LONGITUDINAL BEAM STABILITY IN HL-LHC[*]

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Abstract

Recent studies showed that the broadband impedance in synchrotrons can significantly alter the longitudinal multi-bunch instability threshold. The results of the beam-based impedance measurement campaign in the Large Hadron Collider (LHC) reveal a discrepancy with predictions based on the present impedance model. A larger imaginary impedance with a lower roll-off frequency would reproduce the observations. Since the impedance will be impacted by the High-Luminosity (HL) LHC upgrades, longitudinal beam stability needs to be carefully re-evaluated. This contribution discusses the outcome of the semi-analytical analysis for the HL-LHC parameters together with the updated broadband impedance model. Future benchmark measurements are proposed to probe the multi-bunch instability threshold driven by the partially compensated main RF cavity impedance. Finally, possible mitigation measures to increase the instability threshold are discussed.

INTRODUCTION

Interaction of a charged particle beam with the beam-coupling impedance of a synchrotron can lead to undamped or exponentially growing coherent oscillations. The instability threshold of a multi-bunched beam in the longitudinal plane was recently revisited, and a generalised approximation for the combination of narrow- and broadband impedances was proposed [1]:

$$1/N_{\mathrm{th}} \approx 1/N_{\mathrm{th}}^{\mathrm{nb}} + 1/N_{\mathrm{th}}^{\mathrm{bb}}. \tag{1}$$

Here, $N_{\mathrm{th}}^{\mathrm{nb}}$ is the intensity threshold of a coupled-bunch instability (CBI) driven by a narrow-band (NB) impedance source, and $N_{\mathrm{th}}^{\mathrm{bb}}$ is the loss of Landau damping (LLD) threshold defined by the broad-band (BB) impedance, both evaluated separately. In the Large Hadron Collider (LHC), LLD was observed since 2010 [2], cured by applying the controlled longitudinal emittance blow-up during acceleration [3]. The longitudinal CBIs were measured only in dedicated machine development (MD) studies [4, 5]. The instability was driven by the fundamental impedance of the 400 MHz radio-frequency (RF) acceleration system after careful adjustments of the feedback RF system. Longitudinal CBI driven by other higher-order modes (HOM) was not yet observed in LHC [6].

The LHC impedance was initially estimated [7], then summarised in the form of a model in the technical design report [8], and later became available for detailed beam dynamics studies [9]. Macro-particle simulations in the longitudinal plane using this model consistently agreed with measurements [10]. However, recent beam-based evaluations with two different techniques indicated about 70% higher $\mathrm{Im}Z/k$ and a lower resonant frequency of the corresponding effective BB resonator impedance [11, 12]. The High-Luminosity (HL) LHC upgrade requires modifying existing and installing new equipment, thereby affecting the overall accelerator impedance. The latest longitudinal beam stability assessment based on the updated impedance model will be described below.

HL-LHC STABILITY PREDICTION

The (HL-)LHC cycle can be divided into three distinct phases critical for the longitudinal stability: (i) beam accumulation at 450 GeV, (ii) energy ramp, and (iii) beam storage at 7 TeV. During the accumulation process, the mismatch between the longitudinal phase-space distribution of the injected beam and the LHC RF bucket leads to oscillations of bunch phase and length. These oscillations vary from bunch to bunch due to the bunch parameter spread defined by the injector complex. The injected bunch train, moreover, affects the circulating beam due to the action of the beam-based feedback loops. In addition, uncontrolled longitudinal emittance blow-up is caused by Intra-Beam Scattering (IBS) and RF noise [13]. Later in the cycle, the controlled emittance blow-up is applied during the energy ramp, resulting in about 1.2 ns-long bunches at the arrival to the flat top. In collision at the maximum beam energy, the bunch length decrease due to the synchrotron radiation is counteracted by periodic single-tone phase excitation [14, 15].

Ideally, macro-particle simulations are needed to include all these effects simultaneously. However, they are not feasible in the LHC scenario with up to ~3000 circulating bunches. Therefore, a semi-analytical analysis at injection and collision energies was performed based on solving the linearised Vlasov equation with the numerical code MELODY [16]. It computes the growth rates of the uniformly filled ring for a combination of resonator-like impedance sources defined by:

$$Z(\omega, R, Q, \omega_r) = \frac{R}{1 + iQ\left(\omega/\omega_r - \omega_r/\omega\right)}, \tag{2}$$

where R is the shunt impedance, Q is the quality factor, and f_r is the resonant frequency. The present LHC impedance model is approximated by a single BB resonator with $Q_{\mathrm{bb}} = 1$, $f_{r,\mathrm{bb}} = 5$ GHz, and $R_{\mathrm{bb}} = 38$ kΩ. The assumption is based on the concept of the effective BB impedance [17, 18]. Recent measurement results suggest using $f_{r,\mathrm{bb}} = 3.4$ GHz, and $R_{\mathrm{bb}} = 44$ kΩ [11, 12]. The lowest threshold of longitudinal CBI is expected to be defined by HOMs of the Double Quarter Wave (DQW) crab cavities [19], which will be installed during the Long Shutdown 3 (LS3). In the

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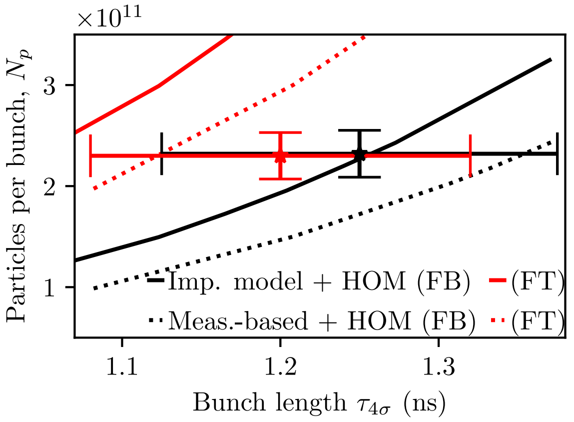

Figure 1: Thresholds of longitudinal multi-bunch instability for two impedance models at flat bottom and flat top. Stars indicate average target beam parameters, and the error bars cover a ±10% spread.

worst case scenario, when the HOM resonance frequencies of all crab cavities overlap, one expects $R_{\mathrm{nb}} = 4 \times 73$ kΩ, $f_{r,\mathrm{nb}} \approx 582$ MHz, and $Q_{\mathrm{nb}} = 1360$ [20].

Results at 450 GeV and 7 TeV Beam Energies

The instability thresholds were evaluated for two sets of input impedance models, based on parameters summarised in Table 1 (Fig. 1). We assume that the binomial function defines the bunch distribution, $\mathcal{F}(\mathcal{E}) \propto (1-\mathcal{E}/\mathcal{E}_{\max})^{\mu}$, where $\mathcal{E}$ is the energy of synchrotron oscillations with the maximum value $\mathcal{E}_{\max}$, and μ determines the bunch shape ($\mu \approx 2$ in LHC). The bunch length presented in this work corresponds to four times the Root-Mean-Square bunch length of the equivalent Gaussian bunch. It is computed from the Full-Width Half-Maximum (FWHM) bunch length τ_{FWHM} as $\tau_{4\sigma} = \tau_{\mathrm{FWHM}}\sqrt{2/\ln 2}$. The results for both the present impedance model and the measurement-based BB impedance parameters indicate that an important fraction of the bunch parameters (Fig. 1, black error bar) lie above the instability threshold at the flat-bottom (FB) beam energy. The full beam parameter space is covered for the present impedance model at the flat top (FT) beam energy, while only a small fraction of short bunches appear above the instability threshold. Based on this, the beam stability is very critical at 450 GeV, and we propose beam-based measurements for a better estimate of stability margins.

Table 1: Main RF-Related Parameters of LHC [8]

Parameter	**Unit**	**Flat bottom**	**Flat top**
Circumference, C	m	26658.86	
Harmonic #, h		35640	
Gamma trans., γ_{tr}		55.76	
RF frequency, f_{rf}	MHz	400.79	
Beam energy, E_0	TeV	0.45	7
RF voltage, V_0	MV	8	16

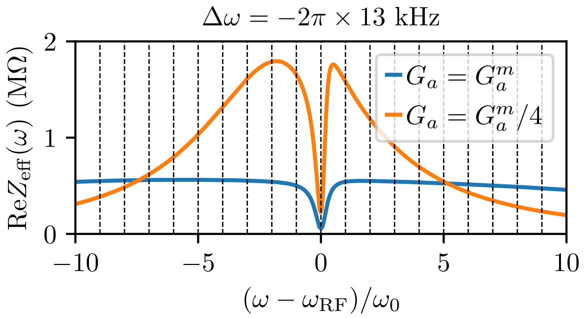

Figure 2: Effective FM impedance for nominal and reduced direct RF feedback gains.

INSTABILITY DRIVEN BY FUNDAMENTAL MODE IMPEDANCE

The longitudinal CBI driven by the fundamental mode (FM) impedance of the accelerating RF cavities is normally suppressed by the RF feedback system (e.g., [21]). The LHC RF system is equipped with direct RF feedback and one-turn delay feedback systems [22]. Past measurements have shown that the longitudinal CBI can be driven for a specific LHC RF feedback system configuration [4, 5]. We determine a configuration of the direct RF feedback that triggers instability with a threshold and growth rate similar to the one driven by crab-cavity HOMs. Injecting several bunch trains with HL-LHC beam parameters should enable better assessment of beam stability, accounting for relevant aspects of beam accumulation at 450 GeV. Such tests are also important to evaluate the stability margin for the fundamental mode and possibly reduce RF power requirements by relaxing the RF feedback gain.

The effective impedance *seen by the beam* (Fig. 2) in the presence of the direct RF feedback is [22]

$$Z_{\mathrm{eff}}(\omega) = \frac{Z_{\mathrm{fm}}(\omega)}{1 + H_{a,d}(\omega) Z_{\mathrm{fm}}(\omega) e^{-i\tau_{\mathrm{delay}}\omega + i\phi_{\mathrm{adj}}}}. \qquad (3)$$

Here $Z_{\mathrm{fm}}(\omega) = Z(\omega, R_{\mathrm{fm}}, Q_{\mathrm{fm}}, \omega_{r,\mathrm{fm}})$ is the impedance of the fundamental cavity mode, $R_{\mathrm{fm}} = 0.9\,\mathrm{M\Omega}$, $Q_{\mathrm{fm}} = 2 \times 10^4$, $\omega_{r,\mathrm{fm}} = \omega_{\mathrm{RF}} + \Delta\omega$, with ω_{RF} is the RF frequency, $\Delta\omega$ is the cavity detuning, τ_{delay} is the loop delay, and ϕ_{adj} is the phase adjustment required to correctly set the feedback negative at the detuned cavity resonant frequency. The RF feedback contains analogue and digital branches with a combined transfer function expressed in Laplace notation

$$H_{a,d}(s) = G_a \frac{\tau_a s}{1 + \tau_a s} + G_d \frac{1}{1 + \tau_d s}, \qquad (4)$$

where G_a is the analogue gain, τ_a is the high-pass filter time constant, G_d is the digital gain, and τ_d is the time constant of the low-pass filter. In the LHC, the following values are used in operation: $\tau_a = 170\,\mu\mathrm{s}$, $\tau_d = 400\,\mu\mathrm{s}$, $G_d = 10 \times G_a$, and $G_a = G_a^m = 6.79 \times 10^{-6}\ 1/\Omega$ is chosen to obtain a flat closed-loop response for loop delay of $\tau_{\mathrm{delay}} = 650\,\mathrm{ns}$, $1/G_a^m = 2(R_{\mathrm{fm}}/Q_{\mathrm{fm}})\omega_{\mathrm{RF}}\tau_{\mathrm{delay}}$ [21].

Based on semi-analytical analysis, we find that disabling the one-turn delay feedback, reducing of the analogue and

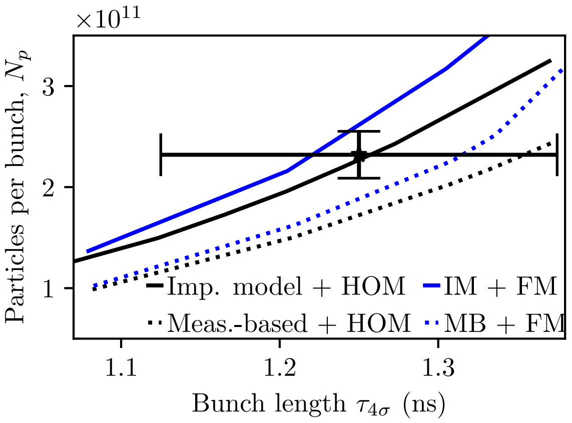

Figure 3: Thresholds of longitudinal multi-bunch instability for two impedance models at flat top. Black lines correspond to HOM-driven instability, while blue lines represent FM-driven instability (Fig. 2).

digital gains of the direct RF feedback by a factor of four, and a detuning of $\Delta\omega = -2\pi\times 13$ kHz results in a comparable threshold of longitudinal multi-bunch instability as the one driven by crab-cavity HOMs (Fig. 3).

MITIGATION MEASURES

Assuming that dedicated measurements indeed confirm the risk of instabilities at 450 GeV, the following mitigation schemes can be foreseen.

Bunch Flattening

It was shown that the LLD threshold is sensitive to the small-amplitude steepness of the particle distribution [23]. The suppression of LLD-driven bunch oscillations was also demonstrated [14]. Assuming a distribution function [24]

$$g(\mathcal{E}) = \begin{cases} 1 - \frac{\mathcal{E}^2}{a\mathcal{E}_{\max}^2}, & 0 \leq \mathcal{E} < a\mathcal{E}_{\max} \\ \frac{1}{1-a}\left(1 - \frac{\mathcal{E}}{\mathcal{E}_{\max}}\right)^2, & a\mathcal{E}_{\max} \leq \mathcal{E} < \mathcal{E}_{\max}, \end{cases} \quad (5)$$

where $0 < a < 1$, we computed the modification of the instability threshold due to the distribution flatness (Fig. 4). Increasing the parameter a at first raises the instability threshold since the LLD threshold increases [17]. At the same time, the NB-driven threshold [24] is lowered, eventually compromising the effectiveness of bunch flattening. This approach has several potential challenges. The corresponding distribution can potentially be produced already at the flat top in the Super Proton Synchrotron (SPS). However, it may not be preserved after injection and filamentation in LHC. Performing bunch flattening in the LHC requires disabling the beam-based phase loop, which triggers a phase kick and increases RF noise. After all, IBS will reduce flatness and increase the bunch length with time.

Double-Harmonic RF System

The most robust solution to prevent the instability is a double-harmonic RF system. Depending on the harmonic ratio, r_h, and the voltage ratio, r_v, both CBI and LLD thresholds strongly rise by a factor $1 + r_v r_h^3$ when both RF systems are in phase at the bunch centre [25,26]. The semi-analytical results for combined NB and BB impedance sources show that an additional 800 MHz RF system with $r_v = 0.15$ should be sufficient to significantly improve beam stability (Fig. 5).

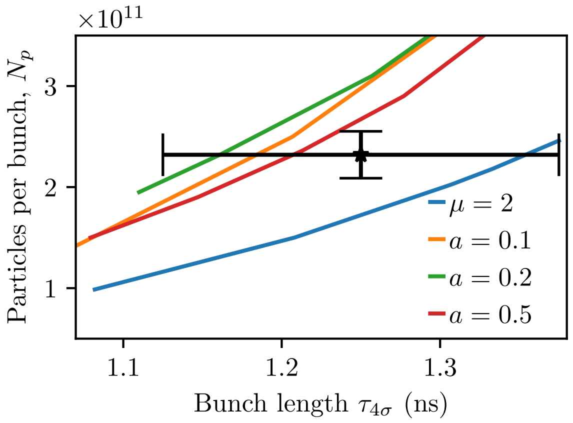

Figure 4: Thresholds of longitudinal multi-bunch instability at flat bottom for the measurement-based impedance model and different bunch distributions.

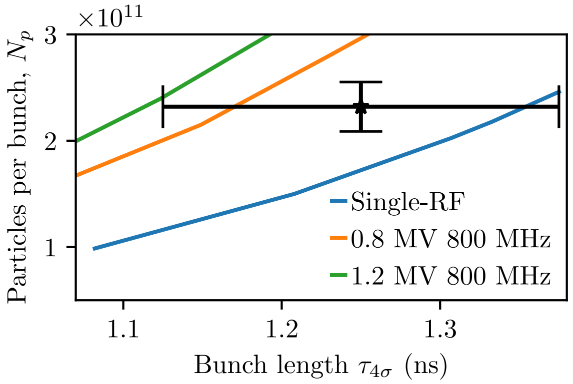

Figure 5: Thresholds of longitudinal multi-bunch instability at flat bottom for the measurement-based impedance model and different RF voltages at the higher-harmonic RF system.

CONCLUSION

In the present work, we re-evaluate longitudinal multi-bunch stability in the HL-LHC using an updated impedance model motivated by recent beam measurements. We show that the measurement-based broadband impedance significantly reduces the instability threshold, in particular at injection energy, where a large fraction of the nominal parameter space may lie above the threshold. The analysis is performed using a semi-analytical approach based on the linearised Vlasov equation, including both broadband and relevant narrow-band impedance sources. Dedicated measurement scenarios based on adjustments of RF feedback settings are proposed to probe the predicted instability threshold under realistic conditions. We find that mitigation by bunch flattening is limited, while a double-harmonic RF system provides a substantial increase in the stability margin.

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