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PULSE-PICKING BY RESONANT EXCITATION (PPRE) FOR TIMING USERS AT THE MAX IV 3 GeV STORAGE RING

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Abstract

At synchrotron light storage rings there is demand for serving both high-brilliance and timing users simultaneously. At many rings this is commonly achieved by operating fill patterns with gaps of sufficient length, but this is not favorable for rings that operate with passive harmonic cavities to damp instabilities and increase Touschek lifetime by lengthening the bunches. For such rings, gaps in the fill pattern could severely reduce the achievable bunch lengths. For the MAX IV 3 GeV storage ring, sufficient bunch lengthening is also essential for conserving the ultralow emittance and reducing heat load on vacuum components at high current. It is therefore of interest to study methods to serve timing users while operating without gap in the fill pattern. Once such method is PPRE, where the transverse emittance of one bunch in the bunch train is increased by an incoherent betatron excitation. This paper presents simulations for the MAX IV 3 GeV storage ring and discusses the machine requirements as well as the achievable performance for timing users.

INTRODUCTION

The MAX IV 3 GeV storage ring has been designed with the purpose of providing world leading brilliance to users by reducing the bare lattice transverse emittance as low as 328 pm rad. To achieve this, the ring employs a strong focusing multibend achromat lattice with narrow vacuum chambers to obtain the required high magnet gradients. This increases the challenge to achieve stable beam with sufficient Touschek lifetime and acceptable heat load on vacuum components. To meet this challenge, the ring operates with harmonic cavities to damp instabilities and increase the Touschek lifetime by lengthening the bunches [1]. In addition, the harmonic cavities are essential for preserving the ultralow emittance at high current [2]. The harmonic cavities are operated passively, meaning the bunch lengthening depends on both the cavity tuning and the fill pattern. Studies at other rings, e.g. [3–8], have shown that fill patterns with gaps give rise to transients in the cavities that decrease the average bunch lengthening. The MAX IV 3 GeV storage ring was therefore designed to operate with a uniform, multibunch fill pattern [9] to maximize the performance of the harmonic cavities.

A discussion on timing modes has been initiated by the MAX IV user community and several research areas have been identified that would benefit from other repetition rates than provided by the baseline fill pattern [10]. At many rings this is commonly achieved by operating fill patterns with gaps of sufficient length for beamline choppers or gated detectors. So far the MAX IV Laboratory has only committed to operate a timing mode at the less challenging MAX IV 1.5 GeV storage ring, but the discussion has lead to an interest to also study the possibilities for timing modes at the 3 GeV ring. Due to the importance of the harmonic cavities for the ring performance, it is of special interest to study methods that have the potential to serve both timing and high-brilliance users simultaneously without requiring a gap in the fill pattern. Pulse picking by resonant excitation (PPRE) [11] has this potential. The method has been developed and operated for users at BESSY II. It relies on excitation of incoherent betatron oscillations in a single bunch in the bunch train, resulting in an increased emittance for this bunch. Part of the light emitted from the excited bunch can then be separated from the light produced by the multibunches by an aperture in the beamline, resulting in single-bunch light for the beamline while the ring is operated in multibunch mode.

The excitation can be achieved in either transverse plane by a gated stripline kicker feed by an input signal with a frequency close to the betatron tune. The tune spread of the electrons in the bunch caused by chromatic and amplitude-dependent tune shifts, instabilities and tune variations results in an incoherent excitation of the electrons [11]. If the incoherent excitation is sufficiently large, this results in an emittance increase which is greater than the induced beam oscillation [12]. First measurements of PPRE has been conducted at the MAX IV 3 GeV storage ring, and they indicated that excitation frequencies exist were the emittance increase is greater than the induced beam oscillation [13]. This paper presents beam dynamics simulations to study the influence of the optics on the emittance growth vs beam oscillation. The paper also presents calculations of the undulator radiation to estimate the required emittance growth to achieve a certain user performance.

EMITTANCE GROWTH VS BEAM OSCILLATION

Beam dynamics simulations were performed for the design optics in Accelerator Toolbox with cavity and radiation effects utilizing the *atfastring* function which allowed tracking for several damping times including quantum diffusion [14]. The function includes linear chromaticity and amplitude-dependent tune shifts, and it was modified to also include second order chromaticity. During the simulations 1000 particles were used. The particles were first tracked for 60 000 turns without excitation to reach nominal values for beam size and emittance in the straight sections. The parti-

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cles were then tracked another 100 000 turns while kicked by a sinusoidal varying kick every turn

$$\theta = A\cos(2\pi f t), \quad (1)$$

where A is the excitation amplitude, f the excitation frequency and t the time from the start of the simulation given by iT_{rev}, with $i = 0, 1, 2\ldots$ and T_{rev} being the revolution period. The simulations were only performed with horizontal excitation since the previous measurements were done in this plane. The amplitude of the Dimtel bunch-by-bunch feedback system [15] used for excitation were calibrated to estimate the achievable kick amplitudes to between roughly 0.3-1.7 µrad. Since the measurements were performed, the achievable excitation amplitude has increased somewhat due to an upgrade. Since the measurements were performed at the delivery optics at that time (which had slightly different tunes and likely different nonlinear optics compared to the design optics) and the beam sizes were measured at the position of the diagnostic beamline, it is not possible to directly compare with these simulations, but the simulations show similar behaviour as the measurements. Figure 1 displays simulated beam oscillation and beam size for the design optics (which has a linear chromaticity of +1 in both transverse planes) with a 50 nrad kick. It is evident than an increase in beam size without equally large increase of the beam oscillation can be achieved when exciting at the synchrotron sidebands, which agrees with the observations during the measurements [13]. During the measurements, excitation at low amplitude resulted in a beam size increase of roughly 1.5 times close to the second left synchrotron sideband. In the simulations, this is achieved for a 50 nrad kick, which is consistent with the excitation amplitudes being lower during the measurements. However, the amplitude increase was likely below this, indicating that the simulations are perhaps somewhat overestimating the beam size increase.

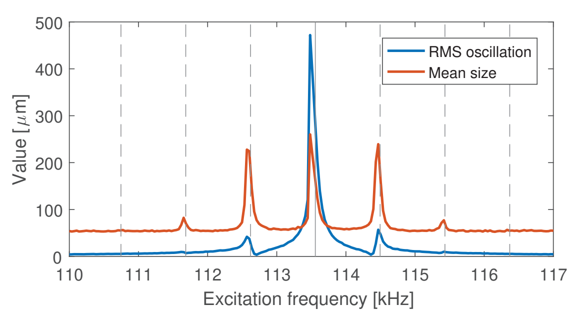

Figure 1: Simulation of beam oscillation (RMS) and size as function of horizontal excitation frequency for the design optics with a 50 nrad kick. The position of the betatron tune (solid) and the synchrotron sidebands (dashed) are marked.

Figure 2 displays simulated ratio between beam oscillation and size, as well as emittance increase for the design optics. It can be seen that the resulting pattern of the excitation depends on the kick amplitude, and that large emittance increase can be achieved already for low excitation amplitudes.

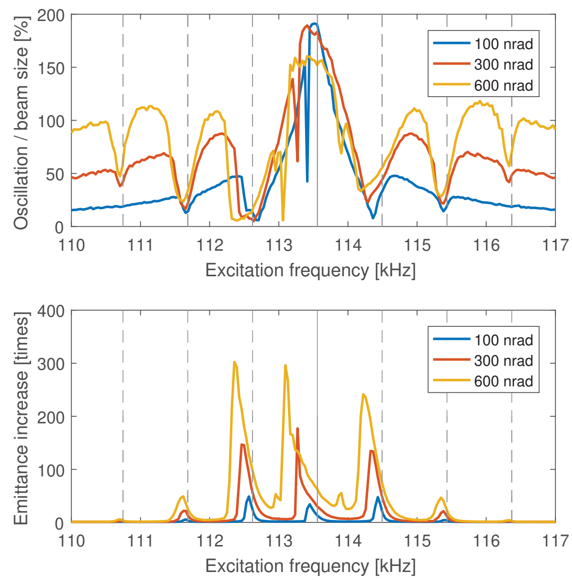

Figure 2: Ratio between simulated beam oscillation and beam size (top) and emittance increase (bottom) as function of horizontal excitation frequency for the design optics for different kick amplitudes. The position of the betatron tune (solid) and the synchrotron sidebands (dashed) are marked.

To study if small changes of the nonlinear optics could increase the emittance growth, the simulations were repeated with different second order chromaticity and amplitude-dependent tune shifts. The changes were done on the nonlinear element in the *fastring* element instead of modifying the strength of the sextupoles and octupoles in the lattice to be able to study the effects independently. As displayed in Figure 3, up to 100% increase of the second order chromaticity had no significant effect on the emittance increase. Greater difference could be seen by increasing the amplitude-dependent tune shifts, but mainly when exciting around the betatron tune. It is therefore not expected that small modifications of the nonlinear optics will result in any major improvements of the emittance growth.

PERFORMANCE FOR USERS

For the users both the flux and the purity with regard to the light emitted from the multibunchs are of importance. This can to some degree be optimized by the position of the aperture which separates the light, but fundamentally it is determined by the emittance increase of the excited bunch. However, since the separation is performed on the emitted photon beams, the diffraction contribution to the beam sizes cannot be neglected. Assuming beamlines with no intermediate focus before the monochromator (meaning the separation of the light will be performed at a position with unfocused photon beams) the separation depends on the beam divergence. Figure 4 displays the ratio between the horizontal photon beam divergence of an excited and unexcited bunch as function of photon energy for some dif-

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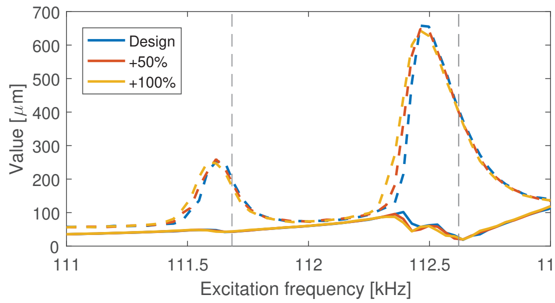
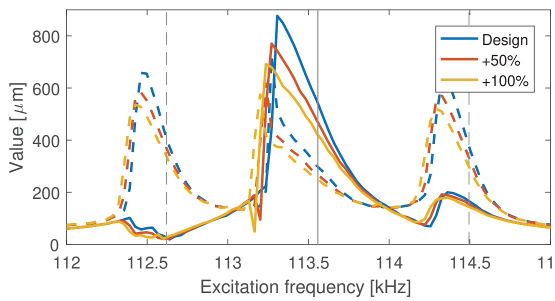


(a) Increase of second order chromatic tune shift.



(b) Increase of amplitude-dependent tune shifts.

Figure 3: Simulated beam oscillation (RMS) (solid) and size (dashed) as function of horizontal excitation frequency for the design optics with increased chromatic and amplitude-dependent tune shifts for a 300 nrad kick. The position of the betatron tune (solid) and the synchrotron sidebands (dashed) are marked.

ferent emittances for two typical examples of soft and hard X-ray beamlines at the MAX IV 3 GeV storage ring. It is clear that for lower photon energies, the beam divergence becomes diffraction-limited and thus a larger emittance increase is required to achieve a large ratio between the beam divergence of an excited and unexcited bunch.

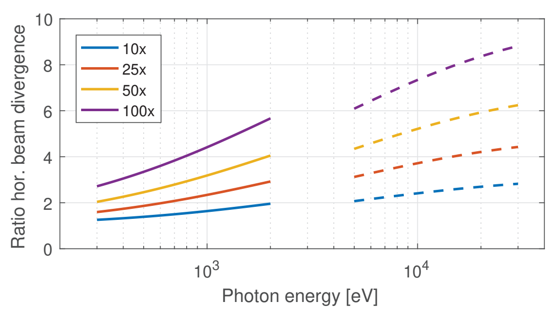
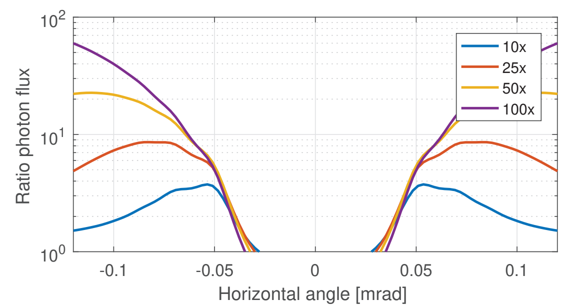
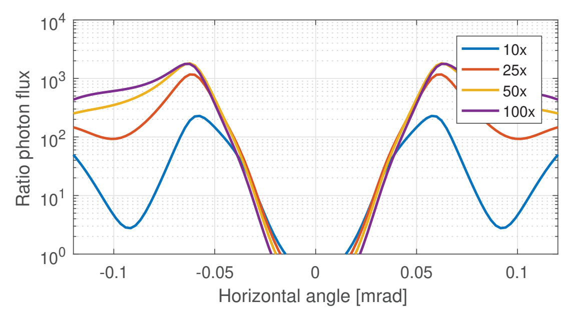


Figure 4: Ratio between horizontal photon beam divergence for excited and unexcited bunch as function of photon energy and 10, 25, 50 and 100 times emittance increase. Two typical examples for soft (solid) and hard (dashed) X-ray beamlines are displayed.

To study the required emittance increase to achieve a certain purity for users, calculations of the undulator radiation were performed using SPECTRA [16]. In the simulations, the vertical aperture was set to ±2 times the vertical photon beam divergence for an unexcited beam, whereas the horizontal aperture was set to ±2 times the horizontal beam divergence for a beam with 100 times emittance increase to compare flux through the same aperture. Figure 5 displays the ratio between the photon flux of an excited and unexcited bunch for some different emittances for the two example beamlines. It is evident that the emittance increase has to be substantially larger at low photon energies to achieve similar purity as at high photon energies.



(a) [Photon energy 263 eV (first harmonic).



(b) Photon energy 5010 eV (third harmonic).

Figure 5: Ratio between photon flux for excited and unexcited beam for 10, 25, 50 and 100 times emittance increase. Two typical examples for soft (top) and hard (bottom) X-ray beamlines are displayed.

CONCLUSIONS AND OUTLOOK

Both beam dynamics simulations and previously conducted measurements show that it is possible to substantially increase the emittance of a single bunch in the bunch train of the MAX IV 3 GeV storage ring without equally large increase of the beam oscillation by exciting at a synchrotron sideband. The limitation of the PPRE method is, however, set by by the photon energy range of interest for the users and their purity requirements, which remains to be determined. It is, however, expected that the method could serve at least some users with sufficient performance at the hard X-ray beamlines. The purity could also possibly be improved by increasing the charge of the excited bunch, but the limitations on bunch charge remains to be studied. In addition, the effects of harmonic cavities and insertion devices have not yet been included in the simulations.

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