MAX IV 1.5 GeV Storage Ring
Recent Developments in Lattice, Optics, and Beam Dynamics
Reminder: 1.5 GeV Storage Ring

“No problem is too small or too trivial if we can really do something about it.”
— Richard P. Feynman
Outline

• Recent lattice/model modifications
• Updated linear optics
• Updated nonlinear optics
• Realistic performance: ID’s & errors
• Injection: single dipole kicker & pulsed sextupole magnet

1.5 GeV
12-fold DBA lattice
96 m circumference
12 × 3.5 m straights
10 straights for ID’s
$\varepsilon_0 = 5.982 \text{ nm rad}$
Lattice Modifications

• **Lattice model completed**
  – Pingers, dipole kicker, and PSM included

• **Magnet engineering feedback**
  – Shifted sextupoles to make room for coils & field clamps
  – Hard-edge magnet lengths closer to mechanical lengths

• **Vacuum engineering feedback**
  – Realistic vacuum apertures in model (incl. septum)

• **Slice model**
  – 28 slices to model gradient dipoles
  – 3/4 slices to model focusing quads with sextupole component
  ➔ Longitudinal field profiles properly modeled (can also include crosstalk and systematic multipoles)

➡ Restore linear optics, re-optimize nonlinear optics, revisit injection, verify expected performance...
Updated Linear Optics (1)

• Gradient dipoles
• Focusing quadrupoles contain sextupole component
• Discrete sextupoles for defocusing
Updated Linear Optics (2)

• Corrections
  – Pole-face strips to correct focusing gradient in dipoles
  – Correction sextupoles for correction of sextupole component in iron
  – Dipole corrector coils on SCi/o
  – Extra windings on SCi/o (skew quads, aux. sext) and SDi/o(aux. sext)
  – BBC: active shunts on SQFi/o (in addition to regular shunts)
• Original design optics restored
  ➡ Several iterations with magnet design in order to get ratios right
• Vertical tune 3.14 ➔ 3.15 (nonlinear optics optimization)

\begin{align*}
\varepsilon_0 &= 5.982 \text{ nm rad} \\
\nu_x &= 11.22 \\
\nu_y &= 3.15 \\
\xi_x &= -22.964 \\
\xi_y &= -17.154 \\
\sigma_x^* &= 184 \mu\text{m} \\
\sigma_y^* &= 13 \mu\text{m} \\
\eta_x^* &= 33 \text{ cm}
\end{align*}
Updated Nonlinear Optics

• Follow “standard MAX IV“ optimization process:
  – Correct natural chromaticities
  – Minimize RDT’s via weighted SVD
  – Tailor tune shifts over relevant range by tweaking \((b_3L)\)
  – Adjust linear optics (if necessary)
  – Verify (DA, MA, FMA, etc.)
  – Iterate...

PRST-AB 12, 120701 (2009)
PRST-AB 14, 030701 (2011)
Updated Nonlinear Optics

• Follow “standard MAX IV“ optimization process:
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  – Minimize RDT’s via weighted SVD
  – Tailor tune shifts over relevant range by tweaking ($b_3L$)
  – Adjust linear optics (if necessary)
  – Verify (DA, MA, FMA, etc.)
  – Iterate...

• In iron: 521 nonlinear optics, $\xi_{x,y} = +2.0$

• User operation: 523 nonlin. optics using SCi/o, $\xi_{x,y} = +1.0$
  – Reduce chromatic and amplitude-dependent tune shifts

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PRST-AB 14, 030701 (2011)
Follow “standard MAX IV“ optimization process:

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Reduce chromatic and amplitude-dependent tune shifts

![Graph showing amplitude excursion vs. displacement]

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Reduce chromatic and amplitude-dependent tune shifts

Simon C. Leemann

4th MAX IV MAC Meeting, May 29-30, 2012
Follow “standard MAX IV“ optimization process:

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- Iterate...

In iron: 521 nonlinear optics,
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- Reduce chromatic and amplitude-dependent tune shifts

Simon C. Leemann
4th MAX IV MAC Meeting, May 29-30, 2012

PRST-AB 12, I20701 (2009)
PRST-AB 14, 030701 (2011)
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  - Tailor tune shifts over relevant range by tweaking \( b_3 L \)
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    - Compact tune footprint clear of potentially dangerous resonances
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  – Tailor tune shifts over relevant range by tweaking $(b^3_L)$
  – Adjust linear optics (if necessary)
  – Verify (DA, MA, FMA, etc.)
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0$^\text{th}$ MAX IV MAC Meeting, May 29-30, 2012

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PRST -AB 14, 030701 (2011)
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    ➡ Compact tune footprint clear of potentially dangerous resonances
    ➡ Large DA, large off-momentum DA (confirmed with FMA)
Follow "standard MAX IV" optimization process:

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- Minimize RDT's via weighted SVD
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Updated Nonlinear Optics

References:
- PRST-AB 12, 120701 (2009)
- PRST-AB 14, 030701 (2011)

Dynamic Aperture, $\delta = 0.0\%$
Dynamic Aperture, $\delta = +4.0\%$
Dynamic Aperture, $\delta = -4.0\%$
Vacuum Chamber
Physical Aperture
Required Aperture
Follow "standard MAX IV" optimization process:
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  – Iterate...

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  – Reduce chromatic and amplitude-dependent tune shifts
    ➤ Compact tune footprint clear of potentially dangerous resonances
    ➤ Large DA, large off-momentum DA (confirmed with FMA)
    ➤ Large momentum acceptance (MA)

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PRST-AB 14, 030701 (2011)
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Simon C. Leemann
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      ➤ Large momentum acceptance (MA)
      ➤ Good Touschek lifetime

PRST-AB 12, 120701 (2009)
PRST-AB 14, 030701 (2011)
Follow "standard MAX IV" optimization process:

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- Minimize RDT's via weighted SVD
- Tailor tune shifts over relevant range by tweaking $b^3_{\text{L}}$
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- Iterate...

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$\rightarrow$ Compact tune footprint clear of potentially dangerous resonances

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$\rightarrow$ Good Touschek lifetime

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Updated Nonlinear Optics

PRST -AB 12, 120701 (2009)
PRST -AB 14, 030701 (2011)

$\tau_{\text{ts}}$ [h] vs $U_{\text{cav}}$ [kV]

34 h with LC’s
23 h with LC’s
3.5% $\rightarrow$ $\sim$ 6 h

$\tau_{\text{ts},6D}$, $\tau_{\text{ts},4D}$, $\delta_{\text{rf}}$

$\tau_{\text{ts}}$, $\delta_{\text{rf}}$
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Realistic Performance

• Is the lattice stable?
• How do perturbed optics behave?
  – Machine with misalignments, field errors & multipole errors
  – Machine with strong ID’s (Solaris) → matching?
Realistic Performance: Errors

• Misalignments
  – Similar to updated model for 3 GeV ring
## Realistic Performance: Errors

### Misalignments
- Similar to updated model for 3 GeV ring

<table>
<thead>
<tr>
<th></th>
<th>Transverse displacements</th>
<th>Roll error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girders (magnet blocks)</td>
<td>50 micron rms</td>
<td>0.2 mrad rms</td>
</tr>
<tr>
<td>Dipole slices (!)</td>
<td>25 micron rms</td>
<td>0.2 mrad rms</td>
</tr>
<tr>
<td>Quadrupole slices (!)</td>
<td>25 micron rms</td>
<td>0.2 mrad rms</td>
</tr>
<tr>
<td>Sextupoles</td>
<td>25 micron rms</td>
<td>0.2 mrad rms</td>
</tr>
<tr>
<td>Correctors</td>
<td>25 micron rms</td>
<td>0.2 mrad rms</td>
</tr>
<tr>
<td>BPM calibration</td>
<td>3 micron rms</td>
<td>0.1 mrad rms</td>
</tr>
</tbody>
</table>

Gaussian, 2σ cutoff
Realistic Performance: Errors

• **Misalignments**
  - Similar to updated model for 3 GeV ring
  - Results indicate no DA problems
Malignments

- Similar to updated model for 3 GeV ring
- Results indicate no DA problems
Realistic Performance: Errors

• **Misalignments**
  – Similar to updated model for 3 GeV ring
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• **Systematic field errors**
  – Analytic estimates indicate chosen PS’s reasonable
• **Misalignments**
  - Similar to updated model for 3 GeV ring
  - Results indicate no DA problems

• **Systematic field errors**
  - Analytic estimates indicate chosen PS’s reasonable

• Quadrupole gradients:
  - 1 PS for PFS’s, SQFi, and SQFo
  - $10^{-4}$ jitter on PS will lead to tune jitter of roughly $1 \times 10^{-3}$ (H/V)

• Sextupole gradients:
  - 1 PS for SQFi, SQFo, SDi, and SDo
  - $10^{-4}$ jitter on PS will lead to chromaticity jitter below 0.01 (H/V)
Realistic Performance: Errors

• **Misalignments**
  – Similar to updated model for 3 GeV ring
  – Results indicate no DA problems

• **Systematic field errors**
  – Analytic estimates indicate chosen PS’s reasonable

• **Random field errors**
  – Work in progress, modeling issues (slices, girder hierarchies)
  – Likely: need low gradient spread among dipoles → shunt to gradients
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• **Systematic / random multipole errors**
  – Same model as for 3 GeV ring, so far no problems
  – To-do: include systematic contributions per magnet design report (crosstalk)
Realistic Performance: Errors

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⇒ So far, DA including all error sources appears ok
Realistic Performance: Errors

• Misalignments
  – Similar to updated model for 3 GeV ring
  – Results indicate no DA problems

= So far, DA including all error sources appears ok
Realistic Performance: ID’s

• Lattice with SCW
  – 3.5 T, 25 x 61 mm, 10.2 mm gap
  – Local: optics matching $\rightarrow$ 4.5% on local gradients via PFS
  – Global: restore working point (−0.17 on $v_y$) $\rightarrow$ 0.5% on all gradients via PFS
    • Tune shifts very close to bare lattice $\rightarrow$ comparable tune footprint

PAC’11, TUP235
Realistic Performance: ID’s

• Lattice with SCW
  – 3.5 T, 25 x 61 mm, 10.2 mm gap
  – Local: optics matching → 4.5% on local gradients via PFS
  – Global: restore working point (–0.17 on $\nu_y$) → 0.5% on all gradients via PFS

• Tune shifts very close to bare lattice → comparable tune footprint

PAC’11, TUP235
Realistic Performance: ID’s

• Lattice with SCW
  – 3.5 T, 25 x 61 mm, 10.2 mm gap
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    • Sufficiently large DA

PAC’11, TUP235
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![Diagram](image)
Realistic Performance: ID’s

• **Lattice with SCW**
  - 3.5 T, 25 x 61 mm, 10.2 mm gap
  - Local: optics matching \(\rightarrow 4.5\%\) on local gradients via PFS
  - Global: restore working point \((-0.17\text{ on } v_y) \rightarrow 0.5\%\) on all gradients via PFS
    - Tune shifts very close to bare lattice \(\rightarrow\) comparable tune footprint
    - Sufficiently large DA
  - \(\varepsilon_0 = 5.3\text{ nm rad, losses }+25.2\text{ keV/turn, }\delta_{rf} = 3.95\%\)
    - MA & lifetime still fine
Lattice with SCW

- Local: optics matching → 4.5% on local gradients via PFS

- Global: restore working point → 0.5% on all gradients via PFS

- Tune shifts very close to bare lattice → comparable tune footprint

- Sufficiently large DA

\[ \varepsilon_0 = 5.3 \text{ nm rad}, \text{losses } +25.2 \text{ keV/turn, } \delta_{\text{rf}} = 3.9\% \]

- MA & lifetime still fine

- Overall MA

\[ 560 \text{ kV, } \delta_{\text{rf}} = 3.95\% \]

\[ 402 \text{ kV, } \delta_{\text{rf}} = 3.0\% \]

- Touschek lifetime: 6.4h / 23.7 h (LCs)

PAC’11, TUP235

Realistic Performance: ID’s

\[ b_{\text{acc}}\% ] [s \text{ [m]}]

560 kV, \( \delta_{\text{rf}} = 3.95\% \)

402 kV, \( \delta_{\text{rf}} = 3.0\% \)

Overall MA

Touschek lifetime: 6.4h / 23.7 h (LCs)
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• **Lattice with SCW**
  - 3.5 T, 25 x 61 mm, 10.2 mm gap
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  - Global: restore working point (−0.17 on \( \nu_y \)) → 0.5% on all gradients via PFS
    * Tune shifts very close to bare lattice → comparable tune footprint
    * Sufficiently large DA
  - \( \varepsilon_0 = 5.3 \) nm rad, losses +25.2 keV/turn, \( \delta_{rf} = 3.95\% \)
    * MA & lifetime still fine (Touschek 6.4h / 23.7 h)

• **Lattice with EPU**
  - IPAC’12: A. Wawrzyniak et al., TUPPC025 → effect of EPU96 on optics comparable to SCW → EPU96 appears manageable
Realistic Performance: ID’s

• **Lattice with SCW**
  - 3.5 T, 25 x 61 mm, 10.2 mm gap
  - Local: optics matching $\rightarrow$ 4.5% on local gradients via PFS
  - Global: restore working point ($-0.17$ on $v_y$) $\rightarrow$ 0.5% on all gradients via PFS
    - Tune shifts very close to bare lattice $\rightarrow$ comparable tune footprint
    - Sufficiently large DA
  - $\varepsilon_0 = 5.3$ nm rad, losses $+25.2$ keV/turn, $\delta_{rf} = 3.95$
    - MA & lifetime still fine (Touschek 6.4h / 23.7 h)

• **Lattice with EPU**
  - IPAC’12: A. Wawrzyniak et al., TUPPC025 $\rightarrow$ effect of EPU96 on optics comparable to SCW $\rightarrow$ EPU96 appears manageable

• **Work in progress**
  - No show-stoppers discovered so far
  - But we see need for strong (local) tuning to properly match strong ID’s
  - Narrow-gap chambers? In-vacuum ID’s? Vertical acceptance?
• Modified optics → update injection (retaining strategy)
• Modified optics → update injection (retaining strategy)

• Pulsed sextupole magnet (PSM) for top-up injection
  – Excellent performance: high capture efficiency, transparent to users
  – But tricky in new machine? → want robust injection for commissioning

• Single dipole kicker (KI) for commissioning
  – User operation: single dipole kicker becomes horizontal pinger (adjacent dedicated vertical pinger)
Injection

• Modified optics → update injection (retaining strategy)

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  – User operation: single dipole kicker becomes horizontal pinger (adjacent dedicated vertical pinger)
Injection: Pulsed Sextupole Magnet
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Optimum settings: \( (b_3 L) = 74 \text{ m}^{-2} \) for \( \theta_{pm} = +2.36 \text{ mrad} \)
Optimum settings: $b_3L = 74 \, \text{m}^{-2}$ for $\theta_{pm} = +2.36 \, \text{mrad}$
Injection: Pulsed Sextupole Magnet

Error tolerance: bunch energy spread increased to $\sigma_\delta = 1.8\%$
Injection: Pulsed Sextupole Magnet

Error tolerance: bunch emittance increase (4-fold) / optics mismatch
Injection: Pulsed Sextupole Magnet

Reduced strength: \((b_3L) = 27 \text{ m}^{-2}\) for \(\theta_{pm} = +0.85 \text{ mrad}\)
Injection: Pulsed Sextupole Magnet

Two-turn injection with reduced strength: \((b_3 L) = 59 \text{ m}^2\) for \(\theta_{pm} = +1.9 \text{ mrad}\)
Injection: Single Dipole Kicker

Submitted to NIM-A
Injection: Single Dipole Kicker

On-axis injection: $\theta_{ki} = +2.9\ \text{mrad}$ (inject at $-0.84\ \text{mrad}$)
Injection: Single Dipole Kicker

Standard injection: $\theta_{ki} = +2.4$ mrad
Injection: Single Dipole Kicker

Optimum settings: $\theta_{ki} = +2.4$ mrad
Injection: Single Dipole Kicker

Error tolerance: bunch energy spread increased to $\sigma_\delta = 2.0\%$

Submitted to NIM-A
Injection: Single Dipole Kicker

Error tolerance: bunch emittance increase (3-fold) / optics mismatch
Injection: Single Dipole Kicker

Reduced strength $\theta_{ki} = +1.4$ mrad → allows for accumulation!
“Where’s the Beef?”

- DDR Chapter 3: “MAX IV 1.5 GeV Storage Ring”
  http://www.maxlab.lu.se/maxlab/max4/DDR_public

- MAX-lab Internal Note 20120313: “Updates to the MAX IV 1.5 GeV Storage Ring Lattice”
  http://www.maxlab.lu.se/maxlab/max4/max_iv_reports_public

- Lattice m5-20120313-521-bare.lat & m5-20120313-523-bare.lat
  http://www.maxlab.lu.se/maxlab/max4/max_iv_reports_public

- Effect of strong ID’s on lattice optimization: IPAC’12, TUPPC025
  http://www.ipac12.org/proceedings.htm

- Pulsed sextupole injection into MAX IV rings: PRST-AB 15 050705 (2012)
  http://prst-ab.aps.org/abstract/PRSTAB/v15/i5/e050705