Studies on use of a radio frequency quadrupole cavity for Landau damping in HL-LHC

M. Schenk, A. Grudiev, K. Li, E. Métral, K. Papke
CERN, Geneva, Switzerland

Abstract

Landau damping is employed against various types of beam instabilities in circular particle accelerators and is present in the transverse planes when there is a large enough incoherent betatron frequency spread among the beam particles that overlaps with the coherent frequencies of the unstable modes. Traditionally, octupole magnets are used to introduce such incoherent betatron tune shifts with the transverse particle oscillation amplitudes. Their damping efficiency depends on the transverse geometric beam emittances and hence decreases with increasing beam energy and brightness.

A novel approach to Landau damping is presented here that would also improve the stability of the high brightness beams circulating in the High Luminosity Large Hadron Collider (HL-LHC). The novelty of the method is to introduce the incoherent betatron frequency spread through detuning with the longitudinal instead of the transverse particle oscillation amplitudes. This can be achieved by means of a radio frequency quadrupole cavity and the approach is motivated by the orders of magnitude larger longitudinal emittance compared to the transverse ones. This report is a summary of studies performed for the rf quadrupole. It is demonstrated that such a device with even a short active length of less than one meter could significantly relax the required currents of the magnetic octupoles for the HL-LHC thanks to its high betatron detuning efficiency.

Keywords: HL-LHC, Landau damping, impedance, head-tail instabilities, intra-bunch, transverse
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1 Introduction

The use of radio frequency (rf) quadrupole cavities against coherent beam instabilities has first been discussed in Refs. [1,2] to suppress coupled-bunch modes, and later in Refs. [3,4] to raise the intensity threshold of the transverse mode-coupling instability (TMCI). Here, rf quadrupoles are considered to operate in the Landau damping regime to mitigate weak single-bunch head-tail modes [5–7]. Detailed theoretical, experimental, and simulation studies of the latter are reported in Refs. [8–12] and a summary of relevant extracts thereof is given here.

The purpose of the rf quadrupole for Landau damping is to generate transverse quadrupolar kicks on the beam particles with a strength that depends on their longitudinal coordinate. Every particle feels a different focusing (defocussing) force as it passes through the device and hence experiences a change in the betatron tunes depending on its longitudinal position within the bunch. The result is an incoherent betatron tune spread which leads to Landau damping in the transverse planes. Other than for magnetic octupoles, the tune spread from an rf quadrupole is dependent on the longitudinal action \( J_z \) spread within the bunch [7,8]. Thanks to the orders of magnitude larger spread in the longitudinal compared to the transverse actions of the High Luminosity Large Hadron Collider (HL-LHC) beams, and of beams in future hadron colliders in general, the tune spread can be produced more efficiently with an rf quadrupole. This in turn translates into an improved Landau damping efficiency as the amount of Landau damping is related to the amount of available incoherent tune spread through the dispersion relation. The difference in Landau damping efficiency between magnetic octupoles and rf quadrupoles is particularly important for increasing beam energies and reduced transverse emittances. In addition to the improved detuning efficiency compared to magnetic octupoles, the performance of the rf quadrupole also remains unaffected by beam manipulations in the transverse planes, such as beam halo cleaning through collimation, for example. Recently, it has also been demonstrated that transverse linear coupling can strongly reduce the incoherent betatron tune spreads generated through detuning with the transverse amplitudes (e.g. from magnetic octupoles) [13]. This in turn can lead to a loss of Landau damping, as observed, for example, in the LHC, and requires hence an accurate correction of the linear coupling in the (HL-)LHC [14]. It is hence expected that there is no loss of Landau damping in that case. Another effect that is currently under detailed investigation is transverse noise that can locally significantly reduce the stability diagrams generated by magnetic octupoles and hence lead to a loss of Landau damping [16]. It is believed that this effect will not be present for an rf quadrupole due to the separation of the transverse planes where tune spread is created and the longitudinal action space for this type of Landau damping.

Berg and Ruggiero developed the basic formalism for the new type of Landau damping in Ref. [17], also demonstrating that it differs to some extent from Landau damping introduced by octupole magnets. The theory is analyzed more thoroughly in Ref. [9] and the damping mechanism is experimentally verified in Ref. [10].

1.1 Cavity designs

Two cavity designs for a superconducting rf quadrupole have been proposed and optimized primarily for integrated quadrupolar gradient, but also for transverse and longitudinal beam-coupling impedance, and peak electric \( E_{pk} \) and magnetic \( B_{pk} \) surface fields. The two geometries and the corresponding electric and magnetic field distributions are shown in Fig. 1. The study method and outcome are discussed in detail in Ref. [12]. A short summary of the main aspects of the optimization procedure is given here.

The first cavity type is based on an elliptical geometry and operates in a transverse magnetic (TM) quadrupolar mode. The second one is a four-vane cavity operating in a transverse electric (TE) quadrupolar mode. The geometry of the latter is motivated by the rf quadrupole linac (RFQ) [18] and its design was chosen to reach higher quadrupolar field strengths at reduced cavity size. The main advantages of the four-vane compared to an elliptical cavity are: (i) the quadrupolar field strength is up to two to five times larger than that of the elliptical design, given that the aperture has a radius \(< 50 \text{ mm}\), and (ii) the four-vane cavity is more compact and requires smaller cryomodules with less cooling power. As a result, the system provides the same amount of Landau damping, but with fewer cavities and hence
at reduced total impedance and cost. This is of particular importance as the longitudinal impedance of the elliptical cavity design is large compared to the total machine impedance budget of e.g. the LHC [12]. In the transverse planes, neither of the two cavities contribute significantly to the total machine impedance. Both cavity types have been designed to operate at an rf frequency of 800 MHz. The main reason is that the bunches of the HL-LHC are foreseen to have a length of $\sigma_z = 0.076$ m [14]. An rf quadrupole operating at 800 MHz has an rf wave length that matches the bunch length and provides the best beam stabilizing efficiency according to numerical simulations [12].

1.2 Working principle

In the thin-lens approximation, an ultra-relativistic particle of index $i$, and electric charge $q$ traversing an rf quadrupole along the $z$-axis experiences transverse kicks

$$\Delta p_i^\perp = q b_2 \left( y_i e_y - x_i e_x \right) \cos \left( \omega t_i + \varphi_0 \right),$$

(1)

where $b_2$ denotes the integrated quadrupolar gradient, $\omega$ is the rf quadrupole angular frequency, $e_x$ and $e_y$ are the unit vectors along the $x$ and $y$ coordinates respectively, $\varphi_0$ is a constant phase offset, and $t_i$ is the time when the particle traverses the device. The latter is defined with respect to the particle which is at the zero-crossing of the main rf voltage, the so-called synchronous particle, and $t_i = 0$ coincides with the bunch center. The substitution $t_i = z_i / \beta c$ gives the longitudinal dependence of the quadrupolar kick strength along the particle bunch, where $\beta$ is the relativistic beta and $c$ the speed of light.

The kicks in Eq. (1) lead to a change in the betatron tunes of every particle

$$\Delta Q_{x,y}^i = \pm \beta_{x,y} \frac{b_2}{4\pi B_0 \rho} \frac{1}{\beta c} \cos \left( \frac{\omega z_i}{\beta c} + \varphi_0 \right),$$

(2)

where $\beta_{x,y}$ are the transverse beta functions of the machine lattice at the location of the quadrupole kicks, and $B_0 \rho$ is the magnetic rigidity. Equation (2) describes the incoherent tune shift that particle $i$ experiences from a single passage through the device according to its current longitudinal position $z_i$ in the bunch. As the particle undergoes synchrotron motion, its longitudinal position changes turn after turn. Given enough time, the longitudinal turn-by-turn position of the particle will be evenly distributed over the interval $[-\hat{z}_i, \hat{z}_i]$, where $\hat{z}_i$ is its maximum synchrotron oscillation amplitude. This is illustrated in Fig. 2. The grey background represents the particle distribution (Gaussian) in the longitudinal plane.
Fig. 2: Illustration of the incoherent tune shift that a particle (red) experiences as it passes through an rf quadrupole (orange) turn after turn for $\varphi_0 = 0$ [8]. The resulting effective tune shift is shown in white.

One particle (red) is observed over time as it passes through the rf quadrupole (orange). The black dashed line corresponds to the interval $[-\hat{z}_i, \hat{z}_i]$ that the particle eventually traces out as it passes through the device for many turns. It is worth noting that the explanation is analogous for detuning with the transverse amplitudes, such as from magnetic octupoles, see e.g. Ref. [19].

Eventually, it can be shown that the effective incoherent detuning is approximately given by [8]

$$\Delta Q_{x,y} (J_z) \approx \mp \beta_{x,y} \frac{b_2}{8\pi B_0 \rho} \frac{\omega^2}{\beta^2 c^2} \eta R Q_s \pm a_{x,y} J_z,$$

where $\eta$ is the slip factor, $R$ the physical radius of the accelerator ring, and $Q_s$ the synchrotron tune. All the constants have been combined in the parameter $a_{x,y}$ called the detuning coefficient, similar to the transverse detuning coefficients for Landau octupoles (aka. anharmonicities). The approximation holds assuming linear synchrotron motion, and $\omega \sigma_z / \beta c \ll 1$.

Note that by choosing $\varphi_0 = \pm \pi/2$, the effective tune shift averages to zero over time. In that case, no Landau damping is provided for the slow head-tail instabilities. This operational mode of the rf quadrupole has been studied in Refs. [3, 4] to increase the TMCI intensity threshold.

1.3 Other features and optimization strategies

Equation (3) demonstrates that a single rf quadrupole produces incoherent tune shifts with opposite signs in the two transverse planes. The tune distributions in the horizontal and the vertical plane are hence strictly asymmetric and mirrored with respect to each other. This is a consequence of the quadrupolar nature of the device. Theory predicts that the stability diagrams also follow this asymmetry, meaning that the stabilizing efficiency in the two transverse planes can be very different for a given head-tail mode [8]. This is illustrated in Fig. 3 where the incoherent tune distributions (top) as well as the corresponding stability diagrams (bottom) are shown for a single rf quadrupole for both transverse planes. Due to the asymmetric areas of stability created by a single rf quadrupole, a head-tail mode occurring in one plane may be suppressed already for low quadrupolar strength, while it would remain unstable in the other plane. To suppress the instabilities in both planes simultaneously, it would need a large amount of quadrupolar kick strength. An asymmetry between the incoherent tune spreads in the horizontal and vertical planes has also been observed for magnetic octupoles [20]. This impracticality can be resolved by installing octupole magnets both at the focusing and defocusing main quadrupoles in the lattice. In a similar manner, one can install two independent rf quadrupole families that operate with a phase difference of $\Delta \varphi_0 = \pi$ at two different locations in the machine lattice. One of them at high $\beta_x$, low $\beta_y$ to improve beam stability mainly in the horizontal plane, and the other one at low $\beta_x$ and high
for stability mainly in the vertical plane. The advantages of this scheme were demonstrated using macroparticle tracking simulations and the results are discussed in detail in Ref. [8]. It was shown in particular that the asymmetry in the quadrupolar field strengths required to stabilize the two transverse planes can be removed, and lowered overall. The use of this configuration is thus highly recommended.

![Figure 3](image.png)

**Fig. 3:** *Top:* Incoherent horizontal (red solid) and vertical (blue dashed) tune distributions introduced by a single rf quadrupole [8]. *Bottom:* Corresponding stability diagrams in the complex tune space [9, 17]. Weak head-tail modes with an unperturbed coherent tune shift $\Delta Q_{coh}$ lying below the stability boundaries are Landau damped.

Apart from introducing Landau damping, described by the dispersion relation and the corresponding stability diagrams, a distinct peculiarity of the rf quadrupole is that it can also directly affect the interaction between the beam and the impedance with the result that the effective impedance changes [9, 17]. This originates from the fact that the device acts on the betatron tunes as a function of the longitudinal coordinate by which it introduces a correlation between the betatron and the synchrotron motion. This effect is similar to a chromaticity which can be accounted for by the head-tail phase parameter describing the frequency shift of the beam spectrum with respect to the impedance [6]. A change of the effective impedance leads to a modification of the complex coherent tune shift of the instability under consideration. This manifests itself for example as a change of the instability rise time which can become faster or slower depending on the machine impedance and the unstable head-tail mode at hand. For large enough rf quadrupole strengths it is also possible that a mode is excited on a different synchrotron side band [8]. This phenomenon must not be confused with Landau damping.

2 Summary of results

Detailed theoretical, experimental, and simulation studies on the rf quadrupole with experimental proof of the underlying beam dynamics mechanisms are described in Refs. [8–11]. Here, we limit ourselves to the simulation results relevant for the HL-LHC.

2.1 Simulation study for HL-LHC

To understand the practicality and usefulness of an rf quadrupole for the HL-LHC, it is important to assess its interplay with magnetic octupoles. The reason is that for the HL-LHC, the octupole magnets currently installed in the LHC will remain an essential part of the instability mitigation toolset. The stabilizing performance of an ensemble of 800 MHz superconducting rf quadrupole cavities is evaluated in presence of the LHC Landau octupoles. A single-bunch instability driven by the dipolar accelerator
impedance for foreseen operational beam and machine parameters serves as a study case. The main values of the machine setup are summarized in Table 1. An idealized, transverse bunch-by-bunch feedback system with a damping time of $\tau_{fb} = 50$ turns is also included in the simulation model. At a first-order chromaticity of $Q'_{x,y} = 10$, the most unstable mode is a slow head-tail instability with azimuthal and radial mode numbers $l = 0$ and $m = 2$ respectively. This is consistent with experimental observations made in the LHC at 6.5 TeV [21].

![Graph](image)

**Fig. 4:** PYHEADTAIL tracking simulations illustrating the combined stabilizing effect from LHC Landau octupoles and an rf quadrupole in the HL-LHC for the machine and beam parameters given in Table 1.

PYHEADTAIL [22, 23] simulations were carried out with $N_{mp} = 8 \times 10^5$ macroparticles tracked over $N_{turns} = 6 \times 10^5$ turns. They predict that beam stability from the LHC Landau octupoles alone is achieved as soon as $I_{oct} = 170 \pm 10$ A or higher. This is about one third of the maximum reachable current of the installed LHC Landau octupole system. It is important to note here that the parameters used for the study are from 2017 and hence outdated. Latest beam stability studies for the HL-LHC predict that the required Landau octupole current will be around 570 A, which corresponds to the maximum achievable value [24]. This includes stricter assumptions on the particle distribution (parabolic bunch with tails cut at around 3$\sigma$), reduced transverse emittance, increased bunch intensity, lower transverse feedback gain, and an additional factor 2 that accounts for the discrepancies observed between LHC models and measurements. The difference in required Landau octupole current between the latest results and the study from 2017 can mainly be explained by the reduced transverse emittance (from 2.5 rad to 1.7 rad), the increase in the bunch intensity (from $2.2 \times 10^{11}$ p to $2.3 \times 10^{11}$ p), and the additional factor 2 that accounts for model discrepancies. By including all these effects through linear scaling, the 2017 result scales up to a required Landau octupole current of about 520 A. Nevertheless, in the following, the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Beam energy</td>
<td>$E_0$</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$N$</td>
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<tr>
<td>First-order chromaticity</td>
<td>$Q'_{x,y}$</td>
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<tr>
<td>Norm. transverse emittance</td>
<td>$\varepsilon_{x,y}$</td>
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<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
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<tr>
<td>Transverse feedback</td>
<td>$\tau_{fb}$</td>
</tr>
<tr>
<td>Number of macroparticles</td>
<td>$N_{mp}$</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$N_{turns}$</td>
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damping effect of the rf quadrupole is only studied in relative terms to the predicted required octupole currents from 2017, i.e. $170 \pm 10 \, \text{A}$.

By adding an rf quadrupole to the simulation model the stabilizing current in the Landau octupoles can be lowered as demonstrated in Fig. 4. The beta functions at a potential location of the rf quadrupole in the HL-LHC lattice are set to a conservative $\beta_{x,y} = 200 \, \text{m}$. Although there is a minor effect on the threshold current $I_{\text{oct}}$ up to a cavity strength of about $b_2 = 0.1 \, \text{Tm/m}$, the simulations predict that already for $b_2 \geq 0.27 \, \text{Tm/m}$ the Landau octupoles are no longer required to mitigate the instability. Given the possible cavity designs, the latter strength could in principle be provided with one rf cavity of the four-vane type (see Ref. [12]) with an active length of about $0.3 \, \text{m}$. In terms of active length, this is an improvement of a factor 55 compared to the LHC Landau octupoles. Furthermore, the required rf quadrupole strength can be linearly reduced by increasing the beta functions at the location of the kicks. While this will also increase the impact of the transverse impedance of the cavities, the contribution of the rf quadrupole to the total transverse impedance is negligible overall as explained above.

Given that the latest results reported in Ref. [24] predict that the LHC octupoles can provide just enough Landau damping for the HL-LHC beams, the rf quadrupole could be a valuable option to consider to relax the required octupole currents and enhance the Landau damping effect.

### 2.2 Potential limitations

In terms of collective effects, numerical simulations demonstrate that the rf quadrupole can indeed be successfully used to mitigate single-bunch instabilities through Landau damping. However, the impact of the device on the single-particle dynamics is yet to be studied in detail. Here, we will discuss qualitatively three effects that still need to be thoroughly evaluated.

**Synchro-betatron resonances**

The rf quadrupole produces, among others, a horizontal kick on a particle $i$ as a function of its longitudinal coordinate. Hence, if a synchronicity condition between the longitudinal and the transverse particle motion is fulfilled, the rf quadrupole kicks may add up coherently over time and drive a synchro-betatron resonance (SBR). Since the device does not couple the horizontal and the vertical motion at first order, the SBR condition can be simplified. For the horizontal plane ($k = 0$)

$$jQ_{x,i} + lQ_{x,i} = n,$$

with $j, l, n \in \mathbb{Z}$, but not all zero at the same time.

SBR excited by an rf quadrupole have already been brought up as a potential downside of the device in Refs. [3, 4]. The authors demonstrated analytically and numerically that an rf quadrupole operating at the zero-crossing of the rf wave ($\varphi_0 = \pm \pi/2$) can indeed be employed to increase the TMCI threshold. To have an impact on the TMCI, however, the necessary amount of tune shift must be of the order of the synchrotron tune or higher\(^1\), requiring large quadrupole strengths. The operational mode of the cavity for the mitigation of the TMCI is different from the rf quadrupole for Landau damping presented here. Weak head-tail modes typically have (real) coherent tune shifts that are much smaller than the synchrotron tune. To suppress these modes, a tune spread that has the width of a fraction of the synchrotron tune is hence usually sufficient, translating into relatively small quadrupole strengths.

The frequency map analysis (FMA) is a numerical tool developed by Laskar to study the dynamics of quasi-periodic systems and the stability of orbits in celestial mechanics [25]. This technique is equally applicable to the trajectories in particle accelerators to examine, for example, the resonances introduced by the rf quadrupole more systematically. One computes the tune diffusion $d_Q = |Q_{x,2} - Q_{x,1}|$ for every particle between two equally long time intervals from single-particle tracking data at the beginning (1) and end (2) of the simulation period. The tune diffusion is directly linked to the stability of a particle trajectory. For regular, i.e. stable, trajectories the tune diffusion remains small. On the other hand, a particle that follows a chaotic, unstable, trajectory will have a large diffusion. As a result, by plotting

\(^1\)This “spread” is not amplitude dependent, but instead similar to the odd orders of chromaticity and hence averages out over the synchrotron period. It does not provide Landau damping for the slow head-tail modes.
the diffusion in the tune space (here $Q_s$ vs. $Q_x$), one can visualize regions of unstable and stable single-particle motion.

Despite the lower rf quadrupole strengths required in the Landau damping regime, SBR were observed when studying scenarios for a potential future prototype test of the rf quadrupole in the Super Proton Synchrotron (SPS). A summary of the results is shown in Fig. 5. Distinct lines appear in the tune space where the tune diffusion is much larger than elsewhere. They correspond to the SBR lines that are expected from Eq. (4), using $j = 1$, $n = 20$, and $l \in [-11, -5]$ (blue, dashed). Since the resonances are of relatively low order, they are strongly pronounced. The reason why they are low-order resonances is that the fractional betatron tune is relatively close to zero ($q_x \in [0.09, 0.17]$), while at the same time the synchrotron tune is comparatively large ($Q_s \in [0.015, 0.019]$). The strong dependence of the SBR on the synchrotron tune has also been observed at the Large Electron Positron collider (LEP) at CERN which was operating at high synchrotron tunes [26, 27]. One can also recognize that the higher the order of the SBR, the weaker the tune diffusion and hence the strength of the resonance.

![Diffusion map in $Q_s$ vs. $Q_x$ space for a single rf quadrupole kick per turn in the SPS at 26 GeV. SBR lines expected from the theory [Eq. (4), $j = 1$, $n = 20$] are overlaid and the corresponding orders $l$ are indicated by the numbers along the plot (blue, dashed).](image)

A first evaluation of SBR from an rf quadrupole was also done for the HL-LHC at collision energy (7 TeV) with a single rf quadrupole kick of the same relative strength as in the SPS case ($b_2 = 0.5$ Tm/m). The design betatron tunes at collision energy are $Q_x = 62.31$ and $Q_y = 60.32$ respectively. The small-amplitude synchrotron tune is at $Q_s = 0.0021$. Compared to the SPS, the fractional betatron tune is hence much larger, while the synchrotron tune is a factor ten smaller. By consequence, we expect that the SBR lines close to the HL-LHC working point are of high orders and hence less likely to cause beam degradation. This is confirmed by the results from the FMA given in Fig. 6. The PYHEADTAIL simulations did not reveal any excitation of SBR over the simulated time period. Analytical predictions indicate that the expected SBR would be of orders $l \in [137, 159]$. Although these preliminary studies indicate that SBR are less likely an issue for HL-LHC parameters, detailed follow-up studies on this subject are required, for example using the SIXTRACK code with a complete machine lattice and tracking over longer time periods [28, 29].

**Feed-down**

A bunch passing through a normal magnetic quadrupole with a transverse offset also experiences a dipole kick from feed-down which introduces a distortion of its closed orbit. For the rf quadrupole the magnetic field is rf-modulated, meaning that a bunch traversing the device with a transverse offset will be subject to an rf dipole feed-down kick. To understand the consequences of feed-down effects
Fig. 6: Diffusion map in $Q_x$ vs. $Q_z$ space for a single rf quadrupole kick per turn in the HL-LHC at 7 TeV. SBR lines expected from the theory [Eq. (4), $j = 1$, $n = 62$] are overlaid and the corresponding orders $l$ are indicated by the numbers along the plot (blue, dashed).

from the rf quadrupole, one can infer information from the crab cavity studies, in particular from the global crabbing scheme [30]. The closed orbit distortion introduced by the rf dipole kicks is a function of the longitudinal coordinate. The result is that, depending on the chosen rf phase, the bunch will be curved or tilted and oscillate about the unperturbed closed orbit all around the accelerator ring. This puts additional constraints on the collimation system of a machine, for example [31]. The oscillation amplitude depends on the strength of the rf dipole kick and hence on the magnitude of the transverse offset of the bunch. A qualitative example of the effect is shown in Fig. 7 at an energy of 7 TeV assuming a horizontal offset of $-4 \times 10^{-3}$ m of the bunch at the location of the rf quadrupole kick, with $\varphi_0 = 0$ and a strength of $b_2 = 0.5$ Tm/m. The cavity voltage has been ramped up adiabatically over 50 turns. The red arrow marks the amplitude of the closed orbit distortion. It is linearly dependent on the offset of the beam and on the rf quadrupole strength. Depending on the parameters of the collider where the rf quadrupole system would be installed, studies will be required to assess whether the feed-down introduces issues for the operation of the machine. The studies will provide an answer to whether orbit corrector dipoles are required around the location of the rf quadrupole to ensure that the beam passes as close through the center of the device as possible.

![Diagram](image1.png)

**Fig. 7:** Illustration of local closed orbit distortion (blue) from rf quadrupole feed-down.

**Dynamic aperture**
A particle travelling in a storage ring may experience an increase in its amplitude of oscillation over time due to various beam dynamics effects, such as resonances (not necessarily driven by the rf quadrupole, but other non-linear elements in the lattice). The dynamic aperture (DA) is defined as the maximum oscillation amplitude for which the particle motion still remains stable. A particle situated outside of the DA is in the regime of chaotic motion and will eventually be lost from the beam.

The DA is strongly related to the size of the footprint of a beam in the tune space. A beam with a large tune footprint is more likely to contain particles that coincide with resonance lines that are driven by errors in the machine lattice. From a single-particle dynamics point-of-view, it is hence desirable to limit the amount of incoherent detuning, e.g. introduced by chromaticity, to keep the tune footprint as small as possible. On the other hand, one also tries to avoid strong excitations (drivers) of resonances. In the same manner, an amplitude-dependent tune spread required for Landau damping can have an important impact on the DA. In fact, introducing a tune spread for Landau damping usually comes at the expense of a reduced DA. The effect of the Landau octupoles on the DA, for example in the LHC, has been studied in Refs. [32–34] and demonstrates their detrimental impact on the beam lifetime, especially in combination with linear coupling. For similar reasons, also the rf quadrupole is expected to reduce the DA. It is, however, potentially possible to find operational modes where the octupole magnets (and possibly the rf quadrupole) can also have a positive impact on the DA, e.g. when partially compensating the beam-beam tune spread. Assessing the effect of an rf quadrupole on the DA was not within the scope of this study, but is currently under evaluation.

3 Conclusions

Collective effects beam dynamics studies with an rf quadrupole demonstrate the potential of this device together with the underlying method in order to suppress impedance-driven head-tail instabilities. It was shown that in terms of active length the Landau damping efficiency of the device for HL-LHC beams can be factors of > 50 larger compared to the traditionally employed Landau octupoles. To fully validate the practicality of the rf quadrupole, it still remains to be verified in detail what its effect on the single-particle dynamics is (dynamic aperture and beam lifetime).

Current simulation models of the HL-LHC beam dynamics indicate that the already available means of stabilization, i.e. most notably the LHC Landau octupoles and the transverse feedback system, should be sufficient to guarantee beam stability, at least against impedance-driven head-tail modes. However, there is not a lot of margin left since the octupole magnets would need to be powered at their maximum strength according to model predictions. Hence, should additional Landau damping become necessary in the future, the rf quadrupole, and more generally, detuning with longitudinal amplitude, for example from even orders of chromaticity, remains an interesting option for the HL-LHC.

4 References


[16] S. Vik Furuseth et al.,


