal profile was 'rectangular' as if the bunch centre was not excited (MR 112, not displayed).

Empirically we then shifted the spectrum up by 5 Hz still with 195 mV_{pp} on the AWG. The resulting longitudinal bunch profile looked much better on the scope (MR113, Fig. 4). For an RF voltage of 5.2 MV as measured in reality, this is also the theoretically expected optimum range. The blow-up, starting around 11 s, trace 110, is rather fast initially but the rate soon decreases (around 13 s, trace 130). There seems also to be a second decrease in rate (around 50 s, trace 500).

For the next test the previous noise settings were kept but the amplitude was reduced by a factor 3 (58 mV_{pp} on the AWG). The increase in bunch length was steadier (MR 114, Fig. 5). A blow-up over 20 minutes with identical conditions was also done (MR117, Fig. 6). It shows that the bunch length increase consists of a fast, about linear, rise for about 3 minutes which then decreases rather sharply – without any deliberate changes – to a lower, also about linear, rate of rise.

Tab. 1a: Settings for triangular smooth noise

Nr file	Figures	f_{Low} [Hz]	f_{Up} [Hz]	ampl. on AWG [mV_{pp}]	4σ-BL end/end [ns]	4σ-BL ratio
MR113	4 a, b, c	200	225	195	2.33/1.42	1.64
MR114	5 a, b, c	200	225	58	1.82/1.44	1.26
MR117	6 a, b, c	195	225	68	2.33/1.39	1.67
MR118	8			No noise	-	

Tab. 1b: Settings for monochromatic sliding line

Nr file	Figures	Range f_{mono} [Hz]	Change rate	ampl. on synth. [mV]	4σ-BL end/start [ns]	4σ-BL ratio
MR119	7 a, b, c	225 → 217	1 Hz all 3 s	300	2.16/1.41	1.53

The creation of a hollow bunch was tried using a single passage of sliding monochromatic noise of 300 mV amplitude, starting at 225 Hz and sliding down to 217 Hz with a rate of change of 1 Hz/(3 s) (MR119). Fig. 7 shows the development of the bunch length and the initial and final bunch distribution.

A reference measurement without any artificial RF noise was taken (MR118, Fig. 8) and it shows no significant blow-up, hence the observed effects are truly due to the added artificial noise.

5. Conclusions

The observed blow-up corresponds well (for relative noise amplitudes) to the expectations from simulations with triangular noise. The latter excites the bunch centre with the maximum amplitude, falling off towards a pre-defined synchrotron oscillation amplitude within the bunch; the outermost parts of the bucket are not excited at all.

The bunch length could be increased smoothly by a factor of more than 1.6, corresponding to a longitudinal emittance blow-up of 2.5, as is required in LHC between injection and coast.

The excitation frequencies match very well those calculated in the absence of beam loading.

Also the blow-up rate behaves as theoretically expected, proportional to the noise power, hence the *square* of the noise amplitude. With 195 $\mathrm{mV_{pp}}$ (Fig. 4) the bunch length blow-up rate (in the first 30 s) is about 23 ps/s, with 58 $\mathrm{mV_{pp}}$ (Fig. 5) the bunch length blow-up rate (200 s) is about 2.25 ps/s; using the theoretical scaling law one would expect about 2.0 ps/s. With 68 $\mathrm{mV_{pp}}$ (Fig. 6) the bunch length blow-up rate (in the first 150 s) is about 3.3 ps/s; using the theoretical scaling law (with respect to Fig. 4, 195 $\mathrm{mV_{pp}}$) one would expect about 2.8 ps/s.

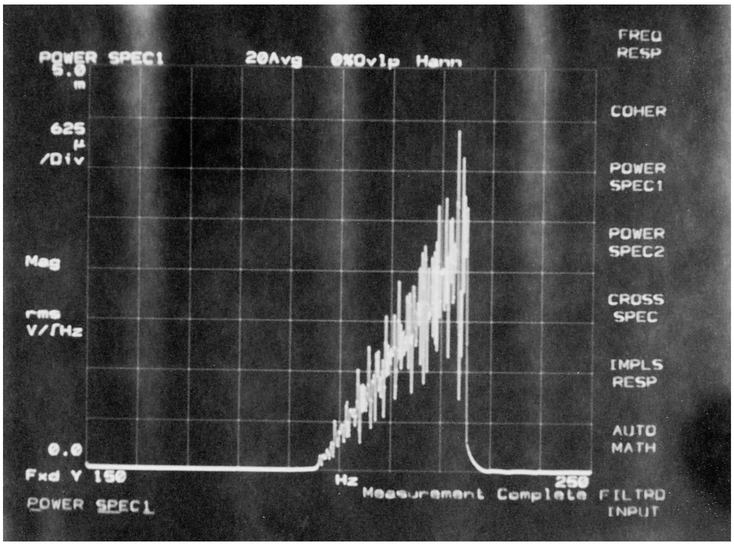
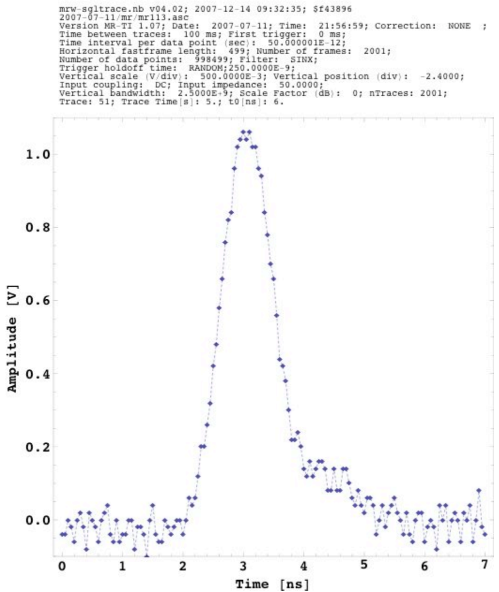


Fig 3: Measured triangular spectrum (linear scale) as received from the arbitrary waveform generator previously loaded with data from the numerical noise generator. The spectrum corresponds exactly to the specifications (triangular 195 Hz–225 Hz, MR117): there is a linear amplitude rise over the nominal range but no tails outside.



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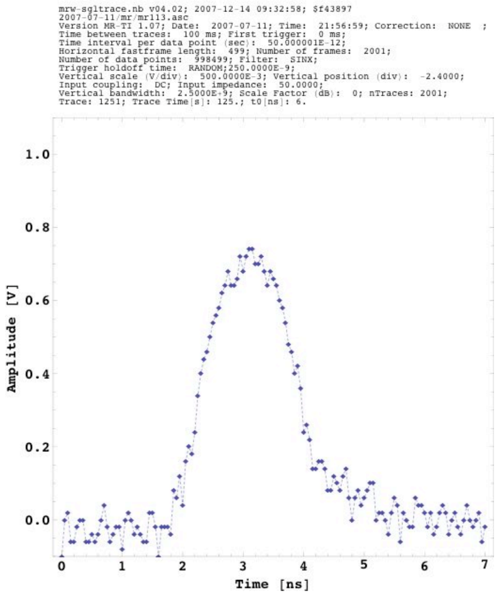
Time between traces:  100 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  2001;
Number of data points:  998499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  500.0000E-3; Vertical position (div):  -2.4000;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 2001;
Trace: 51; Trace Time[s]: 5.; t0[ns]: 6.
```

Fig 4a: MR113: The short bunch after injection, before blow-up (raw data, uncorrected for cable effects). Cable effect corrected 4σ BL = 1.42 ns.



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2007-07-11/mr/mr113.asc
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Time between traces:  100 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  2001;
Number of data points:  998499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  500.0000E-3; Vertical position (div):  -2.4000;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 2001;
Trace: 1251; Trace Time[s]: 125.; t0[ns]: 6.
```
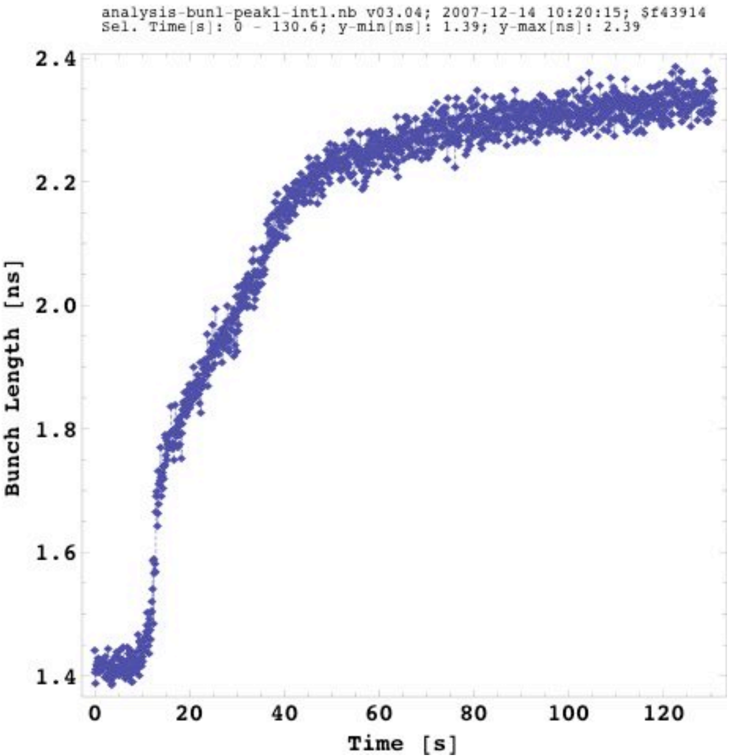
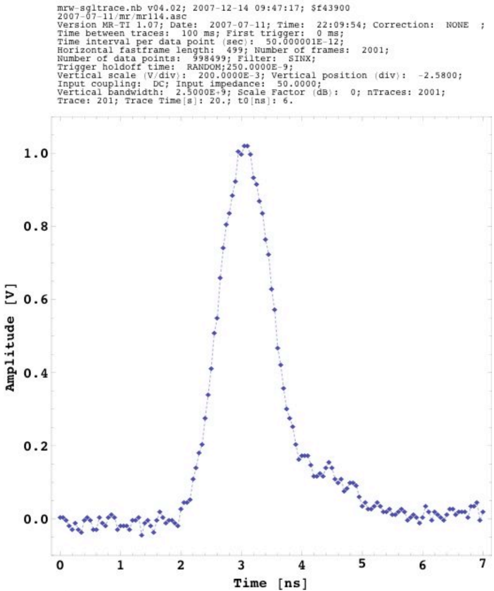

Fig 4b: MR113: After blow-up with noise at the ‘good’ frequency (200 Hz-225 Hz, 195 mV_{pp}), resulting in a parabolic bunch shape on the sampling scope (at 125 s, raw data). Corrected 4σ BL = 2.33 ns.



```
analysis-bunl-peakl-intl.nb v03.04; 2007-12-14 10:20:15; $f43914
Sel. Time[s]: 0 - 130.6; y-min[ns]: 1.39; y-max[ns]: 2.39
```

Fig 4c: MR113: Development of the 4σ Gaussian bunch length during blow-up (200 Hz–225 Hz, 195 mV_{pp}), spacing between traces 0.1 s. The bunch length increase is initially fast but levels off soon.

Blow-up in bunch-length: 150 ps/s in the first 2 s, 15 ps/s up to 30 s, levelling off to about 2.4 ns like an exponential saturation curve



```
mrw-sgltrace.nb v04.02; 2007-12-14 09:47:17; $f43900
2007-07-11/mr/mr114.asc
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Time between traces:  100 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  2001;
Number of data points:  998499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.5800;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 2001;
Trace: 201; Trace Time[s]: 20.; t0[ns]: 6.
```
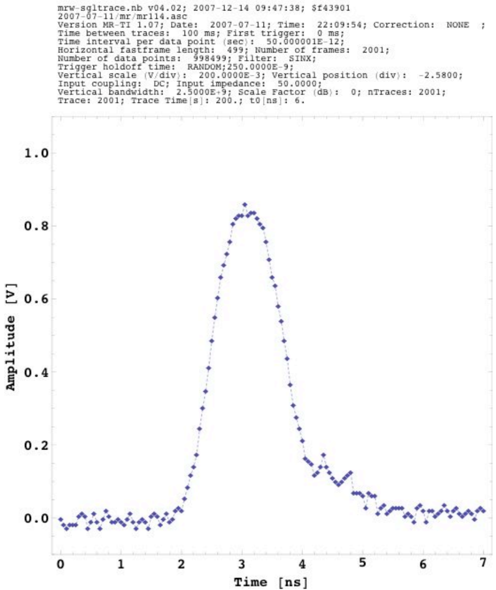

Fig 5a: MR114: The short bunch after injection, before blow-up (raw data). Corrected 4σ BL = 1.44 ns.



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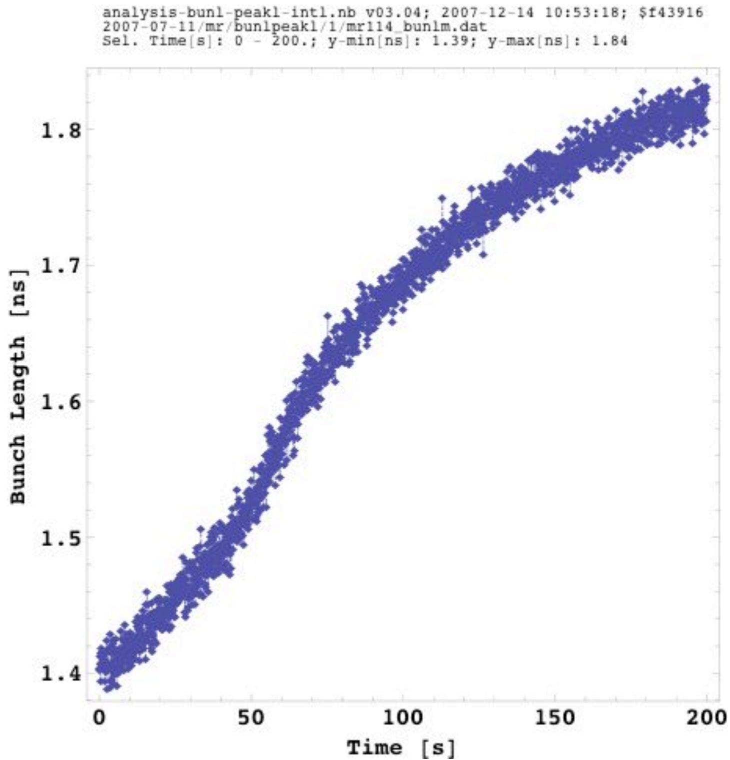
Version MR-TI 1.07; Date:  2007-07-11; Time:  22:09:54; Correction:  NONE  ;
Time between traces:  100 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  2001;
Number of data points:  998499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.5800;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 2001;
Trace: 2001; Trace Time[s]: 200.; t0[ns]: 6.
```

Fig 5b: MR114: After *slow* blow-up with noise at 'correct' frequency 200 Hz-225 Hz, only 58 mV_{pp}, (at 200 s, raw data). Corrected 4σ BL = 1.82 ns.



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2007-07-11/mr/bunlpeakl/1/mr114_bunlm.dat
Sel. Time[s]: 0 - 200.; y-min[ns]: 1.39; y-max[ns]: 1.84
```
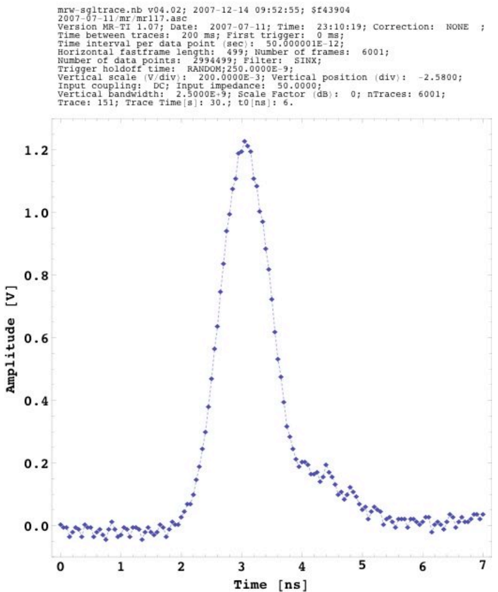

Fig 5c: MR114: Development of the 4σ Gaussian bunch length during blow-up (200 Hz–225 Hz, 58 mV_{pp}), spacing between traces 0.1 s. The bunch-length increase is about linear with 2 ps/s slope.



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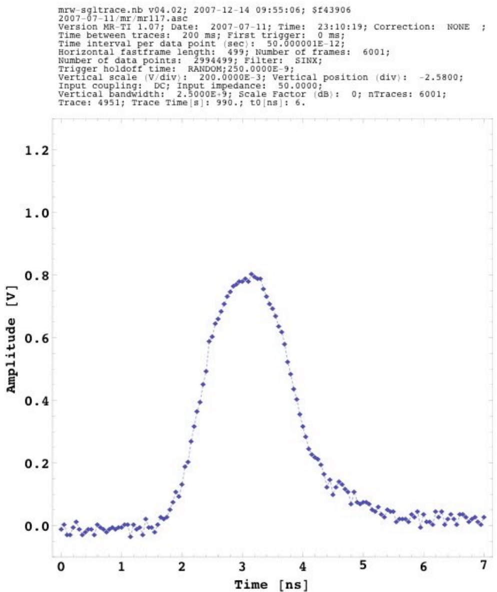
mrw-sgltrace.nb v04.02; 2007-12-14 09:52:55; $f43904
2007-07-11/mr/mr117.asc
Version MR-TI 1.07; Date:  2007-07-11; Time:  23:10:19; Correction:  NONE  ;
Time between traces:  200 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  6001;
Number of data points:  2994499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.5800;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 6001;
Trace: 151; Trace Time[s]: 30.; t0[ns]: 6.
```

Fig 6a: MR117: The short bunch after injection, before blow-up (raw data). Corrected 4σ BL = 1.39 ns.



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Version MR-TI 1.07; Date:  2007-07-11; Time:  23:10:19; Correction:  NONE  ;
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Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  6001;
Number of data points:  2994499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.5800;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 6001;
Trace: 4951; Trace Time[s]: 990.; t0[ns]: 6.
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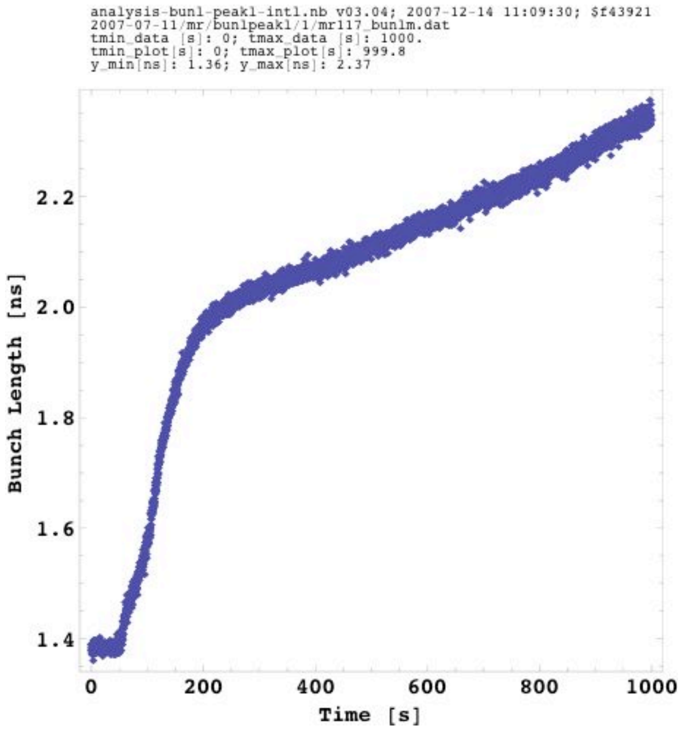
Fig 6b: MR117: After *slow* blow-up with noise at the ‘correct’ frequency 200 Hz-225 Hz, only 68 mV_{pp} (at 990 s, raw data). Corrected 4σ BL = 2.33 ns.



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tmin_plot[s]: 0; tmax_plot[s]: 999.8
y_min[ns]: 1.36; y_max[ns]: 2.37
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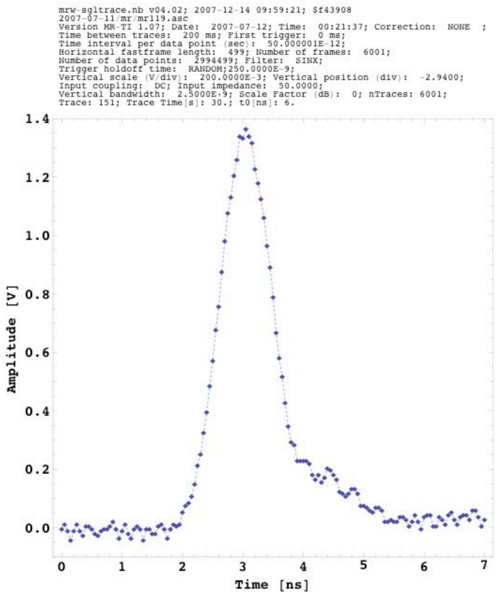
Fig 6c: MR117: Development of the 4σ Gaussian bunch length during the *slow* blow-up (frequency 200 Hz–225 Hz, only 68 mV_{pp}), spacing between traces 0.1 s. Initial blow-up 4 ps/s up to about 200 s, then 0.5 ns/s



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Version MR-TI 1.07; Date:  2007-07-12; Time:  00:21:37; Correction:  NONE  ;
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Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  6001;
Number of data points:  2994499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.9400;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 6001;
Trace: 151; Trace Time[s]: 30.; t0[ns]: 6.
```
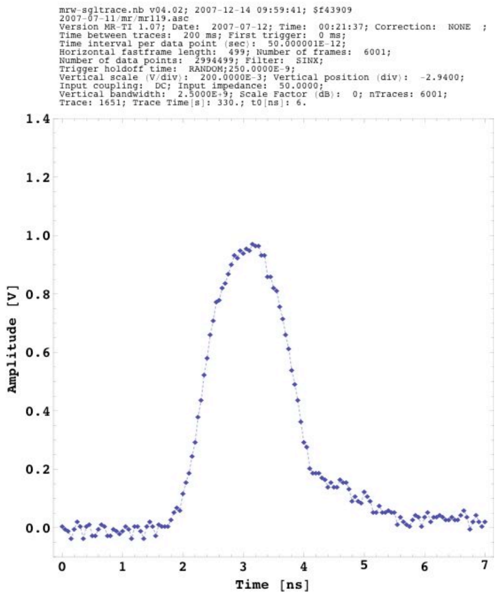
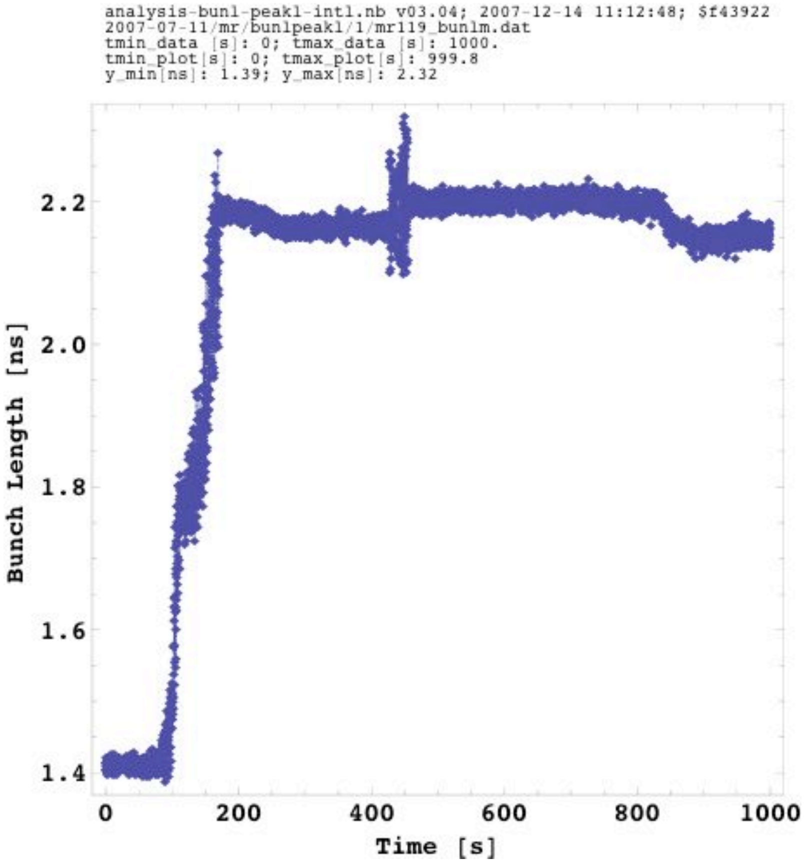

Fig 7a: MR119: The bunch short after injection, before blow-up (raw data). Corrected 4σ BL = 1.41 ns.



```
mrw-sgltrace.nb v04.02; 2007-12-14 09:59:41; $f43909
2007-07-11/mr/mr119.asc
Version MR-TI 1.07; Date:  2007-07-12; Time:  00:21:37; Correction:  NONE  ;
Time between traces:  200 ms; First trigger:  0 ms;
Time interval per data point (sec):  50.000001E-12;
Horizontal fastframe length:  499; Number of frames:  6001;
Number of data points:  2994499; Filter:  SINX;
Trigger holdoff time:  RANDOM;250.0000E-9;
Vertical scale (V/div):  200.0000E-3; Vertical position (div):  -2.9400;
Input coupling:  DC; Input impedance:  50.0000;
Vertical bandwidth:  2.5000E+9; Scale Factor (dB):  0; nTraces: 6001;
Trace: 1651; Trace Time[s]: 330.; t0[ns]: 6.
```

Fig 7b: MR119: After blow-up with strong monochromatic 'sliding' noise (at 330 s, raw data). Corrected 4σ BL = 2.16 ns.



```
analysis-bunl-peakl-intl.nb v03.04; 2007-12-14 11:12:48; $f43922
2007-07-11/mr/bunlpeakl/1/mr119_bunlm.dat
tmin_data [s]: 0; tmax_data [s]: 1000.
tmin_plot[s]: 0; tmax_plot[s]: 999.8
y_min[ns]: 1.39; y_max[ns]: 2.32
```

Fig 7c: MR119: Development of the 4σ Gaussian bunch length during blow-up (strong monochromatic 'sliding' noise) to produce hollow bunches. Around 450 s we have 'played' with the amplitude, causing the irregular bunch-length function

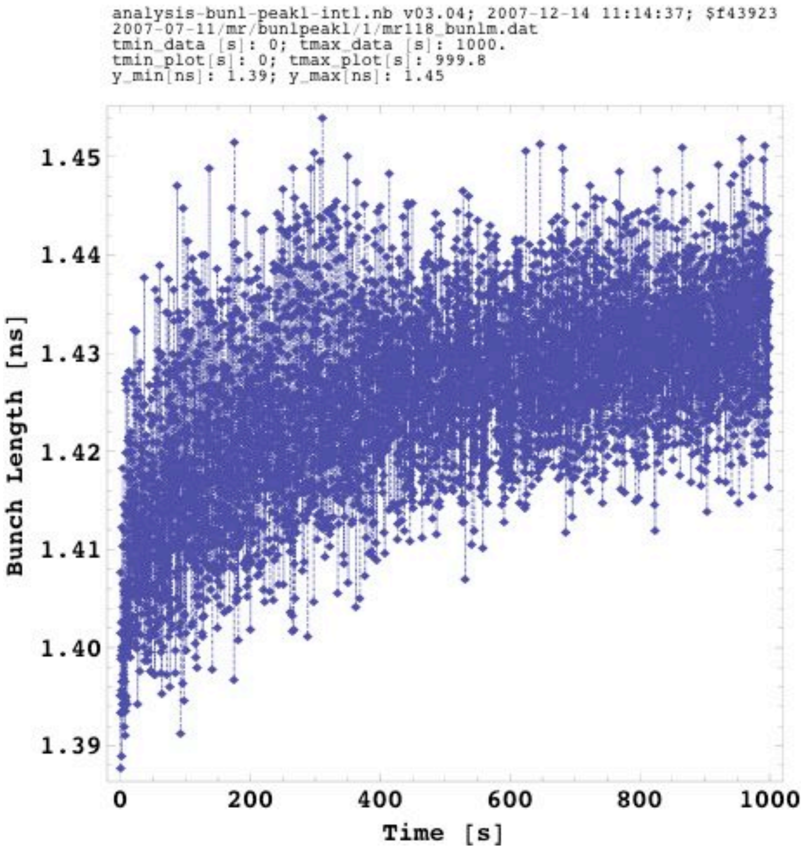


Fig 8: MR118: Bunch length measured for about 20 min. without any artificial RF noise. The absence of any significant blow-up here shows that the previously observed effects are due to the induced RF phase noise

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References

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http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/emt.html
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