Pulsed Magnet Injection for the MAX IV 3 GeV Storage Ring

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The content of this report was last updated in May 2011. Since then, more detailed studies have been performed also taking into account changes to the lattice and optics. These results were not added to this report. They can however be found in Phys. Rev. ST Accel. Beams 15, 050705 (2012)[2].

Abstract

This report investigates the use of a pulsed magnet for injection into the MAX IV 3 GeV storage ring. Such an injection would not require a local injection bump and thus avoid the alignment and synchronization issues associated with the four kickers and pulsers used in conventional injection schemes. The note starts off with a few theoretical considerations and proceeds to demonstrate the feasibility of injection into the 3 GeV storage ring with a single pulsed sextupole. The conclusion is that a pulsed sextupole (half-sine pulse with base $\tau = 3.5$ μs) with an integrated strength of $(b_3L) \approx 54$ m^{-2} installed at end of the long straight following the injection straight is adequate for injecting into the 3 GeV storage ring. Alternatively, two-turn injection (half-cosine pulse with base $\tau = 7$ μs) with an integrated strength of $(b_3L) \approx 28$ m^{-2} can be applied. Such an injection should be transparent to the beamlines. Hence, frequent low-charge top-up shots become possible allowing for almost perfectly constant stored current in the machine.

[1]This most current version of this document can be found at `http://www.maxlab.lu.se/node/999`
[2]`http://prst-ab.aps.org/abstract/PRSTAB/v15/i5/e050705`

1 Introduction

Injection with a pulsed quadrupole magnet [1] and a pulsed sextupole magnet [2] have both been successfully demonstrated at KEK. In principle, the pulsed magnet injection scheme relies on the fact that the stored beam passes the center of the pulsed magnet receiving no kick while the injected beam passes the pulsed magnet with a deviation from the magnet center thus receiving a kick. The goal is to adjust this kick in such a way that the injected bunch can pass through the rest of the ring and clear the septum in the second (and subsequent) turns.

The key advantage of such an injection over conventional injection is that stored beam does not need to be kicked onto an injection bump. Since adjusting this bump to be perfectly closed is almost never entirely achieved, a residual betatron oscillation usually remains for the stored beam. Thus, for the duration of a few damping times (MAX IV 3 GeV storage ring damping time $\tau_x < 16$ ms) the stored beam will remain perturbed and the users will notice this as movement of their source point. Furthermore, if the injection bump contains sextupoles and/or octupoles, it can never be closed perfectly for all particles within the stored beam.

With the (ideal) pulsed magnet injection scheme the only portion of the beam that receives a kick is the injected bunch. In top-up operation this corresponds to $< 0.1\%$ of the overall stored charge and hence isn't noticeable at the beamlines. For the details of the theory behind the pulsed magnet injection refer to [1, 2]. Here only a brief introduction will be given. The invariant of transverse motion for the injected bunch is given by

$$A^2_{\text{inj}} = \gamma_{\text{inj}} x^2_{\text{inj}} + 2\alpha_{\text{inj}} x_{\text{inj}} {x'}_{\text{inj}} + \beta_{\text{inj}} {x'}^2_{\text{inj}}, \tag{1}$$

where the subscript indicates at the injection point. After injection the injected bunch should be kicked to a reduced invariant

$$A^2_{\text{red}} = \gamma_{\text{pm}} x^2_{\text{pm}} + 2\alpha_{\text{pm}} x_{\text{pm}} {x'}_{\text{pm}} + \beta_{\text{pm}} {x'}^2_{\text{pm}}, \tag{2}$$

where the subscript indicates a position immediately after the pulsed magnet. This reduced invariant should be smaller than the admittance of the storage ring for accumulation to be possible. Assuming that this admittance is determined in the horizontal by the septum blade, one can formulate a criterium for the reduced invariant:

$$A_{\text{red}} \overset{!}{<} A_{\text{septum}} \tag{3}$$

The goal is to then calculate the kick strength of the pulsed magnet θ_{pm} and its location given by its phase advance with respect symmetry point ϕ_{pm}. Following [1, 2] it can be shown that the ideal location of the pulsed magnet is given by the invariants alone. Ideally, one would require a phase advance given by

$$\cos \hat{\phi}_{\mathrm{pm}} \stackrel{!}{=} \pm A_{\mathrm{red}}/A_{\mathrm{inj}} \tag{4}$$

in order to minimize the required kick which is then given by

$$\hat{\theta}_{\mathrm{pm}} = \frac{A_{\mathrm{inj}}}{\sqrt{\beta_{\mathrm{pm}}}} \left|\sin \hat{\phi}_{\mathrm{pm}}\right| . \tag{5}$$

Since the pulsed magnet only applies a kick, the position of the injected bunch in the pulsed magnet must obviously already lie within the the boundary set by the reduced invariant:

$$\left|\frac{x_{\mathrm{pm}}}{\sqrt{\beta_{\mathrm{pm}}}}\right| < A_{\mathrm{red}}. \tag{6}$$

For the kick calculated in Eq. 5 a pulsed quadrupole magnet (PQM) or a pulsed sextupole magnet (PSM) can be used. The required integrated strengths are given by:

$$\begin{aligned}(b_2 L) &= \frac{\theta_{\mathrm{pm}}}{x_{\mathrm{pm}}} = \frac{\theta_{\mathrm{pm}}}{\sqrt{\beta_{\mathrm{pm}}} A_{\mathrm{inj}} \cos \phi_{\mathrm{inj}}} \\ (b_3 L) &= \frac{\theta_{\mathrm{pm}}}{x_{\mathrm{pm}}^2} = \frac{\theta_{\mathrm{pm}}}{\beta_{\mathrm{pm}} A_{\mathrm{inj}}^2 \cos^2 \phi_{\mathrm{inj}}}\end{aligned}$$

As pointed out in [2] the PSM has various advantages over the PQM. In summary:

- The PQM introduces a gradient error to the stored beam for the duration of the magnet pulse. This gives a beta beat and hence a beam size variation along the ring. The result is that for the duration of the pulse the users will see fluctuating photon intensity. For the PSM the stored beam sees only a slight shift of chromaticity during the injection pulse. This does not lead to a change of beam size at the insertion device.
- For a given injection orbit the required PSM will be weaker than the PQM.
- The PSM kick is symmetric and flat around the magnet center. For the same injection kick, the residual kick to a stored beam particle at x will be reduced by a factor x/x_{inj} for the PSM compared to the PQM. Considering that typically, $\sigma_x \approx 50\mu$m and $x_{\mathrm{inj}} > 10$ mm, this factor lies well below 10^{-2}. Therefore, stored beam perturbation by the PSM is extremely small.

2 Application to MAX IV: A First Approximation

For the MAX IV 3 GeV storage ring we define the injection point as the end of the septum magnet in the injection straight (LS1). This is located 1902 mm downstream of the center of the injection straight or 487 mm upstream of the center of the first BPM in the first achromat[3]. At this location $\beta_{\mathrm{inj}} = 9.402$ m and $\alpha_{\mathrm{inj}} = -0.211$. With an injected beam at $x_{\mathrm{inj}} = -13.5$ mm (cf. Fig. 1) we arrive at an injection invariant of $A^2_{\mathrm{inj}} = 20.25$ mm mrad. If we take into account that in the conventional injection scheme [3] the injected bunch has an offset of -5.5 mm with respect to the stored beam (-8 mm injection bump; septum spans -12.5 mm to -10 mm) we arrive at a reduced invariant of $A^2_{\mathrm{red}} = 3.36$ mm mrad which is well below the admittance defined by the septum at $A^2_{\mathrm{septum}} = 11.11$ mm mrad. Therefore this can be set as a target value for the reduced invariant in the pulsed magnet injection scheme.

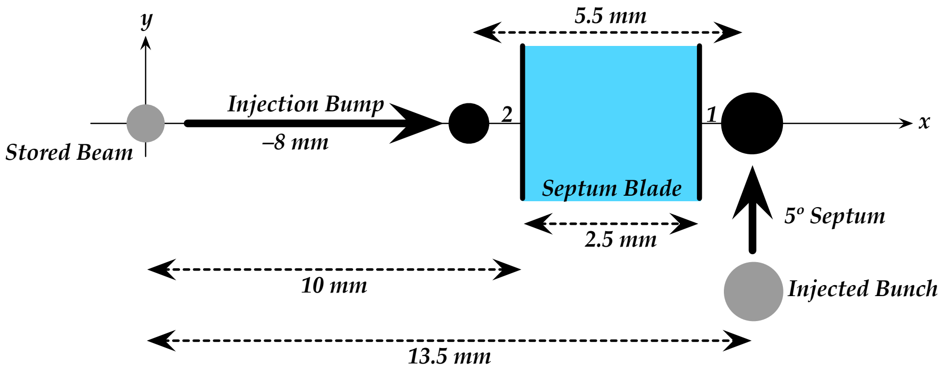

Figure 1: Schematic of the conventional injection scheme for the MAX IV 3 GeV storage ring as detailed in [3].

Hence, Eq. 4 gives ideal phases $\hat{\phi}_{\mathrm{pm}}$ of ± 1.15 and ± 1.99. The former lies within the first matching cell so it is not a feasible candidate. The latter lies close to the beginning of the first short straight section (SS) which appears feasible. However, from Eq. 5 we note that a large beta function at the location of the pulsed magnet is of advantage to reduce the required kick strength and thus the beginning of the first SS could require a too strong magnet. High beta function values are encountered in the long straight section (LS); since injection occurs at the end of the 1st LS, the 2nd LS becomes a possible candidate. Therefore, we shall now inspect several possible locations and determine the required kick strength as well as the achievable

[3]Distances according to the m4-20110117 lattice branch.

reduced invariants. Figure 2 shows examples of different locations for the pulsed magnet along with achievable reduced invariants and required magnet strengths. The observed cut-off is determined by Eq. 6.

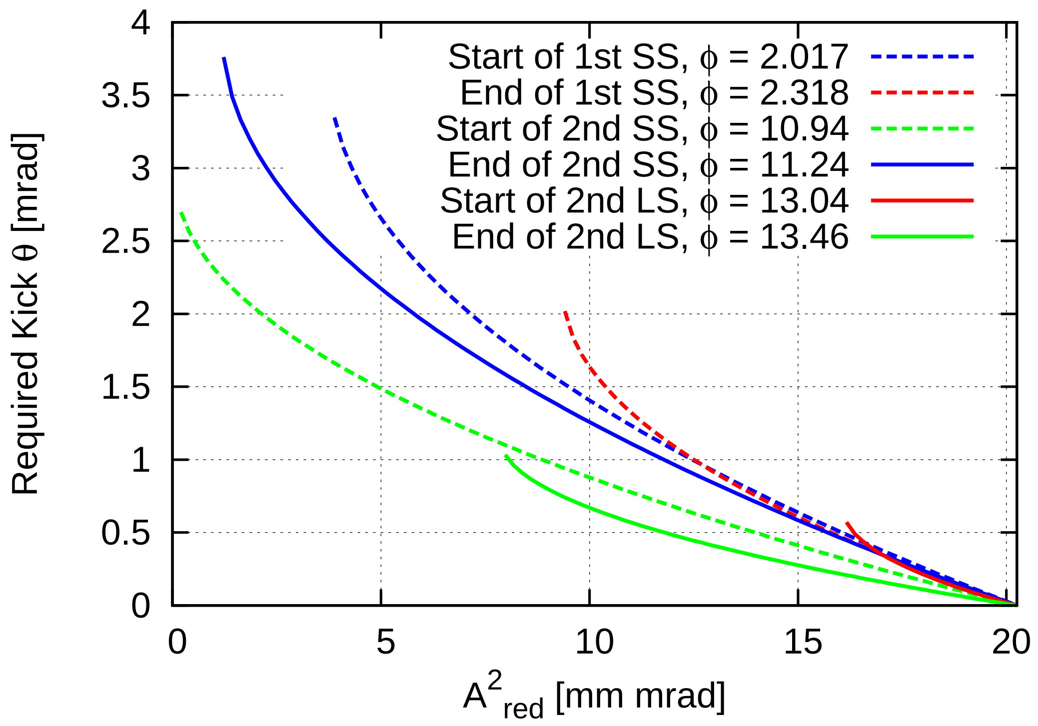

Figure 2: Kicks required from the pulsed magnet in order to achieve a certain reduced invariant. Different locations in the lattice for the pulsed magnet are displayed along with their phase advance with respect to the symmetry point.

From Fig. 2 it appears that several candidates render a suitably low reduced invariant. However, it remains to be seen if the required kick strength is feasible. Since the kick depends on the orbit of the injected bunch in the pulsed magnet x_{inj}, the required magnet strength depends also on the location within the lattice. This is displayed in Figs. 3 and 4. For both types of pulsed magnets the end of the 2nd LS appears as a suitable location. At this location a reduced invariant of $A^2_{\mathrm{red}} \approx 8$ mm mrad can be achieved. This is sufficient since the septum defines the horizontal admittance at $A^2_{\mathrm{septum}} \approx 11$ mm mrad.

It is important to point out here that the underlying assumption for the above conditions derived from the invariants is that betatron motion is linear. Nonlin-

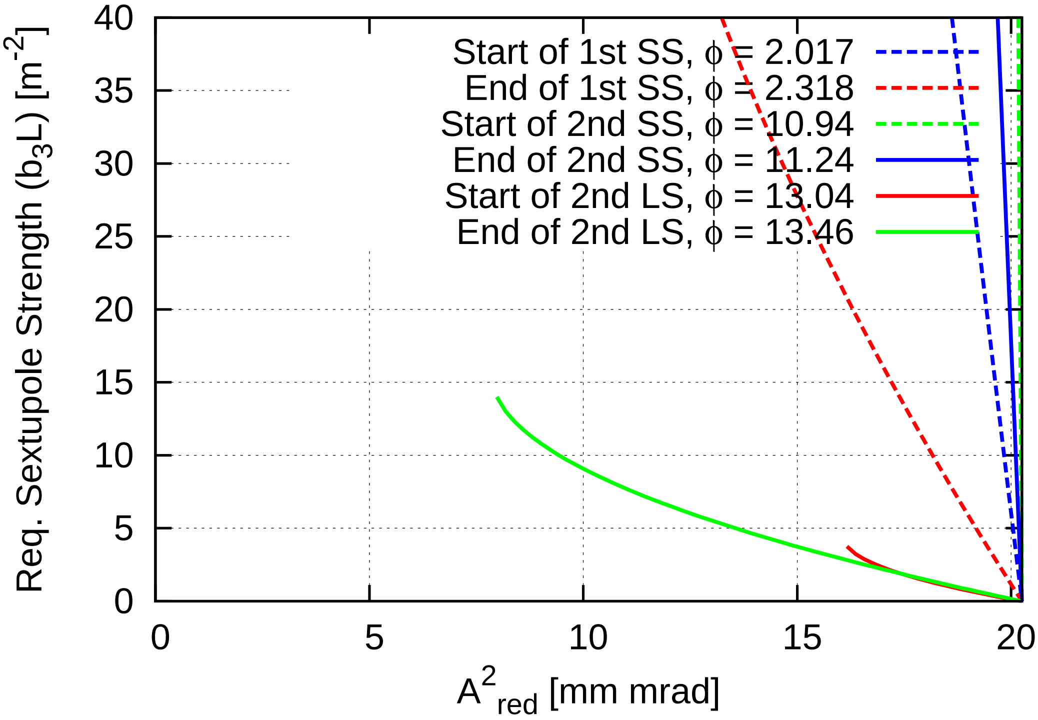

Figure 3: Field strength required from the pulsed sextupole magnet in order to achieve a certain reduced invariant. Different locations in the lattice for the pulsed sextupole magnet are displayed. A sextupole strength of $(b_3L) \approx 21\ \mathrm{m}^{-2}$ corresponds to the strongest sextupoles used in the storage ring lattice.

earities distort the phase space ellipses and perturb these "invariants". For the large amplitudes of the injected bunch the strong sextupoles in the lattice give rise to considerable nonlinearities which perturb this linear approximation considerably. Therefore, the actual solution should be derived from tracking. This shall be presented in the next section. Additional examples from tracking for different locations of the pulsed magnet can be found in [4].

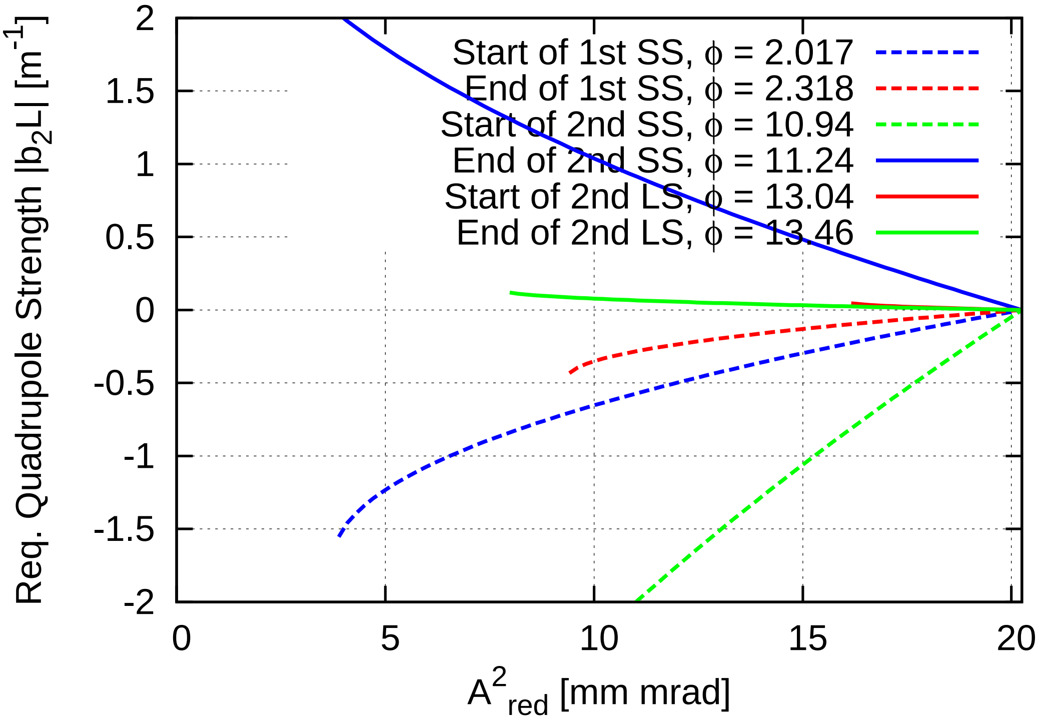

Figure 4: Field strength required from the pulsed quadrupole magnet in order to achieve a certain reduced invariant. Different locations in the lattice for the pulsed sextupole magnet are displayed. A quadrupole strength of $(b_2 L) \approx 1$ m^{-2} corresponds to the strongest quadrupoles used in the storage ring lattice.

3 Actual Implementation in MAX IV

For the reasons specified in the first section, a pulsed sextupole magnet shall be used for injection into the MAX IV 3 GeV storage ring. The PSM is installed at the end of the 2nd LS, that is the end of the LS that follows the injection straight. The position of the PSM in the 2nd LS is exactly the same as the position of the injection point in the 1st LS: 1902 mm downstream of the LS center or 487 mm upstream of the center of the first BPM in the following achromat[4]. At this position the storage ring optics in the horizontal are determined by $\beta_{\mathrm{x,pm}} = 9.402$ m and $\alpha_{\mathrm{x,pm}} = -0.211$. The injected bunch is injected into the storage ring at the injection point with $(x_{\mathrm{inj}}, x'_{\mathrm{inj}}, y_{\mathrm{inj}}, y'_{\mathrm{inj}}) = (-13.5\,\mathrm{mm}, 0, 0, 0)$ where it oscillates around the design orbit with large amplitudes, but can still be contained within the admittance of the first achromat. At the location of the PSM it reaches $(x_{\mathrm{pm}}, x'_{\mathrm{pm}}, y_{\mathrm{pm}}, y'_{\mathrm{pm}})$ and receives a kick $\theta_{\mathrm{pm}} = (b_3 L)x^2_{\mathrm{pm}}$. Thus, with $(x_{\mathrm{pm}}, x'_{\mathrm{pm}} + \theta_{\mathrm{pm}}, y_{\mathrm{pm}}, y'_{\mathrm{pm}})$ it continues to oscillate through the rest of the ring.

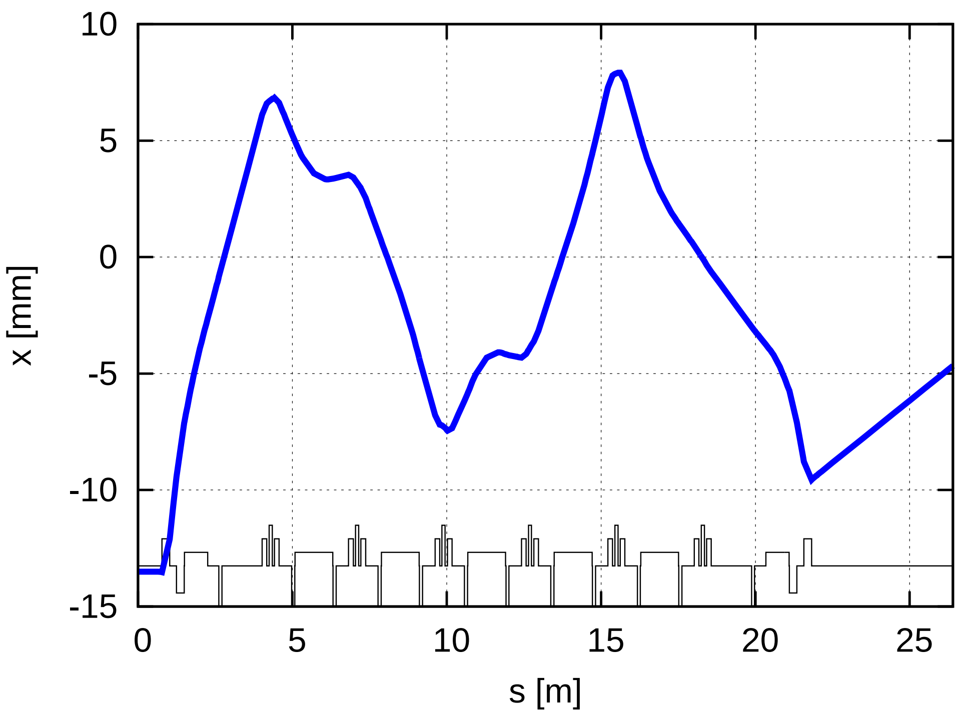

Figure 5: Orbit of the Injected bunch starting at the injection point and ending at the location of the PSM in the 2nd LS.

[4] Distances according to the m4-20110117 lattice branch.

Figure 5 shows the orbit of the injected bunch from the injection point through the first achromat. Note that in the final focusing quadrupole the injected bunch approaches the vacuum chamber aperture at -11 mm. At this location we should consider if an increase of horizontal aperture is of benefit. With the straight section following immediately however, it is quite possible tapering of the vacuum chamber has already started at this position thus increasing the available horizontal aperture.

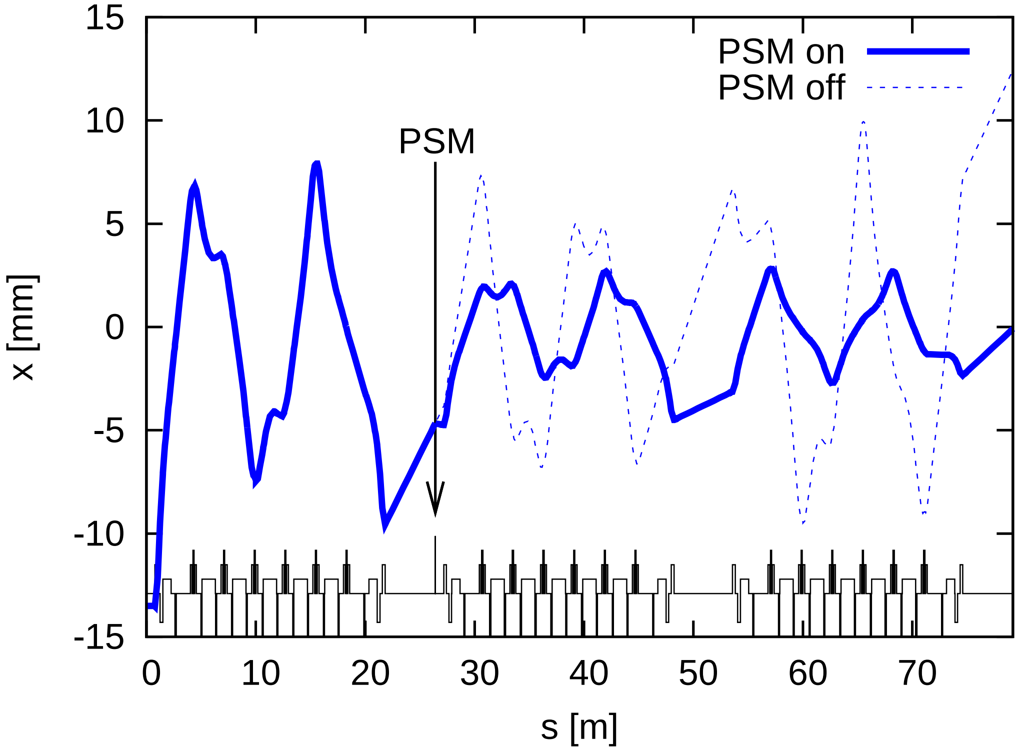

Figure 6: Orbit of the Injected bunch starting at the injection point further on through the PSM up to then end of the 4th LS. The dashed line indicates the orbit of the injected bunch if the PSM is turned off. Without the PSM the injected bunch will eventually hit the aperture as can be seen at the end of the 4th LS.

From tracking we gather that $x_{\rm pm} = -4.665$ mm and $x'_{\rm pm} = 1.067$ mrad. Hence a kick strength of $(b_3 L) = x'_{\rm pm}/x^2_{\rm pm} = 49.03\ {\rm m}^{-2}$ is determined. But in fact, tracking reveals that the minimum reduced invariant is achieved if the injected bunch is kicked to -0.1 mrad rather than to zero angle. Therefore, the required kick is set at $(b_3 L) = (x'_{\rm pm} + 0.1\ {\rm mrad})/x^2_{\rm pm} = 53.63\ {\rm m}^{-2}$. This knocks the injected bunch onto a reduced ellipse in phase space (corresponding to the reduced invariant

$A^2_{\rm red} = 2.3$ mm mrad). The injected bunch then continues betatron oscillations around the ideal orbit with a reduced amplitude and eventually damps down to the stored beam within a few damping times ($\tau_x < 16$ ms). Figure 6 shows the orbit of the injected bunch from the injection point and through the PSM using the above mentioned parameters. Tracking confirms that this reduced invariant fits the admittance of the storage ring for all locations along the ring and for the entire time required for damping to take place. Fig. 7 shows tracking results for the injection process, capture, and the first 100 turns in the storage ring.

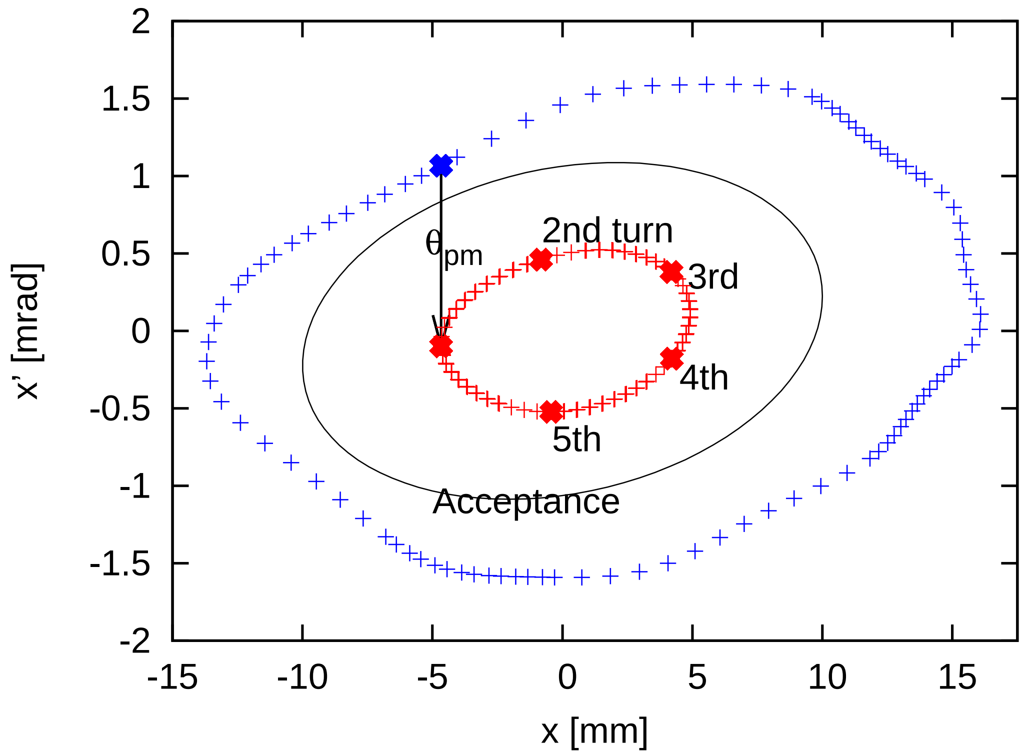

Figure 7: Injection with the PSM into the storage ring. Tracking data is shown for capture at the PSM (blue ×) and for the first 100 turns in the storage ring (red +). The outer "ellipse" (blue +) is distorted due to the nonlinearities of betatron motion at large amplitudes (strong sextupoles!). The inner ellipse corresponds to more linear motion at the reduced invariant $A^2_{\rm red} \approx 2.3$ mm mrad.

Of course not all injected particles have the ideal coordinates used above. The injected bunch has a normalized emittance of $\varepsilon_n \approx 1.5$ mm mrad which corresponds to a transverse emittance of $\varepsilon_{x,y} \approx 0.26$ nm rad at 3 GeV. With such a small emittance and the large acceptance of the storage ring, we do not have to perfectly match the transfer line optics at the injection point to the ring optics. In fact, we can tolerate a rather large mismatch. We chose to keep the transfer line simple: it merely mirrors the linac optics at the extraction point to the storage ring injection point. For the linac, a convenient optics gives an extraction optics with $\beta_x^* = 11.205$ m, $\alpha_x^* = -0.4575$ [5]. The injection optics are thus assumed identical with a sign change of α_x of course. With this transfer line optics we arrive at the following rms beam size and divergence for the injected beam: $\sigma_x^* = \sqrt{\varepsilon_x \beta_x^*} = 53.506\,\mu$m, $\sigma_{x'}^* = \sqrt{\varepsilon_x \gamma_x^*} = 5.2512\,\mu$rad. In addition, an energy spread of $\sigma_\delta = 0.1\%$ for the injected bunch has to be expected.

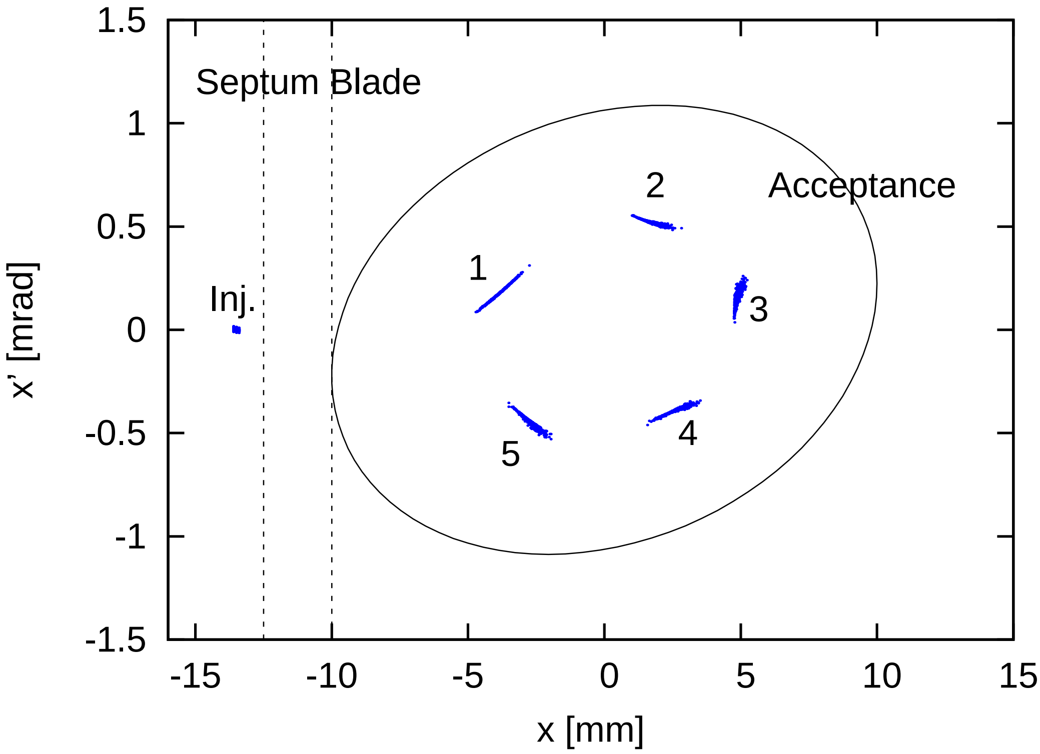

Figure 8: Injection with the PSM into the storage ring. Tracking data is shown at the injection point for injection and the first five turns in the storage ring. The blue dots are DIMAD tracking results for 1000 injected particles with $\varepsilon_n = 1.5$ mm mrad, $\sigma_\delta = 0.1\%$, and a cut-off at 3σ.

Tracking has been performed for 1000 seeds using a 3σ cut-off for the injected bunch. Tracking results for injection, capture with the PSM, and the first turns are shown in Fig. 8. From the plot it can be seen that the finite emittance and energy spread of the injected bunch lead to some smearing out of the bunch during its first turns in the machine. As further investigations revealed, the emittance of the injected bunch roughly determines the "length" of the spreading out, while the energy spread determines its "width". Clearly, the optics mismatch does not present a problem at this low emittance and energy spread. Hence injection efficiency should be very high. This motivates why a more elaborate matching of the injected beam to the storage ring optics [6, 7, 8] should not be necessary in the MAX IV 3.0 GeV storage ring.

There is however one more issue connected to the energy (spread) of the injected bunch. The injected bunch actually consists of three 3 GHz bunches in a bunch train that is injected into a single 100 MHz bucket. Therefore, only one third of the injected charge can arrive at the ideal phase with respect to the 100 MHz rf. The other two thirds are offset by ±330 ps. In order to verify that injection with this phase structure is still efficient, tracking is performed with bunches that have been offset in energy by a certain amount. After a quarter synchrotron period (roughly 110 turns), the ±330 ps phase error transforms into an energy offset of roughly $\delta = \pm 0.85\%$. Tracking reveals that injection appears almost identical for $\delta = \pm 0.85\%$, however, $\delta = -0.85\%$ uses slightly less aperture than $\delta = +0.85\%$. Tracking revealed that injection at $\delta = -1.7\%$ is still very good. Hence, it can be contemplated if injection should be carried out with a phase offset of 330 ps so that the centroid is injected at a phase corresponding to $\delta = -0.85\%$.

Finally, one must investigate the influence of the PSM on the stored beam. The stored beam itself has a finite emittance that leads to stored particles receiving very minor kicks from the PSM even when the beam centroid has been perfectly aligned to the PSM center. This leads to a perturbation while the PSM is on. The sextupoles in the lattice are usually tuned in such a way to correct linear chromaticity to $\xi_{x,y} = +1.0$ and while the PSM is on this correction is disturbed. This is not expected to have a measurable effect on the electron beam in the IDs, but tracking should be applied to verify. Tracking of stored beam particles before passage of the PSM and after five turns is displayed in Fig. 9. Tracking confirms that the effect of the PSM on the stored beam is negligible.

It is however crucial to align the PSM exactly to the stored beam in order to avoid kicking the stored beam while pulsing the PSM. For this purpose the PSM should be manufactured so that its position on the support can be aligned to a very high degree. If the stored beam passes the PSM 50 μm off center in both planes, the residual vertical kick to the stored beam is 0.27 μrad. The pointing stability across a user straight is however held constant to within $\approx 0.1\,\mu$rad by the fast orbit

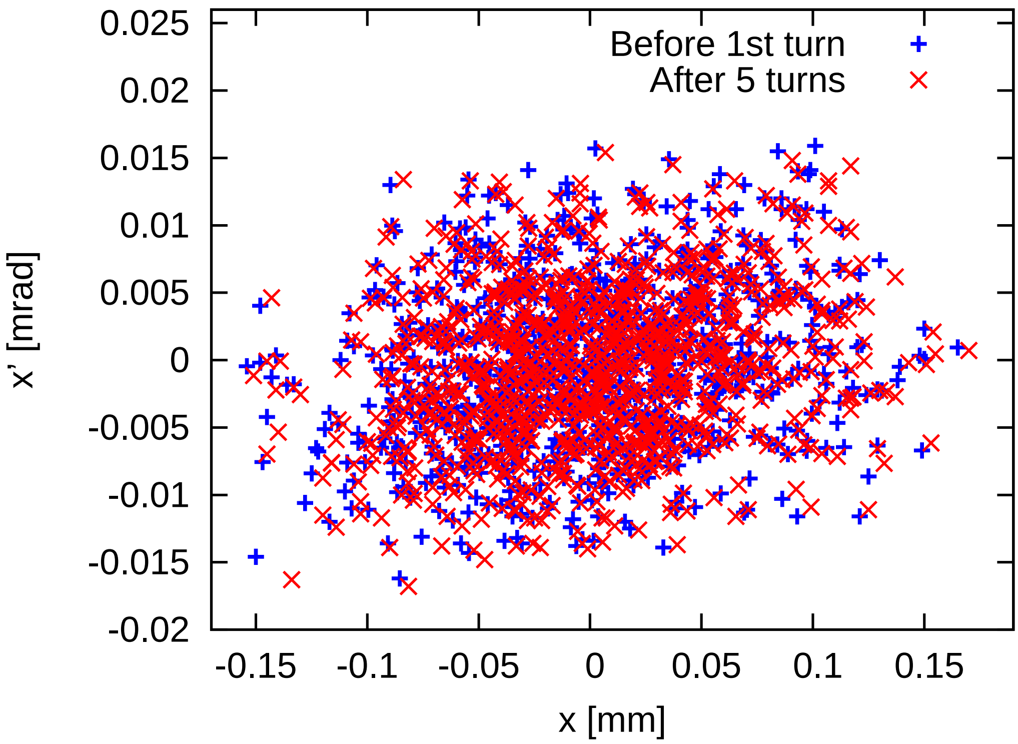

Figure 9: Effect of the PSM on the stored beam. The DIMAD tracking data shown here is taken at the location of the PSM with a cut-off at 3σ. The blue $+$ indicate stored beam particles before passage of the PSM. The red $\times$ are tracking results for the same particles after the fifth turn. These particles received a kick from the PSM when it was pulsed during the first passage.

feedback. This example illustrates why beam-based alignment of the PSM on a precision stage is crucial in order to make PSM injection fully transparent to users.

4 Two-turn Injection Option

In principle the pulser driving the PSM can be a made a bit slower so that the injected bunch receives a kick during *both the first and the second turn* in the machine. In this case, we can also reduce the required kick strength: we assume a half-sine pulse in the PSM synchronized to the injected bunch in such a way that the pulse maximum coincides with the passage of the injected bunch through the PSM. The injected bunch receives the first kick $(b_3L)_1 = 27.457$ m-2. When the injected bunch passes the PSM during its second turn it receives the second and final kick $(b_3L)_2 = (b_3L)_1 \times \sin(3\pi/4) = (b_3L)_1/\sqrt{2} = 19.428$ m^{-2}. From here on the PSM has no more effect on the stored or the injected beam.

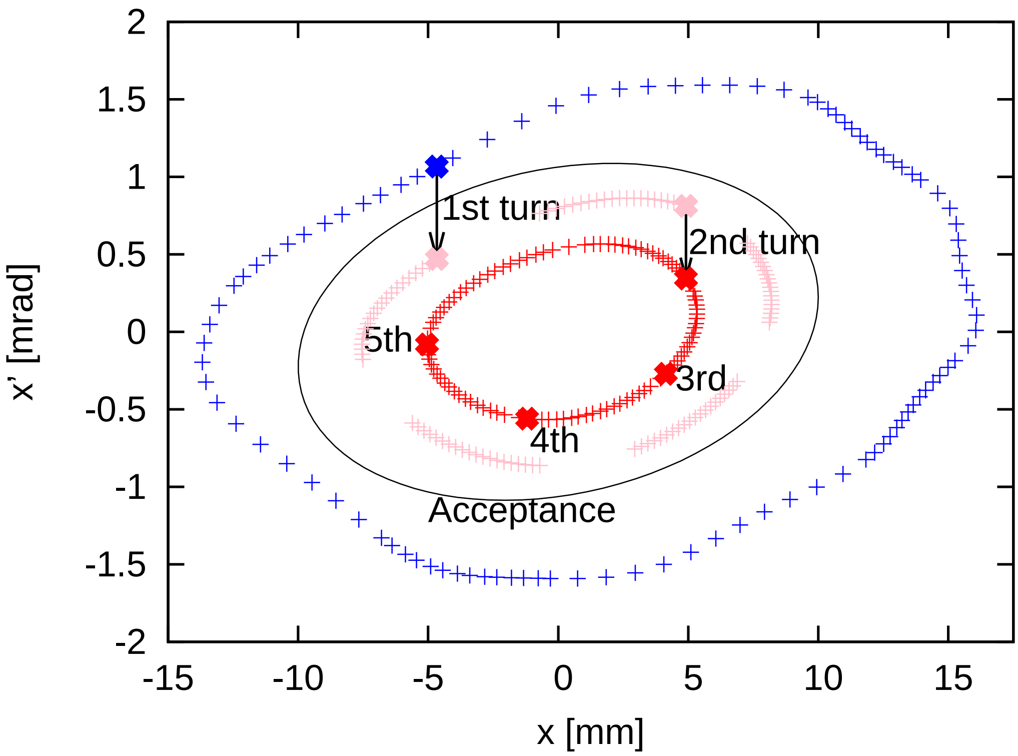

Figure 10: Two-turn injection with the PSM into the storage ring. Tracking data is shown for capture at the PSM (blue $\times$) and for the first 100 turns in the storage ring (red $+$). The outer "ellipse" (blue $+$) is distorted due to the nonlinearities of betatron motion at large amplitudes (strong sextupoles!). The inner ellipse corresponds to more linear motion at the reduced invariant $A^2_{\rm red} \approx 3.1$ mm mrad.

From tracking (cf. Fig. 10), we gather that on the second turn the injected bunch arrives at the entrance of the PSM with $x_{\rm pm} = 4.915$ mm and $x'_{\rm pm} = 0.813$ mrad where it receives kick $(b_3L)_2$. Although the second kick is reduced by $\sqrt{2}$, the amplitude of the injected bunch is actually larger and hence, the 2nd kick becomes comparable to the first. After the 2nd kick, the bunch leaves the PSM with the coordinates $x_{\rm pm} = 4.915$ mm and $x'_{\rm pm} = 0.343$ mrad. The resulting reduced invariant is $A^2_{\rm red} = 3.08$ mm mrad, which is only slightly larger than in the case of single-turn injection using significantly more PSM strength. Tracking results indicate two-turn injection should work just as well as single-turn injection. This can however not be extended to three-turn injection or further. Because of the fractional horizontal tune, kicks in the third turn and beyond will no longer reduce the invariant of the injected bunch.

5 Conclusions

Injection into the MAX IV 3 GeV storage ring with a pulsed magnet is possible. Compared to conventional injection, this approach offers the great advantage that it does not require a pulsed injection bump and hence no pulsed kicker magnets or any alignment and synchronization of these magnets are required. Since the septum is DC (Lambertson septum), the only synchronization necessary is that between the injected bunch and the PSM.

It is of advantage to use a PSM instead of a PQM as the sextupole doesn't lead to a measurable perturbation of the stored beam. Thus top-up injection into the storage ring can be performed in a way transparent to the beamlines. And hence much shorter top-up intervals can be tolerated which in turn allows to further reduce the variation of the stored current level in the storage ring. The PSM would be placed exactly one achromat length downstream of the injection point. This puts both the injection point and the PSM at the end of a long straight section (487 mm upstream of the first BPM). Since the PSM is short it can co-exist with an ID in the same straight. In light of the large amplitudes of the injected bunch before it reaches the PSM, a close eye should be kept on the vacuum chamber geometry at the end of the first achromat.

The required ideal strength of the PSM for two-turn injection is $(b_3 L) = 27.5\ \mathrm{m}^{-2}$. If an effective length of 30 cm is chosen for the PSM this gives 917 $\mathrm{T/m}^2$ of required sextupole gradient. This is fairly relaxed; the regular focusing sextupoles in the storage ring are more than twice as strong. Compared to the PSM used at KEK [2] which has an integrated sextupole gradient of 53.3 T/m, the PSM required at MAX IV seems comparably strong at 275 T/m. However, if one takes into account the bore diameter of 66 mm used in the KEK PSM, it becomes clear that, using the usual 25 mm magnet gap at MAX IV, we can build a sextupole that requires 26% less pole-tip field than the one built at KEK. For the pulse duration (base length of the half-sine pulse), we require between two (single-turn injection) and four (two-turn injection) revolution periods which is roughly 3.5–7.0 μs. This is also more relaxed than the 2.4 μs pulse duration achieved with the pulser used at KEK.

Finally, it has also been investigated if the PSM can be moved closer to the BPM should it become necessary to free up as much of the long straight section as possible. The result is that this could indeed be done if additional PSM strength is provided (because of the reduced orbit of the injected bunch towards the end of the long straight). If for example the PSM is placed adjacent to the BPM (i.e. by moving it downstream by ≈ 300 mm), an additional 13% PSM strength is required. The resulting reduced invariant would then however be even lower.

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