RESISTIVE WALL GROWTH RATE MEASUREMENTS IN THE FERMILAB RECYCLER

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Abstract

Impedance could represent a limitation of running high intensity beams in the Fermilab recycler. With high intensity upgrades foreseen, it is important to quantify the impedance. To do this,studies have been performed measuring the growth rate of presumably the resistive wall instability. The growth rates at varying intensities and chromaticities are shown. The measured growth rates are compared to ones calculated with the resistive wall impedance.

INTRODUCTION

For high intensity operations in the Recycler, high chromaticity is used to help stabilise the beam against the resistive wall instability. Thus, it is important to understand the instability itself and the associated impedances.

The real part of the transverse impedance can be found by measuring the growth rate of the instability. In the case of an evenly filled ring and a coasting bunch [1], the real part of the impedance and the growth rate are related by the following

$$\frac{1}{\tau} = \frac{N_t r_0 c}{2\gamma T_0^2 \omega_\beta} \Re[Z_1^\perp(\omega_q)] \quad (1)$$

where $1/\tau$ is the growth rate, N_t is the total number of protons, c is the speed of light, γ is the relativistic factor, T_0 is the revolution time and $\omega_q = n\bar{\omega}_0 + \omega_\beta$ where $\omega_\beta = Q_v\bar{\omega}_0$ and $\bar{\omega}_0$ is the ideal angular revolution frequency. It should be noted that the measurements shown later will be for an unevenly filled ring distribution and thus there will be some differences which are discussed in the Theory section. The coasting beam approximation is justified when $\omega_q << 53$ MHz.

MEASUREMENTS

Four batches were injected in the Recycler with the dampers turned on and with chromaticity set to 0 in both planes. Each batch contained 81 53 MHz bunches and were separated by a gap equal to 3 bunches. The harmonic number for the Recycler is 588 meaning only 4/7 of the ring is occupied. After allowing the beam to circulate for 24250 turns, the dampers were turned off and the beam was allowed to blow up. Bpms were used to measure the growth. Data was measured at varying intensities using both 1 and 2 RF cavities.

In order to measure the growth rate, a fit is performed of the nature

$$A + Be^{\alpha x} \quad (2)$$

Table 1: Default Parameters for Recycler Measurements

Parameter	Unit	RR
Batches		4
Bunches	[bunches per batch]	81
N_b	[protons per bunch]	3×10^{10}
E	[GeV]	8.884
T_0	[μs]	11.135
Q_h		25.4395
Q_v		24.3926
Q_s	1 RF cavity	0.0029
Q_s	2 RF cavities	0.0039
$\xi_{h,v}$		0±0.5
$\varepsilon_{n,95\%}$	[π mm mrad]	15
σ_t	[ns, 1 RF cavity]	1.7
$\sigma_{\delta p/p}$	[1 RF cavity]	3.3×10^{-4}

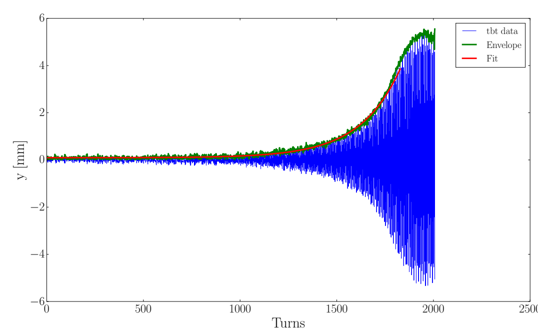

Figure 1: Turn by turn data taken showing a blow up due to the resistive wall instability. The green line shows envelope of the data and the red line shows a fit to this envelope.

where alpha is the growth rate in inverse turns. To convert to s^{-1}, one divides by the revolution time. In order to make the fit easier, the envelope is found first using a hilbert transform. An example envelope and fit is shown in Figure 1.

A linear function $y = ax+b$ was used to fit the dependence of the measured growth rate (y) on the bunch intensity (x). For 1 RF cavity, the results in the vertical plane show a dropoff in at high intensity. The beam was seen to have become unstable before the dampers were turned off. For the long-wave coupled-bunch instability sufficiently above its threshold, the growth rate has to be independent of RF voltage. Indeed, for the vertical degree of freedom the slopes dy/dx for 1 and 2 cavities agree within 4%; for the horizontal dimension, which measurement error bars are larger, this discrepancy is 15%. The constant term comes about from Landau damping resulting in a threshold intensity of the instability to occur.

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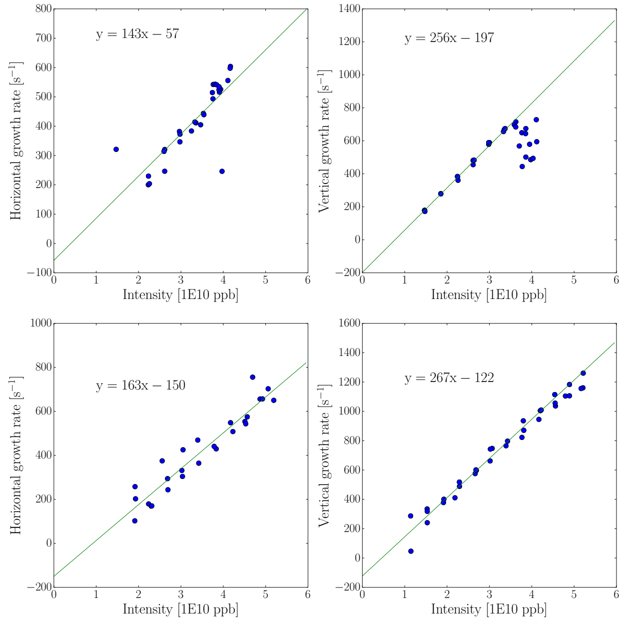

Figure 2: The growth rate as a function of intensity for 1 (top) and 2 (bottom) rf cavities.

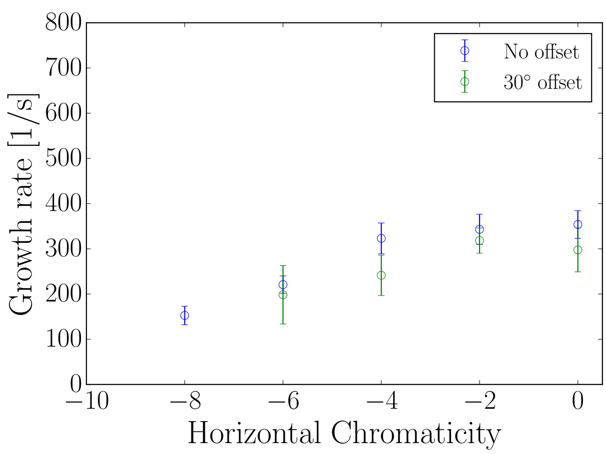

Figure 3: The growth rate in the horizontal plane as a function of chromaticity with and without an injection phase offset.

The measurements were then repeated by keeping the intensity (3E10 ppb) constant and varying the chromaticity in both planes. Measurements were performed with the bunches injected into the center of the bucket and then with a 30° injection phase offset as this should result in a larger bunch length. Operationally, the bunch is injected into the bucket with an phase offset to allow operation with lower chromaticity. The offset measurement was to verify that this is indeed reducing the growth rate of the instability. The results are shown in Figure 3 and Figure 4. Examples of the instability at different chromaticities are shown in Figure 5.

THEORY

The simplest estimation of the coupled-bunch growth rate is given by the single-particle model, when every bunch is considered as a macro-particle. For many bunches, this estimation is identical to the coasting beam approach of (1). This simplified approach requires a sufficiently small head-tail phase $|\chi| = |\xi|\delta p/(pQ_s) \ll 1$ and negligible Landau damping, where ξ is the chromaticity, Q_s is the synchrotron tune and $\delta p/p$ is the momentum spread. If these conditions are satisfied, the growth rate is proportional to the impedance, so the former gives the latter. Application of the conventional formulas such as (1) to the vertical growth rates of Fig.2 for two cavities thus yields the measured real part of the transverse impedance $\Re Z_v^{meas} = 44$ MOhm/m. From the other side, the resistive wall impedance can be computed for the RR flat stainless steel vacuum chamber which conductivity $\sigma_{wall} = 1.25 \times 10^{16} s^{-1}$, the half-gap $b = 2.2$cm and the thickness $d = 1.65$mm. For the most unstable coupled-bunch mode which develops at the frequency $f_{\min} = (1 - [Q_v])f_0 = 55$ KHz, the resulting real part of the impedance $\Re Z_v^{rw} = 39$ MOhm/m, where the finite thickness was taken into account according to Ref. [2]. If the finite thickness were to be ignore, the thick wall formula would give an even smaller value by 17%.

The remaining 14% of the disagreement between the measured and calculated impedances relate to the train structure: only 4/7 of the RR is occupied by the beam. To take this into account, one may use either Ref. [3] or Ref. [4], which amazingly yields exactly these missing 14%. However, taking into account the detuning (or the quadrupole) wake will not make agreement that exact, resulting in a few percent of a discrepancy between the measured and computed vertical impedances, which still lies within the error bars of the measurements. The measured value of the horizontal impedance is 59% of the vertical one, which is close enough to the theoretical expectations of 1/2 for the flat chamber.

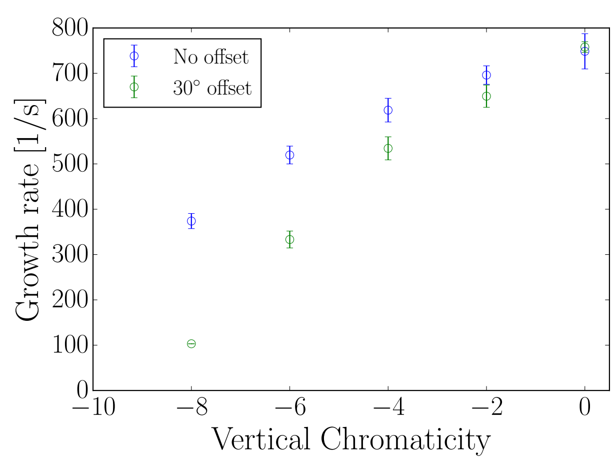

Figure 4: The growth rate in the vertical plane as a function of chromaticity with and without an injection phase offset.

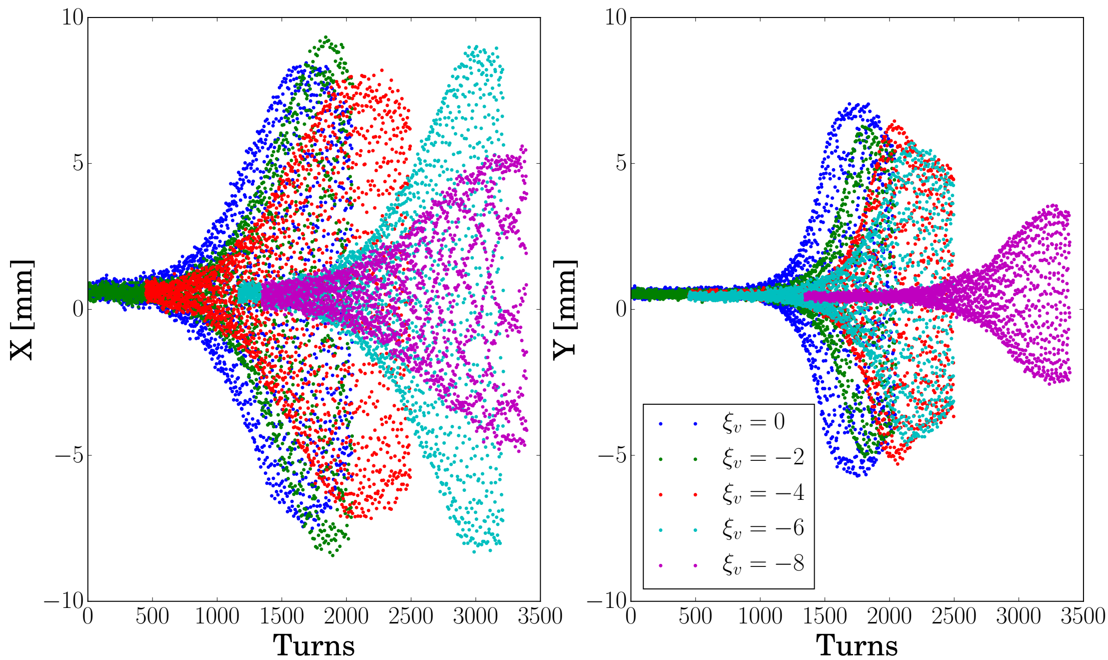

Figure 5: Turn by turn bpm data showing the instability growth at different chromaticity settings.

If the head-tail phase is not small as in the case when we increase chromaticity, the coupled-bunch growth rate is shared between the head-tail modes, see Ref. [5]. In our case the space charge is strong, i.e. its tune shift is much bigger than the synchrotron tune. Application of the related formulas of the Ref. [5] for the parameters of Table 1 leads to a conclusion that the vertical growth rate of the most unstable mode when the bunch is centered in the bucket is reduced twice at the chromaticity $\xi \approx -10$, which is reasonably close to the data of Fig.4.

SUMMARY

The growth rate of what is believed to be the resistive wall instability has been measured at various intensities and chromaticities. The measured growth rate compares well with theory if the finite thickness of the wall and uneven fill of the ring is taken into account.

As expected, increasing the chromaticity results in a reduction in growth rate and the growth rate is reduced further if the bunch is injected with a phase offset resulting in a larger head-tail phase which will enhance sharing of the coupled-bunch growth rate between the head-tail modes.

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