EXPERIMENTAL AND THEORETICAL STUDIES OF TRANSVERSE SINGLE BUNCH INSTABILITIES AT THE ESRF

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Abstract

At the ESRF, the transverse instability threshold which limits the maximum intensity per bunch is pushed by increasing the vertical chromaticity to large positive values. To overcome the induced reduction in lifetime, a feedback has been developed, but it has turned out less effective than the chromaticity overcompensation. With the increased impedance resulting from the installation of low gap vacuum chambers, the accumulation of high single bunch current becomes increasingly difficult. To understand the underlying physics and thereby to explore better settings, the transverse single bunch effects are being thoroughly investigated experimentally as a function of the parameters involved such as chromaticity, beam current, bunch length. In parallel, an attempt is made to give a comprehensive theoretical description of the transverse single bunch instabilities observed at the ESRF is attempted with the development of a multiparticle tracking code. In both approaches, the influence of the chromaticity on the merging of the head-tail modes and the impact of the beam spectrum shift with chromaticity and bunch lengthening are studied. The performance of the feedback for different settings of the machine is also evaluated.

1 INTRODUCTION

At the ESRF, **single bunch** and associated modes (16 Bunch, 32 Bunch, Hybrid,..) represent about 30% of the machine operating time. The high **peak brilliance** requested by the users has always to be weighed against the associated moderate **lifetime**.

The threshold of **transverse instabilities** which limit the maximum intensity per bunch is increased by pushing the vertical chromaticity to large positive values. The induced reduction of transverse acceptance and tune spread leads to injection saturation and lifetime reduction.

For tuning and improving the performances of the machine in single bunch, a study based on experiment and simulation has been initiated [1].

2 EXPERIMENTAL OBSERVATIONS

Machine parameters for single bunch experiments:

- Vert. and hor. chromaticities $\xi = \frac{\Delta\upsilon / \upsilon}{\Delta p / p}$
- Vert. and hor. tune
- Bunch length (RF voltage from 6 to 12 MV)
- Optics (beta functions and dispersion)
- Resonance corrections
- Single bunch feedback

Diagnostics and data recording:

- Sweeping tune monitor (the high sensitivity of the detection allows a precise recording, even at very low current in single bunch).
- Transverse profile monitor using pin hole camera.
- Streak camera

2.1 Zero vertical chromaticity

At zero chromaticity, according to theory, we could observe the coupling of mode 0 and -1 (Fig. 1).

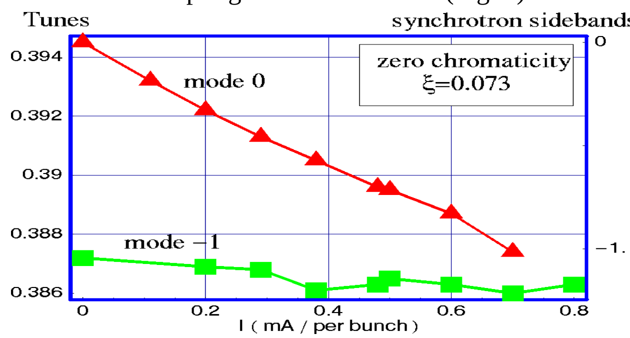

Figure 1: Observation of mode coupling

2.2 Low vertical chromaticity

At low chromaticity, the two or three instability thresholds could be explained by a weak coupling and de-coupling of higher order modes or by head-tail instability of mode -1,-2 or -3 (Fig 2).

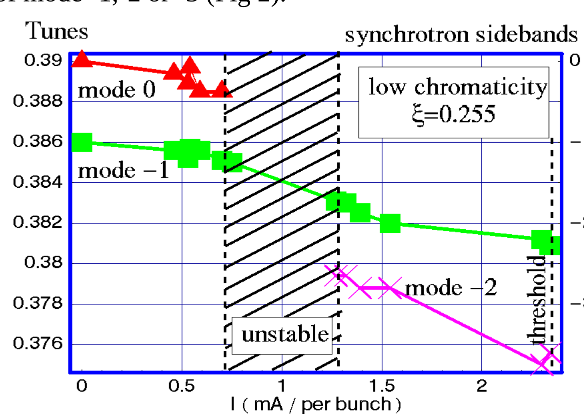

Figure 2: Observation of double threshold

2.3 High vertical chromaticity

At high ξ, the strong detuning of the main peak of the tune spectrum covers a large number of synchrotron satellites with no sign of mode coupling (Fig. 3). At a given ξ, the large variation of the bunch length as a function of the current (factor 2.5 between 0 and 15 mA) contributes to the shift of the peak observed in the low frequency range [2]. The instability threshold is given by the head-tail mechanism of high order modes.

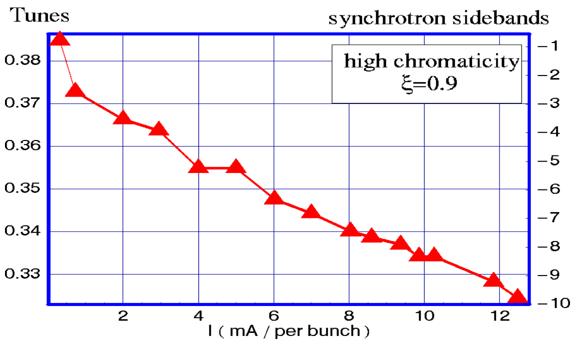

Figure 3: High chromaticity regime

2.4 Intensity threshold

The simulation predicts a strong dependency of the instability threshold on a chromaticity larger than 0.5 which was checked for different bunch lengths (Fig. 4). At very high value, the maximum current is limited by the saturation of the injection possibly induced by the reduction of the transverse acceptance. The current instability threshold is determined by the blow-up of the vertical transverse profile and the spontaneous signal on the tune monitor.

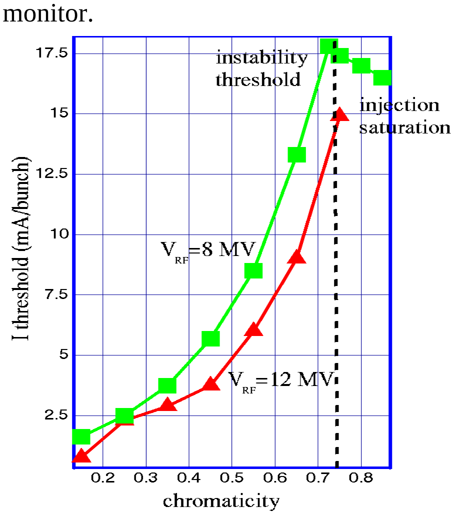

Figure 4: Intensity threshold

This curve had a direct implication for operation. The minimisation of the RF voltage and chromaticity for 15 mA resulted in a consequent increase of the lifetime.

2.5 Feedback

The performance of the transverse single bunch feedback [3], developed for the ESRF declined as the chromaticity increased for the delivery of single bunch at high current. The gain of 3 obtained at low chromaticity was reduced to almost zero at the increased chromaticity needed to reach more than 15 mA. The feedback, which acts on the low frequency transverse signal, will therefore be simulated and tested for the different regimes.

3 THEORETICAL STUDY

The understanding of the complicated mechanism governing the high current regime, including the important role of the chromaticity is the primary objective. The modelling of the impedance therefore becomes the key issue. We have firstly focused on the low current and low chromaticity regime, namely the mode merging regime, since it is well understood by the existing theory. The mode merging instability has been clearly observed at the ESRF as well, while at higher currents the head tail instability seems to dominate. Besides the analytical approaches, we have developed simulation tools in both the frequency and time domains.

3.1 Developed Tools

The Vlasov-Sacherer formalism in the **frequency domain** is followed [4,5], by using the code MOSES that works with an extended Sacherer’s theory to the mode merging [6]. A modified version using Mathematica has been created in order to work with any kind of impedance and not only the original BBR (Broad Band Resonator). As anticipated, this approach is very efficient and fast to compute detuning curves at low chromaticity when the modes are still close to the zero-current Hermitic base and only a few of them participate. However, beyond the mode-merging regime, it is found that the results strongly depend on the matrix size, affecting also the computation time. This illustrates the fact that at high chromaticity, the instability mechanism involves the interaction of many zero-current modes.

We have also developed a **time domain tracking code** [7]. The impedance effect is averaged over one turn, and represented by a single kick for the turn by turn computation of the particle distribution. The quantities of interest, such as the detuning curves, are derived from the transverse signal recorded at each turn. The spectrum of the different modes is extracted from the computation with a precision smaller than f_s (Fig. 5).

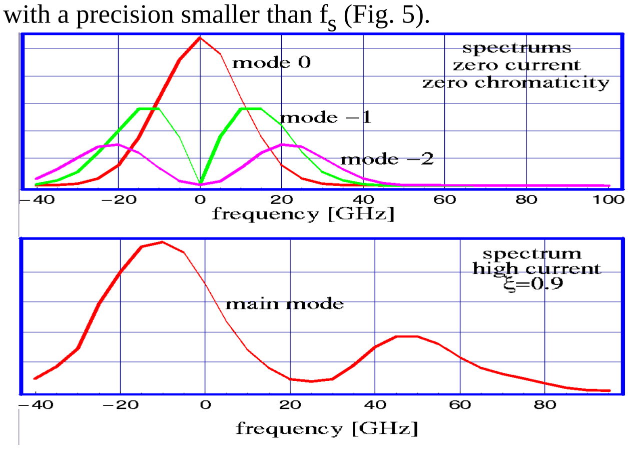

Figure 5: Mode Spectra

At low chromaticity, tracking results show a perfect agreement with the Moses method. However at high chromaticity, the tracking is more efficient since different modes do not need to be treated explicitly.

3.2 Impedance model

The ESRF storage ring vacuum chambers may be grouped into two classes: the first one is the low gap insertion chambers. It corresponds to the **resistive wall** type impedance, which is preponderant at low frequency. The rest of the vacuum chamber elements, including tapers, bellow, RF cavities..., is represented by a **BBR impedance** peaked at high frequency. The installation of two new cavities (on top of the four existing) ones did not have a large effect on the transverse instability threshold. This confirms the low contribution of the cavities.

The fit of the observed merging of the two modes 0 and -1 with the BBR model gives

$$f_r=20 \text{ GHz}, R=4.3 \text{ M}\Omega/\text{m}, Q=1.$$

These figures were obtained by using a vertical beta value of 2.7 meters. The influence of the beta function on the instability threshold will be simulated and looked at experimentally. The resistive wall impedance model can equally fit the detuning observed at low chromaticity. However, the estimation using the realistic ESRF low gap chamber configuration explains only a part of the detuning curve observed.

At higher chromaticities, the fit with the BBR model leads to different results depending upon different detuning curves. This discrepancy would indicate that the model is not adequate at high current. The fact that different results are obtained may be the consequence of sampling the impedance effect in different frequency ranges with chromaticity and bunch length.

We may speculate that at a low chromaticity, namely in the low frequency range, the ESRF impedance is resistive wall dominated, while at higher chromaticities, it would be a mixture of the former and of the BBR. The future work will quantify the impedance model along this direction.

3.3 Studies at higher current

As observed, the tracking shows no coupling and no detuning of modes but a negative shift over many synchrotron sidebands of a single large peak (Fig. 3).

The curve (Fig. 6) deduced from the experiments (Fig.4) shows that the spontaneous tune shift at threshold does not depend on the RF voltage. The coherent shift may be interpreted as successive head-tail mode excitations from low to very high orders.

An approximate relation may be obtained from Sacherer's equation for mode 0:

$$(\Delta\upsilon)_{threshold} = \frac{(\tau^{-1})_{damping}}{2\pi f_0} \cdot \frac{\operatorname{Im} Z_\perp(\omega_\xi)}{\operatorname{Re} Z_\perp(\omega_\xi)}$$

It may therefore exclusively represent the impedance characteristics, which could provide complementary information to the damping time measurement.

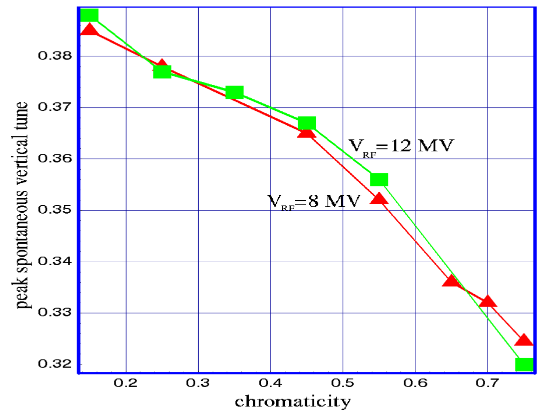

Figure 6: Tune shift at theshold

To explore the real part of the impedance up to high frequencies, the measurement of the damping time has been attempted in the same spirit as the growth rate measurement made at CERN PS. A first set of measurements however indicates a much lower value than the radiation damping time. The discrepancy will be looked at in more detail by taking into account the decoherence induced by the effect due to tune spread.

4 CONCLUSION

The new emphasis put on single bunch transverse motion studies last year had already produced results which are applied to the operation of the machine. After the initial work at low current and low chromaticity, the study is now focused on the high current regime. The unification of the resistive wall model and the broad band resonator for the characterisation of the impedance is under way.

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