Status of the MAX IV Accelerators

IPAC 2019

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on behalf of the MAX IV team
Outline

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- The MAX IV Accelerators
- MAX IV Injector LINAC Highlights
- MAX IV 1.5 GeV Ring Highlights
- The MAX IV 3 GeV ring
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MAX IV: The Swedish National Synchrotron Radiation Facility

MAX IV Laboratory: Inaugurated June 2016

Max-lab: 1986 - 2015
Conceptual Basis of the MAX IV Design

- Scientific Case calls for high brightness radiation over a wide spectral and time structure range: IR to Hard R-rays, Short X-Ray Pulses.

- Need for high brightness: low emittance and optimized insertion devices.

- This is hard to achieve in a single machine
  - higher electron beam energy favours harder photons
  - lower electron beam energy favours softer photons
  - Hard to produce short pulses in storage rings

One size does not fit all!
The MAX IV Approach

• Different machines for different uses:
  • A high energy ring with ultralow emittance for hard X-ray users.
  • A low emittance low energy ring for soft radiation users
  • A LINAC based source for generating short pulses and allowing for future development of an FEL source.

All sharing common infrastructure and technical solutions
The MAX IV Accelerators

- **3 GeV ring**
  - 528 m circ, MBA, 330 pmrad

- **1.5 GeV Ring**
  - 96 m circ., DBA, 6 nmrad

- **Linear accelerator**
  - (ca 250 m)

- **Short Pulse Facility**

- **Electron sources**
LINAC Highlights: Short bunches

On May 23rd 2018 we measured below 100 fs fwhm for the first time. Lowest measurement was 45 fs FWHM, and 28 fs RMS.

We could compress more, but didn’t have resolution to measure anything shorter.

Slide by Sara Thorin
Transverse Deflecting Cavity Setup

- S-band
- Solid State Modulator and SLED
- >100 MV integrated field
- 1 fs resolution → long setup, large beta
- Switchable polarization (phase II)

Electric field in the TM_{110} mode
Highlights 1.5 GeV Ring

Design Current - 500 mA

![Plot by Francis Cullinan](image)

TRIBS
Thanks to Paul Goslawski and the BESSY team

Picture by D.K.Olsson

Single Bunch

Plot by Francis Cullinan

Global Tune Feedback

![Global Tune Feedback](image)
MAX IV 3 GeV ring: 528 m, 330 pmrad

7BA, 20 periods

100 MHz RF Passive HC

Circular, copper NEG-coated chambers

Compact Magnets
3 GeV Ring – achieved performance

● 500 mA stored current in multibunch mode demonstrated during accelerator studies
  – Regular delivery to beamlines at ~ 250 mA (RF power limitations)
● ~ 9 mA stored current in single-bunch mode.
● ~ 20 A.h lifetime current product from gas scattering
● ≥ 90% injection efficiency
● Emittances: $\varepsilon_x = 320 \pm 18$ pm rad; $\varepsilon_y = 6.5 \pm 1$ pm rad
● RMS orbit stability (up to 5 kHz) better than 2.0/5.0 % of beam size (H/V).
● Beta beats < ± 2 %, Residual Vertical Dispersion < 0. 6 mm RMS
3 GeV Ring Commissioning & Operations Timeline

- **Aug 2015**: Stored beam
- **Dec 2015**: First turn
- **Apr 2016**: First light
- **Nov 2015**: Top-up
- **Jan 2016**: 90 mA
- **Jun 2016**: 2 IVUs
- **Sep 2016**: 175 mA
- **Dec 2016**: 200 mA
- **Aug 2017**: Expert Users
- **Dec 2017**: Start of Regular User Operations
- **Aug 2018**: Multipole Injection Kicker
- **Nov 2018**: Long. Kicker Cavity
- **Apr 2019**: Top-up (open shutters)
- **Aug 2019**: Start of Beamline Commissioning
- **Dec 2019**: 500 mA
- **Aug 2020**: 400 mA
- **Aug 2021**: 369 mA
- **Apr 2022**: 300 mA
- **Dec 2022**: 369 mA
- **Aug 2023**: 500 mA
- **Dec 2023**: 400 mA
- **Aug 2024**: 369 mA
- **Apr 2025**: 300 mA
- **Dec 2025**: 369 mA
- **Aug 2026**: 500 mA
- **Dec 2026**: 400 mA
- **Aug 2027**: 369 mA
- **Apr 2028**: 300 mA
- **Dec 2028**: 369 mA
- **Aug 2029**: 500 mA
- **Dec 2029**: 400 mA
- **Aug 2030**: 369 mA
- **Apr 2031**: 300 mA
- **Dec 2031**: 369 mA
- **Aug 2032**: 500 mA
- **Dec 2032**: 400 mA
- **Aug 2033**: 369 mA
- **Apr 2034**: 300 mA
- **Dec 2034**: 369 mA
- **Aug 2035**: 500 mA
- **Dec 2035**: 400 mA
- **Aug 2036**: 369 mA
- **Apr 2037**: 300 mA
- **Dec 2037**: 369 mA
- **Aug 2038**: 500 mA
- **Dec 2038**: 400 mA
- **Aug 2039**: 369 mA
- **Apr 2040**: 300 mA
- **Dec 2040**: 369 mA
- **Aug 2041**: 500 mA
- **Dec 2041**: 400 mA
- **Aug 2042**: 369 mA
- **Apr 2043**: 300 mA
- **Dec 2043**: 369 mA
- **Aug 2044**: 500 mA
- **Dec 2044**: 400 mA
- **Aug 2045**: 369 mA
- **Apr 2046**: 300 mA
- **Dec 2046**: 369 mA
- **Aug 2047**: 500 mA
- **Dec 2047**: 400 mA
- **Aug 2048**: 369 mA
- **Apr 2049**: 300 mA
- **Dec 2049**: 369 mA
- **Aug 2050**: 500 mA
Beta-beat correction

Beat beats reduced from ± 20/25 % to less than ± 2/1.5 %.

Betatron Functions from LOCO fits
Correction of horizontal dispersion beating

RMs deviation to model reduced from 15 mm to 3.5 mm
Correction of residual vertical dispersion

RMS reduced from 5 mm to 0.6 mm

40 dispersive skews reducing the vertical dispersion. Maximum strength is roughly half of the available.
Correction of betatron coupling

40 non-dispersive skews reducing the coupling. Maximum strength is roughly half of the available.

Slide by Å. Andersson
Non-linear Lattice Optimization

Thanks to Xiaobiao Huang for providing the RCDS code

RCDS (**Robust Conjugate Direction Search**) applied using all sextupole (5) and octpole families (3) as knobs and beam loss rate while kicking the beam as a proxy for dynamic aperture.

Data by M. Sjöström and D. K. Olsson
Dynamic Aperture Measurements

- Excite oscillations with pulsed magnets and look for amplitudes that lead to beam loss.
- Turn-By-Turn BPM data
Non-Linear Lattice Studies

Sextupole Calibration from second-order dispersion beating

Data and plots by D.K. Olsson

Sextupole Strength determination from off-energy orbit response matrix fits
Orbit Stability – Short Term

Average of 13 long straight flanking BPMs
April 2019, 250 mA beam current

Integrated up to 5 kHz
- Horizontal RMS < 2.0 % of RMS beam size
- Vertical RMS < 5.0 % of RMS beam size
3 GeV Ring Highlights: Multipole Injection Kicker (MIK)

- Objective: achieve near transparent top-up injection.
- Joint project with SOLEIL based on original concept from BESSY.
- First prototype installed in the 2017 shutdown.
- Injection with MIK (up to 500 mA) demonstrated.
- Perturbation to the stored beam reduced by a factor ~60.

Injection with the MIK

![Diagram of MIK setup and injection graph]

Drawings by SOLEIL
P. Lebasque
P. Alexandre
Residual Orbit Perturbations

- Store 10 consecutive bunches
- Scan of stored beam position at the MIK
- Amplitudes measured from Turn-By-Turn libera data stream
- One BPM at $\beta_x = 9.6\ m\ \beta_y = 4.80\ m$
- Amplitudes scaled to centre of long straigt where $\beta_x = 9.0\ m\ \beta_y = 2.0\ m$

Horizontal = $\pm 13\ \mu m$  
Vertical = $\pm 8\ \mu m$
Residual Beam Size Perturbation

Transverse beam profile in a diagnostic beamline during MIK injection

- Multi bunch fill at 150 mA
- Camera Integration time: ~82 turns
- Camera acquisition synchronized with kicks

Poster: TUPGW063
Effective Impedance Measurements

Progress on measurements of longitudinal effective impedance \((Z/n)_{\text{eff}}\)

- Last component to be precisely measured

New energy-spread measurement to remove effect of IBS

- Especially significant due to low horizontal emittance
- Increase in of around 20% at 4 mA, agrees with IBS prediction

Systematic uncertainties still large
Long Bunches and ID spectra

Experimental data courtesy Thomas Ursby and Ana Gonzalez

BioMAX undulator @ 15th harmonic
Flux in 10x10 μrad² rect. aperture

- 3.5 mA
- 150 mA, Harmonic Cavity Voltage = 408 kV
- Calculated: $\theta_0 = 328$ pmrad, $\sigma_\phi = 7.7 \times 10^{-4}$
Harmonic Cavities
Suppression of Coupled Bunch Instabilities and Bunch Lengthening

Energy Spread Normalized to Natural Energy Spread

Total Harmonic Cavity Voltage [kV]

l=149 mA
f_0 = 950 Hz

2018/10/20
2018/10/24
Harmonic Cavities: Lifetime and Chamber Heating

Harmonic cavities **OUT**, BbB **ON**

Harmonic cavities **IN**, BbB **OFF**
Vacuum performance

Beam lifetime: the normalized beam lifetime $I \cdot \tau$ [mA h] vs. accumulated beam dose [Ah]

After each shutdown there is increase in the average pressure and reduction in the lifetime, but recovery is relatively fast (18-30 Ah), depends on the shutdown scope.
Vacuum lifetime

Test was done where the effective bunch length was very large (beam longitudinally unstable), the total lifetime is mainly gas lifetime, total lifetime was around 90h ($l \tau_{gas} \approx 20\text{Ah}$).
Neon Venting in the 3 GeV Ring

● A conventional vacuum intervention in R3 takes 2-3 weeks due to the need to reactivate the NEG coating.

● In the 2018 summer shutdown, we tested a new procedure (developed originally at CERN) in which
  – the chambers are vented with ultra-pure neon gas (instead of nitrogen).
  – The time the chamber remains open is minimized by careful planning of the intervention.
  – The chamber is pumped down WITHOUT reactivation (i.e., no baking at ~200 °C)

● This reduces the intervention time to just a few days.

● The big question was: how does the vacuum pressure and beam lifetime recover after such an intervention?
Vacuum conditioning after neon venting intervention.

The average pressure recovered after around 18Ah, highest pressure readings were close to the areas where we have exchanged the vacuum chambers.
Life time after neon venting

3 GeV ring: Normalized lifetime vs accumulated dose
\( I \cdot \tau \) [mA\( \cdot \)h] vs Dose [A\( \cdot \)h]

Closer look
Beam-based BPM calibration and magnet saturation

- At MAX IV, BPM based calibration is done with respect to nearby sextupoles.
- Trim coils are used to generate a quadrupole field on a sextupole yoke.
- Early during commissioning a dependence of the measured offsets on the excitation of the sextupole main coils.
- Magnet saturation was suspected early on, but 2D simulations could not explain the magnitude of the effect.

Calculations and pictures by Alexey Vorozhtsov
Simulation vs Experiments

simulated data by Alexey Vorozhtsov
experimental data by Robin Svärd
2018 3 GeV Ring Operations Summary

- 24/7 Accelerator operations since January 2018.

- 4068 scheduled delivery hours
- 96.2 % availability
- 34.5 h MTBF
- 1.3 h MTTR

Plots and data by Stephen Molloy
Future Perspectives: A soft X-ray free-electron laser @ MAX IV

A working group co-chaired by Anders Nilsson and Stefano Bonetti at Stockholm University.

• A workshop at Stockholm University March 21-23, 2016
• 120+ participants

• Uses the existing 3 GeV MAX IV injector LINAC
• 1-5 nm wavelength range

Funding (~30 MSEK) for a CDR from Stockholm University, Upsalla University, KTH, Lund University, MAX IV and the Wallenberg Foundation (KAW).

CDR to be delivered in Q1 2021
Future Perspectives: A soft X-ray free-electron laser @ MAX IV

- Wavelength: 1-5 nm
- Pulse length: 1-50 fs
- Rep rate: 100 Hz

TUPTSO61: Pre-injector for SXL
TUPRB071: EEHG for SXL
TUPRB072: Undulators for SXL
THPGW052: Photocathode laser diffuser
Conclusions

- MAX IV has successfully demonstrated the first fourth generation storage-ring based ultra-low emittance source that used the Multi-Bend Achromat.
- Next immediate plans at MAX IV: a soft X Ray FEL
- Further brightness improvements are on the way.

Thank you for your attention