Pseudo-single-bunch mode for a 100 MHz storage ring serving soft X-ray timing experiments

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A B S T R A C T
At many storage rings for synchrotron light production there is demand for serving both high-flux and timing users simultaneously. Today this is most commonly achieved by operating inhomogeneous fill patterns, but this is not preferable for rings that employ passive harmonic cavities to damp instabilities and increase Touschek lifetime. For these rings, inhomogeneous fill patterns could severely reduce the effect of the harmonic cavities. It is therefore of interest to develop methods to serve high-flux and timing users simultaneously without requiring gaps in the fill pattern. One such method is pseudo-single-bunch (PSB), where one bunch in the bunch train is kicked onto another orbit by a fast stripline kicker. The light emitted from the kicked bunch can then be separated by an aperture in the beamline. Due to recent developments in fast kicker design, PSB operation in multibunch mode is within reach for rings that operate with a 100 MHz RF system, such as the MAX IV and Solaris storage rings. This paper describes machine requirements and resulting performance for such a mode at the MAX IV 1.5 GeV storage ring. A solution for serving all beamlines is discussed as well as the consequences of beamline design and operation in the soft X-ray energy range.

1. Introduction
At synchrotron light storage rings there is demand for serving both high-flux and timing users.2 Maximum average flux is achieved when the storage ring is operated in multibunch mode, but timing users usually require single-bunch repetition rates or lower. To be able to serve both user groups simultaneously many storage rings currently operate with inhomogeneous fill patterns, e.g. fill patterns with a camshaft bunch placed in a gap of sufficient length for operation with beamline choppers. However, for rings that employ passive harmonic cavities (HCs) to damp instabilities and increase Touschek lifetime by lengthening the bunches, operation of inhomogeneous fill patterns is not favorable. Studies performed at several storage rings operating with or planning for passive HCs, e.g. [1–5], show that inhomogeneous fill patterns give rise to transient effects that decrease the average bunch lengthening. It is therefore of interest to develop methods that can deliver suitable repetition rates for timing users while operating the ring in multibunch mode. A few methods that have this potential have been demonstrated or are under development, pseudo-single-bunch (PSB) [6–9], pulse picking by resonant excitation (PPRE) [10] and transverse resonance island buckets (TRIBs) [11,12].

The MAX IV 1.5 GeV storage ring is designed to operate with a 100 MHz RF system and a 500 mA [13] homogeneous multibunch fill pattern [14], but discussions on timing modes have been initiated by the user community. Several research areas have been identified that require kHz–MHz repetition rates which currently cannot be provided at the MAX IV facility [15]. These discussions have led to the submission of a science case for a single-bunch mode at the 1.5 GeV ring [16], but such a mode can only serve timing users a few weeks per year. Therefore other solutions are of interest to increase the beamtime available for timing experiments. The ring employs passive harmonic cavities (HCs) [13,17] and bunch elongation is an essential part of the design. In addition, conventional beamline choppers require a gap of a few hundred ns [18], and since the revolution period of the ring is only 320 ns [14] a gap of sufficient length would result in a substantial decrease in flux for high-flux users. It is therefore preferable to operate the ring with the planned homogeneous multibunch fill pattern to maximize flux to the high-flux...
The PSB method has been developed and operated for users at ALS in a hybrid fill pattern with a camshaft bunch in a 100 ns gap [6–8]. In this method, one bunch in the bunch train is kicked onto another orbit by a fast stripline kicker. The light from the kicked bunch can then be separated from the light produced by the multibunch train by an aperture in the beamline, resulting in a single-bunch light without disturbing high-flux users at other beamlines. The PSB method is of special interest for MAX IV due to the 100 MHz RF system, which provides 10 ns interval between bunches. Ongoing development in fast kicker design has shown pulse lengths which puts PSB operation in a 100 MHz multibunch mode within reach [19,20]. A kicker pulse shorter than 20 ns enables operating PSB in multibunch mode, and serving high-flux and timing users simultaneously without compromising the performance of the HC. This is also of wider interest for other storage rings operating with a 100 MHz RF system, such as Solaris [21] or the ultralow emittance MAX IV 3 GeV storage ring and future multibend achromat rings where the performance of passive harmonic cavities is essential for preserving the ultralow emittance [22].

### 2. Prerequisites for a PSB mode at the MAX IV 1.5 GeV storage ring

The MAX IV 1.5 GeV storage ring is designed to serve UV and soft X-ray users. It has a 96 m double-bend achromat lattice resulting in an emittance of 6 nm rad [17,23]. An overview over the parameters of the ring can be found in Table 1. For timing experiments, three temporal properties are of interest: the repetition rate, the bunch spacing and the bunch length. These properties are listed in Table 2. The ring has so far five funded beamlines, of which FlexPES and FinEstBeAMS beamlines have expressed strong interest for a future timing mode, such as PSB. Furthermore, the ring has five straight sections available for new beamlines. The ring is not planned to include bending magnet beamlines, and thus all beamlines will utilize insertion devices for light production. The photon energy ranges of the five planned beamlines span 4–1500 eV [24–28]. The present energy range of interest of the MAX IV timing user community spans 4–700 eV, but it is possible that higher energies will also be of interest in the future. The required repetition rates at the sample span from tens of kHz to the single-bunch repetition rate of 3.125 MHz [16].

The PSB mode described in this paper utilizes one kicker and, unlike the implementation at ALS, focuses on the optimization of this mode to serve as many beamlines and users as possible. The reasons for relying on a single kicker is the technical challenge to synchronize several kickers and the available space in the ring. In addition, a kick-and-cancel (KAC) design, where the PSB is kicked onto another orbit and then kicked back after a few turns, is pursued. This ensures a well-defined orbit at all times and by adjusting the period between the KAC cycles, the repetition rate of the light seen by the beamlines can be selected [6]. Lower repetition rates than provided by the single-bunch repetition rate can also be supplied by a chopper in the beamline [18] and therefore this paper will also discuss the possible performance gains when operating PSB in combination with choppers. Finally, to conserve the polarization properties of the radiation emitted from the PSB and to enable the beamlines to quickly switch between multibunch and PSB operation without realignment, local orbit bumps which place the PSB on-axis through the insertion devices will be required.

### 3. Connection between photon beam separation and the electron beam orbit

For user operation of a PSB mode it is essential to achieve sufficient separation between the light from the PSB and the light from the rest of the multibunch train. The photon beam separation can be defined as the distance between the center of the PSB photon beam and the center of the multibunch photon beam. The separation of unfocused photon beams at a distance $d$ from the beamline source point is given by

$$S = u + du'.$$

where $u$ and $u'$ are the position and angle of the PSB electron beam centroid at the source point. The separation can be expressed in sigmas of the convoluted photon beam size as $S = N\sigma_u$, where

$$N = \frac{u}{\sigma_0} + d\frac{u'}{\sigma_d},$$

and $\sigma_u$ is the RMS photon beam size at the distance $d$ from the source point. While the separation at the beamline source point is purely given by the position of the PSB electron orbit, as the distance from the source increases, the angle of the electron orbit becomes the dominating factor for the resulting separation. Therefore, for beamlines in which the source is imaged into an intermediate focus before the monochromator where the separation can be performed with focused photon beams, it is the PSB electron beam position that is of relevance. On the other hand, for beamlines without intermediate focus, where the separation has to be performed with defocused photon beams, both the PSB electron beam position and angle have to be taken into account. Hereafter, these two different principles for separating the light are denoted focused and unfocused separation in reference to the state of the photon beams at the separation point.

For a beamline with an intermediate focus utilizing focused separation of the light, the separation is given by

$$S = N_1\sigma_0,$$

where

$$N_1 = \frac{u}{\sigma_0},$$

and $\sigma_0$ is the RMS photon beam size at the source. For a beamline without intermediate focus utilizing unfocused separation, the evolution of the beam size along the beamline can be described by Gaussian beam formalism resulting in

$$\sigma_d = d\sigma_{0}',$$

where $\sigma_{0}'$ is the RMS photon beam divergence at the source. The separation at a distance $d$ from the source point is in this case given by

$$S = N_uf\sigma_d,$$

where

$$N_uf = \frac{u}{d\sigma_{0}'} + \frac{u'}{\sigma_{0}'},$$

the performance of passive harmonic cavities is essential for preserving the ultralow emittance [22].

<table>
<thead>
<tr>
<th>Parameters of the MAX IV 1.5 GeV ring [14,23].</th>
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</thead>
<tbody>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>Main RF frequency</td>
</tr>
<tr>
<td>Harmonic number</td>
</tr>
<tr>
<td>Design current</td>
</tr>
<tr>
<td>Circumference</td>
</tr>
<tr>
<td>Number of achromats</td>
</tr>
<tr>
<td>Length of straight sections</td>
</tr>
<tr>
<td>Beta functions in straight (hor./vert.)</td>
</tr>
<tr>
<td>Equilibrium emittance (bare lattice)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 Time structure of the MAX IV 1.5 GeV ring.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-bunch repetition rate</td>
</tr>
<tr>
<td>Bunch spacing in multibunch mode</td>
</tr>
<tr>
<td>Bunch length (RMS)</td>
</tr>
</tbody>
</table>

| * Dependent on stored current, HC tuning, and main RF cavity setting. |

users and avoid degrading the performance of the HC.

### Table 1 Parameters of the MAX IV 1.5 GeV ring [14,23].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>Main RF frequency</td>
<td>99.931 MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>32</td>
</tr>
<tr>
<td>Design current</td>
<td>500 mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>96 m</td>
</tr>
<tr>
<td>Number of achromats</td>
<td>12</td>
</tr>
<tr>
<td>Length of straight sections</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Beta functions in straight (hor./vert.)</td>
<td>11.22/3.15</td>
</tr>
<tr>
<td>Equilibrium emittance (bare lattice)</td>
<td>5.980 nm rad</td>
</tr>
</tbody>
</table>

### Table 2 Time structure of the MAX IV 1.5 GeV ring.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-bunch repetition rate</td>
<td>3.125 MHz</td>
</tr>
<tr>
<td>Bunch spacing in multibunch mode</td>
<td>10 ns</td>
</tr>
<tr>
<td>Bunch length (RMS)</td>
<td>49–213 ps</td>
</tr>
</tbody>
</table>
Comparing Eqs. (4) and (7), it can be noted that the required electron beam orbit is determined by either the photon beam size or divergence at the source depending on the separation method.

Fig. 1 displays the RMS photon beam size and divergence for a 2.5 m undulator as a function of photon energy. It is apparent that for the photon energy range of interest for the MAX IV timing users, the contribution from diffraction to the photon beam size and divergence cannot be neglected. For the majority of the photon energies the beam size and divergence are larger in the horizontal than the vertical plane. Therefore, the required kick to achieve a certain separation is minimized by performing the kick in the vertical plane.

4. Betatron tune choice

4.1. KAC requirements

The kicker requirements can be relaxed by modifying the vertical betatron tune of the ring from the nominal 3.15 such that only kicks of equal angle and polarity are required by the KAC scheme. This is achieved by finding a combination of tune and kicks where the orbit is restored within a few turns [32]. For two kicks this results in the tune requirement

\[ iQ = 0 \]

where \( i \) is the number of turns between kicks and \( m \) an integer. The number of turns in a KAC cycle and the resulting required kick frequency for different solutions utilizing two kicks can be found in Table 3.

The nominal lattice of the MAX IV 1.5 GeV storage ring was modified to the desired vertical tunes using OPA [33]. Sufficient optimization was considered achieved when reaching the desired vertical tune without major changes to the optical functions. The resulting optical functions for different vertical tunes are displayed in Fig. 2. The changes are only negligible for the vertical tunes 3.167 and 3.25, and therefore these choices were considered preferable for operation in the real machine.

The tune change required modification of the quadrupole gradient in the combined quadrupole–sextupole magnet family SQFi, and therefore resulted in a modification of the corresponding sextupole gradient. Since this magnet family is chromatic, the gradient modification had to be compensated by the chromatic sextupole magnets SCi and SDi to restore the nominal +1 chromaticity in both transverse planes. Studies of the dynamic aperture and Touschek lifetime with these modifications were performed using Tracy [34] with and without errors. The same error models were utilized as during the design studies of the ring [23]. The studies showed no reduction of dynamic aperture affecting injection and only a change of Touschek lifetime on the level of \( \pm 0.2\% \). Therefore, both lattices are considered to be feasible for operation in the real machine.

4.2. Optimization for beamlines

The choice of tune is also of importance to optimize the feasibility of the PSB mode in as many beamlines as possible. The electron beam orbit at a position \( s_2 \) when applying a kick \( \theta \) at a position \( s_1 \) upstreams for all kicks has to be zero [32]. For two kicks this results in the tune requirement \( Q = 0.5 + m \), where \( i \) is the number of turns between kicks and \( m \) an integer. The number of turns in a KAC cycle and the resulting required kick frequency for different solutions utilizing two kicks can be found in Table 3.

Table 3

<table>
<thead>
<tr>
<th>Turns between kicks</th>
<th>Fractional tune</th>
<th>Kick frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>3.125 MHz</td>
</tr>
<tr>
<td>2</td>
<td>0.25, 0.75</td>
<td>1.563 MHz</td>
</tr>
<tr>
<td>3</td>
<td>( \frac{1}{4} \approx 0.167, 0.5, \frac{3}{4} \approx 0.833 )</td>
<td>1.042 MHz</td>
</tr>
<tr>
<td>4</td>
<td>0.125, 0.357, 0.625, 0.875</td>
<td>0.781 MHz</td>
</tr>
<tr>
<td>5</td>
<td>0.1, 0.3, 0.5, 0.7, 0.9</td>
<td>0.625 MHz</td>
</tr>
</tbody>
</table>

Fig. 2. Beta functions, horizontal (solid) and vertical (dashed), and dispersion (dotted) for lattices with vertical tune 2.833, 3.15 (nominal), 3.167, 3.25 and 3.75, respectively.
is given by

$$u(s_2) = \sqrt{\beta_2 \beta_3} \sin(\Delta \varphi) \theta$$

(9)

$$u'(s_2) = \sqrt{\beta_2 \beta_3} \left( \cos(\Delta \varphi) - \alpha_{s_2} \sin(\Delta \varphi) \right) \theta,$$

(10)

where $\Delta \varphi$ is the phase advance between $s_1$ and $s_2$ [35]. For the simplest design of a PSB mode, the kicker and the source points of the beamlines are placed in the middle of the straight sections. For the MAX IV 1.5 GeV storage ring this gives $u_{\text{kick}} = u_{\text{source}} = 0$ and $\beta_{\text{kick}} = \beta_{\text{source}} = \beta$, where $\alpha_1$, and $\beta_1$ are the Twiss parameters at the positions of the beamlines, and $\alpha_{\text{kick}}$ and $\beta_{\text{kick}}$ the Twiss parameters at the position of the kicker. This gives the electron beam orbit at the beamline positions

$$u(s_n) = \theta \beta \sin(\Delta \varphi_{s_n})$$

(11)

$$u'(s_n) = \theta \cos(\Delta \varphi_{s_n}),$$

(12)

where $\Delta \varphi_{s_n}$ is the phase advance between the kicker and the corresponding beamline. Since the phase advance of the MAX IV 1.5 GeV storage ring bare lattice is equal for each achromat, it is given by

$$\Delta \varphi_{s_n} = 2 \pi n \frac{Q}{N_{\text{achr}}} = 2 \pi n \Delta \varphi_{\text{achr}},$$

(13)

where $n$ is an integer describing how many achromats away the beamline is from the kicker and $N_{\text{achr}}$ the total number of achromats. The phase advance per achromat is denoted by $\Delta \varphi_{\text{achr}}$. To evaluate the separation at different beamlines, a transfer function $T$ describing the transfer between the applied kick and the resulting separation was defined as

$$S = T \theta.$$

(14)

For beamlines with an intermediate focus, the focused transfer function $T_{\text{f}}$ was defined as

$$S = T_{\text{f}} \theta,$$

(15)

with

$$T_{\text{f}} = \frac{N_f \sigma_0}{\theta} = \beta \sin \left(2 \pi \Delta \varphi_{\text{achr}} n\right),$$

(16)

where the sine function has the frequency $\Delta \varphi_{\text{achr}}$ and is sampled in the points $n$. Similarly, for beamlines without intermediate focus, the unfocused transfer function $T_{\text{uf}}$ was defined as

$$S = T_{\text{uf}} d \theta$$

(17)

with

$$T_{\text{uf}} = \frac{N_u \sigma_0'}{\theta} = \beta \sin \left(2 \pi \Delta \varphi_{\text{achr}} n\right) + \cos \left(2 \pi \Delta \varphi_{\text{achr}} n\right).$$

(18)

Note that the definition of the unfocused transfer function was made such that the influence of the distance from the source easily could be evaluated. It is apparent that the influence of the electron beam position depends on the ratio between the beta function and the distance to the source. Due to these definitions, the focused transfer function has the unit of length whereas the unfocused transfer function is unitless.

The two lattice candidates were evaluated for each beamline position over all $n$ turns by the merit functions

$$M_A = \max_{1 \leq n \leq N} \left| \left| T_{f} \right| \right|,$$

(19)

which describes the maximum of the absolute transfer function over all turns, and

$$M_B = \left| \left| T_{\text{max}} - T_{\text{max-1}} \right| \right|.$$

(20)

which describes the absolute difference between the transfer functions of the turn with maximum transfer and the turn closest to it. The focused and unfocused $M_A$ are displayed in Fig. 3. For unfocused separation the merit functions depend on the distance to the source so separation could be preferred at different distances depending on the beamline position. Studying the $M_A$, the vertical tune 3.167 is more promising than 3.25 for maximizing the separation in as many beamlines as possible for both focused and unfocused separation. This is because the PSB makes more turns before kicked back, and thus the probability increases for having at least one turn with sufficient value of the transfer function at every beamline. For a given $M_A$, the required kick to achieve a certain focused or unfocused separation can be dimensioned according to

$$\theta_k = \frac{N_f \sigma_0}{M_A}$$

(21)

$$\theta_{\text{uf}} = \frac{N_u \sigma_0'}{M_{A,\text{uf}}}$$

(22)

If the kick, for example, is dimensioned for $M_A = 2.5$ m or $M_{A,\text{uf}} = 1$, the resulting required kick angles to achieve $10\sigma$ separation of the photon beams are presented in Table 4. This separation is chosen here as an example and is discussed in more detail in Section 7. It can be noted that the ratio between the required kick angles are given by

$$\frac{\theta_k}{\theta_{\text{uf}}} = \frac{M_A \sigma_0}{M_{A,\text{uf}} \sigma_0'} \approx \frac{1}{2} \frac{\sigma_0}{\sigma_0'}.$$  

(23)

Since $\sigma_0' < 2.5$ m in the vertical plane for the whole photon energy range of interest, focused separation is more effective than unfocused separation for reducing the required kick. This results from the magnitude of the beta function in combination with the diffraction contribution to the photon beam size and divergence. Generally, for a diffraction-limited beam according to Eq. (8)

$$\frac{\sigma_0}{\sigma_0'} = \frac{\sigma_0}{\sigma_0'} = \frac{L}{\pi},$$

(24)

where $L$ is the undulator length, which is often smaller than the beta function in the straight section.

The $M_B$ for several vertical tune choices are displayed in Fig. 4. More turns before the PSB is kicked back increases the difficulty to separate the radiation emitted from different turns, and thus leads to
Table 4
Estimated required kick to achieve $10\sigma$ separation in the vertical plane for $M_{AF} = 2.5$ and $M_{AF} = 1$, respectively.

<table>
<thead>
<tr>
<th>Photon energy</th>
<th>Focused</th>
<th>Unfocused</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 eV</td>
<td>148 $\mu$rad</td>
<td>789 $\mu$rad</td>
</tr>
<tr>
<td>200 eV</td>
<td>123 $\mu$rad</td>
<td>355 $\mu$rad</td>
</tr>
<tr>
<td>1000 eV</td>
<td>72 $\mu$rad</td>
<td>164 $\mu$rad</td>
</tr>
</tbody>
</table>

(a) Focused separation.

(b) Unfocused separation for a distance 8 m (solid), 12 m (dashed) and 16 m (dotted) from the source. The distances correspond to positions where light separation is possible in the present MAX IV 1.5 GeV ring beamlines.

Fig. 4. The merit function $M_B$ for the two vertical tune choices.

a smaller $M_B$. This can cause problems for some experiments since not only light from the turn with largest separation from the multibunch train will be seen by the beamline, but also some of the light produced by the PSB during other turns. Comparing the $M_B$ values it is evident that overlapping of light from different PSB turns is a larger concern for unfocused than for focused separation, but it is a problem for some beamlines in both cases. It can, however, be solved by requiring choppers in the beamlines that wish to utilize the PSB mode. By setting this requirement it is possible to choose a PSB mode operated at the vertical tune 3.167 instead of 3.25, which gives large separation in all beamlines.

5. Electron beam orbit

The PSB electron orbit when applying a series of kicks was simulated with DIMAD [36] and compared to simulations performed with Accelerator Toolbox [37]. The two codes showed consistent results. The electron orbit for the kicks in Table 4 for a vertical tune of 3.167 are displayed in Fig. 5. The chosen kicks lead to maximum electron orbits between 0.48 and 0.99 mm for focused separation compared to 1.1–5.2 mm for unfocused separation. Presently the orbit limitations for machine protection are set to $\pm 0.5$ mm [38], but the studies behind this limitation did not consider a certain fill pattern so the effects from irradiating parts of the vacuum chamber have to be further analyzed to determine requirements for a PSB mode.

Simulations of several KAC cycles were performed in Accelerator Toolbox with cavity and radiation effects. The simulations were performed using the atfastring function for a lattice with and without PSB kick which allowed tracking for several damping times including quantum diffusion [39]. The lattice without PSB kick were first tracked for 60 000 turns to reach nominal values for beam size, energy spread, bunch length and emittance. The lattice was then tracked with or without PSB kick according to a given KAC scheme. As previously mentioned, a KAC scheme allows for variation of the PSB frequency, but due to resonances it is not feasible to operate at all frequencies [7]. If the KAC period is $N \text{ turns}$, the PSB frequency becomes

$$f_{PSB} = \frac{f_{rev}}{N}$$

where $f_{rev}$ is the revolution frequency. Resonances causing unstable orbits occur when [7]

$$NQ = k,$$
Fig. 6. Coupling increase due to vertical kicks at high frequency for different kicks. In the simulations 10,000 particles and a KAC scheme with $N = 7$ were used. The results every 100th turn are plotted.

where $k$ is an integer, and at the coupling resonances

$$m_x(NQ_x) + m_y(NQ_y) = k.$$  \hspace{1cm} (27)

For the coupling resonances the orbit can be stabilized by adjusting the horizontal tune \cite{7}, but this is not possible for the integer resonances. For a vertical tune of 3.167, assuming a maximum available kick frequency according to Table 3, the maximum stable PSB frequency is at $N = 7$ corresponding to 446 kHz. It would also be possible to operate at $N = 4$ or $N = 5$, but this requires a kicker that can kick with higher frequency than required by the tune choice. The simulations showed that the orbit becomes unstable at the resonances predicted by theory.

If the PSB is not at the correct betatron tune, an orbit deviation will remain after a KAC cycle, which after several cycles translates into a stable oscillation of the bunch. The design specifications of the ring allow for oscillation of the electron beam centroid up to 10% of the electron beam size \cite{14}, corresponding to 1.3 μm in the vertical plane. It is however likely that the requirement on maximum electron beam oscillation can be relaxed since the PSB is only one of 32 bunches for the multibunch users, and since the timing users are mostly interested in photon energies where the photon beam size is dominated by diffraction and thus substantially larger than the electron beam size. The lattice optimization was performed to put the working point at the correct vertical tune to simulate the effect of operating the multibunches on a resonance, which resulted in a small tune deviation for the PSB due to chromatic and amplitude-dependent tune shifts. The effect of this was simulated and it was found that it could be compensated by a small modification of the working point such that the tune of the PSB becomes correct including the nonlinear tune shifts.

In addition, the coupling increase caused by the PSB going off-axis through the sextupoles and kicking the beam at high frequency was evaluated by studying the increase of the vertical emittance. For the ideal, uncoupled lattice the vertical emittance at the initial equilibrium was zero but, as displayed in Fig. 6, a new equilibrium is reached when running KAC. The coupling increase for a 789 μrad kick for the maximum stable PSB frequency $N = 7$ is considered to large for operation, but for a 355 μrad kick the increase is below 2%, which is considered acceptable. The coupling increase is, however, dependent on the PSB frequency and becomes smaller further away from resonances.

In the ring tune deviations occur due to insertion device gap motion and power supply jitter and the tune has to be sufficiently stable not to give rise to too large PSB oscillations. The residual orbit amplitude after a KAC cycle is given by

$$\Delta u \approx 2\pi \beta \Delta u \Delta Q,$$

where $\Delta n$ is the number of turns before the beam is kicked back. For the vertical tune 3.167 and the kicks in Table 4 this gives maximum allowed tune variations between $1.7 - 3.4 \cdot 10^{-4}$ for focused separation and $1.5 - 3.1 \cdot 10^{-5}$ for unfocused separation.

6. Beamline simulations

The output from the simulations of the electron beam orbit was used to simulate the photon beam separation for undulator radiation using XRT \cite{40}. For these simulations, an example undulator with period length 59.5 mm, total length 2.5 m and a maximum $K$ value of 6 was
(a) Photon energy 40 eV. Separation to multibunch: 4.11 FWHM/2. Separation to closest PSB: 2.09 FWHM/2.

(b) Photon energy 200 eV. Separation to multibunch: 9.54 FWHM/2. Separation to closest PSB: 4.85 FWHM/2.

(c) Photon energy 1000 eV. Separation to multibunch: 19.94 FWHM/2. Separation to closest PSB: 10.13 FWHM/2.

Fig. 8. XRT simulations for a vertical tune of 3.167 for different photon energies at a screen 8 m from the source. In this example 355 \(\mu\)rad kick and a beamline position four achromats from the kicker was used. The photon energy ranges were set to 0.1%BW.

Fig. 9. XRT simulations for a vertical tune of 3.167 (top) and 3.25 (bottom) at a screen 8 m from the source. In this example 355 \(\mu\)rad kick, 200 eV photon energy and a beamline position three achromats from the kicker were used.

used. The parameters were chosen to represent a common undulator in the MAX IV 1.5 GeV storage ring. For this undulator, 40 eV and 200 eV are first harmonics whereas 1000 eV is a third harmonic. Since undulator radiation is not Gaussian, the beam size was described by \(\text{FWHM} = \sqrt{2\ln 2} \sigma \approx 1.18 \sigma\) since this resulted in a better measure of the size of the central peak of the radiation. For focused separation it is the separation at the source that is of interest since this will be imaged onto the plane where the separation is performed, whereas for unfocused separation the separation 8 m from the source was studied since this is the position in the present MAX IV 1.5 GeV ring beamlines which would result in largest \(M_A\) for most beamlines.

For a kick of 123 \(\mu\)rad (dimensioned to achieve 10\(\sigma\) separation at 200 eV photon energy for focused separation) a comparison for different photon energies at the source is displayed in Fig. 7. A similar comparison for 355 \(\mu\)rad kick (dimensioned to achieve 10\(\sigma\) separation at 200 eV photon energy for unfocused separation) at 8 m from the source is displayed in Fig. 8. It is evident that for photon energies below 200 eV, which the kick is dimensioned for, the maximum separation is reduced for both focused and unfocused separation, whereas for higher photon energies it is increased.

As discussed earlier, overlap between the light from different PSB turns can occur if the \(M_A\) value is too small. Fig. 9 displays a comparison for a beamline position three achromats from the kicker that utilizes unfocused separation. At this position, overlap between PSB turns occurs for the vertical tune 3.167, but not for 3.25, as expected considering the \(M_A\) values. The XRT simulation displays the situation as seen when integrating over time, thus the radiation from different PSB turns in this case cannot be separated without a chopper in the beamline.

7. Purity

For the users, the purity between the light from the PSB and the light from the rest of the multibunch train is of great importance. In this paper the purity is defined as the ratio between the light from the PSB and one of the multibunch bunches. Since the principle of the PSB method is to place an aperture such that the radiation emitted from the multibunches is blocked, the purity will depend on the size of the aperture. Therefore, for a given separation the flux and purity
Depending on exact user requirements, for focused separation sufficient function of electron beam position and angle at the source, respectively. This ring pattern can be recognized in the beam profiles presented in Fig. 8. It is evident that the ring pattern caused by the angular beam profile can seriously reduce the purity if the kick is such that the PSB will be situated at the same angle as the rings produced by the multibunches. The angular position of the rings is given by

$$\theta_{nl} = \frac{2l}{\lambda_u} \sqrt{n \left(1 + \frac{K^2}{2}\right)}$$

(29)

where \(l\) is the harmonic, \(l = 1, 2, 3\ldots\) and \(K\) the undulator parameter. Applying the on-axis undulator equation \(\lambda = \frac{\gamma}{2n} \left(1 + \frac{K^2}{2}\right)\) [41], this can be written as

$$\theta_{nl} = \frac{2l}{\lambda_u} \sqrt{n \frac{\gamma}{2}}$$

(30)

where \(\lambda_u\) is the undulator period. The wavelength is connected to the PSB kick by Eq. (22) and (8) as

$$\theta_{ad} \approx N_{ad} \sigma'_0 \approx N_{ad} \sigma'_f = N_{ad} \frac{\lambda}{2L}$$

(31)

resulting in

$$\theta_{nl} = \frac{4L \theta_{ad}}{\lambda_u} N_{ad}$$

(32)

A kick beyond a ring requires \(\theta_{nl} < \theta_{ad}\), which leads to the requirement

$$N_{ad} > \frac{4L}{\lambda_u}$$

(33)

and a separation above 10\(\sigma\) as found in Fig. 12.

From the purity, the integrated purity that will be seen by a beamline which integrates over time can be calculated for a given charge distribution in the ring, KAC operation scheme and beamline configuration by calculating the number of multibunches per PSB and taking into account the charge distribution among the buckets. If the purity for nominal charge per bunch is \(P\), the integrated purity is given by

$$P_{int} = \frac{q_{rel} P}{N_{MB}}$$

(34)

where \(q_{rel}\) is the relative charge in the PSB compared to the nominal charge in the multibunches and \(N_{MB}\) the number of multibunches seen by the beamline per PSB. In the case of no chopper in the beamline, the number of multibunches per PSB will depend on the period between KAC cycles. Avoiding periods between cycles that lead to resonances and assuming the maximum frequency of the kicker is given by the required frequency for KAC in Table 3, the maximum frequency with which a PSB could be seen in a beamline is, in accordance with the discussion in Section 5,

$$f_{PSB} = \frac{f_{rev}}{2\pi + 1}$$

(35)

where \(f_{rev}\) is the revolution frequency and \(i\) the number of turns between kicks in the KAC cycle. The number of multibunches seen by the beamline during a PSB period (if the PSB during turns not used by the beamline are counted as multibunches) is

$$N_{MB} = \frac{h f_{rev}}{f_{PSB}} - 1 = hN - 1$$

(36)

where \(h\) is the harmonic number of the ring and \(N\) the number of turns before the KAC scheme repeats. On the other hand, with a chopper in the beamline the number of multibunches are given by the chopper window. The number of multibunches seen by the beamline is then

$$N_{MB, chopper} = \Delta f_{rev} h - 1$$

(37)

where \(\Delta t\) is the time duration of the chopper window. As displayed in Fig. 13, the integrated purity increases linearly with the PSB frequency and proportionally to the relative charge in the PSB compared to the multibunches. However, when using a chopper the integrated purity is given by the length of the window and is no longer dependent on the PSB frequency.
8. Kicker requirements

The ALS PSB mode utilizes a stripline kicker for deflecting the PSB transversely [42], and a similar design is considered for a PSB mode at the MAX IV 1.5 GeV storage ring. For this kicker, three parameters are set by the PSB mode design: pulse length, repetition rate and kick amplitude. Since the aim of the development of PSB modes at the MAX IV rings is to serve timing users without requiring gaps in the multibunch fill, the pulse length is critical and determined by the interval between bunches in the multibunch train, resulting in a rise/fall time of \( <10 \, \text{ns} \) and a maximum total pulse length of \( \leq 20 \, \text{ns} \). The maximum repetition rate is set by the tune choice or the maximum PSB frequency that should be available for users if this is higher than determined by the tune. Finally, the required kick is determined by the purity requirements of the users.

The maximum pulse length sets a limit on the maximum length of a stripline since the propagation time of the pulse along the stripline and the bunch length also has to be taken into account. The maximum length is given by

\[
L \leq \tau_G - \tau_R - \tau_b, \quad (38)
\]

where \( \tau_G \) is the gap between adjacent bunches, \( \tau_R \) the rise/fall time of the pulse and \( \tau_b \) the bunch length [43]. The profile of a lengthened bunch in the MAX IV 1.5 GeV storage has a full width of roughly 1.3 ns, which, with 10 ns spacing between bunches, leads to a maximum rise time of 6.7 ns for a 0.3 m kicker, 4.7 ns for a 0.6 m kicker, or 2.0 ns for a 1 m kicker.

The kick requirement determines the necessary voltage on each stripline according to

\[
\pm V = \frac{E \cdot h \cdot \theta}{4 \cdot L \cdot g}, \quad (39)
\]
where $E$ is the beam energy in eV, $h$ the transverse distance between the striplines, $\theta$ the kick, $L$ the length of a stripline, and $g$ a geometry factor [42]. Since the length of a stripline is a factor in Eq. (39), the voltage and pulse length are not independent. It is possible to decrease the voltage requirement by placing several stripline modules after one another (thus increasing the total length without requiring shorter rise/fall time). This, however, means the kicker will occupy more space in the ring (due to required spacing between modules), in addition to requiring several pulsers [44], which have to be synchronized to a high degree in order to preserve the PSB beam quality.

The kicker specifications for some different designs can be found in Fig. 14. A geometry factor between 0.95 and 1 is expected to be feasible. In these calculations, 20 mm spacing vertically have been used in accordance with the nominal vacuum chamber dimensions in the straight sections of the MAX IV 1.5 GeV storage ring [14].

The required corrector strength was calculated both analytically and with SVD using response matrices in Accelerator Toolbox with consistent results. To put the PSB on-axis throughout a straight section, at least four correctors are required, but due to the positions of correctors and BPMs a four corrector bump will lead to a non-zero orbit in the arc BPM. For a 355 $\mu$rad kick this orbit is below 80 $\mu$m. To force a zero orbit in the arc at least five correctors are required. The results show that the available corrector strength is not sufficient, but has to be increased depending on the chosen PSB kick. To achieve 1$\sigma$ separation at 200 eV the peak corrector strength has to be increased by roughly a factor 2 for focused separation compared to 5–6 for unfocused separation depending on if the orbit is allowed to grow in the arcs or not. However, only the corrector strengths surrounding the straight sections that are interested in operating in PSB mode have to be increased.

9. Local orbit bumps

As mentioned previously, to be able to quickly switch between PSB and multibunch operation without realigning the beamline and to conserve the polarization properties of the emitted radiation, local orbit bumps that put the PSB on axis through the straight sections are required. In the MAX IV 1.5 GeV storage ring lattice, dipole correctors are formed by individually powered extra windings on some of the sextupole magnets. The correctors have been designed to supply 0.25 mrad kick [14].

The required corrector strength was calculated both analytically and with SVD using response matrices in Accelerator Toolbox with consistent results. To put the PSB on-axis throughout a straight section, at least four correctors are required, but due to the positions of correctors and BPMs a four corrector bump will lead to a non-zero orbit in the arc BPM. For a 355 $\mu$rad kick this orbit is below 80 $\mu$m. To force a zero orbit in the arc at least five correctors are required. The results show that the available corrector strength is not sufficient, but has to be increased depending on the chosen PSB kick. To achieve 1$\sigma$ separation at 200 eV the peak corrector strength has to be increased by roughly a factor 2 for focused separation compared to 5–6 for unfocused separation depending on if the orbit is allowed to grow in the arcs or not. However, only the corrector strengths surrounding the straight sections that are interested in operating in PSB mode have to be increased.

10. Consequences for the MAX IV 1.5 GeV storage ring

None of the five current beamlines at the MAX IV 1.5 GeV storage ring has an intermediate focus [24–28] and therefore comparison with other methods are required to determine if a PSB mode is the best choice for increasing the available beamtime for timing users at these beamlines. However, as mentioned previously, space exists for five new beamlines and if these beamlines are designed with an intermediate focus a PSB mode can serve timing users at these beamlines with high purity while the ring is operated in multibunch mode without extensive machine upgrades. For this PSB mode three requirements are proposed:

- Kick performed in the vertical plane.
The purity requirements of the users remains to be fully determined. However, for the photon energy range of interest, diffraction substantially influences the machine requirements and it is not expected to be feasible to achieve sufficient purity for all users over the whole energy range 4–1500 eV. For the lowest photon energies a single-bunch mode or another method will still be required. The choice of kick magnitude therefore has to be a balance between user requirements and machine limitations. For focused separation the 1σ separation estimated in this article could possibly be reduced after more detailed studies of the purity including the quality and stability of the beamline optics. Beamline experiments will be required to obtain a better estimation of the purity and separation requirements. Presently, the beamlines at the MAX IV 1.5 GeV ring are under construction or commissioning, but such studies will follow once they come online. For unfocused separation, however, the purity is limited by the angular beam profile and a substantial gain in purity would require kicks that are beyond machine limitations. Once the purity requirements have been determined, further studies could be conducted to find undulator designs or operation modes that would improve the purity, but this might pose restrictions on the photon energy range or polarization.

Adding a chopper to the beamline offers several advantages. It will greatly improve the integrated purity and make it feasible for beamlines to choose their operation frequency independently of one another. The requirements for such choppers are similar to the requirements for choppers for operation in single-bunch mode and they could thus be utilized for operation in both modes. In addition, by requiring a chopper in each beamline that wishes to utilize the PSB mode, it will be possible to choose a mode operated at a vertical tune of 3.167 despite the overlap of radiation from different PSB turns. Compared to a vertical tune of 3.25, this gives $M_\perp$ in all beamlines. This choice also reduces the required repetition rate of the kicker to 1.04 MHz compared to 1.56 MHz for a 3.25 tune.

11. Conclusions

The studies presented in this paper highlight that machine requirements (i.e. kicker strength and stability, tune stability, coupling increase, corrector strength, and orbit limitations due to machine protection) for a PSB mode to achieve a certain purity are greatly reduced if the beamlines have an intermediate focus before the monochromator where the photon beams can be separated. This emphasizes the importance of studying both machine and beamline design in order to fully optimize the performance of a PSB mode, as well as other methods with the purpose of serving both high flux and timing users simultaneously. It is evident that a solution with optimal performance for users can only be achieved by a design that includes measures on both the machine and the beamline side.

The feasible photon energy range is bounded by machine limitations since the separation required to achieve sufficient purity at low energies are determined by diffraction. This is the case for all methods that aim to provide single-bunch light when operating a ring in multibunch mode by separating photon beams transversely. Since some timing users are interested in UV energies, transverse methods are not sufficient to serve the whole timing user community when simultaneously serving high-flux users at the same ring. For these photon energies, methods based on separation in longitudinal phase space might be more attractive and require further consideration. For example, methods where one bunch in the bunch train is off energy by tailoring the nonlinear momentum compaction and thus creating several energy points [45,46]. If sufficient energy deviation can be achieved, the light from different bunches could be separated by a monochromator in the beamline.

This paper presents the possibility to operate a PSB mode serving all beamlines with only a single kicker by adequately choosing the tune and requiring choppers in the beamlines. This reduces the required kick frequency and the position of the kicker can be chosen independently of the position of the beamlines interested in PSB operation. In addition, choppers allow beamlines to choose frequency independent of one another and greatly increase the integrated purity.

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