# TURN-BY-TURN MEASUREMENTS AT THE KEK-ATF

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*Abstract*

The ATF damping ring has been upgraded with new read-out electronics for the beam position monitors (BPM), capable to acquire the beam orbits on a turn-by-turn basis, as well as in a high resolution averaging mode. The new BPM system allows to improve optic corrections and to achieve an even smaller vertical emittance (<2pm). Experimental results are presented based on turn-by-turn beam orbit measurements in the ring, for estimating the $\beta$ functions and dispersion along the lattice. A fast method to measure spectral line amplitude in a few turns is also presented, including the evaluation of chromaticity.

## INTRODUCTION

The Accelerator Test Facility (ATF) Damping Ring (DR) has successfully achieved emittances which are close to the ILC requirements [1]. In this context, the 96 new BPM electronics with turn-by-turn capability are an important diagnostics and optimization tool [2]. The turn-by-turn measurements over, e.g. 1024 turns can be used to measure amplitude, phase and frequency of the spectral components at each BPM using Laskar's NAFF algorithm [3] or SUSSIX [4]. From the measurement of these spectral lines at each BPM, Twiss functions can be deduced, allowing to compute a correction (see [5], software developed for the optics measurement and correction in the LHC and adapted to ATF). Dispersion and amplitude of the energy oscillation can also be deduced.

Also, all 96 BPM measurements can also be combined to obtain amplitude and frequencies of spectral lines within just a few ten turns [6]. This allows to measure the evolution of the betatron tunes along the recorded time span, enabling the estimation of chromaticity.

Results, analysis, and some preliminary interpretation of the turn-by-turn BPM data from the ATF DR are presented, using the above mentioned methods.

## TWISS FUNCTION DETERMINATION ANALYZING EACH BPM INDIVIDUALLY

Horizontal and vertical positions are measured during the first 1024 turns after beam injection into the DR. The data is cleaned, by removing residual BPM noise using a Singular Value Decomposition (SVD) analysis. The tunes are determined by Fourier transforms of the position signal from all BPMs. Hamming and Hann window functions have been tried out to further reduce the noise. Figure 1 shows the spectra averaged over all BPMs using these window functions:

$$\begin{aligned}
&\text{Hann windows:} && w(n) = 0.5\left(1-\cos\left(\frac{2\pi n}{N-1}\right)\right)\\
&\text{Hamming windows:} && w(n) = 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right)\\
&\text{FT}\,(s)\ \text{with window:} && S(k) = \sum_{n=0}^{N-1} s(n)w(n)e^{-2i\pi k\frac{n}{N}}
\end{aligned} \quad (1)$$

Due to the fast decoherence in the ATF DR, the oscillation amplitudes are only large during the first few turns, therefore the window functions decrease the amplitude of the spectra (approximately by a factor of 10). However, noise is effectively reduced, and sidebands near the main tune signal become visible. These sidebands are even clearer when window functions are used (see Fig. 2). The Hann window has been chosen, as it gives the best signal-to-noise ratio.

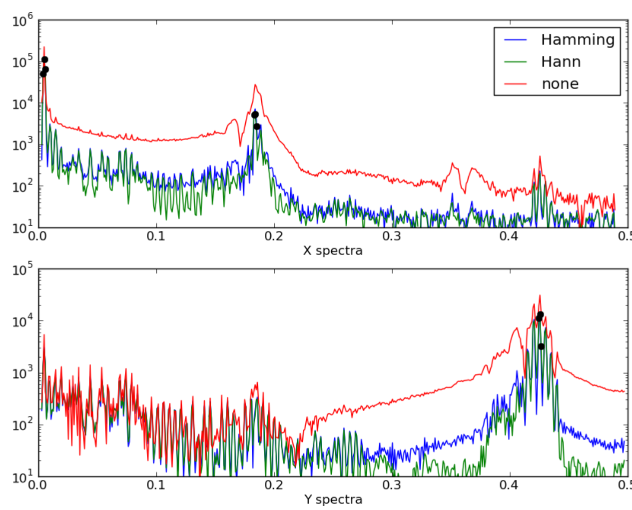


Figure 1: Average over the 96 BPMs of the spectra of the beam position during one thousand turns after injection .

Once the tunes are identified by searching for the maximum peaks, a detailed frequency analysis[3] was performed at and in proximity of the tunes, as well as at other spectral frequencies of interest. This method returns frequency, phase and amplitude of the spectral lines with much higher precision than the standard FFT.

$\phi_x$ and $\phi_y$ correspond to the phase of the spectral lines $(1,0)_h$ and $(0,1)_v$ respectively. $\beta_x$ and $\beta_y$ functions are obtained from the model and from the measured $\phi_x$ and $\phi_y$ (as described in [7]).

The betatron phase calculation is not affected by BPM calibration errors,therefore this method returns accurate phase results. The procedure estimates the $\beta$ functions for every 3 consecutive BPMs, its application around the ring



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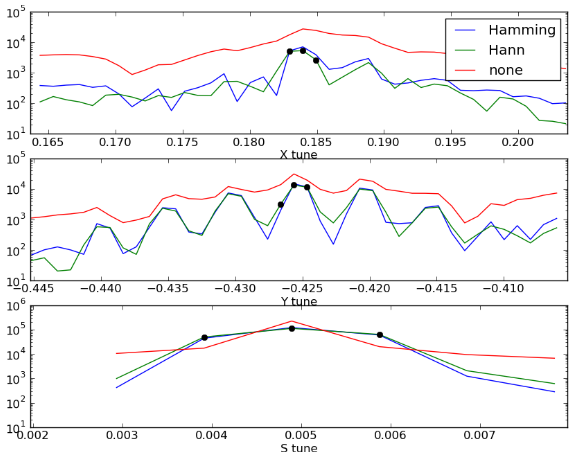


Figure 2: Average near the tunes over the 96 BPMs of the spectra of the beam position during one thousand turns after injection .

provides three different values per BPM, allowing an error estimation (see Figs. 3 and 4).

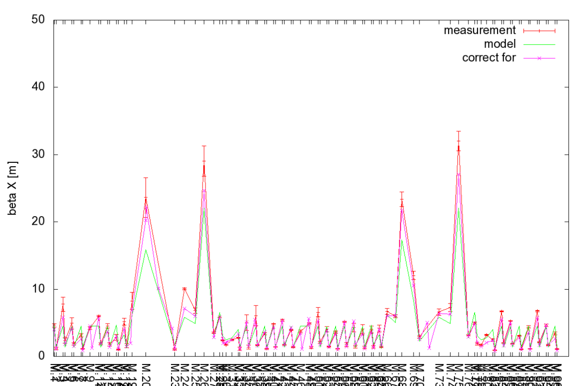


Figure 3: Nominal $\beta_x$ compared to measurement using the phase of the spectral line $(1,0)_h$. "Correct for" line correspond to what must be the measurement in order to have a nominal lattice after applying the computed correction.

Taking the measured betatron amplitude and phase injection mismatch, also the response matrices obtained by varying quadrupole strengths in MAD, we were able to compute a correction to reduce the $\beta$ beating, based on a least square minimization.

The amplitude of the spectral line at $f = Q_s$ in the horizontal plane $A_{Q_s}$ is proportional to the horizontal dispersion $D_x$ and to the amplitude of the relative energy oscillation $\frac{\Delta E}{E}$ (the factor 2 accounts for the spectral mirror component at $f = -Q_s$):

$$2A_{Q_s} = D_x \frac{\Delta E}{E} \tag{2}$$

The factor $2\frac{\Delta E}{E}$ is fitted to minimize the difference between the amplitude of the synchrotron tune and the dispersion from model. The same factor is used to measure the vertical dispersion from the amplitude of the synchrotron tune in the vertical plane. That factor is fitted using all BPMs, therefore is not much compromised by individual BPM scale errors. Figure 5 shows the result of this measurement. The fit determines the value of $\frac{D_x}{A_{Q_s}}$ which gives the amplitude of the relative energy oscillation $\frac{\Delta E}{E} = 2\frac{A_{Q_s}}{D_x}$.

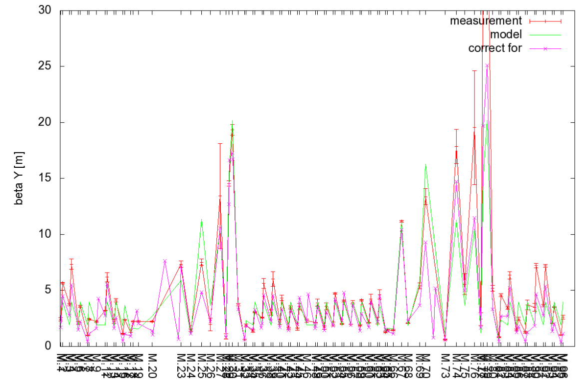


Figure 4: Nominal $\beta_y$ compared to measurement using the phase of the spectral line $(0,1)_v$. "Correct for" line correspond to what must be the measurement in order to have a nominal lattice after applying the computed correction.

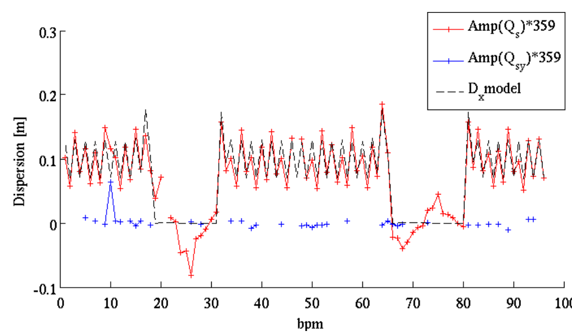


Figure 5: Measured horizontal (red) and vertical (blue) dispersion, as compared to the model (green). Note that the vertical model dispersion is zero.

## FAST SPECTRAL LINE MEASUREMENT COMBINING SEVERAL BPMS

When the BPMs are distributed regularly around the ring, one can use the sequential reading through all the BPMs as in [6] instead of acquiring turn-by-turn data of an individual BPM as in [3]. The phase information of the spectral line at each BPM is lost, just global values of frequency and amplitude of the spectral lines are found. This method reduces the number of turns required by dividing it by the number of BPMs. For example measuring tunes and amplitude of spectral lines can be done in few ten turns instead of about 1000 turns, as in the ATF DR 96 BPMs are available.

Care has to be taken to multiply the frequency obtained this way by the number of combined BPMs. Also fractional




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tunes $< 1/(2N_{turns})$ cannot be probed (that is why 400 turns have been used for the estimation of the synchrotron frequency).

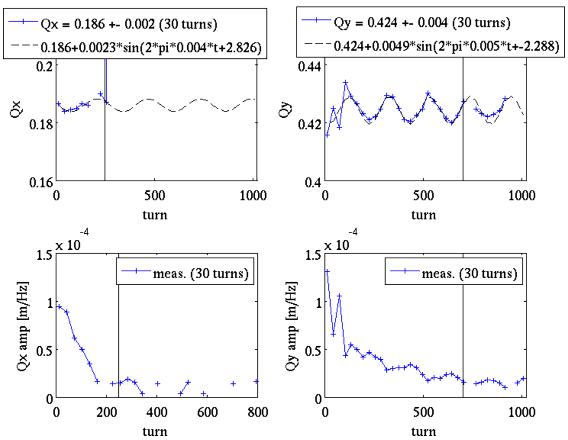


Figure 6: Fractional tune (upper plots) and amplitude (lower plots) of the horizontal (left plots) and vertical tunes (right plots) measured every 30 turns.

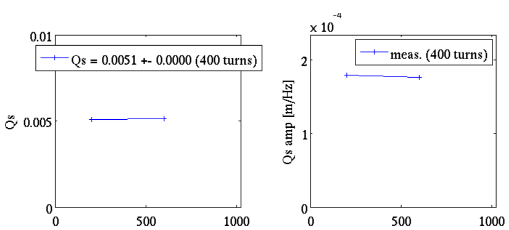


Figure 7: Fractional tune (left plot) and amplitude (right plot) of the synchrotron tune measured every 400 turns.

A frequency analysis was performed on 30 turns using the data of all BPM combined to compute amplitude and frequency of the tunes. Their evolution during the first 1000 turns is shown in Figs. 6 and 7. We can see the rapid decrease of the horizontal and vertical tune amplitudes due to the decoherence, but the synchrotron tune amplitude seems almost constant. The tune modulation, due to the synchrotron oscillations in presence of chromaticity is very clear on the vertical plane, but not so much in the horizontal plane, as the oscillation amplitude drops bellow the detection limit after 200 turns, which correspond to just one synchrotron oscillation.

By definition, the chromaticity $Q'$ is the tune shift $dQ$ divided by the relative energy variation of the beam $\frac{dE}{E}$:

$$Q' = \frac{dQ}{\frac{dE}{E}} \qquad (3)$$

If we look at the amplitude of the tune modulation $\Delta Q$ (the factor in front of "sin" in Fig. 6) which is caused by the chromaticity $Q'$ in presence of a relative energy oscillation of amplitude $\frac{\Delta E}{E}$ we get:

$$\Delta Q = Q' \frac{\Delta E}{E} \qquad (4)$$

As the longitudinal damping time is much larger than our 1000 turns acquisition period, and as the beam energy is constant, the amplitude of the energy oscillation $\frac{\Delta E}{E}$ can be assumed constant. For small amplitudes, the beam is making a circle in the longitudinal phase space, $(\frac{\Delta E}{E}, z)$, i.e. $\frac{\Delta E}{E} = \left| \frac{\Delta E_O}{E} + i \frac{\sigma_E}{\sigma_z} z_0 \right|$, with $\frac{\Delta E_o}{E}$ the relative energy mismatch at injection and $z_0$ the longitudinal position of the beam at injection.

Using the previously fitted $\frac{\Delta E}{E}$ value obtained previously (see Fig. 5), we can determine the chromaticity:

$$\begin{aligned} Q'_x &= \frac{\Delta Q_x}{\frac{\Delta E}{E}} = \frac{\Delta Q_x}{2 * \frac{A_{Q_s}}{D_x}} = 0.41 \\ Q'_y &= \frac{\Delta Q_y}{\frac{\Delta E}{E}} = 0.88 \end{aligned} \qquad (5)$$

## CONCLUSION AND PROSPECTS

A method to measure the Twiss functions, as well as a method to measure the dispersion using turn by turn BPM measurements are presented, including experimental results. The measurement of the dispersion also allows the estimation of the amplitude of the relative energy oscillations.

A method to retrieve the spectral line amplitudes with a few turns by combining turn-by-turn data of all BPM has been successfully demonstrated. In the presence of energy oscillations, the tune is modulated at the synchrotron frequency and the amplitude of this modulation can be used to measure the chromaticity.

The corrections of betatron amplitude and phase mismatch, based on these measurement methods will soon be evaluated, in our simulations the method looks very promising. Similar measurements for coupling and sextupoles induced resonances are also considered for future studies.

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