# BUNCH LENGTH MEASUREMENTS WITH PASSIVE HARMONIC CAVITIES FOR UNIFORM FILL PATTERNS IN A 100 MHz RF SYSTEM

T. Olsson*, S. C. Leemann, P. Lilja,
MAX IV Laboratory, Lund University, Lund, Sweden

*Abstract*

The MAX IV facility includes two storage rings operated at 1.5 GeV and 3 GeV. Both rings make use of a 100 MHz RF system and are designed to operate with a uniform multibunch fill pattern as well as 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. This implies operating the rings with other fill patterns than the originally planned multibunch mode and therefore detailed studies of the performance of the harmonic cavities are of interest. This paper presents bunch length measurements at the 100 MHz MAX II storage ring for uniform fill patterns. The purpose of the measurements was to evaluate the employed measurement method and simulation codes for future studies of fill patterns in the MAX IV storage rings.

## INTRODUCTION

The MAX IV facility is currently under commissioning in Lund, Sweden. The facility includes two storage rings (operated at 1.5 GeV and 3 GeV). The 1.5 GeV ring has a DBA lattice, producing an emittance of 6 nm rad, whereas the 3 GeV ring employs many novel technologies, such as a MBA lattice, to achieve an emittance as low as 0.2 nm rad with insertion devices [1]. Both rings employ a 100 MHz main cavity (MC) RF system and have a design current of 500 mA [2]. They will be operated with a uniform, multibunch fill pattern with 5 nC per bunch [3]. Both rings employ passive harmonic cavities (HCs) [2] to increase Touschek lifetime by elongating the bunches and damp instabilities by enhanced Landau damping [1]. For the 3 GeV ring, the HCs are also essential for conserving the ultralow emittance at high bunch charge [4]. Simulations of collective effects for the 3 GeV ring have shown that the HC performance is of great importance for achieving the design current of the machine [5]. Recently, a discussion on timing modes at the MAX IV storage rings has been initiated by the user community [6, 7] and this raises the interest for detailed studies of the performance of the HCs.

The MAX II and MAX III storage rings were shut down on December 13, 2015. Both rings were operated with a 100 MHz RF system and passive HCs. Since the design of the MAX II storage ring was similar to the MAX IV 1.5 GeV ring, MAX II was suitable for evaluating the measurement method and simulation codes to be used for future studies of fill patterns in the MAX IV rings. This paper presents measurements and simulations for uniform fill patterns in the MAX II storage ring. Measurements and simulations for non-uniform fill patterns are presented in an additional paper [8].

## MEASUREMENT METHOD AND SIMULATION CODES

Bunch length measurements were performed at the D111 beamline at MAX II with an optical sampling oscilloscope. A similar setup has previously been used for bunch length measurements both at MAX II [9] and MAX III [10]. For each measurement, the synchrotron frequency with the HC tuned out and the resonance frequency of the HC when tuned in were measured. The measured synchrotron frequency was used to determine the MC voltage. The bunch length was then simulated using the codes described below and compared to the measured bunch lengths.

Three different codes were applied for simulations, one code developed by Tavares and Andersson [10] (hereafter denoted Code 1), one code implemented by Milas [11] according to the model presented by Byrd [12] (Code 2) and mbtrack [13] (Code 3). The bunch form factor was already accounted for in Code 1 and Code 3, whereas it was added to Code 2 in the scope of these studies. The implementation is described in [8].

In the simulations a lattice model previously implemented in MATLAB Accelerator Toolbox was used [9]. The parameters given by the model are displayed in Table 1. MAX II had three 100 MHz MCs and one 500 MHz passive HC. No recent measurements of the MAX II cavity parameters had been conducted, but measurements had been performed on cavities in the MAX III storage ring [14, 15]. These cavities were very similar in design to the MAX II cavities and therefore the parameters displayed in Table 2 were used in the simulations for MAX II.

Table 1: MAX II Model Parameters

| | |
|---|---|
| Energy [GeV] | 1.5 |
| Energy loss per turn [keV] | 133.4 |
| Momentum compaction | 0.00382 |
| Natural energy spread [%] | 0.0701 |
| Longitudinal damping time [ms] | 3.38001 |

## MAX II DOUBLE RF SYSTEM

A detailed discussion on the dynamics of a double RF system can be found in e.g. [10, 16, 17]. The voltage seen by a beam in a double RF system is given by

$$V(\varphi) = V_{\mathrm{rf}}\left[\sin(\varphi + \phi_s) + k\sin(n\varphi + n\phi_h)\right], \quad (1)$$

* teresia.olsson@maxiv.lu.se







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Table 2: Cavity Parameters

| **Main cavities (100 MHz)** | |
|---|---|
| Shunt impedance $\left(\frac{V^2}{2P}\right)$ [MOhm] | 1.794 [14] |
| Q value | 20785 [14] |
| Coupling (specific for MAX II) | 3 [18] |
| **Harmonic cavity (500 MHz)** | |
| Shunt impedance $\left(\frac{V^2}{2P}\right)$ [MOhm] | 1.57 [15] |
| Q value | 21720 [15] |

where $V_{\rm rf}$ is the MC voltage, $\varphi$ the phase deviation from the stable phase, i.e. the synchronous phase, $\phi_s$ of the MC, $k$ the ratio between the HC voltage and the MC voltage, $n$ the harmonic of the HC and $\phi_h$ the stable phase of the HC. We can choose the HC voltage $k$ and phase $\phi_h$ such that the first and second derivatives of the voltage at the synchronous phase become zero. This forms a quartic potential well and the conditions when this happens [10] are therefore often referred to as flat potential conditions.

For a passive HC, the voltage is given by the field induced in the cavity,

$$V_{\rm hc} = kV_{\rm rf} = -2FR_sI\cos\psi_h, \tag{2}$$

where $I$ is the stored current, $R_s$ the cavity shunt impedance, $F$ the bunch form factor and $\psi_h$ the tuning angle of the cavity related to the HC detuning through $\tan\psi_h = -2Q\frac{\Delta f}{f_r}$. The required shunt impedance and tuning angle for the flat potential conditions then become

$$R_{\rm s,fp} = \frac{k_{\rm fp}V_{\rm rf}}{2IF_{\rm fp}|\cos\psi_{\rm h,fp}|} \tag{3}$$

$$\psi_{\rm h,fp} = \frac{\pi}{2} - n\phi_{\rm h,fp}, \tag{4}$$

and, therefore, for a given shunt impedance it is only possible to reach flat potential conditions for one specific current. Figure 1 displays the required HC shunt impedance in MAX II to reach flat potential conditions as functions of the stored current for the four measurements in Table 3. It is apparent that the HC shunt impedance available in MAX II was too low to be able to reach flat potential conditions for regular operating currents and MC voltages.

## BUNCH LENGTH WITH HC

In Table 3, measured FWHM bunch lengths are displayed for four different measurements. Code 1 was used to simulate the bunch length for the measurement settings and the energy spread given by the lattice model ($\sigma_e$ = 0.07%). It was clear that this energy spread was not sufficient to achieve the measured bunch lengths. Code 1 was therefore also used to estimate the energy spread required to achieve the measured bunch lengths. The estimated energy spreads are also displayed in Table 3. This shows that the MAX II HC was not able to completely damp the instabilities. Unfortunately,

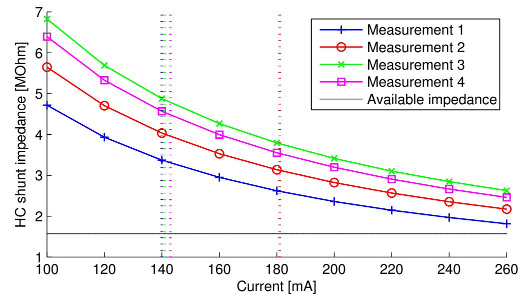


Figure 1: Required HC shunt impedance in MAX II to reach flat potential conditions simulated with Code 1. The vertical lines indicate the four measurement currents presented in Table 3.

diagnostics to measure the energy spread were not available at MAX II at the time of the measurements. Therefore it was not possible to verify the estimated energy spreads.

Table 3: Measurement Data for Uniform Fills

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Current [mA] | 140 | 181 | 140.94 | 143 |
| Sync. freq. [Hz] | 6699 | 7020 | 7375 | 7250 |
| MC voltage [kV] | 358.19 | 388.66 | 424.42 | 411.59 |
| RF frequency [MHz] | 99.9606 | 99.9602 | 99.959 | 99.959 |
| HC detuning [kHz] ($\Delta f = f_r - 5 \cdot f_{rf}$) | 107.07 | 139.00 | 109.92 | 79.04 |
| Meas. length (FWHM) [ps] | 442.93 | 451.34 | 435 | 664 |
| Sim. length (FWHM) [ps] ($\sigma_e$ = 0.07%) | 256.51 | 229.64 | 202.77 | 285.83 |
| Est. $\sigma_e$ [%] ($\sigma_s$ = meas. length) | 0.1335 | 0.152 | 0.163 | 0.226 |

## CODE COMPARISON

The three codes were used to simulate bunch lengths for different energy spreads for the four measurements, which are displayed in Fig. 2. The results show good consistency between the three codes.

## ROBINSON INSTABILITY

The lack of shunt impedance made it impossible to reach flat potential conditions in MAX II, but this could be partially compensated for by tuning the HC closer to resonance. This gives bunch lengthening and thus improved lifetime, but can also lead to a growth in Robinson instability and

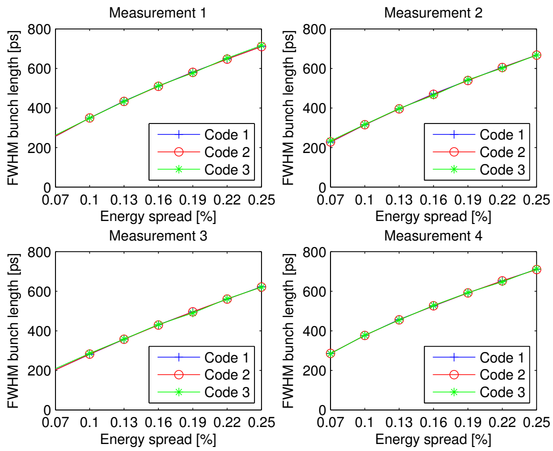


Figure 2: Bunch length as a function of energy spread simulated with the three simulation codes.

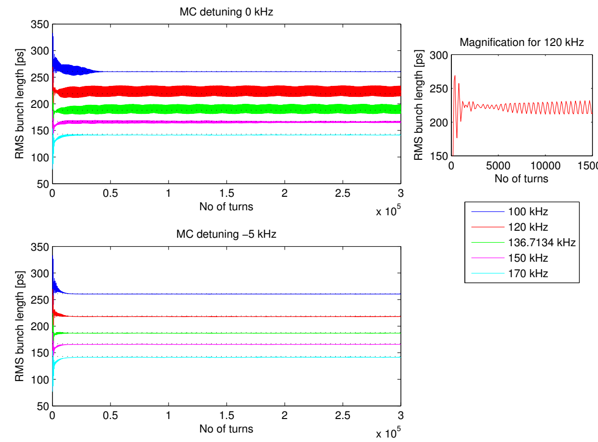


Figure 3: Simulations of measurement 1 using Code 3 for different MC and HC detunings, $\sigma_e = 0.07$ % and $R_{\mathrm{s,hc}} = 3.36963$ MΩ. The dotted lines indicate the expected bunch length simulated by Code 1. $\Delta f_{\mathrm{hc}} = 136.7134$ kHz corresponds to flat potential conditions. The oscillations correspond to the bunch profile oscillating between one and two humps.

resulting energy spread if not compensated for by tuning the MCs below resonance [10]. The simulations with Code 3 in Fig. 2 resulted in stable beam without MC detuning, which indicated no problems with the Robinson instability for the settings used in the measurements, especially since the MCs in MAX II were always operated with a detuning. However, as indicated in Fig. 3, the situation would have been different if the shunt impedance in MAX II had been sufficient to reach flat potential conditions. According to the simulations, detuning the MCs would have been necessary for stable beam. This could have implications for MAX IV since the effect of the HCs at flat potential conditions have been simulated with Code 3 for the 3 GeV ring without need of MC detuning [13]. It is possible that the Robinson instability is a more important issue for the 1.5 GeV ring, as was the case for MAX II.

## DISCUSSION AND FURTHER WORK

The measurements showed presence of instabilities in MAX II which the HC was not able to fully suppress. A reason for this could be the lack of HC shunt impedance, but also excitation of HOMs at certain HC detunings. Further studies would have been required to explain the behavior of the instabilities in MAX II. This was not performed due to lack of required diagnostics, but also because the purpose of the measurements was to evaluate the measurement method and simulation codes for future use at MAX IV. The measurements also proved valuable for adapting the three simulation codes to be able to compare to measurement data.

The measurements highlighted the importance of determining the energy spread and bunch length simultaneously in order to properly evaluate the effect of a HC. This is not only important for understanding how the energy spread varies with HC detuning, but also in order to evaluate the error of the bunch length measurement. The optical sampling oscilloscope measures time-averaged lengths. If instabilities are present the measured bunch length will be the sum of overlapping bunch profiles. It would therefore be advantageous to also develop a measurement method utilizing a fast diode. This was attempted during these measurements, but the setup was too unstable to give reliable results.

In these measurements the resonance frequency of the HC was measured with a spectrum analyzer, but this required dumping the beam first. This introduces a possible error source since the thermal load of the cavity changes, in addition to rendering a more tedious measurement process. Calibration of the HCs so the cavity detuning can be calculated from a measurement of the induced voltage would therefore be preferred. This is planned for MAX IV [18].

The simulations of MAX II give rise to new questions concerning the Robinson instability. Simulations 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 when operating the HC at flat potential conditions. This would require detuning of the MCs, which gives rise to beam loading that has to be compensated for by a feedback. The implementation of such a feedback in the code could then substantially influence the results. This has to be studied further for MAX IV, especially when considering non-uniform fill patterns as discussed in [8].

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