Operating manual

LuQY Pro

Radiative efficiency meter

Model no. LP20-32

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Issue 09.08.2023
Original Operating manual

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Please read this Operating manual completely and carefully. This Operating manual is part of the Radiative efficiency meter and contains important information on its commissioning and handling. Always observe all safety instructions. Prior to commissioning, check for the correct voltage and the correct assembly of all components.

If you have any questions or problems handling the LuQY Pro, please contact your dealer or service centre. Please keep this Operating manual in a safe place and pass it on to third parties if necessary.

1 Notes and explanations

	***DANGER*** ***Dangers due to hazardous electrical voltage (24 V_{DC})***. ***Failure to observe may result in slight injuries.***
	***Crushing, danger of injury to hands*** *(closing movements of specimen holders).* ***Failure to observe may result in slight injuries.***
	***Dangers due to laser radiation (Class 3B)*** *are marked with a warning triangle and the word "Laser radiation".* ***Failure to observe may result in serious injury or death.*** *Do not look into the laser beam. Do not expose unprotected skin or body to radiation.*
	***WARNING*** ***Do not open device; Caution: Laser Class 3B!*** ***Failure to observe may result in serious injuries.***
	***WARNING*** *"**Do not operate after a fall / after dropping the device**"* ***The safe functioning of the device can no longer be guaranteed.*** ***Failure to observe may result in serious injuries.***
	***CAUTION*** *"CAUTION" combined with the warning symbol indicates dangerous situations. Avoid these dangerous situations!* ***Failure to observe may result in light or minor injury.***
	***NOTE*** *This is what you should do!* *Follow the action recommendations to **avoid damage to property** and any issues**!***

	***NOTE*** *Read the instructions!* *Follow the action recommendations to **avoid damage to property** and any issues**!***
	***NOTE*** ***Eco-label** indicates environmental protection measures (warning of environmental pollution, see chapter Disposal).* ***Failure to observe will result in damage to the environment.*** *Incorrect disposal can cause major environmental damage.*

2 Safety instructions

2.1 Scope

The documentation applies to all persons who perform work on the Radiative efficiency meter. Read this documentation completely and follow the instructions exactly before commencing any work on the LuQY Pro.

Always keep the documentation close to the Radiative efficiency meter and make sure it is accessible to all personnel at all times. The documentation is part of the LuQY Pro and must always be accessible and updated throughout its entire operating time.

2.2 Other applicable regulations

The Radiative efficiency meter was developed, designed and constructed in accordance with German and European technical regulations.

The Radiative efficiency meter may only be operated in compliance with the technical and safety regulations applicable at the site of operation according to:

- Applicable health, occupational and fire safety regulations
- Laws, regulations and safety rules

2.3 Personnel deployment and responsibility

Prior to the description of each activity in the documentation, the personnel deployment and responsibilities are specified. There are the following groups of persons:

Qualified trained personnel

- Qualified for functions at management level.
- Interdisciplinary supervision for all activities.
- Authorised by the operator.
- Know and understand functional sequences and their interaction with the environment.

Operating personnel

- Qualified for operation.
- Authorised by the operator.
- Know and understand functional sequences and their interaction with the environment.

Maintenance staff

- Qualified for maintenance activities.
- Authorised by the operator.
- Know and understand functional sequences and their interaction with the environment.

Qualified electricians

- Authorised by the operator.
- Demonstrably qualified to work on electrical systems through approved training.
- Know and understand the technology and functional sequences of the LuQY Pro and their interaction.

Operating company

- Any natural or legal person who uses the LuQY Pro or places it at the disposal of third parties, and who is responsible for the safety of the user, personnel or third parties during use.

External persons

- Any person who is not included in above-mentioned groups of persons.
- External persons are prohibited from entering the working area of the LuQY Pro.

2.4 Operator's responsibilities

The Radiative efficiency meter was designed for commercial use. The operator of the LuQY Pro is therefore subject to the legal obligations concerning occupational safety. In addition to the warnings and safety instructions in this manual, the safety, accident prevention and environmental protection regulations applicable to the operation site of the LuQY Pro must be observed.

In particular, the operator must:

- read up on the applicable industrial safety regulations;
- identify, by means of a risk assessment, potential additional dangers arising from the specific conditions of use at the operation site of the LuQY Pro and minimise them by taking suitable measures;
- implement the necessary code of conduct for the operation of the LuQY Pro at the site of operation via operating instructions;

- regularly check the established operating instructions for compliance with the current rules and standards throughout the entire operating time of the LuQY Pro;
- adapt the operating instructions, where necessary, to new regulations, standards and conditions of use;
- establish all responsibilities for the installation, operation, maintenance and cleaning of the LuQY Pro clearly and unambiguously;
- ensure that all employees working on the LuQY Pro know the protective measures for safe operation;
- ensure that all employees working on the LuQY Pro have read and understood the operating manual and the general safety instructions.

In addition, the operator must train the personnel at regular intervals in the handling of the LuQY Pro and keep them informed on the possible dangers. The operator is also responsible for ensuring that the LuQY Pro is always in a technically perfect condition.

2.5 Special requirements for Laser Class 3 electrical equipment

Target group: User, technician

Due to the output generated by the laser system, the electrical equipment is a device of laser class 3 electrical equipment (classification as per DIN EN 60825-1). This results in additional requirements:

- Electrical safety requires compliance with the DIN EN 60204-1 (EN 61010-1) standard.
- Regarding possibly dangerous laser radiation, the standards DIN EN 60825-1 must be observed.
- For occupational safety, a risk assessment of the workplace is necessary. Employees who are subject to the *BetrSichV* must be instructed. PPE (personal protective equipment) must be provided for residual risks that cannot be eliminated.

In particular, the following assemblies are required:

- For class 3, the protective enclosures must comply with EN 60825-4 and be capable of non-destructively absorbing the laser output; the device must comply with EN ISO 11553-1.
- When the laser is active, an optical or audible alarm (fail-safe or redundant) must be active and visible (DIN EN 60825-1, chap. 6.7).
- The device must possess a beam limiter or attenuator that prevents radiation above AR Class 1M during operation and adjustment activities (DIN EN 60825-1, chap. 6.8).

2.6 General safety instructions

Basics

- Always perform all activities responsibly and in accordance with the safety regulations.
- Malfunctions that impair safe operation must be corrected immediately.
- Until the malfunction has been corrected, the LuQY Pro must be taken out of operation.
- All markings and labelling on the LuQY Pro must be legible and complete.
- The housing of the LuQY Pro may only be opened by the manufacturer.

Dangers during normal operation

- Only operate the LuQY Pro if it is put down on a level surface with dimensions greater than or equal to the footprint of the LuQY Pro.
- Before switching on the LuQY Pro, ensure that the device cannot fall off the work surface.

Dangers due to electrical power

- Any work on electrically operated assemblies may only be performed by the manufacturer.
- Check the electrics of the LuQY Pro regularly. Have loose connections and damaged cables repaired or replaced immediately.
- Do not open the housing.

Dangers during maintenance and assembly

- The LuQY Pro must be switched off and disconnected from the mains for any and all activities.

2.7 Safety measures when handling laser systems

Fundamentally, the optical radiation from lasers and conventional light sources does not differ in its biological effects. However, due to the strong concentration of the laser radiation, the intensity (irradiation intensity or irradiation) may be high enough for special tissue responses to be induced (see "Laser applications – Effects"). Special protective and precautionary measures are therefore required when using laser radiation. To allow for the immediate identification of the possible danger to the user, the laser devices are grouped into different classes by the manufacturer, according to their hazard potential. This way, the user can easily estimate how to behave and which protective measures are required. The classification is such that the higher the number of the class, the greater the health hazard and the more extensive the required protective measures. The accident prevention regulation "Laser radiation" BGV B2 and the DIN standard EN 60825-1 (VDE 0837 Part 1) are decisive for the classification. In the new version of DIN EN 60825-1 of November 2001, the classification was changed to some extent. BGI 832 "Operation of Laser Equipment" provides useful instructions for risk assessment and the definition of protective measures.

- The operator of a laser system is responsible for complying with the safety measures. For instance, the operator must ensure that the laser equipment is classified and labelled accordingly. The commercial operation of class 3R laser equipment must be reported to the trade supervisory board and the occupational insurance association. When operating such lasers, a laser zone must be defined and marked. Additionally, the operator must appoint qualified trained personnel as laser safety officers for these laser devices.
- Non-instructed personnel are not permitted to operate the LuQY Pro. Persons < 18 years are not permitted to work on the LuQY Pro!
- The LuQY Pro powers a class 3B laser (invisible strong laser radiation); this laser type may cause damage to the body due to direct exposure to laser radiation or easy ignite combustible material; Emissions and the generation of toxic or harmful gases during the procession of certain material.

On the installation site of the LuQY Pro, the operator must provide fire-fighting equipment. Do not store combustible or explosive material in the vicinity of the machine and provide for an adequate and functional extraction (depending on the processed material and the generated intermediate products).

Laser classes and their hazards, typical output and applications			
Laser class	**Hazard or protection option**	**Typical power P (continuous-wave laser)**	**Typical application**
1	safe under all conditions of normal use	less than 0.4 milliwatts (mW)	barcode scanner, DVD player
1M	hazardous to the eye when using magnifying instruments (otherwise equivalent to class 1)	less than 0.4 milliwatts, but beam diameter more than seven millimetres (mm)	-
2	Do not stare directly into the beam – prolonged eye exposure (more than 0.25 seconds) could lead to eye damage	less than one milliwatt	laser pointer, laser spirit level
2M	hazardous to the eye when using magnifying instruments (otherwise equivalent to class 2)	less than one milliwatt, but beam diameter more than seven millimetres	-
3A	only hazardous to the eye when using magnifying instruments	less than five milliwatts, but beam diameter more than seven millimetres and power density – in relation to pupil diameter – equivalent to class 2 laser	-
3R	hazardous to the eye	less than five milliwatts	show and projection lasers, material processing lasers
3B	always hazardous to the eye (UV-A: also hazardous to skin)	less than 500 milliwatts	show and projection lasers, material processing lasers
4	always hazardous to the eye and skin	more than 500 milliwatts	show and projection lasers, material processing lasers

2.8 Briefing certificate

Employees must be specifically instructed for work with laser radiation. The briefings are documented on a form with the following content:

Security briefing on working with laser radiation		
Company:		O new employees
Department:		O yearly briefing
Type of instruction:	O theoretical / lecture and discussion O video / multimedia O practical / on the machine on site	
Objective:	O The instruction aims to inform the employee about laser-specific dangers, safety equipment and protective measures to prevent personal injury.	
Topics:	O Properties and dangers of the applied laser radiation O Radiation effect on skin and eye O Laser classes (signage) O other hazards (fire, explosion protection, protection against secondary radiation, electrical hazards) O Protective regulations and operational instructions (who has access to which areas/rooms?) O Laser protective devices and their effect O Conduct in the event of malfunctions O Use of the laser protection or adjustment eye-protectors for _____ O Conduct in the event of accidents O additional topics! _____	
Place of instruction: _____		Date: __/__/20__
Instruction conducted by: _____		Management ack. _____
I hereby confirm that I have been instructed on the above-mentioned topics of laser-specific occupational safety. With my signature, I confirm that I have taken part in the briefing and have understood the instructions.		
Instructed persons:		Signatures of the instructed persons:
Names		*Signature*

This list must be updated by the operator after each briefing.
The participants confirm their participation and understanding by their signature.

2.9 Appointment as Laser Safety Officer

Appointment as Laser Safety Officer

As per §5 section 2 OStrV
As per §6 BGV B2

Mr/Mrs/Ms _____ will be appointed as laser safety officer

as of _____ for the area / operation _____

in accordance with §5 section 2 of the German Ordinance on the Protection of Employees from the Hazards of Artificial Optical Radiation (OStrV).

Tasks:
Support the employer in the realisation of protective measures

- Participate in the enforcement and implementation of the measures defined in the risk assessment.
- Participate in the instruction and briefing
- Prepare operating instructions
- Organise preventive occupational medical care and counsel on medical care in the event of eye accidents

Monitor the safe operation of lasers

- Participate in the commissioning of laser equipment
- Motivate employees
- Regularly review the documentation on the effectiveness of the implemented protective measures
- Report faults
- Participate in the testing of laser equipment and personal protective equipment
- Organise maintenance work – cooperate with outside companies

Closely cooperate with safety experts and the company physician

Note:
☐ Delegation of duties
☐ Additional tasks of the laser safety officer by further delegation of duties as per §13 "Grundsätze der Prävention" (Principles of Prevention, BGV A1) with authority to issue instructions and responsibility for the operation of laser systems:

Correct faults, if necessary shut down the laser systems
Arrange medical examinations in the event of suspected laser accidents

_____ _____
Place, date Signature of the laser safety officer

_____ _____
Place, date Signature of the employer

2.10 Laser note in accordance with BGV B2 (VBG 93)

BGV B2

Annex 5

Template for a laser note as per accident prevention regulation "Laser radiation" (BGV B2)

Laser note as per accident prevention regulation "Laser radiation" (BGV B2)

Registering company: _____

(Company, street, postal code, city): _____

Phone: _____ Telefax: _____

Membership number: _____

Subject: Laser registration

Manufacturing company: _____

Laser product name: _____

Laser type and wavelength λ: _____

Pulsed laser power: P_{El} _____ Pulse repetition frequency F = _____

CW laser power: P_{MAX}= _____

Laser class during production: _____

Laser class during maintenance: _____

Site of operation: _____ Department: _____

Place: _____

For lasers subject to MD: Please find a copy of the declaration of conformity attached.

_____ was appointed as laser safety officer.

Commissioning of the Laser system expected on: _____

_____ _____

Place/date Signature / printed name

2.11 Damage

Damage caused by failure to observe this Operating manual will invalidate the warranty. We accept no liability for consequential damage!

We accept no liability for damage to property or personal injury caused by improper handling or failure to observe the safety instructions / intended use!

Caution when connecting power supply!
Pay close attention to the order the power supply is connected. To avoid damage, always connect the power supply to the LuQY Pro first before connecting to the grid.

Avoid danger to life due to electric shock!
Only the delivered power supply unit may be used to operate the device.

This is what you should do!
Install the LuQY Pro in an environment that is protected from moisture, dirt and excessive heat.

Always stay alert! Always pay attention to what you are doing and always use common sense. Never use the LuQY Pro if you are lacking in concentration or feel unwell.

Familiarise yourself with all instructions and illustrations in this Operating manual and with the LuQY Pro itself, before commencing operation.

3 Intended use

The device is used to measure the radiative efficiency and determine the quantum efficiency of semiconductors.

Reasonably foreseeable misuse

The Radiative efficiency meter is intended for use in industrial / public facilities and is only suitable for operation in dry / heated indoor areas (in compliance with the technical data). Do not operate in damp / wet environments, in EX atmospheres or in fire risk areas; do not operate underground. Do not operate outside public facilities and industrial environments (EMC directive, emission).

The LuQY Pro has been designed exclusively for above-mentioned purpose. Any other use beyond this or any modification without the manufacturer's written agreement is not permitted.

Mechanical and electrical modifications are only permitted after consultation with the manufacturer and must be performed by certified specialists. All modifications to the LuQY Pro must comply with the safety requirements.

The manufacturer accepts no liability for damage resulting from improper use.

4 Hardware

4.1 Overview

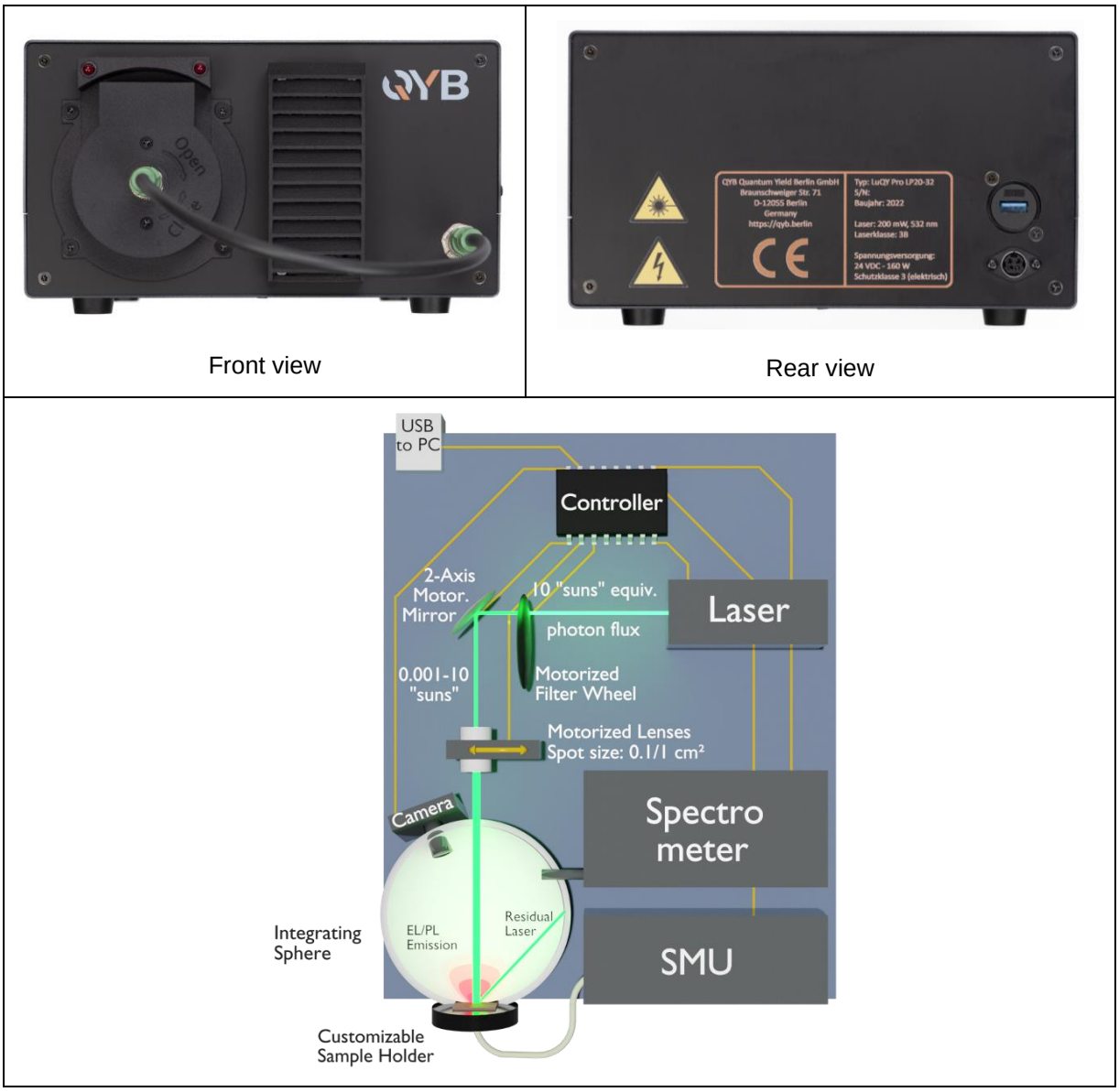


Fig. 4-1. ***Overview of the Radiative efficiency meter****. Top two images show the external view of the instrument and the bottom image schematically demonstrates the key components of the instrument.*

The "LuQY Pro", type no. LP20-32, consists of:	
1 Aluminium housing	9 Shutter with servomotor
2 Controller board	10 Laser (Class 3b)
3 Integrating sphere	11 Filter wheel with servomotor
4 Moving lens with servomotor	12 RFID coded safety sensor (sample holder)
5 Sample holder	13 Sensors for housing monitoring
6 USB camera	14 Spectrometer
7 2-axis adjustable mirror with stepper motor	15 External $230V_{AC} \rightarrow 24V_{DC}$ power supply unit
8 SMU (Source Measure Unit)	

4.2 Commissioning

When connecting to the mains, observe the power ratings and the technical data. The LuQY Pro was delivered to the operator by the manufacturer in fully functional condition. Assembly and disassembly must be performed in agreement with the manufacturer and in accordance with the manufacturer's instructions.

- Leave at least 15 cm free space at the front and side vents to ensure good cooling of the LuQY Pro.
- Lay the connecting line to protect against tripping.
- Do not operate the LuQY Pro while disassembled.
- Only operate the LuQY Pro while it is standing on its feet.
- In case of faults or non-function, contact the manufacturer.

(1) Connect the KPJX-PM-4S plug of the power supply (not powered!) and the USB 3.0 cable to the LuQY Pro.

Fig. 4-2. Rear view of the LuQY Pro System

(2) Connect the power supply to the grid.

Fig. 4-3. Power supply of the LuQY Pro System.

(3) Connect the USB 3.0 cable with the measurement computer.
(4) Power on the device by pressing the power button on the top of the housing.
(5) Tilt the sample holder by ca. 45° clockwise to release it from the housing. In case the laser is running, an integrated interlock will turn off the laser immediately. To close the sample port again, attach the sample holder tilted by ca. 45°, move it onto the sample port opening and turn the sample holder counter-clockwise by ca. 45°.

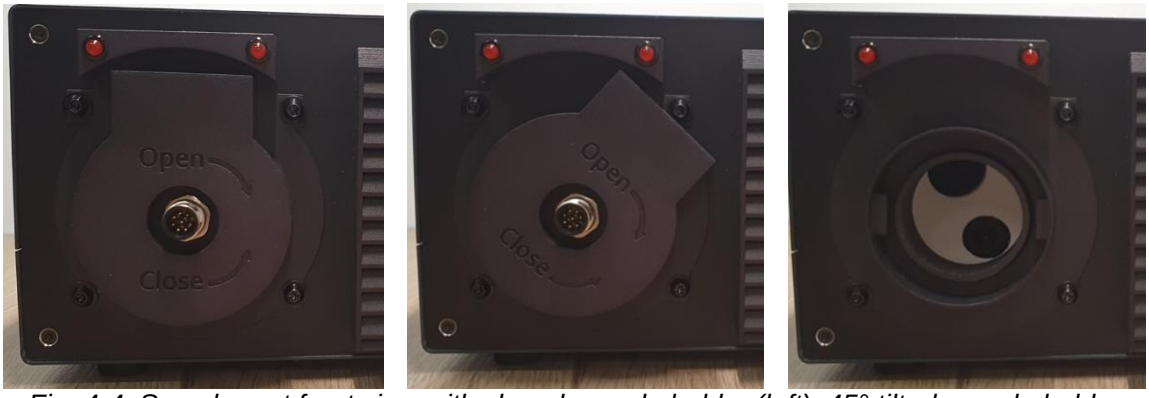


Fig. 4-4. Sample port front view with closed sample holder (left), 45° tilted sample holder (middle) and opened sample port (right)

(6) A 10 pin Phoenix Contact cable connects the two connectors on the LuQY Pro front (bottom right) and the sample holder rear side. This cable establishes the connection between the SMU and the sample in the holder. Make sure to tighten the fixation screws on the outsides of the cable connectors.

4.3 Technical data

The technical data of the LuQY Pro can be taken from the type plate. The name plate is located on the back of the device.

Operating voltage:	24 V_{DC}
Protection class:	1
Temperature range:	+10° … +30°C
Storage temperature range:	+10° … +40°C
Relative humidity:	20 – 60 / < 50%
Protection class (housing):	IP 50
Protection class (electrical):	3
Degree of pollution:	1
Max. installation height:	< 1000 m a.s.l.
YOM	2021

4.4 Weight and dimensions

Width:	approx. 220 mm
Depth:	approx. 275 mm
Height:	approx. 130 mm
Weight:	approx. 6 kg

5 Software

5.1 Installing software

The software comes pre-installed on a provided laptop and should run upon start. In order to ensure reliable operation, modification to the software of any sort (re-installation, updates etc.) should be done in consultation with a QYB representative.

5.2 Startup software

At launch of the program it will check communication to the devices. If one of the disks is not green, restart the LuQY Pro and the program. Turn on the LuQY first before the program. All disks need to be green to use all functionalities of the setup.

Fig. 5-1. Startup screen checking the availability of internal components

5.3 Main interface

5.3.1 Spectrum

The graph on the main window shows the spectrum measured by the spectrometer. When the '**Live View'** button is active (orange), the graph continuously shows the raw spectrum from the spectrometer. The dashed line indicates the threshold of the noise filter. Signal below this threshold will not be converted to absolute photon numbers. Also see section 5.3.8 for more information When a measurement is being recorded, the live switch turns off and the graph shows the calibrated spectrum used for LuQY calculation. To see the live spectrum again '**Live View'** has to be turned back on. Switching the live view off will display the last measurement result. In this view mode, an additional **'Log'** button appears above the photon flux axis which allows to show the data on logarithmic scale.

The '**Integration Time**' input field allows to manually change the integration time of the spectrometer in live mode to a desired time in milliseconds.

Manually enter an integration time in milliseconds of the spectrometer. Min./Max. values are 1 – 65.000 ms. Typical values are 50 – 10.000 ms.

'Auto-Integration Time' When clicking this button, the software tries to detect a luminescence signal and scale the integration time automatically to ensure a good signal-to-noise ratio.

Fig. 5-2. Main window, highlighted live spectrum and integration time control of the spectrometer

In the case that the spectrometer goes into saturation (signal too strong), the software by default will automatically re-adjust the integration time. If you want to turn this function off, go to **Tools'** in the top menu → **'Application Settings'** and deactivate the button '**Auto-adjust integration time on saturation'**.

The button next to the field with two orange arrows activates the '**Auto-Integration Time'** function. Clicking this button will adjust the integration time, so that the detected luminescence signal will allow a good signal-to-noise ratio.

5.3.2 Sample

Fig. 5-3. Main window, highlighted is section (1) Sample

Here, the operator selects the necessary information about the sample in order for an accurate calculation of the implied V_{OC}. If the bandgap value of the material is known it can be input here to increase the iV_{OC} calculation accuracy. Same goes for the short circuit current density under standard testing conditions (J_{SC}) and the external quantum efficiency of the material at the laser wavelength (532 nm).

When the **play buttons are activated (orange)** the program **guesses** these values from the live spectrum. The maximum energy of the luminescence signal is used as the guessed band gap energy (if exceeding a signal intensity threshold of 800 counts). From this bandgap, the software guesses the J_{SC} as 85% of the detailed balance limit J_{SC} for the respective bandgap and an absorber emitting to one side. The guessed EQE at laser wavelength is simply 90% in all cases. A yellow indicator next to the data input fields will highlight that the currently shown values are guessed values.

For higher accuracy of the iV_{OC} prediction, the **'Load EQE'** button further allows to input external quantum efficiency (EQE) or absorptance data of your sample to determine the bandgap energy, J_{SC} and EQE @ 532 nm. Clicking the button opens the following sub-window:

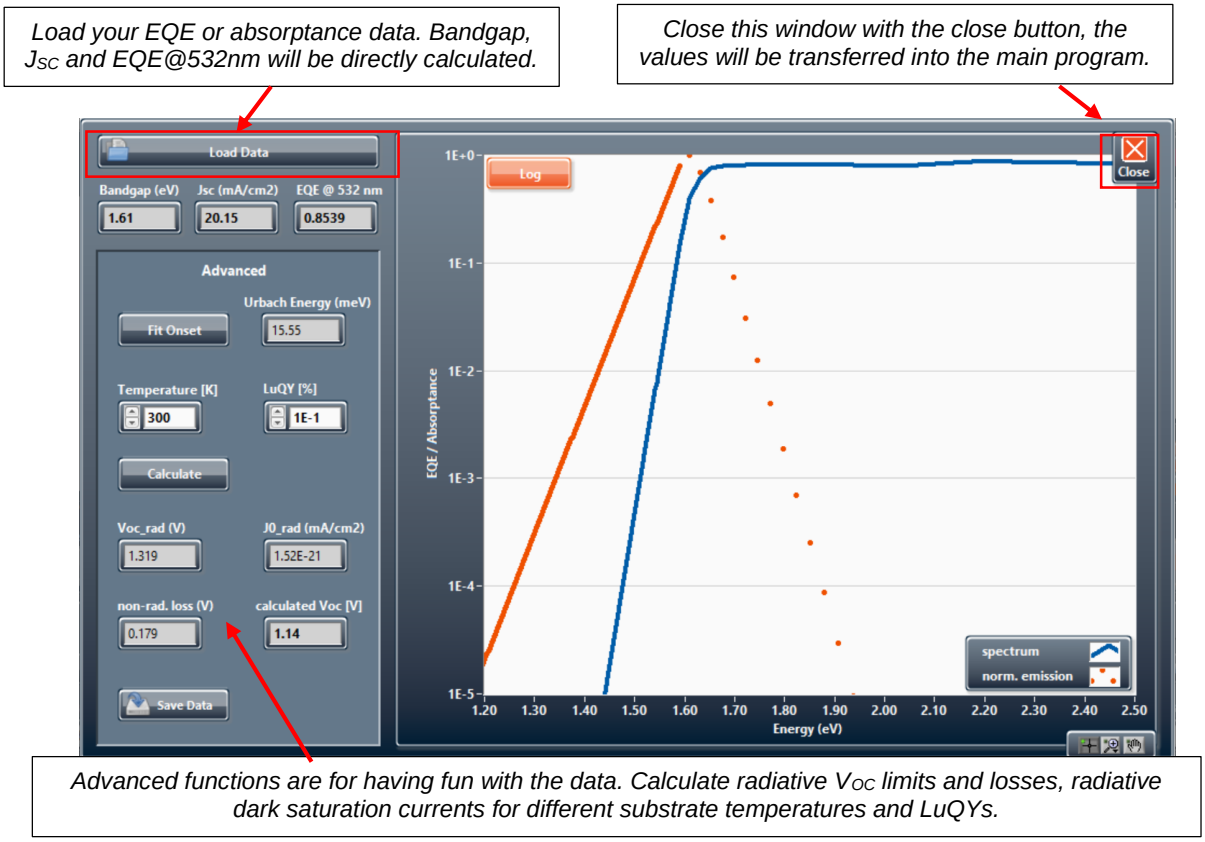


Fig. 5-4. 'Load EQE' window with possibility to have external quantum efficiencies or absorption data of your sample analysed to extract band gap, J_{SC} and EQE at the laser wavelength.

'Load Data' allows to import your EQE or absorptance data. Your input file must be ASCII with two coloumns, **first coloumn with Wavelength (nm) or Energy (eV) and second coloumn with EQE/absorptance (% or absolute values).** There must be no units behind the values, no file header and numbers must use a decimal point. Examples are:

Wavelength vs. EQE in %		Wavelength vs. EQE in % - Scientific		Wavelength vs. EQE in abs. values		Energy vs. EQE in absolute values	
300	4.76	3.00E+2	4.76E+0	300	0.0476	4.13	0.040
310	16.9	3.10E+2	1.69E+1	310	0.169	4	0.10
320	39.4	3.19E+2	3.94E+1	320	0.394	3.875	0.237
…		…		…		…	

The bandgap energy is calculated from the infliction point of the absorption onset, J_{SC} by convolution of the data with the AM1.5G spectrum and the EQE @ 532 nm is interpolated from the given data.

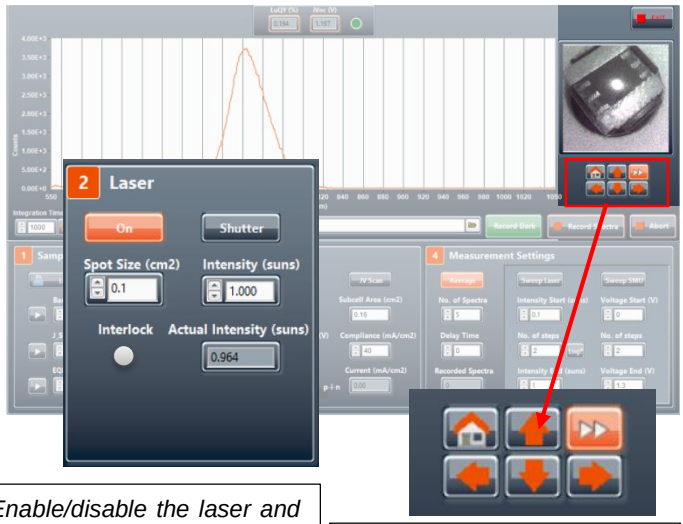
Further, some advanced functions are available in this window. To use them, two dashed lines first need to be shifted to enclose the absorption onset (recommended in logarithmic view). By then clicking **'Fit Onset'** the orange extrapolation line appears and the Urbach Energy for this fitted line is given.

With this, a sample temperature and a luminescence quantum yield (LuQY) can be entered. Another click on **'Calculate'** then yields the theoretical values: radiative V_{OC} limit, non-radiative V_{OC} losses, the expected V_{OC} as well as the reverse diode saturation current.

5.3.3 Laser

This field controls the laser spot size and intensity. Clicking the '**Off**' or '**On**' button will turn the laser on or off, respectively. An orange button indicates its active state. Same goes for the '**Shutter**' button, which closes or opens the shutter intermitting laser light to irradiate onto the sample.

The laser spot size can be changed by the respective '**Spot Size**' input field between 0.1 or 1 cm² in the standard configuration of the LuQY Pro. The '**Intensity**' input allows to adjust the laser intensity in suns-equivalent excitation. The corresponding laser intensity is automatically calculated for the selected spot size as well as J_{SC} and EQE @ 532 nm values in the '**(1) Sample**' section.



Enable/disable the laser and shutter, change spot size and the intensity of the laser excitation in this section 3.

This panel controls the laser spot position. When the fast forward button is deactivated the movement is slower.

Fig. 5-5. Main window, highlighted is section (2) Laser and its position control

The sample holder is equipped with an interlock which disables the laser as soon as the sample holder is taken off. In this case, the '**Interlock**' status indicator will turn orange and the laser will be disabled in the software. If the interlock is resolved again, there is a safety waiting time of 5 s before the laser can be turned on again. **Always make sure that all openings of the housing are shaded and no damages are visible on the device before turning on the laser**.

Changing the value for intensity keeps the spot size constant and changes the excitation power of the laser. Changing the spot size keeps the excitation power the same, which effectively changes the intensity. The '**Actual Intensity**' displays the measured power output from the laser. Should the set intensity value differ drastically from the actual intensity, please double check that the set intensity value is not too high. The maximum value that can be achieved again depends on the spot size, the J_{SC} and EQE @ 532 nm of the sample. The absolute maximum values of the excitation over the bandgap assuming a step-function EQE according to the detailed balance limit are depicted in Fig. 5-1 left. Should the actual intensity not reach these values, please contact QYB support. Also make sure that the values are stable before measuring.

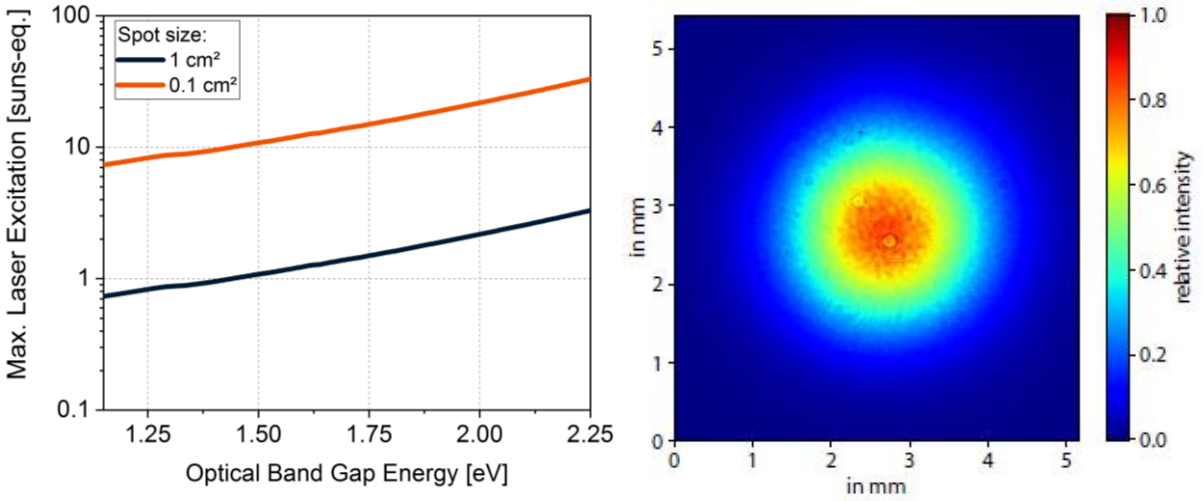


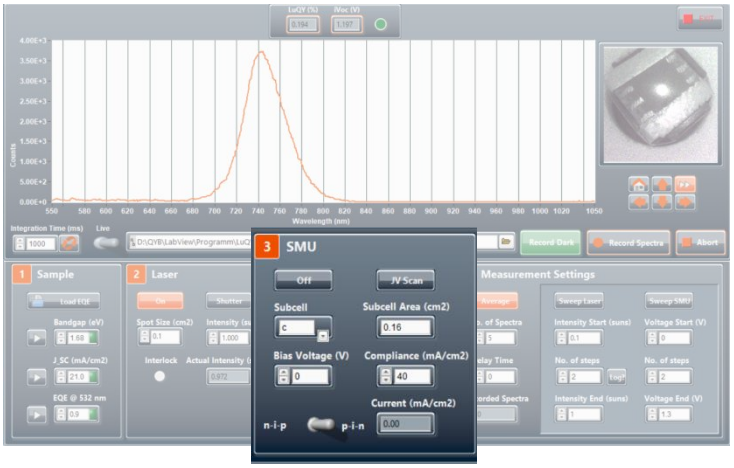
Fig. 5-6. Left: laser intensity for 0.1 and 1 cm² spot size over optical bandgap of sample (assumption: ideal absorption of sample, zero for photon energies below and one for energies above optical bandgap energy). Right: exemplary 3D beam profile of the 0.1 cm² laser spot in the sample plane.

Please note, that the laser beam profile is not homogeneous across the spot but has a rather Gaussian distribution of intensity (Fig. 5-1 right). The setpoint laser intensity is thus the average photon flux within the $1/e^2$ diameter of the laser beam. In case of strongly differing recombination dynamics for different excitation intensities, this can lead to a deviation between measured LuQY and actual LuQY for the respective setpoint excitation.

Finally, the arrows below the camera image of the sample allow to move the laser up, down, left and right. The **'Home'** button will re-initialize the laser position to its starting point. The **'Arrows'** button allows to switch the movement speed between fast when activated and slow when deactivated.

5.3.4 Source Measure Unit (SMU)

The source measure unit can be independently controlled in section 3. Choose a subcell of your sample holder in the '**Subcell**' section and enter the corresponding '**Subcell Area**' in cm². Next, the desired '**Bias Voltage**' as well as a current '**Compliance**' can be set. Further, you can select the polarity of your sample by the '**n-i-p/p-i-n**' switch. Upon clicking the '**Off**' button, the set bias voltage is being applied. Monitor the current on the bottom right that flows through the cell. When the current compliance is reached, the program reduces the voltage to a value with which the current is below the compliance again in 0.1 V steps.



Apply a bias voltage to a subcell on your sample or open the JV scan sub-window in this panel.

Fig. 5-7. Main window, highlighted is section (3) SMU

The current range of the measuring SMU is set to maximum as standard with a decent accuracy until ~0.1 mA. For higher accuracy, call the '**Application Settings**' in the top menu and change the range. The manually set range will stay active during runtime until the SMU output is turned off again. If the maximum current of the given range is exceeded, the current protection will kick in and avoid a voltage application. In this case, turn the SMU off/on again (range will be again at max. 100 mA).

Click on '**JV Scan**' turns off the continuous voltage application and opens a sub-window for current-voltage scanning of the subcell selected in the main window:

With a click on Go the current-voltage scan is performed with the set values on the top. In the application settings menu, a delay time between voltage application and current measurement can be configured as described in the section 'Application Settings' below.

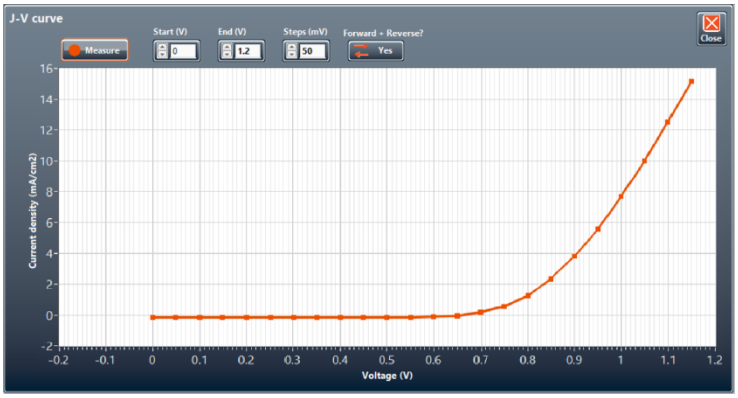


Fig. 5-8. 'JV Scan' window showing an exemplary JV curve.

Please note, that the laser beam profile is not a homogeneous flat-top but a rather Gaussian distribution of intensity. Thus the laser intensity in the centre of the spot is higher than on the edges. When illuminating an active area smaller than the spot area, the effective excitation within this area can differ from the setpoint excitation intensity due to this effect. In this case, please first on the main interface apply 0 V '**Bias Voltage**' to the cell under investigation and move the laser spot until the measured J_{SC} matches your expected J_{SC} of the cell. Vice versa if the laser spot size is smaller than your active area, please enter the spot size as '**Subcell Area**' on the main interface to read the currect J_{SC} during JV scanning.

5.3.5 Measurement settings

This section configures the recording of luminescence spectra. There are two different record modes. As standard, **'Average'** is activated (recommended). Here, the program collects a **'No. of Spectra'** with a **'Delay Time'** between each spectrum and will average the final spectrum over all recorded ones. This improves the signal-to noise ratio, in general <10 spectra will be sufficient. However, for samples with transient phenomena the final spectrum will represent an average of the changing spectrum.

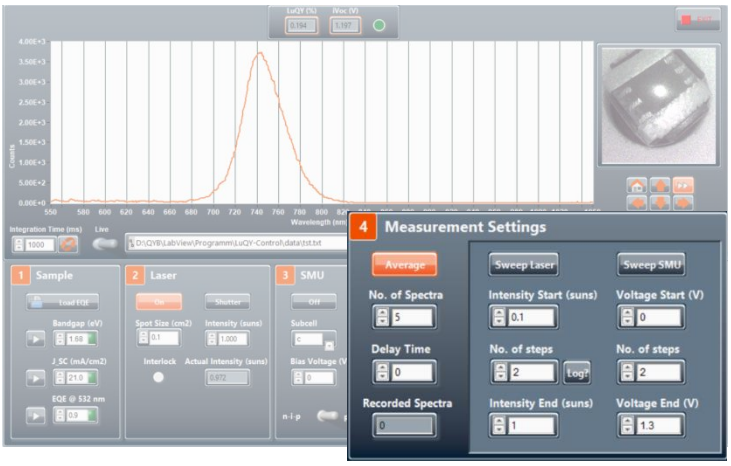


Fig. 5-9. Main window, highlighted is section (4) Measurement Settings

To record such transient changes of the steady state luminescence, the second record mode **'Continuous'** is available by clicking the 'Average' button. In this case, the program will collect a **'No. of Spectra'** with a **'Delay Time'** between each spectrum and will save the raw data and the absolute photon fluxes in separate .txt files. The raw data measured by the spectrometer is stored under the given savefile name but with a '_raw.txt' extenstion.

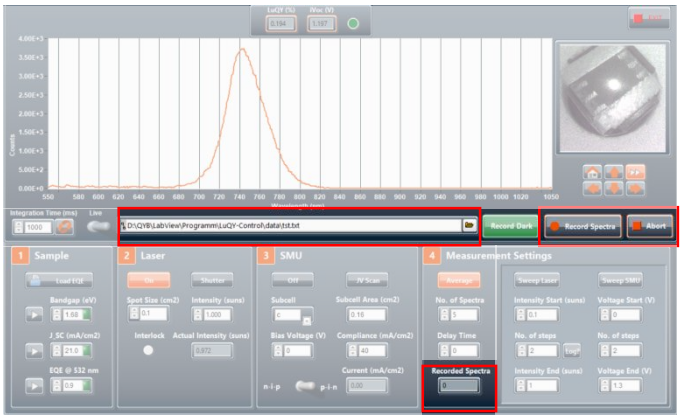
If **'Sweep Laser'** OR **'Sweep SMU'** is active: record spectra will start an automatic sweep of the parameters and save a file with the sweeped parameter and a LuQY calculation for every step. Sweeps can only be performed with "average spectra" activated. Check the number of spectra before starting a sweep. **'Log?'** next to the number of intensity steps will create a logarithmic ramp of intensities instead of the linear measurement, it is advisable after prolonged measurements (>10 min) to record a new dark reference to improve signal-to-noise ratio. Clicking abort during the automatic sweep will finish the current parameter, finish saving the file until that point and then abort the measurement. Here again, the absolute photon flux and the raw data will be stored in separate .txt files.

5.3.6 Perform measurement

(1) Before every measurement, it is advised to click on 'Record Dark' first. This will collect a dark reference measurement with the shutter being closed, using the 'Number of Spectra'

setting in the Application Settings, standard value is five spectra (see section 5.3.8). After changing the integration time, a new dark reference measurement is necessary for good accuracy, particularly if the new integration time is drastically different than the initial. Even if the integration time is not changed during the measurement, it is advisable after prolonged measurements (>10 min) to record a new dark reference to improve signal-to-noise ratio.

Fig. 5-10. Main window, highlighted is the 'Record Dark' button



(2) Enter a folder and filename and click 'Record Spectra' to start a measurement. The **'Recorded Spectra'** field displays the number of spectra which have already been recorded. When starting a measurement, the live mode of the luminescence view is switched off and the graph will no longer display the raw signal of the spectrometer but the **luminescence photon flux in photons/s/nm.**

Fig. 5-11. Main window, highlighted are record spectra relevant sections

(2.1) Background noise filter

Note, that the background noise is filtered when translating the raw spectrum from the spectrometer to the calibrated photon flux spectrum. The degree of filtering can be adjusted in the application settings from **'Off' to 'Low', 'Medium', 'High' or even 'Manual'** (see section 5.3.8.). The threshold value of the noise filter is displayed in the spectrum graph as a dashed line. Signal below this line will be set to zero when being converted to absolute photon fluxes. If the noise filter is set to 'Manual', you can drag and drop the dashed line vertically to set your desired filtering threshold. All signals below the noise filter level will be 0 when converting the spectrometer signal to absolute photon flux.

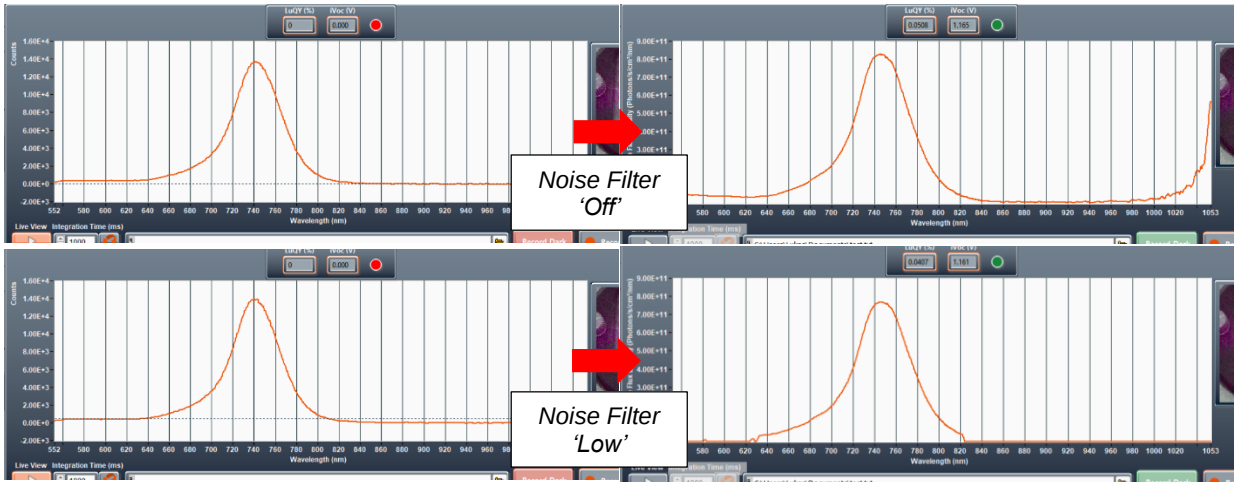


Fig. 5-12. Live (left) and resulting absolute (right) spectra for different noise filtering settings: Top row: noise filter 'Off', bottom row: noise filter 'Low'

(2.2) Sweeps

If a voltage or intensity sweep has been selected, the software will perform individual measurements at the given setpoints. On default, the software will automatically adjust the integration time and will do a dark reference measurement at each setpoint. If you want to turn this functionality off, go to **Tools'** in the top menu → **'Application Settings'** and deactivate 'Record dark measurement during sweeps' and/or 'Auto-adjust integration times during sweeps'.

(3) At the end of the measurement, **the calculated external luminescence quantum yield ('LuQY') as well as the estimated implied V_{OC} ('iV_{OC}') will be displayed at the top of the program window.** Details about the calculation method for these values can be found in section 5.4.The indicator next to it will turn green if the iV_{OC} estimation was successful or red if unsuccessful (e.g. luminescence signal too low). The values will also be stored together with the photon flux spectrum as well as the raw signal from the spectrometer in the savefile specified before.

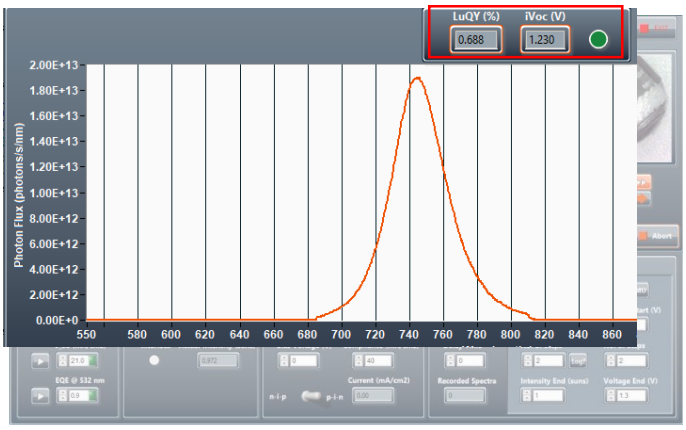


Fig. 5-13. Main window, highlighted is the recorded spectrum view and LuQY & iV_{OC} values

5.3.7 Laser position scanning

Go to **'Tools'** in the top menu → **'Laser Position Scanning'** to open the sub-window 'Laser positions' shown on the right. The **'Current X position'** and **'Current Y position'** fields display the current position of the laser spot. When moving the spot by the arrows in the main window (see section 5.3.3), the values will update with the movement. The table '**Coordinates to run**' allows to enter several laser spot positions in a x-y format. Each row of the table is one measurement point at the given x-y laser position. Clicking '**Start**' will perform a luminescence measurement with the settings defined on the main window (laser intensity, integration time, no. of spectra to record, etc.) for each position listed in the table. The recorded spectra for each position will be saved as separate coloumns in a single output file.

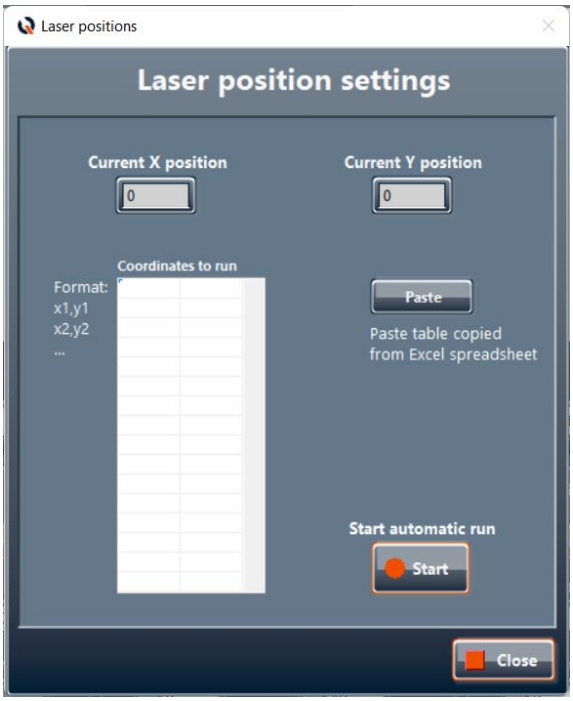


Fig. 5-14. Laser position settings window

5.3.8 Application settings

Go to **'Tools'** in the top menu → **'Application Settings'** to open the sub-window shown on the right.

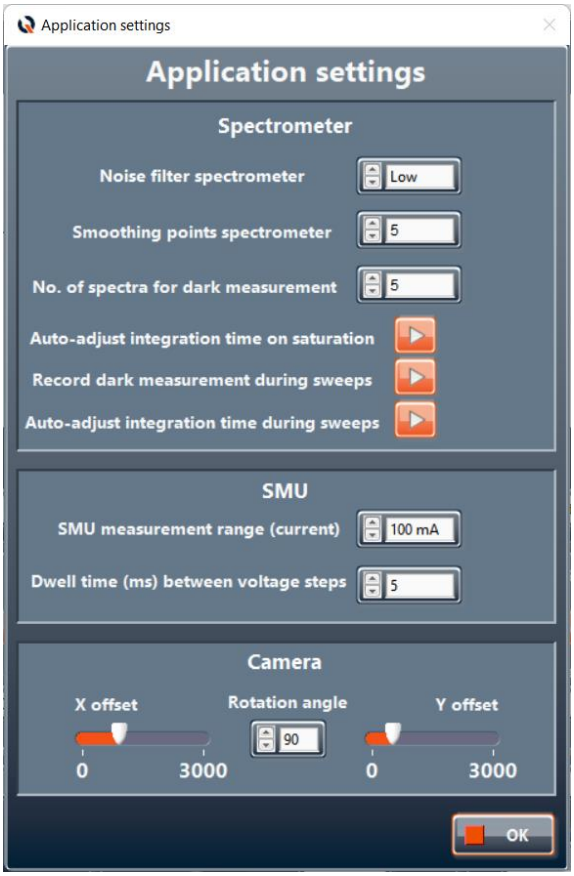


Fig. 5-15. Application settings window

The first part of this window controls the spectrometer settings. Here you can select the degree of background noise filtering in **'Noise Filter Spectrometer'**. Background noise is filtered when translating the raw spectrum from the spectrometer to the calibrated photon flux spectrum. Standard is 'Low', 'High', 'Medium', 'Off' or 'Manual' are also possible. 'Manual' allows to manually drag the noise filter threshold vertically (dashed line in live spectrum view) to set it to a desired value (also see section 5.3.6). Further, the '**Smoothing Points Spectrometer**' option allows to smoothen the display spectrum by averaging over the defined number of spectrally neighboring measurement points. Finally, the '**No. of spectra for dark measurement**' entry field defines the number of spectra which are recorded for the dark reference measurement when clicking '**Record Dark**' on the main interface.

When the spectrometer saturates due to a too intense signal, the software by default will automatically re-adjust the integration time. If you want to turn this function off, deactivate the button '**Auto-adjust integration time on saturation'**. The next two buttons relate to measurement sweeps and allow to deactivate the recording of a dark reference and/or the re-adjustment of the integration time at each measurement point

The next part of the sub-window focuses on the SMU settings. **'SMU measurement range (current)'** selects the current measurement range of the SMU. Lower ranges allow more accurate measurement of low currents. However, when exceeding the defined maximum current the SMU will switch off. The manually set range will stay active during runtime until the SMU output is turned off again. **'Dwell time (ms) between voltage steps'** refers to the JV scan function and defines the waiting time before measurement after applying a voltage step.

Finally, the **X- and Y-offset as well as the 'Rotation angle' of the camera view** can be adjusted in the lower part of the window. Changing the values will directly move your region of interest of the camera view in the main program.

5.3.9 Save and load measurement settings

Go to **'Tools'** in the top menu → **'Save Measurement Settings'** to save the current settings entered in the GUI. This includes all button settings, entry fields and selector boxes in the sections 1 (sample) to 5 (measurement settings). The settings are stored as a .qyb file.
To load a set of pre-saved measurement settings, go to **Tools'** in the top menu → **'Load Measurement Settings'** and select the respective '.qyb' file in the file dialog.

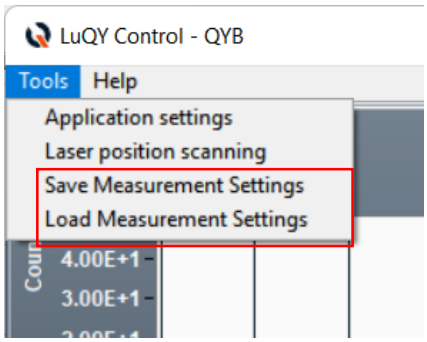


Fig. 5-16. Menu for saving and loading measurement setting of the GUI

5.4 LuQY Calculation and implied open circuit voltage prediction

The external luminescence quantum yield displayed by the software is calculated by

$$\mathrm{LuQY} = \eta_{ext} = \left(\frac{\int_0^\infty \phi_{lum}(E)dE}{\int_0^\infty \phi_{exc}(E)dE - \int_0^\infty \phi_{exc,R}(E)dE + I_{SMU}}\right), \qquad (1)$$

where η_{ext} = external quantum yield LuQY, ϕ_{lum}= absolute luminescence flux density, E = photon energy, ϕ_{exc}= excitation photon flux density (laser in LuQY Pro), $\phi_{exc,R}$= non-absorbed excitation photon flux density (reflected laser in LuQY Pro), I_{SMU} = current sourced by the SMU. Note, that sinked current is not taken into account for the LuQY calculation, i.e. PL emission at short circuit condition will yield a lower LuQY than emission at open circuit (assuming that luminescence is quenched by extraction of charge carriers at short circuit current).

Further, the software uses two different methods to predict the implied open circuit voltage iV_{OC} of a sample. Depending on the user input and the fitting accuracy, the software will use:

(1) **If Eg & EQE input is not provided:**

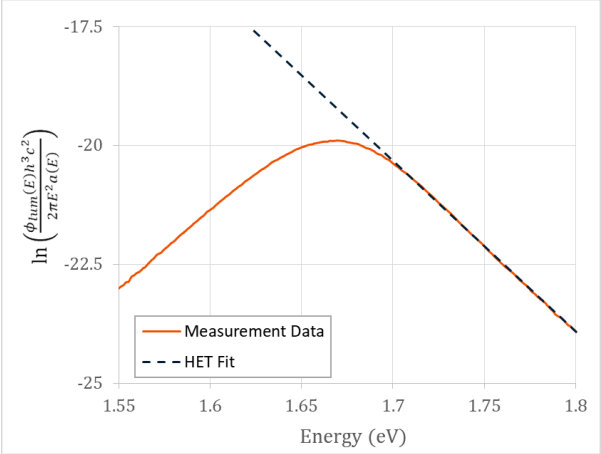


Fig. 5-17. Exemplary luminescence emission data and high energy tail fit. The intersection of the fitted line with the ordinate at 0 eV yields $q \cdot iV_{OC}/k/T$.

High energy tail fit:

$$\ln\left(\frac{\phi_{lum}(E)h^3c^2}{2\pi E^2 a(E)}\right) = -\left(\frac{E - q \cdot iV_{OC}}{kT}\right), \qquad (2)$$

where ϕ_{lum}= absolute luminescence flux density, E = photon energy, h = Planck constant, c = speed of light, a = absorptance of sample, q = electric charge, k = Boltzmann constant, T = Temperature of electron gas. Please note, that the measurement data provided by the LuQY Pro system needs to be transformed from wavelength- to energy-dependent before applying formula (2).

[1] Unold, T.; Gütay, L. Photoluminescence Analysis of Thin-Film Solar Cells. In *Advanced Characterization Techniques for Thin Film Solar Cells*; Wiley-VCH Verlag GmbH & Co. KGaA, 2011; pp 151–175.
[2] Kirchartz, T.; Márquez, J. A.; Stolterfoht, M.; Unold, T. Photoluminescence-Based Characterization of Halide Perovskites for Photovoltaics. *Adv. Energy Mater.* **2020**, 1904134.

(2) **If Eg & EQE input is provided or fitting residual exceeds threshold (1):**

LuQY based prediction:

$$iV_{OC} = V_{OC,SQL,AM1.5G}(E_g) + \frac{kT}{q}\ln(\eta_{ext}) + \frac{kT}{q}\ln\left(\frac{\int_{Eg}^{\infty}\phi_{lum}(E)dE}{\int_{0}^{\infty}\phi_{lum}(E)dE}\right) + \frac{kT}{q}\ln\left(\frac{\int_{0}^{\infty}a(E)\phi_{exc}(E)dE}{\int_{Eg}^{\infty}\phi_{AM1.5G}(E)dE}\right), \quad (3)$$

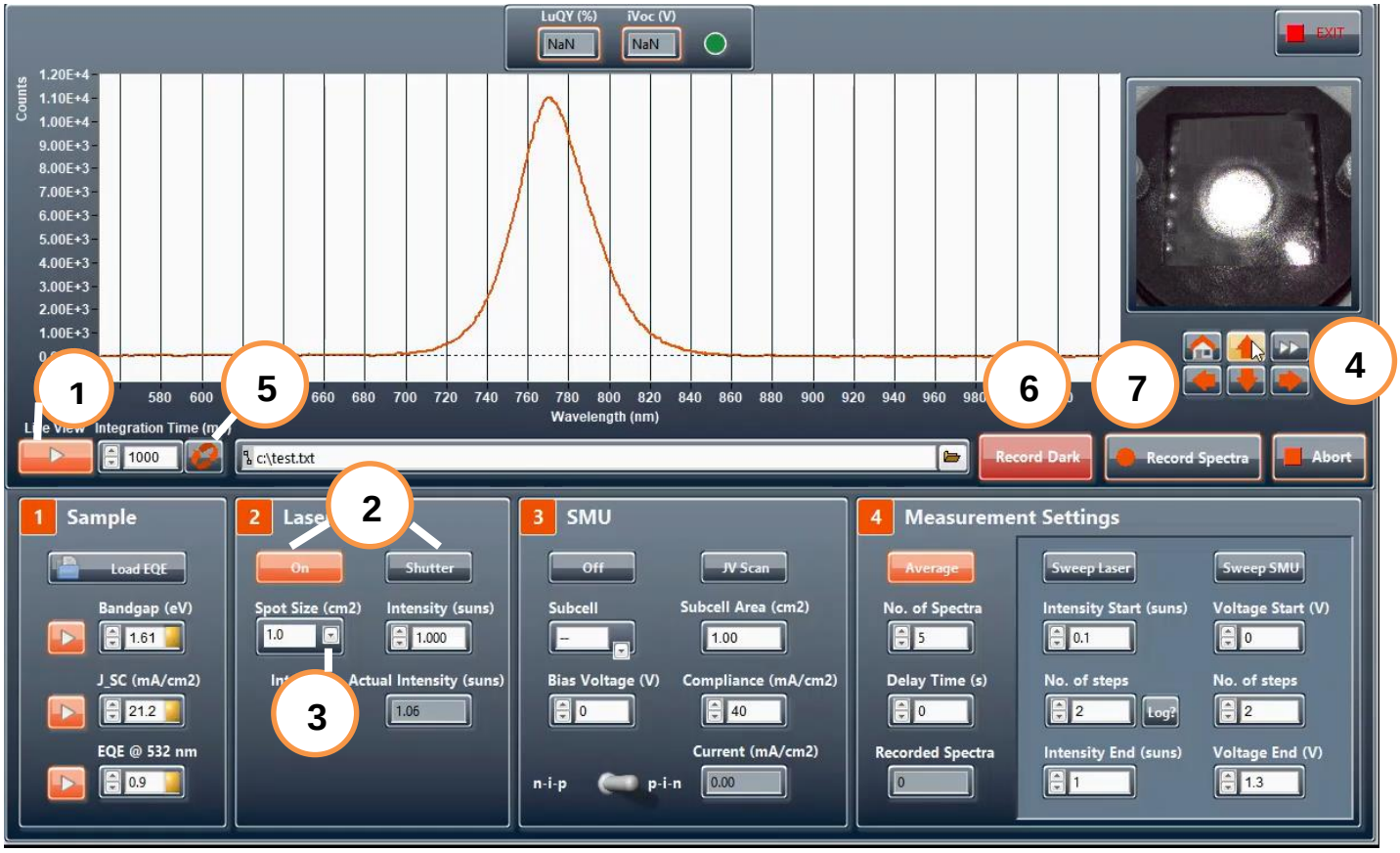
where $V_{OC,SQL,AM1.5G}$ = Shockley-Queisser limit V_{OC} under AM1.5G illumination, E_g = Bandgap Energy, $\phi_{AM1.5G}$= photon flux of AM1.5G illumination.

[3] Ross, R. T. Some Thermodynamics of Photochemical Systems. *J. Chem. Phys.* **1967**, *46* (12), 4590–4593. https://doi.org/10.1063/1.1840606.
[1] Unold, T.; Gütay, L. Photoluminescence Analysis of Thin-Film Solar Cells. In *Advanced Characterization Techniques for Thin Film Solar Cells*; Wiley-VCH Verlag GmbH & Co. KGaA, 2011; pp 151–175.

6 Quick Start Guide

To swiftly measure the PLQY of a sample and get a first estimation of its iV_{OC}, follow these simple steps:

0 Load sample into sample holder and attach the holder to the setup
1 Activate the spectrometer live view if not already active
→ "Live View" button must light up orange
2 Activate the Laser & open the shutter
3 Select the 1 cm² laser spot size; we recommend to always use the 1 cm² spot if possible as this will allow for higher PLQY resolution and better signal-to-noise ratio of the PL detection. 0.1 cm² spot is useful for high excitation or to probe local spots on the sample.
4 Move laser spot to your region of interest
5 Click the “Auto-Integration” time button
6 Perform dark measurement
7 Record the spectrum
8 To switch back to the live mode of the spectrometer, activate the "Live View" button (1) and start further measurements



7 Declaration of conformity

The company QYB Quantum Yield Berlin GmbH hereby declares that the LuQY Pro complies with the requirements of the applicable European and national directives:

- Electrical equipment 2014/35/EU (& DIN EN 61010-1),
- Electromagnetic compatibility 2014/30/EU (& DIN EN 61000-6-2,-4),

Conformity has been demonstrated. The corresponding declarations and supporting documents may be viewed at the manufacturer's premises.

Note on the application of EU directive **EMC 2014/30/EU**:
As per DIN EN 61000-6-4 (basic technical standard for emission, industrial environment), the LuQY Pro must not be operated in residential, commercial and light-industrial environments.

In residential, commercial and light-industrial environments, interference with other electrical loads may occur. Danger of other devices / machines malfunctioning. *In residential, commercial and light-industrial environments, the standard DIN EN 61000-6-3 (emission, residential environment) must be observed.*

Berlin, 07.02.2021

Dr. Lukas Kegelmann (CEO)

8 Malfunctions

Disconnect the device from the mains in the following situations:

- Voltage supply cable is damaged;
- Power-On switch is damaged;
- Smoke is detected;
- Liquid entered the Radiative efficiency meter;
- The Radiative efficiency meter was exposed to moisture;
- The Radiative efficiency meter does not work correctly as per this Operating manual.
- The Radiative efficiency meter was dropped or damaged, or the device shows clear signs of a defect (contact the manufacturer).

A qualified trained person establishes the cause and determines further measures.
Work on the LuQY Pro may only be performed by authorised personnel of the manufacturer.

9 Transport

When moving the device, take the operating manual with you and keep it near the device, or provide the operating manual in an electronically readable form.

LuQY Pro transport:

1. Switch off the LuQY Pro before transport.
2. Disconnect the following items:
    - Voltage supply cable,
    - Electrical connection to the sample holder,
    - USB cable
3. The LuQY Pro can be transported to the new site of operation.

Transport and return shipment in original packaging only.

10 Maintenance and cleaning

Before commencing any cleaning work, disconnect the Radiative efficiency meter from the mains (disconnect the power supply plug). **Do not use liquid or aerosol cleaners.** This would result in damage to the LuQY Pro. Use a dry and lint-free cloth for cleaning. The LuQY Pro must be protected from moisture. Only a qualified electrician or EIP ("electrically instructed person") may open the device. Check the housing for damage, cables and plug connections for kinks and chafe marks, correct insulation, and dirt.

No.	Work to be done	Frequency	Remark
1	Check air inlet and outlet.	daily	Keep the air inlet and outlet at the ventilation grilles free.
2	Check cable for sound condition and tight fit. • Power cable • Connecting cable	daily	Immediately dispose of damaged cables and replace with new ones.
3	Clean the outside of the device.	weekly	Clean the housing from dust.
4	• Maintenance • Calibration • Clean the inside of the device.	every year	Any and all work inside the device must be performed by the manufacturer only!

Calibration: Calibration of the measuring unit (integrating sphere and spectrometer) is performed by the manufacturer.

11 Installation of spare and wear parts

Spare and wear parts can be purchased from the manufacturer.

12 Service

If required, these parts can be obtained from:

Company: QYB Quantum Yield Berlin GmbH
Braunschweiger Str. 71, 12055 Berlin / Germany

E-mail: contact@qyb.berlin

13 Scope of delivery

The scope of delivery of the LuQY Pro includes:

- LuQY Pro
- $230V_{AC} \rightarrow 24V_{DC}$ power supply unit
- Measurement computer with analysis software and power supply
- This Operating manual (in digital form)

Always check immediately after unpacking that the complete scope of delivery has been supplied and that the LuQY Pro is in sound condition. **Keep the original packaging for transport!**

14 Warranty provisions

The implied warranty by producer / distributor is limited to 12 months from the date of delivery or handover on site after commissioning. The device was carefully produced and subjected to a precise quality control. Within the warranty period, all material or manufacturing failures will be repaired free of charge. Excluded from the warranty are damages caused by improper handling, failure to observe the Operating manual or manipulation by unauthorised persons or wear parts. The warranty period of 12 months is neither extended nor renewed by the warranty service.

15 Disposal

The Radiative efficiency meter is made of metal and plastic (the electrics excluded) and must be disposed of in accordance with the current local environmental regulations. National laws and regulations must be observed.

Depending on condition, applicable regulations and in compliance with current provisions, disposed of the parts as, for example:

- Electrical waste
- Fluorescent / energy-saving lamps (collection points)
- Plastics / Rubber
- Batteries (collection points)

The packaging and packaging material is made exclusively of environmentally friendly materials. They can be disposed of in local recycling containers. In the European Union, the separate components must be disposed of separately. Marked products must not be disposed of as normal household waste, but must be taken to a collection point for the recycling of electrical and electronic equipment. By recycling, you can help minimise the demand for raw materials and reduce the burden on the environment.

We recommend that you have the device disposed of by the manufacturer.

16 Annex