CHROMATICITY MEASUREMENTS IN THE ESRF BOOSTER

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Abstract

In view of optimising the performance of the ESRF Booster, a series of experiments have been conducted in order to measure the chromaticity during the cycle for different sextupole settings. To this end, the betatron tunes were measured for different values of the RF frequency using the new tune-meter application. The experimental results were finally analysed and compared to theoretical data of the Booster model, showing good agreement.

THE ESRF BOOSTER

The ESRF Booster is a 300 m electron synchrotron which serves as the injector to the ESRF storage ring [1]. It accelerates electrons, coming from a 200 MeV linac, to a final energy of 6 GeV in 50ms and extracts them into the storage ring with a repetition rate of 1-10 Hz. The lattice is based on a FODO structure with a missing dipole, forming 39 cells with 12 straight sections and respecting a 3-fold symmetry. All magnets of the same family are independently powered by a resonant "white circuit", cycling at 10 Hz. The optics functions computed with MAD [2], along one super-period, for the nominal working point at injection $(11.8, 9.8)$, are pictured in Fig. 1 and a set of basic Booster parameters is displayed in Tab. 1.

Table 1: Main ESRF Booster parameters.

Parameter	Value
Circumference C	299.622 m
Extraction Energy E_{ext}	6 GeV
Repetition rate f_{rep}	1-10 Hz
Harmonic number h	352
Accelerating cycle t_{cycle}	50 ms
Working point (Q_x, Q_y)	$(11.8, 9.8)$
Momentum compaction factor α_c	9.6 10^{-3}
Emittances at 6GeV $(\epsilon_{x;\text{ext}}, \epsilon_{x;\text{ext}})$	(120,3) nm rad
Energy spread at 6GeV $(\delta E/E)_{\text{ext}}$	1.1 10^{-3}
Bunch length l_s	2.61 cm (87 ps)
Nominal current I_{nom} (long bunch)	5 mA

The chromaticity control is essential for the good performance of the Booster, especially at low energies. A new challenge under development is the cleaning of parasitic bunches inside the Booster [3]. This process, usually done in the storage ring, will enhance the bunch purity, improving the performance, especially of the "few-bunches" modes available for users at the ESRF, in the newly implemented "front-end" open operation procedure. For this purpose, the control of beam parameters such as the tune or the chromaticity are fundamental.

Two families of 21 horizontal and 30 vertical sextupoles are used to control the chromaticity in the Booster. A large amount of theoretical and experimental studies were performed a few years ago [4], including chromaticity measurements [5]. However, due to the poor performance of the tune meter, the accuracy of these measurements was not better than 10% as compared to theoretical calculations, especially for the horizontal plane. With a new tune monitor system installed, we aimed to improve these measurements with respect to precision and reproducibility. The method for measuring the chromaticity is straightforward: the RF frequency is varied and thus the momentum spread of the beam is changed. For small variations, the chromaticity should be a linear function of the tune shift, $\xi_{x,y} = -\alpha_c f_{\text{RF}} \frac{\Delta Q_{x,y}}{\Delta f_{\text{RF}}}$. Note that the momentum compaction factor α_c is normally a constant depending on the lattice. An independent measurement of this parameter can be done through the measurement of the sychnotron frequency for different accelerating voltages [4]. Taking into account the difficulty and the error introduced by this measurement, theoretical values were used, following previous experience.

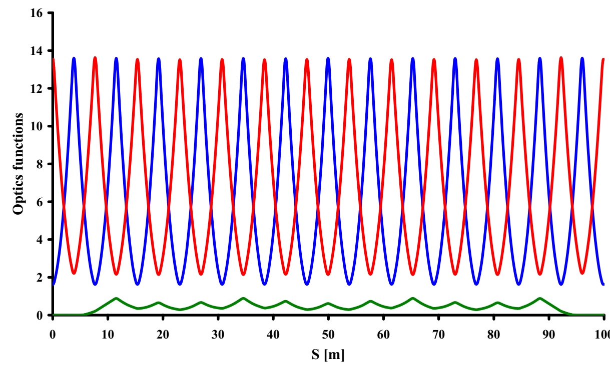

Figure 1: Horizontal (blue), vertical (red) β functions and dispersion (green) of the Booster for the nominal tunes.

TUNE MEASUREMENTS

One of the latest developments in the Booster, was the installation of a new tune monitor enabling the measurement of the tunes along the 50 ms acceleration cycle with a 1ms resolution, in both planes. The method consists of an FFT analysis of a BPM signal during the beam oscillation induced by a single turn kick given by a horizontal or vertical shaker . With a 1 MHz sampling rate and 1024 samples, a 1 KHz frequency and 1 ms time resolution can be achieved. At its actual state the system permits the acquisition of one measurement per plane, per accelerating cycle for a specific time during this cycle. Horizontal tune-shift measurements are presented in Fig. 2 for the whole magnet cycle of 100 ms, and different RF frequencies. The reproducibility of the measurement is excellent apart from the

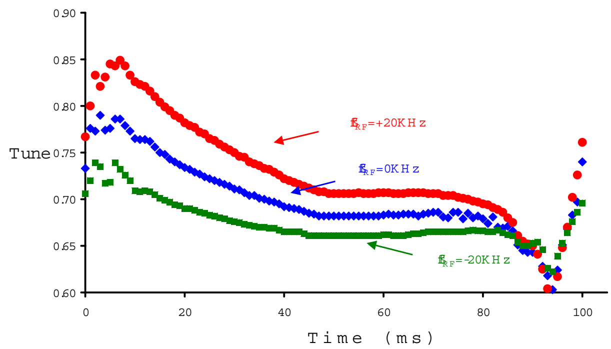

Figure 2: Horizontal tune measurements during one full Booster magnet cycle for different RF frequencies.

beginning and end of the cycle where the magnet settings are rapidly varying.

CHROMATICITY MEASUREMENTS

The total chromaticity in a sychnotron is a sum of three different terms. The first contribution comes from the natural chromaticity defined as the integral around the machine:

$$\xi_{x,y}^{\text{nat}} = \frac{1}{4\pi} \oint \beta_{x,y}(s) k_{x,y}(s) ds \quad , \tag{1}$$

with $\beta_{x,y}$ the beta functions and $k_{x,y}$ the quadrupole normalised strengths. In addition, there is a contribution from the eddy currents induced on the metallic vacuum chamber of the dipoles, as a result of the field variation. It can be evaluated as:

$$\xi_{x,y}^{\text{eddy}}(t) = \pm \frac{1}{4\pi} \oint S^{\text{eddy}}(s,t) \eta_x(s) \beta_{x,y}(s) ds \quad , \tag{2}$$

where S^{eddy} is the associated normalised sextupole strength produced by the eddy currents and $\eta_x(s)$ the horizontal dispersion (we imposed $\eta_y(s) = 0$). Finally, sextupoles with strengths $S_{h,v}$ used to control the chromaticity are producing an effect given by:

$$\xi_{x,y}^{\text{sext}}(t) = \frac{1}{4\pi} \oint \left[\pm S_h(s,t) \mp S_v(s,t)\right] \eta_x(s) \beta_{x,y}(s) ds. \tag{3}$$

The sextupole component due to dipole eddy currents in an elliptic vacuum chambers is given by [6]

$$S^{\text{eddy}}(t) = \frac{1}{B\rho} \frac{d^2 B_y}{dx^2} = \frac{1}{B\rho} \frac{\mu_0 \sigma_c d \dot{B}_y}{h} F(a,b) \quad , \tag{4}$$

with μ_0 the free space permeability, σ_c the stainless steel conductivity and d the vacuum chamber thickness. The function depends on the vacuum chambers ellipticity a/b

$$F(a,b) = 1/2 \left[1 + \frac{b^2 \text{arcsinh}(\sqrt{a^2 - b^2}/b)}{a\sqrt{a^2 - b^2}} \right] \quad , \tag{5}$$

and, for an almost circular vacuum chamber, as in the case of the Booster, it converges towards one. Taking into account that the dipole field has a sinusoidal behaviour

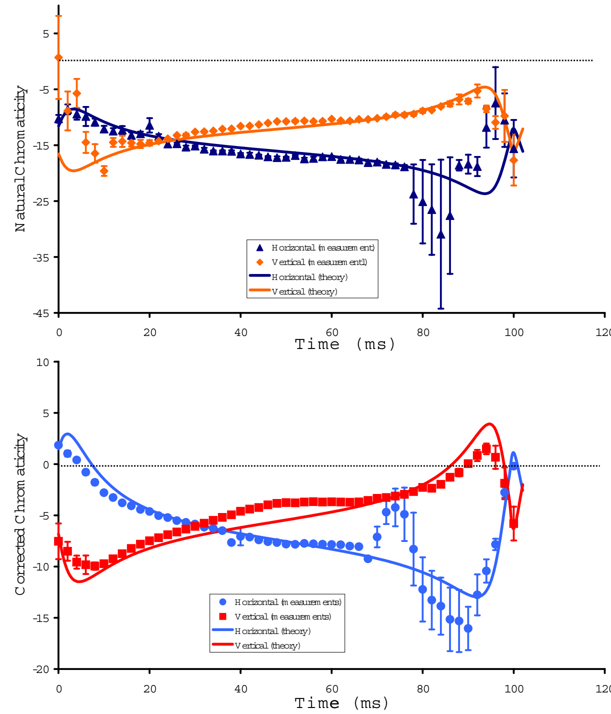

Figure 3: Booster chromaticity without [top] and with correction [bottom] from measurements (points) and theory (solid curves).

$$B_y(t) = \frac{B_{\max}}{1 + a_E} \left(a_E - \cos(\omega t)\right) \tag{6}$$

with ω the cycle frequency and the constant $a_E = \frac{E_{\max} + E_{\min}}{E_{\max} - E_{\min}}$ depending on the maximum and minimum energy, the sextupole strength due to the dipole eddy currents is

$$S^{\text{eddy}}(t) = \frac{\mu_0 \, \sigma_c \, t \, \omega}{h \, \rho} \frac{\sin(\omega t)}{a_E - \cos(\omega t)} F(a,b) \quad . \tag{7}$$

Finally, the chromaticity sextupole strengths can be considered that they are scaled linearly with the total sextupole current using the simple formula

$$S_{h,v}(t) = \frac{6 \mu_0 N I_{h,v}^{\text{sext}}(t)}{B\rho \, a_s^3} \quad , \tag{8}$$

where $I_{h,v}^{\text{sext}}(t) = I_{h,v}^{\text{DC}} - I_{h,v}^{\text{AC}} \cos(\omega t + \phi_{x,y})$ with N the number of windings and a_s the sextupole aperture radius. Note that the beam rigidity $B\rho$ increases along the cycle.

A series of experiments have been performed in order to measure the chromaticity in the Booster with the following machine setup: a normal long bunch mode was used with optimised settings in the main power supplies with respect to beam losses. A reproducible 5mA current was accelerated with a 1Hz repetition rate. The chromaticity was measured, as described, from the slope between the tune-shift versus the momentum spread, for 5 different values of the RF frequency. The measurement error was estimated by the error in the slope coming from the linear data fit.

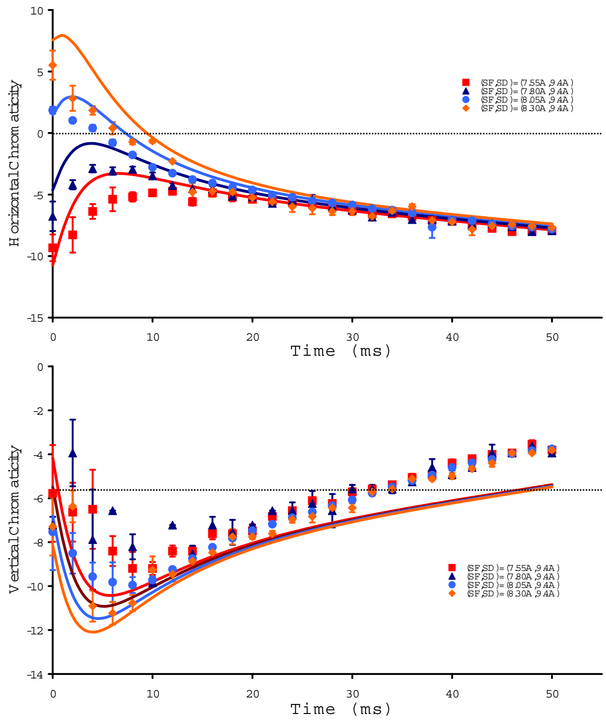

Figure 4: Horizontal [top] and vertical [bottom] Booster chromaticity for different settings of the horizontal sextupole DC current from measurements (points) and theory (solid curves).

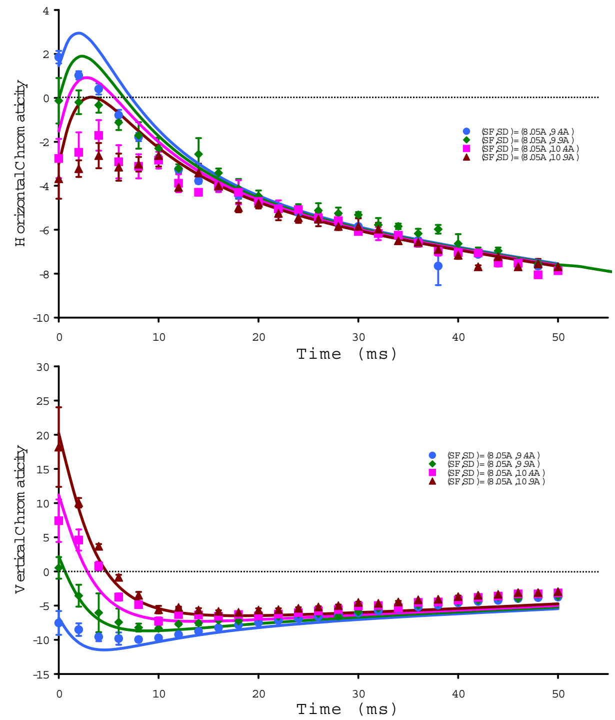

Figure 5: Horizontal [top] and vertical [bottom] Booster chromaticity for different settings of the vertical sextupole DC current from measurements (points) and theory (solid curves).

In Fig. 3, the natural chromaticity behaviour is presented along the full magnet cycle (100 ms). Note that during the normal injection process to the storage ring the beam is extracted in the middle of this cycle, i.e. at 50 ms. The points represent the chromaticity measurements and the solid lines the theoretical values. In the top plot, the natural chromaticity is displayed, whereas in the bottom plot we present the chromaticity after correction with the chromaticity sextupoles. The agreement between the measurements and the theoretical evaluation is quite good, apart from the beginning of the cycle for the vertical (without correction) and the end of the cycle for the horizontal chromaticity. In all the cases, the discrepancy should be attributed to the strong values of the chromaticity at these areas: in that case, the FFT signal appears with strong synchrotron sidebands around its make peak which reduce the precision in the tune determination.

A series of measurement for different values of the horizontal and vertical DC current settings are presented in Figs. 4 and 5, respectively, for only the accelerating cycle of 50 ms. As before, the theoretical values are represented with solid lines. There is a fair agreement with the measurements apart from the beginning of the cycle, in most cases. As the agreement is very good when comparing the differences between the chromaticity and the applied currents, we suspect that the discrepancy should be due to the simplistic formula (8) used to compute the sextupole strength dependence with the current.

CONCLUSION

We have measured the ESRF Booster chromaticity along the cycle using the new tune monitor recently installed. The agreement between theory and experiment was very good (within a few percent) for the natural chromaticity and the nominal current settings in the sextupole power supplies. However, we found larger discrepancies when applied different power supplies DC settings, probably due to the simplistic form of the sextupole dependence to current in our theoretical evaluation and the occurrence of beam loss. In the future, we will perform more measurements varying also the AC currents in view of calibrating the sextupole settings. As the chromaticity control is essential for the bunch cleaning process, our perspectives include the use of a new application using up to 10 different harmonics for controlling the sextupole currents and finally writing a chromaticity control application, for the automatic setting of currents for a desired chromaticity along the cycle.

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