IMPEDANCE CHARACTERIZATION AND COLLECTIVE EFFECTS IN THE MAX IV 3 GeV RING*

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Abstract

Collective instabilities in the MAX IV 3 GeV storage ring are enhanced by combination of high beam current, ultralow emittance and small vacuum chamber aperture. To mitigate instabilities by Landau damping and improve lifetime three passive harmonic cavities are installed to introduce synchrotron tune spread and bunch lengthening respectively. We present the results of the studies of collective effects driven by the machine impedance. Bunch lengthening and detuning were measured to characterize the machine impedance and estimate the effect of the harmonic cavity potential. Investigations of collective effects as a function of parameters such as beam current and chromaticity are discussed.

INTRODUCTION

The study of collective effects in a particle accelerator is of high importance because they can lead to a deterioration in the machine performance. The MAX IV 3 GeV machine [1] is based on a multibend achromat lattice where the emittance is pushed down to a bare-lattice value of 0.33 nm rad, which is further reduced to 0.2 nm rad when loaded with insertion devices. Achieving such a small emittance requires strong-focusing, small-bore magnets which necessitate the use of a small nominal vacuum chamber aperture (11 mm radius). This, in turn, leads to a large machine impedance and enhanced collective effects.

Numerical characterization of beam instabilities is typically done using an impedance model describing the machine in the frequency domain followed by particle tracking accounting for this impedance.

In this paper we present the first experimental results of longitudinal and transverse instability studies on the MAX IV 3 GeV machine and compare them to numerical results obtained with the particle tracking code *mbtrack* [2]. The geometric impedance model of the complete MAX IV 3 GeV ring was created and processed to be used in the tracking. Description of the machine impedance budget and simulations of possible longitudinal and transverse instabilities can be found in [3] and [4]. Here we will compare the results to measured values for the potential-well bunch lengthening and tune shift with bunch current and discuss the TMCI, head-tail, resistive-wall and ion-driven instabilities present in the machine.

The MAX IV 3 GeV ring is equipped with a diagnostic beam line for beam size measurements [5] using the visible synchrotron radiation emitted from the center of a dipole magnet. This beam line was used for the bunch length measurements presented below and for observation of the transverse beam profile and any beam blow-up indicating that the beam is unstable. For more accurate measurements of transverse instabilities, the bunch-by-bunch feedback system from Dimtel [6] was used as a diagnostic tool. At the time of the measurements, only two in-vacuum insertion devices were installed and these were left in the open position. Round vacuum chambers were installed at all other straight sections.

LONGITUDINAL SINGLE-BUNCH

A single, high-current bunch was obtained by injecting a train of nine bunches into the ring and then using the bunch-by-bunch feedback system to clean eight and leave only one bucket filled. By using an optical sampling oscilloscope resolving the time structure of synchrotron light, the bunch length could be measured as the current was decreased in steps by scraping. The synchrotron tune was measured to be 0.00157 and the other parameters of the MAX IV 3 GeV ring were assumed to be at their design values during the experiment, i.e. momentum compaction $\alpha_c = 3.07 \times 10^{-4}$ and energy spread $\sigma_E = 7.82 \times 10^{-4}$.

The measured bunch lengthening due to potential well distortion is presented in Figure 1 and compared to simulation. The length of each error bar is equal to the standard

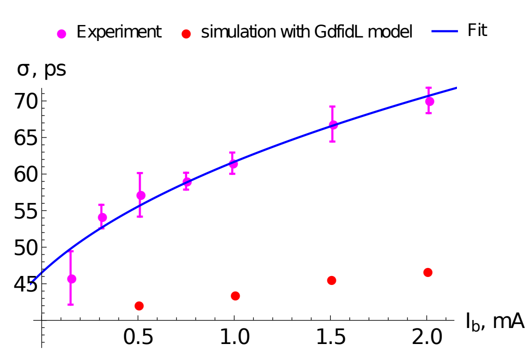

Figure 1: Bunch length vs. current: measurements in magenta (set of five measurements), simulations with *mbtrack* with full numerical machine impedance in red and fit including a single broadband resonator in blue.

deviation of 5 bunch length measurements using the oscillo-

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scope. The red dots are the tracking results with the resistive wall impedance and the numerical model of longitudinal impedance obtained from simulations with the GdfidL electromagnetic field solver [7] included. The blue line is a fitted bunch-lengthening curve where the geometric impedance is reproduced by a single broadband resonator at 6 GHz with a quality factor of unity and a shunt impedance of 732 Ω. The resonant frequency was chosen to be at 6 GHz since a number of clear resonances was seen around this frequency in the numerical impedance data.

TRANSVERSE SINGLE-BUNCH

The shift of the vertical coherent tune with bunch current was measured at low vertical chromaticity (0.25). As in the bunch length measurements, a train of nine bunches was initially injected and then all but one was cleaned out using the bunch-by-bunch feedback system. The feedback was then used to damp the beam oscillations. This results in a notch in the Fourier transform of the turn-by-turn position measurements of the single bunch and this notch is at the betatron frequency. Figure 2 shows the detuning measured

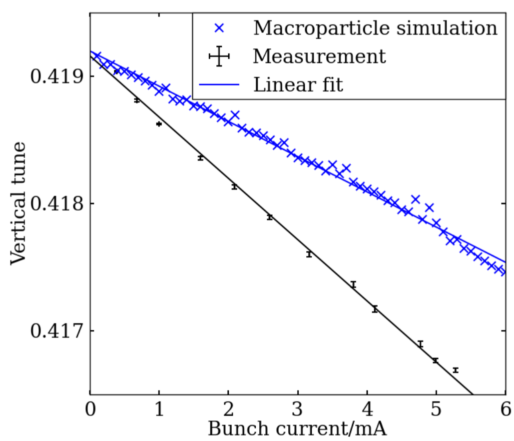

Figure 2: Tune as measured using the bunch-by-bunch feedback system as a function of single bunch current at low chromaticity.

as a function of the beam current compared to macroparticle tracking of the zero chromaticity case using *mbtrack* and the impedance model calculated using GdfidL. The tune shift obtained experimentally, $-0.481 \pm 0.002\,\mathrm{A}^{-1}$, is a factor of 1.8 larger than the one obtained in tracking, a similar level of discrepancy as in the longitudinal plane, see previous section. Furthermore, the macroparticle tracking predicts a transverse mode-coupling instability (TMCI) at a single bunch current of 5.5 mA, about where the total tune shift reaches one synchrotron tune. No signs of TMCI (beam loss, hard limit on accumulated current) were seen in experiment despite the impedance being larger than predicted.

In order to make the higher-order head-tail modes visible in the BPM spectra, the chromaticity was increased, first to 0.70 and then to 1.15. The bunch-by-bunch feedback system was then used to drive the beam at a range of frequencies around the vertical betatron tune. In this configuration, at certain currents, multiple peaks could be seen in the BPM spectrum and the frequencies at which these peaks occurred were measured. Figure 3 shows the peak frequencies for the

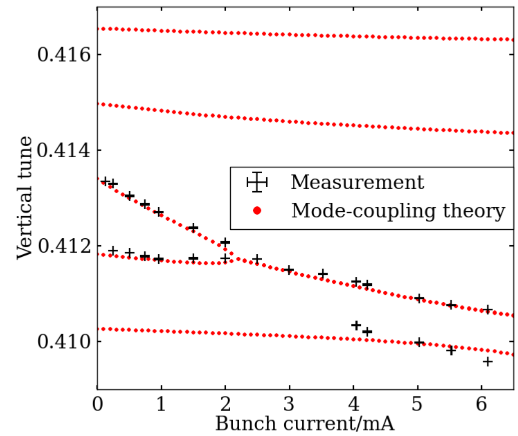

Figure 3: Peak frequencies as measured using an excitation around the betatron frequency for different bunch currents at a vertical chromaticity of 0.7.

chromaticity of 0.7. The observed head-tail modes can be identified from their peak frequencies at low current, as they are each separated from the dominant, betatron tune line by their order multiplied by synchrotron tune. The detuning of the zeroth order head-tail mode with bunch current is similar to in the low chromaticity case. Conversely, the frequency of the -1 head-tail mode stays almost constant and so, when the zeroth order head-tail mode has been detuned by about one synchrotron tune, the frequencies of the two modes are the same. This occurs at a current between 2 and 3 mA. Nevertheless, no obvious signs of TMCI are observed and it is still possible to inject above this current. Provided that the bunch lengthening, as measured and presented above, is taken into account, the shifts in the frequencies of the -1 and 0 head-tail modes are well reproduced by mode-coupling theory [8] for the resistive wall impedance plus a resonator at 6 GHz of shunt impedance $360\,\Omega\,\mathrm{mm}^{-1}$ and a quality factor of unity. This resonator accounts for the impedance missing in the numerical model evaluated using GdfidL but the two cannot be directly compared since the latter contains multiple broadband resonators. In the current range considered, the growth times predicted by the theory are in the same order of magnitude as the radiation damping time, suggesting that decoherence, and in particular, the amplitude-dependent tune shift could be preventing a clear observation of the expected instability,

TRANSVERSE MULTIBUNCH

As may be anticipated during the conditioning phase of the vacuum system, ion-driven instabilities have been observed during multibunch operation at currents as low as 40 mA. Data from bunch-by-bunch, turn-by-turn diagnostics was decomposed into coupled-bunch modes and the typical symptoms of an ion-driven instability (nonexponential growth of a wide band of coupled-bunch modes of low, negative frequency followed by saturation at an amplitude of a few micrometers) were confirmed. Uneven filling patterns were then experimented with until these features were successfully suppressed by the clearing of ions between bunch trains. Initially, a filling consisting of five trains of 25 bunches with four gaps of 10 RF buckets and one of 11 RF buckets was tried but this was found to be insufficient. Introducing a 3 bunch gap into the middle of each of these trains using bunch-cleaning sufficiently suppressed the ion-driven instabilities so that the resistive wall instability could be measured. Figure 4 shows the coupled-bunch mode spectra of a

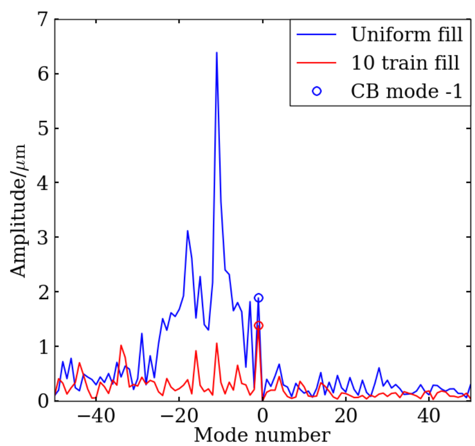

Figure 4: Coupled-bunch mode spectra for two filling patterns: a uniform fill of 47 mA and 52 mA in a fill of ten bunch trains with gaps between them of 3, 10 or 11 bunches.

uniform bunch filling pattern at 47 mA and the filling pattern described above at a current of 53 mA. The large, broad peak that is due to the ion-driven instablity is successfully supressed leaving coupled-bunch mode -1, whose presence suggests a resistive-wall instability, and other coupled-bunch modes that can be attributed to the uneven filling pattern.

With the uneven filling pattern and close to zero chromaticity (0.28), a grow-damp measurement, where the bunch-by-bunch feedback system is switched off for a period of 100 ms and then turned back on, was performed. Figure 5 shows the amplitude of the -1 coupled-bunch mode during the measurement. Although the oscillation amplitude reached in 100 ms was very small, the exponential growth in the amplitude of the coupled-bunch mode is clear and can be measured. A fit to the natural logarithm of the data gives a growth time of 31.6 ms. Assuming the theoretically-predicted radiation damping time of 29 ms in the vertical plane and a growth rate proportional to the beam current, an estimate of 27.4 mA can be obtained for the threshold current of the resistive-wall instability. This is around 20 % larger than the values of 21.6 mA previously predicted using frequency domain calculations and 21.9 mA using macroparticle tracking with no longitudinal impedance included [9]. This discrepancy

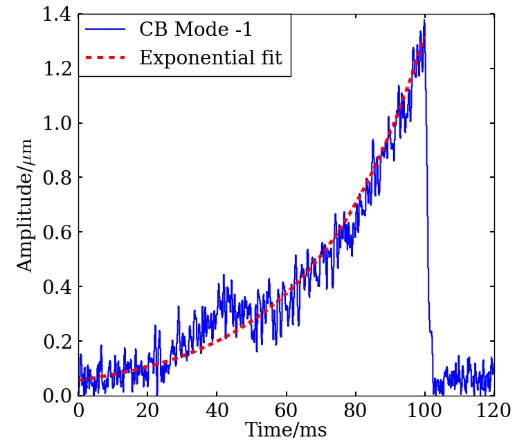

Figure 5: Amplitude of the -1 coupled-bunch mode with the bunch-by-bunch feedback turned off for the first 100 ms and then turned on again.

can be explained by the slightly positive chromaticity during the measurement.

CONCLUSION AND OUTLOOK

The first measurements of collective effects in the MAX IV 3 GeV ring have been made. In the longitudinal plane, the bunch lengthening with bunch current was measured using the synchrotron radiation from a bending magnet. The effect is significantly larger than predicted in simulation. In the transverse plane, the vertical tune shift with bunch current was measured and compared to simulation and a similar discrepancy was found. It is probable that the unidentified source of impedance accounting for this discrepancy is the same in both planes. At higher chromaticity, the frequencies of multiple head-tail modes were also followed as a function of bunch current. The zeroth order head-tail mode appears to merge in frequency with head-tail mode -1 at a current between 2 and 3 mA but no obvious signs of TMCI are observed, possibly due to decoherence effects. Ion-driven instabilities have been seen during multiple-bunch filling modes. A filling mode was found where the ion-driven instability was suppressed and the growth rate of the resistive-wall instability could be measured. This should be repeated at different values of chromaticity and with the harmonic cavities tuned in as the effect of harmonic cavities on the evolution of the resistive-wall instability with chromaticity is predicted to be large [9]. In any case, the resistive-wall instability does not limit the beam current; up to 200 mA has been accumulated in uniform filling without the use of the bunch-by-bunch feedback system.

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