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TRANSVERSE MODE-COUPLING INSTABILITY WITH LANDAU CAVITIES AT THE MAX IV LABORATORY 1.5 GEV RING

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Abstract

Collective effects can have a strong influence on the beam stability and performance in synchrotron light sources. Landau cavities or RF harmonic cavities are a tool that is employed at 4th generation storage ring light sources to reduce the impact of or even prevent instabilities arising from collective effects. The positive effect of Landau cavities is based on the lengthening of the electron bunches and an increase in synchrotron tune spread. Recent theoretical calculations by M. Venturini (2018) predict however, that at zero chromaticity, the threshold current of the transverse mode-coupling instability (TMCI) was reduced in the presence of Landau cavities.

This contribution presents measurements conducted at the MAX IV 1.5 GeV storage ring, where, to test the prediction, the TMCI threshold was measured with and without bunch-lengthening using passive Landau cavities. The effect at non-zero chromaticity was also investigated.

INTRODUCTION

In modern storage ring based synchrotron light sources, Landau cavities (higher harmonic cavities) are often used to lengthen the electron bunches and increase the synchrotron tune spread in an effort to raise the overall stability to achieve the conditions required to maintain ultra-low emittances. Therefore, the interplay of Landau cavities and collective effects is an active topic of research. Two relevant single-bunch instabilities in such machines are the transverse mode-coupling instability (TMCI) for zero chromaticity and at non-zero chromaticity the transverse head-tail instability which can lead to strong bunch movements and often partial or complete loss of beam current.

The interplay of Landau cavities and these transverse instabilities was experimentally studied at the 1.5 GeV ring at the MAX IV laboratory [1]. While the 1.5 GeV ring is a third-generation synchrotron light source, it operates with two passive Landau cavities at 300 MHz [2]. The two main RF cavities are driven at 100 MHz. The ring has a circumference of 96 m and serves currently 5 beam lines with a focus on UV synchrotron radiation. It consist of an ultra-compact double-bend achromat lattice with combined function magnets providing a horizontal emittance of 6 nmrad. During standard operation, the ring is operated in top-up mode.

Theoretical prediction

In the recent paper [3] by M. Venturini, theoretical calculations show that for the TMCI, under the assumption that it is purely driven by the resistive wall impedance, the threshold current is lowered by the presence of tuned-in Landau cavities.

Their method of calculation is based on mode analysis of the linearized Vlasov equation. They used two modifications to the traditional approach, to account for the non-linearity of the perturbation to the single-particle longitudinal dynamics resulting in a singularity in the linearized equations for the collective modes. Representing the radial functions of the modes on a grid is combined with using a more complex characteristic polynomial instead of a linear eigenvalue problem to find the growth rates of unstable modes.

The calculations show, that the transverse single-bunch motion is unstable for zero chromaticity at any currents. As the growth rate decreases with decreasing current, the radiation damping is expected to stabilize the beam at low enough bunch currents. The final estimate for 4th generation light sources is, that for resistive wall dominated impedances, the threshold current of the TMCI is lowered by at least a factor of two, compared to the case without Landau cavities present.

MEASUREMENT METHOD

The presented measurements were conducted during special study shifts, where the beam parameters could be varied as required. This included, for example, lowering the vertical chromaticity and changing between a single bunch and multi-bunch filling pattern.

In a first step the vertical instability threshold current was determined using a single-bunch fill at different values of the vertical chromaticity. These points serve as reference for the thresholds without a Landau cavity present, as in single bunch operation the beam current is too low to drive the passive cavities. Additionally, the cavities were detuned. Previous experiments have shown, that the vertical TMCI threshold current can differ slightly for the case when the threshold is crossed from unstable to stable beam opposed to crossing it from stable to unstable beam, due to the inherent blow up of the transverse size in the unstable state ([4] Sec. IV A). For the presented measurements, the threshold is determined by injecting with a rather low injection rate (low charge per shot) while continuously monitoring the fluctuations (rms) of the center-of-mass position measured from a BPM. To this end, a Bunch-by-Bunch (BBB) feedback system by Dimtel is used [5]. This also allows, the monitoring of the beam spectra, which will show a strong peak at the tune frequency as soon as the instability threshold is crossed. When the threshold is crossed the injection is stopped and the purity of the single bunch filling pattern is checked with the help of a time-correlated single-photon counting (TC-

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Table 1: Beam Parameters

Parameters	Values
RF voltage / kV	520
Synchrotron freq. / kHz	7.178
Beam energy / GeV	1.5
Vertical tune	3.15
Horizontal tune	11.22
Chromaticity (vert.)	0.06 - 3.2
Chromaticity (hori.)	1.3
Harmonic number	32
Nominal beam current / mA	500

SPC) setup [6] installed at the visible light diagnostic beam line [7].

To determine the threshold current with the Landau cavities tuned in, the measurements were repeated with a homogeneous multi-bunch filling pattern. In this way, the beam current is sufficient to drive the tuned-in Landau cavities resulting in a significant bunch lengthening effect. Again, the threshold current was determined by injecting with a low injection rate while monitoring the beam stability. To ensure that the determined Instability threshold current is from the single-bunch instability, the BBB feedback system was configured to act on all bunches except one in the vertical plane and on all bunches in the longitudinal plan. This stabilised the bunches longitudinally and prevented multi-bunch instabilities to arise. The Landau cavities amplitudes were set to generate flat-potential conditions, which was crosschecked by measuring the longitudinal bunch profiles with a dual sweep streak camera set up at the visible light diagnostic beam lines. A flat-potential value for the Landau cavity voltage of 170 kV was calculated.[1]

In the presented measurement, only the vertical TMCI and Head-Tail instability were discussed. The horizontal TMCI threshold was observed at significantly higher threshold currents (≈ 27 mA at near zero chromaticity) in single bunch operation without Landau cavities in comparison to the vertical threshold. The determination of the threshold in the presence of tuned-in Landau cavities, was unsuccessful due to the limitation on the total beam current. This limit was reached before the instability threshold could be observed.

RESULTS

The results of the measurement are depicted in Fig. 1. The dots indicate the measurements made in single-bunch operation where the Landau cavities were detuned and not driven by the beam. The threshold current without Landau cavities is 8.45 mA for a vertical chromaticity close to zero ($\xi_v = 0.06$). With increasing chromaticity, the threshold first decreases to around 3 mA in the range of $\xi_v \approx 1-2$ and then increases again with increasing chromaticity. For negative

[1] Since independent control of voltage and phase is not possible with passive Landau cavities, this does not provide the strict flat-potential condition assumed by Venturini but is close for the relevant beam currents.

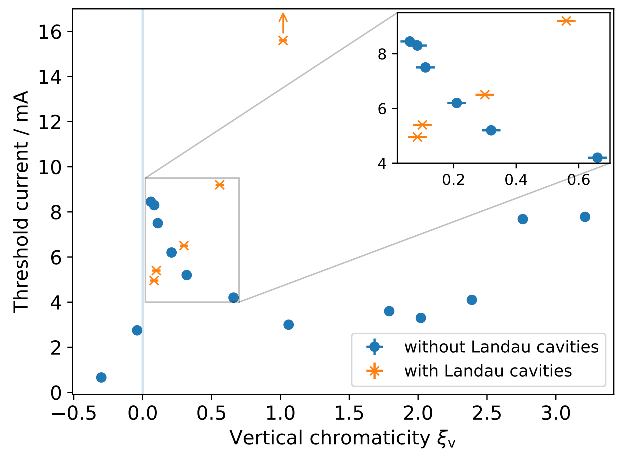

Figure 1: Measured thresholds currents for the vertical single-bunch instability are shown as a function of the vertical chromaticity. Measurements with de-tuned Landau cavities are shown as blue dots and measurement with the Landau cavities tuned-in are shown as orange crosses. The arrow at $\xi_v \approx 1$ indicates that threshold (with Landau cavities) was determined to be above the bunch current limit in multi-bunch operation and therefore outside the measurable range.

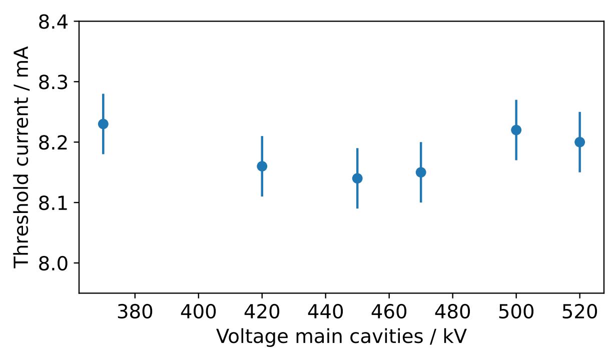

Figure 2: Measured threshold current at $\xi_v \approx 0.08$ without Landau cavities as a function of the RF voltage in the main cavities.

chromaticity values, the threshold is lower and also shows the tendency to decrease towards more negative chromaticity values. The depicted threshold currents were measured at a main acceleration voltage of 520 kV (see Table 1 for beam parameters). In Fig. 2, it is visible that the dependency of the threshold current (at $\xi_v \approx 0.08$) on the main acceleration voltage is small compared to the dependence on the chromaticity and shows no clear correlation. This indicates that the influence of the RF slope and the synchrotron tune is canceled out [8] in the absence of Landau cavities.

The measurements with the tuned-in Landau cavities are depicted by crosses (Fig. 1). For a near-zero chromaticity, the threshold is around 4.95 mA and significantly below the threshold current observed in the case without Landau cavities. With increasing chromaticity the threshold with Landau cavities rises fast. Already at a chromaticity of 1, the thresh-

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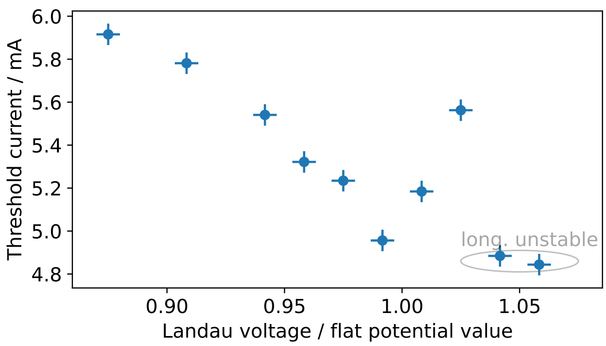

Figure 3: The measured TMCI threshold (at $\xi_v \approx 0.08$) as a function of the Landau-cavity voltage (shown as a fraction of the flat-potential value). For two points at the highest voltage, the beam was longitudinal unstable.

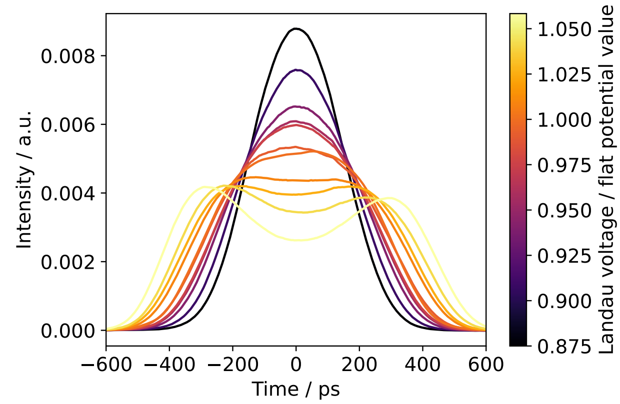

Figure 4: Longitudinal bunch profiles measured for different Landau-cavity voltages around the flat-potential condition to show the changes in the bunch lengthening.

old is higher than the individual bunch current limit when all RF buckets are filled (15.625 mA × 32 = 500 mA, the maximum allowed stored beam current), so that the threshold could not be determined for a chromaticity of 1 and higher. The measured thresholds at close to zero chromaticity show a destabilizing effect on the TMCI instability by bunch lengthening with Landau cavities, as predicted by Venturini. The threshold of the TMCI is lowered by the presence of tuned-in Landau cavities by a factor ≈ 1.7 at $\xi_v \approx 0.08$. Which, when following the trend for each threshold (Fig. 1) to zero chromaticity, is close to the estimated factor of two in the prediction.

To check the influence of the Landau cavity tuning parameters, a scan of the TMCI threshold (at $\xi_v \approx 0.08$) as function of the voltage in the Landau cavities was conducted. The voltages is shown as a fraction of the flat-potential value. Figure 3 shows the measured threshold currents and Fig. 4 shows the corresponding average longitudinal bunch profile measured with a streak camera. The threshold current has a minimum at a Landau voltage around 1, which corresponds to the condition at the flat potential. This means for "under"stretched bunches as well as over stretched bunches the threshold current is higher. For the two points at the highest voltage, the beam was additionally longitudinally unstable, which could explain why these point do not follow the trend. Towards smaller Landau voltages, corresponding to less stretched bunches, the trend shows that the TMCI threshold increases. This fits very well to the observation and prediction that the threshold without Landau cavities lengthening the bunch is significantly higher than for a stretched bunch. This also already suggests, that operating at Landau setting slightly off the full flat-potential conditions could lead to a less drastic decrease of the threshold current. These observations fit to the observed influence of "non-ideal lengthening" conditions on single bunch instabilities which were shown in simulations recently [9].

In conclusion, it can be said that, for close to zero chromaticity, the dependence on the main acceleration voltage (in the case without Landau cavities) as well as the dependence on the precise Landau-cavity voltage is not nearly as big as the observed decrease in threshold current caused by tuning in the Landau cavities. This is only valid at close to zero chromaticity, so for the TMCI instability. Already at a chromaticity of $\xi_v \approx 0.2$, this inversion ceases and the Landau cavities lead to an increase in observed threshold current.

SUMMARY

Measurements of the vertical single-bunch instability threshold were conducted at the 1.5 GeV ring at the MAX IV Laboratory. The threshold current was determined as a function of the vertical chromaticity, and that for two conditions: first with the Landau cavities de-tuned (no bunch-lengthening) and second with the Landau cavities tuned in to lengthen the bunches.

The experimental results agree with the prediction by M. Venturini. It could be shown, that in the case of zero (or very near to zero) chromaticity the presence of tuned-in Landau cavities lowers the TMCI threshold compared to the case without Landau cavities. For standard operation, this effect does not affect the stability, as for higher chromaticities, the threshold current with Landau cavities increases rapidly. The threshold curves for the two cases cross at 0.22 vertical chromaticity.

A scan over the voltage in the Landau cavities shows that the TMCI threshold is the lowest for the measurements closest to the full flat-potential condition. The threshold increases in the direction of less lengthening as well as in the direction of overstreched bunches. This again confirms, that the drastic reduction of threshold current is not connected to the simple lengthening of the bunch but is coupled to the flattening of the RF potential.

As a future step, one could attempt the measurement in an even fill where only every other or every third bucket is filled and therefore increasing the possible bunch current. On the other hand, such a fill pattern would be more influenced by short-range longitudinal wakes which could cause the bunch lengthening to be further from ideal.

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REFERENCES

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

[2] F.J. Cullinan and Å. Andersson and P.F. Tavares, "Longitudinal Stability with Landau Cavities at MAX IV", *Proc. IPAC'20*, June 2020. doi:10.18429/JACoW-IPAC2020-WEVIR05

[3] M. Venturini, "Harmonic cavities and the transverse mode-coupling instability driven by a resistive wall," *Phys. Rev. Accel. Beams*, vol. 21, no. 2, p. 024402, Feb. 2018, doi:10.1103/PhysRevAccelBeams.21.024402

[4] M. Brosi, F. Cullinan, Å. Andersson, J. Breunlin, and P. F. Tavares, "Asymmetric influence of the amplitude-dependent tune shift on the transverse mode-coupling instability," *Phys. Rev. Accel. Beams*, vol. 27, no. 10, p. 104402, Oct. 2024, doi:10.1103/PhysRevAccelBeams.27.104402

[5] Dimtel, Inc., https://www.dimtel.com/.

[6] M. Brosi, J. Schmand, J. Breunlin, and F. Curbis, "Time-Correlated Single-Photon Counting for versatile longitudinal diagnostics at the MAX IV Laboratory storage rings," *J. Inst.*, vol. 20, no. 03, p. P03011, Mar. 2025, doi:10.1088/1748-0221/20/03/P03011

[7] J. Breunlin and Å. Andersson, "Emittance Diagnostics at the Max Iv 3 Gev Storage Ring", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2908–2910. doi:10.18429/JACoW-IPAC2016-WEPOW034

[8] R. Nagaoka and K. L. F. Bane, "Collective effects in a diffraction-limited storage ring," *J. Synchrotron Radiat.*, vol. 21, no. 5, pp. 937–960, Sep. 2014, doi:10.1107/S1600577514015215.

[9] H.-S. Xu, J.-Y. Xu, and N. Wang, "Influences of harmonic cavities on single-bunch instabilities in electron storage rings," *Nucl. Sci. Tech.*, vol. 32, no. 9, p. 89, Sep. 2021, doi:10.1007/s41365-021-00926-7.