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DISCLAIMER

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

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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. Benefit of the AC dipole 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].

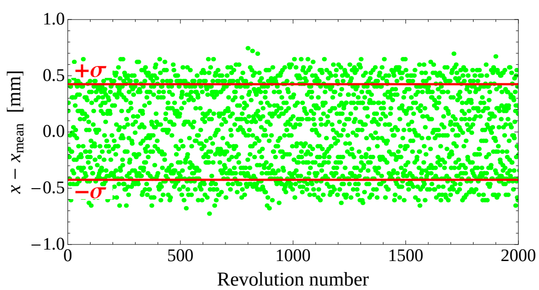

Figure 1: A typical AC dipole excitation of a 3.5 TeV LHC beam recorded by one BPM in arc ($\beta_x \simeq 180$ m).

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 in unit of 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'. Emittance is also affected by 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 magnets 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 and the relay is 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 230 V and 50 Hz AC source is used only for a short time to close the relay and another 12 DC source maintains it closed[2]. Figure 2 shows a schematic of the new relay driver. This solution is adapted since the necessary energy to close the relay is more important than that to maintain it closed.

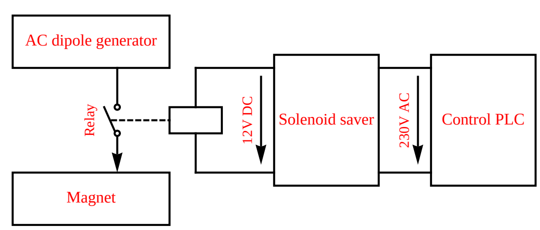

Figure 2: Schematic of the new relay driver.

Figure 3 shows a measured current spectrum of the LHC AC dipole. Here, a sine wave is fitted to the data and the fit

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[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.

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

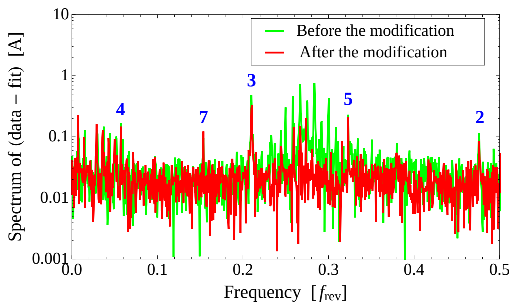

Figure 3: Measured current spectrum of the LHC AC dipole before and after the modification (main frequency component subtracted). Numbers represent orders of harmonics. The level of the noise floor corresponds to RMS white noise of 0.74 A (0.04% of the maximum current).

EMITTANCE GROWTH SIMULATIONS

As discussed previously, we must choose proper amplitude and $|\delta|$ to ensure the adiabaticity of the AC dipole. To study margins of amplitude and $|\delta|$ in the current operational conditions, we perform simulations of emittance growth. We also study an influence of the signal quality on 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 ten thousand particles at the location of the AC dipole. No other structure is considered and the map between the AC dipole kicks depends only on tune, synchrotron tune, linear chromaticity, and nonlinear detuning. Table 1 summarizes parameters of our simulation. In the table, RMS beam size, RMS momentum spread, tune, and synchrotron tune are the design values. Chromaticity of five units is a typical value at present operations. Detuning has not been measured at 3.5 TeV yet. The listed value is an 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 measurements in the previous section. We know the adiabaticity of the LHC AC dipoles is preserved for these values by experience. However, for a smaller $|\delta|$ and/or a larger amplitude, we have occasionally observed non-adiabatic behaviors such as beam losses and emittance growths.

Figure 4 shows the simulated emittance growth as function of $|\delta|$. In the simulation, the AC dipole field is adjusted depending on $|\delta|$ so that the amplitude is kept to a constant 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 of LHC and so that may not be always possible. Three local maxima shown in the range $|\delta| < 0.007$ are caused when driving tune is on one of synchrotron sidebands. We could suppress magnitude of this effect if we could lower chromaticity. We note that $|\delta|$s of these local maxima are different for the good and bad sides due to detuning. Hence, avoiding these $|\delta|$s is not trivial and we need to know the value of detuning. The simulation predicts the emittance growth becomes significant when $|\delta|$ is around 0.006-0.007 and this agrees to our experimental experiences.

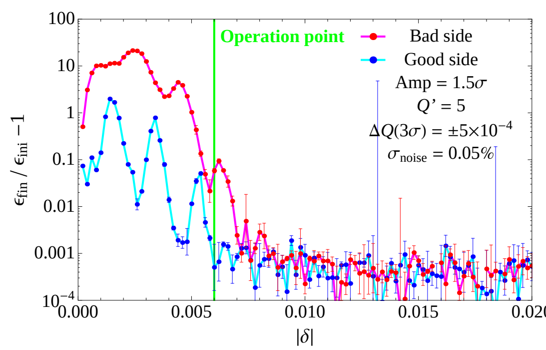

Figure 4: Simulation of emittance growth vs. $|\delta|$ in a typical condition at 3.5 TeV. "Bad" and "good" sides denote the direction of detuning. Local maxima are due to synchrotron sidebands.

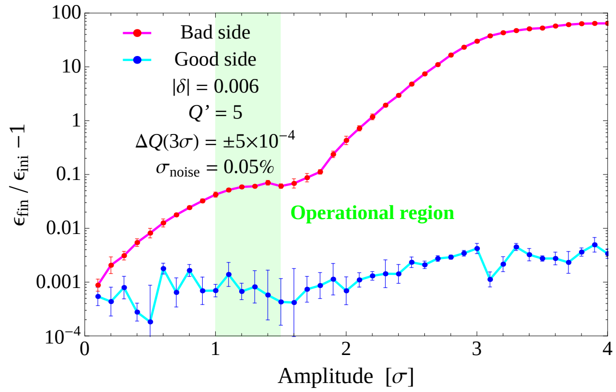

Figure 5: Simulation of emittance growth vs. amplitude of the AC dipole excitation.

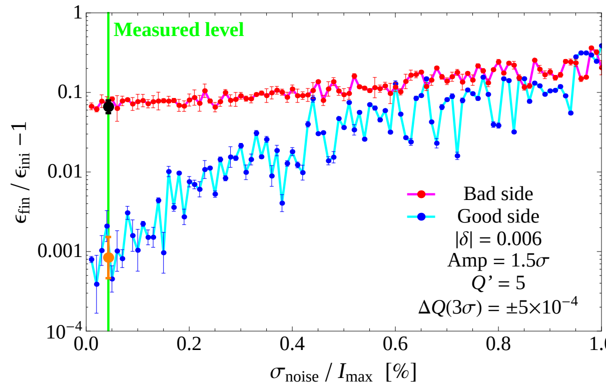

Figure 6: Simulation of emittance growth vs. noise of the AC dipole field. In simulations of red and blue points, white noise is added to the pure AC dipole field. In simulations of black and orange points, a measured current of an AC dipole, such as one in Fig 3, is used.

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. emittance growth.

Figure 6 shows the simulated emittance growth as a function of the noise level in the AC dipole field. In simulations of the red and blue data points, white noise of the given values are 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 shown in Fig. 3, is implemented to model a more realistic AC dipole field. Although the measured AC dipole current includes some frequency components in addition to white noise as shown in Fig. 3, the simulation based on the real signal and that with just white noise agree. This indicates the emittance growth is mostly due to white noise. For the bad side, the emittance growth is dominated by the detuning and insensitive to the noise level. On the other hand, 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.

CONCLUSIONS

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

ACKNOWLEDGMENT

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