MULTI-PARTICLE SIMULATION CODES IMPLEMENTATION TO INCLUDE MODELS OF A NOVEL SINGLE-BUNCH FEEDBACK SYSTEM AND INTRA-BEAM SCATTERING*

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Abstract

The beam tracking codes HEAD-TAIL and C-MAD have been enhanced to include a detailed model of a single-bunch feedback system. Such a system is under development to mitigate the electron cloud and the transverse mode coupling instability (TMCI) in the SPS and LHC at CERN. This paper presents the model of the feedback sub-systems: receiver, processing channel, cables, amplifiers and kicker, which takes into account the frequency response, noise, mismatching and technological limitations. With a realistic model of the hardware, it is possible to study feedback systems and prototypes to be installed in the SPS. The multi-particle codes C-MAD, which takes advantage of parallelization and optimization for speed, and IBS-Track now include a detailed model of Intra-Beam Scattering (IBS), and radiation damping and quantum excitation. It allows investigating IBS during damping and its effect on the beam distribution, especially on the beam tails, which analytical methods cannot investigate. Intra-beam scattering is a limiting factor for ultra-low emittance rings such as the CLIC Damping Rings and Super-B.

INTRODUCTION

Single-bunch instabilities induced by electron clouds and strong head-tail interactions are one of the limiting factors to reach the maximum beam currents in the LHC complex. Feedback techniques might stabilize single-bunch instabilities induced by either electron clouds and by transverse mode coupling instability (TMCI).

The application of feedback control to stabilize the bunch is technologically challenging because it requires sufficient frequency bandwidth to sense the transverse position and apply correcting electromagnetic fields to different parts of a nanosecond-scale bunch [1]. An effort has been directed to implement in HEADTAIL (G. Rumolo *et al.*) and C-MAD (M. Pivi *et al.*) codes realistic models for the feedback system that include the real sampling frequency of the processing channel, technical and bandwidth limitations of the different hardware components, noise and signal perturbations.

Intra-Beam Scattering (IBS) is associated with small angle multiple scattering events leading to emittance growth, see Figure 1. IBS growth rates increase with bunch charge density and small beam sizes, and for machines such as CLIC Damping Rings (DR) and Super-B [2, 3], that operate with high bunch charges and very low emittances, the IBS growth rates can be large enough to observe significant emittance increase.

Formalisms have been developed for calculating IBS growth rates, notably those by Piwinski, Bjorken and Mtingwa, and their high energy approximations CIMP and Bane [4, 5, 6]. However the analytical models are based on Gaussian bunch distributions and cannot investigate some aspects of IBS such as its impact during the damping process and its effect on the beam distribution. To investigate the effects of IBS in detail, we implemented C-MAD and IBS-Track (T. Demma) [7], with the Zenkevich-Bolshakov algorithm [8, 9]. In this paper we present the structure of the code and some simulation results obtained with particular reference to the CLIC DR and SuperB.

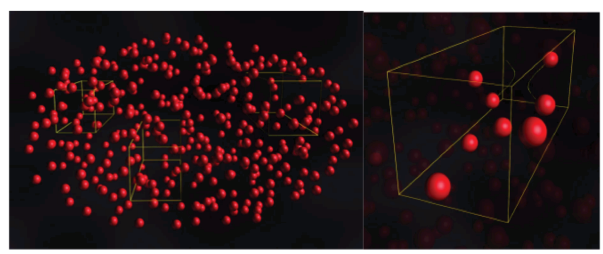

Figure 1: Modelling of IBS. Longitudinal bunch slices are assigned to each computer processor. In each 3D cell (right), Monte-Carlo method is applied in a stochastic process in which beam particles are randomly coupled and the momentum exchanged.

SINGLE-BUNCH FEEDBACK SYSTEM

Simulation codes as HEADTAIL, C-MAD and WARP [10] are used to analyze and estimate the behaviour of the bunch interacting with electron clouds and machine impedances. The simulation takes into account the electron cloud produced by the preceding bunches, with a cloud density as inferred from build-up simulations. Both protons and electrons species are represented by macro-particles. The protons-electrons interaction at each bunch slice is computed by particle-in-cell algorithms. The equations of motion for protons and electrons [11, 12] is:

$$x''_{p,i}(s) + K(s)x_{p,i}(s) = \Delta p_{e,i}\left(x_{p,i}(s)\right) + \Delta p_{T,x,y}(t)\Big|_{SL}$$
$$x''_{e,j}(s) = \Delta p_{p,j}\left(x_{e,i}(s)\right) \quad (1)$$

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with parameters as described in [1]. The bunch is divided into N_{SL} longitudinal slices and interacts with the cloud on successive time steps. Simulation codes have adopted different ways of defining the bunch slices. In particular, C-MAD has two options: either with constant slice length along the bunch or with constant particle charge per slice.

The feedback control system interacts with the macro-particle simulator by measuring the absolute transverse and longitudinal position of the centroid corresponding to each slice and generating a momentum or kick signal that drives each bunch slice. The momentum kick signal per slice is modelled by the additive term $\Delta \boldsymbol{p}_{T,x,y}(t)\big|_{SL}$ in the differential equation (1) representing the bunch dynamics

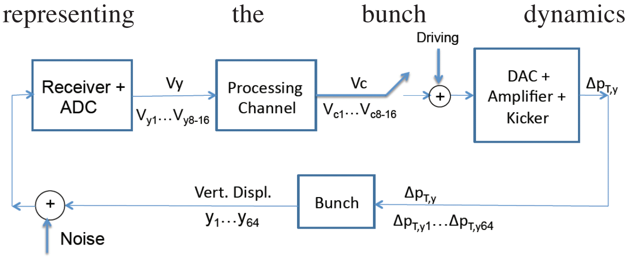

Figure 2: Block diagram of single-bunch feedback system

Figure 2 depicts a block diagram of the feedback control system for the vertical axis interacting with the proton bunch as implemented in the macro-particle simulation codes HEAD-TAIL and C-MAD. In this plot, the vertical displacement of the centroid of 64 slices of the bunch is labelled as $< y(t) > = [< y_1(t) > < y_2(t) > \cdots < y_{64}(t) >]^T$ and the momentum or kick signal for those slices is $\Delta p_{T,y}(t) = \left[\Delta p_{T,y1}(t) \ldots \Delta p_{T,y64}(t)\right]^T$.

The feedback system is defined by three major blocks: the *receiver* that measures and processes the signal from the beam pick-up and estimates the vertical position/dipole of the different slices of the bunch, the *processing channel* that computes, from the vertical signal the appropriate control signal $V_C(t)$ and the *power stage* (Amplifier, Kicker) that amplifies and delivers a different momentum kick to each longitudinal slice.

In simulations, appropriate modelling of each feedback sub-system is necessary to understand the real limitations of the feedback channel in the stabilization of the bunch dynamics. The *receiver* and *power stage* blocks are characterized using Hammerstein-Wiener models. In HEADTAIL and C-MAD, those blocks represent the cascade of several components in the system as the DAC, cables, amplifiers and kicker in the power block and, similarly in the receiver it accounts for the detector, cables, anti-aliasing filter and ADC. Importantly, the number of samples in the controller not necessarily is the same as the number of bunch samples.

In these preliminary results shown below for the CERN SPS, the feedback loop in the simulation code was configured using a 5 tap FIR filter processing channel and including the model of the real exponential strip-line kicker. The kicker exhibits a transfer function, as shown in Figure 3, with a dominant single pole that is changed in this study to analyse the impact of the bandwidth in the bunch stability and performance. The sampling frequency of the controller was set to 10 GSamples/sec.

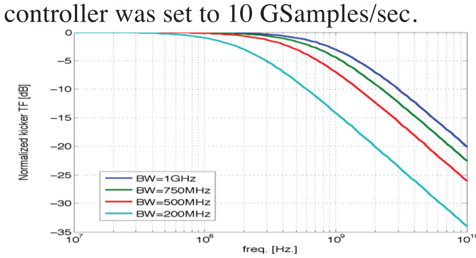

Figure 3: Normalized kicker transfer functions.

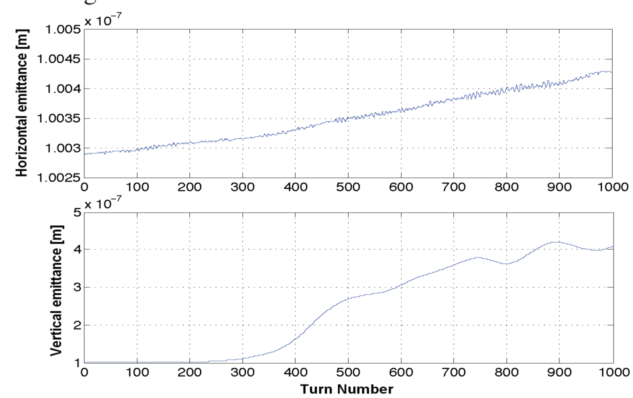

Figure 4: Simulated emittance growth (note vertical > 400%) in the CERN SPS with cloud density 0.5×12e/m^3 and without feedback.

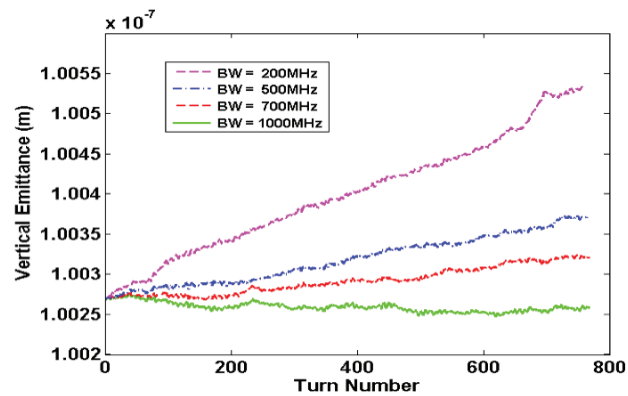

Figure 5: Vertical emittance stabilization with different feedback kicker bandwidth and fixed amplifier gain 0.5.

The bunch intensity was assumed to 1.1×10^{11} protons, SPS magnets at 0.117 T and the electron cloud density to 0.5×12e/m^3. The beam emittance for the open loop (no feedback) case is depicted in Figure 4. Figure 5 shows that the feedback system is able to stabilize the bunch dynamics under the conditions previously cited and defines the impact of the kicker bandwidth on the bunch vertical emittance due to the electron cloud perturbation.

For the feedback system operating in closed loop, the kicker bandwidth was changed at 200MHz, 500MHz, 700MHz and 1GHz and the loop gain was fixed at 0.5.

The actual implementation including realistic feedback components allows evaluating the impact of the frequency response and technical limitation, noise and other perturbations affecting the bunch performance.

INTRA-BEAM SCATTERING

To simulate the IBS effect we adopted the macro-particle algorithm, based on the binary collision BCM model, introduced in [8]. The steps of this algorithm can be summarized as follows:

1. The complete lattice is read from MAD output files containing Twiss functions and transport matrices
2. At each element in the ring, the IBS scattering routine is called.
3. A 3D grid is applied to the bunch, and longitudinal slices are assigned to each of the computer processors
4. The particles of the beam are grouped in cells.
5. Particles inside a cell are randomly coupled and momentum is changed because of scattering.
6. Particles are 6D transported to the next element.
7. Radiation damping and excitation effects are evaluated at each turn.

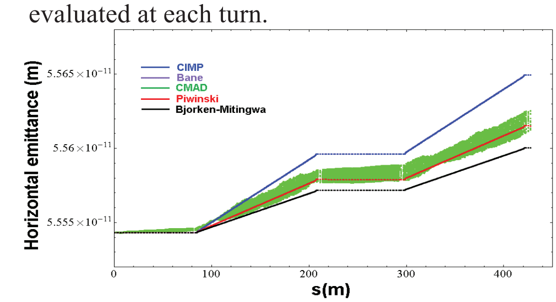

Figure 6: CLIC DR, effect of IBS on the one turn evolution of the horizontal emittance growth. Multi-particle code C-MAD compared with theoretical models.

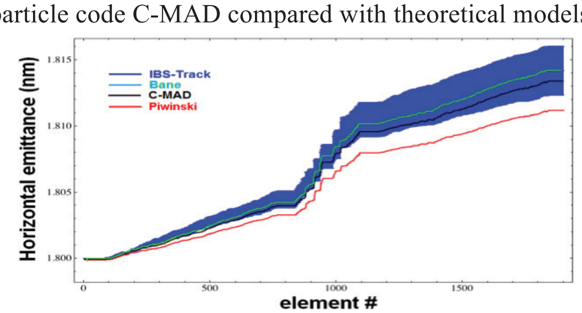

Figure 7: Emittance growth with IBS during one turn in SuperB. C-MAD (black) and IBS-Track (blue) codes, and theoretical models Bane (green) and Piwinski (red).

The code uses as input the MAD generated "sectormap" and "Twiss" files that respectively include the information on the first and second order transfer maps and the Courant-Snyder lattice parameters for each element of the ring. The beam is then 6D tracked along the ring by first order R transfer maps. The code evaluates the emittances along the lattice to verify in which elements the IBS effect is stronger. C-MAD now includes electron cloud, IBS, radiation damping and quantum excitation.

The codes have been used to simulate IBS effects in the CLIC DR and Super-B with parameters shown in Table 1.

Table 1: CLIC DR / Super-B, IBS Simulation Parameters

Parameters	CLIC DR	Super-B
Beam Energy (GeV)	2.86	4.19
Circumference (m)	427.5	1258
Bunch Population (10^{10})	0.407	6.5
Emittances (H/V) (pm)	55.5, 0.58	1818, 4.5
Bunch length (mm)	1.4	4
Momentum spread (%)	0.12	0.066
Damping Times (H/V/L) (ms)	2,2,1	40,40,20
Number of grid cells (H/V/L)	64,64,128	64,64,64

The effect of IBS on the one turn evolution of the horizontal beam emittance growth is shown in Figure 6. Figure 7 shows the IBS effect in Super-B. In both cases, multi-particle simulations are in very good agreement with theoretical models.

Recently, we have included vertical dispersion and betatron coupling, through magnet vertical misalignments and rotation, important to estimate IBS effects and vertical emittance growth. Benchmarking of IBS effects is underway for CesrTA and SLS rings, as discussed in [13].

CONCLUSIONS

We have implemented HEAD-TAIL and C-MAD codes with realistic models of a single-bunch feedback system. Simulations indicate that feedback techniques are very promising to stabilize single-bunch instabilities as Electron Cloud and TMCI. The design and construction of a prototype single-bunch feedback system is on-going for the CERN SPS.

To investigate the effects of Intra-Beam Scattering in detail, we implemented the multi-particle tracking codes. Theoretical models of IBS and simulation codes are in very good agreement. Besides, benchmarking of IBS effects is underway in existing machines with promising results. Very important aspects of the IBS effect on the vertical emittance such as coupling, vertical dispersion, the impact of radiation damping and the possible generation of non-Gaussian tails will be investigated with tracking codes for CLIC Damping Rings and Super-B.

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