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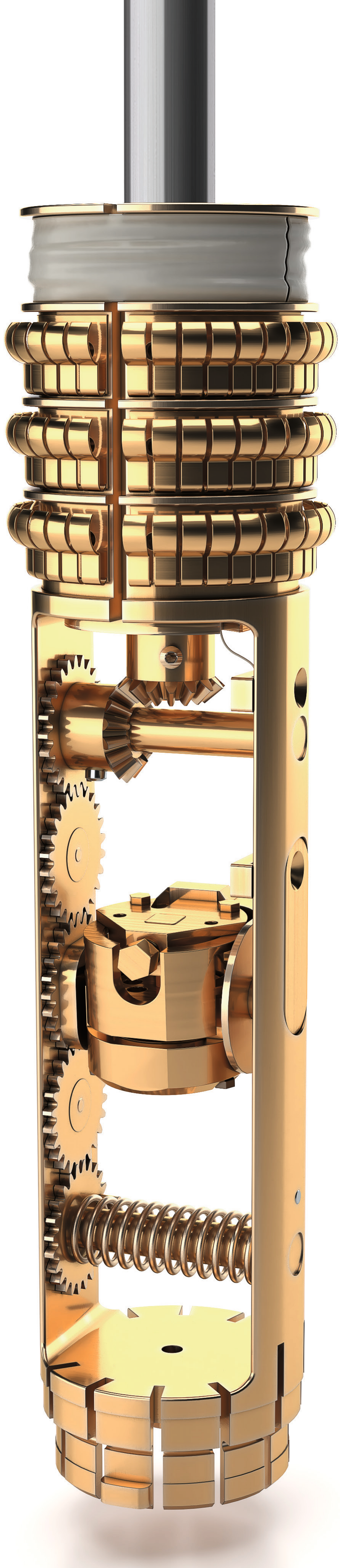

MANUAL
IN-SITU PPMS-DILATOMETRY PROBE

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In-Situ Rotational PPMS Dilatometry Probe

1.1 Overview

The in-situ rotational PPMS dilatometry probe is designed to enable manual rotation of a mini-dilatometer inside a Quantum Design PPMS while maintaining full thermal and mechanical stability. This probe allows the dilatometer to be rotated in situ at any angle between $-90° \leq \mu \leq +90°$ in PPMS over a temperature range from 320 to 1.8 K. This capability enables efficient and systematic anisotropy studies with minimal measurement time.

The dilatometer is mounted on a mechanical rotator integrated into the probe, allowing precise angular positioning without removing the probe from the PPMS.

1.2 Mechanical Design and Rotation Mechanism

A mini-dilatometer (1) is mounted on a C-shaped dilatometer holder (2). This holder is attached to a mechanical rotator that enables horizontal, manual in-situ rotation of the sample within the PPMS sample space. The rotation axis is perpendicular to the direction of the applied magnetic field.

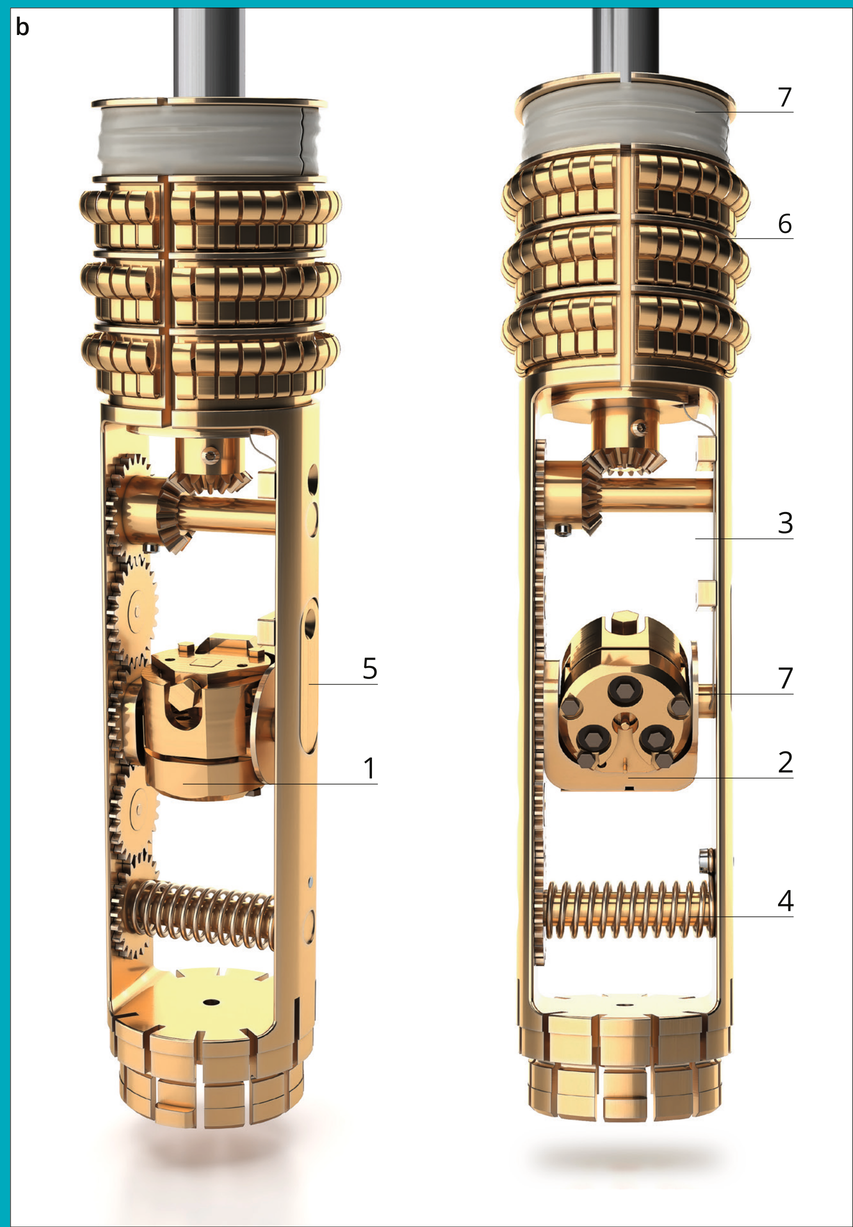
An anodized aluminum probe head (a) is attached to the upper end of the probe rod. The probe head contains a rotary knob that allows the user to manually rotate the dilatometer over an angular range from −90° to +90°. A mechanical locking mechanism limits the rotation to 180° in order to protect the ultra-thin coaxial cables used for electrical wiring from over-twisting and mechanical failure.

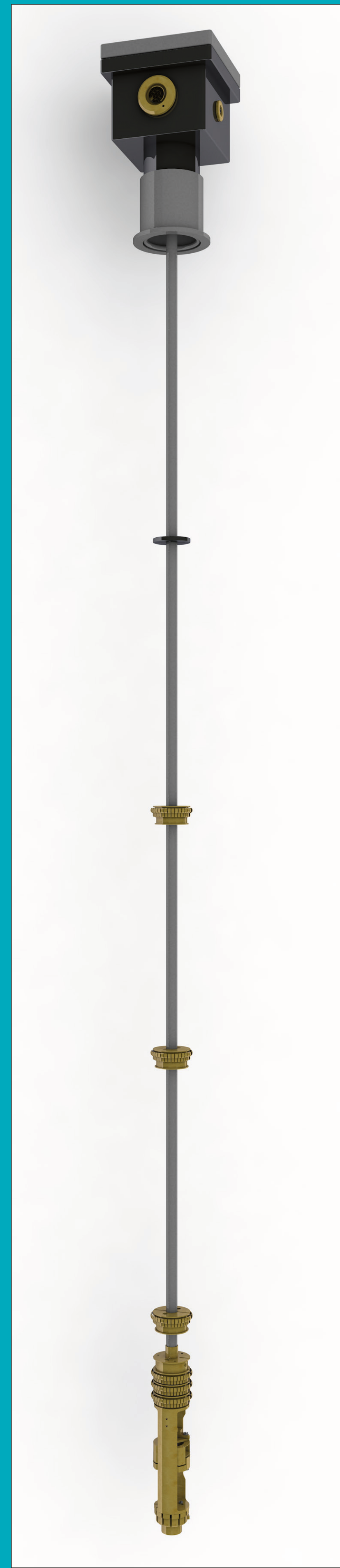
For special experimental configurations, the locking pin can be removed to allow rotations of up to 360°. In this case, the user is responsible for ensuring that the coaxial cables are not damaged during operation.

The rotary knob on the probe head (a) is mechanically connected to an inner stainless-steel tube. This tube runs through a hermetic feedthrough along the length of the probe rod and terminates at the cage (b) located at the lower end of the probe. At this point, the tube is rigidly connected to a bevel gear.

The rotational motion is transmitted through a bevel gear stage and a subsequent spur gear train to the C-shaped dilatometer holder (2).

(a) Head of the probe and (b) cage of the in-situ PPMS dilatometry probe shown from two different views.
Components are:
(1) dilatometer
(2) C-shaped dilatometer holder
(3) cage
(4) spiral spring
(5) leaf spring
(6) gold-plated contact springs
(7) position of the coaxial cables.
Right: Complete PPMS dilatometry probe assembly.





A preloaded spiral spring (4), coupled to the lowest gear in the train, suppresses backlash and prevents unintended reverse motion of the gear system. This ensures reproducible, stable, and precise angular positioning of the dilatometer.

1.3 Mechanical Stability and Thermal Coupling

A leaf spring (5), integrated into the outer frame of the cage, applies a defined contact force to both the dilatometer holder and the intermediate gear. This spring improves the mechanical stability of the assembly and enhances the thermal coupling between the dilatometer and the cage.

The cage itself is thermally anchored to the ring-shaped temperature control region located in the lower section of the PPMS. This thermal coupling is achieved via three rows of gold-plated contact springs (6), which provide reliable thermal contact while allowing mechanical compliance.

Within this temperature control region, helium exchange gas is regulated to the desired temperature using integrated heating elements located at the PPMS pin connector. The thermal anchors are positioned directly above the dilatometer and are in direct contact with the lower section of the inner chamber of the PPMS cooling channel.

Only this lower section of the cooling channel is fabricated from a highly thermally conductive material (copper) and is maintained at the same temperature as the pin connector. This design ensures efficient and uniform thermalization of the dilatometer.

To minimize parasitic heat loads introduced by the coaxial cables, the cables are wrapped several times around the upper end of the cage above the contact springs (7). This winding acts as a thermal anchor, allowing excess heat to be dissipated before reaching the dilatometer region.

The sample chamber should be maintained under a helium atmosphere at a typical pressure of 5–7 Torr. This helium environment further enhances the thermal stability of both the dilatometer cell and the sample. The corresponding setting in MultiVu is PPMS chamber mode: Purged. The probe also contains radiation shields to prevent additional heating.

1.4 PPMS Interface and Mechanical Fixation

At the lower end of the cage, the probe incorporates the exact geometric form of a standard PPMS sample puck. This interface includes contact springs for thermal connections. One of these contact springs additionally functions as a mechanical locking tab, ensuring secure and reproducible fixation of the dilatometry probe within the PPMS sample chamber.

02

Additional Equipment Required to Operate the In-Situ Rotational PPMS Dilatometry Insert

This chapter describes the additional equipment required to operate the In-Situ rotational PPMS dilatometry insert and outlines recommended measurement configurations to achieve optimal resolution and low-noise performance.

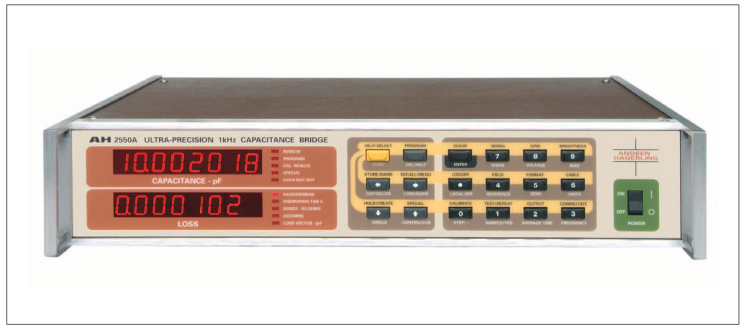
2.1 Required Equipment

2.1.1 Capacitance Bridge

High-resolution capacitance measurements are essential to fully exploit the performance of the dilatometer. We recommend the use of one of the following Andeen-Hagerling capacitance bridges:

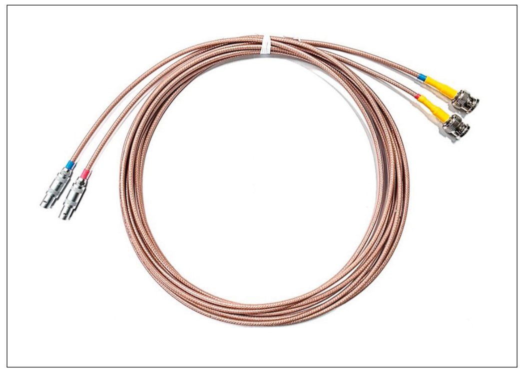
- **AH 2550A** (1 kHz)
- **AH 2500A** (1 kHz, predecessor model)
- **AH 2700A** (50 Hz – 20 kHz; significantly higher cost)

These instruments provide a maximum achievable resolution of up to 10^{-6} pF, which is required to reach the intrinsic resolution of the dilatometry insert. All listed models are among the most accurate capacitance and loss bridges currently available.



2.1.2 Probe–Capacitance Bridge Connection Cables

A matched pair of coaxial cables for connecting the PPMS dilatometry probe to the capacitance bridge **is included with the delivered probe package**. These cables are fully shielded and optimized for low-noise capacitance measurements.



2.2 Optional Equipment for Optimal Performance

To achieve the highest possible measurement resolution, especially in electrically noisy environments, the following additional components are strongly recommended:

2.2.1 USB Optical Isolation

Icron Ranger 2324 USB transmitter, or any equivalent USB-over-fiber optical repeater.
This device provides galvanic isolation between the measurement electronics and the data-acquisition computer.

2.2.2 GPIB–USB Converter

Required when the capacitance bridge communicates via GPIB and is used in combination with a USB optical transmitter.

2.3 Electronic Isolation and Noise Reduction

Capacitance measurements belong to the most demanding classes of electrical measurements. Achieving sub-micro-pF resolution requires careful suppression of electrical noise. The dominant noise sources in dilatometry measurements include:

- Stray capacitance between measurement cables and surrounding structures
- Ground loops between different instruments
- Electrical noise from auxiliary electronics (measurement computer, temperature and magnet controllers, pumps, etc.)

2.3.1 Suppression of Stray Capacitance

In the present setup, stray capacitance is minimized by using fully shielded coaxial cables between the dilatometer capacitor plates and the Andeen-Hagerling capacitance bridge. The outer shields of these cables are soldered to the metallic body of the dilatometer cell.

Because the probe contact springs are in electrical contact with the inner wall of the PPMS sample chamber, the shielding of the measurement cables is galvanically connected to the PPMS cryostat. As a result, the PPMS itself acts as an extension of the electromagnetic shielding, significantly reducing the influence of external stray capacitance.

2.3.2 Ground Loops and Their Impact

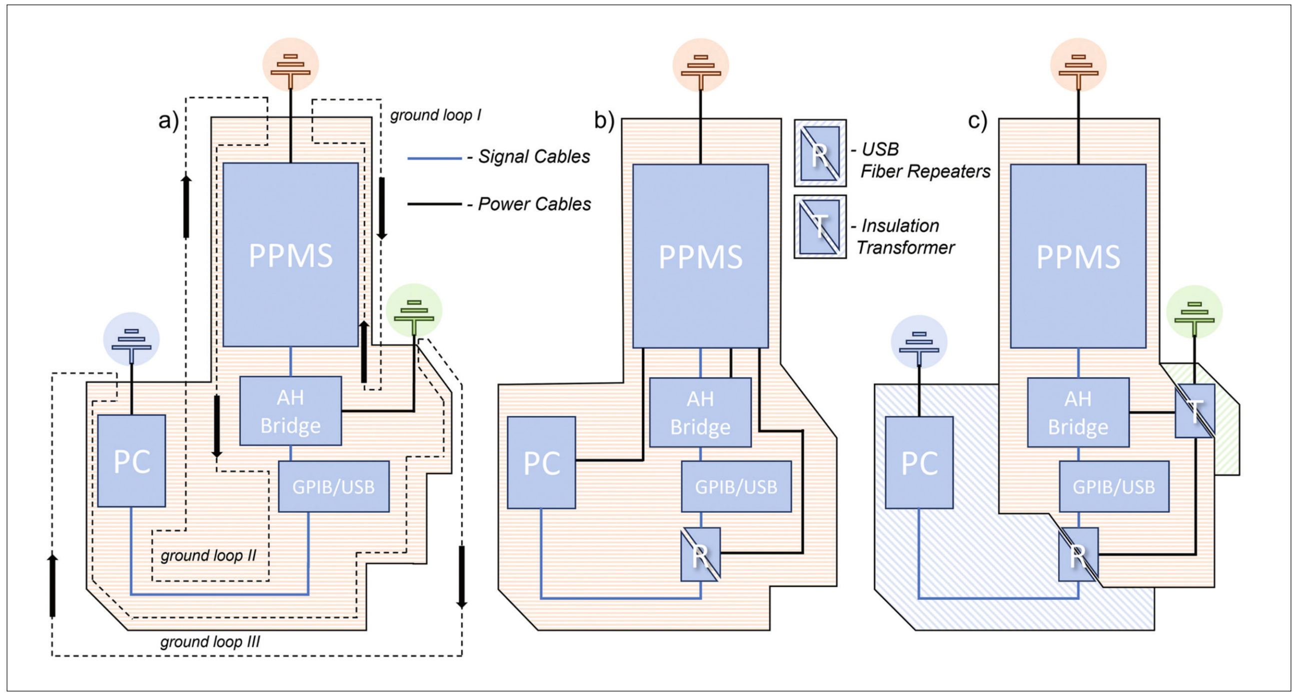
While the above shielding strategy effectively suppresses stray capacitance, it can introduce additional noise if the cryostat, capacitance bridge, and measurement computer are connected to different ground potentials. Ground loops are a major source of low-frequency noise and can severely degrade capacitance resolution.

Ground loops may arise when:

- Instruments are connected to different power outlets
- Galvanic connections exist between devices via USB or GPIB cables

2.4 Recommended Measurement Configurations

Several instrument configurations can be used, depending on the required performance level and experimental constraints.



Three ways of electrical connections of the measuring system. (a) An incorrectly connected circuit exposed to the ground loops noise. (b) The entire system is powered by a common PPMS power supply. (c) Physical separation of the AH Bridge (capacitance bridge), PPMS (physical property measurement system including its controllers), and the PC (measuring computer).

2.4.1 Configuration B: Common Power Ground (Recommended)

In this configuration, all measurement instruments, including the measurement computer, are connected to the same PPMS power outlet. This approach limits ground-loop currents by referencing all electronics to a single common ground point. Using this setup, we achieved high measurement resolution and low noise levels.

Advantages:

- Simple and convenient setup
- Compatible with most PPMS installations

Limitations:

- Electronics are not galvanically isolated
- Noise from the measurement computer or other digital electronics may still couple into the measurement

2.4.2 Configuration C: Fully Galvanically Isolated Setup (Recommended)

For maximum resolution and lowest noise, we recommend the fully isolated configuration, which was used in our high-resolution measurements on the Quantum Design DynaCool system (see R. Küchler et al., Rev. Sci. Instrum. 94, 045108 (2023)).

In this setup:

- The **capacitance bridge is grounded to the cryostat sample chamber**
- The bridge is **electrically isolated from the power grid using an insulating transformer** (e.g., ETTK 2500, 230 VAC isolating transformer)
- Communication between the capacitance bridge and the measurement computer is **fully optically isolated**

Galvanic isolation from the computer is achieved as follows:

- The **AH 2550A** capacitance bridge is connected to a GPIB-to-USB adapter
- The USB signal is transmitted via an **Icron Ranger 2324 USB-over-fiber system**
- Data are transferred over multimode optical fiber to the receiver and then to the measurement PC

This configuration completely eliminates ground loops between the cryostat, capacitance bridge, and computer.

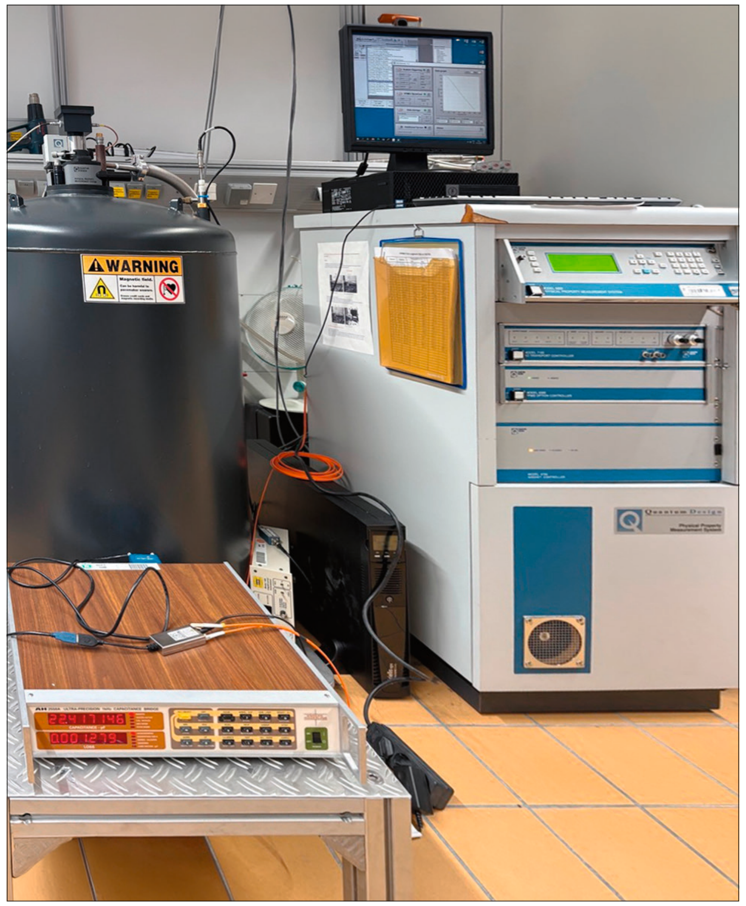
Advantages of the Fully Isolated Configuration

Although configuration C requires additional hardware, it offers several important benefits:

1. Compatibility with cryostat systems from any manufacturer. The isolating transformer not only breaks ground loops but also acts as a low-pass filter, suppressing high-frequency noise from the power line
2. Optical isolation prevents digital noise and grounding imperfections from USB and GPIB interfaces from affecting the measurement

2.4.3 Recommendation

For routine measurements, configuration a) may be sufficient. However, to achieve the **maximum capacitance resolution of 10^{-6}pF** and the highest measurement quality, we recommend using **configuration b) or, preferably, configuration c)**.



Setup according to configuration B)

03

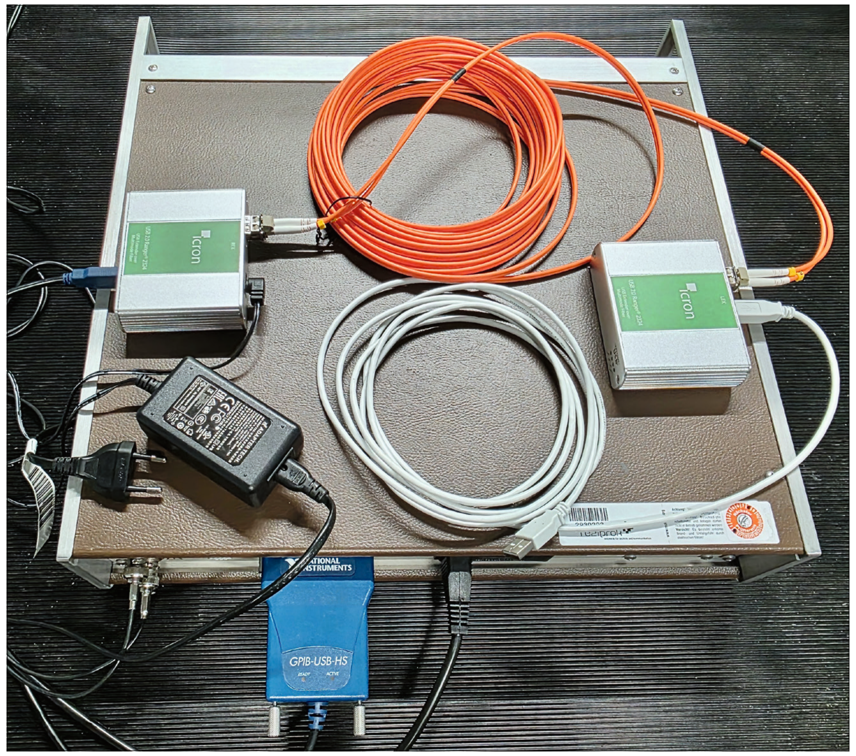
Dilatometry Measurement Setup

In this chapter, we describe the design and setup of **Configuration B** introduced in Chapter 2 in detail. This configuration provides a simple and convenient implementation and is compatible with nearly all PPMS installations. Furthermore, it requires only minimal additional hardware.
Before assembling the measurement setup, ensure that the appropriate **LabVIEW Runtime Engine** and the **LabVIEW dilatometry program** are installed on the PPMS control computer.

3.1 Electrical Connection and Galvanic Isolation

Galvanic isolation of the Andeen-Hagerling capacitance bridge is achieved using an optical USB connection. In this configuration, the **AH2500 capacitance bridge** is connected via a **USB-to-GPIB adapter** to an **Icron Ranger 2324 USB transmitter**. The signal is transmitted through a **multimode optical fiber** to the corresponding **Icron Ranger 2324 USB receiver**, which is then connected via USB to the PPMS measurement PC.

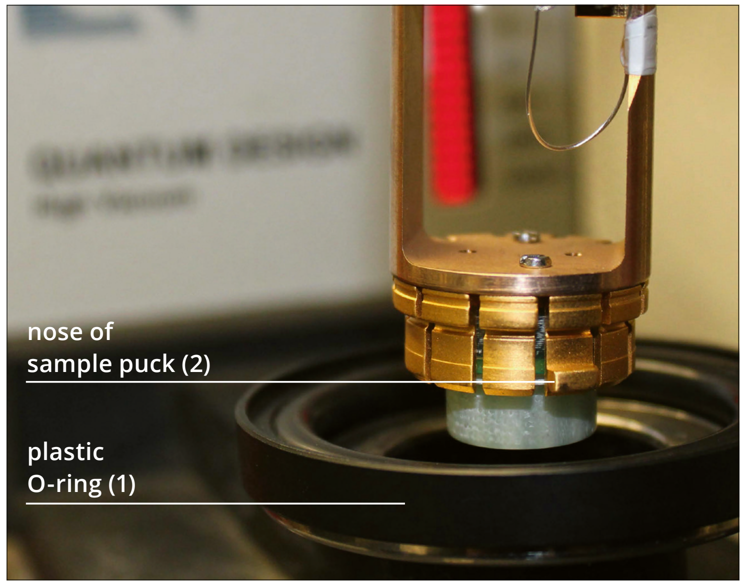
Important: All measurement instruments, including the AH2500 capacitance bridge, the PPMS system, and the measurement computer, must be powered from the same PPMS power outlet. Connecting all electronics to a single common ground point effectively minimizes ground-loop currents and ensures stable, low-noise measurements (see schematic diagram on page 14).

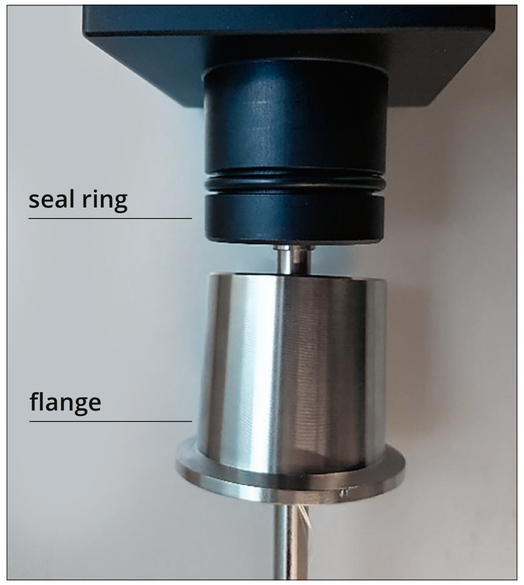


This connection scheme has been proven to provide a reliable data link while fully isolating the capacitance bridge from the computer electronics, thereby minimizing electrical noise and ground-loop effects.

3.2 Probe Installation

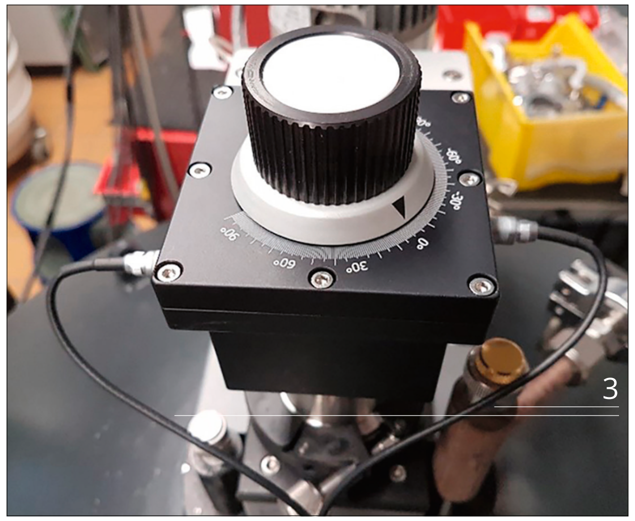
1. Place the plastic **O-ring (1)** onto the PPMS probe port.
2. Carefully insert the **PPMS dilatometry probe** into the PPMS system.
3. Ensure that the **nose of the sample puck (2)** is oriented forward and properly locks into position.
4. The **flange on the probe head** slides over a rubber sealing ring and can be moved gently up or down to adjust the correct probe insertion depth. Adjust the height carefully to ensure proper sealing without applying excessive force.





3.3 Capacitance Bridge Connection

Finally, connect the **capacitance measuring bridge** to the head of the PPMS dilatometry probe using the **supplied pair of coaxial capacitance bridge-probe cables (3)**.



04

Installation and User Guide for PPMS Dilatometry Software

Prerequisites: Before installing the dilatometry software, ensure that all required drivers and runtime components are available on the measurement computer. Administrator rights may be required for installation.

4.1 Requirements

Quantum Design MultiVu must be installed on the PPMS measurement computer before installing or running the dilatometry software.

4.1.1 Install the LabVIEW Runtime Engine

The dilatometry program is written in LabVIEW and requires the appropriate LabVIEW Runtime Engine.

- For the current dilatometry software (version 2026 or later), **LabVIEW Runtime Engine 2022** must be installed.
- LabVIEW Runtime Engine 2022 is compatible with **Windows 10** and **Windows 11**.

Download the LabVIEW Runtime Engine 2022 free of charge from the National Instruments website, or install it from the USB drive supplied with the system.
Run the installer and follow the on-screen instructions. Restart the computer if prompted before continuing with the software installation.

4.1.2 Install the Dilatometry LabVIEW Program

1. Locate the provided dilatometry software package on the PPMS measurement computer.
2. Copy the executable program (Version 2) to the PPMS measurement computer.
3. Start the software by launching **Dilatometry.exe**.

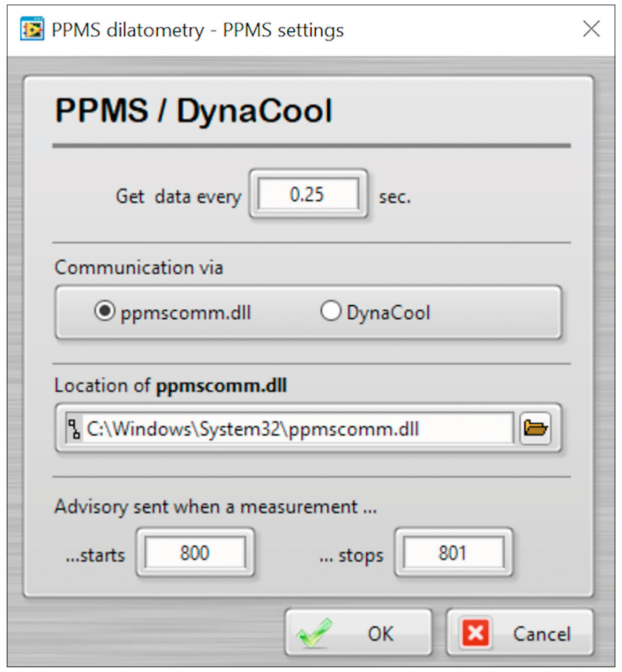
The program should now start and run correctly.
In the executable directory, you will also find a file named **readme.txt** containing additional information about the correct startup procedure. Please review this file if necessary.

4.1.3 Special Instructions for PPMS Users

If you are operating the software with a **PPMS system**:

1. Open the **PPMS/DynaCool settings** by clicking the gear icon in the top-right corner of the PPMS/DynaCool window.
2. Select communication via **ppmscomm.dll** (not via DynaCool).

Specify the required file path for **ppmscomm.dll**:
C:\Windows\System32\ppmscomm.dll

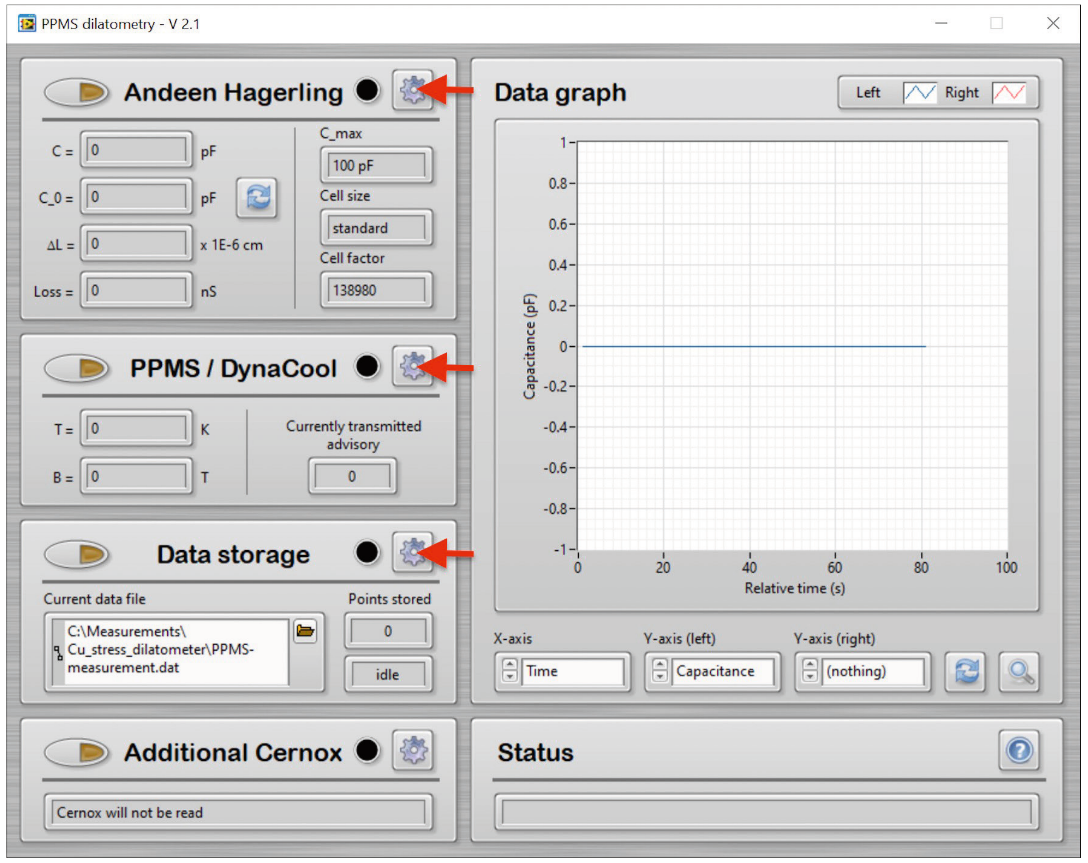


Important notes:

- The file ppmscomm.dll is used only when operating the software with a **PPMS** (not with a DynaCool system).
- If another program (e.g., MultiVu) is also accessing the PPMS via this DLL, all programs must use the **same** ppmscomm.dll file.
- This file is typically located in: C:\Windows\System32

If the file is not located there, search the measurement computer for ppmscomm.dll and assign the correct directory path in the PPMS settings of the dilatometry LabVIEW program.

4.2 Device Settings



When starting the program for the first time:

1. Open the **Settings** window for each connected device by clicking the gear icon in the top-right corner of the respective device window (see red arrow).
2. Configure and define the appropriate parameters for each device. Ensure that all device settings are correctly configured before beginning measurements.

4.2.1 Andeen-Hagerling Capacitance Bridge Settings

GPIB Address

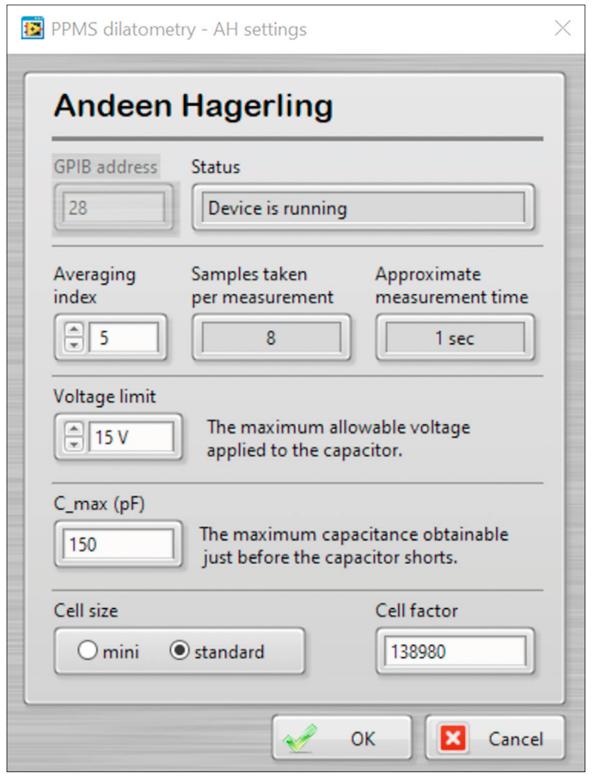
In the AH settings, first assign the correct GPIB address of the Andeen-Hagerling capacitance bridge.

Default address: **28**.

Ensure that this address matches the hardware configuration of the bridge.

Averaging Index

The averaging index sets the effective measurement (integration) time over which the capacitance bridge averages individual readings. Increasing the averaging time improves measurement resolution



because random noise decreases approximately with the inverse square root of the averaging time. However, longer averaging times also reduce the measurement rate and therefore result in fewer data points per unit time. Select an averaging index that provides an appropriate compromise between noise level and acquisition speed for the experiment.

Averaging Index (recommended setting)

For typical PPMS measurements with a temperature sweep rate of about 0.3 K/min, an Approximate measurement time of 1 s (Averaging index: 5) provides an excellent compromise between noise reduction and data density.

For high-resolution measurements or very small signals, the averaging time may be increased to 2–3 s. Longer averaging times should only be used at stabilized temperature, as they reduce the number of recorded data points during temperature or field sweeps.

Voltage Limit

The voltage limit defines the maximum excitation voltage applied by the capacitance bridge during a measurement. The instrument automatically selects an optimal measurement voltage that is equal to or below this specified limit and reports the actual voltage used.

A higher excitation voltage improves the signal-to-noise ratio and therefore reduces measurement noise. For most dilatometry measurements, using the maximum voltage limit of **15 V provides** the best resolution.

For most measurements, the maximum voltage limit of 15 V should be used, as it provides the lowest noise and best resolution. A lower voltage limit is only required for very sensitive or soft samples, as the measurement voltage may otherwise generate electrical forces that can influence the measurement.

C_max (pF)

In the **C_max (pF)** field, enter the short-circuit capacitance specific to your dilatometer. This value is provided on the delivery note supplied with the probe. C_max corresponds to the maximum capacitance reached just before the capacitor plates come into electrical contact (short circuit).

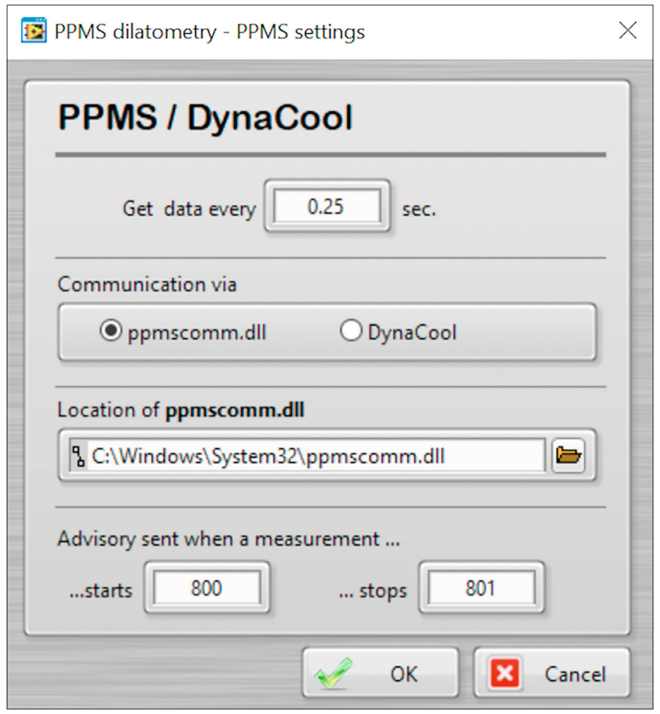
If necessary, C_max (pF) can also be determined experimentally. To do so, carefully and slowly increase the capacitance by tightening the adjustment screw of the dilatometer while monitoring the capacitance reading. The highest stable capacitance value obtained immediately before the capacitor shorts corresponds to C_max (pF).
This value is required for correct conversion of capacitance into length change and must be entered accurately.

Cell Size
Select either the standard dilatometer or the mini-dilatometer. The cell size determines the cell factor:
$f = \varepsilon_0 \pi r^2$
where ε_0 is the electric field constant and r is the radius of the circular capacitor plates. The cell factor differs only due to the plate radius:

- Mini-dilatometer: r = 5 mm
- Standard dilatometer: r = 7 mm
- **Note:** The correct choice of cell size is crucial for the accurate determination of the sample's length change.

4.2.2 PPMS/DynaCool Settings

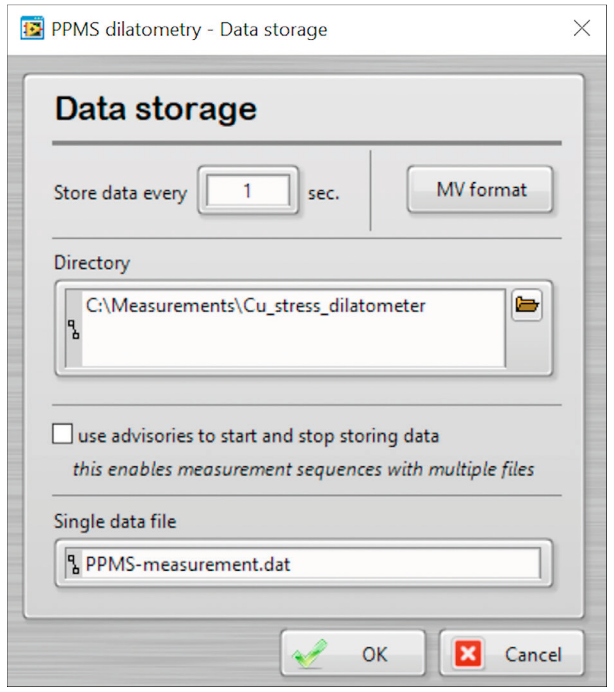
Select the system you want to communicate with. Both instruments are manufactured by Quantum Design and belong to the PPMS (Physical Property Measurement System) family. Although the DynaCool is technically also a PPMS, it uses a different controller and communication interface. Therefore, the software must know which hardware it is connected to.



- **PPMS:** Select this option for standard/legacy PPMS systems (e.g. PPMS-9, PPMS-14, EverCool).
- **DynaCool:** Select this option if you are using a **DynaCool** system. This is a newer, cryogen-free PPMS platform with its own controller hardware and drivers.

For the PPMS, the required location of the ppmscomm.dll has to be assigned (see detailed description in 4.1.3).
First window: The number shown in the first window determines the number of seconds after which data from the PPMS will be transmitted.

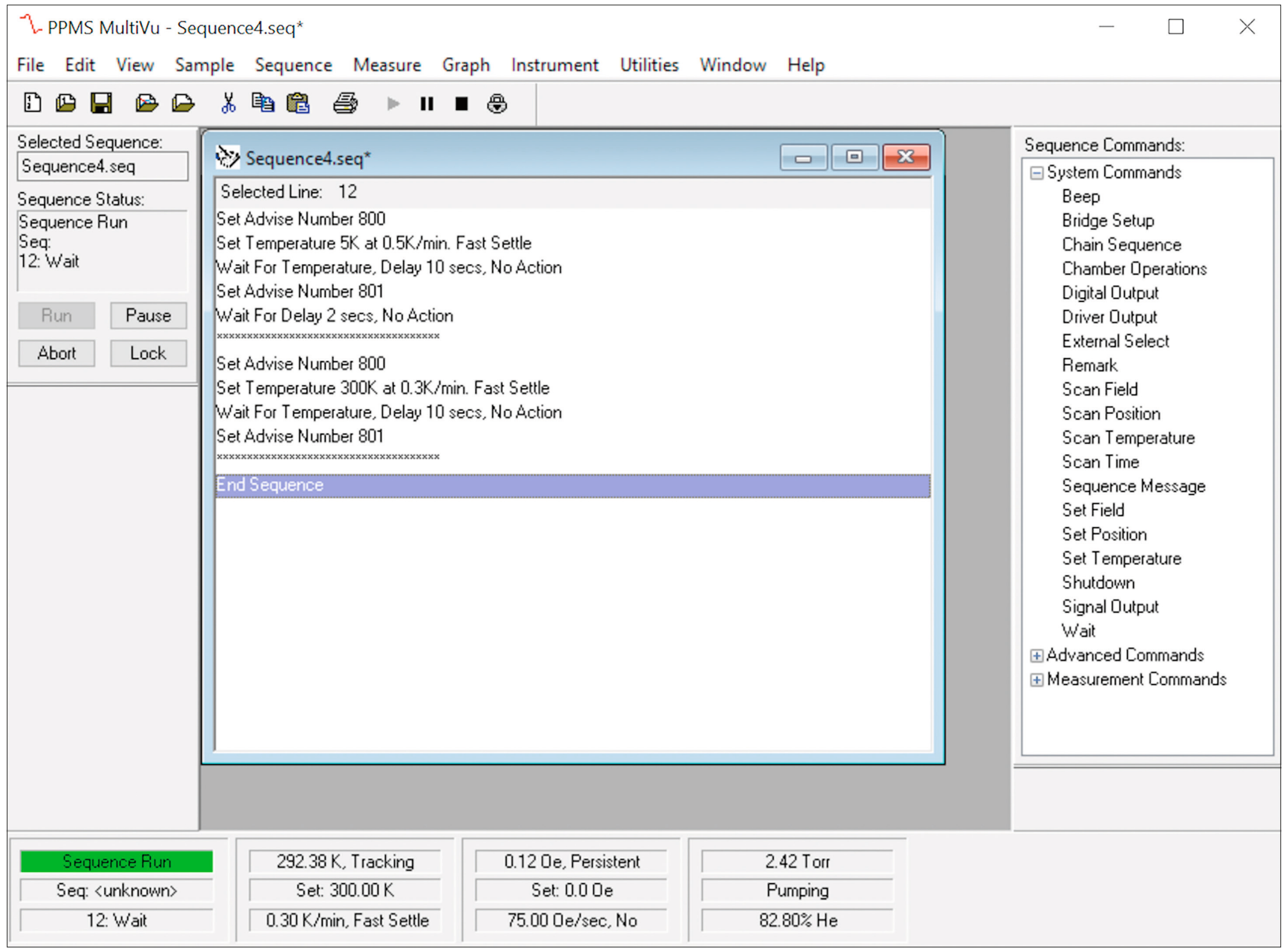
4.2.3 DATA STORAGE Settings



The **number displayed in the first window** determines the interval, in seconds, at which data obtained from the PPMS and the capacitance bridge will be stored.
The **Directory** field defines the location where the collected data will be saved.
You can choose between storing a **single data file** or **multiple measurement files**:

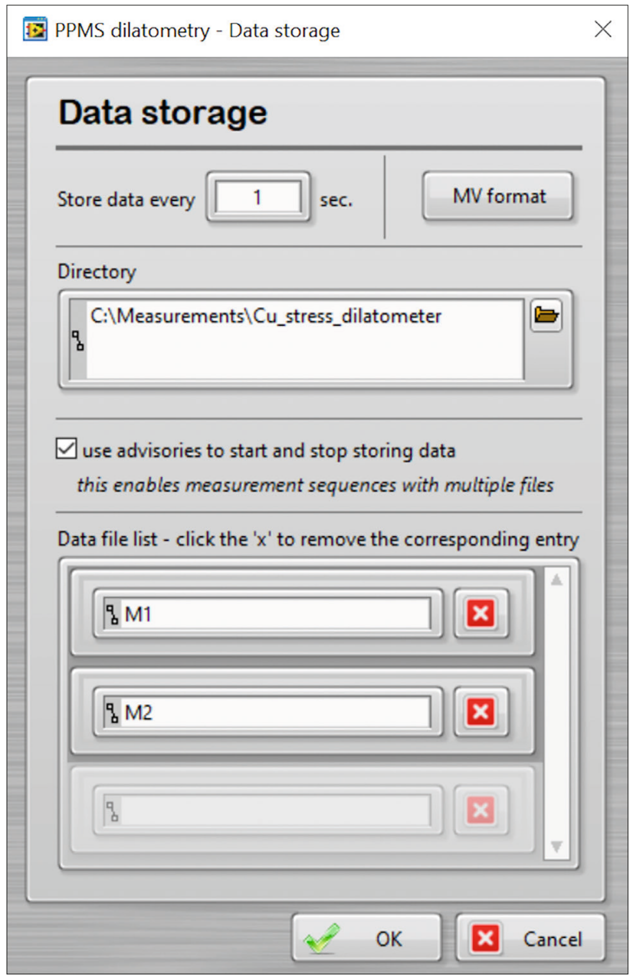
Single Data File: All measurement data will be stored continuously in a single file.
Multiple Data Files: Data is saved in separate files, controlled by MultiVu advisories that start and stop data storage.

Note: The multiple-file option is not available on the **DynaCool** platform. Quantum Design has removed the advisories functionality from DynaCool systems, so only the single-file data storage mode can be used there.



For multiple files, follow these steps:
Create the appropriate measurement sequence in MultiVu.
Set two advisories for the sequence:

- **First advisory (800):** Sent when the measurement starts.
- **Second advisory (801):** Sent when the measurement finishes.

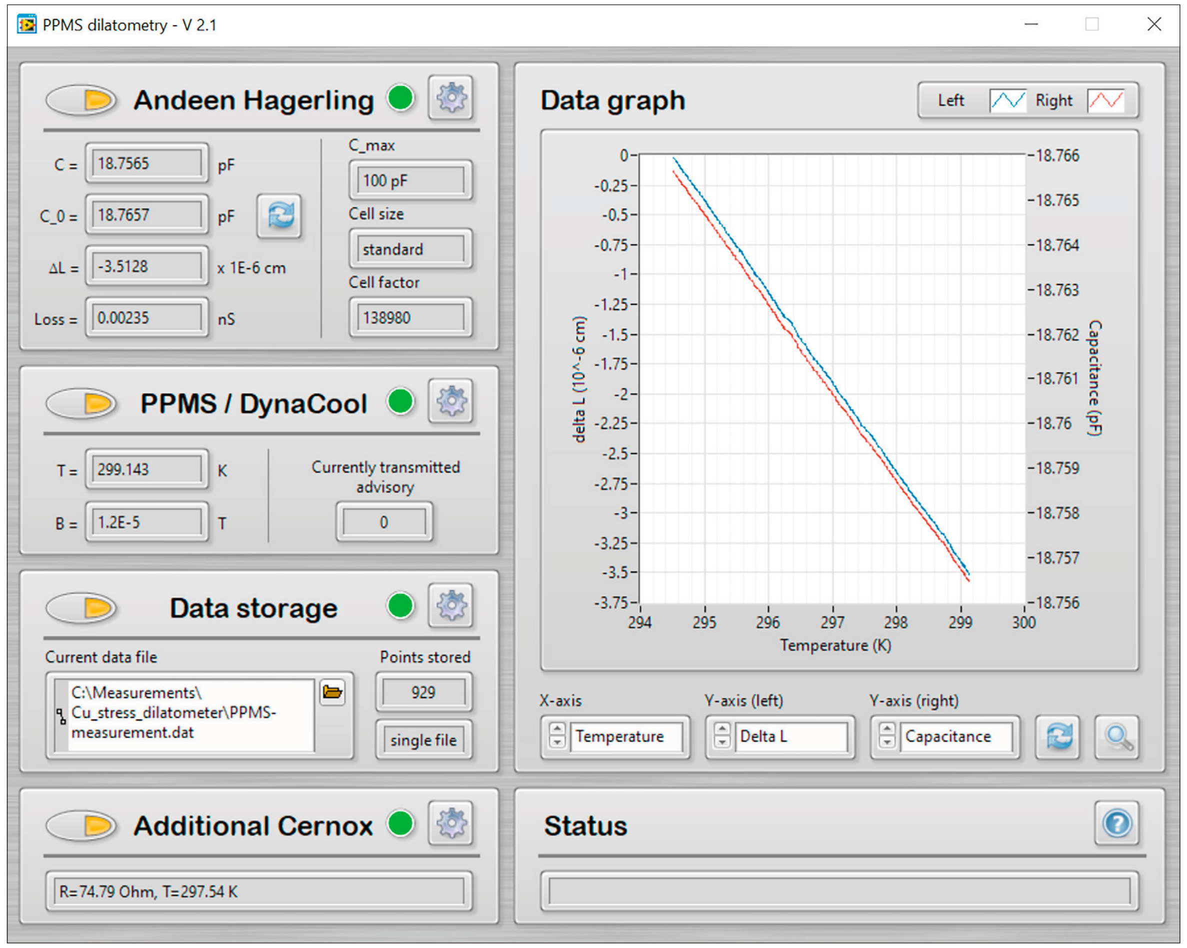


Our **LabVIEW program** works in conjunction with MultiVu. It only recognizes which file to store after the correct advisories are sent.
To start data storage manually, press the **Start** button in the data storage window. A **green light** will illuminate, indicating that data storage has begun.

Note: Starting the MultiVu sequence automatically initiates data storage as well.

4.3 Main Window

The LabVIEW program is used to read out and record the dilatometry signal. It also displays the temperature and magnetic-field values received from the PPMS via the Quantum Design MultiVu software. Temperature and magnetic-field sweeps themselves are defined and controlled in MultiVu.



The LabVIEW program displays and records the following data:
From the Andeen-Hagerling capacitance bridge

1. **C (pF)**
   Shows the currently measured capacitance.
2. **C_0 (pF)**
   Indicates the initial capacitance. Before starting a measurement, set C_0 to the current capacitance value. This ensures that the first recorded length change begins with $\Delta L = 0$. If C_0 is not set correctly, the entire measured length-change curve must later be shifted by a constant offset.
3. **ΔL (10^{-6} cm)**
   Displays the calculated absolute length change in units of 10^{-6} cm. The value is calculated from the capacitance change using the formula for slightly non-parallel capacitor plates.

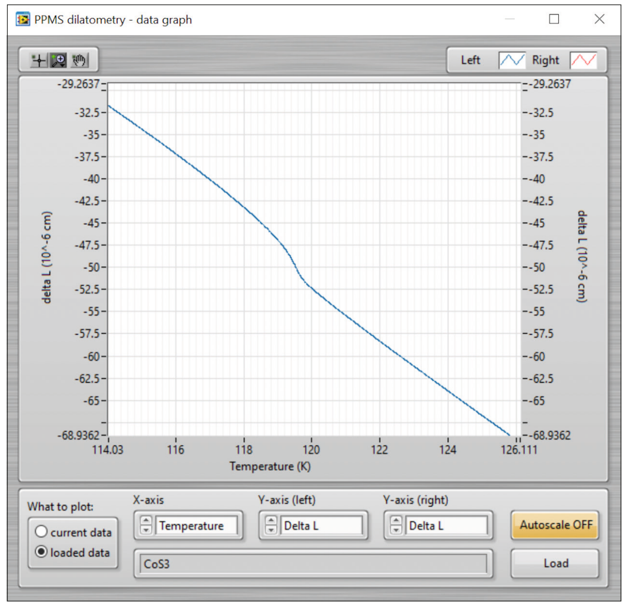
From the PPMS system (via MultiVu)

- **T (K)**
  Displays the temperature at the PPMS bottom pin connector.
- **B (T)**
  Displays the current magnetic field.

4.3.1 Data Graph Window

The Data Graph window displays the measured data in real time.

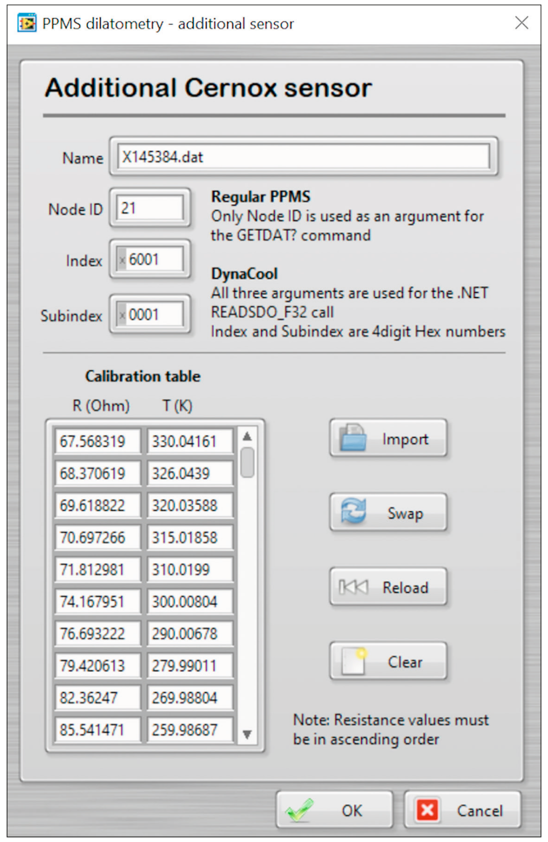
- The magnifying-glass button located in the lower right corner allows previously saved measurement data to be loaded and viewed.
- The following quantities can be selected for the X-axis: *Time (s), Temperature (K), Magnetic Field (T),* or *Cernox-R (K).*
- For both the left and right Y-axes, the following parameters can be displayed: *Capacitance (pF), ΔL (10⁻⁶ cm), Loss (–) dissipation factor (dimensionless), Magnetic Field (T)*, and *Cernox-R (K).*
- To zoom in on the image, click the magnifying glass icon in the topleft corner.



4.3.2 Additional Cernox Sensor

An additional Cernox temperature sensor is used with the **standard** and **stress dilatometer probes**, but not with the **in-situ rotational PPMS dilatometry probe**.

Due to its very small mass and low heat capacity, the mini-dilatometer exhibits only minimal temperature gradients when the temperature is swept slowly (e.g., 0.3 K min^{-1}). Under these conditions, any gradient across the device can generally be neglected. To verify the thermal coupling to the platform, a Cernox CX-SD thermometer was temporarily mounted directly on the mini-dilatometer. Its temperature readings were then compared with those recorded at the PPMS bottom-pin connector during a controlled warm-up.



- During a sweep from 2 K to 300 K at 0.3 K min^{-1}, the temperature difference between the two sensors was < 0.2 K up to 50 K, increased to ~0.5 K by 100 K, and remained approximately constant up to 300 K.
- When starting from higher temperatures, the difference stayed below 0.2 K over a wide temperature range.
- At a slower sweep rate of 0.1 K min^{-1}, no measurable temperature difference was observed below 50 K.

These results demonstrate that, under slow temperature sweeps, the temperature difference between the mini-dilatometer and the PPMS bottom-pin connector is essentially negligible. This confirms that the thermal coupling to the PPMS platform is more than adequate for precise and reliable measurements.

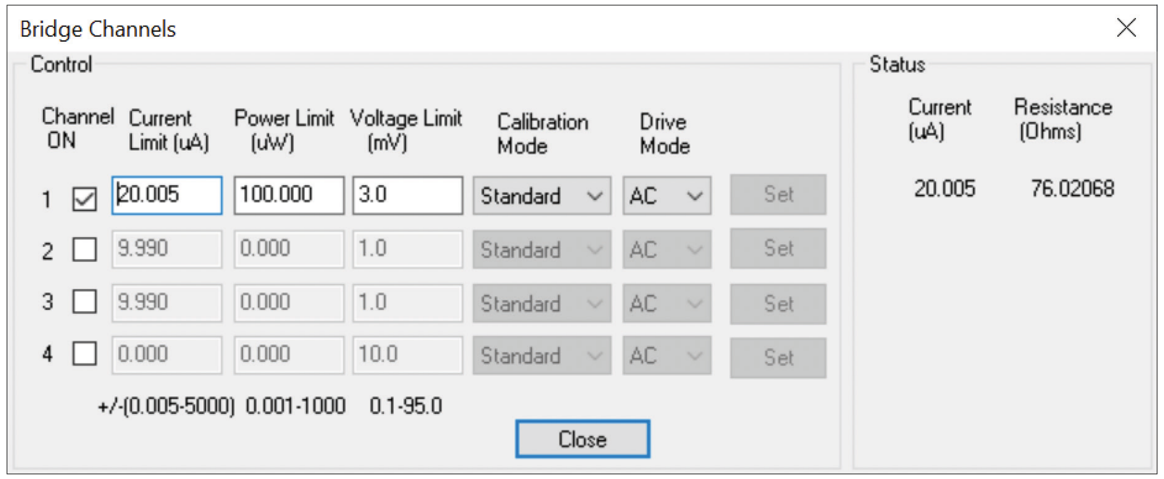
The **standard** and **stress dilatometer probes** contain an additional Cernox resistance sensor located inside the dilatometer holder, close to the sample. This sensor is read out using the resistance bridge integrated in the **Quantum Design PPMS** system.

In the **Additional Cernox Sensor** settings, you will be prompted to load the calibration file corresponding to the installed Cernox sensor. The calibration file is included in the software package (see section *Cernox Sensor*).

If the calibration file lists temperature in the left column and resistance in the right column, use the **Swap** button to exchange the columns before loading.

To use the PPMS resistance bridge for this sensor, activate the appropriate bridge channels in **MultiVu**:

MultiVu → Instruments → Bridge Channels.



05

Dilatometer Design and Measuring Principle

The mini-dilatometer is based on our **patented design** following the **Pott–Schefzyk principle**, which utilizes two flat, parallel leaf springs to guide motion with high precision. While the original Pott–Schefzyk dilatometer consisted of many individual components, our redesigned version is manufactured from a single piece of Be–Cu using precision milling and spark erosion.
This patented manufacturing approach enabled the development of the world's smallest high-resolution capacitive dilatometer. The instrument has extremely compact dimensions:

- **Height × Width × Depth:** 1.5 cm × 1.4 cm × 1.47 cm
- **Weight:** 13,5 g

Despite its small size, the device achieves a length resolution of **ΔL = 0.01 Å**, an unprecedented performance for a capacitive dilatometer of this scale. The reduced size and mass also significantly improve thermalization during measurements.

5.1 Materials and Eddy Current Reduction

All components, except for electrically insulating washers, are fabricated from ultrapure **beryllium copper (Be–Cu)**. The alloy contains 1.84% Be, which reduces electrical conductivity compared to pure copper.
This material choice minimizes eddy currents induced by time-varying magnetic fields. Compared to dilatometers made of pure copper or silver, the induced eddy currents during magnetic field sweeps are substantially lower.

Additional design features further suppress eddy currents:

- Reduced overall material volume
- Numerous recesses to interrupt continuous ring current paths
- Countersunk screw heads to minimize external dimensions

Together, these measures significantly reduce heating and magnetic interference effects.

5.2 Mechanical Design

The mini-dilatometer consists of four primary components:
(A) Lower Component
Contains the **lower capacitor plate (6)** and forms part of the external frame.
(B) Body
The central element (single-piece Be–Cu construction), incorporating:

- Two parallel leaf springs
- **The upper capacitor plate (5)**

This component defines the mechanical function and geometry of the device.
(C) Cover
Screwed onto the body. It includes a **lock screw (12)** used to secure the sample clamping mechanism.
(D) Sample-Adjusting Tool (11)
Includes a fine-threaded **adjusting screw (9)** used to clamp the sample (4).

5.3 Sample Insertion Procedure

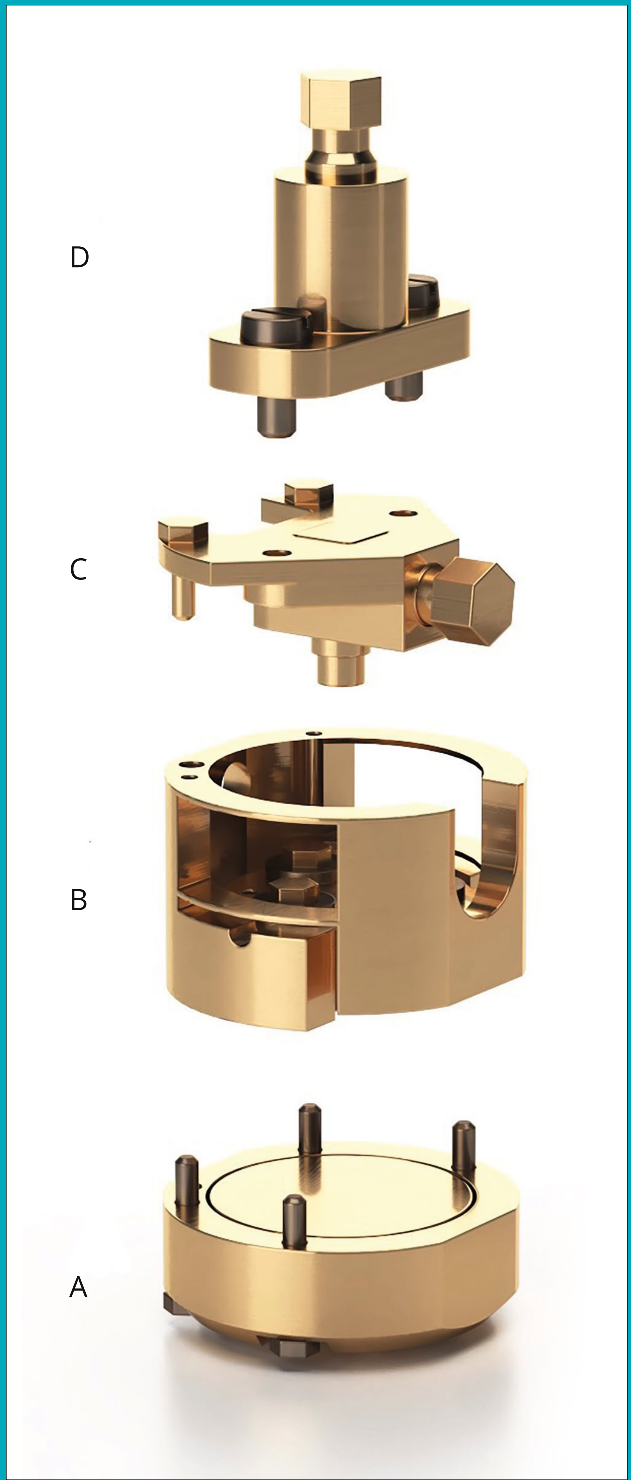
1. Unscrew and remove the sample-adjusting tool (11) and the cover.
2. Place the sample onto the center of the body from above.
3. Reattach the cover.
4. Screw in the sample-adjusting tool.
5. Tighten the adjusting screw (9) to clamp the sample.

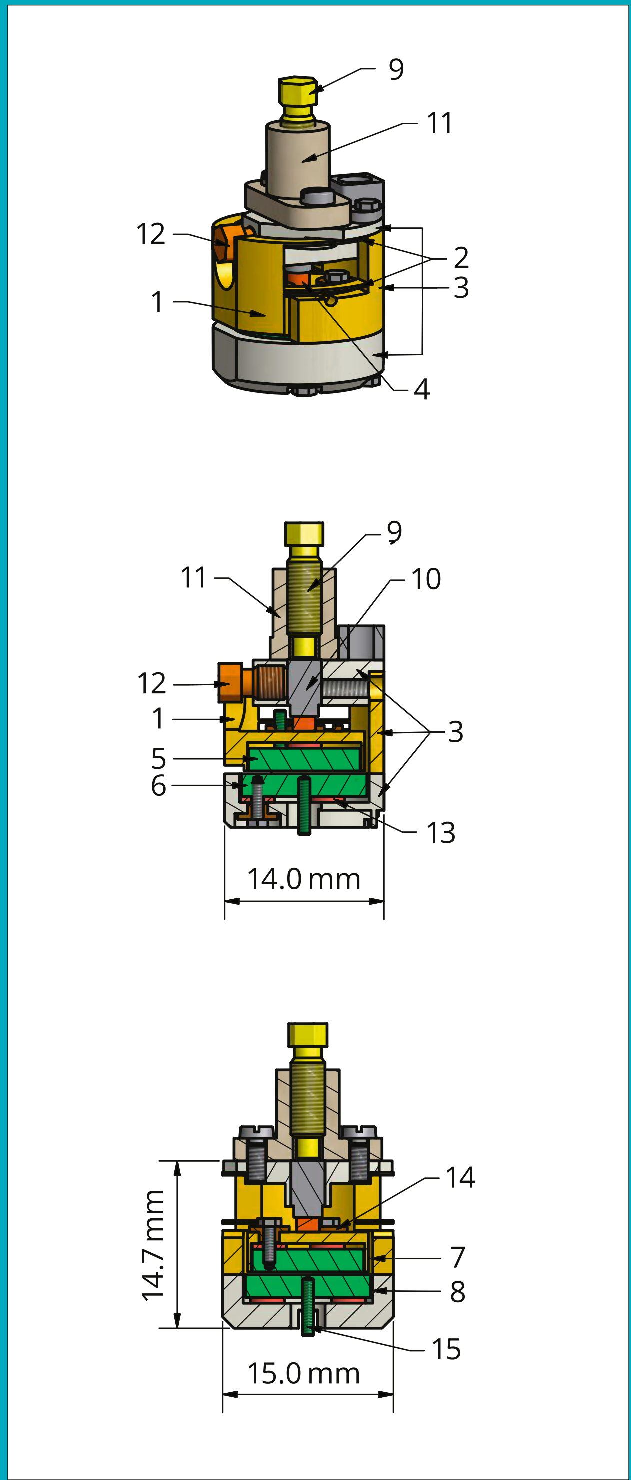
Importantly, the screw does not press directly onto the sample. Instead, it pushes against a **cubic piston (10)** that moves horizontally within the cover. This prevents sample twisting during clamping.
Once the sample is secured, the **lock screw (12)** fixes the piston in place. The sample-adjusting tool can then be removed, allowing the device to maintain its minimal construction height of 1.47 cm.

5.4 Operating Principle

The dilatometer consists of:

- An external **C-shaped frame (3)**
- A mobile part (1)
- Two leaf springs (2), each 0.25 mm thick





Left: Mini-dilatometer consists of four main parts: (A) bottom part, (B) main body, (C) cover, and (D) sample-adjusting tool.

Right: Schematic drawing of our new mini- dilatometer. The top picture shows a 3D view, the middle picture shows a side cut-away view, and the one at the bottom shows a front cut-away view of the dilatometer. (1) Moving part, (2) two Be–Cu flat leaf springs, (3) external frame, (4) sample, (5) upper capacitor plate, (6) lower capacitor plate, (7) and (8) guard rings, (9) adjusting screw, (10) cubic piston, (11) removable sample-adjusting tool, (12) locking screw, (13) sapphire washer, (14) insulating piece of vespel, and (15) the electrical connection has been removed and is now directly soldered onto the screw.

The lower capacitor plate (6) is mounted on the frame, while the upper capacitor plate (5) is attached to the mobile part. The leaf springs form a **parallelogram suspension**, ensuring that the mobile plate moves strictly perpendicular to the fixed plate.

The sample is clamped between the mobile part and the frame using the adjusting screw. At the measuring capacitance of 20 pF a force of approximately **4 N** is applied against the spring force. For more details please see R. Küchler et al., Rev. Sci. Instrum. 94, 045108 (2023).
When the sample changes length due to temperature variation or magnetic field sweeps, the distance between the capacitor plates changes accordingly. This alters the capacitance.
The capacitance change is measured using a commercial capacitance bridge. The plate-capacitor equation is then used to convert capacitance changes into absolute length changes. For more details please see R. Küchler et al., Rev. Sci. Instrum. 88, 083903 (2017).
On the website, www.dilatometer.info, a video showcases the precision operation of the dilatometer and guides you through sample installation using a clear, interactive 3D animation.

5.5 Capacitor Geometry and Performance

- Initial plate separation: **0.25 mm**
- Initial capacitance: ~ **3 pF**

During measurement, the capacitance is typically adjusted to **15 – 20 pF**.

At **20 pF**:

- Plate spacing ≈ **70 µm**
- Applied force ≈ **4 N**

For millimeter-sized samples with cross-sectional areas between approximately (1 – 6 mm)^2, the applied force is generally sufficiently small that it does not influence the intrinsic material properties. However, for very thin or delicate samples, the mechanical load must be carefully considered, as it may affect the measurement results.

All fabricated mini-dilatometers exhibit an electrical short circuit at capacitances exceeding 60 – 100 pF, thereby defining a very high and clearly reproducible upper operational limit.

With a capacitance resolution of **10^{-6} pF**, the system achieves:
$\Delta L = 0.01$ Å

This sensitivity makes the mini-dilatometer an extremely high-resolution instrument despite its compact size.

5.6 Electrical Insulation and Shielding

Each capacitor plate is:

- Electrically insulated by three **Vespel spacers (14)**
- Further insulated using three **sapphire washers (13)**
- Surrounded by protective rings (7 and 8) to minimize stray electric fields

Guard Rings: The protective rings (7 and 8) surrounding the capacitor plates minimize edge effects and enhance measurement accuracy. They shape the electric field so that changes in capacitance reflect only the displacement of the moving part, not distortions at the plate edges. Furthermore, the guard rings reduce leakage currents and electrical noise, ensuring stable and highly precise measurements, essential for detecting nanometer-scale changes in the sample.

5.7 Performance in the PPMS

A crucial production step is the **post-assembly polishing** of the mounted capacitor plates within their protective rings. The performance of the dilatometer strongly depends on the precise parallel alignment of:

- The two capacitor plates
- The external housing contact surfaces

To ensure near-perfect parallelism, we developed a patented polishing device. This guarantees an almost absolute parallel orientation of the plates.

When operated in a PPMS system configured as described in Chapter 2 ("Recommended Measurement Configurations"), the mini-dilatometer achieves a length resolution of:
$\Delta L = 0.01$ Å

5.8 Summary

The mini-dilatometer combines:

- Patented single-piece Be–Cu construction
- Parallelogram spring suspension
- Optimized eddy-current suppression
- Ultra-precise capacitor plate alignment

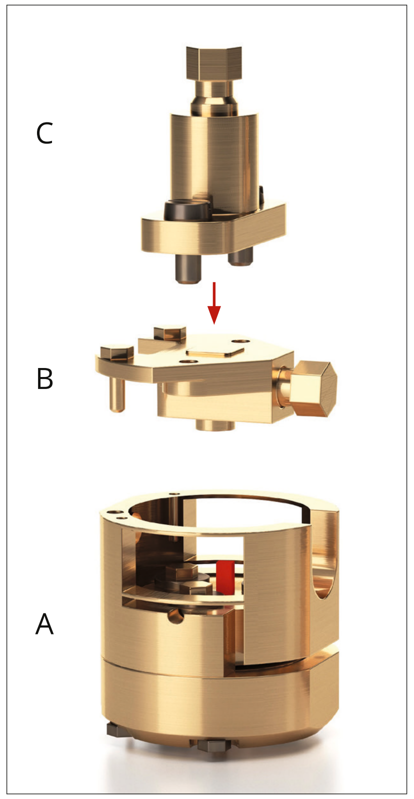
The result is a compact (13,5 g), thermally efficient, and extremely high-resolution capacitive dilatometer capable of resolving sub-ångström length changes in millimeter-sized samples.

06

Sample Mounting

6.1 Standard Sample-Mounting Procedure for the In-Situ PPMS Dilatometry Probe

The figure illustrates the commonly used procedure for inserting a millimetre-sized sample into the dilatometer. The sample (red cuboid) is introduced vertically from above into the center of the dilatometer body. For reliable positioning, the sample must have a sufficiently large cross-section to remain upright and must be aligned along the vertical measurement axis (z). After insertion, the cover (B) and the sample-adjusting tool (C) are attached.

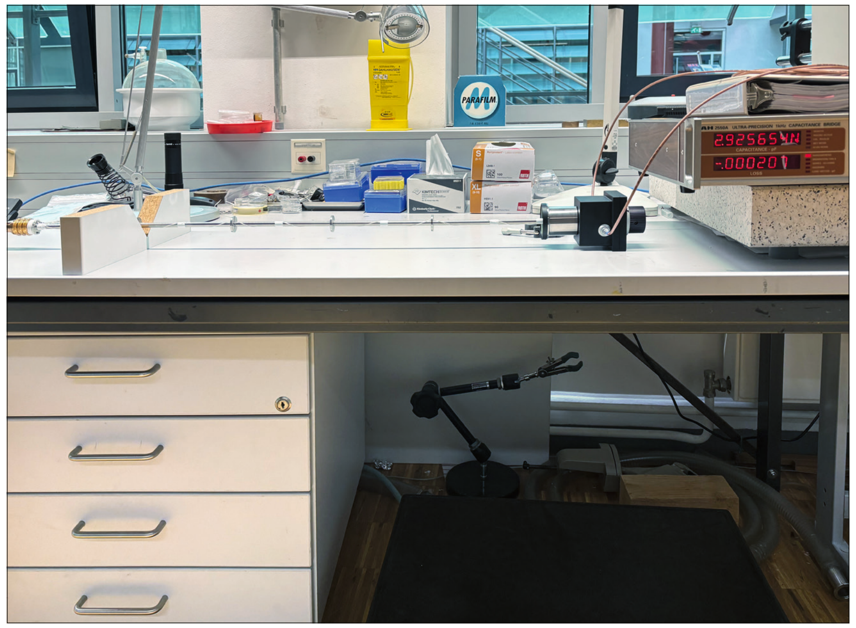


Common sample mounting procedure with cube-shaped stamp (indicated by a red arrow). After assembling the bottom part and the main body (see Section 5.2, Mechanical Design), the mini dilatometer consists of only three components: (A) main body with sample (dark red) positioned in its center, (B) cover, and (C) sample-adjusting tool.

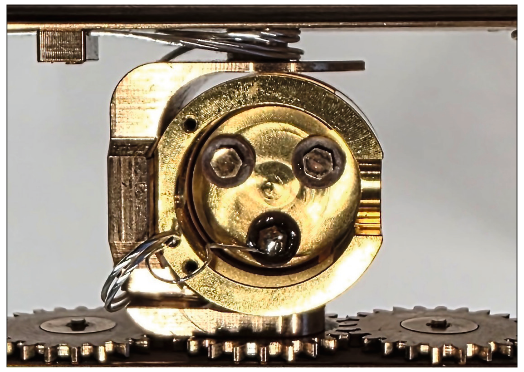
This method works reliably for samples with cross-sections ≥ 0.3 × 0.3 mm². For smaller cross-sections, maintaining a stable upright position becomes more difficult, as such samples tend to tip or shift before clamping. Clamping is achieved by gently tightening the adjustment screw located on top of the sample-adjusting tool (C). Importantly, this screw does not act directly on the sample. Instead, it applies force to a cube-shaped stamp (see red arrow in figure above) that is constrained to move only vertically within the cover (B). This design prevents rotational or angular displacement during clamping and preserves the crystallographic orientation. Once the sample is clamped, the locking screw on the right side of part (B) secures the cubic stamp, allowing the sample-adjusting tool (C) to be removed.

6.1.1 Step-by-Step Mounting Procedure

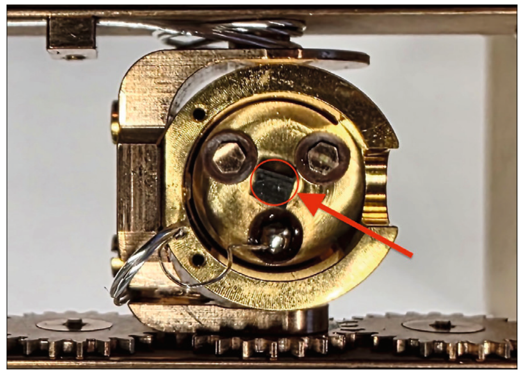
1. **Preparation**
   Place the in-situ PPMS dilatometry probe on a stable table. Before mounting the sample, connect the PPMS probe to the AH capacitance bridge so that capacitance can be monitored during installation. The initial reading corresponds to the empty dilatometer and should be approximately **3 pF**.



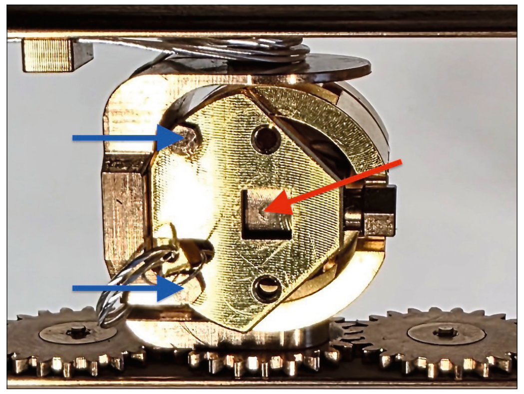
2. **Open the dilatometer**
   Unscrew and remove the sample-adjusting tool (C) and the cover (B). The picture shows the open dilatometer.



3. **Insert the sample**
   Carefully place the sample in the center of the dilatometer body (see red arrow).



i) The sample must be aligned along the vertical measurement axis (z).
ii) Ensure that the sample does not come into contact with the brown insulating Vespel spacers surrounding the screws.
iii) Samples with complex geometries may be stabilized with a small amount of epoxy or GE varnish to keep them upright.



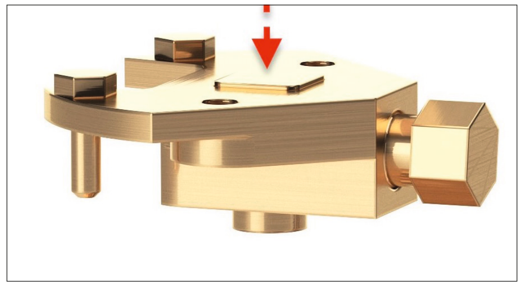
4. Reattach the cover

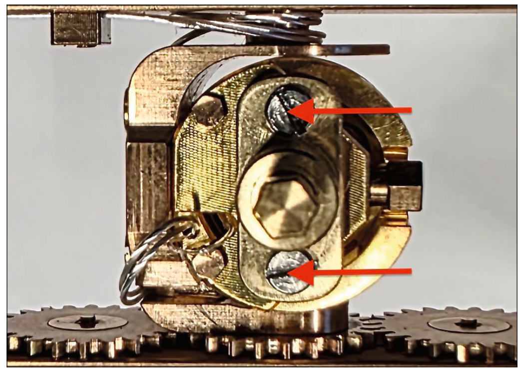
Use the two M1 screws (see blue arrows) to mount the cover onto the body. Before attaching the cover, remove the cubic stamp (see red arrow) so that the sample position can be checked after the cover is installed.

The sample should remain unattached and stand in the center of the dilatometer body.

5. Insert the cubic stamp

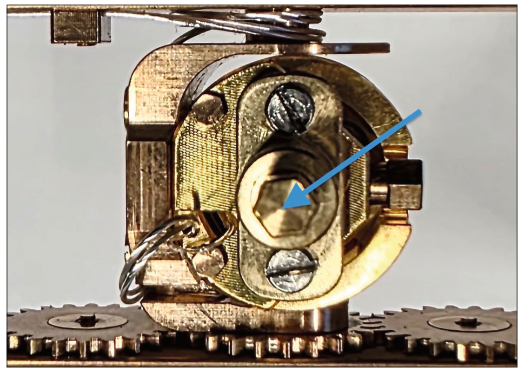
Once the sample is correctly positioned, insert the cubic stamp into the cover and press it down gently until the sample is held in place.





6. Mount the sample-adjusting tool

Attach the sample-adjusting tool using the two M1.6 screws (see red arrows).

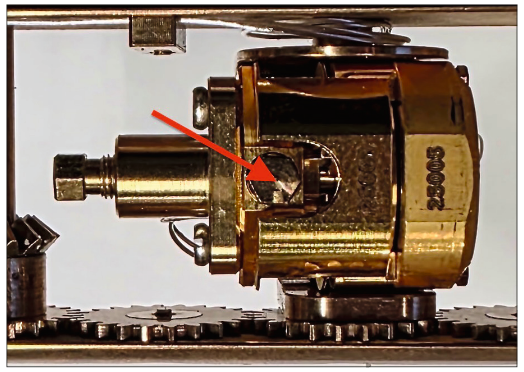


7. Apply clamping force

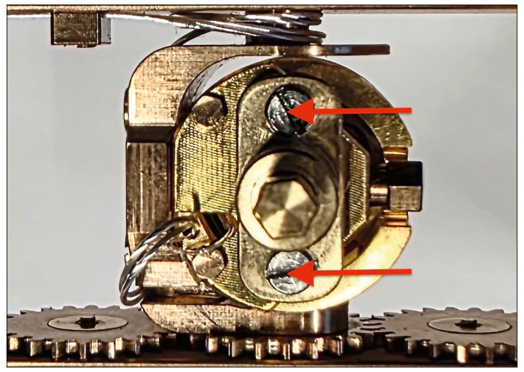
Tighten the adjustment screw (see blue arrow) to increase the force on the sample.

The adjustment screw presses only on the cubic stamp, which moves strictly vertically and prevents twisting of the sample. The adjustment screw has very fine threading and can be precisely controlled using an M3 socket wrench. Tighten carefully until a capacitance of **15 – 20 pF** is reached.

8. Lock the stamp



Tighten the locking screw (see red arrow) to secure the cubic stamp. The sample is now clamped with a force of approximately **3 N**. As described in Chapter 5, the dilatometer design with two 0.25 mm leaf springs applies a modest total force of about **3 – 4 N**, which typically does not affect the intrinsic properties of millimeter-sized samples.

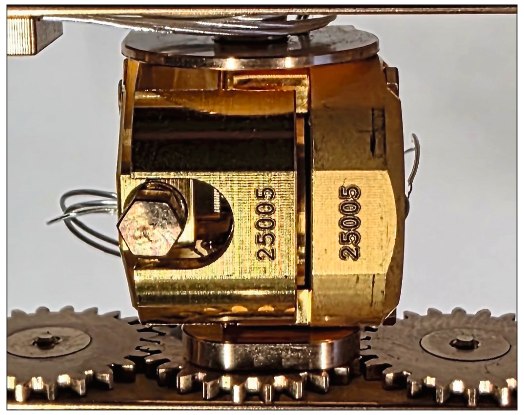


9. Remove the adjusting tool

Remove the sample-adjusting tool by using the two M1.6 screws (see red arrows). The cubic stamp remains locked in place.

Important: During measurements in the PPMS, **the sample-adjusting tool must always be unscrewed and removed** before inserting or operating the probe.

If the tool remains attached, it can get stuck against the PPMS cooling channel at rotation angles near 90°, which may also cause the probe to become trapped, potentially resulting in serious damage to both the dilatometer and the PPMS system.



10. Final inspection

After assembly, inspect the mounted sample under a microscope to verify that it is perfectly aligned along the vertical axis.

Optical microscope view, single crystal mounted in the mini dilatometer.

6.1.2 Sample Mounting Tools

For easier installation, dedicated mounting tools are provided, including M1.8 and M3 socket wrenches. The M1.8 socket wrench is a modified standard tool that has been machined at the tip to ensure a proper fit.

Sample mounting is also demonstrated in the video available at: www.dilatometer.info

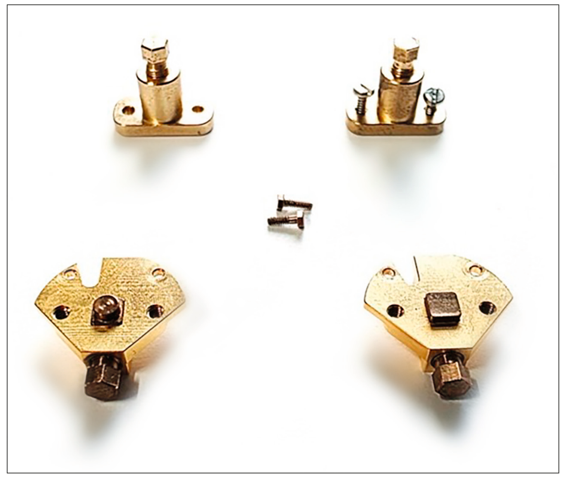
6.1.3 Sample Mounting Instructions

The cubic stamp (piston) can be inserted into the dilatometer cover in two orientations, each suitable for different sample sizes:

1. **Cylindrical Section Facing Upward (Left Configuration):**
   Allows measurement of samples up to **2.25 mm in length**. In this orientation, the cylindrical section of the stamp fits securely into the threaded hole of the sample-adjusting aid. If the sample's cross-section is smaller than that of the stamp, samples up to **2.75 mm in length** can be accommodated. By placing small washers between the dilatometer cover and the sample-adjusting tool, even samples slightly larger than **3 mm** can be clamped securely.

Note: Very small samples cannot be measured in this orientation, because the downward-facing cubic stamp would come into contact with the insulating Vespel spacers attached to the three screws.

2. **Cylindrical Section Facing Downward (Right Configuration):**
   Enables measurement of very **small samples**. Also allows measurement of the **empty dilatometer cell**.

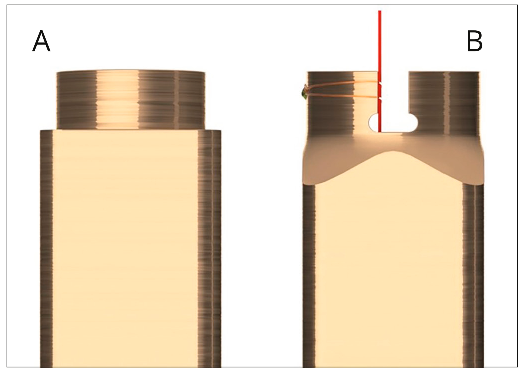


The two opposite orientations of the mounting stamp: Cylindrical Section Facing Upward (Left Configuration) Cylindrical Section Facing Downward (Right Configuration)

6.2 Additional Option: Sample Mounting Technique Using a Slot-Based Stamp for Platelet-Shaped Microscopically Thin Crystals

This technique is designed for mounting platelet-shaped, microscopically thin crystals.
For detailed information on this method, refer to R. Küchler et al., Review of Scientific Instruments, 97, 025209 (2026).

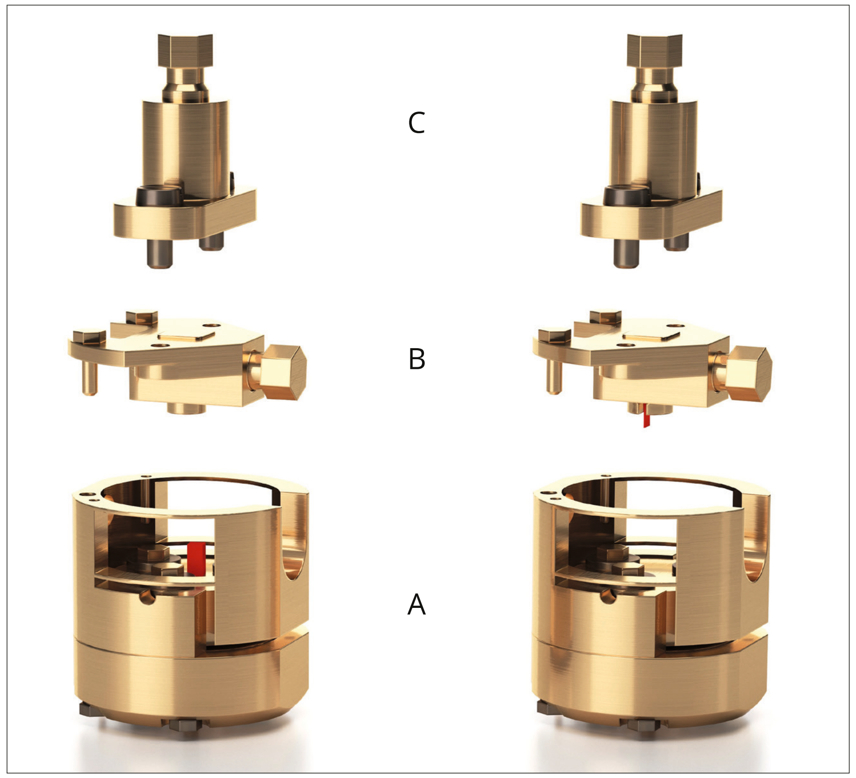
The core of this approach is a slotted mounting stamp, fabricated with a narrow 0.5 mm wide slot produced by precision wire erosion.



(A) Standard cube-shaped mounting stamp commonly used for sample mounting. (B) Slotted cube-shaped stamp with an ultra-thin sample (red) mounted. Two 30 µm-thick PTFE-coated silicon threads are looped around the sample.

To secure the sample within the slot, a 30 µm-thick PTFE-coated silicon thread is looped around the sample and fixed to the outer side of the stamp using adhesive. For samples exceeding 1mm in length, two such loops are used to further enhance mechanical stability during stamp handling and installation.

Once secured, the stamp containing the mounted sample is inserted vertically through the cubic opening of the cover piece (B) and held in place using the right-side lock screw of the cover piece (B), as shown below.



Left: Standard sample mounting procedure with cube-shaped stamp (indicated by a red arrow). Dilatometer consists of three main parts: (A) main body with sample (dark red) positioned in its center, (B) cover, and (C) sample-adjusting tool.

Right: Sample mounting procedure using the slotted cube-shaped stamp, shown here with a mounted sample of 50 µm thickness (dark red).

After initial positioning, the cover (B) is reattached to the dilatometer body (A). The lock screw is then loosened, and the stamp is carefully lowered by hand or a toothpick until the sample gently contacts the bottom surface of the dilatometer body (A), using controlled force to avoid damaging the sample. With the sample in position, the standard mounting procedure can be continued as described earlier in 6.1.1.

The sample mounting can be inspected using a microscope to verify that the sample remains straight and has not bent under the applied spring force of typically 3 up to 4 N. This slot-based method significantly reduces the risk of sample tipping or misalignment.

07

Cleaning the Dilatometer

Contamination caused by sample particles or foreign material within the capacitor gap may result in an electrical short circuit between the capacitor plates. In such cases, the **AH capacitance bridge** typically indicates a **"loss too high"** condition or, in rare instances, displays an alternative error message.
If such an error occurs, the dilatometer shall be cleaned carefully in accordance with the procedure described below.

7.1 Initial Cleaning (Without Disassembly)

1. **Inspect the capacitor** gap for visible particles or contamination.

2. Attempt to remove sample particles or foreign material by:

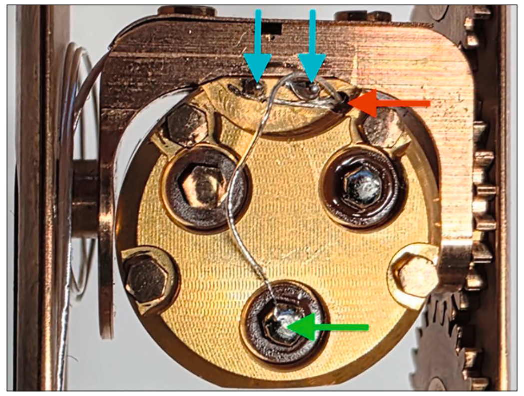
Left: Carefully insert and clean using a clean, lint-free paper strip between the capacitor plates, or

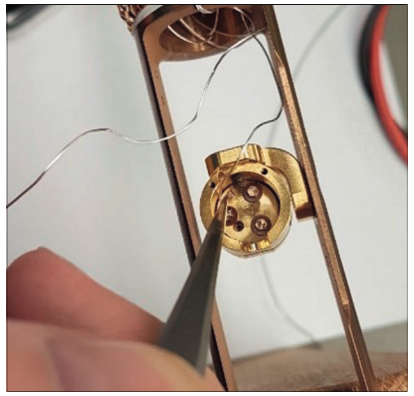
Right: Cleaning by blowing dry, oil-free compressed air between the plates.

If the short circuit persists after this step, proceed with disassemble.

7.2 Disassembly and Internal Cleaning

1. **Unsolder the coaxial cables** from the dilatometer.





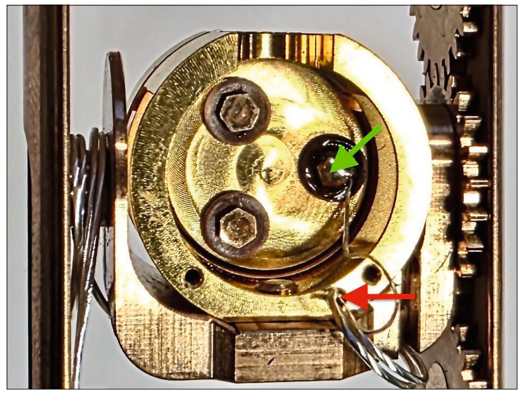
First, de-solder the **inner conductor** of the coaxial cable from the screw on the lower capacitor plate (see green arrow).

During de-soldering, hold the coaxial cable with tweezers positioned between the solder joint and the cable insulation. This allows heat to be dissipated through the tweezers rather than into the coaxial cable. Failure to do so may result in thermal damage to the cable insulation.

Next, de-solder the **outer shields** of both coaxial cables. Each shield was previously twisted, both shields were fed together through the feedthrough hole, and each shield was soldered to a separate pin (see blue arrows). Carefully remove the solder and detach the shields from their respective pins.

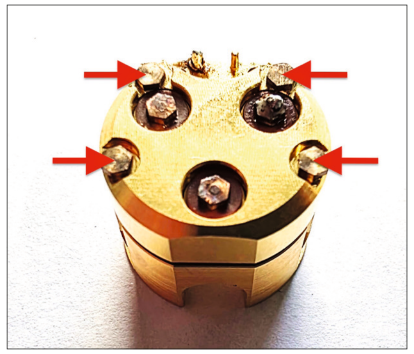
After de-soldering, straighten and prepare the inner conductor and the twisted outer shields so that they can be carefully pushed back through the designated feedthrough hole in the housing (see red arrow). Do not apply excessive force in order to prevent damage to the conductors or their insulation.

Turn the dilatometer upside down and unscrew the cover. Then de-solder the inner conductor of the second coaxial cable from the screw (see green arrow).



After completing these steps, all coaxial cables can be carefully pulled out through the designated feedthrough hole in the housing (see red arrow).

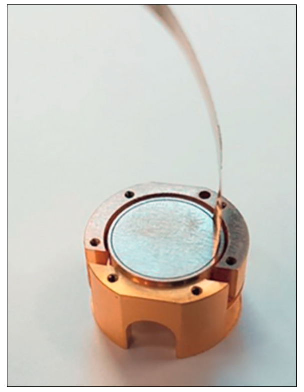
2. **Unscrew and carefully open** the dilatometer housing.



Place the dilatometer on a stable table with the main body facing downward.
Using an M3 socket wrench, carefully unscrew the four outer screws located on the bottom part of the dilatometer (see red arrows).
Once the screws are removed, gently open the dilatometer. Separate the lower capacitor plate and its components from the main body.

Inspect both the lower capacitor plate and the upper capacitor plate (still attached to the body) individually for any contamination.

3. Clean the following components thoroughly:
   - The capacitor plates
   - The gap between the capacitor plates and the housing (guard rings)



Pay special attention to the gap between the capacitance plate and the housing. This gap is very narrow, particularly at the upper capacitor plate, and is the area most prone to trapped particles or metal shavings that could cause a short circuit.

Use thin, lint-free paper or other suitable precision cleaning materials to carefully remove any contamination. Cleaning under an optical microscope is highly recommended, as it allows you to see whether particles are present and confirm that they have been fully removed.

Important: Avoid using abrasive tools or materials, as these can scratch or damage the surfaces.

4. Inspect all cleaned parts under an **optical microscope** to ensure:
   - All contamination has been removed
   - The capacitor plates are completely clean
   - No particles remain in the gap areas

7.3 Electrical Verification

After cleaning and reassembly:

Use a multimeter to measure the electrical resistance between:
- The insulated capacitor plates and
- The cell body (housing)

There must be **no measurable electrical continuity** between these components.
If a short circuit is still detected, very small particles may be trapped beneath a capacitor plate.

7.4 Ultrasonic Cleaning (If Required)

If the above steps do not resolve the issue:

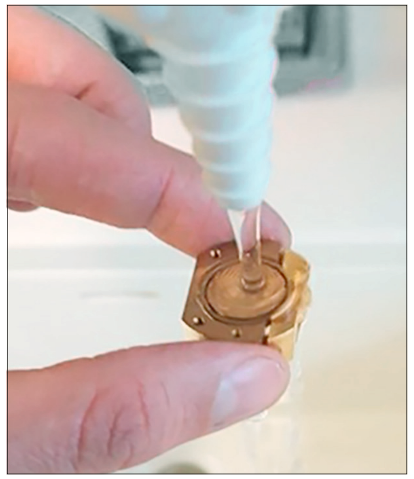
1. Clean the part in an **ultrasonic cleaner**, following the manufacturer's safety and material compatibility guidelines

2. Place the main body (corpus) or the lower part of the dilatometer carefully at the bottom of a large glass, ensuring that the capacitor plates are facing upward.

3. Slowly fill the glass with Isopropanol until the parts are fully submerged.

4. Place the glass in an ultrasonic cleaner and clean the dilatometer parts for 30 minutes.
Caution: Make sure the glass remains stable and does not tip over during cleaning, as this could damage the polished capacitor plates.

5. After ultrasonic cleaning, gently rinse the parts with calcium- and salt-free water.



6. Allow the parts to dry completely before reassembly.

7.5 Final Check

After completing all cleaning steps:

- Reassemble the dilatometer carefully.
- Repeat the electrical resistance measurement
- Confirm that the device is free of short circuits before returning it to operation.

08

Calibration of the Cell Background

The use of different materials in the dilatometer assembly results in a temperature-dependent background signal due to their differing thermal expansion coefficients. In the present design, this effect is minimized by machining nearly all structural components from $Cu_{0.98}Be_{0.02}$ (Be–Cu alloy). The only exceptions are sapphire washers and electrically insulating spacers made of Vespel.

The remaining background contribution is determined experimentally by a reference measurement using high-purity copper (99.999%). The thermal expansion of copper in the relevant temperature range is well established in the literature (F. R. Kroeger and C. A. Swenson, J. Appl. Phys. 48, 853–864 (1977)).

8.1 Principle of the Background Calibration

In a thermal expansion experiment, both the sample length and the effective length of the dilatometer cell change with temperature. Therefore, the measured length change of a sample,

ΔL_{sample}^{meas},

contains two contributions: $\Delta L_{sample}^{meas} = \Delta L_{sample} - \Delta L_{cell}$.

Here:

- ΔL_{sample} is the true length change of the sample,
- ΔL_{cell} is the temperature-dependent length change of the cell.

To determine the cell contribution, we measure a copper reference sample of the same initial length L_0 as the investigated sample. For copper we obtain:

$\Delta L_{Cu}^{meas} = \Delta L_{Cu}^{lit} - \Delta L_{cell}$,

where:

- ΔL_{Cu}^{lit} is the literature value of the copper length change,
- ΔL_{Cu}^{meas} is the measured value of copper.

From this relation, the cell contribution is:

$\Delta L_{cell} = \Delta L_{Cu}^{lit} - \Delta L_{Cu}^{meas}$.

8.2 Correction of Sample Data

To obtain the true length change of an arbitrary sample, the calibrated cell contribution must be added to the measured signal:

$$\Delta L_{sample} = \Delta L_{sample}^{meas} + \Delta L_{cell}.$$

Substituting the expression for ΔL_{cell}:

$$\Delta L_{sample} = \Delta L_{sample}^{meas} - \Delta L_{Cu}^{meas} + \Delta L_{Cu}^{lit}.$$

The relative length change, normalized to the room temperature length L_0, is therefore:

$$\frac{\Delta L_{sample}}{L_0} = \frac{\Delta L_{sample}^{meas} - \Delta L_{Cu}^{meas}}{L_0} + \left(\frac{\Delta L}{L_0}\right)_{Cu}^{lit}.$$

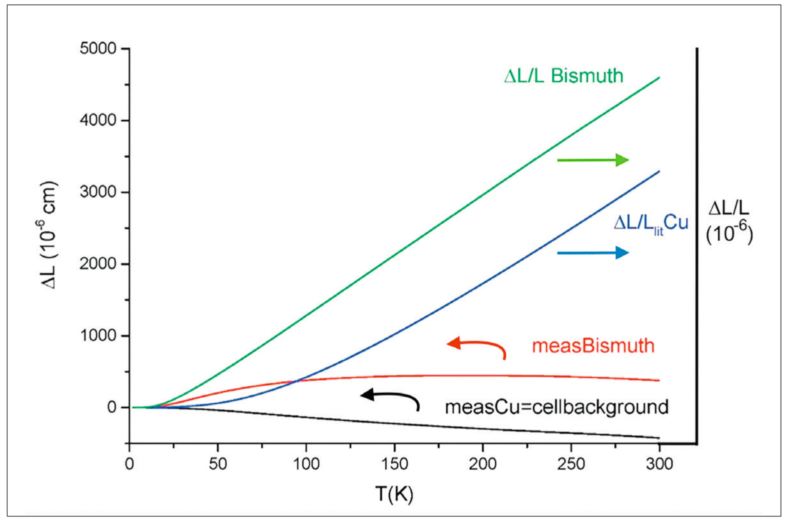
The last term represents the literature value for the relative thermal expansion of pure copper and is independent of the sample length.

8.3 Example: Bismuth Single Crystal

As an example, the corrected length change of a bismuth single crystal is given by:

$$\frac{\Delta L^{Bismuth}}{L_0} = (\Delta L_{meas}^{Bismuth} - \Delta L_{meas}^{Cu})/L_0 + (\Delta L/L)_{lit.}^{Cu}$$

It is essential that the copper reference sample has exactly the same initial length L_0 as the investigated Bismuth sample.



8.4 Physical Origin of the Cell Effect

The cell background signal (cell effect) arises from the differential thermal expansion between the sample and the dilatometer frame. When a sample of initial length L_0 is inserted, it replaces an equivalent segment of the cell body along the measurement axis. Consequently, the instrument measures the relative displacement between the samples expansion and that of the corresponding portion of the frame.

The use of a Beryllium-Copper alloy (Cu-Be with 1.84% Be) for the cell body is significant for the instruments performance for the following reasons:

- Minimized Background Offset: Since the thermal expansion coefficient of the Cu-Be alloy is nearly identical to that of pure copper, the absolute background contribution remains minimal. This significantly reduces systematic errors and simplifies data correction.
- Thermal Homogeneity: Due to the high thermal conductivity of the alloy, the cell reaches thermal equilibrium rapidly. This eliminates internal thermal gradients that could otherwise lead to measurement artifacts or drifts.
- Mechanical Resilience: The 1.84% beryllium content provides the alloy with high yield strength and elasticity (comparable to spring steel). This prevents plastic deformation of the frame during repeated thermal cycling, ensuring long-term reproducibility.

This combination of matched thermal expansion, excellent conductivity, and mechanical stability accounts for the very high precision and reliability of the dilatometer.

8.5 Length Dependence of the Cell Background

The cell background is linear with respect to the measured copper sample length. Therefore, it is sufficient to measure two copper reference samples:

- a short sample (e.g., 0.5 mm),
- a long sample (e.g., 2 mm).

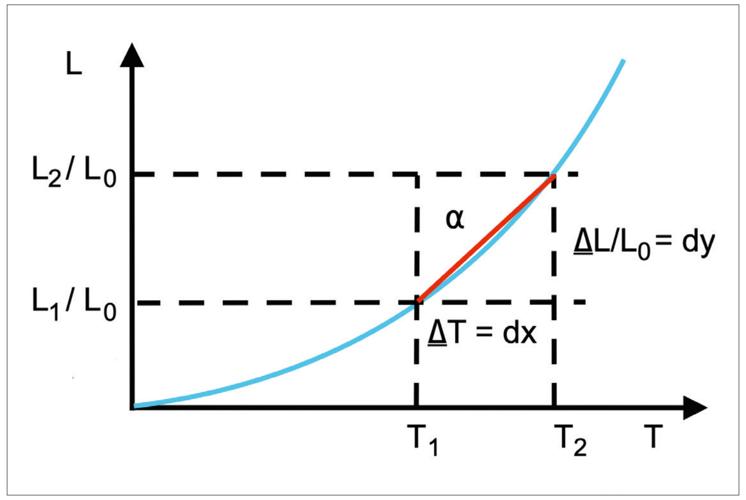
The background for any intermediate sample length can then be obtained by linear interpolation. A detailed description of this procedure can be found under Thermal Expansion Measurements: Background Correction, originally written by Christian Stingl. The method was initially developed for thermal expansion measurements performed on the Physical Property Measurement System (PPMS) using the larger standard dilatometer (see R. Küchler et al., Rev. Sci. Instrum. 83, 095102 (2012)).

Although the procedure was designed for the larger dilatometer, the underlying principles of background correction, signal evaluation, and data treatment are equally applicable to measurements performed with the mini dilatometer. Therefore, the same correction strategy can be adopted for the mini dilatometer probe.

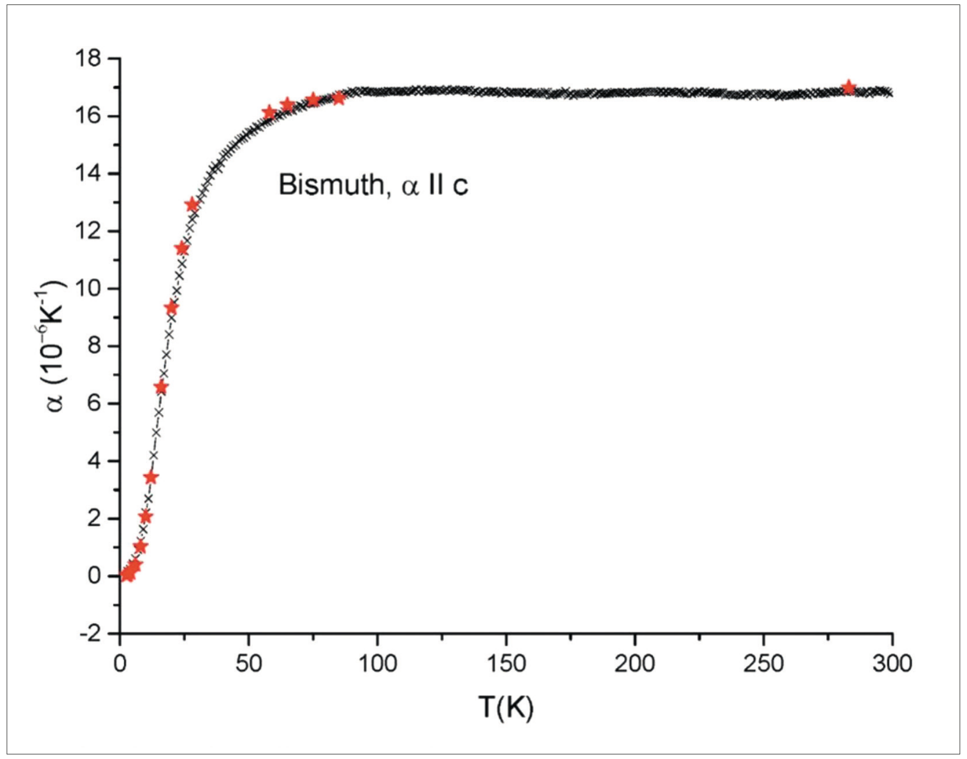
8.6 Calculation of the Thermal Expansion Coefficient

From the corrected relative length change $\Delta L(T)/L_0$, the linear thermal expansion coefficient is calculated as:

$$\alpha(T) = \frac{1}{L_0}\frac{d\Delta L(T)}{dT}.$$



$$\alpha_1 = \frac{(L_2 - L_1)/L_0}{T_2 - T_1} \qquad \text{where } T_m = \frac{T_1 + T_2}{2}$$



The calculated thermal expansion coefficient using a derivative interval of 0.5 K, with red data points representing values reported in the literature.

In practice, the derivative is determined numerically using an interval (finite difference) method with a temperature window between 0.01 K and 0.5 K, depending on the required temperature resolution and noise level.

09

Safety Information: Dilatometer Probe (CuBe Components)

9.1 Material Information

This product contains components manufactured from copper-beryllium alloy (CuBe, Alloy 25) containing approximately 1.84% beryllium.

Only the dilatometer elements are made of CuBe. The probe cage is manufactured from copper-tin alloys and does not contain beryllium. The product is supplied as a finished article.

9.2 Intended Use and Exposure Information

Under normal and intended laboratory use, the CuBe components do not present a health hazard.

The beryllium is metallurgically bound within a solid alloy matrix.
No exposure to beryllium is expected during routine handling, installation, or measurement operation.

This product is not intended to release beryllium under normal conditions of use.

9.3 Hazard Information – Mechanical or Thermal Processing

Health risks may arise if CuBe components are mechanically or thermally processed in a manner that generates airborne dust, particles, mist, or fumes.

Examples of such operations include, but are not limited to:

- Cutting
- Grinding
- Machining
- Drilling
- Sanding
- Polishing
- Welding
- Brazing
- Melting

Inhalation of airborne beryllium-containing dust or fumes may cause serious health effects, including lung disease, sensitization, or cancer.

9.4 Restrictions on Modification

The CuBe components of the dilatometer are not intended to be:

- Machined
- Ground
- Welded
- Thermally processed
- Modified in any way
-

Any such activities must only be performed by appropriately trained personnel using suitable industrial hygiene measures and engineering controls.

9.5 Regulatory Information – European Union

This product is an article within the meaning of Regulation (EC) No. 1907/2006 (REACH).

No exposure to beryllium is expected under normal and reasonably foreseeable conditions of use.

If the product is modified or processed in a manner that generates airborne particles, the operator is responsible for compliance with applicable occupational safety and environmental protection legislation within the European Union and relevant Member States.

9.6 Regulatory Information – United States

Beryllium is regulated under the U.S. Occupational Safety and Health Administration (OSHA) Beryllium Standard, 29 CFR 1910.1024.

This product does not present an exposure hazard during normal and intended use.

If CuBe components are processed in a manner that generates airborne dust or fumes, such activities must be conducted in accordance with applicable federal, state, and local regulations, including the OSHA Beryllium Standard.

Appropriate engineering controls, exposure monitoring, respiratory protection, and medical surveillance may be required under U.S. law.

9.7 User Responsibility

The purchaser, employer, or operator is responsible for ensuring compliance with all applicable occupational safety, health, environmental, and hazard communication regulations in their jurisdiction.

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