

# TRACKING STUDIES IN THE LHeC LATTICE

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## Abstract

The Large Hadron Electron Collider (LHeC) is a proposed upgrade of the LHC to provide electron-proton collisions and explore a new regime of energy and luminosity for nucleon-lepton scattering. A nominal design has previously been presented, featuring a lattice and optical configuration to focus one of the proton beams of the LHC (reaching a value of  $\beta^*=10$  cm) and to collide it head-on with an electron beam to produce collisions with the desired luminosity of  $L=10^{33}$  cm<sup>-2</sup>s<sup>-1</sup>. The proton beam optics is achieved with the aid of a new inner triplet of quadrupoles at  $L^*=10$  m from the interaction point and the extension of the Achromatic Telescopic Squeezing (ATS) Scheme used for the High Luminosity-LHC project. In this work, particle tracking is performed in a thin lens approximation of the LHeC proton lattice to compute the dynamic aperture and perform frequency map analysis for different types of chromatic correction schemes, in order to find the one who will provide the most beam stability and to study the effects of nonlinearities.

## INTRODUCTION

The LHeC interaction region (IR), first proposed in [1] contemplates the implementation of a new set of quadrupoles closer to the interaction point (IP), called the inner triplet (IT), at a distance  $L^*$  from the interaction point 2 (IP2) to achieve head-on electron-proton collisions at a luminosity of  $L=10^{33}$  cm<sup>-2</sup>s<sup>-1</sup>. In order to change the trajectory of the proton beams, the polarity of the two dipoles close to the IP (D1 and D2) must be reversed, compared to the present polarity, and the strength of D2 should be 1.21 stronger and the one of D1 3.43 stronger.

A first integration of the LHeC IR into the HL-LHC lattice, was done in [2] with an extension of the Achromatic Telescopic Squeezing Scheme (ATS), successfully applied for the HL-LHC lattice in [3]. This extension was done in the arc 23 performing a telescopic squeeze to further reduce the value of  $\beta^*$  in IP2 while leaving the HL-LHC insertions (IP1 and IP5) with round optics undisturbed. Achieving a value of  $\beta^* = 10$  cm for IP2 and  $\beta^*=15$  cm in IP1 and IP5.

The flexibility of this design was studied in [4] in terms of minimising  $\beta^*$  to study the reach in luminosity, and in terms of increasing  $L^*$  to reduce the synchrotron radiation.

Using a thin lens version of this LHeC lattice, tracking studies can be done to study the stability of the beam for the nominal case with  $\beta^*=10$  cm and  $L^*=10$  m.

## CHROMATIC CORRECTION

One of the characteristics of the ATS is the locality of the chromatic correction of the inner triplet by using one

single arc of sextupoles of either side of the small  $\beta^*$  insertions. However, in the LHeC case, the achromaticity is broken due to the telescopic squeeze in arc 12 shared by both IP1 and IP2. In this section, three different chromatic corrections are studied using a thin lens version of the lattice to study the impact of each correction scheme on the stability of the beam.

These chromatic corrections are performed by a matching procedure in MADX. The first correction, named “LHC-like” takes as 2 variables the strengths of the focussing and defocussing families of sextupoles, to fix as constraints the global values of the horizontal and vertical chromaticity ( $q_x, q_y$ ) to a value of 2. The second correction, named “LHeC-like” increases the number of variables to allow every family of sextupoles to vary independently, accounting for 32 variables (2 for every arc of the LHC), to adjust not only the global value of the chromaticities to 2 as the previous case, but also to adjust the horizontal and vertical Montague functions ( $W_x$  and  $W_y$ ) below 200 in the collimation insertions interaction region 3 (IR3) and interaction region 7 (IR7). Finally the third correction, named “second order”, takes the same variables and constraints as the LHeC-like correction but adds as further constraints the variation of the horizontal and vertical chromaticity with momentum below a value of 7.

Figures 1 and 2 illustrate the change of tune over momentum for the three different chromatic corrections. The presence of nonlinearities is clear, specially for the cases LHC-like and LHeC-like, with the first one having a larger variation in the tune. On the other side, the second order correction is linear for the vertical tune, although for the horizontal tune, this linearity was not achieved for the whole momentum spread.

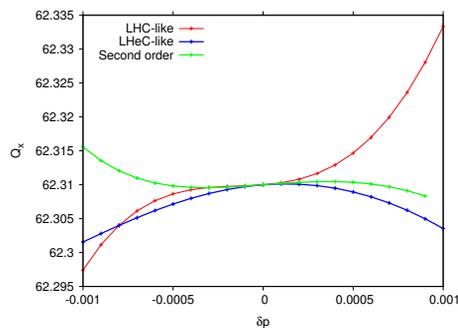


Figure 1:  $Q_x$  vs  $\delta_p$  for three different chromatic corrections: LHC-like, LHeC-like and second order.

Figure 3 shows the chromatic variation over momentum

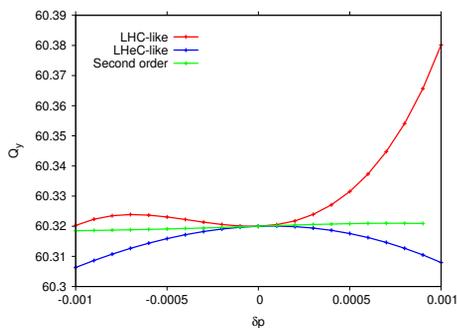


Figure 2:  $Q_y$  vs  $\delta_p$  for three different chromatic corrections: LHC-like, LHeC-like and second order.

in a resonance map of order 10. The effect of these resonances aims to be studied with frequency map analysis.

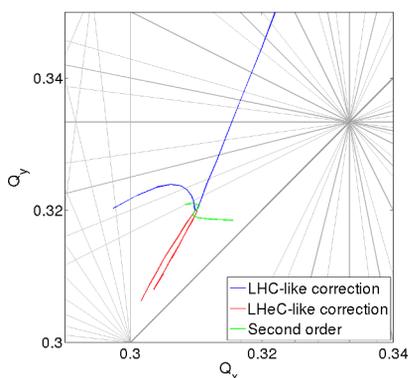


Figure 3: Tune spread over a resonance map of order 10 for three different chromatic corrections, LHC-like, LHeC-like and second order.

## DYNAMIC APERTURE

The Dynamic Aperture (DA) is the largest amplitude of the domain in phase space where the particle motion is stable.

The DA studies were computed in SixTrack [5] using a polar grid of initial conditions with 30 particles for each  $2\sigma$  interval and 5 different phase angle, over  $10^5$  turns. The momentum offset is set to  $2.7 \times 10^{-4}$ . Concerning the magnetic errors, 60 different realisations (seeds) were considered for the LHC magnets. In this study, the errors of the new IT and recombination dipoles of IR1, IR2 and IR5, as well as the quadrupoles Q4 and Q5 for the the insertions IR1 and IR5 have not been considered.

Figure 4 shows the computed dynamic aperture for the three different chromatic corrections. The three corrections show similar results except at bigger angles where the second order had bigger DA, followed closely by the LHeC-like correction. On the other side the LHC-like correction DA reduces considerably.

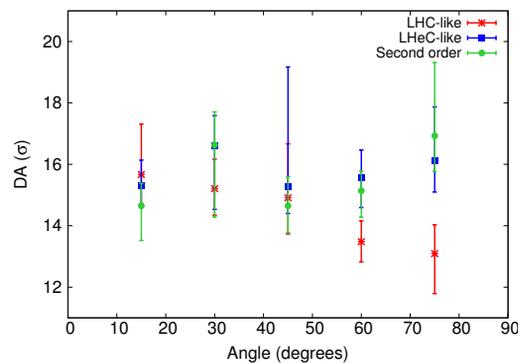


Figure 4: Dynamic Aperture for beam 2 of the LHeC with different chromatic corrections: LHeC-like, LHC-like and Second Order.

## FREQUENCY MAP ANALYSIS

The Frequency Map Analysis relies on a high precision calculation of the frequencies of motion to obtain the tunes. By studying the behaviour of the tunes over different turns over a range of initial conditions it is possible to obtain an indication of the stability of the system and the effect of the nonlinearities.

The FMA studies were performed in SUSSIX [6] and applied to calculate the variation of the tunes over 5,000 and 10,000 turns for a sample of initial amplitudes via the tune diffusion given by:

$$D = \log_{10} \sqrt{(\Delta Q_x)^2 + (\Delta Q_y)^2} \quad (1)$$

The tune diffusion in a frequency map of order 12 is represented for the LHeC like correction in Fig. 5, very similar results are shown for the second order correction in Fig. 6 as for clear differences are found for the LHC-like correction in Fig. 7.

These frequency maps also show the resonance lines  $m_x Q_x + m_y Q_y = l$  where  $m_x, m_y$  and  $l$  are integers. The resonance lines causing a disruption in the diffusion factor are labelled in the figure.

This tune diffusion is also plotted for the different initial amplitudes and angles for the different corrections. Similarities are again found for the LHeC-like (Fig. 8) and second order correction (Fig. 9), except for the region where  $Q_x \sim Q_y$  where a stable region is bigger for the latter case. Also, for bigger angles ( $I_x=0-5\sigma$  and  $I_y \approx 20\sigma$ ) where the second order correction does not show the instability region observed in the LHeC-like case caused by resonance line  $(-1,4)$ . The same regions are also different for the LHC-Like case (Fig. 10). In this case the region for bigger angles show a bigger instability, but the main difference is observed in the region with  $Q_x \sim Q_y$  in which a stable region seen in the other corrections is not longer present.

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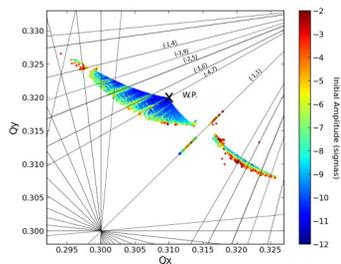


Figure 5: Diffusion factor on a tune map for the initial angles varying from 0-90 degrees and initial amplitudes  $I=0-22 \sigma$  over a resonance diagram of order 12 for the LHeC-like chromatic correction.

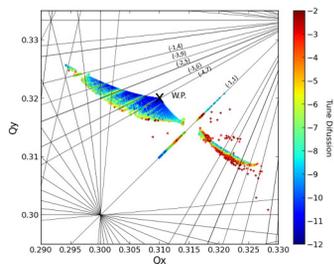


Figure 6: Diffusion factor on a tune map for the initial angles varying from 0-90 degrees and initial amplitudes  $I=0-22 \sigma$  over a resonance diagram of order 12 for the second order chromatic correction.

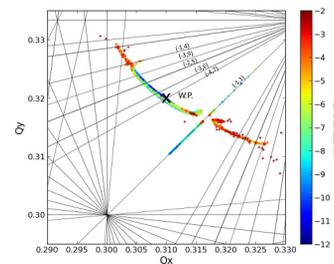


Figure 7: Diffusion factor on a tune map for the initial angles varying from 0-90 degrees and initial amplitudes  $I=0-22 \sigma$  over a resonance diagram of order 12 for the LHC-like chromatic correction.

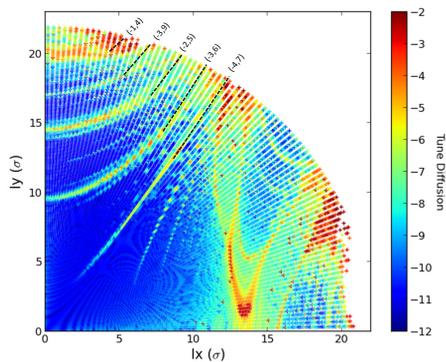


Figure 8: Diffusion factor  $D$  over the initial amplitudes  $I=0-22 \sigma$  and 90 initial angles for the lattice LHeC-like chromatic correction.

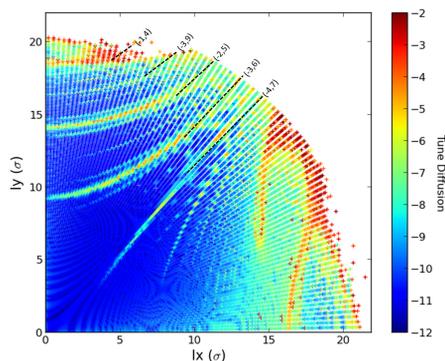


Figure 9: Diffusion factor  $D$  over the initial amplitudes  $I=0-22 \sigma$  and 90 initial angles for the second order chromatic correction.

Figure 10: Diffusion factor  $D$  over the initial amplitudes  $I=0-22 \sigma$  and 90 initial angles for the LHC-like chromatic correction.

## CONCLUSIONS

Tracking studies for the LHeC lattice for different chromatic correction schemes allow for a comparison in terms of long stability of the beam and the possible effects of nonlinearities.

LHeC-like and second order approaches demonstrate very similar DA and FMA. Second order features a slightly better results at large angles. On the other hand the LHC-like correction showed the contrary effect for bigger angles with a lower DA and a larger diffusion in the FMA. Furthermore the larger stable region in FMA for  $Q_x \sim Q_y$  is no longer found in this case.

In summary a more refined chromatic correction approach than in LHC is needed in LHeC and either LHeC-like or second order would provide sufficient DA.

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