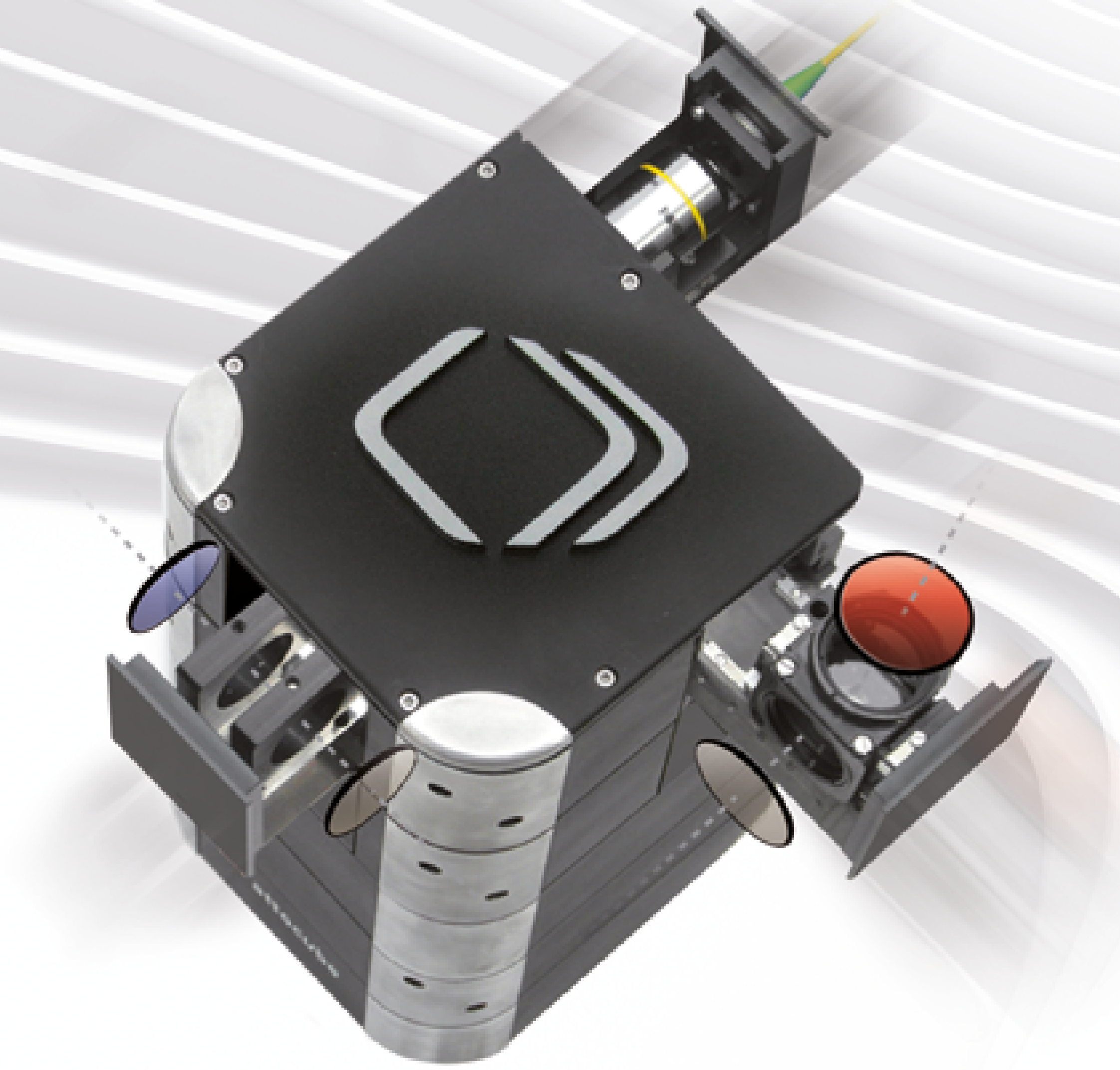
attocube
WITTENSTEIN Group



attocube systems AG | Königinstrasse 11a | D - 80539 München | Germany
Tel.: +49 89 2877 809 - 0 | Fax: +49 89 2877 809 - 19 | info@attocube.com
www.attocube.com

Brochure version: 2018 - 01

attocube
WITTENSTEIN Group



# attoCFM

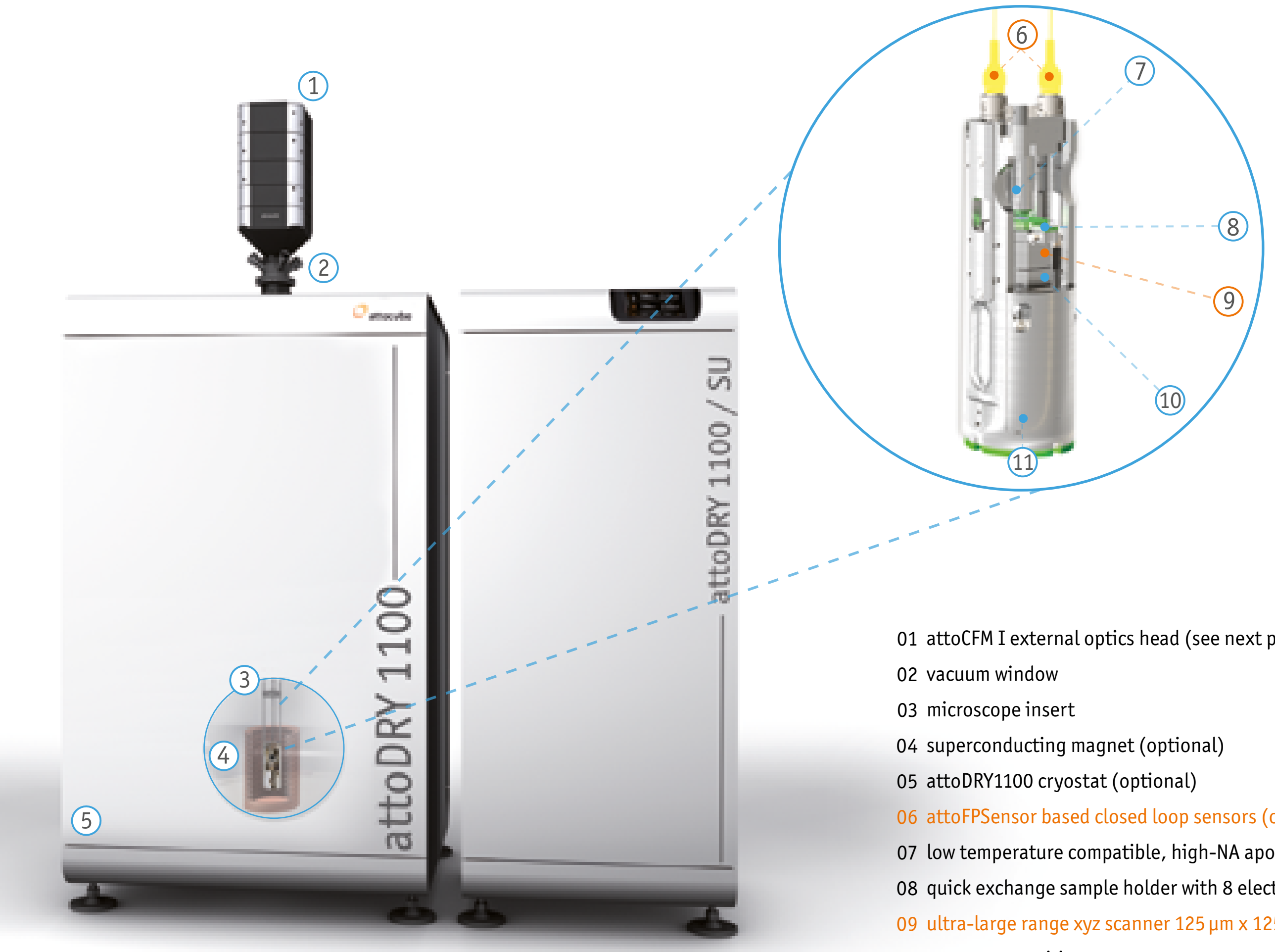
## Multichannel Low Temperature Confocal Microscopes

attoMICROSCOPY
Sophisticated Tools for Science

# attoCFM I

## low temperature confocal microscope, free-beam optics

The attoCFM I has been developed to offer a maximum amount of flexibility for a convenient adaptation to a large number of different quantum optics applications. This is realized by an external optics head, positioned outside the cryostat. Furthermore, the free-beam optical design allows for completely independent adjustment of the excitation and collection port. Therefore, applications such as Raman spectroscopy become accessible by appropriately filtering of the excitation and detection signals. The easy handling opens up new possibilities in quantitative surface characterization in the sub-micron range. The attoCFM I can optionally be equipped with an interferometric encoder for closed loop operation with 1 nm resolution, and an ultra large range scanner with 125 µm scan range at 4 K.




*Schematic drawing of the low temperature attoCFM I and the attoDRY1100 cryostat (optional)*

01 attoCFM I external optics head (see next page for details)
02 vacuum window
03 microscope insert
04 superconducting magnet (optional)
05 attoDRY1100 cryostat (optional)
06 attoFPSensor based closed loop sensors (optional)
07 low temperature compatible, high-NA apochromatic objective
08 quick exchange sample holder with 8 electrical contacts
09 ultra-large range xyz scanner 125 µm x 125 µm x 15 µm @ 4 K (optional)
10 xyz coarse positioners 5 mm x 5 mm x 5 mm
11 ultra stable titanium housing

### Available Upgrade Options

- closed loop scanning & global sample coordinates
- ultra large scan range (125 µm @ 4 K)
- closed loop upgrade for positioners

*...for further details, see accessories section*

### PRODUCT KEY FEATURES

- low temperature apochromatic objectives with NA up to 0.82
- quick exchange sample holder with 8 electrical contacts
- sample monitoring via CCD camera (field of view: 50-75 µm)
- interferometric encoders for closed loop scanning with 1nm resolution (optional)
- 125 µm scan range @ 4 K (optional)
- optical setup offering highest flexibility
- modular beam splitter head outside of cryostat
- wavelength and polarization filtering of the excitation and collection signal possible
- large coarse positioning range at low temperatures
- interferometric optional encoders for closed loop scanning (optional)

### BENEFITS

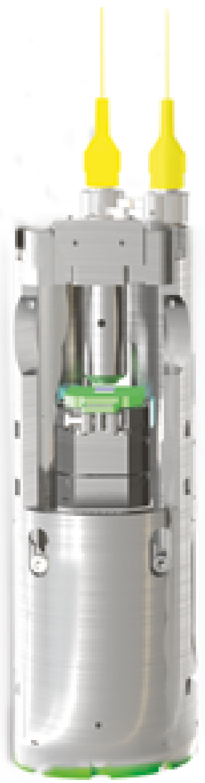
- fits standard cryogenic and magnet sample spaces
- very broad variety of applications, ranging from classical CFM measurements to Raman spectroscopy
- excellent stability in high magnetic fields
- highest measurement sensitivity
- access to a large area on the sample surface
- easy tracking of regions of interest & distortion-free images (closed loop scanning; optional)

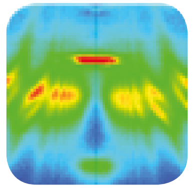
### APPLICATION EXAMPLES

- solid state physic and quantum dot optics
- fluorescence, photoluminescence and photoconductivity of quantum dots, nanowires, 2D-layered materials, photonic crystals, single molecules

### COMPATIBLE COOLING SYSTEMS

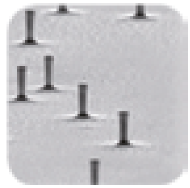
- attoDRY700/1000/1100/2100
- attoLIQUID1000/2000, attoLIQUID3000/5000 (on request)





*Quantum Dot Spectroscopy*

*Magneto-optical Kerr effect (MOKE)*



*Cryogenic Photolithography*

# Retrieve nano-features over millimeter ranges!

closed loop scanning & global sample coordinates

Science and technology delve deeper and deeper into the nanoworld. In particular, scanning probe & confocal microscopy have been concerned with features on the nanoscale ever since its invention. Reliably scanning over tens of micrometers range down to a few hundred nm is comparatively easily achieved by using piezo based scanners.

However, using piezo-based scanners usually relies on the assumption that the relation between applied voltage and displacement is linear. In reality, most scanners show large non-linear behaviour and hysteresis, especially for large scan ranges. Creep, i.e. drift in position after approaching a certain location, is a further phenomenon which is common to all piezo scanners.

In many experiments, reproducibly locating a small feature on a surface is crucial, and sometimes hysteresis and non-linearity in the acquired image are not acceptable. Sometimes, SPM images need to be evaluated for particularly and for the specific mutual distances of certain features, and hence, any distortions due to those nonlinearities may impede such analyses significantly.


Much more often, however, finding a certain region of interest or a particular feature on a macroscopic sample at all, or retrieving such locations repeatedly is a critical task.

Based on our patented FPSensor, a fiber-based interferometer, our microscopes can now be equipped with position closed loop sensors with featuring a steady-state resolution of down to 1 nm even in a, despite the cryogenic working environment.

At the same time, we implemented a fully digital scan engine in the ASC500 SPM controller, which now features location based data acquisition (as opposed to time-triggered data acquisition on open loop systems). In closed loop mode, this results in perfectly linearized images. The sophisticated scan engine even allows for an adjustment of the scan acceleration to smoothen the scanning motion at the turning points, which can be is especially useful especially for higher scan speeds.

The most useful new features however is that since the FPSensor covers the full 5 mm x 5 mmm range of the positioners, the scan widget now contains 'global' sample coordinates: usually, the maximum range accessible in closed loop mode is limited by the maximum range of the scanners. If the user wants to scan outside of this area, he can simply use the global sample coordinate system for navigation. To further facilitate this, any measured SPM images can simply be decorated onto the scan widget's sample 'canvas' via drag-and-drop, where they are put exactly at the measured coordinates. Hence, a virtual map of the whole sample gradually evolves within the scan widget.

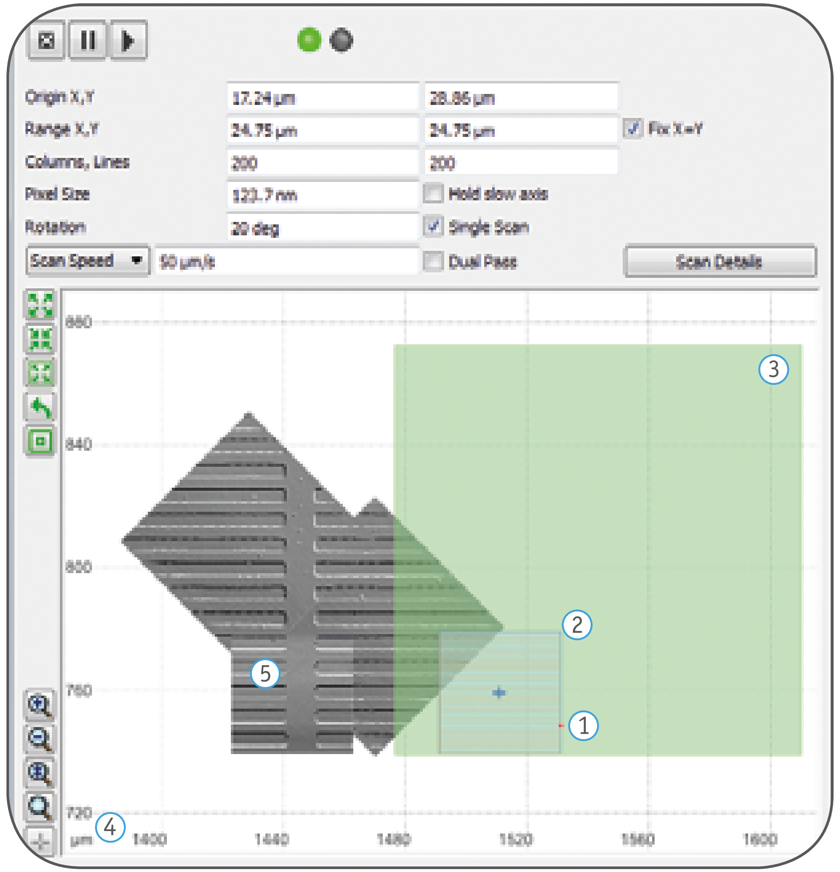
Retrieving regions of interest on the nanoscale, which has always been extremely difficult and time consuming especially at low temperatures, is now an easy task thanks to this global sample coordinate system.

> **CUSTOMER FEEDBACK**
>
> Prof. Dr. Peter Michler
>
> *Our attoCFM I LT-lithography setup is not only the best choice when it comes to stability requirements. Its closed loop scanning feature also allows us to optically pre-select quantum dots suitable for desired experiments and mark them in-situ via lithography with nanometric precision.**
>
> *(University of Stuttgart, Germany)*

*For more details, see*
**[1] Sartison et al. Scientific Reports 7, 39916 (2017)*

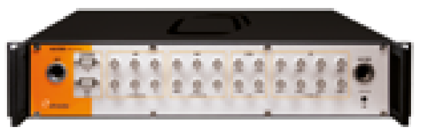
# CFM with Built-In Sample GPS

closed loop scanning & global sample coordinates




01 SPM tip position indicated by red dot
02 current scan area
03 max. scan range at this position
04 global sample coordinate system
05 SPM image decoration in global sample coordinate system

ASC500
fully digital SPM Controller



# attoCFM I External Optics Head

flexibility you would only expect from room temperature equipment

The external optics head of the attoCFM I has been designed with the goal to offer a maximum amount of flexibility and mechanical stability. At the same time, it provides an unmatched ease-of-use through clever and convenient features for alignment and exchange of optical components.

The head consists of two or more identical optical channels, each of which can be independently configured for excitation or detection of optical signals. Each channel features an FC/APC fiber port (removable for free-beam coupling), a collimator (adjustable for different wavelengths), easily accessible theta/phi tilt mirrors, removable drawers for exchangeable filters, and a exchangeable beam splitter mount.

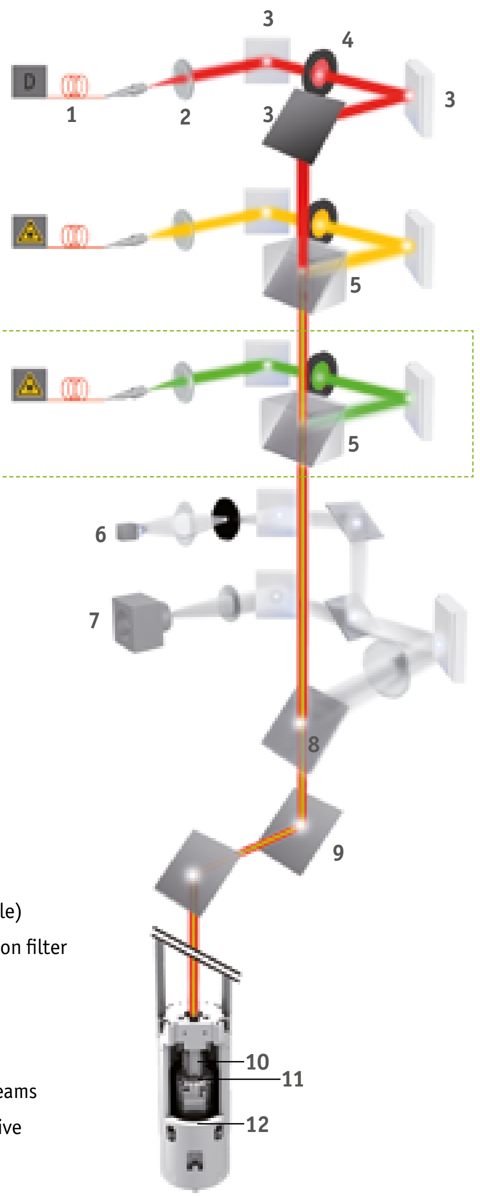
The concentric optical beams of all channels can be guided altogether via a steering mirror, before they enter (or leave) the cryostat insert through an optical window on top of the microscope insert. Besides, the head includes a convenient and powerful inspection optics with CCD camera.
In fact, with this head, the attoCFM I for cryogenic operation offers a flexibility and convenience usually only seen in room temperature instruments.

Detection channel (e.g. Si detector for photoluminescence/ fluorescence, or a grating spectrometer)

Excitation channel

Optional: additional excitation channel (e.g. for lithography)

Optical inspection unit




COMPONENTS

01 FC/APC fiber port
02 Collimator
03 Mirror
04 Up to two filter mounts (optional) or rotatable polarizer (optional)
05 Dichroic beam splitter (exchangeable) with optional laser filter and detection filter
06 LED illumination (broadband)
07 CCD camera for inspection
08 Beamsplitter
09 Steering mirror for the combined beams
10 Low temperature compatible objective
11 Sample
12 XYZ coarse positioners + XY scanner

# Set up your own experiment

flexibility you would only expect from room temperature equipment

This figure gives an overview of all options regarding filters, beamsplitters and rotators, which can be configured for every channel of the attoCFM I separately.


1. Collimator -> beam diameter ~ 5 mm optional free-beam coupling (also in conjunction with attoDRY1000/1100 see next page); easily adjustable for different wavelengths (single mode fibers)
2. FC/APC coupled single mode fiber to/ from excitation laser or detector/ spectrometer serves as blocking pinhole in confocal detection covering the following ranges: 305 - 450 nm; 405 - 532 nm; 450 - 600 nm; 600 - 800 nm; 780 - 970 nm; 970 - 1650 nm; 1260 - 1620 nm
3. Beamsplitter position easily switchable from outside: remove from beam to disengage channel
4. Two additional filter mounts on beamsplitter cube: up to two 1" filters (thickness < 11 mm) or SM1 threaded lens tube filters
5. Beamsplitter options
Default: modified Zeiss cube, compatible with any plate beamsplitter of dimensions 25.2 mm x 35.6 mm x 1.05 mm (e.g. dichroic beamsplitters 400-800 nm center wavelength)
6. Optional: polarizing beamsplitter cube
7. Optional: non-polarizing beamsplittercube
8. Filter drawer: up to two 1" filters (thickness < 11 mm) or SM1 threaded lens tube filters optional rotator with/without encoder and 1" filter mount (thickness <12 mm)
9. Theta/phi mirrors for each channel easily adjustable from the outside

# Cryogenic Compatible Achromatic High NA Objectives

maximum collection efficiency, low focal displacement

Many high spatial resolution spectroscopy measurements, such as confocal micro-luminescence, fluorescence & micro-Raman require cryogenic temperatures, where conventional room temperature objectives cannot be employed.

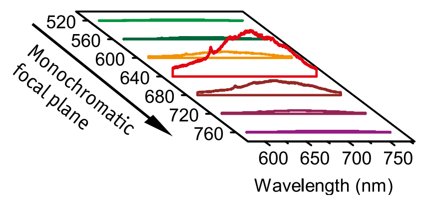
Now, attocube offers two versions of apochromatic objectives for low temperature operation. Whereas one version features high numerical apertures (NAs) of 0.81-0.82 within six color bands ranging from the UV to the IR, the other line of apochromatic objectives boosts the working distance to 5.0 mm while maintaining high NA of 0.63-0.65.

The key features of all apochromatic objectives are their small chromatic shifts. Optimized for diffraction-limited performance in the respective design wavelength ranges of 350-395, 405-470, 465-590, 565-770, 700-985 and 985-1350 nm, the LT-APOs keep the focal plane within one depth of focus and thus ensure both uniform spot size and constant collection efficiency for all colors within the apo-range. The series of LT-APO-LWDs combine this performance with a long working distance. Take a look at the overview on the right side to see how your application can benefit from the new LT-APOs and LT-APO-LWDs!

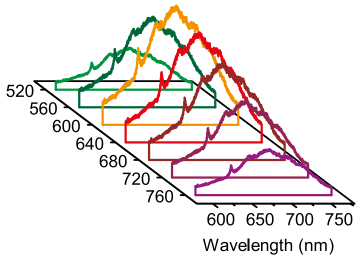
The operation of both lines is optimal when paired with RT-APO broadband collimators, designed exclusively to match the collimated beam to the clear apertures of LT-APOs and LT-APO-LWDs and to provide highest transmission of 99% over broad spectral ranges..

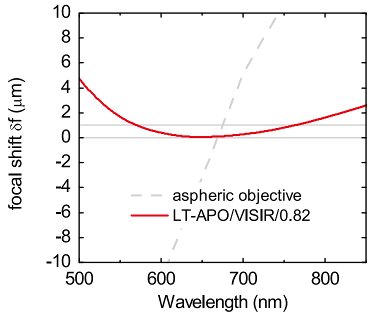
To illustrate the main advantages, see below performance simulations compared between an aspheric objective and a LT-APO. The spectra are plotted for different focal planes, each set by monochromatic best focus for a given wavelength (see the 3rd graph on the right for the so-called chromatic focal displacement or focal shift of both objectives which describes how the focal plane depends on the wavelength used to identify best focus). In actual experiments, the focal plane is defined by the user with a wavelength of his choice. The effect of different choices of alignment wavelengths (in equidistant steps on the axis 'monochromatic focal plane') is exemplified by the simulations in the two graphs on the left for the spectrum of negatively charged NV-color centers in diamond. Compare the spectra you would measure with a single aspheric lens (left panel) and the LT-APO-VISIR/0.82 (central panel), both operated in best monochromatic focus. Note the faithful spectra obtained with the LT-APO-VISIR/0.82 for a broad range of alignment wavelengths!

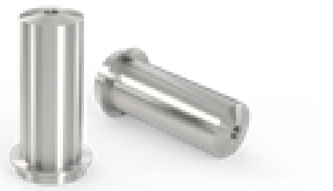
aspheric lens (NA = 0.65)




LT-APO (NA = 0.82)

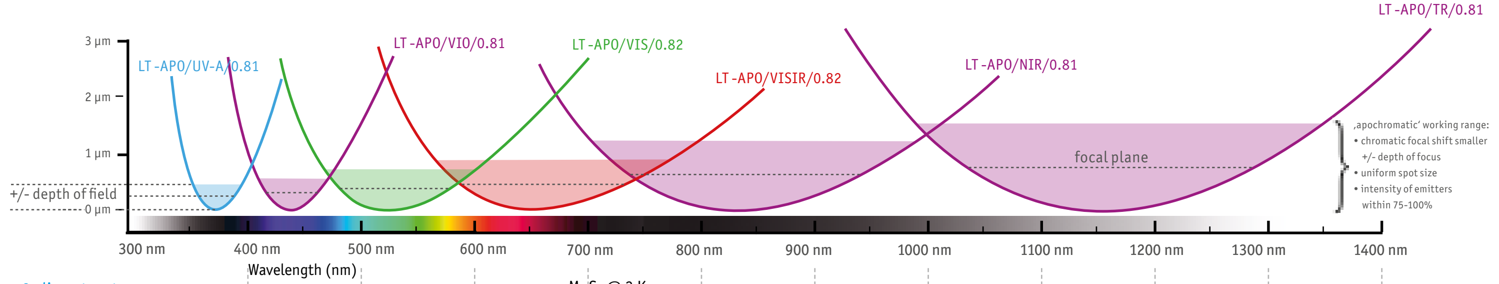


# LT-APO objective ranges

chromatic focal shift & wavelength ranges of typical emitters



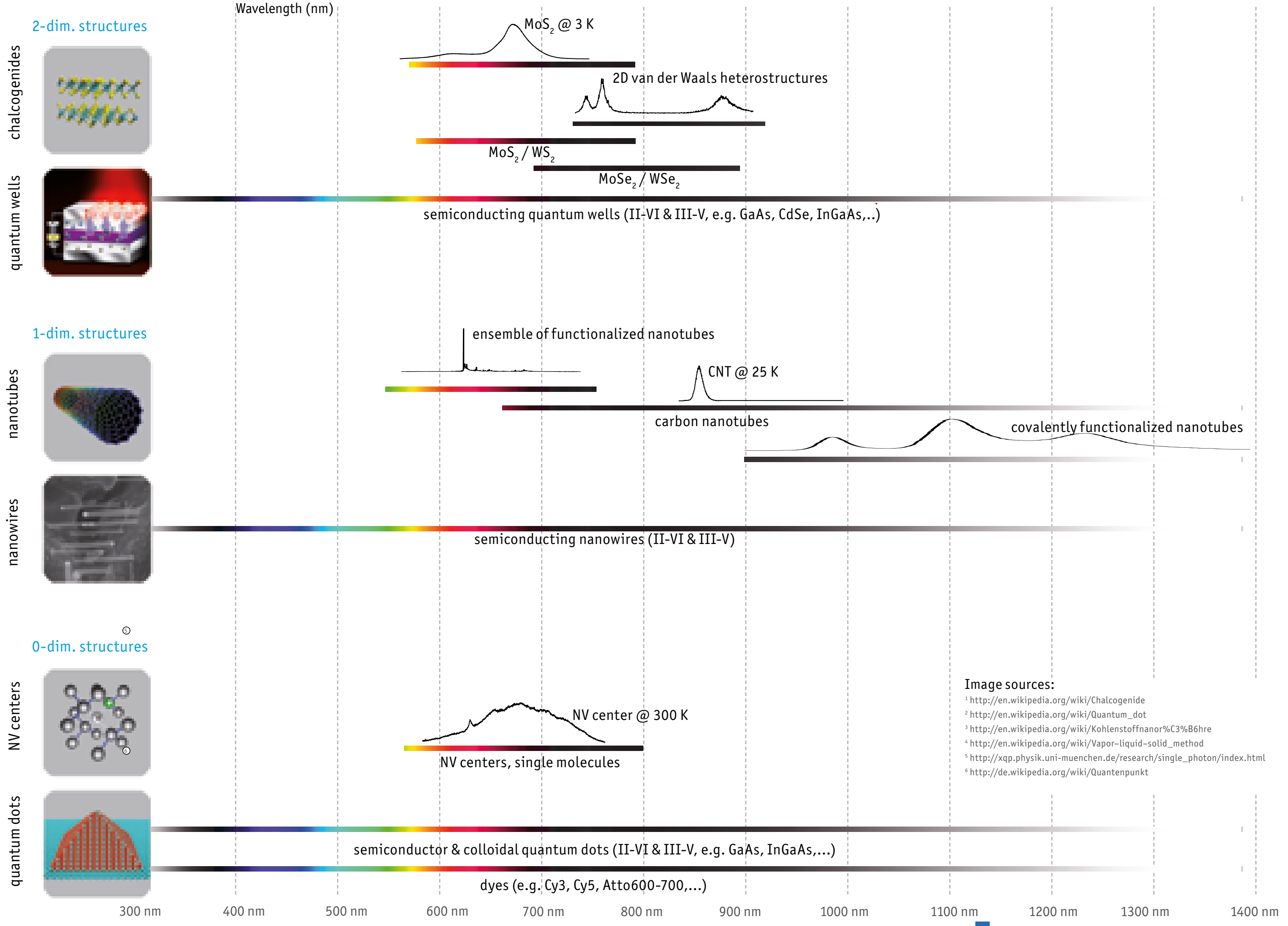




Image sources:

[1] http://en.wikipedia.org/wiki/Chalcogenide
[2] http://en.wikipedia.org/wiki/Quantum_dot
[3] http://en.wikipedia.org/wiki/Kohlenstoffnanor%C3%B6hre
[4] http://en.wikipedia.org/wiki/Vapor-liquid-solid_method
[5] http://xqp.physik.uni-muenchen.de/research/single_photon/index.html
[6] http://de.wikipedia.org/wiki/Quantenpunkt

# Voigt & Faraday Geometry

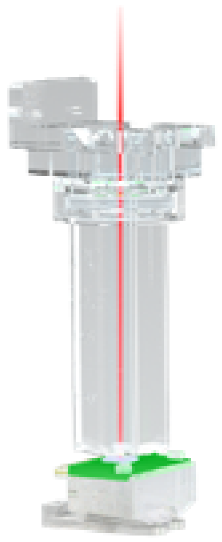
attoCFM I configurations

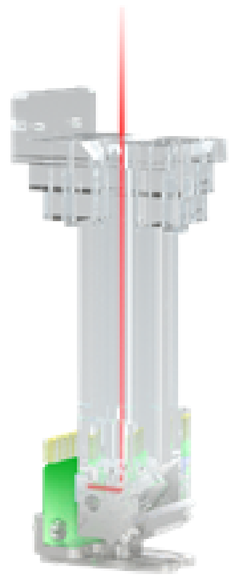
For many samples studied with confocal microscopy under magnetic fields, switching between the out-of-plane (Faraday) and in-plane (Voigt) geometry reveals inter-esting differences in behavior. Our new ASH/QE/4CX/CFM sample holder in conjunction with the LT-APO and Voigt objectives respectively allows to study both configurations for one sample within only a few minutes for switching between both set-ups ex-situ (i.e. after warming up the microscope insert).

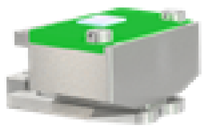
In Faraday geometry, the sample is aligned horizontally, such that the vertical magnetic field of a typical single solenoid (such as in the attoDRY1000/1100/2100) is out-of-plane. In this configuration, any of the LT-APO objectives can be used. In Voigt geometry on the other hand, the PCB that hosts the sample is mounted vertically parallel to the magnetic field onto the quick exchange slider, and the LT-APO is exchanged by the Voigt-IWDO objective. The latter takes care that the optical beam is deflected by 90° into the horizontal direction, and focused onto the sample by the IWDO lens.

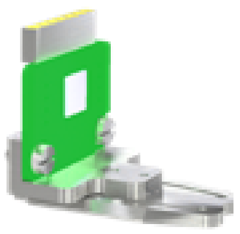
The ASH/QE/4CX/CFM sample holder consists of a base plate including a calibrated temperature sensor and a heater, and a quick exchange slider for the sample PCB in two alternative configurations. In addition, it features 8 electrical contacts on the PCB, which is identical for both configurations. Hence, upon switching from Faraday to Voigt, no rebonding of the sample wires is required – only the PCB is unmounted from the Faraday holder, and remounted on the Voigt holder plate.

Only the 8 pin connectors for the wiring need to be unplugged and re-connected. Typically, the 8 pins are connected to 4 coaxial wires in our microscope insert, that terminate in a vacuum feedthrough with SMA connectors on the outside.Both configurations are compatible with the closed loop scanning option (attoFPS based interferometer with 1 nm resolution). In case a scanner is required, the large range scanners ANSxy100/lr and ANSz100/lr yield a combined scan range of 50 µm x 50 µm x 50 µm @ 300 K or 30 µm x 30 µm x 30 µm @ 4 K, and hence allow for horizontal or vertical scans with the same full range of 50 µm in either configuration.









Faraday geometry

Voigt geometry

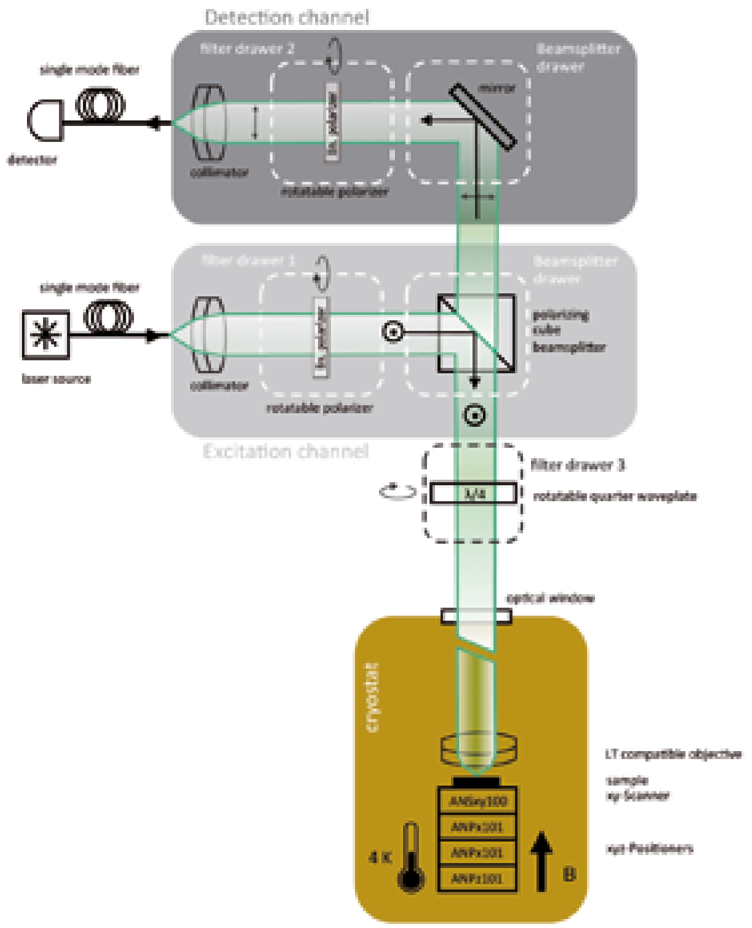
| Technical Specifications of Voigt-IWDO Objective | |
|---|---|
| clear aperture | 5.0 mm |
| numerical aperture (NA) | 0.68 |
| working distance (WD) | 1.5 mm |
| spectal range[1] | 400..1600 nm[1] |
| objective type | aspheric |
| compatibility | attoCFM I |

| Related Articles for Voigt Geometry Upgrade | Art. No. |
|---|---|
| Voigt-IWDO objective for the attoCFM I | 1007621 |
| ASH/QE/8/CFM incl. base plate with temperature sensor & heater as well as Faraday slider, Voigt slider and 3 PCB with 8 electrical contacts) | 1012172 |
| ANSxy100lr/LT large range xy-scanner | 1000352 |
| ANSz100lr/LT large range z scanner | 1005230 |

# Upgrade Package: Polarization Extinction

for resonant fluorescence excitation

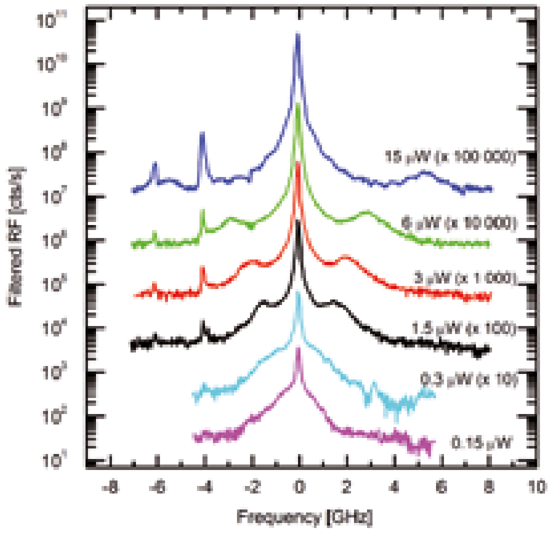
Using a technique called polarization extinction, one gains access to resonance fluorescence, which is of utmost importance in the study of semiconductor quantum dots, color centers in diamond, and novel materials of great interest such as silicon carbide and single molecules. The excitation laser is polarized such that it is reflected by a polarizing beam splitter (s) towards the sample. The back reflected light of the laser is then blocked by the same polarizing beam splitter and further suppressed, to obtain an extinction ratio of up to $10^7$ with the attoCFM I. The fluorescence occuring at the same optical (i.e. resonant) wavelength, but different polarization (p) can be detected. For the purpose of alignment and calibration a rotatable quarter waveplate is mounted in the combined optical path down to the cold sample.

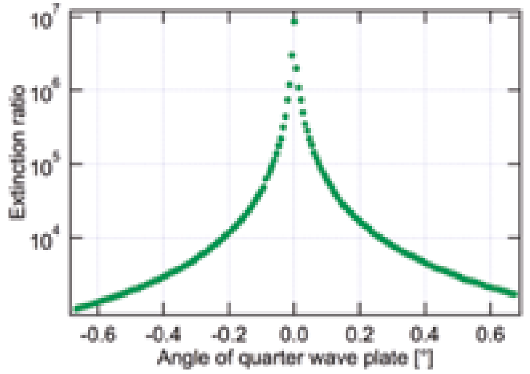



## Configuration

| | |
|---|---|
| Excitation channel | rotatable polarizer* |
| beamsplitter | polarizing beamsplitter cube |
| Detection channel | rotatable polarizer* |
| extinction ratio | up to $10^7$ depending on the laser (not included) |
| Combined beam | rotatable quarter waveplate* |
| wavelength range(s) | 480-550 nm, 500-600 nm, 565-770 nm, 700-1000 nm |

*closed loop rotation incl. electronics & software control




## Resonant Spectroscopy on a Single Quantum Dot

Spectroscopy of semiconductor quantum dots (QDs) under **resonant optical laser excitation** and of other single photon emitters, such as vacancy-centers often yields more information about the emitters than more ubiquitous non-resonant excitation. However, it is a technically challenging measurement to perform. The difficulty lies within the separation of the excitation laser photons from the re-emitted and scattered photons. One way in which this can be achieved is by means of polarization suppression: in a geometry where the scattered laser photons have a well-defined polarization, they can be filtered from the detected signal facilitating the detection of resonance fluorescence (RF) of a single quantum dot or any other quantum emitter.

The attoCFM I can be upgraded with a **resonant fluorescence package (see left page)**, which features an apochromatic performance that permits alignment free switching between off resonant PL measurements and RF. This feature is fully enabled by our novel cryogenic compatible apochromatic objectives designed to hold the focus plane at the same position on the sample independently from the photon wavelength.

For the first this time combines the use of high precision rotators with the flexible beam management confocal head attoCFM I. It provides extinction ratios of $10^7$, just a factor 10 away from the world record in research labs [1] while allowing an unprecedented flexibility of use.

The **top figure** shows the resonance fluorescence of a quantum dot measured with the attoCFM I equipped with the **Polarization Extinction** Option and a narrow band tunable laser. In order to resolve the Mollow triplet, the emission is filtered through a high resolution spectrometer. Here, the extinction ratio exceeds $10^6$, using the low temperature near infrared apochromatic objective LT-APO\NIR.

The **bottom figure** shows the extinction ratio of the **Polarization Extinction** option for the attoCFM I as a function of the rotation angle of the inbuilt piezo rotator equipped with a quarter wave plate. In an angular region of 30 m° an extinction of more than $10^6$ can be reached with a tunable narrow band diode laser (<1 pm line width).

*[1] A.V. Kuhlmann et al., Review of Scientific Instruments 84, 073905 (2013).*

*(Measurement and data by E. Kammann[1], S.H. E. Müller[1], K. Puschkarsky[2], M. Hauck[2], S. Beavan[2], A. Högele[2], and K. Karrai[1], [1]attocube systems AG, Munich, Germany, [2]Ludwig Maximilian Universität, Munich, Germany)*

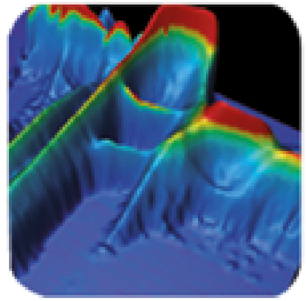
# Specifications

attoCFM I

| | |
|---|---|
| **General Specifications** | |
| type of instrument | free-beam based room temperature optics head coupled to low temperature objective |
| sensor head specifics | unique low temperature compatible achromatic objectives with high numerical aperture, optimized for different wavelength ranges |
| **Confocal Unit** | |
| configuration | compact and modular design, two or more optical channels<br>standard configuration: 1 excitation channel,1 detection channel |
| quick-exchange of optical components | beamsplitters, filter mounts for up to 4 filters/ polarizers (1" diameter), optional piezoelectric rotator with filter mount |
| LT- compatible objective | LT-APO/VIS, LT-APO/VISIR, LT-APO/NIR<br>(see accessory section for more information) |
| inspection unit | sample imaging with large field of view: ~75 µm (attoDRY), ~56 µm (attoLIQUID) |
| **Illumination** | |
| excitation wavelength range | 400 .. 1000 nm<br>default: 650 nm (others on request) |
| **Detection** | |
| detection mode | e.g. reflection, luminescence, flourescence, Raman (optional) |
| **Sample Positioning** | |
| total travel range | 5 x 5 x 5 mm³ (open loop) |
| step size | 0.05..3 µm @ 300 K, 10..500 nm @ 4 K |
| fine scan range | 50 x 50 µm² @ 300 K, 30 x 30 µm² @ 4 k (optional, open loop) |
| closed loop scan resolution (steady state, 100 ms sample time) | 1 nm rms typ. |
| sample holder | ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts and integrated heater with calibrated temperature sensor |
| **Suitable Operating Conditions** | |
| temperature range | 1.5 K..300 K (dependent on cryostat); mK compatible setup available on request |
| magnetic field range | 0..15 T+ (dependent on magnet) |
| operating pressure | designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request) |
| **Suitable Cooling Systems** | |
| titanium housing diameter | 48 mm |
| bore size requirement | designed for a 2" (50.8 mm) cryostat/magnet bore |
| compatible cryostats | attoDRY1000/1100/2100<br>attoLIQUID1000/2000 (attoLIQUID3000/5000 on request) |
| **Electronics** | |
| scan controller and software | ASC500 (for detailed specifications please see attoCONTROL section) |
| laser | LDM600 laser/detector module (for detailed specifications please see attoCONTROL section) |
| **Options** | |
| closed loop scanning & global sample coordinates | interferometric encoders for scan linearization and closed loop sample navigation |
| ultra-large scan range upgrade | 80 x 80 @ 300 K<br>125 x 125 @ 4 K |
| *in-situ* inspection optics | incl. with CFM I external optics head |
| closed loop upgrade for coarse positioners | resistive encoder, range 5 mm, sensor resolution approx. 200 nm, repeatability 1-2 µm |
| sample holder upgrade | ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts and integrated heater with calibrated temperature sensor |

# Selected Applications

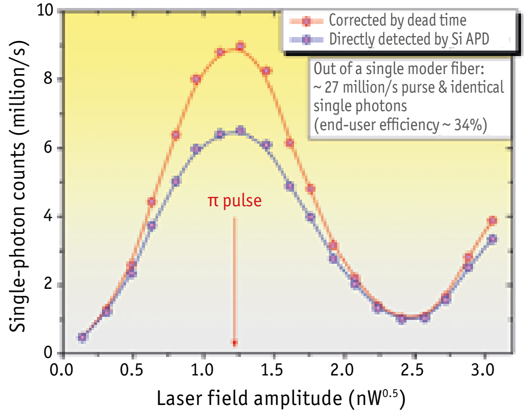
attoCFM I



## Observation of Many-Body Exciton States

The image on the left shows a 3D map of the photoluminescence of a single InAs/GaAs quantum dot in a charge-tunable device [1]. It was found that the coupling between the semiconductor quantum dot states and the continuum of the Fermi sea gives rise to new optical transitions, manifesting the formation of many-body exciton states. The experiments are an excellent proof for the stability of the attoCFM as the measurements took more than 15 hours without the need for re-alignment.

*[1] N. A. J. M. Kleemans et al., Nature Physics 6, 534 - 538 (2010).*




## Scalable Architecture for Multi-Photon Boson Sampling

Research groups led by Jian-Wei Pan & Chao-Yang Lu in China and Sven Höfling in Germany & UK have successfully demonstrated the first quantum simulator based on single photons that beats early classical computers. In Nature Photonics, they report on "High-efficiency multiphoton boson sampling", implementing 3-, 4-, and 5-boson-sampling with rates which are more than 24,000 times faster than all previous experiments, and 10-100 times faster than the first electronic computer (ENIAC) and transistorized computer (TRADIC) in human history. Their work, which was carefully prepared and accompanied by their 3 previous papers published in PRL (see below), kick starts a new era of photonic quantum technologies—going beyond proof-of-principle demonstrations and building a quantum machine to actually race against different generations of classical computers. In recognition of their achievements in quantum teleportation research, the very active and highly respected Chinese group recently also won the 2015 Physics World Breakthrough of the Year award and the 2015 State Nature Science First Class Award in China. In addition, Chao-Yang Lu was portrayed by Nature last summer as one of the "Science stars of China". For their quantum dot experiments, his group uses three attoDRY cryostats equipped with attocube positioners, scanners and cryogenic objectives. Visit the group's homepage for more information on their experiment.

*[1] Hui Wang, Yu He, et al., Nature Photonics 11, 361–365 (2017).*
*[2] Yu He, X. Ding, et al., Phys. Rev. Lett. 118 , 190501 (2017).*
*[3] Xing Ding, Yu He ,et al., Phys. Rev. Lett. 116, 020401(2016).*
*[4] Hui Wang, Z.-C. Duan, et al., Phys. Rev. Lett. 116, 213601 (2016).*

NEW

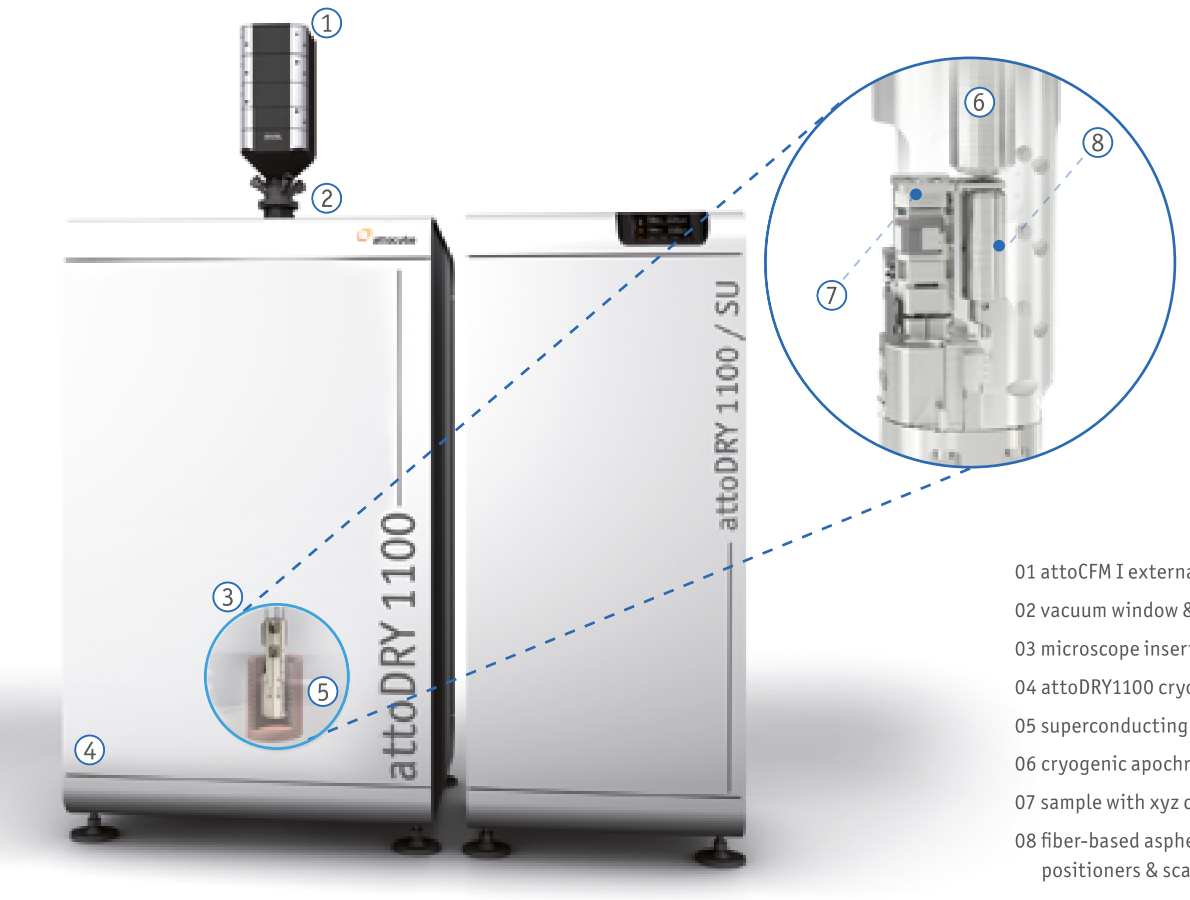
# attoCFM IV

combined free-beam and fiber-based confocal microscope for transmission

Transmission experiments in confocal microscopy sometimes also require filtering and shaping of the optical beam, and hence free-beam access instead of purely fiber-based can have quite some advantages in terms of flexibility.

This instrument literally consists of a ‚conventional' attoCFM I, which has a free-beam based channel with any of our apochromatic objectives above the sample, and a fiber-based channel from below just like in the attoCFM III. So, despite fitting into any of our toploading cryostats, which usually features only 1 top and no side or bottom windows, this setup allows for at least either the excitation or the detection to be free-beam. This provides the user with all the flexibility of the external optics head just like in case of the attoCFM I for one channel (plus potential reflection measurements).

At the same time, there are 3 degrees of freedom for the sample (xy translation under the fixed LT-APO objective as well as focussing), and another 3 degrees of freedom in xyz to position the fiber-based objective underneath the sample. All positioners are usually equipped with a /RES encoder for closed loop control, and there is an additional scanner for the sample in xy direction.




01 attoCFM I external optics head
02 vacuum window & fiber feedthrough
03 microscope insert and cryogenic microscope module
04 attoDRY1100 cryostat (optional)
05 superconducting magnet (optional)
06 cryogenic apochromatic free-beam objective (LT-APO)
07 sample with xyz coarse positioners & scanners
08 fiber-based aspheric objective with xyz coarse positioners & scanners

## Cryogenic Apochromatic Objectives

- negligible chromatic focal shift in working range
- uniform spot size and intensity within apochromatic range

### PRODUCT KEY FEATURES

- confocal microscope for transmission with free-beam access from above, and fiber-based objective from below the sample
- independent xyz degrees of freedom for sample and fiber-based objective
- modular beam splitter head outside of cryostat
- sample monitoring via CCD camera (field of view: 50-75 µm)

### BENEFITS

- wavelength and polarization filtering of the free-beam channel for excitation or collection signal possible
- independent wavelengths for excitation and detection due t
- lateral separation between excitation and detection spot of up to 3 mm
- fits standard cryogenic and magnet sample spaces
- very broad variety of applications, ranging from classical CFM measurements to Raman spectroscopy
- excellent stability in high magnetic fields
- highest measurement sensitivity
- access to a large area on the sample surface

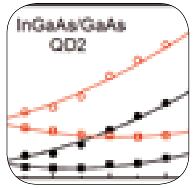
### APPLICATION EXAMPLES

- solid state physic and quantum dot optics
- fluorescence/photoluminescence of quantum dots, nanowires, 2D-layered materials, photonic crystals, single molecules

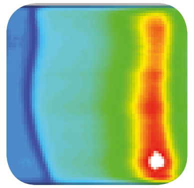
### COMPATIBLE COOLING SYSTEMS

- attoDRY1000/1100/2100
- attoLIQUID1000/2000

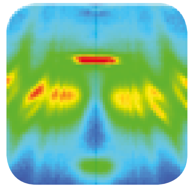
*The attoCFM IV microscope module*




*Confocal Imaging*



*Photoluminence Spectroscopy*

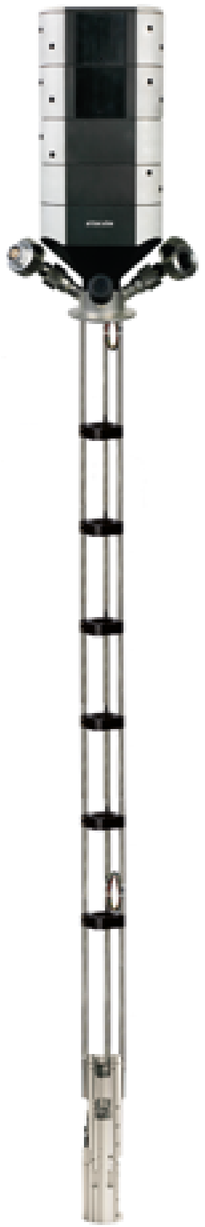


*Quantum Dot Spectroscopy*

# Specifications

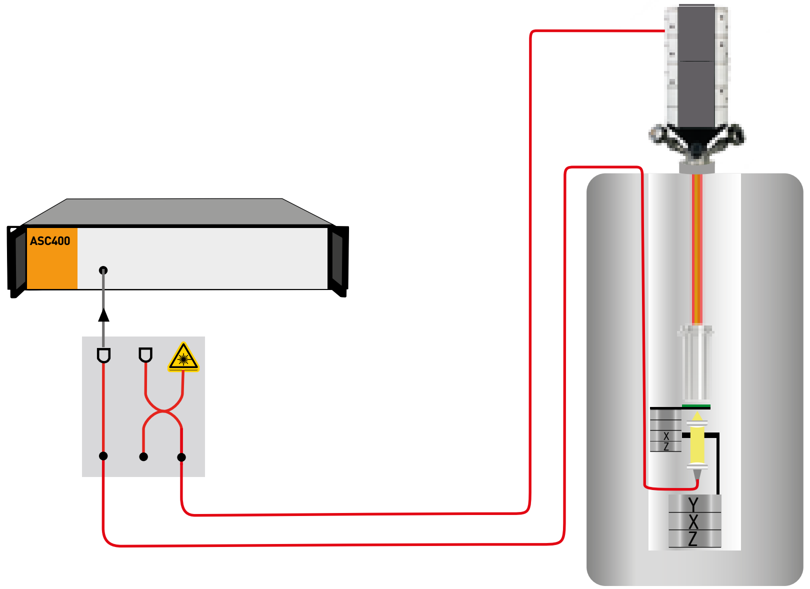
## attoCFM IV

| General Specifications | |
|---|---|
| type of instrument | confocal microscope for transmission experiments with one free-beam and one fiber based channel |
| sensor head specifics | one channel with unique low temperature compatible achromatic objectives with high numerical aperture, optimized for different wavelength ranges, and one channel with fiber-coupled low temperature compatible aspheric objective |
| **Confocal Unit** | |
| configuration | compact and modular design, two or more optical channels<br>standard configuration: 1 excitation channel,1 detection channel |
| quick-exchange of optical components | beamsplitters, filter mounts for up to 4 filters/ polarizers (1" diameter), optional piezoelectric rotator with filter mount |
| LT- compatible objective | LT-APO/VIS, LT-APO/VISIR, LT-APO/NIR<br>(see accessory section for more information) |
| inspection unit | sample imaging with large field of view: ~75 µm (attoDRY), ~56 µm (attoLIQUID) |
| **Illumination** | |
| excitation wavelength range | free-beam channel: 400 .. 1000 nm<br>default: 650 nm (others on request)<br>fiber channel: limited to wavelength range of single mode fiber<br>default: 650 nm (others on request) |
| **Detection** | |
| detection mode | e.g. transmission, reflection, luminescence, flourescence, Raman (optional) |
| detection wavelength range | free-beam channel: 400 .. 1000 nm<br>default: 650 nm (others on request)<br>fiber channel: limited to wavelength range of single mode fiber<br>default: 650 nm (others on request) |
| **Sample Positioning** | |
| total travel range | independent degrees of freedom for sample of 3 x 3 x 2.5 mm³ (closed loop) and for fiber-based objective of 3 x 5 x 5 mm³ (closed loop) |
| step size | 0.05..3 µm @ 300 K, 10..500 nm @ 4 K |
| fine scan range | sample: 30 x 30 µm² @ 300 K, 12 x 12 µm² @ 4 K (open loop) |
| sample holder | Ti plate with aperture of 8 mm in diameter with integrated heater and calibrated temperature sensor |
| **Suitable Operating Conditions** | |
| temperature range | 1.5 K..300 K (dependent on cryostat); mK compatible setup available on request |
| magnetic field range | 0..14 T (dependent on magnet)<br>(16 T compatible version available on request) |
| operating pressure | designed for He exchange gas |



| Suitable Operating Conditions | |
|---|---|
| temperature range | 1.5 K..300 K (dependent on cryostat); mK compatible setup available on request |
| magnetic field range | 0..14 T (dependent on magnet)<br>(16 T compatible version available on request) |
| operating pressure | designed for He exchange gas |
| **Suitable Cooling Systems** | |
| titanium housing diameter | 48 mm |
| bore size requirement | designed for a 2" (50.8 mm) cryostat/magnet bore |
| compatible cryostats | attoDRY1000/1100/2100<br>attoLIQUID1000/2000 |
| **Electronics** | |
| scan controller and software | ASC400 (for detailed specifications please see attoCONTROL section) |
| laser | LDM600 laser/detector module (for detailed specifications please see attoCONTROL section) |
| **Options** | |
| closed loop upgrade for coarse positioners | incl. |

** Resolution may vary depending on applied tip, sample, and cryostat*

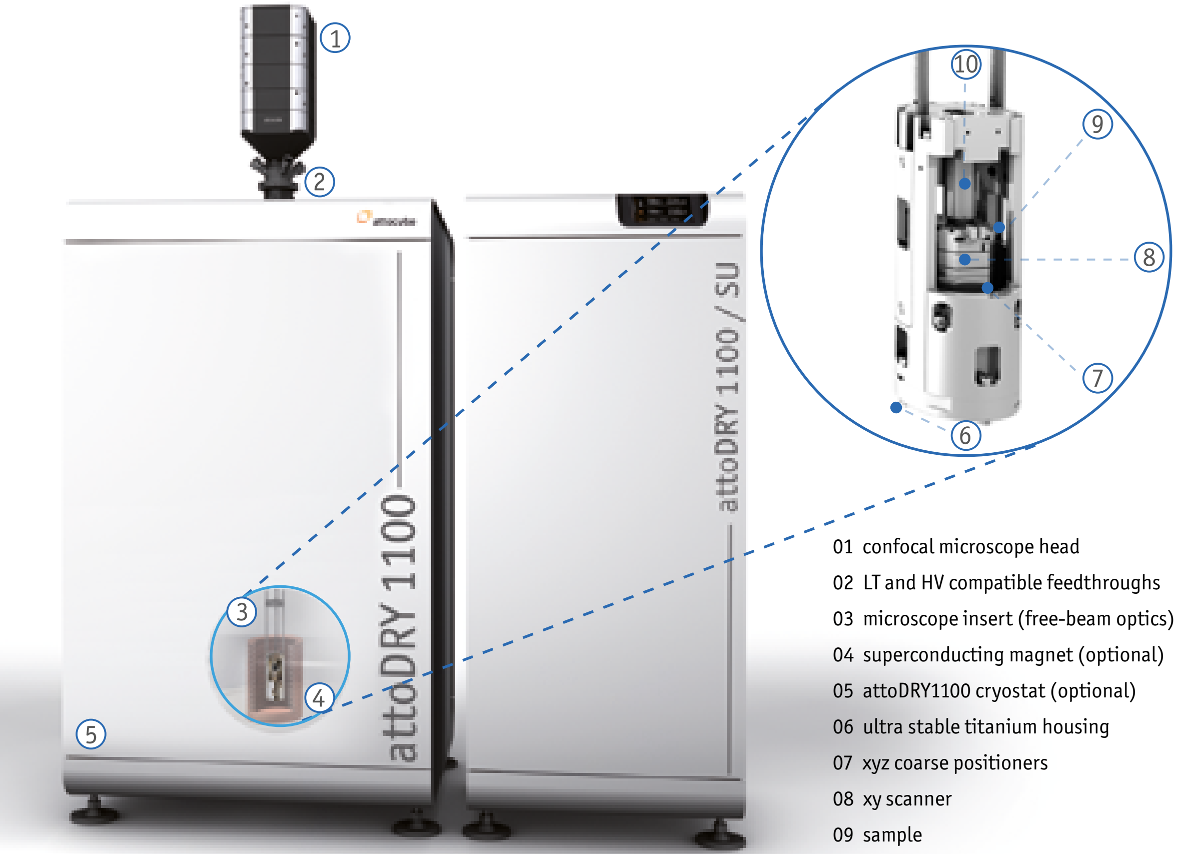


# attoRAMAN

## low temperature micro-Raman spectroscopy

The cryogenic Raman instrument combines a high resolution, low temperature confocal microscope with ultra sensitive Raman optics. This innovative product enables state of the art confocal Raman measurements at cryogenic environments combined with magnetic fields of up to 15 T. The attoRAMAN is a ready-to-use system and is delivered with a Raman laser source (532 nm / 633 nm wavelength as excitation source available), ultra-high throughput spectrometer including a peltier-cooled, back-illuminated CCD, and a state-of-the-art Raman controller/software package.

The attoRAMAN uses a set of xyz-positioners for coarse positioning of the sample over a range of several mm, and is also available with an interferometric encoder for closed loop operation. Developed particularly for cryogenic applications, the piezo-based scanner provides a large scan range of 50 µm x 50 µm at room temperature, and 30 µm x 30 µm at liquid helium temperature. The Raman image is obtained by raster scanning the sample with respect to the laser focus and measuring the spectral distribution of the Raman signal for each point.




Schematic drawing of the low temperature attoRAMAN and the attoDRY1100 cryostat (optional)

01 confocal microscope head
02 LT and HV compatible feedthroughs
03 microscope insert (free-beam optics)
04 superconducting magnet (optional)
05 attoDRY1100 cryostat (optional)
06 ultra stable titanium housing
07 xyz coarse positioners
08 xy scanner
09 sample
10 low temperature compatible objective

### PRODUCT KEY FEATURES

- optical setup offering highest flexibility
- modular beam splitter head outside of cryostat
- wavelength and polarization filtering of the excitation and collection signal possible
- large coarse positioning range at low temperatures
- low temperature objectives with NA up to 0.82
- sample monitoring via CCD camera (field of view up to 50 µm)

### BENEFITS

- fits 1" clear bore cryostats and magnets
- highest flexibility and sensitivity combined with minimal light loss
- highly stable long term measurements
- ultra-sensitive room temperature Raman optics
- state-of-the-art Raman controller/software package

### APPLICATION EXAMPLES

- nanotechnology and nano-structured surface inspection
- defect and residue analysis
- surface modification
- stress measurements
- waveguides
- imaging of surface plasmon waves
- surface structure and properties
- chemical constitution and compound distribution
- defect analysis and phase separations
- nanotube properties characterization
- graphene characterization and layer analysis
- diamond films and inclusions
- stress measurements

### COMPATIBLE COOLING SYSTEMS

- attoDRY800/1000/1100/2100
- attoLIQUID1000/2000, attoLIQUID3000/5000 (on request)

### CUSTOMER FEEDBACK

Thiam Tan

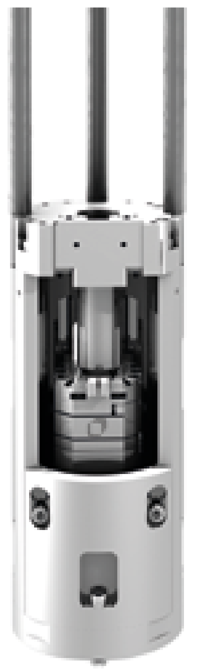
*I am impressed with the ingenuity of the attocube system. It's an amazing system that opens up exciting possibilities in materials research. Along with a strong team of experienced and expert technical staffs providing support, it certainly helps to smoothen the learning curve for the system.*

*(University of New South Wales, Australia)*

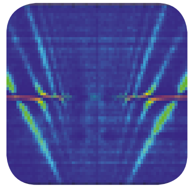
## Available Upgrade Option

- closed loop upgrade for positioners

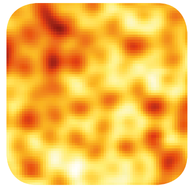
*...for further details, see accessories section*



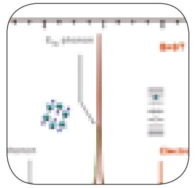
*The attoRAMAN microscope module*



*Raman Spectroscopy*



*Phase Transitions*

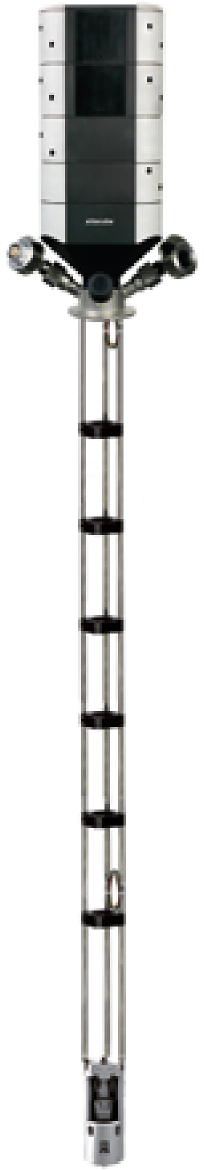


*2D layered Materials*

# Specifications

attoRAMAN

| | |
|---|---|
| **General Specifications** | |
| type of instrument | free-beam based room temperature optics head coupled to low temperature objective and ultra-high transmission spectrometer |
| sensor head specifics | unique low temperature compatible achromatic objectives with high numerical aperture, optimized for different wavelength ranges |
| **Confocal Unit** | |
| configuration | compact and modular design, two or more optical channels<br>standard configuration: 1 excitation channel,1 detection channel |
| quick-exchange of optical components | beamsplitters, filter mounts for up to 4 filters/ polarizers (1" diameter), optional piezoelectric rotator with filter mount |
| LT- compatible objective | LT-APO/VIS, LT-APO/VISIR, LT-APO/NIR<br>(see accessory section for more information) |
| inspection unit | sample imaging with large field of view: ~75 µm (attoDRY), ~56 µm (attoLIQUID) |
| **Illumination** | |
| excitation wavelength range | 400 .. 1000 nm<br>default: 532 nm (others on request) |
| light source | dedicated Raman laser, single mode fiber coupled |
| light power on the sample | typically 1 pW..10mW |
| optical filter | laser line filter |
| **Detection** | |
| detection mode | 2D Raman images, time and single point Raman spectra |
| spectrometer | ultra-high transmission spectrometer, f=300 mm |
| total optical transmission | greater 60% at 532 nm |
| filters | dichroic mirror & edge filter for signal detection as close as 90 cm-1 to the laser line |
| gratings | typ. 600/mm and 1800/mm grating |
| spectral resolution | 1 cm-1 at 1800/mm grating |
| CCD camera | back-illuminated CCD, peltier-cooled to -60 °C at 20 °C room temperature, 1024x127 pixels, 90% quantum efficiency at 532 nm, 100 kHz readout converter |
| **Sample Positioning** | |
| total travel range | 5 x 5 x 5 mm³ (open loop) |
| step size | 0.05..3 µm @ 300 K, 10..500 nm @ 4 K |
| fine scan range | 50 x 50 µm² @ 300 K, 30 x 30 µm² @ 4 k (open loop) |
| sample holder | ASH/QE/0 quick exchange sample holder and integrated heater with calibrated temperature sensor |
| **Suitable Operating Conditions** | |
| temperature range | 1.5 K..300 K (dependent on cryostat); mK compatible setup available on request |
| magnetic field range | 0..15 T+ (dependent on magnet) |
| operating pressure | designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request) |
| **Suitable Cooling Systems** | |
| titanium housing diameter | 48 mm |
| bore size requirement | designed for a 2" (50.8 mm) cryostat/magnet bore |
| compatible cryostats | attoDRY1000/1100/2100<br>attoLIQUID1000/2000 (attoLIQUID3000/5000 on request) |

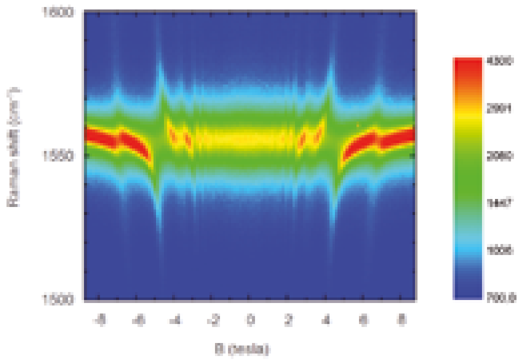


*Complete microscope stick attoRAMAN*

# Selected Applications

attoRAMAN

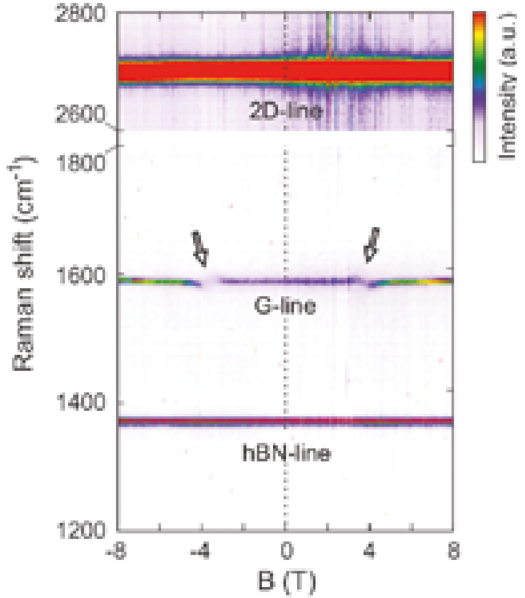
| | |
|---|---|
| **Electronics** | |
| scan controller and software | dedicated FPGA-based RAMAN controller providing coarse positioning and scanning signals for sample positioning and scanning in x, y, and z direction; control software for extensive RAMAN signal data acquisition and post processing |
| **Options** | |
| sample holder upgrade | ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts and integrated heater with calibrated temperature sensor |




## Raman Spectroscopy on Graphene

The figure to the left shows magneto-Raman measurements recorded at 4 K on an exfoliated single crystal of natural graphite with unprecedented spatial resolution (approx. 0.5 µm), while sweeping the magnetic field from -9 T to +9 T. The data were recorded on a single graphene flake and demonstrate the crossing of the E2g phonon energy with the electron-hole separation between the valence and conduction Landau levels (-N,+M) of the Dirac cone. Resonant hybridization of the E2g phonon is a specific signature of graphene flakes which display very rich Raman scattering spectra varying strongly as function of magnetic field [1].

*[1] C. Faugeras et al., Phys. Rev. Lett. 107, 036807 (2011); (attocube application labs, 2011; work in cooperation with C. Faugeras, P. Kossacki, and M. Potemski, LNCM I - Grenoble, CNRS_UJF_UPS_INSA France)*




## Magneto-Raman Microscopy for Probing Local Material Properties of Graphene

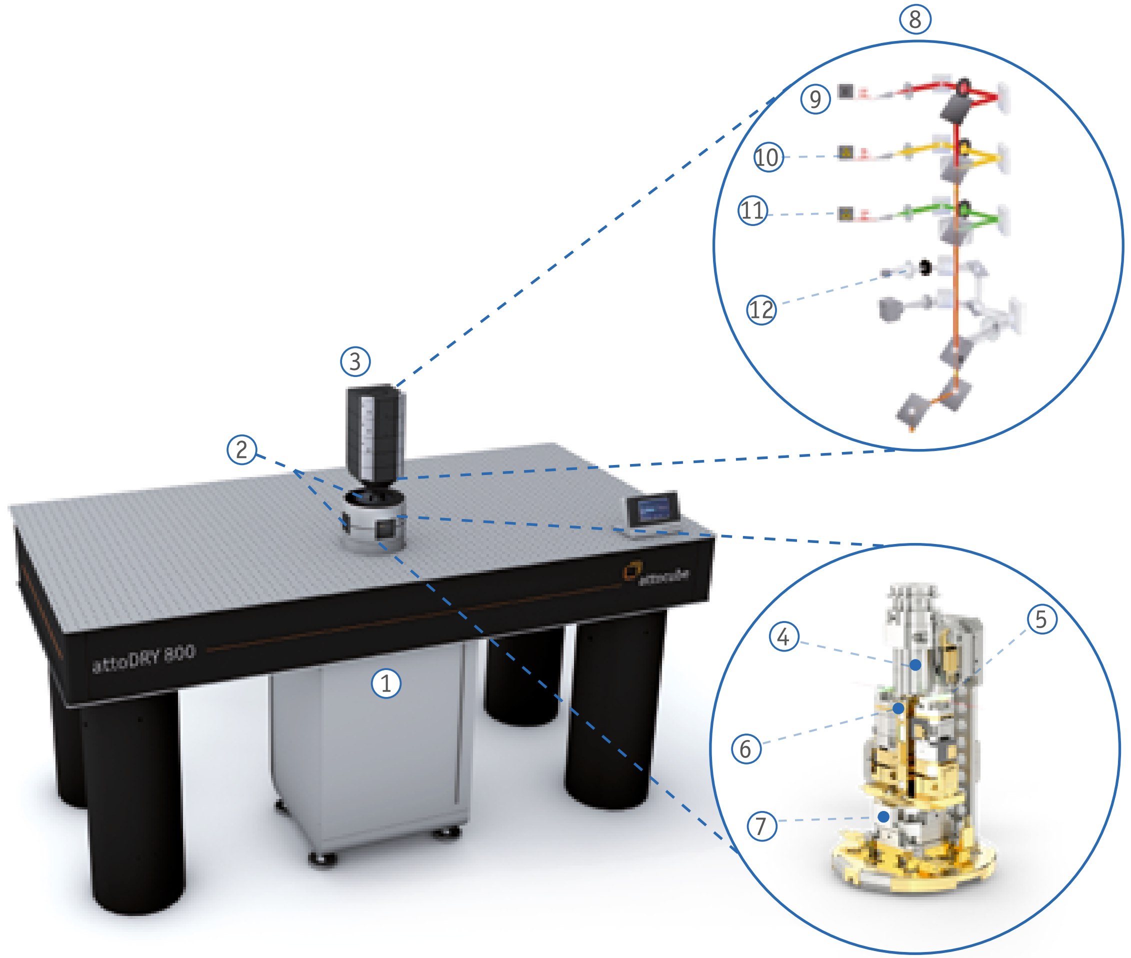
The combination of confocal Raman microscopy and magnetic fields at 4 K yields the opportunity to investigate and tune the electron-phonon interaction in graphene and few-layer graphene. In particular, excitations between Landau levels can resonantly couple to the Raman active long wavelength optical phonon (G-phonon), when their energies are matched, resulting in magneto-phonon resonances (MPRs). Such resonances at ±3.7 T are presented in the figure and highlighted by arrows. The details of the coupling depend on various material properties of the investigated graphene layer. From the MPRs, device parameters such as the electron-phonon coupling constant or the Fermi velocity of the charge carriers can be extracted. Interestingly for low charge carrier doping, the Fermi velocity shows signatures of many-body interaction effects [2].

*[2] Nat Comms, Nature Publishing Group, 2015, 6, 8429*

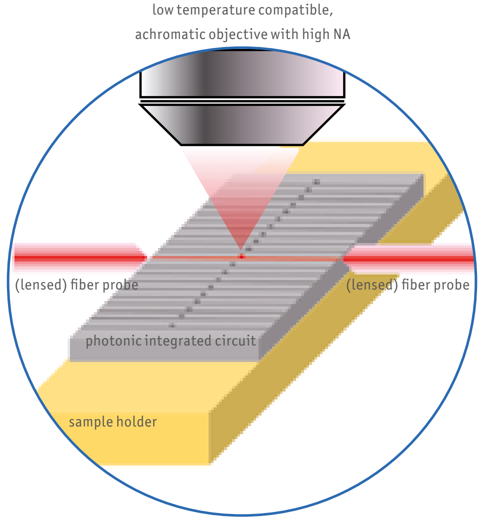
# Cryogenic Photonic Probe Station

combined probe station and confocal microscopy

Photonic Integrated Circuits (PIC) are hot candidates for becoming the key components of the next generation of optical and quantum communication systems because of the promise of very high information transfer speed, robustness and the compatibility with standard microelectronics devices technology. Furthermore, the extremely high sensitivity of resonant nanophotonics structures to light-matter interactions makes them candidates for a new classes of sensors with broad range of possible applications in physics, biology and chemistry. The Photonic Probe Station, which combines two optical fiber probes and a free optical beam Confocal Microscope (CFMI) provides an ideal, ultra stable, extremely compact and easy-to-use table top setup for nano photonic device characterization. The lensed fibers couple light into and out of the the sample planar wave guides. The confocal microscope allows not only for sample surface probing, but also for out-of-plane coupling into photonic structures. The combination with the attoDRY800 cryo-optical table offers a powerful easy-to-use setup for characterization of photonic nanostructures in a  temperature range from 4 K up to 320 K.




01 attoDRY800 cryostat
02 optical access to sample
03 multi-beam optical head
04 LT high NA objective with z focus
05 lensed fiber for light coupling into waveguide with xyz degrees of freedom
06 removable sample holder
07 xy degrees of freedom for complete setup of sample and fiber probes
08 optical head schematics
09 detection channel
10 excitation channel
11 second excitation channel (optional)
12 inspection optics




## PRODUCT KEY FEATURES

- large area sample positioning (6 mm x6 mm)
- 2 independently movable optical probes (lensed fibers)
- ultra low drift at low temperature

## BENEFITS

- quick and easy sample exchange
- inspection optics 90 µm x 70 µm (field of view)
- accurate & flexible *in-situ* optical probing of photonic nanostructures

## APPLICATION EXAMPLES

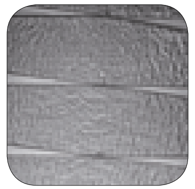
- characterization of nanophotonic structures
- spectroscopy of single QD in nanoresonator
- biosensors
- nano-plasmonics
- opto-electronics devices

## CUSTOMER FEEDBACK

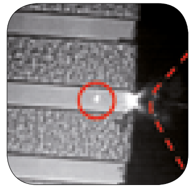
Dr. Ivan Favero

*The photonic probe station has essentially solved cryogenic and mechanical stability problems in our experiments, such that we can today concentrate our efforts on other conceptual and technical aspects. Simply a great scientific instrument!*

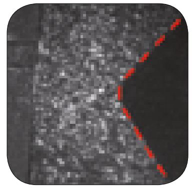
*(Université Paris Diderot, CNRS, Paris, France)*



*Nano-resonators and planar wave guides*



*Coupling from the lensed fiber (red dashed line) into the planar wave guide; the red circle indicates the confocal spot*



*Lensed fiber (red dashed line) at the edge of a planar wave guide sample (courtesy of Ivan Favero,  Université Paris Diderot-CNRS)*

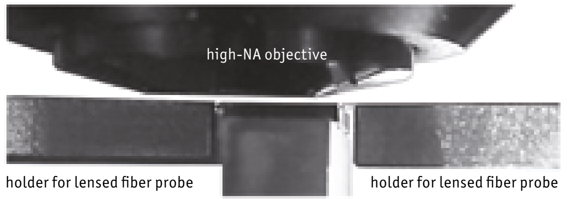
# Specifications

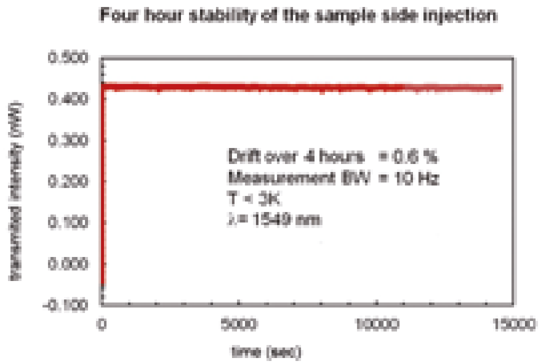
## Cryogenic Photonic Probe Station

| | |
|---|---|
| **General Specifications** | |
| type of instrument | combined side injection into planar waveguide structures and perpendicular confocal optics on top of the sample, perpendicular injection is possible |
| sensor head specifics | two independent lensed fiber probes with 3 individual degrees of freedom, low temperature compatible apochromatic objective and external confocal optics head |
| **Confocal Unit** | |
| configuration | compact and modular design, two or more optical channels standard configuration: 1 excitation channel,1 detection channel |
| quick-exchange of optical components | beamsplitters, filter mounts for up to 4 filters/ polarizers (1" diameter), optional piezoelectric rotator with filter mount |
| LT- compatible objective | LT-APO/VIS, LT-APO/VISIR, LT-APO/NIR<br>(see accessory section for more information) |
| inspection unit | sample imaging with large field of view: approx. 100 µm |
| long-term stability | lateral drift of confocal spot typically <2 nm/h |
| **Sample Positioning** | |
| total travel range | Sample: 6 mm x 6 mm (closed loop)<br>fiber probes: 3 x 3 x 2.5 mm³ (closed loop)<br>sensor resolution approx. 200 nm, sensor repeatibility approx. 1-2 µm |
| step size | 0.05..3 µm @ 300 K, 10..500 nm @ 4 K |
| sample holder | carefully thermalized, quick exchange mechanism, including calibrated temperature sensor and heater |
| temperature range | 4..320K |
| operating pressure | 1E-6 mbar .. 1 bar |
| **Suitable Cooling Systems** | |
| compatible cryostats | attoDRY800<br>(flow cryostats on request) |
| laser | LDM600 laser/detector module (for detailed specifications please see attoCONTROL section) |

# Selected Applications

## Cryogenic Photonic Probe Station




### Ultra-Low Drift

The integration of the Photonic Probe Station into the attoDRY800 cryostat allows for characterization of photonic structures in a temperature range from 4 K up to 320 K.

The stability of the light injection and detection is outstanding: ultra low drift of the transmitted signal intensity in the range of only a few percent in a period of several days is detected. A typical 4 h measurement is presented. The experiment schematics is shown below.