BUNCH LENGTH MEASUREMENTS WITH PASSIVE HARMONIC CAVITIES FOR NON-UNIFORM FILL PATTERNS IN A 100 MHZ RF SYSTEM

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Abstract

The MAX IV facility includes two storage rings operated at 1.5 GeV and 3 GeV, which are both designed to operate with a uniform, multibunch fill pattern. Both rings have a 100 MHz RF system and employ passive harmonic cavities to damp instabilities and increase Touschek lifetime. Recently, a discussion on timing modes at the MAX IV storage rings has been initiated by the user community. Creating opportunities for timing experiments implies operating the rings with other fill patterns than the planned multibunch mode. Such operation can, however, cause transient effects in the passive harmonic cavities which affect the performance of the machine. It is therefore of interest to study the effect on the beam when operating with non-uniform fill patterns. This paper presents bunch length measurements at the 100 MHz MAX II storage ring for fill patterns with gaps. The purpose of the measurements was to evaluate the employed measurement method and simulation codes for future studies of various alternate fill patterns in the MAX IV storage rings.

INTRODUCTION

The MAX IV facility includes two storage rings, operated at 1.5 GeV and 3 GeV. The 1.5 GeV ring has a DBA lattice with an emittance of 6 nm rad, whereas the 3 GeV ring employs many novel technologies, such as a MBA lattice to achieve an ultralow emittance [1]. Both rings are designed to operate with a 100 MHz main cavity (MC) RF system [2] and a uniform, multibunch fill pattern with 5 nC per bunch [3], giving a total beam current of 500 mA. To damp instabilites and increase Touschek lifetime, both rings employ passive harmonic cavities (HCs) [2]. For the 3 GeV ring the HCs are also essential for conserving the ultralow emittance at high bunch charge [4], and simulations of collective effects have shown that the performance of the HCs is of great importance for achieving the design current [5].

Since the completion of the MAX IV DDR [3], a discussion on the possibilities for timing-based experiments at the MAX IV storage rings has been initiated by the user community [6, 7]. Several research areas have been identified where users would benefit from other repetition rates and/or pulse lengths than the ones given by the baseline design of the rings. For these types of experiments the requirements for the time structure of the electron beam are set by the beamline instrumentation and/or the process to be studied. This could require operating the rings with other fill patterns than the originally foreseen multibunch mode.

Since the HCs operate in passive mode, the effect of the cavities depends both on the cavity tuning and the fill pattern in the storage ring. Previous studies for other storage rings show that the introduction of gaps in the fill pattern causes transients that affect the performance of the HCs, e.g [8–13].

The MAX II and MAX III storage rings were shut down on December 13, 2015, but before, both rings had been operated with a 100 MHz RF system and passive HCs. The MAX IV 1.5 GeV ring has a design similar to MAX II, thus MAX II was suitable for evaluating the measurement method and the simulation codes for future studies of transient effects in the MAX IV storage rings. Additionally, the MAX II injector allowed creating gaps in the fill pattern by only filling a few of the buckets in the ring. This paper presents measurements and simulations for fill patterns with gaps in the MAX II storage ring.

MEASUREMENT METHOD AND SIMULATION CODES

To benchmark the employed simulation codes, measurements were first conducted for uniform fill patterns in MAX II. These results are presented in [14]. For uniform fill patterns the results show good agreement between the codes, but due to beam instabilities it was not possible to fully benchmark the codes against measurements.

The measurements of fill patterns with gaps were performed using the same setup as described in [14]. The length of each bunch in the bunch train was measured by introducing a delay to the optical sampling oscilloscope trigger that made it possible to step between bunches in the fill pattern. Two different codes were used for simulations, one code implemented by Milas [9] according to the model presented by Byrd [8] (hereafter denoted Code 2 in line with the notations in [14]) and mbtrack [15] (Code 3). The storage ring and cavity parameters used in the simulations are detailed in [14].

TRANSIENT EFFECTS IN A DOUBLE RF SYSTEM WITH PASSIVE HCS

In a passive HC the field in the cavity is induced by the beam. For a uniform fill pattern the voltage in the cavity in steady-state is given by

$$V_{\mathrm{hc}} = -2FR_sI\cos\psi_h\cos(n\phi-\psi_h), \qquad (1)$$

where F is the bunch form factor, R_s the cavity shunt impedance, I the stored current and ψ_h the tuning angle

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of the cavity, given by

$$\tan\psi_h = -2Q\frac{f_r - nf_{\rm rf}}{f_r}, \tag{2}$$

with the cavity harmonic n, quality factor Q, resonance frequency f_r and RF frequency $f_{\rm rf}$ [16]. For non-uniform fill patterns, the voltage induced by a bunch will decay before the next bunch arrives, giving rise to transient effects. The fundamental theorem of beam loading states that the particles in a bunch only see one half of the induced field when passing through the cavity. This leads to the induced voltage after a bunch has passed the cavity [17]

$$V_b = -2kq, \tag{3}$$

where k is a loss factor defined according to

$$k = \frac{\omega_r R_s}{2Q} \tag{4}$$

and q the bunch charge [8]. For multiple bunches passing the cavity, the induced voltage is added to the voltage already present in the cavity from previous bunches. In between two bunches, the voltage in the cavity decays exponentially [17] as

$$e^{-\frac{\omega_r}{2Q}\Delta t}, \tag{5}$$

where the time between two bunches is

$$\Delta t = \frac{\Delta\phi}{2\pi f_{\rm rf}} + \frac{N_b}{f_{\rm rf}}, \tag{6}$$

with N_b the number of buckets between the bunches [8]. The induced voltage in the cavity after $i+1$ passes can be described by the phasor [8]

$$\tilde{V}_{\rm b,i+1} = \tilde{V}_{\rm b,i}e^{[j\omega_r - \omega_r/(2Q)]\Delta t} - 2kq. \tag{7}$$

BUNCH FORM FACTOR

The bunch form factor relates the voltage induced by an arbitrary charge distribution to the voltage induced by a point charge [18]. The real part of the bunch form factor is given by

$$F[\rho(\varphi)] = \left|\frac{\mathcal{F}[\rho(\varphi)]_{\omega=n\omega_{\rm rf}}}{\mathcal{F}[\rho(\varphi)]_{\omega=0}}\right|, \tag{8}$$

which is the absolute value of the Fourier transform of the bunch density distribution $\rho(\varphi)$ at the harmonic of the cavity, normalized to the DC component [19]. The form factor was already accounted for in Code 3, whereas the real form factor had to be implemented in Code 2 such that [18]

$$\tilde{V}_{\rm b,i+1} = \tilde{V}_{\rm b,i}e^{[j\omega_r - \omega_r/(2Q)]\Delta t} - 2kFq. \tag{9}$$

The benchmarking of the implementation for uniform fill patterns is displayed in Table 1. For the range of settings measured in MAX II, the implementation gives reliable results, but for settings close to optimal bunch lengthening conditions the code has problems reaching steady-state. Thus the form factor depends on the number of tracking turns in the simulation and varies along the bunch train even for uniform fill patterns. This has to be resolved before employing the code for simulations of the MAX IV storage rings. So far only the real part of the form factor of the HC has been implemented. It would be straight-forward to also implement the real form factor for the MC beam loading in the code, but this requires modification of the MC feedback and code optimization to reduce run time. These are possible opportunities for further development of the code. It could also be of interest to include the imaginary part of the form factor.

Table 1: Benchmarking of the Form Factor for a Uniform Fill. Measurement 1 presented in [14] with natural energy spread is used as an example. Code 1 refers to the code implemented by Tavares and Andersson, also mentioned in [14]. For Code 2, 100 000 tracking turns were used.

	Code 1	**Code 2**
No HC	0.98024	0.98022
HC measurement settings	0.94621	0.94620
HC flat potential conditions	0.83720	0.83210± $2.74 \cdot 10^{-3}$

BUNCH LENGTHS FOR NON-UNIFORM FILL PATTERNS IN MAX II

MAX II provided 30 buckets, of which all were filled during the usually operated multibunch mode. The measurements for fill patterns with gaps were conducted by only filling some of these buckets. The settings for two different measurements are displayed in Table 2 and the results in Fig. 1.

Table 2: Measurement Data for Fills with Gap

	1	**2**
Current [mA]	59.47	48.75
No of filled buckets	10	11
Gap length [ns]	210	200
Sync. freq. [Hz]	6625	7125
Main voltage [kV]	351.43	399.02
RF frequency [MHz]	99.9602	99.959
HC detuning [kHz] ($\Delta f = f_r - 5\cdot f_{rf}$)	49.00	26.370

During the measurements the HC settings were set by a feedback system, which means they were set far from optimal bunch lengthening conditions since MAX II was not intended to operate with a gap in the fill pattern. In addition, as discussed in [14], the low shunt impedance of the HC and the instability issues also heavily influenced these measurements. It was therefore not possible to use

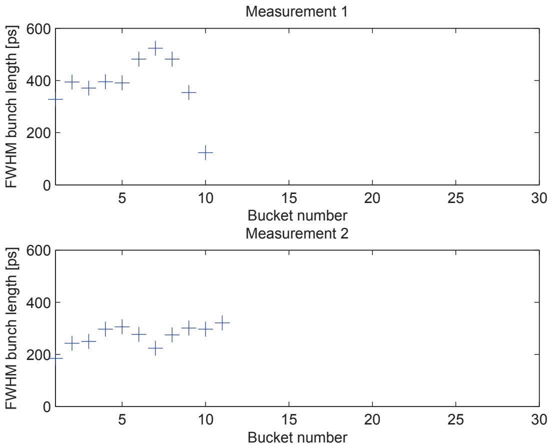

Figure 1: Measurement results for fill patterns with gaps in MAX II.

these measurements to benchmark the simulation codes, but they give a first indication of variations of the bunch length when introducing gaps in the fill pattern.

The measurement conditions were simulated using the two simulation codes. The results for measurement 1 are displayed in Fig. 2. Despite the HC settings being far from optimal lengthening conditions, it is possible to see a variation of bunch length across the bunch train. Code 2 predicts a larger transient effect than Code 3. The reason for this has not yet been fully understood, and further studies have to be performed. Apart from possible issues when calculating the transient, the two codes employ different implementations of a feedback to compensate for beam loading in the MCs. The two codes predict a slightly different synchronous phase and bunch centroid offset across the bunch train, which could be connected to how well the feedback manages to compensate for transients in the MC beam loading. Large differences in the performance of the compensation would affect the bunch length variation across the train. However, the simulated bunch length variations are both too small to be measurable with the current setup, which indicates that the bunch length variations seen in the measurements were not mainly caused by transients in the HC.

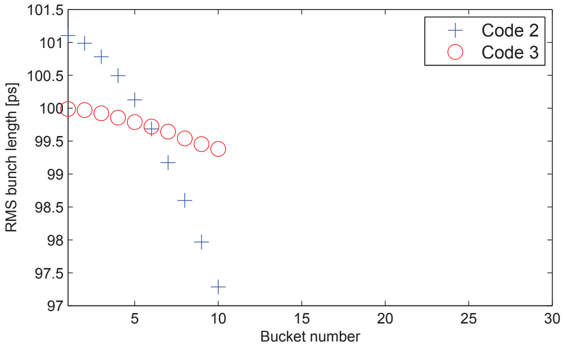

Figure 2: Simulation results for measurement 1 with gaps in MAX II.

ROBINSON INSTABILITY

As in the case for uniform fill patterns [14], the simulations with Code 3 highlighted issues with the Robinson instability. Detuning of the MC was necessary in order not to lose the beam in the simulations. Also, the settings for compensating the MC beam loading were more sensitive than for simulations with uniform fill patterns.

DISCUSSION AND FUTURE WORK

Measurements of fill patterns with gaps in MAX II raised many new questions that have to be investigated further. Issues concerning the measurement setup and method are discussed in greater detail in [14] since they are similar for measurements with uniform fill patterns. However, for measurements with non-uniform fill patterns at MAX IV it is of great importance to develop a faster method to measure bunch lengths than the employed optical sampling oscilloscope. The sampling oscilloscope can be employed at MAX II and the MAX IV 1.5 GeV ring, but for the 3 GeV ring the measurement process would be too cumbersome to measure the length of every bunch in the ring.

The three employed simulation codes show potential for simulation of non-uniform fill patterns in the MAX IV rings, but further benchmarking and development are required before the results can be fully trusted. The implementation of the real part of the bunch form factor gives consistent results for uniform fill patterns, but effects for non-uniform fill patterns have to be studied further. In addition, the importance of the MC beam loading and the compensating feedback also have to be investigated further and evaluated in comparison to the performance of the feedback in the real machine.

Both the simulations for uniform and non-uniform fill patterns in MAX II indicate that the Robinson instability could be a more important issue for the MAX IV 1.5 GeV ring than for the 3 GeV ring. The Robinson instability has not yet been studied in detail for the MAX IV rings, but this is of interest for further studies, especially for the 1.5 GeV ring.

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