Measurement of electric and magnetic material properties

Material properties

- (absolute) permittivity - ε
  - a measure of the polarizability of a dielectric in reaction to external electric field; interaction of the material with the electric field
  - relation between the „electric displacement field“ D and the „electric field“ E:

$$D = \varepsilon E$$

  - relative permittivity ε_r:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r''$$

  - the real part expresses the amount of energy stored in the material, the imaginary part represents the losses

Vlastnosti materiálů

- (absolute) permeability - μ
  - measure of magnetization produced in a material in response to an applied magnetic field
  - relation between the „magnetic flux density“ B and the magnetic (magnetizing) field H:

$$B = \mu H$$

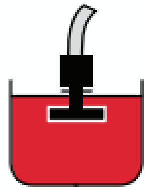
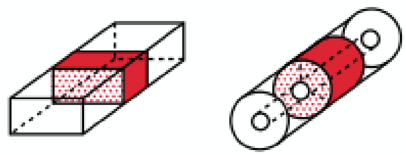
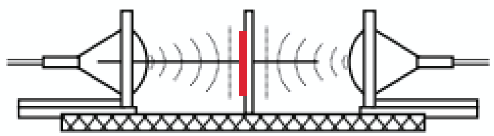
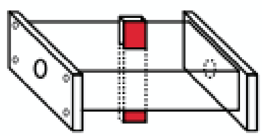
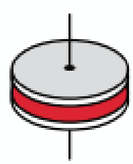
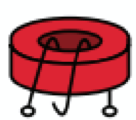
  - relative permeability μ_r:

$$\mu_r = \frac{\mu}{\mu_0} = \mu_r^{'} - j\mu_r^{''}$$

Measurement methods

- Keysight N1500A software offers the following methods for measurement of the electric/magnetic material properties:
  - transmission line / free space method
  - „arch reflectivity“ method
  - measurement using resonators (SPDR, SCR)
  - measurement with coaxial probe
  - measurement in a low frequency dielectric/magnetic fixture

Measurement methods

Coaxial probe ε_r		Broadband convenient, non-destructive. Best for lossy MUTs; liquids and semi solids
Transmission line ε_r and μ_r		Broadband Best for lossy to low loss MUTs; machineable solid
Free space ε_r and μ_r		Broadband; non-contacting Best for flat sheets, powderrs, high temperatures
Resonant cavity ε_r		Single frequency; accurate Best for low loss MUTs; small samples
Parallel plate ε_r		Accurate Best for low frequencies; thin, flat sheets
Inductance measurement μ_r		Accurate, simple measurement,a toroidal core structure is required

1) Transmission line / free space method

- **N1500A – opt. 001**
- universal method – dielectric and magnetic properties; wide frequency range from hundreds of MHz to THz
- usable for homogenous solid samples
- samples can be inserted into a coaxial transmisson line, waveguide or between two (horn) antennas
- samples have to be manufactured so they fit into the sample holder as precisely as possible
    - toroidal shape into an airline or a rectangular block to a waveguide
- basic measurement accuracy of 1 % to 2 %

1) Transmission line / free space method

- Keysight offers the following accessories usable as sample holders (coaxial verification kits and waveguide calibration kits):
  - 3,5 mm airline 85053BR03 (from the 85053B cal kit)
  - APC7 airline 85051BR03 (from the 85051B cal kit)
  - Type-N airline 85055AR03 (from the 85055A cal kit)
  - WR90 waveguide calibration kit X11644A – 8,2 GHz to 12,4 GHz
  - WR62 waveguide calibration kit P11644A – 12,4 GHz to 18 GHz
  - WR42 waveguide calibration kit K11644A – 18 GHz to 26,5 GHz
  - WR28 waveguide calibration kit R11644A – 26,5 GHz to 40 GHz

1) Transmission line / free space method

- supportless airline:

1) Transmission line / free space method

- waveguide calibration kit:

1) Transmission line / free space method

- example of the free space measurement setup:

1) Transmission line / free space method

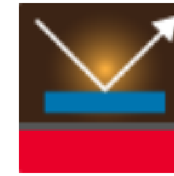
- it is possible to choose from nine different calculation algorithms, which are suitable for different purposes
  - calculation of **permittivity and permeability** or **permittivity** only
  - input data – reflections and/or transmissions
- a sample thickness calculator can be used as a convenient tool to estimate the optimal sample size
  - the sample thickness should be close to ¼ or ½ (depending on the method used) of the wavelength in the given material at the mean measurement frequency

1) Transmission line / free space method

- a description of the individual methods is available:

N1500A	Alternate	S-parameters measured	Result	Description	References
Reflection/ Transmission Mu and Epsilon	Nicholson-Ross -Weir, NRW	S11, S21, S12, S22	εr, μr	Originally developed by Nicholson and Ross, and later adapted to automatic network analyzers by Weir to calculate permittivity and permeability from transmission and reflection coefficients. Can have discontinuities for low loss samples with thickness of > ½ wavelength. Best for magnetic materials such as ferrites and absorbers.	AM. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time domain techniques," IEEE Trans. Instrum. Meas., IM-19(4), pp. 377-382, 1970. W.W. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," Proc.IEEE vol. 62 pp.33-36, Jan 1974
Reflection/ Transmission Epsilon Precision	NIST Precision	S11, S21, S22	εr	Developed by NIST to calculate permittivity from transmission and reflection coefficients. Best for longer samples of low-loss dielectric materials.	Improved Technique for Determining Complex Permittivity with the Transmission/Reflection Method, James Baker-Jarvis et al, IEEE transactions on microwave Theory and Techniques vol 38, No. 8 August 1990.
Transmission Epsilon Fast	Fast Transmissi on	S21, S12	εr	An iterative technique that estimates permittivity and then minimizes the difference between the S-parameter value calculated from that	

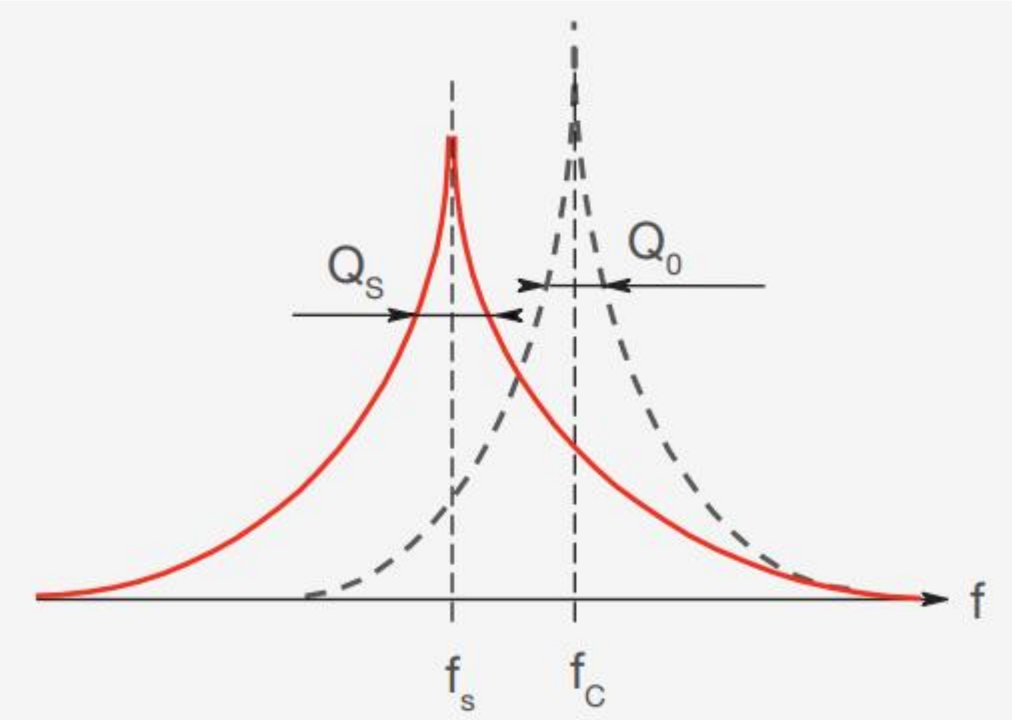
2) „Arch reflectivity“ method



- **N1500A – opt. 002**
- measuring the reflection from a given material at a certain angle
  - two antennas (transmitting and receiving)
  - arched antenna holder allowing the desired angle to be set
- dielectric and magnetic materials, reflection loss
- basic accuracy of 1 % to 2 %
- can be used for planar sheet sufficiently large samples; usually solids

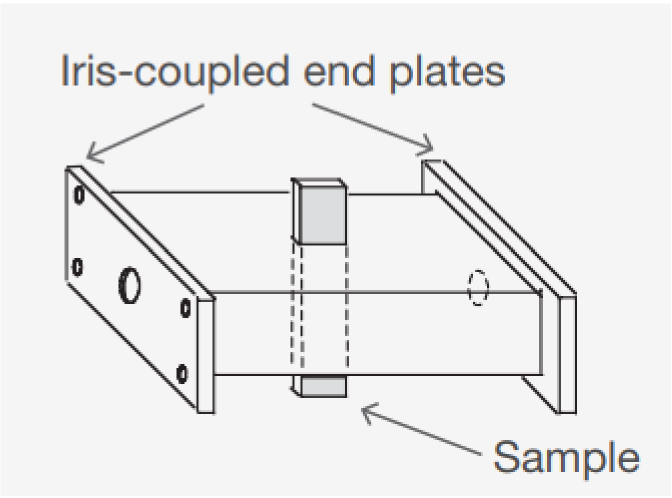
3) Resonant methods

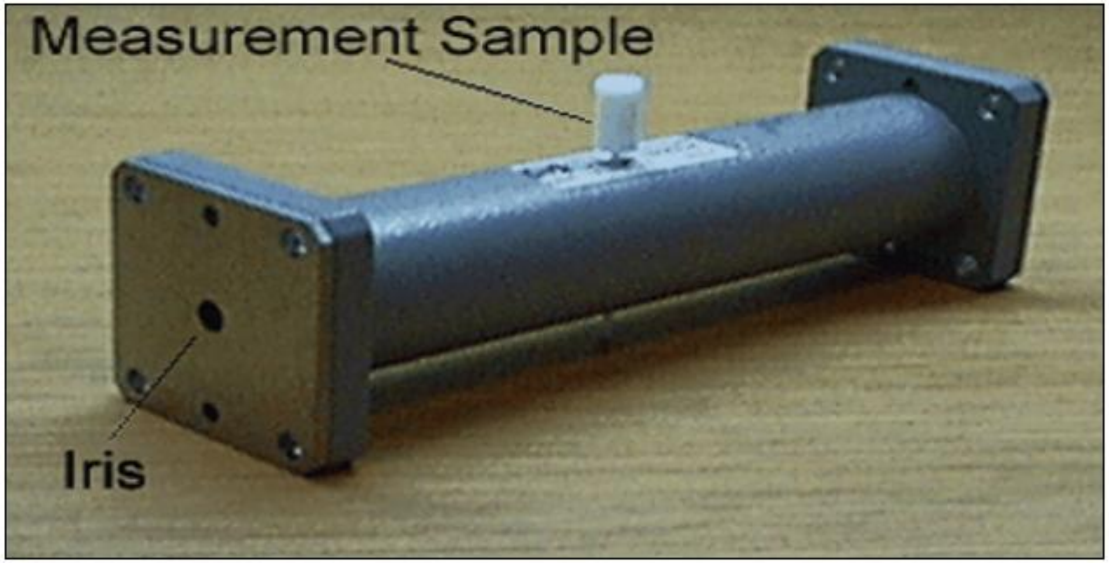
- **N1500A – opt. 003 and 007**
- resonance measurement methods generally offer high sensitivity, resolution and accuracy
  - suitable for thin low-loss samples (high quality substrates)
- the disadvantage is the possibility of measuring at a single frequency only (given by the properties of the resonator)
- dielectric parameters are calculated from the change in resonant frequency and Q of the resonator after the sample is inserted



3) Resonant methods

- **N1500A – opt. 003** – available calculation methods:
  a) ASTM 2520 – uses a resonator made of a rectangular waveguide (coupling holes on the front surfaces and a transverse hole for inserting the sample)
    - it is relatively easy and cheap to fabricate a custom measuring resonator

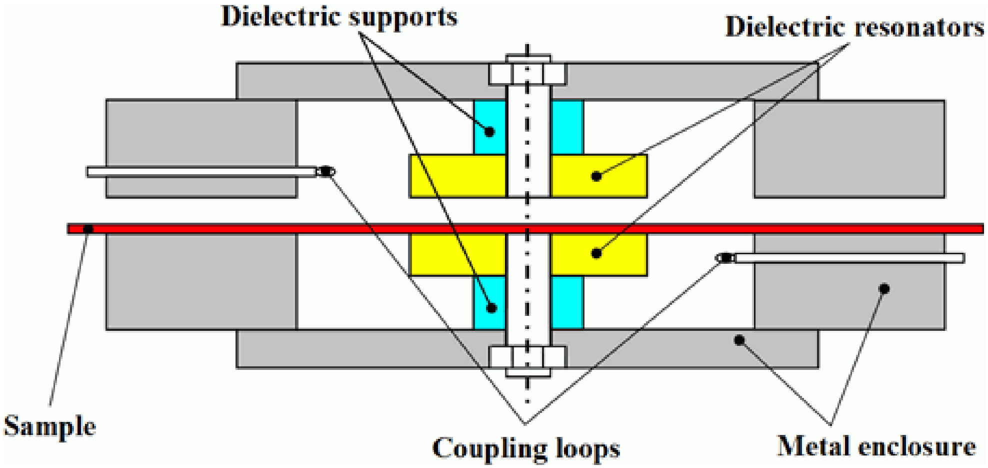


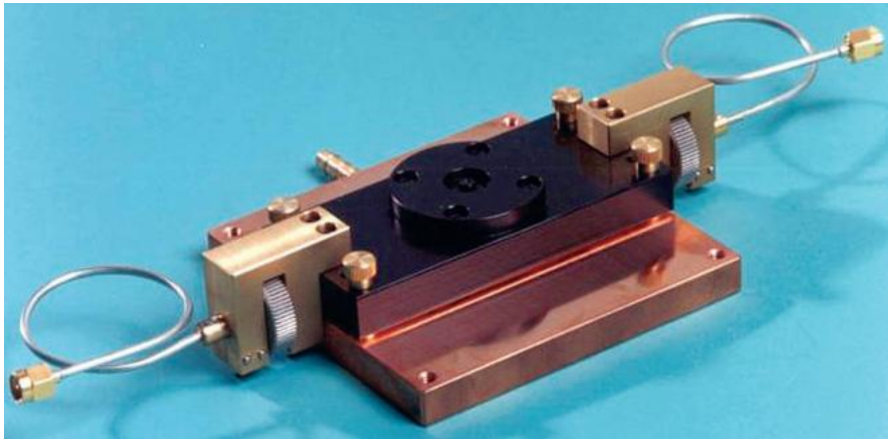


3) Resonant methods

b) „split post“ method – uses SPDRs (split post dielectric resonator) made by the QWED company

- uses low-loss dielectric material; higher Q, better temperature stability and lower cost compared to classic metal resonators
- suitable for measuring thin planar samples (substrates)
- different models with resonance frequency from 1,1 GHz to 15 GHz

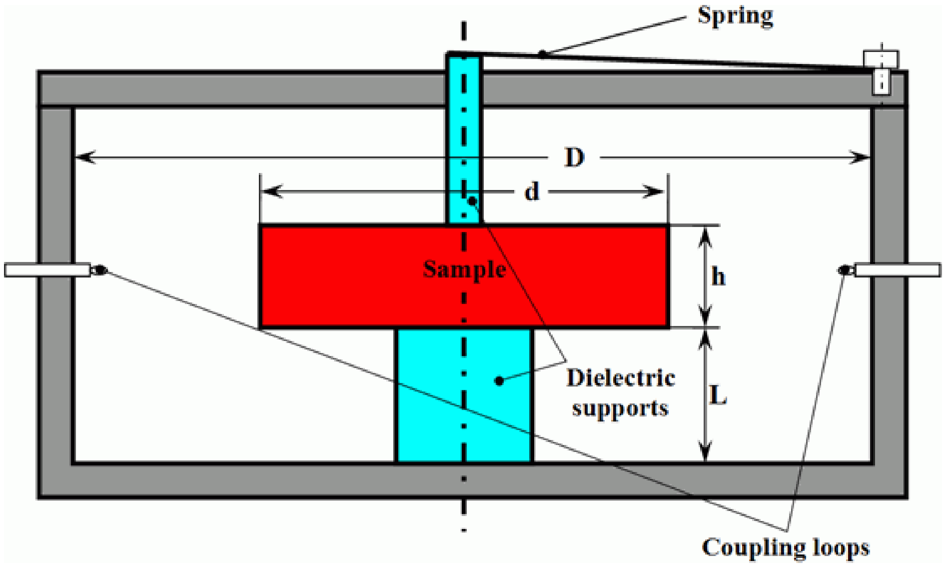




3) Resonant methods

c) „TE01 delta“ method – uses metal cavity resonators from QWED

- metal cylindrical cavity with low loss dielectric supports
- a sample in the shape of a cylinder or disk is inserted in a defined position near the center of the resonator and held by the supports

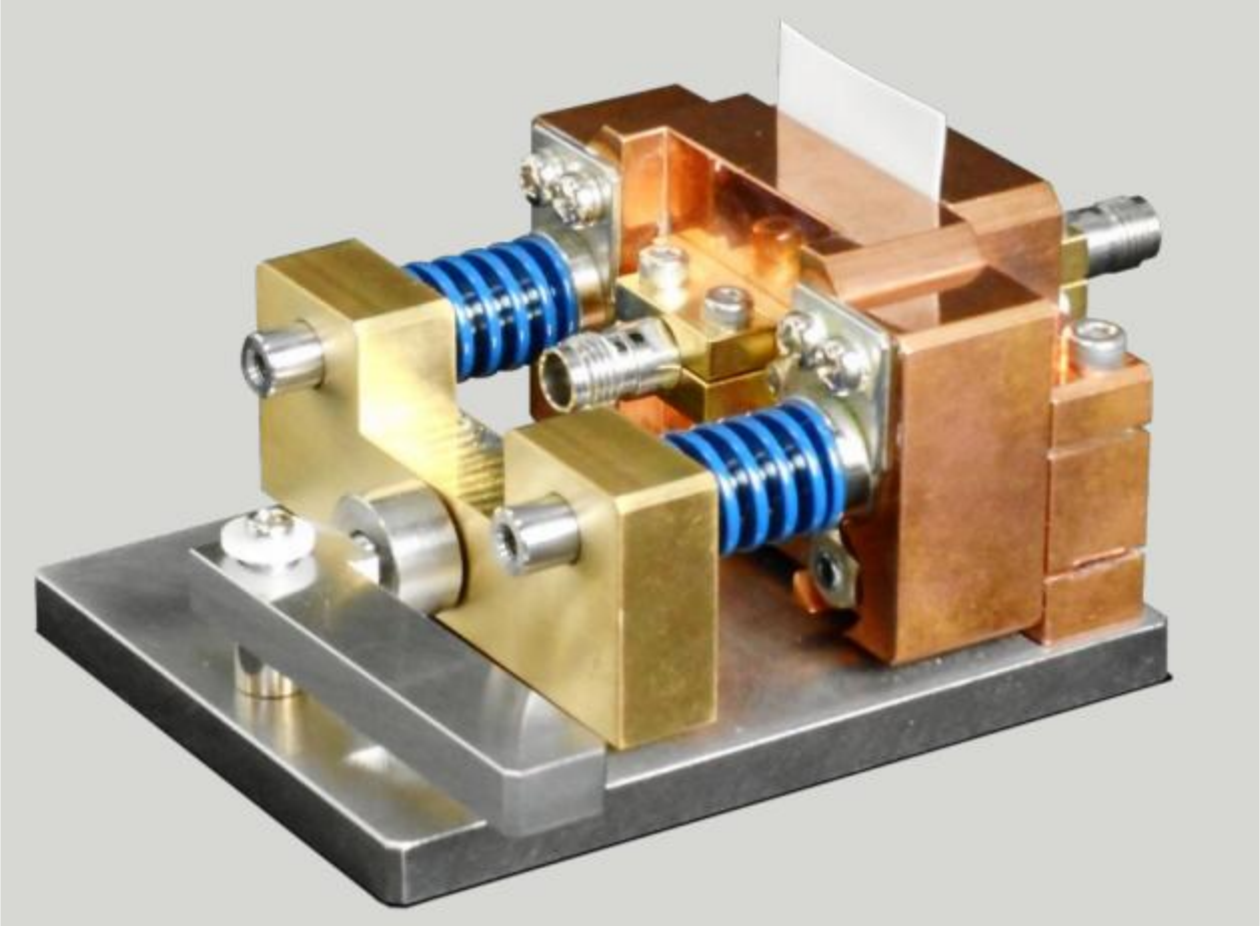


3) Resonant methods

- **N1500A – opt. 007**
  - uses newly available SCR (Split Cylinder Resonator) resonators from the Keysight N1501AKEAD-7xx series
    - nine different models from 10 GHz to 80 GHz
    - the resonator cavity is divided into two parts; a measured sample is inserted into the gap
    - the recommended maximum sample thickness is relatively small (fractions of mm) and depends on permittivity and material loss
    - the measurement cycle is very short and the results are repeatable

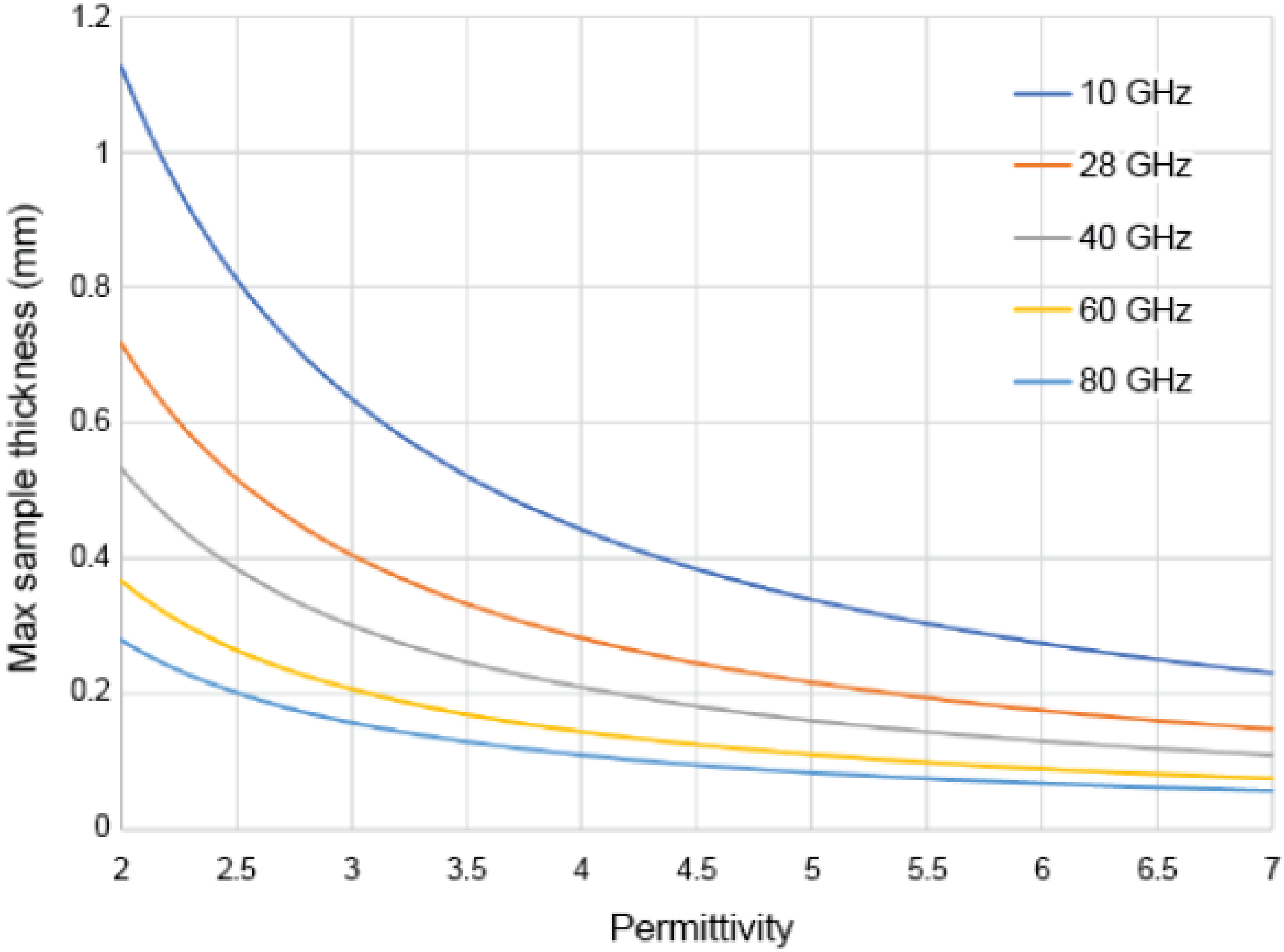
3) Resonant methods

- N1501AKEAD-7xx SCR:



3) Resonant methods

- N1501AKEAD-7xx SCR – recommended maximum sample thickness:

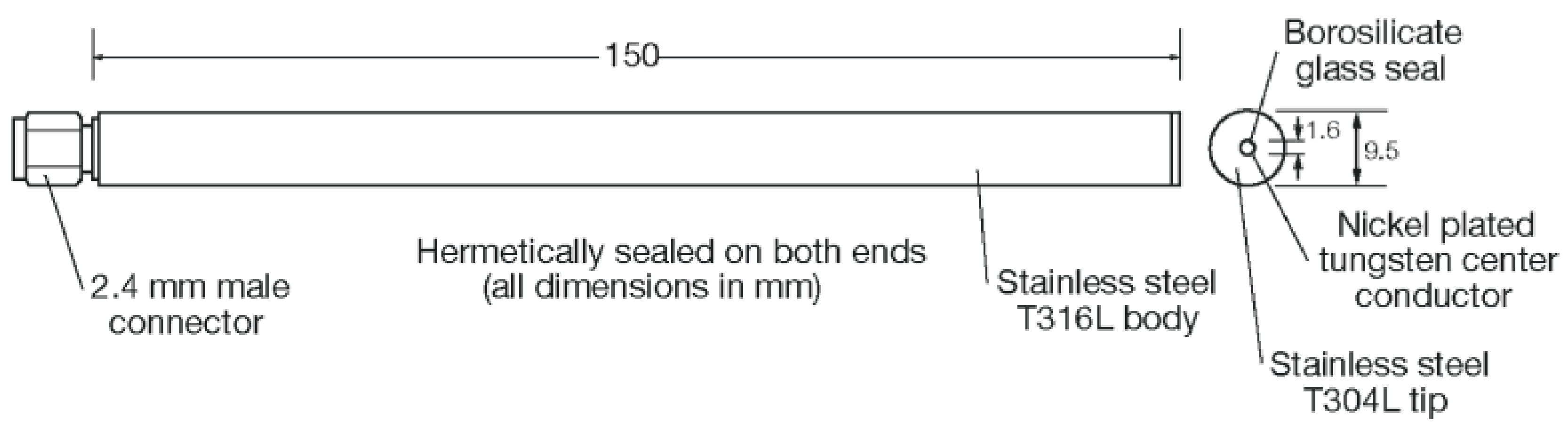


4) measurement with a coaxial probe

- **N1500A – opt. 004**
- measuring method suitable for measuring the dielectric parameters of liquids and semi-solids
  - also applicable (to a certain extent) for flat solid materials
- the probe is in a form of a sealed open end of a coaxial line
  - the space between the center and the outer conductor is filled with glass and hermetically sealed
- only for dielectric materials; basic accuracy of 5 % to 10 %
- Keysight offers three N1501A coaxial probes that differ in the frequency range and in the intended application

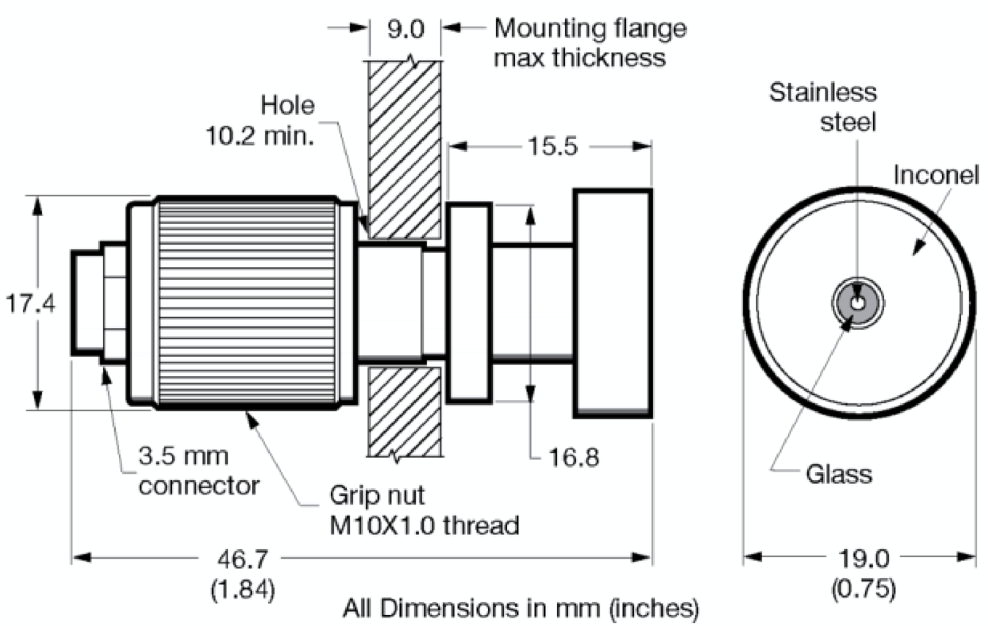
4) measurement with a coaxial probe

- **N1501A-104** – „performance“ probe
  - 2.4mm connector – 500 MHz to 50 GHz
  - wide temperature range from -40 °C up to +200 °C
  - rugged probe for the most demanding applications
  - relatively thin – can be inserted in tight places



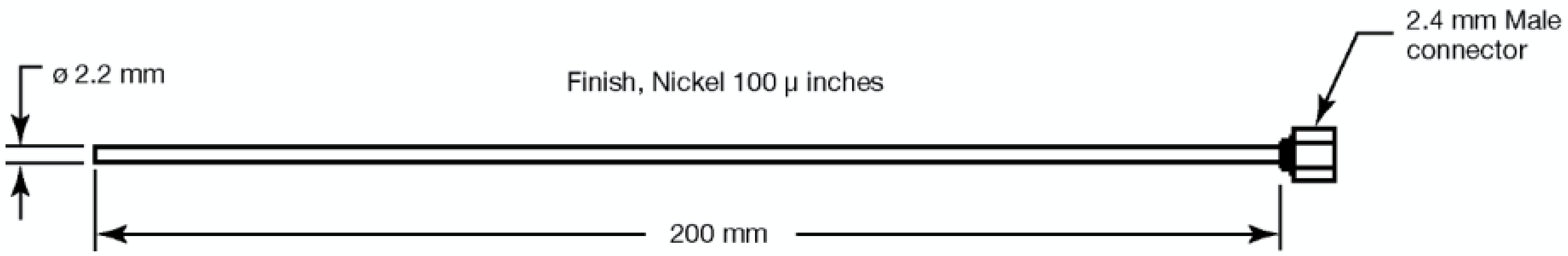
4) measurement with a coaxial probe

- **N1501A-101** – high-temperature probe
  - 3.5mm connector – 200 MHz to 20 GHz
  - temperature range from od -40 °C to +200 °C
  - larger measurement aperture compared to other probe models
    - relatively good even for solid materials (good contact with the surface)
    - larger measured sample volume



4) measurement with a coaxial probe

- **N1501A-102** – “slim form” probe
  - 2.4mm connector – 500 MHz až 50 GHz
  - very thin with just 2,2 mm in diameter
  - usable only with liquids and semi-solid materials
  - relatively low price (supplied in a set of three pieces) – can be also used for one-time applications like casting into the tested material



4) measurement with a coaxial probe

	Performance Probe	Slim Form Probe	High Temperature Probe
Frequency Range (nominal)	500 MHz to 50 GHz	500 MHz to 50 GHz	200 MHz to 20 GHz with network analyzer
	Maximum limited by MUT properties $f_{max} < \frac{\lvert 285-125j \rvert}{\sqrt{\lvert \varepsilon_r^* \rvert}}$ GHz where *j* indicates a complex value	Maximum limited by MUT properties $f_{max} < \frac{\lvert 285-125j \rvert}{\sqrt{\lvert \varepsilon_r^* \rvert}}$ GHz where *j* indicates a complex value	10 MHz to 3 GHz with E4991A/E4991B Impedance analyzer with option 10. Maximum limited by MUT properties $< \frac{100\ \text{GHz}}{\sqrt{\lvert \varepsilon_r^* \rvert}}$
Temperature range	–40 to +200 °C	0 to +125 °C	–40 to +200 °C
Temperature slew rate	< 10 degrees/minute	< 10 degrees/minute	< 10 degrees/minute
Immersable length (approximate)	140 mm	200 mm	35 mm
Connector	2.4 mm male	2.4 mm male	3.5 mm male
Sample size (requirements)	Minimum 5 mm insertion and 1 mm around tip of probe	Minimum 5 mm insertion and 5 mm around tip of probe	Diameter: > 20 mm Thickness: $> \frac{20}{(\sqrt{\lvert \varepsilon_r^* \rvert})}$ mm Granule size [4]: < 0.3 mm

4) measurement with a coaxial probe

- calibration is performed at the end of the coaxial probe using these standards: open (air), short (using the supplied shorting device) and some precisely defined material (most often water)
- it is possible to insert an electronic calibration kit between the VNA and the probe, enabling automatic calibration refresh

5) „parallel plate/inductance“

- **N1500A – opt. 006 (do 120 MHz) and 005 (do 1 GHz)**
- relatively low-frequency measuring methods using LCR meters or impedance analyzers (bridge or RF-IV)
- calculation of permittivity from the measured capacitance in a precision measuring plate capacitor
- calculation of permeability from the measured inductance in a fixture forming a current loop around the measured sample
- compared to high-frequency methods, these are significantly more accurate

5) „parallel plate/inductance“

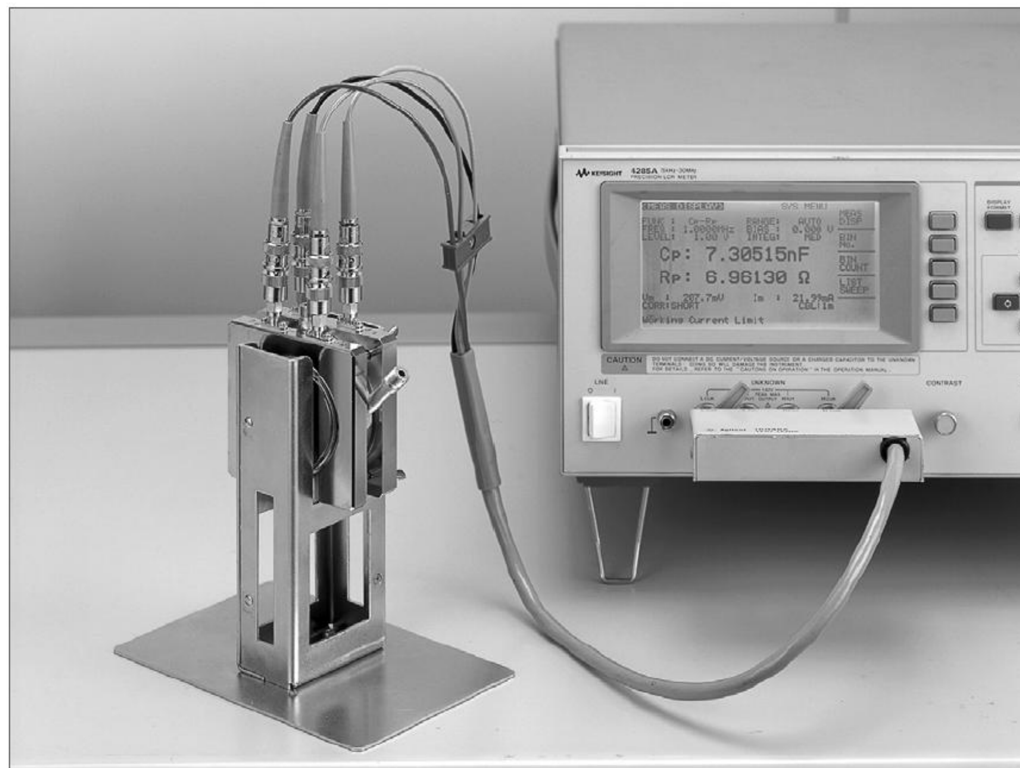
- 16451B dielectric fixture
  - frequency up to 30 MHz; 4TP connection
  - four interchangeable electrodes for different sample sizes and contacting methods (with or without the thin film electrode)
  - guard electrode - eliminates the influence of stray capacitances

5) „parallel plate/inductance“

- 16453A dielectric fixture
  - from 1 MHz to 1 GHz; can be used with the E4991B
  - open, short and load compensation
  - temperature range from -55 °C to +150 °C

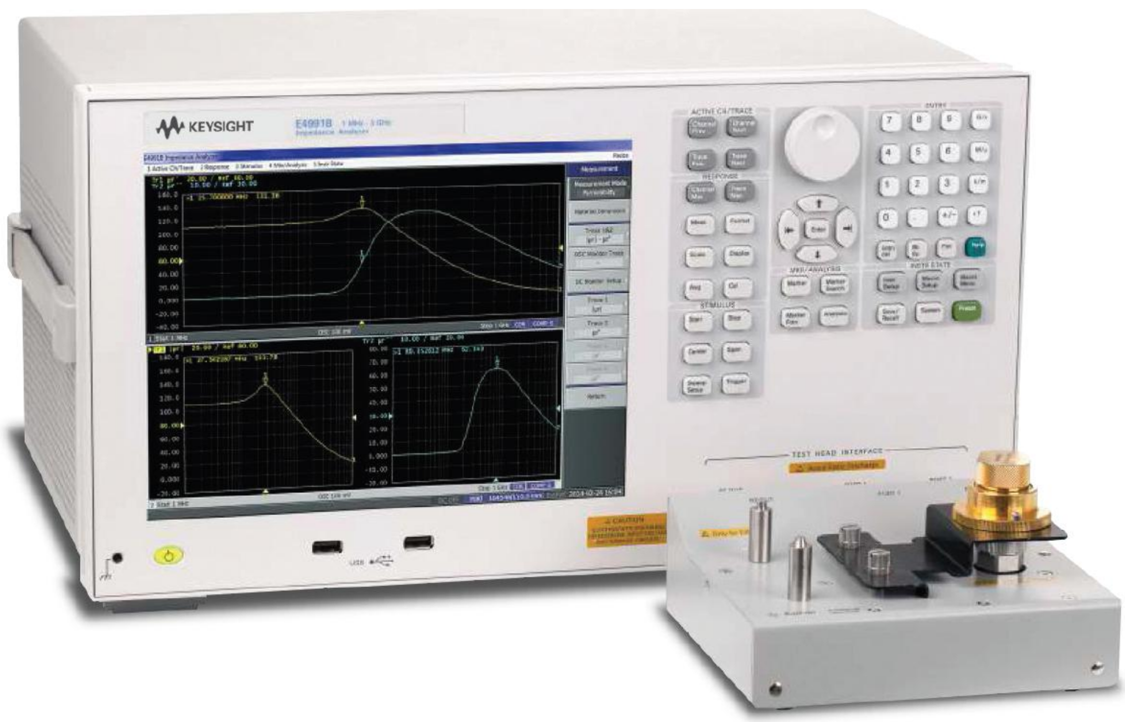
5) „parallel plate/inductance“

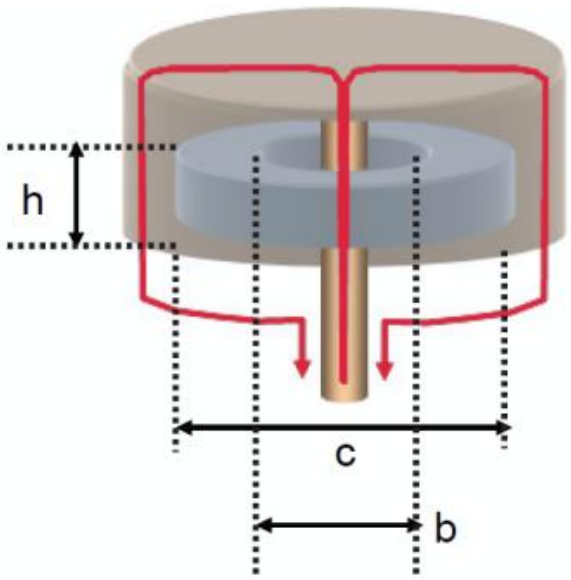
- 16452A fixture
  - can be used for permitivity measurements of liquids or semi-liquids
  - up to 30 MHz; 4TP (four BNCs) connection
  - small volume of the measured liquid



5) „parallel plate/inductance“

- 16454A fixture
  - magnetic fixture for permeability measurements
  - frequency range from 1 kHz to 1 GHz; APC-7 connection
  - toroidal solid samples; two different sizes
  - temperature range from -55 °C to +150 °C





Low/high temperature measurements

- specialized material measurement systems for temperature characterisation exist - the sample area can be heated or cooled to the desired temperature
- these systems most often use the parallel plate or magnetic fixture method
- simpler systems can only heat the sample (from ambient temperature up), more advanced systems allow cooling
  - cooling can utilize Peltier modules or liquid nitrogen

Low/high temperature measurements

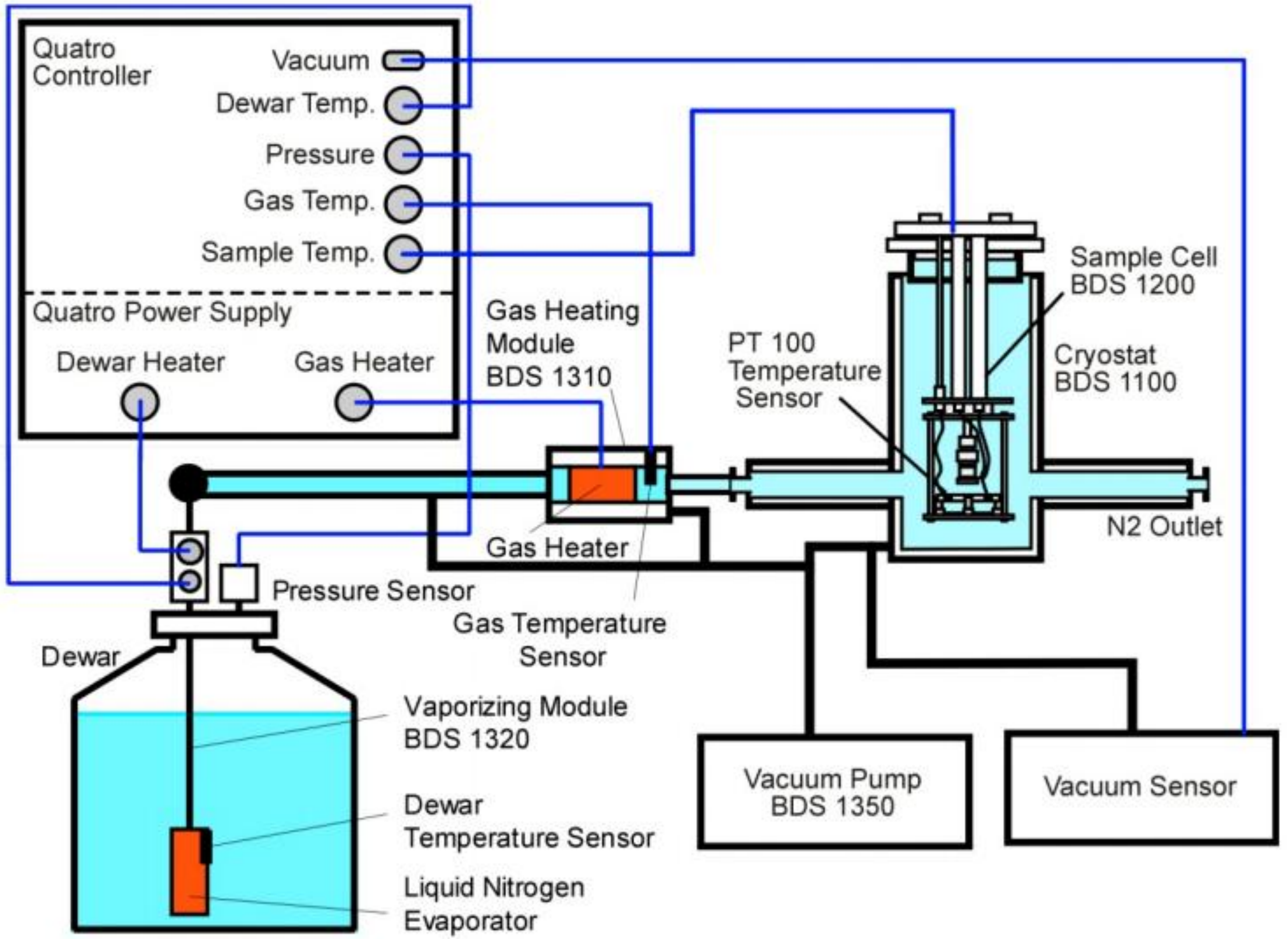
- Novocontrol offers an extensive range of systems for thermal characterization (and also general imp. measurements):

  1) „Quatro Cryosystem“

    - heating and cooling – widest range from -160 °C to +400 °C
    - 0,01 °C temperature stability
    - temperature ramps from 0,01 °C/min to 20 °C/min
    - usable for both low and high frequency measurements (in combination with the RF I/U E4991B analyzer)
    - can be used even without the liquid nitrogen if the cooling is not needed (with compressed air or nitrogen)

Low/high temperature measurements

- „Quatro Cryosystem“ – block diagram:



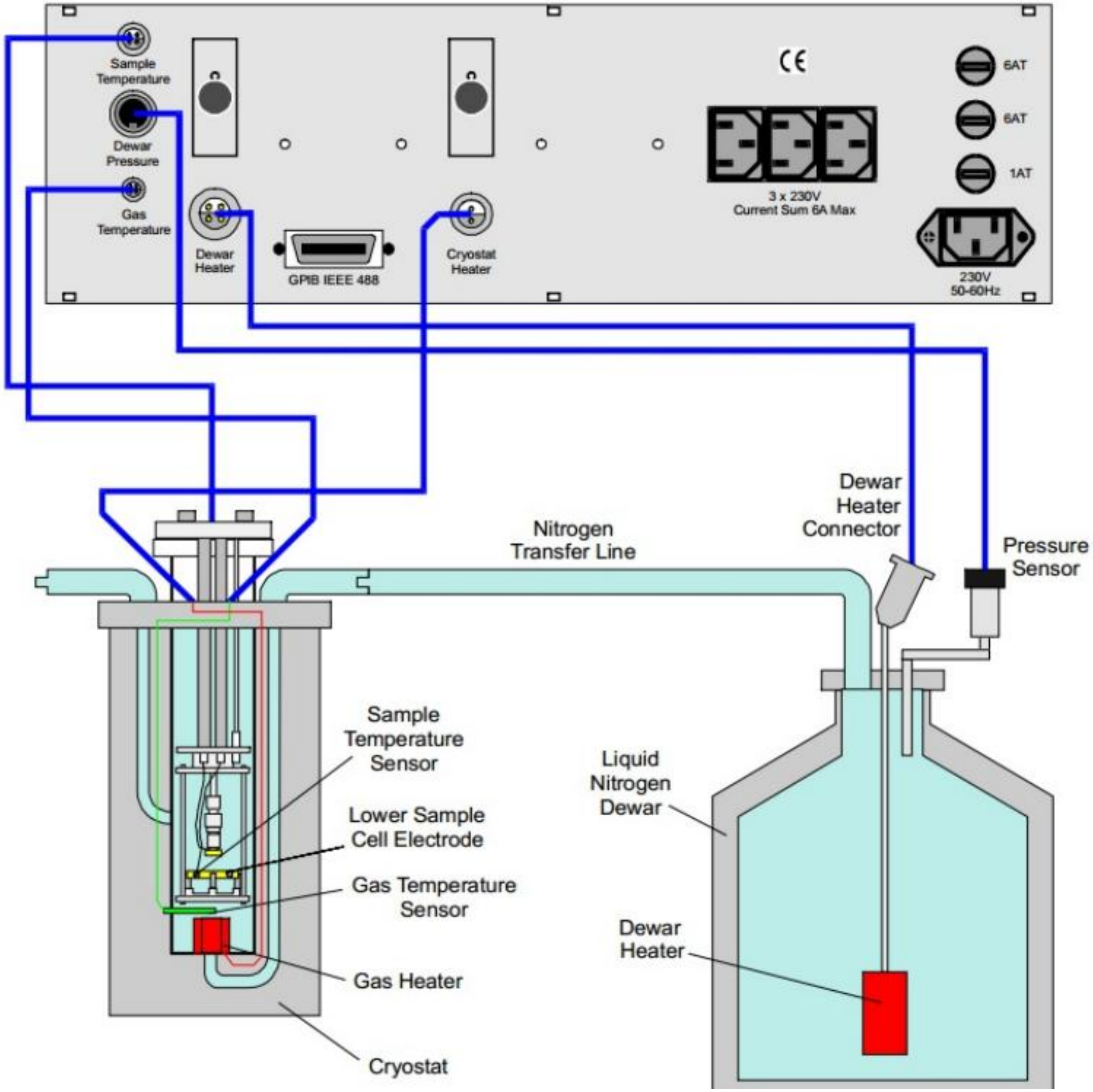
Low/high temperature measurements

2) „Novocool“

- simpler and cheaper system
- heating and cooling – from -100 °C to +250 °C
- 0,1 °C temperature stability
- temperature ramps from 0,1 °C/min to 20 °C/min
- can be used with multiple different fixtures and analyzers for both low and high frequency measurements

Low/high temperature measurements

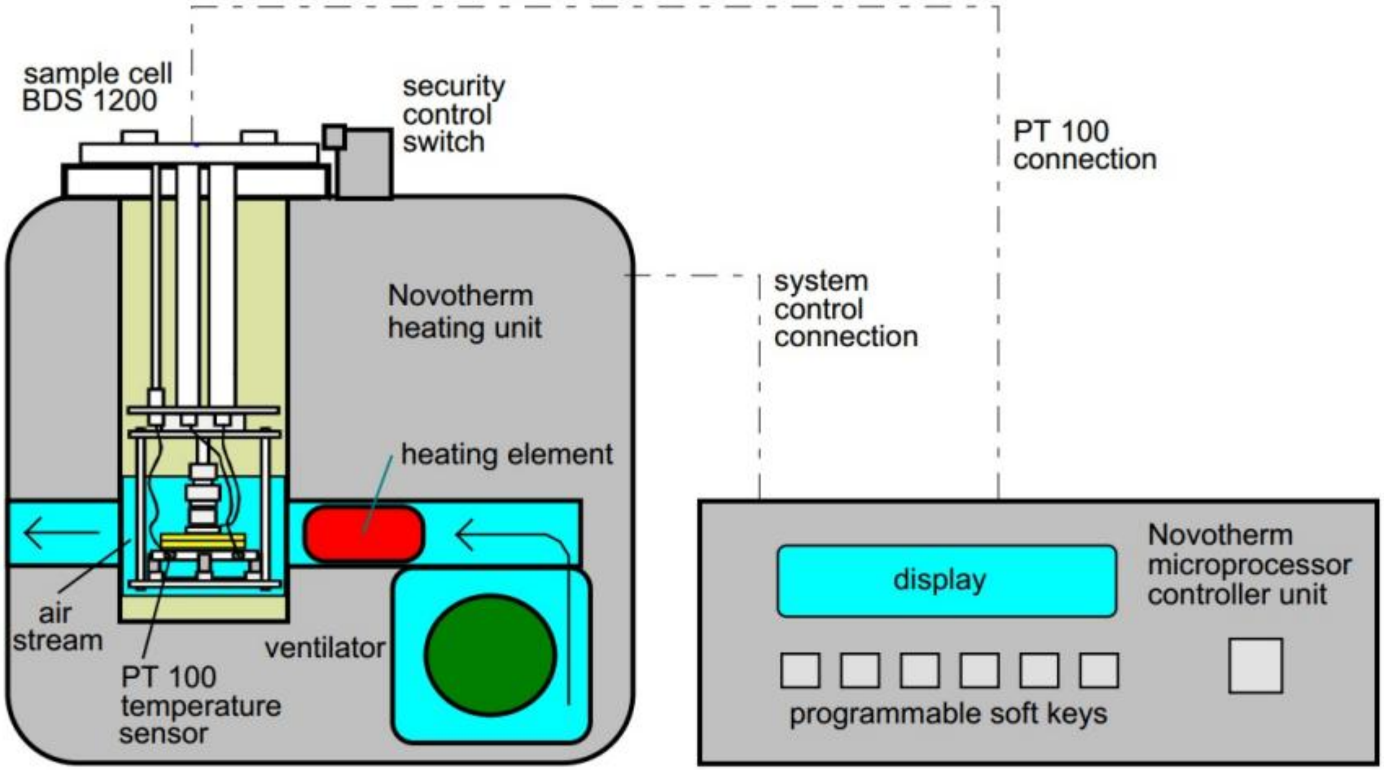
- „Novocool“ – block diagram:



Low/high temperature measurements

3) „Novotherm“

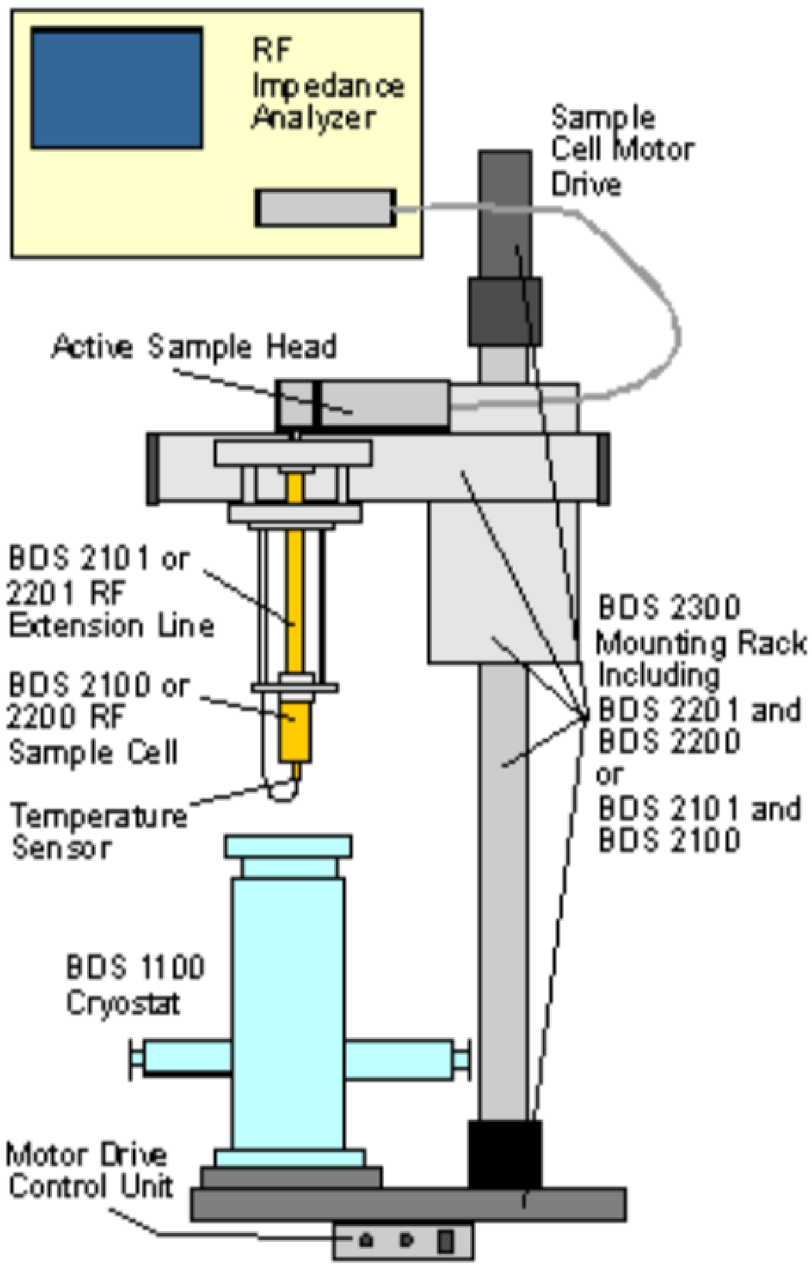
- cheapest system which can be used for RF measurements
- heating only – from ambient up to +400 °C
- 0,1 °C stability; ramps from 0,01 °C/min to 20 °C/min

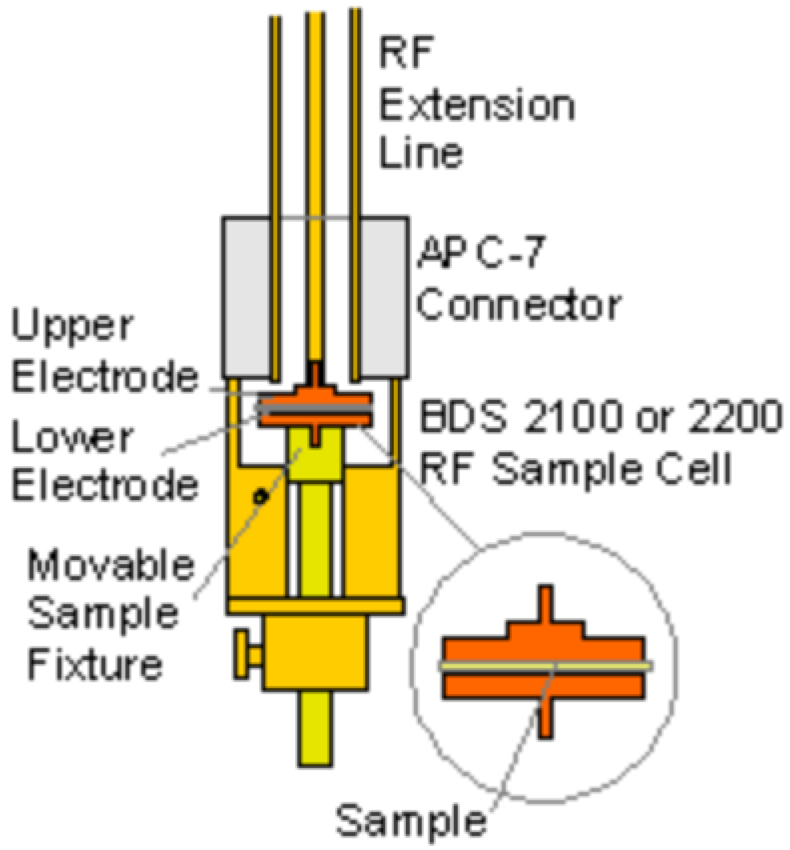


Low/high temperature measurements

- high frequency measurements are possible with the optional RF extension, which includes:
  - RF fixture (parallel plate)
  - extension coaxial line between the fixture and the E4991B's remote head
  - motorised holder allowing sensitive insertion of the fixture into the cryostat (the assembly is otherwise susceptible to mechanical damage)

Low/high temperature measurements





Thank you for your attention !