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SIMULATION OF TRANSIENT BEAM-FEEDBACK INTERACTION AND APPLICATION TO EXTRACTION OF CNGS BEAM FROM THE SPS

W. Hofle, E. Vogel,
CERN, Geneva, Switzerland

Abstract

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For present and future high energy proton accelerators, such as the LHC, transverse feedback systems play an essential role in supplying the physics experiments with high intensity beams at low emittances. We developed a simulation model to study the interaction between beam and transverse feedback system in detail, bunch-by-bunch and turn-by-turn, considering the real technical implementation of the latter. A numerical model is used as the non linear behaviour (saturation) and limited bandwidth of the feedback system, as well as the transient nature at injection and extraction, complicates the analysis. The model is applied to the practical case of the CNGS beam in the SPS accelerator. This beam will be ejected from the SPS in two batches causing residual oscillations by kicker ripples on the second batch. This second batch continues to circulate for 2167 turns after the first batch has been extracted and oscillations are planned to be damped by the feedback system. The model can be extended to examine transient effects at injection (LHC), and coupled bunch instability effects can be included.

INTRODUCTION

Transverse feedback systems stabilize beams whose parameters are otherwise far away from stable regions. Hence, they have a significant influence on beam dynamics.

The interaction between the beam and a feedback system depends strongly on the real technical implementation and limitations of the latter. Limited available correction kick strengths and limited bandwidths are typical features.

Experimental verification of the simulation model is essential. For future tests of our initial simulation model we have chosen a particular beam condition in the SPS for which the beam is relatively stable – this is with CNGS type beams at extraction energy. It is later planned to extend the model to include beam instabilities for the examination of other operational conditions and other accelerators (e.g. the LHC).

The CERN neutrinos to Gran Sasso (CNGS) experiment [1] requires two SPS batches of 400 GeV proton beams to be shot 50 ms in succession 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 field have to be shorter than the gaps between the two batches, in order to extract the first batch without influencing the one which is still circulating. This condition is not perfectly fulfilled. Bunches of the second batch will also receive kicks during the first extraction, leading to transverse beam oscillations. Because of the large decoherence time of about 10 000 turns [2], the oscillations will persist. 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 a 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 is not designed to provide rapid damping of large oscillation amplitudes at top energy, such as induced by the extraction kicker ripple and finite kicker rise time. When damping these oscillations with a high gain, the feedback amplifiers can become saturated. In this non-linear regime higher coupled bunch modes may no longer be damped.

We use Simulink [4], a Matlab extension for modelling, simulating and analyzing dynamic systems. Its graphical user interface allows a representation of the complete system by ‘drawing’ the corresponding signal flow diagram. This is very efficient in saving development and code implementation time.

SIMULATION MODEL

The first central part of the simulation model describes the horizontal oscillations of the CNGS type beams in the SPS without coupling impedance. Emittance blow up by decoherence is taken into consideration using algebraic expressions, bunch-by-bunch and turn-by-turn [5]. The model offers inputs for injecting and extracting bunches together with bunch parameters such as injection offsets, normalized bunch sizes, kick angles caused by extraction kickers and the electric field value of the feedback kicker. Further input values are the tune and the total particle energy. Output values are beam position signals measured at two beam monitors. For diagnostic purposes the normalized bunch size and the betatron oscillation amplitude are supplied.

The second central part is the transverse feedback, with the essential components of the actual system. The first step in signal processing is the combination of the signals of the two beam position monitors into a single signal to ensure the necessary feedback phase. A one turn delay is implemented by a first-in, first-out (FIFO) buffer, guaranteeing that a measured transverse position of a bunch leads to a signal applied to the same bunch. A periodic notch filter, with zeros at multiples of the revolution frequency, supresses the signal caused by the sampling of closed orbit distortions. The behaviour of the final stage amplifier, together with the connected kicker, is described by a limiter and a finite impulse response (FIR) filter. These elements model the limited power and the gain frequency characteristics with lower gain for higher frequencies. The overall loop gain is adjusted by changing a gain value in front of the limiter.

At the start of a simulation, the beam model describes an empty accelerator. Bunches must first be ‘injected’, attention being paid to the timing to obtain the correct filling pattern. The ‘extraction’ acts in the same way. Within the turn that extraction of the first batch takes place, kicks are applied to the bunches of the second batch. All these time-dependent patterns for injection end extraction are the main input values for the beam model.

The betatron oscillation amplitudes and the normalized rms bunch sizes are analyzed to check whether the CNGS target constraints are fulfilled. The damping times and the times until CNGS constraints are fulfilled are determined.

For a detailed description of the simulation code, see [6].

CONSIDERATION ON BEAM LOSSES

At extraction the beam is steered towards the septum via an orbit bump to keep the required extraction kick angle low. Therefore, the physical aperture is reduced to eight times the nominal CNGS beam size [7]. The first bunches of the second batch receive a kick from the extraction kicker, resulting in initial betatron oscillation amplitudes of about five to six times the bunch size. Hence, we obtain a remaining aperture of two to three times the beam size. Beam starts to be lost in the case of $3\,\sigma$ apertures.

As the extraction kick deflects the bunches directly towards the septum, all particles with coordinates larger that eight times the bunch sizes $x > 8\,\sigma$ are lost. If there is no damping mechanism, bunch centres will rotate along circles in phase space due to the betatron oscillations. For reasonable tune values[1], we obtain circular cuts after less than 30 turns (Fig. 1). The loss factors for circular cuts, calculated by numerical integration, are confirmed by multi-particle tracking [8].

Large betatron oscillations of CNGS beam at top energy are damped by the feedback within several hundred turns. Because the time needed for all loss of particles to occur is much less (30 turns) we can estimate the total losses by calculating the losses due to circular cuts from the initial betatron amplitudes.

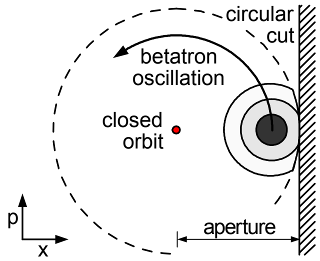

Figure 1: Phase space picture of beam loss at septum.

RESULTS

As input parameter for our simulations, we use the measured shapes of the extraction kicker strength [9]. Figure 2 shows the normalized kicker pulse.

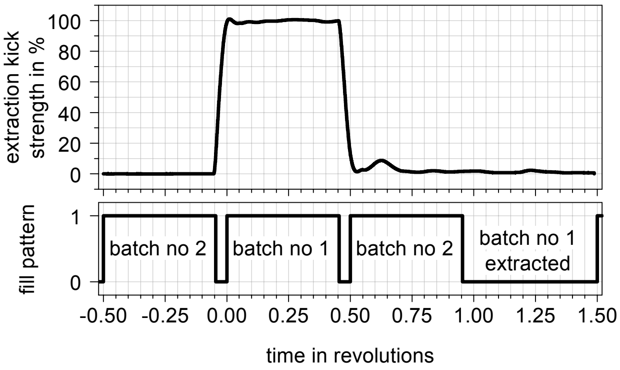

Figure 2: Normalized ($100\,\% = 0.6\,\mathrm{mrad}$) measured kicker pulse and nominal fill pattern (2100 bunches per batch).

Switching off the kicker field is more critical than switching it on. The falling edge is longer than the rising edge and some unwanted ripples appear afterwards. One turn earlier, the rising edge will also kick the last bunch of the second batch (see Fig. 3).

The analytical approach which we used for the determination of the emittance blow up is not valid in the case of large initial betatron amplitudes and the absence of damping with feedback. Nevertheless, the reduction of the betatron oscillation amplitude according to the decoherence time is still correct. It leads to a slow damping of the oscillations. In simulations without feedback, we only check whether the betatron oscillation amplitudes at the second extraction are below the acceptance value for the target. In reality the blow up reduces this limit.

Figure 4 shows bunch-by-bunch after how many turns the remaining betatron oscillation amplitude is below the acceptance value. The extraction of the second batch takes place 50 ms (about 2170 turns) after the extraction of the first. For this reason, we stop our simulation after 2173 turns. Bunches still showing betatron oscillation amplitudes above the acceptance value after 2173 turns are in-

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[1] ‘reasonable’ tune values are away from integer and half integer values to avoid optical resonances

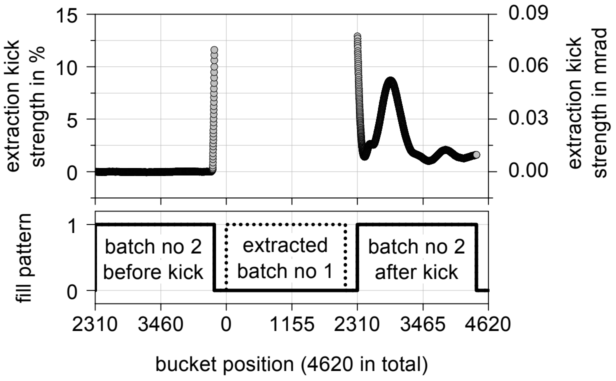

Figure 3: Kicks of the extraction kicker, applied to the second batch at the extraction of the first batch.

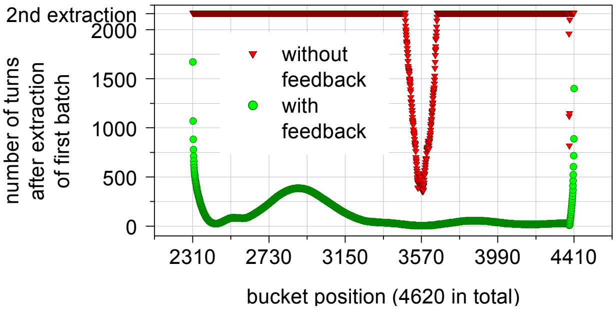

Figure 4: Number of turns after extracting the first batch, necessary to meet the CNGS constraints.

dicated in Fig. 4 with the value 2173. This is the case for almost all bunches in the batch. As the blow up is not taken into account for the acceptance check, Fig. 4 shows an estimate which is too optimistic in the absence of feedback.

With feedback on we obtain in the most unfavourable case a total damping time of about $1/10$ of the decoherence time. Then we can trust the emittances, determined by the analytical approach [6]. In order to decide whether the CNGS target constraints are fulfilled, we add the normalized beam size increase after the first extraction, and the actual normalized betatron amplitude. The sum of these has to be below the acceptance value in order to meet the constraint. Results are shown in Fig. 4.

The longest times for damping the betatron oscillations are always required for the first and last bunch of the batch. This is due to the bandwidth limitation of the feedback kicker. As a consequence, there is about 50 % less kick voltage applied to the bunches at the edges of the batch as compared to bunches in the middle.

We calculate from the initial betatron oscillation amplitudes the loss factors in the second batch (Fig. 5). The calculated losses are very small and it may be difficult in practice to measure them. We find total relative losses of $1.1 \cdot 10^{-7}$ per second batch.

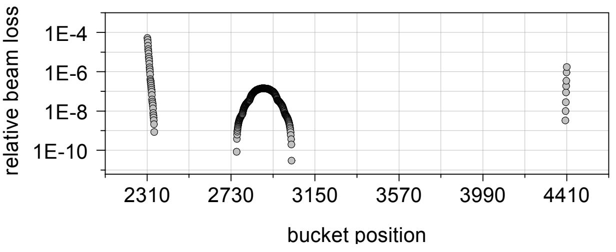

Figure 5: Relative beam loss, estimated from the initial betatron oscillation amplitudes after the extraction of the first batch.

CONCLUSION AND OUTLOOK

The simulation model developed describes the transverse beam-feedback interaction, including the essential technical details of the SPS feedback. It gives a first answer to the question of whether the SPS feedback system is able to damp beam oscillations caused by residual kicks on the second CNGS batch during the extraction of the first batch.

For ideal CNGS fillings in the SPS, i.e. zero population of the two kicker gaps and two batches of bunches with equal initial intensities and emittances, the effect of the actual residual extraction kick can be cured by the SPS feedback system. Beam losses seem to be negligible. This is no longer the case if the kicker gaps are already populated. Particles in the gaps will be kicked directly into the extraction septum.

It is planned that the results presented here will be verified experimentally during machine studies in 2004.

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