METIS 1000

TIME-OF-FLIGHT MOMENTUM MICROSCOPE

KEY FEATURES

- Direct imaging of energy resolved momentum space with $\Delta k < 0.01$ Å^{-1}
- Parallel energy detection of ≤ 400 slices with $\Delta E < 15$ meV
- Start energies 0-2000 eV
- LHe-cooled hexapod stage
- Optional imaging spin filter

SPECS™

SPECS™

SPECS SURFACE NANO ANALYSIS GMBH - A STORY OF CONSTANT INNOVATION

SPECS leads the way for state-of-the-art technology, cutting-edge components and individually designed complex systems for surface analysis.

SPECS Surface Nano Analysis GmbH

SPECS has more than 130 employees at its headquarters in Berlin and its subsidiaries in Switzerland, USA and China. The company also has liaison offices in Spain and BeNeLux. Through the international sales channels customers in sixteen countries are supported. A team of scientists and engineers is involved in developing and producing scientific instruments for surface analysis, materials science and nanotechnology. Since the company has been founded in 1983 its success is based on a continuous gain in experience, driven by a large network of customers and scientists around the world. SPECS is your essential partner in scientific instrumentation due to our focus on service, know-how and its international support. Scientists all over the world can rely on SPECS product quality and be inspired by the continuous development of new products.

SPECS specialist assembles a high voltage 2D-CCD detector to a PHOIBOS 150 HV

Surface Concept GmbH

Surface Concept GmbH was founded in 2005 based on a spin-off from the Physics Institute at the University of Mainz. The company bundles strong skills of experienced physicists working on delayline detector developments for more than 12 years, on analytical electron microscopy for more than 15 years, and the key developers have about 20 years experience in the field of electron spectroscopy methods, particularly under ultra-high vacuum conditions. Today, Surface Concept designs, produces, and delivers between 20 and 30 highly sophisticated photon and particle detectors each year.

SURFACE CONCEPT

METIS 1000

NEXT GENERATION TIME-OF-FLIGHT MOMENTUM MICROSCOPE

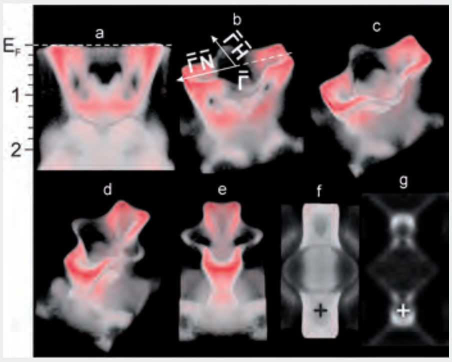
Time-of-Flight Momentum Microscopy is a unique time resolved method to study the electronic structure in small surface areas with high k and energy resolution

Time-of-Flight Momentum Spectroscopy and Microscopy

Novel materials like graphene or topological insulators show intriguing structural and electronic properties that radically influence the developments in microelectronics. Topological insulators, for example, are characterized by their particular electronic structure which enables metallic-like conductivity at surfaces of otherwise insulating materials. Angle-resolved photoemission spectroscopy (ARPES) is the obvious choice for studying the electronic structure of surfaces. Since samples are often smaller than one millimeter, inhomogeneous and clean surfaces can be delicate even under UHV conditions. Thus ARPES measurements are required to be fast and efficient, without compromising highest angular and energy resolution. Furthermore the signal should be originating from a well-defined and selectable small spot. This extended method is named Momentum Microscopy. Technological developments in the field of electron spectrometers have led to new possibilities in electronic structure determination with maximum acceptance angle from small acceptance area.

There are two principal strategies to determine the kinetic energy of a charged particle: either by energy dispersion in deflecting electrostatic or magnetic fields, or by measuring the time-of- flight for a given distance. Previous work on time-of-flight spectrometers and microscopes has shown that it is necessary to separate the imaging part (microscope column) from the field-free ToF section [2] . Strategies with optimized lens systems allow for tayloring the observed momentum distributions (width, resolution) to the specific needs of the experiment. The photoelectrons have to be excited by pulsed photon sources, like synchrotron sources, pulsed lasers or table-top high-harmonic sources. Using a two-dimensional detector allows to measure the complete two-dimensional representation of the reciprocal space vs energy, within one photon pulse, enabling fast measurements without any movement of the sample. Such a setup also allows measurements of the real space in a PEEM-like mode. Modern spectrometers are capable of delivering a complete image of the probed specimen, both in real space and reciprocal space.

The METIS instrument aims on such fields of material science, where momentum and high energy resolution, high time resolution in pump and probe measurements and k and real space measurements are required.



METIS tomographic 3D data array (k_x, k_y , E_B) of Mo(110) valence band structure. RAW data obtained by the METIS without further treatment. [1]

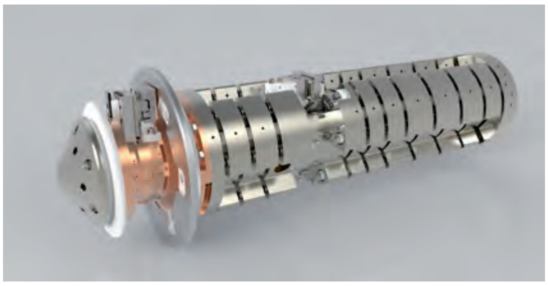
METIS 1000

TIME-OF-FLIGHT MOMENTUM MICROSCOPE

Technical Concept

Overview

METIS is a joint development of the Johannes-Gutenberg-Universität Mainz and the MPI für Mikrostrukturphysik Halle. It is produced by Surface Concept, sold and integrated by SPECS into complete and versatile UHV systems. It consists of a LHe-cooled sample stage, a sophisticated lens system optimized for ultimate resolution in k-space and an analyzer section, being completely decoupled from the imaging optics. The sample stage is a motor-driven high precision 6-axes hexapod for optimal alignment of the sample towards the lens entrance. The k-microscopy column comprises two retarding zoom lens systems with a high extractor voltage to analyze the full half space of photoelectrons with diameters up to 6 Å^{-1} [6]. The analyzer section is a drift tube with a choice of detectors, either for imaging (2D-DLD detector), or for direct spin imaging (DISpin detector).



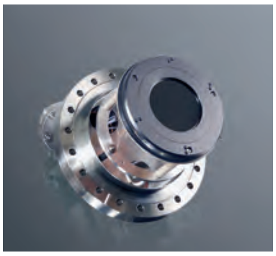
k-microscope column with piezo motors for adjusting apertures in k- and real space image planes

k-Microscope Column

The core of METIS is the lens system. With its high extractor voltages up to 29kV it records photoelectrons over the full half space above the sample surface with an initial kinetic energy up to 70 eV, simultaneously in k_x and k_y direction. This is a major advantage compared to conventional hemispherical analyzers, where only a small fraction can be measured at once. The result is a 3D data array of $I(E_{kin}, k_x, k_y)$. The lens system allows for such k-space mapping as well as real space imaging. Additional apertures in real and reciprocal image planes can reduce the field of view for ARPES spectra of small areas down to µm regions or enhance the contrast for photoelectron microscopy with chemical information.

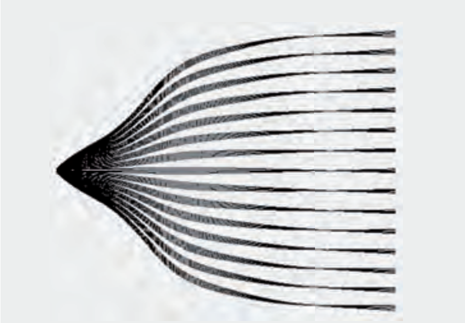
Delayline Detector

A delayline detector (DLD) is a position (x, y) and time (t) sensitive microchannel plate area detector for imaging of single particles with temporal resolution in the picosecond range. The (x, y, t) histograms are gathered over a large number of excitation cycles of the particle generating process as the system is a single counting device. Particle images can be collected from continuous running processes with randomly incoming particle sequences without time correlation as well. The dead times of these single counting devices are typically between 6 - 20 ns, depending on the positions of subsequent hits. That enables live imaging with highest sensitivity, collecting high count rates of randomly incoming particles in the multimillion counts per second range, as well as imaging with a very high dynamic range of 10^6. Unlike other picosecond imaging devices, delayline detectors collect all incoming particle hits continuously without any gate window duty cycles, thus (besides the device dead time limits) all hits are collected even when they represent random time positions within the excitation cycle time period. In METIS the DLD records data with a time resolution of 150 ps and a maximum count rates of 8 Mcps.



Delayline detector for 3D data recording (k_x, k_y, t)

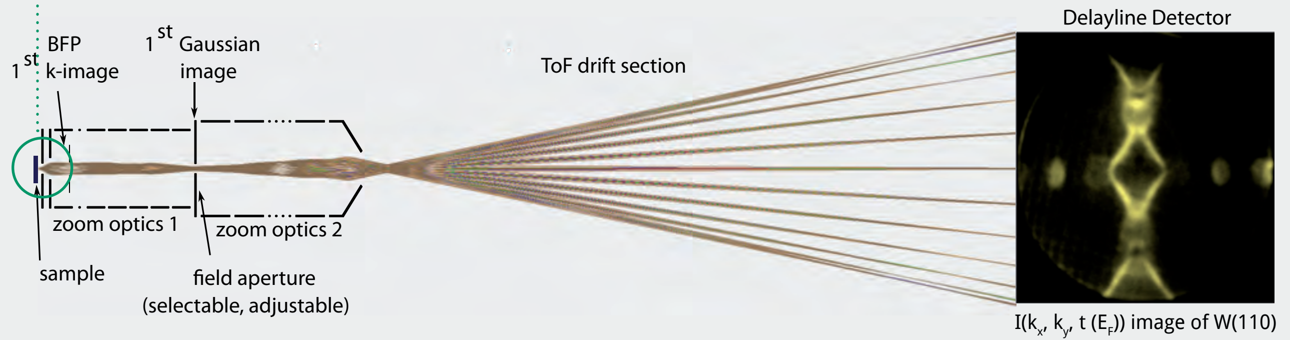
Modes of Operation



Full half space imaging is possible up to an initial kinetic energy of 70 eV

Momentum Microscopy Mode

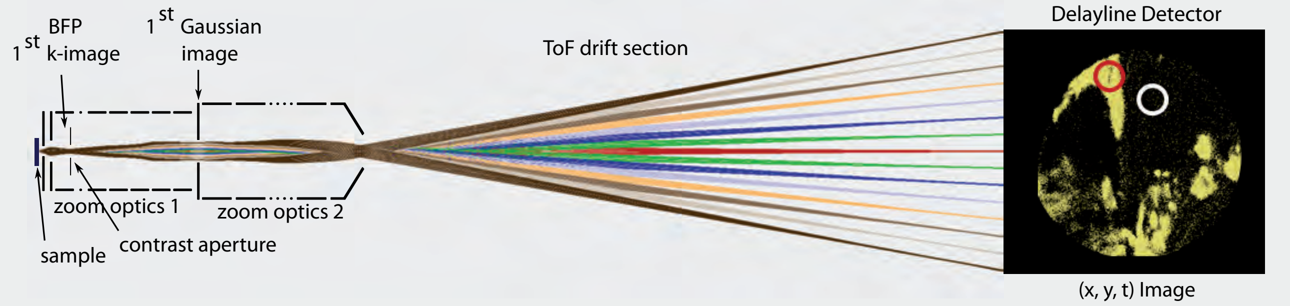
In angle-resolved operation mode a ToF momentum microscope records a 3D data set. Electrons are detected as a function of the two orthogonal surface wave vector components k_x and k_y and the kinetic energy E_{kin}. The high extractor voltage allows acceptance angles up to ± 90°. For low kinetic energies, k_x and k_y are only limited by the photoemission horizon. Apertures in the 1st Gaussian image are capable of confining the field of view on the sample down to 2 µm diameter.



Working principle of METIS in momentum microscopy mode

ToF-PEEM Mode

The time-of-flight photoelectron emission microscopy (ToF-PEEM) mode offers real space images of the sample with lateral resolution better than 50 nm. Due to 3D data acquisition the PEEM images can be recorded in parallel for many (up to 400) kinetic energies. By shifting a contrast aperture into the backfocal plane (BFP) the image contrast can be optimised. Variabel apertures in PEEM-mode allow to select acceptance areas down to 2 µm in diameter for site-selective k-microscopy.



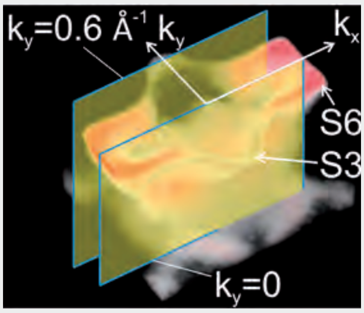
Beam path for real space imaging. PEEM image of freshly-cleaved SmB_6-sample showing microregions with samarium and boron termination.The two circles denote size and positions of the field aperture for analysis of the two microareas.

Applications

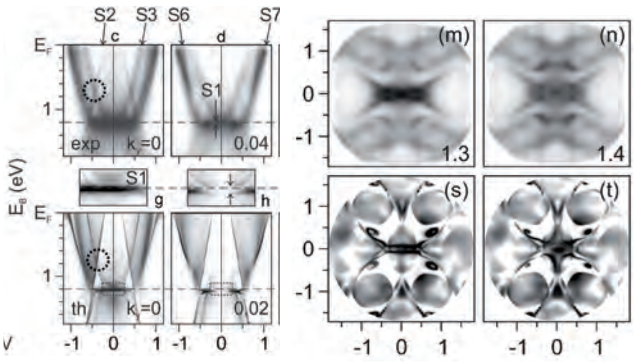
METIS 1000 2D-DLD AND METIS 1000 DISPIN

d-like Surface Resonances on Mo(110)

The electronic surface states on Mo (110) have been investigated using time-of-flight momentum microscopy with synchrotron radiation (hν = 35 eV). This novel angle-resolved photoemission approach yields a simultaneous acquisition of the $E_B(k)$ spectral function in the full surface Brillouin zone and an energy interval of several eV. $I(k_x, k_y, E_B)$-maps with 3.4 Å^{-1} diameter reveal a rich structure of d-like surface resonances, partly with Dirac-like signature in the spin–orbit induced partial band gap [1].



Sectional planes through the 3D data array. Such E-vs-k sections can be cut in any desired orientation, offline after completion of the experiment.

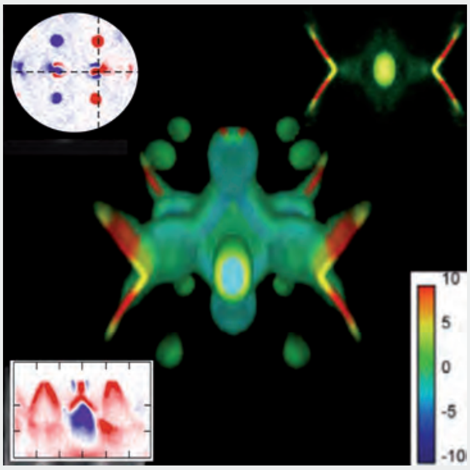


Cuts through the k-space in (k_x, E) and (k_x, k_y) directions for Mo(110) [1]

Direct 3D Mapping of Fermi Surface and Fermi Velocity

The shape of the Fermi surface and the Fermi velocity v_F as a function of direction in k-space are of high importance for the design of materials with tailored electronic properties. Moreover, the topology of the Fermi surface plays a crucial role in the existence of topologically non-trivial electronic states like the metallic states in the surface region of topological insulators. Time-of-flight momentum microscopy has been applied for the first time in the soft X-ray range at PETRA III, DESY, Hamburg. There the topology of the Fermi surface and the character of p- or n-type conductivity was determined and v_F was quantified on the full Fermi surface for the prototypical high-Z bcc metal Tungsten [2].

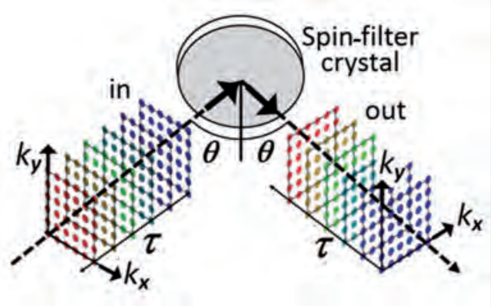
Blue and red correspond to electron and hole conductivity, respectively. For hole pockets v_F varies from 10^5 to $2.7 \cdot 10^6$ m/s and for electron pockets from 10^5 to $7 \cdot 10^5$ m/s. Data have been extracted from the measured 4D spectral distribution function $I(k_x, k_y, k_z, E_B)$ by numerical differentiation.



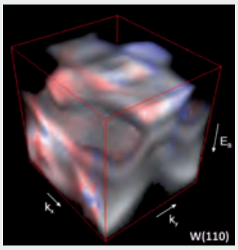
Experimentally-determined Fermi surface of Tungsten. The contour denotes the Fermi velocity as quantified by the color bar (in 10^5 m/s). [2]

METIS with Direct Imaging Spin Detector DISpin

In an imaging spin filter all three coordinates of the three-dimensional electron distribution are preserved (see scheme). This is achieved be projecting the two-dimensional electron distribution onto a single crystal surface and projecting the diffracted image onto a two-dimensional detector. The time-of-flight encodes the energy coordinate within a certain interval. The spin contrast is caused by spin dependent reflectivity of low-energy electrons due to spin-orbit interaction, and can be highly spin selective for high-Z materials like W or Ir. Usable maxima of the spin asymmetry function reach 80% [3-6].



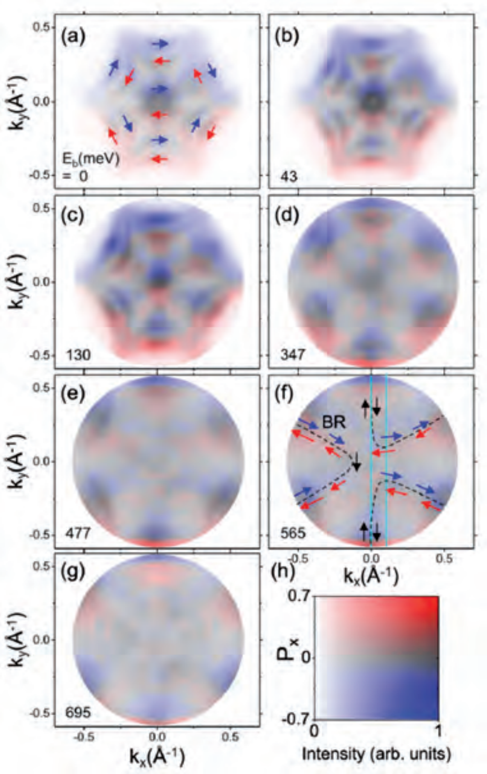
Schematics of operation of the imaging spin filter in real space



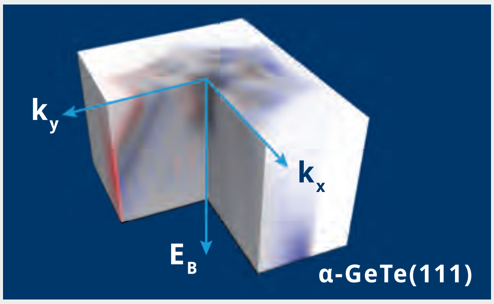
Experimentally determined spin polarized states of W(110)

The schematics for the operation of the imaging spin filter are shown above. The single crystal surface serves as an electron mirror for one spin component, being perpendicular to the scattering plane.

A comprehensive mapping of the spin polarization of the electronic bands in ferroelectric α- GeTe(111) films has been performed using this technique. A Rashba type splitting of both surface and bulk bands with opposite spin helicity of the inner and outer Rashba bands is found revealing a complex spin texture close to the Fermi energy [3].



Mapping of spin polarized states of α-GeTe(111) [3]



3D representation of spin polarized states of α-GeTe(111) [3]

System Integration

FLEX METIS SYSTEM

METIS System Design and Integration

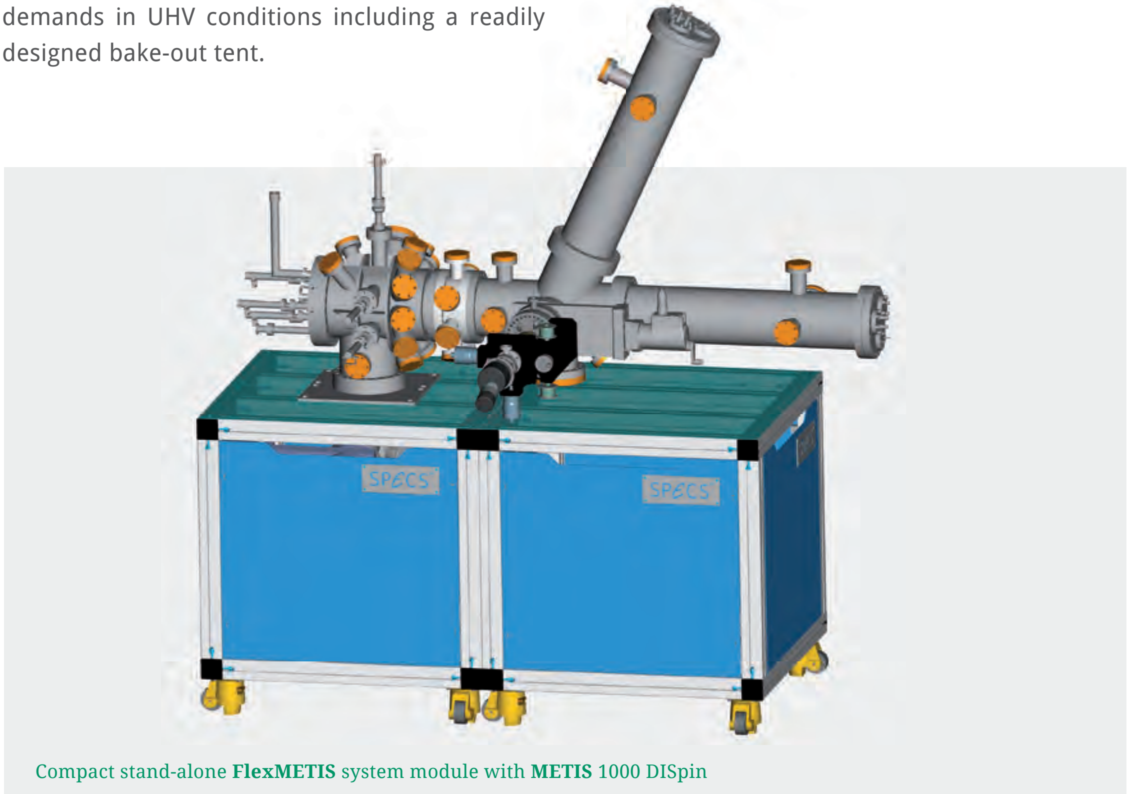
The METIS spectrometer is a fully equipped UHV system consisting of an analysis chamber with sample manipulation, lens system and detector section.

The analysis chamber is made from µ-metal and designed for versatile application in laboratory or research facilities, such as synchrotrons. The sample manipulation is performed by a high precision hexapod for the parallel alignment of the sample to the lens entrance. The METIS is ready to use for SPECS SH2/12 sample holders. The sample can be cooled below 35 K. A load lock and basic sample preparation (ion sputtering) is included in the main METIS concept. Variable pumping configurations account for highest demands in UHV conditions including a readily designed bake-out tent.

Sample Preparation and Thin Film Deposition Modules

For advanced sample preparation and/or thin film deposition different types of preparation and deposition chambers can be connected to the analysis chamber. These modules can include the following techniques:

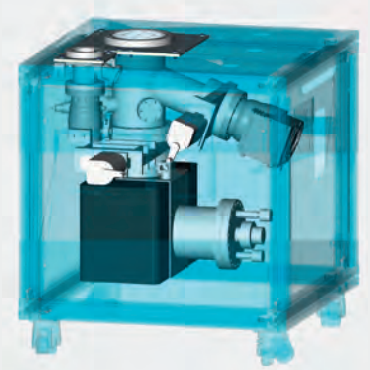
- High temperature sample treatment (up to 2600 K)
- Thermal or electron beam evaporation for MBE
- Plasma atom/ion sources
- Pulsed Laser Deposition (PLD)
- High pressure surface modification (up to 20 bar)
- Electrochemical surface modification



Compact stand-alone **FlexMETIS** system module with **METIS** 1000 DISpin

System Concept FlexMod

The METIS spectrometer is fully integrated into the versatile SPECS UHV system family. The basis is the reliable and easy-to-use FlexMod system concept, providing the FlexMETIS as a stand-alone system, with the option to be combined with any standard FlexMod system module. As a basis the FlexMod frame with bake-out tent is a proven concept for microscopy and spectroscopy applications with high resolution.

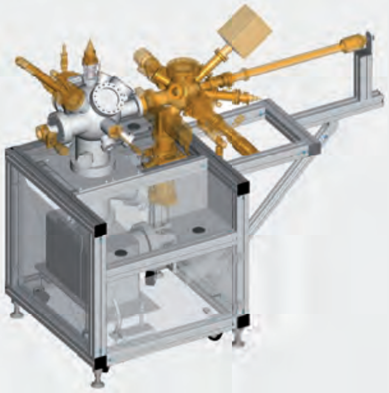


FlexMod
system frame with pumping system **FlexVac**

A connection to a FlexPS module adds standard XPS characterization of a samples for elemental analysis.

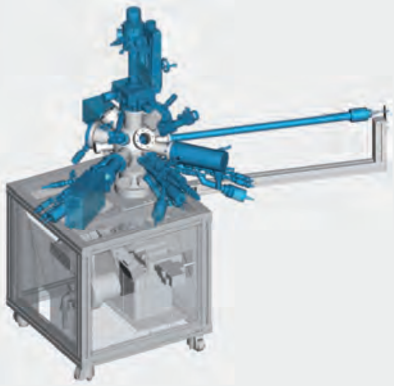
FlexPS System
standard XPS/UPS system module

With a connection to a FlexPM module VT-SPM measurements with a atomical resolution can be performed on the same samples as the characterization with METIS.



FlexPM System
standard VT-SPM system module

For complex surface preparation or thin film deposition FlexPrep module can be added.



FlexPrep System
standard preparation system module

Combinations of several modules can be realized either in direct connection or via a linear transfer system. Contact SPECS for your customized combination of different methods.

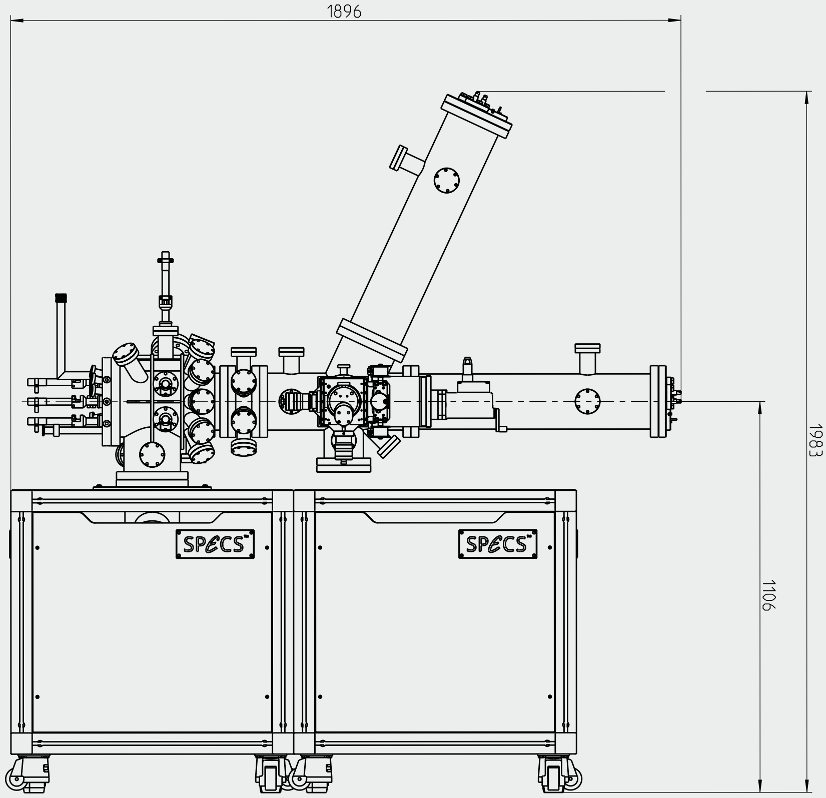
Technical Data

Specifications

METIS	
Mounting Flange	DN150CF
Start Energy	0 -2000 eV
Energy Resolution	<15 meV
Angular Resolution	<0.1°
k-Resolution	< 0.01 Å^{-1}
Lateral Resolution (PEEM-mode)	< 50 nm
Lateral Resolution (ARPES-mode)	< 2 µm
Acceptance Angle	up to +-90°
Exctractor Voltage	up to 29 kV
Field Apertures	200 µm down to 2 µm (in sample coordinates)

Delay Line Detector	
max. permanent measurement count rate	> 8x10^{6} cps (10^{8} tolerant)
Count Rate Linearity Range	> 2x10^{6} cps
Typical Time Resolution (position integrated)	< 180 ps < 110 ps (best achieved)
Start Repetition Rate	≤ 150 MHz; ≤ 9 MHz without prescaler
Typical Lateral Resolution	< 100 µm < 50 µm (best achieved)
Multi Hit Designs	optional, up to 30 simultaneous hits (with multianode detector layout)
Standard Anode Layout	buried lithographic meanders (crossed serpentine)
MCP Stack	Chevron @ typ. gains of 3x10^{6}, typ. lifetime > 5000 h @ 10^{6} cps equally distributed
Standard Coms	USB 2.0 (>30 Mbyte/s permanent streaming); USB 3.0 (> 200 Mbyte/s random permanent)
Hardware Triggering	time reference start input, acquisition start, acquisition finished
List Mode Streaming and Tagging	up to 6 coordinates (x, y, t, start counter, user tagging, time stamp)

Dimensions



FlexMETIS system module

References

[1] S.V. Chernov et al. “Anomalous d-like surface resonances on Mo(110) analyzed by time-of-flight momentum microscopy”, Ultramicroscopy 159 (2015) 453 - 463.

[2] K. Medjanik et al. "Direct 3D Mapping of the Fermi Surface and Fermi Velocity", Nature Materials, in print DOI: 10.1038/NMAT4875 (2017).

[3] H.J. Elmers et al. “Spin Mapping of Surface and Bulk Rashba States in Ferroelectric a-GeTe(111) Films”, Phys. Rev. B: Condens. Matter 94 (2016) 201403(R).

[4] D. Kutnyakhov et al. “Imaging spin filter for electrons based on specular reflection from iridium(001)”, Ultramicroscopy 130 (2013) 63.

[5] J. Kirschner et al. “Spin-polarized electron scattering from pseudomorphic Au on Ir(001)“, Phys. Rev. B: Condens. Matter 88 (2013) 125419.

[6] Patents no. DE 10 2005 045 622 B4, DE 10 2013 005 173 B4 and DE 10 2014 018 555 B3.

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