OPTIMIZING TOUSCHEK LIFETIME WITH OVERSTRETCHED BUNCH PROFILES IN THE MAX IV 1.5 GEV RING

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Abstract

Synchrotron light sources often use higher-harmonic rf cavities for bunch lengthening to enhance Touschek lifetime. By adjusting the harmonic voltage, a flat-potential condition for the longitudinal voltage can be achieved, typically improving Touschek lifetime by 4 to 5 times. It is known that exceeding the flat-potential voltage results in double-peaked bunch profiles, referred to as overstretched conditions. Simulations suggest overstretched profiles can surpass flat-potential improvements on lifetime. In this paper we report on experimental results from the MAX IV 1.5 GeV storage ring, demonstrating a longer beam lifetime with a stable beam in overstretched conditions compared to the flat-potential case. Additionally, a remarkable agreement between measured bunch profiles using a streak camera and predictions from a semi-analytical equilibrium solver was obtained for all tested harmonic voltages.

RING PARAMETERS

MAX IV is a synchrotron light source facility in Lund, Sweden. The complex has two storage rings, one operating at 1.5 GeV and the other is a fourth-generation ring operating at 3.0 GeV [1]. This work is focused on lifetime improvement with harmonic cavities (HCs) in the 1.5 GeV ring, whose relevant parameters for these studies are presented in Table 1. Two passive normal-conducting HCs operating close to the third-harmonic of the rf frequency are installed in the ring.

Table 1: Main parameters for the MAX IV 1.5 GeV ring.

Energy	E_0	1.5 GeV
rf frequency	f_{rf}	99.931 MHz
Harmonic number	h	32
Momentum compaction	α	3.05×10^{-3}
Energy spread	σ_δ	7.45×10^{-4}
Energy loss per turn	U_0	114.4 keV
HC shunt impedance (V^2/P)	R_s	5.5 MΩ/cavity
HC quality factor	Q	20 800

VOLTAGE CALIBRATION

Main cavities

With a low-current single-bunch stored in the ring and the HCs parked (no HC fields), the synchrotron frequency was measured as $f_s = 7.18$ kHz. For a single-rf system, the relation between synchrotron frequency and main rf voltage is well-known [2]. Given a measured value of synchrotron frequency f_s, the relation can be inverted to determine the main voltage:

$$V_{rf} = \left[\left(\frac{f_s}{f_{rf}} \right)^4 \left(\frac{\alpha}{2\pi h E_0} \right)^2 + U_0^2 \right]^{1/2}. \tag{1}$$

For the parameters of Table 1, the measured synchrotron frequency corresponds to a main rf voltage of $V_{rf} = 522.3$ kV. This value was used throughout the analysis.

Harmonic cavities

For zero detuning and uniform fill, the peak HC voltage should be simply $V_{HC} = R_s I_0$ [5], where R_s is the HC shunt impedance and I_0 is the stored beam current. To calibrate the voltage of the HCs , 2.3 mA was accumulated uniformly in the ring and the HCs were tuned to resonance. This was achieved by maximizing the HC voltage readouts. The stored current was then reduced in steps to 0.3 mA using a beam scraper and the corresponding HC voltages were recorded for each current value. For each current, the HCs tuning was adjusted to keep the cavities on resonance. A linear calibration curve was obtained from the measured HC voltage in hardware units vs. expected voltage by $R_s I_0$.

FITTING HARMONIC VOLTAGES FROM STREAK-CAMERA MEASUREMENTS

The bunch profiles were measured with a streak-camera. The streak-camera provides a 2d image with an axis corresponding to a fast scan, with a timescale within bunch separations (ns) and an axis related to a slow scan, with a timescale within a revolution period (µs) [3]. In Fig. 1 an example streak-camera image is shown. The time axis can be converted to the z-coordinate by $\tau = z/c$, where c is the speed of light.

The equilibrium bunch profiles in the presence of HC voltage can be calculated by solving self-consistently the Haissinski equation [4]. Let $\lambda_{meas}(z_i)$ be the measured bunch profile along the axis z_i and averaged over bunches. The goal was to find the HC voltage that best reproduces the measured bunch profile. Two fitting parameters were used: the HC voltage $V_{fit}(z)$ (amplitude and phase determined by the HC detuning) and an offset z_{fit} to match the measured and simulated z_i-axis. This offset was included as an optional fitting parameter just to automatically account for the undetermined offsets between the axis.

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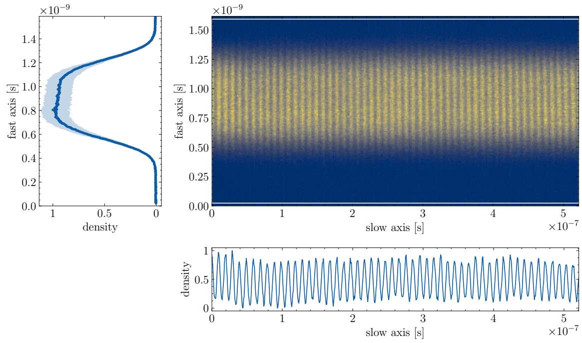

Figure 1: Example of streak-camera image acquired with 200 mA in uniform fill. Left: the solid curve is the average projection along the slow axis and the shaded region is the std variation over bunches.

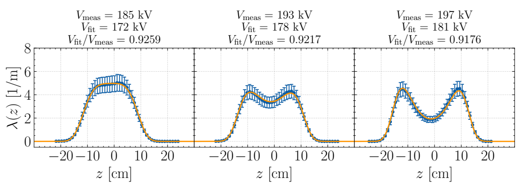

Figure 2: Measured and calculated bunch profiles for 200 mA. Dots represent the average and error bars represent the variation of charge densities over bunches.

The HC voltages were obtained by solving the least-squares minimization problem:

$$\chi^2 = \sum_i \left[\lambda_{\mathrm{meas}}(z_i) - \lambda(z_i - z_{\mathrm{fit}}, V_{\mathrm{fit}})\right]^2, \tag{2}$$

where $\lambda(z, V_{\mathrm{fit}})$ is the equilibrium bunch distribution calculated in the double-rf system. We noted the same results were obtained when including beam-loading voltage from main cavities and, for simplicity, only beam-loading from HCs was considered.

A comparison between measured and calculated bunch profiles is presented in Fig. 2. The HC voltages needed to match the calculated and measured bunch profiles are systematically lower than the measured voltages. A constant difference could be explained by an error in the shunt impedance considered in the calibration, for example. However, the discrepancy increases linearly with the total voltage[1], as shown in Fig. 3.

Based on the difference between fit and measured voltages, the linear coefficient of HC voltage calibration curve was readjusted by a factor 0.93. This makes the total measured voltage of 180 kV match with the value that reproduces the measured bunch profiles. However, a small discrepancy that increases with the voltage remains, reaching an error of $0.915/0.93 = 0.98$ for the highest measured voltage of 210 kV. The adjustment of 0.93 could be interpreted as if the actual shunt impedance of the two HCs is 5.115 MΩ, i.e., 7% lower than the value of 5.5 MΩ considered previously. This estimated error is considerably larger than bench measurements indicate. Even so, for this study, the HC voltage values were adjusted by the 0.93 factor.

[1] The calibration of HC voltages was measured at low currents, setting the cavities on resonance which is impossible at higher currents. The discrepancy makes us question the validity of this linear calibration curve for higher currents. Perhaps some non-linearity in the voltage measurement device in the cavity could explain a non-linear calibration curve.

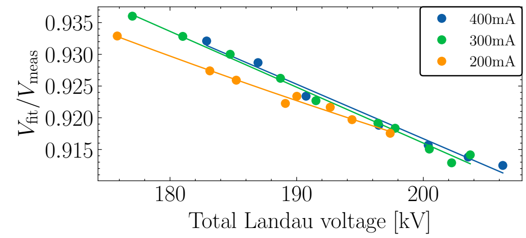

Figure 3: Ratio between calculated and measured HC voltages for fitting bunch profiles at different beam currents.

LIFETIME OPTIMIZATION

The increment in Touschek lifetime due to the bunch lengthening provided by the HCs can be estimated by [5]:

$$\frac{\tau_{\mathrm{HC}}}{\tau_0} = \frac{\int \lambda_0^2(z)dz}{\int \lambda_{\mathrm{HC}}^2(z)dz}, \tag{3}$$

where $\lambda_0(z)$, $\lambda_{\mathrm{HC}}(z)$ are the normalized bunch profiles without and with HC fields, respectively. This calculation assumes that the effect of HCs on energy acceptance is small, which is typically a good approximation.

It is known from simulations that profiles corresponding to HC voltages higher than the flat potential case can be better for lifetime improvement [4, 6]. In this condition, referred as overstretched, the bunch profiles have a double-peaked shape. To investigate this experimentally, the HC voltage was adjusted above flat potential, while measuring the bunch profiles and the beam lifetime as well. For the main rf voltage of 522.3 kV used during the experiment, the flat potential HC voltage is 169.3 kV. The measurements were carried out with three different values of stored currents in uniform fill.

In the first run with 200 mA, we observed that for 185 kV (9% above the flat potential voltage), a coupled-bunch mode-0 instability was excited, probably a Robinson instability driven due the small detuning of the harmonic cavities (130 kHz in this case). The mode-0 instability limited the maximum value of HC voltage for the scan at 200 mA. Figure 4 show the results for the first sequence of measurements.

For the second run, the stored current was increased to 300 mA. At higher currents the same HC voltage is achieved with a larger detuning, thus the Robinson instability could be avoided. However, for 188 kV, coupled-bunch instabilities were excited by higher-order modes (HOMs) of the HCs. After temperature tuning of HCs , the HOMs' frequencies shifted and the instabilities were suppressed. At the new operating temperatures, it was possible to further increase the HC voltage while keeping the beam stable.

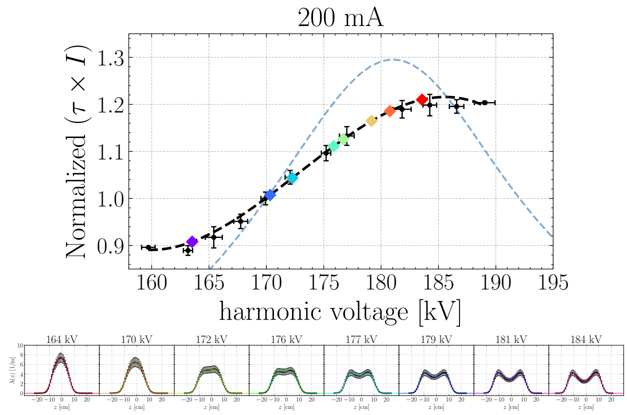

Figure 4: Experimental results of the product lifetime × current, normalized by the same product measured with HC voltage of 170 kV (flat potential). Measurement carried out with 200 mA in the ring. The normalization value is $(\tau \times I)_{\text{flat}} = 4604$ mA h, corresponding to a total lifetime of 23 h at 200 mA. The blue dashed curve is the calculated lifetime from Eq. (3) with the corresponding bunch profiles for each HC voltage. The black dots and error bars represent the mean and variation of voltage measured in a short period, respectively. The colored markers indicate the voltages in which bunch profile measurements were taken. The sequence of measured and calculated profiles for each HC voltage is presented in the bottom plots.

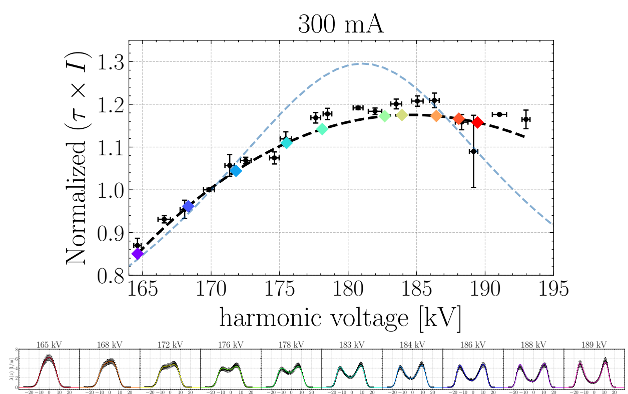

Figure 5: Same experiment as shown in Fig. 4 with a higher current of 300 mA. The normalization value measured with HC voltage of 170 kV is $(\tau \times I)_{\text{flat}} = 5712$ mA h, corresponding to a lifetime of 19 h at 300 mA.

The results obtained at 300 mA are shown in Fig. 5, where the negative impact of the coupled-bunch instabilities on lifetime is evident at 188 kV.

A final set of measurements at 400 mA was made. The temperature tuning that cured the coupled-bunch instabilities at 300 mA was maintained. Different from the other two cases, the initial value of HC voltage was already set to flat potential voltage of 170 kV, taking into account the identified calibration error. No instabilities were experienced in this run and the results are shown in Fig. 6.

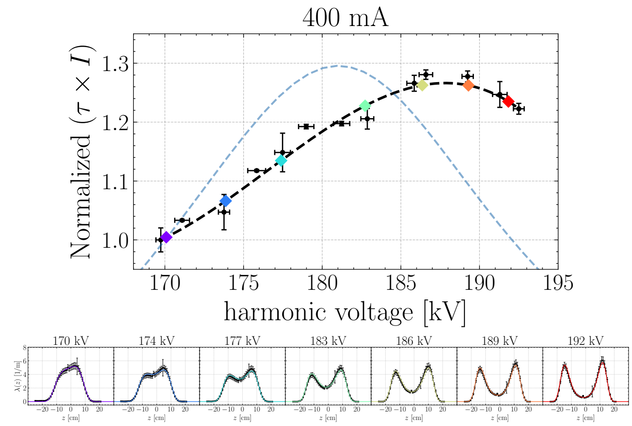

Figure 6: Same experiment as shown in Figs. 4 and 5 with a higher current of 400 mA. The normalization measured with 170 kV of HC voltage is $(\tau \times I)_{\text{flat}} = 4642$ mA h, corresponding to a lifetime of 11.6 h at 400 mA. The point close to $z = 5$ cm with large variation in intensity should be just an artifact from the streak-camera acquisition.

DISCUSSION AND CONCLUSION

The results shown in Figs. 4, 5 and 6 confirm that operating with HC voltages beyond the flat potential can help to improve beam lifetime. Moreover, we were able to find in simulation the HC voltages that produced bunch profiles in close agreement with streak-camera measurements. This fitting process has the potential to be useful as a beam-based calibration of HC voltages at high current. Benchmarking against other calibration methods is required for validation.

Experiments with stored beam currents of 200 mA and 300 mA were limited by beam instabilities. The product (lifetime × current) was higher with 300 mA compared to 200 mA and 400 mA, suggesting that other uncontrolled factors were affecting the lifetime in this case. Interestingly, the beam remained stable at the highest current of 400 mA, allowing acquisitions with highly overstretched bunches.

Overall, the observed improvement in lifetime with HCs did not match the theoretical expectation based on Eq. (3). The best HC voltage for lifetime was consistently higher than expected and the range of voltages producing longer lifetimes in practice is broader than predicted. This could be because Eq. (3) assumes that, except for the longitudinal density, all parameters remain constant, while they may vary in reality. Additionally, the formula only considers the impact of HCs on Touschek lifetime, while the total lifetime was measured. Further studies are needed to investigate these differences.

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REFERENCES

[1] MAX IV Detailed Design Report, https://www.maxiv.lu.se/beamlines-accelerators/accelerators/accelerator-documentation-2/

[2] M. Sands, "The Physics of Electron Storage Rings: An Introduction" *Conf. Proc. C* **6906161**, 257–411 (1969), SLAC-R-121, SLAC-121.

[3] M. Brosi, "Diagnosing collective effects in the MAX IV storage rings" presented at I.FAST, Karlsruhe, 2022, https://indico.scc.kit.edu/event/2592/contributions/10368/attachments/5037/7789/IFAST_presentation_mbrosi.pdf

[4] M. B. Alves and F. H. de Sá, "Equilibrium of longitudinal bunch distributions in electron storage rings with arbitrary impedance sources and generic filling patterns" *Phys. Rev. Accel. Beams 26*, 094402 (2023)

[5] J. M. Byrd and M. Georgsson, "Lifetime increase using passive harmonic cavities in synchrotron light sources" *Phys. Rev. ST Accel. Beams* **4**, 030701 (2001), https://link.aps.org/doi/10.1103/PhysRevSTAB.4.030701.

[6] G. Penco and M. Svandrlik, "Experimental studies on transient beam loading effects in the presence of a superconducting third harmonic cavity" *Phys. Rev. ST Accel. Beams* **9**, 044401 (2006), https://link.aps.org/doi/10.1103/PhysRevSTAB.9.044401.