TRANSVERSE HEAD-TAIL MODES ELIMINATION WITH NEGATIVE CHROMATICITY AND THE TRANSVERSE MULTI-BUNCH FEEDBACK SYSTEM AT ELETTRA

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Abstract

The rigid dipole head-tail mode shift at Elettra is by now quite large and increasing the chromaticity does not bring a much overall advantage in the machine performance. Using the transverse multi-bunch feedback [1] a small improvement has been observed but only until the onset of the transverse mode coupling, since higher modes being bunch shape modes cannot be detected and therefore suppressed by the feedback system. This situation changes with negative chromaticity. In this case the rigid mode is unstable but a feedback system could in principle stabilize it, while the higher modes should be stable. In this paper this hypothesis is investigated and experimental measurements are analyzed and discussed.

INTRODUCTION

A severe limitation to the single bunch current in the 3rd generation synchrotron light sources like Elettra comes from the transverse mode coupling. This is due to the fact that these machines have usually high transverse impedance whose main contribution comes from the resistive wall that can be very large if many narrow gap vacuum chambers are installed. Thus the transverse impedance of Elettra now is 13 times higher [2] than it was during commissioning [3] because since then many low gap straight section vacuum chambers have been replacing the original ones.

As is known, short-range transverse wake fields excited by particles at the head of the bunch may excite oscillations at its tail. Due to the synchrotron motion these oscillations will grow if they add in phase due to the finite chromaticity ξ = dq/q/dp/p, where dq is the tune change and dp/p the relative momentum spread; the beam spectrum will give spectrum frequencies $(p+q)\omega_0 \pm m\omega_s$ centered at $\omega_\xi = q\omega_0\xi/\alpha$ where ω_0 is the revolution frequency, ω_s the synchrotron frequency, α the momentum compaction and m is the bunch shape mode.

The lowest mode m=0 (rigid dipole mode) is stable for positive chromaticity and the beam particles oscillate in phase at the betatron frequency. For m>0 the beam particles oscillate at the synchrotron sideband frequencies and the modes are unstable for positive chromaticity and stable for negative one, this being impedance source dependent.

Even though the m=0 mode is stable for positive chromaticity, its betatron frequency shift with current eventually gets coupled to the next (m=-1) mode resulting to violent energy exchange the so called fast head tail instability. This will roughly happen when the m=0 tune shift equals the distance of the two modes. A question that naturally arises is whether a bunch-by-bunch transverse feedback system can be used to counter fight this instability. For positive chromaticity no modes can be detected without excitation including the m=0 (since it is stable), thus for positive chromaticity a feedback is not really effective. On the other hand for negative chromaticity and an impedance source mainly due to resistive wall the m>0 modes are stable and a feedback could in principle be used to suppress the unstable m=0 mode. At the same time using the feedback, rise times can be easily measured and comparison with theory can be made.

Throughout these tests the zero current tunes were set to q_x=0.285 and q_y=0.185 and the machine energy set to 900 MeV with synchrotron tune q_s (=ω_s/ω_0) =0.014 (thus the m=-1 tune is at 0.171).

THRESHOLDS

Single bunch currents of up to 10 mA were achieved with a small positive chromaticity before the onset of the strong mode coupling whose threshold can be approximately predicted [3] by:

$$\frac{q_y}{I} = -\frac{R\beta_y}{2\pi\sigma E/e} Im(Z_T^{eff}) \tag{1}$$

The threshold should in principle increase with chromaticity mostly due to Landau damping but a noticeable increase has never been observed at Elettra. Tune shift measurements with current [2] indicate that $\Delta q_y/\Delta I$ is ~1.3×10^{-3}/mA thus for a tune shift of 0.014 (distance between m=0 and m=-1) roughly 10 mA can be stored before strong mode coupling occurs.

With accumulated current the feedback detector did not reveal any modes and the injection kickers had to shake the beam. Figure 1 shows the approaching of modes m=0 and m=-1 with feedback off, kickers on and $\xi \geq 0$. All figures in this section are the FFT of the single bunch transverse position. No effects in the horizontal plane were seen.

In figure 2 a similar picture is shown with kickers on and feedback on. No net improvement is observed; just marginally the maximum current reached is 11 mA instead of the 10 mA with the feedback off. The mode coupling threshold remains unaltered and in both cases the beam starts getting unstable at about 8 mA. The only difference is a smoothing out of the m=0 mode shape and an enhancement of the m=-1 mode when the feedback is on.

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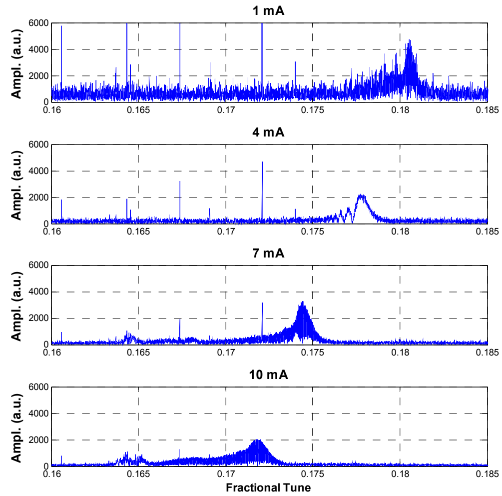

Figure 1: The m=0 and m=-1 mode merging with positive chromaticity (0.4, 0.4), feedback off and kickers on, vertical plane.

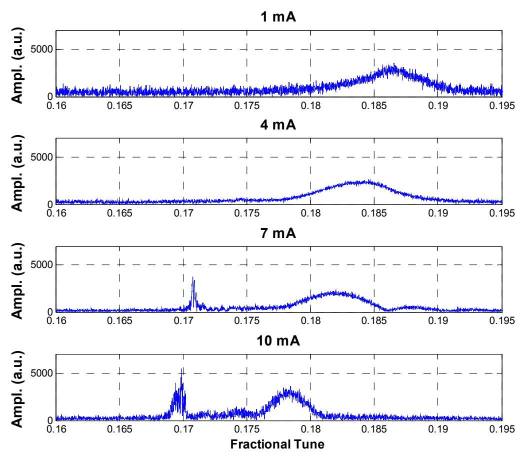

Figure 2: The m=0 and m=-1 mode merging with t positive chromaticity (0.4, 0.1), feedback on and kickers on, vertical plane.

To investigate the negative chromaticity region threshold current data were taken with the feedback off for various negative vertical chromaticities up to -2.5 as shown in Figure 3. Again the most significant effect is seen in the vertical plane. With negative chromaticity the accumulation saturates early due to head tail m=0 mode instability and no further accumulation is possible without activating the feedback. At the same time the beam was clearly unstable.

From equation 1 and reasoning similar to that of ref. [4] the following equation is written to be tested against threshold measured data:

$$I_{th} = \frac{q_s}{(\Delta q_y / \Delta I)} \frac{q_y}{\xi} \quad (2)$$

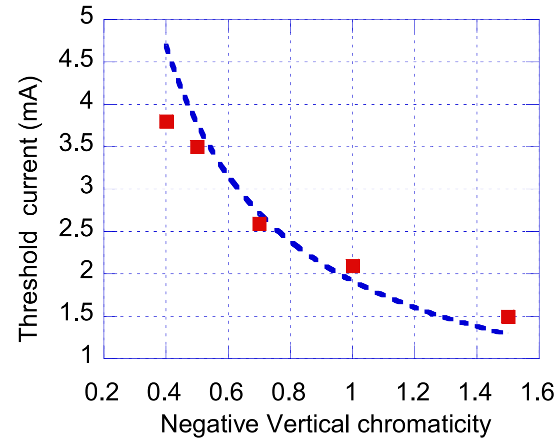

Figure 3: Single bunch maximum current vs. negative vertical chromaticity and the model prediction (dashed line).

The predictions of equation 2 fit the data very well.

Switching the feedback on, the beam becomes stabilized and accumulation continues. It was interesting to observe that saturations occurred from 6 mA onwards depending upon the fine tuning of the machine and the feedback system. The maximum stable current achieved was 15 mA but could not be easily reproduced. Usually saturations occurred between 6-10 mA and in all cases setting the feedback in off, current losses were observed in accordance to the thresholds shown in figure 3. On the other hand while in saturation, no m>0 modes were observed. The m=0 mode is shown in figure 4, shifting with current when the vertical chromaticity is –2 and horizontal 0. The same picture applies up to 10 mA the only difference being the tune shift.

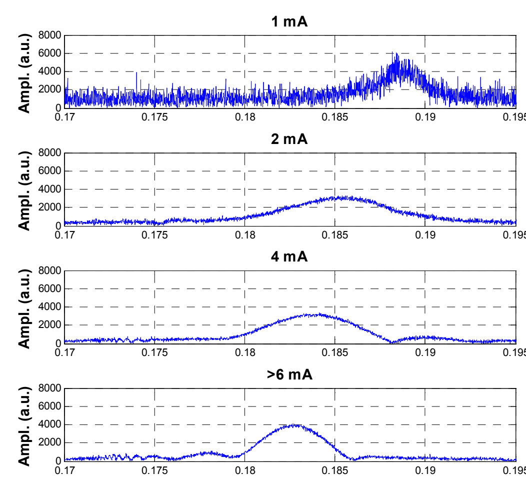

Figure 4: The m=0 mode shift with vertical negative chromaticity (0,-2), feedback on and kickers on.

Although no tune shifts were observed in the horizontal plane, both feedbacks were activated to fully stabilize the beam. The saturations may be attributed to a reduction of Landau damping.

RISE TIMES

Continuing the investigation with negative chromaticity beam transients were produced at various conditions as seen in figure 5. The transients were obtained injecting relatively low current ≤ 5 mA with feedback on. At a certain instant the feedback is set off and the feedback detector registers many turns of the unstable beam until the feedback is set on again and damping occurs. The procedure is automatic, programmable and incorporated in the feedback control system. From the transients the rise time of the head tail instability was extracted as seen in table 1.

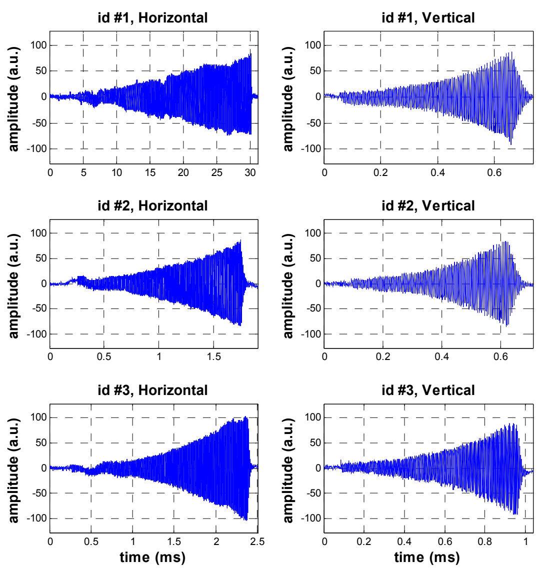

Figure 5: Beam transients for negative chromaticity.

Table 1: Rise times for some negative chromaticities

id	I (mA)	ξ_h	ξ_v	τ_h (ms)	τ_v (ms)
1	4.3	-0.06±0.192	-2.4±0.22	15	0.26
2	4.6	-1.3±0.28	-2.24±0.59	-	0.26
3	5.1	-0.09±0.1	-0.214±0.30	-	0.39

For short bunches and resistive wall type impedance the growth rate of the m-th mode is given [5, 6] by the equation:

$$\frac{1}{\tau_m} = -\frac{Ic}{2\pi^{5/2}\frac{E}{e}} Z_{T0}^{RES} \frac{\xi\sqrt{\sigma_t\omega_0}}{\alpha} J_m \quad (3)$$

Where Z_{T0}^{RES}=R Z_0 δ_0 / b^3 with δ_0 the skin depth at ω_0 and b the chamber half height. The factor J_m for m=0,1,2 is 2.871, -0.574 and –0.191 respectively and for negative chromaticity the rise time is positive for m=0 and negative for the higher modes. The plot of equation 3 versus chromaticity and the experimental results are shown in Figure 6.

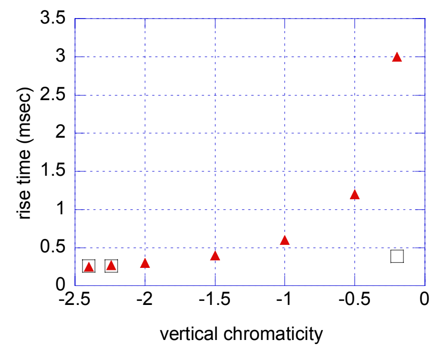

Figure 6: Vertical rise time measured (squares) and model (triangles) versus chromaticity.

CONCLUSIONS

The negative chromaticity region is investigated and trials have been made to fight the head tail coupling threshold by using the transverse multi-bunch feedback in both reactive and resistive mode. Only once an accumulated current increase by 50% beyond the 10 mA limit was achieved. Much depends upon the machine and feedback fine settings. Nevertheless operating with negative chromaticity in the single or 4 bunch mode, even when higher thresholds could not be reached, the beam was very stable at all reached currents whereas when at positive chromaticity the beam started becoming unstable after 7 mA.

Measurements of vertical rise times and thresholds could be predicted quite well and agree well with our understanding of Elettra impedance and its main source coming from the resistive wall.

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