# TRANSVERSE MODE COUPLING INSTABILITY MEASUREMENTS AT TRANSITION CROSSING IN THE CERN PS

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*Abstract*

Transition crossing in the CERN PS is critical for the stability of high intensity beams, even with the use of a second order gamma jump scheme. The intense single bunch beam used for the neutron Time-of-Flight facility (n-ToF) needs a controlled longitudinal emittance blowup at flat bottom to prevent a fast single-bunch vertical instability from developing near transition. This instability is believed to be of Transverse Mode Coupling (TMCI) type. A series of measurements taken throughout 2009 and 2010 aims at using this TMCI observed on the ToF beam at transition, as a tool for estimating the transverse global impedance of the PS. For this purpose, we compare the measurement results with the predictions of the HEADTAIL code and find the matching parameters. This procedure allows a better understanding of the different mechanisms involved and can suggest how to improve the gamma jump scheme for a possible intensity upgrade of the n-ToF beam.

## INTRODUCTION

The CERN Proton Synchrotron uses a second order $\gamma_{\rm tr}$ jump scheme to cross transition. Fast beam losses due to a vertical single bunch instability can be observed near transition on a high intensity beam ($700 \cdot 10^{10}$ protons) if the longitudinal emittance is not sufficiently large. This effect is believed to be a transverse mode coupling instability (TMCI). Increasing the longitudinal emittance of the beam from 2 eV.s to 2.5 eV.s is sufficient to prevent the transverse turbulence [1]. However the instability could be a strong limitation in case of a PS upgrade. Transverse profile measurements have been carried out to understand the mechanism of the instability. The measurements have been performed without the $\gamma_{\rm tr}$ jump to be comparable with HEADTAIL [2] simulations which does not include yet the possibility to make a $\gamma_{\rm tr}$ jump. The status of the simulations will be presented and compared to the measurements. This will give in the future an estimation of the transverse impedance of the machine, which is crucial for further studies concerning the PS upgrade.

## EXPERIMENTAL OBSERVATIONS

A dedicated single bunch beam has been set up to observe the transverse instability without the $\gamma_{\rm tr}$ jump. Its parameters are presented in the Table 1. The intensity of the beam is lower than the operational beam since the $\gamma_{\rm tr}$ is kept constant during the transition crossing. Indeed the

Table 1: Beam parameters for measurements.

| | |
|---|---|
| Total energy at $\gamma_{\rm tr}$ | $E \simeq$ 6.1 GeV |
| $\gamma_{\rm tr}$ | 6 |
| Transverse tunes | $Q_{x,y}$=6.2 |
| Chromaticities | $\xi_{x,y} \sim 0$ |
| RF Harmonic | h=8 |
| Bunch intensity (single bunch) | $60 \cdot 10^{10}$-$165 \cdot 10^{10}$ |
| Full bunch length | 30 ns |
| Longitudinal emittance | 1.50, 1.92, 2.30 eV.s |
| Transverse $\epsilon_{x,y}^{norm}(1\sigma)$ | $\epsilon_x = 1.17 - 2.38$ mm.mrad<br>$\epsilon_y = 1.34 - 2.33$ mm.mrad |

$\gamma_{\rm tr}$ jump has been designed in the past to prevent the development of a longitudinal microwave instability on high intensity beams. In order to avoid other instabilities such as the transverse head-tail one, the horizontal and the vertical chromaticities are set close to zero several millisecondes around transition. In the real machine, the exact time at which the chromaticities change sign cannot be determined precisely. Figure 1 shows the vertical instability measured with a wide band pick-up [3], that has a band width between 2.5 MHz-1 GHz [4]. Figure 2 represents the longitudinal profile of the same bunch. The measured vertical signal shows that the head of the bunch is stable whereas the center, i.e. at the maximum peak intensity, oscillates at high frequency. From a frequency analysis of the profile of Fig. 1, one can deduce that the frequency of the instability is about 719 MHz. The mechanism involved is the beam breakup [1]: the head excites the tail of the bunch due to a high frequency resonator and a short range wake field. Once the particles oscillating with a high amplitude are lost in the vacuum chamber, a hole is observed in the line-charge density of the bunch. The longitudinal profile is not repopulated since the synchronous motion is very slow at transition. The horizontal plane remains stable.

## RISE TIME MESUREMENTS OF THE TRANSVERSE INSTABILITY

The measurements consists of taking the vertical bunch profile turn-by-turn through transition thanks to a fast signal system. The sampling of the signal is about 4 GSamp/s which is sufficient to observe the desired high frequency oscillations on the bunch profile. In addition the oscilloscope can be used with a multi-trigger system in order to save 8000 traces turn-by-turn per cycle, which corresponds to 17 ms. In our case, we took 2500 turns in both vertical and longitudinal planes to see the developement of the instability. The rise time of the instability is defined here by

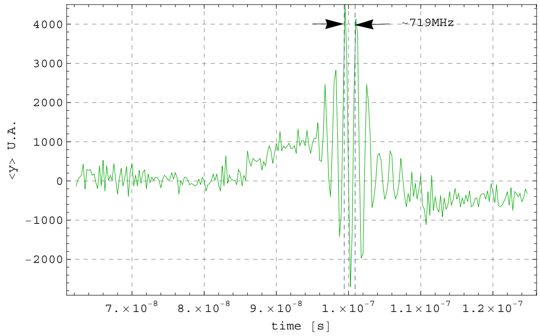


Figure 1: High frequency instability observed on a single turn signal from a vertical beam position monitor.

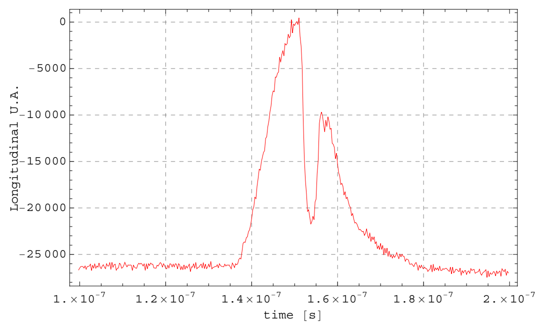


Figure 2: Longitudinal single turn signal from a beam position monitor during the losses due to the vertical instability.

how fast the frequency responsible of the turbulence grows, i.e. by the rise time of the highest peak recognized in the power spectrum in the frequency domain. An example is shown in the Fig. 3. The maximum of the power spectrum for each trace is used to compute the rise time: the amplitude of the oscillation increases exponentially as a function of time. An example of a computed rise time is shown in Fig. 4. The measurements have been repeated for three different longitudinal emittances, 1.50 eV.s, 1.92 eV.s and 2.30 eV.s and for a range in intensities. The results are presented in the Fig. 5, Fig. 6 and Fig. 7.


Figure 3: Power spectrum of a single turn vertical bunch profile obtained by a fast Fourier transform. The longitudinal of the beam was 2.3 eV.s and the intensity about $165 \cdot 10^{10}$ protons.

Three regimes are observed. Below the intensity threshold, the rise time is infinite. Close to the instability threshold, the regime is non-linear and the measurements can be fitted with $\frac{a}{t^2}$ or $\frac{a}{t^3}$ or eventually with $a \cdot e^{-c/t} + b$. At intensities much higher than the threshold, the measurements are in a linear regime and even at saturation for the set at 1.50 eV.s. In the Fig. 8, we observe that the threshold in intensity of the instability versus the longitudinal emittance can be fitted linearly.

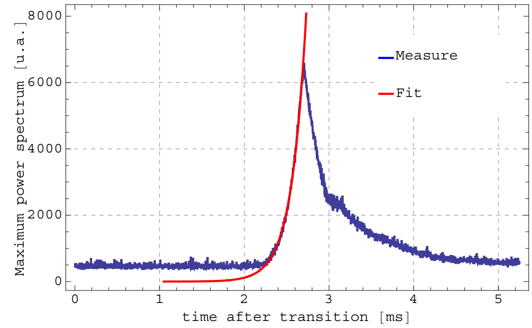


Figure 4: Maximum power of the mode responsible of the vertical instability for a beam with $165 \cdot 10^{10}$ protons and a longitudinal emittance of 2.30 eV.s. The blue curve is the mesured data and the red one is the fit of the rise time which is about 0.173 ms or 82 turns after transition.

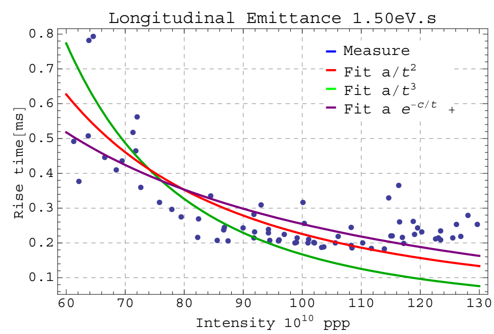


Figure 5: Rise time in ms as a function of the beam intensity for a longitudinal emittance of 1.50 eV.s. The threshold in intensity is around $60 \cdot 10^{10}$ protons.

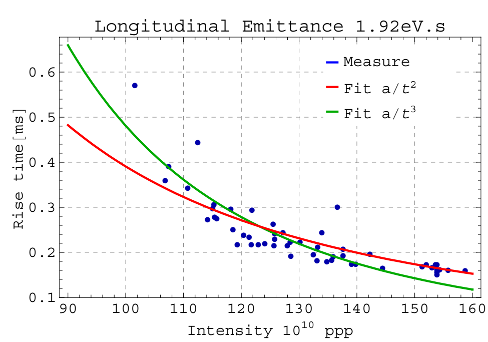


Figure 6: Rise time in ms as a function of the beam intensity for a longitudinal emittance of 1.92 eV.s. The threshold in intensity is around $100 \cdot 10^{10}$ protons.

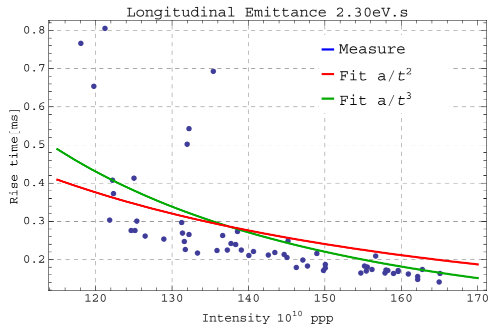


Figure 7: Rise time in ms as a function of the beam intensity for a longitudinal emittance of 2.30 eV.s. The threshold in intensity is around $120 \cdot 10^{10}$ protons.

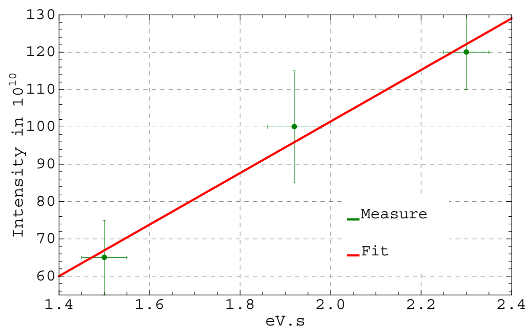


Figure 8: Measured instability thresholds in intensity as a function of the measured longitudinal emittance fitted with a linear function.

## FIRST COMPARISON WITH HEADTAIL

HEADTAIL simulations are used to benchmark the measured rise time. A broad band impedance model has been set [1] in the simulation with a resonator frequency $f_r = 1$ GHz, a quality factor $Q = 1$ and a transverse vertical shunt resistance of $R_y$ =3 M$\Omega$/m. The chromaticities were set to zero. A fast Fourier transform is applied to the simulated profiles in order to take the maximum of the power mode as a function of time. The intensity is about $100 \cdot 10^{10}$ protons and the longitudinal emittance is 2 eV.s. According to the Fig. 9, the rise time computed by simulation of 0.1 ms is faster than the measured one 0.6 ms at the same intensity for a measured longitudinal emittance between 1.9 and 2 eV.s. The measurements of this latter could vary by 0.1 eV.s maximum shot to shot. The threshold of the vertical instability of the HEADTAIL model is about $70 \cdot 10^{10}$ protons whereas the measured one is around $100 \cdot 10^{10}$ protons. The impedance model has to be improved in HEADTAIL to benchmark the measurements by decreasing the vertical shunt resistance. The other difference with the measurements is the time at which the instability appears, which is a few hundred turns before transition in HEADTAIL whereas 2 ms after transition in the measurements. In the theory, this should depend of the absolute value of $|\eta|$ [5]. This difference could be due to the way how the chromaticies are set in the machine. Since it is not possible to measure precisely their evolution around transition, a simulation campaign is planned to test different chromaticities model in HEADTAIL.

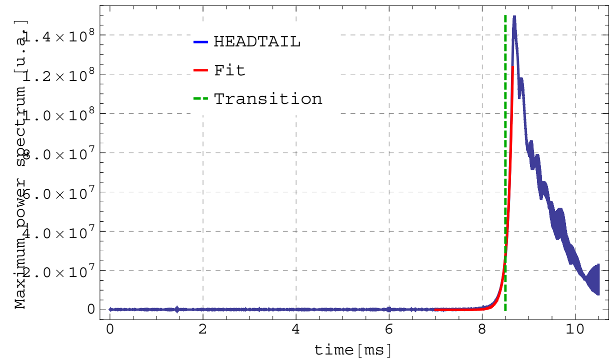


Figure 9: HEADTAIL maximum power mode with $100 \cdot 10^{10}$ protons and a longitudinal emittance of 2 eV.s. The blue curve is the HEADTAIL data and the red one is the exponential fit of the rise time which is about 0.10 ms or 55 turns.

## CONCLUSIONS

The rise time of the vertical instability near transition has been measured for different intensities and longitudinal emittances and three regimes have been qualitatively identified. However the HEADTAIL simulations done so far do not match with experimental results. Future works are planned to test different chromaticities model in the simulation and to finish the matching of the impedance models. In parallel the same measurements with the $\gamma_{\rm tr}$ jump are scheduled to understand its influence on the instability and improve it for a possible PS upgrade.

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