



Simulations of single-bunch instability on the SPS flat top

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1. Introduction

The HL-LHC requires up to four batches of 72 bunches per SPS extraction of beam with 25 ns bunch spacing, with 2.3×10^{11} p⁺ per bunch. At these intensities the beam is heavily affected by longitudinal instabilities [1]. Therefore, it is needed to study what is the cause of this intensity limitation and how it can be remedied.

To get a better understanding of longitudinal single bunch instability a series of simulations was run using BLongD code [2] and the present SPS impedance model [3]. Simulations were done only at flat top (no ramp). The initial bunch distribution was matched for given intensity and bunch length using the SPS impedance model. Number of turns on the SPS flat top was increased to 100 000 (2.304 s). This was done, in order to see instabilities that develop slowly or start very late in the cycle. An impedance model has a big impact on longitudinal beam stability so two impedance model variations were used: full SPS impedance model and SPS impedance model with all vacuum flanges removed. The aim of these studies was to determine how vacuum flanges affect single bunch stability on flat top.

1.1. Scan of beam and RF parameters

Various situations were simulated in order to determine which conditions can make the bunch more stable. Simulations were run using a single RF and a double RF systems. To analyse the effect of different bunch distributions three different μ values were used. Where μ is an exponent in distribution function (1.1).

$$F(H) = F_0 \left(1 - \frac{H}{H_0}\right)^\mu, \quad (1.1)$$

where F_0 is normalisation constant, H is Hamiltonian and H_0 is Hamiltonian value at bunch edge.

Two RF voltages were used for both 200 MHz and 800 MHz cavities, although the voltage in 800 MHz RF system was set to be 10% of V_{200MHz} voltage. Intensities were scanned from low intensities to extremely high ones (up to 4.0×10^{11} for double RF case). To present the results of this study, calculated emittance (ϵ_{calc}) was used. Bunch length measured in simulations is used with Hamiltonian to calculate emittance. The same technique is used in measurements, which means by using ϵ_{calc} it is possible to compare simulation results that are closer to measurement results. Input emittance ϵ_0 was also used in this study to indicate what value was used for a particular case.

Table 1: Parameters scanned in simulation

	Single RF	Double RF		
Distribution density exponent μ	1.0, 1.5 and 2.5			
RF voltage V_{200MHz} , MV	2.0, 7.0	2.0	and	7.0
RF voltage V_{800MHz} , MV	0	0.2		0.7
Intensity N, p	$(0.5 - 2.6) \times 10^{11}$	$(0.5 - 4.0) \times 10^{11}$		
Calculated emittance ε_{calc} , eVs	0.2 – 0.6			

2. Criteria to determine the beam instability thresholds

First step to study the effects that cause single bunch instability is to define what instability is. To do this it is important to analyse two cases: the bunch length is obtained from Gaussian fit (RMS) and Full Width Half Maximum (FWHM).

2.1. Instability criteria for bunch length obtained from RMS

For bunch length obtained from RMS, there are two conditions under which the bunch is considered unstable:

1. If bunch length oscillating amplitude exceeds **1.5%** of τ_0 .
2. If $\tau_f/\tau_0 > \mathbf{2.5\%}$ (2.1.1)

where τ_f - bunch length average of the last 500 turns, τ_0 - bunch length average of the first 500 turns.

2.2. Instability criteria for bunch length obtained from FWHM

Instability conditions for bunch length obtained using FWHM:

1. If bunch length oscillating amplitude exceeds 5% of τ_0 .
2. If $\Delta\tau_{[1000]}/\tau_{0[1000]} > \mathbf{0.07}$ in any point of the simulation (2.2.1)

where $\Delta\tau_{[1000]}$ – bunch length peak to peak oscillating amplitude in 1000 turn range.

3. RMS and FWHM stability maps and stability islands

3.1. Stability maps – comparison between RMS and FWHM

After all the simulations are finished post processing is applied. The result of this is the stability maps – a collection of simulations put together in one plot to show where the instabilities start and how pronounced they are. Two types of stability maps were produced: bunch length was obtained using RMS (Figure 1: (a)) and one obtained using FWHM (Figure 1: (b)). For RMS case, RMS instability condition (2.1.1) was used as an indicator for instability, for FWHM – FWHM instability condition (2.2.1). One can notice that depending on bunch length definition used, slightly different results arise. In the plots bellow FWHM stability maps will be used.

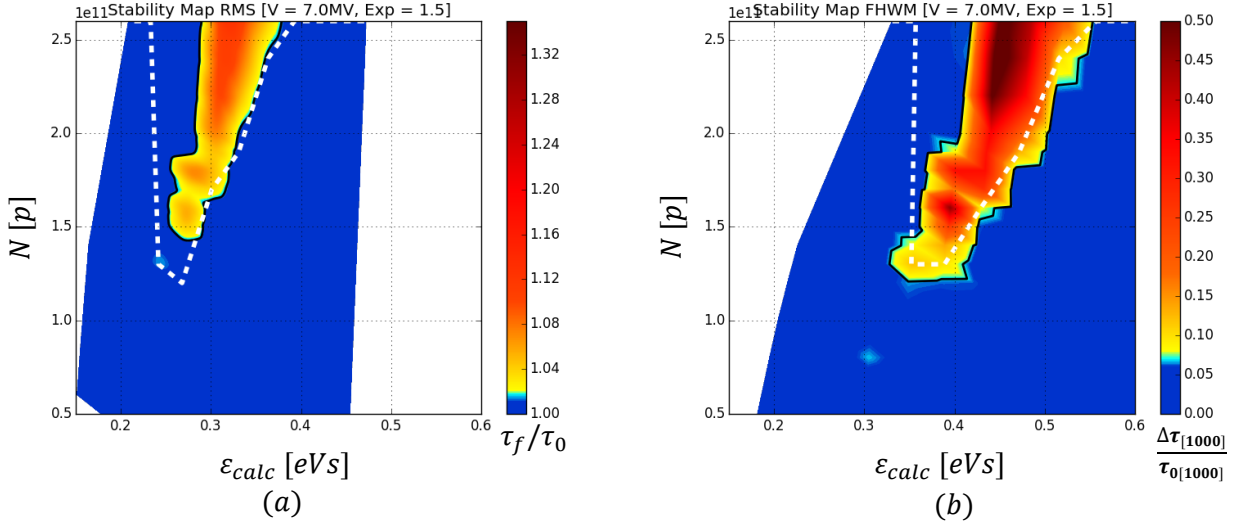


Fig. 1: Single RF stability maps for $\mu = 1.5$, $V = 7$ MV with bunch lengths obtained from: a) – RMS b) – FWHM. White line represents instability threshold for a particular case. White space in the plot represent areas where the data is not provided.

3.2. Stability islands

When looking at Figure 1, it is hard not to notice that instability threshold is not at all monotonic as one might expect. In fact, they seem to have stability islands at lower emittances and higher intensities. This kind of behaviour is not expected. It is also noticeable that by increasing emittance predicted instabilities start. *One should take into account that these simulations were done at the flat top. This means that some bunches might not even get through the ramp.*

3.3. In depth analysis of stability islands

To get a better understanding of what is happening in these stability islands, in-depth analyses were made. For this particular example three points were taken for 1.8×10^{11} intensity: one bunch in a stability island, one in unstable zone and one for high emittance – at which the bunch is regularly stable. One of the analyses conducted was to check the stability island bunch profile in the beginning (Figure 2 (a)). It is quite obvious that this profile is just as regular as the stable case profile. Another way to understand this case is to look at synchrotron frequency distribution. For the unstable case (Figure 2 (c)) we see that synchrotron frequency distribution is very small – most of the particles have similar synchrotron frequency. For the input emittance at the stability island (Figure 2 (a)), synchrotron frequency distribution is increased due induced voltage. That is why these cases are stable.

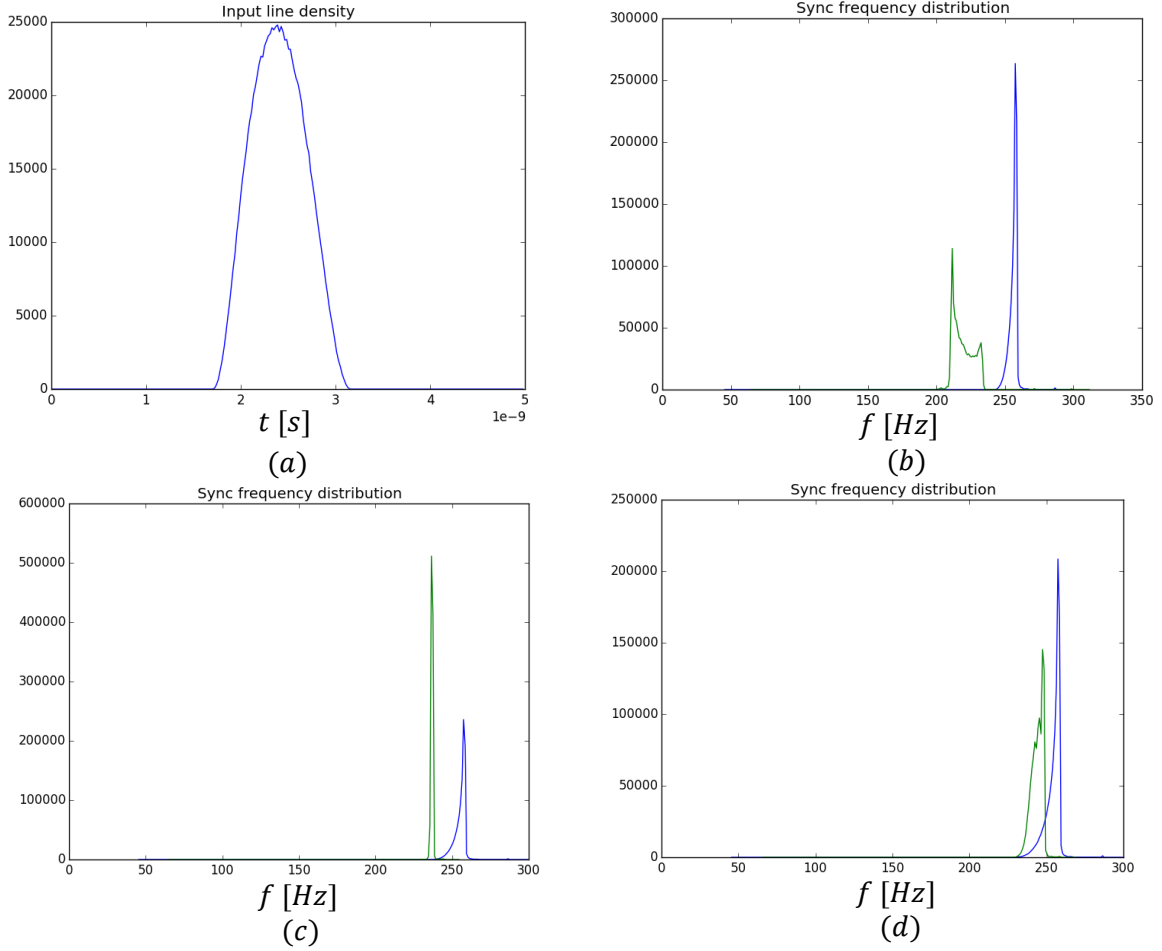


Fig. 2: In-depth analysis for $V = 7.0$ MV; $N = 1.8 \times 10^{11}$ p; $\mu = 1.5$, single RF cases. a) Bunch in a stability island profile, with $\varepsilon_0 = 0.35$ eVs. Frequency distribution with input emittance: b) $\varepsilon_0 = 0.35$ eVs (stability island) c) $\varepsilon_0 = 0.50$ eVs (unstable case) d) $\varepsilon_0 = 0.70$ eVs. Blue line in these plots represent synchrotron frequency distribution without intensity effects, green line – with intensity effects.

4. The effect of vacuum flanges on beam stability

SPS impedance is one of the main causes of longitudinal instabilities, so it is important to know which components of this impedance model affect bunch stability at flat top the most. In this study all vacuum flanges were removed from the SPS impedance model to observe how this improves bunch stability.

4.1. The effect of vacuum flanges on beam stability for single RF

Stability maps in Figure 3 show that removing vacuum flanges from the impedance model for low voltage (2 MV) makes stability islands even more pronounced and marginally improves stability overall. On the other hand, the situation is different for high voltages (7 MV). From Figure 3 (c) it is clear that in this case vacuum flanges improve stability for low emittances. Most likely, they cause stability islands to appear in low emittances (see also Figure 1 (b)). Though, for emittances higher than ~ 0.35 eVs, removing vacuum flanges improves stability significantly. For emittances higher than ~ 0.35 eVs increasing voltage does not improve stability, with or without vacuum flanges.

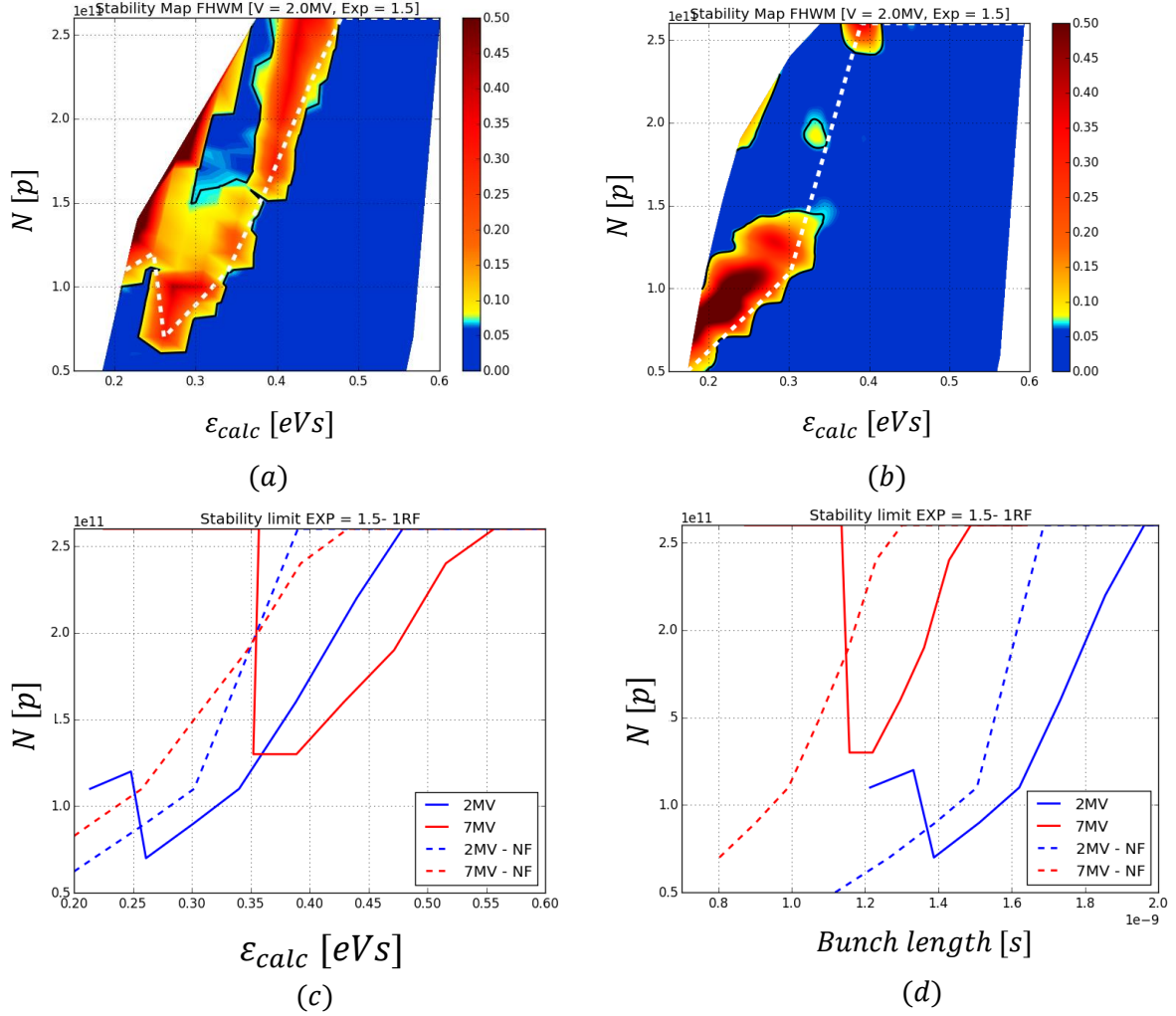


Fig. 3: Single RF stability maps with $\mu = 1.5$, $V = 2$ MV: a) with vacuum flanges b) without vacuum flanges. Single RF stability thresholds for 2 and 7 MV in: c) calculated emittance (ϵ_{calc}) d) bunch length

4.2. The effect of vacuum flanges on beam stability for double RF

By comparing double RF to single RF setup a significant reduction of stability islands can be observed in double RF case. In addition, stability thresholds are more monotonic (Figure 4). In contrast to single RF case, removing vacuum flanges improves stability for all emittances. It is obvious, that with vacuum flanges removed, high voltage (7 MV) gives the most stable beam. In fact, higher voltages always improve stability for double RF setup.

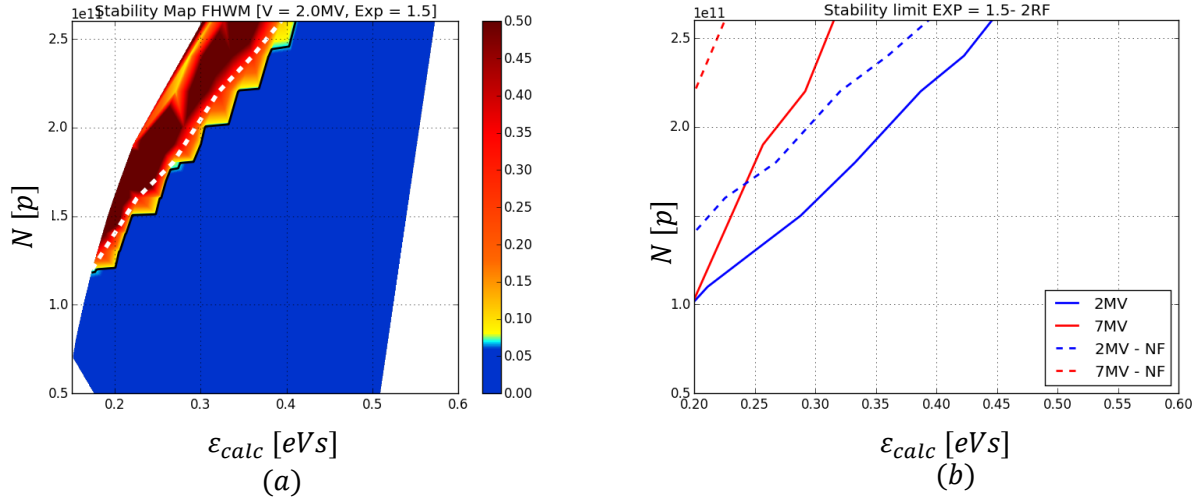


Fig. 4: a) Double RF stability map with $\mu = 1.5$, $V = 2$ MV and vacuum flanges removed. b) Double RF stability thresholds for 2 and 7 MV in calculated emittance (ϵ_{calc})

5. The effect of voltage on bunch stability

As seen in previous chapters, different voltage programs usually provide different results regarding the bunch stability. Simulation results give us a hint that an increase in voltage will influence bunch stability at flat top differently for single RF and double RF. For example, for single RF, 7 MV voltage removes stability islands and makes stability worse overall compared to 2 MV. For double RF, on the other hand, 7 MV increases instability threshold for specified emittance (ϵ_{calc}).

6. Conclusions

This study has shown that there is a number of factors that might affect bunch stability at flat top. The main discovery in this study was - so called stability islands. They were observed at lower emittances and higher intensities, for which stability is not expected. It is worth noting that these islands are more evident for single RF setup. The most likely explanation for this is the effect of induced voltage on synchrotron frequency distribution. Of course, it should also be noted that simulations were run only for flat top. Some bunches from stability island might not even get through the ramp in the first place, that is why the next step is to study instabilities in full ramp.

Furthermore, this study has shown that vacuum flanges truly have an effect on bunch stability. For single RF with vacuum flanges removed at 2 MV, stability islands become more pronounced and for 7 MV stability islands disappear without improving stability overall. For double RF removing flanges improves stability for all cases. Although, stability increase is most significant for 7 MV voltage.

References

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