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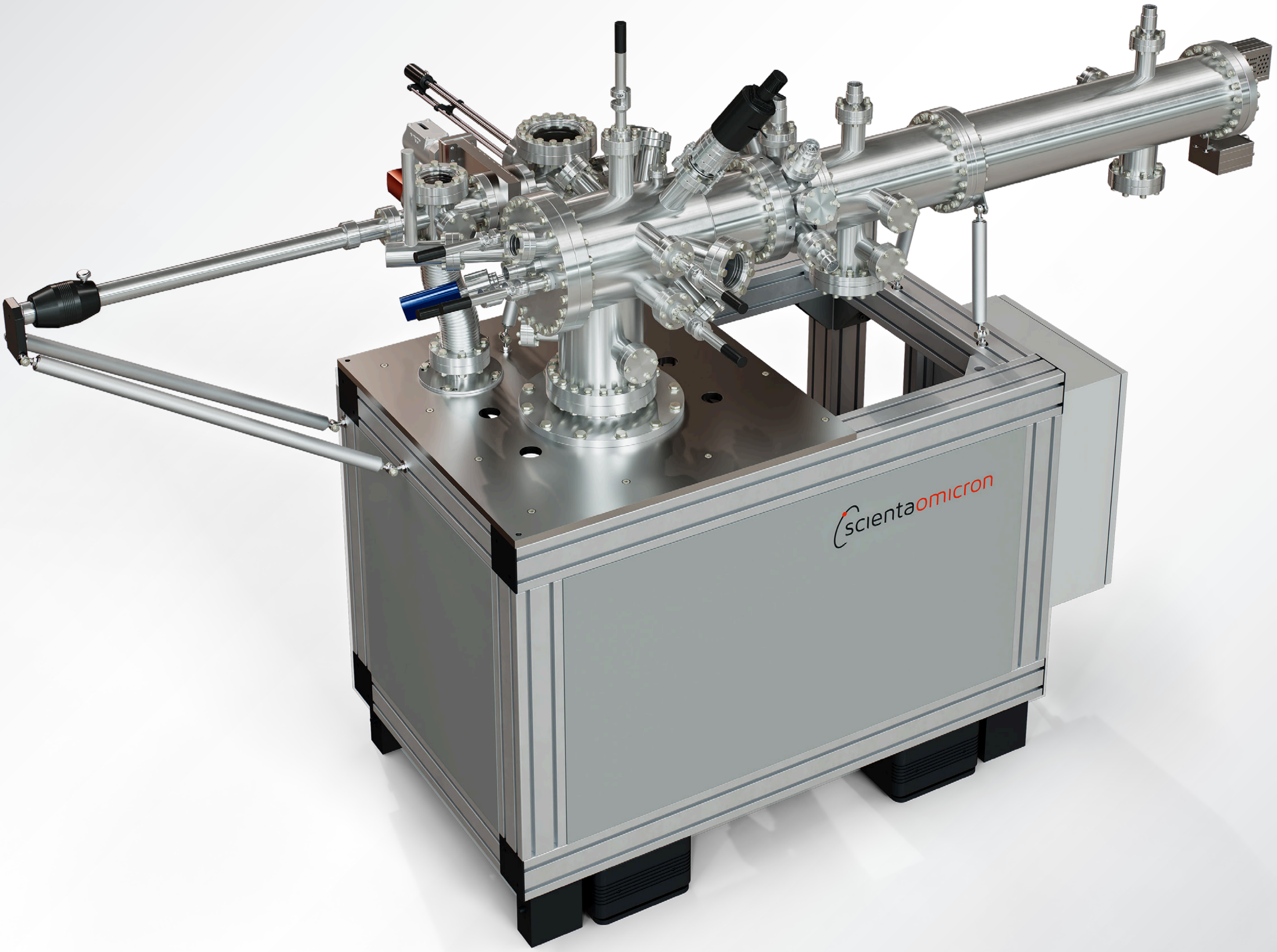
The ToF MIM

Time of Flight Momentum and Imaging Microscopy



The ToF MIM advantages:

- Best energy resolution in Momentum Microscopy
- Collection of all electrons emitted from the sample in a 3-dimensional (E_{kin} ,k_x, k_y) data cube in a single measurement
- Easy switching between real space and momentum space imaging
- Focus on any feature of interest by piezo-driven adjustable apertures

The global electronic band structure and its dynamics are of great interest in quantum materials. Scienta Omicron's Time-of-Flight Momentum and Imaging Microscope (ToF MIM) provides an efficient tool to characterise global electronic band structure and microstructure at once. It is ideally suited to study ultrafast electron dynamics in pump-probe experiments using ultrashort laser pulses.

Time-of-Flight Photoelectron Emission Microscopy

The Basics

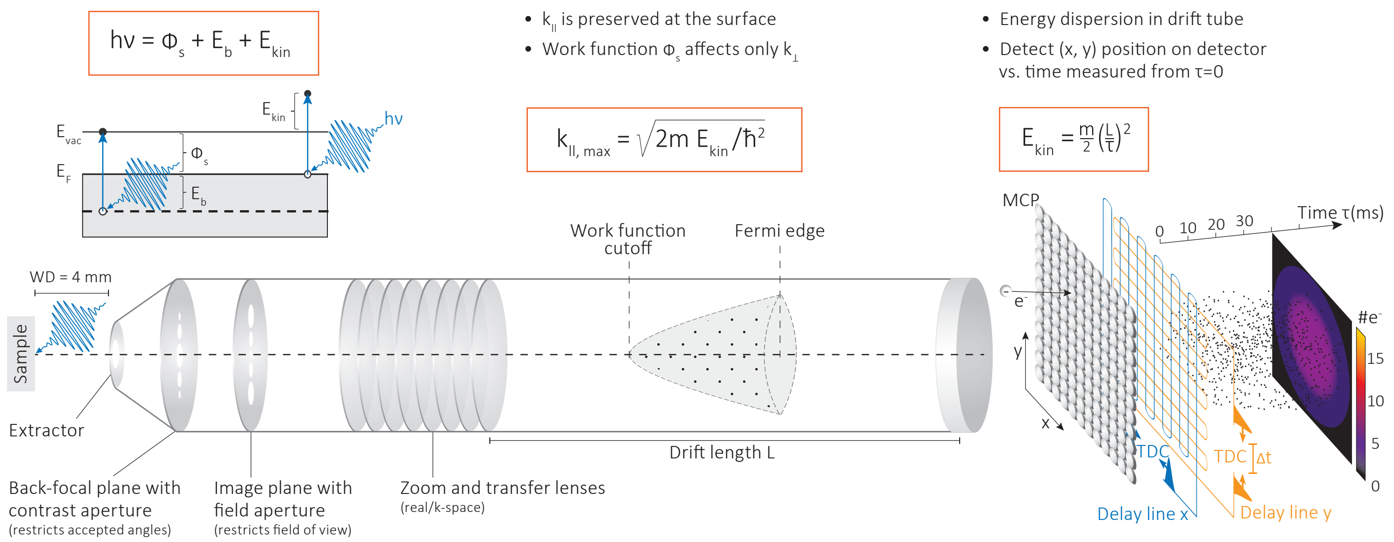


Figure 1: Schematic illustration of the ToF MIM. Photoelectrons are excited by a pulsed light source and collected into the analyser lens by a high extraction field. Two sets of laterally adjustable apertures of multiple sizes are provided to pick a field of view: the contrast aperture in the back-focal plane chooses a region in momentum space to create a real space image of the sample. It also restricts the accepted angles, thereby reducing aberration. The field aperture in the image plane selects a region of interest in real space from which a momentum image is produced. The electron optics create either a momentum or a real space image of the sample at the detector position. The kinetic energy and and position of the photoelectrons are analysed by a delay line detector at the end of the drift tube, resulting either in a momentum space (E_{kin}, k_x, k_y), or real space (E_{kin}, x, y) image of the part of the sample that has been chosen by the respective aperture.

Static Real and Momentum Space Imaging

A time-of-flight momentum microscope is an advanced photoemission instrument that records the full 3D electronic structure of a material in a single measurement (Figure 1). By combining photoelectron emission microscopy with time-of-flight energy analysis, it captures either the spatial or the momentum distribution of the emitted electrons together with their binding energies. Electrons emitted into the full 2π solid angle above the surface are collected in parallel by the extractor lens, yielding exceptional detection efficiency. Acquisition of full 3D data sets (E_{kin}, k_x, k_y) in reciprocal or (E_{kin}, x, y) in real space in one go eliminates the need to repeat measurements on different days with potentially altered conditions, which is a critical factor for accurate and reproducible science. This facilitates band-structure mapping of small sample regions on inhomogeneous samples, e.g. quantum material monolayers.

Switching between real space and momentum space mode is quick and easy, enabling efficient exploration of a region of interest and immediate access to its corresponding electronic structure. Piezo-driven contrast and field apertures allow the field of view to be adjusted precisely and without moving the sample, and the size of the field of view is easily tuned by the magnification settings of the electron optics. Precisely drilled apertures offer a well-defined, reproducible field of view with a well-defined shape in contrast to a conventional iris aperture. One can easily pick an interesting feature in real space imaging and obtain the full band structure in momentum imaging, or one can find a characteristic band feature in momentum imaging and obtain real space imaging of it (dark-field imaging). The real space field of view in momentum imaging can be as small as 1 μm using the smallest aperture size in the imaging plane. ToF MIM provides high spatial resolution (40 nm achieved) and energy resolution (17.6 meV achieved), ideal to observe fine structures (Figure 2).

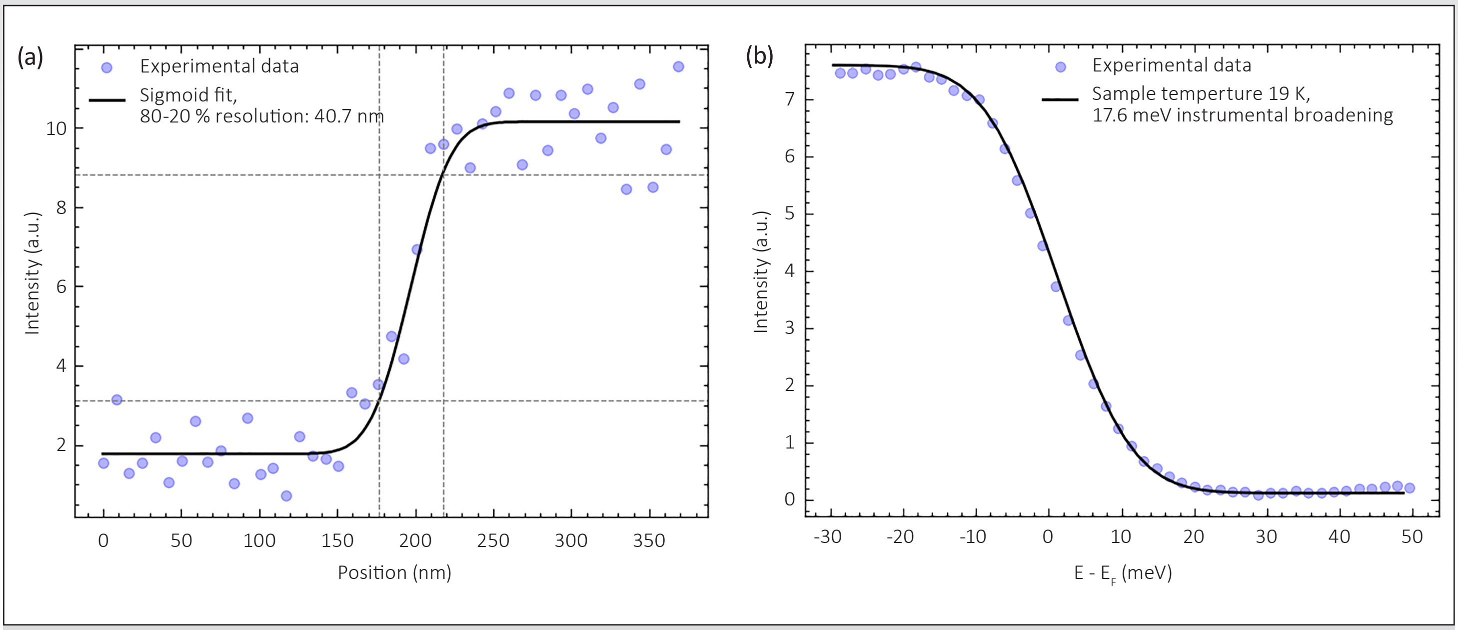


Figure 2: High resolution of ToF MIM. (a) Spatial resolution of 40 nm measured on a “Chessy” test sample with 1 µm Au squares on a Si substrate (see Figure 6). (b) Fermi edge measured on a 10 ML Au/Re(0001) sample, excitation with 15 ps laser pulses (6.4 eV photon energy, spectral bandwidth 0.2 meV, repetition rate 80 MHz). The data are fitted with a convolution of a Fermi-Dirac distribution at 19 K and a Gaussian instrument function with only 17.6 meV FWHM.

Data courtesy: (a) M. Kallmayer, Surface Concept GmbH, (b) Prof. H.-J. Elmers, University of Mainz, Germany

Capturing Ultrafast Dynamics

To understand the dynamics of hot charge carriers after optical excitation, it is necessary to follow the ultrafast dynamics in the entire E-k space. In the past, pump–probe photoemission spectroscopy setups have often lacked the photon energy required to access the entire Brillouin zone. Since the early 2000’s, big advances have been made in the generation of ultrashort laser pulses and especially in the field of High Harmonic Generation (HHG), which is even commercially available today. ToF MIM in combination with such ultrafast EUV/XUV sources now enables 4D data acquisition–energy (E), momentum (k_x, k_y), and time delay between pump and probe pulse (Δt)–providing access to global ultrafast dynamics across the full Brillouin zone.

The delay-line detector used in ToF MIM inherently requires a pulsed light source, because each light pulse serves as the timing reference for the drift-time measurement that determines the kinetic energy of the emitted electrons with high precision. This built-in timing requirement makes ToF MIM naturally compatible with ultrafast pump–probe experiments and ideally suited for studying electron dynamics at surfaces (Figure 3). Ultrafast EUV/XUV sources, such as High Harmonic Generation (HHG) or free-electron lasers (FELs), provide sufficient photon energy to release electrons from the full surface Brillouin zone, enabling comprehensive access to the electronic structure.
The high repetition rates achievable with these sources help to reduce space-charge effects and support high-throughput data collection.

A dark-field momentum microscopy mode further extends the capabilities of ToF MIM (Figure 4). This ultrafast technique enables real-space imaging at using only electrons with a selected momentum by adjusting the location of the contrast aperture, allowing researchers to directly visualize quasiparticle excitations and their temporal real space evolution on the microscale, even when the excitation is inaccessible with purely optical techniques.

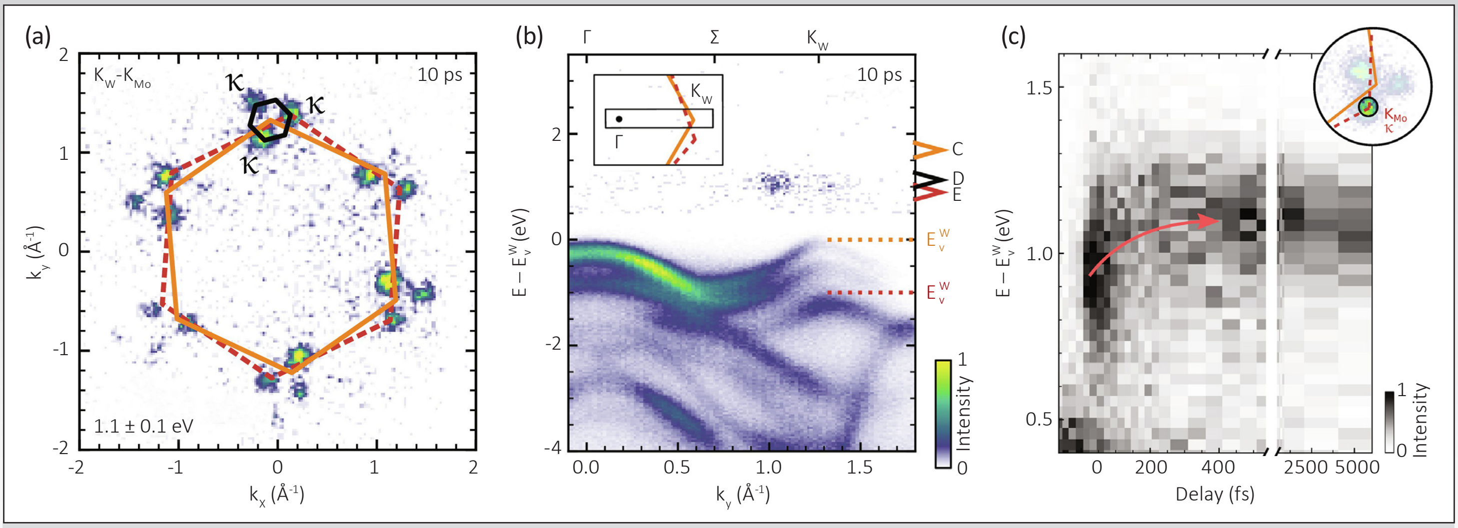


Figure 3: 4D (E, k_x, k_y, Δt) data acquisition to characterise the exciton landscape in a WSe_2 /MoS_2 heterostructure (Δt: time delay between pump and probe laser pulse). (a) k_x-k_y momentum space mapping and (b) E-k_y photoemission spectrum after resonant excitation of the excitons with 1.9 eV light pulses at a delay of 10 ps. (c) E-Δt map showing the evolution of the energy distribution curve filtered at the momentum region in the inset as a function of the time delay Δt. The probe pulse is a High Harmonic Generation (HHG) source with an excitation energy of 26.5 eV.

Data courtesy: J. P. Bange et al., Science Advances, **10**, eadi1323 (2024)

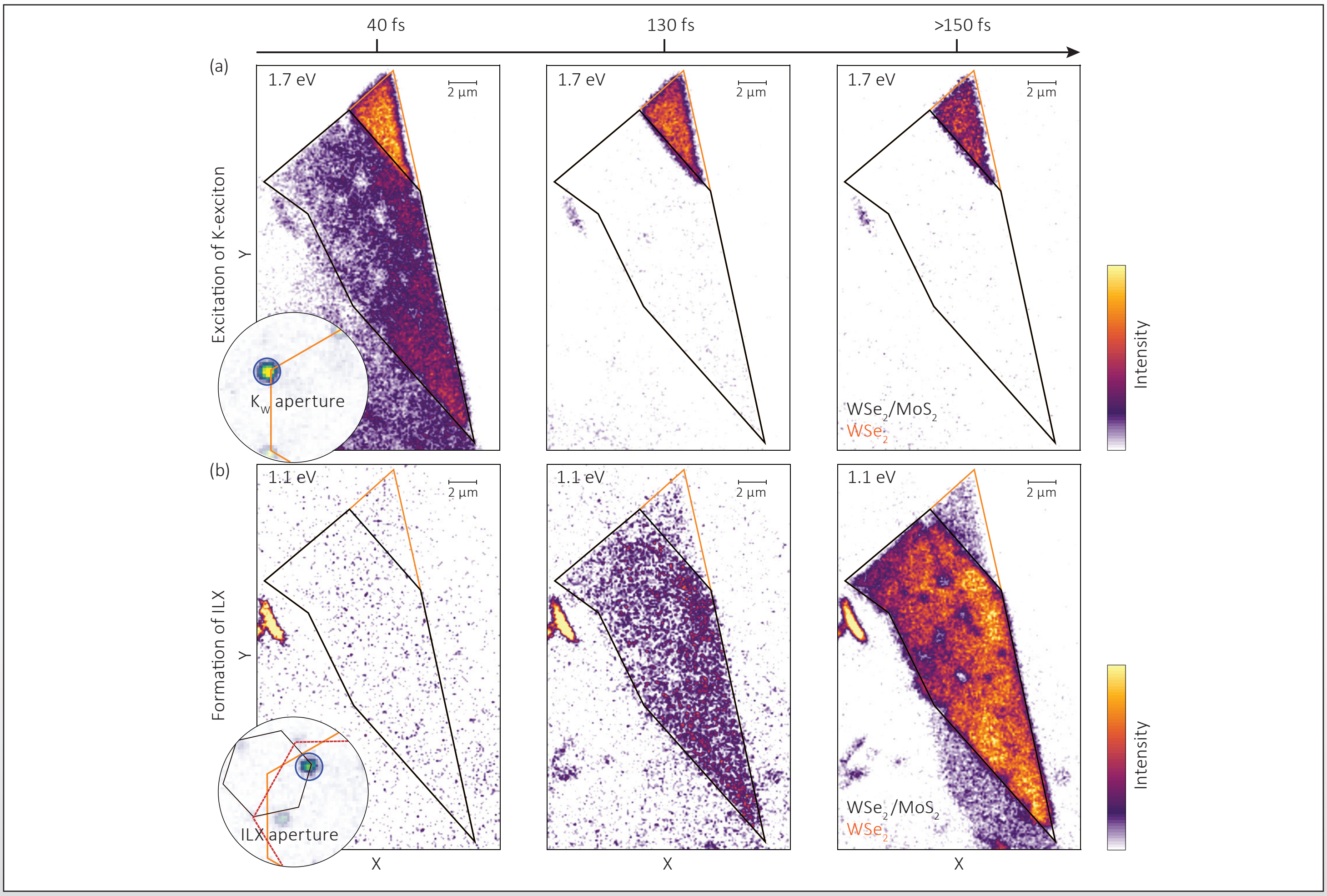


Figure 4: Dark-field momentum microscopy mode on a WSe_2 /MoS_2 heterostructure. Time- and real-space-resolved snapshots of the filtered photoemission yield from (a) bright excitons and (b) dark interlayer excitons. The circular insets show the position of the contrast aperture (blue circle) in the corresponding momentum-resolved measurement evaluated at the photoemission energies of the two excitons. The pump pulse is 1.7 eV, and the probe pulse is 26.5 eV.

Data from: D. Schmitt et al., Cambridge University Apollo Repository (2025), DOI:10.17863/CAM.115329.

Journal version: D. Schmitt et al., Nature Photonics **19**, 187 (2025).

Ready for Discovery

The ToF MIM is offered through a collaboration that combines Scienta Omicron's expertise in advanced surface analysis instrumentation with Surface Concept's leading delay-line detector technology with 20 years experience. The ToF MIM adopts the excellent delay line detector with high count rate.

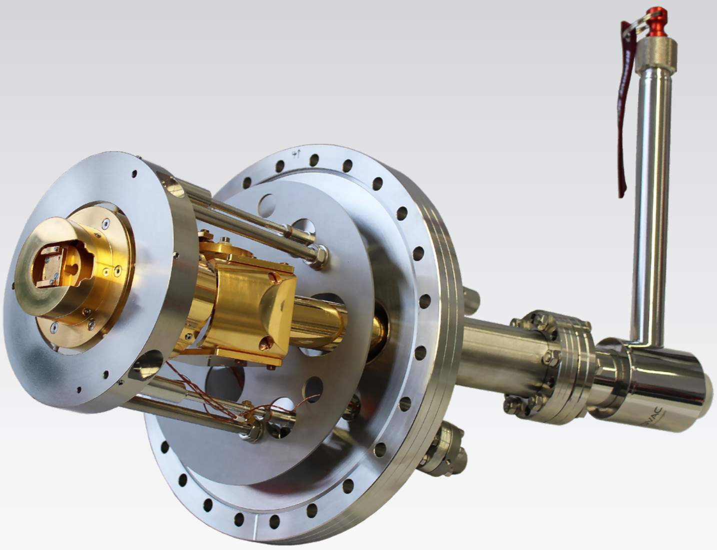


Figure 5: Hexapod sample stage with LHe flow cryostat

The sample stage is a fully motorized hexapod with ex vacuo motors and a LHe flow cryostat. Its simple and robust design enables high uptime and easy maintenance, as well as high long-term stability and precise positioning.

The software for instrument control and data acquisition is based on the widely used EPICS framework (Figure 6). Intuitive control and calculated lens voltages as starting points for further optimization facilitate the fine tuningg to obtain high-resolution data. Images and spectra can be stored either as image stacks or as a stream of events in the open HDF5 format. In the latter case, it is also possible to store additional information such as an analog input signal, e.g. from a thermocouple, a state or a counter signal together with the data stream.

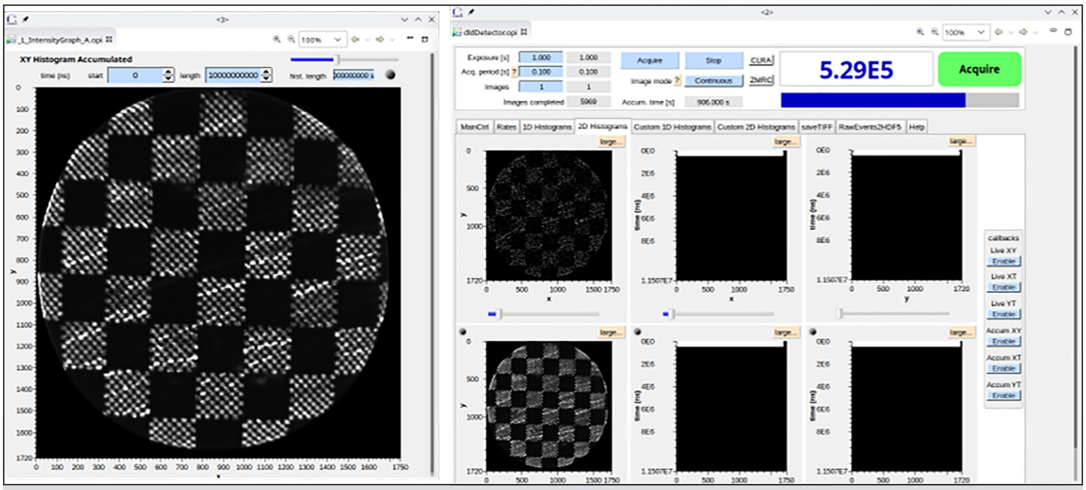
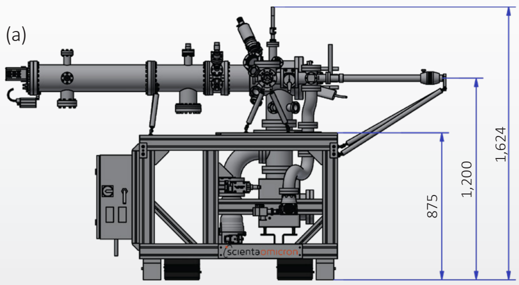
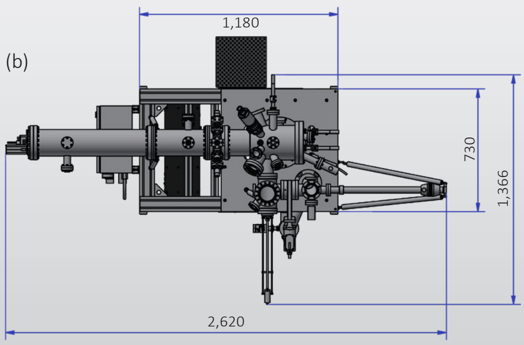


Figure 6: Data acquisition software

The system design allows many configurable options, including the option to connect the ToF MIM to Scienta Omicron's proven Multiprobe Prep module for sample preparation. The Multiprobe Prep offers ports for evaporators and other common sample preparation and characterization tools such as a sputter gun, LEED/Auger, RGA, etc., as well as the option to mount Scienta Omicron's workhorse VT-XA SPMs. This combination enables a fast cycle of sample preparation and multi-technique characterisation (Figure 7).





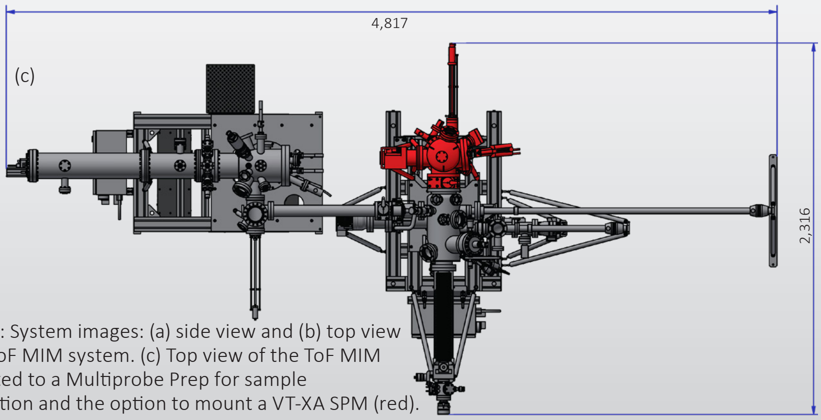


Figure 7: System images: (a) side view and (b) top view of the ToF MIM system. (c) Top view of the ToF MIM connected to a Multiprobe Prep for sample preparation and the option to mount a VT-XA SPM (red).

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Key Specifications

Max. k-space acceptance	±3 $Å^{-1}$ (Excitation energy: 40 eV)
Max. acceptance angle	±90 degrees
Momentum resolution	< 0.01 $Å^{-1}$
Min. real space field of view in k-space mode	< 1 µm (determined by field aperture)
Real space field of view	11...1,000 µm
Spatial resolution	< 50 nm guaranteed (< 40 nm achieved)
Energy resolution	< 25 meV guaranteed (< 20 meV achieved)
Drift energy range	5...500 eV (typically used: 10...30 eV)
Simultaneously focussed energy range	Up to 10 eV
Optimal light source repetition rate	250 kHz...2 MHz
Extractor voltage	80 V...29.9 kV (typically used: 6...20 kV)
Off-centered selection of real/momentum space	Possible using piezo-driven adjustable contrast/field apertures
Contrast apertures *)	9 aperture sizes + 200 mesh for alignment
Field apertures *)	14 aperture sizes + 200 mesh for alignment
Working distance	4...6 mm (typically used: 4 mm)
Max. integral count rate	5 x 10^6 cps (assuming a homogeneous distribution)
Sample stage	
Sample stage type	Hexapod with open cycle LHe cooling
Axes	• x, y, z • Azimuthal rotation • Tilt around 2 orthogonal axes All axes are motorised
Travel range	5 mm x 5 mm x 5 mm
Travel accuracy	1 µm
Azimuthal rotation	±5° (Optional upgrade: ±90°)
Tilt rotations	±2°
Lowest temperature with LHe cooling	< 15 K guaranteed (< 9 K achieved)
Highest temperature	400 K (counter heating)
System integration	
Laser port	DN63CF (horizontal)
Pump configuration	Ion getter (300 l/s) and Ti sublimation pump Optional: turbo-molecular pump (260 l/s)
Guaranteed pressure	$3x10^{-10}$ mbar
Options	
Alignment and verification of system health	UV LED
Sample bias	Electrical sample contacts
Normal incidence mirror	Compact mirror integrated into the electron optics allows access under 5° off the sample normal
Spin resolved measurement	Parallel spin imaging based on the spin-dependent reflectivity of a Au/Ir target

*) All piezo-driven apertures are adjustable in x and y.

Get in touch with us at **info@scientaomicron.com**