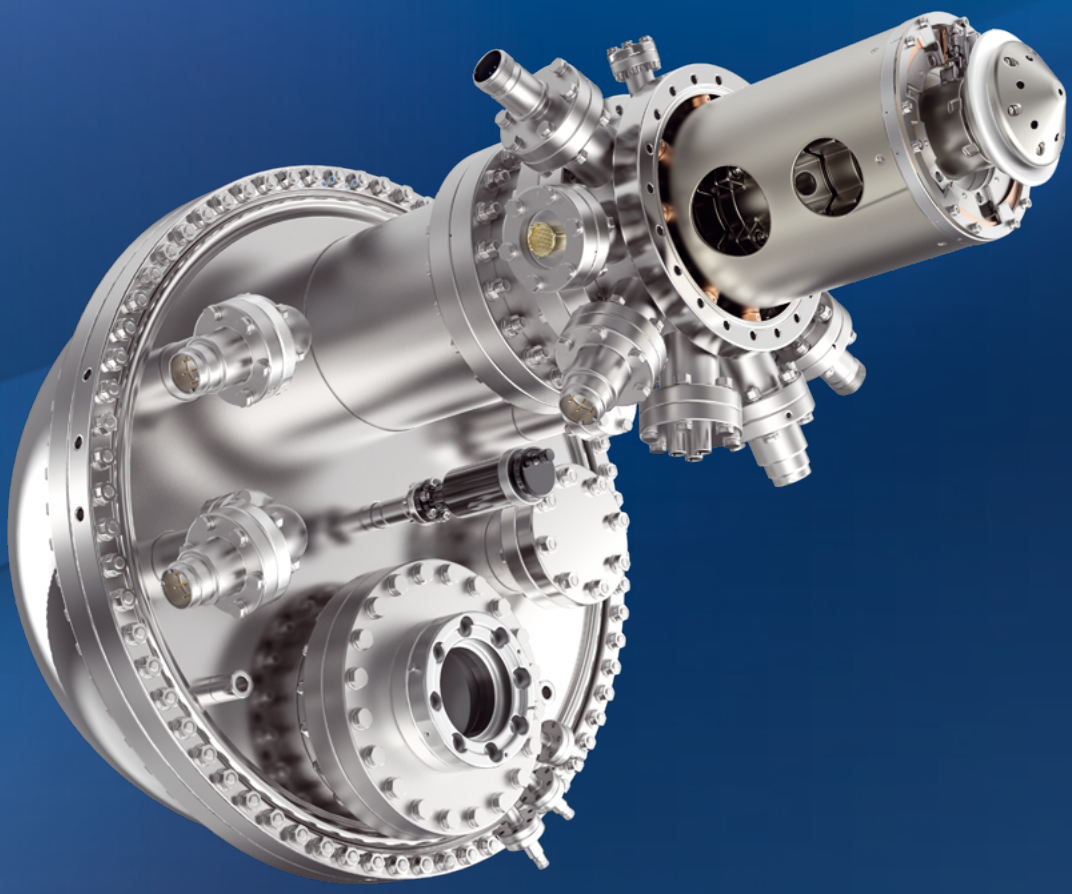
KREIOS 150 Series

NEXT GENERATION ELECTRON ANALYZER
FOR SMALL SPOT ARPES AND MOMENTUM MICROSCOPY

KEY FEATURES

- Full 180° angle ARPES
- μ-ARPES (< 2 μm field of view)
- Lateral resolution < 50 nm (PEEM mode)
- Kinetic energy range 0 – 1500 eV
- Energy resolution < 10 meV
- Angle resolution < 0.1°



SPECS™
A member of SPECSGROUP

KREIOS 150 Series

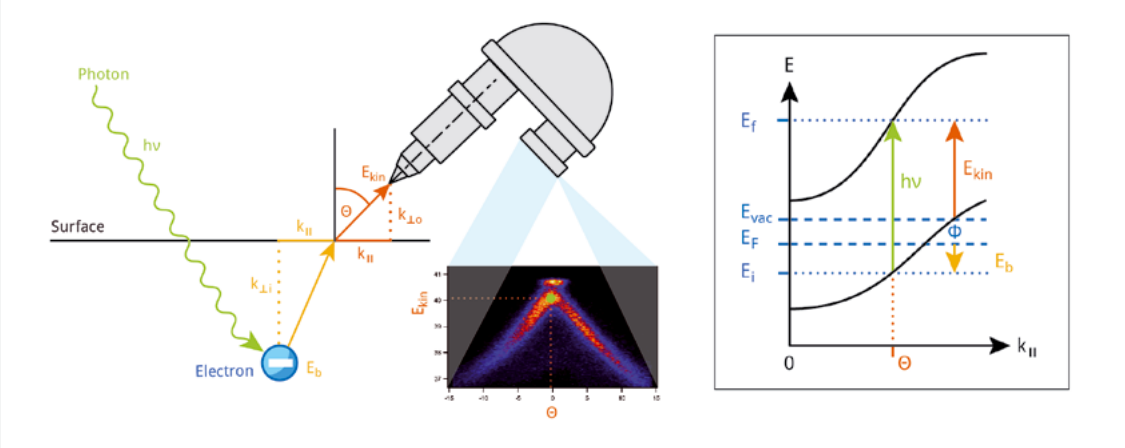
ELECTRON MOMENTUM
SPECTROSCOPY AND MICROSCOPY

Understanding the Electronic Structure of Solid Materials

Photoelectron spectroscopy is one of the most powerful and frequently used spectroscopic techniques in solid state physics, physical chemistry and materials science. Using the photoelectric effect, discovered by Hertz in 1887 and later described by Einstein, PES provides a material sensitive and non-destructive probe for modern scientists to examine the electronic structure of matter.

By illuminating a sample with light of a certain frequency (photon energy), electrons are released from a solid, using the photon energy to overcome their binding energy in the solid. The remaining energy provided by the photons is transferred into the kinetic energy of the photoelectrons, which can be analyzed in an electron spectrometer. On this basis, a spectrum over the electrons' binding energy in the material can be obtained.

Angle-resolved photoemission spectroscopy (ARPES) is a technique to access the electron band structure of matter. In such an experiment the emission angle of an electron is here determined by the in-plane momentum of the electron within the surface. Information about the electronic structure is important in novel materials in semiconductor industry and advanced basic research. Current analyzers, hemispherical analyzers as well as time-of-flight spectrometers, can only access a limited area of the photoemission sphere, as the lens entrance only passively collects electrons from a relatively small solid angle. Increasing the acceptance angle can be done in two ways: reducing the working distance and increasing the opening of the lens cone. However, both methods have a negative influence on the accuracy of the performance of the spectrometer, as larger angles are more difficult to process in the classical lens system.



Angle-resolved photoelectron spectroscopy.



KREIOS 150 S



KREIOS 150 MM

Combining ARPES and momentum microscopy

KREIOS spectrometer uses a k-microscope column as lens and the extractor lens applies a high voltage between sample and lens, which collects photoelectrons with up to ± 90° emission angle. With this lens the barrier of passive electron collection can be overcome and allows analyzing the complete electronic structure. This new lens system also provides a high lateral resolution in real space.

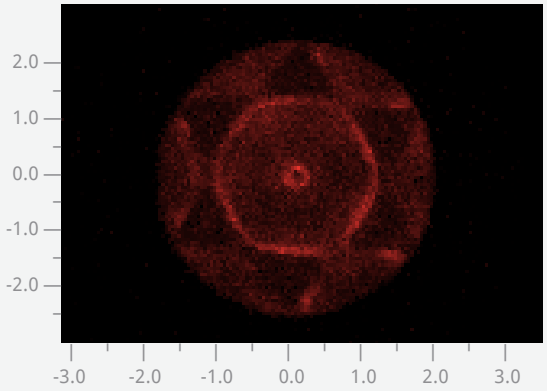
A selection of data collection from small surface areas is possible, opening the field of µ-ARPES, so far only possible on synchrotron beamlines with special photon optics.

The new SPECS KREIOS 150 analyzer combines the k-lens column and extractor lens with a hemispherical analyzer to use the ultimate angular information together with an electron analyzer for CW light sources, making this technique available for every light source.

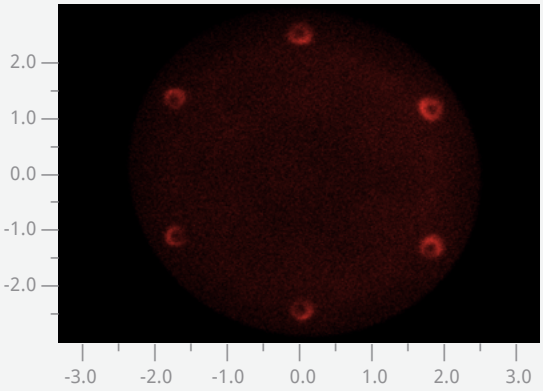
Next-generation ARPES

The electronic structure of matter reveals important information about its properties and prospects for technological application. Modern microelectronics is heavily influenced by the development and characterization of novel materials, such as graphene, topological insulators or thin magnetic films. The method of choice is angle-resolved photoelectron spectroscopy (ARPES) to gain insight into the electronic band structure and hence the fundamental material properties.

Samples get smaller, often smaller than a millimeter, and more sensitive to their environment. Laser systems with low and medium photon energies become easier to handle. The next generation of ARPES instruments is developed to fulfill modern requirements: small spot analysis down to the nm scale, combined microscopy and spectroscopic analysis, and even electron analysis down to the spin level. SPECS offers a series of instruments, capable of these modern applications, the KREIOS 150 product family.



Au (111) Constant Energy Map (Å^{-1}) using k-microscope lens column technology.



Graphene constant energy map (Å^{-1}) using momentum microscope.

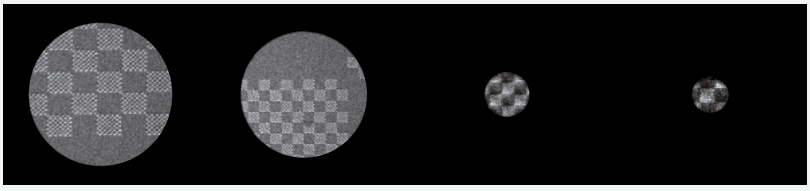
Real and k-space imaging

Technology overview

The KREIOS product family is based on a new kind of electron lens system, based on a joint development of SPECS, the Johannes Gutenberg University in Mainz and the MPI für Strukturphysik in Halle. Together with Surface Concept we produce a sophisticated lens system, adaptable to hemispherical electron analyzers and time-of-flight instruments for momentum microscopy, ARPES and real space microscopy.

The so-called MM lens is a PEEM lens optimized for highest k-space resolution and transmission in ARPES. The objective lens is biased to several kV to extract the electrons from the sample, allowing photoelectron collection from the full half sphere of the sample (± 90° acceptance angle). Depending on the photon energy that allows measurements up to ± 3.6 $Å^{-1}$. The electrons are then processed by the following lens system. This lens consists of 4 single spot shifting deflectors for systematic measurements and alignment of the acquired electron signal in both real space and reciprocal space. The acquired image can be shifted in all directions without moving the sample.

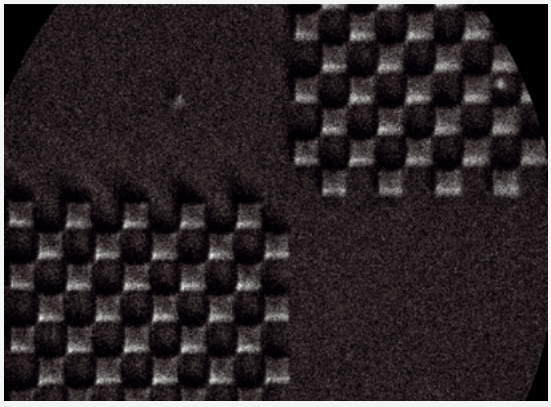
The PEEM lens is equipped with a series of apertures in the k-space and real space image plane, the contrast and field apertures, respectively. The contrast aperture is located in the back-focal plane of the lens system. It can be used to select a defined k-space area before the data is transformed into the real space image. Field apertures are located in the real space (or Gaussian) plane of the lens system. It refines the real space field of view to perform µ-APRES or momentum microscopy from a defined small space. These apertures can be used for contrast enhancement in PEEM, µ-ARPES selection down to 2 µm field of view in ARPES and dark field PEEM. After being processed the photoelectrons can be analyzed in several ways, a classical hemispherical analyzer for ultimate ARPES and µ-ARPES (KREIOS 150 S) or a single hemisphere in momentum microscopy operation mode (KREIOS 150 MM).



Real-space field aperture imaging



k-space contrast aperture imaging



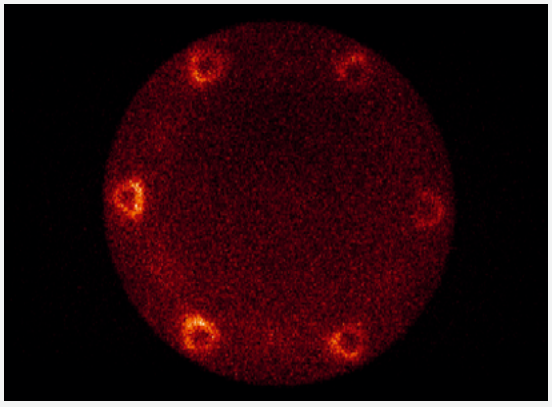
PEEM mode

Lens Modes

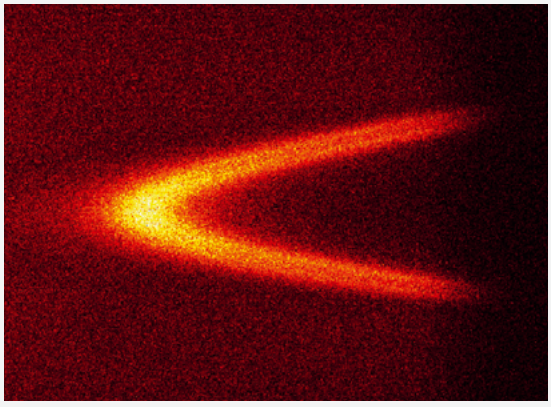
MM mode: In momentum mode the emission angle is conserved while the electrons are processed through the lens system. In angle-resolved photoemission this corresponds to the emission angle of the sample. The KREIOS can typically accept ± 90° emission angle in a wide energy range suitable for ARPES. Above 50–70 eV electron kinetic energy the electric field applied between the lens and the sample is not high enough to collect ± 90° anymore, however here the field of view in k-space becomes constant, up to ± 3.6 $Å^{-1}$. The result of such an experiment is a dataset directly observed in k-space, in contrast to classical hemispherical analyzers, which only display angular space. In the KREIOS 150 S, the entrance slit selects a constant line of k_x momentum for energy filtering, yielding an energy spectrum over the acquired k_x coordinate. In the KREIOS MM, the collected two-dimensional image k_x vs. k_y is transferred directly into the hemisphere and the energy filtering yields an image from a defined energy window.

ARPES mode: In this mode, KREIOS gives direct access and ability to display the kinetic energy of electrons as a function of reciprocal space (k-space), thus E vs k band dispersion information. Here, the MM lens at the hemisphere outlet simply magnifies the energy-dispersed image onto the detector instead of performing the Fourier transformation used in MM mode. In ARPES mode $\Delta E < 10$ meV compared to MM mode $\Delta E < 25$ meV, making it the preferred mode for high spectroscopic resolution.

PEEM mode: The lens system can acquire a real space image and process the information to the hemispherical energy filter. The typical field of view accessible by the KREIOS 150 is 50–200 µm. A special mode is available for up to 1000 µm. The PEEM image is built up by a scan over the surface, where at each line an energy dispersive real space profile is collected. The KREIOS 150 MM collects an energy filtered image directly; however, the energy window is fixed by the energy filter setting.



MM mode



ARPES mode

KREIOS 150 S

SCANNING REAL- AND K-IMAGING



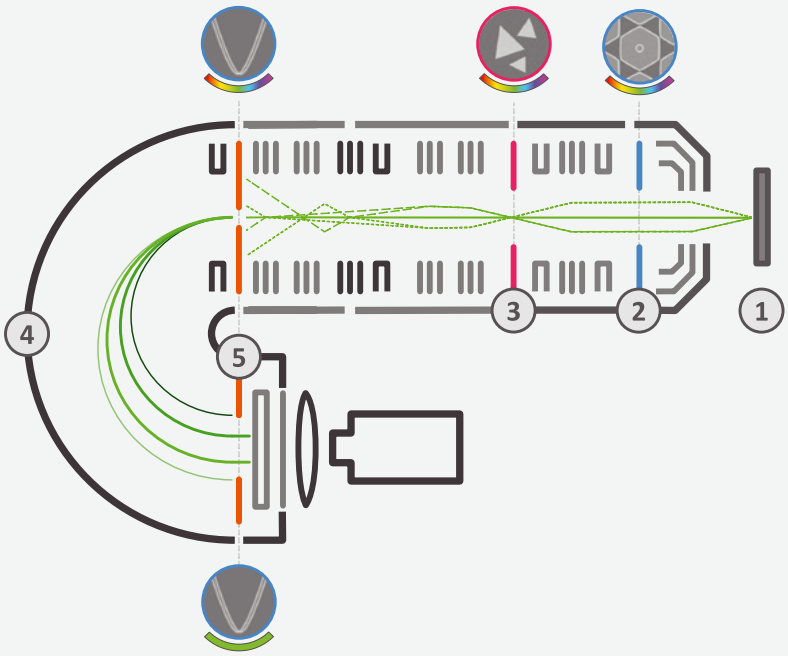
KREIOS 150 S

The combination of the PEEM lens with a classical hemispherical analyzer yields an ultimate APRES spectrometer for fast and small spot analysis of modern samples. The analyzer is operated in a standard energy dispersive mode where the photoelectron image is refined by an entrance slit, analyzed by the hemisphere and displayed onto the detector section through the exit slit of the hemisphere.

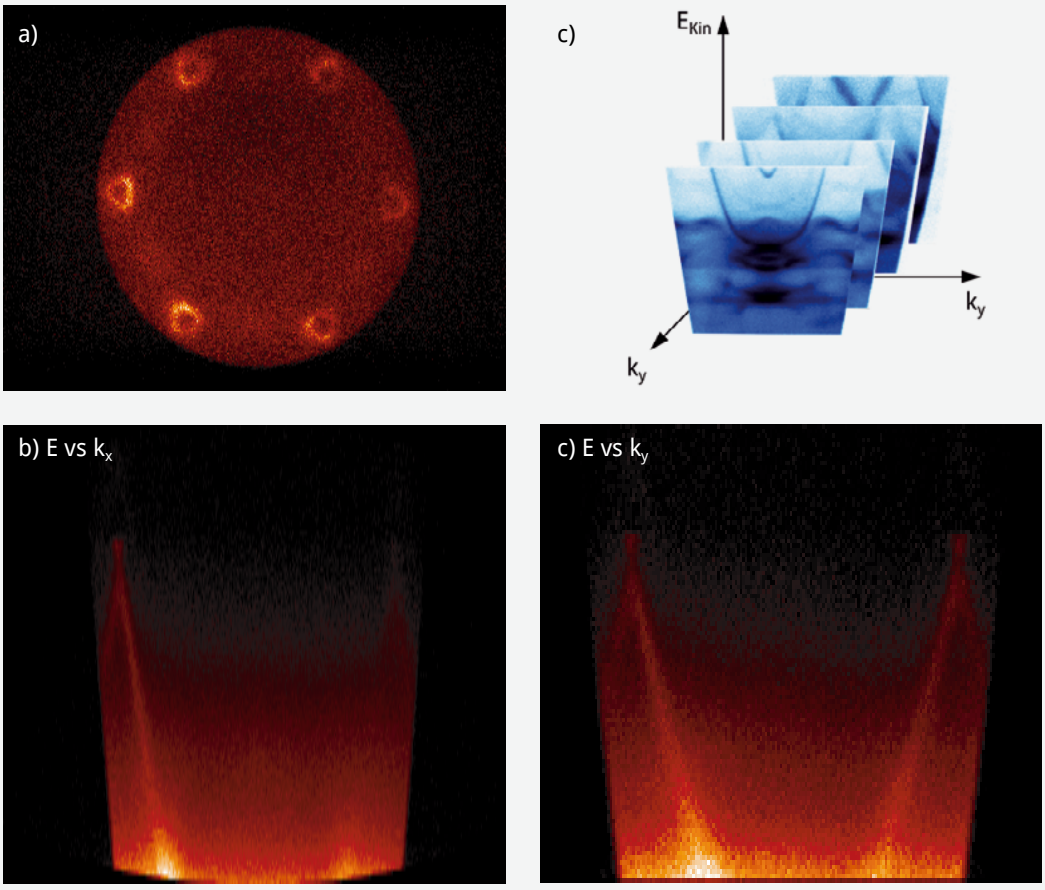
The analyzer is linked to the PEEM lens by zoom optics, transferring the small image from the MM lens into a proper large image covering the entrance slit. The zoom lens in combination with the integrated single spot shifting optics allows displaying either the full ± 90° angular dispersion image or a zoom into higher angular dispersive modes. The deflector can be used to align the photoelectron image to any coordinate within the extracted angular cone to zoom at any place in the real or reciprocal space.

By using the integrated field apertures it is possible to select photoelectrons from a defined area and hence refining the ARPES data to a small region of interest. The area can be refined from 200 µm down to 2 µm by fixed apertures. A fast scanning mode is implemented to visualize the second in-plane component (real space or reciprocal space). This mode is comparable to the image acquisition in commercial SEMs.

The KREIOS 150 S electron momentum spectrometer performs best, where highly resolved spectroscopic data is required. The technological approach allows efficient handling of the smallest samples (µ-ARPES) or unknown samples with an extended and complex electronic band structure (large angular acceptance). The combination of energy dispersive PEEM with spectroscopic data opens new approaches in the identification, selection and analysis of modern samples.



In the schematic image on the left for KREIOS 150, electrons leaving the sample (1) are imaged prior to the energy filtering by the hemispherical analyzer (4) at contrast aperture (2) and field aperture (3) are for k-space and real-space operation, respectively. There is an exit slit at (5).



Band structure mapping of Graphene/SiC with KREIOS 150 S showing (a) Fermi surface (k_x, k_y) plot, (b) E vs k_x, (c) E vs k_y slices.

Top right: measured band structure E vs k of Au (111) for both in-plane directions obtained using deflector scans.

KREIOS 150 MM

DIRECT REAL- AND K-IMAGING



KREIOS 150 MM

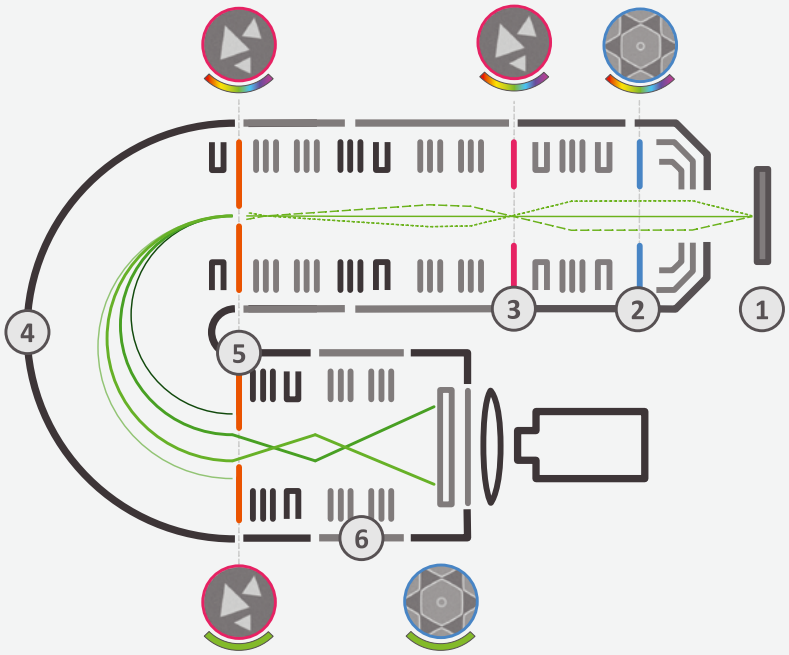
As an extension to the ARPES functionality it is possible to operate the KREIOS in MM mode. In this mode the real space or reciprocal space image is displayed directly on the detector. The energy dispersion is performed on the two-dimensional data directly, yielding energy filtered PEEM and momentum microscopy data. For that purpose additional optics are attached to the outlet of the hemisphere. The small image from the lens is analyzed through the hemisphere and enlarged after exiting the hemisphere. For that mode, no artificial aberration correction is needed, but integral parts of the existing analyzer technology are able to compensate the appearing small distortions.

Like the KREIOS 150 S, this analyzer detects a large field of view of the reciprocal space (± 3.6 $Å^{-1}$), corresponding to ± 90° acceptance angle up to typical photon energies in ARPES.

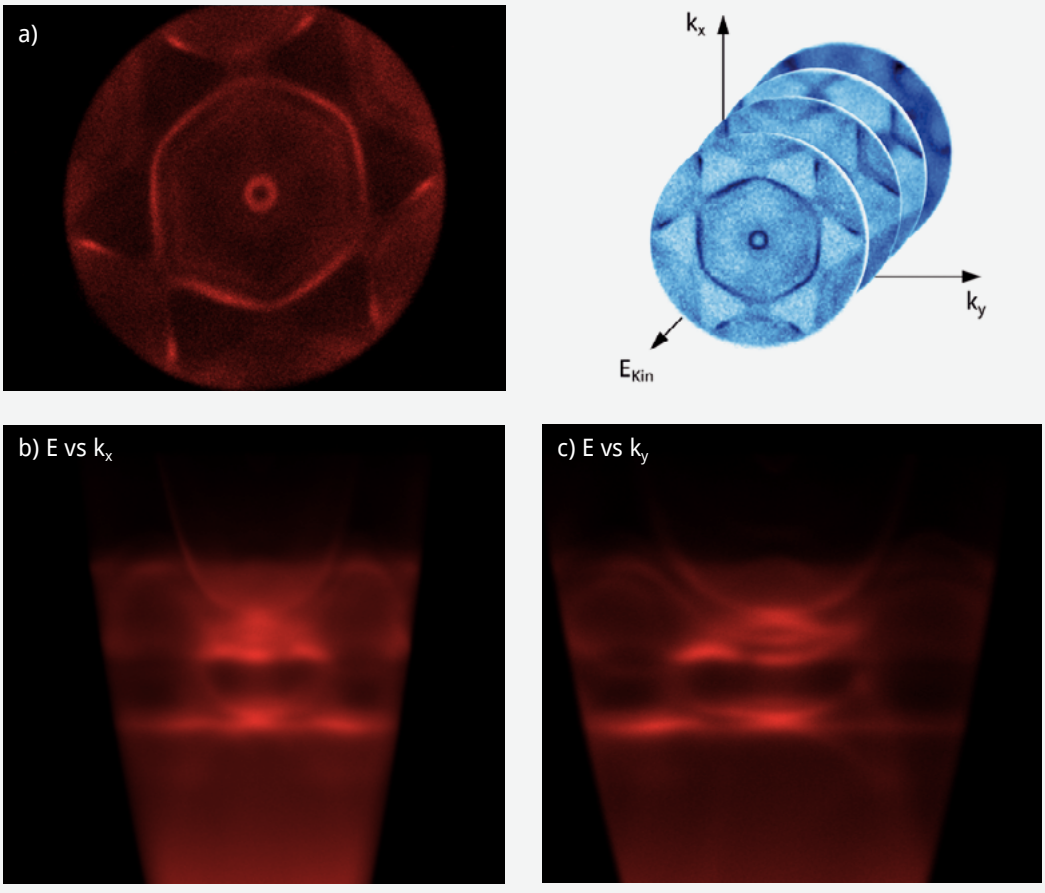
The energy spectrum can be scanned with reasonably high resolution (linked to the overall transmission, and hence spectral intensity) through the hemisphere.

This operation mode is an add-on to the ARPES functionality of the KREIOS 150 and the instrument can be operated in either mode.

The KREIOS 150 MM is designed to provide direct access to lateral information of the sample for fast identification and location of small spot samples. Identified samples can then be analyzed in terms of momentum microscopy giving access to energy filtered angle-resolved data in two dimensions and energy scans over the acquired region in the reciprocal space. The KREIOS MM Series is ideally suited for the use of direct imaging spin detectors, yielding direct access to spin and angle-resolved data.



In the schematic image on the left electrons leaving the sample (1) are imaged prior to the energy filtering by the hemispherical analyzer (4) at contrast aperture (2) and field aperture (3) are for k-space and real-space operation, respectively.
For KREIOS 150 MM, there are additional projector lenses at (6) and exit aperture at (5).



Band structure mapping of Au with KREIOS 150 MM showing (a) Fermi surface (k_x, k_y) plot, (b) E vs k_x, (c) E vs k_y slices.

Top right: constant energy plot (k_x vs k_y) structure of Au (111) directions obtained using energy scans.

Accessories

Detectors

2D CMOS with 3D Spin detection: There are two possible combinations. 2D CMOS detector with rotator lens, combined with Mini-Mott detector for spin-resolved studies. Here there are 1 out-of-plane, 2 in-plane measurable spin components. Alternatively, 2D CMOS can be combined with VLEED (FERRUM) spin detector with 90° deflector; spin rotator changes the in-plane spin orientation. Here all 3 spin components are measurable.

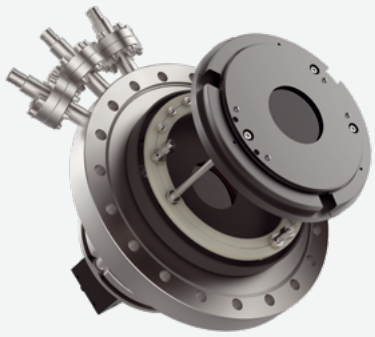
Imaging Spin detector (DI-Spin): This detector is capable of producing 2D spin-resolved images and adaptable to KREIOS 150 MM. Direct Imaging (DI) spin detector has a very versatile electron optical lens system and can be operated in several different lens modes. It allows the flexibility to generate 2D k-images or real-space images which can be spin resolved. This is achieved by combining magnetic deflectors and rotators.

2D CMOS: The 2D CMOS detector conveys both the energy and angular information, which facilitates band mapping, angular mapping, high resolution XPS/UPS and image state spectroscopy with 2PPE. The design of the detector is optimized for the detection of low kinetic energy electrons. The data collection is performed via a single event detection, which yields a digital map of all registered electron impacts on the phosphor screen and, hence, an image with real count rate.

2D DLD: In 2D delay-line detectors the “delay line” is formed by an anode. The detector assembly includes microchannel plates (MCPs) for multiplying striking photoelectrons, which allow the anode to pick up a signal. The anodes are made up of a thin wire on a Kapton foil, sweeping in a meander path and arranged orthogonally to each other. By reading the induced signals from the ends of the wire, it is possible to determine the positions of incident particles.



Spin detector.



2D CMOS Detector.

UV Source

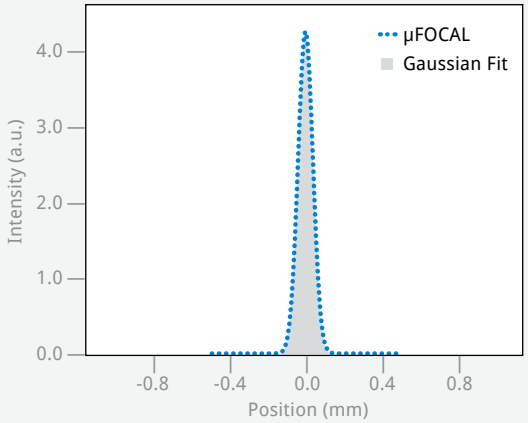
Next generation UV discharge light source based on the duo-plasmatron principle. It comes with fully UHV compatible housing made by additive manufacturing, leading to enhanced cooling efficiency and optimized plasma shape. The long filament lifetime and highly stable operation, even with heavy gases, form the perfect basis for the unique small spot operation. Adaptable to monochromators for efficient He I and He II source. Single source solution for both lines with special operation mode.

Image below shows Gaussian fitted intensity profile of UV spot generated by focused light source (μSIRIUS). Here it clearly demonstrates the low spread of the beam profile and sharp spot size < 100 μm obtained. This shows that the μSIRIUS μFOCAL optics successfully manages to achieve an extremely high photon flux density of > 3×10^{14} (photons $s^{-1}mm^{-2}$) allowing small spot based photoemission spectroscopy.

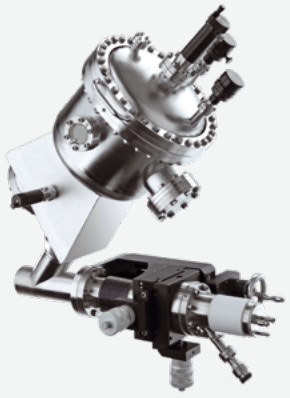
X-ray source

The small spot monochromator μFOCUS 500 operates according to Bragg's Law of X-ray diffraction. A single wavelength of X-rays is reflected from a quartz single crystal mirror at a specific angle of reflection. The mirror has a 500 mm Rowland circle diameter for μFOCUS 500. Due to its overall compactness, the μFOCUS 500 is suitable for mounting on almost any analysis chamber as a bolt-on component. The port length for μFOCUS 500 is 177 mm. A moveable aluminized polymer window (shutter) is provided on the monochromator housing for differential pumping or to shield the crystal assembly during sputtering.

The μFOCUS 500 monochromator is equipped with microfocus high performance X-ray source XR 50 MF which is specially designed for the use with the monochromator. This small spot source is equipped with an Al anode. The μFOCUS 500 monochromator together with the XR 50 MF microfocus X-ray source is perfectly suited for small spot, high resolution and high intensity XPS measurements.



Spot sizes below 100 μm.



Small spot monochromator μFOCUS 500.

Accessories

Sample stage

Momentum microscopes (KREIOS 150 MM) and electron momentum spectrometers (KREIOS 150 S) require a precise and stable sample stage for operation. The HESTIA sample stage is a true 6-axis sample stage for precise alignment of the lateral components x, y and z as well as both tilt directions and the azimuthal rotation.

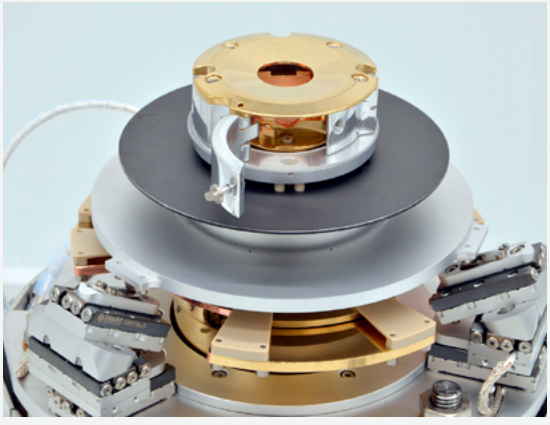
A unique design of piezo actuators allows positioning of the sample in front of the microscopy lens. An additional independent azimuthal rotation allows for fine adjustment of the detected structure, e.g. for aligning a reciprocal high symmetry direction along the entrance slit of the analyzer. The achievable sample temperature can be lower than 9 K while having a low helium consumption. A well designed cooling shield and tight thermal contact of the sample to the stage ensure highest cooling performance. The sample stage features an open cycle flow cryostat. An external closed cycle cryostat is available on request.

Hg-lamp

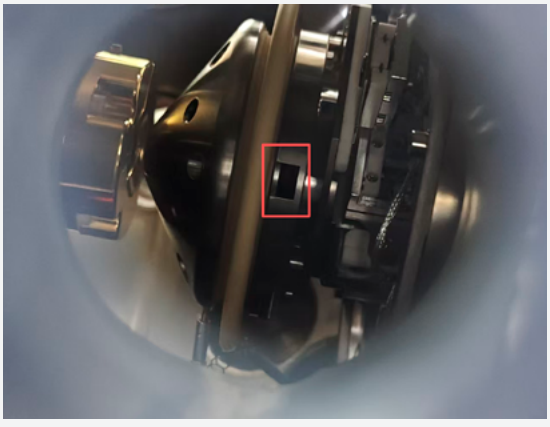
The short-arc Hg-lamp produces broadband UV radiation dominated by the characteristic mercury emission lines (notably 254 nm / 4.88 eV, and lines in the near-UV). In MM systems like KREIOS this is typically used for UV-PEEM (Photoemission Electron Microscopy) — illuminating the sample with UV light to generate photoelectrons that are then imaged by KREIOS.

Normal incidence mirror

The normal incidence mirror is an optional motorized mirror situated behind the extractor inside the objective lens of SPECS momentum microscopes like KREIOS. It enables photoemission experiments at almost normal incidence (≈ 2° from the surface normal), which is critical for certain ARPES and PEEM measurement geometries. The normal incidence mirror redirects the incident photon beam, so it arrives perpendicular to the sample surface. This is especially important for time resolved and light polarization dependent studies.



HESTIA sample stage.



Normal incidence mirror.

Software and configurations

Software SpecsLab Prodigy

SpecsLab Prodigy is a data acquisition and experiment control software package which sets a new standard in electron spectroscopy. The modular software concept allows multi-dimensional data handling, fully integrated with optional remote device controls and experiment automation.

SpecsLab Prodigy offers a modular, integrated acquisition and automation package for scientific tasks with a stunning new handling concept. This includes angle resolved photoemission spectroscopy, chemical mapping of surfaces, automation of experiments by integration of different experimental techniques and sample treatments. The software consists of a Base Package for the spectrometer control part; experiment automation modules for acquisition automation by remote device control.

Aside from the standard devices for spectrum acquisition SpecsLab Prodigy can control more than 50 external devices out-of-the-box. Additionally it offers configurable and programmable generic interfaces to support even more devices for a seamless integration into the customer's environment.

Configurations

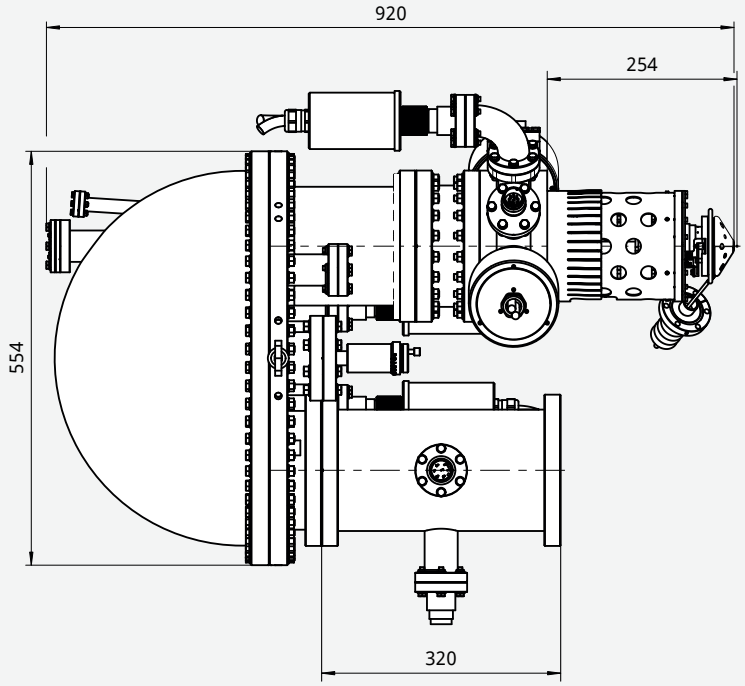
KREIOS 150 MM and KREIOS 150 S, both can be configured with identical items except a few design and application specific accessories. KREIOS 150 MM can host imaging spin filter such as the DI spin detector while KREIOS 150 S can only host non-imaging 3D-VLEED and 3D-Mott spin detectors. The other key difference is measurement technology. For KREIOS MM, both MM and PEEM mapping are direct scans whereas for the KREIOS S, MM and PEEM images are obtained by scanning.

	KREIOS 150 S	KREIOS 150 MM
HESTIA sample stage	✓	✓
2D CMOS	✓	✓
2D DLD	✓	✓
3D-Spin VLEED	✓	
3D-Spin Mott	✓	
DI Spin detector		✓
µSIRIUS | µFOCAL | Optics	✓	✓
µFOCUS 500	✓	✓
Laser	✓	✓
Synchrotron	✓	✓
Hg light source	✓	✓
HSA 3500+	✓	✓
SpecsLab Prodigy software	✓	✓
Spectroscopy	✓	
Direct MM/PEEM		✓
Scanned MM/PEEM	✓	
Switching spectroscopy /MM		✓

Technical Data

Specification	KREIOS 150 S	KREIOS 150 MM
Operation type	ARPES and PEEM	ARPES, MM and PEEM
Energy resolution	< 10 meV (5 meV)	< 25 meV (20 meV)
k-Resolution	0.008 $Å^{-1}$	0.008 $Å^{-1}$
Acceptance angle	± 90° up to 70 eV	± 90° up to 70 eV
Field of view in k	± 3.6 $Å^{-1}$	± 3.6 $Å^{-1}$
Lateral resolution	50 nm (40)	50 nm (40)
Smallest acceptance spot	2 µm	2 µm
Kinetic energy range	0–1500 eV	0–1500 eV
Pass energies	0–550 eV	0–200 eV
Lens modes	Momentum, PEEM and transmission	Momentum, PEEM and transmission
Operation modes	E vs. k E vs. x	k_x vs. k_y x vs. y Switching to E vs. k_x
Detector	2D CMOS or DLD optional 3D spin detector	2D CMOS or DLD optional spin imaging detector
Detector channels	1275 × 730 channels	1275 × 730 channels
Slits / apertures	8 entrance slits, field and contrast apertures	8 entrance/exit apertures, field and contrast apertures
Energy window	12.5% of pass energy	12.5% of pass energy
Working distance	4–10 mm	4–10 mm
Magnetic shielding	Double µ-metal shielding	Double µ-metal shielding
Electric insulation	up to 3500 V (lens), up to 29 kV (extractor)	up to 3500 V (lens), up to 29 kV (extractor)
Data format	SPECS, VAMAS, ASCII and Igor Pro	SPECS, VAMAS, ASCII and Igor Pro

Dimensions



KREIOS 150 MM analyzer; dimensions in mm

SPECS Surface Nano Analysis GmbH
Voltastrasse 5
13355 Berlin / Germany
www.specs-group.com

T +49 30 46 78 24 0
E info@specs-group.com

Version 10.26

SPECSGROUP