SIMULATION OF INSTABILITY AT TRANSITION ENERGY WITH A NEW IMPEDANCE MODEL FOR CERN PS

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Abstract

Instabilities driven by the transverse impedance are proven to be one of the limitations for the high intensity reach of the CERN PS. Since several years, fast single bunch vertical instability at transition energy has been observed with the high intensity bunch serving the neutron Time-of-Flight facility (n-ToF). In order to better understand the instability mechanism, a dedicated measurement campaign took place. The results were compared with macro-particle simulations with PyHEADTAIL based on the new impedance model developed for the PS. Instability threshold and growth rate for different longitudinal emittances and beam intensities were studied.

INTRODUCTION

In the CERN Proton Synchrotron (PS) the operational beams have to cross the transition energy. During the transition crossing the synchrotron motion is frozen and the beam is particularly sensitive to the force of the wake fields produced by the beam itself [1, 2]. With increased beam intensity, a fast vertical single bunch instability was observed around transition energy [3-5]. This instability can induce beam emittance blow-up and beam losses. Many studies have been performed on this subject. In reference [6] an extensive measurements campaign has been presented and compared with HEADTAIL code [7] simulations using a simple broadband impedance model (f_r=1 GHz, Q=1), as there was no detailed impedance model available [6, 8-9]. A complete impedance model was recently developed for the PS both for longitudinal [10] and transverse plane [11, 12], which makes it possible for us to do the simulations with a more realistic model of the excited wake field. The goal of this work is, therefore, first to measure the characteristics of the instability with the n-ToF beam [13], such as the intensity threshold and its growth rate, and then to benchmark the measurements with simulations based on the available PS impedance model. This study further benchmarks the impedance model and the assumptions of the simulation framework, which are crucial for the PS LIU upgrade studies [14].

INSTABILITY MEASUREMENTS

A dedicated single bunch n-ToF beam was set up for the instability measurements. The beam parameters are presented in Table 1. In order to simplify the beam dynamics, a zero chromaticity plateau is programmed around transition in the vertical plane, and the measurements are performed without the gamma jump [6].

Table 1: Beam Parameters

Parameter	Value
Circumference, C	628 m
Transition gamma, γ_t	6.08
RF voltage, V_{rf}	200 kV
Harmonic number, h	8
Number of protons/bunch, N_b	90E10 – 200E10
Longitudinal emittance, ε_L	1.9 – 2.9 eV·s
Transition time	312 ms

Both the longitudinal bunch profile, and the vertical position are measured with a wall current monitor during transition. Figure 1 shows a measurement example. The particles close to the peak intensity become unstable and oscillate at high frequency in the vertical plane. The amplitudes of these particles increase rapidly until they are lost on the vacuum chamber.

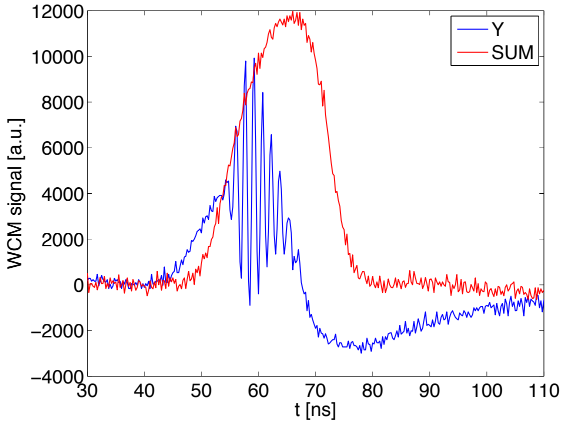

Figure 1: Bunch profile measured with the wall current monitor. Red curve: longitudinal bunch profile. Blue curve: vertical difference signal.

A Fast Fourier Transform analysis of the vertical signal gives a characteristic frequency of the instability in the range 600~700 MHz, as shown in Fig. 2.

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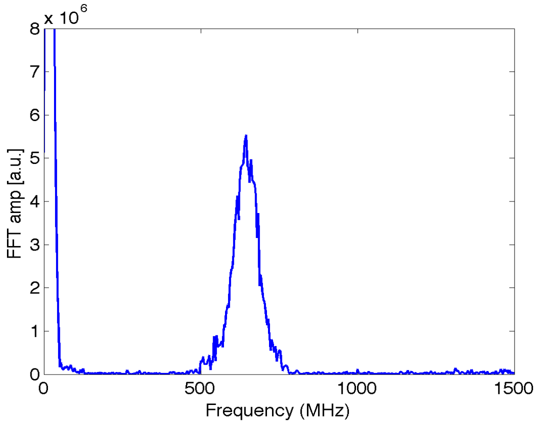

Figure 2: Amplitude spectrum of the vertical signal.

Instability Growth Time

With the multi-turn acquisition system, we can acquire the vertical beam signal for several thousands of consecutive turns. By a spectral analysis of all the consecutive traces, we can get the spectrum evolution with respect to time, as presented in Fig. 3.

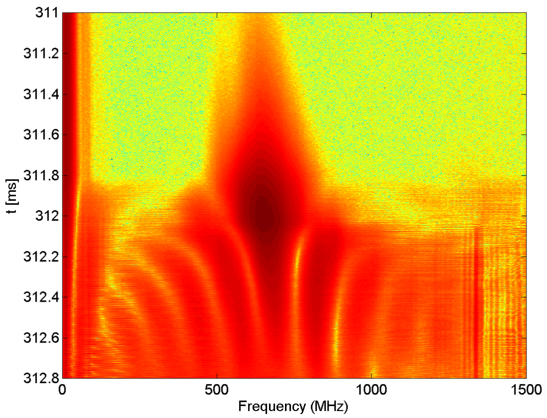

Figure 3: Evolution of the vertical bunch position in frequency.

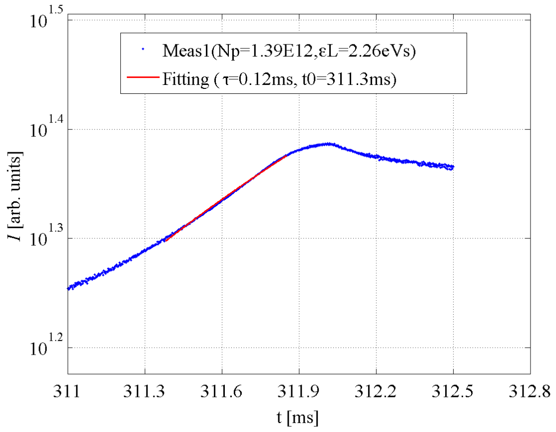

Figure 4: Computed integral, I, of the bunch frequency spectrum with time. Blue points: measured data. Red curve: fitting of the growth time.

The integral, I, over the vertical signal spectrum of each trace is our observable to measure the instability rise time. Figure 4 presents an example of the computed integral as function of time in log scale. The growth time of the instability is obtained by fitting the linear part of the curve. At a beam intensity of 140E10 p/b and with a longitudinal emittance of 2.26 eV·s, the measured instability growth time is 0.12 ms, which indicates that the instability develops in ~60 turns.

Intensity Scans for Different Longitudinal Emittances

We also measured the dependence of the instability on beam intensity and longitudinal emittance. Beam intensity was varied in the range from 90E10 to 200E10 p/b, whilst the longitudinal emittance was adjusted from 1.9 to 2.9 eV·s. Figure 5 shows the dependence of the instability growth rate on bunch intensity and longitudinal emittance.

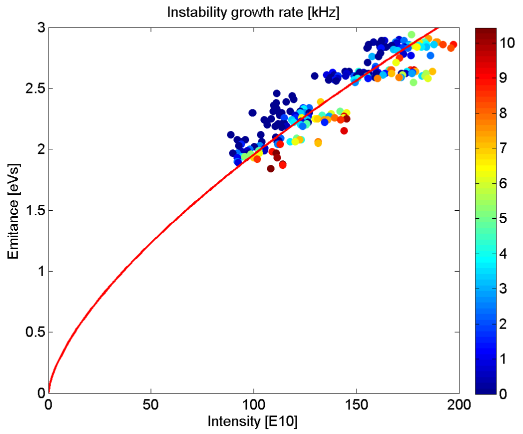

Figure 5: Bunch intensity versus longitudinal emittance color-coded with the instability growth rate. (Dots: measurements, Red line: I_{th}=37 $(\varepsilon_L)^{1.5}$).

For a certain emittance, the instability growth rate increases with the bunch intensity as expected. The threshold intensity, I_{th}, is expected to go to zero for zero intensity. The fit shown in Fig. 5 assumes $I_{th} \propto (\varepsilon_L)^{1.5}$. Further simulations and measurements are needed to validate the proposed fit in the low emittance region.

MACRO-PARTICLE SIMULATIONS WITH PYHEADTAIL

In order to better understand the instability mechanism, macro-particle simulations with PyHEADTAIL [15] have been performed based on the new PS impedance model. The initial longitudinal distribution has been obtained by fitting the measured longitudinal profile with a Gaussian function. The bunch dynamics has been simulated during the acceleration without gamma transition jump and taking into account the machine parameters, such as RF voltage, bending magnetic field, transverse tunes and chromaticity setting.

Impedance Model

The transverse impedance model used in the simulation is shown in Fig. 6 and compared with the broadband impedance model used in Ref. [6]. Both dipolar and quadrupolar impedances are considered. The impedance shows a low Q resonance around 700 MHz. The resonance is mainly driven by the kickers impedance, which should be the main reason for the fast vertical single bunch instability described above.

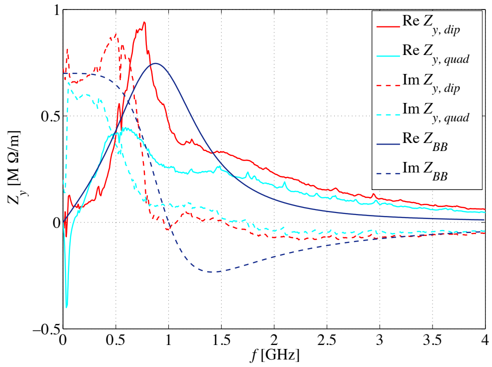

Figure 6: Transverse impedance model compared with the broadband impedance model used in Ref. [6]. The red curves are the dipolar impedance; the cyan curves are the quadrupolar impedance; the blue curves are the broadband impedance model (f_r=1 GHz, Q=1, R_s=1 MΩ/m).

Instability Growth Time

By taking into account the PS impedance model, the beam dynamics has been simulated with the PyHEADTAIL code. Using the same analysis applied to the measurements, a spectrogram of the instability has been computed from the simulation results. The spectrum obtained from the simulation (Fig. 7) features the same frequency behaviour of the one observed in the measurement (Fig. 3).

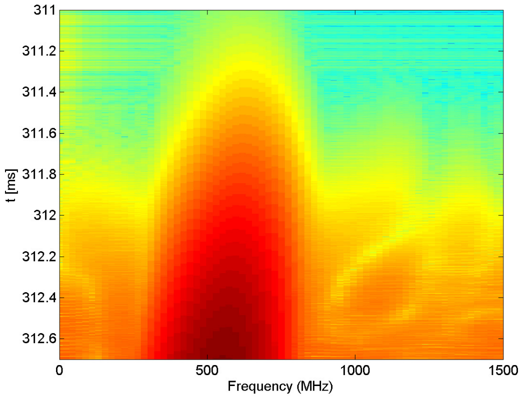

Figure 7: An example of the frequency spectrum evolution obtained in simulation (same machine condition as Fig. 3).

With an intensity of 140E10 and a longitudinal emittance of 2.26 eV·s, the simulated growth time is ~0.075 ms, in comparison to the measured value of 0.12 ms.

Dependence on Beam Intensity

In addition, the instability growth rate as a function of the beam intensity has been simulated. Figure 8 shows the comparison between the simulation and the measurement for similar beam conditions.

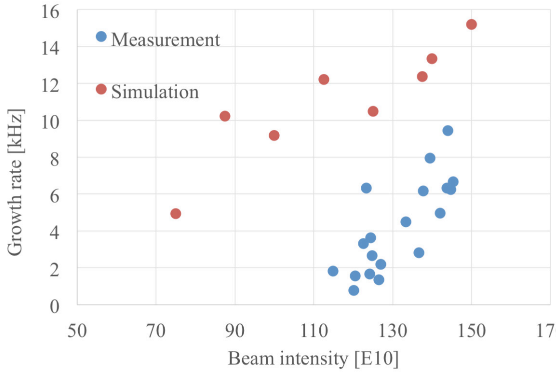

Figure 8: Simulated instability growth rate as a function of the beam intensity, and compared with the measurement.

The results indicate that the simulation gives a lower instability threshold and a stronger growth rate with respect to the measurement. The difference between the two increases for low intensity beams. This can be explained by the lack of stabilizing factors in the simulations, which do not take into account space charge tune spread and magnetic non-linearities of the machine. In addition, measuring the chromaticity during transition is challenging due to the vanishing slip factor. Simulations were done with the measured chromaticity and with zero chromaticity for comparison. The difference in the instability time constant between the two cases was marginal.

CONCLUSIONS

In this work we presented the results of a measurement campaign on the instability of the n-ToF bunch occurring in the PS during the transition crossing. Instability growth time and intensity threshold versus longitudinal emittance are obtained. Simulations based on the new PS impedance model have been performed and compared to the measurements. A fairly good agreement has been reached between simulations and observations. The residual differences could be explained by taking into account additional stabilizing ingredients such as space charge and nonlinear effects, presently neglected but to be considered in future studies.

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REFERENCES

[1] E. Métral and D. Möhl, Transition Crossing, CERN-2011-004, June 2011, pp. 59.

[2] E. Métral, “Effects near transition”, CERN Topical CAS on High Intensity Limitations, 2015.

[3] E. Métral, “Stability criteria for high-intensity single-bunch beams in sychrotrons”, in *Proc. EPAC’02*, Paris, France, June 2002, pp. 1532-1534.

[4] R. Cappi, E. Métral, G. Métral, “Beam breakup instability in the CERN PS near transition”, in *Proc. EPAC’00*, Vienna, Austria, June 2000, pp. 1152-1154.

[5] S. Hancock and E. Métral, “Ghost bunches and blow-up losses with high-intensity beams”, PS/RF Note 2002-198.

[6] S. Aumon, “High Intensity Beam Issues in the CERN PS”, Ph. D. thesis, CERN-THESIS-2012-261.

[7] G. Rumolo, F. Zimmermann, “Practical user guide for HEADTAIL”, SL-Note-2002-036-AP, CERN.

[8] S. Aumon, et al, “Transverse mode coupling instability measurements at transition crossing in the CERN PS”, in *Proc. IPAC’10*, Kyoto, Japan, May 2000, pp. 2036-2038.

[9] S. Aumon, et al, “Transverse mode coupling instability measurements at transition crossing in the CERN PS”, in *Proc. HB’10*, Morschach, Switzerland, 2010, pp. 681-685.

[10] M. Migliorati et al., Phys,.Rev. STAB 2013, 16, 031001.

[11] S. Persichelli et al., “The Proton Synchrotron Transverse Impedance Model”, in *Proc. IPAC’14*, Dresden, Germany, 2014, pp. 4096-4098.

[12] S. Persichelli et al., “Transverse beam coupling impedance of the CERN Proton Synchrotron”, Phys. Rev. STAB 19, 041001, 2016.

[13] “n-ToF Technical Design Report on experimental Area”, CERN-INTC-2000-018, CERN, Geneva, November, 2000.

[14] R. Garoby et al., “Plans for the upgrade of the LHC injectors”, in *Proc. IPAC’11*, San Sebastian, Spain, pp. 2517-2519.

[15] https://github.com/PyCOMPLETE/PyHEADTAIL.