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EXPERIMENTAL OBSERVATION OF HEAD-TAIL MODES FOR FERMILAB BOOSTER*

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Abstract

The Fermilab Booster is known to suffer from beam transverse instabilities. An experimental attempt of head-tail modes extraction from the stable beam motion by periodic excitement of betatron motion has been performed. The shapes of head-tail modes have been successfully obtained while eigenfrequencies separation from the betatron tune were too small to be resolved. The qualitative agreement between the theory and an experimental data has been demonstrated. This is an important step towards the understanding of general theory of collective instabilities for strong space charge case, which is a rather typical case for hadron machines.

INTRODUCTION

The goal of experiment was an observation and decomposition of head-tail modes. Usually head-tail modes can be observed when beam is in an unstable regime. Here we used a different approach studying the stable beam motion and exciting a betatron motion by pinging a beam every 100 turns [1]. Further analysis of collected data allowed to resolve the spatial structure of intra-bunch modes. Obtained experimental results have been interpreted according to the existing theory of collective beam motion and they do coincides with existing qualitative picture of beam motion in a Booster. This experimental activity is a very important step in order to build the bridge from theoretical expectations to real machine life; it should help with the further understanding of collective instabilities and possible ways to suppress them or move further the transverse mode coupled instability mode threshold.

FERMILAB BOOSTER

The FNAL Booster accelerator is a proton synchrotron, originally designed and constructed in the beginning of 1970's to match the beam from the linear accelerator to the Fermilab Main Ring, see Fig. (1). Since the 70's the whole accelerator complex has undergone many changes. At the present time, Booster accumulates the 400 MeV proton beam from the LINAC and then gives an intermediate boost to the beam energy. Booster was build as a fast cycling machine operating at 15 Hz which goes through repeated acceleration cycles delivering extracted 8 GeV beam pulses (referred to as a batch) to different experiments or filling the Main Injector ring which is about seven times larger. A multiple turn injection system increases the Booster intensity; it allows to stack successive turns of LINAC beam layered on top of each other. LINAC provides Booster with 400 MeV debunched H^- ion beam. The H^- ions and circulating beam passes through the stripping foil, which removes electrons of the ions and made of a thin layer of carbons. Operationally, the practical limit for maximum intensity is about 7 to 8 turns; fractional turns are not used normally.

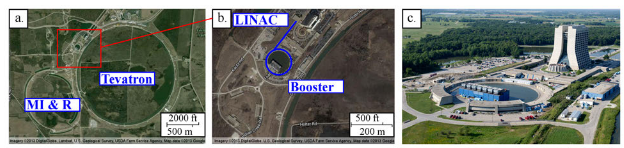

Figure 1: (a.), (b.) Satellite images of the Fermilab site showing Linear Accelerator (LINAC), Booster, Main Injector (MI), Recycler (R) and Tevatron ring. (c.) Photo of the Fermilab Willson Hall, LINAC and Booster.

Booster lattice consists of 96 combined function magnets which are arranged in 24 superperiods of the FOFDOOD-type cells; each superperiod containing two horizontally focusing magnets (F magnet) and two horizontally defocussing magnets (D magnet), along with short (O) and long (OO) straight sections, 1.2 and 6 meters respectively. All magnets are combined function magnets which bend the beam (a dipole magnet function) and focuses the beam either horizontally or vertically (a quadrupole function) and are powered by a resonant power supply with sinusoidal current waveform.

SSC THEORY FOR GAUSSIAN BUNCH

Below we will consider the case of Gaussian bunch which has a special practical importance; it corresponds to a thermal equilibrium when the bunch length is much shorter than the rf wavelength, in which case the longitudinal distribution function is

$$f(v,\tau) = \frac{N_{\rm b}}{2\,\pi\,\sigma\,u(\tau)}\,e^{-v^2/2\,u^2-\tau^2/2\,\sigma^2}.$$

The equation describing strong space charge no-wake head-tail modes for a bunch with Gaussian distribution [2]

$$y''(\tau) + \nu\,e^{-\tau^2/2}\,y(\tau) = 0, \qquad y'(\pm\infty) = 0,$$

leads to **Burov-Balbekov functions**, $y_k^0(\tau)$. The natural system of units is employed: the distance τ is measured in units of the RMS bunch length σ, and, eigenvalues ν_k is measured in units of $u^2/\sigma^2 Q_{\rm eff}(0) = Q_s^2/Q_{\rm eff}(0)$.

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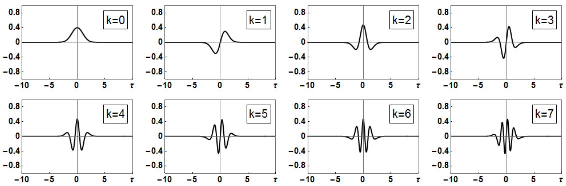

Figure 2: The first eight zero chromaticity local dipole moments of Gaussian bunch, $\rho(\tau) y_k^0(\tau)$.

The full set of eigenfunctions form a full orthogonal basis with normalization

$$\int_{-\infty}^{\infty} \rho(\tau) y_i^0(\tau) y_j^0(\tau)\, \mathrm{d}\tau = \delta_{ij}, \qquad (1)$$

where δ_{ij} is a Kronecker delta and

$$\rho(\tau) = \int_{-\infty}^{\infty} f(\nu, \tau)\, \mathrm{d}\nu = (2\pi)^{-1/2} \exp(-\tau^2/2)$$

is the normalized line density of the beam. Few bunch local dipole moments, $\rho(\tau) y_k^0(\tau)$, are plotted in Fig. 2, and proportional to the signal induced by each mode on the plates of ideal linear bunch-by-bunch pickup. These dipole moments are subject of interest, and we will try to decompose them from experimental data.

HEAD-TAIL MODES OBSERVATION EXPERIMENT

Experimental Setup

The experimental data gathered for the regular operational setup of the Booster. Data has been obtained for two settings of chromaticity and three different intensities provided by 3, 7 and 14 turns of injection from LINAC. Data collection has been performed at 4 different time spots in a Booster cycle. Here we will present results for 3 turns of injected beam (0.63×10^{12} particles) right before the transition (16.40 msec from the beginning of the Booster cycle).

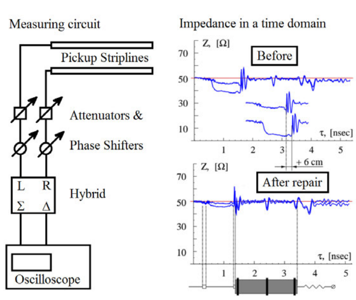

Figure 3: Schematic draw of the measuring circuit for head-tail modes observation experiment (left figure) and impedance in a time domain of pickup striplines before and after repair (right column of figures).

In order to excite head-tail modes all bunches were pinged every 100 turns in both directions. Fig. (3) shows the experimental setup. Signals from plates of a Booster pickup go to oscilloscope with 10 GSample/sec resolution through the passive hybrid in order to maximize signal-to-noise ratio in difference signal; hybrid convert signals form left and right plates (or top and bottom ones) to difference, Δ, and sum ,Σ, signals. Attenuators and phase-shifters are used in order to exclude common mode from signal.

Decomposition of Head-tail Modes

In order to extract head-tail modes, one can construct the following matrix consisting of signals obtained for train consisting of 81 bunches and N turns:

$$\left[\Xi^{(1)}(1), \ldots, \Xi^{(1)}(N), \ldots, \Xi^{(81)}(1), \ldots, \Xi^{(81)}(N)\right]^{\mathrm{T}},$$

where

$$\Xi^{(k)}(n) = \frac{\Delta^{(k)}(n)}{\sqrt{\Sigma^{(k)}(n)}}.$$

Such a choice of $\Xi^{(k)}(n)$ ensures the normalization condition given by Eq. (1).

Performing the singular value decomposition (SVD) one will obtain spatial and time modes along with corresponding singular values showing the amplitudes. Spatial mode represents an intra-bunch structure, $\rho(\tau) y_k^0(\tau)$, while time mode shows its behavior over turns. Further split of time mode for different bunches with subsequent Fourier allow to see spectrum of corresponding spatial mode (such a spectrum for different bunches should be added to each other to reduce noise). Few first and last bunches in a train can be dropped out of matrix in order to minimize the effect of the notch. Results are presented in Figs. (4,5). As one can see first mode responds on unity frequency and accounts for betatron motion of a beam; its time mode almost a constant over turns and spatial mode shows remnant from hybrid. Almost all further modes responds on a frequency close to a betatron one and correspond to a strong space charge head-tail modes.

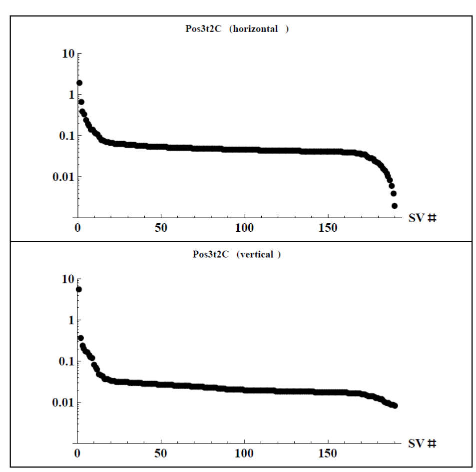

Figure 4: SVD singular values for horizontal and vertical degrees of freedom respectively.

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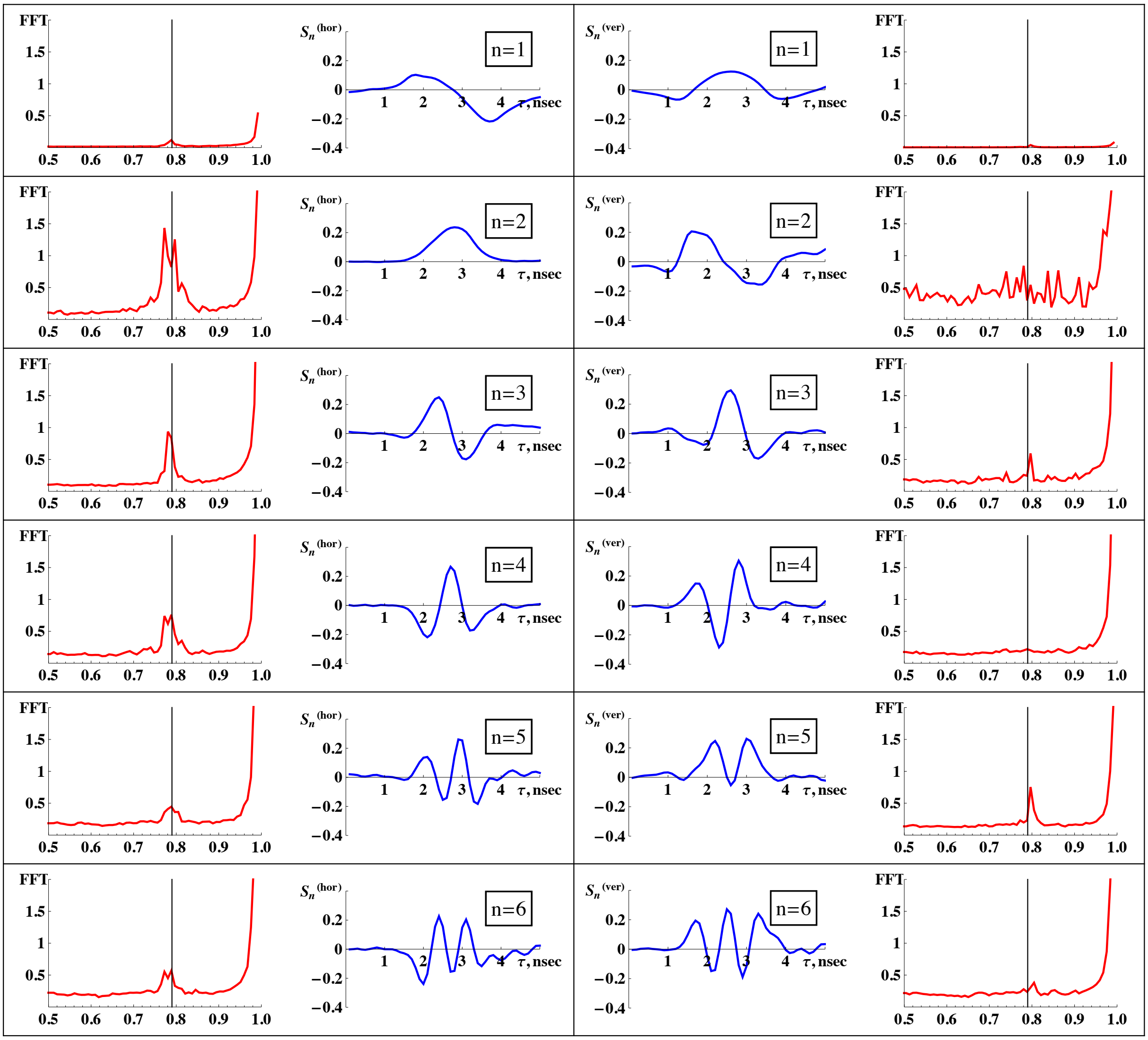

Figure 5: Local dipole moments of Booster beam (spatial modes of SVD) for horizontal and vertical degrees of freedom (second and third columns respectively) and averaged spectrum of their time modes (first and fourth columns respectively). Circular modes before the transition ($\nu_x = \nu_y = 6.79$).

SUMMARY AND CONCLUSIONS

The theory of collective instabilities for strong space charge [2] needs to be compared with both, simulations and measurements. Usually only in the case of unstable beam one (or two) most unstable modes can be observed. An attempt to directly observe head-tail modes from the stable beam motion has been performed in order to experimentally verify SSC theory and obtain additional information about other (not only most unstable) collective modes. Based on studies performed at FermiLab Booster ring we were able to extract up to 8 modes for both horizontal and vertical degrees of freedom associated with collective beam motion [1]. Those modes are very close to the prediction of model while it should be emphasized that shape of modes slightly perturbed, which is due to signal distortion in a measuring circuit and idealization of processing algorithm; the Singular Value Decomposition technique used in analysis provides orthonormal space and time functions which is not a true case when we have either unstable mode or strong decoherence. Notwithstanding that experimental setup were pushed to the available limit, unfortunately the resolution of collected data did not allow to resolve eigenfrequencies, which are just slightly separated for the case of strong space charge. The studies have been performed for different intensities and two different post-transition chromaticity setups. The change of modes shape is in agreement with theory prediction: the increase in intensity enhance the wake influence and modes becomes more asymmetric. The qualitative agreement in between theory and experiment has been demonstrated. This result is an important step towards the development of a theory of instabilities for space charge dominated beams.

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