ESTIMATION OF ECLOUD AND TMCI DRIVEN VERTICAL INSTABILITY DYNAMICS FROM SPS MD MEASUREMENTS - IMPLICATIONS FOR FEEDBACK CONTROL*

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Abstract

We present analysis of beam motion data obtained in high intensity SPS MD studies in 2009 and 2010. The single-bunch vertical E-cloud motion seen in parts of the bunch train after injection shows large tune shifts (roughly 0.02 above the 0.185 tune) developing between tail and head of unstable bunches. The unstable vertical motion has spectral content up to roughly 1.2 GHz and a quasi-periodic growth and decoherence relaxation oscillation effect is seen with time scales of hundred turns. Beam slice FFT and RMS techniques are illustrated to extract parameters important for the design of wide-band vertical feedback system, such as a growth rates of unstable motion, tune shifts within a single bunch and characterization of the bandwidth of the unstable structures within a bunch. We highlight the impact of synchrotron motion and injection transients on a proposed vertical processing channel. We present our MD plans including the beam driving process, developments in reduced model / identification techniques to extract dynamics from experimental and simulation data.

INTRODUCTION

Earlier work [1] presents summaries of 2009 MD data and analysis techniques used to reveal unstable vertical motion and to help quantify important bandwidth, gain and time structure parameters of the instability observed in the SPS. In this work we continue with new 2010 MD data including TMCI measurements, and develop additional analysis methods. Our overall goal is to extract beam instability dynamics from MD data, as well as from numeric simulation models, and to use information from the models and the MD effort to estimate required feedback system parameters for a wideband channel to control E-cloud and TMCI instability.

DATA ANALYSIS AND OBSERVATIONS

The original analysis methods [1] concentrated on using sliding window FFT techniques to identify tune shifts between portions of the beam as these instabilities develop, and to quantify the internal frequencies. As seen in figure 1 the Ecloud instability shows tune shifts of nearly 0.015 between head and tail. However, the unstable transients showed rapidly developing relaxation oscillation effects [6] and it was difficult to extract simple (exponential) trajectories growing from equilibrium and estimate growth rates for a linear analysis.

While the FFT methods provide insight into the oscillation frequencies and tune spreads, another metric is using total RMS motion of the beam samples (vertical amplitude of all slices added in quadrature). While this approach does not reveal internal modes or frequency structure, it does give insight into the time scale of the instability growth, and relaxation oscillations. As seen in figure 2 this approach clearly shows the time scale of the relaxation oscillations (roughly 130 turns), and makes it possible to estimate an overall growth rate as the motion develops.

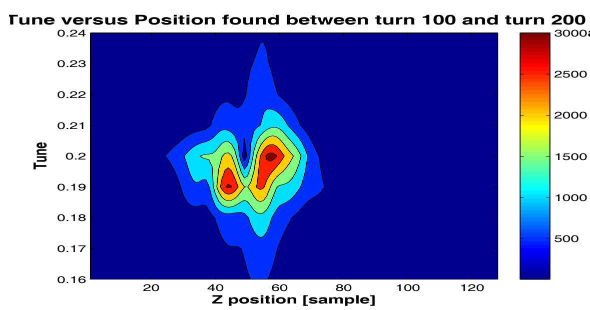

Figure 1: Tune Shift of the Bunch tail about the nominal value of 0.185 due to E-Cloud.

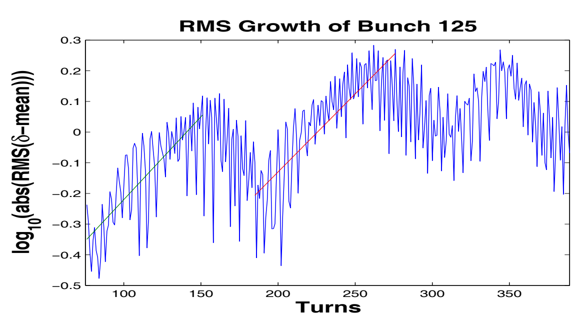

Figure 2: RMS of all slices vs. turn number.

Another focus of this analysis was to compare the E-cloud instability data with the TMCI data, with the intent to understand essential parameters for a common control channel useful to control both instabilities simultaneously. While this work is ongoing, comparisons of the internal frequencies (via FFT techniques) and time scales of devel-

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opment do show differences between the TMCI and Ecloud transients. Figures 3, 4 highlight the frequency content differences and initial conclusions from RMS time studies suggest the E-cloud growth rate is 5 times faster than the TMCI for the cases studied.

One important system consideration revealed in these studies is the impact of the injection transient, and synchrotron motion, on the signals that would be present in a practical feedback system. While these analysis methods suppress synchrotron motion through post processing which time aligns the bunch centroids every turn, significant signal content at the synchrotron frequency is still seen in the transients (possibly from dispersive effects at the pickups). Similarly, the horizontal injection is seen strongly in the vertical processing signal despite the receiver topology using hybrids to isolate horizontal and vertical pickup signals (the horizontal tune is clearly seen at the beginning of the transients). In considering the design of a practical feedback channel, these signals must not mask the true vertical instability signal through saturation effects in the processing filter or power stages, or get impressed as vertical driven motion on the beam.

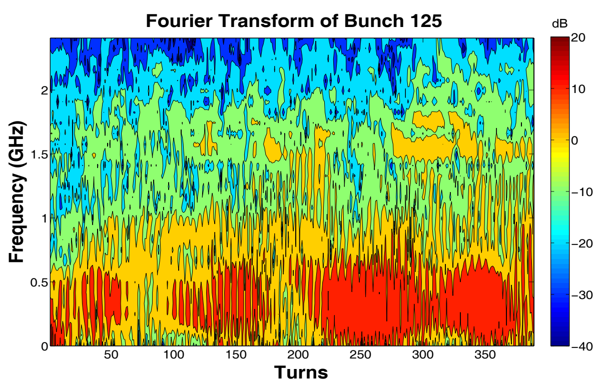

Figure 3: Spectrum at E-cloud motion shows primary content below 500 MHz and relaxation oscilations.

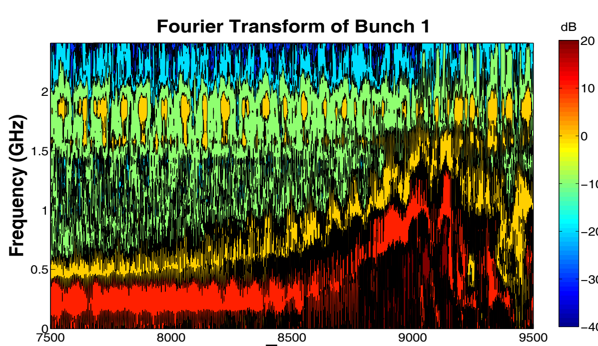

Figure 4: Spectrum for TMCI data shows initial 300-500 MHz signals growing to 1.5 GHz bandwidth.

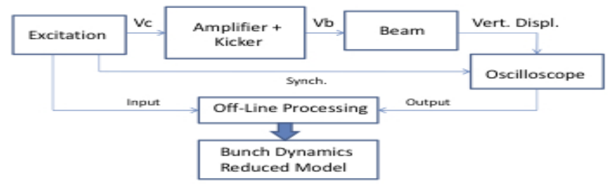

Figure 5: Block diagram for system identification via beam excitation/response measurement.

NEXT MD: DRIVING THE BUNCH

The effort to quantify the system dynamics has used unstable transients to date. While the idea was to watch instabilities develop from injection, and study the interval from injection through small amplitude motion, the actual dynamics, with relaxation oscillations and complex structure in the beam has made it difficult to fit linear models intended for the design of the feedback channel. To help with this goal, we are using system identification methods. For a known input signal one can use the corresponding measured output signal to understand basic dynamics of the system. This approach is applicable to stable beams, though we expect to see changes in the dynamics from the development of the E-cloud and the interaction with the beam as intensity is increased to near the instability threshold. Figure 5 shows the beam excitation via existing diagnostic striplines from a fast 4 Gs/sec digital system with 400W of 20 - 1000 MHz power amplifiers, and observation of the beam response via another set of diagnostic striplines [4]. While the focus of this study is to quantify the internal dynamics of the bunch, it also is a valuable test-bed for the back-end and power stages of a practical feedback system.

REDUCED MATHEMATICAL MODEL AND IDENTIFICATION

Development of reduced (simplified) mathematical models to describe the bunch dynamics is important to design the feedback control taking into account not only the intrinsic bunch dynamics but also noise, system perturbations and other uncertainties and limitations. Our reduced model is represented by coupled harmonic oscillators with time varying parameters. The model represents the vertical coordinates of discrete portions of the bunch and incorporates synchrotron motion of the particles within the bunch. We are investigating methods to identify the bunch dynamics directly from measurements based on the reduced models. While this approach is being directed at MD data, it is also applicable to study of the numeric simulation results, and may provide another method to compare the numeric simulation results to beam data (useful for both stable and unstable data sets).

In general, although linear time invariant (LTI) system identification is well developed, techniques for linear time varying (LTV) systems are less mature. We are using observable canonical forms [7] with some modifications to mitigate our identification problem. Since our system shows time dependent characteristics we use an algorithm in which time is also a parameter. As for the LTI identification, we excite the system with some band-limited inputs and measure system output to this input. Sliding time window techniques are used with the reduced model to identify time varying system parameters. These parameters are used to modify the reduced model until our reduced model and machine measurements match within a certain error bound. Figure 7 shows for a numeric simulation (C-MAD) [12] representative bunch slices, and our reduced model reproduces the output motion for the given input signal. We have some amplitude error at the very end of the 300 turns, some of this deviation is due to initial conditions and small differences between the reduced model and the numeric simulation.

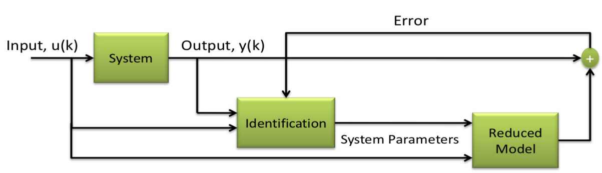

Figure 6: Block diagram of LTV system identification and model parameter estimation.

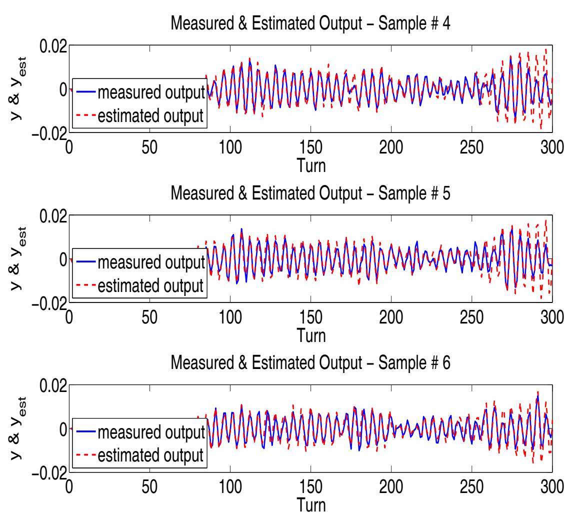

Figure 7: Results show that vertical displacements for different longitudinal bunch slices can be recovered using identification methods for time varying system.

FUTURE WORK AND CONCLUSION

Estimation of a useful feedback system parameters is an ongoing project, and is tightly coupled with parallel efforts to use nonlinear beam simulation models, in conjunction with simplified feedback models, to estimate the dynamics of the controlled system [8], [9], [10]. Our plan is to use the 4 GS/sec beam excitation system in summer 2011 to quantify dynamics below the instability threshold, and to use these measurements to further develop tools to design useful feedback controllers. The next-year goal is to fabricate a limited functionality 4 GS/sec input and processing block, which in conjunction with the existing SPS pickups, and the hardware of the excitation system, could demonstrate the feasibility of these control concepts before the planned 2012 SPS shutdown.

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