SIGNAL QUALITY OF THE LHC AC DIPOLES AND ITS IMPACT ON BEAM DYNAMICS[*]

R. Miyamoto[†], BNL, Upton, NY, USA
M. Cattin, J. Serrano, R. Tomás, CERN, Geneva, Switzerland

Abstract

The adiabaticity of the AC dipole might be compromised by noise or unwanted frequency components in its signal. An effort has been put to characterize and optimize the signal quality of the LHC AC dipoles. The measured signal is used in realistic simulations in order to evaluate its impact on beam dynamics and to ultimately establish safe margins for the operation of the LHC AC dipoles.

INTRODUCTION

An AC dipole produces a sinusoidally oscillating dipole magnetic field, excites a large sustained transverse motion in a ring, and provides clean signals to beam position monitors (BPMs) for beam optics measurements [1]. Figure 1 is an AC dipole excitation of a 3.5 TeV LHC beam, showing its sustained coherence. An advantage to use the AC dipole's clean signal has been demonstrated in BNL AGS and RHIC [2, 3, 4], CERN SPS [5], and FNAL Tevatron [6]. If strength of the AC dipole is adiabatically changed, excitations are produced with no significant emittance growth [1, 7, 8, 9], allowing multiple measurements with one beam unlike single-turn kickers. This nondestructive nature is particularly useful for a slow cycled LHC. Total of four AC dipoles (one per transverse plane per beam) have been installed in LHC [10] and used as the primary probe to beam optics above the injection energy [11].

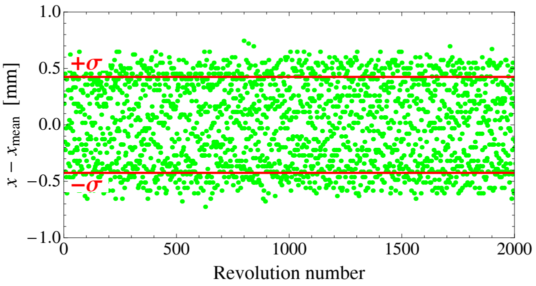

Figure 1: A typical AC dipole excitation of a 3.5 TeV LHC beam recorded by one BPM in arc ($\beta_x \simeq 180$ m).

Relative emittance growth due to one AC dipole excitation is determined by three parameters of the AC dipole and two machine parameters [8]: number of turns for the AC dipole to reach its maximum strength n_r, the excitation amplitude relative to the initial RMS beam size a/σ, separation of the AC dipole's driving tune Q_d and (machine) tune Q, $|\delta| = |Q_d - Q|$, (nonlinear) detuning, and chromaticity Q'. The emittance is also affected by the signal quality of the AC dipole. In operations of the AC dipole, we adjust the amplitude and $|\delta|$ (sometimes chromaticity as well) to keep the emittance growth to a negligible level (a few percents or less) to allow multiple measurements with one beam[1]. Operational conditions of the LHC AC dipole was studied in detail [12] but, since then, the top energy has been limited to 3.5 TeV and we have acquired knowledge of LHC and its AC dipoles. Hence, to assure non destructive operations of the LHC AC dipoles, we perform detailed studies of the emittance growth due to the AC dipole for the present operational conditions at 3.5 TeV. We also report an effort to improve the signal quality of the LHC AC dipoles.

SIGNAL QUALITY OF LHC AC DIPOLES

The AC dipole magnet in LHC can be also used as two types of single-turn kickers. The magnet is connected to the AC dipole generator and generators of high voltage pulses for the kicker modes through a relay controlled by a Programmable Logic Controller (PLC). Originally, the relay was closed with 230 V and 50 Hz AC voltage provided by the PLC. However, we observed the relay chopped the sine wave of the AC dipole generator and produced 100 Hz sidebands around the main frequency (3 kHz). To overcome this problem, the relay driver has been modified and now the original AC source is used only for a short time to close the relay and another 12 DC source maintains it closed[2] (Figure 2). This solution is adapted since the necessary energy to close the relay is more important than that to maintain it closed.

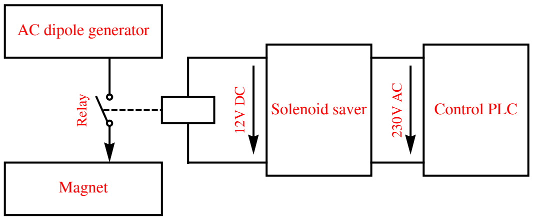

Figure 2: Schematic of the new relay driver.

Figure 3 shows measured current spectra of the LHC AC dipole. Here, sine waves are fitted to the data and the fits are subtracted from the data to observe only unwanted fre-

---

[*] This work partially supported by the US Department of Energy through the US LHC Accelerator Research Program (LARP).

[†] miyamoto@bnl.gov

[1] Obviously, the amplitude must be kept under the aperture too to avoid beam losses.

[2] The new relay driver is called "Solenoid Saver®" and based on a circuit produced by ROSS ENGINEERING INC.

quency components and the noise level. The sampling frequency is chosen to be the beam revolution frequency of the LHC, $f_{\mathrm{rev}} \simeq 11\,\mathrm{kHz}$, to observe what is seen by the beam. We may see that the modification suppresses the components near the main frequency, $3\,\mathrm{kHz} = 0.267 f_{\mathrm{rev}}$. The simulations in the next section indicate that influences of the remaining frequency components have negligible impacts. The level of the noise floor corresponds to RMS white noise of $\sigma_{\mathrm{noise}} = 0.74\,\mathrm{A}$ in the time domain. This is only 0.04% of the maximum current (1.7 kA) and the simulations predict that this is also below the level to affect the emittance.

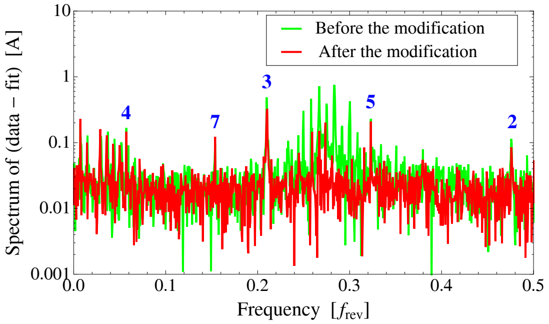

Figure 3: Measured current spectrum of the AC dipole before and after the modification (the main frequency component subtracted). The numbers represent the orders of harmonics. The noise floor is equivalent to RMS white noise of 0.74 A (0.04% of the maximum current).

EMITTANCE GROWTH SIMULATIONS

As discussed previously, we must choose a proper amplitude and $|\delta|$ to ensure the adiabaticity of the AC dipole. To study margins of these two parameters in conditions of the current 3.5 TeV operation, we performed simulations of the emittance growth. We also studied an influence of the signal quality on the emittance, based on the measurement in the previous section.

Table 1: Parameters for the emittance growth simulation.

LHC (3.5 TeV)	
RMS beam size in arc [mm]	0.425
RMS momentum spread (normalized)	1×10^{-4}
Fractional tune	0.31
Synchrotron tune	0.0019
Chromaticity	5
Nonlinear detuning (for 3σ amplitude)	$\pm 5 \times 10^{-4}$
AC dipole	
Excitation amplitude	1.5σ
Separation of Q_d and Q	0.006
Turns to ramp up and ramp down	2250
RMS noise (w.r.t. the maximum amplitude)	0.05%

In the following simulations, we observe one dimensional motion of 10,000 particles at the location of the AC dipole. No other structure is considered but the single-turn map between the AC dipole kicks includes the linear chromaticity and detuning. Table 1 summarizes parameters of our simulation. In the table, the RMS beam size, RMS momentum spread, tune, and synchrotron tune are the design values. The chromaticity of five units is a typical value in present conditions. The detuning in the LHC has not been measured at 3.5 TeV. The listed value is the worst estimate from magnet measurements [13]. The amplitude and $|\delta|$ of the AC dipole are typical values of the present operations. The speed of the ramp up and ramp down has been determined by simulations [8, 12] and the noise level is from the measurement in the previous section. We know by experience the adiabaticity of the LHC AC dipoles is preserved for these values. However, for a smaller $|\delta|$ and/or a larger amplitude, we occasionally observed non-adiabatic behaviors such as the emittance growth and beam loss.

Figure 4 shows the simulated emittance growth as function of $|\delta|$. In the simulation, the AC dipole field is adjusted along with $|\delta|$ so that the amplitude is kept to 1.5σ. Other parameters are fixed to the values listed in Table 1. The red data points represent the case when tune moves toward driving tune for higher amplitudes ("bad side") and the blue data points represent the opposite case ("good side"). Clearly, it is ideal to use the AC dipole on the good side, but the separation of horizontal and vertical tunes is only 0.01 for the collision lattice and so that may not be always possible. Three local maxima in the range $|\delta| < 0.007$ are caused when the driving tune is on one of synchrotron sidebands. We could suppress magnitude of these maxima by lowering the chromaticity. We note that $|\delta|$s of these maxima are different for the good and bad sides due to the detuning. Hence, to avoid these maxima, we need to know the detuning this is not trivial. The simulation predicts the emittance growth becomes significant when $|\delta|$ is around 0.006-0.007 and this agrees to our experimental experiences.

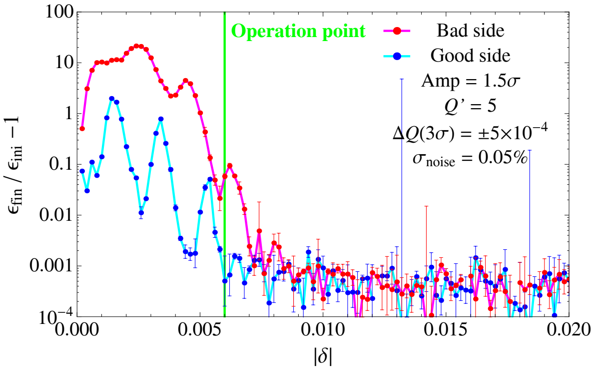

Figure 4: Simulation of the emittance growth vs. $|\delta|$ in a typical condition at 3.5 TeV. "Bad" and "good" sides denote the direction of the detuning. The local maxima are due to the synchrotron sidebands.

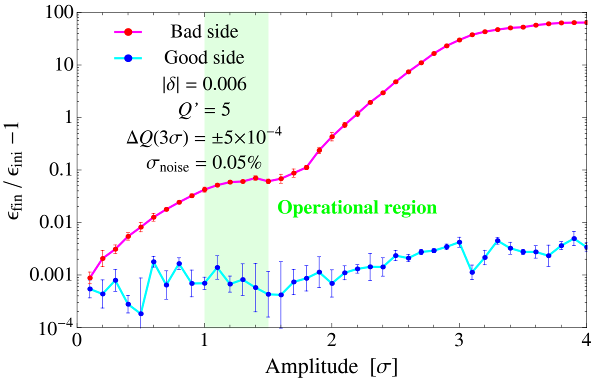

Figure 5: Simulation of the emittance growth vs. the amplitude of the AC dipole excitation.

Figure 5 shows the simulated emittance growth for different values of the amplitude. The simulation predicts that it is necessary to use the AC dipole on the good side to adiabatically produce excitations larger than the current operational range of 1-1.5σ.

Figure 6 shows the simulated emittance growth as a function of the noise level in the AC dipole field. The red and blue data points represent simulations where white noise of the given value is added to the pure AC dipole field. Whereas, the black and yellow data points represents simulations where the measured current of the LHC AC dipole, such as one in Fig. 3, is implemented to more realistically model the AC dipole field. Although the measured AC dipole current includes some frequency components in addition to the white noise (Fig. 3), the simulation based on the real signal and that including just the white noise agree. This indicates the emittance growth is mostly due to the white noise. For the bad side, the emittance growth is dominated by the detuning and insensitive to the noise level. On the contrary, for the good side, the emittance growth is within the acceptable level of a few percents even when the noise level is 0.4%, which is ten times of the measured level. Hence, the LHC AC dipoles have a large margin in the noise level.

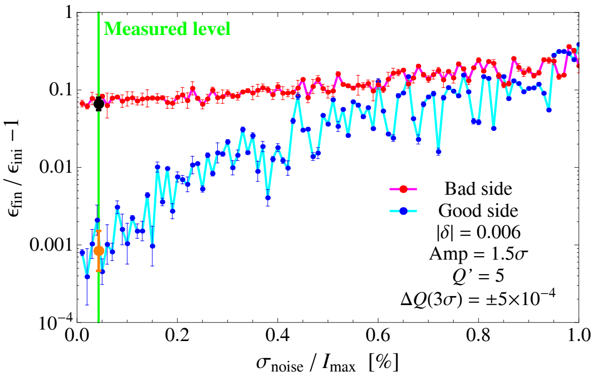

Figure 6: Simulation of the emittance growth vs. noise in the AC dipole field. The red and blue points represent the case when the white noise is added to the pure AC dipole field. The black and orange points are based on the measured current, such as one in Fig 3.

CONCLUSIONS

A nondestructive instrument of an AC dipole has been used as the primary probe to beam optics in the LHC. To ensure nondestructive and safe operations of the LHC AC dipoles, the signal degradation caused by the relay of the AC dipole generator has been compensated and simulations to estimate the emittance growth are performed for the present operational conditions. The simulations indicate that the current conditions have only small margins for some parameters, particularly in driving tune, and this agrees to our experiences. On the contrary, the simulation indicates that the signal quality of the LHC AC dipoles is an order of magnitude better than the required level. As shown in our simulations as well as pointed out in [12], the detuning has a large impact on the emittance growth due to the AC dipole. Hence, if we could measure the detuning and use it as an input, the presented simulations could be improved.

ACKNOWLEDGMENT

Authors would like to thank to E. van der Bij and CERN BE-OP Group for their support.

REFERENCES

[1] M. Bai *et al.*, Phys. Rev. E **56**, p. 6002 (1997).

[2] M. Bai *et al.*, "Measuring Beta Function and Phase Advance in RHIC with AC Dipole", PAC'03, WPAB072, p. 2204.

[3] M. Bai *et al.*, "Measurement of Linear Coupling Resonance in RHIC", PAC'03, WPAB073, p. 2207.

[4] R. Tomás *et al.*, Phys. Rev. ST Accel. Beams **8**, 024001 (2005).

[5] F. Schmidt *et al.*, "Completion of the Sextupole Driving Terms Measurement at the SPS", CERN AB Note 2003-031-MD, 2003.

[6] R. Miyamoto, "Diagnostics of the Fermilab Tevatron Using an AC Dipole" (VDM Verlag, Germany, 2009).

[7] O. Berrig *et al.*, "Excitation of Large Transverse Beam Oscillations without Emittance Blow-up Using the AC-Dipole Principle", DIPAC'01, CT07, p. 82.

[8] R. Tomás, Phys. Rev. ST Accel. Beams **8**, 024401 (2005).

[9] R. Miyamoto *et al.*, "Initial Tests of an AC Dipole for the Tevatron", BIW'06, p. 402.

[10] J. Serrano and M. Cattin, "The LHC AC Dipole system: an introduction", CERN BE Note 2010-14-CO, 2010.

[11] R. Tomás, "LHC Optics Model Measurements and Corrections", these proceedings, TUXMH02.

[12] R. Tomás *et al.*, "Reliable Operation of the AC Dipole in the LHC", EPAC'08, WEPP026, p. 2575.

[13] S. Fartoukh and O. Brüning, "Field Quality Specification for the LHC Main Dipole Magnets", CERN LHC Project Report 501, 2001.