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FCC-hh TRANSVERSE IMPEDANCE BUDGET*

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Abstract

Contributions of different machine elements of the proposed Future Circular Collider (FCC-hh) impedance budget are calculated based on beam stability considerations. For each element (the beamscreen, the collimators, etc), effective impedances are calculated at the injection energy and at the collision energy for the considered instabilities. The considered instabilities include the transverse coupled bunch instability (TCBI) and the transverse mode coupling instability (TMCI). Limitations to each total effective impedance are estimated and the critical contributions to the impedance budget are determined.

INTRODUCTION

Longitudinal and transverse coupling impedances can drive beam instabilities and cause heating of machine components, ultimately limiting the beam intensity. In the proposed Future Circular Collider (FCC-hh), the heat load is expected to be dominated by the intense synchrotron radiation and not by the impedance. The main focus of this study is transverse impedances and beam stability. To ensure operation with 10^{11} protons per bunch and some safety margin, the transverse impedances should not exceed certain limits given by the mitigation techniques.

For the beam as a whole to be stable, all of the head-tail modes must be stable (the modes are classified by their azimuthal and radial head-tail numbers m and q). One way to stabilize the head-tail modes is to produce a sufficient tune-spread using Landau octupoles. However, due to the higher energy, the amount of the integrated octupole strength required to produce a given tune-spread is about 20 times higher in the FCC-hh than in the Large Hadron Collider (LHC). For this reason, the FCC-hh relies on octupoles only to stabilize higher order head-tail modes ($|m| \geq 1$), wheres the rigid-bunch mode ($m = 0$) is stabilized by the transverse feedback system. This scheme is expected to ensure the stability of all head-tail modes over a certain range of chromaticity, even with the less effective octupoles. Alternatives to this scheme are also being explored, possibly involving RF quadrupoles [1] or an electron lens [2] to produce the tune-spread.

In the chosen scheme, the maximum allowed growth rate of the transverse coupled bunch instability (TCBI) is given by the gain of the transverse feedback system. We require the rigid mode stability at zero chromaticity, which ensures stability at all positive chromaticities. Using Sacherer's formalism [3, 4], the maximum allowed growth rate at zero chromaticity can be translated to the maximum allowed effective impedance $Z_{\text{eff}}^{\text{CB}}$.

Apart from the coupled bunch instability, beam intensity can also be limited by single bunch effects such as the transverse mode coupling instability (TMCI). This instability can occur if real tune shifts of neighboring head-tail modes become so large that the tunes of the two modes overlap. In the FCC-hh such an overlap could occur between the head-tail modes $m = 0$ and $m = -1$, with most of the tune difference covered by mode 0. The instability can be avoided if the real tune shift of mode 0 is limited to a fraction of the synchrotron tune, which is achieved by limiting the single bunch effective impedance $Z_{\text{eff}}^{\text{SB}}$ to a certain level. We require single bunch stability at zero chromaticity and with the transverse feedback off. Such an approach can be considered conservative, as there is evidence that operating the feedback system in the partially reactive mode [5] can increase the TMCI threshold.

The effective impedances $Z_{\text{eff}}^{\text{CB}}$ and $Z_{\text{eff}}^{\text{SB}}$ can be independently computed for different elements of the ring, giving rise to an impedance budget similar to that of the LHC [6]. The simplicity of this approach allows to quickly determine which element of the machine needs to be optimized for impedance reasons. However, in the end, full-scale stability simulations are necessary to confirm beam stability, including also the ($|m| \geq 1$) modes as well as the mitigation mechanisms.

The current impedance model includes the identified most critical components:

- RW beamscreen - resistive wall impedance of the cold beamscreen without an e-cloud surface coating
- E-cloud treatment - an amorphous carbon or a titanium-nitride beamscreen surface coating for electron cloud mitigation (laser treatment is also discussed below)
- Pumping holes - beamscreen pumping holes [7]
- Warm pipe - the vacuum pipe in the straight sections [8]
- Collimators - resistive and geometrical impedance of betatron and momentum collimators
- Interconnects - the interconnects between the cryo-magnets [7]
- 400 MHz RF cavities
- Crab cavities.

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The total vertical dipolar impedance of the FCC-hh is shown in Fig. 1 for the two studied cases: at the injection energy (3.3 TeV) and at the collision energy (50 TeV). The significant increase in the impedance at the collision energy comes from the squeezed collimators settings, the larger betatron function in the final focusing system, and the magneto-resistance of the beamscreen.

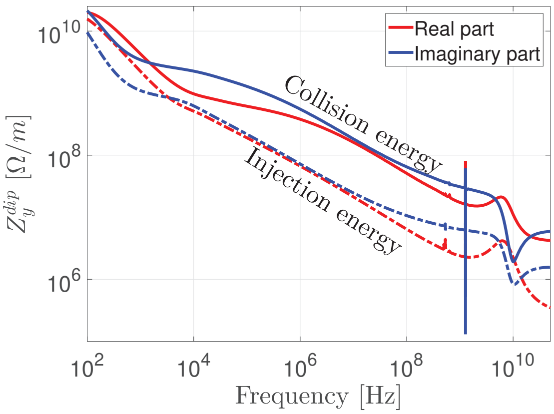

Figure 1: Total dipolar impedance of the FCC-hh (the vertical impedance is shown as the most critical). The dashed lines represent the impedance at injection, and the solid lines at the collision energy.

COUPLED BUNCH IMPEDANCE BUDGET

For each machine element placed at a location with betatron functions $\beta_{x,y}$, and characterized by the dipolar coupling impedances $Z_{x,y}$, we define the effective coupled bunch impedance as

$$\mathrm{Re}\left(Z_{x,y}\right)^{\mathrm{eff}}_{\mathrm{CB}} = \frac{\beta_{x,y}}{\langle\beta\rangle_{x,y}} \sum_{k=-\infty}^{k=\infty} \mathrm{Re}\left(Z_{x,y}(\omega_k)\right) h_{0,0}(\omega_k), \tag{1}$$

where the sum is done over the frequency lines $\omega_k = (\mathrm{frac}\left[Q_{x0,y0}\right] - 1 + kM)\Omega_0$ for the most unstable coupled bunch mode number $n_{cb} = -(\mathrm{int}\left[Q_{x0,y0}\right] + 1)$. The power spectrum of the head-tail mode $m = 0$, $q = 0$ is $h_{0,0}(\omega) = e^{-(\omega\tau_b/4)^2}$ for the Gaussian bunch shape, and $\langle\beta\rangle_{x,y}$ are defined as the smooth approximation betatron functions $\langle\beta\rangle_{x,y} = \frac{C}{2\pi Q_{x0,y0}}$. Here C is the circumference, $Q_{x0,y0}$ are the unperturbed x and y betatron tunes, M is the total number of bunches in the ring, $\Omega_0 = 2\pi f_{rev}$ is the angular revolution frequency, τ_b is the 4σ bunch length in seconds.

Contributions of different elements to the total coupled bunch effective impedance are shown in Fig. 2. The resistive wall impedance of the beamscreen sampled at a fraction of the revolution frequency is the primary driver of the coupled-bunch instability. Novel features of the beamscreen such as the enlarged pumping holes and possibly the laser treatment of the surface, do not affect the CB impedance as their contribution only happens at much higher frequencies. Nevertheless, the effective impedance per unit length of the beamscreen is several times higher than that in the LHC due to the smaller aperture, the higher wall temperature, and the lower revolution frequency. The warm beam pipe contribution is lower but significant at the collision energy due to the higher β function in the final focusing system [8]. The contribution of the collimators is almost negligible due to the inductive by-pass effect.

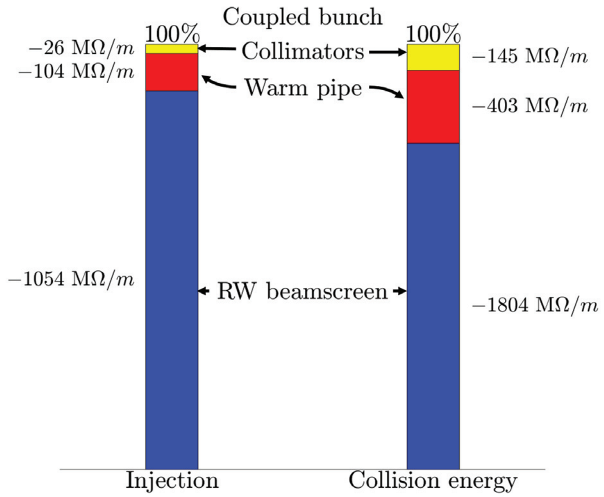

Figure 2: Relative contributions to the coupled bunch impedance budget at injection and the collision energy. The numbers on the sides correspond to effective coupled bunch impedances of each element $\mathrm{Re}\left(Z_y\right)^{\mathrm{eff}}_{\mathrm{CB}}$. Only the vertical plane is shown as the most critical.

The total effective coupled bunch impedance is −988 MΩ/m (x-plane) and −1185 MΩ/m (y-plane) at injection, and −2057 MΩ/m (x-plane) and −2353 MΩ/m (y-plane) at the collision energy. Given the effective impedance, the CB instability growth rate in the number of turns can be estimated as

$$n_{turns}^{-1} = -\frac{e^2 N_b M c}{8\sqrt{\pi} E Q_{x0,y0}} \sum_{\text{element}} \mathrm{Re} Z^{\mathrm{eff}}_{\mathrm{CB}\ x,y} \tag{2}$$

where e is the elementary charge, $N_b = 10^{11}$ is the bunch intensity, $M = 13068$ is the total number of bunches assuming a symmetric fill, c is the speed of light and E is the energy. The resulting growth rates in the most critical y-plane are 69 turns (injection) and 525 turns (collision). The planned feedback gain corresponds to the damping rate of 20 turns at injection and 170 turns at collision energy, and is sufficient to damp the instability with a safety factor of 3.

SINGLE BUNCH IMPEDANCE BUDGET

Similar to the coupled bunch case, for an element with $\beta_{x,y}$ and $Z_{x,y}$ we define the single bunch effective impedance as

$$\mathrm{Im}\left(Z_{x,y}\right)^{\mathrm{eff}}_{\mathrm{SB}} = \frac{\beta_{x,y}}{\langle\beta\rangle_{x,y}} \frac{\sum_{k=-\infty}^{k=\infty} \mathrm{Im}\left(Z_{x,y}(\omega_k)\right) h_{0,0}(\omega_k)}{\sum_{k=-\infty}^{k=\infty} h_{0,0}(\omega_k)}, \tag{3}$$

where in this case the summation is done over the frequency lines $\omega_k = (k + Q_{x0,y0})\Omega_0$.

At the collision energy, the single bunch impedance budget is dominated by the collimators (Fig. 3, right). To bring their impedance down to an acceptable level, jaws of all but one secondary collimators are planned to be made of molybdenum-graphite and coated with pure molybdenum. Due to the heat load, the remaining secondary collimator and all the primary collimators must be made of a more robust material such as CFC.

At injection, no single element dominates the budget (Fig. 3, left). The resistive impedance of the beamscreen plays an important role. The beamscreen surface coating for electron cloud mitigation is expected to give an about 30% increase in the effective impedance if an amorphous carbon or a titanium-nitride coating is used. Alternatively, a laser treatment of the beamscreen surface [9, 10] is proposed (not shown in Fig. 3). However, in this case, the impedance considerations may limit the treated area to only a small fraction of the surface [11]. Another potentially dangerous source of impedance is the beamscreen pumping holes that are much larger than in the LHC. However, their impedance is effectively reduced to a negligible level by a novel concept of shielding the holes from the beam [7]. The interconnects between the cryo-magnets incorporate synchrotron radiation absorbers to protect the joints from a direct hit, which also results in a significant impedance.

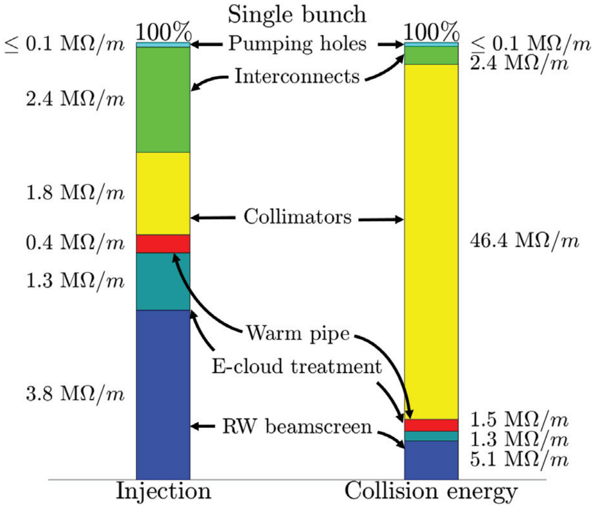

Figure 3: Relative contributions to the single bunch impedance budget at injection and the collision energy. The numbers on the sides correspond to effective single bunch impedances of each element $\mathrm{Im}\left(Z_y\right)^{\mathrm{eff}}_{\mathrm{SB}}$. Only the vertical plane is shown as the most critical.

The single bunch impedance budget does not include beam position monitors (BPMs) and the injection kicker magnet (MKI). At injection, these elements are expected to give non-negligible contributions which were not yet estimated. In the current impedance model without the unknown contribution of the BPMs and the MKI, the total effective single bunch impedance is 8.58 MΩ/m (x-plane) and 9.70 MΩ/m (y-plane) at injection and 58.6 MΩ/m (x-plane) and 57.2 MΩ/m (y-plane) at the collision energy. Given the effective impedance, the TMCI threshold N_b^{th} can be roughly estimated as

$$N_b^{th} = \alpha \frac{4\pi E \tau_b Q_s \Omega_0 Q_{x0,y0}}{e^2 c \sum_{\mathrm{element}} \mathrm{Im}\left(Z_{x,y}\right)^{\mathrm{eff}}_{\mathrm{SB}}} \qquad (4)$$

where Q_s is the synchrotron tune given by the RF voltage and $\alpha \approx 0.65$ is a correction factor to account for the nonlinear dependence of tune with N_b in the proximity of N_b^{th}. The assumed RF voltage is 12 MV at injection and 32 MV at the collision energy. The resulting TMCI thresholds in the most critical y-plane are 3.60×10^{11} (injection) and 3.88×10^{11} (collision), giving a safety factor of 3.

CONCLUSIONS

An impedance budget for the coupled bunch instability and the single bunch instability in FCC-hh was developed. In the coupled bunch case, the effective impedance is dominated by the resistive wall contribution of the beamscreen at both injection and the collision energies. A transverse feedback system with a damping rate of 20 turns (injection) and 170 turns (collision) provides a factor of 3 margin over the instability growth rates. In the single bunch case, the effective impedance is dominated by the collimators at collision energy but consists of several important contributions at injection. This effective impedance corresponds to a TMCI threshold more than a factor of 3 greater than the nominal bunch intensity. However, several important elements are still missing from the budget, such as the BPMs and the MKI.

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