TRANSVERSE INSTABILTIES IN THE ESRF STORAGE RING: SIMULATION, EXPERIMENTAL RESULTS AND IMPEDANCE MODELLING

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Abstract

Transverse coherent single bunch motions are studied theoretically and experimentally for the ESRF machine. Starting from the mode-merging instability observed at low chromaticities, the head-tail mode frequencies and current thresholds are measured systematically in the vertical plane as functions of chromaticity, beam current, RF voltage and optics. Measurement of damping and growth rates of the dipolar mode is also attempted as a function of chromaticity to characterise the machine impedance empirically. Theoretical analysis is made in parallel to investigate the dynamics and to fit the model impedance to best reproduce the observations. Two numerical methods are employed: the multi-particle tracking and solution of an extended Sacherer's equation with the program MOSES. It is found that the machine impedance can be well represented by a simple BBR (Broad Band Resonator) impedance, the parameters of which are quasi uniquely be determined from the fit of the mode-merging instability. It is experimentally shown that the low gap vacuum chamber sections contribute largely to the machine impedance. The resultant model is found to describe the observed thresholds at higher chromaticities as well, the dynamics of which is analysed to consist of higher-order head-tail instabilities.

1 INTRODUCTION

Associated with increasing low gap insertion device vacuum chambers in the ring, the encountered reduction of the threshold current of the transverse instabilities has been compensated at the ESRF by the use of large positive chromaticities, which, however, generally induce adverse effects of reducing the dynamic acceptances. To improve the machine performance, theoretical and experimental studies have been initiated [1]. The primary objective of the theoretical studies is to understand the dynamics occurring at high currents. As the dynamics is determined by the way the beam mode spectra interact with the machine impedance, the modelling of the impedance becomes one of the central issues. Numerical tools are employed and developed in both the time domain (multi-particle tracking) and the frequency domain (the program MOSES), in which a BBR (Broad Band Resonator) impedance is taken as the starting point. Experiments are made to survey systematically the coherent transverse motions in **various regimes** to provide inputs for the theoretical analysis, with a particular effort to measure the damping and growth rate of the dipolar mode to empirically **characterise the ESRF storage ring impedance**.

2 MODE-MERGING REGIME

At low chromaticities $|\xi_V| = |(\Delta Q_V/Q_V)/(\Delta p/p)| < 0.2$, in accordance with theory the single bunch stability is largely limited by the merging of 0 and -1 vertical head-tail modes, whose threshold current is measured around 0.8 mA (Fig. 1).

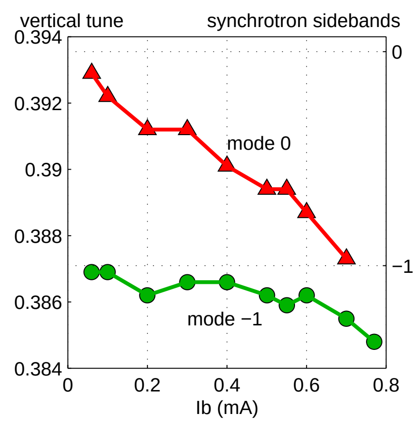
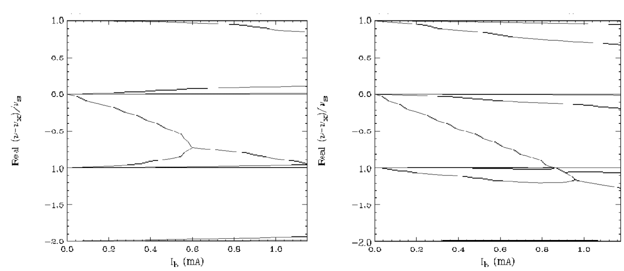


Figure 1: Observed mode-merging instability.



Figures 2: Fit with the BBR parameters. (f_R GHz, R_T MΩ/m, Q) = (5, 8, 1) left and (22, 5, 1) right. β = 2.7 m.

In the model of a Gaussian beam interacting with a BBR impedance, the tracking and MOSES give identical results for the mode coupling (the bunch lengthening included as a function of beam current). Fitting the observed merging with the BBR parameters leads to

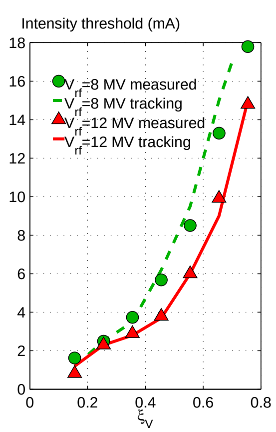
$$f_R = 22 \text{ GHz},\ R_T{\cdot}\beta = 13.5 \text{ M}\Omega \text{ and } Q = 1. \qquad (1)$$

While the resonant frequency f_R is found to influence the merging frequency, the product of the shunt impedance R_T

and the beta function β affects the threshold current. The BBR parameters are thus quasi uniquely determined from the fit. An observation that -1 mode is also slightly defocused requires f_R to be 22 GHz instead of e.g. 5 GHz (Figs. 2). The implication of the fitted BBR impedance shall be discussed further below.

3 DYNAMICS AT HIGHER CHROMATICITIES

With chromaticities slightly above that of the mode-merging, the beam becomes unstable at a certain current and stabilises again as the current is increased, without any merging of the modes. Several of such unstable points may be observed before reaching saturation. The measured coherent tunes indicate that higher-order modes -1, -2, ... are excited one after the other. Instead of mode-merging instabilities among higher-order modes that might be expected to take place, the observations therefore match with the classical picture of the head-tail instabilities [2]: With a shift of chromaticity, modes that overlap with a large real part of the impedance in the negative frequency region are unstable, while those that have passed this region are stabilised by the impedance in the positive frequency region. The fact that both the observations and the analysis indicate less detuning of the modes as the chromaticity is increased, is also in favour of this interpretation, as it results in weaker interactions among themselves.



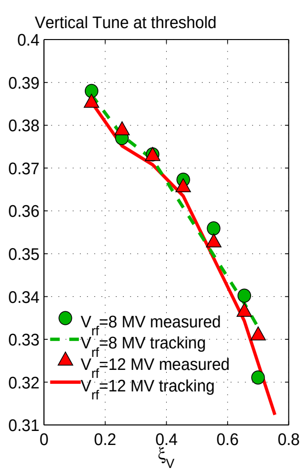


Figure 3: (Left) Measured threshold current versus chromaticity.

Figure 4: (Right) Measured coherent tunes at threshold versus chromaticity. Curves are the theoretical calculation using the BBR impedance of Eq. 1.

To see if the observed trend continues over larger chromaticities, mappings of the current I_{th} and the coherent tune $(Q_V)_{th}$ at threshold versus chromaticity ξ_V, were constructed for two RF voltages V_{RF}'s (Figs. 3 and 4). The expected fast non-linear rise of I_{th} with ξ_V is observed until the stability is limited by optical reasons. A large increase of I_{th} is also noticed as the bunch is lengthened via V_{RF}. Whereas, the relation between $(Q_V)_{th}$ and ξ_V (Fig. 4) exhibits two noteworthy features: i) a large excursion of $(Q_V)_{th}$ across ξ_V that amounts to excitation of head-tail modes higher than $|m|$=10; ii) accordance of the curves of $(Q_V)_{th}$ for two different V_{RF}'s (in contrast to the variation of I_{th}), which is supposed to be non-accidental.

It becomes a key issue to verify if the observed instability thresholds at high chromaticities can be described with the assumption of successive head-tail instabilities using the obtained BBR parameters. As reproduction of I_{th} requires the knowledge of damping forces, we focused on the relation between $(Q_V)_{th}$ and ξ_V. The computations were made in three ways; a semi-analytical, MOSES and tracking. In the first two methods, the mode with the largest growth rate was searched by taking the measured I_{th} for a given ξ_V, and its mode frequency was identified as $(Q_V)_{th}$. Whereas with the tracking, I_{th} and $(Q_V)_{th}$ were fully computed. Although the radiation damping time had to be shortened, it managed to reproduce the entire I_{th} versus ξ_V. In view of the Landau damping that exists in reality, the overall agreement is considered as meaningful. Note that all methods include the bunch lengthening by taking the measured data. All three approaches produced similar results, which agree well with the measured points (Fig. 4).

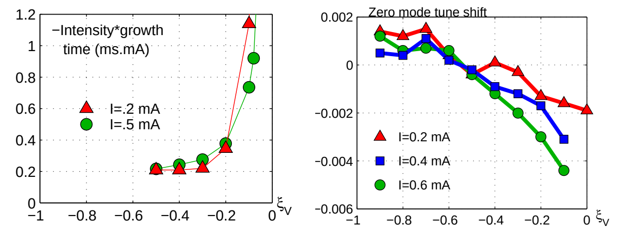
The agreement implies that the unstable modes interact with the negative resistance of the BBR impedance peaked at -22 GHz and not with the resistive wall impedance at low frequencies.

4 IMPEDANCE MODELLING

The fact that no resistive wall impedance is required at low frequencies appears to be contradicting to the continuously limited vertical stability with increasing low gap chambers as well as with the observation of resistive wall instabilities in the multibunch operation. Further studies have been made experimentally and theoretically to assess the obtained model.

4.1 Dipole mode frequency measurement

Attempts were made to measure the damping and growth rates of the dipolar mode versus chromaticity to characterise the real part of the impedance. Details are given in Ref. 3. With $\xi_V > 0$, damping times were measured by fitting the peaks of the chromatically modulated amplitude decaying exponentially in time. Growth rates were measured with $\xi_V < 0$, thanks to the sufficiently large tune spread with amplitude to store beam as well as to the time gated transverse feedback to suppress the initial amplitude. However, the chromatic frequency could only go down to about -15 GHz due to the loss of beam signal. The monotonous decrease of the measured growth time as $|\xi_V|$ is increased is in favour of the high resonant frequency of 22 GHz of the BBR impedance (Fig. 5 left). Furthermore, a preliminary measurement of the dipolar frequency versus negative chromaticities for different beam currents shows convergence of the curves at around the expected position (Fig. 5 right).



Figures 5: Measured growth times (left) and the frequency shifts (right) of the dipolar mode versus negative chromaticity.

4.2 *Effect of low gap chamber sections*

To explore the impact of the low gap vacuum vessels, the measurement of I_{th} versus ξ_V was repeated with an optics that increases the vertical β function by nearly a factor of 4 at every two straight sections without affecting much the rest of the optics (the low gap chambers are installed in the straight sections). The observed drastic reduction of I_{th} by a factor of 2 to even larger values at high currents (Fig. 6) confirms a large contribution of the low gap sections to the impedance.

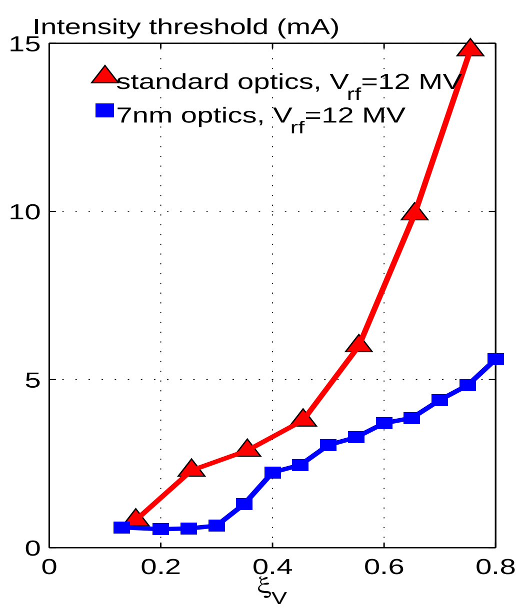


Figure 6: Current threshold I_{th} versus ξ_V measured in an increased β optics as compared to those of the standard optics.

4.3 *Resistive wall effects*

Even though the real part of the resistive wall impedance may not be seen by the beam due to its odd function nature, the same may not be true for the imaginary part. The effect of the resistive wall impedance was investigated in the mode-merging regime where its influence could be relatively important. The impedance of the existing low gap chambers was evaluated with the expression,

$$Z_{\perp R.W.}(\omega) = \frac{2R}{\varepsilon_0 b^3}\cdot\left[\sqrt{\frac{\kappa\omega}{2\varepsilon_0}}(1-j) + j\frac{\omega^2 b}{2c}\right]^{-1} \quad (2)$$

derived by solving the Maxwell equation without the long range approximation (symbols have their usual meanings). Unlike the standard formula, the corresponding wake function converges correctly to zero in the t=0 limit. With these functions, MOSES and tracking computations were made to estimate the dipolar detuning. Taking the beta value at the centre of the low gap vessels, the resistive wall explains at most 10% of the observed detuning.

A systematic evaluation of the various vacuum chamber impedances in the ring is to be made and compared with that empirically obtained. One such study has already been made evaluating the tapers of the low gap chambers in an approximate way with TBCI [4]. The mostly inductive nature found, along with the experimental evidence, leads one to assume that the tapers are largely responsible for the imaginary part of the obtained BBR impedance. The contribution of the resistive wall to the BBR is to be investigated in more detail.

5 CONCLUSION

A simple BBR impedance with the resonant frequency f_R at 22 GHz, the product of the shunt impedance R_T and the beta function β of 13.5 MΩ and Q equal to 1, fitted from the mode-merging instability, appears to give a good overall description of the observed vertical instabilities. The dynamics at high currents is analysed to consist of high order head-tail instabilities extending beyond $|m|$=10. The measured growth times and the detuning of the dipolar mode are basically consistent with f_R > 20 GHz. A large contribution of the low gap chambers to the machine impedance was experimentally demonstrated.

ACKNOWLEDGEMENT

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6 REFERENCES

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