Status MAX IV Accelerators
CERN, May 2019

Pedro F. Tavares
on behalf of the MAX IV team
Outline

● MAX IV Laboratory Overview
● Why Synchrotron Radiation? Why High Brightness?
● The MAX IV Accelerators
● The MAX IV 3 GeV Ring
  – Conceptual Design
  – Achieved Performance & Commissioning Timeline
  – Highlights (as time allows...)
● Conclusions and Perspectives
MAX IV: The Swedish National Synchrotron Radiation Facility

MAX IV Laboratory: Inaugurated June 2016

Max-lab: 1986 - 2015
Materials on all length scales
What is Synchrotron Light?

Properties:
- Wide band
- High intensity/Brightness
- Polarization
- Time structure

Picture: https://universe-review.ca/I13-15-pattern.png
NanoMAX: Electrochemistry on Pt, Au, Pd (20-60 nm particles)

In-situ EC experiment performed @ NanoMAX in May 2018
A. Bjorling, J. Solla-Gullon (Alicante), D. Carbone

Particles are unstable in the beam, but good signal is measured even for short counting time (0.1 s). Highest q-range corresponds to ~ 8nm

Compact cell for EC.

Scale = 50 pixels ~ 12 nm
Spectral Brightness

Photon Phase Space

$B(E, \phi, \theta, x, y) = \frac{dN}{dt d\delta d\theta d\phi dx dy}$

Density in photon phase space

In an ideal optical transport system, brightness is conserved – a property of the source. Several derived quantities are often used:

**Central Brightness**

$B_0 = \left. \frac{dN}{dt d\delta d\theta d\phi dx dy} \right|_{x=y=\theta=\alpha=0}$

**Angular density of flux**

$F_0 = \int B d\phi dx dy$

H. Wiedemann, *Part. Acc. Phys., Vol II*
Brightness from a real beam

Convolute the angular distribution of radiation from a single electron with the electron beam transverse spatial and angular distributions

For the n-th harmonic of an undulator of length L

\[
B_{0n} = \frac{F_n}{(2\pi)^2 \sigma_{Tx} \sigma_{Ty} \sigma_{Tx'} \sigma_{Ty'}}
\]

Spectral flux (E, I, B, n)

\[
\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_r^2}
\]

Electron beam

\[
\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}
\]

Effective source size and divergence

\[
\sigma_r \sigma_{r''} = \frac{\lambda}{4\pi}
\]

Diffraction Limit:

\[
\sigma_r \sigma_{r''} = \frac{\lambda}{4\pi}
\]

e-beam emittance

\[
\varepsilon_x = \sigma_x \sigma_{x'}
\]

\[
\sigma_r = \frac{1}{4\pi} \sqrt{\frac{\lambda L}{}}
\]

\[
\sigma_{r'} = \sqrt{\frac{\lambda}{L}}
\]
Lowest emittance $\Rightarrow$ Highest Brightness!

$e = C q \frac{\text{Energy}^2}{(N_{\text{Cells}} N_d)^3}$

MAX IV “Multi-Bend Achromat” ($N_{\text{cells}} = 20$, $N_d = 7$):

- Many small gap dipole magnets: small, machined out of bulk!
- Strong focusing in each cell: quad-, sextu-, octopoles
  $\Rightarrow$ complicated optics & dynamics & modeling
- Vacuum & magnets considered together
The Quest for higher brightness

- 1970’s - 1980’s
- 1990’s - 2014
- MAX IV
- Under Construction/Planned

- ALS-U
- Sirius
- APS-U
- HEPS
- SLS-2
- ELETTRA II
- ESRF-II
- PETRA IV
-Tau-USR
- Spring 8-II
- DIAMOND II
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**

Slide by S.Werin
The MAX IV approach to implementation of the MBA

MBA Lattice
Ultra-low emittance robust, high stability. large momentum aperture

Multi-purpose Strong Magnets
Compact Magnet Design. High precision, High vibration frequencies

Small Magnet Apertures

Large Number of Magnets

Wake-Fields

Narrow vacuum Chambers

Low Vacuum Conductance

High Heat Load Density

100 % NEG Coating

Low RF frequency

IBS

Long Bunches Landau Cavities

Copper Chambers

Full Energy Injector LINAC: Short Pulses

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Full Energy Injector LINAC: Short Pulses

Low Vacuum Conductance

High Heat Load Density

100 % NEG Coating
MAX IV 3 GeV ring: 528 m, 330 pmrad

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; \( \varepsilon_y = 6.5 \pm 0.1 \) pm rad (down to 2 pm rad observed)
- RMS orbit stability (up to 100 Hz) better than 1.3/5.5 % of beam size (H/V).
- Beta beats < ± 2 %, Residual Vertical Dispersion < 0.6 mm RMS
3 GeV Ring Commissioning & Operations Timeline
MAX IV 3 GeV Ring Highlights
Beta-beat correction

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

Betatron Functions from LOCO fits—2017/04/17
Correction of horizontal dispersion beating

Deviation to Theoretical Model

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

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

RMS reduced from 5 mm to 0.6 mm
Correction of betatron coupling

40 non-dispersive skews reducing the coupling. Maximum strength is roughly half of the available.
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
Orbit Stability – Long Term

RMS beam sizes at source points
- Horizontal: 47 µm
- Vertical: 2 µm

Stability goals (RMS)
- Horizontal: < 4.7 µm
- Vertical: < 0.2 µm

Slow Orbit feedback ON
Orbit Stability – Short Term

Integrated up to 100 Hz

- Horizontal RMS < 710 nm ~ 1.3 % of RMS beam size at BPM position
- Vertical RMS < 170 nm ~ 5.5 % of RMS beam size at BPM Position

 Plot By Brian Jensen

R3, Average of All Flanking BPMs, Integrated Electron Beam Vibrations 2017-06-20, 46.7 mA
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 300 mA) demonstrated.
- Perturbation to the stored beam reduced by a factor ~60.

![Image of MIK prototype]

Injections with the MIK

- Injection rate=20 mA/min @ 2 Hz LINAC rep rate

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 straight where $\beta_x = 9.0$ m $\beta_y = 2.0$ m

Horizontal = ±13 $\mu$m  
Vertical = ±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

Horizontal and vertical beam sizes during MIK injection
Measured at diagnostic beamline
Values are scaled to the centre of the long straight
Camera integration time = 140 µs ~ 82 turns
BioMAX undulator @ 15th harmonic
Flux in 10x10 µrad² rect. aperture

- 3.5 mA
- 150 mA, Harmonic Cavity Voltage = 408 kV
- Calculated: $\varepsilon_0 = 328$ pmrad, $\sigma_p = 7.7 \times 10^{-4}$
Harmonic Cavities: Suppression of Coupled Bunch Instabilities and Bunch Lengthening

Energy Spread Normalized to Natural Energy Spread

Total Harmonic Cavity Voltage [kV]

I = 149 mA

\( f_{s0} = 950 \text{ Hz} \)

2018/10/20

2018/10/24
Harmonic Cavities and Lifetime

Harmonic cavities OUT

Harmonic cavities IN
Harmonic cavities and MIK heating

- Thin titanium coating of MIK ceramic chamber heated by image currents

Harmonic cavities OUT

Harmonic cavities IN

BbB ON, HCs out, MZD OFF

BbB OFF, HCs in, MZD ON
Harmonic cavities and Energy Spread

Harmonic cavities OUT

Harmonic cavities IN

Energy Spread Normalized to Low Current Energy Spread

Current [mA]

BbB ON, HCs out, MZD OFF

BbB OFF, HCs in, MZD ON

08/11/2018

08:00 10:00 12:00

1.20 1.15 1.10 1.05 1.00 0.95

Energy Spread Normalized to Low Current Energy Spread

Current

Normalized Energy Spread

08/11/2018

20:00 21:00 22:00 23:00
Neon venting for vacuum interventions

6th DLSR workshop: Oct. 2018. Experience with NEG coated chambers as absorbers and pumps E. Al-Dmour
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·h] vs Dose [A·h]

Closer look
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.
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 (I.tau_{gas} \approx 20Ah).
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
SXL Layout

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1-5 nm</td>
</tr>
<tr>
<td>Photon energy</td>
<td>0.25-1 keV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10-100 fs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>

- Laser rooms
- FemtoMAX beamline
- FemtoMAX undulators
- Bunch Compressor 2
- End of linac (3 GeV)
- "Future klystron gallery"
Conclusions

- MAX IV has successfully demonstrated the first fourth generation storage-ring-based ultralow emittance light source that used the Multi-Bend Achromat. Many more are coming will the next years.
- Further brightness improvements are on the way.
- Next immediate plans at MAX IV: a soft X Ray FEL

Thank You for your Attention!