Pulsed Sextupole Injection for the MAX IV 1.5 GeV Storage Ring

Simon C. Leemann

August 20, 2010 (updated June 11, 2012)

MAX-lab Internal Note 20100820[1]

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 1.5 GeV storage ring. Such an injection would not require a local injection bump (likely spanned across several achromats) and thus avoid alignment and synchronization issues associated with the four kickers and four pulsers of a conventional injection scheme. The conclusion is that a pulsed sextupole (half-sine pulse with base $\tau = 0.64\ \mu$s) with an integrated strength of $(b_3L) \approx 47\ \mathrm{m}^{-2}$ installed at beginning of the third straight is sufficient for injecting into the MAX IV 1.5 GeV storage ring. For two-turn injection (half-sine pulse with base $\tau = 1.3\ \mu$s) the strength requirement can be reduced to $(b_3L) \approx 32\ \mathrm{m}^{-2}$. 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 Preface

This note closely follows the studies for pulsed sextupole magnet injection in the MAX IV 3 GeV storage ring [1]. The theoretical background can be found there as well as in the papers on the original proof-of-principle experiments performed at KEK [2, 3]. This note will dive directly into the application at the MAX IV 1.5 GeV storage ring.

2 Approximate Solution

For the MAX IV 1.5 GeV storage ring we define the injection point as the end of the septum magnet in the injection straight (which we refer to as the first straight). This is located 1252 mm downstream of the center the injection straight or 523 mm upstream of the center of the first BPM in the first achromat[3]. At this location $\beta_{\text{inj}} = 5.939$ m and $\alpha_{\text{inj}} = -0.221$. If the septum blade occupies the space from -15.5 mm to -18 mm (cf. Fig. 1), the injected beam can be placed at $x_{\text{inj}} = -19$ mm. We arrive at an injection invariant of $A^2_{\text{inj}} = 63.76$ mm mrad.

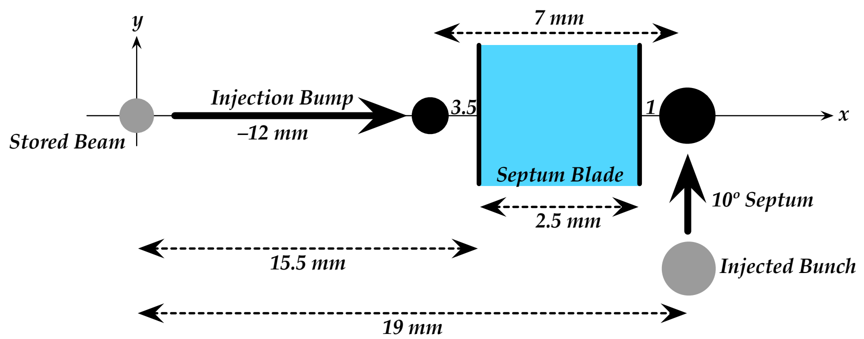

Figure 1: Schematic of the conventional injection scheme for the MAX IV 1.5 GeV storage ring according to [4].

If we take into account that in a "conventional" injection scheme with a four-kicker bump, the separation of the bumped stored beam and the injected bunch would be roughly 7 mm, we arrive at a reduced invariant of $A^2_{\text{red}} = 8.65$ mm mrad which is well below the admittance defined by the septum at $A^2_{\text{septum}} = 42.43$ mm mrad. It is also within the required dynamic storage ring acceptance of 17.7 mm mrad (Table 3.1 in DDR Section 3.2.1). Therefore this can be set as a target value for the reduced invariant in the pulsed sextupole injection scheme.

[3]Distances according to the m5-20110201 lattice branch.

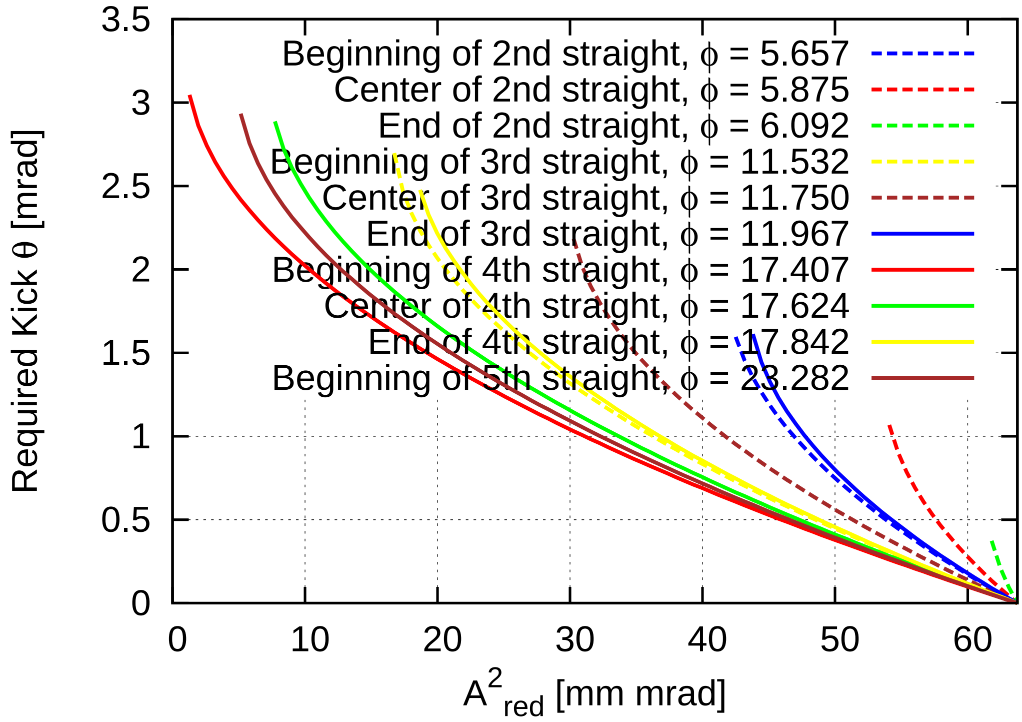

Figure 2: Kicks required from the pulsed magnet in order to achieve a certain reduced invariant. Different locations in the lattice for the pulsed magnet are displayed along with their phase advance with respect to the symmetry point.

From these considerations we derive ideal locations for the pulsed sextupole magnet (PSM). The phase advance with respect to the symmetry point in the injection straight is 1.194 rad or 1.948 rad which corresponds to 0.19 and 0.31 in horizontal tunes. Unfortunately these locations are not available as they lie within the first dipole. We are forced to search for "harmonics" of these phases further downstream. The beginning of the third straight, that is, a location 573 mm downstream of the center of the last BPM in the second achromat (or 1202 mm upstream of the center of the third straight) comes fairly close. Here the horizontal tune is 1.835 which transforms to a minimum achievable reduced invariant of $A^2_{\rm red} = 8.80$ mm mrad. This is not as low as the target value we would have achieved using the ideal phases, but it lies well within the required dynamic acceptance of the storage ring and is hence suitable. Figure 2 shows an analytic evaluation of possible locations for the pulsed magnet (nonlinearities have been neglected).

From Fig. 2 it appears that the beginning of the third straight is indeed a suitable candidate allowing us to reduce the reduced invariant to the level of the required dynamic acceptance of the storage ring. According to the linear approximation shown here, there are however other candidates that appear to allow even lower reduced invariants without requiring a larger kick: beginning and center of the fourth straight as well as beginning of the fifth straight.

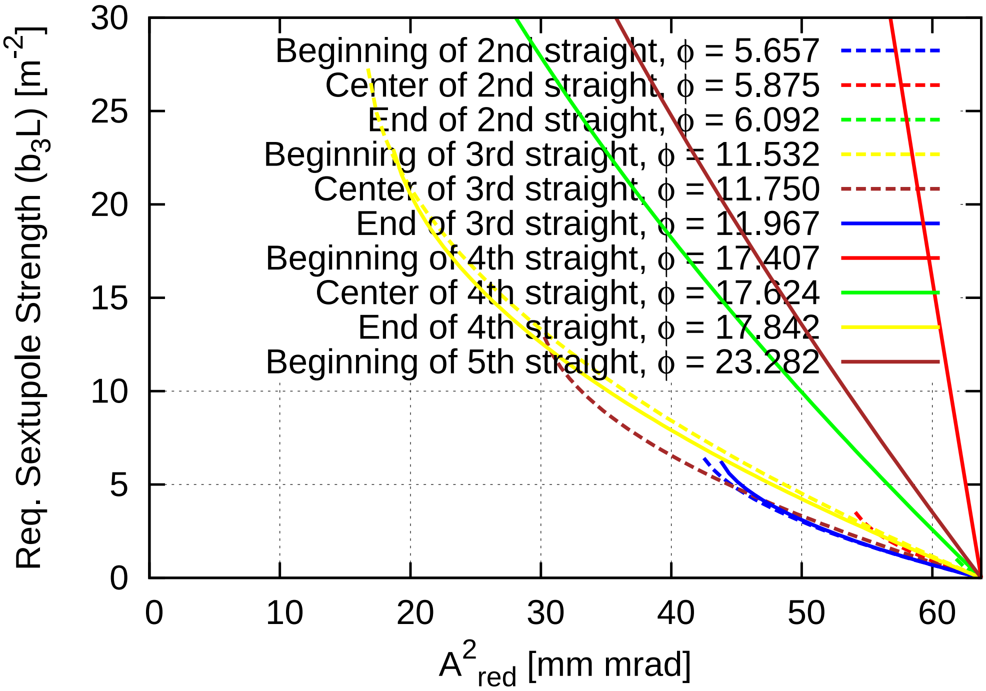

Figure 3: Field strength required from the PSM in order to achieve a certain reduced invariant. Different locations in the lattice for the PSM are displayed. A sextupole strength of $(b_3L) \approx 21$ m^{-2} corresponds to the strongest sextupoles used in the storage ring lattice.

It is important to note here however, that because kick strength depends on the orbit of the injected bunch in the pulsed magnet x_{inj}, the resulting required magnet strength depends on the location of the magnet within the lattice. This is displayed in Fig. 3 where one can see that various apparent candidates from Fig. 2 now have to be abandoned because of their required sextupole strengths. In short: although their required kick was not very large and their reduced invariant was low, the injected particle's amplitude at the these locations is so low that the required sextupole magnet would become far too strong.

On the other hand, Fig. 3 does confirm that the beginning of the third straight appears as a suitable location. At this location a reduced invariant below the required storage ring acceptance can be achieved with an integrated sextupole strength of $(b_3 L) \approx 25\ \mathrm{m}^{-2}$.

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. Nonlinearities 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.

3 Detailed Solution Derived from Tracking

The PSM is installed at the beginning of the third straight (where the injection straight is considered the first straight). The position of the PSM in the third straight is exactly 573 mm downstream of the center of the last BPM in the second achromat (or 1202 mm upstream of the center of the third straight)[4]. At this position the storage ring optics in the horizontal is determined by $\beta_{\mathrm{x,pm}} = 5.917$ m and $\alpha_{\mathrm{x,pm}} = 0.212$. The injected bunch is injected into the storage ring at the injection point with $(x_{\mathrm{inj}}, x'_{\mathrm{inj}}, y_{\mathrm{inj}}, y'_{\mathrm{inj}}) = (-19.0\,\mathrm{mm}, 0, 0, 0)$ where it oscillates around the design orbit with large amplitudes, but can still be contained within the admittance of the first achromats. At the location of the PSM it reaches $(x_{\mathrm{pm}}, x'_{\mathrm{pm}}, y_{\mathrm{pm}}, y'_{\mathrm{pm}})$ and receives a kick $\theta_{\mathrm{pm}} = (b_3 L) x_{\mathrm{pm}}^2$. 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.

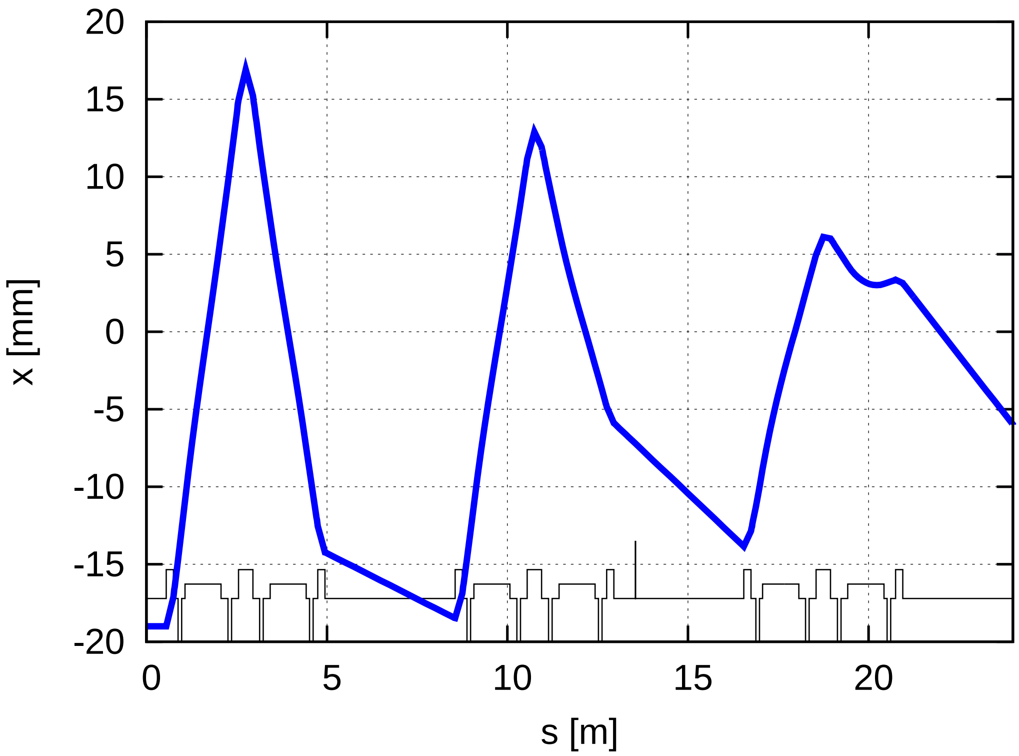

Figure 4: Orbit of the injected bunch starting at the injection point and on through the first three achromats.

[4]Distances according to the m5-20110201 lattice branch.

Figure 4 shows the orbit of the injected bunch from the injection point through the first three achromats. From tracking we gather that $x_{\rm pm} = -7.216$ mm and $x'_{\rm pm} = -2.211$ mrad. Tracking also reveals that the minimum reduced invariant is achieved for a kick to +0.25 mrad rather than zero divergence. Hence a kick strength of $(b_3 L) = (x'_{\rm pm} - 0.25\,\text{mrad})/x^2_{\rm pm} = -47.26$ m^{-2} is determined. This knocks the injected bunch down to a reduced invariant $A^2_{\rm red} = 8.80$ 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 ($\tau_x \approx 6$ ms). Figure 5 shows the orbit of the injected bunch from the injection point and through the PSM using the above mentioned parameters.

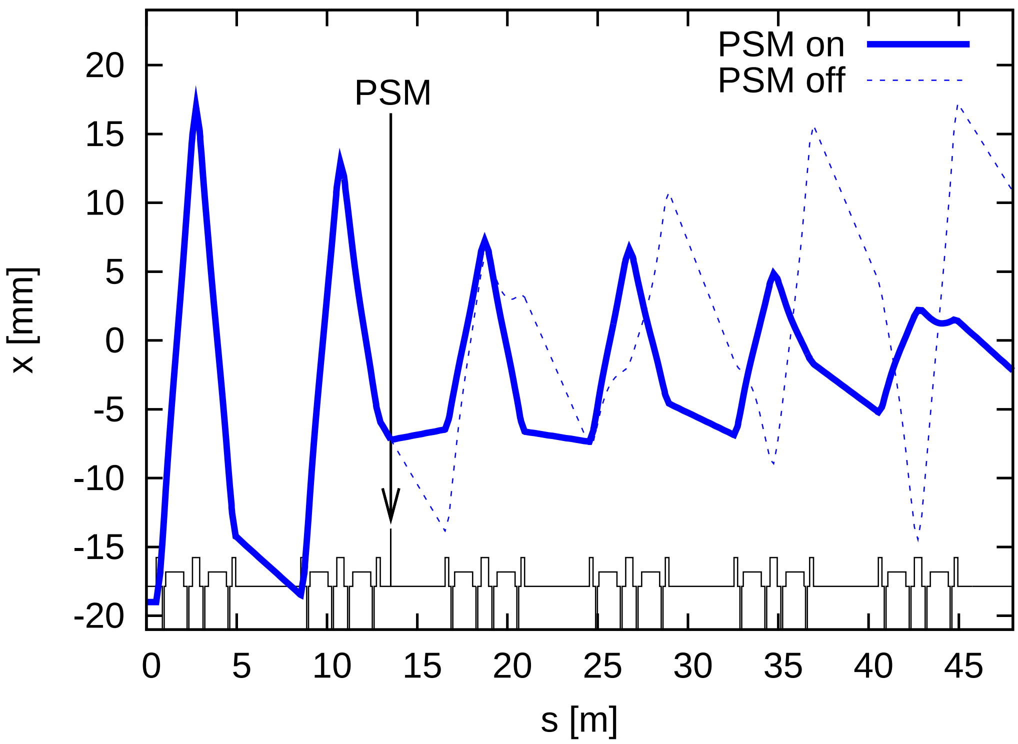

Figure 5: Orbit of the injected bunch starting at the injection point further on through the PSM up to the 7th straight. The dashed line indicates the orbit of the injected bunch if the PSM is turned off.

Tracking confirms that this reduced invariant easily fits the acceptance of the storage ring. Fig. 6 shows tracking results for the injection process, capture, and the first 100 turns in the storage ring.

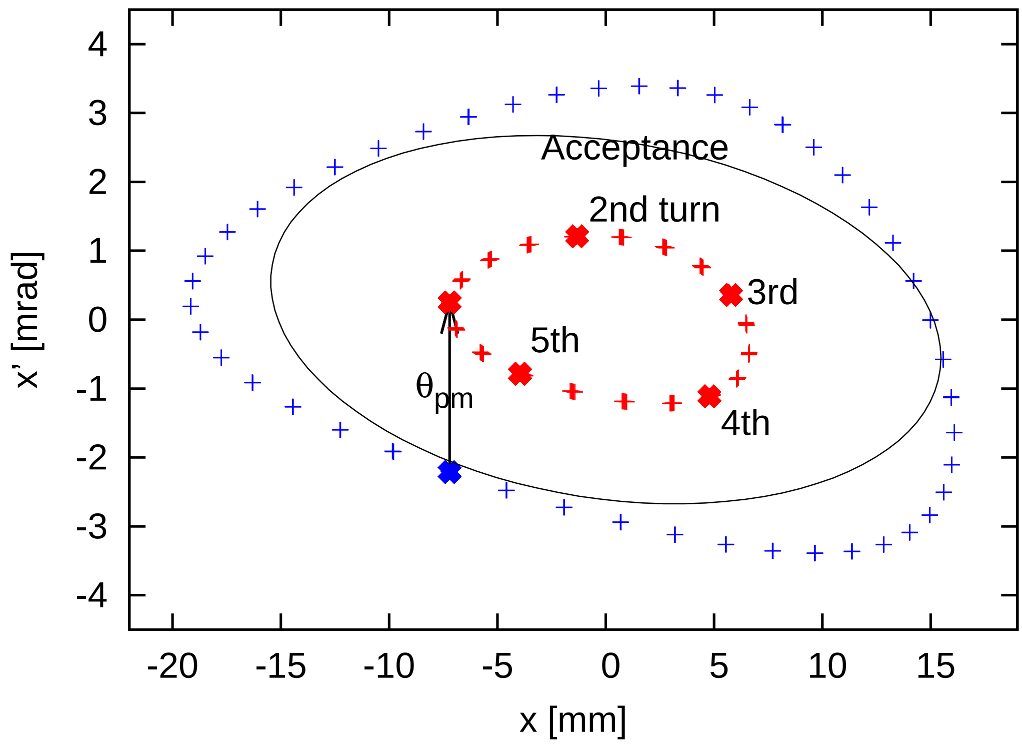

Figure 6: Injection with the PSM into the storage ring. Tracking data is shown from capture at the PSM (blue ×) and for the first 100 turns in the storage ring (red +). The outer "ellipse" (blue +) is distorted due to the nonlinearities of betatron motion at large amplitudes. The inner ellipse corresponds to more linear motion at the reduced invariant $A^2_{red} \approx 8.80$ mm mrad.

Of course not all injected particles have the ideal coordinates used above. The injected bunch is expected to have a normalized emittance of $\varepsilon_n = 1.5$ mm mrad which corresponds to a transverse emittance of $\varepsilon_{x,y} = 0.51$ nm rad at 1.5 GeV. This is very small compared to the stored beam's emittance of roughly 6 nm rad. 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 $\beta_x^* = 20.408$ m, $\alpha_x^* = -0.132$ [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: $\sigma_x^* = \sqrt{\varepsilon_x \beta_x^*} = 102.12\,\mu$m, $\sigma_{x'}^* = \sqrt{\varepsilon_x \gamma_x^*} = 5.047\,\mu$rad. In addition, an energy spread of $\sigma_\delta = 0.1\%$ for the injected bunch has to be expected.

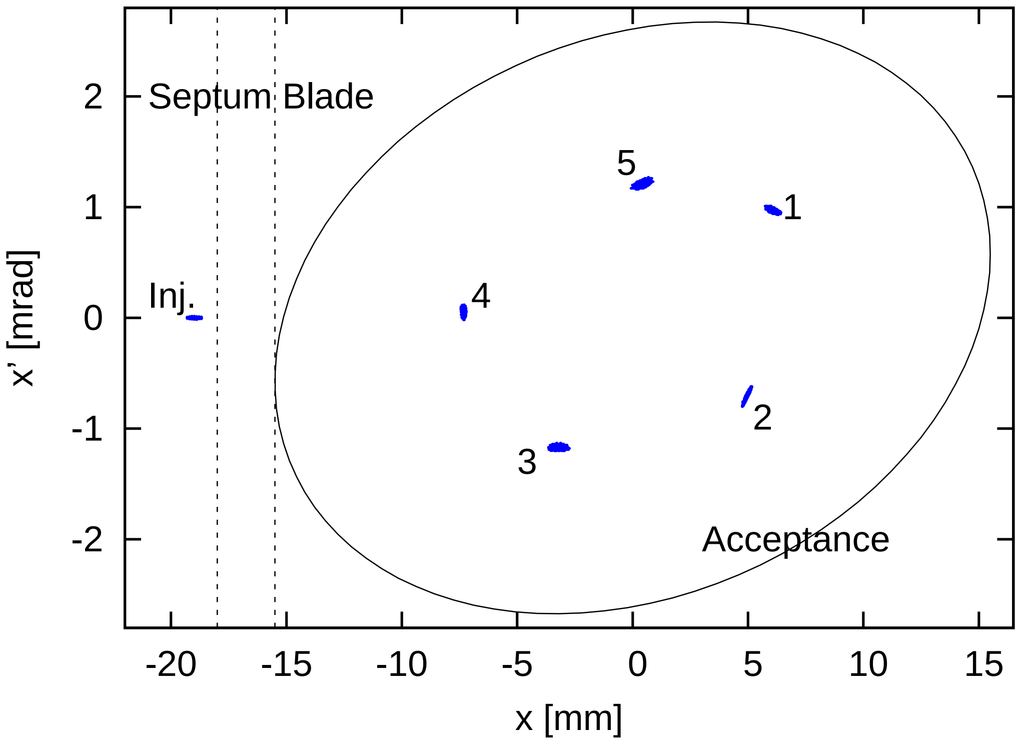

Figure 7: Injection with the PSM into the storage ring. Tracking data is shown at the injection point for injection and the first five turns in the storage ring. The blue dots are DIMAD tracking results for 1000 injected particles with $\varepsilon_n = 1.5$ mm mrad, $\sigma_\delta = 0.1\%$, and a cut-off 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. 7. From the plot it can be seen that the finite emittance and energy spread of the injected bunch lead to minute smearing out of the bunch during its first turns in the machine. 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 1.5 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 100 turns), the ±330 ps phase error transforms into an energy offset of roughly $\delta = \pm 0.55\%$. Tracking reveals that injection appears almost identical for $\delta = \pm 0.55\%$ as for the on-energy injected bunch. Therefore, phase shifts for two of the three injected 3 GHz bunches should not endanger efficient capture.

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. 8. 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 0.24 μrad. The pointing stability across a user straight is however held constant to $< 0.7\,\mu$rad by the fast orbit feedback. This example illustrates why beam-based alignment of the PSM on a precision stage is desirable in order to make PSM injection fully transparent to users.

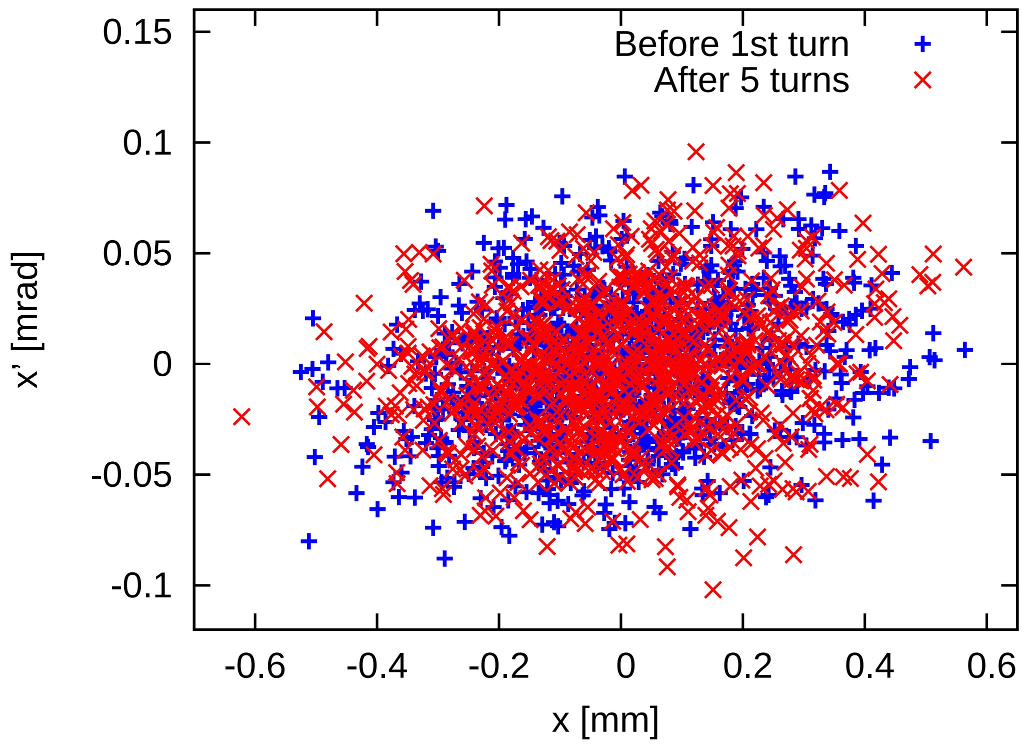

Figure 8: Effect of the PSM on the stored beam. The DIMAD tracking data shown here is taken at the location of the PSM with a cut-off at 3σ. The blue $+$ indicate stored beam particles before passage of the PSM. The red $\times$ are tracking results for the same particles after the fifth turn. These particles received a kick from the PSM when it was pulsed during the first passage.

4 Implementation

The required ideal strength of the PSM is $(b_3 L) = 47.26\ \mathrm{m}^{-2}$. If an effective length of 40 cm is chosen for the PSM this gives 591 $\mathrm{T/m}^2$ of required sextupole gradient. This is comparable to the strongest sextupole otherwise found in the lattice (the SDo has 460 T/m). Compared to the PSM used at KEK [3] which has an integrated sextupole gradient of 53.3 T/m, the PSM required for the MAX IV 1.5 GeV storage ring seems very strong at 236 T/m. However, one must take into account that the bore diameter used in the KEK PSM was 66 mm, while we can expect to use the standard 45 mm magnet aperture of the MAX IV 1.5 GeV storage ring magnets. But despite the reduced aperture in the MAX IV 1.5 GeV storage ring, the PSM still requires considerable strength: at the standard aperture the pole-tip field is 1.2 T. An alternative PSM injection scheme with reduced PSM strength would be highly desirable.

The PSM is placed at the beginning of the third straight section (573 mm downstream of the center of the last BPM in the second achromat). Since the PSM can be kept relatively short it can co-exist with a short ID or RF cavities in the same straight. For the pulse duration (base length of the half-sine pulse), we require two revolution periods for single-turn injection, corresponding to 0.64 μs. This is definitely a tougher requirement than the 2.4 μs pulse duration achieved with the pulser used at KEK. The next section shall attempt to relax this requirement.

5 Two-Turn Injection Option

In principle the PSM pulser 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. For this purpose 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 $(b_3L)_1 = 47.27$ m^{-2}. When the injected bunch passes the PSM during its second turn it receives the second and final kick $(b_3L)_2 = (b_3L)_1 \times \sin(3\pi/4) = (b_3L)_1/\sqrt{2} = 33.42$ m^{-2}. From here on the PSM has no more effect on the stored or the injected beam.

From tracking (cf. Fig. 9), we gather that on the second turn the injected bunch arrives at the entrance of the PSM with $x_{\mathrm{pm}} = -1.319$ mm and $x'_{\mathrm{pm}} = 1.210$ mrad where it receives kick $(b_3L)_2$. This kick is now already in the wrong direction, but because of the bunch's small amplitude compared to the first turn, the effective kick is much smaller than the $\sqrt{2}$ reduction from the phase. This is confirmed in tracking: after the second kick the particle leaves the PSM with $x'_{\mathrm{pm}} = 1.268$ mrad; it has received a net kick of only 58 μrad. When the particle returns to the PSM on the third turn it will no longer receive kicks from the PSM. It has now reached an "invariant" of 9.11 mm mrad. This is only 3.5% higher than what is achieved in single-turn injection and it is still lower than the acceptance of the ring and hence the injected bunch can be contained in the storage ring.

Since the nominal PSM strength is challenging, we can investigate how much the requirement can be relaxed in two-turn injection. The maximum kick strength which is applied during the first passage obviously has to kick the injected bunch to within the ring acceptance. Further reduction of the reduced invariant can usually be achieved on the second turn. In the situation of the MAX IV 1.5 GeV storage ring, the kick only points in the right direction during the first turn. So the strategy

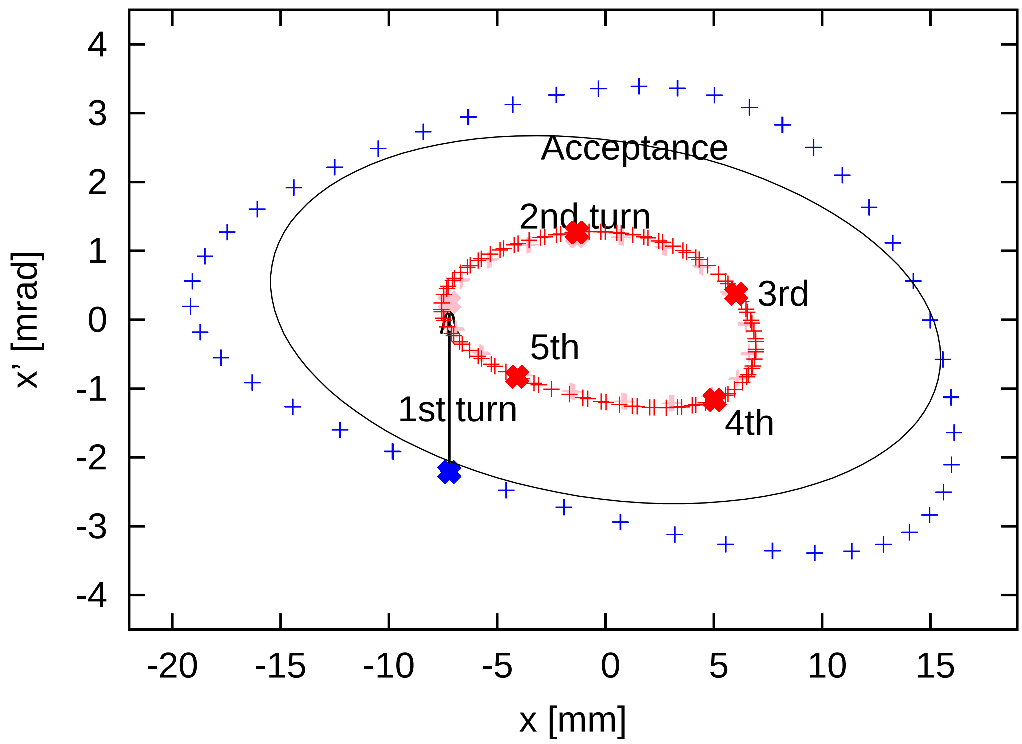

Figure 9: Two-turn injection with the PSM into the storage ring. Tracking data is shown for capture at the PSM (blue $\times$) and for the first 100 turns in the storage ring (red $+$). The outer "ellipse" (blue $+$) is distorted due to the nonlinearities of betatron motion at large amplitudes (strong sextupoles!). The red ellipse corresponds to more linear motion at the reduced invariant $A^2_{\rm red} \approx 9.1$ mm mrad. The second kick (from pink $\times$ to red $\times$) is so small, it can hardly be recognized in the plot.

here will be to find the minimum kick that can still ensure the injected bunch ends up within the ring acceptance after the second (outward) kick. The minimum strength required for capture has been determined to be $(b_3L)_1 = 32$ m^{-2}, corresponding to a one-third reduction of the originally specified PSM strength. At the first passage, the angle of the injected bunch is reduced from $x'_{\rm pm} = -2.211$ mrad to $x'_{\rm pm} = -0.545$ mrad. On the second turn, the injected bunch arrives at the PSM with coordinates $x_{\rm pm} = -6.436$ mm and $x'_{\rm pm} = 1.062$ mrad where it receives kick $(b_3L)_2$, which now increases its angle to $x'_{\rm pm} = 1.999$. At this point the final reduced invariant $A^2_{\rm red} = 25.51$ mm mrad is achieved which can just be accepted by the storage ring. This two-turn injection scheme is displayed in Fig. 10.

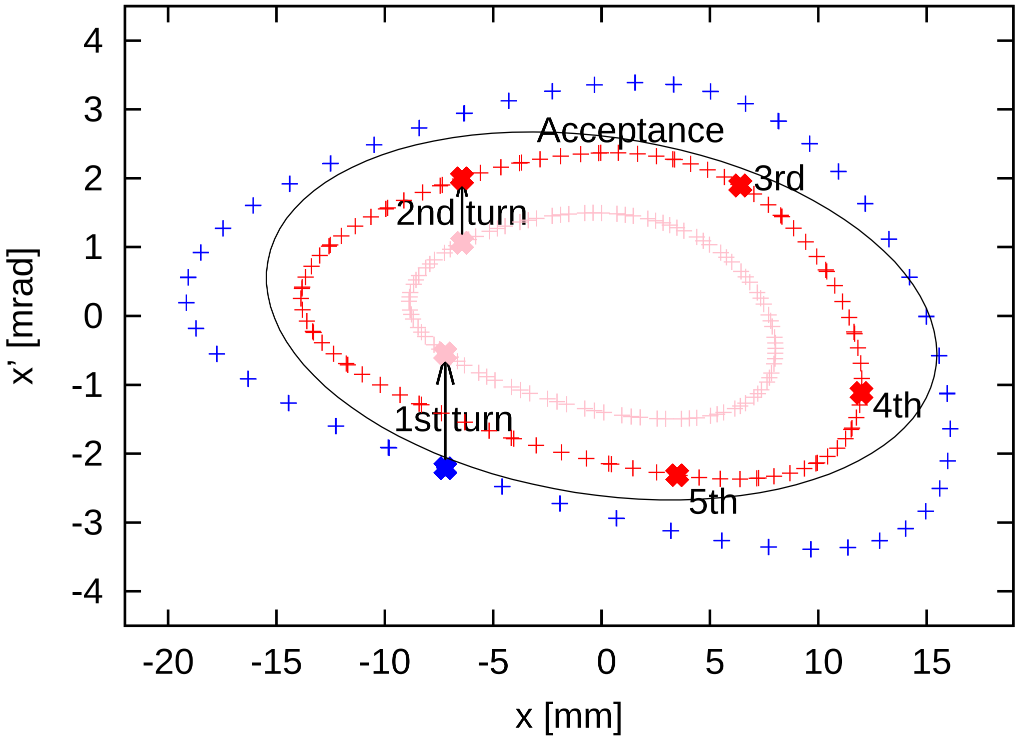

Figure 10: Two-turn injection with the PSM into the storage ring using a reduced PSM strength of $(b_3L)_1 = 32$ m^{-2}. Tracking data is shown for capture at the PSM (blue $\times$) and for the first 100 turns in the storage ring (red $+$). The distortion of the "ellipses" is due to the nonlinearities of betatron motion at large amplitudes (strong sextupoles!). The final ellipse (red $+$) corresponds to the reduced invariant $\mathrm{A}^2_{\mathrm{red}} \approx 26$ mm mrad.

We note that tracking results indicate two-turn injection should work almost as well as single-turn injection. The PSM strength requirement can be reduced by up to one third. Most importantly, with two-turn injection the pulser requirements can be relaxed: a half-sine with base length $\tau = 1.28$ μs is sufficient. 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.

6 Afterthoughts

Since two-turn injection has shown to relax the pulser and PSM strength requirements, one is tempted to try to further relax the sextupole gradient requirement. We note that by choosing an initial injection amplitude of $x_{\text{inj}} = -19$ mm we have been a bit generous. The injection amplitude was derived from the position of the septum which had been -15.5 mm $< x_{\text{sep}} < -18$ mm. The horizontal acceptance limitation from the septum thus defined a momentum acceptance (MA) of $\delta_{\text{acc}} \approx \min(a_x)/\max(\eta_x) \approx x_{\text{sep}}/\max(\eta_x) = 4.7\%$ (cf. DDR Section 3.3.4). Since we however also know that the maximum RF acceptance will be limited by the available transmitter power at roughly $\delta_{\text{rf}} = 4\%$ (cf. DDR Section 3.6.2) we can conclude that the septum could be moved closer to the stored beam without reducing the overall MA of the storage ring. As a consequence the injected beam could be injected closer to the stored beam thus reducing the injection invariant.

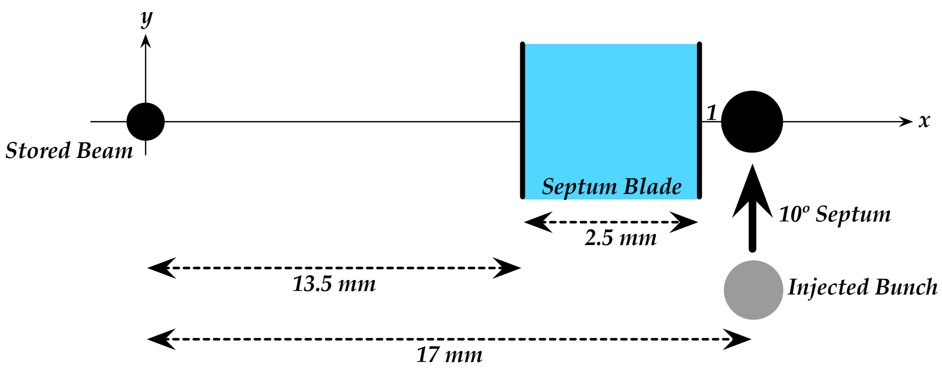

Figure 11: Schematic of an alternate PSM injection scheme for the MAX IV 1.5 GeV storage ring.

For example, if the blade is positioned at -13.5 mm $< \tilde{x}_{\text{sep}} < -16$ mm, the beam can be injected at $\tilde{x}_{\text{inj}} = -17$ mm (cf. Fig. 11). At this septum position the lattice MA of the storage ring is limited at 4.1% which is still beyond the maximum RF MA. The injection invariant however, is now $A^2_{\text{inj}} = 51.04$ mm mrad compared to the 63.75 mm mrad in the original case. In this situation, a minimum reduced invariant of $A^2_{\text{red}} = 8.0$ mm mrad can be achieved with PSM strength set to $(b_3 L) = 46.78$ m^{-2} (kicking the injected bunch to $x' = +0.25$ mrad after the PSM). So the reduced invariant is now 9% lower, but using almost the exact same PSM strength. Apart from a lower reduced invariant, a further advantage of this scheme is lower amplitudes between the septum and the PSM (compare Fig. 5 with Fig. 12).

A more relaxed setting is achieved if the PSM uses $(b_3L) = 36.2$ m^{-2} which kicks the injected bunch to $x' = -0.25$ mrad after the PSM. The reduced invariant here is $A^2_{\rm red} = 9.45$ mm mrad. Tracking (shown in Figs. 12 and 13) reveals efficient injection in this scheme despite relaxed PSM strength.

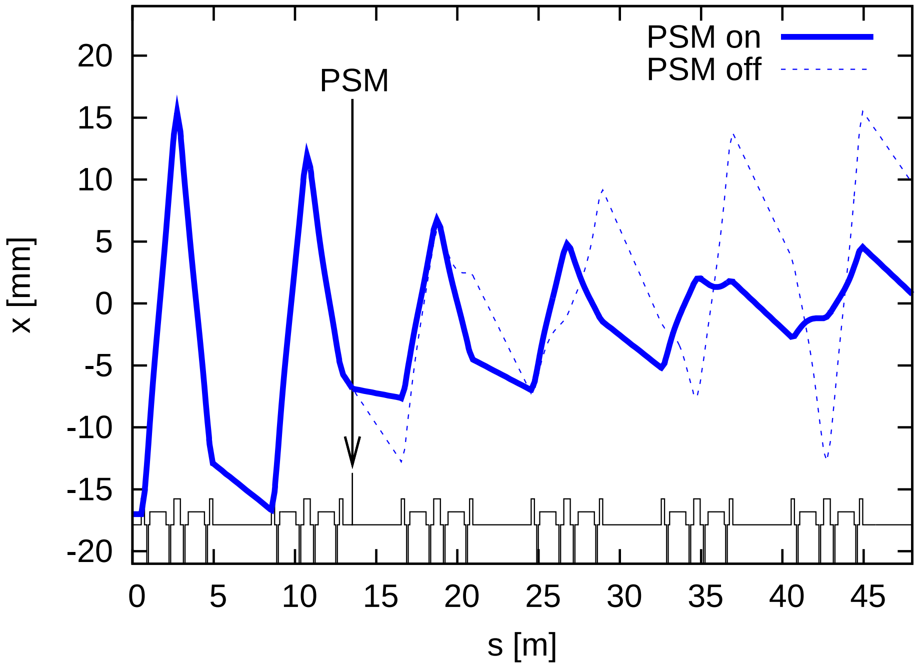

Figure 12: Injection at $\tilde{x}_{\rm inj} = -17$ mm using $(b_3L) = 36.2$ m^{-2}. Orbit of the injected bunch starting at the injection point further on through the PSM up to the 7th straight. The dashed line indicates the orbit of the injected bunch if the PSM is turned off.

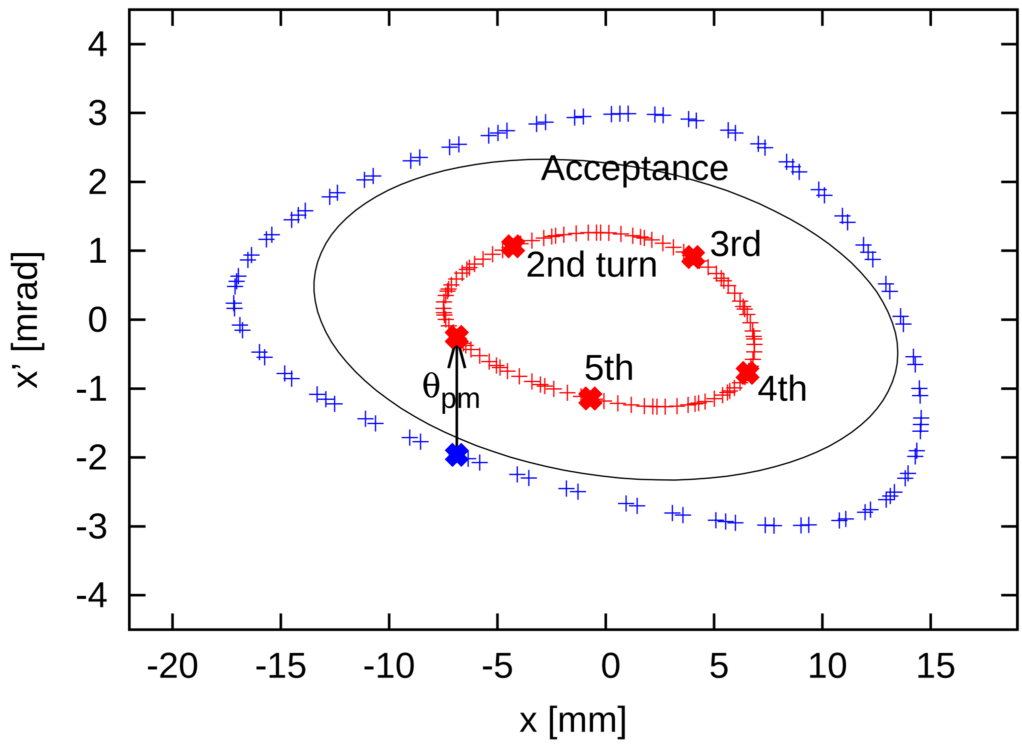

Figure 13: Injection at $\tilde{x}_{\text{inj}} = -17$ mm using $(b_3L) = 36.2$ m^{-2}. Tracking data is shown from capture at the PSM (blue $\times$) and for the first 100 turns in the storage ring (red $+$). The outer "ellipse" (blue $+$) is distorted due to the nonlinearities of betatron motion at large amplitudes. The inner ellipse corresponds to more linear motion at the reduced invariant $A^2_{\text{red}} = 9.45$ mm mrad.

In fact, for injection at $\tilde{x}_{\text{inj}} = -17$ mm one can even contemplate running the PSM at the reduced strength $(b_3L) = 32$ m^{-2} derived for two-turn injection in the previous section. In this scenario the injected bunch is kicked to $x' = -0.45$ mrad after the PSM, resulting in a reduced invariant of $A^2_{\text{red}} = 10.86$ mm mrad which is moderately increased (expect at maximum an extra 1.1 mm amplitude), but still acceptable.

For the setting $(b_3L) = 36.2$ m^{-2} tracking studies have also been performed to asses capture efficiency. With the nominal linac emittance of $\varepsilon_n = 1.5$ mm mrad, injection efficiency is expected to be very high (cf. Fig. 14). In fact, even if the linac emittance is allowed to grow to $\varepsilon_n = 10$ mm mrad, efficient capture should still be possible as seen in Fig. 15.

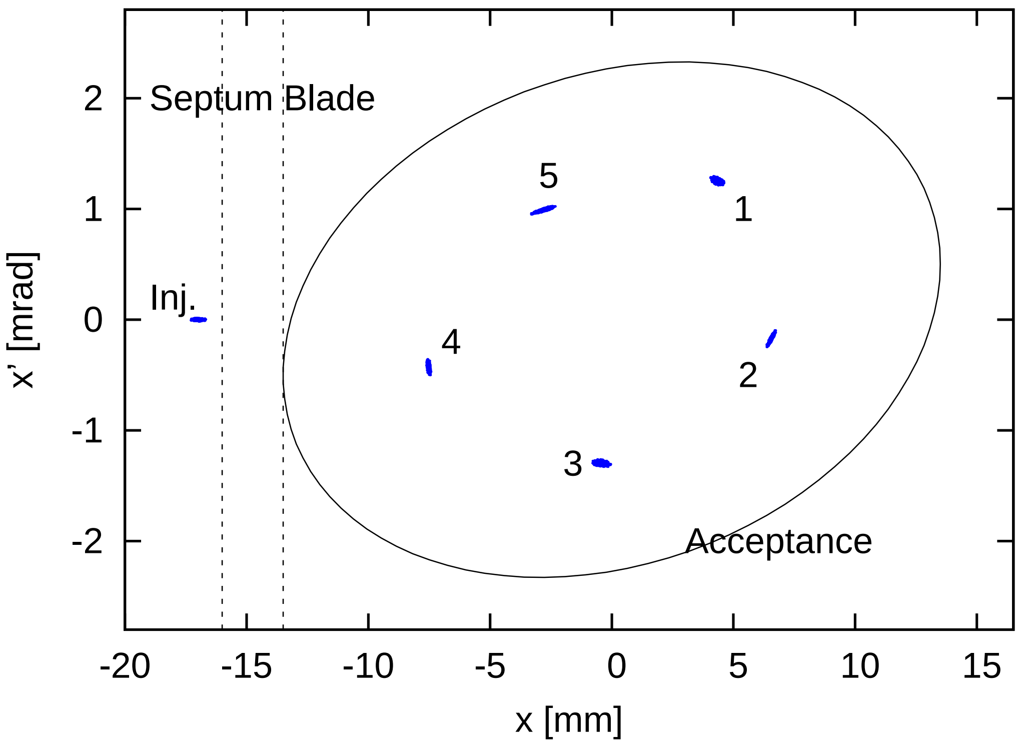

Figure 14: Injection at $\tilde{x}_{\rm inj} = -17$ mm using $(b_3L) = 36.2$ m^{-2}. Tracking data is shown at the injection point for injection and the first five turns in the storage ring. The blue dots are DIMAD tracking results for 1000 injected particles with $\varepsilon_n = 1.5$ mm mrad, $\sigma_\delta = 0.1\%$, and a cut-off at 3σ.

The conclusion here is that reducing the injection amplitude will reduce the residual amplitude of the injected bunch after injection and/or allow a reduction of the required sextupole gradient. Moving the septum closer to the stored beam should therefore be contemplated. Because large amplitudes are still encountered for the injected bunches between the IP and the PSM, it is however not advisable to reduce the horizontal aperture in all straights. The septum can remain the localized limiting horizontal aperture. On the other hand, opening up the horizontal aperture at the center of the DBA should be investigated as this has the potential to increase lattice acceptance to the maximum available rf acceptance (and consequently increase Touschek lifetime by more than 20%).

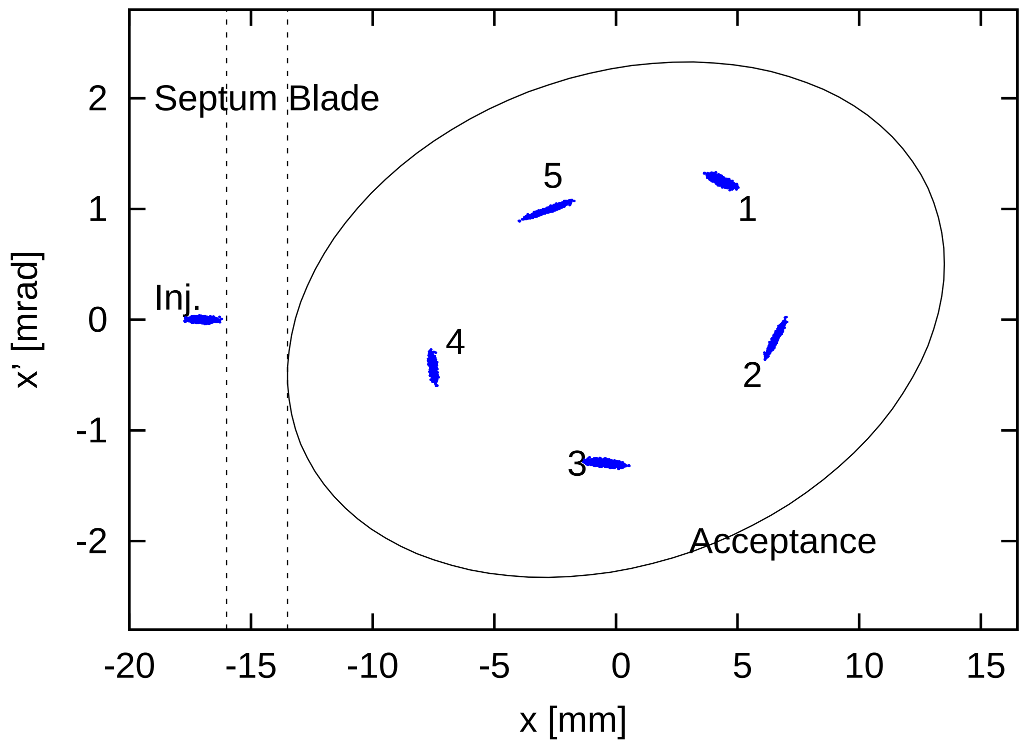

Figure 15: Injection at $\tilde{x}_{\mathrm{inj}} = -17$ mm using $(b_3 L) = 36.2$ m^{-2}. Tracking data is shown at the injection point for injection and the first five turns in the storage ring. The blue dots are DIMAD tracking results for 1000 injected particles with $\varepsilon_n = 10$ mm mrad, $\sigma_\delta = 0.1\%$, and a cut-off at 3σ.

References

[1] S.C. Leemann, Pulsed Magnet Injection for the MAX IV 3 GeV Storage Ring, MAX-lab Internal Note 20100512, available at `http://www.maxlab.lu.se/node/999`

[2] K. Harada et al., New injection scheme using a pulsed quadrupole magnet in electron storage rings, Phys. Rev. ST Accel. Beams 10, 123501, 2007.

[3] H. Takaki et al., Beam injection with a pulsed sextupole magnet in an electron storage ring, Phys. Rev. ST Accel. Beams 13, 020705, 2010.

[4] The MAX IV Detailed Design Report, available at `http://www.maxlab.lu.se/node/1136`

[5] S. Thorin, Main linac optic modes, unpublished internal note.

[6] A. Streun, SLS booster-to-ring transfer line optics for optimum injection efficiency, SLS technical note SLS-TME-TA-2002-0193.

[7] R.P. Fliller, Optimal Twiss Parameters for Top Off Injection in a Synchrotron Light Source, Proceedings of IPAC'10, Kyoto, Japan, 2010, TUPEC040, p. 1814.

[8] C. Sun, Z. Fischer, C. Pappas, D. Robin, Pulsed Multipole Injection for the ALS Upgrade, Proceedings of IPAC'10, Kyoto, Japan, 2010, WEPEA068, p. 2642.