Stability limits with Landau damping in the FCC-hh

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ABSTRACT: The resistive wall impedance is one of the expected main drivers of transverse beam instabilities in the proposed Future Circular Collider hadron-hadron option (FCC-hh). We obtain the resistive wall impedance for the FCC-hh beam screen from a two-dimensional finite element solver. The impedances and resulting growth rates are compared to the LHC, using similar models for the resistivity of the copper layer. Similar to the LHC and in addition to active feedback, dedicated octupole magnets together with a finite chromaticity should be employed for Landau damping, as a cure against transverse beam instabilities. The stability boundary provided by an LHC-like octupoles configuration in combination with an electron lens is obtained from a dispersion relation including the two-dimensional tune spreads. The prediction from the simple dispersion relation are compared to the corresponding beam transfer function and to the stability boundaries reconstructed using particle tracking with an effective impedance. The electron cloud induced tune spreads and their scaling with higher energy and smaller beam pipe radius are estimated. Besides the important estimation of growth rates and stability threshold for FCC-hh we also try to improve the understanding of the scaling of coherent instabilities and their thresholds with energy towards a possible highest-collider limit, using the example of two high-energy colliders, the existing LHC and the proposed FCC-hh.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Coherent instabilities

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1 Introduction

The FCC-hh [1] should provide proton-proton collisions with a centre-of-mass energy of 100 TeV, about seven times higher than in the LHC. The layout of the collider has been developed to integrate with the existing CERN accelerator complex as injector facility. Very similar to the LHC, coupling impedances can drive beam instabilities and cause heating of machine components, ultimately limiting the beam intensity. In the FCC-hh the heat load will be dominated by synchrotron radiation, which will be absorbed by a dedicated beam chamber design, the induced transverse coupled-bunch and single-bunch instabilities are expected to be the most critical impedance induced intensity limitations. Collective beam instabilities are mitigated in the FCC-hh already by several design choices. For example, in the baseline design an injection energy of 3.3 TeV from a modified LHC has been chosen ([1, 2.2.6]) and a copper (Cu) coated beam screen design, to reduce the resistive wall instability growth rate. To ensure operation at the intensity of about \(10^{11}\) protons per bunch with some safety margin, active and passive damping mechanisms are foreseen. The planned transverse feedback system should provide a damping rate of 20 turns at injection and 150 turns at top energy and is sufficient to stabilize the rigid \((k = 0)\) bunch modes for all chromaticities [1]. Octupoles [2] are foreseen as a passive mitigation measure. In this study we focus on the transverse single beam stability, without beam-beam interaction, at injection energy and at top energy. We do not account
Table 1. LHC and FCC-hh parameters used in this study. Here, “inj” and “top” denote the injection and top (without collision) energy.

| Parameter                        | LHC     | FCC-hh  |
|----------------------------------|---------|---------|
| beam energy, $E_0$ [TeV]         | 0.45/7  | 3.3/50  |
| circumference, $C$ [km]          | 27      | 100     |
| betatron tune (inj), $Q_x/Q_y$   | 59.28/63.31 | 111.28/109.31 |
| betatron tune (top), $Q_x/Q_y$   | 59.31/63.32 | 111.31/109.32 |
| synchrotron tune (top), $Q_s$    | $2.2 \times 10^{-3}$ | $1.2 \times 10^{-3}$ |
| bunch intensity, $N_b$ [ppb]     | $1.15 \times 10^{11}$ | $10^{11}$ |
| $4\sigma$ rms bunch length (top), $\tau_b$ [ns] | 1.08  | 1.07   |
| bunch spacing [ns]               | 25      | 25      |
| norm. emittance, $\varepsilon_n$ [µm] | 2.5     | 2.2     |
| transition gamma, $\gamma_t$    | 55.7    | 99.33   |
| averaged $\beta$-function, $\beta^{avg}$ [m] | 72    | 141     |
| energy spread (inj), $\Delta E/E_0 \times 10^{-3}$ | 0.8  | 0.29    |
| energy spread (top), $\Delta E/E_0 \times 10^{-3}$ | 0.26 | 0.12    |

for active feedback systems and estimate the beam stability due to passive damping only, also for non-rigid modes, for which the feedback system is expected to be less effective.

Absolute predictions of growth rates and stability boundaries require a realistic impedance database (see also [3]) together with multi-bunch, multi-mode bunch simulations [4]. Because of uncertainties in the electromagnetic material properties and missing component details at the present design stage, such absolute estimations would carry large error bars and are also beyond the scope of the present contribution. Instead we focus on the scaling of growth rates and tune shifts with energy and geometry from LHC to FCC-hh, as this can relate actual observations from an existing collider to a new one, with many similarities. Within this simplified scope we concentrate on the potentially dominant transverse impedance contribution from the resistive beam pipe for the growth rate predictions and scaling. Other impedance contribution, like the one from the collimators, which will be important at top energy, are neglected so far. Besides impedance induced effects, we also estimate the scaling of electron cloud induced tune shifts.

In general, the scaling of growth rates, tune shifts and stability boundaries towards a possible highest-energy collider limit is a relevant topic, and the scaling from LHC to FCC-hh represents an important example.

2 FCC-hh and LHC main parameters and beam chamber design

The FCC-hh and LHC parameters used in this study are given in table 1. We will focus on the transverse impedance of the FCC-hh beam pipe and the resulting resistive wall instabilities. The resistive wall instability for FCC-hh is expected to be important both at injection and top energy due to the lower revolution frequency, the smaller vertical beam screen half aperture, the increased

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1https://fcc.web.cern.ch/Pages/fcc-hh.aspx.
resistivity of the inner copper layer (at 50 K) and higher magnetic fields, relative to LHC. In the FCC-hh the increase of the pipe impedance at the lowest betatron sideband outweighs the benefit of the larger rigidity for the instability growth rate, as we will see later more in detail. The high total power of the synchrotron radiation in the cold arcs is one of the main reasons for the complex design of the FCC-hh beam screen, in comparison with the relatively simple LHC beam pipe.

As can be seen in figure 1, two slits in the primary chamber are used to extract the photons generated by the beam. The synchrotron radiation will be absorbed when photons reflect from the saw-teeth on the secondary chamber. In our impedance calculations a beam screen without the pumping holes will be assumed, as the shielded holes only represent a minor contribution [3].

Figure 1 shows the beam screens of the LHC and the FCC-hh prototype, respectively. The LHC beam screen transverse size is 36.8 mm in the vertical plane and 46.4 mm in the horizontal plane. The thickness of the stainless steel screen is 1 mm and the thickness of copper coating is 75 µm. Since the copper layer is contaminated with the stainless steel layer during the manufacturing, the copper coating thickness in the simulations is reduced to an effective thickness of 50 µm as done in [4, 5]. The FCC-hh beam screen transverse size is supposed to be 24.44 mm in the vertical plane and 27.65 mm in the horizontal plane. The stainless steel screen is supposed to be 1 mm thick and the copper plating thickness is 300 µm. The choice of the value of 300 µm is explained later. Furthermore, the amorphous carbon (a-C) coating is considered to prevent the electron cloud buildup in the machine. Figure 2 shows the beam screen drawings and finite element method (FEM) meshes for the FCC-hh and LHC, respectively.

![Figure 1. LHC [6] and FCC-hh [7] beam screen photo.](image1)

![Figure 2. Examples of FEM meshes for quarters of the LHC and the FCC-hh beam screen cross sections.](image2)
3 Transverse resistive wall impedance

For the LHC and FCC-hh beam screens (see figure 1) the transverse impedances were obtained from the finite-element (FEM) frequency-domain solver BeamImpedance2D [8], using realistic geometries and conductivities. The conductivity of the Cu layer at low temperatures is characterized by the residual-resistivity ratio, defined as $\text{RRR} = \rho(300\,\text{K})/\rho(4\,\text{K})$. For the thin copper layer, used in the LHC, an RRR of 70 is used [5] instead of initially assumed 100 due to the selected manufacturing process [9]. Our estimates of the Cu resistivity for the FCC-hh are based on a RRR of 70, keeping in mind that it could be possible to use higher purity copper, resulting in a lower impedance. The resistivity of the copper screen layer is assumed as $\rho = 7.5 \times 10^{-10}\,\Omega\,\text{m}$ (see [10]) at the FCC-hh screen temperature of $T = 50\,\text{K}$ and for a magnetic field $B = 0\,\text{T}$. For the LHC ($T = 20\,\text{K}$) the corresponding resistivity would be $\rho = 2.4 \times 10^{-10}\,\Omega\,\text{m}$ [4]. Following Kohler’s rule for the magnetoresistivity [11], the resistivities at maximum magnetic fields are $\rho = 1.4 \times 10^{-9}\,\Omega\,\text{m}$ for the FCC-hh ($B = 16\,\text{T}$) and $\rho = 7.7 \times 10^{-10}\,\Omega\,\text{m}$ for the LHC ($B = 8\,\text{T}$).

It is worth noting that in the case of the LHC beam screen, at high frequency the copper resistivity is additionally affected by the anomalous skin effect, which occurs due to the low temperature [12]. As for the FCC-hh, the anomalous skin effect in the relevant frequency and temperature range can be neglected and is not accounted for in our study.

The obtained real parts of vertical impedances in $\Omega/\text{m}^2$ are shown in figure 3. Comparing the impedances at the lowest betatron sidebands $f_{\text{min}} = (n - Q_y)f_0$, with $f_0$ is the revolution frequency, for the LHC top energy and the FCC-hh top energy we obtain a factor 5 – 6 larger impedance. At the FCC-hh top energy the impedance is larger compared to injection, due to magnetoresistivity. The error bar on the impedance plot, shown in figure 3, is represented by the uncertainties in the temperature and the purity of the copper. The working temperature was initially defined as a range between 40 K and 60 K with the further reference temperature of 50 K [1]. We will take the highest temperature and lowest RRR and lowest temperature and highest RRR as possible extremal deviations from the working point.

Thus, the lowest limit in the error bar is presented by the case of RRR = 100 and $T = 40\,\text{K}$ with $\rho_{\text{RRR}=100,40\,\text{K}} = 3.8 \times 10^{-10}\,\Omega\,\text{m}$, while the highest limit — RRR = 70 and $T = 60\,\text{K}$ with $\rho_{\text{RRR}=70,60\,\text{K}} = 1.2 \times 10^{-9}\,\Omega\,\text{m}$ [10]. Using Kohler’s formula, the magnetoresistivities at injection energy and in the presence of the magnetic field ($B = 1.06\,\text{T}$) are $\rho_{\text{RRR}=100,40\,\text{K}} = 4.2 \times 10^{-10}\,\Omega\,\text{m}$ and $\rho_{\text{RRR}=70,60\,\text{K}} = 1.3 \times 10^{-9}\,\Omega\,\text{m}$.

It is worth pointing out that both, the FCC-hh and LHC resistive wall impedances can be approximated quite well by the respective thin and thick wall analytical expressions (see figure 3), using different beam pipe radii for the horizontal and vertical planes. Using the vertical beam screen half aperture for $b$, the copper layer thickness and resistivity for $d$ and $\rho_{\text{Cu}}$ in

$$Z_{y}^{\text{thin}} = \frac{c\rho_{\text{Cu}}}{\pi b^3 \omega d}$$

the impedances at the lowest betatron sidebands can be reproduced (see figure 3) at injection energy as well as at top energy. The expression for the thick wall is obtained by replacing the layer thickness $d$ in the above equation by the skin depth $\delta_s$. 

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Figure 3. Real part of the vertical impedance per unit length of the LHC and FCC-hh beam screen obtained from BeamImpedance2D [8]. The vertical dotted lines indicate the lowest frequencies relevant for the coupled-bunch resistive wall instability. The black dotted and dashed lines correspond to the analytical expressions for the thin and thick wall impedance, with the pipe radius $b = 13$ mm used as a fit parameter.

The optimal (minimum) copper thickness $d$ can then be obtained by equating $f_{\text{min}}$ to the intersection of the thin and the thick wall expressions, leading to

$$d = \delta_s = \frac{c \rho_{\text{Cu}}}{\pi Z_0 f_{\text{min}}}.$$  \hspace{1cm} \hspace{1cm} (3.2)

where $\delta_s$ is the skin depth and $Z_0 = 377$ $\Omega$. The obtained result is close to the chosen design $d$ of 300 $\mu$m.

For the horizontal resistive wall impedance we observe a slight deviation from the simple thin/tick wall approximations (see figure 4). At $f_{\text{min}}$ the difference between both planes is only marginal, as expected from the aspect ratio of about 1 : 1. However, at higher frequencies the slit plays a significant role. We have indicated a relevant high frequency by the inverse FCC-hh bunch length in figure 4). The asymptote for the horizontal impedance has a larger value than for the vertical one, however, we observe a long, broadband transition to this value. As a consequence the growth rates for single bunch instabilities are larger in the horizontal plane. From our FEM simulations we identified the uncoated edges of the beam screen (see sketch on the right in figure 4) as the source of the larger horizontal impedance. Applying a copper layer to those edges would reduce the horizontal impedance to a value comparable to the vertical impedance.
Figure 4. Left: vertical (red) and horizontal (blue) impedances (real parts) per unit length of the FCC-hh beam screen obtained from BeamImpedance2D [8]. The colored vertical dotted lines indicate the lowest frequencies relevant for the coupled-bunch resistive wall instability. The black dotted and dashed lines correspond to the analytical expression for the thin and thick wall impedance, with the pipe radius $b$ used as a fit parameter ($b = 13$ mm, very close to the actual vertical FCC-hh beam screen half aperture). Right: the edges of the FCC-hh beam screen with applied additional copper coating (left) and the zoomed edges (right) (in red).

4 Instability growth rate estimates and scaling

From the vertical impedance we obtain the growth rate $\tau_k^{-1} = \omega_0 \Im \Delta Q_k$ for transverse coupled-bunch instabilities using the complex tune shift [13]

$$\Delta Q_k = -\frac{1}{1 + k} \frac{g M I_b}{4 \pi E_0} \hat{\beta}_y Z_y (\omega_{\text{min}}) F_k' (\omega_{\text{min}} - \chi / \tau_b),$$

where $\omega_0 = 2 \pi f_0$ is the angular revolution frequency, $k$ is the bunch mode number, $M$ is the number of bunches, $I_b$ is the average current per bunch, $E_0 = \gamma mc^2$ is the reference particle’s energy with relativistic parameter $\gamma$ and particle mass $m$. $\hat{\beta}_y$ is the vertical $\beta$-function, $Z_y$ is the vertical impedance, $\omega_{\text{min}}$ is the lowest betatron sideband, and $F_k'$ is a form factor. $\chi = Q' \gamma^2 \omega_0 \tau_b$ is the chromatic phase shift with the chromaticity $Q'$, the transition energy $\gamma_t$, and the bunch length $\tau_b$.

From the impedances shown in figure 3 and for $Q' = 0$ we obtain growth rates corresponding to 100 turns at the FCC-hh injection energy and 900 turns at top energy. For the LHC at top energy we obtain a growth rate corresponding to 4800 turns. The corresponding ratio of the coherent tune shifts at top energies are

$$\frac{\Delta Q^{\text{FCC}}}{\Delta Q^{\text{LHC}}} = \frac{n_t^{\text{LHC}}}{n_t^{\text{FCC}}} \approx 5,$$

with $n_t = c \tau / C$ the number of turns. In $s^{-1}$ the growth rates in LHC and FCC-hh are similar at top energies.

For $Q' = 15$ the growth rates for the $k = 0$ coupled-bunch mode would be lower by a factor 0.6, but the $k = 1$ mode would be present in addition (growth rate corresponding to 600/5000 turns at FCC-hh injection/top energy).
From the scaling of the (thin) resistive wall impedances (at \( f_{\text{min}} \approx f_0 \)) we obtain for the scaling of the growth rate from LHC to FCC-hh

\[
\tau^{-1} \propto \frac{C \hat{\beta}_y \rho_{\text{Cu}}}{E_0 b^3 d},
\]

which also results in similar \( \tau^{-1} \) in LHC and FCC-hh and can be used for very rough estimates of the growth rate and its dependence on the beam screen properties, for example.

Coupling between modes \( k \) should be negligible, in order for Equation (4.1) to be applicable. Above a threshold intensity transverse mode coupling can result in coupled-bunch instabilities including \( k > 0 \) modes. The prediction of such thresholds for coupled bunches requires dedicated simulation studies (see for example [4] for the LHC). It is expected that mode coupling will affect the coupled-bunch instability in FCC-hh. An indication is \( \Re \Delta Q \) from Equation (4.1), which is of the order of the synchrotron tune

\[
Q_s = \frac{\Delta E}{\gamma_t^2 \omega_0 E_0 \tau_b},
\]

where \( \Delta E/E_0 \) is the energy spread.

Despite the fact that mode coupling might be relevant for the FCC-hh design parameters, Equation (4.1) is used here as an estimate for the growth rates in FCC-hh and LHC, in order to determine and compare the Landau damping requirements. Mode coupling might result in unstable \( k > 0 \) bunch modes for \( Q^* = 0 \), which can also be stabilized by Landau damping depending on their growth rate.

For a single bunch the transverse mode coupling intensity threshold can be estimated from the merging of the \( k = 0 \) and \( k = -1 \) modes. The downward frequency shift of the \( k = 0 \) mode as the beam intensity increases from zero is a general behavior for short bunches [14]. The intensity threshold can be estimated by equating the transverse mode shift of the \( k = 0 \) mode and the synchrotron tune (see for example [15, Ch. 11]) which results in

\[
N_b^{\text{th}} \approx \frac{4 \pi E_0 Q_s \tau_b}{e^2 \hat{\beta}_y \gamma_t^2 Z_{y,0}^{\text{eff}}},
\]

where \( Z_{y,0}^{\text{eff}} \) is the effective impedance for the \( k = 0 \), defined as the weighted average of the impedance over the mode power spectrum [13, 15]. For a fixed bunch emittance and an energy-independent impedance one obtains the scaling

\[
N_b^{\text{th}} = \frac{4 \pi R \Delta E}{e^2 \hat{\beta}_y \gamma_t^2 Z_{y,0}^{\text{eff}}} \propto Q_s^{-1}
\]

for the threshold intensity, which gives about a factor 10 larger threshold for the LHC bunches compared to the FCC-hh. \( R \) is the radius of the synchrotron.

Including the energy-dependence of the impedance due to magnetoresistance, the threshold intensity at FCC-hh top energy is about a factor 2 larger than at injection.

For the single bunch mode coupling threshold also the foreseen amorphous carbon coating of the inner beam screen can be of relevance. This material has a low secondary electron emission yield, and a relatively weak effect on the machine impedance, provided that the coating is sufficiently
thin. The required thickness of the a-C coating to decrease the secondary emission yield below 1 is approximately 30 nm (100–150 carbon monolayers). However, to achieve a homogeneous coating layer a thicker coating such as 200 nm is being considered. The effect of the a-C coating on the imaginary high frequency part of the resistive wall impedance is shown in figure 5, assuming a resistivity of $\rho_{a-C} = 10^4 \Omega \text{m}$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Imaginary part of transverse vertical impedance as a function of the frequency in case of no coating and with different thicknesses of the amorphous carbon coating.}
\end{figure}

Depending on the a-C layer thickness the single bunch mode coupling threshold at the FCC-hh injection energy varies according to

$$\frac{N_{th}^{FCC}}{N_{th}^{FCC+a-C}} \approx \begin{cases} 
1.0 & 50 \text{ nm coating}, \\
1.2 & 200 \text{ nm coating}, \\
2.4 & 1 \mu \text{m coating},
\end{cases}$$

where $N_{th} \propto 1/Z_w(f_{SB})$ with the single bunch frequency $f_{SB} = 1/\tau_b \approx 0.93$ GHz. In the horizontal plane, the instability threshold is smaller because of the higher impedance.

5 Dispersion relation with two-dimensional tune spreads

The transverse coupled-bunch instability in the FCC-hh will be stabilized with a dedicated transverse feedback system, which should provide a damping rate of 20 turns at injection and 150 turns at top energy and should be sufficient to damp $k = 0$ bunch modes, also for finite chromaticities [1]. The non-rigid modes should be damped passively by dedicated Landau octupoles. In this section we estimate the stability boundaries from Landau damping only and ignore any active dampers.

For an analytical description of Landau damping due to a two-dimensional, amplitude dependent, incoherent tune spread $\Delta Q_{icoh}(J_x, J_y)$, the following dispersion relation in the form $\Delta Q_{coh}r_0(\Omega) = 1$ is used [16–18],

$$\Delta Q_{coh} \int \frac{1}{\Delta Q_{icoh}(J_x, J_y) - kQ_s - \Omega/\omega_0} J_x \frac{\partial y_s}{\partial J_x} dJ_x dJ_y = 1. \quad (5.1)$$
Here, the coherent frequency is $\Omega$, $\Delta Q_{\text{coh}}$ is the coherent tune shift due to interaction with the transverse impedance, in the case without tune spread and Landau damping. The integral expression $r_0(\Omega)$ is the transverse beam transfer function in the absence of collective effects. In the case of a constant $Q_s$, independent of amplitudes, there is no effect on the stability boundary. $J_x, J_y$ are the corresponding action variables. The complex mode frequency $\Omega$ can be obtained from Equation (5.1) for a given impedance, tune spread, and beam distribution function $\psi_\perp(J_x, J_y)$. The stability boundary is determined by $\Omega = 0$. Equation (5.1) has been derived in [19] from the Vlasov equation as a function of the mode number $k$, in the absence of mode coupling. In order to be valid for non-rigid modes the incoherent tune spread should also be smaller than the mode spacing (determined by the synchrotron tune $Q_s$), which still holds for FCC-hh parameters. In the next sections the different sources of tune shift, relevant for Landau damping in FCC-hh will be discussed.

6 Tune shifts due to octupoles in FCC-hh

Similar to the LHC, octupoles will be used in the FCC-hh to stabilize the beam against transverse coupled-bunch instabilities. For a set of octupole magnets the tune shifts are given by [20]

$$\Delta Q_x = \left\{ \frac{3}{8\pi} \sum \beta^2_x \frac{O_3 L_m}{B \rho_B} \right\} J_x - \left\{ \frac{3}{8\pi} \sum 2 \hat{\beta}_x \hat{\beta}_y \frac{O_3 L_m}{B \rho_B} \right\} J_y,$$

$$\Delta Q_y = \left\{ \frac{3}{8\pi} \sum \beta^2_y \frac{O_3 L_m}{B \rho_B} \right\} J_y - \left\{ \frac{3}{8\pi} \sum 2 \hat{\beta}_x \hat{\beta}_y \frac{O_3 L_m}{B \rho_B} \right\} J_x,$$

(6.1)

where $O_3$ is the octupole strength, $L_m$ their length, $B \rho_B$ is the magnetic rigidity, $\hat{\beta}_x, \hat{\beta}_y$ are the horizontal, vertical $\beta$-functions.

In a short form this is

$$\Delta Q_x = a_x J_x - b_{xy} J_y,$$

$$\Delta Q_y = a_y J_y - b_{xy} J_x.$$  

(6.2)

In the LHC the two families of the Landau octupoles are located close to the main arc quadrupoles [18]. There are 84 “F–Octupoles” and 84 “D–Octupoles”, each one fed with the same currents. The only difference is the relation between the horizontal and the vertical $\beta$-function. “F–Octupoles” are at a large $\beta_x$ and a small $\beta_y$, for the “D–Octupoles” it is other way around.

In a good agreement with [18] we use the following coefficients for the octupole tune shifts from eq. (6.1),

$$a_x \epsilon_n = 3.28 \times \frac{I_{\text{oct}[A]} \epsilon_n[m]}{E^2[\text{TeV}]}$$

$$b_{xy} \epsilon_n = 2.33 \times \frac{I_{\text{oct}[A]} \epsilon_n[m]}{E^2[\text{TeV}]}$$

$$a_y \epsilon_n = 3.43 \times \frac{I_{\text{oct}[A]} \epsilon_n[m]}{E^2[\text{TeV}]}$$

(6.3)

Here $E$ is the beam energy and $\epsilon_n$ is the transverse normalized rms emittance.
For the maximum current \( I^\text{max}_{\text{oct}} = 550 \, \text{A} \), \( \varepsilon_n = 2.5 \, \mu\text{m} \) and \( E_0 = 7 \, \text{TeV} \) we obtain \( a_x \varepsilon_n \approx 0.92 \times 10^{-4} \), \( a_y \varepsilon_n \approx 0.96 \times 10^{-4} \) and \( b_{xy} \varepsilon_n \approx 0.65 \times 10^{-4} \).

In the FCC-hh we assume an octupole configuration similar to the LHC. Two families of the Landau octupoles will be located close to the main arc quadrupoles, with the opposite \( \beta \)-functions relations [2].

From Equation (6.1) we estimate the tune spreads by equating the action variables to the transverse emittances \( J \approx \varepsilon \). The tune spreads scale as

\[
\delta Q_{\text{oct}} \propto \frac{\beta^2}{\gamma^2} N_{\text{oct}} O_3 L_m. \tag{6.4}
\]

For a rough estimate of the octupoles required for beam stabilisation [13] we equate the above tune spread with the growth rate from the resistive wall instability \( \tau^{-1} \) from Equation (4.3) and obtain

\[
N_{\text{oct}} O_3 L_m \propto C^2 \gamma \frac{\rho_{\text{Cu}}}{\beta \beta^3 d}. \tag{6.5}
\]

Comparing LHC and FCC-hh at top-energies we obtain

\[
\frac{(N_{\text{oct}} O_3 L_m)_{\text{FCC}}}{(N_{\text{oct}} O_3 L_m)_{\text{LHC}}} \approx 50 \tag{6.6}
\]

Such a large number of octupoles (more than 8000 per ring, if existing LHC magnets would be used) is not realistic, also in terms of their possible effect on the dynamic aperture, and also not necessary if only higher-\( k \) modes should be Landau-damped. For higher-\( k \) modes the growth rate is reduced by \( 1/(1 + k) \) (see Equation (4.3)) and so also the number of required octupoles. If we require the same octupole induced tune shifts in LHC and FCC-hh, as an example, the above ratio would decrease to \( \approx 10 \). Using advanced technology magnets would reduce the number of octupoles [21]. In the following we will call this configuration 'LHC-type octupoles', meaning a configuration of octupoles leading to similar tune spread as in LHC.

7 Tune shifts due to electron lenses

Landau damping of beam instabilities by electron lenses has been proposed for the LHC and FCC-hh in [22]. The beam-beam tune shift (counter-propagating beams) induced by one electron lens is

\[
\Delta Q_e = \frac{1 + \beta_e}{\beta_e} \frac{l_p I_e}{2\pi e e \varepsilon_n}. \tag{7.1}
\]

Hereby we assume that the transverse profiles of both, proton and electron, (round) beams overlap ideally. \( r_p \) is the classical proton radius, \( I_e \) is the current of the electron beam, \( l \) is the length of the interaction section, \( \beta_e \) is the velocity of the electrons divided by the speed of light. The tune shift does not depend on \( \gamma \). Implicitly it has been assumed that the \( \beta \)-functions at the electron lens scales with \( \gamma \), in order to achieve the ideal overlap between the two beams at large energies. We assume a beam-beam tune shift of \( \Delta Q_e \approx 0.002 \) provided by one lens, which is still less than the \( \Delta Q_e \approx 0.01 \) assumed in [22]. Assuming a round Gaussian transverse profile for the electron beam, the amplitude dependent beam-beam tune shift is

\[
\Delta Q^e_{xy}(J_x, J_y) = 2\Delta Q_e \int_0^{1/2} \frac{I_0(J_x u) - I_1(J_x u)}{\exp(J_x u + J_y u)} I_0(J_y u) du, \tag{7.2}
\]
where \( J_x = J_x/e_x \) has been used for normalisation, \( I_0 \) and \( I_1 \) are modified Bessel functions of the first kind. The above expression has been used in [22] and it was shown that the maximum Landau damping is achieved for ideally matched beams (with equal rms radii: \( \sigma_e = \sigma_p \)). However, one could think of other than Gaussian profiles for the electron beam resulting in a reduced linear tune shift, for example.

8 Electron cloud induced tune shifts

Detailed electron cloud (EC) buildup and bunch stability studies are beyond the scope of this contribution. Here we discuss simple estimates of the expected differences between LHC and FCC-hh, especially due to a lower pipe radius, \( b \) and beam radius \( \sigma \) in the FCC-hh. For simplicity, we assume a round beam and beam pipe in this section. The EC buildup threshold depends on the secondary electron emission yield (SEY) \( \delta \), and the energy distribution of the electrons.

From the kick approximation, the maximum energy gain of an electron initially located at the pipe wall is [23–26]

\[
\Delta W_e = 2m_e c^2 (N_br_e/b)^2 \approx 800 \text{ eV},
\]

(8.1)

where \( m_e \) is the electron mass, \( N_b \) is the proton beam intensity, and \( b \) is the FCC-hh beam pipe radius, corresponding to the vertical beam screen half aperture. Because of the lower pipe radius electrons in the FCC-hh beam pipe can be assumed to be more energetic

\[
\frac{W_e^{\text{FCC}}}{W_e^{\text{LHC}}} \approx 4
\]

(8.2)

From the SEY expressions for \( \delta(W_e) \) (see for example [27]), which have their maximum at energies 200–300 eV and an energy dependence \( \delta \propto W_e^{(1-s)} \), with \( s = 1.35 \), we obtain a factor 0.6 lower SEY for the FCC-hh case. This in fact would result in a higher tolerable SEY threshold \( \delta_{\text{max}} \) (usually defined at maximum) of the same order. This factor agrees roughly with the result of detailed EC buildup simulation performed with a Particle-In-Cell code [28] for the detailed LHC and FCC-hh beam pipe geometries shown in figure 6.

![Figure 6. SEY threshold \( \delta_{\text{max}} \) for LHC and FCC-hh in the drift and arc dipole.](image-url)
Above the EC buildup threshold the maximum averaged electron density in the pipe can be estimated from the space charge limit (see [28]) in a field-free drift section

\[ \bar{n}_e = \frac{4e_0 W_s}{e^2 b^2}, \]  

where \( e_0 \) is the vacuum permittivity and \( W_s \) is the kinetic energy (a few eV) of the electrons emitted from the wall. The above estimate indicates a larger density for the lower FCC-hh pipe radius, but a similar electron line density \( N_e/l \) in the pipe, assuming the pipe is homogeneously filled with electrons between bunches.

Detailed simulation studies of the tune shifts induced by electron clouds in relativistic proton bunches have been performed in [28–30], for example. In [29] a simple expression was used to describe the tune shift variation along (coordinate \( z \)) the bunch in a round pipe without magnetic fields

\[ \Delta Q_x(z) = \frac{r_p L_c \beta_x}{\gamma} \bar{n}_e \lambda_e(z), \]  

where \( L_c \) is the length of the cloud, \( \lambda_e(z) \) is the electron density along the bunch, averaged over the beam radius \( \sigma \) and divided by \( \bar{n}_e \). At the head of each bunch we therefore have \( \lambda_e = 1 \). Comparing the tune shifts at top energies we arrive at the scaling law

\[ \frac{\Delta Q_{e}^{\text{FCC}}}{\Delta Q_{e}^{\text{LHC}}} \approx \frac{c_{\text{FCC}}}{c_{\text{LHC}}} \left( \frac{b_{ \text{LHC}}}{b_{ \text{FCC}}^2} \right)^2 \frac{\beta_{\text{FCC}}}{\beta_{\text{LHC}}} \lambda_{e,m} \gamma \approx 20 \frac{\lambda_{e,m}}{\gamma}, \]  

where \( \lambda_{e,m} = \max[\lambda_e(z)] \) is the maximum electron density along the bunch, which is expected to also depend on \( \gamma \) via the beam radius \( \sigma \propto \sqrt{\beta_{x,y}/\gamma} \). Because of the shrinking beam radius the density of the pinched electron cloud at the beam center can be expected to be larger for higher energies (see for example [31]).

In order to estimate the variation of the electron density along the bunch we integrate numerically the equation of motion for electrons in the transverse electric field of a relativistic proton bunch with line density \( \lambda \) and rms beam radius \( \sigma \)

\[ r_e'' = -\frac{e^2}{2\pi e_0 m_e c^2} \lambda_e(z) \left[ 1 - \exp \left( -\frac{r_e^2}{2\sigma^2} \right) \right]. \]  

Initially the electrons are at rest and distributed homogeneously in the pipe. The resulting electron line density \( \lambda_e(z) \) along the bunch for different beam radii is shown in figure 7. With decreasing beam radius \( a_b = 2\sigma \) the pinched electron density inside the beam radius increases strongly. However, if we account for the induced tune shift and divide the obtained maximum \( \lambda_{e,m} \) by \( \gamma \propto a_b^{-2} \) we arrive at the result shown in figure 8. Because of the multiplication with \( a_b^2 \), the corresponding tune shift decreases as a function of \( a_b \). For the ease of interpretation we indicate the typical beam radii in LHC and FCC-hh at top energy in figure 8. One should keep in mind that in order to obtain the result shown in figure 8 we assume that the bunch length and the initial electron density do not depend on \( \gamma \). Also \( \gamma \propto a_b^{-2} \) does not exactly hold for two different colliders (with different average \( \beta \)-functions, for example).

In summary, we estimate that in the FCC-hh, relative to the LHC, the electron induced tune shift will still be relevant, simply because of the larger circumference and similar bunch parameters.
The smaller effective beam pipe radius in the FCC-hh potentially increases the threshold for EC buildup. At top energy the tune shift will be further reduced due to the higher $\gamma$. Because of the increase of the local electron line density this reduction is weaker than $1/\gamma$.

Also because of the very large uncertainties in any quantitative estimation of EC density profiles, we will not account for the induced tune shifts in our stability analysis. One has to keep in mind that the EC pinches at the local transverse beam center. Therefore its contribution to Landau damping due to the induced tune shift along the bunch $\lambda_e(z)$ is more indirect and cannot be estimated from the simple dispersion relation presented in [17] for a transverse tune shift along the bunch.
9 Estimation of the stability boundary

In this section we use the dispersion relation Equation (5.1) together with the expression for the tune shifts from octupoles and electron lenses to estimate the stability boundaries in the FCC-hh. The stability curves for LHC-like octupoles (a configuration of octupoles leading to a similar tune spread as in the LHC) and an electron lens providing a tune shift of $\Delta Q_e = 0.002$ are shown in figure 9. The green dot indicates the vertical coherent tune shift from Equation (4.1) induced by the resistive wall impedance at the FCC-hh top energy (assuming $Q_0 = 0$). As expected, LHC-like octupoles would not provide sufficient Landau damping to damp the transverse resistive wall instability for $Q' = 0$ in the FCC-hh. For finite chromaticity ($Q_0 = 15$) octupoles could provide sufficient damping, assuming a constant Landau damping rate for non-rigid bunch modes, as predicted by Equation (5.1). However, including the uncertainties regarding Equation (4.1), the resistive wall impedance and on top additional transverse impedance sources, like the collimators, it is clear that a large safety margin is required. This could be achieved by an additional electron lens. The combination of both (with the right polarity) leads to an enlarged stability area (see figure 9), even for a relatively weak electron lens. Furthermore the octupoles still ensure that unstable bunch oscillations are damped, at the cost of a larger emittance [32].

9.1 Probing the beam transfer function

For a first justification of the dispersion function used in our stability analysis, we compare the beam transfer function (BTF) $r_0(\Omega)$, underlying Equation (5.1), with the results of particle tracking, using actual FCC-hh bunch distributions. We track an FCC-hh bunch distribution through a simplified lattice with octupoles and an electron lens as the only nonlinear elements. As in an actual BTF measurement a localized transverse dipolar kick is applied to the bunch particles. The frequencies of the kick are obtained from a random distribution centered at the bare tune. The obtained BTF amplitude for octupoles and $Q' = 0$ is shown in figure 10 (left plot). Both, the BTF amplitude and phase (not shown) agree well with the prediction. For finite chromaticity ($Q' = 15$) also non-rigid bunch modes are excited by the rigid dipolar kick. The two $k = 1$ sidebands can be seen very clearly in figure 10 (right plot). The respective BTF amplitude from Equation (5.1) can be fitted very well at the sidebands, if one accounts for the relative amplitudes of head-tail modes for a given chromaticity taken from [33] (eq. 10). Our simulations confirm the Landau damping of non-rigid modes by octupoles predicted by Equation (5.1) for FCC-like bunches. We obtain similar results for an electron lens. If octupoles are combined with an electron lens the resulting BTF amplitudes are shown in figure 11. Here the agreement is still rather poor, but the simulation results very roughly resembles the prediction from Equation (5.1). The simulation results indicate that the used dispersion relation agrees with tracking simulations for FCC-hh bunches, for the BTF without impedances. This method will be further elaborated in upcoming studies.

9.2 Stability boundaries with an effective impedance

Another method to compare particle tracking simulation results and stability boundaries from dispersion relations is to apply an effective impedance kick corresponding to a complex coherent tune shift $\Delta Q_{coh}$. This method was previously used to study stability boundaries with space-charge,
Figure 9. Stability curves for LHC-like octupoles, electron lenses ($\Delta Q_e = 0.002$) and their combination. The green dot represents the complex coherent tune shifts for the coupled-bunch instability ($k = 0$ and $Q' = 0$) at top energy.

Figure 10. BTF amplitude from particle tracking and from Equation (5.1) for LHC-like octupoles and zero (left) and finite (right) chromaticity. The vertical lines indicate the synchrotron satellites. The tune shift is normalized by the rms tune spread provided by the octupoles. In the simulations for a finite chromaticity ($Q' = 15$) the $k = -1$ and $k = 1$ modes are excited.

electrons and octupoles and chromaticity in [34]. The effective impedance used in the this study acts on the rigid $k = 0$ mode only (assuming $Q' = 0$).

The coherent tune shift $\Delta Q_{k=0}$ induced by the effective impedance $Z_0^{\text{eff}}$ is implemented as a simple kick in the tracking code

$$\Delta x' = 4\pi \Im \Delta Q_{k=0} \bar{x}' + 4\pi \Re \Delta Q_{k=0} \frac{\bar{x}}{\beta_x}$$

(9.1)

$\bar{x}$ and $\bar{x}'$ are the offset and its derivative averaged over all particles in the bunch and taken at the position of the kick. Within the above implementation of the kick we only excite rigid ($k = 0$) bunch modes, which allows a direct comparison to the dispersion relation discussed in section (5).

For the estimation of the stability boundary from tracking simulations two methods are employed. One is applying a score function to the offset and emittance evolution for each pair of
Figure 11. BTF amplitude as a function of the tune shift (normalized by the octupole induced rms tune spread) from particle tracking and from Equation (5.1) for LHC-like octupoles only (solid line) and in combination (dashed line) with an electron lens ($\Delta Q_e = 0.001$) for $Q' = 0$.

Figure 12. Stability boundaries obtained from the simulation with zero chromaticity $Q' = 0$ and only mode $k = 0$ excited by the effective impedance. On the left: LHC-like octupoles are the only source of non-linearity, On the right: an electron lens with $\Delta Q_e = 2 \cdot 10^{-3}$ is the only source of non-linearity.

$\Re Z \propto \Im \Delta Q$, $\Im Z \propto \Re \Delta Q$. If the beam offset exceeds a threshold value (5 $\mu$m) and the offset envelope fits an exponential or emittance exceeds 10% of its initial value, we consider a beam unstable for the complex impedance $\Re Z$, $\Im Z$. Otherwise, the beam is considered stable and from the set of the stable points stability boundary is visualised. Another method is considering only unstable points with exponential growth and using a linear model to estimate the stability boundary from growth rates. For a fixed value of $\Re \Delta Q$ we are looking at the instability growth rates with a given $\Im \Delta Q$, then a linear model is applied to determine the value of $\Im \Delta Q$ for which the growth rate is zero.

For the LHC-like octupoles the stability boundary obtained from the simulations is predicted by the dispersion relation (figure 12, left plot). Both the score function (orange dots) and growth rate interpolation methods (blue dotted curve) show a good agreement between the two methods and with the analytical estimation. In the case of an electron lens the simulations (figure 12 right plot) predict a slightly shifted stability area. For the combination of an electron lens and LHC-like octupoles (with the beneficial polarity) we obtain a large stable area close to the analytical estimation (figure 13).
Overall we observe a good agreement between the simulated stability boundaries and the ones obtained from the dispersion relation. This gives confidence in the dispersion relation (5.1) for FCC-hh conditions.

Figure 13. Stability boundary obtained from the simulation with zero chromaticity \( Q' = 0 \) and only mode \( k = 0 \) was excited by a controlled impedance source. Non-linearity source is a combination of LHC-like octupoles and an electron lens with \( \Delta Q_e = 2 \cdot 10^{-3} \).

10 Conclusions

In conclusion, the LHC and FCC-hh beam screen impedances were obtained from a 2D solver, using the detailed geometries and surface coating. The transverse impedance of the FCC-hh screen can still be estimated from the simple thin and thick resistive wall formulas, as well as the optimum thickness of the Cu coating. We also give an error bar for the obtained impedances, resulting from the underlying resistivity of the Cu layer. The predictions were made for the present beam screen design. Regarding further impedance reduction, the RRR of the Cu layer could still be improved using higher purity Cu. Furthermore a High-Temperature Superconductor (HTS) coating of the screen (see for example \[35, 36\]) would lead to a very strong reduction of the impedance at lower frequencies and so of the transverse coupled-bunch growth rate. It might lead to an increase of the high frequency part, as pointed out in \[35\]. A lower transverse impedance could allow for reducing the screen radius towards the limits imposed by the dynamic aperture, with a potential reduction of costs. From the transverse resistive wall impedance we estimate the growth rates for transverse coupled-bunch instabilities, which are largest at injection and decrease with \( \rho_{Cu} (B) E_0^{-1} \). Compared to LHC top-energy, the obtained growth rates are similar at FCC-hh top-energy. Stabilisation of transverse instabilities by Landau octupoles is less effective at top energy than at injection energy. Our estimates indicate that an LHC-like octupole configuration, with the same tune spreads, could stabilize the resistive wall coupled-bunch instability, at least for the \( k > 0 \) modes. For finite chromaticity also \( k = 0 \) modes could be stabilized, without any margin. The enlarged stability area of electron lens combined with conventional octupoles might provide enough safety margin to stabilise the bunches without collision. An advantage of this combined scheme is that the octupoles would also stabilize initially (for example after moving the beams out of collision) unstable beams,
Our stability prediction rely on a dispersion relation, which is based on simplifying assumptions and therefore the results have to be treated with caution. Within this study we also performed comparisons with particle tracking. First, for the underlying BTF and, second, for the stability boundary. We showed that for octupoles the underlying BTF can be reproduced by tracking, also for non-rigid bunch modes. For the combination of octupoles with an electron lens the reconstructed BTF shows deviations from the predicted one, which are still under investigation. However, the BTF without coherent tune shifts is less meaningful to validate for stability prediction. More relevant are comparisons with stability boundaries obtained from tracking with an effective impedance source. From tracking with an effective impedance we obtained the stability boundaries with octupoles, an electron lens and their combination. The obtained stability areas agree rather well with the ones from the dispersion relation, which gives confidence in the application of the dispersion relation for FCC-hh conditions. Electron cloud induced tune shifts are expected to still be relevant in FCC-hh, because of the larger circumference and similar bunch parameters. The smaller effective beam pipe radius in the FCC-hh potentially increases the threshold for EC buildup. At top energy the tune shift will be further reduced due to the higher $\gamma$. Because of the increase of the local electron line density this reduction is weaker than $1/\gamma$. Its contribution to Landau damping is more indirect and not estimated in the present study. In general, our study improves the understanding of the scaling of coherent instabilities and their thresholds with energy, using the example of two high-energy colliders, the existing LHC and the proposed FCC-hh.

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