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REVIEW OF HARMONIC CAVITIES IN FOURTH-GENERATION STORAGE RINGS

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Abstract

Several third generation light-source storage rings have used harmonic cavities to lengthen the electron bunches. With the advent of the fourth generation however, they have become an almost universal feature as the small transverse electron beam sizes make long bunches essential for increasing Touschek lifetime and reducing emittance blow-up from intrabeam scattering. Multiple technological solutions exist for the implementation of harmonic cavities and which to use and how to implement it are questions that many facilities have to tackle. This is therefore a very active area of study in which there is strong collaboration within the community. In this proceeding, the approaches taken, as determined from a survey of different projects, are summarised. Avoiding coherent collective beam instabilities is of particular concern and those that are driven by the impedance of the harmonic-cavity fundamental mode are outlined with reference to the relevant theories. Where appropriate, the discussion is complemented by a description of the observations made at the MAX IV 3 GeV ring, the first fourth generation storage ring which was commissioned with normal-conducting passive harmonic cavities already installed.

INTRODUCTION

Harmonic cavities (HCs) are used in storage rings to alter the slope of the RF voltage over the duration of the charged particle bunches. In electron storage rings used as synchrotron light sources, by far the most common aim is to lengthen the bunches in order to increase the Touschek lifetime[1]. For this reason, several third-generation light-source storage rings had harmonic cavities installed [2–6]. Now, the fourth-generation of storage rings are coming online and lengthened electron bunches are even more desirable due to the smaller transverse beam sizes, which lead to shorter Touschek lifetimes. Without bunch lengthening, fourth-generation storage rings also suffer from significant emittance blow-up due to intrabeam scattering [7]. For these reasons, harmonic cavities have become critical components in almost all fourth-generation storage rings and are included in their baseline designs. A significant amount of research has therefore been conducted to develop these harmonic cavities, better understand the beam dynamics and to decide which type and design of HC is best suited to a particular storage ring. Successful collaborations such as the recent one between HZB, DESY and ALBA [8] play a key role in how facilities overcome the technical and theoretical challenges and workshops, such as the dedicated HarmonLIP series in Europe, provide a crucial platform for advances to be shared.

The goal of this proceeding is to present a review of this latest wave of research and the environment and context in which it is being carried out. This is done from a beam dynamics perspective so will leave out the important work that is going into the technical designs, which interested readers may find elsewhere: [8–11] and others. A survey of the world's light-source facilities that have fourth-generation storage-ring projects has been conducted and in the first part of this proceeding, the results of this survey are presented. It is hoped that the results provide a helpful guide to future projects that will be faced with the same considerations.

Of particular interest in the survey were the fill patterns to be used in the storage ring since it is well established that an uneven fill pattern can negatively impact the bunch lengthening that can be achieved and lead to a distribution of different bunch lengths over the bunch train. This aspect in particular been the subject of a lot of research. Byrd and Georgsson [4] used single-particle tracking to predict the effects of this before Bassi et al. [12] took advantage of more powerful computing techniques and employed macroparticle tracking. More recently, a semi-analytical approach was taken by Yamamoto et al [13] and Olsson et al. [14] used a matrix equation and the Newton method to iterate towards a self-consistent solution that showed good agreement with tracking using a fraction of the computational resources. Since then, other approaches have emerged [15, 16] showing improved performance and the potential to include the effects of short-range wakefields.

HARMONLIP

In October 2022, a workshop called HarmonLIP was convened at MAX IV Laboratory in Lund, Sweden [17]. This was the first in a series that is an internal project supported by the League of European Accelerator-based Photon Sources (LEAPS) Working Group 2 [18]. The hybrid workshop had delegates from eleven different synchrotron light-source facilities in Europe come in person or join remotely and was also joined remotely from South America and from Asia. The workshop photo is shown in Fig. 1. Facilities gave an update on the status of their respective harmonic-cavity systems before more general topics were discussed. These discussions included short comment talks briefly presenting the perspective of one facility or one participant. The next edition of the HarmonLIP workshop series is planned for March 2024 and will be hosted by the ESRF in Grenoble.

In preparation for the workshop, a survey was carried out of the technical specifications of the HC systems at each

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[1] Bunch shortening is also sometimes the aim [1]

Figure 1: Workshop photo of the HarmonLIP workshop at MAX IV, Lund, Sweden, 2022.

facility. This provided the basis and inspiration for the more global survey carried out in preparation for this proceeding.

SURVEY

A survey was carried out of all of the projects for fourth-generation storage rings known to the authors that use or foresee the use of harmonic cavities. There is a lot of variety among the different projects, including the project status, which varies from pre-conceptual design to fully operational. As a result, some of the results are likely to change. The survey was carried out by contacting members of staff from the relevant facilities and asking them a series of questions. The storage rings included are SOLEIL-II [19], SLS 2.0 [20], the 3 GeV ring at MAX IV [21], BESSY III [22], the ESRF-EBS [23], ELETTRA 2.0 [24], DIAMOND-II [25], PETRA IV [26], ALBA II [27], the future light source at KEK [28], ALS-U [29], APS-U [30], SIRIUS [31], HEPS [32], HALF [33] and SPS II [34] (the people contacted are in the Acknowledgements section). This section presents the results of the survey's different questions alongside the interpretation of the authors.

Harmonic Cavity Type

Harmonic cavities can be made of normal or superconducting material and can either be active, with an external generator providing power to the cavity, or passive such that the power in the cavity is taken from the electron beam (indirectly from the main RF). HCs can therefore be separated into four distinct combinations of normal or superconducting and active or passive. Figure 2 shows the types of cavity used at different fourth-generation storage-rings. Normal-conducting passive harmonic cavities were opted for in the MAX IV 3 GeV ring, partly due to success in a previous MaxLab storage ring [3]. Most fourth-generation storage rings since then, however, have opted for either superconducting passive or normal-conducting active solutions. This is to limit the total R/Q so that, when running with an uneven fill pattern, the variation in bunch lengthening (and therefore lifetime) between different bunches is reduced. Even at lower R/Q, superconducting passive systems can have more shunt impedance than their normal-conducting passive counterparts. This allows them to be used effectively even in low-current modes of operation (although this shortcoming can be mitigated in the normal-conducting case by reducing the voltage of the main RF [35]).

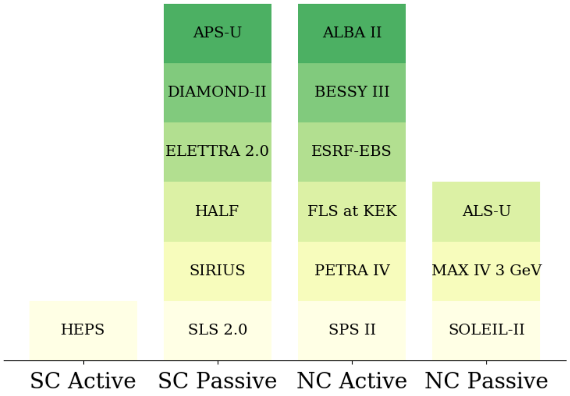

Figure 2: Bar chart of types of harmonic cavity used in fourth-generation light-source storage rings.

Active harmonic cavities offer the most control of the total RF-voltage waveform for any beam current or energy loss to synchrotron radiation. The latter parameter can vary a lot in fourth-generation storage rings since variable sources of radiation (the insertion devices) can dominate the bare-machine magnetic lattice's fixed energy loss, which is typically lower than in third-generation storage rings of the same circumference. Once again though, set voltages can also be adjusted in passive systems to adapt to changing conditions [35]. Active cavities are also less likely than superconducting passive cavities to excite the Robinson D-mode instability when operating at low beam currents (see dedicated section below).

The majority of facilities will have harmonic cavities operating at the 3rd harmonic of the RF frequency. Three however, namely ESRF-EBS, APS-U and the SOLEIL upgrade, have opted for the fourth harmonic instead (although for SOLEIL, other options are still being considered). A higher harmonic means lower power consumption but also less bunch lengthening. However, due to the large impedances of the large APS-U and ESRF-EBS storage rings, the bunch lengthening with the beam current due to potential-well distortion is already quite high and, relative to their natural bunch lengths, these two machines actually expect the largest bunch-lengthening factors (> 6) when the harmonic cavities are engaged [36].

Bunch Lengthening

Figure 3 shows the distribution of bunch lengthening aimed for in the different storage rings. A modest bunch lengthening of around a factor of 3 can be enough to bring the Touschek and intrabeam scattering to within acceptable levels. When requesting this information from the different facilities, whether potential-well distortion should be

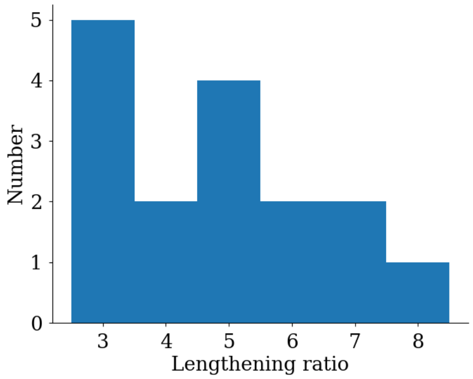

Figure 3: Histogram of bunch lengthening factors expected at each fourth-generation light-source storage ring.

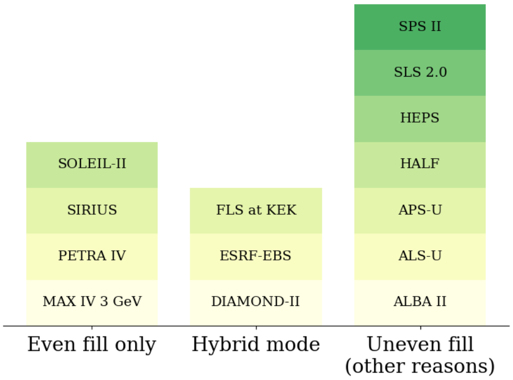

Figure 4: Bar chart of fill patterns used or to be used in fourth-generation light-source storage rings.

included was not specified so this may have led to additional variation. A range was also often given due to the use of an uneven fill pattern, which is also a limiting factor in how much lengthening that can be achieved (see next section). Facilities that can operate with an even fill pattern may decide to lengthen the bunches slightly beyond flat potential conditions as this has been shown to deliver a longer Touschek lifetime.

Fill Pattern

Although it would provide the best results in terms of bunch lengthening, running with an even filling pattern is not always possible in many fourth-generation storage rings, as shown in Fig. 4. The most common reason for using an uneven fill pattern is the need for a larger gap between two of the bunches for the clearing of ions.

Users that require x-ray pulses at reduced repetition rate may be accommodated without sacrificing too much brightness by increasing the number of empty RF buckets between evenly spaced electron bunches, as long as the repetition rates required are not too low and the machine is of sufficiently large circumference. Otherwise, uneven hybrid fill patterns must be used to achieve something similar. These generally consist of a long train of electron bunches for brightness and a long gap with a single so-called camshaft bunch in the middle. Users of pulsed x-rays block the light from the long train using a mechanical chopper.

One project, ALS-U, cited the use of swap-out injection by trains for the need for gaps in the fill pattern. In this scheme, whole trains of bunches in the storage ring are swapped out for a fresh train coming from the injector and a gap before and after each train is required to allow for the injection kickers to reach the necessary kick strength (kicker rise time).

ESRF-EBS does foresee the use of a hybrid fill pattern but only intends to engage the harmonic cavities for higher-charge even fill patterns with fewer bunches.

It is well established that an uneven fill pattern can reduce the amount of bunch lengthening that can be achieved using harmonic cavities. Facilities are therefore considering ways in which to limit the reduction. One promising approach is to use many shorter bunch trains instead of a single long train. Calculations and simulations have shown that this leads to better average bunch lengthening [37]. In addition, the use of higher-charge ‘guard’ bunches at the beginning and end of a bunch train can improve the bunch lengthening of the majority of bunches in the centre. This scheme was first proposed by Milas and Stingelin [38] and it has been shown that these bunches can also improve ion clearing [39].

COLLECTIVE EFFECTS

Although the potential of harmonic cavities to damp HOM-driven longitudinal coupled-bunch instabilities has been demonstrated in the MAX IV 3 GeV ring [40], it has been decided for almost all subsequent fourth-generation storage ring projects to not rely on harmonic cavities for this purpose. The overwhelming majority of facilities prefer to use other methods such as HOM-damped cavities and longitudinal bunch-by-bunch feedback. Indeed, it is not clear that harmonic cavities are beneficial in this respect in all cases. On one hand, they introduce a spread in synchrotron frequency, either within the bunches or between the bunches for Landau damping and increase rejection of high-frequency HOMs by lengthening the bunch duration. On the other hand, they reduce the average incoherent synchrotron frequency within the bunch, and this has a destabilising effect.

A way in which harmonic cavities can impact longitudinal beam stability that cannot be solved by HOM damping is through their own impedance. If the wrong machine parameters and cavity specifications are chosen, instabilities can occur. This section briefly describes three of these instabilities. An important one that is not included is the DC Robinson instability [41].

Robinson Mode Coupling

In order to lengthen the electron bunches, passive harmonic cavities need to be detuned with respect to their RF harmonic in such a way that they drive rather than damp the Robinson instability. For most storage rings, which operate with a positive momentum compaction factor, this means to higher frequency. This is also the case for machines with active harmonic cavities because they must be similarly detuned in order to minimise the power reflected from the cavity. Storage rings with harmonic cavities installed must therefore be designed to avoid this instability, by ensuring that there is enough Robinson damping from the main RF cavities for example. Even if the dipole Robinson mode is stable, however, a Robinson mode coupling with the quadrupole mode can lead to an instability [42]. A measurement of this instability in the MAX IV 3 GeV ring and how it is avoided can be found in [40].

Robinson D-mode Instability

Another type of Robinson instability is the so-called D-mode instability [43]. This was observed in simulation by Gamelin [44] and also by Stingelin [45]. It was since found that by including radiation damping in the usual equation for the Robinson instability, treating each bunch as a single particle, and not linearising the equation, a second Robinson mode appears whose resonant frequency approximately follows the harmonic-cavity detuning. This mode is referred to as the D-mode. Furthermore, a reduction in the radiation damping time actually increases the growth rate of the D-mode, as does a higher quality factor of the HC. Intuitively, this can be seen as the beam motion exciting the HC on resonance while the conventional Robinson dipole mode [46], referred to in [43] as the S-mode, is the cavity exciting the beam on resonance. The relative bandwidths of the beam (in other words, the damping rate) and of the cavity determine which mode is less stable. Storage rings with superconducting harmonic cavities are therefore most prone to a D-mode instability and it is most likely to occur at low current while trying to lengthen the bunches by tuning the HC close enough to the RF harmonic that it resonantly excites motion in the beam. If the detuning is small enough to bring the coherent frequency of the D-mode close to that of the S-mode, a coupling instability can occur [43].

Mode-1 Excitation

At the other end of the scale is the mode-1 instability. This is likely to occur in storage rings with harmonic cavities of lower quality factor, excessive shunt impedance and towards higher currents. In this scenario, the HC must be detuned considerably and its impedance starts to overlap with the resonant frequency of the first coupled-bunch mode, thereby exciting it. This was a known potential issue before this latest expansion in the use of harmonic cavities [42] and has been explored more recently by Venturini [47]. It was also seen independently in simulation [48] and investigated further in [49]. An image of the instability, as observed in the MAX IV 3 GeV ring is shown in Fig. 5. One remarkable characteristic of this instability is its extremely low coherent oscillation frequency of a few Hz. It also takes on quite an asymmetric form when it saturates, which led to it also being referred to as periodic transient beam loading (PTBL) [49].

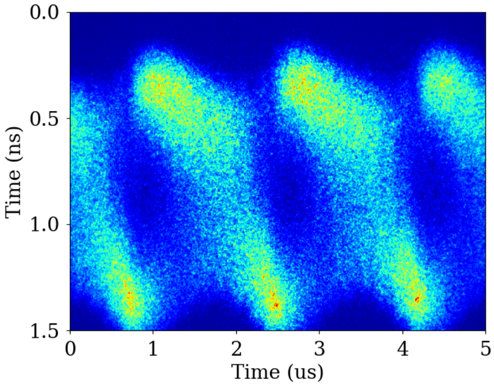

Figure 5: A single-shot streak camera image of a mode-1 instability observed in the MAX IV 3 GeV ring at a current of 200 mA and an RF voltage of 1 MV, a voltage in the passive HCs (8.25 M shunt impedance) of 335 kV, the bare lattice single-electron energy loss per turn of 363.8 keV and the machine parameters otherwise given in [50].

As it is a coupled-bunch mode, it is tempting to use simplified formulas for determining whether mode 1 is stable, as one may do with any other coupled-bunch mode. Another simplified method has come up based on the observation that, owing to its low coherent frequency of oscillation, some approaches designed to determine equilibrium bunch distributions are also capable of making predictions of the mode-1 instability as well [51]. Also readily available is an approximation from [47], although this only predicts the growth rate of the mode-1 instability in the conditions under which it is most likely to occur. However, all of these methods neglect Landau damping. In order to include it, a more comprehensive theory must be used. For a quartic potential the theory of Krinsky [52] (later extended in [53]) can be used while the complete formulation outlined in [47] covers more arbitrary longitudinal potentials but requires the use of a numerical solver.

CONCLUSION

The advantages of using harmonic cavities in fourth-generation storage rings make their use almost universal. The only fourth-generation storage ring that the authors could identify that does not foresee the use of harmonic cavities (at the very least in the conceptual design) is SPring-8-II [54]. However, harmonic cavities come in several types and which type is most suitable for a given light source is heavily dependent on the machine parameters and the user requirements. The variety in the choice of fill pattern is illustrative of the wider variety that exists between the different facilities.

The most important collective effects that come as a byproduct of using harmonic cavities have been outlined. These are caused by the impedance of the harmonic cavities themselves and can lead to beam instabilities. It must be ensured that all foreseen operational modes are within the thresholds of these instabilities so that they do not appear. Other instabilities caused by HOMs in the cavities and the machine impedance more generally are also heavily influenced by the use of harmonic cavities and also need to be avoided. Fortunately, as evidenced by the references in this paper, a good body of research provides a strong basis for any new study and a productive and collaborative community exists to help overcome any new challenges that may arise. Successful workshops such as HarmonLIP packed with detailed presentations demonstrate that this is the case.

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