COPING WITH LONGITUDINAL INSTABILITIES USING CONTROLLED EMITTANCE BLOW-UP

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Abstract

Controlled emittance blow-up is a widely-spread method to mitigate beam instabilities in accelerators. This paper summarises the different methods used to generate and apply RF phase noise or RF phase modulation in the RF systems of the CERN synchrotrons. It also details machine by machine when and how different methods are used.

INTRODUCTION

Many synchrotrons are operated at the limit of longitudinal beam stability, with pushed performance, whether they are already existing machines [1, 2] to be upgraded, or future projects [3] that have to cope with design constraints. To mitigate these instabilities, often a mixture of passive methods, such as impedance reduction and increased synchrotron tune spread due to a double-RF system, and active methods, such as beam and cavity feedbacks, is applied [4]. Controlled emittance blow-up in the longitudinal plane is another mitigation tool complementary to these.

In the synchrotrons at CERN, uncontrolled emittance blow-up can occur for many operational beams, despite using other instability-mitigation methods. An uncontrolled blow-up can lead to violent bunch length increase with a perturbed longitudinal distribution and excessive beam losses. In order to avoid these effects, controlled emittance blow-up can be applied when sufficient bucket area is available, preventively before the typical onset of instability in the cycle, see Fig. 1.

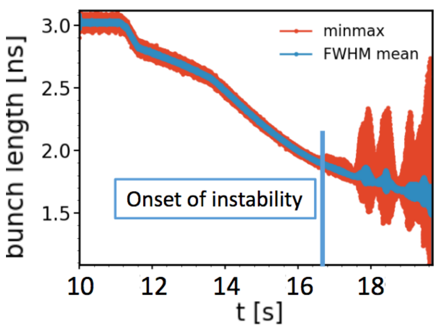

Figure 1: Uncontrolled emittance blow-up of the LHC-type beam occurring during the SPS energy ramp, seen as a violent increase in bunch length of some bunches; simulation with 12 bunches. Red: minimum and maximum bunch length deviations over the beam, blue: mean, four-sigma equivalent FWHM bunch length.

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Controlled emittance blow-up is operationally used in the CERN machines for the LHC-type proton beam, and also some other beams, ranging from the PSB, over the PS and SPS, to the LHC, where it was even anticipated by design. For the FCC-hh [3], it is foreseen during the ramp, and even during physics, to counteract synchrotron radiation damping [5].

It is not only used to mitigate beam instabilities, but there is a wide range of other applications, too. In accelerators at CERN, it is operationally used to stabilise transition crossing and to obtain a large enough emittance for bunch splitting or other RF manipulations. It can be applied to reduce intra-beam scatting, transverse space-charge effects, or synchrotron radiation shrinkage. In addition, controlled emittance blow-up can also be interesting for bunch length control or longitudinal beam profile shaping.

METHODS USED IN CERN MACHINES

This section presents the different methods that can be applied to achieve particle diffusion in the longitudinal phase space of the bunches. At CERN, the methods used are phase modulation applied to a high-harmonic RF voltage[1] and phase noise injection into the principal RF system around the central synchrotron frequency. For the latter, the noise can be generated in frequency or time domain, as shown below. Bunch profile shaping, in particular, can also be achieved through RF phase modulation with a frequency close to the central synchrotron frequency.

RF Phase Noise Generated in Frequency Domain

In order to diffuse particles within a given phase-space area of the bunch, a noise with a band-limited spectrum or with a coloured spectrum can be applied to target exactly this region of the bunch distribution, see Fig. 2. For a diffusion in this phase-space region, noise with a flat spectrum could be generated and injected into the phase of the RF voltage. In practice, however, the beam phase loop is usually required to be closed during the noise injection, and will counteract the noise applied around the central synchrotron frequency [6], see Fig. 3. To better target the bunch core, in some cases it might be required to inject a noise with a coloured spectrum that takes into account the response of the beam phase loop and results in a flat effective spectrum, as is done in the LHC.

One way of generating a band-limited phase noise spectrum is via the algorithm described in [7]. With this algorithm, a white-noise sequence is generated in time domain,

$$w_k = e^{2\pi r_k} \sqrt{-2 \ln q_k}\,, \qquad (1)$$

[1] In this paper, RF voltage refers to the voltage vector of amplitude and phase.

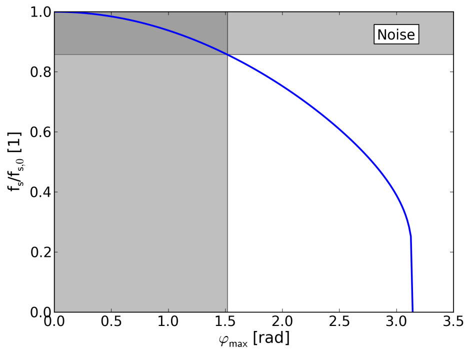

Figure 2: Synchrotron frequency distribution in the single-harmonic RF system of the LHC as a function of synchrotron-oscillation phase amplitude. The shaded regions indicate how the frequency limits of the LHC noise spectrum target the length of the bunch.

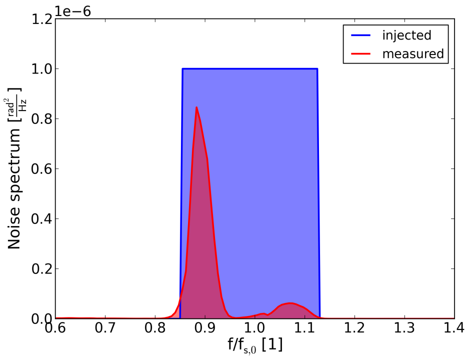

Figure 3: Intended (blue) and effective, measured (red) noise spectrum when injected through the beam phase loop.

where $r, q \in [0, 1]$ are uniformly distributed random numbers and $k \in \mathbb{N}$ is the turn number in the sequence of N turns. In the frequency-domain, the discrete Fourier image of this sequence,

$$W_n = \sum_{k=0}^{N-1} e^{-2i\pi \frac{kn}{N}} w_k \, , \tag{2}$$

is then multiplied with the desired band-limited noise probability density S_n,

$$\Phi_n = S_n W_n \, . \tag{3}$$

The turn-by-turn phase noise sequence applied to the bunch is finally obtained as a backward discrete Fourier transform,

$$\phi_k = \frac{1}{N} \sum_{n=0}^{N-1} e^{2i\pi \frac{kn}{N}} \Phi_n \, . \tag{4}$$

This method has been used operationally in the SPS [8] and the LHC [9], and it has been tested for the LIU upgrade of the PSB [10].

RF Phase Noise Generated in Time Domain

Alternatively, a phase-noise equivalent sequence in turn k can directly be generated in time domain, by summing N single-tone modulations with a given weight (amplitude) A [11],

$$\phi_k = \sum_{i=1}^{N} A_i \sin \left(\int_0^{T_k} 2\pi f_i(t) dt + \varphi_i \right) , \tag{5}$$

where $T_k = \sum_{n=1}^{k} T_{\text{rev},n}$ is the sum of revolution periods elapsed, $f_i(t)$ is a time-dependent frequency component and φ_i a phase offset. During an acceleration ramp, for instance, each $f_i(t)$ can be calculated to track the evolution of the synchrotron frequency distribution by maintaining a fixed ratio relative to the difference between the small-amplitude synchrotron frequency $f_{s,0}(t)$ and the synchrotron frequency at the target longitudinal emittance $f_{s,1}(t)$, or $f_i(t) = f_{s,1}(t) + x_i \left[f_{s,0}(t) - f_{s,1}(t) \right]$, where $x_i \in [0, 1]$. This is illustrated also in Fig. 4.

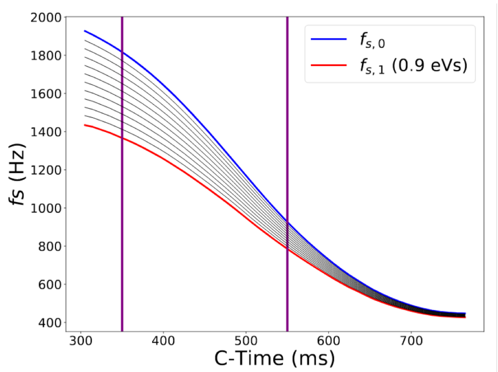

Figure 4: Noise spectrum as a sum of single-tone modulations along the ramp, tracking the time evolution of the central synchrotron frequency in the CERN PSB.

RF Phase Modulation in the Main RF System

Contrary to the previously mentioned methods, RF phase modulation in the main RF system does not result in a diffusion process, but in a resonant excitation of a single frequency within the synchrotron frequency distribution [12]. Shaping the longitudinal distribution by these means can help to improve beam stability, reduce heat load or pile-up density [13, 14]. It is done by modulating the phase of the main RF voltage $V(t)$ with a modulation amplitude ϕ_m and frequency f_m as follows:

$$V(t) = V_1 \sin\left(2\pi h_1 f_{\text{rev}} t + \psi_1(t)\right) = \tag{6}$$

$$V_1 \sin\left(2\pi h_1 f_{\text{rev}} t + \phi_m \sin\left[2\pi f_m t\right] + \phi_1\right) , \tag{7}$$

where V_1, h_1, and ϕ_1 are the voltage amplitude, harmonic, and phase of the main RF system and f_{rev} is the revolution frequency.

An example of measured bunch profile modification due to phase modulation is shown in Fig. 5. The resulting bunch length and bunch profile is determined by the modulation frequency applied [13], and thus allows only for a discrete regulation of the bunch length. In addition, the amplitude of the excitation has to be above a critical value for resonant excitation to occur.

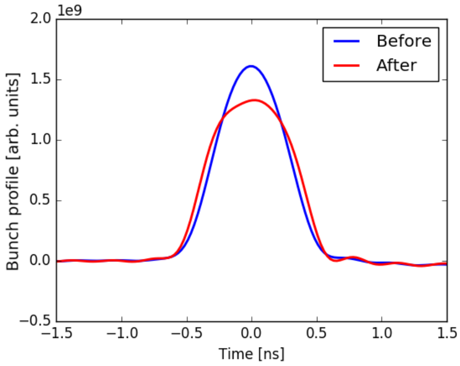

Figure 5: Bunch profile before (blue) and after (red) RF phase modulation applied in the LHC during collisions.

RF Phase Modulation in a High-Harmonic RF System

RF phase modulation can also be performed in a high-harmonic RF system,

$$V(t) = V_1 \sin(2\pi h_1 f_{\text{rev}} t + \phi_1) + \quad (8)$$

$$V_2 \sin(2\pi h_2 f_{\text{rev}} t + \phi_m \sin[2\pi f_m t] + \phi_2), \quad (9)$$

where V_2, h_2, and ϕ_2 are the voltage amplitude, harmonic, and phase of the high-harmonic system, respectively. The effect on the beam can be two-fold. As long as the modulation frequency remains a few times the synchrotron frequency, and the harmonic ratio h_2/h_1 remains small, the effect of the modulation on the bunch remains in the resonant-excitation regime [15, 16]. For larger modulation frequencies, and with growing harmonic ratio, a noise-equivalent regime is entered [17].

APPLICATIONS IN CERN MACHINES

In this Section, we summarise the main operational applications of controlled emittance blow-up throughout the CERN synchrotrons.

Proton Synchrotron Booster

In the PSB, controlled emittance blow-up is used for the emittance regulation of all beams produced. The amount of blow-up used, and the duration of the process, depend on the beam type.

In the course of the LIU upgrade of the PSB, its injection energy will be increased from 50 MeV to 160 MeV, and its maximum extraction energy will be raised from 1.4 GeV to 2 GeV. Proton beams for the LHC required already before the Long Shutdown 2 (LS2) a controlled emittance blow-up to provide uniform and reproducible longitudinal distributions, and to minimise space-charge effects at PS injection; this blow-up, however, was 'only' from 1 eVs to 1.4 eVs. For the future HL-LHC production beams with twice the intensity, a blow-up to 3 eVs is required [10]. This is more challenging not only due to enhanced intensity effects, but also because the cycle time available for the blow-up remains the same.

Prior to LS2, a sinusoidal phase modulation of a high-harmonic (C16) cavity [18] was used for emittance blow-up of all operational beams. This method has the advantage of being relatively fast, however it is also relatively sensitive to uncertainties in machine parameters, such as the relative phase offset between the RF systems. After LS2, the use of blow-up through a high-harmonic is kept solely for longitudinal shaving in the ramp.

For operational beams that do not require shaving, instead, phase noise will be injected directly at the main RF frequency, in single- or double-harmonic RF buckets. As a baseline, the generation of the noise is going to be a sum of distinct frequency components [11], which was used already for the PSB reliability run in 2018 with success, see Fig. 6. This ensures better frequency tracking in the quickly-changing acceleration ramp of the PSB than noise generation in frequency domain, which requires fixing the frequency band of the noise spectrum during a certain amount of time.

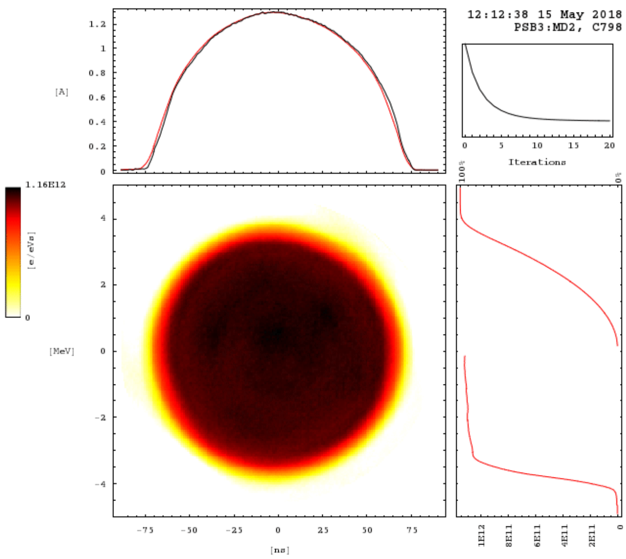

Figure 6: Tomographic reconstruction of a PSB bunch blown up with a sum of single-frequency phase noise components; BCMS-type proton beam from the start of the reliability run in 2018.

Proton Synchrotron

Also in the PS, a single-tone phase modulation of a higher-harmonic cavity at 200 MHz is used for controlled emittance blow-up [17, 19]. For comparison, the main RF system is operated in the range of 2.8 MHz to 10 MHz. The blow-up through the higher-harmonic cavity results in a smooth bunch-length increase over time, see Fig. 7, and it is also approximately proportional to the RF voltage of the 200 MHz system. This allows to easily adjust the final emittance. The longitudinal distribution after the blow-up can moreover be influenced by the choice of the modulation frequency, which is typically in the range of a few kHz, corresponding to several times the synchrotron frequency.

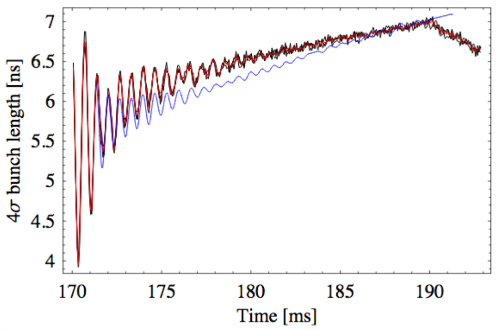

Figure 7: Bunch length growth during controlled emittance blow-up in the PS is approximately linear with time. The strong bunch length oscillations during the first 10 ms are triggered by an intentional longitudinal mismatch at injection and not related to the blow-up with the 200 MHz RF system. Comparison of measurements (black: single measurement, red: average of multiple measurements) and simulations (blue); a plot from [19].

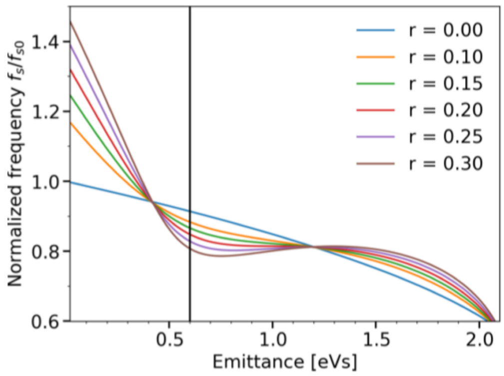

Figure 8: Synchrotron frequency distribution at SPS flat top, without intensity effects, in bunch-shortening mode, relative to the central synchrotron frequency in the single-harmonic RF system. Different voltage ratios of the 800 MHz to 200 MHz voltages r are shown in different colours; a plot from [25].

The blow-up is applied for various reasons at different times and energies of the PS acceleration ramp. As the resonant frequency of 200 MHz cavities cannot sweep with the increasing revolution frequency, the harmonic number is adapted during the cycle. At energies below transition crossing, the blow-up can moreover only be performed at constant-energy plateaus to gain sufficient time within the frequency range of cavities without a harmonic number change.

The proton beam for the LHC is blown up at four distinct times in the cycle. The blow-up is essential for the production and stability of all high-intensity beams. In particular, it is used to (i) obtain a large enough emittance prior to bunch splittings, (ii) stabilise the beam during RF manipulations, (iii) stabilise the transition crossing, and to (iv) regulate the final emittance desired for extraction to the SPS. Also for ions, blow-up is used to stabilize the beam during transition crossing.

Super Proton Synchrotron

In the SPS, the operational method of controlled emittance blow-up is RF phase noise injection through the beam phase loop in the main RF system [8, 20], although in the past also phase modulation in the fourth-harmonic RF system was tried [21, 22]. It is primarily applied for LHC-type protons, and was not needed for ions in the past. First studies suggest that the LHC ion beam produced after LS2 will have additional emittance blow-up during slip-stacking [23, 24].

LHC-type proton beams, in particular, are produced in a double-harmonic RF system of 200 MHz and 800 MHz operated in bunch-shortening mode. The synchrotron frequency distribution for different voltage ratios is shown in Fig. 8. For high-intensity proton beams, adapting the blow-up spectrum to target the desired region of the bunch is challenging. Firstly, because high-intensity protons require a higher 800 MHz to 200 MHz voltage ratio for beam stability. At high ratios the desired ~0.6 eVs region of the bunch cannot be targeted without touching also the halo population, which in return can lead to beam losses. Secondly, intensity effects shift the relative RF phase and distort the synchrotron frequency distribution. For post-LS2 operation, studies are on-going on how to best adapt the frequency limits of the blow-up spectrum for varying, high beam intensity in the future [26].

Large Hadron Collider

By design, nominal-intensity proton beams require a controlled emittance blow-up in the LHC [27] to prevent single- and coupled bunch instabilities [28] during the acceleration ramp. Machine studies showed that for the nominal-intensity beam, the coupled-bunch stability threshold is not lower than the single-bunch threshold for the loss of Landau damping [29]. Thus, the primary reason to use controlled blow-up for the nominal proton beam is the mitigation of single-bunch loss of Landau damping.

For proton beams with low, 'pilot' intensity, the blow-up is not required from beam stability point of view; it is, however, often applied to regulate the bunch length. For the ion beams in the LHC, blow-up is primarily used to minimize intra-beam scattering in physics by using suitably large emittances at arrival to flat top.

Compared to other accelerators at CERN, the blow-up in the LHC has several particularities. Firstly, it happens over almost 13 million turns (1210 s) for a ramp from 450 GeV to 6.5 TeV, much slower than in the injector synchrotrons, and increases the emittance by at least a factor 4, which is much larger than in other machines. In addition, it is used in a single-RF system, without a Landau-cavity being present and stabilising the beam. In exchange, a feedback on the FWHM bunch length regulates the amplitude of the phase noise injected and makes sure that the target bunch length is not exceeded. Indeed, machine studies showed that without the bunch-length feedback, a regulation of the blow-up simply via the noise spectrum and application time span, as is done in other machines, is practically impossible [30]; an example is shown in Fig. 9. Even with the bunch-length feedback present, regulation for the fast, 'parabolic-parabolic-linear-parabolic' ramp is more demanding than for the operational, 'parabolic-exponential-linear-parabolic' ramp.

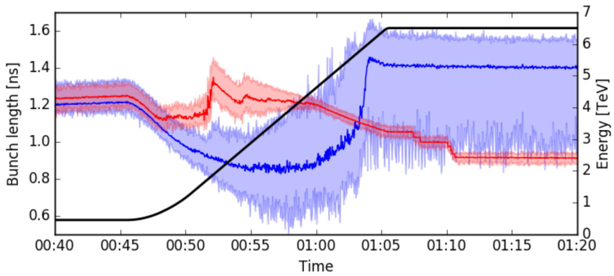

Figure 9: Bunch length evolution of the LHC Beams 1 (blue) and 2 (red) with the bunch length feedback off; the blow-up is started close to the stability threshold of the beam and cannot regulate the bunch length. A plot from [30].

In collisions at 6.5 TeV, both the bunch length and the bunch intensity are decreasing, and in long physics fills, loss of Landau damping is approached slowly, on the timescale of hours, see Fig. 10. As a mitigation measure against loss of Landau damping, and as a bunch length regulation, sinusoidal phase modulation is applied in operation, whenever the bunch length drops below 0.95 ns for nominal-intensity protons. A good bunch length control in physics is also important for the collision-vertex resolution of the LHC detectors.

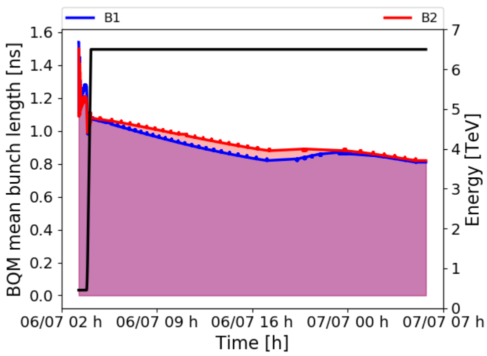

Figure 10: Bunch length evolution in long physics fills in the LHC Beams 1 (blue) and 2 (red). A slow blow-up occurs due to loss of Landau damping.

Future Circular Collider

Also in the FCC-hh, controlled blow-up is foreseen during acceleration to counteract loss of Landau damping [3]. In addition, a constant blow-up via phase noise injection in physics is considered to counteract the fast bunch length shrinkage due to synchrotron radiation; the required double-sided noise spectral density P would be, in small-bunch approximation [5],

$$P = \frac{1}{4}\frac{\Delta E_{\mathrm{SR}}}{E_s} f_{\mathrm{rev}} \left(\frac{h}{Q_{s0}}\tau_0\right)^2 , \tag{10}$$

where ΔE_{SR} is the energy loss per turn due to synchrotron radiation, E_s the synchronous energy, Q_{s0} the central synchrotron tune and τ_0 the initial bunch length.

CONCLUSIONS

Controlled longitudinal emittance blow-up is used in all synchrotrons at CERN to mitigate, among others, single-bunch loss of Landau damping or multi-bunch instabilities. It is also used to stabilise transition crossing, reduce intra-beam scattering and transverse space-charge effects, and to prevent from bunch length shrinkage due to synchrotron radiation. The two main blow-up methods are band-limited RF phase noise injection and RF phase modulation of a high-harmonic RF system. The latter has been used in the PSB ramp and in the PS on intermediate flat tops or towards the end of the ramp. In the SPS and LHC, as well as in the post-LS2 PSB, phase noise injection is used. In the fast-cycling injectors, the blow-up is done over a relatively short period, and the blow-up parameters, such as amplitude and frequency of modulation or noise spectrum, result in reproducible beam quality. In the LHC, a bunch length feedback is required to regulate the resulting bunch length. After LS2, increased intensities will challenge the reproducibility of the bunch length regulation and studies are on-going to improve the noise spectrum and its generation for high-intensity beams.

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