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Wallén, Erik; Leemann, Simon

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*Total number of authors:*  
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LUND UNIVERSITY

PO Box 117  
221 00 Lund  
+46 46-222 00 00

# STRATEGY FOR NEUTRALIZING THE IMPACT OF INSERTION DEVICES ON THE MAX IV 3 GeV RING

E. Wallén and S.C. Leemann, MAX-lab, Lund, Sweden

## Abstract

In order to prepare for the potentially negative influence of insertion devices (IDs) on beam lifetime, injection efficiency and beam size in the MAX IV 3 GeV storage ring, a strategy for neutralizing the foreseen effects of the IDs has been developed. The strategy involves a local correction of the betatron phase advance by adjusting the strength of the quadrupoles adjacent to the ID as well as a global tune correction in order to avoid drift of the working point of the storage ring during operation. Air coils with empirical feed forward tables for the excitation current will compensate for field integral errors. The lattice of the MAX IV 3 GeV storage ring appears to be robust and it tolerates the dynamic multipoles created by the expected initial set of IDs provided that the linear optics matching has been carried out.

## INTRODUCTION

The MAX IV 3 GeV storage ring is part of the MAX IV light source facility [1, 2]. It will operate in top-up mode with 500 mA of stored beam. A large horizontal dynamic aperture (DA) with the IDs in operation is essential for obtaining a high injection efficiency and long beam lifetime. For the beamlines it is essential to have a stable beam position and beam size, which requires transparent gap and phase changes of individual IDs. This study was carried out in order to determine the sensitivity of the MAX IV 3 GeV storage ring to IDs and to derive a compensation scheme for neutralizing the effects of IDs.

## INFLUENCE OF IDs ON THE BEAM

During manufacturing of an ID it is possible to measure the static field integral and the static multipole components of the ID. The static multipole components can be shimmed to sufficiently low values by arrangements of small corrector magnets at the entrance and exit of the ID. In general, there is a variation of the field integrals with gap and phase of the ID that cannot be completely neutralized for all gaps and phases. A set of air coils, four in total, will correct for the gap and phase dependent field integral errors and in that way the beam position around the ring can be kept stable. The feed-forward table for the four air coils is established with the stored beam after installation of the IDs. The quality of the field integral correction is determined by the effort spent on establishing feed-forward tables and the resolution of the DACs for the correction coil power supplies. The IDs are therefore expected to be transparent and not apply kicks or translations to the beam.

The IDs will also give rise to dynamic multipoles which cannot be measured with the flip coil of the magnetic measurement system used during manufacturing. For planar IDs the dynamic multipoles show up as a vertically focusing effect that, if not corrected, leads to a vertical tune shift and a variation of the vertical beta function around the ring, the so called beta beat. The vertical focusing varies with vertical position, i.e. it is nonlinear, thus giving rise to an amplitude-dependent tune shift which can reduce the DA of the storage ring. The problem with dynamic multipoles is especially pronounced at low and medium electron energy rings and for IDs with large transverse gradients like elliptically polarizing undulators (EPUs) or high field wigglers. An elegant method of estimating the effect of an ID on beam optics and DA of a storage ring makes use of the concept of focusing potential to derive tune shifts and kick maps that can be used for tracking calculations [3]. The kick map describes the kick an electron receives when passing the ID. The full horizontal and vertical beam stay clear aperture of the ID is covered by the kick map.

For an EPU, the dynamic multipoles generated in the elliptical mode can be compensated efficiently with L-shaped iron shims [4, 5] but for the inclined mode no passive compensation scheme is available. Active compensation of the dynamic multipoles in the inclined and arbitrary mode can be obtained by using current strips along the vacuum chamber [6, 7].

## TOLERANCES FOR IDs

The nonlinear optics of the multibend achromat design chosen for the MAX IV 3 GeV storage ring make use of many sextupoles and octupoles within each achromat, making it possible to minimize resonance driving terms and shape chromatic and amplitude-dependent tune shifts within each achromat [8, 9, 10] without relying on phase advances across several achromats as in interleaving correction schemes. Therefore, if the linear optics can be matched sufficiently well to an ID, the ID becomes transparent to the nonlinear optics and consequently it should not perturb the design nonlinear compensation scheme, thus preserving good DA and lifetime.

The tolerances for higher order multipoles, the field roll-off, and size of the good-field region for the MAX IV 3 GeV storage ring have been estimated. The good-field region in the ID can be defined according to the required horizontal dynamic aperture in the entire storage ring which is 7.1 mm mrad [8]. In the IDs this corresponds to  $\pm 8$  mm in the horizontal plane. Therefore, the required horizontal good-field region in the IDs was also set to  $\pm 8$  mm.

The maximum tolerable skew quadrupole moment has

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been determined by observing emittance growth from skew quadrupole components in IDs using Tracy-3 [11]. The underlying criterion is that emittance growth from IDs should be limited to about 10% of the emittance coupling. Emittance coupling is expected to be set between 0.5–3% during user operation. Thus, a maximum increase of 0.05% in emittance coupling is tolerated from IDs. Tracking studies indicate that all ID skew quadrupole contributions *combined* should therefore be limited to  $(a_2L) = 0.0035 \text{ m}^{-1}$ .

Maximum tolerable multipoles have been determined using OPA [12] and Tracy-3. Long hard-edge multipoles have been placed at the location of the IDs and limits derived assuming that the multipole contribution should not perturb amplitude-dependent tune shifts, quadratic chromaticity, cubic chromaticity, or first-order sextupole resonance driving terms by more than 10% from their levels in the design nonlinear optics of the bare lattice. The OPA code facilitates this task greatly by displaying changes to all individual terms of the Hamiltonian in real time as a function of the applied multipole strength. From these studies, tolerable limits for contributions from all IDs *combined* have been derived: the total upright sextupole contribution should be limited to  $(b_3L) = 0.687 \text{ m}^{-2}$  (as this perturbs both amplitude-dependent tune shifts  $\partial\nu_x/\partial J_x$  and  $\partial\nu_x/\partial J_y = \partial\nu_y/\partial J_x$  by 10%) and the total upright octupole contribution should be limited to  $(b_4L) = 51.7 \text{ m}^{-3}$  (as this perturbs the horizontal tune shift with horizontal amplitude  $\partial\nu_x/\partial J_x$  by 10%).

## IDS IN THE MAX IV 3 GeV RING

The final choice of IDs for the MAX IV 3 GeV storage ring has not yet been made. The first set of IDs will however most likely be a combination of the IDs summarized in Table 1. The IDs in Table 1 have been modeled with the software package Radia [13], which has also been used to calculate the focusing potential and kick maps. The EPUs have been modeled in 4 different modes: planar, helical, inclined, and vertical. The kick maps cover an aperture of  $\pm 2 \text{ mm}$  vertically and  $\pm 20 \text{ mm}$  horizontally, which covers the expected beam stay clear aperture in the straight sections of the MAX IV 3 GeV storage ring.

An example of a kick map can be seen in Fig. 1, which shows the kick map for epu53 when it is operating in helical mode.

## MATCHING OPTICS TO IDS

The linear optics are matched to the ID in a two-stage process. A first step is *local*: the beta functions of the achromats adjacent to the ID are matched to the ID. This is achieved by tuning the final focusing quadrupole doublets in the matching cells adjacent to the ID so that the beam is over-focussed in the ID. In this way, ID focusing is compensated without increasing the beam size in the ID [2]. This is a rather fine adjustment ( $< 1.3\%$  gradient adjustment for the strongest ID expected) because of the low beta

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Table 1: IDs in the MAX IV 3 GeV storage ring

Name	Type	Length [m]	Period Length [mm]	Gap [mm]
epu48	Ellipt. Pol. Undulator	3.9	48	11
epu53	Ellipt. Pol. Undulator	3.9	53	11
pmuL	In-Vacuum Undulator	3.8	18.5	4.2
pmuS	In-Vacuum Undulator	1.9	18.5	4.2
wig	In-Vacuum Wiggler	1.9	50	5.5

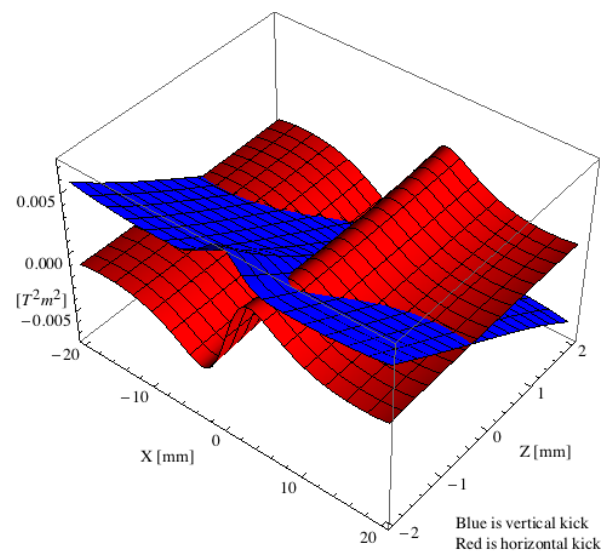


Figure 1: Kick map of epu53 in helical mode.

functions in the ID straights. Despite the only minor adjustment, a phase advance leading to a tune shift for the entire ring is introduced in the process. This is corrected in the second matching step: a *global* matching is carried out where all other final focusing quadrupole doublets around the ring are adjusted to restore the design working point. This adjustment is again rather gentle because of the small phase advance and large number of quadrupoles used ( $< 0.07\%$  gradient adjustment for a single ID).

The final result of these two matching steps is that the ID becomes transparent to the rest of the ring. The beta functions in the sextupoles and octupoles are virtually unchanged and the working point is at its design value. Therefore, the chromatic and amplitude-dependent tune shifts are restored to their design behavior thus replicating the tune footprint of the design lattice and with it the large DA and good lifetime. The first matching step can be implemented as a feed-forward table depending on the ID gap setting. The second step can be implemented either as a

feed-forward table depending on all gap settings or in a feedback scheme. The latter will likely be chosen for the MAX IV 3 GeV storage ring since an online tune measurement is expected to be available at all times.

## RESULTS FROM TRACKING STUDIES

A few examples of this matching process and the resulting DA are given in this section. Tracking with Tracy-3 has been carried out using both an ID model and kick maps. The kick maps should give a more accurate picture of the ID influence on the stored beam. On the other hand, DA resulting from kick maps is not purely dynamic as it is made by the acceptance because of the finite boundaries of the kick maps. This is displayed in Fig. 2 where the solid lines show DA from tracking with an ID model compared to DA from kick maps for pmuL. The resulting DA without ID acceptance extends beyond the physical aperture of the nominal vacuum chamber of the storage ring (solid black line) as a result of proper optics matching. Tracking using kick maps (dashed lines) shows that the boundary of the kick map (i.e. the acceptance of the ID) is limiting DA in the vertical plane.

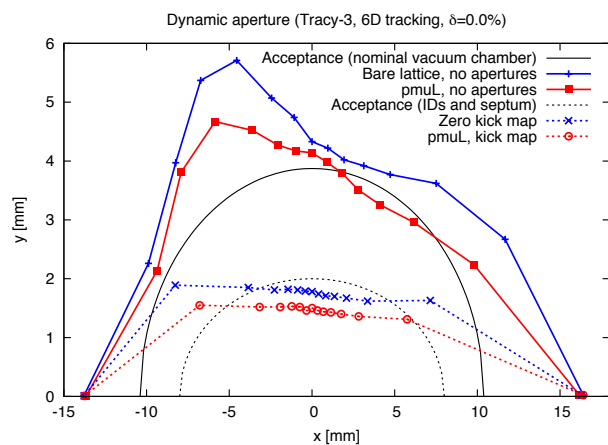


Figure 2: Tracking of DA of the MAX IV 3 GeV storage ring with Tracy-3. The plot compares pure DA (solid lines) with DA masked by ID acceptance (dashed lines).

Tracking studies were performed for all IDs expected in the MAX IV 3 GeV storage ring. Figure 3 shows results for DA with epu53 installed and properly matched linear optics. In the horizontal plane, the DA exceeds the storage ring acceptance in all but one mode. In the vertical plane the acceptance limitation of the ID is clearly visible. For comparison a “zero kick map” is displayed. This map has the same boundary conditions as the other kick maps, but it contains no actual kicks. It conveys only the acceptance of the ID.

## SUMMARY

The strategy for neutralizing the influence of IDs on the beam is that each ID will provide gap and phase to the

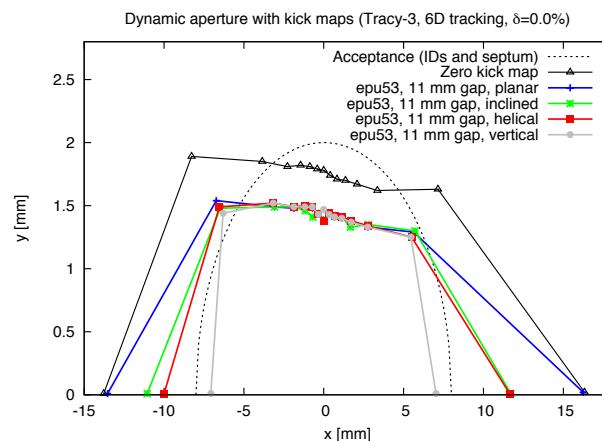


Figure 3: Tracking of DA of the MAX IV 3 GeV storage ring with Tracy-3 using kick maps to show the effect of epu53 in different modes.

machine control system which generates local and global quadrupole detuning settings. Air coils with empirical feed forward tables will compensate for field integral errors. The lattice appears to be robust and it tolerates the dynamic multipoles created by the expected initial set of IDs. The strategy described in this note is still work in progress and it will be adopted to the final choice of IDs.

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