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Damping of betatron oscillations in the SPS appearing at the two step extraction of CNGS beam

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1 INTRODUCTION

The CERN Neutrinos to Gran Sasso (CNGS) experiment [1] requires two SPS batches[1] of 400 GeV proton beams to be shot 50 ms apart onto a graphite target creating pions and kaons. These particles decay into muons and neutrinos, resulting finally in a neutrino beam propagating 732 km through the earth towards the neutrino detector located in Gran Sasso (Italy).

Tight constraints have to be met concerning the extraction kick angle to properly hit the target 590 m downstream of the extraction from the SPS. In addition, the rising and falling edges of the extraction kicker (MKE) field have to be shorter than the gaps[2] between the two batches, in order to extract the first batch without influencing the one which is still circulating. The present installed extraction kicker system[3] does not (yet) fulfill this condition perfectly. Bunches of the second batch will also receive kicks during the first extraction, leading to transverse beam oscillations. Without additional counter measures the oscillations will persist or even grow. At the extraction of the second batch, about 2170 turns later, the bunches still oscillating will not hit the CNGS target properly. Almost all bunches of the second batch will have the wrong transverse position on the target.

The transverse coupled bunch feedback system in the SPS is designed to damp injection oscillations and stabilize coupled bunch oscillations. It was not designed to provide rapid damping of large oscillation amplitudes at top energy, such as those induced by the extraction kicker ripple and finite kicker rise time. When these oscillations are damped with a high gain, the feedback amplifiers can become saturated. In this non-linear regime higher order coupled bunch modes may no longer be damped.

As a first step we studied this scenario by performing simulations [2]. Here, we present results obtained with experimental tests performed in September 2004 in the SPS.

2 MEASUREMENT SETUP

A boundary condition for the studies was that high intensity beams should not be extracted into the transfer path towards the CNGS target which is not yet installed. This was not a real restriction as the damping of betatron oscillations caused by the first extraction kick can be studied without extracting beam towards the CNGS target. Beam consisting only of the second batch was accelerated and the extraction kicker fired at the position of the first batch (i.e. the missing batch), as indicated in Figure 1. About 2200 turns later, the beam was dumped onto the usual SPS internal beam dump.

We determined the absolute time relation between the kicker trigger timing and the beam by varying the kick time

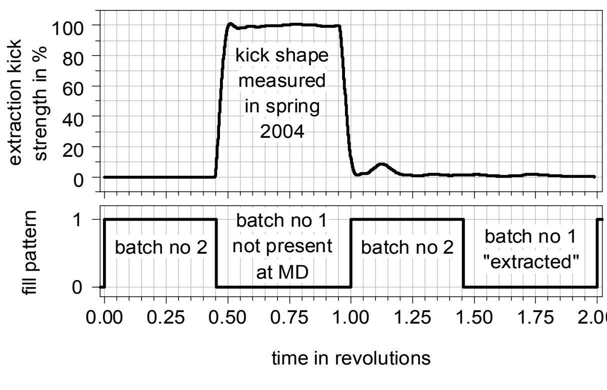

Figure 1: For the accelerator study (MD), the extraction kick was fired at the position of the absent first batch.

[1]Each batch has nominally 2100 bunches, the SPS harmonic number for this type of beam is 4620.

[2]The nominal length of the gaps is 210 bunch positions.

[3]CERN notation: 'SPS MKE LSS4 kicker system'

of the extraction kick and observing beam losses. The first and last nominal bunch of the first batch obtain 99% of the kick strength with the kicker trigger timing chosen.

Beam is extracted horizontally from the SPS. To determine the betatron oscillation amplitudes, we measured the signals of two horizontal beam pick ups (BPH 2.12 and BPH 2.14) with a betatron phase advance of about 90° in between. With a digital Tektronix oscilloscope model TDS 700D in fast frame sample mode we took the difference signals of both monitors and the sum signal of the second monitor. To achieve a sufficiently high resolution of the beam dynamics at the batch edges we chose a sample frequency of 250 MHz. To enable offline notch filtering each trace was 10000 sample points long ($\sim 40\,\mu$s) to cover two subsequent passages of the batch. This restricts the number of possible traces to 13 due to the limited amount of oscilloscope memory.

3 DATA ANALYSIS

To a first order the difference signal $x_{\Delta,\mathrm{pu}}$ of a transverse pick up is proportional to the transverse beam position times the beam intensity. In contrast, the sum signal $x_{\Sigma,\mathrm{pu}}$ depends in the ideal case only on the beam intensity. Hence, from these two measurements we obtain the transverse beam position x_{pu} at the monitor position

$$x_{\mathrm{pu}} = c_{\mathrm{cal}}\,\frac{x_{\Delta,\mathrm{pu}}}{x_{\Sigma,\mathrm{pu}}}$$

where c_{cal} is a calibration constant. The constant c_{cal} can be determined by measurements with closed orbit bumps of known amplitude.

We measured signals at two different intensities without orbit bump and with bumps giving a ± 2 mm displacement of the beam in the pick up. Applying

$$c_{\mathrm{cal}} = \pm 2\,\mathrm{mm} \Bigg/ \left(\frac{x^{(\pm 2\,\mathrm{mm})}_{\Delta,\mathrm{pu}}}{x^{(\pm 2\,\mathrm{mm})}_{\Sigma,\mathrm{pu}}} - \frac{x^{(0\,\mathrm{mm})}_{\Delta,\mathrm{pu}}}{x^{(0\,\mathrm{mm})}_{\Sigma,\mathrm{pu}}} \right)$$

we obtain in our case $c_{\mathrm{cal}} = 5.29\ (\pm 0.53)\,\mathrm{mm}$. The uncertainty is caused by the variations of the values for the different bumps chosen and the uncertainty in the bump displacements.

In the following, we are interested in oscillations around the closed orbit. Hence, we filter the difference signals to suppress closed orbit offsets: We subtract from trace values taken at the second batch passage the values of the first passage, taking into account the revolution frequency value at $400\,\mathrm{GeV}$, limited to $4\,\mathrm{ns}$ precision. From these notch filtered values $x_{\Delta,\mathrm{notch,pu}}$ we obtain the beam oscillation amplitude

$$a_{\mathrm{pu}} = \frac{c_{\mathrm{cal}}}{2\,|\sin\pi\,Q\,|}\,\frac{x_{\Delta,\mathrm{notch,pu}}}{x_{\Sigma,\mathrm{pu}}}.$$

The factor $2\,|\sin\pi\,Q\,|$ takes into account the amplitude change by the notch filtering, which depends on the tune Q [2]. We define a new calibration constant

$$C_{\mathrm{cal}} = \frac{c_{\mathrm{cal}}}{2\,|\sin\pi\,Q\,|}$$

with the nominal horizontal CNGS tune $Q = 26.62$.

Finally we obtain the betatron oscillation amplitude A_{pu} at the monitor positions by combining the two monitor values (phase advance 89°)

$$\begin{aligned} A_{\mathrm{pu}} &= \sqrt{a^2_{\mathrm{pu1}} + a^2_{\mathrm{pu2}}} \qquad (1) \\ &= C_{\mathrm{cal}}\sqrt{\left(\frac{x_{\Delta,\mathrm{notch,pu1}}}{x_{\Sigma,\mathrm{pu1}}}\right)^2 + \left(\frac{x_{\Delta,\mathrm{notch,pu2}}}{x_{\Sigma,\mathrm{pu1}}}\right)^2}. \end{aligned}$$

Before applying this formula, the raw data are corrected so that the data values at empty bucket positions equal zero. Then we calculate the average bunch population within the batch core (from bunch 200 to 1900). A bucket is viewed as occupied in the case where its population exceeds 8 % of the average population in the core. At non-occupied bucket positions the betatron oscillation amplitude A_{pu} is set to zero.

4 UNCERTAINTY ESTIMATE

In the following we estimate the uncertainty in the absolute measured oscillation amplitude values. These uncertainty values determine the confidence level on whether the CNGS target constraints will be fulfilled or not[4].

For tune values around $Q = 26.62$ the uncertainty in the calibration constant C_{cal} is given by

$$\begin{aligned} \Delta C_{\mathrm{cal}} &= \left|\frac{\partial C_{\mathrm{cal}}}{\partial c_{\mathrm{cal}}}\right| \Delta c_{\mathrm{cal}} + \left|\frac{\partial C_{\mathrm{cal}}}{\partial Q}\right| \Delta Q \\ \frac{\Delta C_{\mathrm{cal}}}{C_{\mathrm{cal}}} &= \frac{\Delta c_{\mathrm{cal}}}{c_{\mathrm{cal}}} + \left|\frac{\pi\,Q}{\tan\pi Q}\right| \frac{\Delta Q}{Q} \\ &= \frac{\Delta c_{\mathrm{cal}}}{c_{\mathrm{cal}}} + 33\,\frac{\Delta Q}{Q}. \end{aligned}$$

Under the assumption that the tune was controlled during the study to a level of $\Delta Q/Q = 10^{-4}$, the uncertainty in the calibration constant C_{cal} is dominated by the uncertainty in c_{cal} ($\Delta c_{\mathrm{cal}}/c_{\mathrm{cal}} = 0.1$).

The uncertainty in the beam oscillation amplitude is then given by

$$\frac{\Delta a_{\mathrm{pu}}}{a_{\mathrm{pu}}} = \frac{\Delta c_{\mathrm{cal}}}{c_{\mathrm{cal}}} + \frac{\Delta x_{\Delta,\mathrm{notch,pu}}}{x_{\Delta,\mathrm{notch,pu}}} + \frac{\Delta x_{\Sigma,\mathrm{pu}}}{x_{\Sigma,\mathrm{pu}}}$$

where we have to take into account that the uncertainty $\Delta x_{\Delta,\mathrm{notch,pu}}$ is twice as large as the uncertainty of the raw data $\Delta x_{\Delta,\mathrm{pu}}$ due to the notch filtering.

The uncertainties $\Delta x_{\Delta,\mathrm{pu}}$ and $\Delta x_{\Sigma,\mathrm{pu}}$ in the raw data may be determined by calculating the rms value of samples

[4] Note: The working precision of the transverse feedback is much higher than these values because the sample inputs are the relative changes and not the absolute values.

taken at empty bucket positions. In most cases this would underestimate the uncertainty as the digital resolution of the oscilloscope is larger. Hence, we also calculate the smallest digitalization step which in our case is determined by the 9 bit resolution [3]. The larger value (rms or scope resolution) is taken as uncertainty of the sample.

Finally we obtain in this way the accuracy of our measurements with

$$\frac{\Delta A_{\mathrm{pu}}}{A_{\mathrm{pu}}} = \left|\frac{a_{\mathrm{pu1}}}{a_{\mathrm{pu1}}^2 + a_{\mathrm{pu2}}^2}\right| \Delta a_{\mathrm{pu1}} + \left|\frac{a_{\mathrm{pu2}}}{a_{\mathrm{pu1}}^2 + a_{\mathrm{pu2}}^2}\right| \Delta a_{\mathrm{pu2}} + \frac{\Delta c_{\mathrm{cal}}}{c_{\mathrm{cal}}}. \quad (2)$$

We have not yet considered effects caused by the restricted analog bandwidth of the chosen pick up signals. The difference signal $\Delta x_{\Sigma,\mathrm{pu}}$ is provided with a 3dB bandwidth of $f_{\mathrm{3dB}} = 60\,\mathrm{MHz}$ and the sum signal with 100 MHz. For estimating effects caused by these low pass characteristics, we assume the transfer function may be described by the transfer function of the first order low pass filter

$$G(s) = \frac{1}{1 + \frac{s}{2\pi f_{\mathrm{3dB}}}}.$$

A low pass filter changes the amplitude of a signal and its phase. Phase change causes different signal propagation times depending on the frequency components. From

$$T_{\mathrm{sig}}(f) = -\frac{1}{2\pi}\frac{d}{df}\arg G(i\,2\pi f)$$

we obtain the largest possible signal delay (for DC as compared to $f \to \infty$)

$$T_{\mathrm{sig,max}} = \frac{1}{2\pi f_{\mathrm{3dB}}} = \begin{cases} 2.5\,\mathrm{ns} & \text{for } f_{\mathrm{3dB}} = 60\,\mathrm{MHz} \\ 1.6\,\mathrm{ns} & \text{for } f_{\mathrm{3dB}} = 100\,\mathrm{MHz}. \end{cases}$$

Both values are smaller than the distance of 4 ns between sample points. Hence, uncertainties caused by this effect are much smaller than the uncertainty due to the digitalization.

The change of amplitude by a low pass can be observed as a distorted step response. In case of a unit step it is described by

$$x(t) = 1 - \exp\left(-\frac{t}{\tau}\right) \quad \text{with} \quad \tau = \frac{1}{2\pi f_{\mathrm{3dB}}}$$

resulting in a rise time between 0.2 and 0.8 of

$$T_{20\%\,\mathrm{to}\,80\%} = \frac{1.4}{2\pi f_{\mathrm{3dB}}} = \begin{cases} 3.7\,\mathrm{ns} & \text{for } f_{\mathrm{3dB}} = 60\,\mathrm{MHz} \\ 2.2\,\mathrm{ns} & \text{for } f_{\mathrm{3dB}} = 100\,\mathrm{MHz}. \end{cases}$$

These values are still smaller than the distance between sample points (4 ns) and also the distance between bunches (5 ns). A typical value for the measured raw data signal fall (rise) time is $T_{20\%\,\mathrm{to}\,80\%} = 270\,\mathrm{ns}$. This value is two orders of magnitude larger than the rise time caused by the low pass characteristic. Consequently, no bandwidth limitations are imposed and we can neglect uncertainties caused by the bandwidth restrictions as compared to the uncertainties already discussed.

5 CNGS TARGET CONSTRAINTS

The energy normalized betatron oscillation amplitude $|A_{\mathrm{n}}(l_{\mathrm{kick}})|$ is proportional to the extraction angle φ_{kick} [2]

$$|A_{\mathrm{n}}(l_{\mathrm{kick}})| = \sqrt{\beta\,\gamma}\sqrt{\beta_x(l_{\mathrm{kick}})}\,\varphi_{\mathrm{kick}}. \quad (3)$$

Here $\beta_x(l_{\mathrm{kick}})$ is the β-function at the kicker position and $\beta\,\gamma$ the relativistic factor

$$\beta\,\gamma = \sqrt{1 - \left(\frac{E_0}{E}\right)^2} \cdot \frac{E}{E_0}$$

where E is the particle total energy and $E_0 = m_{\mathrm{P}}\,c^2$ the proton rest energy.

Using complex notation for the betatron oscillation amplitudes $A_{\mathrm{n}}(l_{\mathrm{pu}})$ as defined in [2], the transverse beam position, measured at the pick ups is

$$a_{\mathrm{pu}} = a(l_{\mathrm{pu}}) = \sqrt{\frac{\beta_x(l_{\mathrm{pu}})}{\beta\,\gamma}}\,\mathrm{Im}\,A_{\mathrm{n}}(l_{\mathrm{pu}}). \quad (4)$$

From (3) and (4) we obtain the betatron oscillation amplitude at the pick ups as a function of the MKE kick angle:

$$A_{\mathrm{pu}} = \sqrt{\beta_x(l_{\mathrm{pu}})\,\beta_x(l_{\mathrm{kick}})}\,\varphi_{\mathrm{kick}}$$

With $\beta_x(l_{\mathrm{pu}}) = 102.7\,\mathrm{m}$ and $\beta_x(l_{\mathrm{kick}}) = 75.3\,\mathrm{m}$ this yields

$$\frac{A_{\mathrm{pu}}}{\mathrm{mm}} = 88\,\frac{\varphi_{\mathrm{kick}}}{\mathrm{mrad}}.$$

The CNGS target constraints are given by values corresponding to 1% and 1.5% extraction kicker ripple [5]. With the nominal extraction kick angle of 0.6 mrad this can be expressed in terms of betatron oscillation amplitudes measured at the pick ups:

$$A_{\mathrm{pu,threshold}} = \begin{cases} 0.5\,\mathrm{mm} & \text{for} \quad 1\% \quad \text{constraint} \\ 0.8\,\mathrm{mm} & \text{for} \quad 1.5\% \text{ constraint.} \end{cases}$$

6 RESULTS OBTAINED

Figure 2 shows the intensity distribution along the batch which was typically observed via the pick up sum signal at intensities of $(2.34 \pm 0.02) \cdot 10^{13}$ protons/batch. The small intensity variations with a period of about $2\,\mu$s are caused by the five turn continuous transfer (CT) extraction scheme as used for beam transfer from the PS accelerator to the SPS.

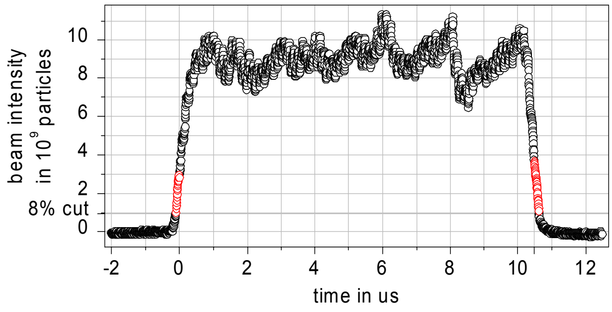

Figure 2: Typical beam intensity distribution along the batch. The distance between the sample points is 4 ns, the bunch spacing is 5 ns and the bandwidth is limited to 100 MHz by the pick up electronics.

In the following analysis we only consider bucket positions as occupied in the case where the intensity exceeds 8 % of the average bucket intensity in the batch core. Using this definition the batch becomes longer than 2100 bucket positions (from 0 to 10.48 μs). These 'additional' bunches contribute with about $0.4\,\%$ to the overall intensity. In Figure 2 and the subsequent mountain range plots these are indicated by the colour red. For lower intensities, we observe shorter batches and much less intensity outside the 2100 bucket positions.

Figure 3 shows the betatron oscillation amplitudes for the case where the transverse feedback is switched off at CNGS extraction energy (400 GeV). Initially the beam oscillation amplitudes do not grow (traces taken at turn 0 and 100). Between the second and third trace of Figure 3 the MKE extraction kick is applied to the empty part of the ring and betatron oscillations are excited. The amplitudes are largest at the beginning and at the end of the batch as bunches located there are affected by the finite rise and fall time of the extraction kick (trace at turn 200). Starting from the extraction kick the beam shows growing oscillation amplitudes, i.e. is unstable. Under these conditions the beam is usually dumped due to losses before the second CNGS beam extraction would take place.

From the data shown in Figure 3 we roughly estimate the instability growth rates $1/\tau_{\mathrm{growth}}$ within the batch. Taking as reference the betatron oscillation amplitudes directly after the first extraction kick ($A_{\mathrm{pu},200}$) and the last measured trace ($A_{\mathrm{pu},1200}$) we can calculate an instability growth rate in units of turns from

$$1/\tau_{\mathrm{growth}} \approx \frac{\ln A_{\mathrm{pu},1200} - \ln A_{\mathrm{pu},200}}{1000}.$$

Figure 4 shows a plot of the growth rates obtained in this way. The *smallest* growth rates are experienced by the bunches which receive a *large* initial kick (e.g. at 2 μs in the batch). Obviously, bunches with large initial amplitude excite wake fields causing disproportionate strong kicks to bunches with small initial amplitudes. Hence, bunches with small initial amplitudes show a much faster growth of betatron oscillation amplitudes (e.g. at 4 μs in the batch). Moreover, we observe larger growth rates towards the end of the batch. This could be caused by broad band impedances including the resistivity of the vacuum chamber, leading to 'beam break up' behaviour like that found

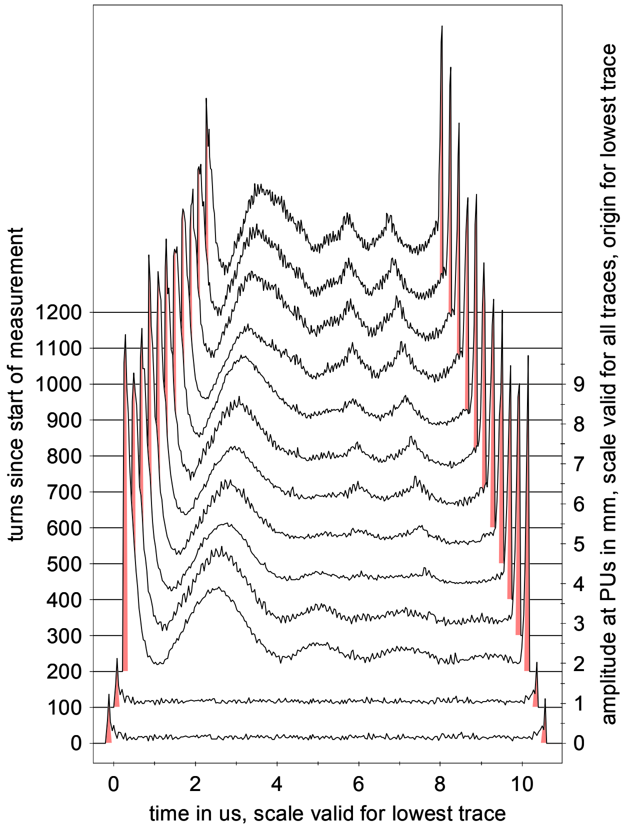

Figure 3: Transverse betatron oscillation amplitudes with transverse feedback switched off at top energy (beam intensity: $(2.34 \pm 0.02) \cdot 10^{13}$ protons/batch). The uncertainties (given by (2)) in the amplitudes shown are $\pm 19\,\%$ in batch tails and $\pm 42\,\%$ in the batch core at trace 0 and 100 (amplitudes $\approx$ 0). At the later traces ($\geq$ 200) the uncertainty in the core is smaller, namely $\pm 16\,\%$.

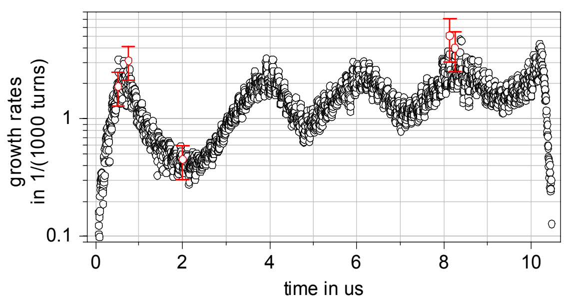

Figure 4: Growth of the betatron oscillation amplitudes after the first extraction kick in the absence of transverse feedback.

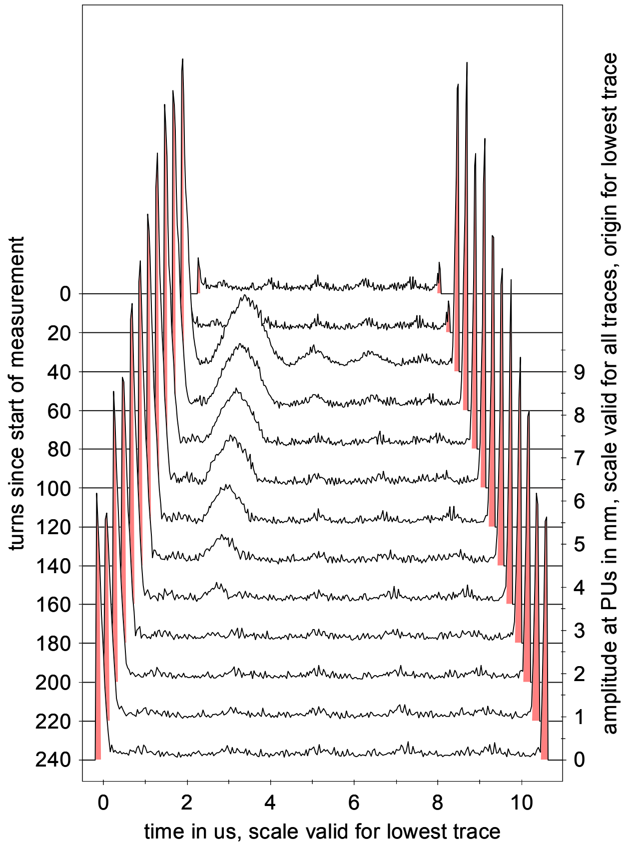

Figure 5: Betatron oscillation amplitude with the transverse feedback in operation (beam intensity: $(2.34\pm0.02)\cdot 10^{13}$ protons/batch). The uncertainties in the amplitudes shown are at batch edges $\pm 20\,\%$ and in the batch core $\pm 40\,\%$ at 'turn' 0 and 20. At later traces (≥ 20) the uncertainties are smaller, namely $\pm 17\,\%$ at the edges and $20\,\%$ in the core.

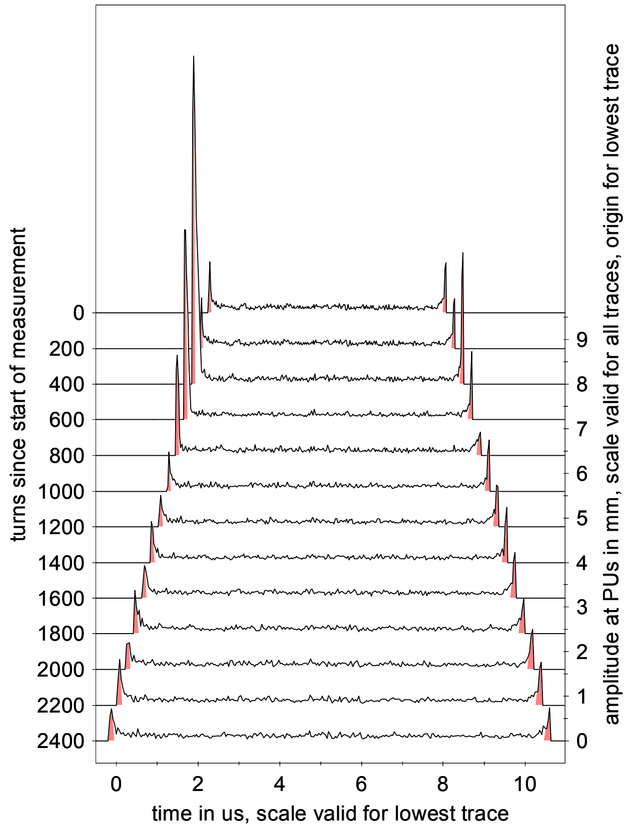

Figure 6: Betatron oscillation amplitudes over the full time range in the case of applied transverse feedback (beam intensity: $(2.34 \pm 0.02) \cdot 10^{13}$ protons/batch). After about 1000 of the available 2200 turns the CNGS target constraint of oscillation amplitudes smaller than $0.5\,\mathrm{mm}$ ($0.8\,\mathrm{mm}$) is already fulfilled.

in linear accelerators. Similar observations at the SPS have been reported [4, Fig. 4]. More detailed examinations using simulations are under way.

Figure 5 shows a mountain range plot with 20 turns between the amplitudes taken with feedback on. The time axis is reversed in the figures with feedback on because of the amplitudes decreasing. Within 140 turns, the transverse feedback completely damps down the betatron oscillation amplitudes in the batch centre. However, damping of the bunches at the batch edges is slow and not visible on this time scale.

Figure 6 shows the full time range between the two extraction kicks. Due to the large distance of 200 turns between traces, the batch core oscillations after the first extraction kick (Fig. 5) are invisible. In contrast, damping of bunches at the batch tails is now visible.

To study the sensitivity of the extraction kicker timing margins, we shifted the trigger timing by $50\,\mathrm{ns}$ with respect to nominal, for taking the data shown in Figure 6. This shift is visible in the larger betatron oscillation amplitudes at the beginning of the batch as compared to the end of the batch ('turn' 400). Even under these circumstances, the oscillations are well damped by the feedback system.

The difference signals $x_{\Delta,\mathrm{pu}}$ of the transverse pick ups scale with the beam intensity. Betatron oscillations of small intense bunches result in smaller signals as compared to betatron oscillations of the same amplitude of high intense bunches. Hence, the feedback gain scales with beam intensity and is reduced for bunches with low intensity at the beginning and at the end of the batch. In addition, the resolution of the digitization limits the minimum betatron oscillation amplitude which can be damped. The consequences can be seen in all three cases (Fig. 3, 5 and 6) where the feedback was in operation before the extraction kick took place. At the beginning and the end of the batch we observe significant higher oscillation amplitudes than in the batch core.

7 CONSIDERATIONS ON BEAM LOSS

As already pointed out in [2], the second batch is kicked towards the septum due to the first batch extraction kick. Depending on the transverse emittance and the kick strength, beam is lost at the septum protection device (TPSG). In contrast to the 10^{-7} relative loss estimate in [2], we have to assume that there will be higher losses in practice. This is due to the fact, that there is about $0.4\,\%$ to $0.5\,\%$ of the batch intensity outside the 2100 bucket positions. For a worst case value for the beam loss we consider this intensity as completely lost, partly at the first extraction and partly at the second extraction.

In order to determine to which extent these loss values are overestimated, we have to take into account the transverse emittance and the population of the beam tails. Small emittances and low bunch tail population ease the situation. During the studies presented here, only one batch was accelerated and the averaged horizontal ($1\,\sigma$) emittance was determined to be about $4\,\mu$m [6], which is three times smaller than the design value of $12\,\mu$m. In the case where the SPS accelerates both CNGS batches with full intensity, we expect emittances larger than $4\,\mu$m and a different tail population.

In summary, at the CNGS extraction we expect the beam loss per batch to be smaller than $0.5\,\%$. This should be checked by measurements after the restart of the SPS in 2006.

8 CONCLUSION AND OUTLOOK

We have shown that the betatron oscillations caused to the second CNGS batch by extracting the first can be sufficiently quickly damped before the second extraction takes place. After about one half of the 2200 turns between the two extractions, the second batch meets the CNGS target constraints. This is even the case if the extraction kick pulse is shifted by 50 ns. Hence, there is enough margin for a permanent operation and also for a potential intensity increase in future.

In the worst case, beam losses will be about $0.5\,\%$ per batch. The real value may only be obtained by measurements during further studies proposed after the restart of the SPS in 2006 and is expected to be smaller than $0.5\,\%$ per batch.

The measurements confirm earlier simulation results [2]. This is in particular the case for the fact that the batch core is damped much faster than the batch edges, due to the bandwidth limitations of the feedback system. A detailed comparison of the measured data with the simulation model [2] is planned with the aim of refining this model. This may also include the implementation of beam instability effects to model the unstable behaviour without feedback.

9 ACKNOWLEDGEMENTS

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