COMPARISON OF TRANSVERSE SINGLE BUNCH INSTABILITIES BETWEEN THE ESRF AND ELETTRA

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Abstract

Transverse single bunch instabilities are measured, analysed and compared between the ESRF and ELETTRA, to obtain a deeper insight, namely how different effects influence coherent transverse motions. Despite the basic similarity of the two machines, being both examples of third generation light sources, it is found that some distinct differences in the relevant parameters such as the energy and optics, as well as the impedance, lead to the appearance of instabilities in a notably different manner. As well as summarising the results of the experiments, modelling of the broadband impedance of the two machines and comparison with expectations are presented.

1 INTRODUCTION

A series of studies, both experimental and theoretical, has been made on transverse single bunch instabilities at the ESRF since 1997 [1]. The primary aim is to improve the operating conditions in the single-bunch as well as in a few-bunch modes, such as the 16-bunch, routinely operated at the ESRF. To combat the growing transverse instabilities associated with continuous evolution of the machine impedance, the magnitude of positive chromaticities empirically set on the machine has been steadily increasing.

Whereas, investigating the transverse single bunch effects on a different machine is an excellent way of assessing the obtained findings. The ELETTRA storage ring in this respect is one of the most interesting, since it stands as another third generation light source, having many similarities with the ESRF machine in terms of the machine structure and components. This is particularly true regarding the presence of low gap chambers for insertion devices, as well as the optics, both linear and nonlinear. One may therefore expect many common features to exist in the physics of single bunch, and yet they may manifest themselves in different ways as many of the involved parameters differ (Table 1), such as the energy, machine circumference, synchrotron frequency, and particularly the machine impedance.

With interest expressed also on Sincrotrone Trieste's part, the two institutes have agreed to carry out a collaboration on this subject [2]. We shall begin from a brief introduction of the transverse characteristics of the ESRF machine [1]. Measurement and analysis made on the mode-merging instabilities in ELETTRA are then presented, followed by discussions on the comparison.

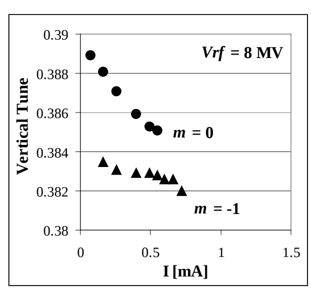
Table 1: Representative parameters of the two machines.

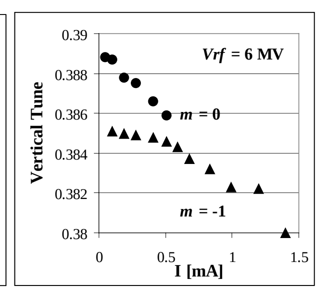
	ESRF	Elettra
Energy [GeV]	6.0	1.0[1]
Circumference [m]	844.4	259.2
RF frequency {MHz]	352.2	499.654
Nominal RF voltage [MV]	9.0	1.76
Momentum compaction	1.86×10^{-4}	1.58×10^{-3}
Synchrotron tune	6.0×10^{-3}	13.5×10^{-3}
Horizontal emittance [nm·rad]	3.7	2.0
Nominal chromaticity[2] H/V	7.6/12.9	0/0
Damping time H/V/L [ms]	7/7/3.5	82/108/64

[1]Injection energy used for the experiment described.
[2]Defined as $\xi = \Delta Q/(\Delta p/p)$.

2 OBSERVATIONS AT THE ESRF

Transverse single bunch effects at the ESRF are present predominantly in the vertical plane.





Figures 1: Detuning of head-tail mode 0 and –1 measured in the mode-merging regime, for two different RF voltages (a) 6 MV and (b) 8 MV.

The transverse mode-coupling instability (TMCI) between mode 0 and –1 sets a severe current limitation at nearly zero chromaticity (Figs. 1). A fit of the mode detuning as well as the threshold in frequency-current plane fixes the parameters of the BBR (Broad-Band Resonator) impedance A shunt impedance of R_T = 6.5 MΩ/m and a resonant frequency of f_r = 22 GHz are derived assuming a quality factor Q of 1. It should be stressed here that the fact that mode –1 is defocused, on top of mode 0, (Figs.1) is mainly responsible for f_r becoming as high as 22 GHz.

Shift of the chromaticity to positive values avoids hitting the TMCI and increases the current threshold nonlinearly (Fig. 2). At the ESRF, the 15 mA single bunch current routinely served to the users is then nearly 20 times higher than that of the TMCI threshold. Such a gain is far above what the transverse feedback provides.

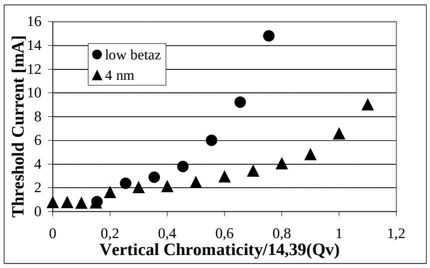
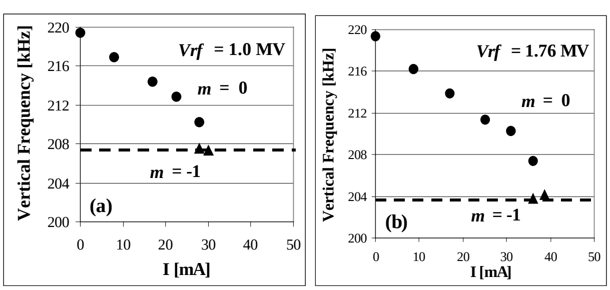


Figure 2: Vertical threshold current versus chromaticity, measured for two different optics.

Studies at the ESRF focused on clarifying the instability mechanism as well as the reason for the reduced feedback efficiency at high currents. It was found that the tracking calculation consistently reproduces the observed threshold curves (Fig. 2) with the above BBR parameters, but with a damping time of 0.2 ms, which is much shorter than that of the radiation, even shorter than the synchrotron period (Table 1). The fact led to introduce a mechanism named as *the post head-tail instability* to explain the observed fast blowups (Details are described in Ref. 3). Comparison of the measured threshold currents versus chromaticity for two different optics (Fig. 2), whose vertical beta function differs mostly over the low gap sections, confirms that the impedance in the respective sections has a large impact on the instability.

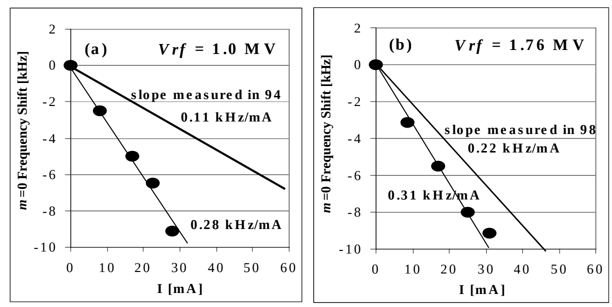
3 OBSERVATIONS IN ELETTRA

In the joint experiment performed on Elettra (July 1999), the detuning of mode 0 was firstly followed by increasing the single bunch current, for several different RF voltages. In contrast to observations in commissioning times in which the single bunch current could be raised above 60 mA without any signature of instability, the current ramping was limited by TMCIs in the vertical plane (Figs. 3).



Figures 3: Detuning of head-tail mode 0 and –1 measured in the mode-merging regime, for two different RF voltages (a) 1 MV and (b) 1.76 MV, in Elettra.

The mode –1 frequency remains unchanged up to the mode merging, in contrast to the defocusing observed at the ESRF. The threshold current reduction with decreasing RF voltage, taking only account of the smaller mode frequency separation, agrees well with the observations. This qualitative difference found for mode –1 implies a lower f_r for Elettra than the ESRF. A fit of the data gives R_T =0.23 MΩ/m and f_r = 5 GHz with Q=1 (*Note that the fitted R_T is also considerably lower than that of the ESRF*). Thanks to the data taken earlier, a clear correlation can be seen in Elettra between the increase of the slope of mode 0 detuning and the number of low gap chambers installed in the ring (Figs. 4), consequently explaining the appearance of TMCIs.



Figures 4: Evolution of mode 0 detuning with installation of low gap chambers, as seen by comparing the present measurement to previous data [4].

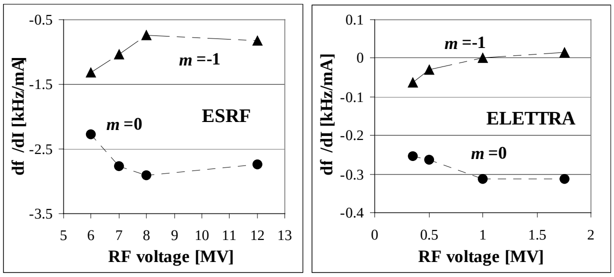
Thresholds were also explored with positive chromaticities. At V_{rf}=0.35 MV and ξ=0.77, the mode –1 threshold came out lower (18 mA) than that of the TMCI (22 mA). At V_{rf}=1.0 MV and ξ=4, modes –1 and –2 successively became unstable ending at 5 mA higher than the TMCI threshold (30 mA). At a higher value of ξ=7.8, no instability appeared until injection saturated at 30 mA. No clear signature of the post head-tail instability was observed.

4 DISCUSSIONS

The measured slopes of mode 0 and -1 detuning are fitted and plotted against V_{rf}'s in Figs. 5, leading to the following observations: 1) m=-1 is much more defocused at the ESRF than Elettra. 2) At the highest voltage in Elettra (i.e. the widest bunch spectra), m=-1 is even slightly focused. 3) The detuning of mode 0 is much larger for the ESRF than for Elettra (factor 9), but with the same trend. All above are in favour of a much lower f_r for Elettra than the ESRF. The second observation, in particular, may be due to m=-1 seeing a capacitive impedance. The analytical expression for mode 0 detuning is given by

$$\frac{df_\beta}{dI} = -\frac{1}{4\pi}\cdot\frac{\beta c}{\sigma_l E/e}\cdot \mathrm{Im}[Z_T]_{eff} \qquad (1)$$

The larger variation of mode 0 at lower low voltage for the is supposed due to a more influential bunch lengthening with decreasing V_{rf} for the ESRF, while for Elettra an improved overlapping of m=0 spectrum with the inductive impedance compensates the former effect.



Figures 5: Measured detuning of modes 0 and -1 versus RF voltage, for the ESRF (left) and ELETTRA (right).

The significance of spectral overlapping with the impedance can be furthermore seen as follows. With the ratio of ~9 found on df_β/dI of mode 0 (Figs. 5), it amounts to the ratio of ~120 on $Im\{Z_T\}_{eff}$ between the two machines, which is much larger than the ratio of 30 on R_T itself. Computing the reduction factor of $Im\{Z_T\}_{eff}$ to R_T for a Gaussian bunch, while 0.95 is found for the ESRF, it is much smaller for Elettra, as shown in Fig. 6 against f_r. The ratio of 120 corresponds to the reduction factor of 0.22 for Elettra, which occurs around 10 GHz in the shown plot. Thus, the smaller impedance for Elettra is effectively reduced further due to its lower f_r.

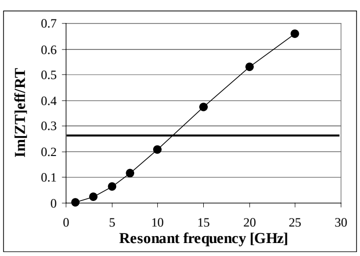


Figure 6: Ratio of effective impedance to shunt impedance, against f_r, computed for ELETTRA at zero current bunch length.Note that the reduction factor is ~0.5 even at 22 GHz for Elettra due to its shorter bunch length at 1 GeV, (factor of 2).

The threshold current I_{th}, on the other hand, is determined both by the slope df_β/dI and the mode separation f_s, i.e. $I_{th} \sim f_s/(df_\beta/dI)$, or in terms of charge, $Q_{th} \sim Q_s/(df_\beta/dI)$, where Q_s is the synchrotron tune. In the previous case where the ratio of df_β/dI is ~9, the ratio of Q_{th} is enhanced to ~15, which is due to nearly a factor of 2 smaller Q_s for the ESRF (Table 1). This difference in Q_s comes mainly from a 10 times smaller momentum compaction for the respective machine. That is to say, the effort made on the optics to lower the horizontal emittance for the ESRF (less than 4 nm·rad at 6 GeV) is detrimental to the threshold, besides the larger impedance of the machine.

To interpret the difference of impedances, a comparison is made on the low gap chambers of the two machines (Table 2). As expected, we see that in number, gap dimension as well as taper angle, the situation is more stringent for the ESRF. To be reminded that the inductance of a taper scales as angle^2×length according to analytical formula. Also, the resistive impedance of a low gap chamber, especially those of stainless steel, gives a significant effect on the single bunch, as found from the studies made at the ESRF [5].

Table 2: Low gap chambers at the times of the experiments. No: Number of elements. Gap: Minimal internal aperture in mm. Taper: angle^2×length in rad^2·mm. Mat: Chamber material

ESRF[1]				ELETTRA			
No	Gap	Taper	Mat	No	Gap	Taper	Mat
16	11.0	1.15	S.S.	1	14.8	1.41	S.S.
2	8.0	1.70	S.S.	1	14.0	1.43	Al

5 CONCLUSION

Observations of transverse single bunch effects in the ESRF and Elettra both indicate that the low-gap chamber sections are the main source of the transverse impedance. The same trend has been reported also elsewhere. The appearance of instabilities was found, however, to alter both qualitatively and quantitatively due to the difference in 1) energy, 2) optics and particularly 3) the impedance characteristics of the two machines. Apart from the energy, the latter two turned out to make the transverse single bunch effects much more relaxed for Elettra. Such comparison would be worth extending to other machines to deepen insight into physics as well as to have an improved scheme for single bunch operation and for the design of a future machine.

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