FEEDBACK TECHNIQUES AND SPS ECLOUD INSTABILITIES - DESIGN ESTIMATES*

J.D. Fox, T. Mastorides, G. Ndabashimiye, C. Rivetta, D. Van Winkle,
Stanford Linear Accelerator Center, Stanford, CA, USA
J.Byrd, J-L Vay, Lawrence Berkeley Laboratory, Berkeley, CA, USA
W. Hofle, G. Rumolo, CERN, Geneva, Switzerland
R. De Maria, Brookhaven National Laboratory, Upton, NY, USA

Abstract

The SPS at high intensities exhibits transverse single-bunch instabilities with signatures consistent with an Ecloud driven instability. While the SPS has a coupled-bunch transverse feedback system, control of Ecloud-driven motion requires a much wider control bandwidth capable of sensing and controlling motion within each bunched beam. This paper draws beam dynamics data from the measurements and simulations of this SPS instability, and estimates system requirements for a feedback system with 2-4 GS/sec. sampling rates to damp Ecloud-driven transverse motion in the SPS at intensities desired for high-current LHC operation.

INTRODUCTION AND MOTIVATION

The SPS suffers from an electron cloud driven transverse instability [1] for intensities above 1.2E11 per bunch and bunch trains of 72 bunches with 25 ns bunch spacing. In the nominal LHC filling scheme the intensity per bunch is 1.15x11 per bunch and up to 4 batches of 72 bunches are foreseen to be accelerated in the SPS.

Mitigation methods to control the Ecloud driven instability in SPS operation have been developed via scrubbing techniques, adjustment of chromaticity, special vacuum chamber coatings and special chamber geometries. A high frequency vertical feedback system is a complementary approach to the vacuum chamber upgrade, as it could also cure the anticipated single bunch TMC instability [3] [4].Development of a wideband front-end and processing channel also offers improved transverse diagnostics.

The basic system formalism studied in our design estimate is a single-pickup transverse receiver, with a high sampling rate channel which has sufficient bandwidth to sample the bunch vertical coordinate multiple times across the several ns bunch length.The feedback control filter is estimated as a multi-tap FIR filter, though the design study can explore IIR and more complex filter options.

ESTIMATES OF SYSTEM DYNAMICS FROM SIMULATIONS AND MD EFFORTS

Estimation of feedback system specifications must begin with knowledge of the beam and Ecloud dynamics obtained via numeric simulation models as well as from machine measurements themselves [1] [6] [5] [8]. One important effort of 2009 has been to focus attention on comparisons of these multiple estimates, and highlight areas of agreement and understand disagreements in the data.

The data from the non-linear time domain simulations provides time slice displacements of a bunch, for the MD data wideband exponential stripline pickups and sum/difference hybrids are recorded at a 10 - 20 GS/sec rate for post analysis. [8]

The first quantitative information to be extracted is thge oscillation frequency of each slice (longitudinal FFTs of each slice over turns) . Figures 1, 2 and 3 show this simple tune vs. slice analysis for the WARP, HeadTail [1] and MD measurement. In the two simulation cases, there is no coherent excitation or centroid kick at the beginning of the transient - the motion is from the growing Ecloud effect.

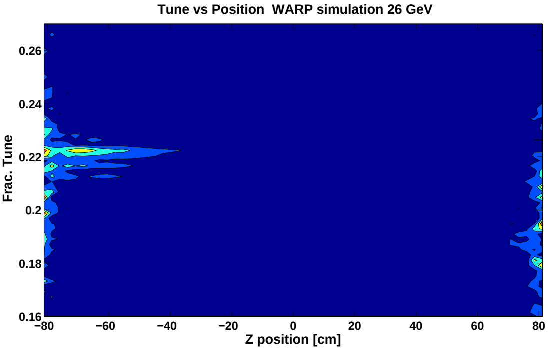

Figure 1: 26 GeV WARP Tune vs.Position data 300 turns of evolution. 1.1E11 p/bunch.

We see unstable motion evolve as the tails of the bunch start growing at shifted tune above the 0.185 betatron tune (the base tune is seen as a weak line in the HeadTail data set). It is very encouraging that all three data sets show shifted Ecloud tunes, though the MD measurement shows motion in all portions of the beam at the shifted tune. The MD measurements also show significant spectral power at low frequencies far from the betatron or shifted Ecloud

---

* Work supported by the U.S. Department of Energy under contract # DE-AC02-76SF00515 and the US LARP program.

[1] The HeadTail simulation code uses a fixed number of samples across the bunch, and as the bunch longitudinal distribution evolves the sampling intervals are not fixed in time. For this sliding window tune analysis we post-process the HeadTail data via an interpolation code which upsamples the bunch coordinates to a higher sampling frequency, then re-samples the bunch information to a fixed sampling interval

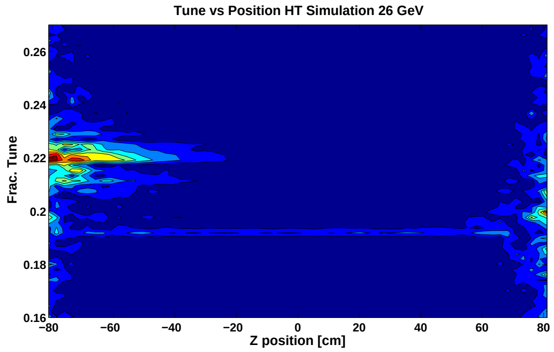

Figure 2: 26 GeV HeadTail Tune vs. Position data 300 turns of evolution. 1.1E11 p/bunch.

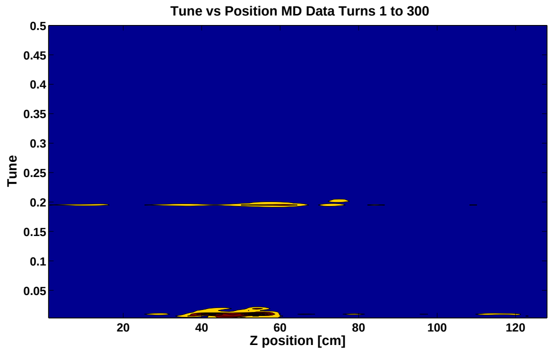

Figure 3: August 2008 MD measurements Tune vs. Position data. Motion of bunch 70 of a 72 bunch batch is shown for 300 turns after injection. The coordinates of each slice position is weighted by the charge per slice to attempt a consistent comparison to the two simulation results. Data is at 26 GeV with 1E11 p/bunch.

tune. More study of the time evolution of these transients is necessary to draw any significance to these differences.

This analysis suggests a feedback bandpass filter processing channel wide enough to control both the betatron and Ecloud motion, and narrow enough to reject the low-frequency noise on the beam. The time delay in the FIR filter and this tune range control requirement will enforce a group-delay gain limit on the control channel. Similarly, if during the accelerating ramp the Ecloud-beam dynamics changes as the bunch length and energy vary, the feedback system must be designed to have good margins over the entire operating range (or track via internal filter changes in synchronism with the beam dynamics evolution).

ESTIMATES OF REQUIRED FEEDBACK BANDWIDTH

To understand the phase relationship between the various oscillating slices (estimate the bandwidth required in the processing), we take the vector of transverse vertical slice offset on each turn, and calculate an FFT of each turn in sesession. This is decomposing the bunch slice motion into a Fourier basis of spatial frequencies (modes) in the bunch. Figure 4 shows averaged spectra from the WARP, HeadTail and MD simulation processed to show the averaged modal amplitudes over the 300 turn initial growth transients. In making conclusions about the spectral content of the MD data we must be careful as it has been low-pass filtered at 1.5 Ghz. The simulation data has no such restriction, and they also show band limited signal components. More measurements and analysis are necessary to confirm this observation. Sampling the Bunch coordinates at 2 - 4 Gsamples/sec. has adequate bandwidth for the growing modes seen in these transients.

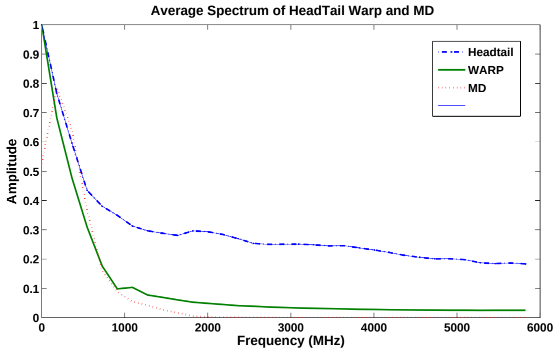

Figure 4: Averaged internal bunch modal spectral amplitudes for WARP, HeadTail and the MD data, all averaged over 300 turns. The spectra bandwidth is similar for all the cases and limited to roughly 1 GHz.

ESTIMATING MODAL GROWTH RATES

The time domain bunch coordinate data shows complex beating with non-exponential trajectories, and we need a method to estimate the fastest growing unstable modes. As a pragmatic choice we project data into a linear coupled-oscillator model[10]. By numeric fitting this model response to simulation or MD data, complex eigenvalues (oscillation frequencies and growth/damping rates) can be estimated. We can then use a linear analytic model of the beam to do the initial feedback design and estimation, allowing tools such as root locus methods to estimate the maximum useful gain and design the stability margins[9]. Once a candidate feedback filter and system operating point is selected using these linear tools, then the feedback model can be evaluated for select cases using the nonlinear time domain models [2][7].

Figure 5 shows the superposition of 200 turn slice trajectories for the numeric simulation and the linear model eigenvalue estimates. The eigenvalue estimates get good agreement for the oscillation frequencies and fit well to the initial transient growth rates, though they cannot model the complex beating and tune shifts that occur at large amplitude in the simulation data. This linear model is important estimating the closed-loop system dynamics and response from noise and disturbances near equilibrium, where the

Ecloud motion first begins. Linear models are being developed for both 26 and 120 GeV simulation data sets.

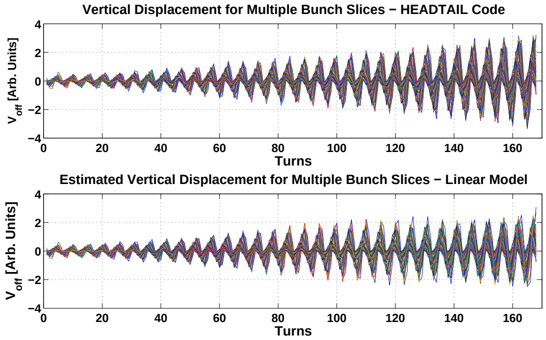

Figure 5: HeadTail Simulation data at 120 GeV vs. fitted eigenvalue linear model for 200 turns of growth. The frequencies and phases are well matched in the two sequences for this quasi-exponential growth from equilibrium.

ESTIMATES OF FEEDBACK SYSTEM COMPUTATIONAL COMPLEXITY

The frequency decomposition into internal modes suggests that a sampling rate of 2 - 4 GS/sec. would allow Nyquist limited sampling of the most unstable modes. This throughput rate sets the scale of the numeric complexity in the DSP processing filter, which is best measured in Multiply/Accumulate operations (MACs)/sec. The SPS processing 16 samples/bunch per turn (16 tap filter) is 6*72*16*16*43kHz or roughly 5 GigaMacs/sec. In comparison, the iGp feedback system at KEKB runs full sampling of 5120 bunches and 500 MHz, 16 tap filters for 8 GigaMacs/sec. rate [11]. The scale of an FIR based control filter using the single-slice diagonal controller model is not very different than that achieved to date with the coupled-bunch systems. What is different is the required sampling rate and bandwidths of the pickup, kicker structures, plus the need to have very high instantaneous data rates, though the average data rates may be comparable.

As each SPS bunch is separated from neighbors by 25 ns a system which implements a full-speed sampling including the interval between the bunches would have significant extra computation. While it is possible to design a system which stops and starts sampling in synchronism with a filling pattern, there are design issues with pipelined processing and internal clock generators in FPGA devices which make this an extra complexity. It is very likely that a practical engineering design would allow the SPS bunch signal to move within the sampling interval as the ramp shifts the synchronous phase and bunch length. For these practical reasons it is likely that an SPS system would have computational complexity similar or greater than the KEKB example, with extra samples taken before and after every populated bucket to allow for this relative motion.

SUMMARY

Much additional analysis and system modeling work is yet to be completed. One vital area that must be estimated is the growth rates of the internal modes, and a base controller designed and validated against linear and non-linear models. We also foresee an important hardware effort to build up a 4 GS/sec. back end modulator and power stage to use in beam testing. This function would allow measurement of beam transfer functions via excitations of a bunch while recording the bunch response in the time domain. Offline analysis would then allow a transfer function estimate of the kicker-beam-pickup system response. This technique would be a very useful diagnostic, as it could be made for stable beam below the instability threshold, where the presence of an electron cloud would be seen in the tune shift and damping change from nominal.

ACKNOWLEDGEMENTS

We thank the SLAC ARD,CERN AB RF departments and the US LARP for support. We thank our collaborators at SLAC,CERN,LBL,KEK and LNF who provide thoughtful ideas and interest in these projects.

REFERENCES

[1] G. Arduini *et al.* 31st Advanced ICFA Beam Dynamics Workshop, Napa, CA, USA, CERN-2005-001,

[2] J. R. Thompson *et al.*, CERN-AB-2008-070, PAC09 FR5RFP076

[3] B. Salvant *et al.*, Proceedings Beam07, p. 113-118, CERN-2008-005, and B. Salvant *et al.* EPAC 08, Genoa, p. 1694-1697

[4] E. Shaposhnikova, "Intensity upgrade plans for CERN-LHC INJECTORS", 42nd ICFA Advanced Beam Dynamics Workshop Nashville, Tenn., USA, 2008, CERN-AB-2008-065

[5] G. Rumolo *et al.*, "Experimental Study of the Electron Cloud Instability in the CERN-SPS," EPAC 08,Genoa, Italy, pp TUPP065 June 2008

[6] Jean-Luc Vay *et al.*, "Simulation of a Feedback System for the Attenuation of E-Cloud Driven Instability", PAC09 FR5RFP077

[7] Jean-Luc Vay *et al.*, " Update on Electron-Cloud Simulations Using the Package WARP-POSINST", PAC09 FR5RFP078

[8] Riccardo De Maria *et al.*,"Performance of Exponential Coupler in the SPS with LHC Type Beam for Transverse Broadband Instability Analysis". 2009 DIPAC MOPD17

[9] L. Beckman, N. Hassanpour, L. Sapozhnikov, D. Teytelman and J. Fox, "Low-mode coupled bunch feedback channel for PEP-II," PAC 03, Portland, Oregon, pp 3389 May 2003

[10] S. Prabhakar, "New diagnostics and cures for coupled-bunch instabilities,", Ph.D. Thesis Stanford University, SLAC-R-554, UMI-99-86494-MC, Feb 2000. 188pp.

[11] K. Furukawa *et al.*,, BEAM INSTRUMENTATION FOR KEK ERL TEST FACILITY, ERL07, Daresbury, UK 2007

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.