Measurement of properties of electronic components

Agenda

9:15	start of the seminar
9:30	impedance - basics
10:00	impedance measurement – methods, instruments, …
11:45	lunch break
12:45	DC components characterisation
13:15	measurement of material properties
14:30	discussion
15:00	end of the seminar

Impedance

- very important parameter used to characterize electrical circuits, components and materials
- impedance is defined as a measure of the total opposition to the flowing alternating current
- complex value
  - can be expressed in a form of a real and imaginary part…
  - … or as an absolute value and phase angle
  - the real part represents the energy losses and the imaginary part the energy stored in the given circuit

Impedance

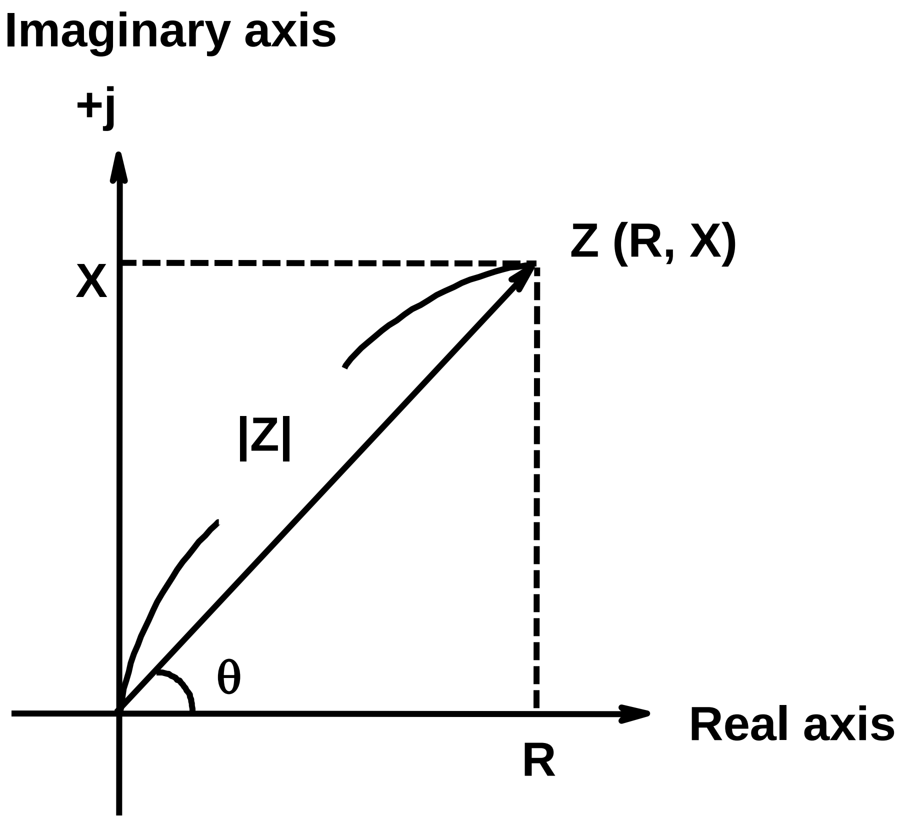
- **impedance**:

$$\vec{Z} = \frac{\vec{U}}{\vec{I}} = R + jX \quad (\Omega)$$ (resistance / reactance)

- reciprocal value is **admitance:**

$$\vec{Y} = \frac{1}{\vec{Z}} = \frac{\vec{I}}{\vec{U}} = G + jB \quad (S)$$ (conductance / susceptance)

Impedance



$$Z = R + jX = |Z|\angle \theta$$

$$R = |Z| \cos \theta$$
$$X = |Z| \sin \theta$$

$$|Z| = \sqrt{R^2 + X^2}$$

$$\theta = \tan^{-1} (X/R)$$

Quality factor / dissipation factor

- quality factor Q can be used to evaluate the „purity“ of reactive components (inductors and capacitors)
  - the ratio between the energy stored in a given component and the energy transformed into heat
  - dissipation factor „D“ is reciprocal of the Q

$$Q = \frac{1}{D} = \frac{1}{\tan\delta} = \frac{X_L}{R} = \frac{-X_C}{R} = \frac{-B_L}{G} = \frac{B_C}{G}$$

Impedance – basic circuit components

- resistor (implements electrical resistance **R**)

$$Z = R$$

- inductor (implements electrical inductance **L**)

$$Z = j2\pi f \cdot L = j\omega L$$

- capacitor (implements electrical capacitance **C**)

$$Z = -j\frac{1}{2\pi f \cdot C} = -j\frac{1}{\omega C}$$

Description of the components

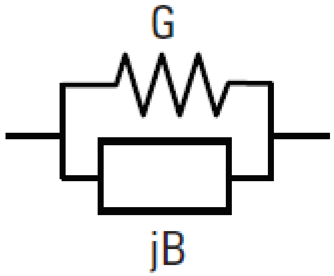
- ideal (nominal) value
  - primary value (R/L/C); omiting all parasitic properties
  - fixed value – doesn’t depend on frequency, …
- real value
  - includes the influence of all the parasitic properties
  - depends on frequency and all the external influences
- measured value
  - value indicated by the measuring instrument during component characterisation
  - real value + errors of the measurement setup

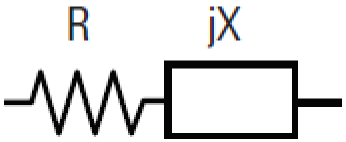
Description of the components

- ideal components do not exist; it is always necessary to take into account their real characteristics
- the influence of the parasitics always depends on the current operating point of the component (frequency, ...)
  - at low frequencies the component can be almost ideal
  - with increasing frequency, depending on the quality of the component, the characteristics deteriorate
  - the resulting properties of the component can be also (negatively) affected by the way it is used – incorrect mounting (overheating), component surroundings, …

Equivalent circuit models

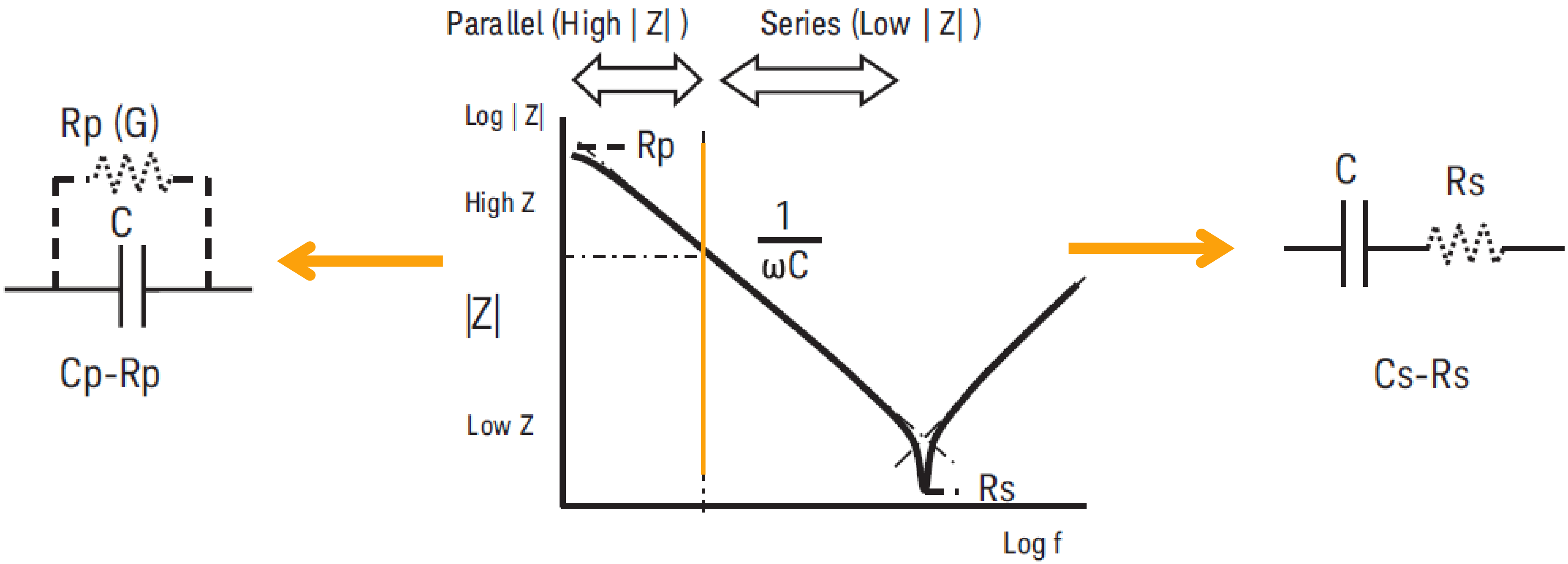
- the component can be described explicitly by measuring it's impedance in the frequency band of interrest; more common approach is to use equivalent circuit models
- **two-element** series/parallel equivalent models
  - L or C in series/parellel with an R
  - usable at low frequencies or in a narrow frequency band
  - can be derived from measurements at a single frequency



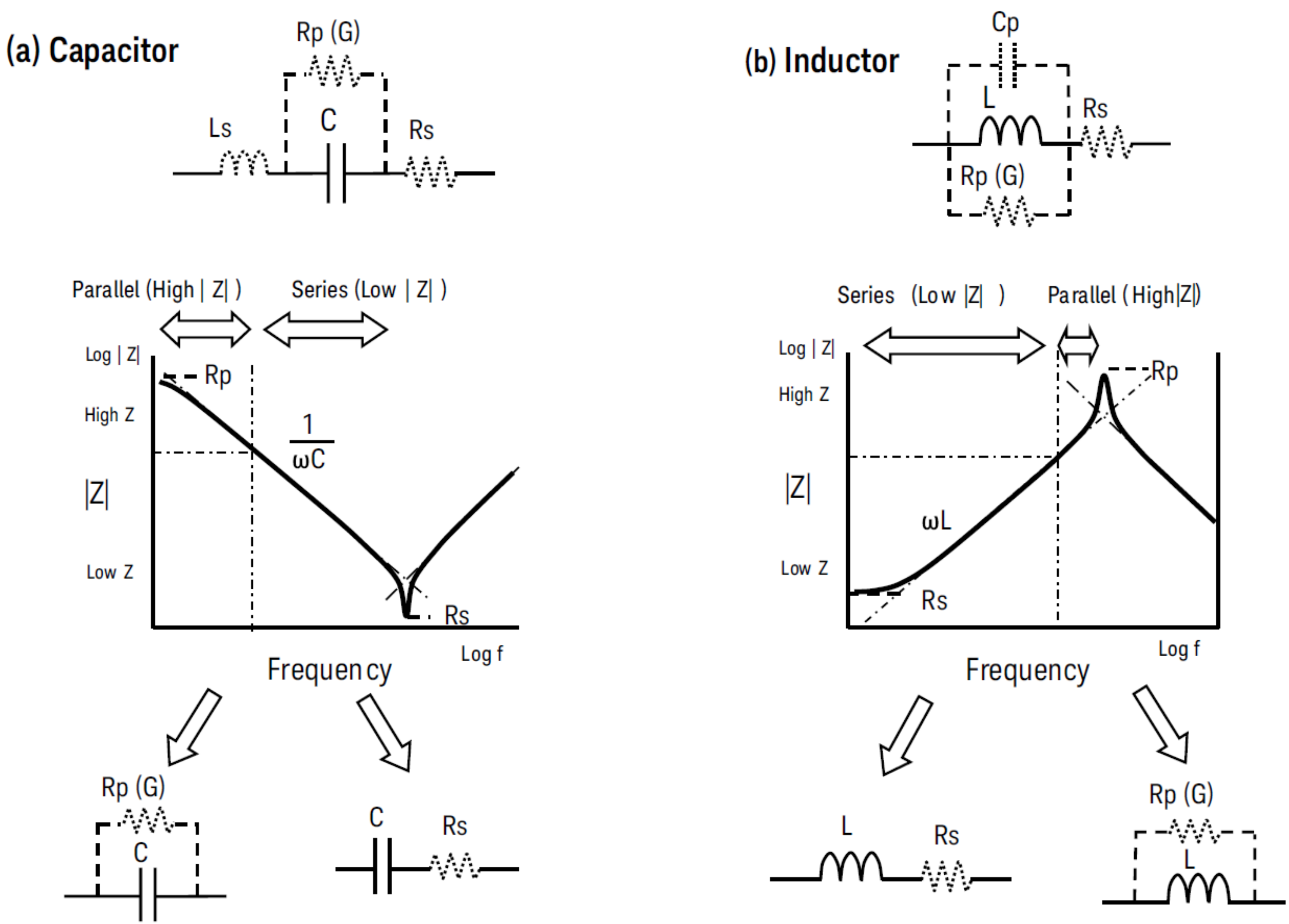


Equivalent circuit models

- the suitable model can be chosen depending on:
  - the nature of the component (inductance/capacitance)
  - the ratio between the impedances of the "main" and parasitic property of the component at a given frequency



Equivalent circuit models



Equivalent circuit models

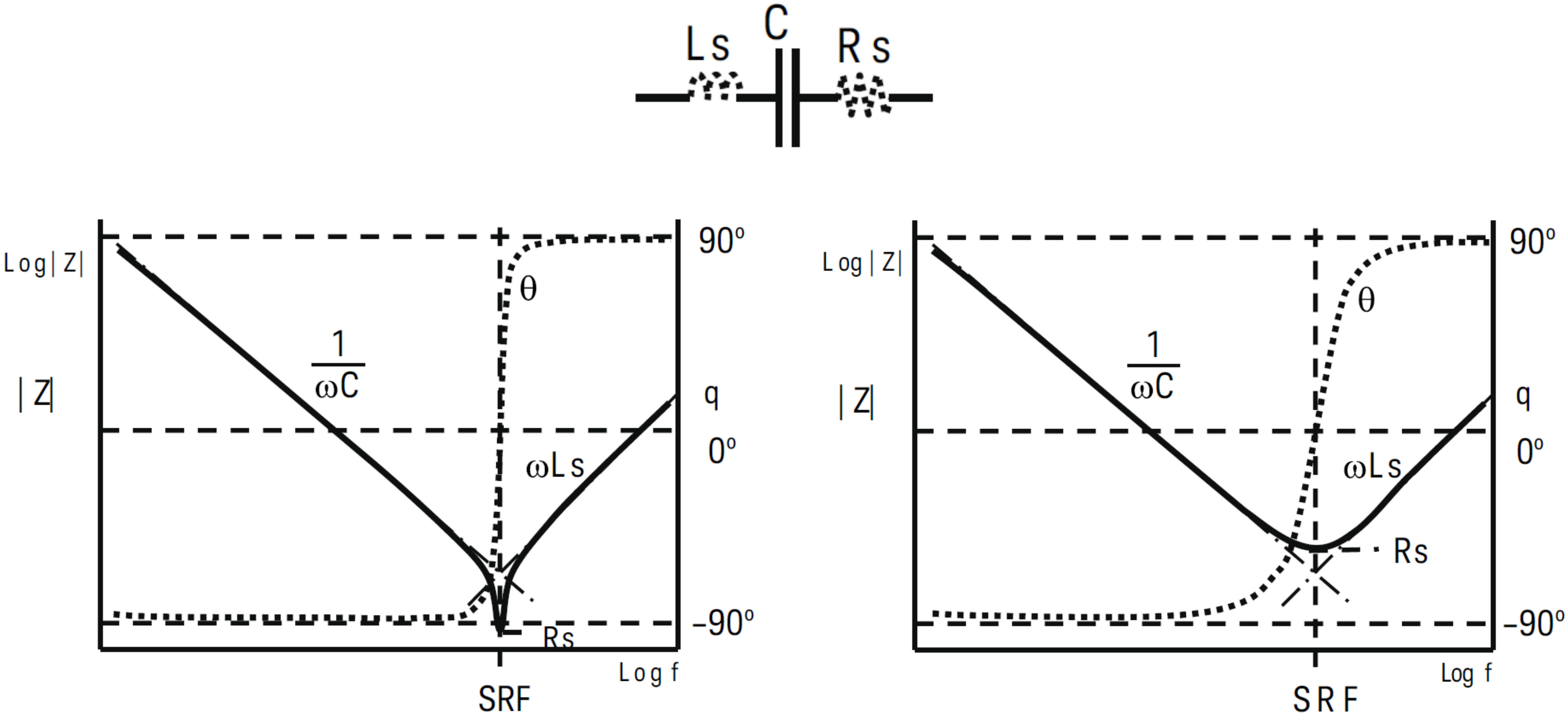
- three- a multi-element models
  - with an increasing number of model elements the component can be described more accurately and in a wider frequency band
  - modern impedance analyzers can select the model automatically
  - in order to correctly calculate the values, it is necessary to measure the impedance at multiple frequencies (frequency sweep)

Component property dependencies

1) frequency
   - frequency dependency is always present
   - it’s influence changes with the ratio between the primary value of the component and the main parasitics
   - it can be quite different depending on the design of the component (it is necessary to choose higher-quality components for high-frequency applications)

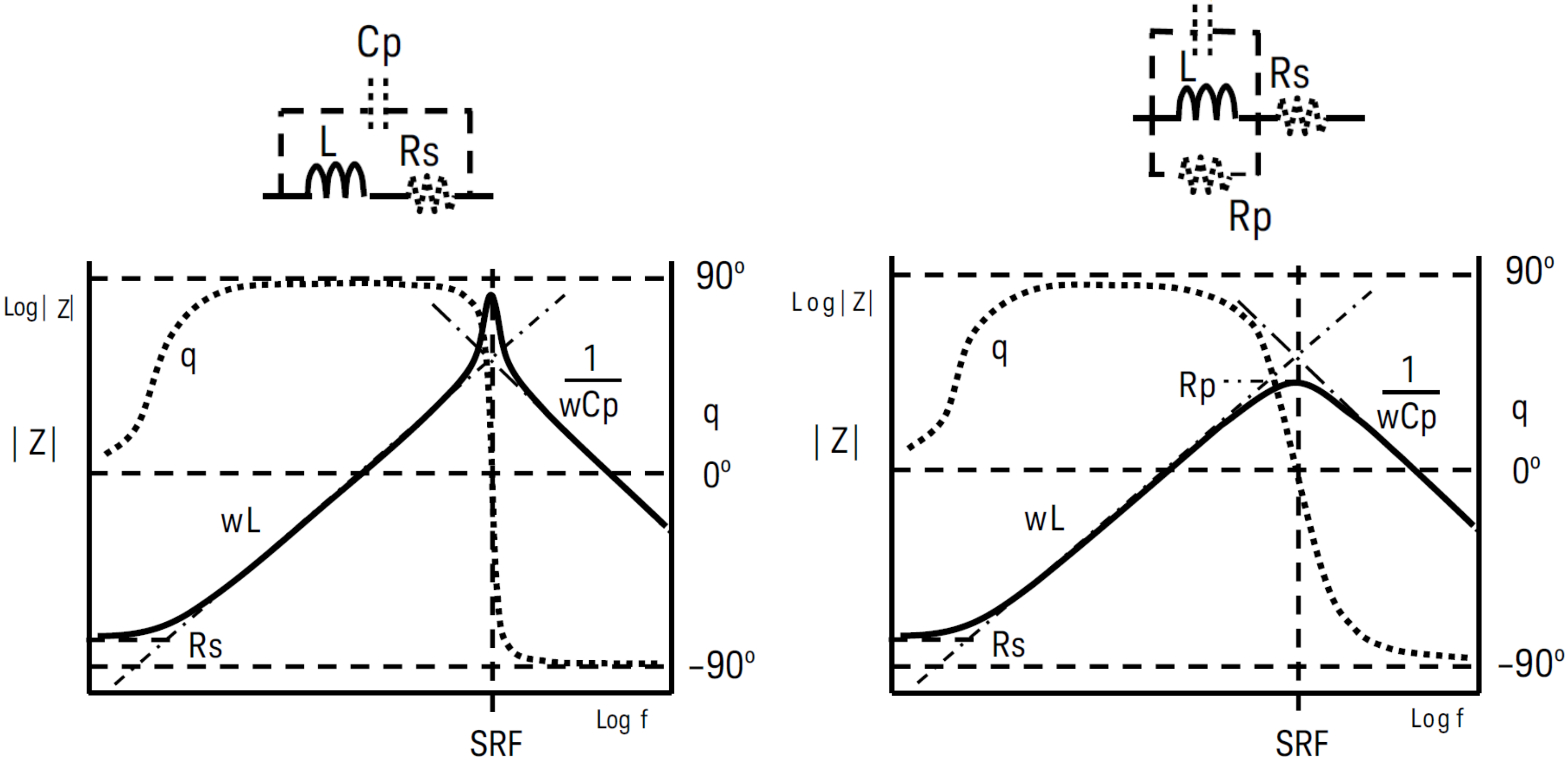
Component property dependencies

- simplified equivalent circuit of a capacitor:



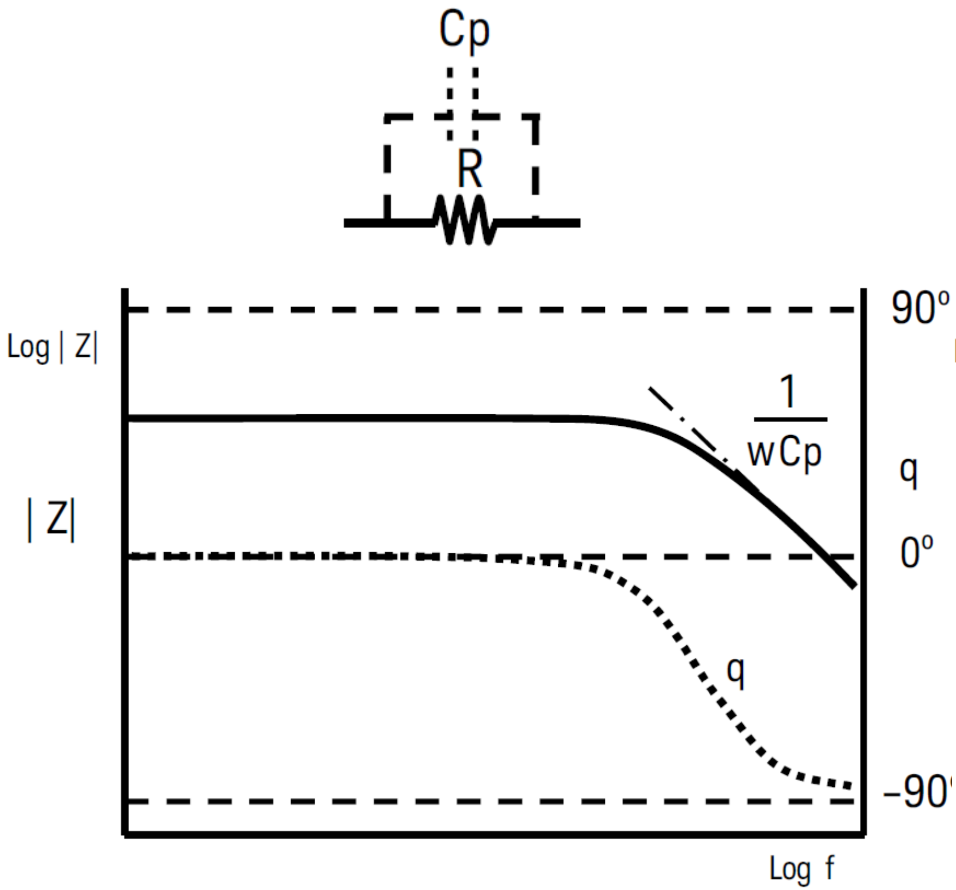
Component property dependencies

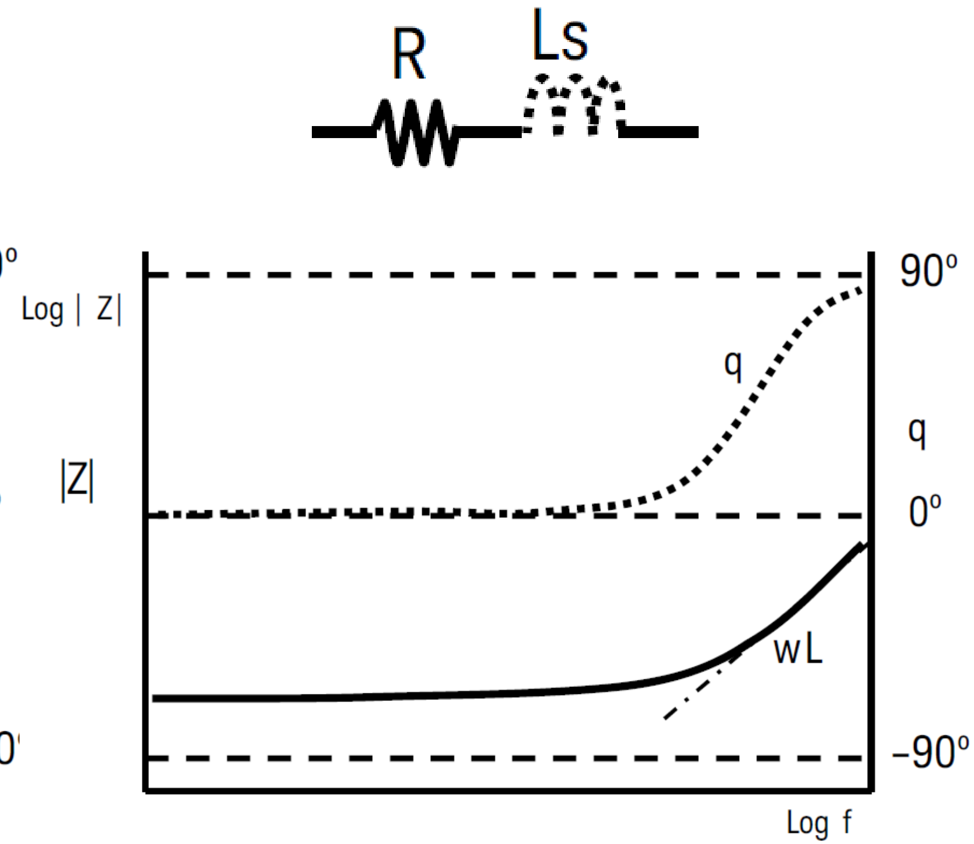
- simplified equivalent circuit of an inductor:



Component property dependencies

- simplified equivalent circuit of a resistor (large and small):





Component property dependencies

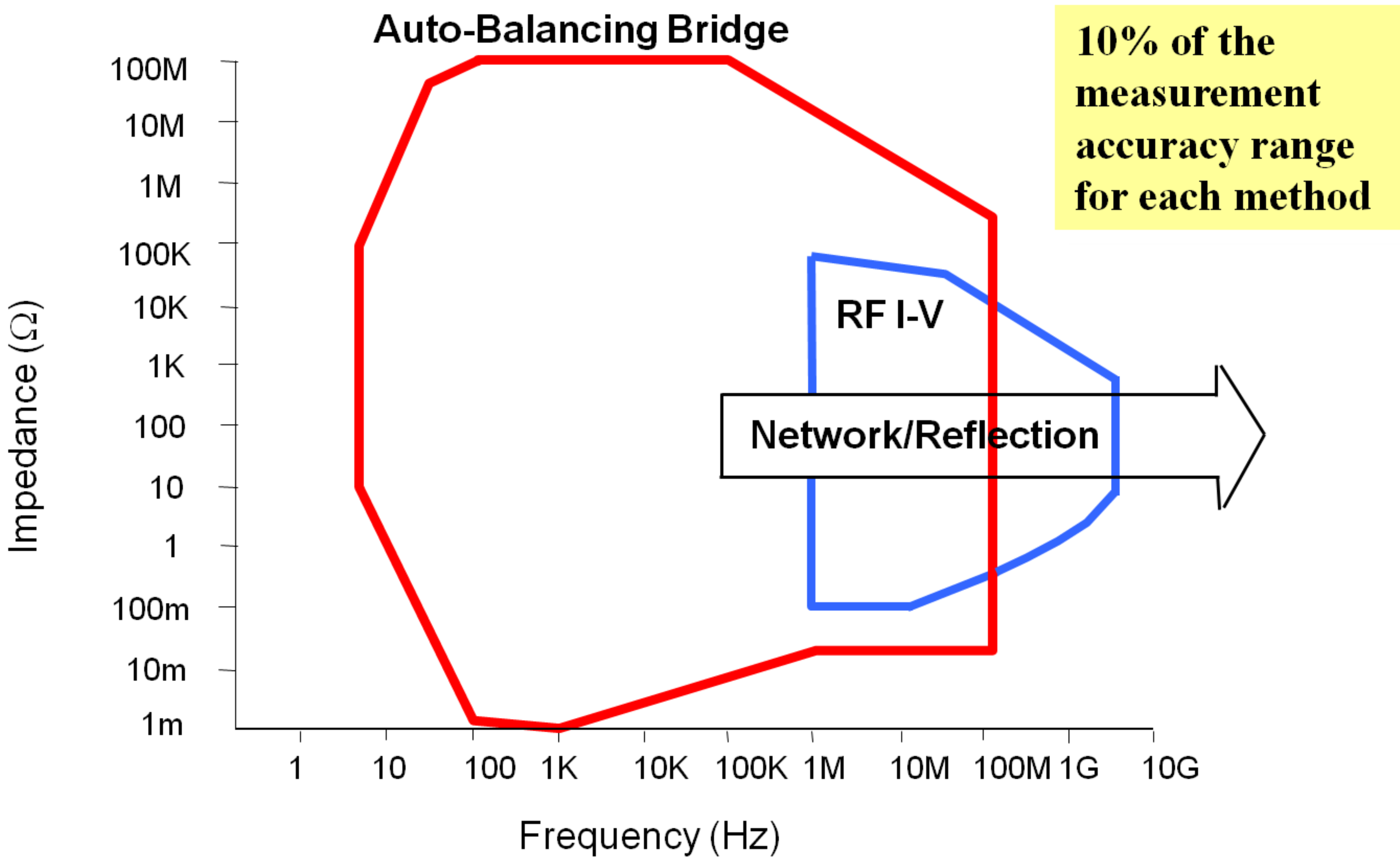
2) test signal level
   - for example with ceramic capacitors (voltage dependence) or cored inductors (current dependence)
3) DC bias
   - strong with semiconductor components - diodes, transistors
   - again ceramic capacitors or cored inductors - saturation
4) temperature
   - temperature dependence for some types of components
5) other external influences
   - humidity, magnetic field, light, time (aging), …

Measurement methods

1) self-balancing bridge
   - frequency range from 20 Hz to 120 MHz
   - high basic accuracy (0,1 %) and wide impedance range
2) RF I-V method
   - frequency range from 1 MHz to 3 GHz
   - relatively good accuracy (0,7 %) a measurement range
3) measurement using a VNA
   - frequency range from 5 Hz up
   - relatively narrow impedance measurement range
   - three different measurement configurations suitable for different impedance values

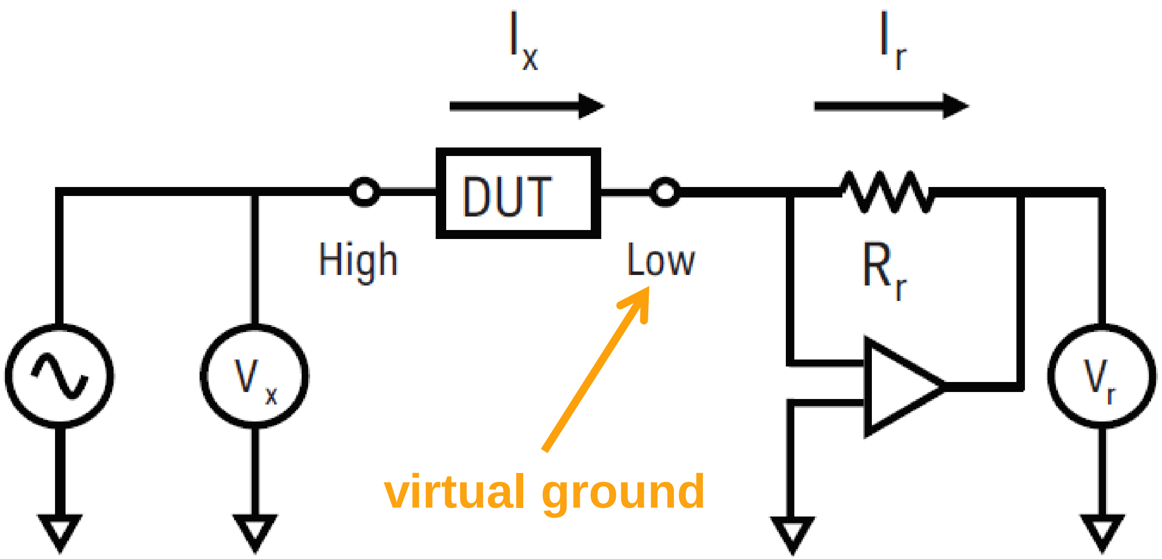
Measurement methods

- comparison of the three basic measurement methods:



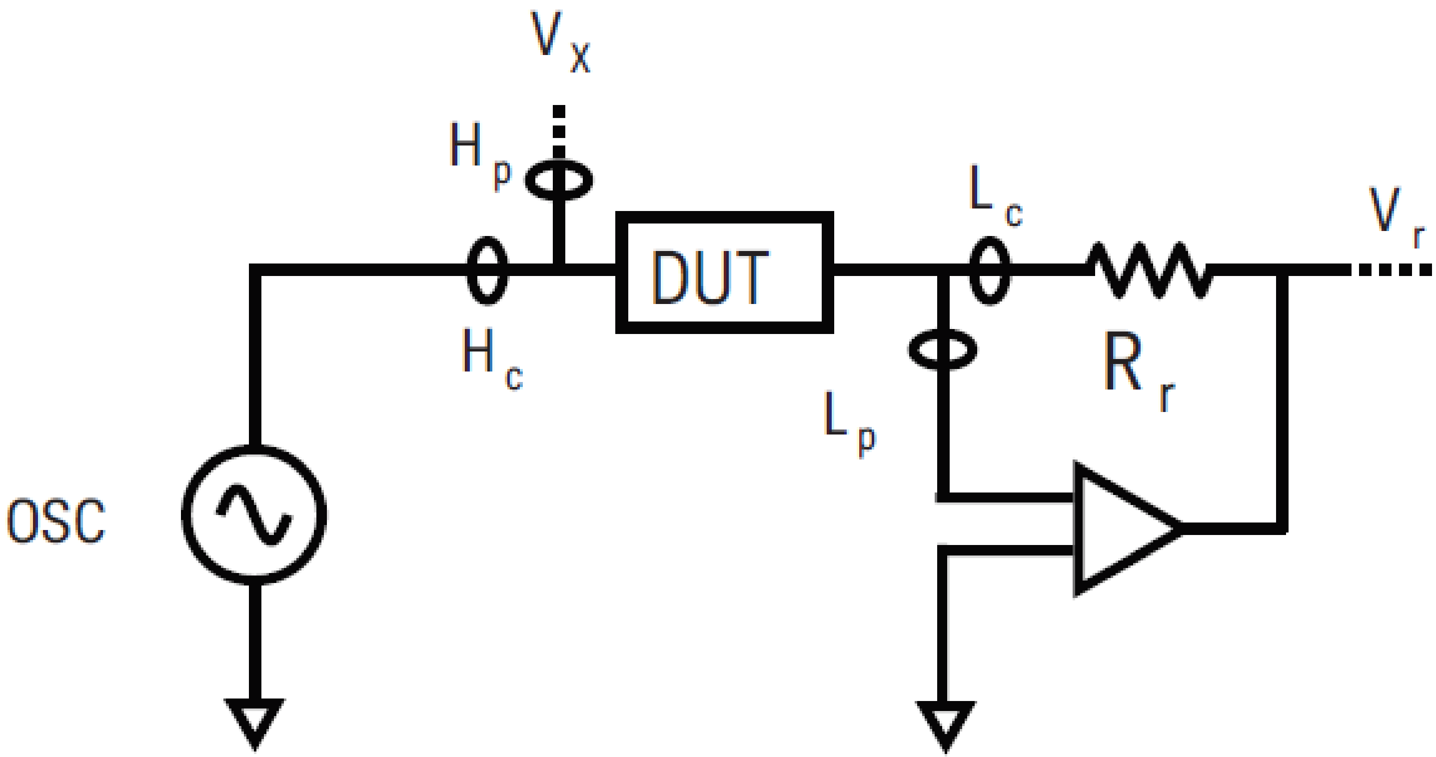
Self-balancing bridge

- bridge circuit maintains a virtual ground voltage on one of the DUT poles; current thru DUT = current thru **Rr**
- **Vx** (on the DUT) and **Vr** (on the **Rr**) are measured using a single switchable vector volt meter
- current flowing through the DUT can be calculated from known **Rr** and measured **Vr**



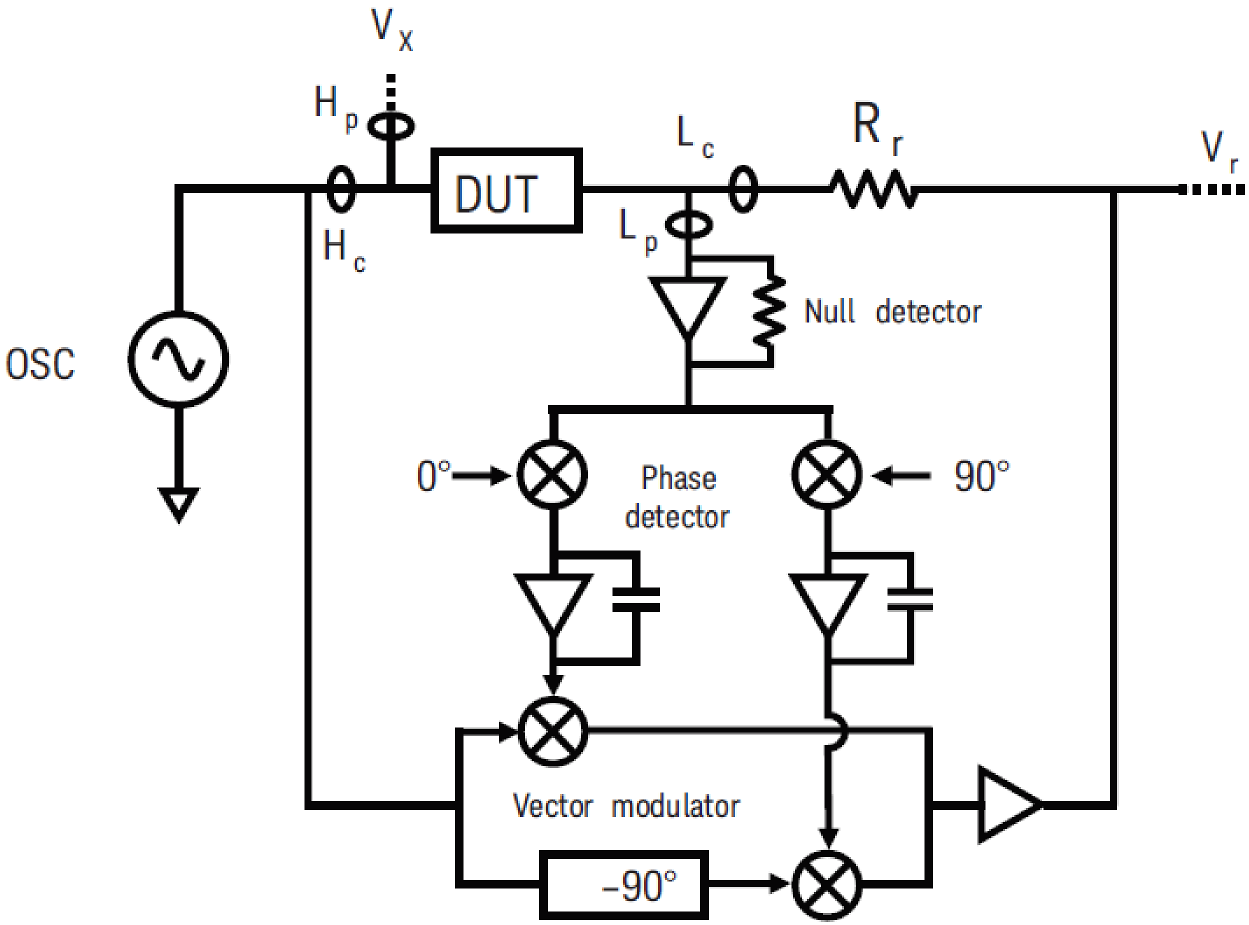
Self-balancing bridge

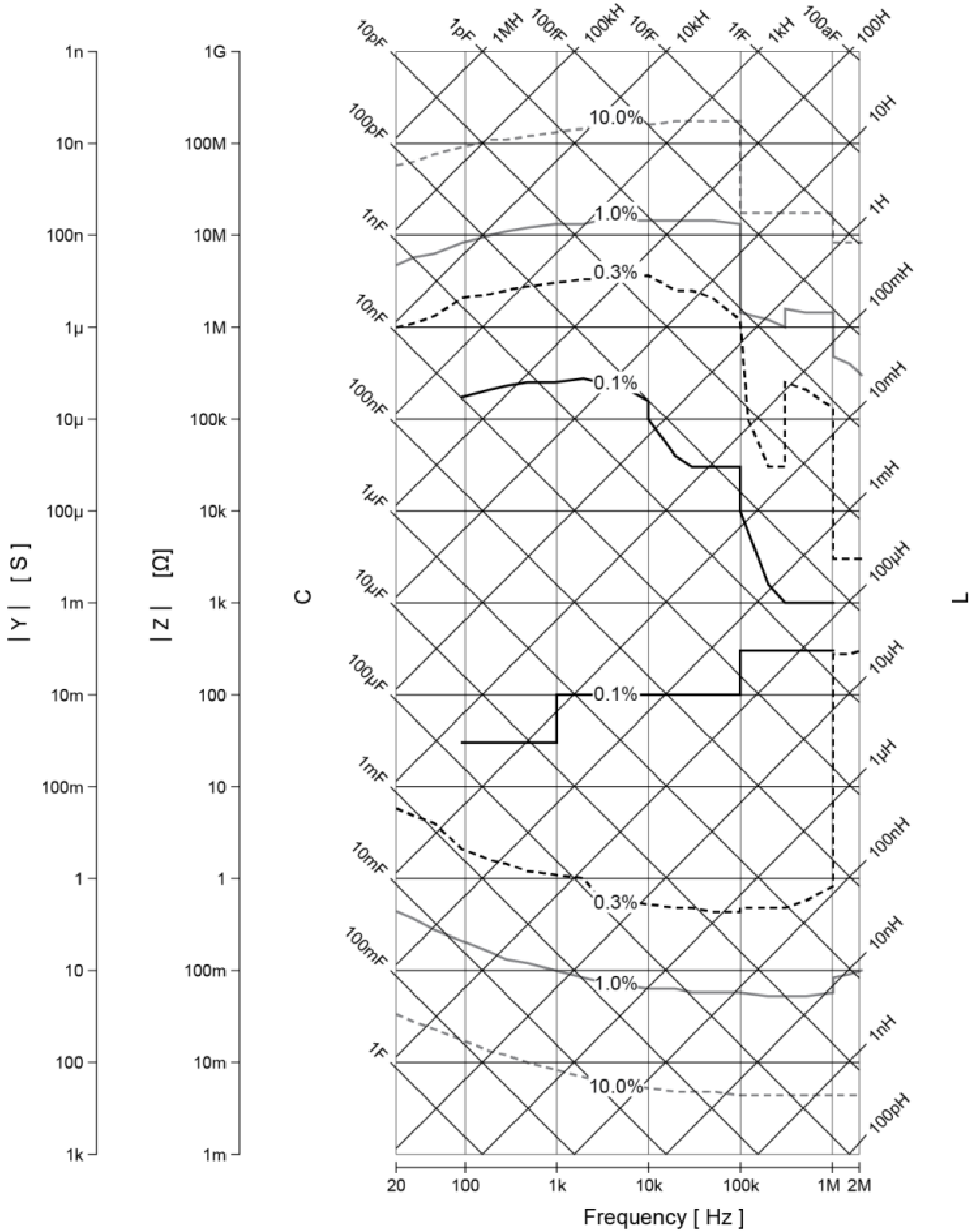
- simplified circuit diagram for low frequency instruments (~ hundreds of kHz):



Self-balancing bridge

- high frequency instruments (> hundreds kHz):

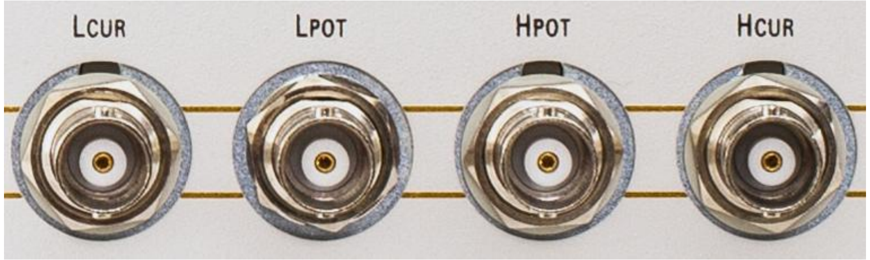




|Y| [S]
1n
10n
100n
1µ
10µ
100µ
1m
10m
100m
1
10
100
1k
|Z| [Ω]
1G
100M
10M
1M
100k
10k
1k
100
10
1
100m
10m
1m
C
10pF
100pF
1nF
10nF
100nF
1µF
10µF
100µF
1mF
10mF
100mF
1F
1pF
100fF
10fF
1fF
100aF
L
1MH
100kH
10kH
1kH
100H
10H
1H
100mH
10mH
1mH
100µH
10µH
1µH
100nH
10nH
1nH
100pH
10.0%
1.0%
0.3%
0.1%
0.1%
0.3%
1.0%
10.0%
20
100
1k
10k
100k
1M
2M
Frequency [Hz]

DUT terminal

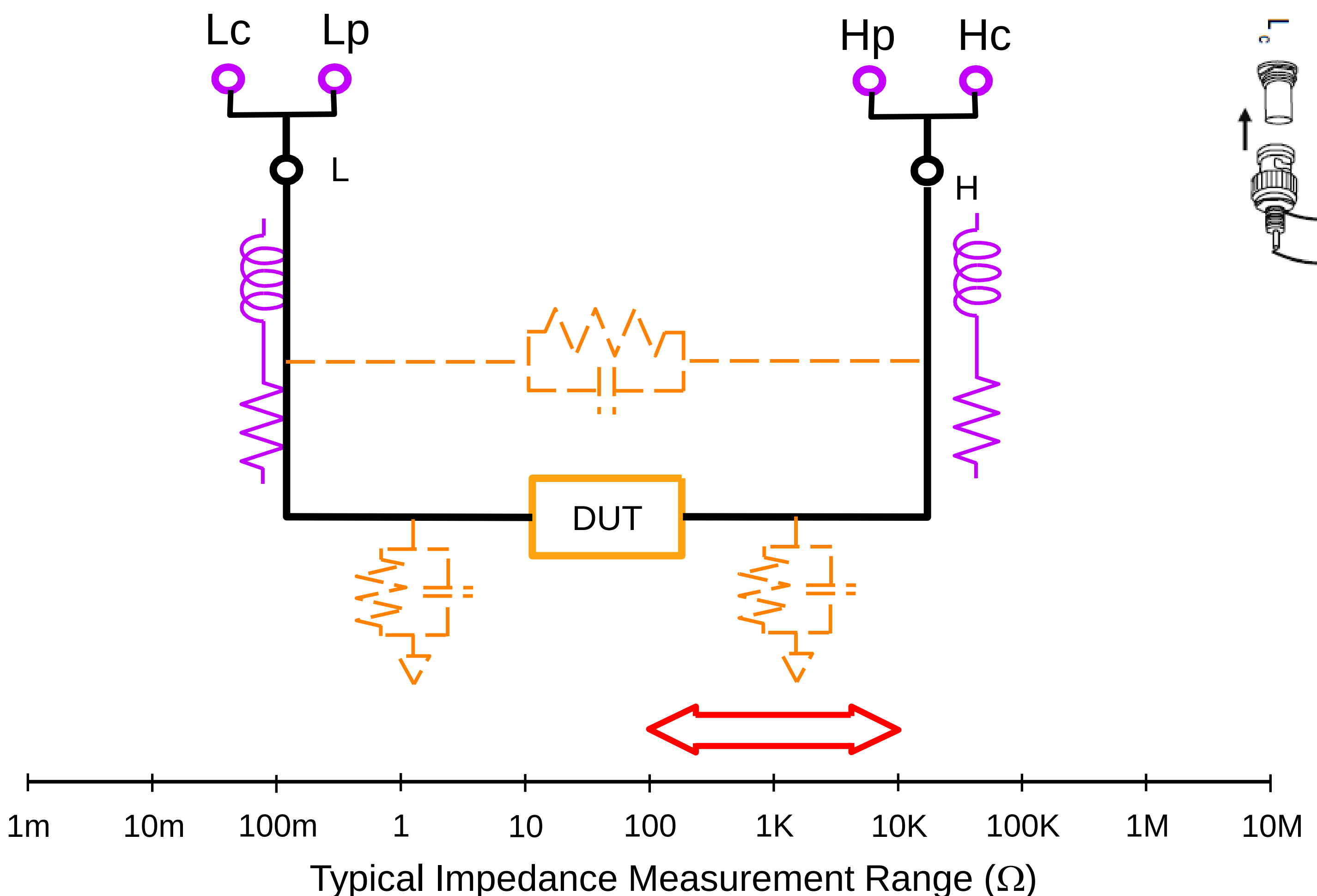
- measuring terminal consists of four BNC connectors
  - two potential and two current terminals; the outer conductors represent a common measuring ground (guard)
  - measurement reference plane

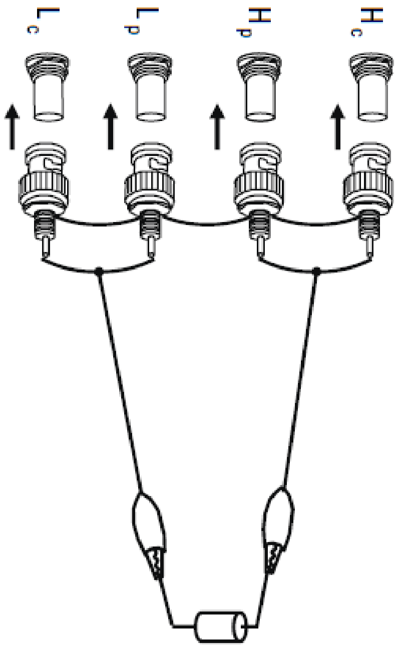


- many BNC measuring fixtures available
  - can be connected directly to the instrument (recommended)
  - or using an extension leads (typically 1, 2 or 4 m long)

Two-terminal configuration (2T)

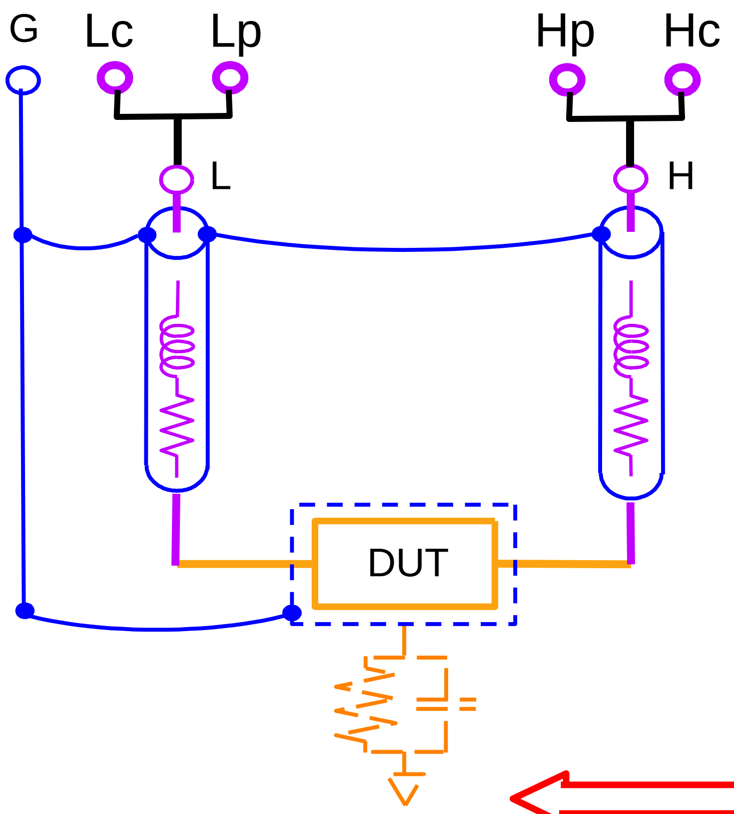
- simplest method, usable up to higher frequencies
- many error sources, limited measurement range

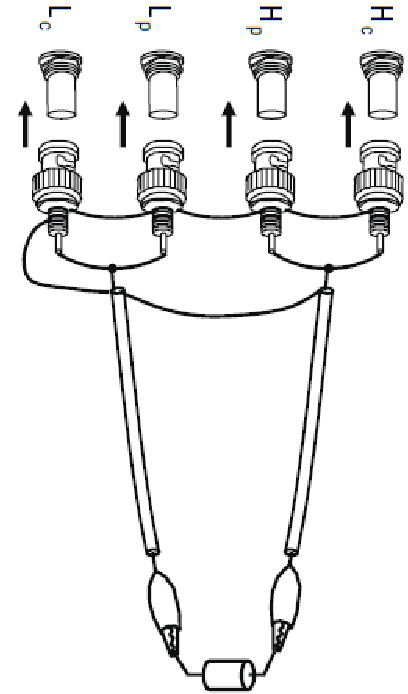


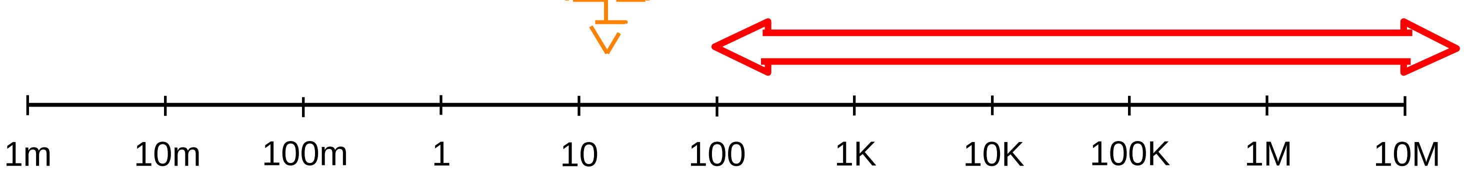


Three-terminal configuration (3T)

- reduce stray capacitance between H and L terminals
- usable for measurement of higher impedances



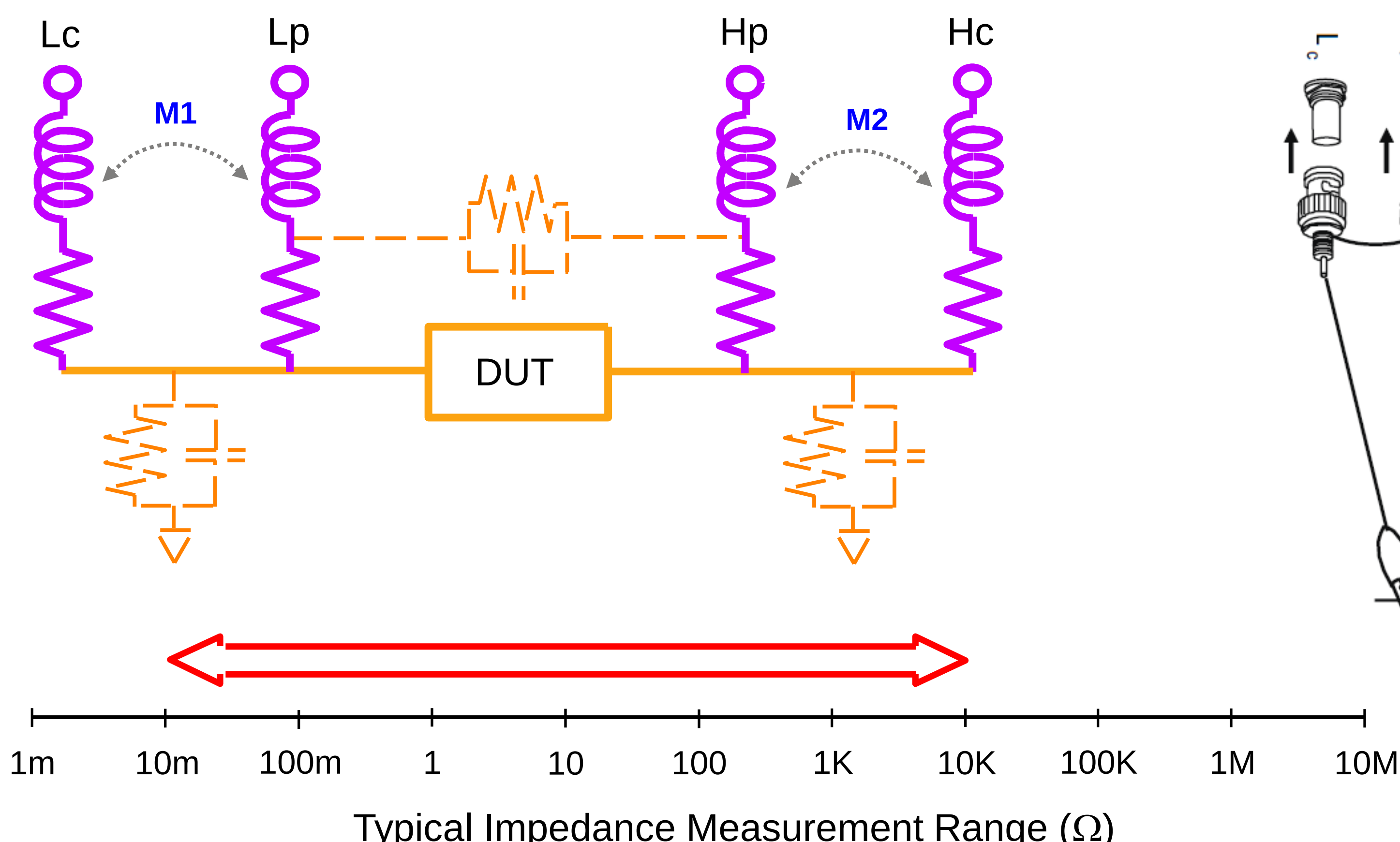


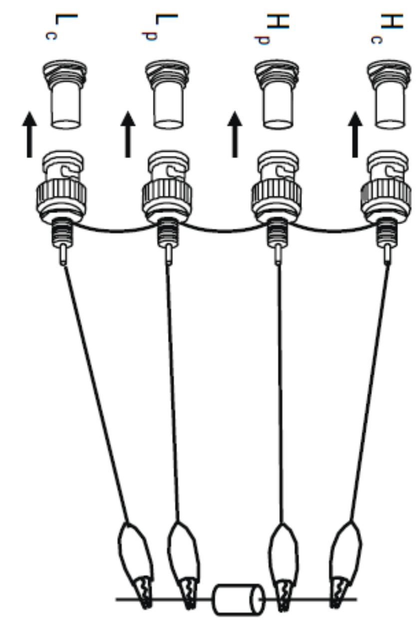


Typical Impedance Measurement Range (Ω)

Four-terminal configuration (4T)

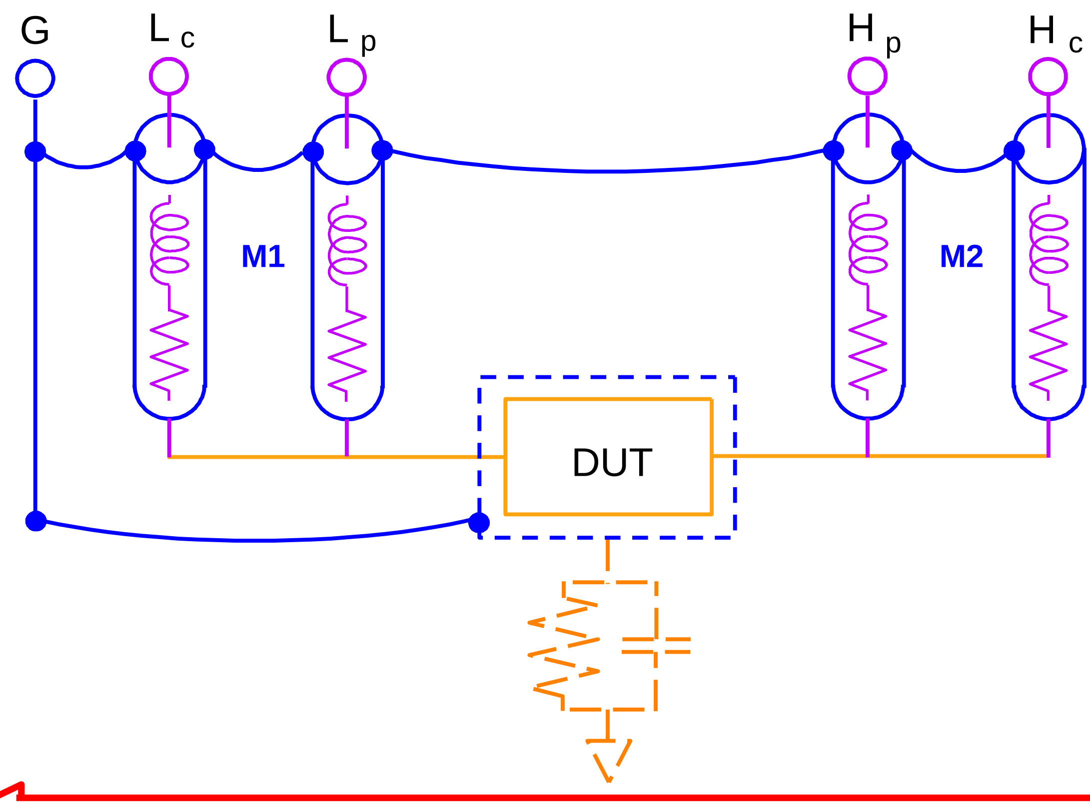
- „Kelvin“ connection
- can be used for measurement of small impedances
- same limitations by the stray capacitance as with the 2T method
- possible mutual coupling between voltage and current conductors

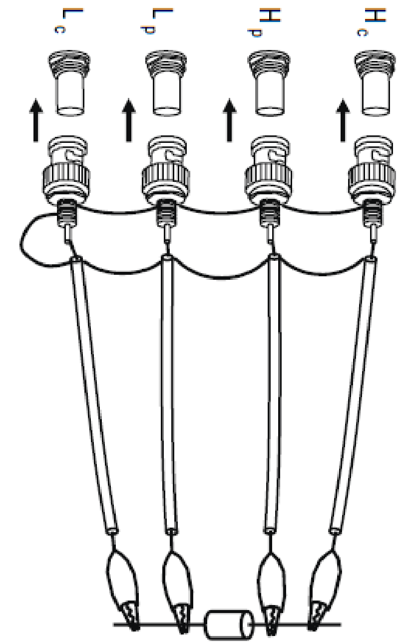


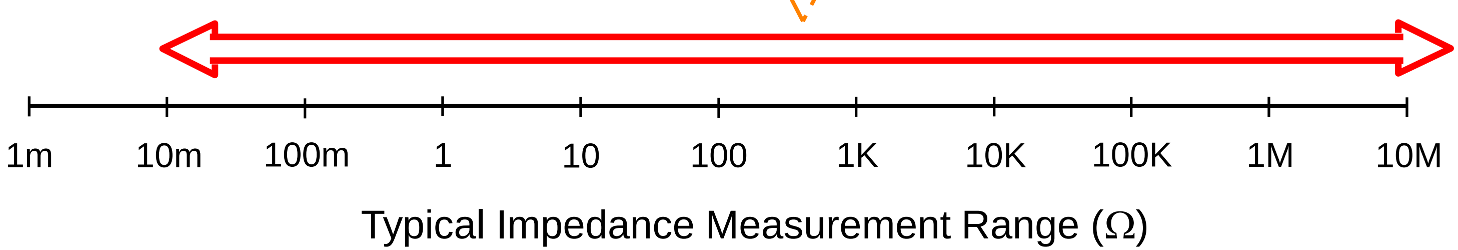


Five-terminal configuration (5T)

- combines the advantages of 4T and 3T (shielding) configuration
- wide measurement range; the mutual coupling remains

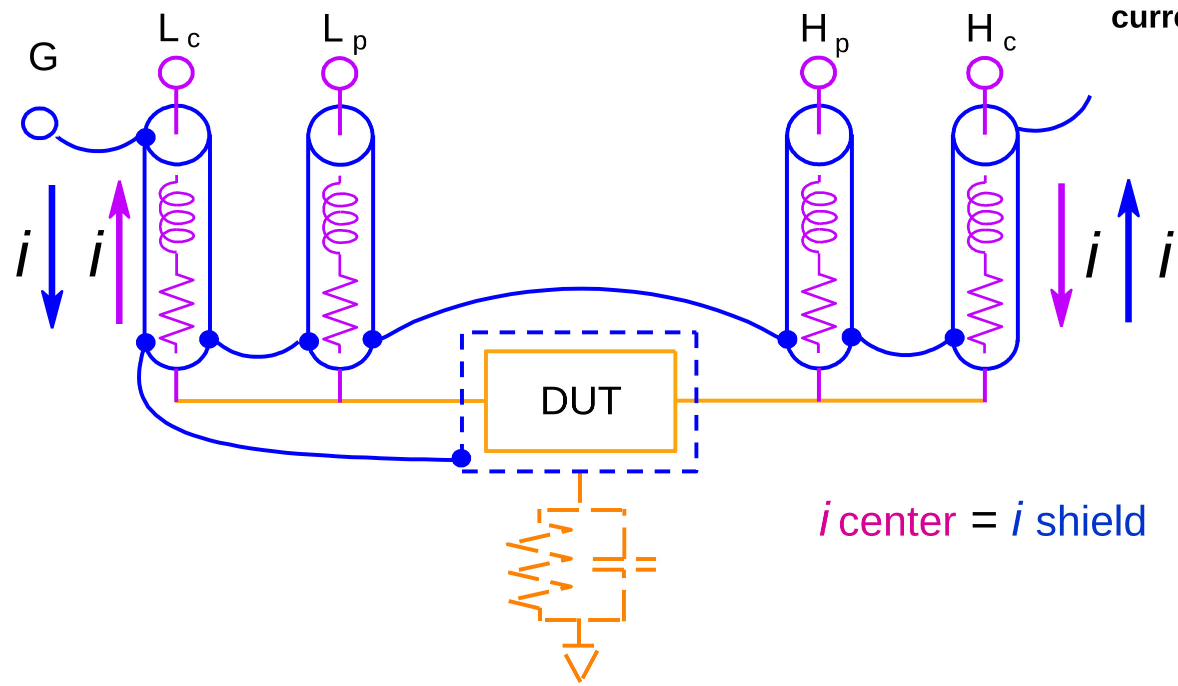


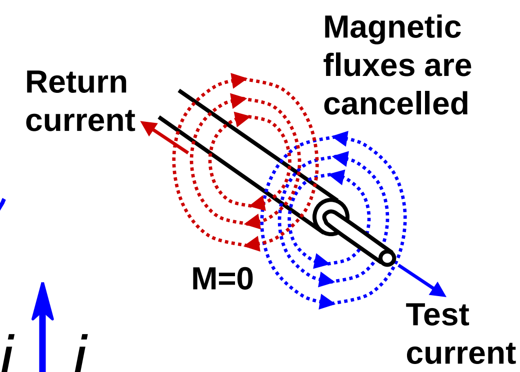


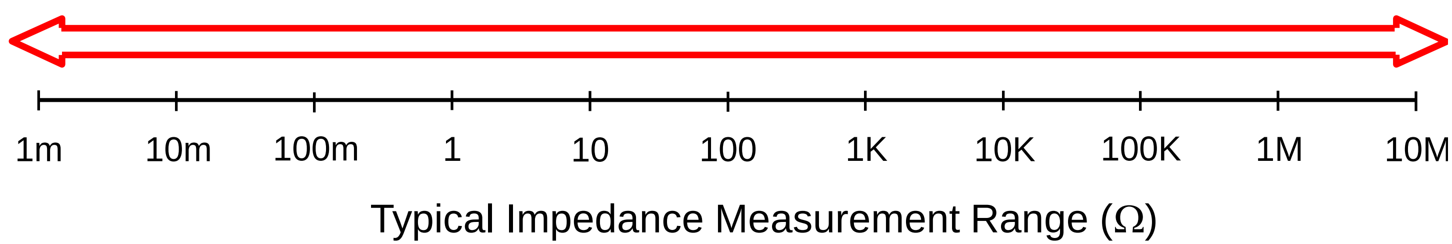


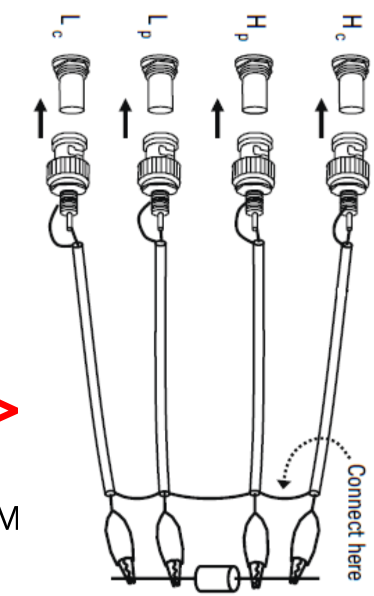
Four-terminal pair configuration(4TP)

- removes the effects of magnetic coupling
- widest measurement range; limited frequency range



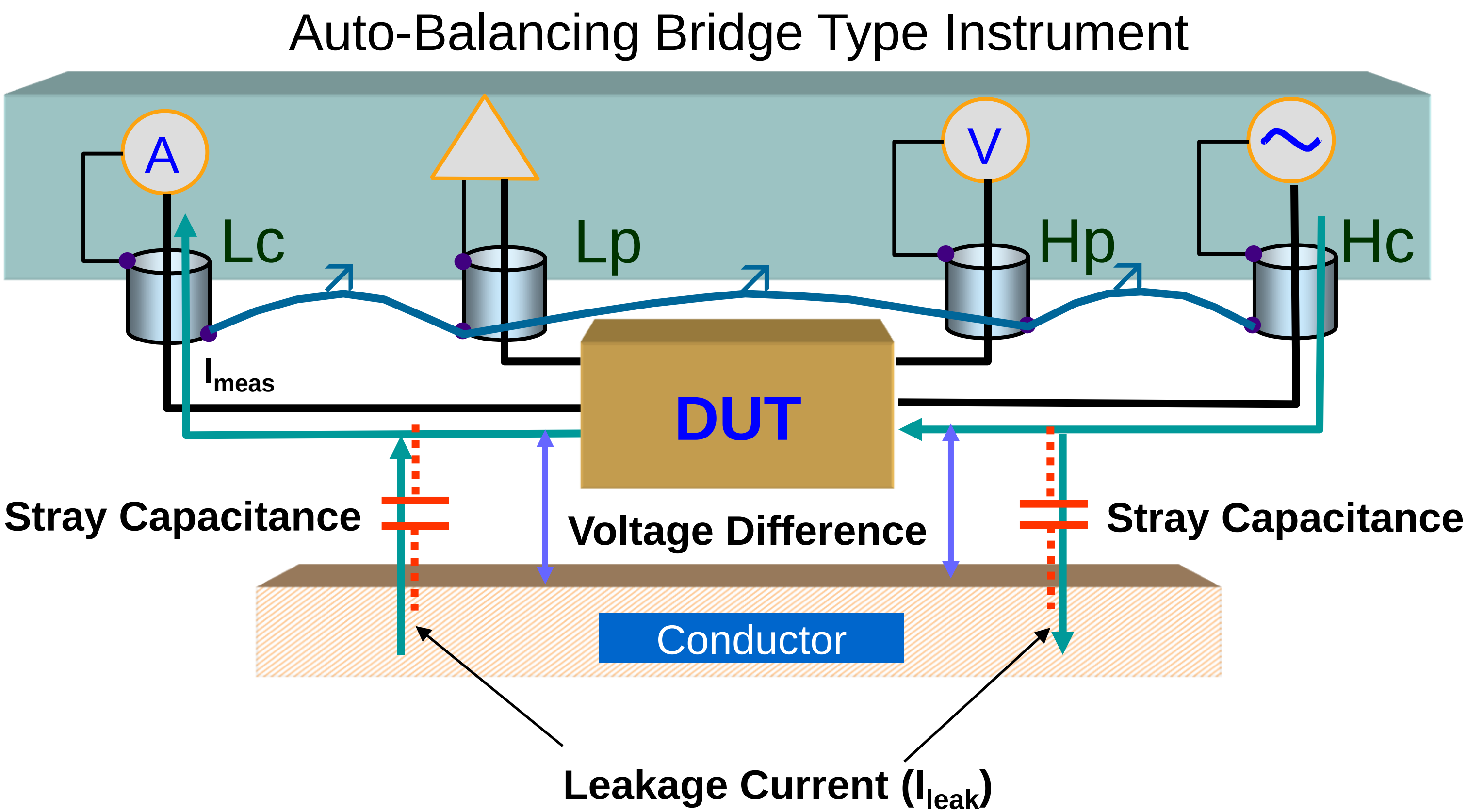






Guard

- stray capacitances can cause leakage currents through nearby conducting objects

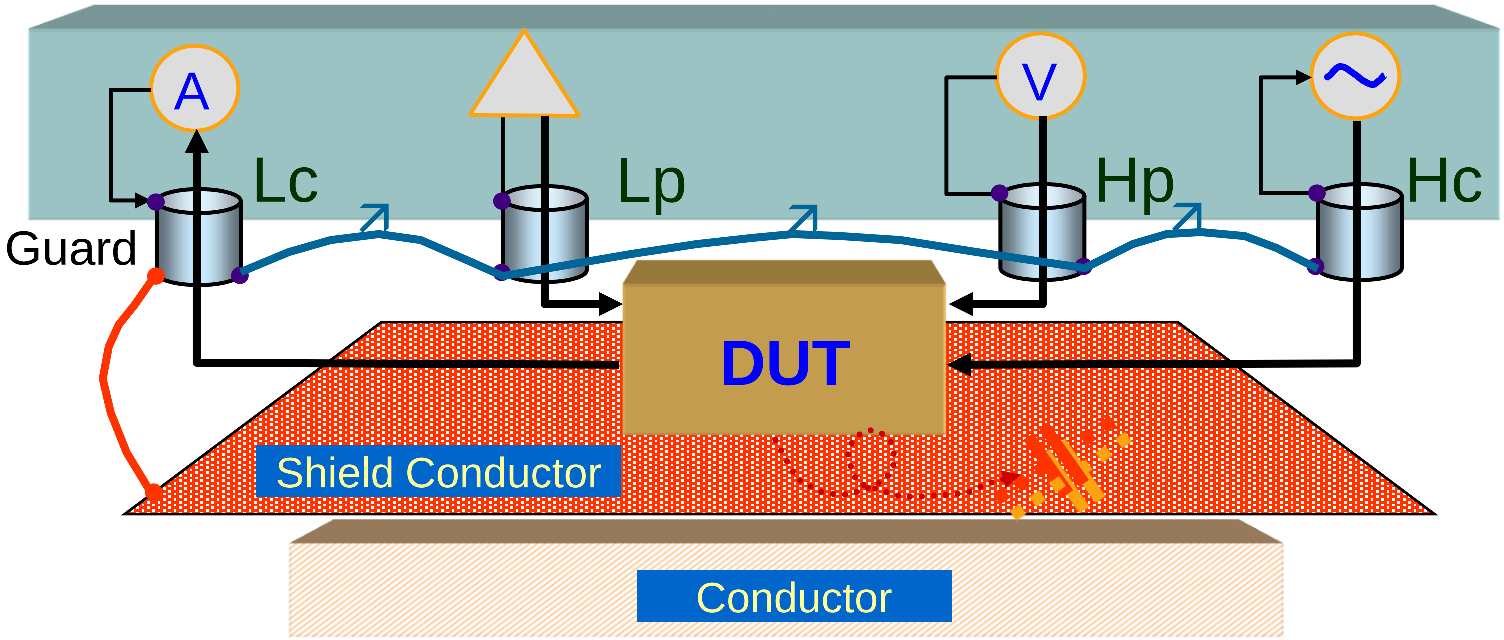


$I_{meas} = I_{dut} + I_{leak}$

Guard

- this effect can be removed using the „Guard“ terminal which has the potential of the virtual ground

Auto-Balancing Bridge Type Instrument

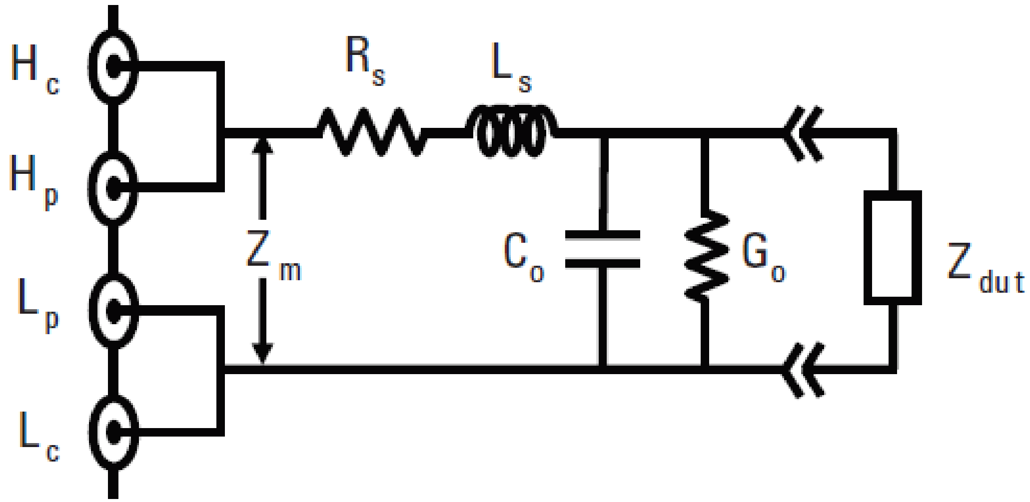


Calibration and compensation

- **calibration** of the instrument (in the reference plane of the BNC connectors) is performed only occasionally (for example once a year)
- in case an extension cable is used, it is necessary to make a correction for it’s length
  - original cables supplied by the manufacturer can be selected in the menu; use of custom cables is not recommended
- after connecting a fixture to the DUT terminal, it is necessary to perform a **compensation**
- **compensation** removes parasitic effects of the fixture; everything between the DUT and the BNC connectors

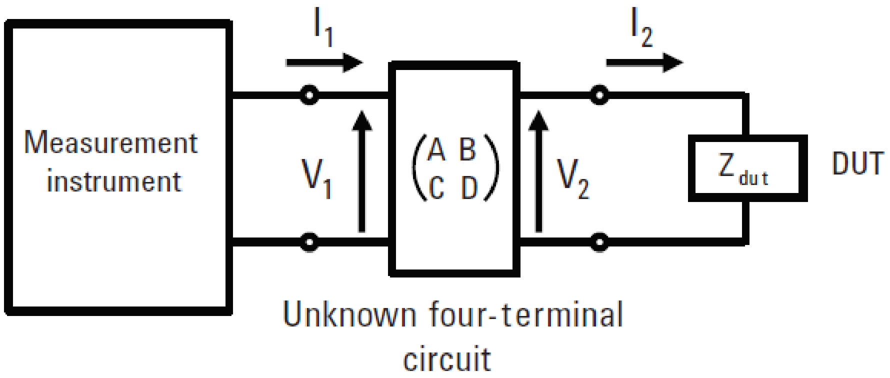
Calibration and compensation

- simplest compensation uses **open** and **short** standards
  - usable (and recommended) on low frequencies and for “uncomplicated” fixtures
  - error model with R and L in series and G and C in parallel:



Calibration and compensation

- **open**, **short** and **load** compensation
  - used for more “complicated” meas. configurations
  - assumes an error four-terminal network
  - requirements on the load standard:
    - well defined and highly stable R or C
    - ideally the same dimensions as DUT

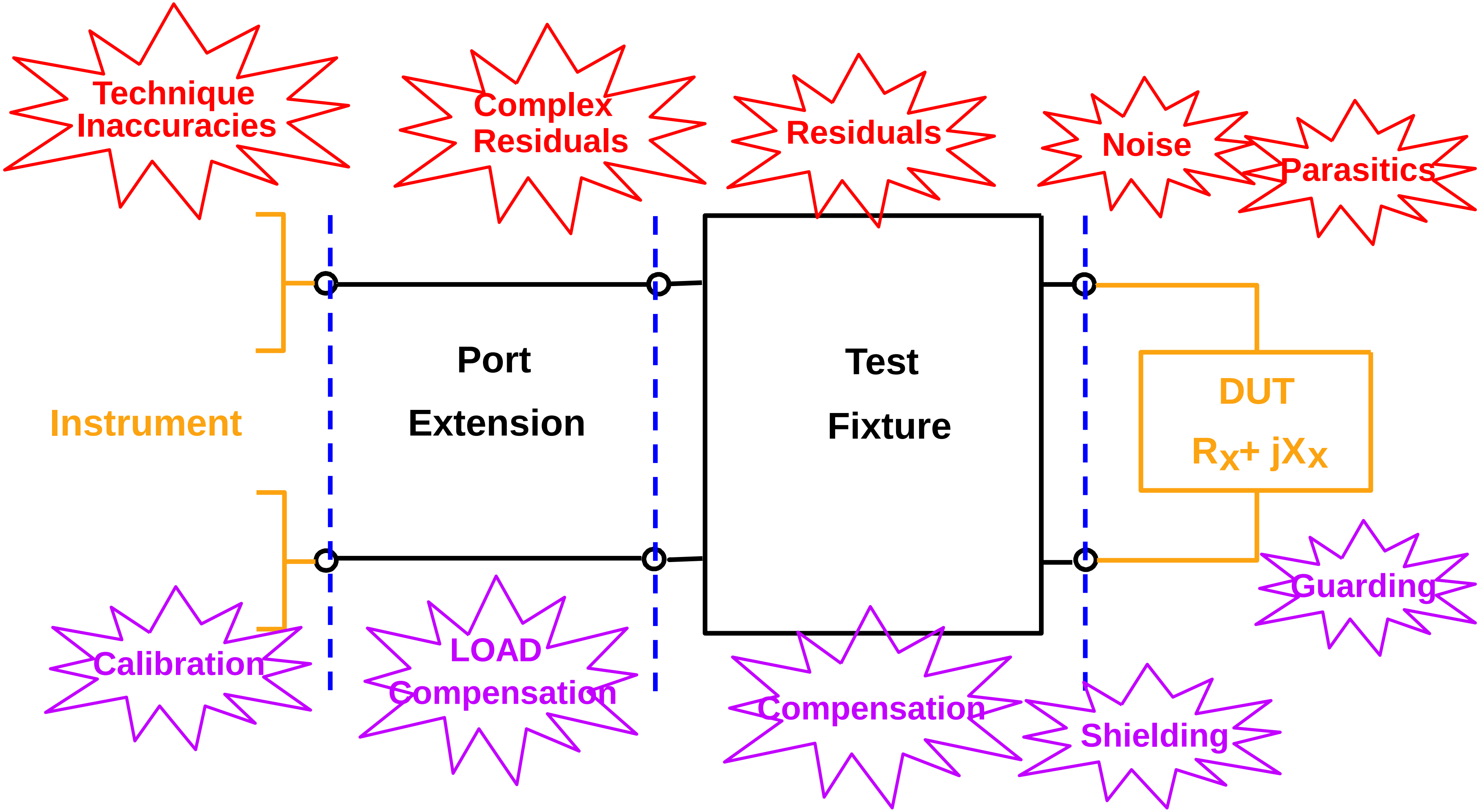


Calibration and compensation

- summary of the common measurement configurations:

1) standard fixture from Keysight directly on the instrument
   - open/short compensation (on lower frequencies)
2) fixture from Keysight connected thru an extension cable
   - cable correction + open/short compensation
3) standard Keysight extension cable + custom fixture
   - cable correction + open/short/load compensation
4) custom extension cable + custom fixture
   - open/short/load compensation only
   - test which method works best

Calibration and compensation



Measuring instruments

- LCR meter Keysight E4980A / E4980AL
  - 20 Hz – 2 MHz

Measuring instruments

- LCR meter GW Instek LCR-6000
  - 10 Hz – 300 kHz

Measuring instruments

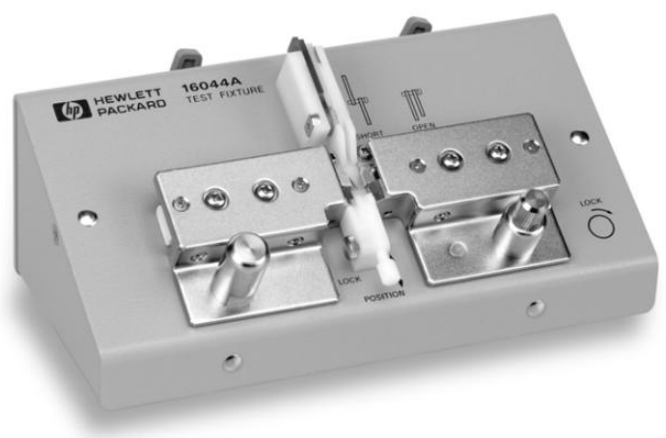
- impedance analyzer Keysight E4990A
  - 20 Hz – 120 MHz

Measuring instruments

- impedance analyzer GW Instek LCR-82xx
  - 10 Hz – 50 MHz

Accessories

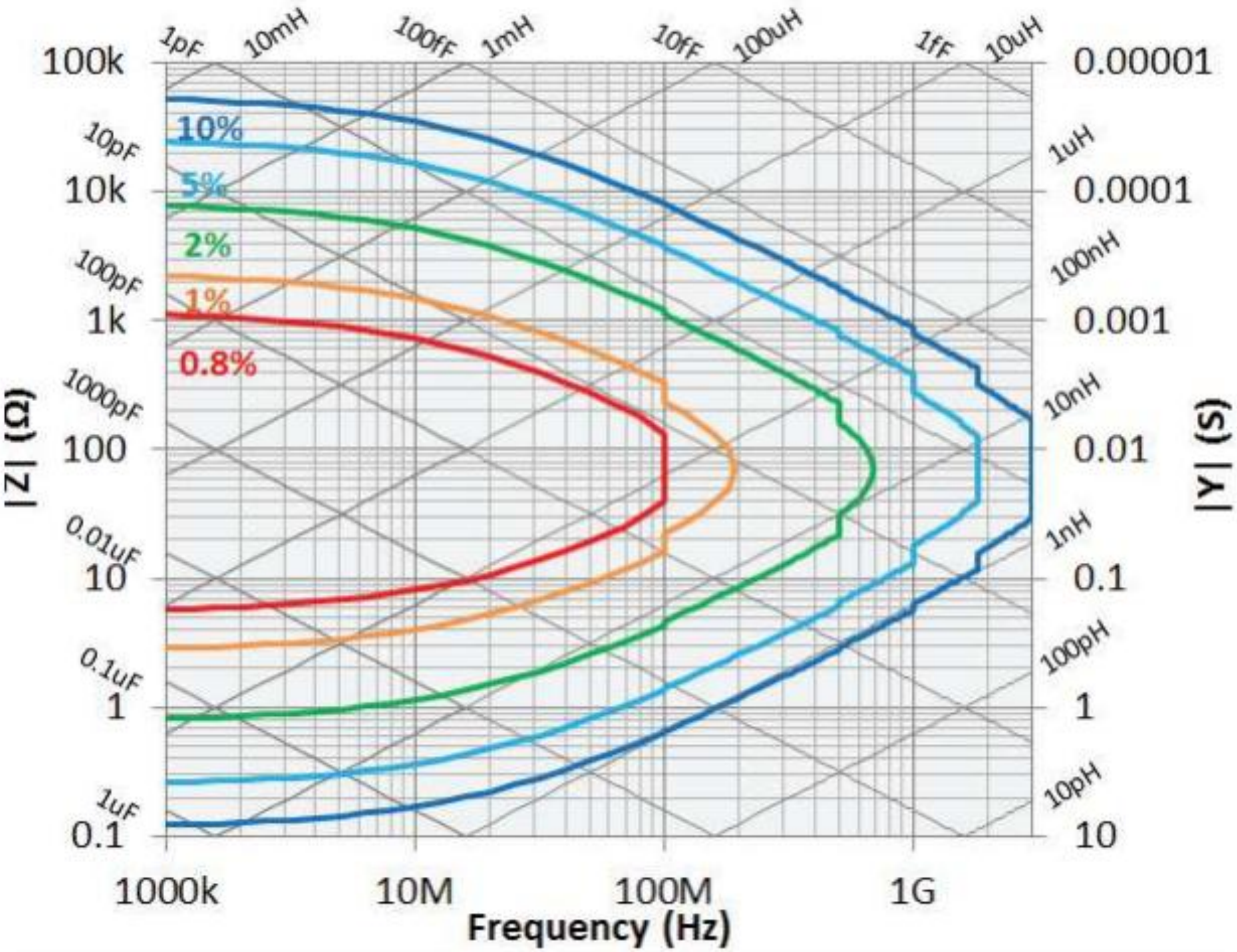
- various test fixtures for all DUT types:
  - SMD components – for different types and sizes
  - 2T or 4T clamps; hand browsers
  - material measurement fixtures – solids, fluids
  - 4xBNC to APC7 adapter
  - extension cables
  - .....



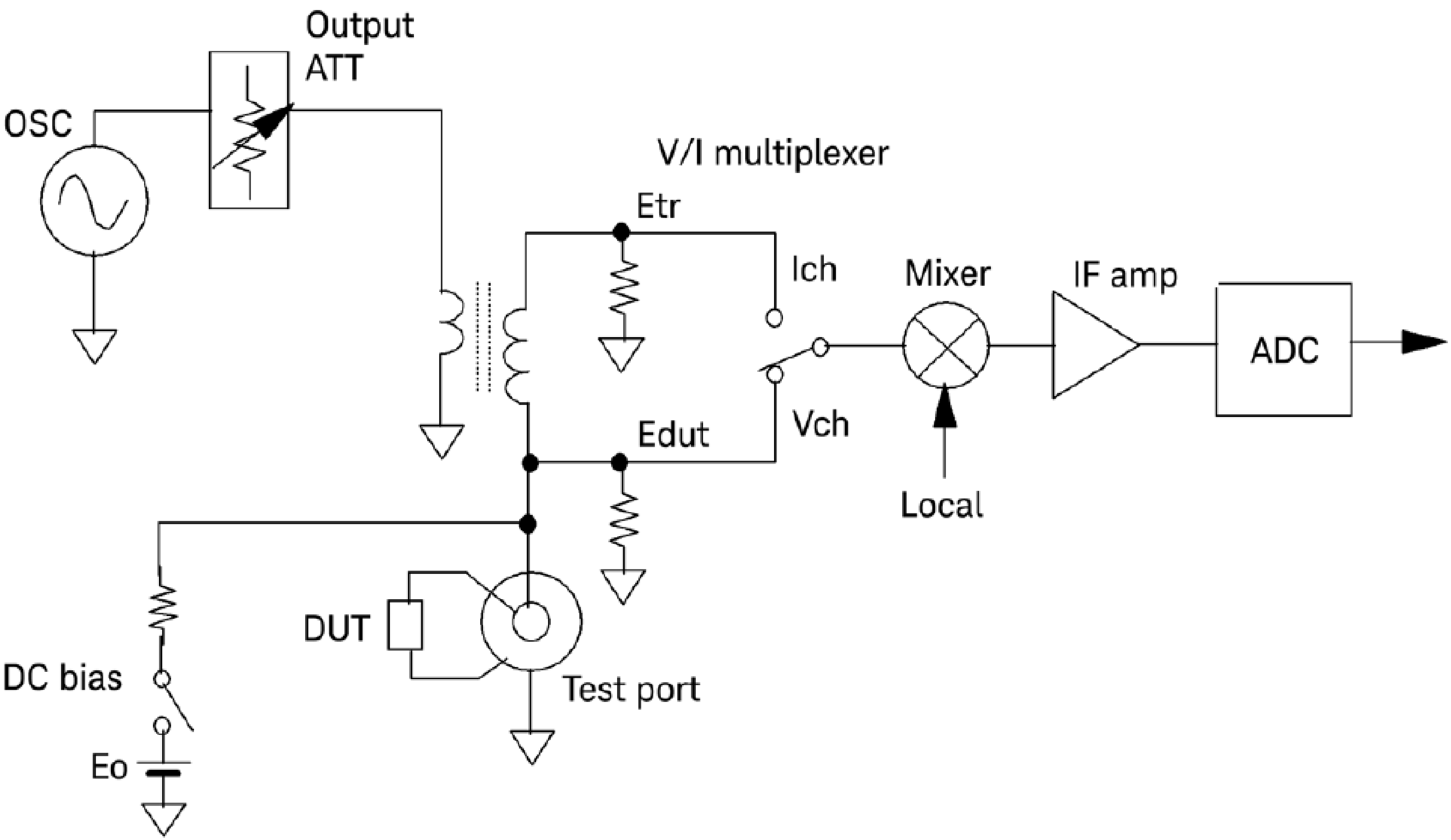
RF I-V method

- an advanced and relatively accurate measurement method for use at higher frequencies
  - frequency range from 1 MHz to 3 GHz
  - preferred method between 120 MHz and 3 GHz
  - beter accuracy and wider impedance measurement range compared to VNAs
  - direct voltage and current measurement – linear impedance dependence → the sensitivity of impedance measurement is theoretically constant

Basic accuracy – RF I-V method



RF I/V method


Output
ATT
OSC
V/I multiplexer
Etr
Ich
Mixer
IF amp
ADC
Vch
Edut
Local
DUT
DC bias
Test port
Eo

DUT connection

- the RF impedance analyzers use a APC-7 coaxial connector for fixture connection

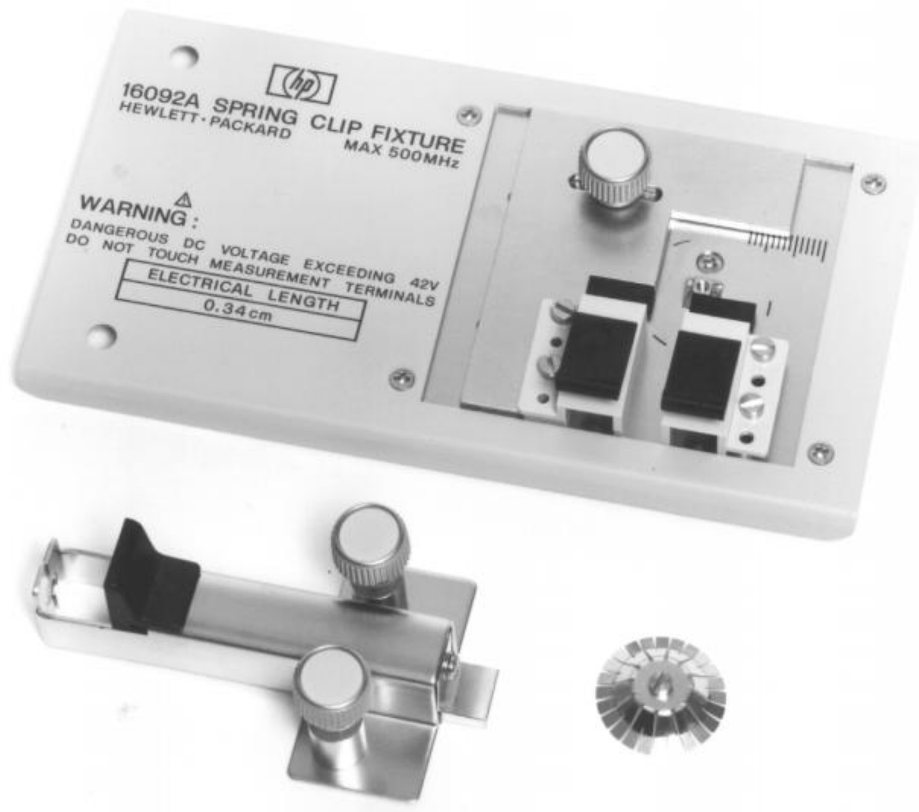
- same as with the LF instruments, various fixtures exist for different types of components

DUT connection

- the influence of parasitic elements increases with increasing frequency
  - from 100 MHz up, the accuracy of the measurement and the usable measuring range decrease significantly
- to minimize the influence of parasitics:
  - minimizing the dimensions of the measuring fixtures and the distance between the DUT and the test port
  - a coaxial line should go as close to the DUT as possible
  - carefull connection of calibration/compensation standards and the DUT to the measuring system
  - use of coaxial fixtures for best results on high frequencies

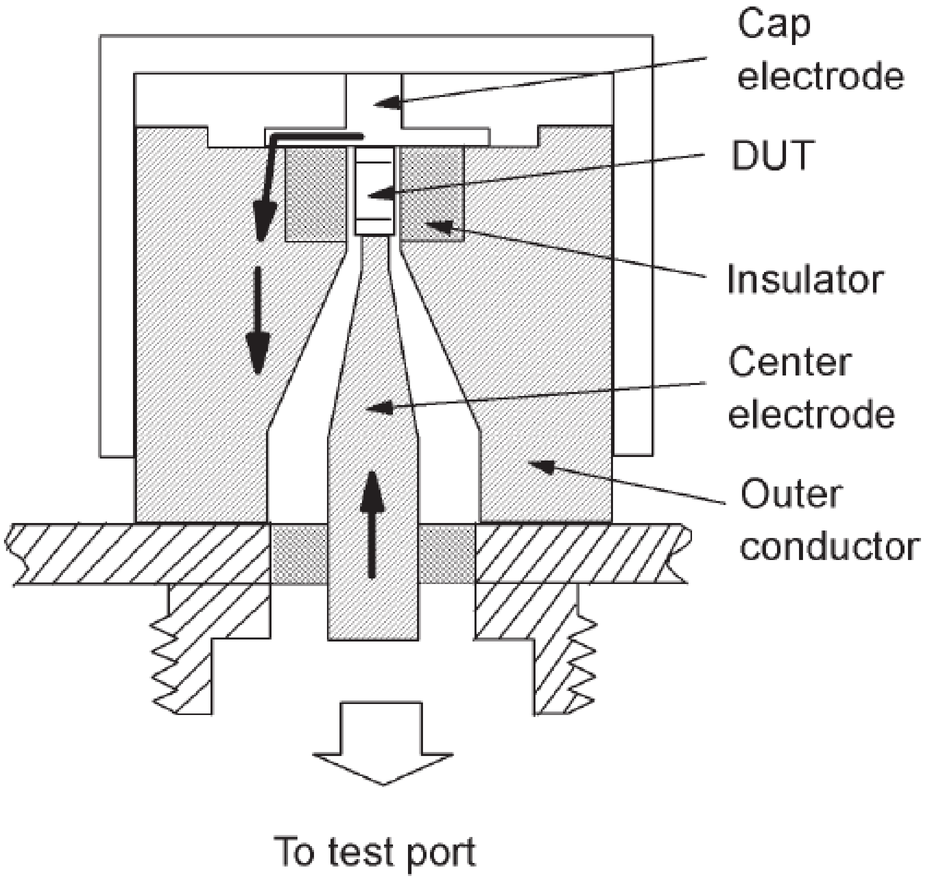
DUT connection

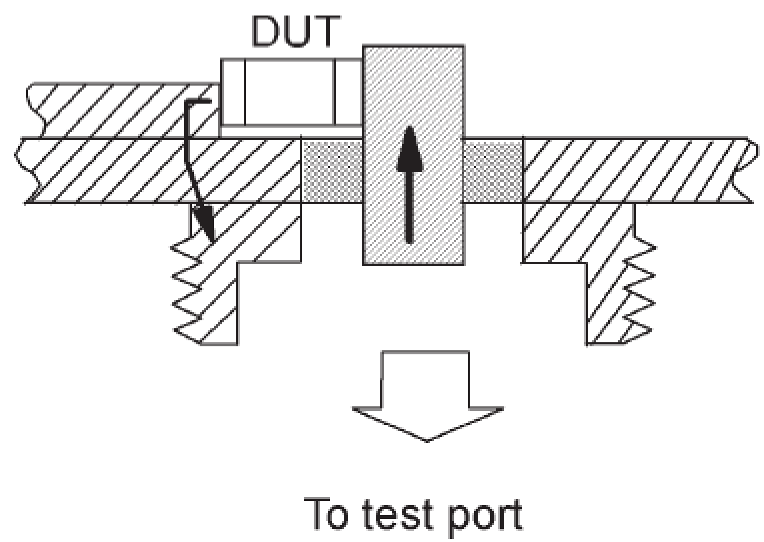
- coaxial vs. non-coaxial (radial) SMD fixtures:



DUT connection

- coaxial vs. non-coaxial (radial) SMD fixtures:



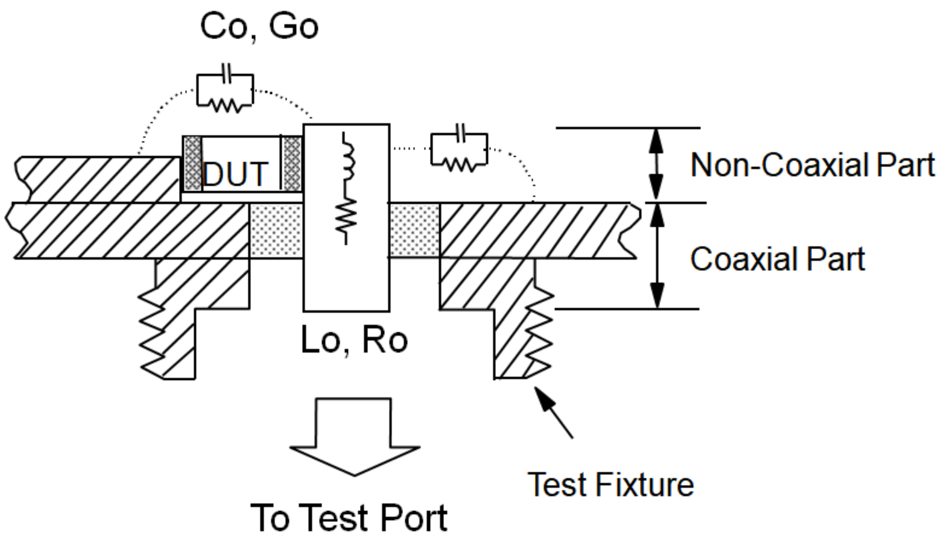


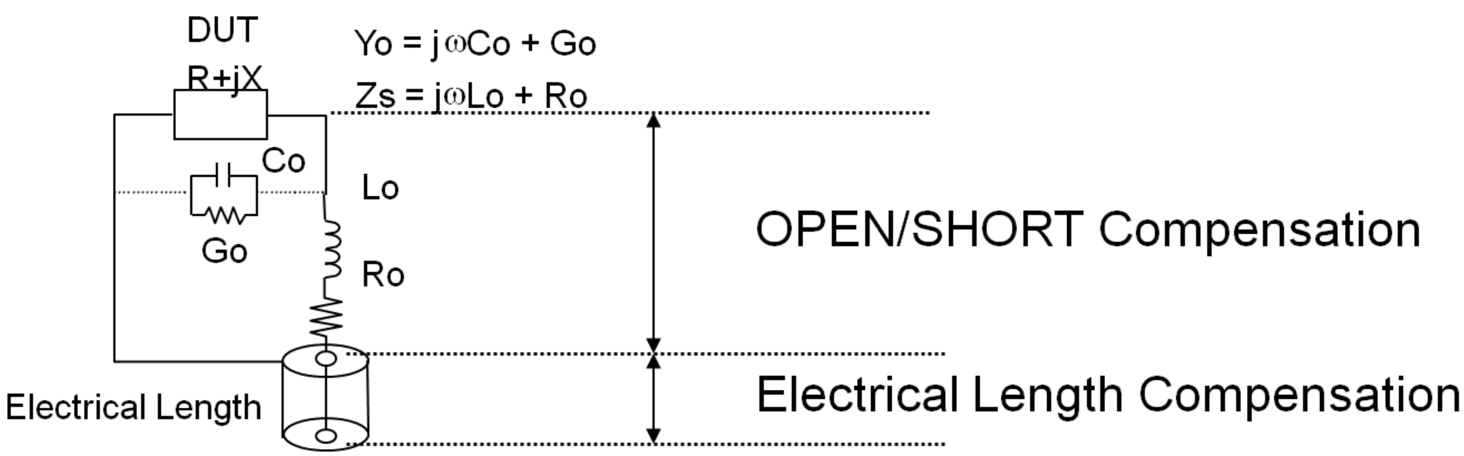
Calibration and compensation

- O/S/L (+ optional C) coaxial **calibration** has to be performed on the APC-7 test port of the analyzer
  - in case an extension coaxial line is used, the calibration is performed at it’s end
- fixture **compensation** has in this case two steps:
  - entering the length of the short coax line in the fixture
  - open/short compensation of the fixture residuals
- for non-standard custom fixtures, it is recommended to do a OSL calibration directly at the DUT connection point (for example with probing stations, …)

Calibration and compensation

- RF fixture error model:





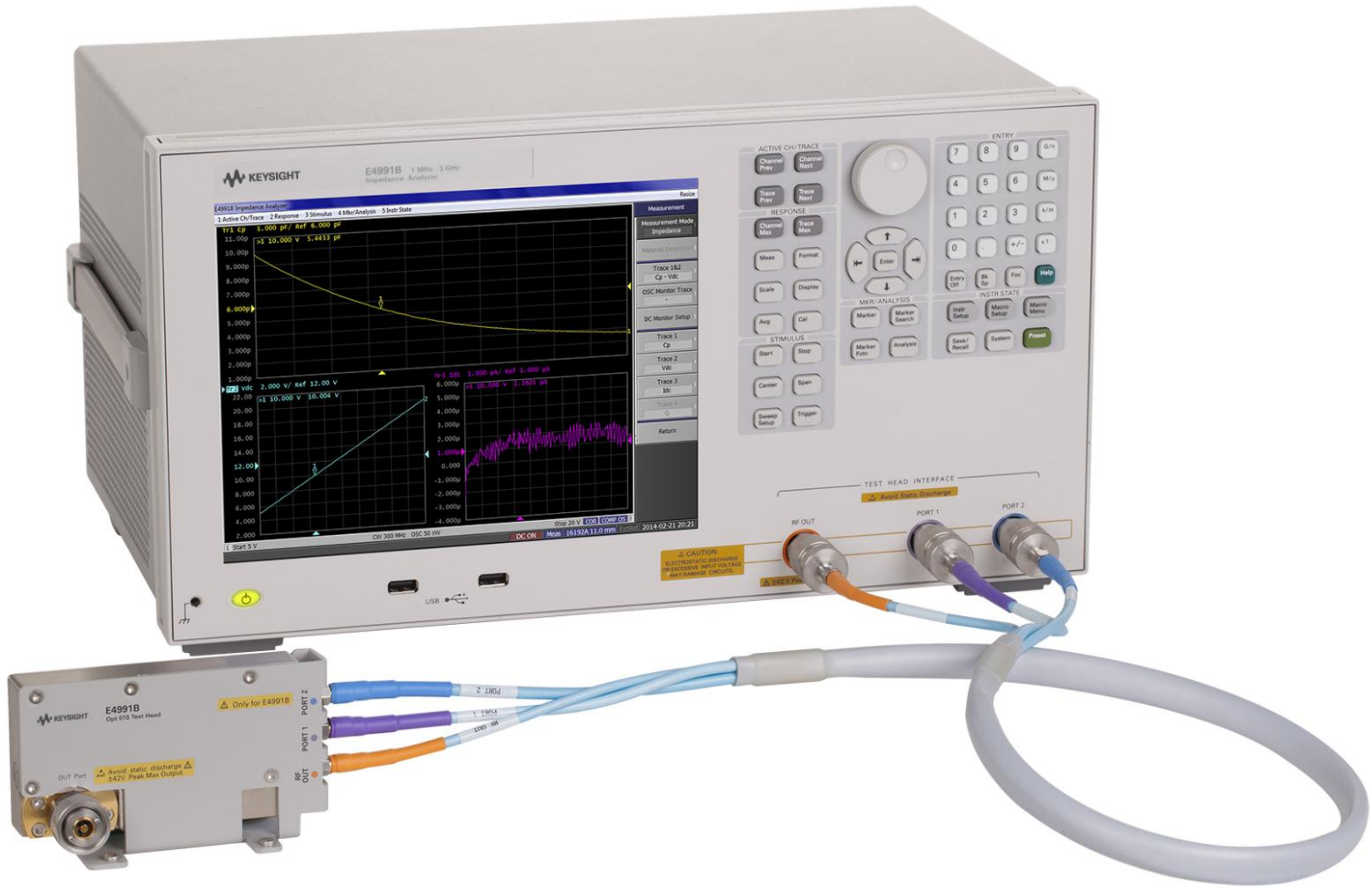
Measurement repeatability

- error sources which can cause bad repeatability:

1) connection of the calibration/compensation standards
   - carefull positioning of the standards
   - contacting – parasitic resistance, …
2) connection of the DUT
3) EM coupling to nearby conductors
   - parasitic capacitance or magnetic coupling
   - sufficient distance from conducting objects
4) environmental changes (temperature drift, …) and other external influences

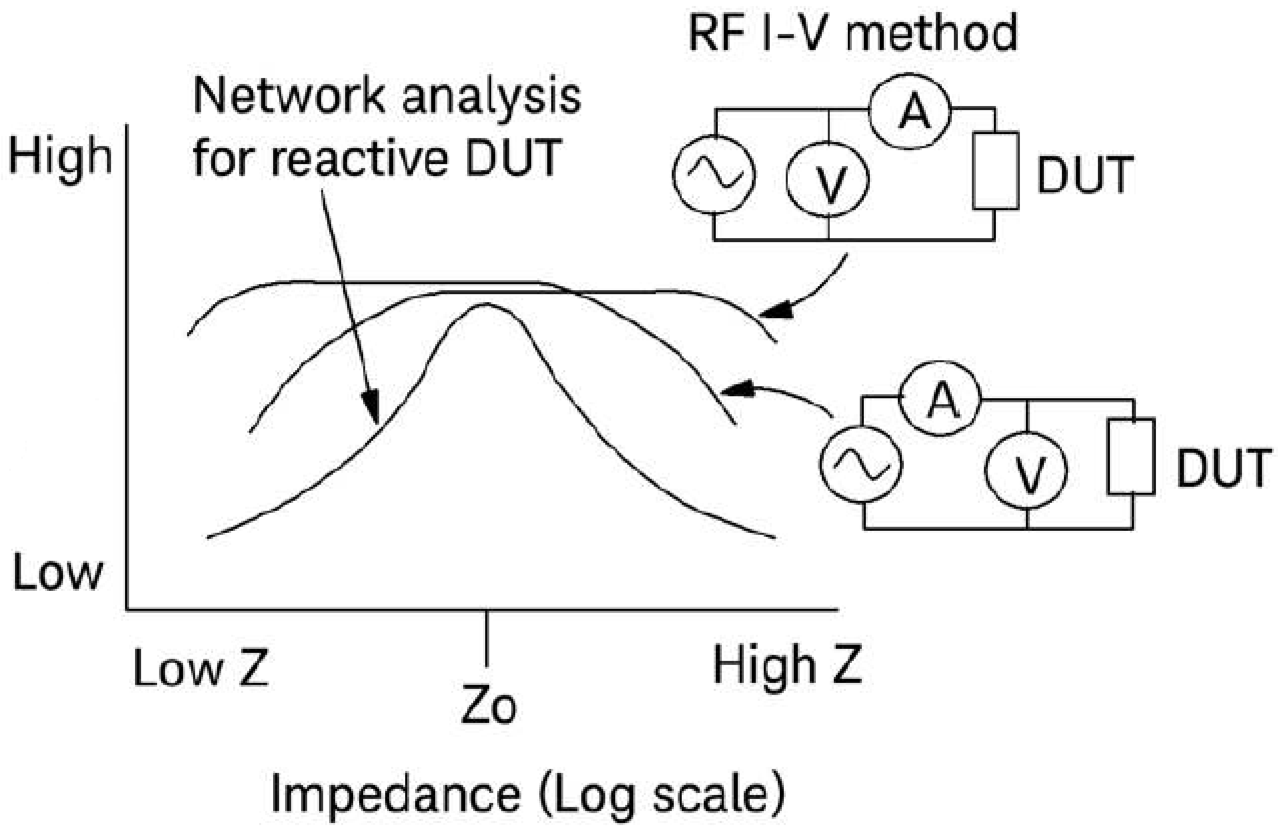
Measuring instruments

- impedance analyzer Keysight E4991B



High frequency measurements

- sensitivity comparison - RF I-V vs. VNA reflection:

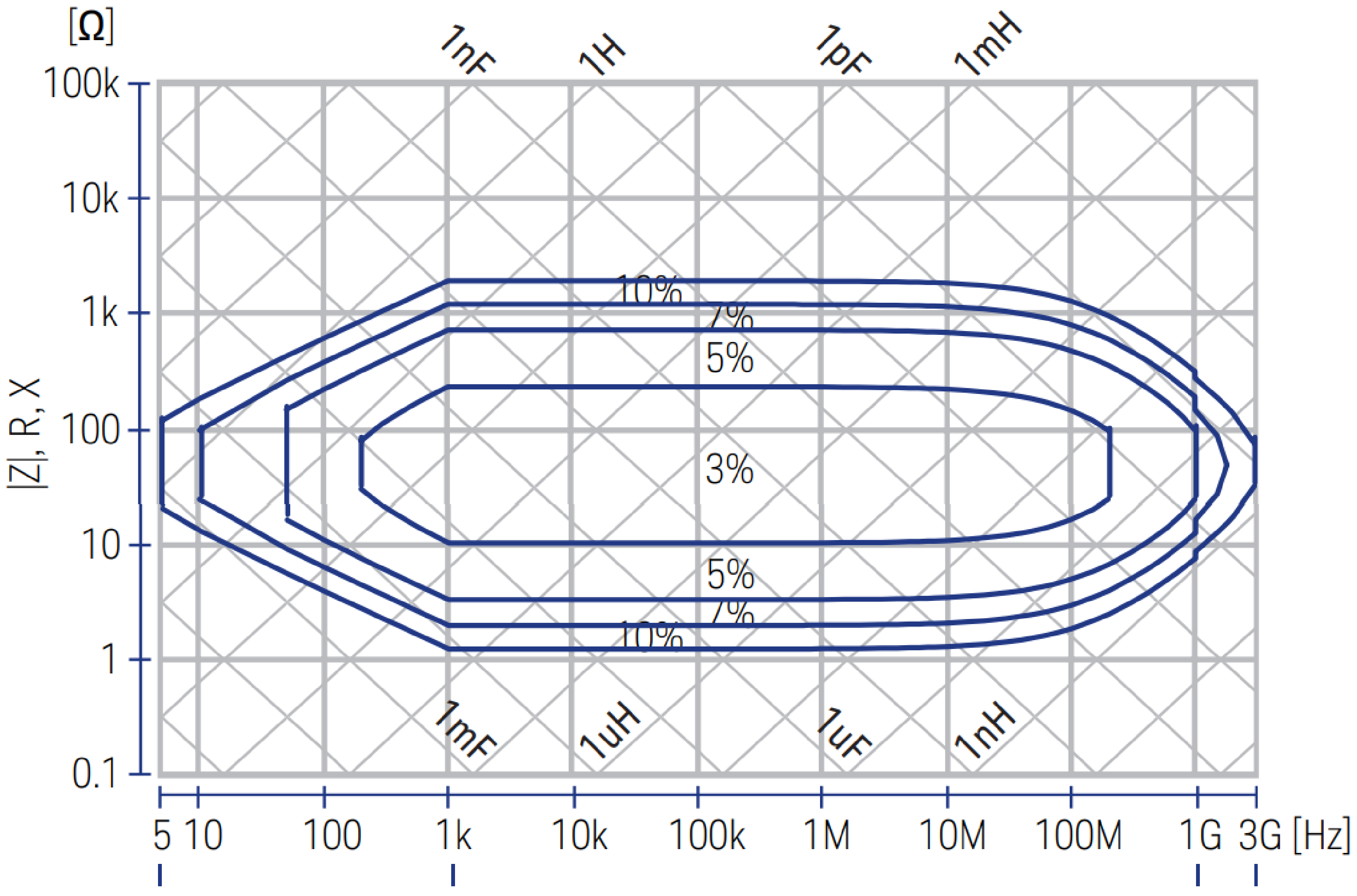


Measurement using VNA

- worse accuracy and limited measurement range
- very wide (virtually unlimited) frequency range
  - from 5 Hz up
- three different methods of imp. calculation using a VNA:
  1) from reflection (S11, S22, …):
     - general and simplest method
     - can be used with the standard fixtures for the E4991A
     - optimal for lower to middle range of impedances (around 50 Ω)

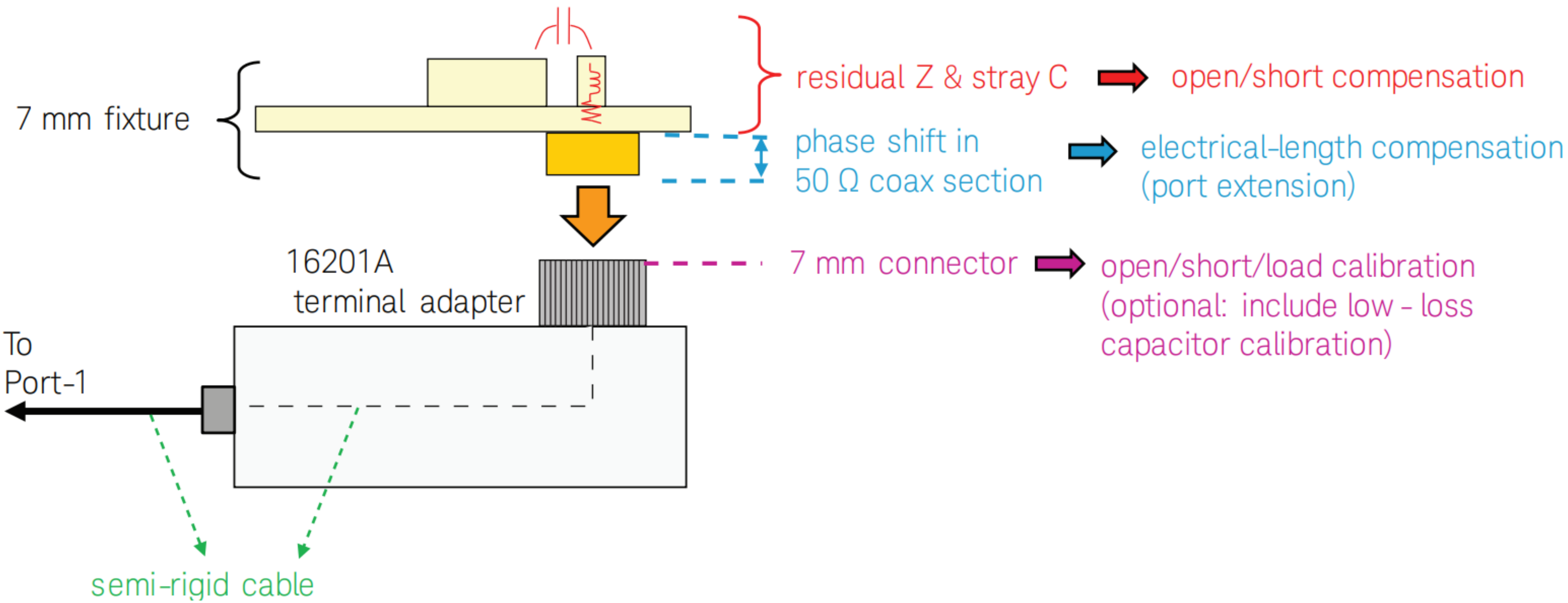
VNA – impedance from reflection

- basic accuracy of the reflection method:



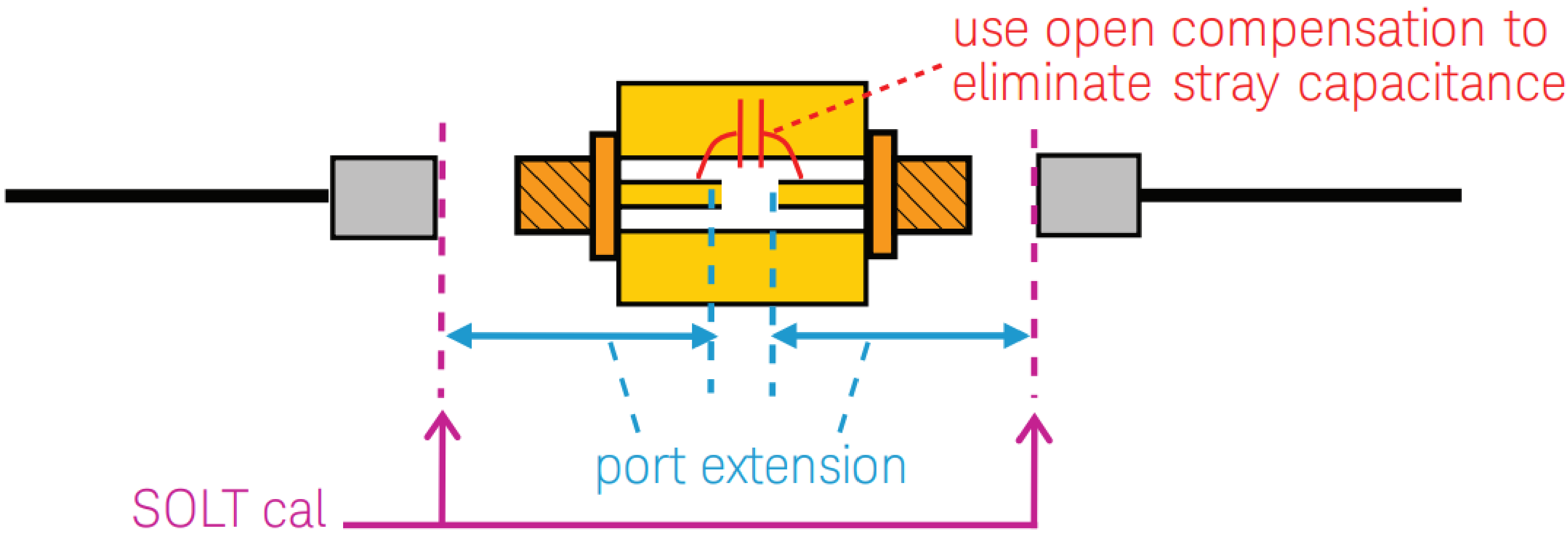
VNA – impedance from reflection

- calibration and compensation (same as with the E4991A)



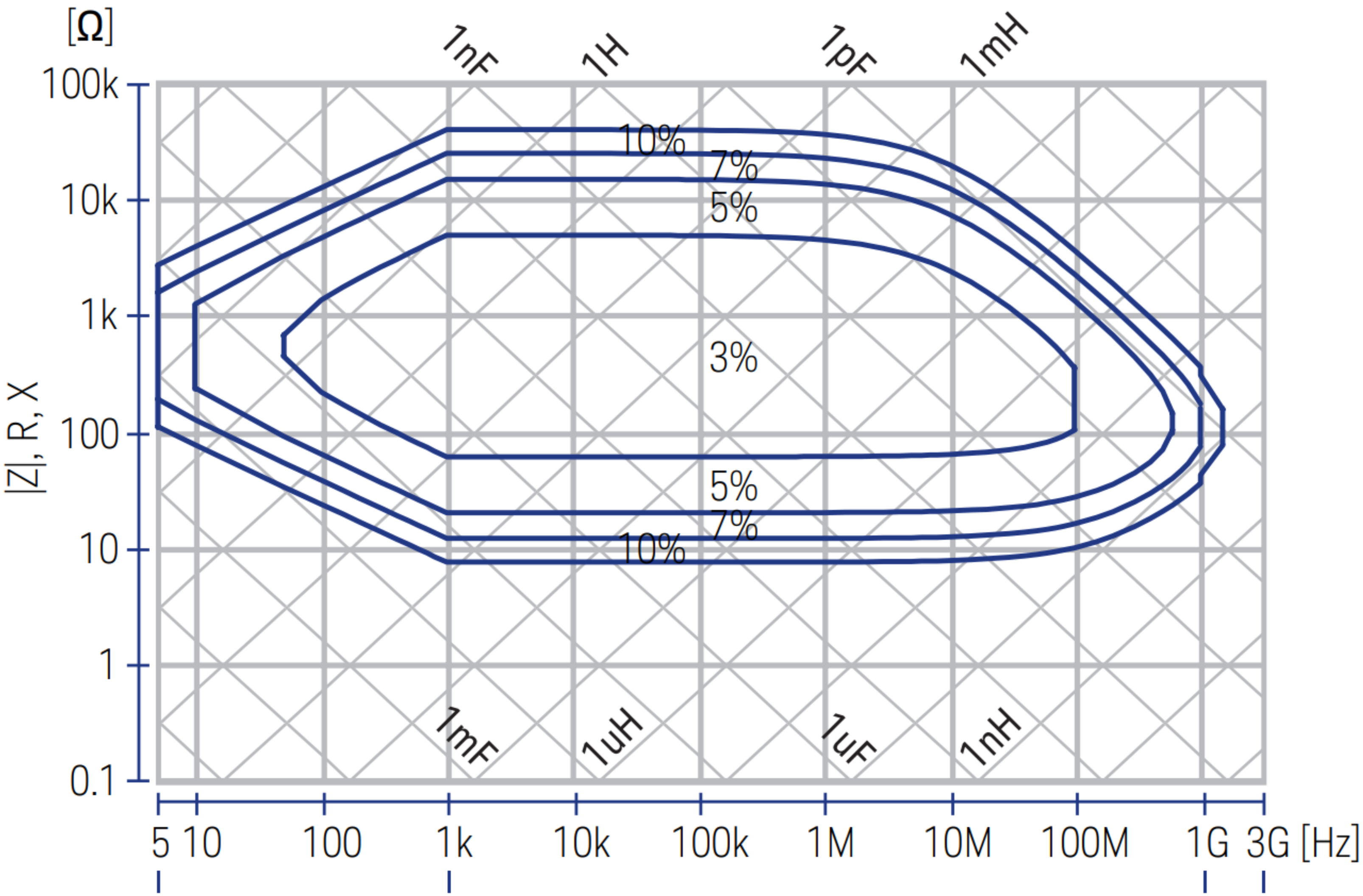
VNA – „series-thru“ method

2) imp. calculation from transmission – „series-thru“:
   - measured impedance is connected in series with the center conductor of a transmission line between two test ports
   - ideal for larger impedances
   - 10 % accuracy between ~ 5 Ω and 20 kΩ



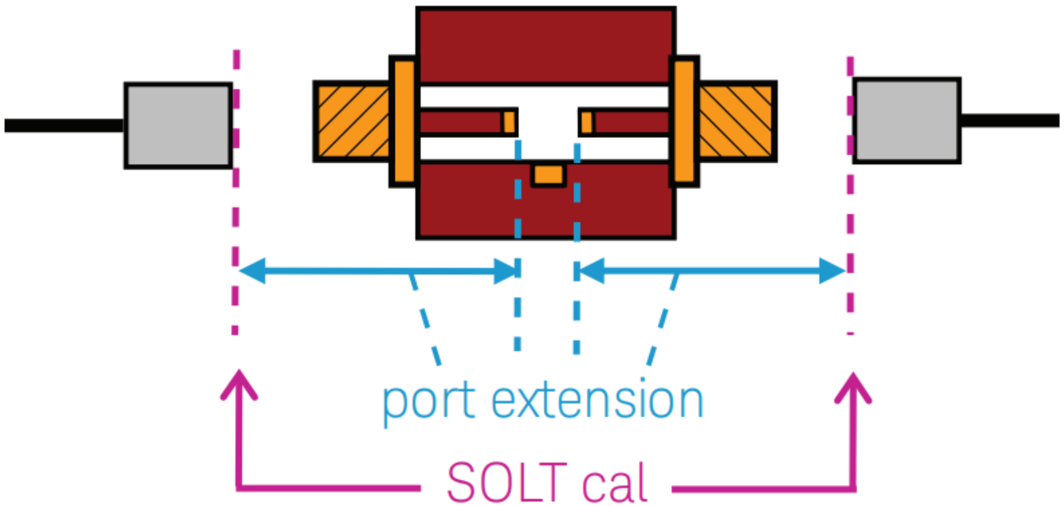
VNA – „series-thru“

- basic accuracy for the „series-thru“ method:



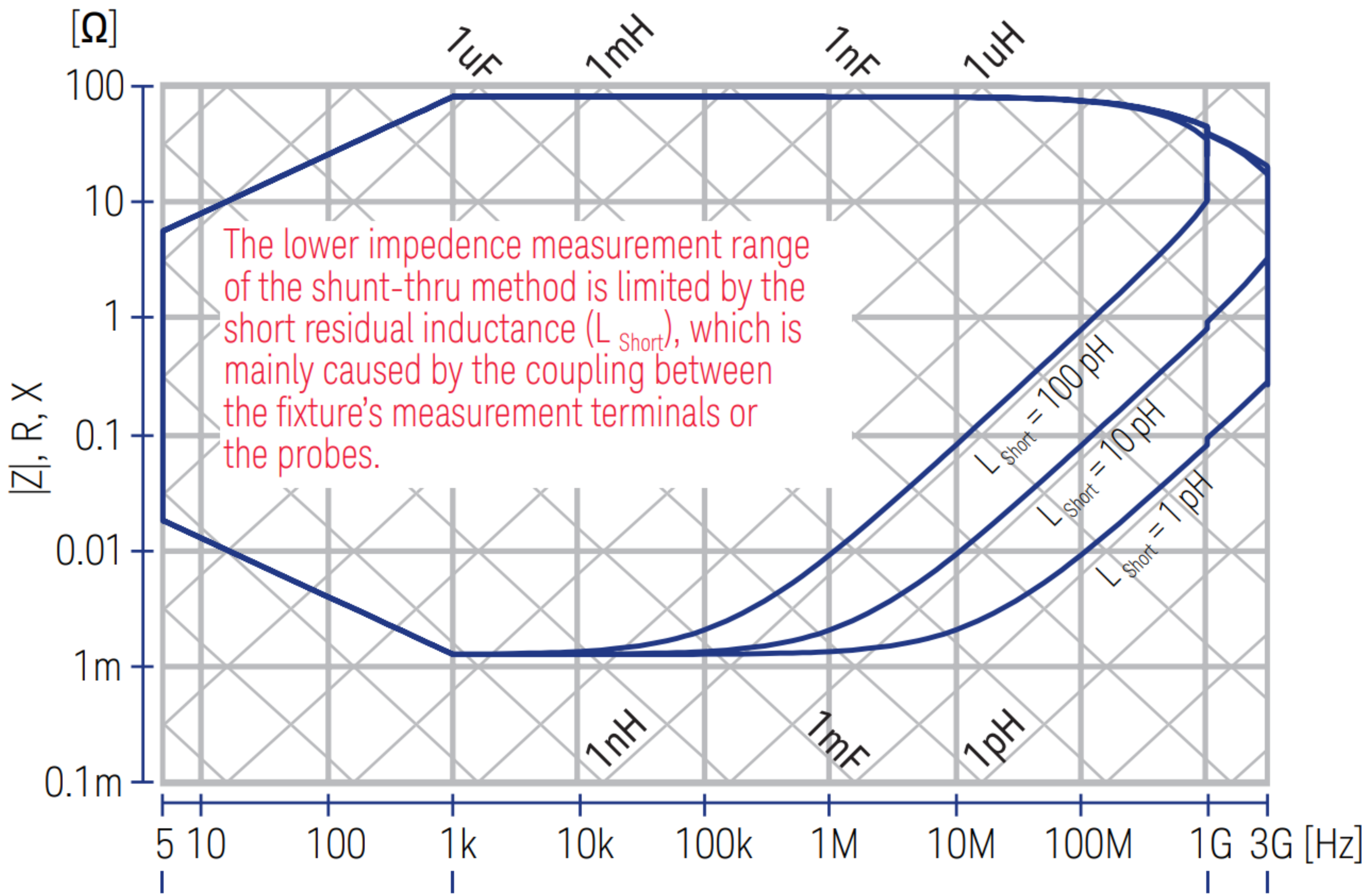
VNA – „shunt-thru“

3) imp. calculation from transmission – „shunt-thru“:
   - measured impedance is connected between the center and ground conductors of the transmission line
   - ideal for small impedances
   - 10 % accuracy between ~ 1 mΩ and 100 Ω



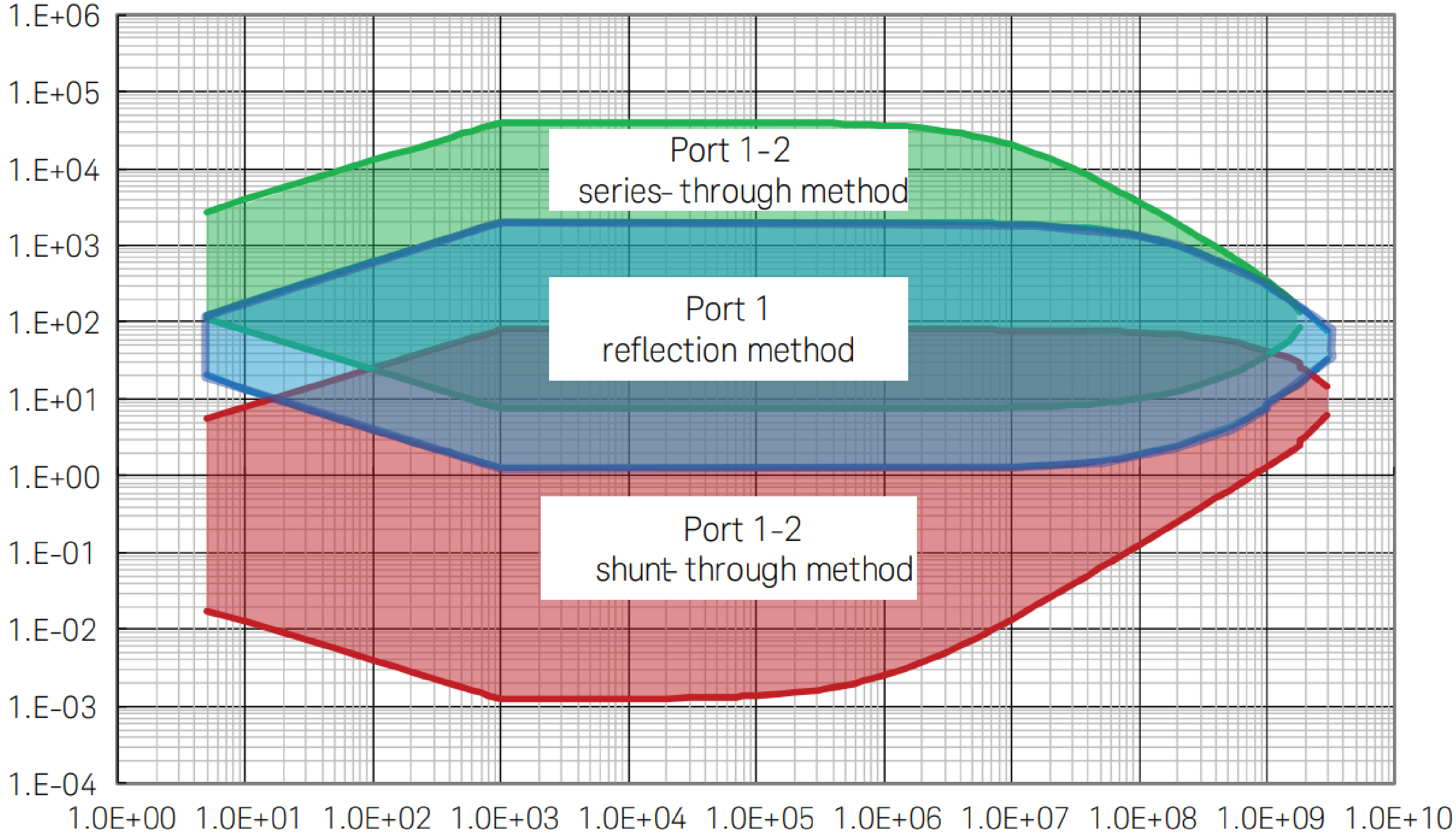
VNA – „shunt-thru“

- basic accuracy for the „shunt-thru“ method:



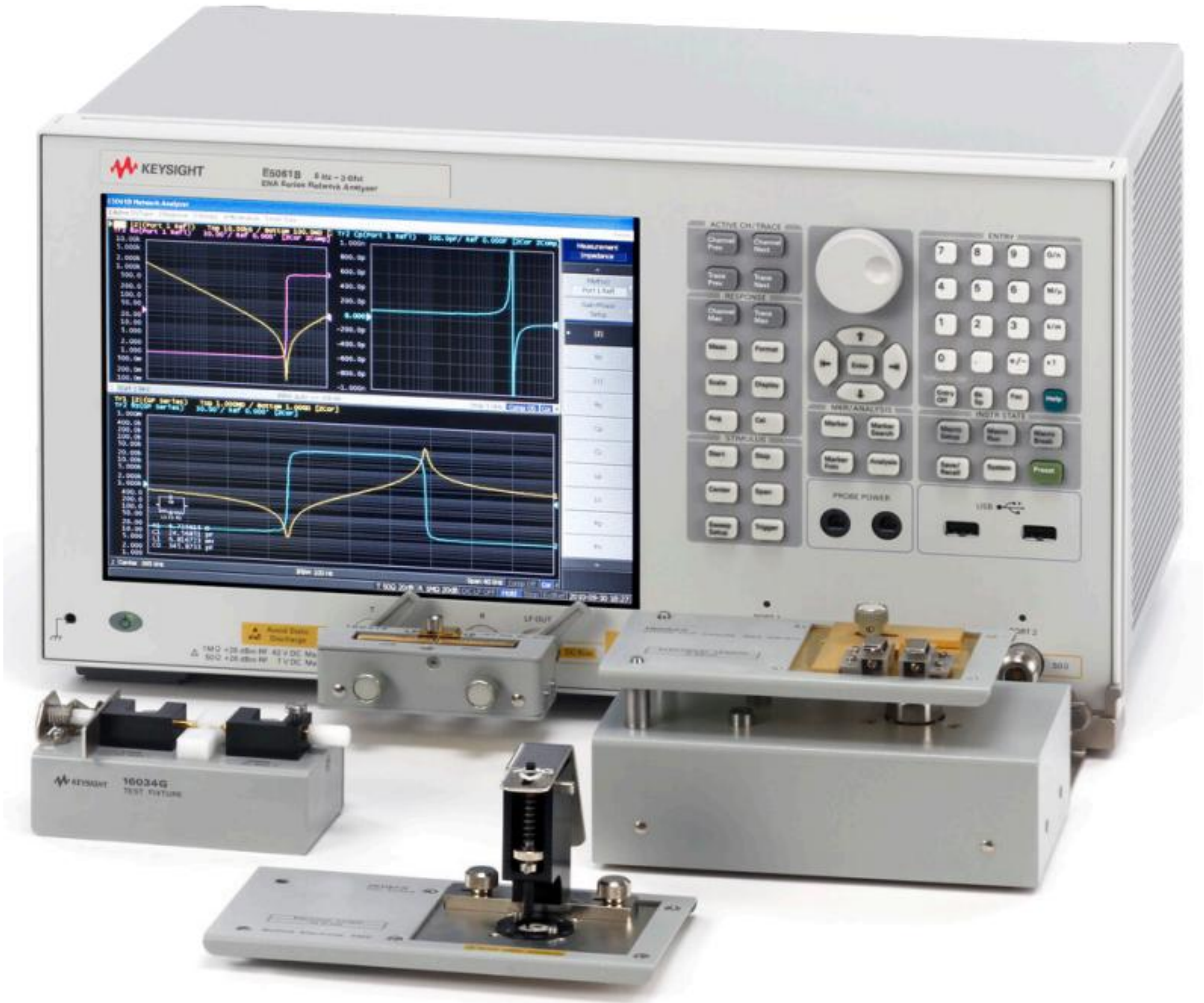
Measurement using VNA

- comparison of the calculation methods using VNA:



Measuring instruments

- VNA Keysight ENA E5061B
- 16201A APC-7 adapter kit



Available accessories

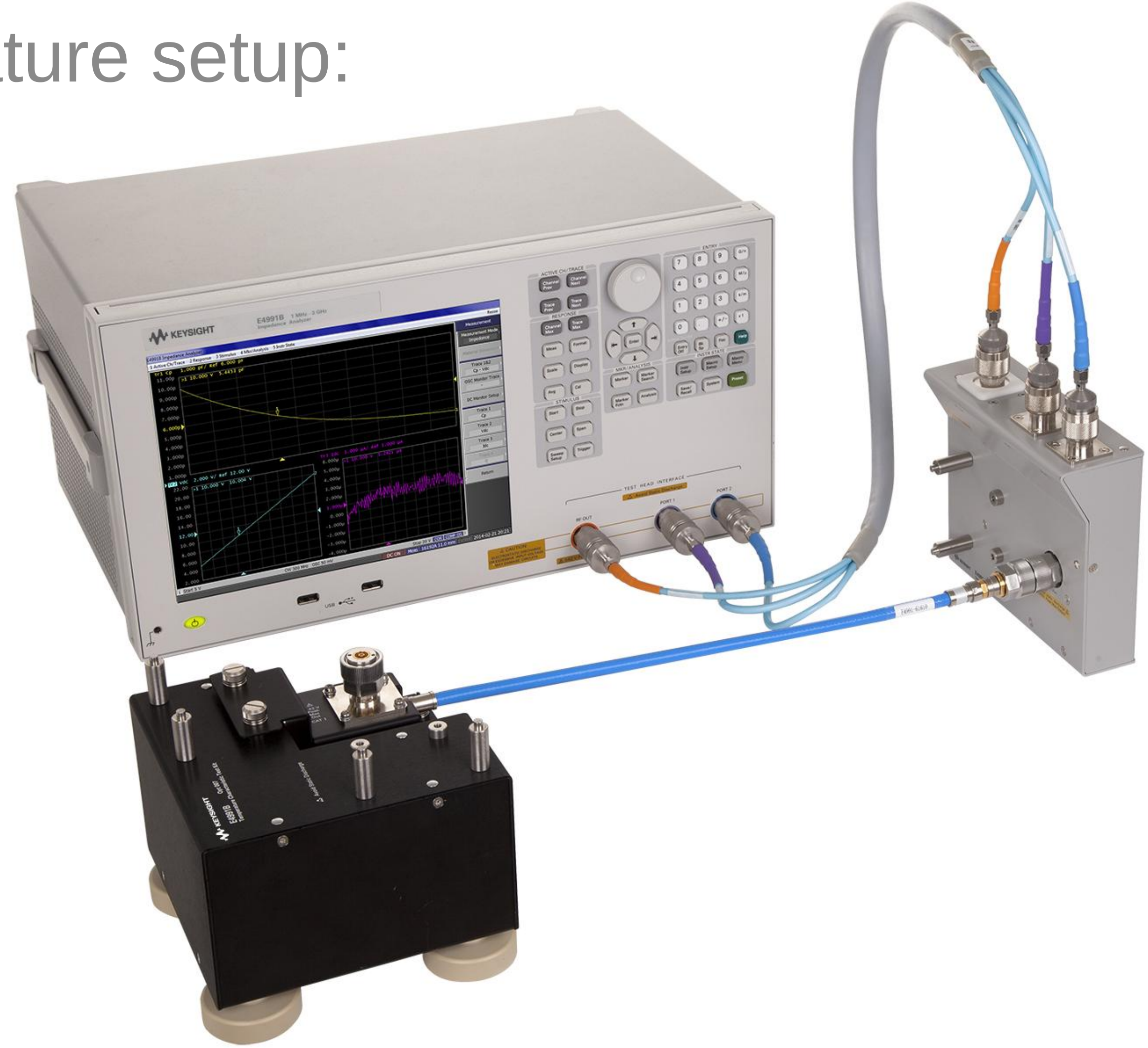
- SMD fixtures
  - for different component sizes
  - coaxial and non-coaxial versions
  - SMDs with parallel (from sides) or bottom contacts
- high temperature fixture (both SMD and lead components)
- fixtures for material measurements
  - dielectric and magnetic materials
- accessories for connecting to probing stations

Available accessories

- FormFactor (former Cascade Microtech)
  - probe stations –from simple manual systems up to advanced semi-automatic stations
  - very broad portfolio of probes and other accessories

Available accessories

- high-temperature setup:



Impedance measurements - information

- comprehensive information in this handbook:

Impedance Measurement Handbook
A guide to measurement technology and techniques
5th Edition
(apliapplication note; Keysight Technologies)

- fixtures and other accessories:

Accessories Selection Guide
For Impedance Measurements
(Keysight Technologies)

Thank you for your attention !