EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1095

RELIABLE OPERATION OF THE AC DIPOLE IN THE LHC

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Abstract

The AC dipole in the LHC will not only provide transverse oscillations without emittance growth but also with a safety guarantee. These two features are due to the adiabaticity of the excitation. However chromaticity and nonlinear fields spoil this adiabaticity. This paper assesses the margins of the relevant beam observables for a reliable and safe operation of AC dipoles in the LHC.

LHC-PROJECT-REPORT-1095
27 Aug 2008

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The AC dipole in the LHC will not only provide transverse oscillations without emittance growth but also with a safety guarantee. These two features are due to the adiabaticity of the excitation. However chromaticity and nonlinear fields spoil this adiabaticity. This paper assesses the margins of the relevant beam observables for a reliable and safe operation of AC dipoles in the LHC.

INTRODUCTION

AC dipoles are used in hadron accelerators to overcome spin resonances [1] and as instruments to measure beam dynamics parameters in the linear and the non-linear regimes [2, 3, 4, 5, 6, 7, 8]. The benefit of the AC dipole is the fact that it forces long lasting betatron oscillation without emittance growth if the AC dipole is ramped up and down adiabatically. Thanks to this slow increase of the oscillation amplitude machine protection should be easier than in the traditional case of applying a single kick.

Measurements of RHIC optics parameters with and without AC dipoles have shown the superiority of the AC dipole [9]. This is basically due to the increased signal to noise ratio of the coherent forced oscillations versus the damped free oscillations due to filamentation.

In LHC AC dipoles could also provide a fast measurement of the machine aperture since one beam could be used several times for increasing oscillation amplitudes before the aperture is reached. Using single kicks would require a fresh beam for every different oscillation amplitude. Another advantage is that filamentation processes do not take place when using the AC dipole.

However to guarantee the adiabaticity of the AC dipole some parameters have to be observed as: the machine and driving tunes, the chromaticity and the amplitude detuning. The parameter space is studied in this paper using analytical expressions and simulations with a modified version of HEADTAIL [10], concluding with recipes for the safe operation of the LHC AC dipoles.

On the hardware side various decisions have been taken in order to guarantee a reliable and safe operation of the AC Dipole in the LHC. These choices are discussed in the next section.

HARDWARE CHOICES

A schematic view of the AC dipole circuit configuration is shown in Fig. 1. The requirement for reliable and safe operation of the AC Dipole has resulted in a number of technical choices for the hardware implementation. Each of the four AC Dipole systems (1 per plane and per beam)
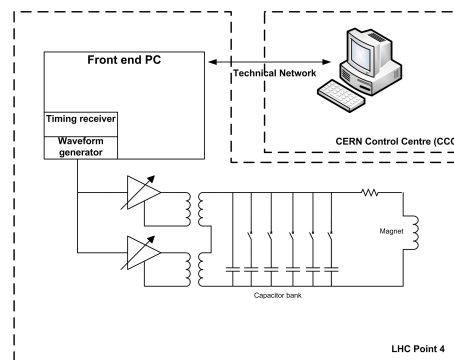

Figure 1: Schematic view of the AC dipole circuit configuration.

will include a dedicated current generator. Inside each generator, a PCI card sitting in a front end PC will generate the enveloped sine waveform and acquire internal diagnostics signals. This card hosts 12 250ks/s ADC channels and 12 1 Ms/s DAC channels, all 16 bits, plus a Field Programmable Gate Array (FPGA) in between and additional digital I/O. The output of one of the DACs will be sent to the input of two high power audio amplifiers and the outputs of the amplifiers will be magnetically combined using transformers before being fed to a resonant RLC circuit. In this circuit, R and L correspond to the magnet and C is a configurable capacitor bank which allows resonance frequency tuning.

The waveform will be internally generated in the FPGA to avoid any possibility of memory corruption coming from any malicious/accidental access to the PC buffers through the technical network. In order to generate sine wave samples of sufficient accuracy in real-time, a COordinate Rotation DIgital Computer (CORDIC) block will be used [11]. The output frequency will depend directly on the accuracy of the frequency of the internal oscillator used in the card. Since a General Machine Timing receiver card will be hosted in the same PC, its very precise Pulse-Per-Second (PPS) output will be fed to the waveform generator card and a count of internal oscillator ticks in between two PPS ticks will be used to monitor the exact oscillator frequency online and use this information to generate a very precise output frequency following control room commands.

On the amplitude side, mappings between magnet current and magnetic field at different frequencies will be gathered during beam commissioning. These tables, combined with online magnet current sensing will allow the system to follow a magnetic field command very precisely by adjusting its output voltage in a current feedback configuration.

Finally, ramping up and down times will also be constrained to no less than 200 ms in hardware. The flat top duration will be fixed to 200 ms in principle until the impact
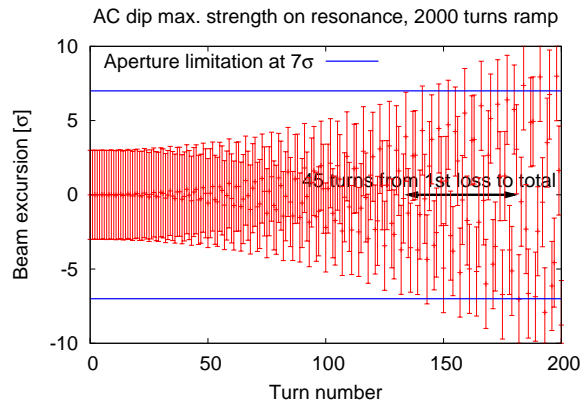
Figure 2: Exciting the AC dipole at the same frequency as the machine betatron tune.

Figure 3: AC dipole resonances relevant for the LHC from Eq. (1). Two possible working points are shown for the horizontal and vertical planes.

of longer excitations on thermal and overall performance is completely understood.

MACHINE AND DRIVING TUNES

If the AC dipole driving tune is equal to the machine tune the resulting oscillation amplitude will increase linearly in time. Fig. 2 shows the beam position and 3σ envelope for equal machine and driving tunes, assuming 2000 turns ramp and the maximum excitation amplitude at the end of the ramp. It is observed that it takes ≈ 45 turns between the first impact of the beam with the aperture limitation and the total beam loss. This situation is much better than a single kick at maximum amplitude, since it would take only a couple of turns for total loss.

Not only the resonance $Q_x = Q_D$, where Q_x and Q_D are the machine and driving tunes respectively, should be avoided but also other resonances excited by non-linear elements. In the ideal 1-D case of an adiabatic excitation close enough to the natural tune ($Q_D \approx Q_x$) the only resonances excited by the Hamiltonian term h_{jk00} are given by the following condition [6]:

$$-Q_x + (k - j + 1)Q_D = p\,, \text{ with } (j, k, p) \in Z^3\,. \quad (1)$$

In this case the resonances of the kind NQ_D=p are never excited. This means that we can safely excite at $Q_D = 0.3333$, for example. Fig. 3 shows the relevant resonances for the LHC operation.

However if we excite far from the machine tune the resonance condition becomes more complex and resonances of the kind NQ_D=p are excited by higher order multipoles [6]. For example the lowest multipoles driving the resonance $3Q_D = p$ is the decapole.

CHROMATICITY

In presence of chromaticity there is a loss of adiabaticity due to the tune fluctuation with the energy of the individual particle. The non-adiabaticity of an AC dipole ramp is expressed in terms of the absolute emittance blow-up [8] after filamentation as:
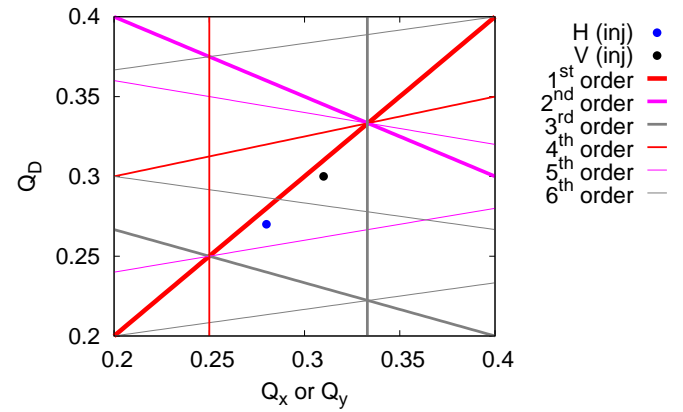
$$\Delta\epsilon_x = \frac{k^{(n)^2}}{2n^2} \sum_{q=-\infty}^{\infty} e^{-\varsigma^2} I_q(\varsigma^2) \frac{\sin^2(\pi Q_{q-}n)}{16\sin^4(\pi Q_{q-})}\,. \quad (2)$$

where $k^{(n)}$ is the excitation amplitude at the top, n is the number of turns of the ramp, ς is an effective chromaticity given by $\varsigma = Q'_x\sigma_\delta/Q_s$, and Q_{q-} is the distance between the driving tune and the qth synchrotron sideband $Q_{q-} = Q_D - (Q_x + qQ_s)$. This emittance growth diverges for $Q_{q-} = 0$, indicating that exciting on top of a synchrotron sideband should be avoided. Adiabaticity improves with n^2 and certain n's have better adiabaticity thanks to the term $\sin(\pi Q_{q-}n)$ in the numerator.

AMPLITUDE DETUNING

Analytical expressions have not been found to assess the adiabaticity of an AC dipole ramp in presence of amplitude detuning and simulations have to be used instead. There is only one obvious recipe to maximize the AC dipole adiabaticity, this is to excite in the opposite side of the detuning with amplitude. i.e. if amplitude detuning is positive one should excite with $Q_D < Q_x$.

LHC SIMULATIONS

The main motivation of using the AC dipole at store energy is to perform good optics measurements, therefore 1σ oscillations seem reasonable. About 10 units of chromaticity could be required in the LHC at top energy for damping collective effects and an amplitude detuning of 5×10^{-4} at 3σ has been estimated [13] at top energy. Taking into account all these ingredients simulations of the emittance growth have been done versus distance between machine and driving tunes. Thanks to the fact that the synchrotron tune is quite low at top energy a $Q_D - Q_x \approx 5Q_s$ is enough to guarantee adiabaticity for a 2000 turns ramp, Fig. 4.
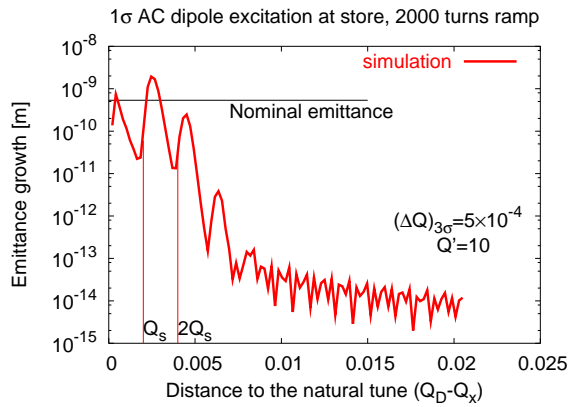
Figure 4: Simulations of emittance blow-up in the LHC at store with nominal assumptions. Safe operation is achieved for $Q_D - Q_x \approx 0.01$.
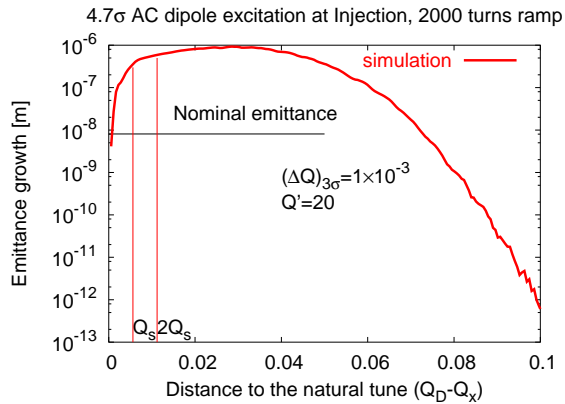

Figure 5: Simulations of emittance blow-up in the LHC at injection with pessimistic assumptions. Emittance blow-up is unavoidable.

The situation is not so favorable at injection where we would like to use the AC dipole to measure aperture, i.e. amplitudes above 6σ are required. Also the chromaticity will be harder to control due to the drifts in the sextupolar errors of the dipoles. Being pessimistic we assume 20 chromaticity units and the maximum expected amplitude detuning of 0.001 at 3σ [13]. This is a too adverse scenario since already for 4.7σ excitation emittance blow-up is unavoidable for $Q_D - Q_x < 0.08$, Fig. 5. Therefore we have to impose constrains in the chromaticity and the amplitude detuning in order to guarantee a safe operation. Both have to be reduced by factors 2 or 3. In particular, Fig. 6 shows the case with $Q' = 7$ and amplitude detuning 5×10^{-4} at 3σ. Adiabatic excitation is achieved within the range $0.022 > Q_x - Q_D > 0.04$ for 7σ oscillation amplitude. One of the dangerous resonance described in Eq. 1 appears at 0.04, this is the resonance $-Q_x - 3Q_D = -1$.

CONCLUSIONS

The AC dipole is a powerful instrument to measure the machine aperture and optical functions. The slow increase
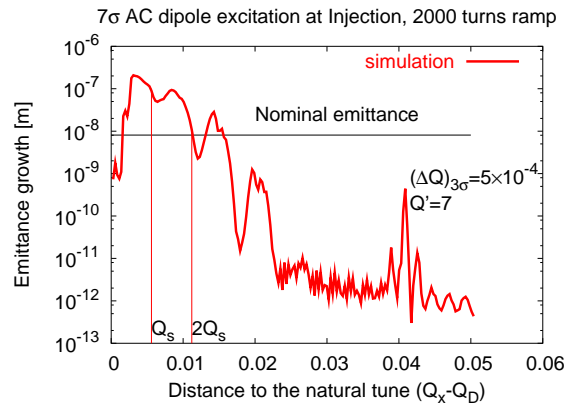

Figure 6: Simulations of emittance blow-up in the LHC at injection with lower chromaticity and lower detuning for a safe operation. The excitation must be at Q_x-Q_D=0.022. The effect of the resonance -Q_x-3Q_D=-1 is observed.

of the amplitude makes it safer than the traditional single kick method. However some beam parameters must be observed. We have shown that its operation at store is safe if applying an excitation comparable to the beam size. However, in order to guarantee a negligible emittance blow up at injection when exciting up to 7σ chromaticity and amplitude detuning must be below 7 units and 5×10^{-4} at 3σ, respectively.

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