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LONGITUDINAL STABILITY WITH LANDAU CAVITIES AT MAX IV

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Abstract

The use of Landau cavities was foreseen for both the 1.5 GeV and 3 GeV storage rings at the MAX IV facility from conception. Along with increasing the Touschek lifetime and reducing the emittance degradation due to intrabeam scattering, their purpose is to stabilise the beam in the longitudinal plane. They now play a crucial role in the everyday operation of the two storage rings. This paper outlines the current status and the aspects of longitudinal beam stability that are affected, positively or negatively, by the presence of Landau cavities. Their effectiveness in the two storage rings is also compared.

INTRODUCTION

MAX IV is a synchrotron light source facility in Lund, Sweden. It includes two storage rings: one at 1.5 GeV and another at 3 GeV whose circumference is more than five times larger than the first. A linac injects both rings at full energy and also functions as a light source for the generation of short x-ray pulses. The smaller of the two storage rings has a double-bend achromat lattice while the larger ring, with its multibend-achromat lattice, is a fourth-generation storage ring that is capable of delivering ultrahigh-brightness X-rays because of the low bare-lattice horizontal emittance of 330 pm rad. Both rings operate in top-up during delivery of light to users. Table 1 lists the main parameters of the two storage rings with focus on the RF cavities which are at the same frequency in both rings [1].

Table 1: Selected machine parameters of the MAX IV storage rings. The lengths of the lengthened bunches are for 500 mA with flat potential conditions.

Parameter		1.5 GeV Ring	3 GeV Ring
RF frequency	MHz	100	
Landau-cavity harmonic		3	
Design current	mA	500	
Landau-cavity...			
...shunt impedance	MΩ	2.5	
...quality factor		20800	
Main-cavity loaded...			
...shunt impedance	MΩ	0.569	0.310
...quality factor		6760	3690
Natural bunch length	ps	49	40
Lengthened bunch	ps	195	196
Harmonic number		32	176
Momentum compaction		0.000306	0.003055
Bare-lattice energy loss per turn	keV	363.8	114.4
Number of...			
...main cavities		2	5
...Landau cavities		2	3

Each ring has a double RF system with Landau cavities at the third harmonic of the main RF. The Landau cavities are made of copper, like the main RF cavities, and are passively loaded by the beam itself. In bunch-lengthening mode, the Landau cavities are detuned so that the resonant frequency of their fundamental mode higher than the RF harmonic and to increase or decrease the field level, the detuning is decreased or increased respectively. During operation, autotuning in the low-level RF is used to maintain the cavity voltage at a fixed value [2]. The variation along the bunch of the voltage in the Landau cavities is opposite to that in the main RF cavities so that the total RF voltage is flatter than with a single-RF system. This leads to longer electron bunches which reduces the scattering of electrons within the bunch and this means lower emittance and energy spread and a longer beam lifetime. Furthermore, lengthening the bunches with Landau cavities increases the threshold of certain collective instabilities in both the transverse [3] and longitudinal planes. This paper deals mostly with longitudinal coupled-bunch instabilities in the longitudinal plane, which are the dominant instabilities in both storage rings at MAX IV. These are driven by higher-order modes (HOMs) in the main and Landau cavities, which have no HOM dampers. Landau-cavity bunch lengthening is advantageous in this regard because of two reasons. The first is that the longer bunches have lower form-factors at the frequencies of the higher-order modes and so excite them less strongly. The second is the large spread in the synchrotron tune within the bunches, which means Landau damping of collective instabilities.

The two storage rings at MAX IV present a rare opportunity because the impedances driving the dominant instability in each ring are so similar, differing only in magnitude due to the different cavity numbers. Furthermore, the two rings have been commissioned and ramped in current more or less simultaneously and the observation of longitudinal instabilities during this time differed considerably. A comparison of the current statuses of the two rings in terms of longitudinal stability is listed in Table 2.

LONGITUDINAL STABILITY

This section summarises the different issues in the two storage rings that affect the longitudinal stability and how they are dealt with.

Robinson Mode Coupling

For bunch lengthening, Landau cavities must be tuned slightly higher than the third harmonic of the main RF. At this frequency, they destabilise the Robinson dipole and

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Table 2: Comparison of the statuses of the two MAX IV storage rings in terms of longitudinal stability. The delivery current in the 1.5 GeV ring is limited by heating of beamline components while in the 3 GeV ring, it is limited by the available RF power.

Ring		**1.5 GeV**	**3 GeV**
Delivery current		400	250
Stable current range	mA	130-500	57–250
Temperature tuning		Minimal	Extensive
Longitudinal feedback		None	Mode-0 phase
Fill pattern		Uniform	Short gap

quadrupole modes (all bunches moving in unison). However, more than enough Robinson damping comes from the main cavities, which are tuned to below the RF generator frequency to match the beam-loaded cavity to the RF transmitter, so that the Robinson dipole and quadrupole modes are stable. However, as the Landau cavities are tuned closer to the third RF harmonic, increasing the field amplitudes and lengthening the bunches, the frequency of the Robinson quadrupole mode decreases while the frequency of the Robinson dipole mode stays roughly constant. This was measured in the two storage rings and compared with theory, as shown in Fig. 1 for the 1.5 GeV ring and Fig. 2 for the

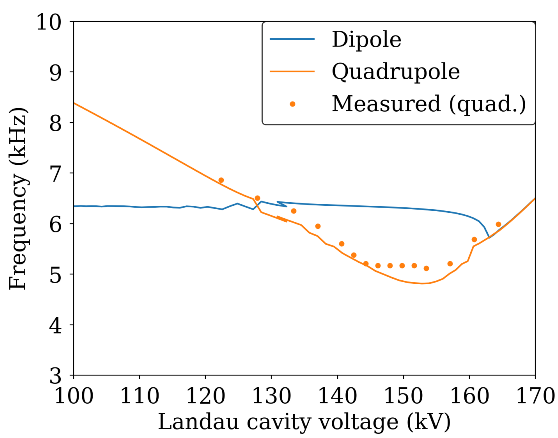

Figure 1: Measured Robinson mode detuning in the 1.5 GeV ring in comparison to the theoretical prediction shown by the solid lines.

3 GeV ring, where the measured energy spread is also shown to show the stability of the beam.

In both rings, it can be seen that at a certain point, which is just before the total RF voltage is fully flattened (zero first derivative at the synchronous phase), the frequencies of the two modes meet. In the 3 GeV ring, a fast-growing coupled Robinson mode instability is observed and so a mode-0 phase feedback [4] was installed for active damping. In the 1.5 GeV ring, on the other hand, no such coupling instability is observed. The most probable reason for this is the excess Robinson damping of the dipole mode in the

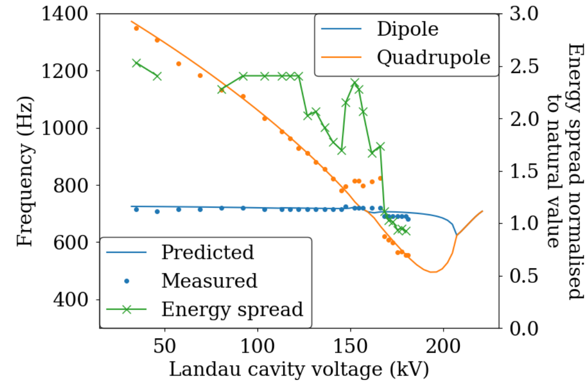

Figure 2: Measured Robinson mode detuning in the 3 GeV ring in comparison to the theoretical prediction shown by the solid lines with the energy spread also shown.

1.5 GeV ring, which is around 100 times faster than in the 3 GeV ring due to the different optimum detuning of the main cavities. This is also thought to be one reason why it was difficult to measure the dipole mode frequency during the experiment in the 1.5 GeV ring. In both rings, the agreement with theory [5] is good, although the horizontal axes for the experimental data had to be rescaled in both cases, most likely due to an error in the calibration of the Landau-cavity fields.

Coupled-bunch Modes

Coupled-bunch modes other than the Robinson mode are typically driven by higher-order modes in the cavities. In the absence of HOM dampers, it is important to try to tune the higher-order modes away from the revolution harmonics. At MAX IV, this has been done using temperature tuning, and again, a large difference was seen between the two rings in terms of the extent to which temperature tuning was necessary, as mentioned in Table 2. One useful tool in the temperature tuning process is transient measurements using the bunch-by-bunch (BBB) feedback system: grow/damp measurements or drive/damp measurements [6]. These are performed above and below the instability threshold respectively and are both ways to directly measure the growth rate of coupled-bunch modes. In the latter case, one coupled-bunch mode is driven by the actuator in the BBB system, which simultaneously damps all other coupled-bunch modes. Then, both the drive and the damping are turned off for a short period (typically ~100 ms) during which time the excited coupled-bunch mode is left to decay at its characteristic rate. In the case of a grow/damp measurement, the spontaneous growth of the least-stable coupled-bunch modes are simply measured above threshold when the longitudinal BBB feedback is switched off for a similarly short period.

Figures 3 and 4 each show the results of drive/damp measurements on a pair of coupled-bunch modes (since the HOM that drives one coupled-bunch mode will damp that mode's complement) in each storage ring. Coupled-bunch mode 167

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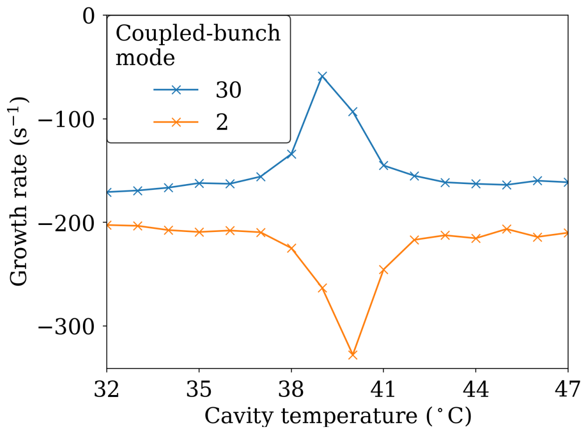

Figure 3: Results of drive/damp measurements of coupled-bunch mode 30 and its complement mode 2 in the 1.5 GeV ring for different temperatures of one of the main cavities.

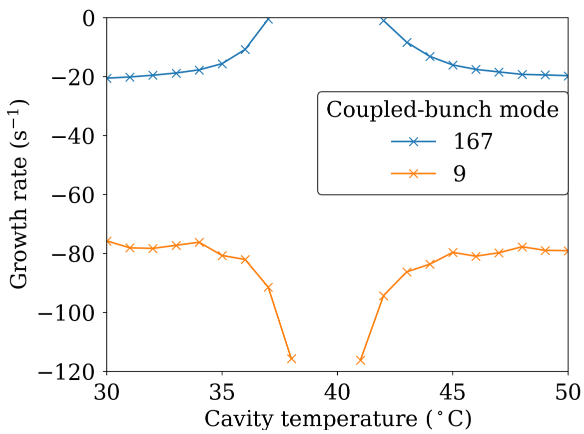

Figure 4: Results of drive/damp measurements of coupled-bunch mode 167 and its complement mode 9 in the 3 GeV ring for different temperatures of one of the main cavities. Data is not shown for coupled-bunch mode 167 at temperatures where it was above threshold and for mode 9, where the BBB feedback was unable to keep the beam stable when on.

in the 3 GeV ring and coupled-bunch mode 30 in the 1.5 GeV ring are both driven by the same HOM which exists in all of the main cavities. Furthermore, these coupled-bunch modes can have very fast growth-rates in both rings when the HOM is tuned close to its nearest revolution harmonic.

As shown in the figures, the drive/damp measurements were performed for different temperatures of a single cavity in each ring. A clear dependence can be seen and the temperatures at which the HOM is resonant, identified. The cavity in question should be run at a temperature that is sufficiently far from this temperature. However, care must also be taken to ensure that the temperature chosen does not bring another mode closer to resonance. Drive/damp measurements are just one way in which the best temperature for a given cavity can be chosen. However, they are limited to modes whose decay differs sufficiently from the radiation damping rate to be measured above the noise and they must be performed at low current, where all coupled-bunch modes are below threshold.

Landau-cavity Tuning

If the harmful HOMs are sufficiently tuned away from the revolution harmonics and there is no risk of a Robinson (mode-coupling) instability, it is possible to stabilise the beam by increasing the fields in the Landau cavities. It is possible to achieve partial stabilisation, where the saturation amplitude of coupled-bunch modes is kept low enough so that the effect on the energy spread is small, or full stabilisation, where the lowest instability threshold is raised to above the stored current. These two situations, though conceptually distinct, can be indistinguishable from the point of view of experimental users.

Experiments have been performed to demonstrate Landau-cavity stabilisation in both rings at MAX IV and here, the results of one such experiment in the 3 GeV ring are presented. The machine was set up with a main RF voltage of 1.045 MV so that full flat potential [7] could be obtained at 149 mA with three passively-driven Landau cavities. Starting from an unstable beam and a uniform machine fill (as opposed to the nonuniform fill used during delivery) at this current, the fields in the Landau cavities were increased gradually, pausing at different steps to measure the energy spread. The results are shown in Fig. 5.

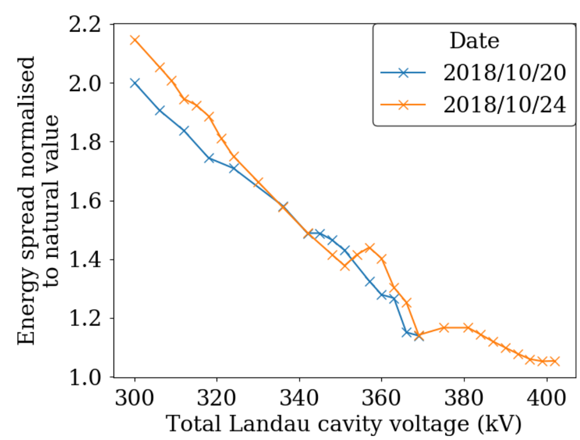

Figure 5: Measured energy spread in uniform fill at 149 mA in the 3 GeV ring as the total Landau-cavity voltage is increased.

As the Landau-cavity field is increased, the coupled-bunch modes that are present begin to saturate at lower amplitudes because of the increased nonlinearity of the RF potential containing the bunches. This continues until the energy spread roughly reaches the level of the natural energy spread. In the 3 GeV ring at lower currents and in the 1.5 GeV ring up to 500 mA, the beam eventually becomes stable with no coupled-bunch modes detected. However, in the 3 GeV ring

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at this current and above, a slow-oscillating coupled-bunch mode is observed that persists until the Landau cavities are too close to resonance and the growth rate of the Robinson dipole mode exceeds the damping provided by the mode-0 phase feedback. These slow-oscillating coupled bunch modes have very large amplitudes in phase but, because their oscillation period is longer than the radiation damping time, there is no increased energy spread between bunches, which is why there is no increase in energy spread where they appear in Fig. 5. Nevertheless, it has been observed that these slow-oscillating coupled-bunch modes still degrade the quality of light delivered to the beamlines, perhaps indirectly through the phase sensitivity of BPMs disrupting the slow-orbit feedback. For this reason, a nonuniform fill pattern is used in the 3 GeV ring during delivery of light to users. A nonuniform fill improves the stability at high Landau-cavity fields and prevents the appearance of slow-oscillating coupled-bunch modes. The disadvantage of a nonuniform fill is that the bunch-lengthening of the Landau cavities is less effective and this is worse for the beam lifetime and intrabeam scattering. The effect of a nonuniform fill on coupled-bunch instabilities has been well documented in the past [8–11] and the subject continues to be studied at MAX IV, both in terms the static effects of transient beam loading [12] and coupled-bunch modes [13].

DISCUSSION AND CONCLUSION

To explain the difference in behaviour between the two storage rings at MAX IV, it is sufficient to mention the following four points. Firstly, the Robinson damping in the 1.5 GeV ring is faster then in the 3 GeV ring because of the tuning of the main cavities, which as mentioned, is chosen to match the beam-loaded cavity to the RF transmitter. Secondly, the radiation damping is also faster. Thirdly, the 1.5 GeV ring has a lower narrowband impedance because it has fewer cavities and finally, it has a larger revolution frequency. This last point means that it is easier to tune all of the harmful higher-order modes away from the revolution harmonics because they are further apart in frequency.

The comparison is very different when carried out in terms of total charge stored, which is five and a half times larger in the 3 GeV ring for the same beam current. However, it would then make more sense to compare the impedances per unit length in the two rings, of which the lower is in the 3 GeV ring. The comparison of the radiation damping time should then be done in turns instead of absolute time and this is also lower in the 3 GeV ring. The Robinson damping time still corresponds to fewer turns in the 1.5 GeV ring but is a larger factor of the Robinson damping time in the 3 GeV ring. Beyond convention, one good reason for comparing the two rings in terms of beam current up until this point is because it is a parameter for which the design value is the same in both rings.

In any case, Landau cavities play a crucial role in the delivery of light to users in both storage rings at MAX IV. A longitudinally-stable beam has been achieved in the the 1.5 GeV ring for a larger range of currents that includes the design current of 500 mA. With its two storage rings with similar RF systems, the MAX IV laboratory presents a rare opportunity to compare the behaviour of HOM-driven coupled-bunch modes in different-size storage rings and such a comparison has now been carried out.

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