BEAM LOADING COMPENSATION FOR THE FUTURE CIRCULAR HADRON-HADRON COLLIDER (FCC-hh)

I. Karpov*, P. Baudrenghien, CERN, Geneva, Switzerland

Abstract

The power consumption of the rf system can be minimised by optimising the cavity detuning and the loaded quality factor. In high-current accelerators, the presence of gaps in the filling results in a modulation of the cavity voltage along the ring (transient beam loading) and as a consequence a spread in the bunch parameters. In addition longitudinal coupled-bunch instabilities can appear, caused by the cavity impedance at the fundamental. Both issues can be mitigated by using an rf feedback around the amplifier and cavity, a technique used in many high intensity machines including the Large Hadron Collider (LHC). Compared to the LHC machine, the energy increase and the radiation loss for the Future Circular hadron-hadron Collider (FCC-hh) will be larger, resulting in a synchronous phase deviating significantly from 180 degrees. The solutions adopted for the LHC must therefore be revisited. This paper evaluates several beam loading compensation schemes for this machine.

INTRODUCTION

The Future Circular hadron-hadron Collider (FCC-hh) is a high-luminosity machine envisioned in a new 100 km tunnel in the Geneva area [1]. Interaction of its high-current beam with the fundamental rf cavity impedance at frequency around 400 MHz can result in transient beam loading issues and longitudinal coupled-bunch instability (CBI). The former comes from non-uniform filling patterns with gaps that are not negligible compared with the cavity filling time $\tau = Q_L/(\pi f_r)$, defined by the cavity resonant frequency f_r and the loaded quality factor Q_L. Without transient beam loading compensation, the modulation of cavity voltage can result in a variation of bunch-by-bunch parameters having negative impact on the accelerator performance.

The longitudinal CBI threshold was evaluated for the FCC-hh in [2], but in general the obtained results cannot be applied for the fundamental rf cavity impedance [3]. This is because its frequency is very close to one of the beam spectral lines defined by the bunch spacing $t_{bb} = 25$ ns. At the flat-top energy of 50 TeV, however, the rf cavity bandwidth $\Delta f_r = f_r/(2Q_L) \approx 0.5$ kHz for the case of minimised power consumption without transient beam loading compensation [4]. As Δf_r is much smaller than the revolution frequency $f_0 \approx 3$ kHz, the estimation of the longitudinal CBI threshold can also be used for the fundamental mode of the cavity. For $N_{cav} = 24$, the number cavities per beam, with $R/Q = 42.3\ \Omega$ (in circuit definition) – the ratio of the shunt impedance to the quality factor of the cavity fundamental mode – the total shunt impedance reaches $450\ M\Omega$. It is significantly higher than the $3\ M\Omega$ threshold of longitu-
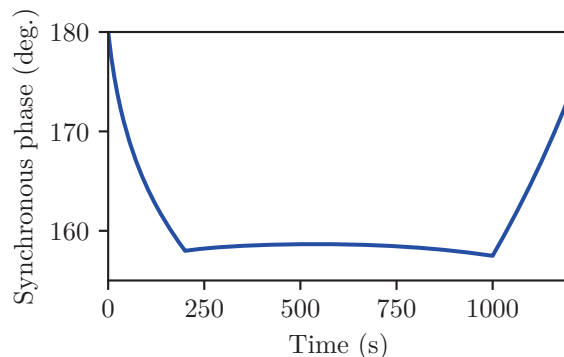
* ivan.karpov@cern.ch

Figure 1: Synchronous phase during the FCC-hh cycle calculated using parameters from [2].

dinal CBI at 400 MHz for the number of particles per bunch $N_p = 1.0 \times 10^{11}$ [2]. Thus, the direct rf feedback [5] must be used to reduce the impedance of the cavity fundamental mode seen by the beam.

The direct rf feedback can also be used for the full or partial beam loading compensation. In the Large Hadron Collider (LHC), for example, the half-detuning scheme [6], that keeps the amplitude and phase of the cavity voltage constant, and the full-detuning scheme [7], for which only the cavity voltage amplitude is constant, are both used in operation. However, during the FCC-hh cycle, optimised for longitudinal and transverse single-bunch stability [2, 8], the synchronous phase significantly deviates from 180 degrees (see Fig. 1), which is not the case in the LHC. In the present work, we reconsider beam loading compensation schemes for the more general case of $\phi_s \neq \pi$ (hadron machine convention) and evaluate the required power.

TRANSIENT BEAM LOADING

The beam gaps in the ring filling pattern generate a modulation of the cavity voltage. In the present scenario, the FCC-hh is filled with 10400 bunches grouped in 130 batches. Two additional batches are reserved for pilot (low intensity) bunches. The number of bunches in a single batch, defined by machine protection requirements, is 80. The length of gaps between the butches is about $430\ \mu s$ given by the injection kicker rise time [9]. To prevent damage of accelerator components due to an asynchronous beam dump caused by erratic firing of the extraction kicker, a filling scheme with four uniformly distributed $1.5\ \mu s$ long abort gaps is planned for operation [9].

If the rf generator is connected to the cavity via a circulator, the following equation relates complex phasors of the generator current I_g, the cavity voltage V, and the rf

MC5: Beam Dynamics and EM Fields

D05 Coherent and Incoherent Instabilities - Theory, Simulations, Code Developments

component of the beam current $I_{b,rf}$ [10]

$$I_g(t) = \frac{V(t)}{2(R/Q)}\left(\frac{1}{Q_L} - 2i\frac{\Delta\omega}{\omega_{rf}}\right) + \frac{dV(t)}{dt}\frac{1}{\omega_{rf}(R/Q)} + \frac{I_{b,rf}(t)}{2},$$ (1)

where $\Delta\omega = \omega_r - \omega_{rf}$ is the cavity detuning, $\omega_r = 2\pi f_r$, $\omega_{rf} = 2\pi f_{rf} = 2\pi h f_0$, $f_{rf} = 400.79$ MHz is the rf frequency, and $h = 130680$ is the harmonic number. The loaded quality factor $Q_L = [1/Q_{ext} + 1/Q_0]^{-1}$ is calculated from the cavity quality factor Q_0 and the coupler quality factor $Q_{ext} = Z_c/(R/Q)$ defined by Z_c, the line impedance transformed to the gap by the main coupler. Considering a superconducting cavity with $Q_0 \gg Q_{ext}$, the generator power can be written as [10]

$$P(t) = \frac{1}{2}(R/Q)Q_{ext}|I_g(t)|^2 \approx \frac{1}{2}(R/Q)Q_L|I_g(t)|^2.$$ (2)

In the following subsections, we consider different schemes with and without transient beam loading compensation, which can be potentially used in the FCC-hh.

No Transient Beam Loading Compensation

Without transient beam loading compensation, the amplitude and phase of the generator current are constant values, which can be obtained from averaging of Eq. (1). The required power can be minimised, if the optimal detuning

$$\Delta\omega_{opt}(\phi_s) = \omega_{rf}\frac{\langle I_{b,rf}\rangle(R/Q)\cos\phi_s}{2V_{cav}},$$ (3)

and the optimal loaded quality factor

$$Q_{L,opt}(\phi_s) = \frac{V_{cav}}{(R/Q)\langle I_{b,rf}\rangle\sin\phi_s},$$ (4)

are used (derived, for example, in [10]). Here, V_{cav} is the average cavity voltage, $\langle I_{b,rf}\rangle = eN_pMf_0F_b(\pi f_{rf}\tau_b)$ the average rf beam current, M the total number of bunches, and the form-factor $F_b(\pi f_{rf}\tau_b)$ depends on the full bunch length τ_b and the particle distribution function. For short bunches of binomial family (see Eq. (3) in [2]),

$$F_b(x) = 2J_{\mu+1}(x)\Gamma(\mu+2)\left(\frac{2}{x}\right)^{\mu+1}.$$ (5)

The synchronous phase ϕ_s in Eqs. (3,4) is given by $V_{cav}\sin\phi_s = (U_{SR} + \Delta E)/(eN_{cav})$, so that at each turn the cavities give a momentum kick which compensates the energy loss due to synchrotron radiation U_{SR} and produces acceleration with the energy gradient ΔE. The minimum required power without transient beam loading compensation is

$$P_{opt}(\phi_s) = \frac{V_{cav}\langle I_{b,rf}\rangle\sin\phi_s}{2}.$$ (6)

Since the direct rf feedback is needed to prevent longitudinal CBI due to the fundamental cavity impedance, the reference signal of the cavity voltage should take into account the beam induced amplitude and phase modulations, to avoid power transients caused by the beam gaps. Thus, some beam phase and bunch length modulations will be present during acceleration and physics (Fig. 2).
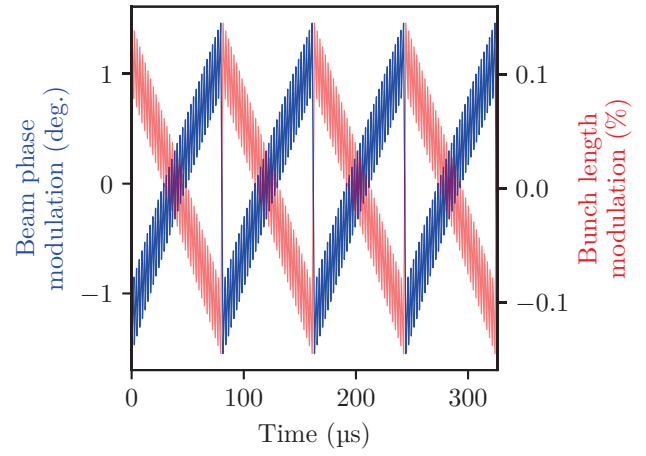

Figure 2: Beam phase and bunch length modulations at 50 TeV without transient beam loading compensation. The optimal detuning $\Delta\omega_{opt}/(2\pi) = -4$ kHz and the optimal loaded quality factor $Q_{L,opt} = 4.5\times10^5$ are used.

Constant Voltage Amplitude and Phase (Half-Detuning Scheme)

To keep cavity voltage amplitude and phase constant $(V(t) = V_{cav} = $ constant), the direct rf feedback will try to compensate the contribution from modulation caused by the gaps. In reality the rf power chain (amplifier, circulator, etc.) has limited bandwidth and cannot track fast bunch-by-bunch variations of the beam current. In the LHC, for example, the value averaged over the bunch spacing is used for processing. Thus, the rf component of the beam current in Eq. (1) should be replaced by a step-wise function – $u(t) = 1$ in filled and 9 adjacent buckets and $u(t) = 0$ otherwise – as

$$I_{b,rf}(t) = i\frac{eN_pF_b(\pi f_{rf}\tau_b)}{t_{bb}}e^{-i\phi_s}u(t) = i\hat{I}_{b,rf}e^{-i\phi_s}u(t).$$ (7)

The power in the no-beam segment, $u(t) = 0$, can be obtained from Eqs. (1,2)

$$P_{NB} = \frac{V_{cav}^2\tau}{4(R/Q)\omega_{rf}}\left[\frac{1}{\tau^2} + \Delta\omega^2\right].$$ (8)

For a given $\Delta\omega$, the minimum power can be achieved for $1/\tau = \Delta\omega$. In the beam segment, $u(t) = 1$, we get similarly

$$P_B = \frac{V_{cav}^2\tau}{4(R/Q)\omega_{rf}}\left[\left(\frac{1}{\tau} + \Delta\hat{\omega}\sin\phi_s\right)^2 + (\Delta\omega - \Delta\hat{\omega}\cos\phi_s)^2\right].$$ (9)

Here we define the peak detuning as

$$\Delta\hat{\omega} = \omega_{rf}\frac{\hat{I}_{b,rf}(R/Q)}{2V_{cav}}.$$ (10)

Depending on the cavity detuning, either P_{NB} or P_B will be larger and the minimum is achieved for

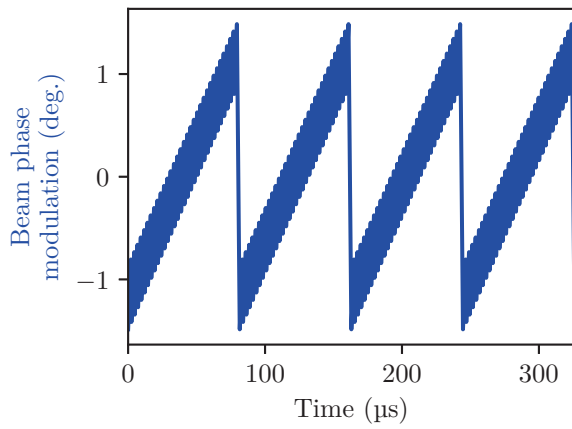$$\Delta\omega(\phi_s) = \frac{1}{2}\frac{\Delta\hat{\omega}}{\cos\phi_s + \sin\phi_s},$$ (11)

so that,

MC5: Beam Dynamics and EM Fields

D05 Coherent and Incoherent Instabilities - Theory, Simulations, Code Developments

Figure 3: Beam phase modulation at 50 TeV for the full-detuning beam loading compensation scheme and the same parameters as in Fig. 2.

Figure 4: Power consumption during the cycle for different transient beam loading compensation schemes calculated using Eqs. (6,12,13).

$$P_{\text{NB}} = P_{\text{B}} = P_{\text{HD}}(\phi_s) = \frac{V_{\text{cav}} \hat{I}_{\text{b,rf}}}{8} \frac{1}{|\cos \phi_s + \sin \phi_s|}, \quad (12)$$

where $P_{\text{HD}}(\phi_s)$ is the optimum power for the half-detuning scheme. For $\phi_s = \pi$ one gets the detuning $\Delta \omega(\pi) = -\Delta \hat{\omega}/2 = \Delta \omega_{\text{HD}}$ of the standard half-detuning scheme [6] presently used in the LHC during the injection process.

Constant Voltage Amplitude (Full-Detuning Scheme)

For partial beam loading compensation, only the cavity voltage amplitude remains constant and the cavity voltage phase ϕ is modulated, so that $V(t) = V_{\text{cav}} e^{i\phi(t)}$. This scheme is used in the LHC during acceleration and in physics since July 2017 [7]. Unlike the case of $\phi_s = \pi$, for $\phi_s \neq \pi$, the peak power in the full-detuning scheme depends on the beam current [4]

$$P_{\text{FD}}(\phi_s) = \frac{V_{\text{cav}} \hat{I}_{\text{b,rf}} \sin \phi_s}{2}. \quad (13)$$

In this scheme, the optimal detuning from Eq. (3) and the following loaded quality factor [4]

$$Q_{\text{L,FD}} = \frac{V_{\text{cav}}}{(R/Q) \hat{I}_{\text{b,rf}} \sin \phi_s}, \quad (14)$$

need to be used. The required power differs from the scheme with no-beam loading compensation, Eq. (6), by a factor $\hat{I}_{\text{b,rf}}/\langle I_{\text{b,rf}} \rangle$. For this scheme, there is no bunch length spread due to transient beam loading, but some bunch-by-bunch phase modulation is present (see Fig. 3).

POWER CONSUMPTION DURING THE CYCLE

The comparison of power consumption for half-detuning and the full-detuning schemes during the FCC-hh cycle is shown in Fig. 4. The former scheme requires about 50% more peak power than the case without transient beam lo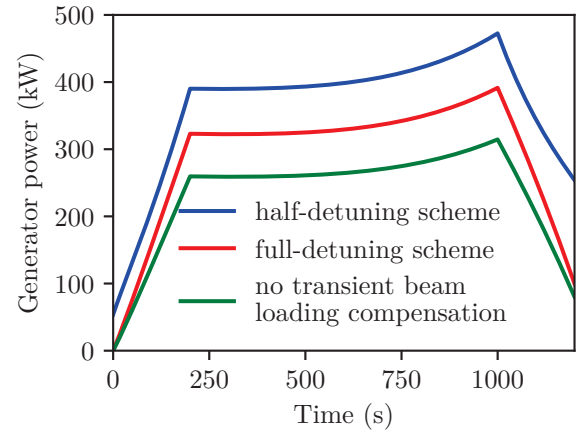ading compensation. For the latter scheme, power consumption is between those two extreme cases with full and no transient beam loading compensation.

At injection energy of 3.3 TeV, literally the power required for the full-detuning scheme is zero (see Eq. (13) for $\phi_s = \pi$). In the LHC, the half-detuning scheme is used. Indeed, the following aspects need to be considered for transient beam loading compensation during the machine filling being a more complicated, non-stationary process. To avoid particle losses and longitudinal emittance growth of the injected bunches, the injector must displace them in the same way as the receiving buckets. In addition, the transient caused by the newly injected beam must not result in a shift of the buckets of the circulating bunches. Finally, the cavity tuner cannot move in one turn (before and after injection). The systematic study of possible transient beam loading compensation schemes during the injection process is ongoing [11].

SUMMARY

The energy gain per turn and the radiation loss will make the FCC-hh to operate with a synchronous phase deviating significantly from 180 degrees. In the present work, the transient beam loading compensation schemes, developed for the LHC with a stable phase between 175-180 degrees, have been revisited for more general case of accelerated buckets.

Keeping constant amplitude and phase of the cavity voltage during the FCC-hh cycle would require about 500 kW peak power (half-detuning scheme). The full-detuning scheme, that keeps constant voltage amplitude but accepts phase modulation, could be a good compromise for power consumption from start of acceleration. It requires about 25% more power compared with the case without transient beam loading compensation.

ACKNOWLEDGEMENTS

REFERENCES

[1] M. Benedikt *et al.*, "Future circular collider, vol. 3: The hadron collider (FCC-hh)", CERN, Geneva, Switzerland, Rep. CERN-ACC-2018-0058, Dec. 2018, submitted for publication.

[2] I. Karpov and E. N. Shaposhnikova, "Longitudinal Coupled-Bunch Instability Evaluation for FCC-hh", presented at the IPAC'19, Melbourne, Australia, May 2019, paper MOPGW083, this conference.

[3] V. I. Balbekov and S. V. Ivanov, "Longitudinal instability threshold of bunched beams in proton synchrotrons", *Soviet Atomic Energy*, vol. 60, no. 1, pp. 58–66, Jan. 1986. doi:10.1007/BF01129839.

[4] I. Karpov and P. Baudrenghien, "Transient beam loading and rf power evaluation for future circular colliders", submitted for publication.

[5] D. Boussard, "Control of Cavities with High Beam Loading", *IEEE Trans. Nucl. Sci.*, vol. 32, no. 5, pp. 1852–1856, 1985, doi:10.1109/TNS.1985.4333745.

[6] D. Boussard, "RF power requirements for a high intensity proton collider; parts 1 (chapters I, II, III) and 2 (chapters IV, V, VI)", CERN, Geneva, Switzerland, Rep. CERN-SL-91-16-RFS, May 1991.

[7] T. Mastoridis, P. Baudrenghien, and J. Molendijk, "Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements", *Phys. Rev. Accel. Beams*, vol. 20, no. 10, p. 101 003, Oct. 2017, doi:10.1103/PhysRevAccelBeams.20.101003.

[8] E. Shaposhnikova, "Longitudinal beam dynamics and RF requirements", presented at FCC Week 2017, Berlin, Germany, Jun. 2017, unpublished.

[9] E. Renner *et al.*, "Optimization of the FCC-hh Beam Extraction System Regarding Failure Avoidance and Mitigation", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 850–853. doi:10.18429/JACoW-IPAC2018-TUPAF058

[10] J. Tückmantel, "Cavity-Beam-Transmitter Interaction Formula Collection with Derivation", CERN, Geneva, Switzerland, Rep. CERN-ATS-Note-2011-002 TECH, Jan. 2011.

[11] I. Karpov and P. Baudrenghien, "Comparison of beam loading compensation scheme at the LHC injection", unpublished.