Commissioning Progress at the MAX IV 3 GeV Storage Ring
Outline

• Introduction
  – MAX IV Facility Overview
  – 3 GeV Storage Ring Lattice & Technology
• Commissioning of the MAX IV 3 GeV Storage Ring
  – Commissioning Timeline
  – Beam Commissioning of the Bare Machine
  – First Insertion Devices
  – Facility Inauguration
• Outlook

Collective Effects → Galina’s talk on Thu
Subsystems Report → Magnus’ talk on Fri
MAX IV Facility Overview

• In the early 2000s, MAX-lab wants to build new x-ray source
• Quickly realize a single new accelerator cannot cover the entire required spectral and temporal range
• After a facility-wide optimization, decide instead to build 3 new accelerators:
  – one ≈3.5 GeV linac as SPF/FEL driver & ring injector (separate guns)
  – two separate storage rings at 1.5 GeV (UV) and 3 GeV (x-rays)
MAX IV Facility Overview (cont.)

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Photo courtesy P. Nordeng
Feb 5, 2015
MAX IV Facility Overview (cont.)

- Facility can accommodate up to 32 user beamlines: 3 @ SPF, 10 @ 1.5 GeV SR, 19 @ 3 GeV SR
- 14 have been funded in our first two beamline phases

![The 14 Funded Beamlines Diagram]
MAX IV 3 GeV Storage Ring

• MAX IV 3 GeV storage ring designed for x-ray users → high brightness via state-of-the-art IDs, high-current top-up operation & ultralow emittance

• Ultralow emittance achieved through MBA lattice ($\varepsilon_x \sim 1/N_b^3$)

$$\varepsilon_0[\text{nm rad}] = 1470 E[\text{GeV}]^2 \frac{I_5}{J_x I_2}, \quad J_x = 1 - \frac{I_4}{I_2} \quad \text{TME}$$

$$= 0.0078 \frac{E[\text{GeV}]^2 \Phi[\circ]^3}{J_x} \frac{F(\beta_x, \eta)}{12\sqrt{15}} \rho, \quad \Phi[\circ]^3 \propto \frac{1}{N_b^3} \quad \text{MBA}$$

Gradient Dipoles

$$I_2 = \oint \frac{ds}{\rho^2} \quad I_4 = \oint \frac{\eta}{\rho} \left( \frac{1}{\rho^2} + 2b_2 \right) ds \quad I_5 = \oint \frac{H}{|\rho^3|} ds \quad H = \gamma_x \eta^2 + 2\alpha_x \eta' + \beta_x \eta^2$$

TME: brute-force approach $I_5/I_2 \to 0$ easily leads to overstrained optics, chromaticity wall
MBA: many weak dipoles, distributed chromaticity correction → allows relaxing optics
Gradient dipoles: reduce emittance, allow for more compact optics → improves MBA
MAX IV 3 GeV Storage Ring (cont.)

• The **multibend achromat** proposed already in the 1990s...

  SPIE Vol. 2013, 1993  EPAC’94, p.627  PAC’95, TPG08, p.177  PAC’95, FAB14, p.2823

• ... became a reality @ MAX IV due to several technological breakthroughs
MAX IV 3 GeV Storage Ring (cont.)

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  – compact magnets (narrow gaps → short but strong), magnet integration (common magnet block = “girder”), use of combined-function magnets

![Photo courtesy A. Nyberg](image1)

![Photo courtesy M. Johansson](image2)

![Photo courtesy M. Johansson](image3)

**JSR 21**, 884-903 (2014)
MAX IV 3 GeV Storage Ring (cont.)

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  – NEG-coated vacuum chambers → narrow magnet gaps & tight magnet spacing
MAX IV 3 GeV Storage Ring (cont.)

- The multi-bend achromat proposed already in the 1990s...

- ... became a reality at MAX IV due to several technological breakthroughs –
  - compact magnets (narrow gaps ➔ short but strong),
  - magnet integration (common magnet block = “girder”),
  - use of combined-function magnets – NEG-coated vacuum chambers ➔ narrow magnet gaps & tight magnet spacing.

Simon C. Leemann
6th Low Emittance Rings Workshop, SOLEIL, October 26–28, 2016

Photo courtesy E. Al-dmour
MAX IV 3 GeV Storage Ring (cont.)

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  – 100 MHz RF system with harmonic cavities → ensure stability, good Touschek lifetime & mitigate emittance blowup from IBS
The multibend achromat proposed already in the 1990s...

... became a reality at MAX IV due to several technological breakthroughs:
- compact magnets (narrow gaps ➔ short but strong), magnet integration (common magnet block = "girder"), use of combined-function magnets – NEG-coated vacuum chambers ➔ narrow magnet gaps & tight magnet spacing
- 100 MHz RF system with harmonic cavities ➔ ensure stability, good Touschek lifetime & mitigate emittance blowup from IBS.

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MAX IV 3 GeV Storage Ring (cont.)
MAX IV 3 GeV Storage Ring Lattice

- 528 m circumference, 500 mA with top-up, 20 achromats
MAX IV 3 GeV Storage Ring Lattice (cont.)

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MAX IV 3 GeV Storage Ring Lattice (cont.)

- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 user straights (4.6 m), 1 long straight for injection
- 40 short straights (1.3 m) for RF & diagnostics

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PRST-AB 12, 120701 (2009)
IPAC’11, THPC059, p.3029
JSR 21, 862-877 (2014)
MAX IV 3 GeV Storage Ring Lattice (cont.)

- 528 m circumference, 500 mA with top-up, 20 achromats
- 19 user straights (4.6 m), 1 long straight for injection
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- 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)

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• 7-bend achromat: 5 unit cells (3°) & 2 matching cells (1.5° LGB)
• 328 pm rad bare lattice emittance ($\varepsilon_y$ adjusted to 2-8 pm rad)

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**References**

PRST-AB **12**, 120701 (2009)
IPAC’**11**, THPC059, p.3029
JSR **21**, 862-877 (2014)
Linear & Nonlinear Optics

- **Gradient dipoles** perform vertical focusing \((\varepsilon_x \sim 1/J_x)\)
- Gradient dipoles interleaved with **horizontally focusing quadrupoles**
  - \(\nu_x = 42.20, \nu_y = 16.28\)
  - \(\beta_x^* = 9 \text{ m}, \beta_y^* = 2 \text{ m}\)
  - \(\sigma_x^* = 54 \mu\text{m}, \sigma_y^* = 2-4 \mu\text{m}\)
Linear & Nonlinear Optics (cont.)

- **Chromatic sextupoles** correct linear chromaticity \((\xi_{x,y} \approx -50 \rightarrow +1)\) & tailor its higher orders → additional sextupoles used to minimize first-order RDTs (low since phase advance \(\approx 2\pi \times 2, 2\pi \times 3/4\))

- **Strong sextupoles** drive large ADTS → **achromatic octupoles** allow tailoring ADTS to first order → minimize tune footprint

![Diagram showing linear & nonlinear optics concepts](image-url)
Expected Performance (cont.)

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)
- Overall tune footprint becomes very compact both on and off momentum → large on/off-momentum DA
Expected Performance (cont.)

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)
- Overall tune footprint becomes very compact both on and off momentum \(\rightarrow\) large on/off-momentum DA
- Large lattice MA in conjunction with appropriately dimensioned RF system \(\rightarrow\) large overall MA

**MAX IV 3 GeV SR**

\(U_{\text{cav}} = 1.8\) MV (max)

Target: \(\delta_{\text{acc}} > 4.5\%\)

**Radiated power [keV/turn]**

- \(U_{\text{cav}} = 1.8\) MV

**No. of installed IVUs**

- RF acceptance always >5%
- Bunch length

**Tracy-3 6D tracking results**

\(U_{\text{cav}} = 1.8\) MV, \(U_{\text{cav}} = 1.0\) MV

**Lattice MA always >5%**

**PRST-AB 12, 120701 (2009)**

**PRST-AB 14, 030701 (2011)**

**PAC’11, TUP235, p.1262**

**IPAC’15, TUPJE038**

**PRST-AB 17, 050705 (2014)**

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Expected Performance (cont.)

- Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)
- Overall tune footprint becomes very compact both on and off momentum → large on/off-momentum DA
- Large lattice MA in conjunction with appropriately dimensioned RF system → large overall MA
- Large overall MA is required for good Touschek lifetime despite ultralow emittance

![Graph showing τs (IBS included for 500 mA) and τs (IBS neglected) with parameters: l = 500 mA, δacc = 4.5%, εy = 8 pm rad.]

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Nonlinear tuning results in small amplitude-dependent and chromatic tune shifts (tracking performed with Tracy-3)

Overall tune footprint becomes very compact both on and off momentum → large on/off-momentum DA

Large lattice MA in conjunction with appropriately dimensioned RF system → large overall MA

Large overall MA is required for good Touschek lifetime despite ultralow emittance

Landau cavities stretch bunches ×5 → extend Touschek lifetime & reduce emittance blowup by IBS
Commissioning Timeline

2014

Mar | Aug
---|---
Linac RF Conditioning | Linac Beam Commissioning

2015

May | Jul
---|---
3 GeV Transfer Line Commissioning

2016

Feb | Mar | Jul | Sep | Nov | Jan | Feb | Mar
---|---|---|---|---|---|---|---
3 GeV TL Installation | First 2 IVUs Installed | 1.5 GeV TL Commissioned | IVW/EPUs & 1.5 GeV TL Installed | 1.5 GeV IDs

2017

Aug | Feb | Mar | Jul | Sep | Nov | Jan | Feb | Mar
---|---|---|---|---|---|---|---|---
3 GeV Storage Ring Commissioning | IVU Commissioned | IVW & EPU Commissioned

Facility Inauguration | First Friendly Users
1st Open User Call
1.5 GeV SR Comm.
3 GeV Storage Ring Commissioning

• At LER 2015 in Grenoble had just reported first turns...

First full turn
• without exciting a single corrector
• all magnets at nominal optics for 3.0 GeV
  (excitations according to magnetic measurement data)
• using a single dipole kicker for injection

NIM-A 693, 117, 2012
3 GeV Storage Ring Commissioning (cont.)

• At LER 2015 in Grenoble had just reported first turns...
• First stored beam on Sep 15 → ≈0.1 mA (≈170 pC from linac)
3 GeV Storage Ring Commissioning (cont.)

• At LER 2015 in Grenoble had just reported first turns...
• First stored beam on Sep 15 → \( \approx 0.1 \text{ mA} \) \( (\approx 170 \text{ pC from linac}) \)
• First stacking observed Oct 8 (@ reduced dipole kicker strength)

\[ NIM-A 693, 117, 2012 \]
3 GeV Storage Ring Commissioning (cont.)

- At LER 2015 in Grenoble had just reported first turns...
- First stored beam on Sep 15 $\rightarrow \approx 0.1$ mA ($\approx 170$ pC from linac)
- First stacking observed Oct 8 (@ reduced dipole kicker strength)
- Phasing 2 ring cavities $\rightarrow$ maximize $f_s$ and improve inj. rate

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**Spectrum Analyzer**

- BPM sum signal when kicker on $f_s = 536$ Hz
- 479 kV $\rightarrow$ expect 540 Hz

**Phase Cav 16**

- Max $f_s = 730$ Hz

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Courtesy D. Olsson

NIM-A 693, 117, 2012
3 GeV Storage Ring Commissioning (cont.)

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- First stored beam on Sep 15 ≈0.1 mA (≈170 pC from linac)
- First stacking observed Oct 8 (@ reduced dipole kicker strength)
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---

Y1

- Y1 - r3-319s2/dia/dcct-01/current
- Y2 - I-TR3/DIA/CT-01/AverageCharge

Transfer Line CT

Storage Ring DCCT

1.25 nC (incl. 0.45 nC offset) @ 0.5 Hz → 13.6 mA/min

19 mA in 4 min → 4.75 mA/min → 35% injection efficiency

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3 GeV Storage Ring Commissioning (cont.)

• First linear optics studies & corrections

![Diagram showing vertical and horizontal integer tune confirmation](attachment:image.png)

Vertical integer tune confirmed 16

Horizontal integer tune confirmed 42

Courtesy M. Sjöström
3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections

**Early LOCO data, before correction**

**After LOCO corrections (quad PSs only)**
• First linear optics studies & corrections

- Early LOCO data, before corrections
- After LOCO corrections (quad PSs only)

- Dispersion improved after first LOCO attempts & fixing sextupole misalignment

- $25\% \rightarrow 14\%$ max $\eta_x$ beating
- $\pm 20 \rightarrow \pm 12$ mm max $\eta_y$
3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections

**Dispersion improvement**

Early LOCO data, before corrections

AFTER LOCO corrections (quad PSs only)

\[ \eta_x \leq 14\% \]

\[ \eta_y \leq \pm 20\% \]

\[ \eta_x \leq 5\% \]

\[ \eta_y \leq \pm 9\% \]

No skew correction yet
• First linear optics studies & corrections
• BPM offsets relative to adjacent sextupole/octupole via auxiliary coil powered as upright quadrupole

H: 111 μm rms
V: 107 μm rms
3 GeV Storage Ring Commissioning (cont.)

- First linear optics studies & corrections
- BPM offsets relative to adjacent sextupole/octupole via auxiliary coil powered as upright quadrupole
  - downloaded to our 200 Libera Brilliance+ units
  - above 3 mA orbit must be within ±1 mm in both planes
  - if 5 BPMs show bad orbit (or any BPM in an ID straight) MPS dumps beam
3 GeV Storage Ring Commissioning (cont.)

• Orbit correction to <1 μm rms in H; larger in V (since $N_{BPM} > N_{VCM}$)
→ apply weighting so orbit always locked down in ID straights
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
  - after adjusting towards design tunes (0.20/0.28)
  - using only 2 chromatic sextupole families
  - limited $\Delta p/p$ range → $\xi^{(2)}$?

$$\xi_x = +1.0$$
$$\xi_y = +3.7$$
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
  - after adjusting towards design tunes (0.20/0.28)
  - using only 3 chromatic sextupole families

\[
\begin{align*}
\xi_x^{(1)} &= +1.0 \\
\xi_x^{(2)} &= -48 (-29) \\
\xi_y^{(1)} &= +1.0 \\
\xi_y^{(2)} &= +8 (+9)
\end{align*}
\]
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

Photo courtesy Å. Andersson.
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

Photo courtesy Å. Andersson

1.5° MC dipole → very weak $n_x$

Courtesy J. Breunlin
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simulation is done for $\varepsilon_x = 320$ pm rad, $\beta_x = 1.5$ m. Both figures show a $2 \times 2$ mm$^2$ area of the image plane. The fringe pattern is too weak to be visible.

Optical magnification of $m=-2.28$ is taken into account in the SRW model
- Horizontal opening angle: 6 mrad
- Vertical opening angle: 8 mrad
- Exposure time: 2.9 ms

Courtesy J. Breunlin
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2

![SRW simulation and Measurement](image)

**Sigma polarized SR, 632.8 nm, SRW calculation (left) and measured image (right). The simulation is done for $\varepsilon_x = 320 \text{ pm rad, } \beta_x = 1.5 \text{ m}$. Both figures show a 2 x 2 mm^2 area of the image plane. The fringe pattern is too weak to be visible.**

*Optical magnification of $m = 2.28$ is taken into account in the SRW model.*

**Total**

- Horizontal opening angle: 6 mrad
- Vertical opening angle: 8 mrad
- Exposure time: 2.9 ms

**Figure 3:** Vertical profile of imaged $\pi$-polarized SR at 488 nm wavelength. Measurement (blue dots) and SRW calculation (red lines). The vertical beam size is 11.5 $\mu$m.

<table>
<thead>
<tr>
<th>Height [mm]</th>
<th>$\sigma_y$ [µm]</th>
<th>$\varepsilon_y$ [µm rad]</th>
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<td>11.5 ± 0.23</td>
<td>6.4 ± 0.9</td>
</tr>
<tr>
<td>5</td>
<td>11.2 ± 0.23</td>
<td>6.2 ± 0.9</td>
</tr>
<tr>
<td>9</td>
<td>11.3 ± 0.21</td>
<td>10.6 ± 0.15</td>
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<tr>
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<tr>
<td>16</td>
<td>11.3 ± 0.21</td>
<td>10.6 ± 0.15</td>
</tr>
</tbody>
</table>

Courtesy J. Breunlin
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
  - installing 2\textsuperscript{nd} diagnostic BL in 2017 (on 3° dipole) $\rightarrow \sigma_\delta$
3 GeV Storage Ring Commissioning (cont.)

• First attempts at measuring/adjusting linear chromaticity
• First light seen on diagnostic beamline Nov 2
  – installing 2\textsuperscript{nd} diagnostic BL in 2017 (on 3° dipole) \( \rightarrow \sigma_\delta \)
• Top-up running since Nov (closed shutters)
  – injector & linac switch between SPF operation and ring injection
    • on-the-fly switching of guns, linac optics, and linac extraction dipoles
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
  - installing 2\textsuperscript{nd} diagnostic
- Top-up running since Nov
  - injector & linac switch
- on-the-fly switching of RH
- injector & linac switch
- MC
  - injector & linac switch

**Figure 5: statemachinegui**

- Range of buckets over which to inject
  - 176
- Step between injections/10 ns
  - 1
- Number of injections per step
  - 1
- Injection kicker voltage/V
  - 5500

- 3-GeV Ring
- Top-up
- Check inj. rate
- Fixed top-up interval/min
- Enable scheduled interval
  - 5 min
- Maximum current/mA
  - 199
- Minimum current/mA
  - 198

- Continue previous
- Stop top-up
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline November 2nd
  - Installing 2nd diagnostics BL in 2017 (on 3° dipole)
- Top-up running since November (closed shutters)
  - Injector & linac switch between SPF operation and ring injection
  - On-the-fly switching of guns, linac optics, and linac extraction dipoles
- Kicker ' & ' septum
- Extrac10n ' & ' GeV
- BC1 ' @ ' 260 MeV
- SPF ' & ' BC2 ' @ ' 3 GeV

- Storage Ring DCCT
  - Transfer Line CT
  - Linac modulator K02 tripped
  - Top-up shots from linac
  - Top-up @ 160 mA over night
  - Decaying beam
  - Injection kicker left on
  - Thunderstorm
  - Machine studies
3 GeV Storage Ring Commissioning (cont.)

• First attempts at measuring/adjusting linear chromaticity
• First light seen on diagnostic beamline Nov 2
  – installing 2\textsuperscript{nd} diagnostic BL in 2017 (on 3° dipole) $\rightarrow \sigma_\delta$
• Top-up running since Nov (closed shutters)
  – injector & linac switch between SPF operation and ring injection
    • on-the-fly switching of guns, linac optics, and linac extraction dipoles
  – injector & linac routinely running at 2 Hz since Nov
  – injection efficiency improved (ring phase acceptance!)
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostics beamline Nov 2 – installing 2nd diagnostics BL in 2017 (on 3° dipole)
- Top-up running since Nov (closed shutters)
- Injector & linac smoothly running at 2 Hz since Nov
- Injection efficiency improved (ring phase acceptance!)

**Graph:**

- Y1: r3-319s2/dia/dcct-01/current
- Y2: I-TR3/DIA/CT-01/AverageCharge

- **Transfer Line CT:**
  - 283 pC (incl. 38 pC offset) @ 2 Hz → 16.7 mA/min

- **Storage Ring DCCT:**
  - 80 mA in 5 min → 16 mA/min → ≈96% injection efficiency
3 GeV Storage Ring Commissioning (cont.)

• First attempts at measuring/adjusting linear chromaticity
• First light seen on diagnostic beamline Nov 2
  – installing 2\textsuperscript{nd} diagnostic BL in 2017 (on 3° dipole) \to \sigma_\delta
• Top-up running since Nov (closed shutters)
  – injector & linac switch between SPF operation and ring injection
    • on-the-fly switching of guns, linac optics, and linac extraction dipoles
  – injector & linac routinely running at 2 Hz since Nov
  – injection efficiency improved (ring phase acceptance!)
  – integrated dose increasing \to improving ring vacuum
• First attempts at measuring/adjusting linear chromaticity

• First light seen on diagnostic beamline Nov 2 – installing 2nd diagnostic BL in 2017 (on 3° dipole)

Top-up running since Nov (closed shu1ers)

– injector & linac switch between SPF operation and ring injection
– on-the-fly switching of guns, linac sections, and linac extrac1on dipoles
– injector & linac routinely running at 2 Hz since Nov
– injection efficiency improved (ring phase acceptance!)
– integrated dose increasing ➔ improving ring vacuum

\[ \sigma \delta \]

Kicker ' & ' septum ' Extrac1on ' 3 'GeV' BC1 ' @ ' 260 'MeV'

BC2 ' @ ' 3 'GeV'

L2A$ L2B$ L3A$ L9B$ L19B$ L1B$ L0$ Thermionic ' RF' gun

Photocathode RF gun

\[ \approx 35 \text{ Ah/month} \]

Xmas SD February SD

Normalised average pressure vs beam dose

\[ S2 \text{ (gauges, no RF)} \]

\[ Y = (1.64 \times 10^{-10}) \times x^{(-0.75)} \]

June 26, 2016

IVUs & striplines installed

Courtesy P.F. Tavares

Courtesy M. Grabski

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3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline
  - installing 2nd diagnostic BL in 2017 (on 3° dipole)
- Top-up running since Nov
  - injector & linac switched between SPF operation and ring injection
- On-the-fly switching of guns, linac optics, and linac extraction dipoles
- Injector & linac routinely running at 2 Hz since Nov
- Injection efficiency improved
- Integrated dose increasing → improving ring vacuum
  → improving beam lifetime (along with effect of bunch lengthening from passive harmonic cavities)
3 GeV Storage Ring Commissioning (cont.)

- First attempts at measuring/adjusting linear chromaticity
- First light seen on diagnostic beamline Nov 2
- Installing 2nd diagnostic BL in 2017 (on 3° dipole)
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- Injector & linac smoothly running at 2 Hz since Nov
- Injection efficiency improved
- Integrated dose increasing → improving ring vacuum
  ➔ improving beam lifetime (along with effect of bunch lengthening from passive harmonic cavities)

Storage Ring DCCT

Top-up @ 160 mA over 30 hours

14 h lifetime → 2.2 Ah integrated lifetime
3 GeV Storage Ring Commissioning (cont.)

- Orbit drifts observed during top-up operation
  - 70 μm / 20 μm observed over 8 hours
  - unphysical BPM spikes observed → implications for bad orbit trip (MPS)

![Graph showing orbit drifts](image)

Storage Ring DCCT

Top-up @ 50 mA over night

BPM x

≈70 μm in H

8 hrs

BPM y

≈20 μm in V

8 hrs

Courtesy P.F. Tavares
3 GeV Storage Ring Commissioning (cont.)

• Orbit drifts observed during top-up operation
  – 70 μm / 20 μm observed over 8 hours
  – unphysical BPM spikes observed → implications for bad orbit trip (MPS)

• SOFB now routinely running at ≈0.5 Hz (target: 10 Hz)
  – sub-micron stability in H, but larger in V (N_{BPM} > N_{VCM})
  – weighting → in ID straights still locked down to 200-400 nm
3 GeV Storage Ring Commissioning (cont.)

- Orbit distortions observed during top-up operation – 70 μm/20 μm observed over 8 hours
- Unphysical BPM spikes observed → implications for bad orbit trip (MPS)

- SOFB now reliably running at ≈0.5 Hz (target: 10 Hz)
- Sub-micron stability in H, but larger in V (NBPM > NVCM)
- Weighting → in ID straights: Ell locked down to 200-400 nm
- Frequency correction not yet incl. in SOFB loop (currently adjusted by operator)
- During ID/FE/BL shifts, use SOFB to create variable local bumps in BPMs in ID straights

Decaying beam
Top-up injections
Injection
Beam loss

BPMs in ID straights

4 hrs with SOFB

200 μm

Courtesy M. Sjöström
3 GeV Storage Ring Commissioning (cont.)

- Orbit disruptions observed during top-up operation – 70 μm/20 μm observed over 8 hours
  ➔ implications for bad orbit trip (MPS)
- SOFB now reliably running at ≈0.5 Hz (target: 10 Hz)
  – sub-micron stability in H, but larger in V (N BPM > N VCM)
  ➔ in ID straights, locked down to 200-400 nm
  – frequency correction not yet incl. in SOFB loop (currently adjusted by operator)
  – during ID/FE/BL shifts use SOFB to create variable local bumps

BPMs in ID straights

4 hrs with SOFB

± 1 μm

Decaying beam

Top-up injections

Beam loss

Injection

200 μm
3 GeV Storage Ring Commissioning (cont.)

- Attempted first scraper measurements
  - mean pressure seen by beam: \( P[10^{-9}\text{ Torr}] = 0.0178 \times I[\text{mA}] + 0.6088 \)
  - lifetimes

At 50 mA & \( f_s = 900 \text{ Hz} \):
- \( P = 2.1e-9 \text{ mbar} \)
- \( \delta_{rf} = 4.2\% \)
  - \( \tau_{el} = 111 \text{ h} \)
  - \( \tau_{bs} = 68 \text{ h} \)
  - \( \tau_{ts} = 18 \text{ h} \)
3 GeV Storage Ring Commissioning (cont.)

- Attempted first scraper measurements
  - mean pressure seen by beam: \( P[10^{-9} \text{ Torr}] = 0.0178 \times I[\text{mA}] + 0.6088 \)
  - lifetimes & ring acceptance (in conjunction with local beta measurements)

![Graph showing mean lifetime vs. scraper position](image)

\( \beta_y = 4.7 \text{ m @ V scraper} \Rightarrow A_y = 2.17 \text{ mm mrad} \)

![Diagram showing acceptance at V scraper](image)

\( A_y = 2.17 \text{ mm mrad} \Rightarrow a_y = 2.1 \text{ mm @ ID straight} \)
3 GeV Storage Ring Commissioning (cont.)

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  - mean pressure seen by beam: \( P[10^{-9} \text{ Torr}] = 0.0178 \times I[\text{mA}] + 0.6088 \)
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\[ \beta_y = 4.7 \text{ m @ V scraper} \Rightarrow A_y = 2.17 \text{ mm mrad} \]
\[ A_y = 2.17 \text{ mm mrad} \Rightarrow a_y = 2.1 \text{ mm @ ID straight} \]

\[ 4.9 \text{ mm @ H scraper} \Rightarrow A_x = 2.5 \text{ mm mrad} \Rightarrow a_x = 4.8 \text{ mm @ ID straight} \]
3 GeV Storage Ring Commissioning (cont.)

• First two IVUs installed during Feb 2016 shutdown
  – Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
3 GeV Storage Ring Commissioning (cont.)

• First two IVUs installed during Feb 2016 shutdown
  – Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
  – for BioMAX and NanoMAX beamlines

NanoMAX floor plan

Courtesy U. Johansson

Courtesy U. Johansson
3 GeV Storage Ring Commissioning (cont.)

- First two IVUs installed during Feb 2016 shutdown
  - Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
  - for BioMAX and NanoMAX beamlines
- ID, FE & BL commissioning started Apr 2016

**NanoMAX commissioning**
- 22 April – front end dipole light
- 27 April – OH screen 1 dipole light
- 11 May – OH screen 1 undulator light

**BioMAX X-ray commissioning**
- 29 April – first undulator light in the front-end and optics hutch
- 11 May – first monochromatic light
- 18 May – first light in the experiment hutch

*Courtesy U. Johansson*
3 GeV Storage Ring Commissioning (cont.)

• First two IVUs installed during Feb 2016 shutdown
  – Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
  – for BioMAX and NanoMAX beamlines

• ID, FE & BL commissioning started Apr 2016

• May 11: 10 mm gaps on both BLs (FB loop for ID correctors closed)

• May 11-19: first monochromatic beams (on detector / 11 keV)
3 GeV Storage Ring Commissioning (cont.)

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  – Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
  – for BioMAX and NanoMAX beamlines

• ID, FE & BL commissioning started Apr 2016

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  – FB loop for ID correctors closed

• May 11-19: first monochromator beams

Courtesy T. Ursby
3 GeV Storage Ring Commissioning (cont.)

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  - Hitachi, 18 mm period, 4.2 mm magnetic gap, 2 m length, 1.3 T peak field
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- June 8/9: First diffraction patterns
3 GeV Storage Ring Commissioning (cont.)

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- June 20: First nano-focus @ NanoMAX
3 GeV Storage Ring Commissioning (cont.)

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• June 8/9: First diffraction patterns

• June 20: First nano-focus @ NanoMAX
  → just in time for inauguration on June 21

• June 30: closed to 4.5 mm gap
MAX IV Inauguration

• Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

While the rest of Sweden was celebrating Midsummer like this...
MAX IV Inauguration (cont.)

• Brightest time of the year: June 21, 2016 @ 13:08:55 (local noon)

...we inaugurated our new facility.

• After inauguration, 3 weeks left until summer shutdown
AerinauguraEon, 3 weeks remained unEl shutdown

ConEnued to increase current, but so far limited by cooling water issues (Cu residue appears to be clogging flow meters) ➔ control pH levels ➔ hot spots & chamber misalignments (mainly downstream of crotch chambers) ➔ use orbit bumps to diagnose, then realign

RF conditioning (5 of 6 cavities operational, ≈40 of 60 kW power reached in 5 cavities; planned for operation with IDs, β = 2 ➔ add 60 kW per RF station)

3 GeV Storage Ring Commissioning (cont.)

198 mA present stored current record

MPS dumps beam @ ≈200 mA

195 mA in 21 min → 9.3 mA/min → 80% inj. efficiency

170 pC @ 2 Hz → 11.6 mA/min
Finally, need to also focus on stability & collective effects

- 3 passive Landau cavities ($R_s \approx 2.5 \text{ M}\Omega$) allow for tuning to flat-potential conditions already @ 150 mA
Finally, need to also focus on stability & collective effects

– 3 passive Landau cavities \( R_s \approx 2.5 \, \text{M} \Omega \) allow for tuning to flat-potential conditions already @ 150 mA
– Achieved >2 Ah under stable conditions (top-up running & BbB FB loop closed)

\[ \tau \approx 2.3 \, \text{Ah} \]
\[ \tau \approx 0.7 \, \text{Ah} \]
3 GeV Storage Ring Commissioning (cont.)

- During recent summer shutdown installed three new IDs

**EPU48 → VERITAS** (RIXS)
**EPU53 → HIPPIE** (AP-XPS, AP-XAS)
3.9 m magnetic length, 69/77 periods,
11 mm min. magnetic gap, ≈1.1 T peak field
Manufactured at MAX IV

**In-vac Wiggler → BALDER** (XAS, XES)
2.0 m magnetic length, 50 mm period,
4.2 mm min. magnetic gap, ≈2.4 T peak field
Manufactured by SOLEIL
Outlook

• Continue commissioning of 3 GeV storage ring
  – optics & IDs
  – diagnostic beamline, longitudinal bunch profile
  – RF conditioning main cavities and LCs (high current)
  – collective effects & BbB feedback commissioning
  – integrate fast corrector PSs & LB+ units → commission FOFB
• Just started commissioning of 1.5 GeV storage ring
  – first IDs to be installed in 1.5 GeV SR during early 2017
• “Friendly users” arrive Nov 2016 & first open user call for Mar 2017
• What remains to be installed during 2017
  – 2nd diagnostic BL on 3 GeV SR
  – 2 additional linac stations (2 stations with 4 structures each → 4 stations with 2 structures each)
  – 3 IDs in 3 GeV SR (2 IVUs, 1 EPU) & 3 IDs in 1.5 GeV SR (2 new EPUs, 1 EPU from MAX II)
Acknowledgements

• Thanks to all who contributed to MAX IV commissioning:
  – MAX IV Operators
  – Technical support at MAX IV
  – Machine Division staff, graduate students, and guests:
    Mikael Eriksson, Sara Thorin, Erik Mansten, Dionis Kumbaro, David Olsson, Sverker Werin, Francesca Curbis, Olivia Karlberg, Joel Andersson, Filip Lindau, Robert Lindvall, Lennart Isaksson, Pedro F. Tavares, Magnus Sjöström, Galina Skripka, Martin Johansson, Eshraq Al-dmour, Åke Andersson, Dieter Einfeld, Les Dallin, Francis Cullinan, Ryutaro Nagaoka, Oleg Chubar
  – Our colleagues at SOLARIS and many other labs
Thanks for your attention!
Backup: The MBA – A Virtuous Circle

The Multibend Achromat Cycle
(courtesy A. Streun, PSI)

Many Short Cells
for a given circumference

Short Magnets

Strong Gradients

Small Magnet Gaps

Small Bend Angle

Low Dispersion

Limited Aperture Required
for decent MA and Touschek lifetime

Low Power/Cost

Low Emittance
Backup: Optics Tuning & Corrections

• **Gradient dipoles** equipped with pole-face strips → adjust vertical focusing within ±4% (requires dipole feedback)

[Photos courtesy M. Johansson and A. Nyberg]
Backup: Optics Tuning & Corrections (cont.)

- **Gradient dipoles** equipped with pole-face strips → adjust vertical focusing within ±4% (requires dipole feedback)

- **Quadrupole doublets** in long straights → match optics to IDs and restore tunes (ideally makes IDs transparent to arc optics)

![Diagram showing alignment of QDend, QFend, and ID elements along the x-y plane.]

Simon C. Leemann
6th Low Emittance Rings Workshop, SOLEIL, October 26–28, 2016

PAC’11, TUP235, p.1262
IPAC’15, TUPJE038
• All sextupoles and octupoles carry auxiliary winding

• Can be powered as: (remotely switchable)
  • auxiliary sextupole → nonlinear corrections
  • skew quadrupole → coupling & dispersion control
  • upright quad → calibrate BPMs to adjacent sext/oct
  • dipole correctors, in addition to...
• All sextupoles and octupoles carry auxiliary winding

• Can be powered as: (remotely switchable)
  • auxiliary sextupole → nonlinear corrections
  • skew quadrupole → coupling & dispersion control
  • upright quad → calibrate BPMs to adjacent sext/oct
  • dipole correctors, in addition to...

• Dedicated dipole correctors → SOFB & FOFB
• These modern rings are really a different beast
  – MBA lattices employ very weak dipoles
  – installed DWs and/or IDs can have huge impact on rad. power
  – emittance & energy spread determined by IDs & gap settings

MAX IV 3 GeV SR:
Bare: 364 keV/turn
Loaded: ≈1 MeV/turn

\[ U_0 \propto \gamma^4 I_2 \]
\[ \varepsilon_0 \propto \gamma^2 \frac{I_5}{I_2 - I_4} \]
\[ I_2 = \int \frac{ds}{\rho^2} \]
\[ I_5 = \int \frac{\mathcal{H}}{[\rho^3]} ds \]
\[ I_4 = \int \frac{\eta}{\rho} \left( 2k + \frac{1}{\rho^2} \right) ds \]

IVU: 3.7 m, \( \lambda_u = 18.5 \text{ mm} \), \( B_{\text{eff}} = 1.1 \text{ T} \)
Backup: First Upgrade Ideas

• Improved matching to IDs (coupling, optics in straights)
  – Transverse coherence and brightness at 1 Å almost doubled by setting $\varepsilon_y = 8 \rightarrow 2$ pm rad
    \[ \tau_{ts} \propto \sqrt{\varepsilon_y} \propto \sqrt{\kappa} \]
  – Good Touschek lifetime maintained by exciting vertical dispersion bumps in all arcs (transparent in ID straights)

• Increase focusing in arc $\rightarrow \varepsilon_x$ reduced to 269 pm rad (-18%) while retaining satisfactory DA & lifetime

• First GLASS/MOGA studies assuming PSs can be exchanged $\rightarrow 221$ pm rad

• Assuming on-axis inj. $\rightarrow \approx 170$ pm rad or $\approx 150$ pm rad (w/ IDs and IBS @ 500 mA)