LONGITUDINAL MICROWAVE INSTABILITY STUDY AT TRANSITION CROSSING IN THE CERN PS

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Abstract

The beam quality of high-intensity proton and ion bunches in the CERN Proton Synchrotron (PS) is limited by a longitudinal microwave instability at transition crossing. This single-bunch instability manifests itself as a rapid longitudinal emittance blow-up and impacts, for instance, the intensity and bunch length to the AWAKE experiment. In this contribution, results of complete parameter scans are presented to experimentally establish the beam stability limits. These are compared to detailed tracking simulations with the BLonD code, including collective effects with the longitudinal impedance model, beam feedback loops, and the gamma transition jump. Remarkable agreement with measurements is obtained for the instability thresholds and micro-bunch structures. Nonetheless, the characteristics of the simulated instability strongly depend on the modelling of longitudinal space charge, which focuses the micro-bunches but also introduces significant numerical noise. The results improve the understanding of performance limitations due to transition crossing and guide future mitigation strategies.

INTRODUCTION

The longitudinal microwave instability has been observed for decades at transition crossing in the CERN Proton Synchrotron (PS) [1]. This instability, manifesting itself as high-frequency density modulations along the bunch, leads to a rapid and uncontrolled longitudinal emittance blow-up. The modulation is driven by high-frequency impedance sources satisfying $f_r \tau_\ell \gg 1$ (where f_r is the resonance frequency and τ_ℓ is the bunch length). For typical PS bunches with lengths on the nanosecond scale at transition, this points to resonant frequencies above 1 GHz.

More recently, the instability was observed with various ion species [2], and its observation, along with proton beams, is presented in this paper. An example acquisition at the onset of the instability close to transition crossing is given in Fig. 1. The AWAKE experiment [3] at CERN requires short, intense single proton bunches ($N_b = 30 \times 10^{10}$ p+) from the Super Proton Synchrotron (SPS), the downstream accelerator of the PS. The beam parameters are set close to the stability limit in the PS and the instability is presently mitigated by applying a controlled longitudinal emittance blow-up with a dedicated 200 MHz RF system before transition [4]. While this preserves global beam quality and reproducibility compared to the turbulent microwave instability regime, the enlarged emittance imposes a minimum on the smallest achievable bunch length for AWAKE. Moreover, following the impedance reduction campaign in the SPS [5, 6], the microwave instability is now one of the main limitations in providing shorter bunches to the AWAKE experiment [7].

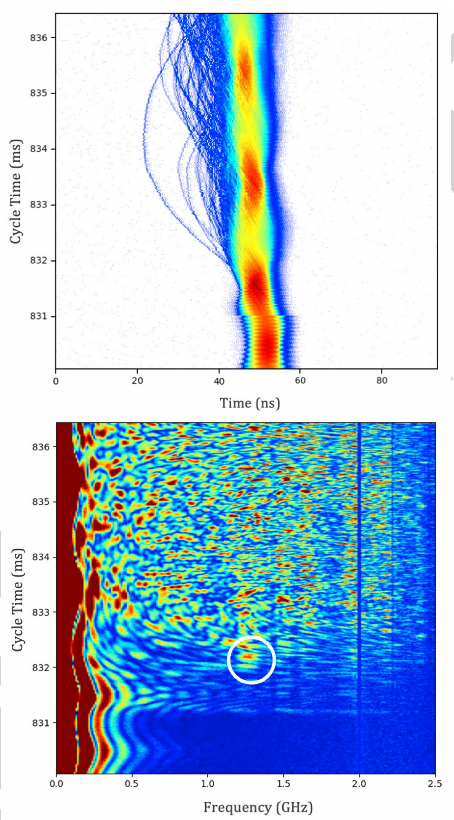

Figure 1: Measured evidence of a 1.3 GHz modulation in a single proton bunch. Evolution of the line density as a waterfall plot (top) and corresponding spectrum obtained from the FFT of each frame (bottom). The effective transition crossing timing happens at a cycle time (c-time) of 831 ms. The colour scale increases from blue to red.

Extensive studies have been conducted since 2017 to identify the source of beam-coupling impedance causing the instability. In particular, an analysis of the spectral components of the modulated bunch profiles was performed both at transition crossing and from dedicated measurements using long bunches with small momentum spread [8, 9]. These provided a more precise measurement of the modulation, 1.3 GHz, compatible with the resonant frequency of the numerous unshielded pumping manifolds located at the downstream end of the main magnet units in the PS [10]. In this paper, a new set of measurements with single proton bunches is presented and compared to tracking simulations using the BLonD simulation code [11], the influence of the pumping manifold impedance as well as space charge is then analysed.

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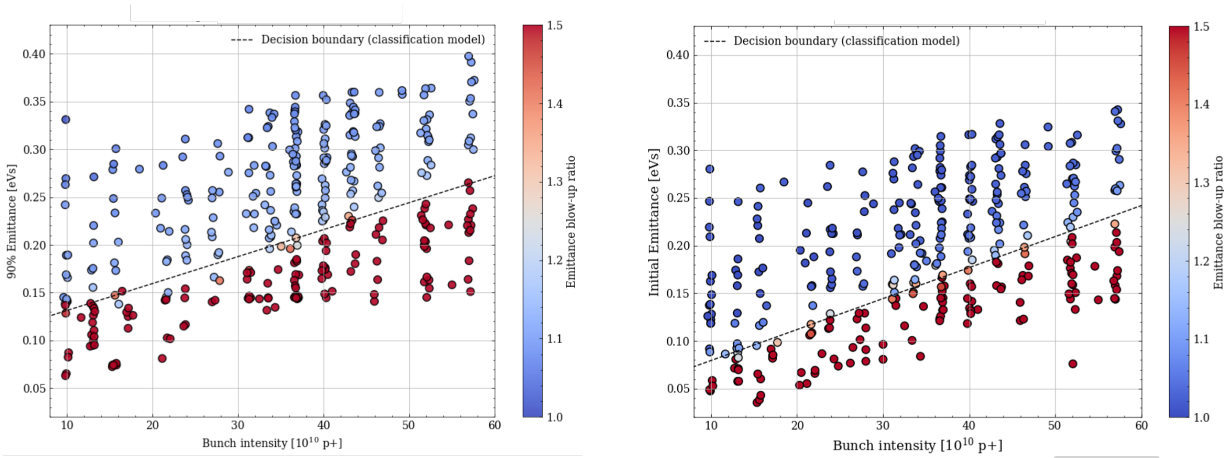

Figure 2: Emittance blow-up due to microwave instability as a function of the bunch intensity and longitudinal emittance. The experimental results (left) are compared directly with BLonD simulations (right). The PS operates for the AWAKE experiment with a bunch intensity $N_b = 30 \times 10^{10}$ p+ and longitudinal emittance $\varepsilon_\ell = 0.2$ eVs.

MEASUREMENTS AND TRACKING SIMULATIONS

A dedicated measurement campaign was conducted in 2025 to better evaluate the dependency of the instability on the initial beam parameters. A complete dataset was acquired to evaluate the longitudinal emittance preservation scanning intensities and initial emittances. Longitudinal bunch profiles were recorded at the start of the acceleration ramp, transition crossing, and top energy to evaluate the amount of emittance increase. The initial emittance and intensity were fine-tuned in the PS injector (PS Booster), while the emittance blow-up was controlled linearly using the dedicated 200 MHz RF blow-up scheme in the PS. An overview of the measured stability map is given on the left of Fig. 2.

To classify bunches as stable or unstable, a logistic regression model was trained using a threshold blow-up ratio of 1.35. This criterion reliably separates stable conditions from cases exhibiting microwave instability (characterized by significant emittance growth, associated with the modulation at transition crossing). The resulting scan reveals a clear instability threshold: below a certain emittance, for a given intensity, the beam becomes unstable after transition.

Detailed macro-particle tracking simulations were then performed using the GPU-accelerated BLonD (Beam Longitudinal Dynamics) code [11] to benchmark against the measured instability threshold. These included a detailed PS impedance model [12], including numerous accelerator components (RF cavities, kickers, vacuum system elements, etc.), and in particular the high-frequency components expected to drive microwave instabilities. The longitudinal space charge forces were also modelled with the beam parameters updated turn-by-turn to reflect the evolution of the transverse beam size, bunch length and momentum spread throughout the whole simulation [13]. The simulation accounted for the complex dynamics around transition with the fast γ_t-jump scheme [14]. The γ_t program was evaluated from the optics using the Xsuite code [15]. To accurately reproduce the transient dynamics after transition, realistic timings for the RF phase jump were set together with an improved modelling of the beam loops [16].

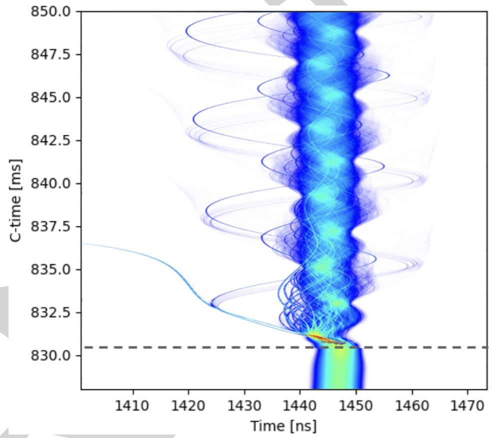

Figure 3: Simulated bunch profile evolution at transition crossing with the BLonD simulation code. The model successfully captures the post-transition focusing and subsequent micro-bunching.

An example of bunch profile evolution for an unstable case in simulation is shown in Fig. 3. The macroscopic agreement between the measurements (see Fig. 4) and the tracking simulations is excellent; the key features of the instability are well reproduced. The high-frequency modulation develops right after transition, breaking the bunch into micro-bunches that closely mirror the experimental waterfall plots. Residual sources of discrepancies nonetheless require some further treatment. Indeed, the space charge impedance had to be scaled down by approximately 20% to reproduce collective effects beyond instability. This remains within the uncertainty associated with the approximations made regarding the vacuum chamber aperture geometry (a detailed aperture model was not available). Additionally, the modulation at 1.3 GHz was well reproduced. In simulations additional spectral component at 1.5 GHz were observed and could be associated with the impedance of the vacuum flanges, for which the model is approximate and likely overestimated.

With the overall instability behaviour established in simulation, the experimental parameter scan was reproduced by initializing simulated bunches with identical conditions to measurements. The result of the scan is presented on the right side of Fig. 2. The results are in good agreement with the measurements, displaying a 20% offset in longitudinal emittance. The stability threshold appears to be higher in simulations than in measurements, indicating that remaining impedance sources are missing from the model.

Synchronous Phase Shift of Micro-bunches

Following transition crossing, the microwave instability leads to the formation of numerous ultrashort micro-bunches (~ 100 ps). Detailed measurements reveal that these structures exhibit unconventional phase-space motion: many do not oscillate around the expected synchronous phase φ_s, but instead show a clear synchronous phase shift $\Delta\varphi_s$. In some cases, the micro-bunch even appears to oscillate distinctly ahead of the main bunch, as shown in Fig. 4.

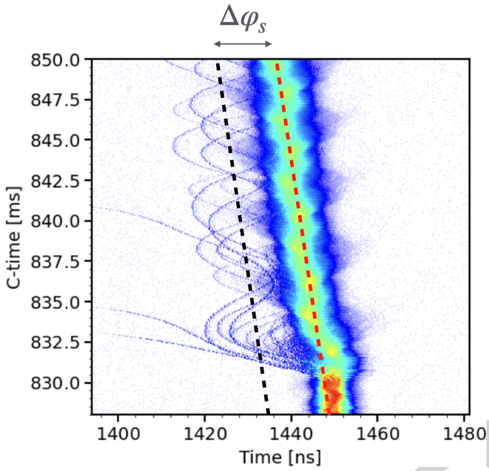

Figure 4: Measurements of a single proton bunch in the PS showing the formation of micro-bunches after transition, with a clear synchronous phase shift $\Delta\varphi_s$. Red dashed line: expected RF synchronous phase; black dashed line: effective synchronous phase for some of the micro-bunches.

Numerical simulations confirm that this deviation is not a measurement artifact but a genuine dynamical consequence of collective beam-impedance interactions. Because micro-bunches are extremely short, their broad frequency spectrum interacts strongly with all resistive impedance components. This generates a high self-induced voltage, resulting in a net energy loss for the micro-bunch. Consequently, the synchronous phase of the micro-bunch is shifted as its energy loss is continuously compensated by the RF system. Meanwhile, the strong focusing forces of longitudinal space charge above transition allow these structures to persist for many synchrotron periods.

IMPEDANCE REDUCTION AND INFLUENCE OF SPACE CHARGE

With the acceptable agreement between measurements and simulations, the model was used to evaluate impedance reduction scenarios. Surprisingly, removing the pumping manifolds from the impedance model suppressed the specific 1.3 GHz spectral signature, but did not significantly modify the global instability threshold. Even when all high-frequency vacuum equipment was removed, the beam remained unstable with no clear spectral signature.

Further simulation scans isolating individual impedance contributions revealed that the instability threshold is dominated by the longitudinal space charge impedance [17]. Above transition energy, the capacitive nature of the space charge impedance drives the negative mass instability. When a small initial density modulation occurs, the longitudinal electric field generated by space charge decelerates leading particles and accelerates trailing ones within a local density peak, resulting in the self-focusing of noisy features within the bunch line density.

This effect is exaggerated in tracking simulations due to numerical noise arising from the finite and limited number of macro-particles [18]. Profiting from the increased computing performance of modern GPU-implemented tracking code, simulations were performed to check convergence up to 50 M macro-particles. Nonetheless, important uncertainties remain regarding the modelling of longitudinal space charge, implying that alternative simulation methods need to be investigated to provide more accurate predictions of how impedance reduction will affect the instability threshold, notably semi-analytical solutions to the Vlasov equations.

CONCLUSION

This study presents a comprehensive comparison between measurements and tracking simulations of the longitudinal microwave instability for proton bunches at transition crossing in the CERN PS. Spectral analysis shows a density modulation at 1.3 GHz, matching the resonant frequency of the unshielded pumping manifolds. High-fidelity tracking simulations using BLonD successfully reproduced the macroscopic micro-bunching structure, the unconventional phase shifts of individual micro-bunches, and the global parameter stability threshold that currently limits the AWAKE beam.

The simulations demonstrate that while specific narrow-band impedance sources dictate the spectral signature of the instability, the stability limit is strongly influenced by longitudinal space charge. Hardware shielding is planned to be tested on one manifold unit this year and the implementation on all the units is expected to effectively remove the spectral signature of the instability. Alternative methods for evaluating the instability threshold are needed to better predict the resulting benefits in terms of achievable beam performance.

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REFERENCES

[1] D. Boussard, “Observation of microwave longitudinal instabilities in the CPS”, CERN, Geneva, CERN-LabII-RF-INT-75-2, 1975. `http://cds.cern.ch/record/872559`

[2] A. Lasheen, H. Damerau, A. Huschauer, and B. K. Popovic, “Longitudinal Microwave Instability Study at Transition Crossing with Ion Beams in the CERN PS”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 3197–3200. doi:10.18429/JACoW-IPAC2021-WEPAB243

[3] E. Gschwendtner *et al.*, “AWAKE, the advanced proton driven plasma wakefield acceleration experiment at CERN”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 829, pp. 76–82, 2016. doi:10.1016/j.nima.2016.02.026

[4] H. Damerau, M. Morvillo, E. N. Shaposhnikova, J. Tuckmantel, and J.-L. Vallet, “Controlled Longitudinal Emittance Blow-up in the CERN PS”, in *Proc. PAC’07*, Albuquerque, NM, USA, Aug. 2007, pp. 4186–4188. doi:10.1109/PAC.2007.4439979

[5] I. Karpov and M. Gadioux, “Mechanism of Longitudinal Single-Bunch Instability in the CERN SPS”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 3161–3164. doi:10.18429/JACoW-IPAC2021-WEPAB227

[6] T. Argyropoulos, H. Damerau, I. Karpov, A. Lasheen, and G. Papotti, “Experimental confirmation of the impedance reduction campaign in the CERN SPS”, in *Proc. IPAC’23*, Venice, Italy, May 2025, pp. 1303–1306. doi:10.18429/JACoW-IPAC2023-TUODA2

[7] I. Karpov *et al.*, “Short high-intensity bunches for the AWAKE experiment”, presented at IPAC’26, Deauville, France, May 2026, paper THP4010, this conference,

[8] T. Bohl, T. P. R. Linnecar, and E. Shaposhnikova, “Measuring the resonance structure of accelerator impedance with single bunches”, *Phys. Rev. Lett.*, vol. 78, no. 16, pp. 3109–3112, Apr. 1997. doi:10.1103/PhysRevLett.78.3109

[9] E. Vinten and A. Lasheen, “Longitudinal microwave instability with long bunches in the CERN Proton Synchrotron”, in *Proc. IPAC’23*, Venice, Italy, May 2025, pp. 2661–2664. doi:10.18429/JACoW-IPAC2023-WEPA011

[10] M. Neroni *et al.*, “Longitudinal beam coupling impedance of unshielded pumping manifolds at the CERN PS”, in *Proc. IPAC’25*, Taipei, Taiwan, May 2025, pp. 2310–2313. doi:10.18429/JACoW-IPAC2025-WEPS031

[11] H. Timko *et al.*, “Beam longitudinal dynamics simulation suite BLonD”, Jun. 2022. doi:10.48550/arXiv.2206.08148

[12] A. Lasheen, Ps longitudinal impedance model, Dec. 2020. doi:10.5281/zenodo.4420903

[13] A. Laut, “Longitudinal space charge modeling in the CERN PS”, Master Thesis, Université Paris Saclay, Number: CERN-THESIS-2021-276, 2021.

[14] W. Hardt, “Gamma-transition-jump scheme of the CPS”, in *9th International Conference on High-Energy Accelerators*, pp. 434–438, 1974. `https://cds.cern.ch/record/415587`

[15] G. Iadarola *et al.*, “Xsuite: An Integrated Beam Physics Simulation Framework”, in *Proc. HB’23*, Geneva, Switzerland, Oct. 2023, pp. 73–80. doi:10.18429/JACoW-HB2023-TUA2I1

[16] O. Naumenko and A. Lasheen, “Modelling of the PS beam phase and radial feedback loops”, CERN-ACC-NOTE-2024-0011, 2024. `https://cds.cern.ch/record/2898501`

[17] J. Salinas, “Study of longitudinal beam instabilities at transition crossing in the CERN proton synchrotron”, Master Thesis, Université Paris Saclay, Centrale Supelec, Number: CERN-ACC-NOTE-2026-0001, 2026. `https://cds.cern.ch/record/2952982`

[18] I. Kourbanis and K.-Y. Ng, “Main ring transition crossing simulations”, in *Fermilab III Instabilities Workshop*, pp. 151–169, Oct. 1990.