

LONGITUDINAL MICROWAVE INSTABILITY IN A MULTI-RF SYSTEM

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Abstract

The longitudinal microwave instability is observed as a fast increase of the bunch length above some threshold intensity. Recently, this type of instability was seen for a single proton bunch at high energies in the CERN SPS and is proven to be one of the limitations for an intensity increase required by the HL-LHC project. In this paper a theoretical approach to the analysis of the microwave instability is verified by particle simulations. The study is applied to the SPS and is based on the current SPS impedance model. Finally, the effect of the 4th harmonic RF system on the microwave instability threshold is investigated as well.

INTRODUCTION

There is a very wide range of phenomena in high-intensity circular accelerators that is called by the same name “microwave (μw) instability”. Usually, but not always, an instability is called μw if

$$f_r \tau \gg 1, \quad (1)$$

where τ is the bunch length and $f_r = \omega_r / (2\pi)$ is the resonant impedance frequency. In proton accelerators μw instability is observed as a fast increase of the bunch length and thus of the longitudinal emittance ε_l . This bunch lengthening can be distinguished from the bunch lengthening due to potential well distortion by a change in the slope of bunch length versus intensity. The break point where the slope changes is considered as the instability threshold.

The operation of the CERN SPS in the past was limited by μw instability. At that time, measurements with long bunches and RF off had allowed the dominant resonant impedances with high R_{sh}/Q to be seen as peaks in the unstable beam spectrum [1], where R_{sh} is the shunt impedance and Q the quality factor. Most of the impedance sources were identified and it was proved, both by measurements and simulations, that the pumping port impedance was the main source of instability. Consequently, shielding these devices led to a significant improvement of the beam stability [2].

Today, the SPS is used as the LHC injector where particles are accelerated by the main 200 MHz RF system. In addition to that, for proton beams, a 4th harmonic RF system (800 MHz) operated in bunch shortening mode (BSM) is used for beam stability (Landau damping). During measurements in 2012, before long shutdown 1 (LS1), a stable LHC proton beam (4 batches of 72 bunches each) with a bunch spacing of 25 ns and a bunch intensity of $N_b = 1.35 \times 10^{11}$ p/b was accelerated to the SPS top energy (450 GeV/c) [3]. Nevertheless, according to the HL-LHC project [4], beams with an intensity of up to 2.5×10^{11} p/b

will be requested from the SPS. This means that one needs to almost double N_b , while maintaining the same bunch length at SPS extraction ($\tau_{4\sigma} \leq 1.7$ ns), restricted by the LHC 400 MHz RF system. The maximum bunch length allowed by the Beam Quality Monitor (BQM) for injection into the LHC is $\tau = 1.9$ ns.

Recent measurements for single high-intensity bunches ($N_b > 2.0 \times 10^{11}$ p/b) showed that longitudinal emittance increases during the cycle, pointing out that a μw instability could be responsible for this effect.

UNCONTROLLED EMITTANCE BLOW-UP

Longitudinal emittance blow-up is observed in the SPS for both single and multi-bunch beams. An example of bunch lengths measured in 2012 for single high-intensity bunches at the SPS flat top is presented in Fig. 1. The measurements were performed in a double RF system in BSM with RF voltages $V_{200} = 2$ MV and $V_{800} = 200$ kV in the 200 MHz and 800 MHz RF systems, respectively [5]. Note that $V_{200} = 2$ MV is much lower than the $V_{200} = 7$ MV that is used in normal operation in order to compress the bunch before extraction to the LHC.

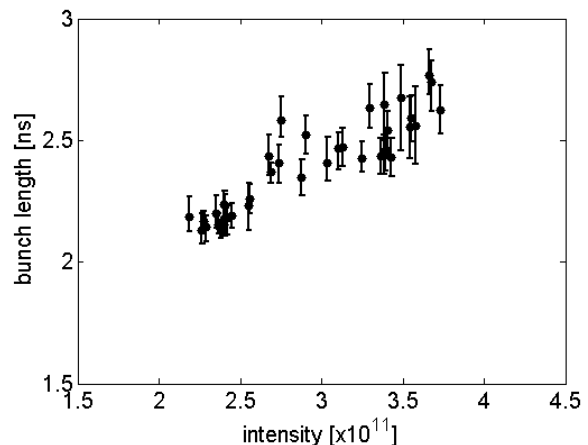


Figure 1: Measured bunch length as a function of intensity for a single bunch at the SPS flat top in a double RF system (BSM). The voltages $V_{200} = 2$ MV and $V_{800} = 200$ kV [5].

A strong increase of the bunch length with intensity is shown in Fig. 1 which can not be attributed to the potential well distortion with the SPS longitudinal impedance model [6]. In particular, in the current model, which includes the RF cavities, resistive wall, injection and extraction kickers, the low frequency reactive part of the SPS impedance is $\text{Im}Z/n \approx 3.5 \Omega$, while much higher

impedance is needed to explain the observed emittance growth ($\text{Im}Z/n \approx 15 \Omega$) [7]. Therefore, a blow-up of the bunch must have occurred during the cycle.

Indeed, measurements performed in 2014 under similar conditions showed that instability occurs during the acceleration ramp. Examples are presented in Fig. 2, where the bunch length evolution during the cycle is depicted. As can be seen in the figure, for intensities above 2.5×10^{11} p a blow-up in emittance takes place during the ramp, leading to larger bunch lengths at the SPS flat top. Note that the voltage program for the 200 MHz RF system was adjusted to have a constant bucket area of 0.5 eVs along the cycle. Usually, 0.6 eVs is used for the LHC type of beams. This was done in order to increase the filling factor and thus to increase Landau damping due to the non-linearity inside the bunch.

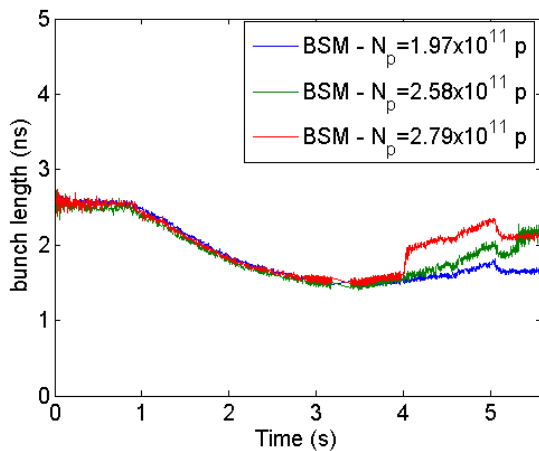


Figure 2: Measured bunch length along the SPS cycle for a single bunch with different intensities in double RF (BSM).

Similar behavior was also measured in the single RF system. However, in that case, the instability during the cycle was observed at lower intensity ($\sim 1.7 \times 10^{11}$ p) compared to the double RF (BSM).

Great effort was made during the last 2 years to identify the impedance sources, responsible for this instability, by beam measurements and simulations [8]. In addition, electromagnetic simulations and measurements in the lab were carried out to determine the impedance of different devices in the SPS ring [9]. An example of beam measurements performed at the SPS flat bottom with very long bunches ($\tau \approx 25$ ns) and RF off, similar to those done in the past [1], is presented in Fig. 3. A strong peak at a frequency around 1.4 GHz was observed [8].

A thorough, element-by-element impedance assessment was then started to find the source of the 1.4 GHz resonance. It has been found that this resonant peak originates from the impedance of certain SPS vacuum flanges [10]. Several types of these flanges are used for the connection of various machine elements and their total number in the ring is around 550. Electromagnetic simulations and RF mea-

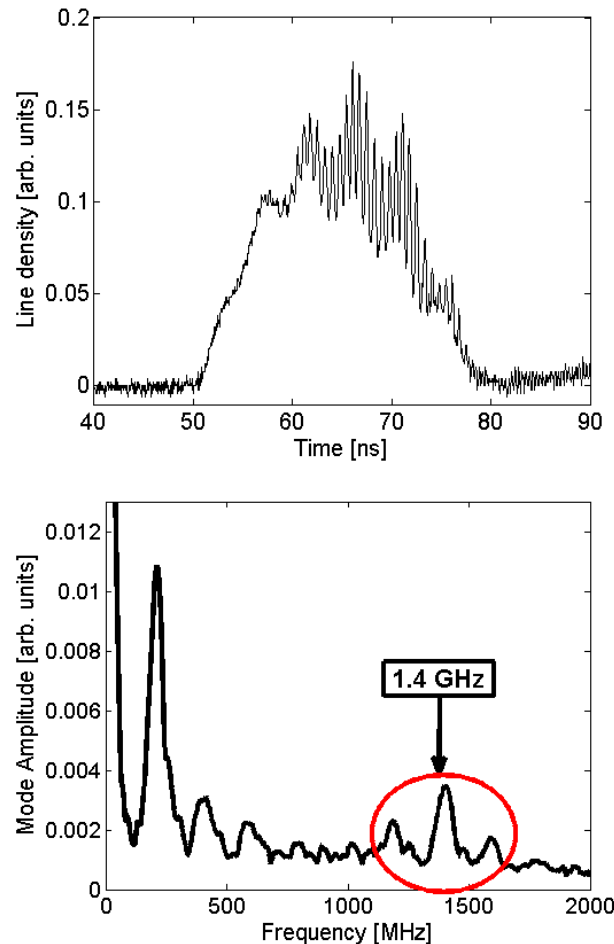


Figure 3: Example of measurements performed on the SPS flat bottom with long bunches ($\tau \approx 25$ ns) and RF off [8]. Top: bunch profile modulated at 200 MHz and at a higher frequency (~ 1.4 GHz). Bottom: projection of the Fourier spectra of all the bunch profiles acquired during ~ 100 ms. Measurements in the Q26 optics with $N_b \sim 1 \times 10^{11}$.

surements [9] were carried out to determine the impedance of these elements, and for a subset of ~ 120 of them, a resonance at 1.4 GHz has been found with an $R_{sh}/Q \sim 9$ k Ω and $Q \sim 200$. Significant resonances were also found from other types of vacuum flanges at around 1.2 GHz, 1.8 GHz and 2.5 GHz.

MICROWAVE INSTABILITY DUE TO RESONANT IMPEDANCE

The effect that a resonant impedance at the high frequency of 1.4 GHz has on the bunch stability was studied in more detail both in single and double RF systems.

The fast μw instability threshold can be estimated for a broad-band impedance using the Keil-Schnell-Boussard criterion [11]. However, when applied for the SPS case in the past, a much lower threshold in intensity was obtained [12]. Analytical solutions for the instability thresh-

olds can be calculated for a fast instability growth for a bunch with Gaussian distribution in the limiting cases of a broad-band ($f_r\tau \gg Q$) or narrow-band ($f_r\tau \ll Q$) resonant impedance [12, 13]. For the instability threshold of a single bunch in a single RF system defined by the interaction with a narrow-band resonator it is the value of R_{sh}/Q which is important, while R_{sh}/n_r is relevant for a broad-band impedance.

Macroparticle simulations were carried out to verify this prediction, using the code BLoND [14]. The simulation was set up to match the experimental conditions at SPS flat top. The particle distribution closest to the measured one was found to be $F(H) = (1 - H/H_0)^2$, where H is the single particle Hamiltonian and H_0 is the Hamiltonian that corresponds to the limiting phase space trajectory. The initial matched distribution was created iteratively and the particles were then tracked for 1.15 s (around twice the time of the SPS flat top). The criterion used to estimate the threshold was based on the bunch length growth and on its oscillation amplitude at the end of the simulation. In particular, the bunch was considered unstable when $\tau_f/\tau_i \geq 5\%$ or $\Delta\tau \geq 100$ ps, where τ_f, τ_i are the final and initial bunch lengths and $\Delta\tau$ is the maximum bunch length oscillation amplitude.

Initially, the case with a single RF system was studied. In order to compare with the above-mentioned expectations, the same $R_{sh}/Q = 10$ k Ω was used while the value of Q (and R_{sh}) was varied. The simulation results are summarized in Fig. 4 where the instability threshold as a function of bunch emittance is plotted.

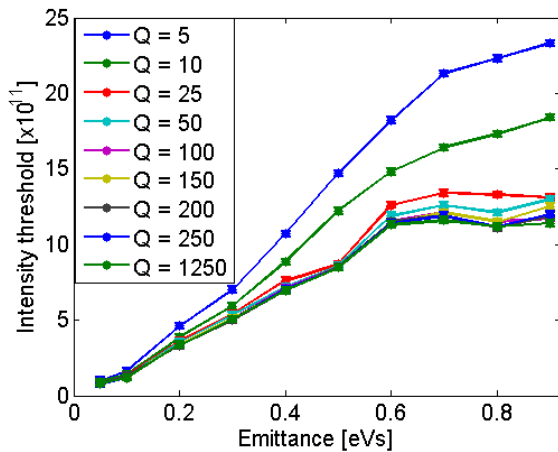


Figure 4: Instability threshold as a function of intensity for different Q values, found in simulations for a single bunch at SPS flat top (450 GeV/c) in single RF and for a resonator with $R_{sh}/Q = 10$ k Ω . The voltage $V_{200} = 2$ MV.

For $Q \geq 50$ the instability threshold is practically unchanged, confirming the fact that only R_{sh}/Q is important for the bunch stability when the resonator is in the narrow-band regime. Note that for all the simulated bunches $f_r\tau < 4 \ll 50$. Instead, when $Q < 50$, R_{sh} becomes important

for stability since the resonator approaches the broad-band regime. As a consequence, for instability in narrow-band impedance regime, damping the resonator does not help much since R_{sh}/Q stays constant. In particular, a damping of more than a factor 50 should be achieved in order to increase the instability threshold.

Similar dependence on R_{sh}/Q and Q was also found for a double RF system when the harmonic and the voltage ratios are $h_2/h_1 = V_1/V_2 = 2$. The two operating modes of the double RF system were studied, namely the bunch-shortening mode (BSM) and the bunch-lengthening mode (BLM) in which, above transition, the phase between the two RF systems is π and 0, respectively. The results for $Q = 250$ are presented in Fig. 5, together with the single RF case for comparison.

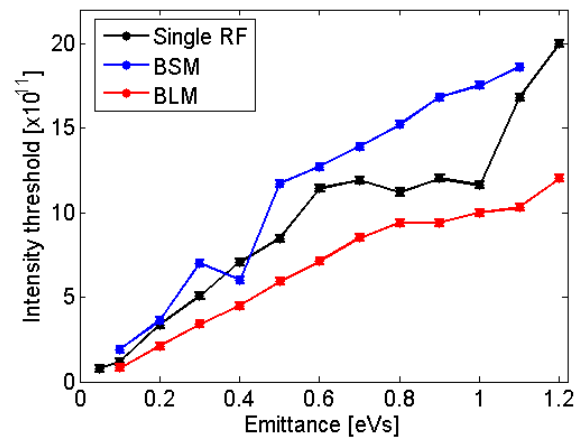


Figure 5: Instability threshold as a function of intensity found in simulations for a single bunch at the SPS flat top (450 GeV/c) in single and double RF systems (BSM and BLM) with $h_2/h_1 = V_1/V_2 = 2$. A resonator with $Q = 250$ and $R_{sh}/Q = 10$ k Ω was used as an impedance source. The voltages $V_{200} = 2$ MV and $V_{800} = 1$ MV.

From μw theory, it is expected that the instability threshold increases with relative momentum spread ($\Delta p/p$) inside the bunch [11, 12, 13]. The fact that BSM, which has the maximum value of $\Delta p/p$, has the highest threshold is in line with this. Similarly, BLM has the lowest threshold amongst the three cases.

However, the previous result is not valid anymore when the harmonic ratio between the two RF systems is $h_2/h_1 = 4$, as presently in the SPS. Particle simulations performed for this harmonic ratio and for two different voltage ratios showed that above a certain emittance the instability threshold is higher in a single RF system (see Fig. 6).

A possible explanation of this fact can be obtained by inspecting the synchrotron frequency distribution inside the bunch $f_s(J)$, where J is the action (similar to the ϵ_l). Examples of distributions calculated for a bunch of $\epsilon_l = 0.6$ eVs are presented in Fig. 7. As one can see, in BSM, there are regions with zero derivative, $f'_s(J) = 0$ in the tails of the bunch which can reduce significantly

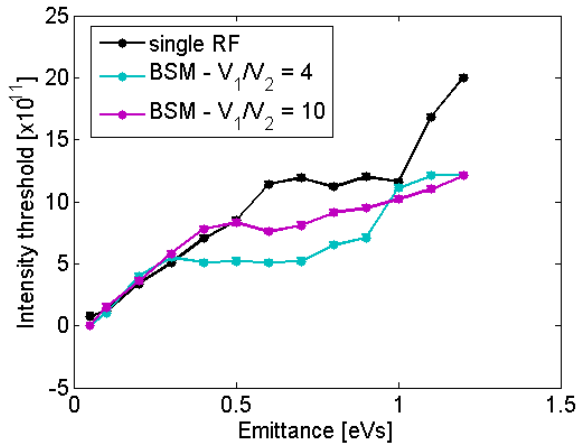


Figure 6: Instability threshold as a function of intensity found in simulations for a single bunch at SPS flat top (450 GeV/c) in single and double RF systems (BSM) with $h_2/h_1 = 4$. A resonator with $Q = 250$ and $R_{sh}/Q = 10 \text{ k}\Omega$ was used. The voltage $V_{200} = 2 \text{ MV}$.

the loss of Landau damping threshold, as has been shown in [15, 16]. Note that $\varepsilon_l \sim 0.6 \text{ eVs}$ corresponds to the typical emittance of LHC-type proton beams at SPS flat top.

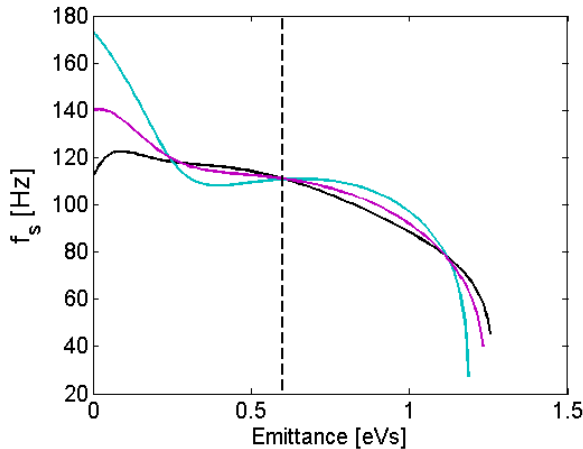


Figure 7: Synchrotron frequency distribution inside the bunch, corresponding to the points with $\varepsilon_l = 0.6 \text{ eVs}$ in Fig. 6, with the same color convention.

SPS LONGITUDINAL INSTABILITY

Macroparticle simulations were performed for comparison with measurements for single- and multi-bunch beams. The SPS impedance model [6], including in addition the impedance of the vacuum flanges, was used. The results for single high-intensity bunches in a double RF system (BSM) are shown in Fig. 8, where bunch lengths found from simulations and measurements at the SPS flat top are plotted together. For both of them, a strong increase of the bunch length with intensity is observed.

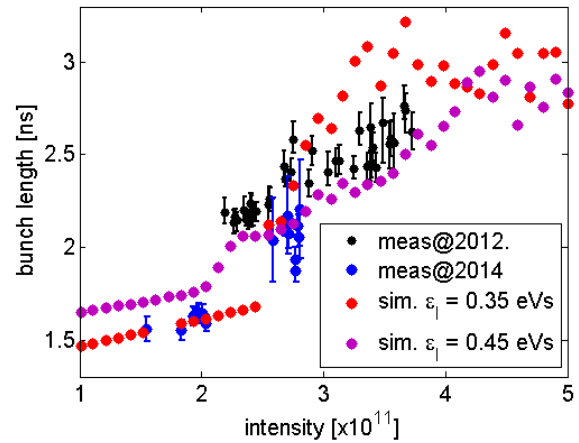


Figure 8: Measured and simulated bunch length as a function of intensity for a single bunch at SPS flat top in double RF system (BSM). The voltages $V_{200} = 2 \text{ MV}$ and $V_{800} = 200 \text{ kV}$.

As aforementioned, this increase cannot be attributed to potential well distortion, but to a μw type of instability instead. Indeed, clear instability thresholds can be observed in simulations. In particular, for the emittances of $\varepsilon_l = 0.35 \text{ eVs}$ and $\varepsilon_l = 0.45 \text{ eVs}$ the thresholds were found at $N_{th} = 2.5 \times 10^{11}$ and $N_{th} = 2 \times 10^{11}$, respectively. The final bunch lengths obtained in simulations are in very good agreement with the measurements. In fact, for the measurements done in 2014, the instability threshold has been found at around $N_{th} = 2.5 \times 10^{11}$, as in the simulations with $\varepsilon_l = 0.35 \text{ eVs}$. Unfortunately, for the measurements performed in 2012, the threshold is not visible, since points at low intensities are missing. Note that in all these measurements the 200 MHz voltage was very low (2 MV), which is good for Landau damping, but unfavorable for μw instability due to the low momentum spread. Furthermore, it was found from simulations that the threshold was increased by increasing the RF voltage, confirming the μw nature of the instability.

Simulations were also carried out with a multi-bunch beam at the SPS flat top. At the moment, only six bunches (spaced by 25 ns) could be simulated and thus only qualitative conclusions can be drawn. For the same longitudinal emittance, the instability threshold for 6 bunches has been found to be almost twice lower than that for a single bunch. This result, presented in Fig. 9, is in agreement with measurements in the double RF system, where the single bunch instability threshold is approximately twice higher than the multi-bunch one.

In addition, in simulations only a coupling between a few bunches (3 or 4) was observed, and no coupled-bunch mode could be identified, similar to all beam observations. Indeed, in measurements bunches spaced by 25 ns or 50 ns are coupled, but the distance of 225 ns between the PS batches is enough to practically fully decouple them; in-

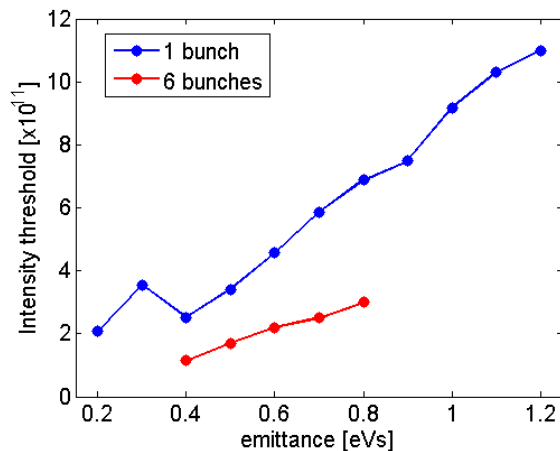


Figure 9: Instability threshold found in simulations for a single- and a 6-bunch beam at SPS flat top and double RF (BSM). The voltages $V_{200} = 7$ MV and $V_{800} = 640$ kV.

stability thresholds in the SPS with 1 to 4 batches are very similar [17].

Finally, simulations performed under similar conditions, both for single- and multi-bunch beams, but without the impedance of the vacuum flanges, showed that the instability threshold is twice higher. Therefore, measures for reducing this impedance should be considered in order to reach the intensity required by the HL-LHC project.

CONCLUSIONS

Uncontrolled longitudinal emittance blow-up has been observed in the CERN SPS both for single- and multi-bunch beams. This is presently one of the main limitations for reaching the intensity required by the HL-LHC. Beam measurements revealed a strong signal at 1.4 GHz coming from the SPS vacuum flanges. The effect of this resonant impedance on beam stability was studied using macroparticle simulations. It was shown that for narrow-band resonators the instability thresholds scales with R_{sh}/Q , while for broad-band, R_{sh} is important, as expected from theory. The cases of single and double RF systems were inspected. In particular, for the double RF system with harmonic ratio $h_2/h_1 = 2$, the intensity threshold scales with the relative momentum spread, i.e. it is higher in BSM and lower in BLM compared to the single RF. On the contrary, above a certain longitudinal emittance, beam stability becomes worse in BSM than in single RF when $h_2/h_1 = 4$. The microwave nature of the instability observed in the SPS was also confirmed by simulations using the current SPS impedance model. SPS vacuum flanges were identified as the responsible impedance source; measures for reducing this impedance are currently being considered.

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