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# LANDAU DAMPING STUDIES FOR THE FCC: OCTUPOLE MAGNETS, ELECTRON LENS AND BEAM-BEAM EFFECTS *

C. Tambasco† J. Barranco, T. Pieloni, L. Rivkin, EPFL, Lausanne,
S. Arsenyev, X. Buffat, D. Schulte, CERN, Switzerland

*Abstract*

Stability studies for the FCC-hh operational cycle are explored using Landau octupoles and electron lenses alone and in the presence of long-range as well as head-on beam-beam effects. Pros and cons of the various methods are compared and an optimum operational scenario to guarantee the maximum stability is proposed.

## INTRODUCTION

The Stability Diagram (SD) is defined as the inverse of the dispersion integral [1]:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y}}{\Omega - \omega_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y . \tag{1}$$

It quantifies the Landau damping of proton beams for a certain amplitude detuning $\omega_{x,y}(J_x, J_y)$ and particle distribution $\psi(J_x, J_y)$ as a function of the transverse actions $J_x$ and $J_y$ in each plane. The SD defines the complex tune shifts $\Delta Q_{x,y}$ at the stability limits for each frequency $\Omega$. In order to be Landau damped, the coherent impedance modes must lie inside the SD; hence the larger the tune spread, the larger the stability area in the complex plane. The detuning with amplitude is given by the machine non-linearities as well as beam-beam (BB) interactions during collisions. In the LHC, the so-called Landau octupoles provide enough tune spread to stabilize the beams [2]. In the presence of BB interactions the SD gets modified [3], therefore it is important to evaluate the beam stability during the full operational cycle. At the FCC (flat) top beam energy (50 TeV) the Landau octupoles become less effective since the detuning is inversely proportional to $\gamma^2$. Table 1 summarizes the main features of the FCC octupole magnet system compared to the LHC design. Different options for Landau damping, applied during the full FCC operational cycle, have been analyzed and are presented in the next sections. The option to use an electron lens (e-lens) for Landau damping [4] is also discussed.

## BEAM STABILITY WITH SINGLE BEAM

The computation of the SD (Eq. 1) is performed with the PySSD code [3]. The detuning with amplitude is evaluated by using the tracking module of MAD-X [5, 6] including octupole magnets (Table 1) and beam-beam interactions according to the operational stage and optics. For the e-lens the tune spread is evaluated thanks to the COMBI code [7] considering the e-lens parameters given in Ref. [4].

* Work supported by the Swiss State Secretary for Education, Research and Innovation SERI
† claudia.tambasco@cern.ch

Table 1: Main Octupole Magnet Features For FCC and LHC

| Parameter | LHC (7 TeV) | FCC (50 TeV) |
|---|---|---|
| Gradient [T $\cdot$m$^{-3}$] | 63100 | 200000 |
| Av. $\beta$-function (arcs) | 100 | 200 |
| Length [m] | 0.32 | 0.5 |
| Int. strength [m$^{-3}$] | 0.865 | 0.600 |
| N. Octupoles | 168 | 480 |

### *Flat Top and Injection Energy*

The Landau octupoles can be powered with positive (LOF > 0) or negative (LOF < 0) polarity. According to the sign of the octupole polarity the tune spread is reversed in the 2D tune diagram, giving different results for Landau damping, as shown in Fig. 1a (flat top energy) where the light blue line and the orange line represent the positive and negative octupole polarity respectively. The corresponding SDs are shown in Fig. 1b where the most unstable coupled-bunch modes (m=1 in the Y-plane) [8] are also plotted as a function of the chromaticity $Q'$ (color bar). In this analysis we assume the rigid bunch m=0 to be damped by the transverse feedback [9]. In a conservative way, the effect of the transverse feedback on the higher order modes is not taken into account in the computation of the coupled-bunch modes. As visible, at flat top energy (single beam), the available Landau octupoles provide sufficient beam stability up to a chromaticity value of 20 units if they are powered with negative octupole polarity (orange line in Fig 1a). For both octupole polarities the Dynamic Aperture (DA) as a function of the octupole current is above 15 $\sigma$ [10] for the maximum octupole strength. The Landau damping provided by the available octupole magnet system is compared to the SD provided by an e-lens powered with a current of 140 mA, purple line in Fig. 2a at flat top energy. Figure 2b shows a comparison between the Landau damping provided by the octupole magnets and by an e-lens at injection energy. In this case, 3.33% of the maximum available octupole strength will be sufficient to damp m=1 up to a chromaticity of 20 units (red line) without important impact on the DA [11]. For completeness, the SD given by an e-lens is also shown for a current of 600 mA that will be sufficient to damp m=1 (purple line).

## BEAM STABILITY IN THE PRESENCE OF BEAM-BEAM INTERACTIONS

For the baseline scenario, collisions are foreseen for a $\beta$-function at the two high luminosity interaction points (IPs), $\beta^*$= 30 cm . When the $\beta^*$ is minimized (end of the betatron

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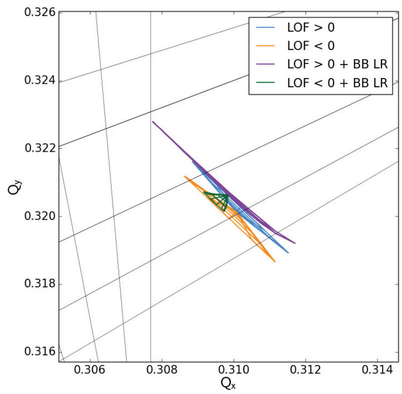
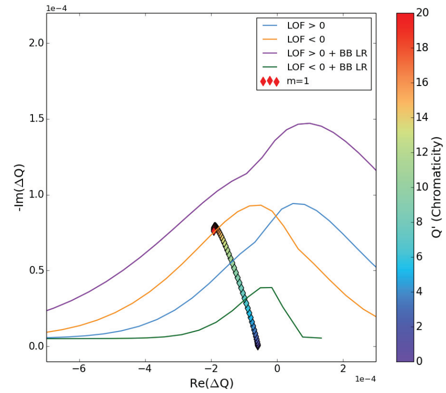
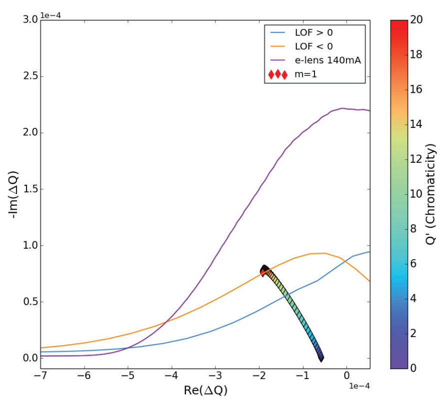



(a) Tune diagrams for negative and positive octupole polarity and LR beam-beam interactions.

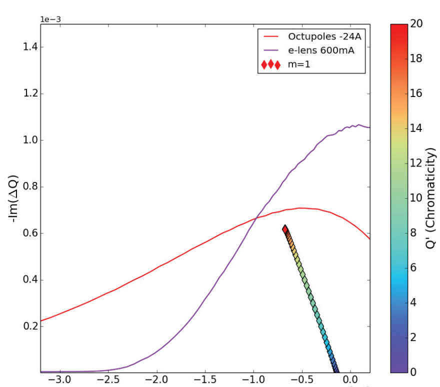



(b) Computed SDs with octupole magnets and LR beam-beam interactions. The head-tail coupled-bunch mode (m=1, Y-plane) is plotted as a function of the chromaticity value (color bar).

Figure 1: Tune diagrams (left) for negative and positive octupole polarity (flat top energy) and LR beam-beam interactions together with corresponding Stability Diagrams (right). Octupole magnets are powered at their maximum strength at flat top energy.




(a) Flat top.




(b) Injection.

Figure 2: Stability Diagrams provided by the octupole magnets and by an e-lens powered with various currents. The most unstable coupled-bunche mode (m=1 with azimuthal number 1, Y-plane) is plotted as a function of the chromaticity $Q'$ (color bar). These modes are expected to be damped by the feedback.

squeeze) the long range (LR) BB interactions become important due to the reduction of the beam to beam separation.

At such low $\beta^*$ at the IPs, LR BB interactions may modify the SD that was up to that moment. This is shown in Fig. 1a where the tune diagrams are shown for negative octupole polarity and with LR BB interactions (green line) and for positive octupole polarity and with LR BB interactions (purple line), the corresponding SDs are shown in Fig. 1b.

A reduction of the tune spread is visible in the presence of negative octupole polarity and LR BB interactions, hence reducing the Landau damping and requiring a tight control on the chromaticity value. Although for positive octupole polarity the tune spread given by the LR BB interactions adds up to the one provided by the octupole magnets at flat top (purple line in Fig. 1a), this choice is not recommended since it provides less Landau damping at flat top and, in addition, a reduction of DA as a function of the octupole strength is expected in the presence of LR BB interactions [12–14]. With the available octupole magnet system, a scenario with negative octupole polarity provides sufficient Landau damping at flat top (Fig. 1a), up to high chromaticity values (20 units) and the DA improves as a function of the octupole

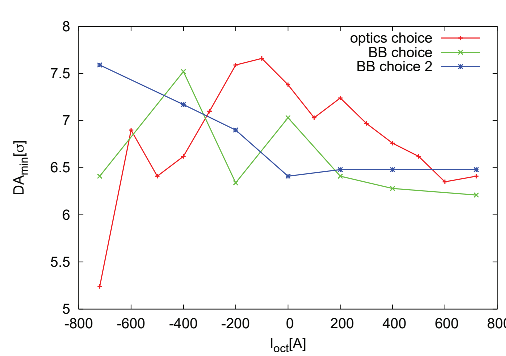



Figure 3: Dynamic aperture as a function of the octupole current and BB interactions ($\beta^*$=30 cm) for various optics.

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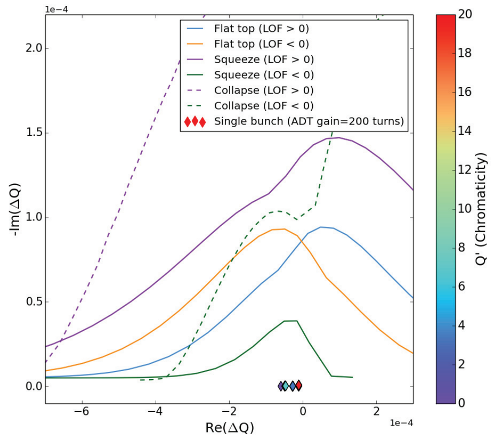


Figure 4: Stability diagrams at the minimum of stability during the collapse of the separation bumps for both octupole polarities. For comparison the SDs at flat top and at the end of the betatron squeeze are also plotted together with the most unstable single bunch modes computed for a transverse feedback gain of 200 turns (dots).

strength (Fig. 3) thanks to the global compensation of the LR BB interactions at the end of the batatron squeeze [12–14]. In Fig. 3 the DA is plotted as a function of the octupole strength for negative and positive polarity for various optics and phase advance. Through an optimization of the phase advance the DA improves up to 7.5/8.5 $\sigma$ (blue line) at the maximum octupole strength. In order to compensate for the reduction of Landau damping at the end of the betatron squeeze for negative octupole polarity, other alternatives may be exploited such as enhancing the octupole effectiveness either by increasing their strength (or the number of octupole magnets) and/or by increasing the $\beta$-function in the arcs by making use of an ATS type of optics [15]. A 50% larger $\beta$-function in the arcs will be sufficient to fully compensate the reduction of Landau damping using the available octupole magnet system. Another option to increase beam stability is the "collide and squeeze", as foreseen for the baseline HL-LHC scenario [16, 17].

The conditions discussed so far refer to an overly pessimistic scenario that does not take into account any beneficial effect of a transverse feedback system on head-tail modes [18]. Preliminary results show that the most unstable single-bunch modes, computed with the BIM-BIM code including a transverse feedback gain of 200 turns (dots in Fig. 4), are stabilised at the end of the betatron squeeze for negative octupole polarity (green line in Fig. 4). Similar results are expected for the coupled-bunch modes for which detailed studies are on-going including the effect of the transverse feedback. During the collapse of the separation bumps both LR and head-on BB interactions modify the beam stability at the end of the betatron squeeze [3] .

During this process a minimum of stability has been found for a parallel beam separation of $\approx 3.0\ \sigma$. Figure 4 shows the SDs at the minimum of stability during the collapse of the separation bumps for negative octupole polarity (dashed green line) and positive octupole polarity (dashed purple line). The crab crossing is turned on and the octupole magnets powered at their maximum strength. For comparison, the SDs at flat top are also plotted in the same figure. As visible this process seems not to be a concern in terms of Landau damping since for negative octupole polarity the instabilities are equally stabilised at flat top and during the collapse. In the presence of an e-lens, this process may be critical: the beneficial effect of the head-on collisions on stability may be compromised due to the counter action of the e-lens. Hence detailed studies should be carried out in this configuration. When in head-on collisions the stability is maximized due to the large tune spread provided by the head-on collisions [19].

## CONCLUSIONS

The coherent beam stability has been analyzed during the complete FCC operational cycle. With single beam the available octupole magnet system provides enough Landau damping to stabilize higher order modes. Although the Landau damping is reduced at the end of the betatron squeeze for negative octupole polarity, this remains the best option to compensate for BB effects on DA thanks to a global compensation of the LR BB interactions [12–14]. The presented studies do not include any beneficial effect of a transverse feedback system on head-tail modes [18]. Preliminary studies on single bunch-modes with transverse feedback, have shown sufficient Landau damping at the end of the betatron squeeze with the available octupole magnet system (Fig. 4). Similar results are expected in the multi-bunch regime, since coupled bunch modes are suppressed by the feedback. Further studies are on-going to confirm this effect. If these studies show a real need to increase the stability at the end of the betatron squeeze several options can be considered. The first one would be to "collide and squeeze", as foreseen for the HL-LHC baseline scenario [16, 17]. Another option is to increase the effectiveness of the Landau octupoles by increasing the field gradient (or increase the number of octupoles) and/or by increasing the $\beta$-function in the arcs. The option of an e-lens for Landau damping [4] has also been presented together with the required currents to damp higher order modes. However, detailed studies of stability during the collapse of the separations bumps have to be carried out since an e-lens may compromise the stability provided by the head-on collisions [20] during this process.

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