# Updates to the MAX IV 1.5 GeV Storage Ring Lattice

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**Abstract**

The optics for the MAX IV 1.5 GeV storage ring have been modified and the lattice has been updated. The new 20111102 branch [1] will replace the previous 20110201 branch. The lattice update has resulted primarily from a first iteration with detailed magnet design [2] using a new slice model for dipoles and quadrupoles. The optics changes are minor and consist mainly in a change of the vertical tune by +0.1. The nonlinear optics were re-optimized with emphasis on increasing the momentum acceptance to 4.0% [3]. The changes to the lattice are significant and therefore the DDR chapters on beam dynamics in the 1.5 GeV storage ring [4] will be rewritten. For the time being, this note will serve as documentation of the changes and expected performance of the new lattice. A list of current lattice files and their purpose is appended.

## 1 Summary of Changes in the New Lattice

The following is a summary of changes applied to branches 20100325 and 20110201 resulting in the new lattice branch 20111102.

- The pulsed sextupole magnet and dipole kicker for injection are now both included in the lattice and have a finite length. The PSM is 400 mm long, while 200 mm have been reserved for the dipole kicker.
- A vertical pinger magnet has been included in the lattice. Its magnetic length has been set at 200 mm. A horizontal pinger is not required because the dipole kicker for injection will be used as a horizontal pinger.

[1] This document is available for download at `http://www.maxlab.lu.se/node/999`

- A dedicated septum element (1252 mm magnetic length) has been added to include the limiting horizontal aperture of 13.5 mm.
- The nomenclature in the lattice file has been updated.
- The apertures of the elements at the center of the double-bend achromat (DBA) structure (SQFi and SCi) have been increased to $\pm 28$ mm (H) and $\pm 14$ mm (V).
- The linear and nonlinear optics have been updated (see below).

# 2 New Linear Optics

A first set of results for the 1.5 GeV storage ring detailed magnet design is presented in [2]. According to this design the following changes have to be made in the lattice model:

- Slice models for DIP (28 slices), SQFo (3 slices), and SQFi ($2\times 2$ slices).
- The magnetic length of DIP is increased form 1000 mm to 1190 mm.
- SDo is moved farther away form the dipole by 30 mm.
- SCi is moved farther away from SQFi by 10 mm.

The new slice models were scaled with several factors in order to restore the design optics. The first scaling was $f_{\mathrm{deg}} = 0.99925907$ which was applied to the dipole field and the gradient in DIP simulating a change of current to the dipole in order to achieve the design 15°. This was followed by three scalings $f_{\mathrm{DIP}} = 1.000561954$, $f_{\mathrm{SQFi}} = 0.982445974$, $f_{\mathrm{SQFo}} = 0.999790668$ where all multipoles within the dipoles and quadrupoles were scaled with a common factor in order to restore the design linear optics.

It was later noticed that an improvement of the nonlinear behavior of the lattice could be achieved by moving the vertical tune $\nu_y = 3.14 \rightarrow 3.15$. This called for a choice of slightly different scaling factors: $f_{\mathrm{DIP}} = 1.000849916$, $f_{\mathrm{SQFi}} = 0.98245855$, $f_{\mathrm{SQFo}} = 0.999814030$. The resulting beta functions at the center of the straights are $\beta_x^* = 5.672$ m and $\beta_y^* = 2.837$ m. An overview if the lattice properties and optics is given in Figs. 1 and 2.

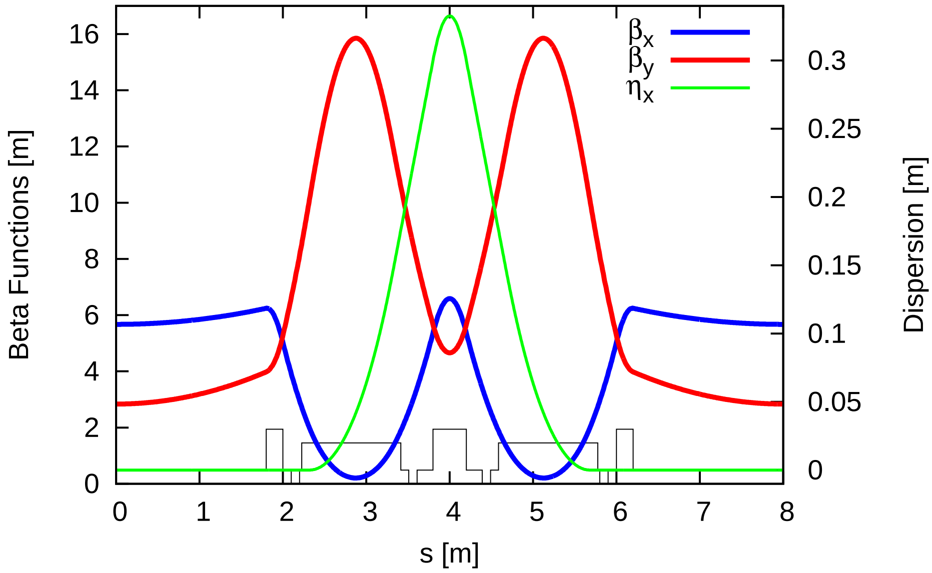



Figure 1: The new optics in one of the 12 DBA's of the MAX IV 1.5 GeV storage ring. The magnetic structure is indicated at the bottom.

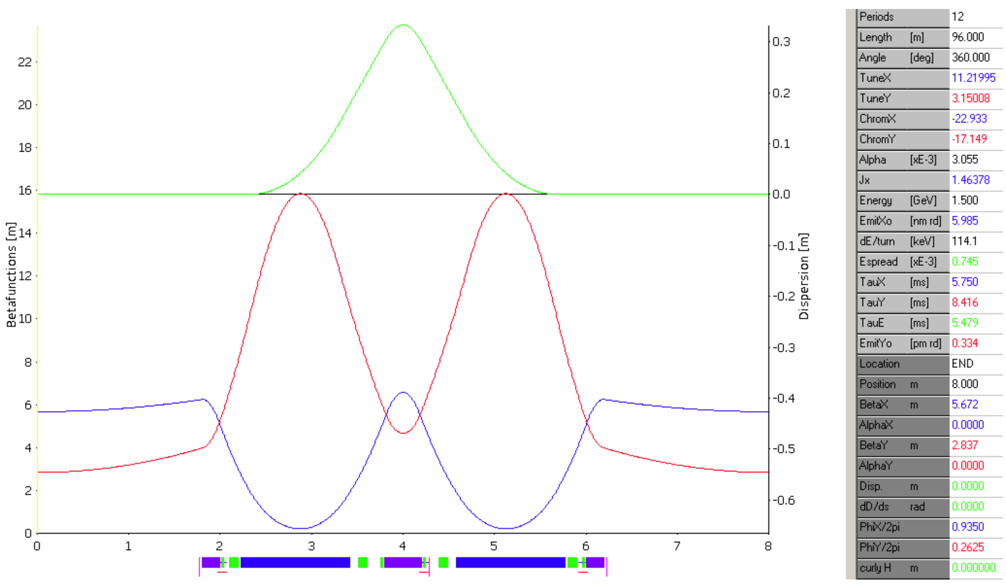



Figure 2: The new lattice in one of the 12 DBA's of the MAX IV 1.5 GeV storage ring. The most important derived properties are indicated on the right.

# 3 Changes to the Nonlinear Optics

As previously mentioned, the vertical tune was increased slightly in order to improve nonlinear dynamics. The resulting natural chromaticity is $\xi_x = -22.933$ and $\xi_y = -17.149$. In order to correct this linear chromaticity to +2.0 in both planes the sextupole component of SQFi is adjusted by scaling with $f_{\mathrm{SQFi},2} = 1.039815$ and setting $(b_3)_{\mathrm{SDi}} = -74.034166$. In addition, the nonlinear dynamics are improved by the following harmonic sextupole settings: scaling the sextupole component of SQFo with $f_{\mathrm{SQFo},2} = 1.236781$ and setting $(b_3)_{\mathrm{SDo}} = -99.92$. This constitutes the 511 nonlinear optics. The tune footprint and dynamic aperture (DA) for the m5-20111102-511 lattice are displayed in Figs. 3 and 4. The large apparent vertical DA available for low horizontal amplitudes is an artifact: an island structure was not recognized by the adaptive step control causing the island to be considered to be part of the continuous DA. The available off-momentum DA for ±4% is required to achieve the target lattice momentum acceptance (MA).

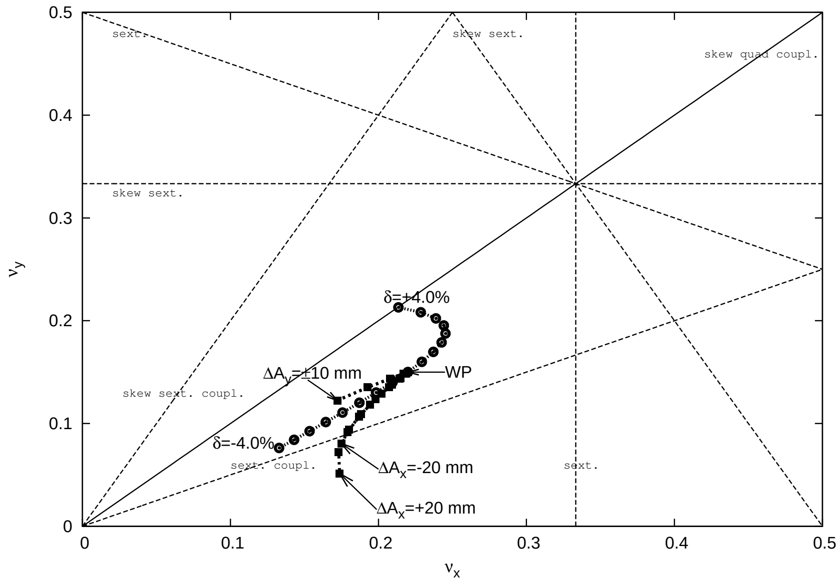



Figure 3: The tune footprint of the new m5-20111102-511 optics of the MAX IV 1.5 GeV storage ring.

Several diffusion and frequency maps have been generated for the new m5-20111102-511 optics. Figs. 5 and 6 show tune diffusion for on and off-momentum particles. The on-momentum diffusion map (DM) was limited so as to exclude the island above the continuous DA. The on-momentum frequency map analysis (FMA)

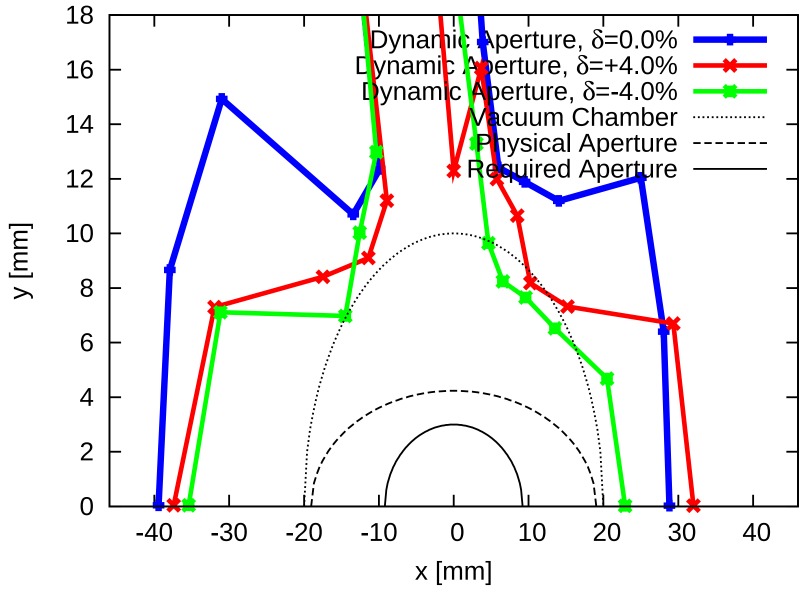



Figure 4: Dynamic aperture calculated with Tracy-3 in 6D for the new m5-20111102-511 optics of the MAX IV 1.5 GeV storage ring.

reveals that the area required for injection and lifetime show low diffusion. The increased diffusion observed in the semicircular strip around $(\pm 20, 0) \times (0, 10)$ is caused by $6\nu_x = 67$ while the semicircular strip around $(\pm 18, 0) \times (0, 12)$is caused by $\nu_x - 2\nu_y = 5$. The lower part of the on-momentum frequency map (FM) appears to show "folded" diffusion, but this is just an artifact of diffusion of particles that have crossed the integer resonance $\nu_y = 3$ (this happens only for very large horizontal amplitudes).

The off-momentum DM reveals increased diffusion around $\delta = -6\%$ caused by crossing the sextupole coupling resonance $\nu_x - 2\nu_y = 5$. The coupling resonance $\nu_x - \nu_y = 8$ is crossed just slightly below $\delta = 4\%$, but this is not resolved by the DM presented here. Slightly elevated levels of diffusion are caused by $6\nu_x = 67$ which is encountered for $\delta = -2.75\%$, $6\nu_y = 19$ which is encountered for $\delta = 1.0\%$, and $2\nu_x - \nu_y = 19$ which is encountered at $\delta = 6.25\%$.

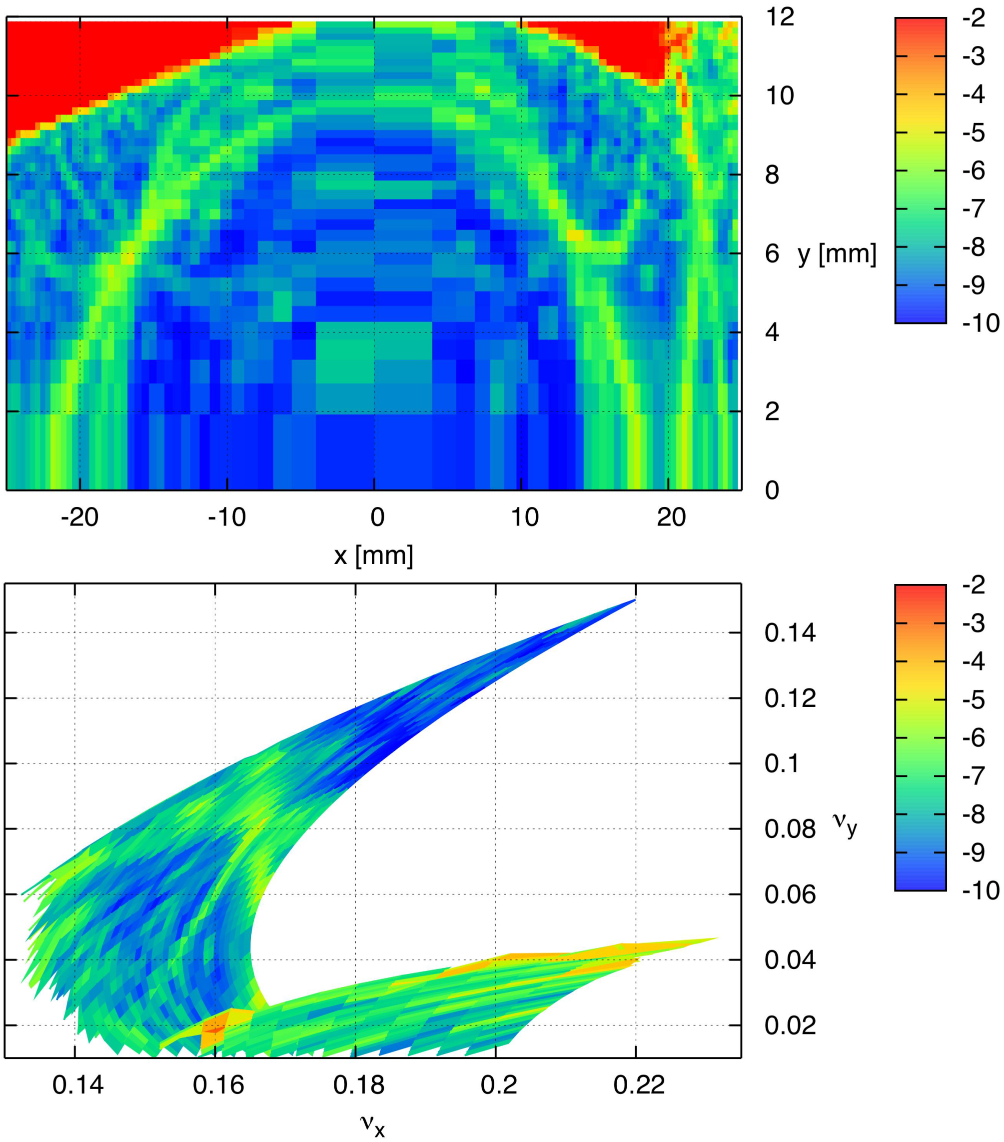



Figure 5: Frequency map analysis with Tracy-3 for the new m5-20111102-511 optics of the MAX IV 1.5 GeV storage ring. Top: Diffusion map for on-momentum particles. Bottom: Frequency map corresponding to data points plotted in top plot.

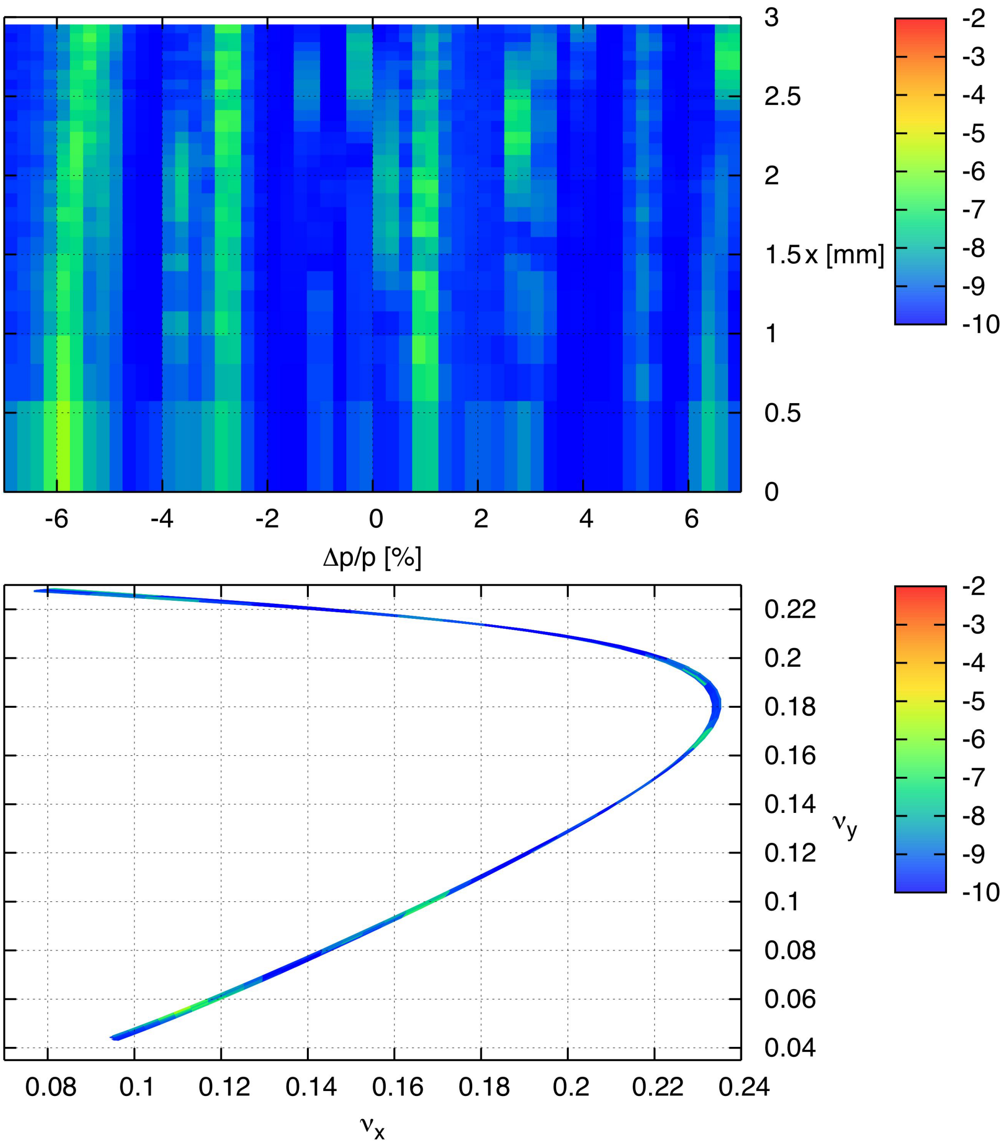



Figure 6: Frequency map analysis with Tracy-3 for the new m5-20111102-511 optics of the MAX IV 1.5 GeV storage ring. Top: Diffusion map for on-momentum particles. Bottom: Frequency map corresponding to data points plotted in top plot (upper lobe corresponds to positive momentum offsets).

In the MAX IV 1.5 GeV storage ring the chromaticity correction and nonlinear optics are achieved by the built-in sextupole components in the SQFi/o magnets as well as the dedicated SDi/o. An alternative nonlinear optics setting attempts to correct the linear chromaticity to +1.0 in both planes. This is achieved by powering the correction sextupoles SCi and changing the current setting on the SDi. In addition, the correction sextupole SCo and SDo settings are varied as well to improve the nonlinear dynamics. The resulting optics is referred to as m5-20111102-513.

Table 1: List of sextupole gradient changes by magnet family required to correct the linear chromaticity to $+1.0$ in both planes.

| Magnet family | Sextupole gradient change | Rel. difference |
|---|---|---|
| SDi | $b_3 = -74.034\,\mathrm{m}^{-3} \longrightarrow -68.731\,\mathrm{m}^{-3}$ | $-7.2\%$ |
| SDo | $b_3 = -99.920\,\mathrm{m}^{-3} \longrightarrow -98.32\,\mathrm{m}^{-3}$ | $-1.6\%$ |
| SCi | $b_3 = 0.000\,\mathrm{m}^{-3} \longrightarrow -21.389\,\mathrm{m}^{-3}$ | n/a |
| SCo | $b_3 = 0.000\,\mathrm{m}^{-3} \longrightarrow -22.000\,\mathrm{m}^{-3}$ | n/a |

The tune footprint and dynamic aperture (DA) for the m5-20111102-513 lattice are displayed in Figs. 7 and 8. The island structure above the continuous DA is again misinterpreted by the DA routine (adaptive step control misses boundaries). Compared to the 511 nonlinear optics, the 513 nonlinear optics show a much more compressed tune footprint both for large amplitudes and momentum offsets. Since the chromatic tune shifts are wrapped up more tightly in the 513 nonlinear optics, the distance to the linear coupling resonance for large positive momentum deviations is increased. This is reflected by the DA: while the on-momentum DA is comparable, the DA at $\delta = \pm 4.0\%$ for 513 is increased so it almost matches the on-momentum DA.

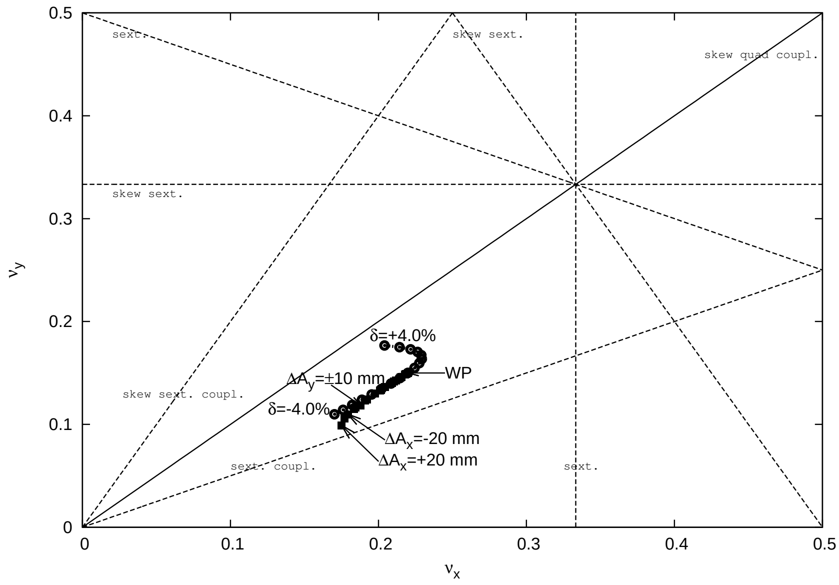



Figure 7: The tune footprint of the new m5-20111102-513 optics of the MAX IV 1.5 GeV storage ring.

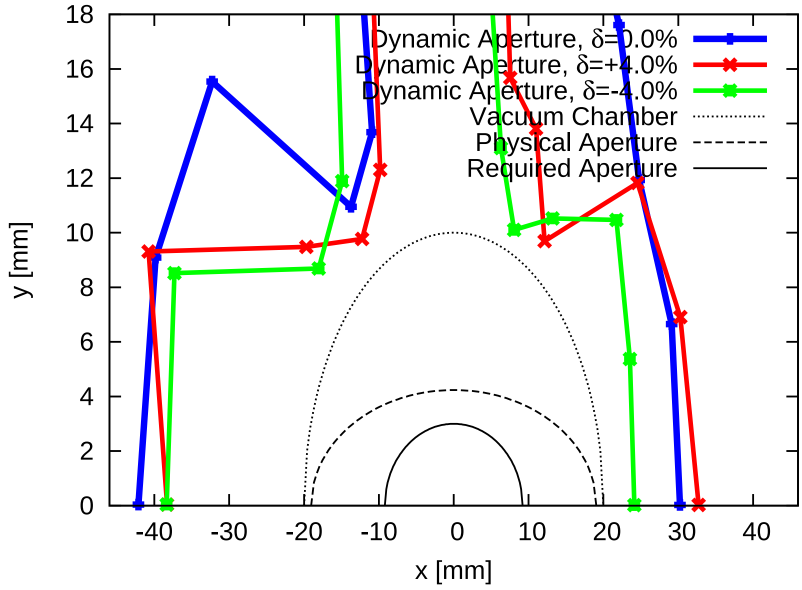
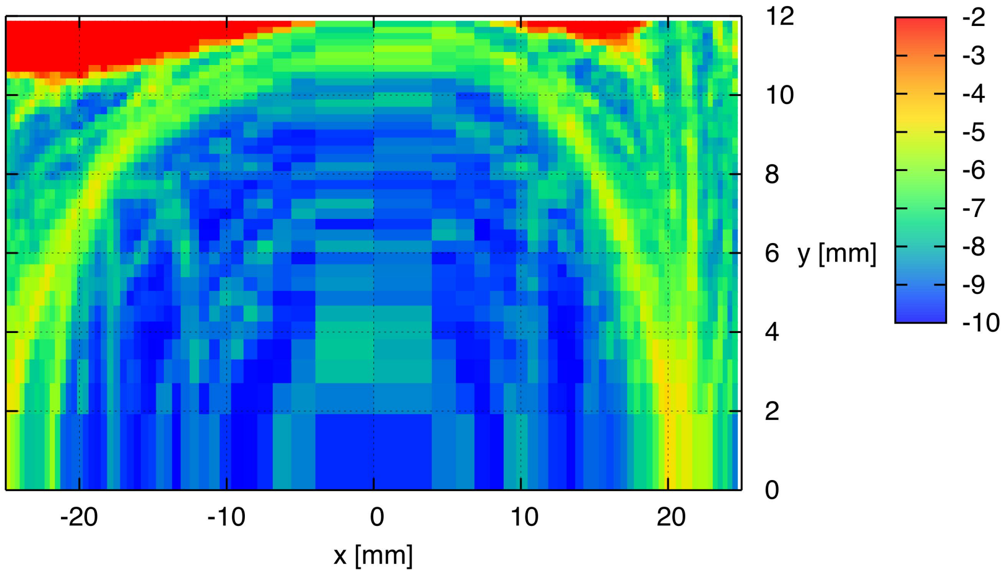



Figure 8: Dynamic aperture calculated with Tracy-3 in 6D for the new m5-20111102-513 optics of the MAX IV 1.5 GeV storage ring.

Frequency map analysis has also been performed for the new m5-20111102-511 optics. Figs. 9 and 10 show tune diffusion for on and off-momentum particles. The on-momentum diffusion map (DM) was again limited so as to exclude the island above the continuous DA. The on-momentum FMA reveals again that the area required for injection and lifetime show low diffusion. The increased diffusion observed in the semicircular strip around $(\pm 21, 0) \times (0, 11)$ is caused by $\nu_x - 2\nu_y = 5$.

The off-momentum DM reveals increased diffusion around $\delta = -5.5\%$ caused by crossing $6\nu_x = 67$ and $\delta = 6.25\%$ caused by crossing $2\nu_x + 4\nu_y = 35$. The coupling resonance $\nu_x - \nu_y = 8$ is crossed just slightly above $\delta = 4.5\%$, but this is not resolved by the DM presented here. Slightly elevated levels of diffusion are caused by $6\nu_y = 19$ which is encountered around $\delta = 2.5\%$.



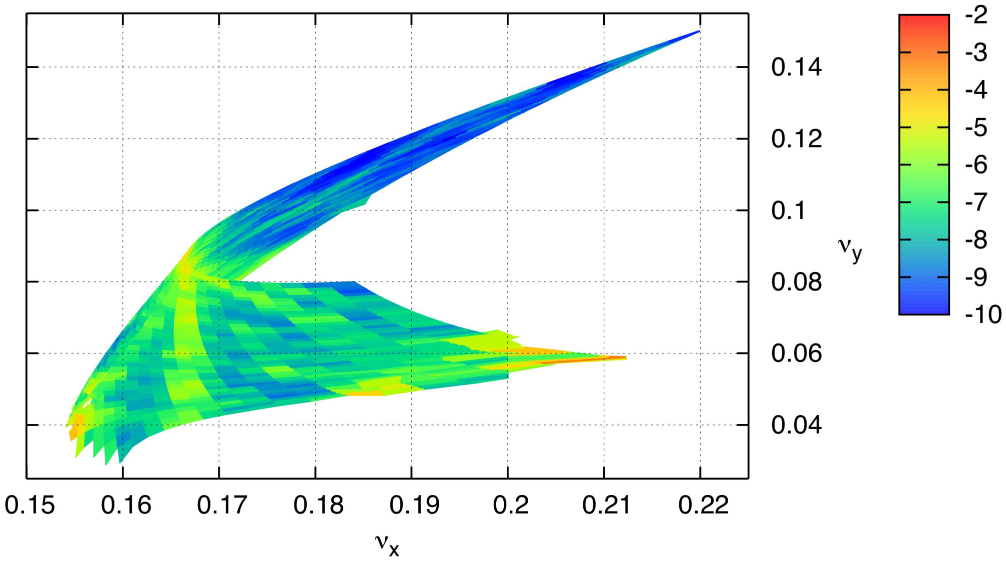




Figure 9: Frequency map analysis with Tracy-3 for the new m5-20111102-513 optics of the MAX IV 1.5 GeV storage ring. Top: Diffusion map for on-momentum particles. Bottom: Frequency map corresponding to data points plotted in top plot.

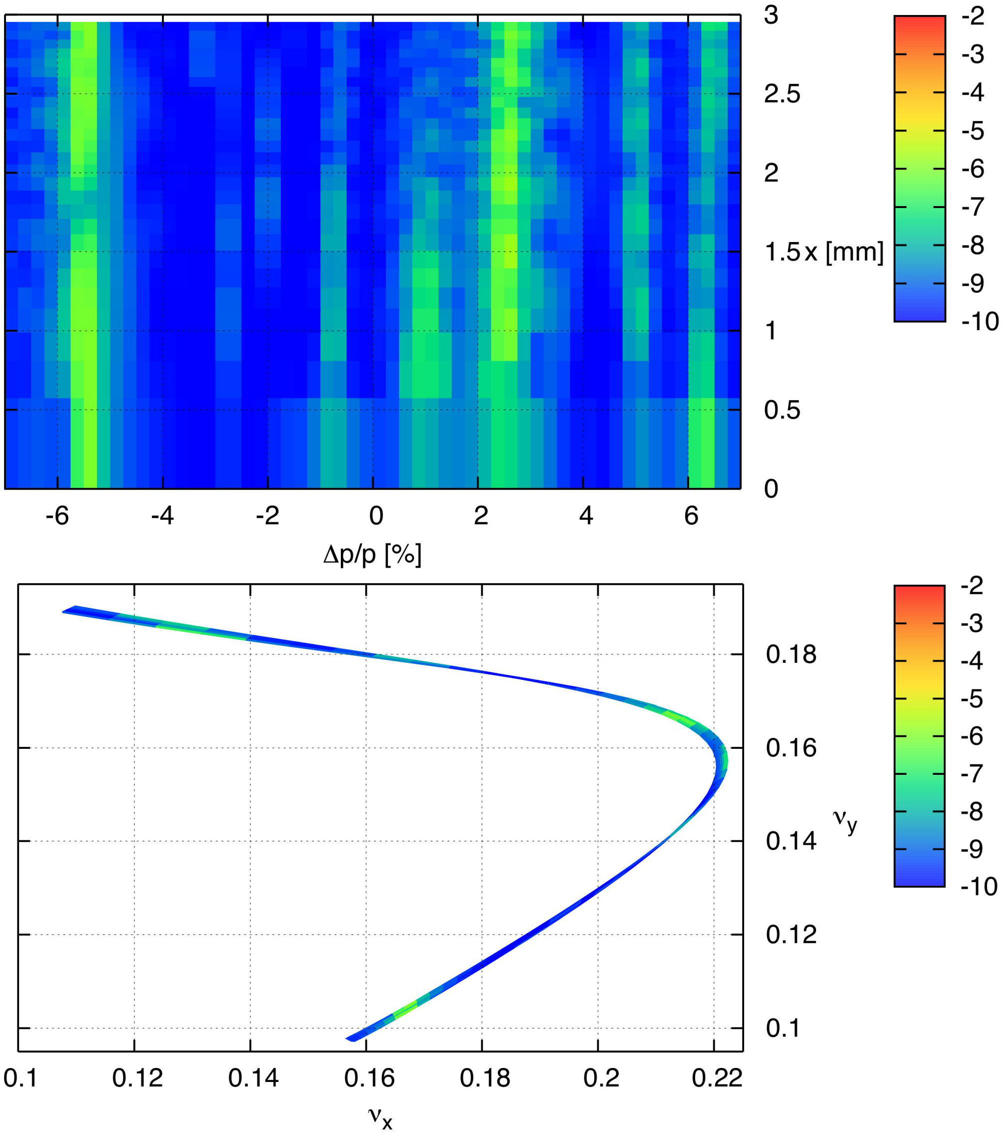



Figure 10: Frequency map analysis with Tracy-3 for the new m5-20111102-513 optics of the MAX IV 1.5 GeV storage ring. Top: Diffusion map for on-momentum particles. Bottom: Frequency map corresponding to data points plotted in top plot (upper lobe corresponds to positive momentum offsets).

# 4 Current Lattice Files

Table 2 lists all current lattice files [1] and what type of elements are included. The lattice files are human-readable and in Tracy-3 format. All lattice files contain BPMs and correctors (SOFB). Girder markers are also included.

Table 2: List of all current lattice files.

| File name | Lattice contains |
|---|---|
| m5-20111102-511-bare.lat | Bare lattice, injection elements included, chromaticity corrected to +2.0 in iron |
| m5-20111102-513-bare.lat | Bare lattice, injection elements included, chromaticity corrected to +1.0 with SCi/o |

# References


[1] The updated lattice files can be found at `http://www.maxlab.lu.se/node/999`

[2] M. Johansson, draft of an updated DDR Chapter 3.5, unpublished, October 28, 2011.

[3] S.C. Leemann, "Recent Improvements to the Lattices for the MAX IV Storage Rings", Proceedings of IPAC'11, San Sebastían, Spain, September 2011, THPC059, pp.3029–3031.

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