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Commissioning of the I-LHC RF low level with beam

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Summary

During the machine development session of 2007-10-03, the energy matching between PS and SPS was completed for the $^{208}\mathrm{Pb}^{82+}$ beam. The I-LHC RF low level, including the phase loop and the synchronisation loop, was commissioned to capture a single bunch of $^{208}\mathrm{Pb}^{82+}$. After commissioning, the beam was used for several non RF related machine developments.

1 Commissioning

In preparation for the first dedicated machine development with I-LHC beam and “RF on” all the necessary hardware had been installed, the RF signals for the PS were provided and the low level had been checked without beam to work fine up to injection and partially even up to the end of flat bottom.

The machine development started with energy matching because the magnetic cycle was different than the cycle used previously in parallel with the proton fixed target physics cycle. The magnetic cycle used for the dedicated machine development reaches Q 450 GeV/c instead of Q 101 GeV/c for the parallel cycle, where Q is the charge of the $^{208}\mathrm{Pb}^{82+}$ ion, $Q = 82$. The B-field in the PS at extraction was fixed to:

setting	measured
12 365 G	12 569.800 G

Fig. 1 shows the debunching with RF off and the revolution frequency error. The contour plot of the bunch profile at injection shows the debunching with the original SPS dipole current setting of $I_{\mathrm{dipole}} = 197.000$ A, (top), and after G. Arduini’s optimisation of first turn and orbit leading to $I_{\mathrm{dipole}} = 197.500$ A, (bottom). This optimisation increased the relative frequency error from 3.0×10^{-6} to 8.2×10^{-6}. For $\gamma = 7.3$ this corresponds to an increase of $\Delta p/p$ from 1.6×10^{-4} to 4.4×10^{-4}. Nevertheless we kept this I_{dipole} setting.

The phase loop and everything which was needed up to injection was already working by Friday 2007-09-28. The next step in commissioning was then to close the synchronisation loop.

It was found that it was not possible to make the synchronisation loop working. The logic to reset the necessary synthesisers in the Slave DDS module had not been implemented yet and therefore it was not possible to have $f_{\mathrm{RF,avg}}$[1] and $f_{\mathrm{RF,prog}}$[2] at the same phase at each injection. This

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[1] equals $4620 f_{\mathrm{rev}}$

[2] RF frequency of the DDS which is controlled by the Frequency Program DSP

produced large and variable phase errors at loop closure. As a way out, $f_{\mathrm{RF,FSK}}$[3] instead of $f_{\mathrm{RF,avg}}$ was used and the synchronisation loop phase discriminator output was sampled at f_{rev}. In this way the synchronisation loop could be closed. Phase and synchronisation loop gain and synchronisation loop bandwidth were optimised and the injected bunch was captured during the second half of the afternoon.

The SPS RF voltage phase jitter was measured at injection by comparing the phase of the instantaneous f_{RF} with $f_{\mathrm{RF,inj,PS}}$, the RF reference sent to the PS, which is derived from an RF synthesiser driven by the frequency programme. The jitter was about 50 ps peak-to-peak over a series of ten SPS cycles.

Initially the bunch peak amplitude was decreasing very fast as a function of time (see Fig. 2). The decay in peak amplitude was practically independent of RF voltage (most of the time 1.5 MV, measured on Voltage Display RA3345) and phase loop gain. The bunch length of the beam injected into the SPS was 3.6 ns (4σ), measured in the PS at extraction. With this bunch length in the PS the longitudinal emittance per nucleon, ϵ/A, was determined to be 0.026 eVs using tomography at $h = 16$ and $V_{\mathrm{RF}} = 120$ kV, or 0.035 eVs using the BSM application just before extraction ($h = 169$, $V_{\mathrm{RF}} = 300$ kV). Using the measured bunch length of 3.6 ns one obtains 0.039 eVs and $\Delta p/p = 1.0 \times 10^{-3}$ for the injected beam. The bunch intensity was typically about 6×10^{9} charges. The SPS BCT at that time looked something like that shown in Fig. 3. It shows that the peak detected signal decays much faster than the BCT signal.

In the SPS the beam was captured with $V_{\mathrm{RF}} = 1.5$ MV, which corresponds to a bucket size of $\mathcal{A}_B = 7.4$ eVs or $\mathcal{A}_B/A$ = 0.035 eVs and a bucket half height of $\Delta p/p = 8.4 \times 10^{-4}$. The SPS bucket was a bit too small for the injected beam, not taking into account an eventual offset in $\Delta p/p$ which would even further reduce the effective bucket size.

Fig. 4 shows the bunch length (4σ) and bunch peak amplitude as a function of time (both obtained through a Gaussian fit of the bunch profile). The first 1.5 s are not shown because during that time a limiter to protect the oscilloscope was limiting the input signal. The same data was used to calculate the bunch length lifetime as 11.0 s $\pm$ 0.3 s, and the bunch peak amplitude lifetime as 1.1 s $\pm$ 0.0 s (assuming a decay $\propto \exp(-t/\tau)$ in both cases, t being the time and τ the lifetime). The shortening of the bunch length was initially surprising although it had been seen earlier with lead ion beam in 1998 and also with proton LHC beam on various occasions (2004-10-25, e.g.). As the bunch length is obtained through a Gaussian fit, the bunch length might change due to a genuine bunch length change or due to a change of the bunch shape which becomes non-Gaussian. To illustrate this, the bunch shape at the beginning and the end of the measurement period is shown in Fig. 5. From visual inspection alone one cannot say that the bunch shape at 3 s after injection is different from the one at 5 s. Scaling the measurement at 3 s by a factor of 3 confirms that there visually there is no difference. However, the uncorrected 4σ bunch length is (3.3 ± 0.03) ns at 3 s and (2.9 ± 0.05) ns at 5 s, i.e. about 10% shorter.

A re-evaluation of the same data, but now fully corrected for pick-up and cable transfer functions, see Fig. 6 and 7, confirms what has been said about the bunch shape. The bunch length lifetime is now 8.5 s $\pm$ 0.2 s and the bunch peak amplitude lifetime 1.2 s $\pm$ 0.0 s.

An important increase in peak amplitude lifetime came then with a decrease of the horizontal and vertical chromaticity, especially the vertical chromaticity. It was adjusted without having been able to measure it. The initial values were $\xi_h = +0.34, \xi_v = -0.33$ and they were lowered to $\xi_h = +0.14, \xi_v = -0.53$ (at around 20:58H). The improvement of the peak detected lifetime is seen in Fig. 8 which should be compared with Fig. 2 (there is no data available to determine the bunch length lifetime after the chromaticity adjustment). Subsequently the RF was kept on for up to 7 s from injection onwards.

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[3] the instantaneous f_{RF} modulated at f_{rev}

PS B-field, setting	12 365 G
PS B-field, measured	12 569.800 G
SPS I_{dipole}	197.45 A
SPS RF Inj. B-field, setting	769.13 G
f_{inj}	199.926350 MHz

Table 1: Parameters for matched condition.

Also the BCT transmission improved with this chromaticity change, as seen in Fig. 9. The transverse tunes were adjusted along flat bottom to $Q_h = 0.13, Q_v = 0.19$ according to the SPS e-logbook.

To minimise the synchronisation loop transient at injection the injection frequency setting was changed to 769.13 G (f_{inj} = 199.926350 MHz measured). The dipole current for the injection flat bottom ended up as 197.45 A. For the complete parameter set for matched conditions see Table 1.

At flat bottom the horizontal emittance looked ok (Gaussian) and was 1.2 μm, the vertical emittance was about 3 μm, expected was 1.2 μm (G. Arduini). A problem with the transfer line optics was suspected as a possible cause for the increased vertical emittance.

To allow the measurement of chromaticity during flat bottom the radial steering was connected to the DSP Frequency Program (usually this is not the case for I-LHC operation as it is the radial loop which should steer the beam). This allowed a radial steering via the synchronisation loop.

The single bunch radial position measurement with the pick-up AERB.313 was used to verify the steering. The sensitivity of the radial pick-up was determined as about 60 mV/mm (see App. A).

Going into coast with beam failed due to injection kicker problems. It was the prepulse which was ignored in the COASTPRE cycle by the kicker system and therefore no beam was injected.

2 Conclusions

The energy matching was completed. The I-LHC RF low level, including the phase loop and the synchronisation loop sampled at f_{rev}, was commissioned to capture a single bunch of $^{208}\text{Pb}^{82+}$. After commissioning, the beam was used for several non RF related machine developments.

It was only realised after the machine development that capture voltage was too low with respect to the longitudinal emittance of the injected beam. It is not yet clear if the observed bunch shortening phenomena can be completely explained by this.

3 Acknowledgements

We would like thank D. Manglunki and G. Arduini for making the I-LHC beam available for commissioning of the RF. We appreciate comments on the manuscript by E. Shaposhnikova and benefited from discussions with T. Linnecar.

A Radial pick-up calibration

The SPS closed orbit programme calculates a value for the mean closed orbit $\langle x_{\mathrm{co}} \rangle$ which is based on the orbit measurement of all available horizontal pick-ups, a selection of pick-ups which can vary.

Assume the closed orbit is centred for a momentum deviation of $\Delta p/p = 0$, then

$$\langle x_{\mathrm{co}} \rangle = \langle D_x \rangle \, \frac{\Delta p}{p} \; ,$$

where

$$\langle D_x \rangle = \frac{1}{N} \sum_{\mathrm{PU}=1}^{N} D_{x,\mathrm{PU}}$$

is the average dispersion in the available pick-ups (their number being N). This means that $\langle x_{\mathrm{co}} \rangle$ depends on the selection of available pick-ups. In addition, the contribution of each pick-up is weighted according to the dispersion at its position[1].

For calibration of a pick-up signal, it is often desired to estimate the change of the closed orbit x_{co} in a particular pick-up with an arbitrary change of $\Delta p/p$, which is

$$\Delta x_{\mathrm{co}} = \frac{D_{x,\mathrm{PU}}}{\langle D_x \rangle} \, \langle x_{\mathrm{co}} \rangle \; ,$$

but as $\langle D_x \rangle$ is not known, because the selection of pick-ups to measure $\langle x_{\mathrm{co}} \rangle$ is not known this is not possible.

However, in practise one can assume $\langle D_x \rangle = (2.63 \pm 0.1)$ m in the SPS[1] for a typical closed orbit measurement and for the optics used for the proton beam for fixed target physics, for the CNGS beam, and for the LHC proton and ion beams.

For the I-LHC beam optics in the SPS, the dispersion at the radial pick-up AERB.313 is $D_{x,\mathrm{AERB}} = 2.33$ m. A 3 mm radial steering produced during the MD a signal of about 230 mV (RF radial position measurement) and a displacement of the mean closed orbit of about 4.6 mm. This means that for 1 mm of radial steering, $\langle x_{\mathrm{co}} \rangle$ is displaced by 1.5 mm. This means that the displacement at the pick-up is 1.5 mm $\times D_{x,\mathrm{AERB}}/\langle D_x \rangle$ or 1.3 mm. For the sensitivity of the radial pick-up this means that it is about 59 mV/mm.

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[1] J. Wenninger, priv. comm., February 2008

B Figures

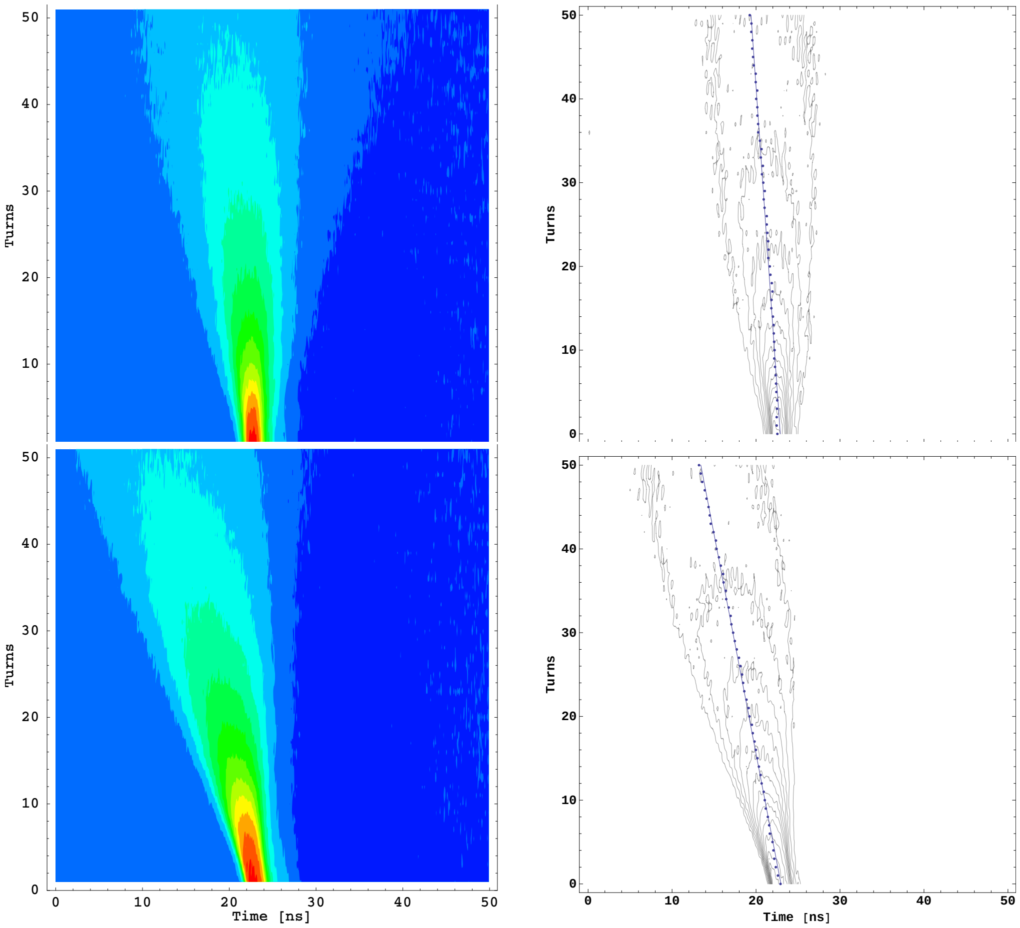


Figure 1: Contour plot of bunch profile at injection for energy matching. For original $I_{\text{dipole}} = 197.000$ A, `mr102` (top), and after G. Arduini's optimisation of first turn and closed orbit, $I_{\text{dipole}} = 197.500$ A, `mr103` (bottom). The frequency error is evaluated with the plots on the right, after application of all corrections to the pick-up signal. These plots show the calculated centre of mass (for data ≥ 0) and a straight line fit from which $\Delta f/f$ is determined.

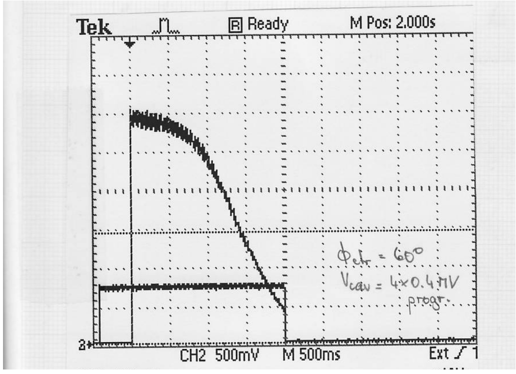
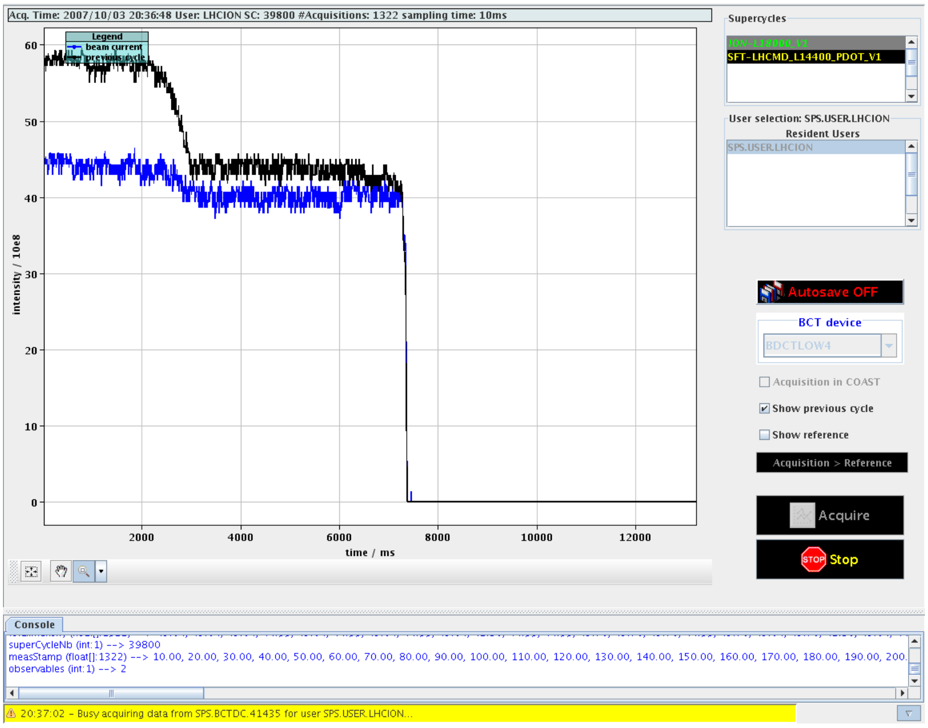


Figure 2: Bunch peak amplitude (signal with strong decay) and RF voltage (signal of constant amplitude) versus time under initial conditions. Injection of beam at $t = 0$ (trigger marker).


Acq. Time: 2007/10/03 20:36:48 User: LHCION SC: 39800 #Acquisitions: 1322 sampling time: 10ms

User selection: SPS.USER.LHCION

BCT device: BDCTLOW4

☐ Acquisition in COAST

☑ Show previous cycle

☐ Show reference

```
superCycleNb (int:1) --> 39800
measStamp (float[]:1322) --> 10.00, 20.00, 30.00, 40.00, 50.00, 60.00, 70.00, 80.00, 90.00, 100.00, 110.00, 120.00, 130.00, 140.00, 150.00, 160.00, 170.00, 180.00, 190.00, 200.
observables (int:1) --> 2
```

⚠ 20:37:02 - Busy acquiring data from SPS.BCTDC.41435 for user SPS.USER.LHCION...

Figure 3: BCT before (black trace) and after (blue trace) correction of injection oscillations at 20:36H. Optimisation by G. Arduini, from SPS e-logbook of 2007-10-03. This Fig. shows that the peak detected signal of Fig. 2 decays much faster than the BCT signal.

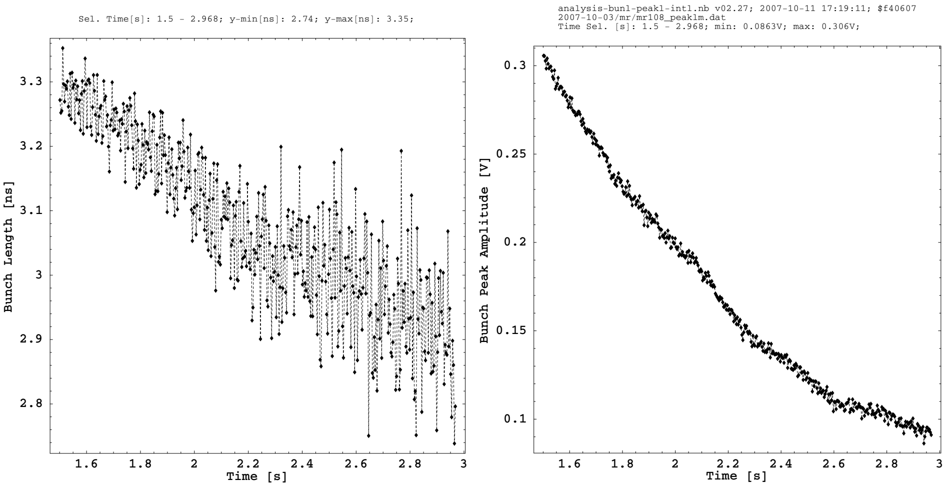


Figure 4: Bunch length (left) and bunch peak amplitude (right) versus time. All data uncorrected. `mr108` (20:20H).

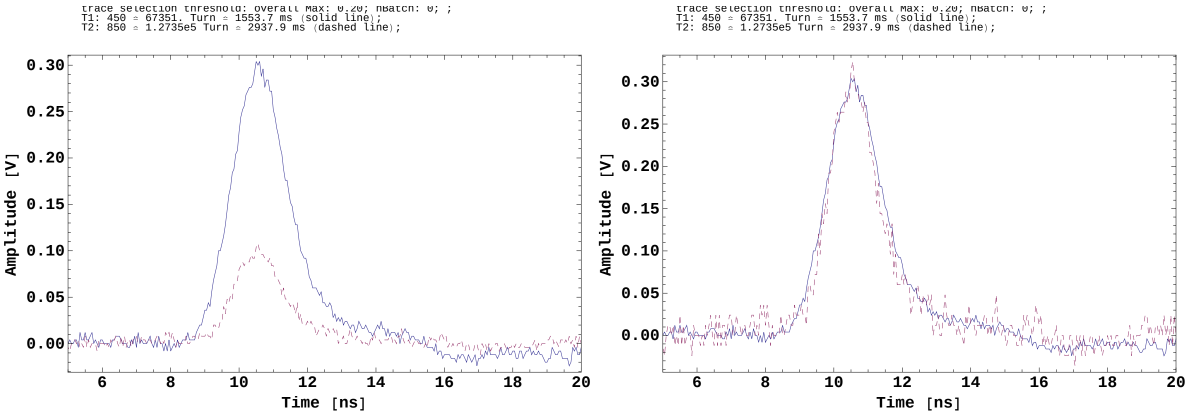


Figure 5: Comparison of bunch profiles at 1.5 s (blue) and 3 s (red) after injection (left) and bunch profile at 3 s after injection scaled by a factor of 3 (right). All data uncorrected. `mr108` (20:20H).

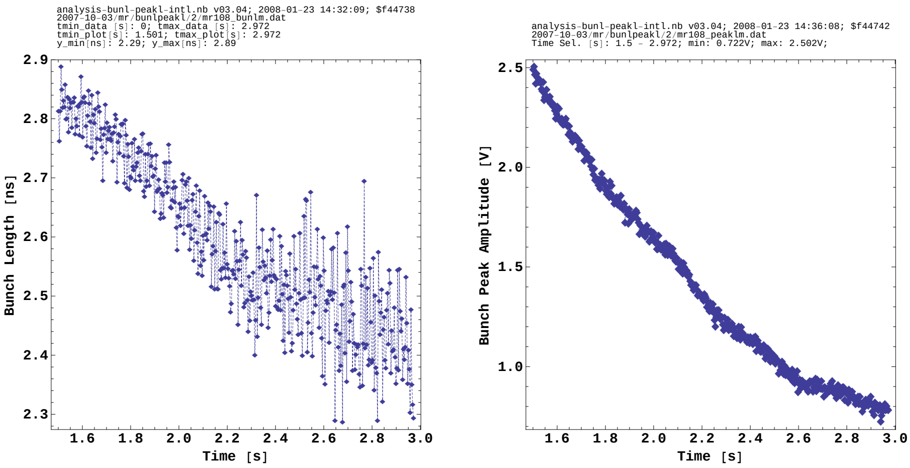


Figure 6: Bunch length (left) and bunch peak amplitude (right) versus time. All data corrected for pick-up and cable transfer functions. `mr108` (20:20H).

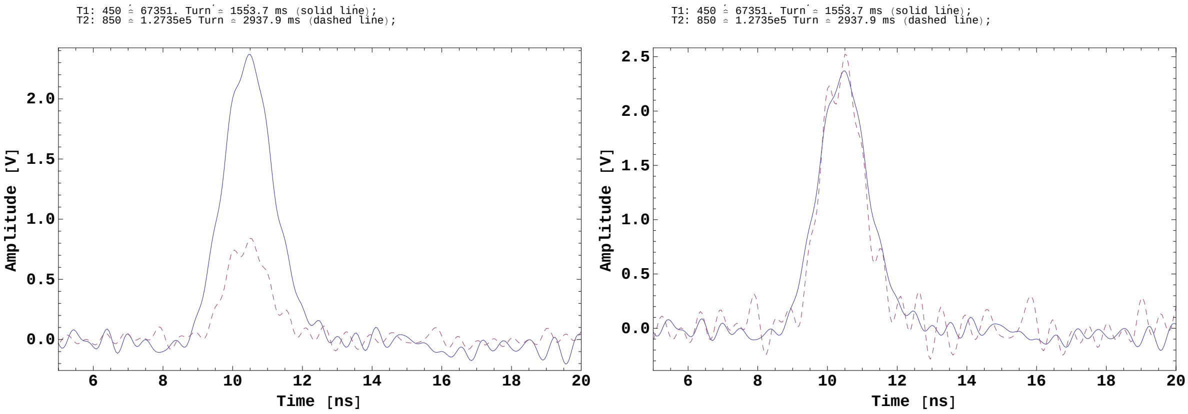


Figure 7: Comparison of bunch profiles at 1.5 s (blue) and 3 s (red) after injection (left) and bunch profile at 3 s after injection scaled by a factor of 3 (right). For the blue profile and the red profile the 4σ bunch lengths are (2.8 ± 0.03) ns and (2.4 ± 0.05) ns, respectively. All data corrected for pick-up and cable transfer functions. `mr108` (20:20H).

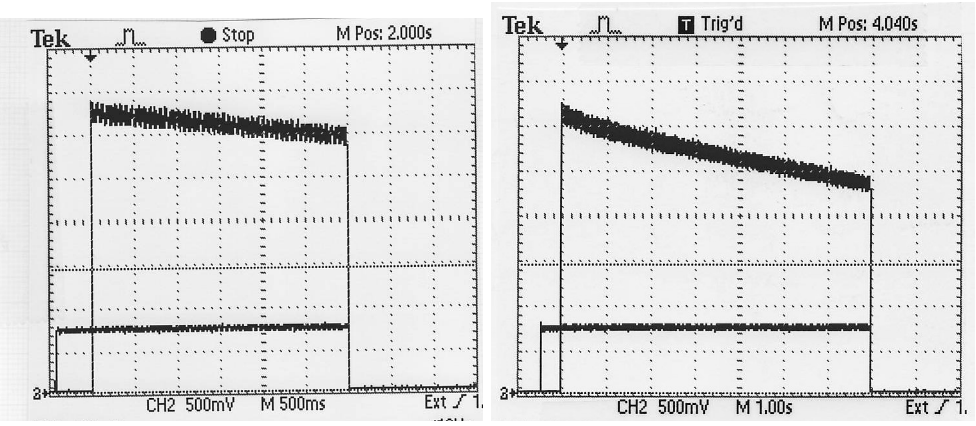
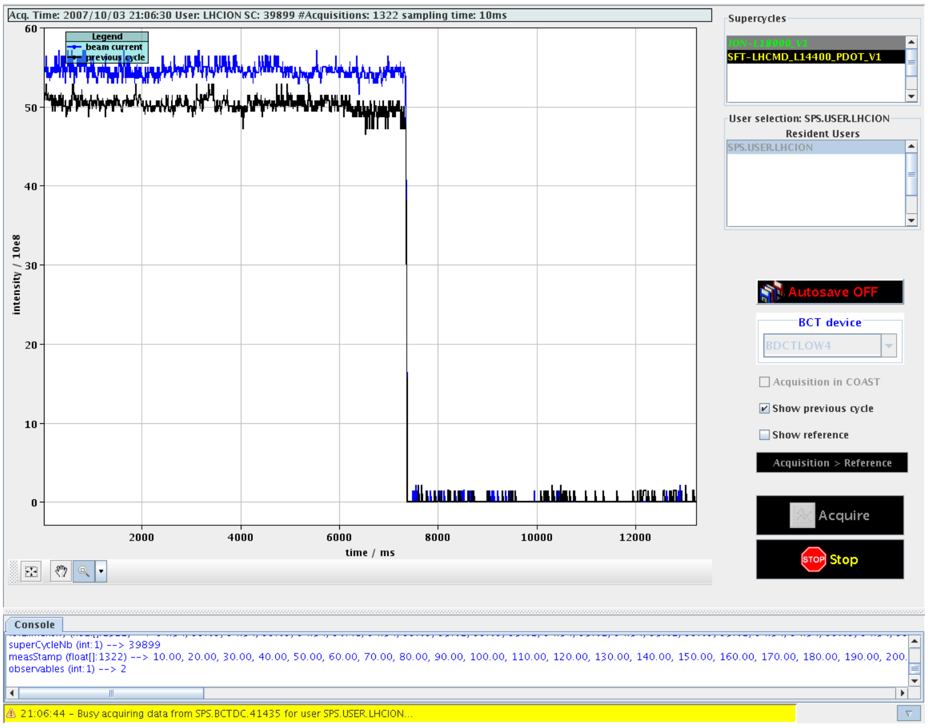


Figure 8: Bunch peak amplitude (upper trace) and RF voltage (lower trace) after chromaticity adjustment. The Figure at the left is for comparison with Fig. 2, horizontal scale 500 ms/div. The Figure at the right shows the bunch peak amplitude and RF voltage over a longer time scale of 1 s/div. Injection of beam at $t = 0$ (trigger marker).



Acq. Time: 2007/10/03 21:06:30 User: LHCION SC: 39899 #Acquisitions: 1322 sampling time: 10ms

User selection: SPS.USER.LHCION

☐ Acquisition in COAST
☑ Show previous cycle
☐ Show reference

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measStamp (float[]:1322) --> 10.00, 20.00, 30.00, 40.00, 50.00, 60.00, 70.00, 80.00, 90.00, 100.00, 110.00, 120.00, 130.00, 140.00, 150.00, 160.00, 170.00, 180.00, 190.00, 200.
observables (int:1) --> 2
```

⚠ 21:06:44 – Busy acquiring data from SPS.BCTDC.41435 for user SPS.USER.LHCION...

Figure 9: BCT after chromaticity adjustment at 21:06H. Two good cycles are shown. They should be compared with the blue curve in Fig. 3. Optimisation by G. Arduini, from SPS e-logbook of 2007-10-03.