An Overview of MAX IV Insertion Devices & Magnetic Measurement System

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On behalf of Insertion Devices Team
MAX IV IDs & MagLab

Outlook:

- MAX IV Facility.
- ID Magnet Lab @ MAX IV.
- IDs @ 3 GeV and first commissioning results & Top Up.
- IDs @ 1.5 GeV.
- IDs for future beamlines @ 3 GeV.
- Conceptual studies for SXL FEL Undulators.
- Conclusions
MAX IV Facility
MAX IV Accelerator Complex

- Linear Accelerator
- 1.5 GeV SR
- 3 GeV Storage Ring
- Short Pulse Facility
# List & Status of IDs @ MAX IV

<table>
<thead>
<tr>
<th>Beamline ID</th>
<th>ID Type</th>
<th>$\lambda_u$ [mm]</th>
<th>Length [m]</th>
<th>$K_{eff}$ -value</th>
<th>Magnetic Gap [mm]</th>
<th>ID Status (April 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3 GeV Ring</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BioMAX</td>
<td>IVU</td>
<td>18</td>
<td>2</td>
<td>2</td>
<td>4.2</td>
<td>Commissioned</td>
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<tr>
<td>NanoMAX</td>
<td>IVU</td>
<td>18</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Hippie</td>
<td>EPU</td>
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<td>3.3</td>
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<td>Veritas</td>
<td>EPU</td>
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<td>3.9</td>
<td>3.3</td>
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<tr>
<td>Balder</td>
<td>IV Wiggler</td>
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<td>CoSAXS</td>
<td>IVU</td>
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<td>2.2</td>
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<tr>
<td>DanMAX</td>
<td>IVU</td>
<td>16</td>
<td>3</td>
<td>1.66</td>
<td>4</td>
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<tr>
<td>SoftiMAX</td>
<td>Q-EPU</td>
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<td>3.3</td>
<td>11</td>
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<td><strong>1.5 GeV Ring</strong></td>
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<td>ARPES</td>
<td>Q-EPU</td>
<td>84</td>
<td>2.6</td>
<td>8.65</td>
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<tr>
<td>FinEstBeam</td>
<td>EPU</td>
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<td>2.6</td>
<td>10.4</td>
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<td>SPECIES</td>
<td>EPU</td>
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<td>MAXPEEM</td>
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<td>FlexPES</td>
<td>PU</td>
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<td>2.6</td>
<td>4.2</td>
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<td><strong>SPF 3 GeV Linac</strong></td>
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<tr>
<td>FemtoMAX</td>
<td>IVU</td>
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<td>5x2</td>
<td>2.2</td>
<td>2.2</td>
<td>Installation by Q4 2017</td>
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</tbody>
</table>

*) Built by collaboration with SOLEIL synchrotron  
*) Built by industry  
*) To be built in-house (Hippie, Veritas & FinEstBeam are finished)  
*) Transfer from MAX-II ring (characterized at MAX IV ID magnet lab)
ID Magnet Lab @ MAX IV

- In-house design, assembly and characterization of undulators is key to meet tight requirements of MAX IV accelerators.
  - Magnet lab infrastructure in 2016.
  - Six EPUs to be built in-house for Soft X-ray BL at the 3 GeV & 1.5 GeV rings.
  - Two undulators from MAX II ring characterization.

  - The bench covers 5.5 m magnetic length.

- Commissioning of the flip coil finished Nov. 2016.
  - ID field integrals measurements & magnet block characterization.

- Lab infrastructure for IO and motion tests to minimize tunnel access during installation.
- Building new wire system dedicated for magnet blocks characterization.
  - Develop pulsed wire system (small gap ID)

Veritas EPU in front of bench  Wire system set-up
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Develop pulsed wire system (small gap ID)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
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<tbody>
<tr>
<td>X, Y max motion speed</td>
<td>200</td>
<td>mm/s</td>
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<tr>
<td>X, Y motion range</td>
<td>300</td>
<td>mm</td>
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<tr>
<td>Coil length</td>
<td>4</td>
<td>m</td>
<td>Can be more, but not tested yet.</td>
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<tr>
<td>Coil width (nominal)</td>
<td>5</td>
<td>mm</td>
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<tr>
<td>Coil number of turns</td>
<td>20</td>
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<tr>
<td>Wire diameter</td>
<td>64</td>
<td>µm</td>
<td>Insulated CuBe</td>
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<td>Field Integral Error, Translate mode</td>
<td>Pk-Pk: 1.5</td>
<td>G.cm</td>
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<tr>
<td></td>
<td>RMS: 1.0</td>
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<tr>
<td>Field Integral Error, Rotate mode:</td>
<td>Pk-Pk: 4.0</td>
<td>G.cm</td>
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<tr>
<td></td>
<td>RMS 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Field Integral Error, Translate mode</td>
<td>Pk-Pk: 500</td>
<td>G.cm²</td>
<td></td>
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<tr>
<td></td>
<td>RMS: 300</td>
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<tr>
<td>2nd Field Integral Error, Rotate mode</td>
<td>Pk-Pk: 600</td>
<td>G.cm²</td>
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<tr>
<td></td>
<td>RMS: 300</td>
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<tr>
<td>Measurement time*, Translate mode</td>
<td>1:15</td>
<td>minutes</td>
<td>-50 to 50 mm, step of 0.5mm</td>
</tr>
<tr>
<td>Measurement time*, Rotate mode</td>
<td>5:00</td>
<td>minutes</td>
<td>-10:10 mm, step of 1mm</td>
</tr>
</tbody>
</table>

Wire system set-up
EPUs Production & Characterization@ MAX IV

- EPUs built in MAX IV based on the concept of cast iron frame and flexible joints developed at BESSY\(^1\) with modifications (girder with higher force, junction points, gap movement, etc.)
- The use of glued magnets blocks developed at MAX IV\(^2\) and wedges\(^3\) for magnet-holder XY shimming.

Individual Magnet Pairs Measurements

Assembly using extra long stone

Sorting

1) J. Bahrdt, et.al. Proceedings of EPAC08, Genoa, Italy
2) E. Wallen, et.al. Proceedings of IPAC14, Dresden, Germany
HIPPIE EPU53 & EPU48 Commissioning

- EPU53 & EPU48, 3.9 m long and K=3.3 (All modes).
- Gap-dependant correction coils characterized at magnet bench. Orbit correction has been established for helical mode so far.
- Tune and Skew Q FF schemes (based on LOCO)
- Operation envelope of gap for different phases to achieve 6 kW power limit.

Horizontal Mode Spectrum

**EPU53**

Spectra on April 3rd

A. Shavorskiy, et.al

Spectra taken with mis-aligned front-end.
Bio/NanoMAX In-vacuum Undulators

- 2 IVUs for BioMAX & NanoMAX beamlines, $\lambda_u=18\text{mm}$, Length of 2 m and $K_{\text{eff}}=1.95$ (Achieved $K_{\text{eff}}=2.19$ for BioMAX and $K_{\text{eff}}=2.10$ for NanoMAX at 4.2 mm magnetic gap).
- Two correctors per plane dedicated for each IVU.
- Measured phase error within 2.5 degrees for all operation gaps.
- Each IVU gap is driven by 4 motors to give a tapered gap option. Change of peak field by 5%/m is required.
- New hot-water (110°C) cooling system will be delivered June 2017 to allow baking the undulator in 60 hours instead of 2 weeks.

![BioMAX: Measured phase error](image)

![NanoMAX: Deviation of peak By](image)
Bio/NanoMAX In-vacuum Undulators

- Two correctors per plane dedicated for each IVU (±500 G.cm per corrector). Orbit correction has been established for all gaps with max. tune shift <3x10^{-3}.
- Future work to establish correction scheme for tapered IVU.

**BioMAX Spectra: 7^{th} Harmonic @ 40 mA Beam & 5 mm Gap**

(© T. Ursby, D. Olsson)

**Measured Kicks of 3 GeV Beam**

- Horizontal-NanoMAX
- Vertical-NanoMAX
- Horizontal-BioMAX
- Vertical-BioMAX

**Kicks seen by beam**

**First spectra**

- measurement
- simulation

**Bio/NanoMAX Spectra: 7^{th} Harmonic @ 40 mA Beam & 5 mm Gap**

- Sim. Baseline lattice
- BBB OFF
- BBB ON
BALDER In-vacuum Wiggler

- BALDER IVW built by SOLEIL, \( \lambda_u=50 \text{ mm}, \) Length of 2 m and \( K_{\text{eff}}=9. \)
- The RF transition limits the max. gap from 70 mm to 50 mm (not fully transparent in R3 and has 830 G peak field).
- Early commissioning started Feb. 2017 and the IVW neutralized to 4.5 mm gap.
- At min gap, max. tune shift \( Q_v=7\times10^{-3} \) and beta beat 5%. Feedforward tables were established for the orbit and tune.
- Preliminary measurements of damping effect showed \(~4\%\) emittance reduction (Theoretically around 5%).

![Graph showing first integral vs. gap]
Top up with IDs Closed Gap

- Vertical scraper closed (2 mm). Injected beam has one passage before scraper.
- Radiation safety permission for injection with open shutter NOT yet in place.
- Interlock and routine operation: Closed gap vs. scraper position AND injection efficiency.
Top up with IDs Closed Gap

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- Radiation safety permission for injection with open shutter NOT yet in place.
- Interlock and routine operation: Closed gap vs. scraper position AND injection efficiency.
EPUs for the 1.5 GeV Ring

3 New EPUs to be built at MAX IV and installed in the 1.5 GeV:

- FinEstBeam EPU95: 2.6 m long and 14 mm min. gap (4.2 eV).
- BLOCH EPU84: Quasi-periodic, 2.6 m long and 14 mm min. gap (8 eV).
- MaxPEEM EPU58: 2.6 m long and 14 mm min. gap (25 eV).

1 EPU and 1 planar undulator transferred from old MAX-Lab.

- FlexPES PU54: Refurbishment: change drive system, base system and to be characterized
Proposal for Short Period Cryo-cooled Undulator

  - $\lambda_u=13$ mm, $K_{\text{eff}}=1.58$, 2 meter long and min. magnetic gap of 3.6 mm.
  - Baseline lattice allows min. physical gap of 3.3 mm for 2 m-long and centered ID.
  - Demagnetization estimate showed feasibility of assembly at room temperature.
  - Brilliance of $10^{19}$ @ 50 keV with R3 baseline lattice.

1) $\lambda=13$ mm
2) Gap @ 4 mm (Fixed gap)
3) $B_{\text{peak}} = 1$ T @ 300 K.
4) The evaluated B coincides with simulated one.

Magnetic performance @ 77 K by Nov. 2017
Undulators for Future Beamlines @ R3
(Not funded BLs yet)

Preliminary BL requirements:

- **DiffMAX:** 3-50 keV (no gap between the 1st and 3rd harmonics)
- **MedMAX:** 12, 25 & 40 keV (Tapering ΔE/E of 3keV may dictate room temp. device).
- **MicroMAX:** 5-30 keV

3 GeV Ring: $\varepsilon_x = 320$ pm.rad, $\varepsilon_y = 8$ pm.rad, $\sigma_E = 0.08\%$, $\beta_x = 9m$, $\beta_y = 2m$

<table>
<thead>
<tr>
<th>Undulator Type</th>
<th>$\lambda_U$ (mm)</th>
<th>$K_{eff}$</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiffMAX CPMU Undulator</td>
<td>15</td>
<td>2.03</td>
<td>2</td>
</tr>
<tr>
<td>MicroMAX Undulator</td>
<td>18</td>
<td>2.0</td>
<td>3</td>
</tr>
<tr>
<td>MedMAX CPMU Undulator</td>
<td>14</td>
<td>1.8</td>
<td>2</td>
</tr>
</tbody>
</table>

Brilliance [Ph/sec 0.1% BW mm² mrad²]

IVU: room temperature ID
CPMU: Cryo-cooled ID
Conceptual Design Studies for SXL Undulators

- Soft X-ray FEL 1-5 nm wavelengths.
- Definition of undulator parameter, mechanical design considerations and structural analysis and small gap measurement system.

Fixed Gap Undulator Structure
- Cost effective.
- Change e-beam energy.
- Accelerator Lattice.

APPLE X Configuration developed at PSI(*)

(*) M. Calvi, et.al. J. Sunch. Rad. March 2017
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Transverse gradient in K @ 1 keV

Up-Down girders

Left-Right girders
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**Fixed Gap Undulator Structure**
- Cost effective.
- Change e-beam energy.
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- Up-Down girders
- Left-Right girders

**Radial Gap Movement Structure**
- Cost
- Fixed e-beam energy.
- Operation modes.

- Transverse gradient in K as a feature

Soft X-ray FEL 1-5 nm wavelengths.
Definition of undulator parameter, mechanical design considerations and structural analysis and small gap measurement system.

- Transverse gradient in K @ 1 keV

- Min. gap: 250 eV
- Gap ΔR=8 mm
- 1 keV

- Cost effective.
- Change e-beam energy.
- Accelerator Lattice.
- Up-Down girders
- Left-Right girders
Conclusions

- Magnet lab @ MAX IV is equipped to assemble, characterize and test out-of-vacuum IDs. Investment for in-vacuum measurement capabilities is foreseen both in hardware and resources.
- New hot-water baking system and new lab infrastructure will reduce the time needed for tunnel access during ID installation.
- Five insertion devices installed in the R3 3 GeV ring and ongoing ID commissioning work follows R3 machine commissioning milestones (long bunches, high current, beam size, etc.).
- Preparation of three IDs for installation in R1 summer 2017.
- FemtoMAX Undulators installation to start after shutdown 2017.
- Five IDs are planned to be installed during 2018 (CoSAXS, DanMAX, SoftiMAX, MaxPEEM and FlexPES).
...Some Photos

BioMAX in-vacuum undulator in ring tunnel

BALDER in-vacuum wiggler in ring tunnel

HIPPIE EPU in ring tunnel
Moving VERITAS EPU to the ring tunnel.

More Photos

BLOCH EPU84 during assembly.

FinEstBeam EPU95 at the Bench.