MEASUREMENT AND CORRECTION OF THE 3RD ORDER RESONANCE IN THE TEVATRON

Y. Alexahin, V. Lebedev, D. Still, A. Valishev, FNAL, Batavia, IL 60510, F. Schmidt, CERN

Abstract

At Fermilab Tevatron BPM system has been recently upgraded resulting in much better accuracy of beam position measurements and improvements of data acquisition for turn-by-turn measurements. That allows one to record the beam position at each turn for 8000 turns for all BPMs (118 in each plane) with accuracy of about 10-20 μm. In the last decade a harmonic analysis tool has been developed at CERN that allows relating each FFT line derived from the BPM data with a particular non-linear resonance in the machine. In fact, one can even detect the longitudinal position of the sources of these resonances. Experiments have been performed at the Tevatron in which beams have been kicked to various amplitudes to analyze the 3rd order resonance. It was possible to address this rather large resonance to some regular machine sextupoles. An alternative sextupole scheme allowed the suppression of this resonance by a good factor of 2. Lastly, the experimental data are compared with model calculations.

INTRODUCTION

In order to reduce the beam-beam effects there are two options under consideration for a new Tevatron working point: one with tunes just above half integer values and the other with the fractional tunes between 2/3 and 7/10 (SPS working point) [1].

Both choices are freighted with specific difficulties, the latter one with closeness to the third order resonances which can be excited by both magnet nonlinearities and long-range beam-beam interaction.

Magnetic field in Tevatron superconducting magnets is formed mainly by coils and therefore has larger non-linear components in comparison with normal warm magnets of the same aperture. But there is another complication for superconducting magnets related to the persistent currents which make non-linear components to be time-dependent (see Ref. [2,3] and references therein). Although a full set of magnetic measurements was carried out for each magnet before its installation in the tunnel, there is little trust in the magnetic measurements of sextupole component. At the time of the measurements it was unknown that the sextupole component strongly depends on time due to persistent currents. Therefore the time of each measurement in the magnet hysteresis cycle was not specified and, consequently, sextupole strength at given time is unknown. Special sextupole circuits correct time dependent chromaticity of the entire ring but redistribution of sextupole component along the ring has not been known.

Strong sextupole fields produce large difference in tunes and coupling on the proton and pbar orbits which is compensated with the help of dedicated feeddown sextupole circuits. There are seven FD circuits, labeled S1-S7, with S1, S2, S3 and S6 being employed at injection to correct differential horizontal and vertical tunes and two components of coupling respectively. The S6 circuit is comprised of just two sextupoles which have to run at a high current since the phase advance difference at their location to S3 family is far from the optimal value of 90°.

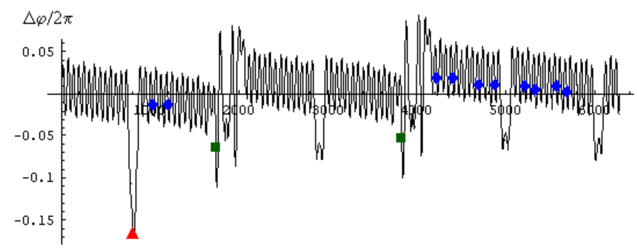

Figure 1: Phase advance difference around the ring, positions of S3 (blue diamonds), S6 (green squares) and S6A0 (red triangle) sextupoles are highlighted.

To achieve a complete decoupling on both orbits the S6 current of 19A was needed. This led to a high sensitivity of tunes on the orbit drift, ~.005/mm. To alleviate the problem the requirement on coupling was relaxed to C≤0.004, allowing to reduce the S6 current to 11A.

As a precaution, in 2004 a warm sextupole, S6A0, was installed at a place with more favorable phase advances (see Fig.1) but has never been used.

THEORETICAL BACKGROUND

For the first time in 1988 [4] the accelerator community has started using TBT data to evaluate the sextupole strength in a real accelerator. Further studies have shown [5] that, in first order approximation, each line in a complex FFT of the TBT data can be related to a resonance. Specifically, the TBT spectra of complex dynamic variables which can be reconstructed from readings of two BPMs as

$$a_z = \frac{i e^{iQ_z \theta}}{\sin(\varphi_{z2} - \varphi_{z1})} \left(\frac{z_1}{\sqrt{2\beta_{z1}}} e^{-i\varphi_{z2}} - \frac{z_2}{\sqrt{2\beta_{z2}}} e^{-i\varphi_{z1}} \right), \quad z = x, y \, .$$

$\theta = s/R$ being the generalized azimuth, provides immediate information on generating functions of the transformation bringing these variables to the normal form [5].

It is instructive to highlight how the spectrum lines can be related to resonances, e.g. all purely horizontal resonances of sextupoles. Sextupoles drive the (3, 0) resonance and the so called sub-resonance (1, 0). These resonances appear in the FFT line spectrum as the 3 lines (-2, 0), (0, 0) and (+2, 0) respectively.

Generally, term $f_{jklm}(\theta)a_x^j a_x^{*k} a_y^l a_y^{*m}$ in the generating function - corresponding to a similar term in the Hamiltonian with coefficient $h_{jklm}(\theta)$ - manifests itself as $(j\text{-}k\text{+}1)Q_x\text{+}(l\text{-}m)Q_y$ (k>0) line in the horizontal spectrum with amplitude $|f_{jklm}(\theta)|I_x^{(k+j-1)/2}I_y^{(l+m)/2}$, $I_z = |a_z|^2$ being the action variable.

More recently, it has been demonstrated (see [6] and references therein) how the generating functions vary around the ring: they propagate as $f_{jklm}(\theta) \sim \text{const}\times\exp\{-i[(j-k)Q_x+(l-m)Q_y]\theta\}$ in the perturbation-free regions and experience abrupt jumps at the longitudinal position of sources of non-linearities. It has also been shown how the tunespread in ensemble of many particles modify the line spectrum of TBT data.

The next important step is to evaluate from the TBT data the resonance driving terms (RDTs) which we define as

$$R_{j-k,l-m} = \frac{1}{\pi}\int_0^{2\pi} h_{jklm}(\theta)e^{in\theta}d\theta = \frac{\Delta}{\pi}\int_0^{2\pi} f_{jklm}(\theta)e^{in\theta}d\theta$$

where n =Round[$(j\text{-}k)Q_x\text{+}(l\text{-}m)Q_y$]. Δ=$(j\text{-}k)Q_x\text{+}(l\text{-}m)Q_y\text{-}n$. This is the value that enters the formula for the resonance width.

MEASUREMENTS AT TEVATRON

The measurements were performed at injection energy. Horizontal dipole oscillations of the beam were excited by a single turn kick with variable amplitude. Data were recorded at each BPM for 8000 turns. Figure 2 shows an example of turn-by-turn data for 3 different amplitudes, A=15, 20, 25 units, for the largest kick the S6 sextupole has been switched off.

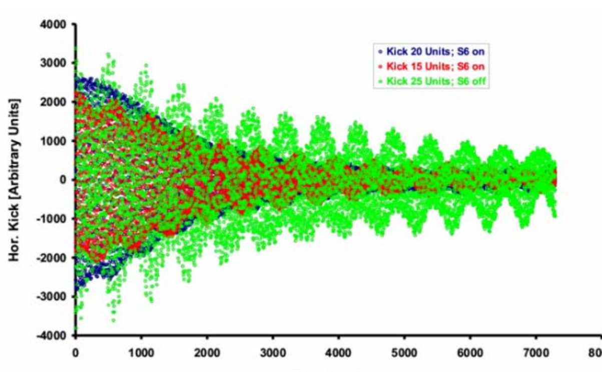

Figure 2: TBT raw data 7300 turns after the kick. Three cases are shown: with the sextupoles S6 switched on with A=20 and 15 units and without this special sextupoles for A=25 units.

The S6 sextupoles create strong detuning with amplitude, i.e. only without the S6 sextupoles the signal (green in the picture) is ringing without much decoherence for many turns.

Figure 3 presents the corresponding spectrum at one of BPMs.

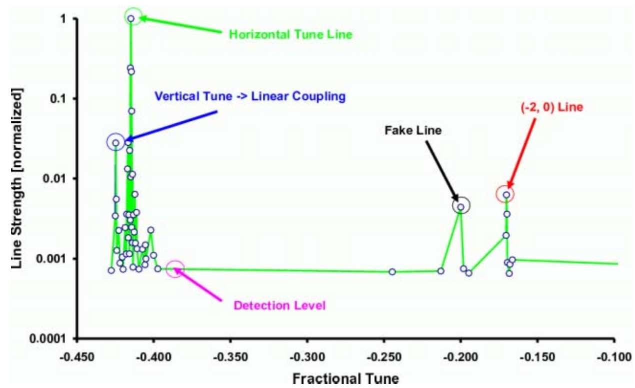

Figure 3: Spectrum of the turn-by-turn signal at one BPM. Kick amplitude 20 units, S6 on.

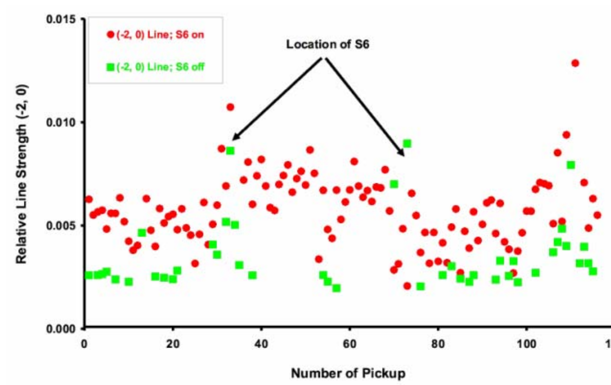

Figure 4: Sextupole Line (-2, 0) as a function of pick-up number starting from HF19.

Figure 4 presents the dependence of spectrum line (-2, 0) on BPM number for two cases: with the S6 sextupoles switched on (red dots) and switched off (green squares). This sextupole family increases the overall sextupole components by a factor 2. Moreover, at the two longitudinal locations where they sit in the machine the sextupole term changes by 50 % respectively.

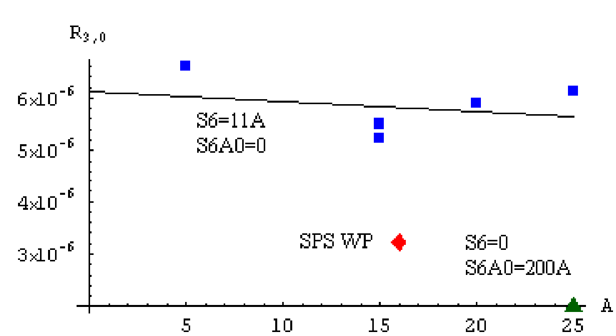

Figure 5: RDT of the (3, 0) resonance vs. kick strength A [π·mm·mrad].

Figure 5 presents dependence of RDT of the (3, 0) resonance on the kick strength A [π·mm·mrad]. The blue boxes show values obtained under nominal conditions: Q_x=20.585, Q_y=20.575, I_S6=11A. Red diamond shows the value measured with tunes moved to Q_x=20.686, Q_y=20.677. Finally, green triangle shows the value obtained with the nominal tunes, S6 sextupoles turned off and S6A0 sextupole turned on with current higher than 160A necessary for compensation of differential coupling.

There are three measurements at A=15 taken on three different occasions: 10/19/2005, 11/04/2005 and 11/18/2005. Small scatter in the $R_{3,0}$ values testifies for good precision of the method at sufficiently large kick amplitudes and stability of the machine. Variation in $R_{3,0}$ with the kick strength is insignificant and most probably is the result of the kicker calibration errors.

With the tunes moved to the SPS working point $R_{3,0}$ becomes by 40% smaller which can be attributed to the changes in phase advances between the sources of sextupole non-linearities.

The most remarkable result is the drastic reduction - by a factor of 3 - in $|R_{3,0}|$ value when S6 sextupoles were turned off and S6A0 sextupole was powered instead.

Table 1

case	$\|R_{3,0}\|\times10^6$	arg $R_{3,0}$
nominal	6.1	146°
S6=0, S6A0=200A	2.0	-33°
S6 only, analytics	5.7	44°

Table 1 shows that at the same time the phase of $R_{3,0}$ changed by 180°: this means that by choosing a proper combination of S6 and S6A0 currents it should be possible to achieve practically complete cancellation of the horizontal 3rd order resonance. For reference Table 1 also cites the analytically obtained $R_{3,0}$ value for S6 sextupoles alone.

Preliminary results obtained under the nominal conditions show that 3rd order sum resonances are also quite strong: $|R_{2,1}|=4.7\cdot10^{-6}$, $|R_{1,2}|=4.3\cdot10^{-6}$, whereas $|R_{0,3}|=0.9\cdot10^{-6}$. Possibility of correction of nonlinear sum resonances has not been studied yet.

NONLINEAR TEVATRON MODEL

In order to validate the measurement results a tracking study has been performed resembling the experiment. The machine model used in simulation was derived from differential orbit data [1] and includes all available details: gradient errors with precision of 0.001, sextupole component in dipole magnets, and lattice sextupoles. Two cases have been simulated, with S6 sextupoles turned on and off. Particle positions have been sampled turn-by-turn at locations of BPMs similar to the real Tevatron data. Figure 6 shows the result of processing of these data. Very good qualitative agreement is seen between the behavior of sextupole line (-2,0) observed in experiment (Fig. 4) and simulated numerical study (Fig. 6).

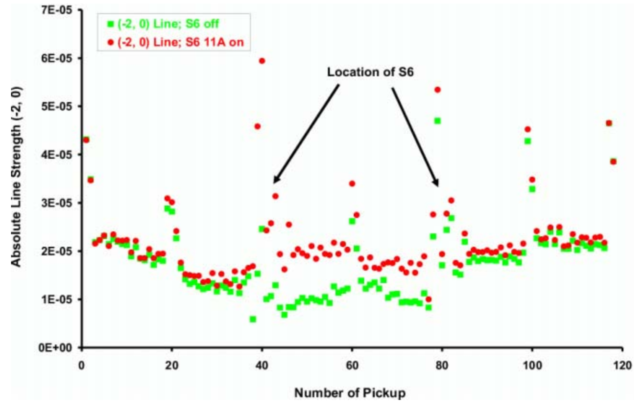

Figure 6: Sextupole Line (-2, 0) as a function of pick-up number starting from HF0D (Numerical simulation). Note, that index on the horizontal axis is different from Fig. 4.

CONCLUSIONS

New Tevatron BPM system showed excellent performance both for closed orbit and turn-by-turn measurements. High resolution of the BPMs allowed us to perform the first reliable measurements of Tevatron sextupole non-linearity. The analysis identifies locations of strong sources of sextupole fields and determines the resonance driving terms. The method should permit compensation of the third order resonance required for change of Tevatron working point.

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