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

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Abstract

Crossing transition energy in the CERN PS is critical for the stability of high intensity beams, even with the use of a second order gamma transition jump scheme. The intense single bunch beam used for the neutron Time-of-Flight facility (n-ToF) needs a controlled longitudinal emittance blow-up at the flat bottom to prevent a fast single-bunch vertical instability from developing near transition. This instability is believed to be of the Transverse Mode Coupling (TMCI) type. A series of measurements performed in 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 will allow predicting the stability of the high brightness LHC beam near transition. The final goal is to study the feasability of a possible cure to the fast vertical instability measured on the ToF beam by applying an improved gamma transition jump scheme instead of compromising the longitudinal density.

INTRODUCTION

The CERN Proton Synchrotron uses a second order gamma transition (γ_t) jump scheme to cross the transition energy. This optics was implemented in the past to cure the "negative mass instability" [1] and the effect of the longitudinal space charge in high intensity beams [2]. However even with the use of the gamma jump, fast losses can be observed near transition with a high intensity single bunch beam of $700 \cdot 10^{10}$ protons if the longitudinal emittance is not sufficiently large. This effect is believed to a Transverse Mode Coupling Instability (TMCI). Increasing the longitudinal emittance (1 σ) from 2 eVs to 2.3 eVs is sufficient to prevent the instability to develop. A series of measurement have been performed on an intense beam with and without the gamma jump scheme in order to determine the behavior of the instability and attempt to benchmark the HEADTAIL code. We use those results as tool to estimate the transverse impedance. In the future, the results of this study could be used to predict the transverse stability of the ultimate LHC beam in the framework of the possible PS injection energy upgrade.

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CROSSING TRANSITION IN THE CERN PS

Transition crossing might produce unfavourable effects. Some of them can be cured by a second order γ_t-jump. This remedy was adapted in the 70's to avoid the negative mass instability which was a severe intensity limitation [1]. The method consists of crossing transition energy much faster than it would be without any special precaution. Then the instabilities for which the rise time is slower than the time spent by the beam close to the transition energy will not develop. Thanks to the γ_t-jump scheme, the intensity limitation at γ_t energy had been pushed forward during several years.

The γ_t-jump consists of an artifical increase of the transition crossing speed by dedicated fast pulsed quadrupoles placed at non-zero dispersion locations in order to adjust the momentum compaction factor η. This depends on the unperturbed and perturbed dispersion functions at the kick quadrupoles places and the amplitude of the γ_t-jump depends of the intensity. The quadrupoles are grouped in doublets and triplets (combined doublets) with two strenghts $\pm K_1$ and $\pm K_2$ separated by π in betatron phase advance in order to obtain a almost zero tune shift [2]. The present situation provides a large $\Delta\gamma_t = -1.24$ performed in 500 μs as presented Fig. 1. However by doing so the dispersion and betatron functions increase and lead to a large horizontal beam size and non negligible beam loss [3]. Nowadays the γ_t-jump is used routinely. Several other tricks are applied to cross transition energy such as the change of the sign of the chromaticities when $\eta = 0$ in order to avoid head-tail instabilities [4] after transition. Despite of these measures, a fast vertical instability is observed on the high intensity single bunch beam nToF when the longitudinal density is not blown up enough [5].

TRANSVERSE INSTABILITY OBSERVATION WITHOUT γ_T-JUMP

A dedicated single bunch beam has been set up to observe the transverse instability without the γ_t-jump. the beam parameters are presented in the Table 1. In order have favorable conditions to study the transverse instability, the vertical chromaticity ξ_v is set close to zero several millisecondes around transition in such a way to obtain a 'plateau'. The values of the chromaticities cannot be measured precisely around transition due to the frozen synchrotron motion therefore there is a large incertainty of the time at which they change sign. However, no headtail instabilities

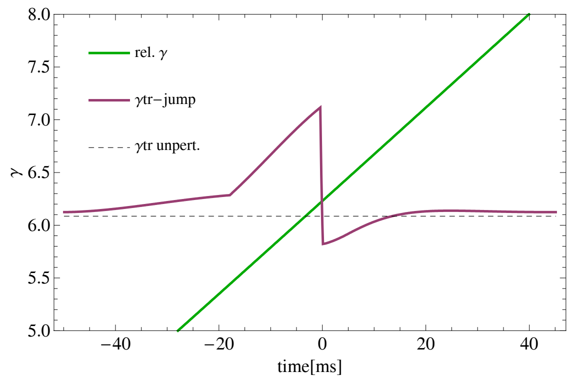

Figure 1: Unperturbed and perturbed γ_t and relativistic γ as a function of time around transition. The transition time occurs at t=0.

Table 1: Beam Parameters for Measurements

Total energy at γ_t	$E \simeq 6.1$ GeV
γ_t	6.08
Transverse tunes	$Q_{x,y} \simeq 6.22$
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 (1σ)	1.50, 1.90, 2.30 eVs
Transverse $\epsilon_{x,y}^{norm}(1\sigma)$	$\epsilon_x = 1.17 - 2.38$ mm.mrad $\epsilon_y = 1.34 - 2.33$ mm.mrad

develop since the synchrotron frequency Q_s=0. The closest measurements of the transition energy are $\xi_v = -0.3$, 7 ms before γ_t energy and $\xi_v = 0.02$, 8 ms above. The theoritical evolution of the vertical chromaticity during the measurements is presented in the Fig. 2.

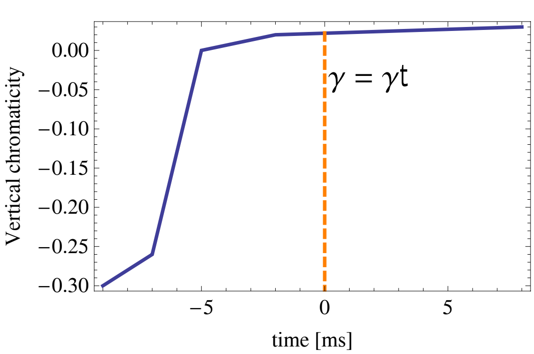

Figure 2: Theoritical vertical chromaticity around transition.

Figure 3(a) shows the vertical instability measured with a wide band pickup [6], that has a band width between 2.5 MHz-1 GHz [7]. Figure 3(b) represents the longitudinal profile of the same bunch. The measured vertical signal shows that the head of the bunch is stable whereas the maximum peak intensity oscillates according to a travelling wave with a high frequency. A Fast Fourier Transform (FFT) analysis of the profile of Fig. 3 gives a frequency of about 700 MHz. The head excites the tail of the bunch due to a high frequency resonator and a short range wake field [5]. 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 synchrotron motion is very slow at transition. The horizontal plane remains stable.

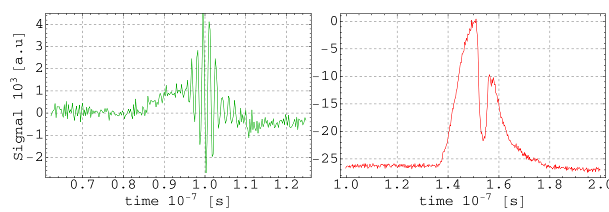

Figure 3: (a) High frequency instability with a travelling wave pattern observed on a single turn signal from a vertical beam position monitor. (b) Longitudinal single turn signal from a beam position monitor during the losses due to the vertical instability.

Instability Rise Time

The measurements consists of taking the vertical bunch profile turn-by-turn through transition. 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 our case, we took 2500 turns in both vertical and longitudinal planes to see the development of the instability. The rise time of the instability is defined here by how fast the frequency responsible of the turbulence grows. An example is shown in the Fig. 9(c). 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 eVs, 1.92 eVs and 2.30 eVs and for a range in intensities. The results are presented in the Fig. 5.

Three regimes are observed. Below the intensity threshold, the rise time is infinite. Close to the instability threshold, the regime is non-linear. At intensities much higher than the threshold, a linear regime appears and even saturation [8]. In the Fig. 6, we observe that the threshold in intensity of the instability versus the longitudinal emittance can be fitted linearly. One can notice that the instability is fast and takes less than one synchrotron period (3 ms) to develop which is a characteristic of the TMCI [16] [9]. A second remark is about the time when the instability appears which is up to 2 ms after transition. However, the TMCI is supposed to start to develop before transition, i.e. as a function of the absolute value of the momentum compaction η. This issue will be discussed later in the paper.

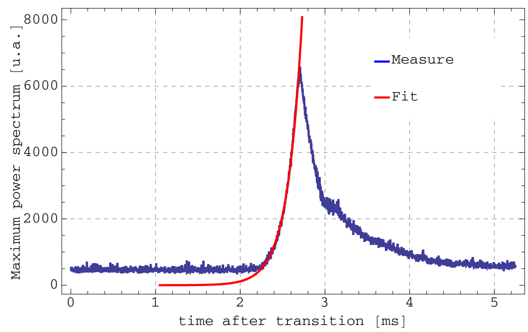

Figure 4: Maximum power of the travelling wave of the vertical instability for a beam with $165 \cdot 10^{10}$ protons and a longitudinal emittance of 2.30 eVs. The blue curve is the mesured data and the red one is the fit of the rise time which is about 0.173 ms or 82 turns.

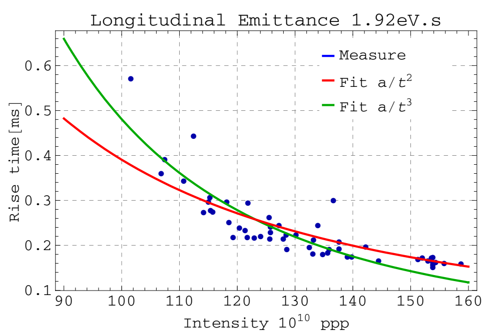

Figure 5: Rise time in ms as a function of the beam intensity for a longitudinal emittance of 1.92 eVs. The threshold in intensity is around $100 \cdot 10^{10}$ protons.

BENCHMARK WITH HEADTAIL

The HEADTAIL [10] code has been used to benchmark the measurements. A broadband resonator impedance is set in the simulation as follow

$$Z_1^{\perp}(\omega) = \frac{\omega_r^{\perp}}{\omega} \frac{R_s}{1 + iQ(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r})} \tag{1}$$

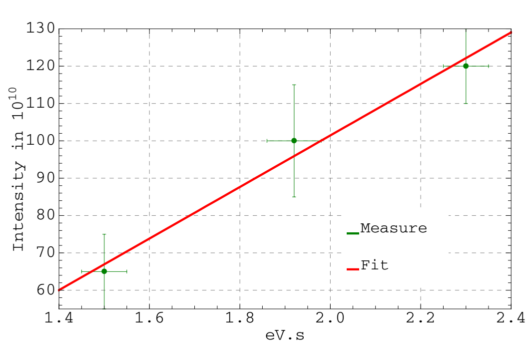

Figure 6: Measured instability thresholds in intensity as a function of the measured longitudinal emittance fitted with a linear function.

Table 2: PS Parameters Used for Simulations

Machine radius R [m]	100
Bdot [T/s]	2.2
RF voltage [kV]	200
RF Harmonic	h=8
Pipe [cmxcm]	7x3.5
Geometry chamber	flat
betatron function [m]	16

with R_s the transverse shunt impedance in Ω/m, $\omega_r^{\perp}$ the resonance frequency in Hz and Q the quality factor. Since the TMCI interacts with imaginary part of the transverse impedance, one has to find the matching parameters (R_s,ω_r,Q) which would fit the measurements. The beam parameters of the Table 1 have been used in the simulations in addition of those presented in the Table 2. The transverse and longitudinal space charge are not included in the simulations and the higher order of momentum compaction factor have been neglected.

Resonator Frequency ω_r

The FFT of each vertical bunch profile allows to identify the frequency of the travelling wave during the instability development. The turn by turn bunch profile in the frequency domain is presented in the Fig. 7(a) and frequencies between 600 MHz and 700 MHz are identified in the measurements with a sampling of about 4 GHz. In the meanwhile, a resonator frequency scan has been performed in HEADTAIL with the impedance model described above in order to match the measurements: the measured frequency in the transverse profile is close to the resonator frequency in the 'Mode Coupling' regime. The bunch has been longitudinaly sliced in 500 parts in HEADTAIL in order to sample the oscillation of the the travelling wave at 20 GHz. The vertical difference signal from a pickup monitor has been simulated with HEADTAIL to be comparable with the measurements. The order of magnitude of the best fit for the resonator frequency ω_r is 1 GHz with Q=1. However the width of the simulated vertical bunch profil in frequency domain is very large: a comparison between the measured travelling wave and simulated one in HEADTAIL is plotted in the Fig. 7(b) and (c).

Transverse Shunt Impedance

The rise time of the tranverse instability is strongly dependent of the chromaticity and of the transverse shunt impedance. A scan in R_s has been performed in HEADTAIL with a broadband impedance model with a resonator frequency ω_r=1 GHz and a quality factor Q=1. The longitudinal emittance matched area is set to 1.9 eVs for a single bunch beam intensity of $120 \cdot 10^{10}$. The vertical chromaticity has been implemented in the code according to the theoritical one shown in the Fig. 2. The horizontal chromaticity is left to zero. In the measurements, the rise time of the

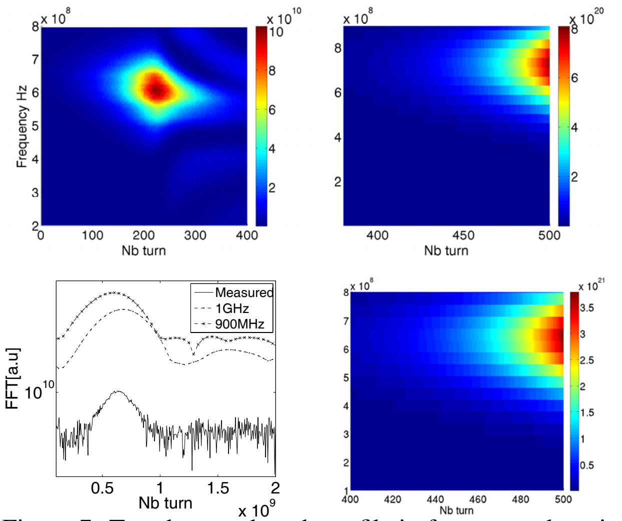

Figure 7: Turn by turn bunch profile in frequency domain. (a) On the left, the frequency of the vertical measured instability is between 600 MHz and 700 MHz. (b) On the right, a simulated broadband resonator with ω_r=1 GHz gives a travelling wave at around 700 MHz.(c) Single turn bunch profile in frequency domain with the peak of the instability for three cases: the measured bunch profile for longitudinal emittance 1σ of 1.92 eVs and 120 10^{10} protons per pulse, the simulated one in HEADTAIL for ω_r=1 GHz, Q=1 and ω_r=900 MHz, Q=1. (d) Simulated broadband resonator with ω_r=900 MHz gives a travelling wave at around 650 MHz.

instability for an beam intensity of about $120 \cdot 10^{10}$ protons and a longitudinal density of 1.9 eVs 1 σ is approximatively 120 turns. The shunt impedance which is matching at best this rise time is 1.4 MΩ/m as presented in the Fig. 8. By doing a scan in beam intensity with this value, we compare the rise time computed by HEADTAIL with the measurements for the same longitudinal emittance. The result of the Fig. 9 shows that the measurements have an offset of approximatively 25 turns with respect to the simulated rise times in the same conditions which is a good agreement. This result indicates that the order of magnitude of ω_r and R_s used in the broadband impedance model set in HEADTAIL agrees with the experimental data.

TRANSVERSE INSTABILITY WITH THE γ_T-JUMP

Similar measurements with the γ-jump are ongoing in order to understand the effect of the optics distorsion on the transverse instability. The setting up of the beam appears easier since the time when $\gamma = \gamma_{tr}$ is imposed by the γ_t-jump timing, i.e. when the currents of the doublet of quadrupoles are inversed [3]. The 'plateau' in vertical chromaticity has been kept in such way that the transition time is standing in the last part of the plateau where the vertical chromaticity is very small and slightly positive ($\xi_v \simeq 0.02$). An example of travelling wave frequency

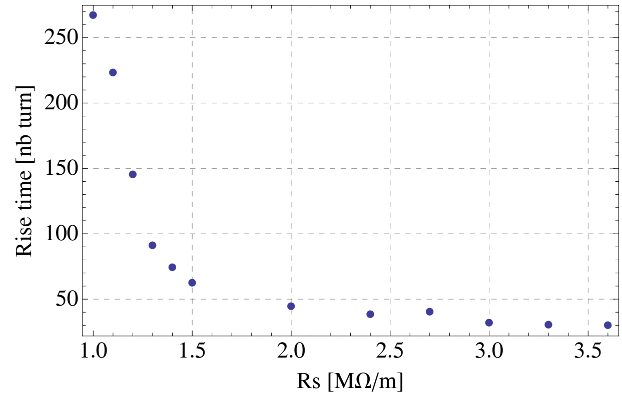

Figure 8: Rise time of the transverse instability in number of turn as a function of the transverse shunt impedance for a broadband impedance model in HEADTAIL of ω_r=1 GHz and Q=1.

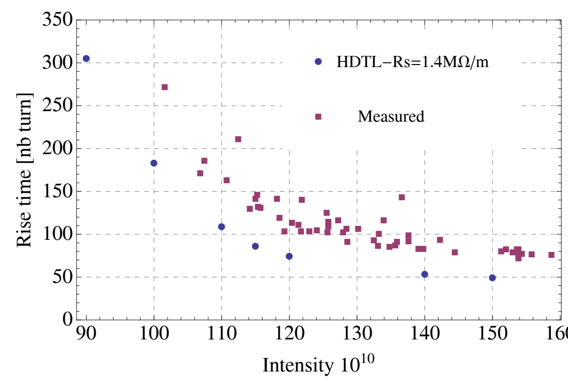

Figure 9: Instability rise time as a function of the intensity of the beam compared to the measurements. The broadband impedance model in HEADTAIL is ω_r=1 GHz and Q=1.

measurement of the instability is presented Fig 10. A similar spectrum frequency as Fig. 7 is found with the γ_t-jump. However at the opposite of the case without the optics distorsion, the instability appears before transition.

DISCUSSIONS

Tune shift measurements at injection were done in 1989 and it was established that the transverse impedance of the PS was Rs=3 MΩ/m [12]. This value was including the dipolar and the quadrupolar component of the impedance [11]. In our HEADTAIL simulations, only the dipolar part is computed because the better impedance model of the PS is not known. Coherent tune shift measurements have to be performed again.

The major difference in the measurements between the cases with and without γ_t-jump is the time of the apparition of the transverse instability. We remind that without the optics distorsion, the instability is delay by up to 2 ms. This difference is not really understood, however several explanations can be pointed out. Without the γ_t-jump, the adia-

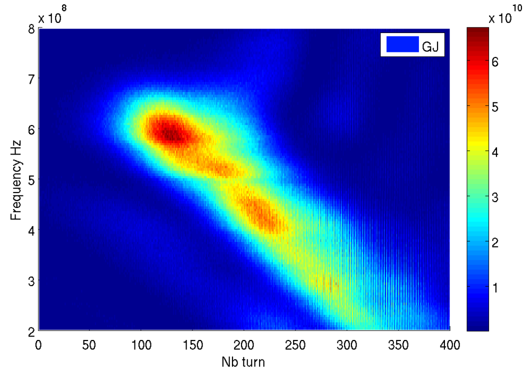

Figure 10: Turn by turn bunch profile in frequency domain with γ_t-jump, with an intensity of $430 \cdot 10^{10}$ and a longitudinal emittance of 1.8eVs 1σ. The frequency of the vertical measured instability is between 600 MHz and 700 MHz.

batic zone is crossed slowly with $\dot{\gamma} = 49.9\ s^{-1}$ whereas $\dot{\gamma}_{gj} = 50\dot{\gamma}$. Refering to the paragraph about crossing transition in the PS, one can understand that the transition time with γ_t-jump is well defined, triggered by the doublets inversion [13], whereas without the jump process this time is determined by the unperturbed γ_t of the machine. Therefore many cares are needed to tune the transition time which can different by several millisecond from the case with γ_t-jump. In order to keep the longitudinal focusing above transition energy, the stable phase of the RF cavities has to be performed from ϕ_s to $-\phi_s$. A scan in timing of RF cavity phase jump allows to observe the time which minimizes dipolar and quadrupolar bunch length (σ_z) oscillations. We complet this method by observing the minimum σ_z thanks to a peak detected pickup. The signal is maximum when σ_z is very short, i.e. at transition. In the PS, this adjustement has to be done at low intensity to avoid bunch length mismatch due to the longitudinal space charge [14]. Experiments show that 1 ms can be admitted as incertainty on the transition time in the case of a beam without optics distorsion. However, another 1 ms delay is left in our measurements. The chromaticity in the plateau might be too small to dump the instability. In order provide a delay up to 2 ms, the HEADTAIL code shows the vertical chromaticity has to follow a step function:

$$\begin{aligned} \xi_v &= -1 \quad if \quad \gamma < \gamma_t \\ \xi_v &= 0 \quad if \quad \gamma \geq \gamma_t \end{aligned}$$

According to Fig. 2 and the rise time (2 ms) of the power supply which control the working point [15], this is technologically impossible. Obviously measurements and simulations with γ_t-jump will likely provide us more informations which would help to understand this delay. Finally, other effects have to be kept in mind. The simulations do not take into account higher order of momentum compaction factor and the transverse space charge. Futher investigations are needed to undertand the impact of a spread in γ_t due to the Umstatter effect [16].

CONCLUSIONS - OUTLOOKS

A fast head-tail instability is observed at transition in the high intensity single bunch beam toF. Rise time measurements of the verticale instability have been used to estimate the transverse impedance. This value is about the same order as deduced in the past [12] from coherent tune shift measurements as a function of the intensity. The next step will consist of improving the impedance model in particulary distinguish the dipolar and the quadrupolar component. Another outlook is to implement the γ_t-jump in HEADTAIL in order to benchmark the measurements done with the optics distorsion.

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