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Preparing the MAX IV Storage Rings for Timing-based Experiments

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Abstract. Time-resolved experimental techniques are increasingly abundant at storage ring facilities. Recent developments in accelerator technology and beamline instrumentation allow for simultaneous operation of high-intensity and timing-based experiments. The MAX IV facility is a state-of-the-art synchrotron light source in Lund, Sweden, that will come into operation in 2016. As many storage ring facilities are pursuing upgrade programs employing strong-focusing multibend achromats and passive harmonic cavities (HCs) in high-current operation, it is of broad interest to study the accelerator and instrumentation developments required to enable timing-based experiments at such machines. In particular, the use of hybrid filling modes combined with pulse picking by resonant excitation or pseudo single bunch has shown promising results. These methods can be combined with novel beamline instrumentation, such as choppers and instrument gating. In this paper we discuss how these techniques can be implemented and employed at MAX IV.

INTRODUCTION

The MAX IV facility consists of a linac and two storage rings (operated at 1.5 GeV and 3 GeV). The linac serves as an injector to the rings and to a short pulse facility (SPF) [1]. Since the completion of the MAX IV Detailed Design Report [2], a discussion on timing modes has been initiated by the user community. Several research areas have been identified where users would benefit from other repetition rates and/or pulse lengths than the ones available in the MAX IV baseline design [3]. While there is no established timing user community at the current MAX I-III rings, several users from Nordic countries perform such experiments at other facilities. These cases include pump-probe techniques for imaging and spectroscopy, application of novel instrumentation for electron and ion time-of-flight spectroscopy, and studies of slow relaxation processes. The demands span several energy ranges and repetition rates. Evidently, no individual proposed timing solution would satisfy all user cases. However, we have concluded that a more urgent and wider interest exists for modification of the photon repetition rate provided by the MAX IV storage rings than for shorter photon pulses, especially since the facility already includes the SPF. Our current priority is therefore to identify methods and techniques to broaden the repetition rates at the MAX IV storage rings.

The 1.5 GeV storage ring is aimed towards producing VUV and soft X-rays. The ring has a circumference of 96 m and employs a double-bend achromat lattice to produce an emittance of 6 nm rad. The 3 GeV storage ring on the other hand is aimed towards ultralow emittance to generate high brilliance hard X-rays. The design of the 3 GeV storage ring includes many novel technologies such as a multibend achromat lattice and a compact, fully-integrated magnet design. This results in a circumference of 528 m and an emittance as low as 0.2 nm rad with insertions devices [4]. Both MAX IV storage rings have a 100 MHz main RF system, a design current of 500 mA [5], and will be operated with a uniform, multibunch filling pattern with 5 nC per bunch [2]. Also, both rings employ harmonic cavities (HCs) [5] to damp instabilities and increase the Touschek lifetime by elongating the bunches [4]. For the 3 GeV ring the HCs are also essential for conserving the ultralow emittance at high bunch charge [6]. Simulations of collective effects for the 3 GeV ring have shown that sufficient bunch lengthening is of great importance to be able to achieve the design current of the machine [7]. The HCs operate in passive mode [4], hence the bunch lengthening depends on both the tuning of the cavities and the filling pattern of the machine.

For timing-based experiments, three temporal properties are of special interest: the repetition rate, the bunch interval and the bunch length. The requirements for these properties are dictated by the user needs for pulse separation and pulse length. The time structures of the MAX IV storage rings and SPF are displayed in Table 1. The repetition rates that can be achieved at the storage rings are four orders of magnitude greater than what can be achieved at the SPF. On the other hand, the pulse lengths produced at the SPF are three orders of magnitude shorter than the pulse lengths produced at the storage rings.

TABLE 1. Time structure for the MAX IV storage rings and SPF.

	Single-bunch repetition rate [Revolution time]	Bunch interval	Bunch length (bare lattice at maximum main cavity voltage)
SPF	100 Hz	10^7 ns	0.1 ps (FWHM)
1.5 GeV ring	3.13 MHz [0.32 μs]	10 ns	~49 ps (RMS) (w/o HCs) to ~213 ps (RMS) (HCs)
3 GeV ring	0.57 MHz [1.76 μs]	10 ns	~29 ps (RMS) (w/o HCs) to ~165 ps (RMS) (HCs)

ACCELERATOR ISSUES

Many synchrotron radiation storage rings nowadays run with several filling patterns to be able to serve different user groups. We have initiated studies to evaluate the performance of our machines for other filling patterns than the uniform multibunch pattern specified in the MAX IV baseline design. Studies performed for other machines operating with passive HCs show that a gap in the filling pattern gives rise to transient beam loading effects that decrease the average bunch lengthening [8]. Considering the previously highlighted importance of the performance of the HCs for the operation of the MAX IV storage rings this could be a serious issue. An initial study of filling patterns with gaps for the MAX IV 3 GeV storage ring is displayed in Fig. 1. The studies were performed with a tracking code developed by Milas [9] using the model described in [8]. These studies show that the bunch lengthening caused by the passive HCs decreases when introducing a gap in the filling pattern. They also show that the effect is greater for longer gaps. It is therefore desirable to develop methods for timing-based experiments at the MAX IV storage rings that require a small, or preferably, no gap in the filling pattern.

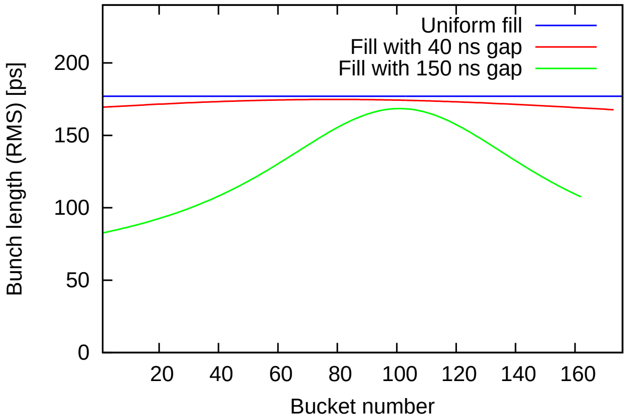

FIGURE 1. Bunch length for a uniform fill, a 40 ns gap and a 150 ns gap in the filling pattern for the MAX IV 3 GeV storage ring. The bunch current is 2.84 mA (5 nC) for all filling patterns. For the main cavities a total voltage of 1.4 MV maximizing the lifetime [6], a shunt impedance of 6×1.715 MOhm and a Q factor of 20400 were used [10]. The detuning of the main cavities was optimized for maximum bunch lengthening. For the HCs a Q factor of 20800 [10] and shunt impedance and detuning according to the flat potential conditions described in [8, 11] were used. Intrabeam scattering and the beam profile form factor have not been taken into account so far. The natural bunch length without bunch-lengthening HCs is 34 ps RMS. For a uniform fill, a bunch length of 177 ps RMS can be achieved by tuning the HCs, but for a gap of 40 ps the mean bunch length is reduced to 172 ps RMS and for a gap of 150 ps to 130 ps RMS.

Pulse picking by resonant excitation (PPRE) [12] and pseudo single bunch (PSB) [13] are two methods that have been developed to enable storage rings to serve both high-intensity experiments and timing-based experiments simultaneously. In PPRE the emittance of one bunch in the train is increased by excitation and an aperture in the beamline ensures that only light from the excited bunch is accepted. In PSB one bunch in the train is kicked onto another orbit for a few turns and the light from this bunch can then be separated by an aperture. In both methods, single-bunch light is created in one (or several) beamlines while all other beamlines receive multibunch light. The PSB method relies on the performance of the kicker magnet. At ALS a 40 ns 1 kV pulse at a maximum repetition rate of 1.5 MHz has been achieved so far [14]. The pulse length of the kicker sets the gap length requirement between the camshaft bunch and neighboring bunches.

BEAMLINE INSTRUMENTATION

Choppers are another way to transmit only a single light pulse from a storage ring. If the chopper is used in hybrid filling mode, the opening time of the chopper has to be shorter than the gap in the filling pattern (hybrid window). For single-bunch operation and PPRE, the use of choppers is necessary if the single-bunch repetition rate needs to be further reduced. The high-speed chopper system at the ID09B beamline at ESRF [15] creates a 300 ns opening window with 3 kHz frequency. A chopper of this kind could possibly be implemented at the MAX IV 3 GeV ring, provided a sufficient hybrid window is available. Another solution is the MHz light chopper developed for use at BESSY II [16], which to this day is the only chopper providing individual light pulses with MHz repetition rate. At BESSY II, it can extract light from a single bunch residing in a 200 ns window with 1.25 MHz. General concerns with high-speed choppers are substantial mechanical complexity, high cost and the need to have a beamline with a suitable intermediate focus where the chopper can be placed. As tolerances are tight, the beam must be small at the point where the chopper is installed. A large beam reduces both transmission of the single pulse, and purity since neighboring pulses can leak through. Choppers are good solutions for facilities with a limited number of dedicated beamlines with strict temporal demands. In particular, this applies to beamlines which host instruments with pre-determined analysis rates (e.g. pulse lasers, TOF instruments and detectors with specified dead-times). The joint operation of PPRE or PSB and choppers can serve several purposes. Choppers can serve as background suppressors [17], but the combination can also further increase the versatility of the timing scheme.

Implementing gating schemes for X-ray detectors can enable timing-based experiments without choppers. Successful operation of a gating scheme has been reported at the 24-bunch filling mode at APS, with 153 ns bunch separation [18]. The gated PILATUS detector requires a bunch separation of at least 130 ns to ensure detection of a given X-ray pulse. The possibility of a gated electron detector in a time-of-flight-based electron spectrometer (ARTOF) has been studied in [19]. A weak pulsed electric field is introduced in front of the MCP and delay-line detector in the ARTOF spectrometer. When the instrument is used in the standard hybrid mode at BESSY II, only the electrons created by the camshaft bunch are resolvable and all other electrons have to be disregarded. The gate deflects unresolvable electrons and prevents them from saturating the detector. The required size of the gap in the filling pattern is dictated by the properties of the instrument, but can be approximated to 100 ns.

For some instruments, coincidence detection can solve timing needs. It has been shown how the ARTOF electron spectrometer can be used to achieve high transmission in a coincidence experiment, while retaining high energy resolution [20]. The detection of an electron in the hemispherical analyser is used as a start trigger for the ARTOF instrument. The measurement uncertainty is determined by the temporal dispersion of the detected electrons, which is ~6 ns for 200 eV pass energy [20]. This uncertainty accounts for half of the total temporal error. At a storage ring with 2 ns pulse separation it is not possible to eliminate this error by assigning electrons to specific light pulses. However, MAX IV makes this possible as the temporal broadening in the hemispherical analyser is less than 10 ns. In a recent experiment at the I411 beamline at MAX II we have verified that 10 ns pulse separation can indeed be used to reference electron detection to specific light pulses. The resolution of the coincident detection then equals the stand-alone resolution of the TOF instrument. It is suggested that the pass energy of the hemispherical analyser can be set below 20 eV before time dispersion exceeds 10 ns [21]. Put into practice, this electron coincidence scheme would provide the MAX IV storage rings with the highest resolution achievable at any storage ring in the world.

CONCLUSIONS

Discussions with the user community reveal a broad interest from timing users for light with lower repetition rates than the baseline 100 MHz provided by the MAX IV storage rings, but several orders of magnitude higher than the 100 Hz provided by the SPF. Novel developments in accelerator technology and beamline instrumentation, such as hybrid modes in combination with PPRE, PSB, choppers and/or gated detectors, open new possibilities to host such timing-based experiments at MAX IV.

The 10 ns bunch interval of the MAX IV storage ring is an advantage when employing many of these methods since it relaxes parameters of the kickers and/or choppers, but also on the hybrid window. This implies the operation of timing modes might not have to compromise other parameters, such as the stored current. We believe that both PPRE and PSB are of great interest for MAX IV. For the PPRE method the 10 ns bunch interval should give sufficient separation to apply the excitation to one bunch within the multibunch train without a hybrid window. If the intensity of the individual PPRE photon pulse and the pulse length are acceptable, the technique can directly serve potential users. PSB would serve a wider range of timing users, but the method implies several technical challenges, e.g. implementation of a hybrid mode and kicker development. In the coming years, kicker performance is expected to increase since several machine upgrades include injections schemes that require ultrafast kickers. This is promising since it could make PSB achievable at MAX IV using only a small hybrid window or perhaps no window at all.

We aim to continue our work to present a science case and prepare the MAX IV storage rings for timing-based experiments. This work has to involve users as well as beamline and accelerator staff. As we have found many exciting and promising solutions to enable timing-based experiments at the MAX IV storage rings, we urge the community to pursue this discussion to ensure that timing-based experiments will also be present in future ultralow-emittance storage rings.

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