Analysis of Vertical Field Data of the SOLEIL MIK for use in the MAX IV 3 GeV Storage Ring

Simon C. Leemann

January 29, 2015 (last revised Jan 30, 2015)

MAX-lab Internal Note 20150129[1]

Abstract

The SOLEIL MIK will be employed in the MAX IV storage rings for top-off injection. This report summarizes analysis performed on vertical field data from simulations performed at SOLEIL. The conclusion is that while the design can deliver sufficient kick strength for injection into the storage ring, further simulations and analysis will be required to determine if the design is actually compatible with transparent top-off as originally required.

Introduction

The SOLEIL team has delivered vertical field data for two MIK modeling cases: static calculation and transient calculation [1]. The analysis presented here intends to determine if this design fulfills design specifications laid out for application of the SOLEIL MIK in the MAX IV 3 GeV storage ring [2, 3]. The 2D geometry for the MIK has been modified since the last such analysis [4, 5]. The most significant difference is that the rods in the MIK have been moved farther away from the beam. In both cases studied by the SOLEIL team a $4\,\mu$m Ti coating was included in the model, however, in static calculations its conductivity has not been included.

[1] This document can be found at `http://www.maxlab.lu.se/node/999`

Analysis of the Static Data

As already shown in the last report [5], the SOLEIL MIK generates an octupolar field in the vicinity of the stored and injected beams. Fig. 1 shows the MIK static calculation results and compares the profile with an ideal PSM [2] and ideal pulsed octupole [3].

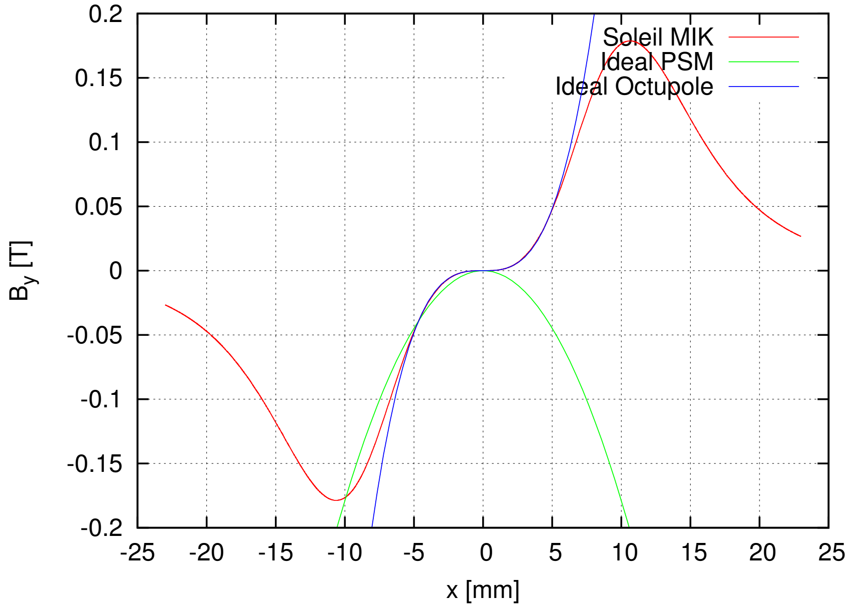

Figure 1: Vertical field profile of the SOLEIL MIK calculated in the static model.

Figure 2 is a magnified view showing the area around the stored beam. The residual vertical field tolerance corresponding to a 0.5 μrad tolerable residual horizontal kick is indicated. The SOLEIL MIK profile data is well within this tolerance within at least $\pm 5\sigma_x$ (278 μm). However, a residual field of -2.14 μT remains at the stored beam. More about this later.

Figure 3 compares the fitted residual gradient (the fit has been performed within $\pm 3\sigma_x$ and is shifted to accommodate for the residual field at the stored beam) to the maximum tolerable (emittance-independent) gradient [3, 6]. Clearly the SOLEIL MIK profile data satisfies the tolerance.

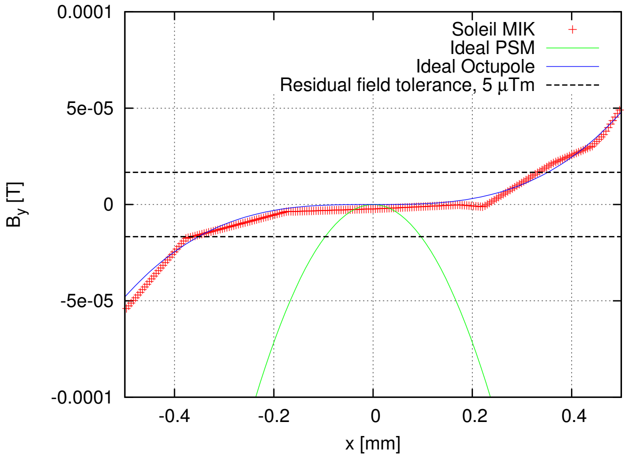

Figure 2: Vertical field profile of the SOLEIL MIK calculated in the static model showing the area around the stored beam and indicating the tolerance for residual vertical field.

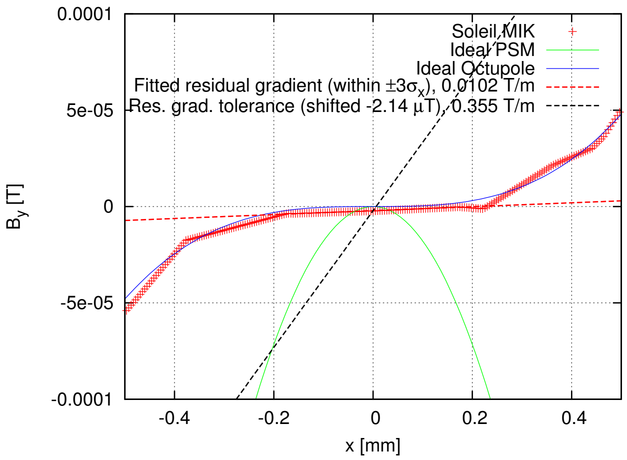

Figure 3: Vertical field profile of the SOLEIL MIK calculated in the static model showing the area around the stored beam and indicating the tolerance for residual gradient.

Figure 4 demonstrates that at the assumed 2455 A/mm^2 or 7704.7 A, the MIK profile data supplies sufficient kick to the injected beam. Clearly also the Soleil MIK resembles an octupole much more closely than a sextupole at the injected beam, but it has already been shown that the increase in kick dispersion this leads to is not detrimental [3].

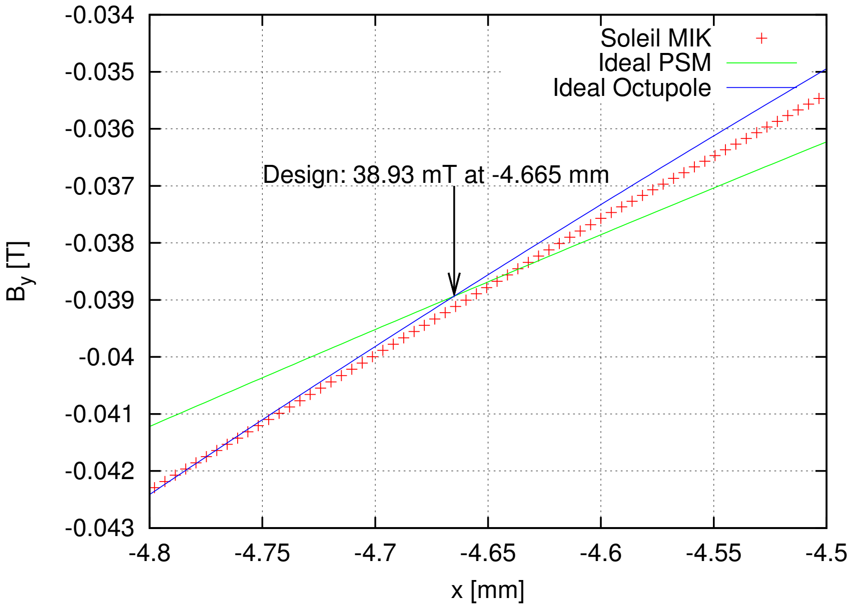

Figure 4: Vertical field profile of the SOLEIL MIK calculated in the static model showing the area around the injected beam.

Returning to the residual field noted in Fig. 2 one could of course contemplate correcting for this by applying an offset to the stored beam to compensate for this (e.g. via symmetric four-kicker bump) or by re-aligning the MIK accordingly. The required horizontal shift to put the stored beam at the zero-field position is -0.23 mm. However, note in Fig. 5 that such a shift actually results in a significant increase in effective residual gradient aside from extending beyond the acceptable residual field already at roughly $2\sigma_x$. In addition, this lowers the kick at the position of the stored beam by about 13% (cf. Fig. 6). This is of course undesirable and hence any such re-alignment is not preferable compared to tolerating a residual horizontal kick to the stored beam on the order of 64 nrad (1% of the natural angular spread at this location).

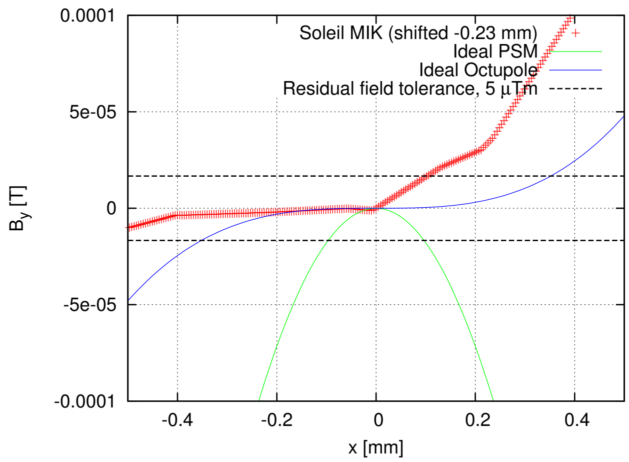

Figure 5: Vertical field profile of the SOLEIL MIK calculated in the static model showing the area around the injected beam assuming the MIK had been shifted so the zero-field position coincides with the stored beam position. The tolerance for residual vertical field is indicated.

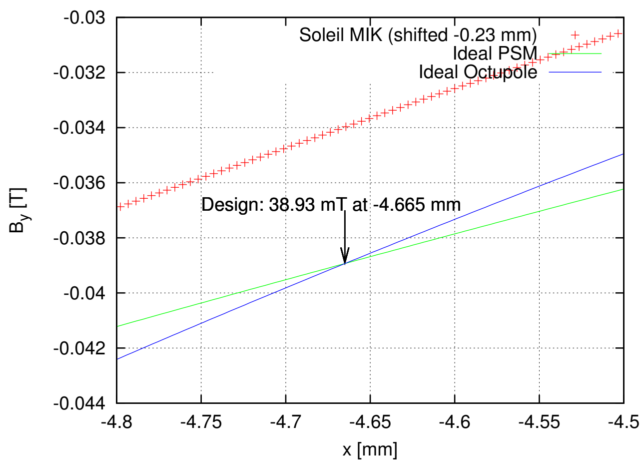

Figure 6: Vertical field profile of the SOLEIL MIK calculated in the static model showing the area around the injected beam assuming the MIK had been shifted so the zero-field position coincides with the stored beam position.

Analysis of the Transient Data

The transient data has been calculated assuming sine-like excitation at 142.857 kHz corresponding to a period of $2 \times 3.5\,\mu$s (i.e. single-turn injection). On this scale one would expect injection corresponding to the injection delay timing $t = 1.75\,\mu$s. The SOLEIL team has supplied data for delays $t = 1.75, 1.8, 1.85, 1.9, 2.45, 3.5, 3.55, 3.6,$ and $3.65\,\mu$s. Note, however, that in the data supplied by SOLEIL for $t = 1.8\,\mu$s the vertical field data is missing for $-8.6\,\text{mm} < x < -6.35\,\text{mm}$.

Figure 7 shows profile data from transient calculation including the $4\,\mu$m Ti coating. At this scale data for $t = 1.75\,\mu - 1.9\,\mu$s are all lying on top of one another.

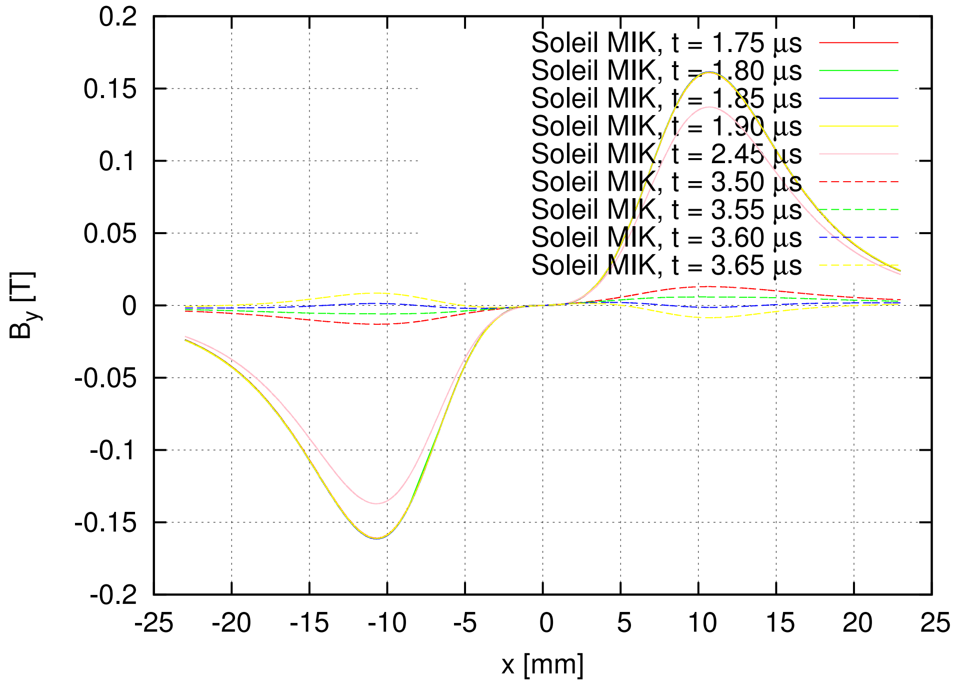

Figure 7: Vertical field profile of the SOLEIL MIK calculated in the transient model showing excitation at various times during the kicker pulse.

Figure 8 shows that actually $t = 1.90\,\mu$s gives the highest field at the injection beam, namely 34.41 mT. This has to be increased by 13.1% in order to achieve the design which corresponds to 8717 A. Figure 9 shows profile data scaled accordingly and compares with the ideal PSM and ideal pulsed octupole. Again a gradient much closer to an ideal octupole than a sextupole is recognized.

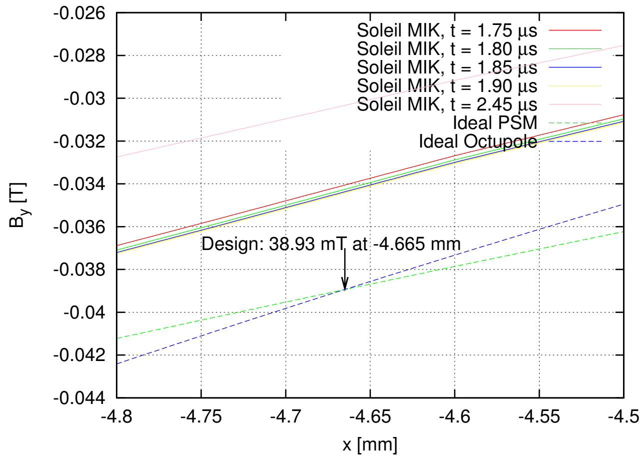

Figure 8: Vertical field profile of the SOLEIL MIK calculated in the transient model showing excitation at various times during the kicker pulse.

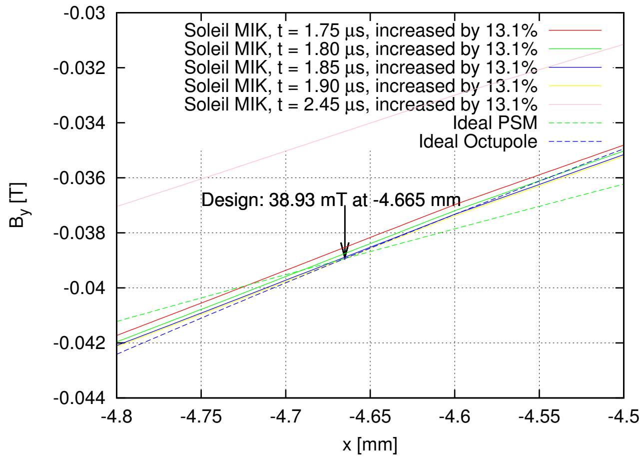

Figure 9: Vertical field profile of the SOLEIL MIK calculated in the transient model and scaled to reach the design kick strength showing excitation at various times during the kicker pulse.

Figure 10 shows the scaled values around the stored beam. The data for $t = 1.85\,\mu$s and $1.90\,\mu$s both follow the ideal octupole nicely. In terms of residual field all profiles between $t = 1.75\,\mu$s $- 1.90\,\mu$s are satisfactory for particles within about $\pm 4\sigma_x$. However, significant gradients are showing up, especially for $t = 2.45\,\mu$s and larger.

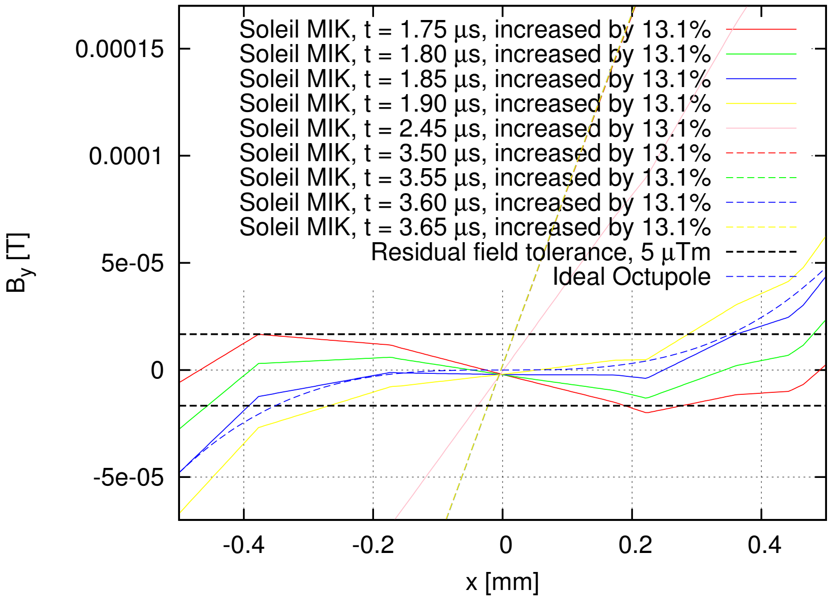

Figure 10: Vertical field profile of the SOLEIL MIK around the stored beam calculated in the transient model and scaled to reach the design kick strength showing excitation at various times during the kicker pulse.

This is demonstrated in Figs. 11 and 12 where different profiles are compared to maximum permissible gradients. While the gradients for $t = 1.75\,\mu$s $- 1.90\,\mu$s are clearly within tolerances and $= 2.45\,\mu$s is only a little bit beyond, clearly $t = 3.50\,\mu$s $-$ $3.65\,\mu$s (curves lie on top one another in Fig. 12) exceed the tolerances. This is potentially serious because it implies that the stored beam in at least 15 storage ring buckets will be perturbed (emittance increase) beyond acceptable levels. In fact, extrapolating for data not presently available, one has to consider that residual gradients for all the buckets between at least $t = 2.45\,\mu$s $- 3.65\,\mu$s are beyond tolerance which could results in as much as 68% of all buckets suffering emittance growth beyond permissible levels.

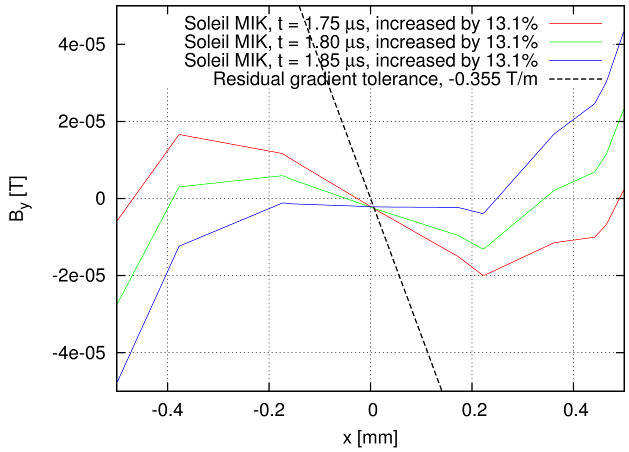

Figure 11: Vertical field profile of the SOLEIL MIK around the stored beam calculated in the transient model and scaled to reach the design kick strength showing excitation at various times during the kicker pulse. The maximum tolerable gradient is also indicated.

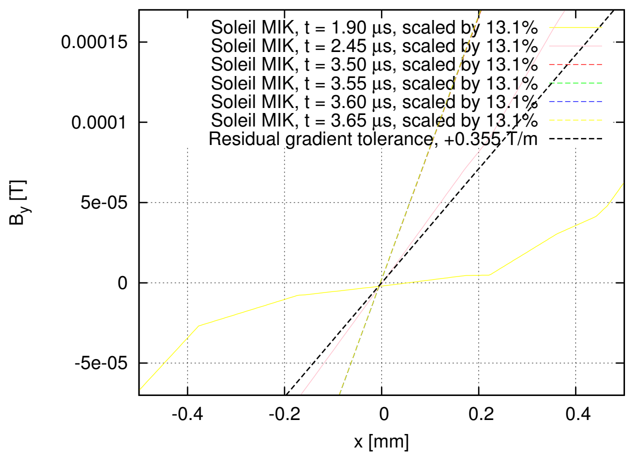

Figure 12: Vertical field profile of the SOLEIL MIK around the stored beam calculated in the transient model and scaled to reach the design kick strength showing excitation at various times during the kicker pulse. The maximum tolerable gradient is also indicated.

A more detailed inspection is performed looking at the stored beam in a bucket that will pass the MIK at $t = 1.75\,\mu$s and then one turn later at $t = 3.5\,\mu$s. The fields acting on this bucket are depicted in Fig. 13. The two gradient fits clearly

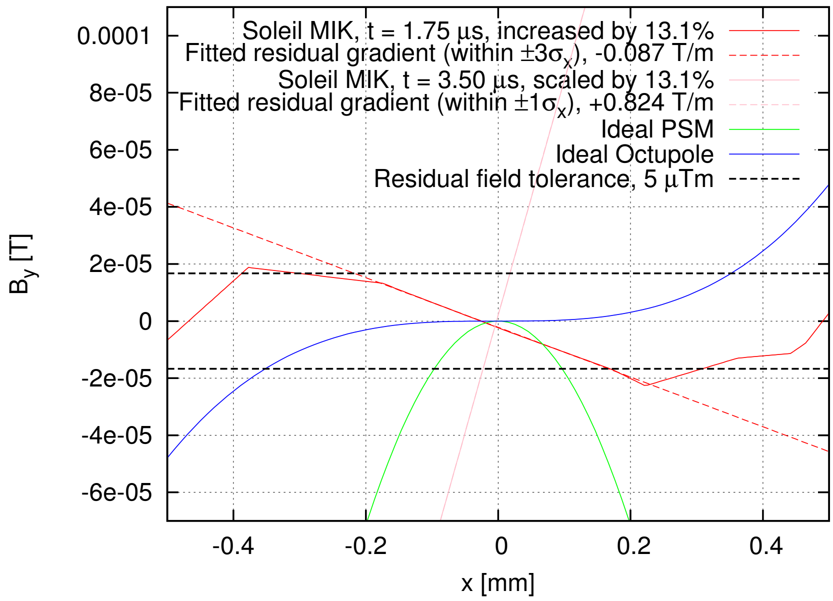

Figure 13: Vertical field profile of the SOLEIL MIK calculated in the transient model showing excitation at the first and second passage of the stored beam. Fits for the gradients have been included as well as an indication of the maximum tolerable gradient.

reveal that upon its second passage the stored beam in this bucket will subjected to a substantially too high gradient. Figure 14 then shows what this does to the particle ensemble in this bucket during the first five turns. One can clearly recognize the emittance growth caused by these two residual gradients. Detailed analysis shows that while hardly any emittance growth is caused by the residual gradient during the first passage gradient (i.e. at $t = 1.75\,\mu$s), it is the residual gradient during the second passage (i.e. at $t = 3.5\,\mu$s) that causes the emittance growth. This is of course no surprise since the former residual gradient is within tolerance whereas the latter lies substantially beyond tolerance. In this sense this tracking study simply confirms that the emittance-independent criterium for gradient tolerance [3, 6] is appropriate to determine acceptable residual fields.

Another example is displayed in Fig. 15 where the bucket corresponding to first passage at $t = 1.85\,\mu$s us is observed. This is also the injection timing that most closely resembles an ideal octupole profile (cf. Fig. 10). At $t = 1.85\,\mu$s the residual gradient is roughly zero (cf. Fig. 11), however, at its second passage the residual gradient is again beyond tolerance and the result is a increase of emittance of the stored beam in this bucket.

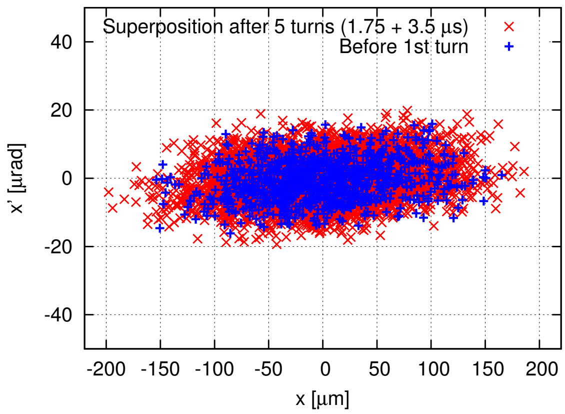

Figure 14: Phase space of the stored beam before passing the excited MIK (transient calculation) and after five turns. This plot shows a bucket corresponding to injection at $t = 1.75\ \mu s$.

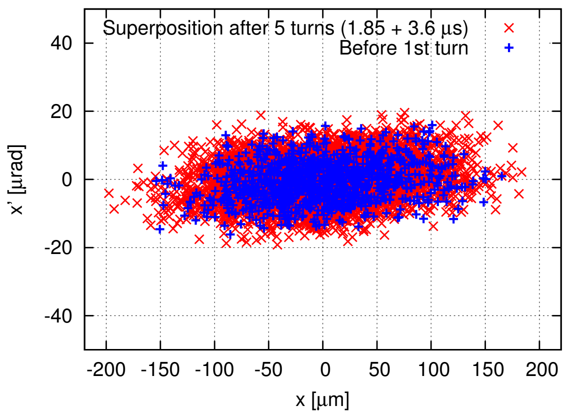

Figure 15: Phase space of the stored beam before passing the excited MIK (transient calculation) and after five turns. This plot shows a bucket corresponding to injection at $t = 1.85\ \mu s$.

The question raised by the SOLEIL team, if a pulse duration increase could be tolerated in order to relax the pulser voltage, cannot be fully answered with the presently available data. If indeed injection timing is shifted to $t = 1.85\,\mu$s or $t = 1.9\,\mu$s in order to achieve the maximum kick in the presence of the $4\,\mu$m Ti coating, stored beam in buckets corresponding to timing $t = 0 - 0.14\,\mu$s will receive a residual kick before the injected bunches arrive. As shown above, it is not necessarily the magnitude of the field that perturbs the stored beam beyond tolerance, it is rather the residual gradient during the transient that causes the damage.

It is important to note that the issue of longer pulse duration has little to do with the actual injection process but rather presents a problem for the stored beam. This can be appreciated by considering Fig. 16 which shows the kick at the position of the injected bunch as a function of the injection delay. Clearly, the kick magnitude

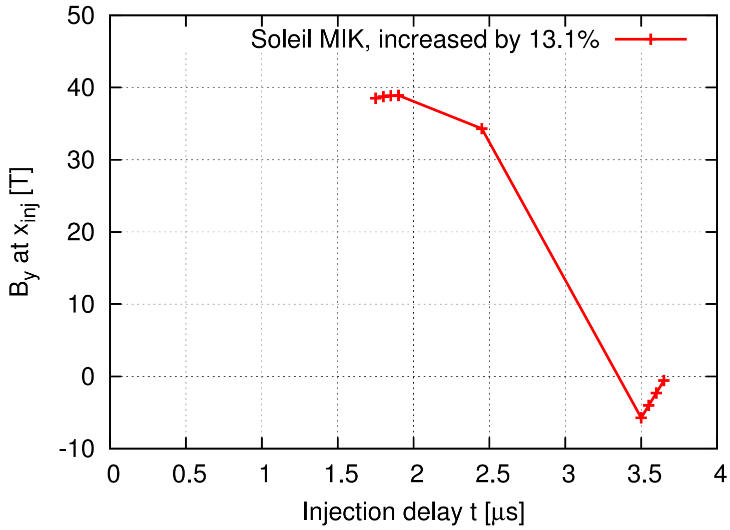

Figure 16: Vertical field of the excited MIK (transient calculation) at the position of the injected beam as a function of injection delay timing.

on the second passage is very small compared to the actual injection kick: if one choses to inject at $t = 1.85\,\mu$s, the residual kick on the second passage is 6% of the first kick. The second kick has a negative sign, but since the orbit on the second passage also has changed sign, the second kick actually points in the right direction (thanks to the octupolar field and contrary to an ideal PSM). Nevertheless, on the second passage of the injected bunch the amplitude in the MIK is reduced by 82% which leads to a reduction of kick angle to only about 0.5% of the above-mentioned

6% and therefore presents a negligible contribution to the injected beam's reduced invariant.

Outlook

The issue of perturbation of stored beam bunches beyond tolerances remains and the analysis here indicates it is the large transient gradients that occur in the late portion of the kicker pulse that cause most damage. In this context it is also important to inspect field data early during the injection pulse. Unfortunately, such data is presently not available. However, considering the large gradients that show up at the stored beam during relaxation of the pulse, it would be important to verify that similar or even larger such gradients do not show up initially when exciting the kicker pulse.

Considering the large residual gradients, two interesting alternatives should be inspected. The first is to investigate if the poor field quality at later times can be improved by reducing the kick amplitude. If for instance the rods could be brought closer to the stored beam, the field maxima would transversely be moved closer to the stored beam, thus generating a larger kick at the injected beam for lower current. A set of field data for such a reduced current could indicate if the residual gradients at the stored beam can be considerably reduced when the required peak fields at injection are lowered. Secondly, since residual kicks to the injected beam on subsequent turns show a very small effect, one could try to reduce the transient gradients by relaxing the specification for the pulse relaxation time. If the kicker fall-time is relaxed this could possibly help reduce these residual gradients at the stored beam.

Other Open Issues

- The effective length has been assumed to be 0.3 m. This needs to be confirmed by analysis of a 3D model.
- The 3D model should contain edge effects incl. terminals and possibly bulky heat sinks in the vicinity of the conductors. It needs to be verified that including these effects does not spoil the field quality demonstrated by this data.
- Estimates should be made for the effect of coating thickness inhomogeneities. These can introduce irregular multipoles and will likely influence the stored beam more than a perfect coating (which mainly attenuates and delays). For example, what field variation is introduced if one half of the chamber shows a

10% variation of coating thickness across the width of the chamber?

- Similar analysis to what is presented here should be repeated for profile data revealing B_x vs. y (at the stored beam position $x = 0\,\mathrm{mm}$) to verify that all tolerances for vertical perturbation are fulfilled. Considering these tolerances are much tighter because of the ultralow vertical emittance of the stored beam, such analysis is required in order to ultimately determine if the Soleil MIK is compatible with transparent top-off operation.

References

[1] P. Lebasque, internal communication, Jan 26, 2015.

[2] S.C. Leemann, Phys. Rev. ST Accel. Beams, **15**, 050705 (2012).

[3] S.C. Leemann and L.O. Dallin, "Progress on Pulsed Multipole Injection for the MAX IV Storage Rings", WEPSM05, PAC 2013, Pasadena, CA, USA.

[4] S.C. Leemann and L.O. Dallin, internal report, March 13, 2013.

[5] S.C. Leemann, internal report, May 15, 2013.

[6] MAX IV–SOLEIL MIK Collaboration Meeting, July 3, 2013.