COMMISSIONING OF THE HARMONIC CAVITIES IN THE MAX IV 3 GeV RING

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Abstract

The MAX IV 3 GeV storage ring operates with beam of high current and ultralow emittance. These beam parameters in combination with the small effective aperture enhance possible collective beam instabilities. Three passive harmonic cavities are installed to introduce bunch lengthening and tune spread, leading to decoupling of the bunch spectrum from the machine effective impedance and mitigating instabilities by Landau damping respectively. In this paper we present the first results of the commissioning of the passive third harmonic cavities in the MAX IV 3 GeV ring. The additional harmonic cavity potential significantly improved the beam lifetime. First observations of the harmonic cavity effect on the damping of collective beam instabilities are discussed.

INTRODUCTION

The MAX IV 3 GeV machine [1] is the first ultralow emittance storage ring based on the multibend lattice, which is currently being commissioned in Lund, Sweden. The main parameters are presented in Table 1. To reach the design 500 mA beam current and emittance of 330 pm rad three harmonic cavities are introduced to relax intrabeam scattering (IBS), thus suppressing transverse emittance blow-up, and to improve Touschek lifetime. Furthermore, the harmonic cavity potential increases the synchrotron tune spread hence providing stronger Landau damping.

Table 1: MAX IV 3 GeV Ring Parameters

Energy	3.0	GeV
Current	500	mA
Circumference	528.0	m
Harmonic number	176	
RMS bunch length w/o HC	40	ps
RMS bunch length at 500 mA	195	ps
RF-frequency	99.931	MHz
Main cavity voltage	1.02	MV
Energy loss per turn w/o IDs	360	keV
Higher harmonic of HC	3	
Quality factor of HC [a]	21600	
Harmonic cavity detuning [a]	48.1227	kHz
Shunt impedance [a]	2.36441	MΩ

[a] listed harmonic cavity parameters provide flat potential at 500 mA current

Current Commissioning Status

MAX IV 3 GeV ring commissioning started in summer 2015 and is currently ongoing. The maximum reached stored current is 123 mA with harmonic cavities parked away from resonance. Two insertion devices were installed during a shutdown in February 2016 and commissioning of two beamlines has now started with the goal of delivering light by the machine inauguration in June 2016. The main commissioning results are presented in Table 2.

Table 2: MAX IV 3 GeV Ring Parameters During Commissioning

		Design	Achieved
Current	mA	500	123
RMS σ_0	ps	40	45
Emittance	pm rad	330	<400
Iτ	Ah	5	2.3

The beam is found to be longitudinally unstable already above 3 mA current. During the tests of bunch by bunch feedback system in February 2016 beam was kept stable up to 35 mA by appropriate choice of filling pattern. Temperature tuning of the main cavities suggested presence of the higher order modes which drive longitudinal coupled-bunch motion.

A diagnostic beamline for beamsize measurements [2] has been commissioned and was used to measure a horizontal emittance below 400 pm rad and a natural bunch length of 45 ps.

MAX IV DOUBLE RF SYSTEM

The harmonic cavities are resonant at the third harmonic of the main RF, f_{RF} = 99.931 MHz, and are operated passively so that the fields inside the cavities are excited by the stored beam. Figure 1 shows one of three harmonic cavities installed in the 3 GeV ring tunnel.

The additional harmonic cavity potential can be used to shape the total RF potential to the so-called flat potential condition where its first and second derivatives are zero at the synchronous phase [3], providing bunch lengthening and introducing synchrotron tune spread. When harmonic cavities are operated passively this condition is reached only at a certain harmonic cavity detuning and beam current. Figure 2 shows the flat potential and lengthened bunch expected with a passive harmonic cavity at the MAX IV 3 GeV ring for 500 mA beam current, as simulated using the tracking code *mbtrack* [4] .

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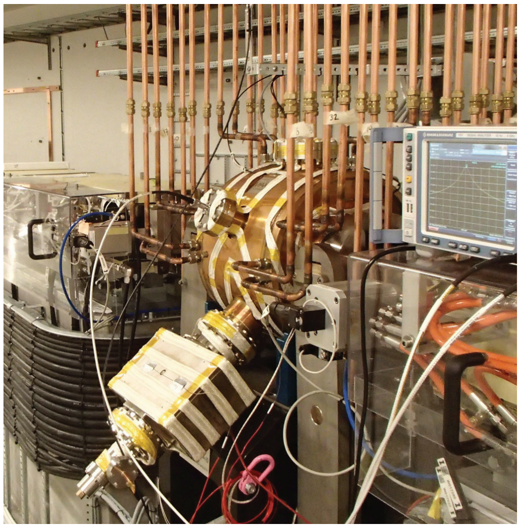

Figure 1: Passive third harmonic cavity in the MAX IV 3 GeV ring tunnel.

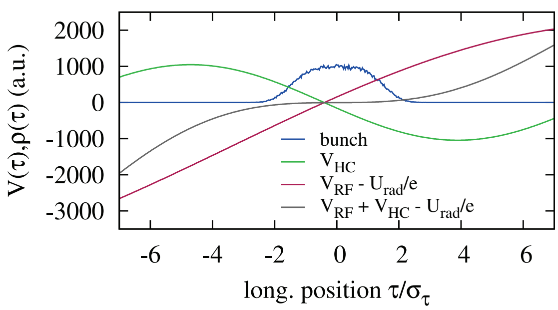

Figure 2: Flat potential provided by the double RF system in the MAX IV 3 GeV ring.

As well as damping instabilities harmonic cavities can also contribute to exciting them. When higher harmonic cavities are added to the RF system of an accelerator, unlike the main cavities, they are operated on the Robinson unstable slope. This requires careful investigation of the new conditions for Robinson damping: the damping provided by the main cavities has to exceed the excitation by the harmonic cavities, implying that the main cavities have to be detuned further away from the resonance to provide same overall Robinson damping.

Six main cavities are designed to provide a total voltage of 1.02 MV at 500 mA current. The shunt impedance of each harmonic cavity is 2.7 MΩ, however to achieve a factor five in bunch lengthening with the flat potential condition at 500 mA current only 2.3 MΩ is required in total. The excess shunt impedance reserved in three different cavities allows the flat potential condition to be achieved at lower currents, while a slightly asymmetric but equally long longitudinal bunch profile will be reached at 500 mA [5].

Tuning of cavities is done using a specially developed mechanism which slightly moves the sidewall of the cavity thereby changing the cavity capacitance. The available tuning range is ±500 kHz and is limited by the maximum copper deformation deemed acceptable.

START-UP OF HARMONIC CAVITIES

Before installation harmonic cavities were preconditioned at about 4 kW power in-house at MAX IV to achieve more stable vacuum levels during operation. Detailed mapping of longitudinal higher order modes in both the main and harmonic cavities was done [6, 7]. When installed, cavities were detuned to the position far from the resonance and 10 mA current was stored in the ring. After verifying that no significant fields were induced in the cavities and the operation of the machine is not affected, the cavity probe signals were calibrated assuming that the shunt impedance is known.

Stabilization of Longitudinal Coupled-bunch Motion

At low current with harmonic cavities detuned and running the machine with five main cavities the synchrotron tune was measured at f_s = 946 Hz corresponding to a total accelerating voltage of 1 MV. While tuning in the harmonic cavities closer to resonance we could follow the reduction in f_s shown in Figure 3 as well as damping of coupled-bunch longitudinal motion.

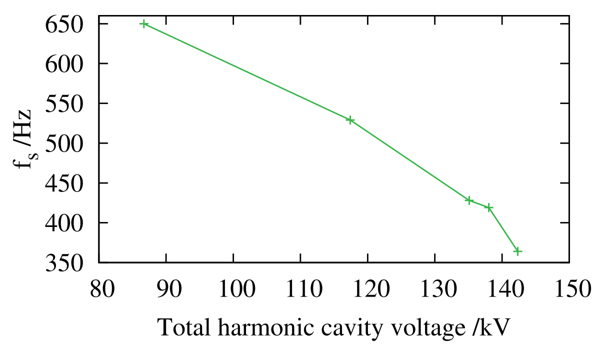

Figure 3: Reduction of f_s with harmonic cavities tuning closer to resonance.

Several experiments aiming to characterize the effect of harmonic cavities on the longitudinal coupled-bunch motion were done at 50 mA, 90 mA and 100 mA currents. With each increase in current more stabilization was achieved by tuning harmonic cavities. During the latest experiment 120 mA current was stored and harmonic cavities were slowly tuned closer to resonance. The beam spectrum was recorded during the tuning and beam spectra around $5f_{RF}$-f_{rev} (f_{rev} here is the revolution frequency) for the case when harmonic cavities are tuned out and the case of tuning point providing the most stable beam are shown in Figure 4

As the harmonic cavities were tuned in the number of sidebands significantly decreased leaving only the longitudinal dipole component seen on the spectrum analyzer. When harmonic cavities were tuned in further the number of synchrotron sidebands started to rapidly increase again. This

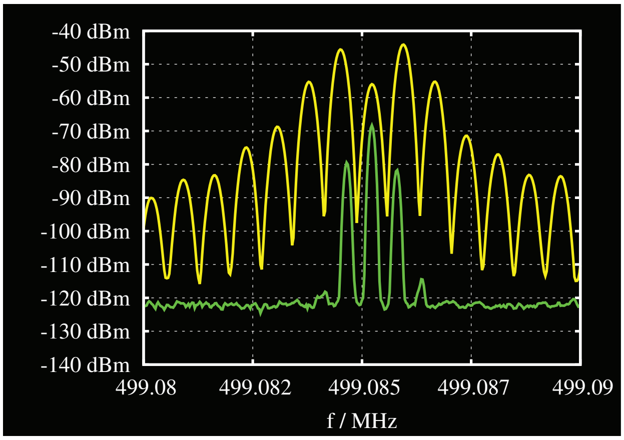

Figure 4: Spectra measured at different tuning points of harmonic cavities. In yellow is spectrum measured with harmonic cavities tuned out, in green is the most stable tuning point found for 120 mA current.

suggests that the beam becomes unstable since Robinson antidamping from the harmonic cavities exceeds damping provided by the main cavities.

Tuning in the harmonic cavities has also resulted in a significant increase of the beam lifetime shown in Figure 5. This proves the effectiveness of harmonic cavities in relaxing Touschek losses.

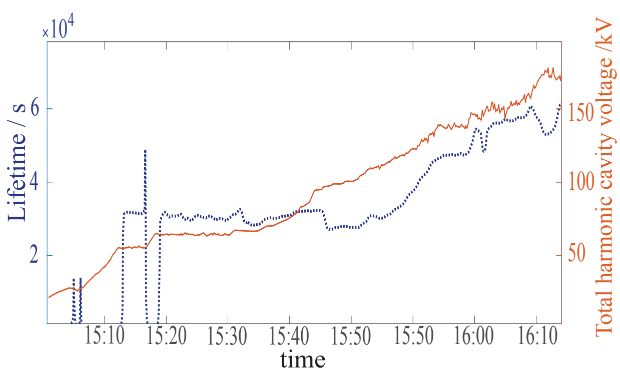

Figure 5: Lifetime(blue, dashed) increase following the increasing total field in harmonic cavities (brown, solid) as they were tuned in during the high current harmonic cavity commissioning shift.

In the current set up of the diagnostic beamline the bunch length can not be resolved in a single shot measurement but is averaged over many turns. Therefore, since bunch lengthening can not be distinguished from longitudinal coupled-bunch oscillations, no measurements of harmonic cavity induced bunch lengthening can currently be done.

DISCUSSION AND OUTLOOK

Characterization of the performance of harmonic cavities in the MAX IV 3 GV ring started in the spring 2016. During the latest experiments at 120 mA current they have shown to be effective in increasing the beam lifetime by a factor two and damp unstable longitudinal motion of higher than dipole order. Full stabilization has not been achieved so far. The possible reason for this is the tuning of the harmonic cavities too close to resonance into the Robinson unstable region where the antidamping exceeds damping from the main cavities and radiation damping. This is not expected to be an issue when machine starts operating with higher stored current.

The chosen parking and tuning of harmonic cavities has not disturbed other commissioning activities. The tuning mechanism was tested and can be used in routine operation of the harmonic cavities.

Future experiments will include measurements of bunch lengthening induced by the harmonic cavity potential. The electronics for measurements of the bunch length with a longitudinally unstable beam are currently not available but design work is ongoing.

To improve the vacuum lifetime the conditioning is continuously ongoing.

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