*ARPES**

External collaborations	Chalmers, LiU, KaU, KTH
Original budget and funders	70.2 MSEK KAW and 12 Swedish universities
Official start	September 2011
Expected date of completion	Regular users November 2017

The key to understanding solids and their interfaces is detailed knowledge of the electronic structure near the Fermi level, since this dictates important properties such as magnetism, conductivity, and optical activity. Angle resolved photoemission spectroscopy (ARPES) is a direct and powerful tool to directly measure the electronic structure of crystalline solids, and in particular 2D layers and surfaces.

Over the last two decades, ARPES has grown to become a cornerstone of research into novel quantum materials such as high-temperature superconductors, quantum wells and transition metal dichalcogenides. In particular, ARPES and spin-resolved ARPES have been indispensable tools for understanding graphene (2010 Nobel Prize) and topological phases of matter (2016 Nobel Prize). The rapid growth of ARPES has been driven to a large extent by impressive progress in electron detectors and synchrotron sources, both of which continue to advance at a rapid pace.

The ARPES beamline at MAX IV will provide world class opportunities for preparing novel materials and studying them with a powerful combination of high resolution angle-resolved photoelectron spectroscopy, core-level spectroscopy and scanning tunnelling microscopy.

Technical description

- Source: elliptically polarising undulator, producing arbitrary photon polarisation.
- Photon energy range (10 - 1000) eV with $\Delta E < 1$ meV below 100 eV. Flux ~1×10^{12} ph/s at 30 eV and $\Delta E=1$ meV, and ~1×10^{13} ph/s at 100 eV and $\Delta E= 10$ meV.
- Higher harmonic suppression using solid state and gas filters.
- Spot size at the sample 25x10 μm^2
- Hemispherical electron energy analyser (DA-30L) with electronic deflection capability.
- Six-axis liquid-He cooled manipulator reaching sample temperatures below 20K.
- Two preparation chambers, with the possibility to add user supplied preparation chambers.
- Scanning tunnelling microscope.
- Spin resolved ARPES on a separate branch line
  (2D Mott detector with an R4000 SCIENTA analyser, transferred from I3 beamline at MAX-lab)

Present status

The first branch line beamline optical components have arrived. The ARPES endstation will arrive late February 2017. The second branch line optical components are expected late 2016 and the design of its spin resolved ARPES endstation is ongoing.

Expected status end 2018

Both the ARPES and Spin-ARPES endstations will be in full user operation.

Major partners and additional funding

- SOLEIL - MAX IV collaboration: In-house built six-axis liquid He cooled manipulator (2 MSEK)
- Karlstad University (KaU): Contribution to the ARPES second branch line for Spin-ARPES (2 MSEK)

Changes made since the start

The second branch line (Spin-ARPES) can be built due to a contribution from Karlstad University. The detector used will be the one from beamline i3 at MAX-lab.

Comparison to beamlines world wide

SIS beamline at SLS (Switzerland), ARPES beamline at Diamond Light Source (UK) and Cassiopia beamline at SOLEIL (France).

* https://www.maxiv.lu.se/accelerators-beamlines/beamlines/ARPES/

Future development

General overview:
We are first and foremost a user facility, and success for the beamline means maximising the quantity and impact of scientific output from our users.
The bare minimum requirement in this respect is to provide users with high performance, fully functional instrumentation. The next level involves more active involvement with users during their experiments, which depending on the users could mean as little as offering expert measurement and scientific consultation, or as much as participating in the planning, measuring, analysis and publication processes. How much of such active user support is possible will depend on the staffing level and in particular on the ability to have postdocs actively engaging in the science.

Specific Instrumentation Upgrades:
A. *Upgrade to a second generation spin detector*
By 2018 the second branch line will be offering spin-resolved ARPES, reusing the first generation 2D Mott detector from the i3 MAX-lab beamline. Before 2023 the second generation of detectors (with much higher efficiency) will have matured and an upgrade is essential to maintain competitiveness.

B. *Flexible sample environments for the second branch line endstation*
To provide users with maximum flexibility in terms of sample environment, the spin-ARPES endstation will be built so that the manipulator can be exchanged without having to vent the analyser chamber. Other manipulators offer possibilities such as cryostats that can reach 4K or lower, precise temperature measurements or specialised sample stages allowing for thermal gradients, strain or small electric fields.

C. *Time resolved measurements and pump probe techniques*
Single-bunch mode operation on the 1.5 GeV ring makes it possible to utilise the time structure for time-of-flight techniques like ARTOF (Angle-Resolving Time of Flight spectroscopy), where one can record energy-momentum information of a full 2D area of the Brillouin zone as compared to the line information obtained by ARPES. Single-bunch mode would also allow pump-probe experiments to study the dynamics of various excitations in matter. Introduction of these techniques will be a collaborative effort between ARPES and existing expertise in time resolved ARPES within Sweden (KTH, Uppsala University).

D. *Inverse photoemission*
In many cases it is essential to also have knowledge of the unoccupied bands which can be provided by k-resolved and spin resolved inverse photoemission (KRIPES). Adding this would further make ARPES unique as no beamline exists today which provides both ARPES and KRIPES.

E. Additionally, the ARPES users have a strong need for a common surface science and material laboratory at MAX IV to prepare and characterise their samples before, under, and after beamtimes.

F. An *in-situ* means of temporarily, nondestructively making electrical contact to the sample would allow users to probe a variety of features such as resistivity, phase transitions, thermoelectric properties, noise spectra, spin transport and photoconductivity. This would make a very potent combination with the high resolution Fermi surface measurements offered by the beamline, and is again not a combination available anywhere else.

G. In-situ laser spectroscopy*.* The addition of a laser source and spectrometer would enable relevant complementary techniques such as Raman spectroscopy of photoluminescence. These are commonly available *ex-situ*, but it would be valuable to have these as *in-situ* techniques since many of the surfaces being studied can only exist in ultrahigh vacuum.