Vacuum gauges for the fine and high vacuum

Karl Jousten, PTB, Berlin

1. Measurement of vacuum pressures and the calibration chain

2. Overview of measurement principles and gauge types

3. Direct gauges, indirectly measuring gauges

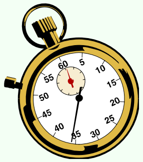
4. Accuracy of vacuum gauges

Measurement of vacuum pressure

The definition of pressure *p*:

$$p = \frac{F}{A}$$

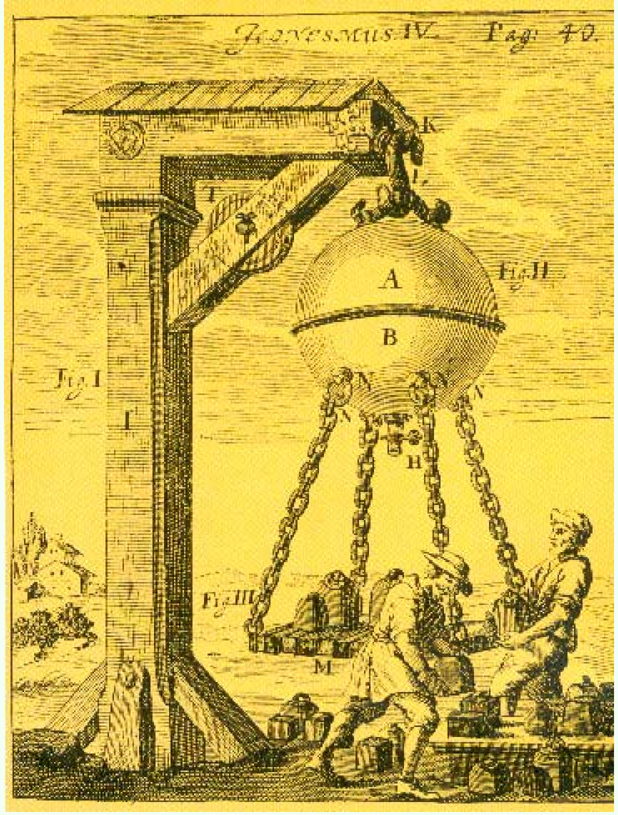
Mass



Time

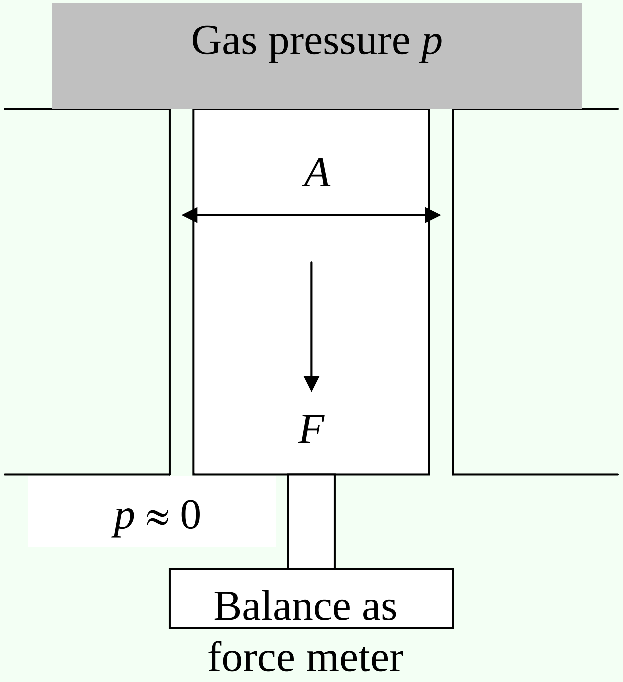
Length

It follows one of the measurement principles.



Measurement of vacuum pressure

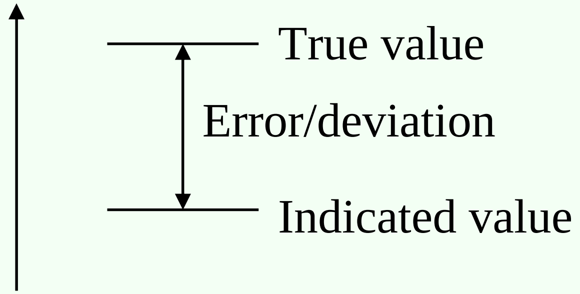
$$p = \frac{F}{A}$$



This is a traceable instrument usable as primary standard

Errors and uncertainties

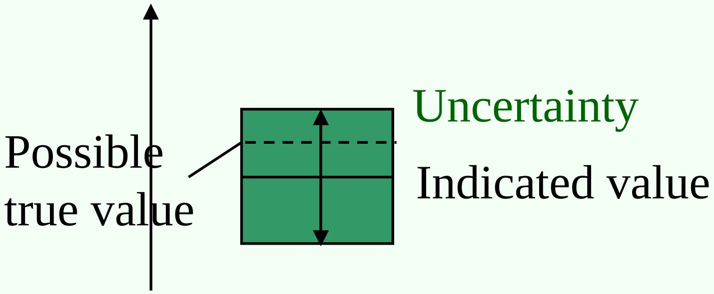
Error: A wrong reading of a gauge. A deviation from a true value defined by the SI units.


True value

Error/deviation

Indicated value

Uncertainty: The possible ***range*** by which a reading ***may*** not reflect the true value defined by the SI units.

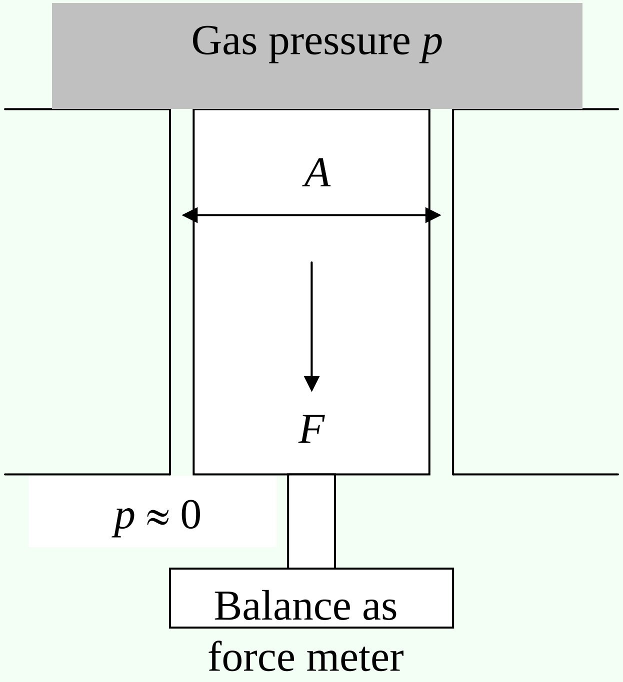

Uncertainty

Possible true value

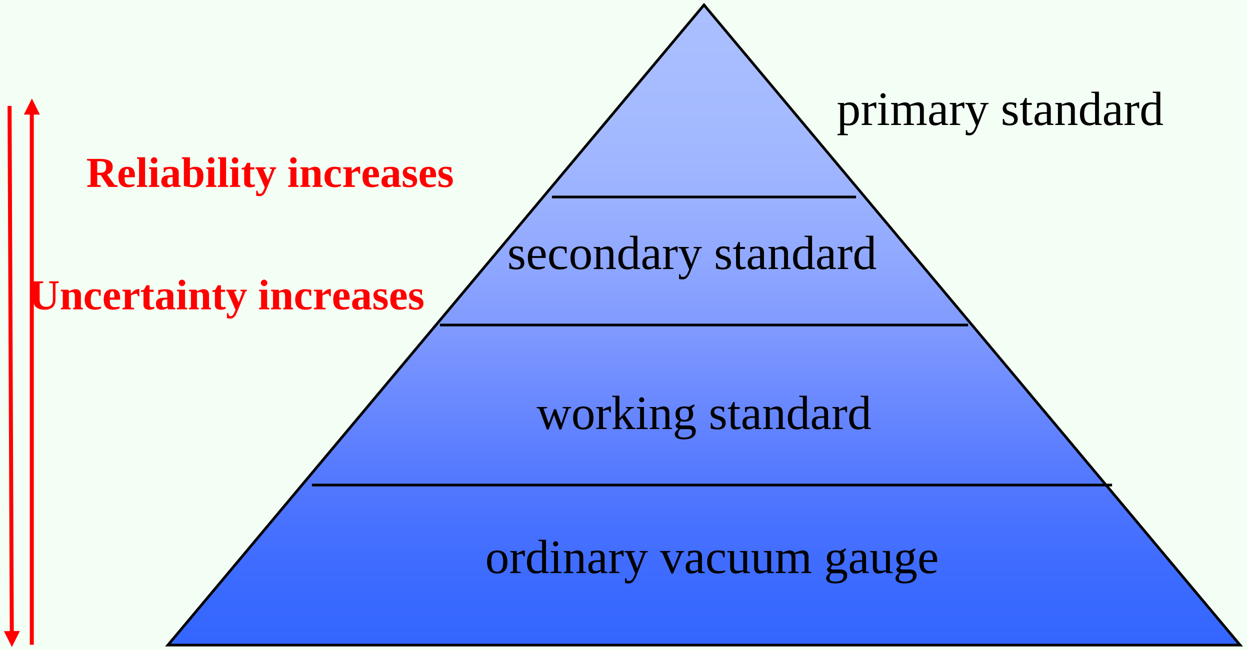
Indicated value

Measurement of vacuum pressure

$$p = \frac{F}{A}$$



The calibration chain


primary standard

Reliability increases

secondary standard

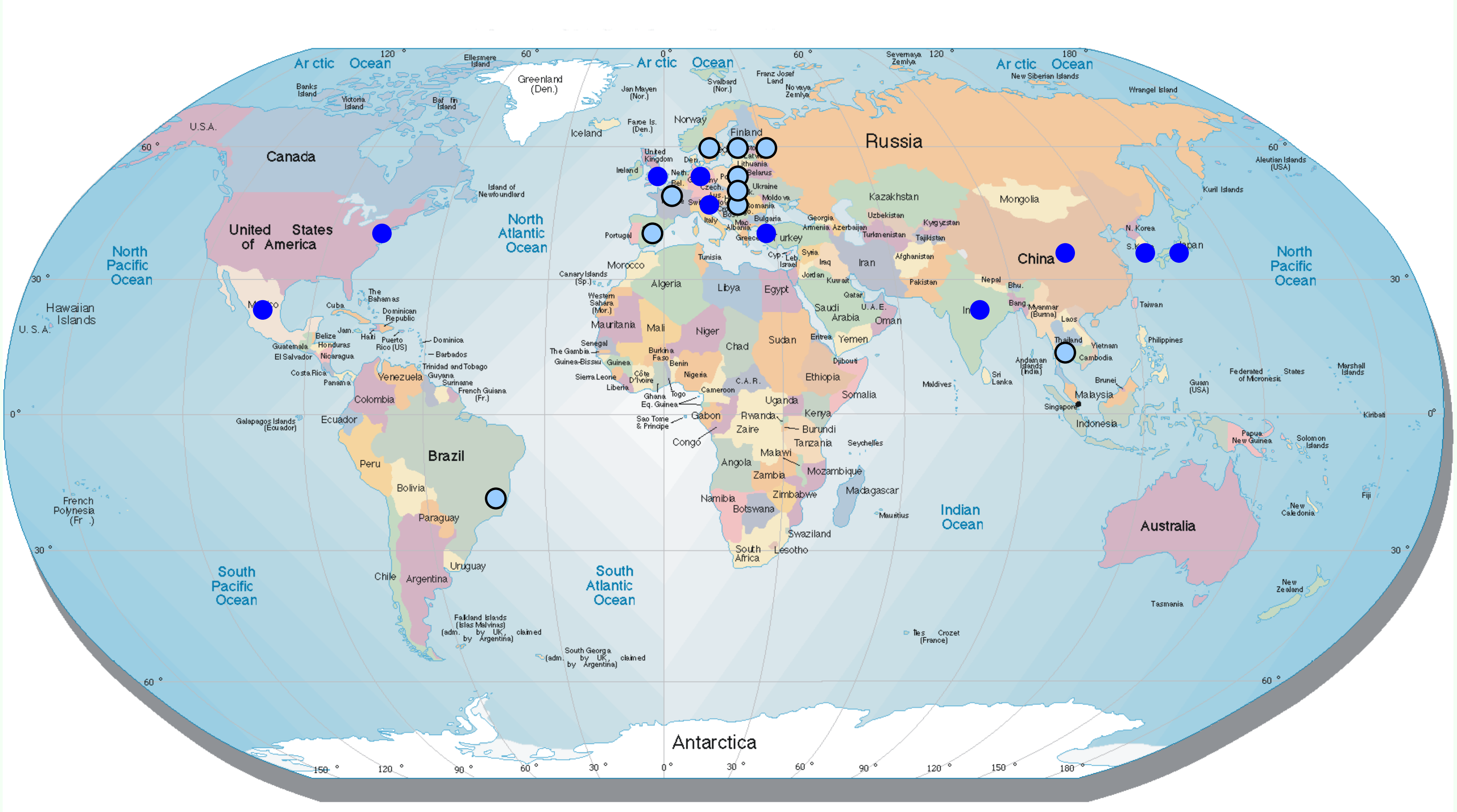
Uncertainty increases

working standard

ordinary vacuum gauge

Traceability and primary standards

● Fully developed primary standards ○ partly developed standards



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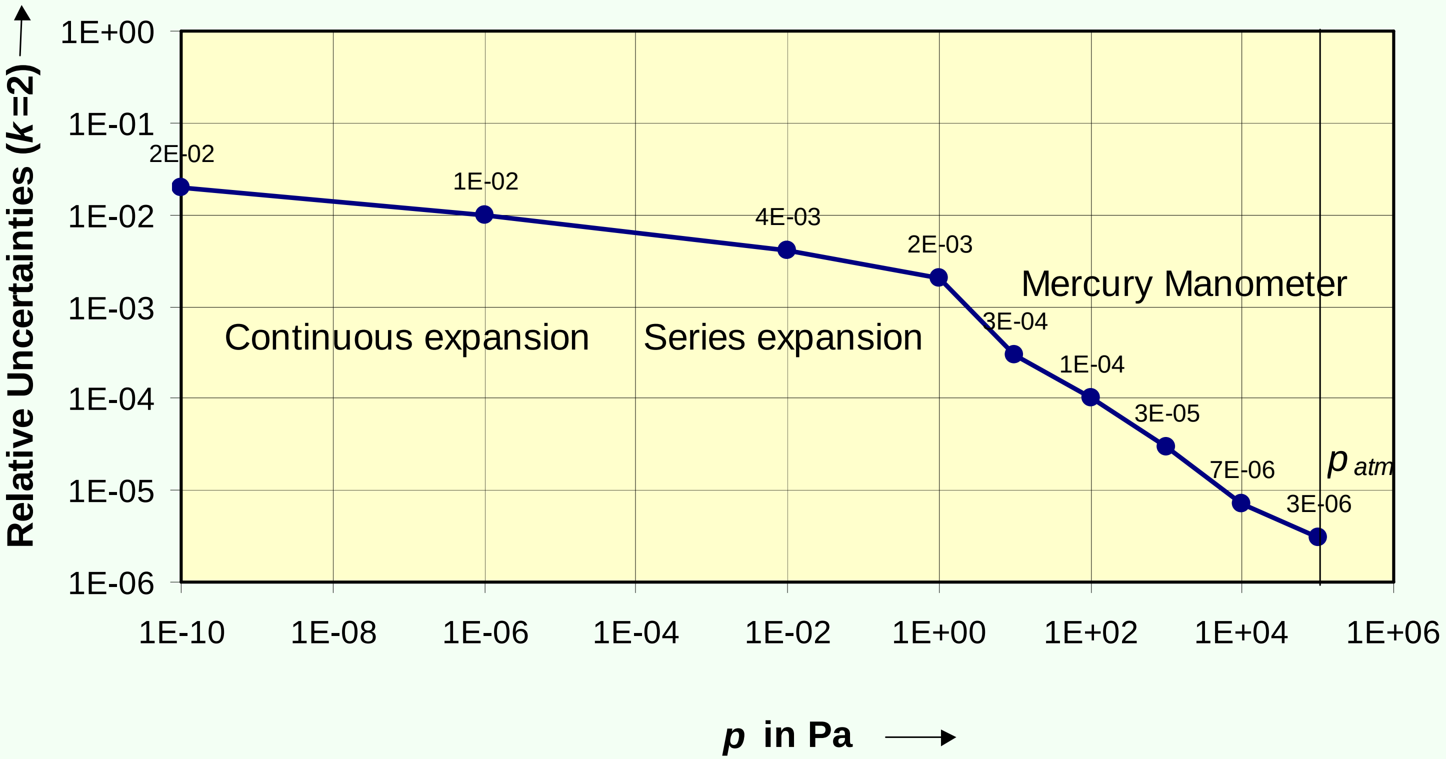
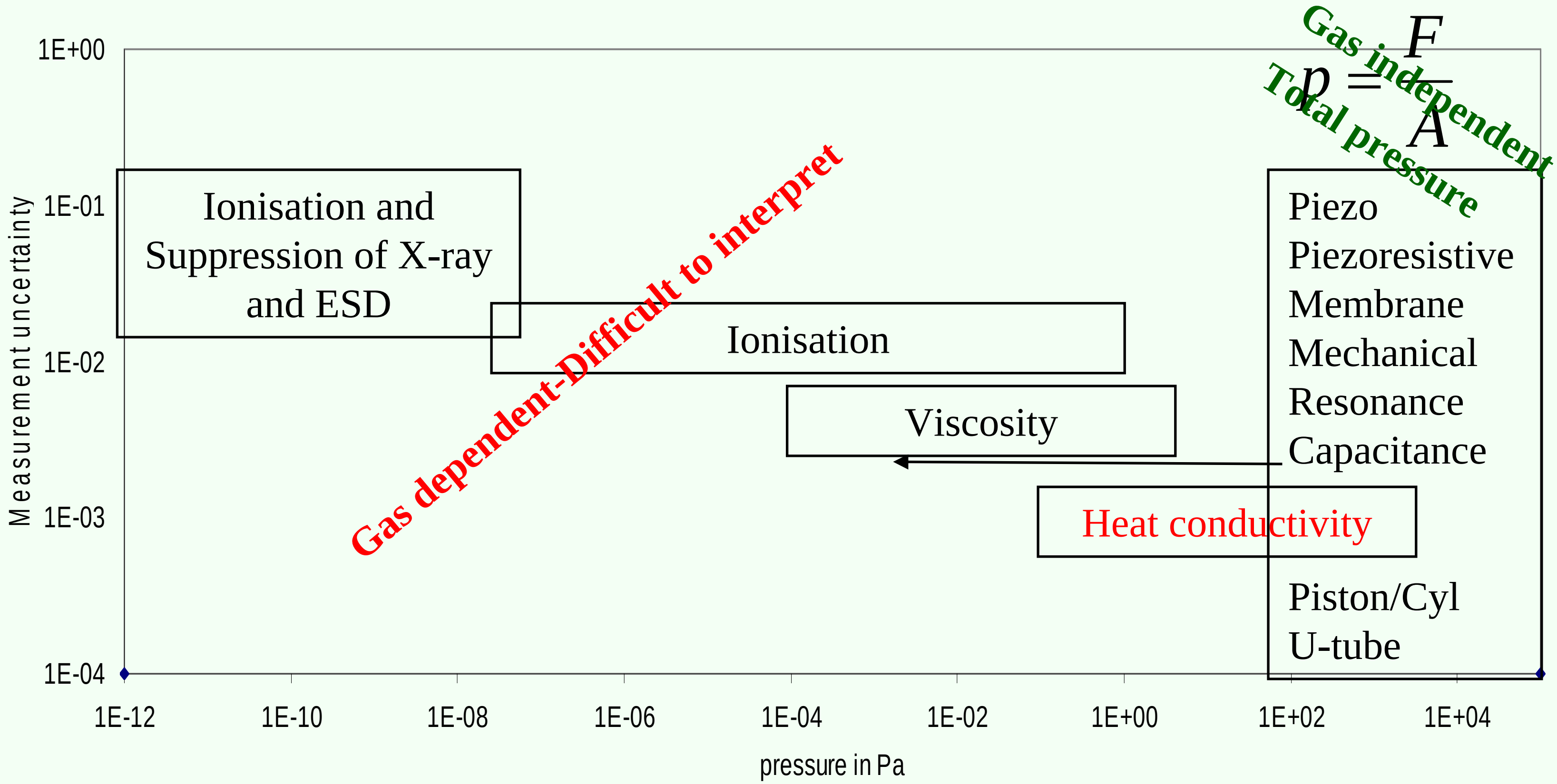
Best accuracy available

Relative uncertainties of pressures in primary standards



Traceability and primary standards

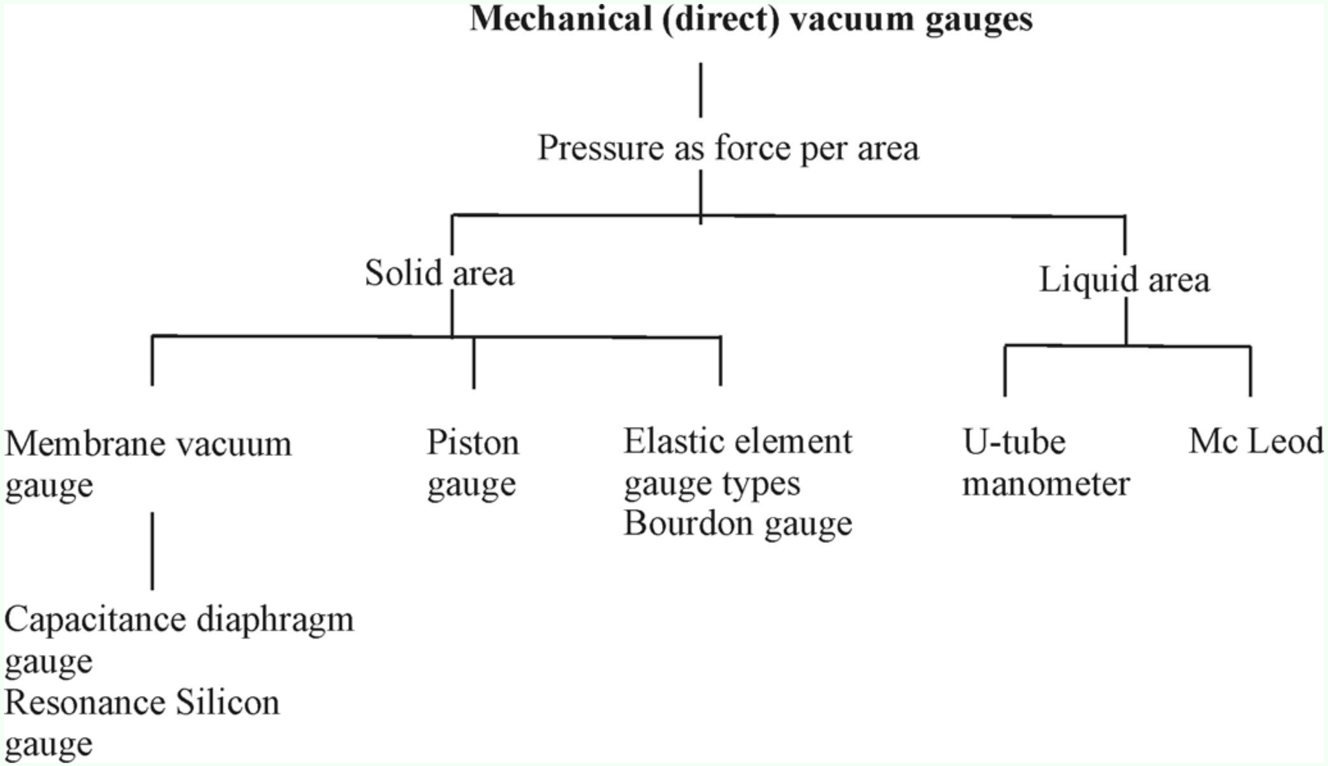
Measurement principles and gauges



$$p = \frac{F}{A}$$

Fine and high vacuum gauges

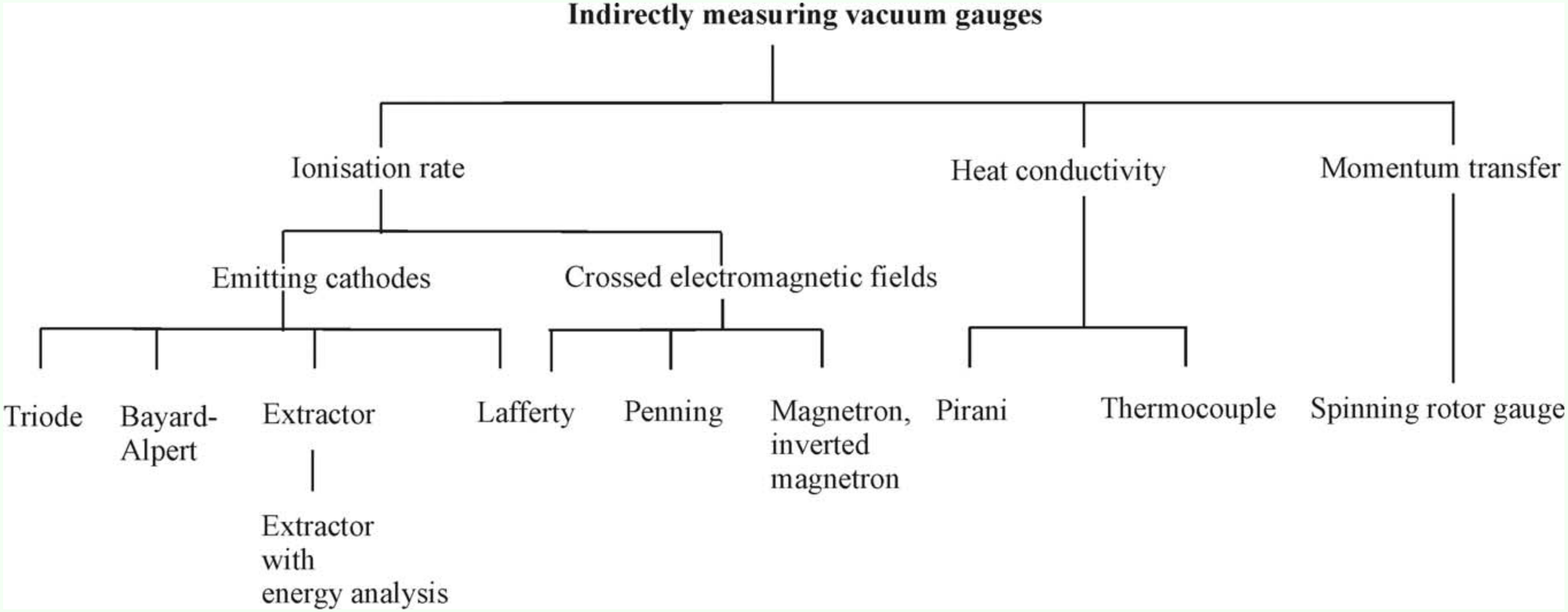
Measurement principles and gauges



Mechanical (direct) vacuum gauges

- Pressure as force per area
  - Solid area
    - Membrane vacuum gauge
      - Capacitance diaphragm gauge
Resonance Silicon gauge
    - Piston gauge
    - Elastic element gauge types
Bourdon gauge
  - Liquid area
    - U-tube manometer
    - Mc Leod

Measurement principles and gauges

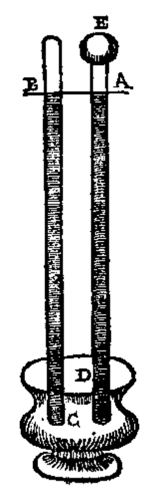


Indirectly measuring vacuum gauges

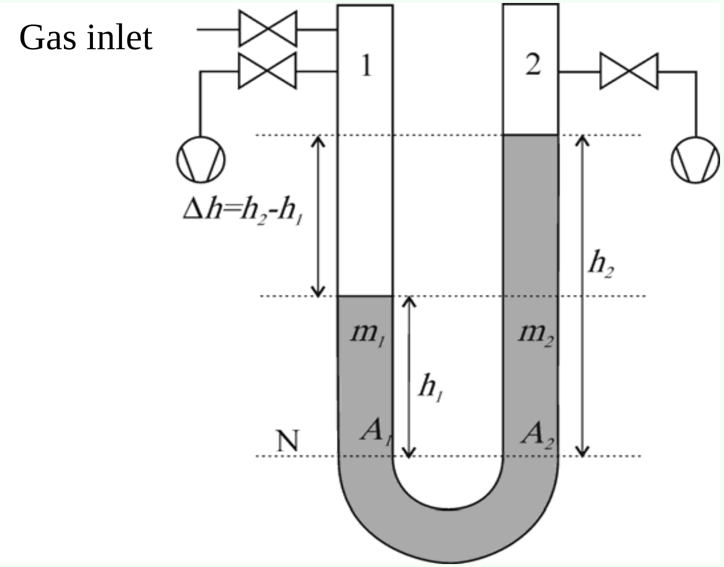
- Ionisation rate
  - Emitting cathodes
    - Triode
    - Bayard-Alpert
    - Extractor
      - Extractor with energy analysis
    - Lafferty
  - Crossed electromagnetic fields
    - Penning
    - Magnetron, inverted magnetron
- Heat conductivity
  - Pirani
  - Thermocouple
- Momentum transfer
  - Spinning rotor gauge

Fine and high vacuum gauges

Measurement principles and gauges



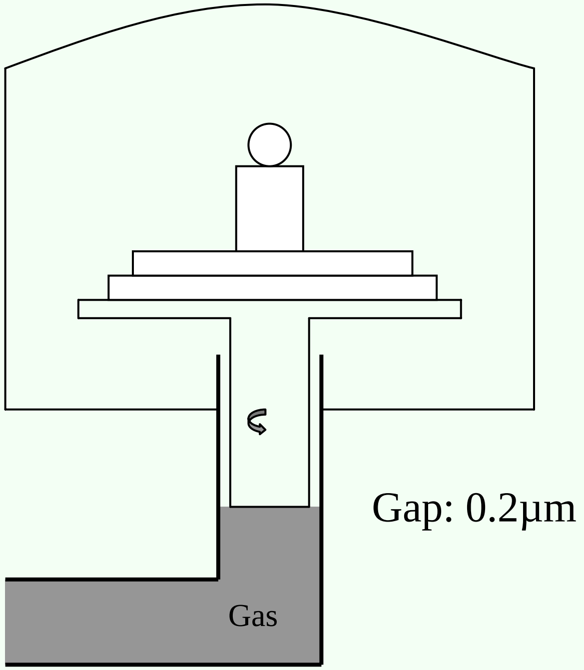
$$p = \frac{F}{A} = \rho g \Delta h$$



The mercury U-tube exists since Torricelli (1644). It is still the most accurate vacuum gauge > 100 Pa (1 mbar)!

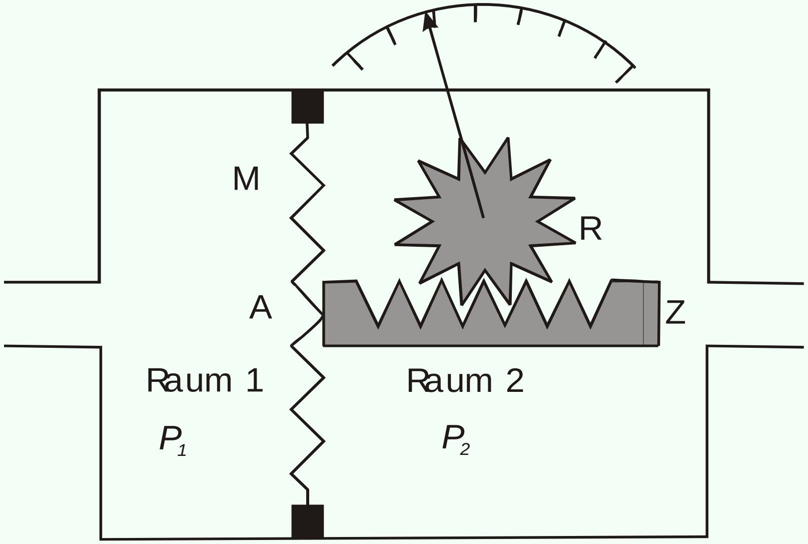
The rotating piston gauge

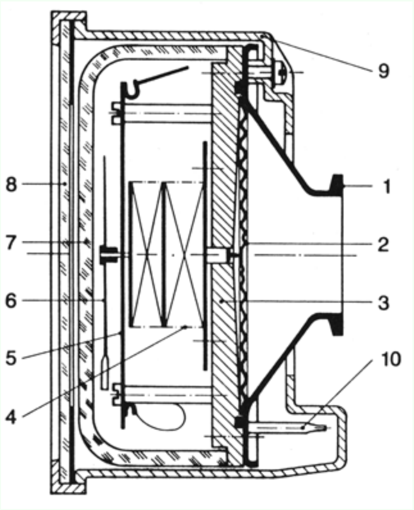
$$p = \frac{F}{A}$$



Measurement principles and gauges

Mechanical gauges





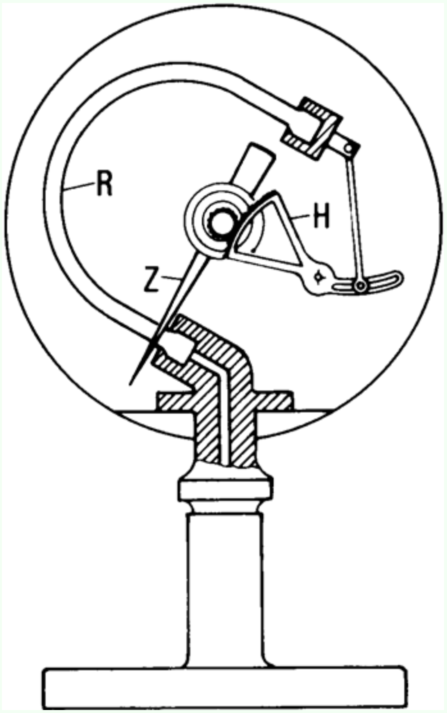
3 Groups:

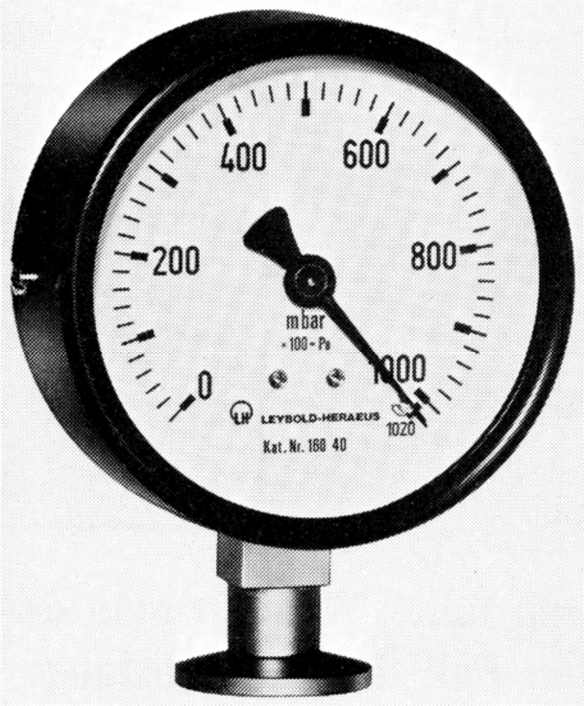
1. Ref.side p_{atm} and contains meas.dev.
2. Ref.side p=0, meas.dev. on test side (1)

3. Ref.side p=0 and contain meas.dev.

Measurement principles and gauges

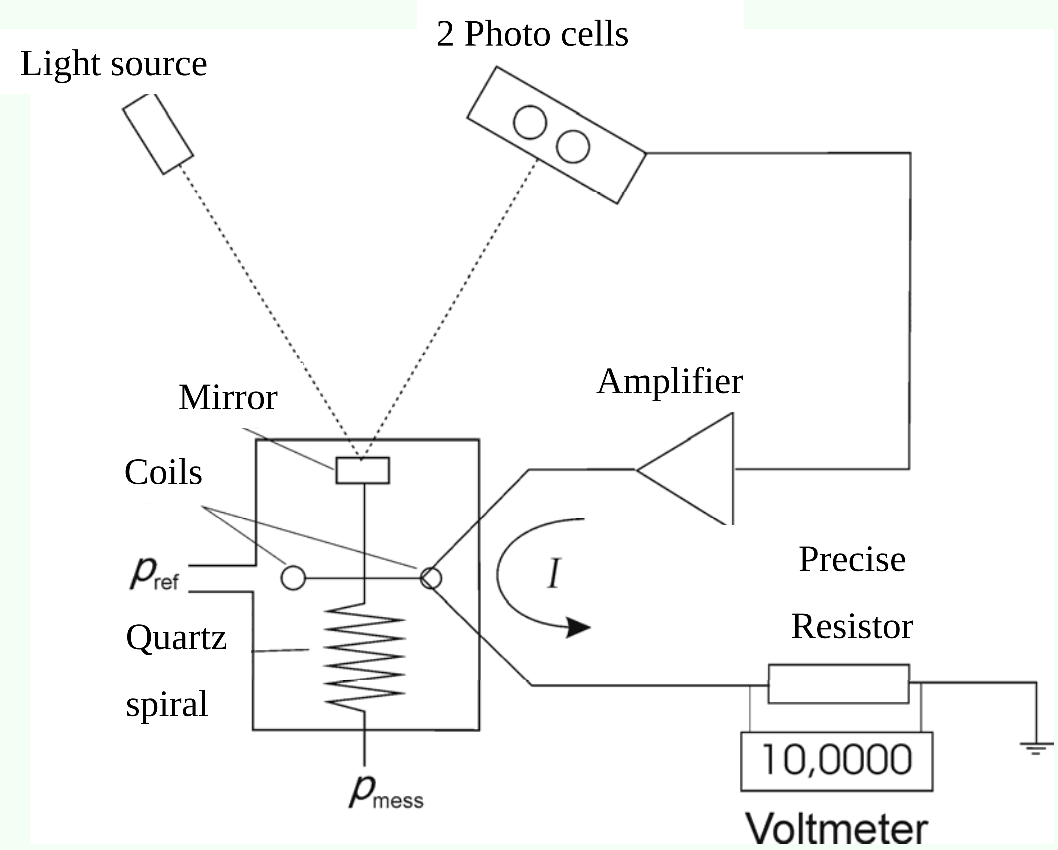
Mechanical gauges: Bourdon gauges





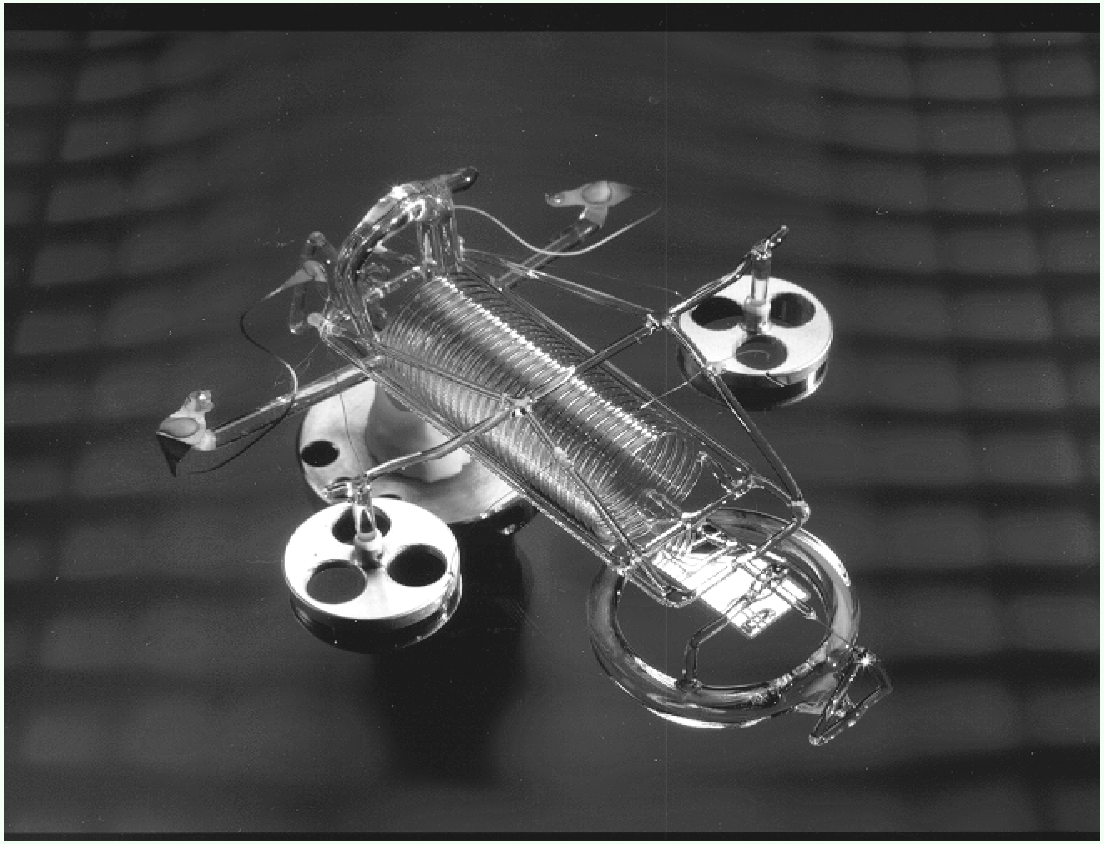
Measurement principles and gauges

Mechanical gauges: Bourdon gauges



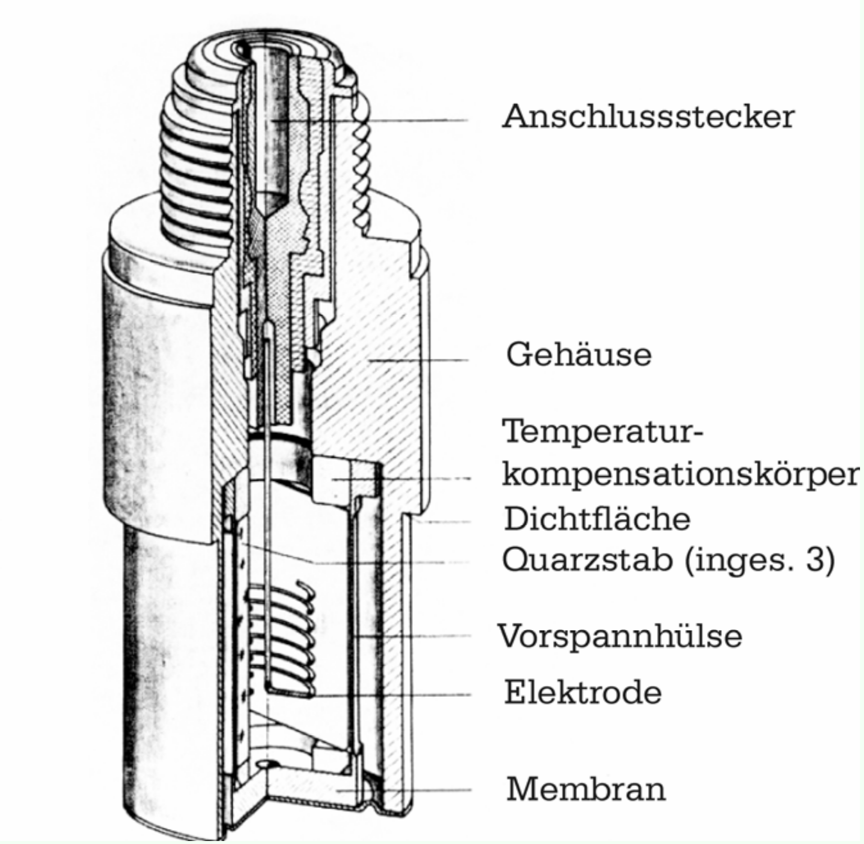
Measurement principles and gauges

Mechanical gauges: Bourdon gauges



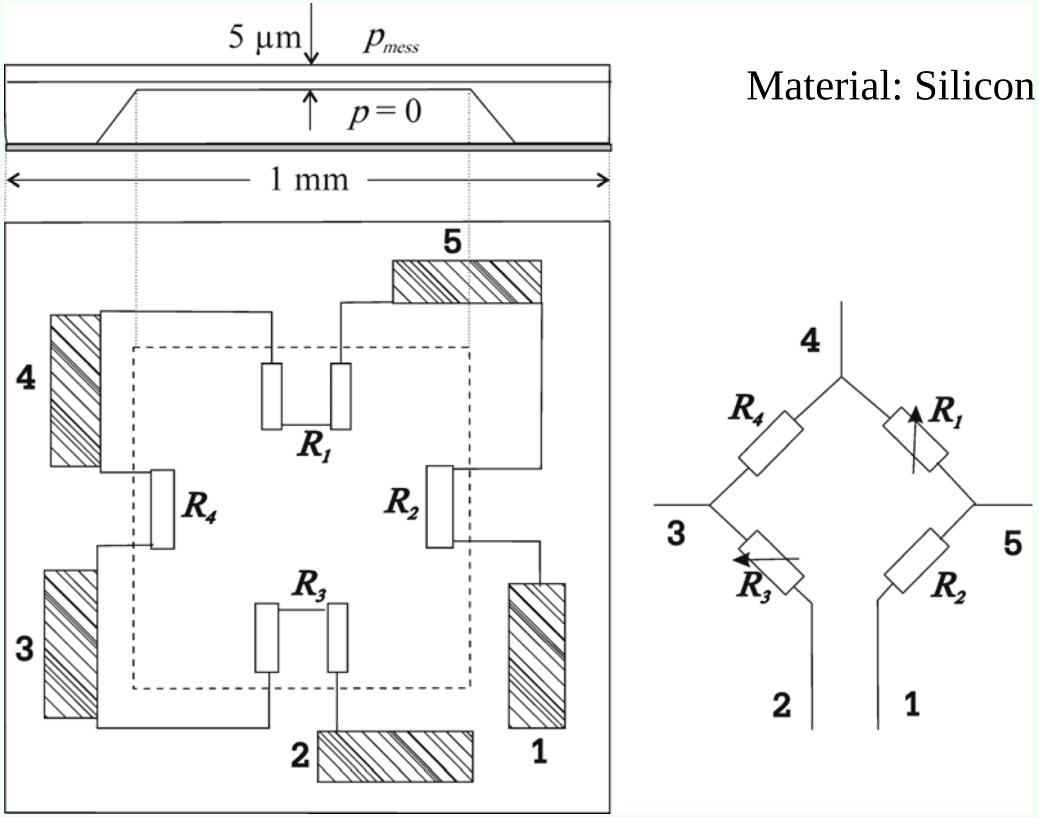
Fine and high vacuum gauges

Piezoeffect used by membrane



Measurement principles and gauges

Piezoresistive effect



Material: Silicon (MEMS)

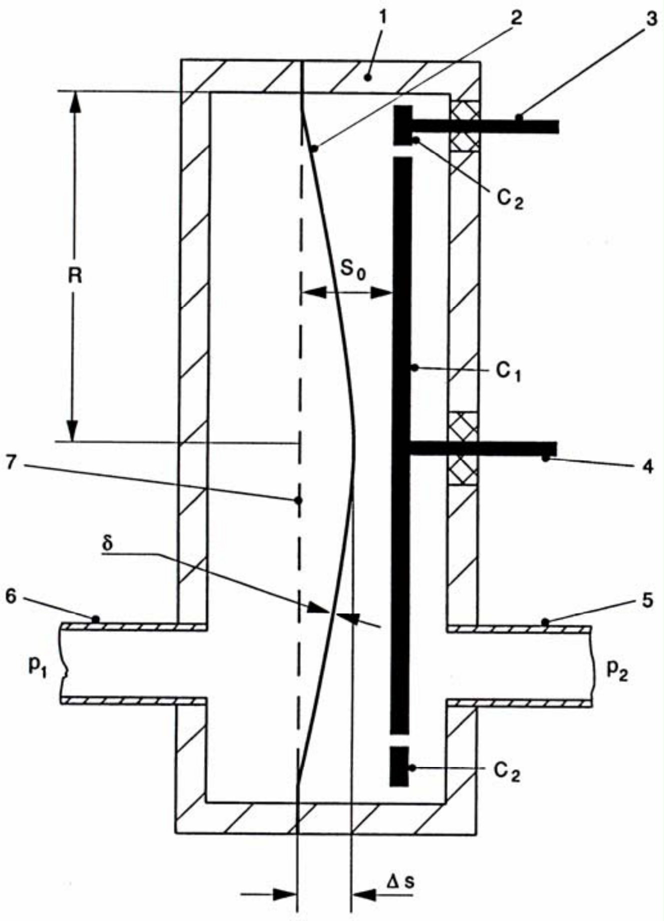
Measurement principles and gauges

Capacitance diaphragm gauge

Sensitivity of deflection: 0.4 nm!

Membrane (INVAR, Ceramic):
as low as 25 µm.

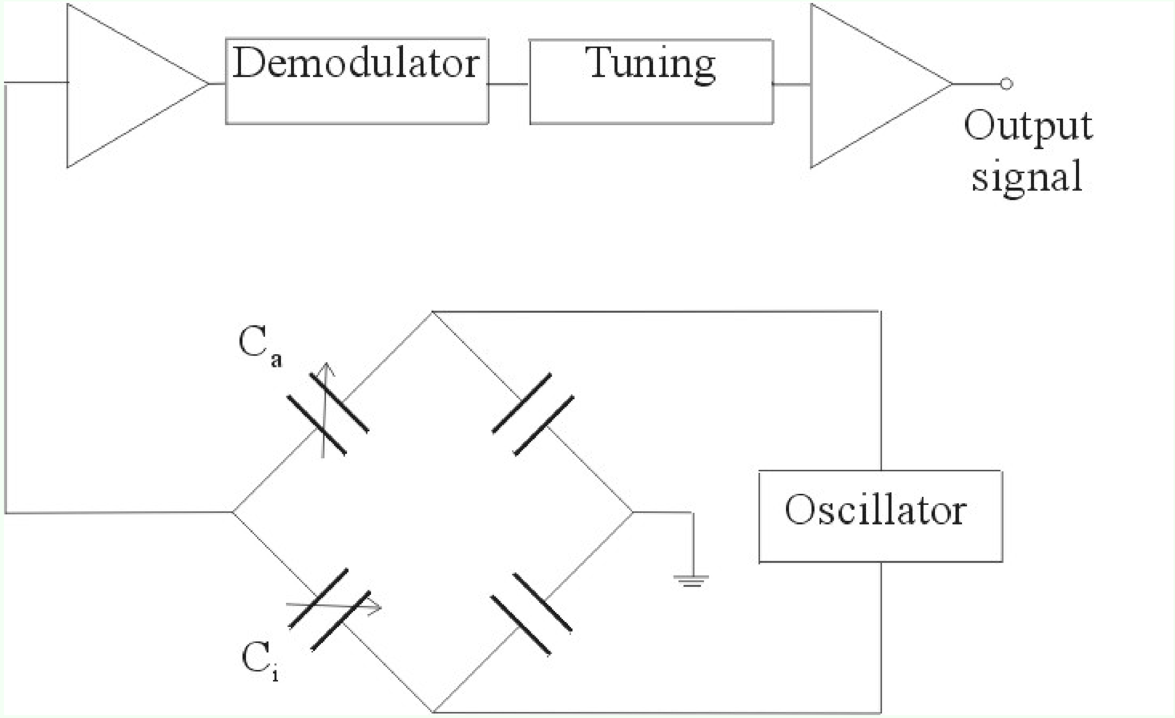
Two improve zero stability:
2 capacitors plus thermostated housing



Fine and high vacuum gauges

Measurement principles and gauges

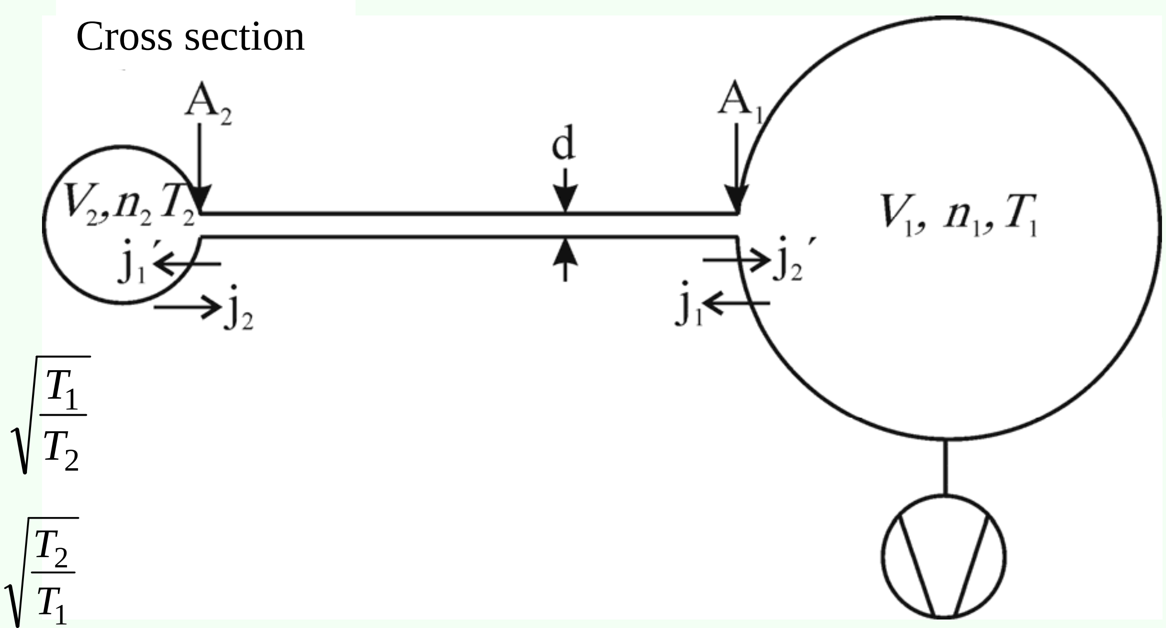
Electrical block diagram of capacitance diaphragm gauge



Fine and high vacuum gauges

Measurement principles and gauges

Thermal transpiration effect



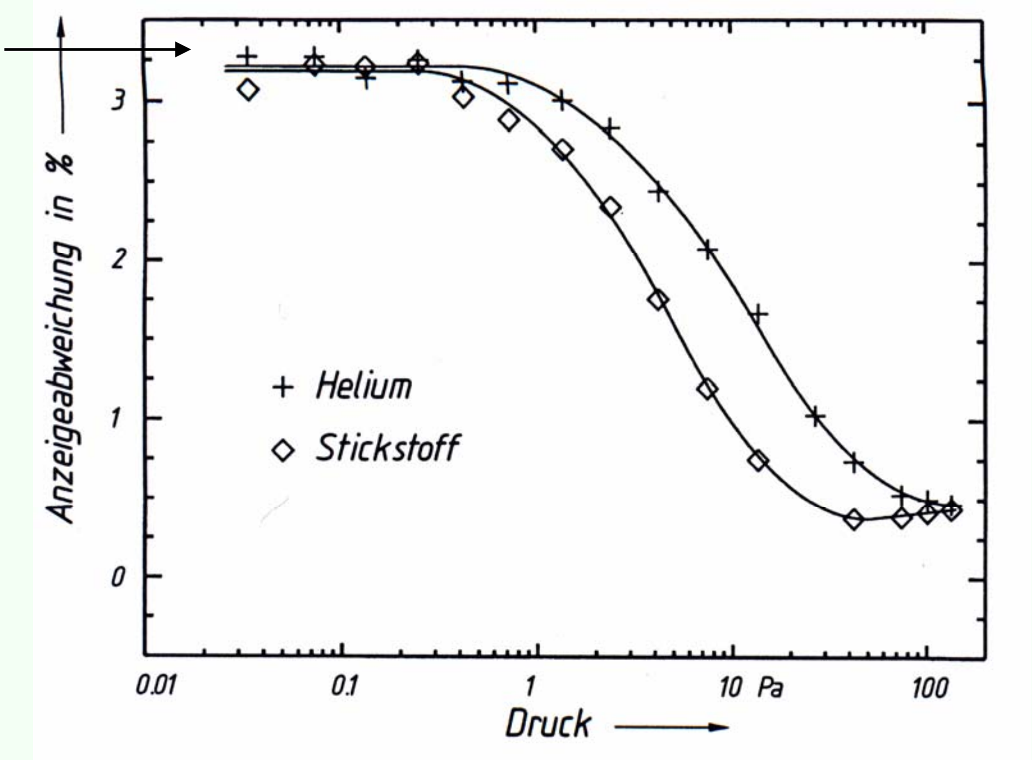
$$\frac{n_2}{n_1} = \sqrt{\frac{T_1}{T_2}}$$

$$\frac{p_2}{p_1} = \sqrt{\frac{T_2}{T_1}}$$

Measurement principles and gauges

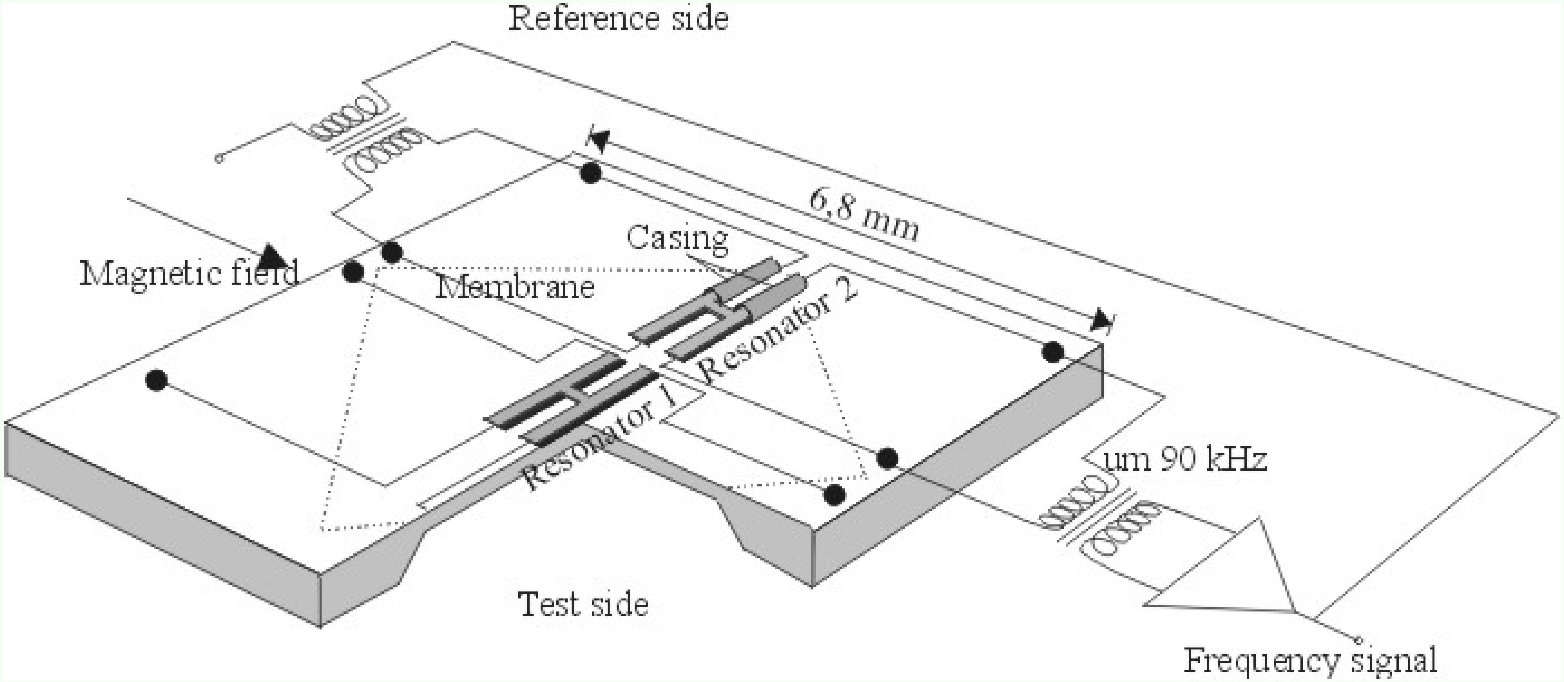
Thermal transpiration effect

$$\sqrt{\frac{318}{296}} = 1.036$$



Fine and high vacuum gauges

Measurement principles and gauges



Resonance Silicon Gauges

Designed by MEMS

Happy Birthday

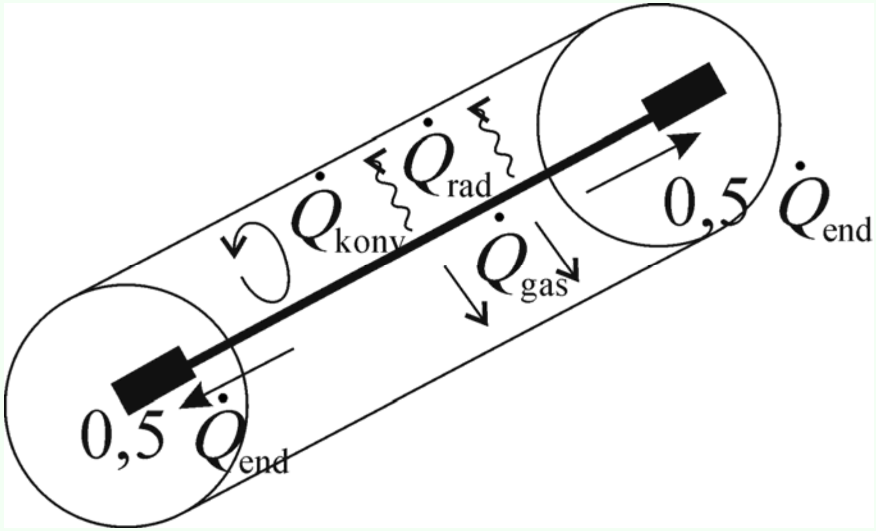
1906-2006

100

THE PIRANI GAUGE

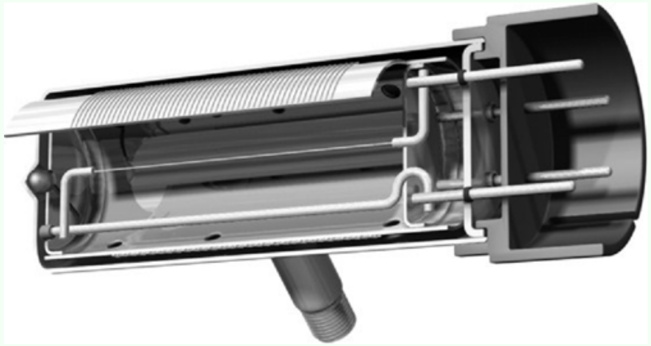
Measurement principles and gauges

Heat conductivity through a gas

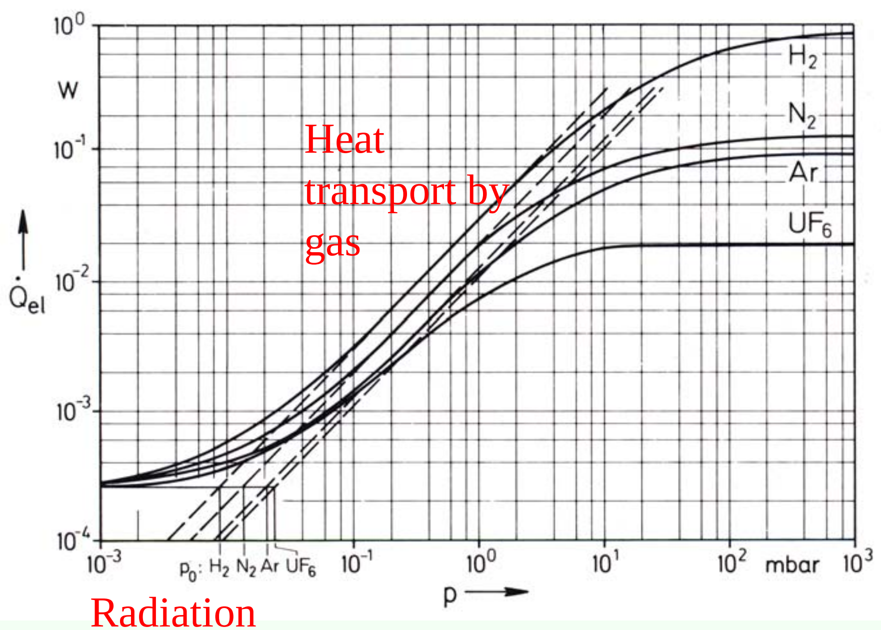


Uncertainties due to the physical principle of measurement

Example: Pirani gauge



convection



Heat transport by gas

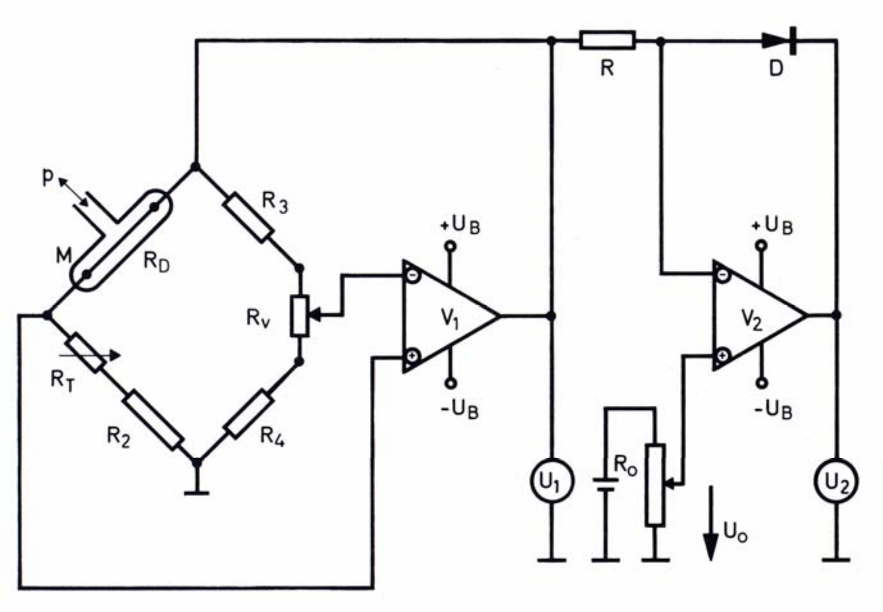
Radiation and conduction

Measurement principles and gauges

Electrical circuit for Pirani gauge

Constant temperature

Constant heating voltage, current, or power

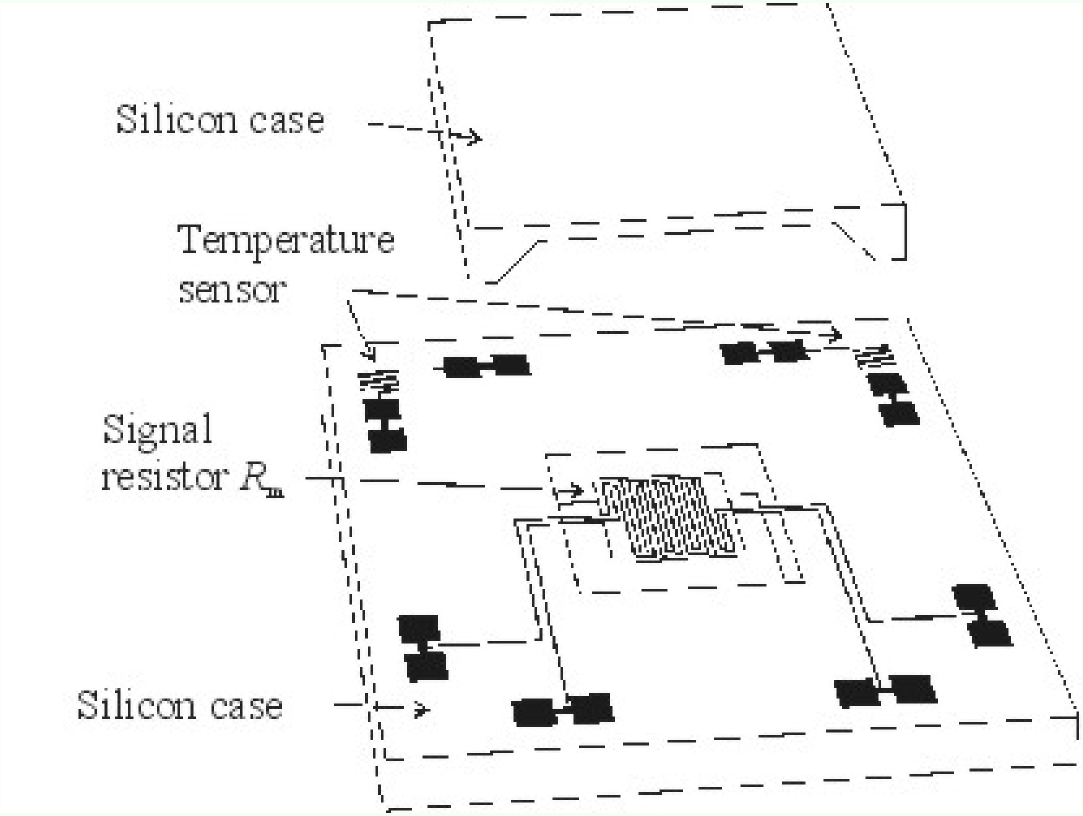


Measurement principles and gauges

Mikro Pirani (MEMS manufactured) by MKS

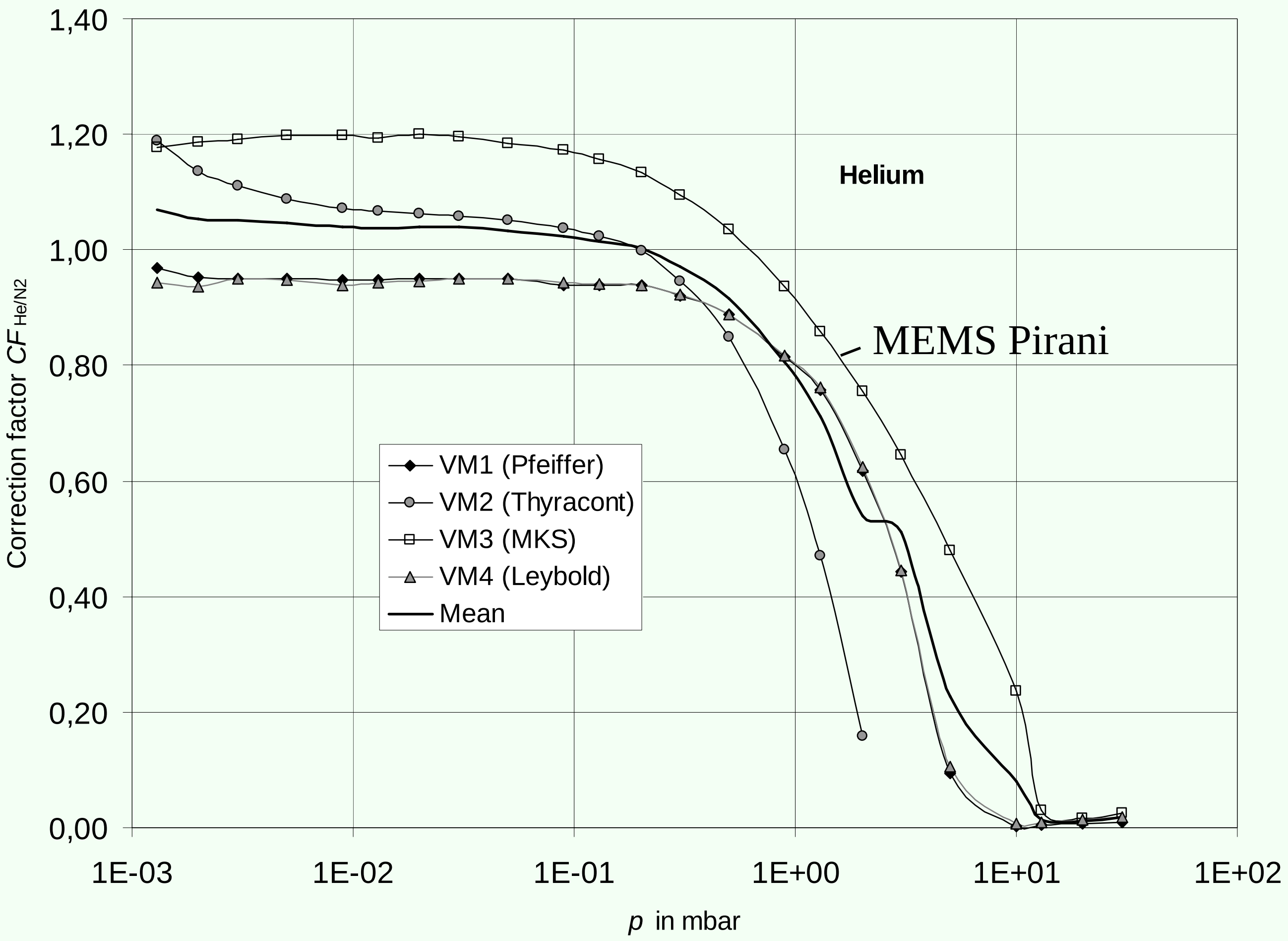
Heated sheet 60°C

MEMS: higher Knudsen number, no convection



Measurement principles and gauges

Correction factor for helium for 4 different Pirani gauges



Fine and high vacuum gauges

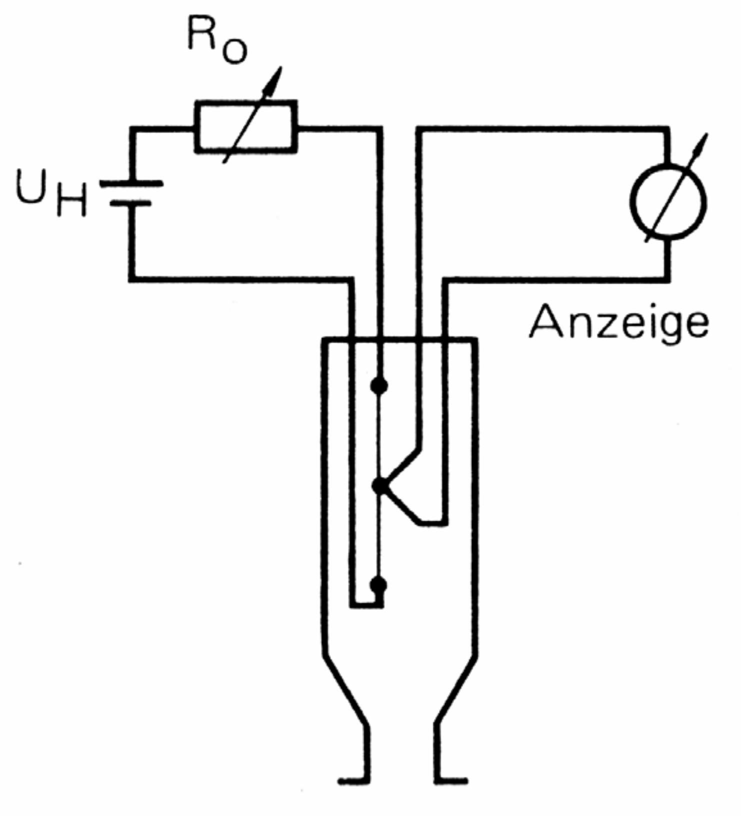
Measurement principles and gauges

Experimental standard deviations of repeat calibrations for 4 different Pirani gauges at various pressures

#	**Gauge**		***s* in %**	
		0,05 mbar	**3 mbar**	**30 mbar**
1	Pfeiffer TPR 280	0,19	0,13	0,09
2	Thyracont VSP52	0,06	0,35	3,30
3	MKS 925C	0,10	0,12	0,19
4	Leybold TTR91	0,03	0,09	0,12

Measurement principles and gauges

Thermocouple gauge

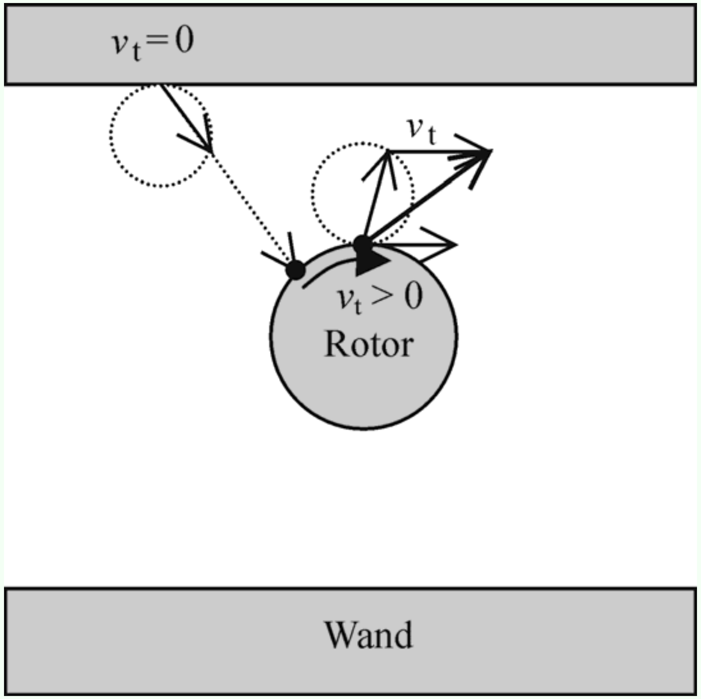


Fine and high vacuum gauges

Measurement principles

Viscosity

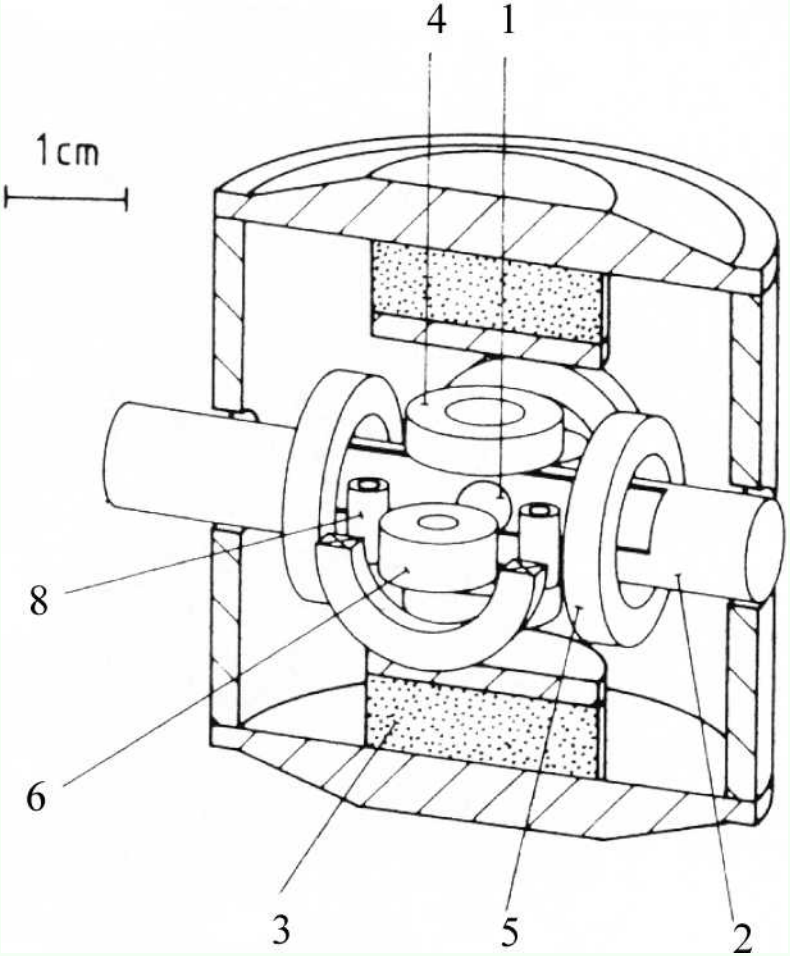
$$p = \sqrt{\frac{8kT}{\pi m}} \cdot \frac{\pi d \rho}{20\sigma}\left(\left(\frac{\dot{\omega}}{\omega}\right) - RD(\omega)\right)$$



Fine and high vacuum gauges

Measurement principles and gauges

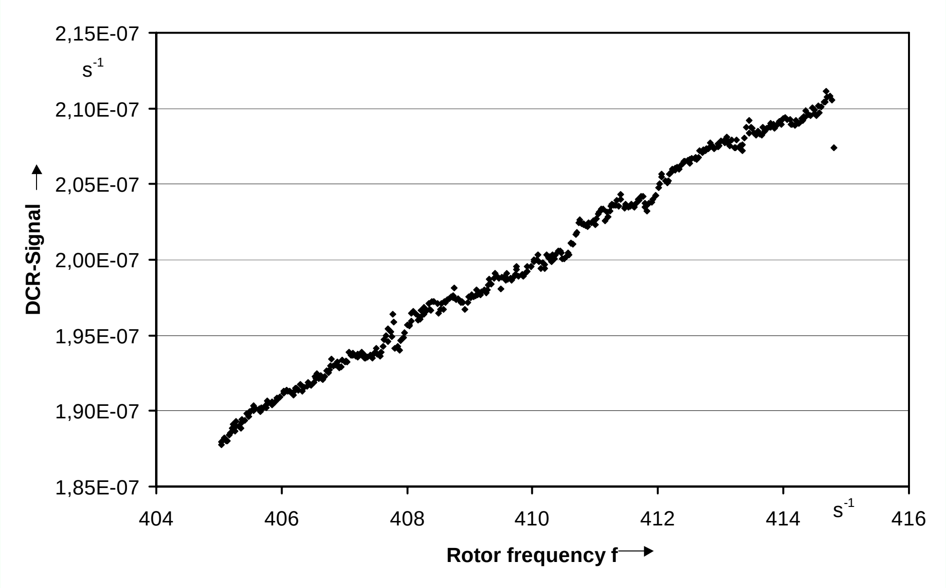
Sprinning
rotor gauge



Fine and high vacuum gauges

Sprinning rotor gauge

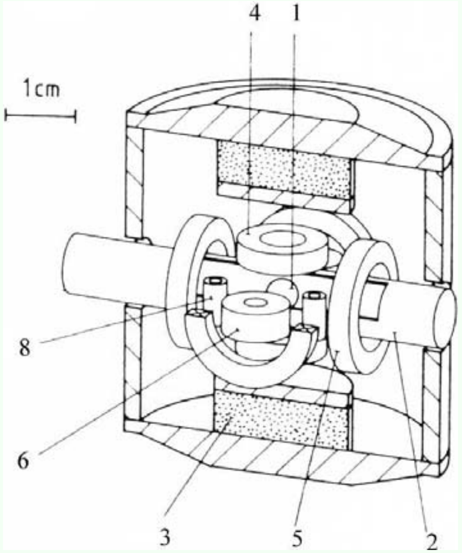
Residual drag vs. frequency of rotor



Measurement principles and gauges

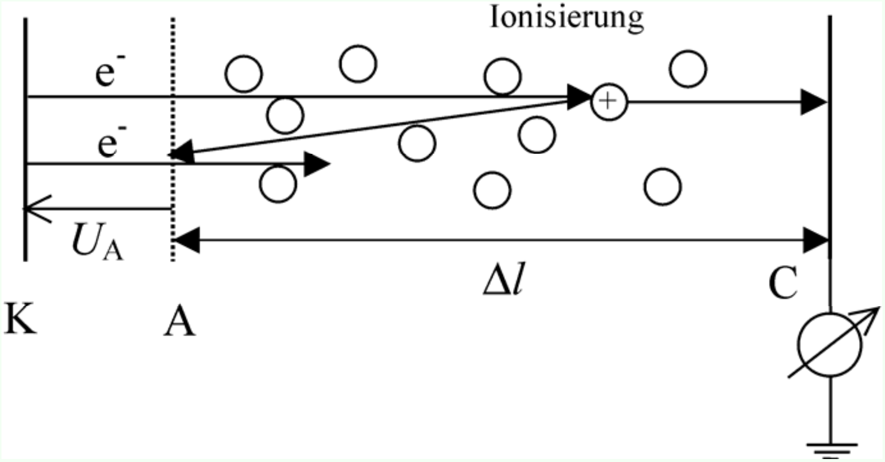
Sprinning rotor gauge

- No gas consumption (e.g. by ionization)
- No dissociation (hot cathode)
- Low outgassing rate
- Predictable reading
- High accuracy
- High long-term stability



Measurement principles

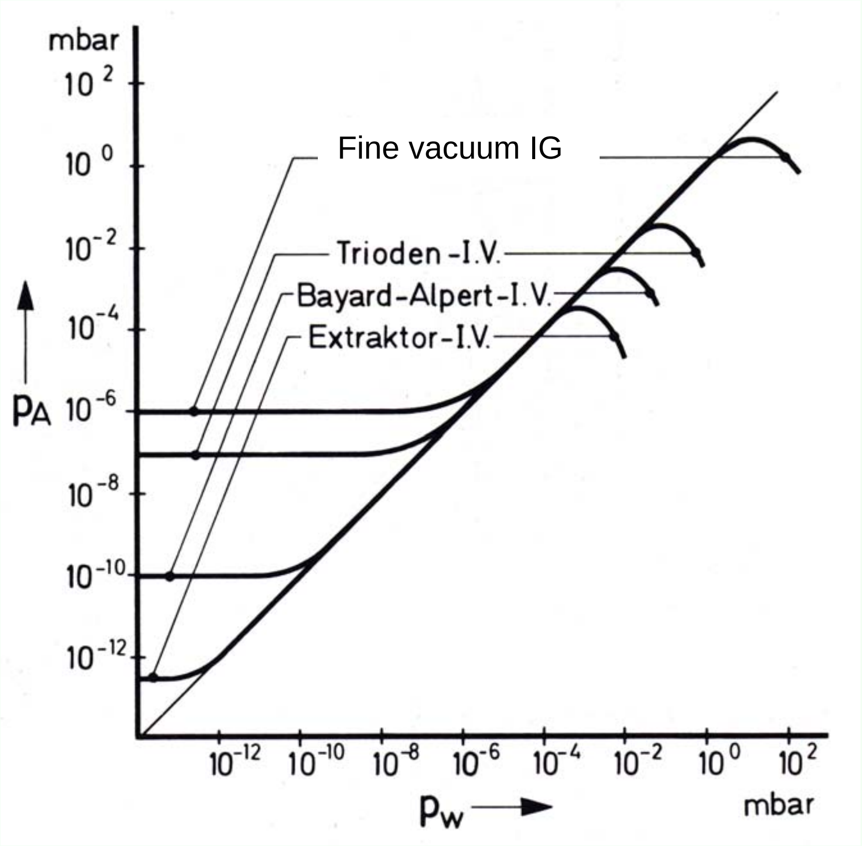
Ionisation



Fine and high vacuum gauges

Measurement principles

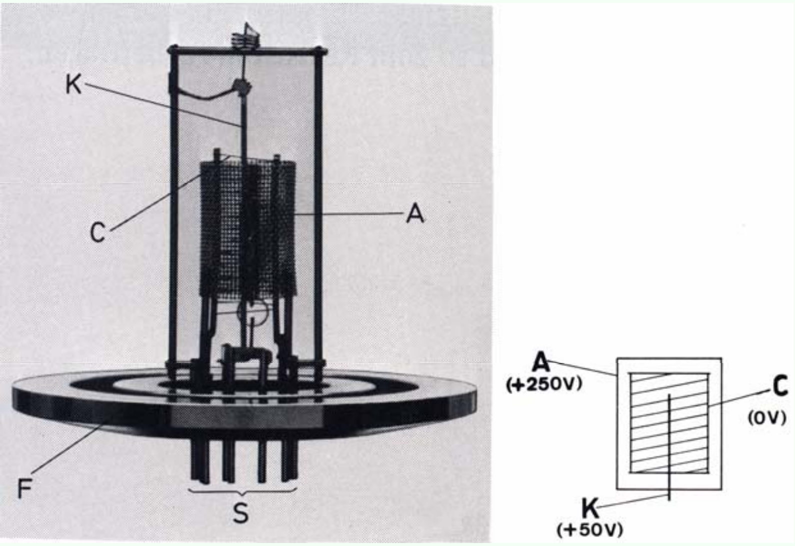
Ionization gauges for different vacuum ranges

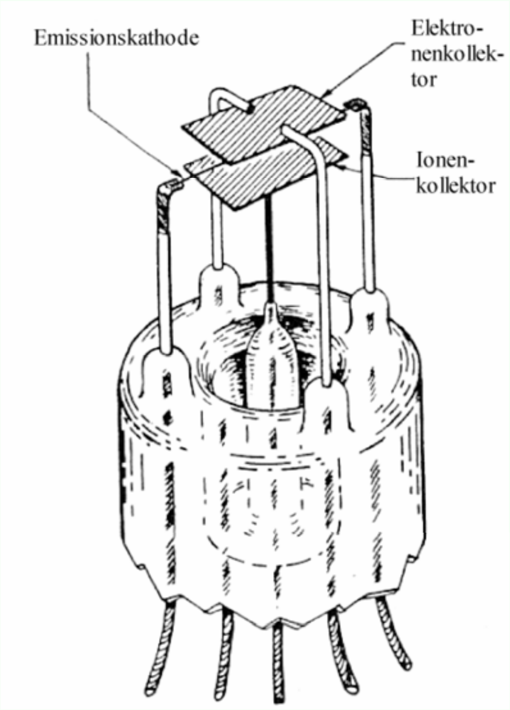


Fine and high vacuum gauges

Measurement principles

Ionisation gauges for fine vacuum

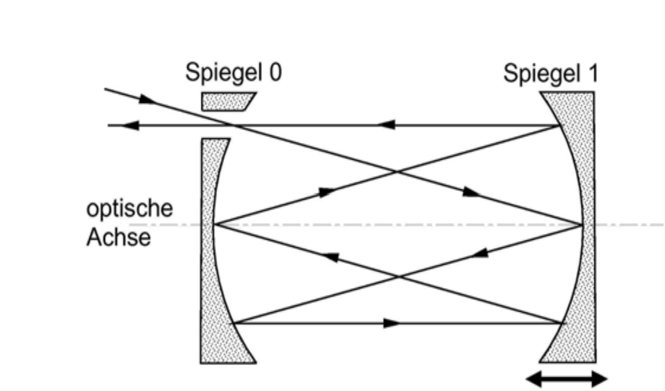




Measurement principles

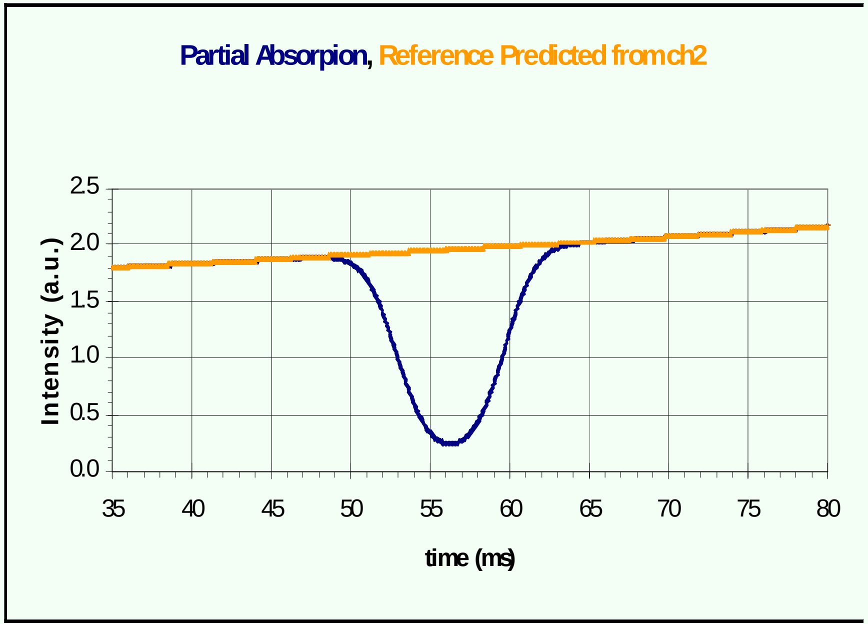
$$I(\lambda^{-1}) = I_0(\lambda^{-1})e^{-S\Phi nL}$$

$$p = \frac{kT}{S(T)\Phi(\lambda^{-1} - \lambda_0^{-1})L}\ln\left(\frac{I_0(\lambda^{-1})}{I(\lambda^{-1})}\right)$$



Previous investigations showed that TDLAS is applicable for vacuum measurement:

CO, mid-infrared (5 µm), resolution down to 10^{-5} Pa, high accuracy.



How accurate are vacuum gauges ?

Reasons for inaccuracies of vacuum gauges

General	Example
Uncertainties due to calibration chain	Has the vacuum gauge been ever calibrated? Against what standard?
Uncertainties due to installation	Pressure at gauge position may not reflect the pressure where the experiment takes place.
Uncertainties due to operation	Outgassing of an ion gauge may falsify an outgassing rate measurement.
Inaccuracies caused by the physical principle of measurement	Thermal conductivity or ion gauge is used, but gas mixture is not (accurately) known.
Uncertainties caused by the device itself	See Table 2.

How accurate are vacuum gauges ?

Reasons for inaccuracies

Gas species dependence:

Real total pressure only for force/area measuring gauges and > 100 Pa (1 mbar)! Below 100 Pa consider the thermal transpiration effect.

Spinning rotor gauges: Use a weighted mean mass, if approximate relative composition is known.

$$m_{eff} = \left(\sum_{i=1}^{n} a_i \sqrt{m_i} \right)^2 \qquad \sum_{i=1}^{n} a_i = 1$$

Thermal conductivity gauges and ionisation gauges : Scaling factors are available, but do have high uncertainties.

$$CF_{eff} = \sum_{i=1}^{n} a_i CF_i$$

How accurate are vacuum gauges ?

Uncertainties due to the vacuum gauge itself

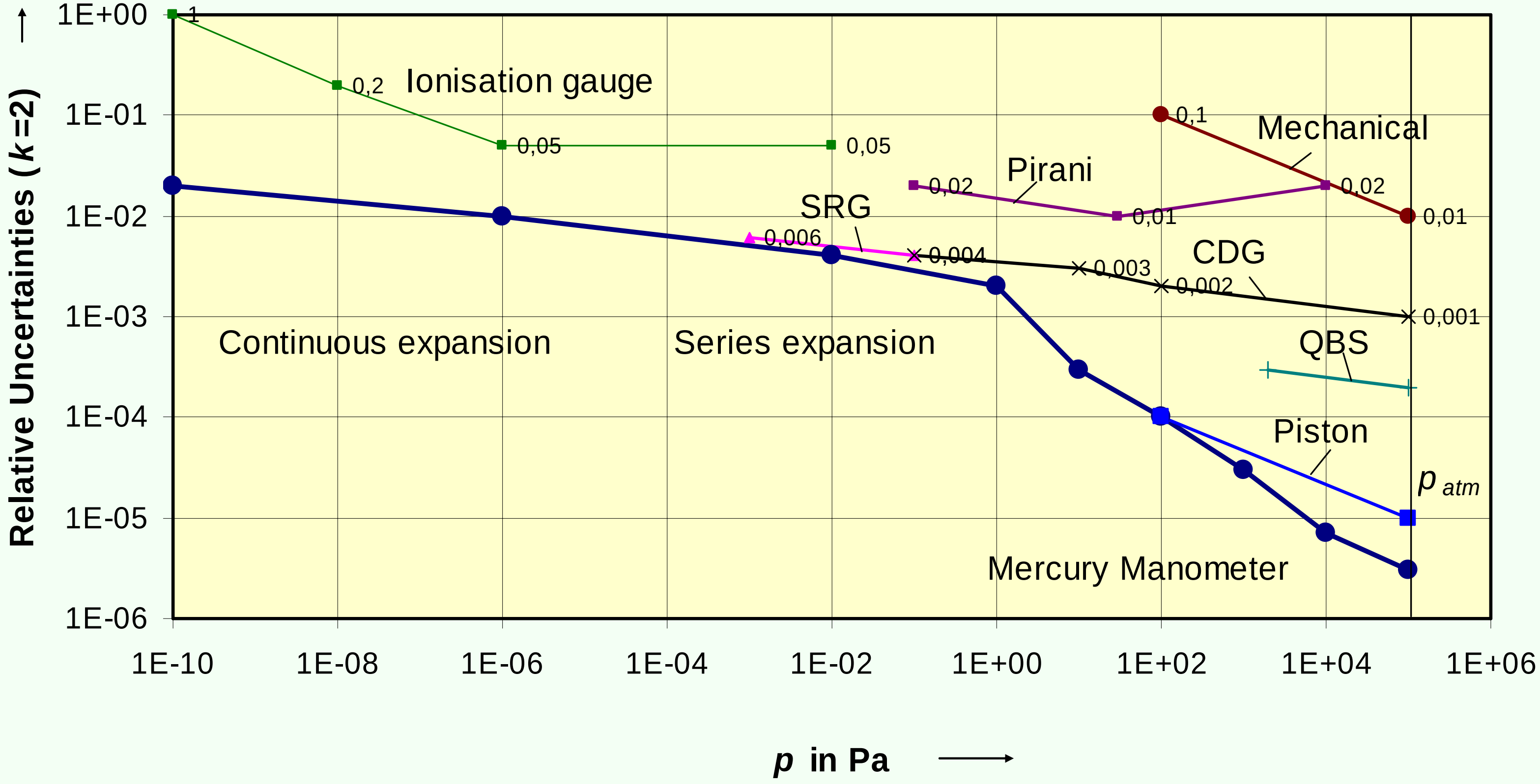
General	Examples
Offset measurement	residual drag in SRG, zeroing of Pirani gauge, X-ray- and ESD-effect for ion gauges
Offset instability (drift)	Offset drifts with environmental temperature (Piroutte effect in SRG), bridge is no more balanced with time
Resolution	Number of digits shown
Influences of environment (mainly temperature)	Enclosure temperature of Pirani changes varies, thermal transpiration effect changes in CDG, amplifier changes amplification
Non-Linearity	Ion gauge (sensitivity changes with pressure)
Integration time (scatter of data), repeatibility	Same signal at repeat measurements? Integration time in SRG, in picoammeter with ion gauge.
Reproducibility (stability of calibration constant)	Calibration constants change with time.
Hysteresis	Mechanical gauges (up, down measurement)
Prior usage, cleanliness	Surfaces change, accommodation coefficients change, secondary yield changes

How accurate are vacuum gauges ?

Table: Relative measurement uncertainty of commercially available vacuum gauges.

Gauge type	**Measurement range in Pa**	**Normal uncertainty**	**Optimum range in Pa**	**Lowest uncertainty**
Piston gauges	$10 ... 10^5$		$10^2 ... 10^5$	$10^{-4} ... 10^{-5}$
Quartz-Bourdon-manometer	$10^3 ... 10^5$		$10^3 ... 10^5$	$3x10^{-4} ... 2x10^{-4}$
Resonance silicon gauges	$10 ... 10^5$	0.003... 0.0005	$100 ... 10^5$	$2x10^{-4} ... 5x10^{-5}$
Mechanical vacuum gauge	$10^2 ... 10^5$	0.1 ...0.01		
Membrane vacuum gauge	$10^2 ... 10^5$	0.1 ...0.01		
Piezo	$10^2 ... 10^5$	1 ...0.01		
Thermocouple gauge	$10^{-1} ... 10^2$	1... 0.3		
Pirani gauges	$10^{-1} ... 10^4$	1 ... 0.1	1 ... 100	0.02 ... 0.01
Capacitance diaphragm gauges	$10^{-4} ... 10^5$	0.1... 0.003	$10^{-1} ... 10^5$	0.006... 0.001
Spinning rotor gauges	$10^{-5} ... 10$	0.1 ... 0.007	$10^{-3} ... 10^{-1}$	0.006...0.004
Penning gauges	$10^{-7} ... 1$	0.5 ... 0.2	$10^{-5} ... 1$	0.3...0.1
Magnetron gauges	$10^{-8} ... 1$	1 ...0.1	$10^{-6} ... 1$	0.1...0.02
Ionisation gauges (Emission cathodes)	$10^{-10} ... 10^{-2}$	1...0.05	$10^{-8} ... 10^{-2}$	0.2...0.02

How accurate are vacuum gauges ?



Lowest relative uncertainties for vacuum gauges and primary standards

Errors > 100 % (error factor > 1) are possible.

Fine and high vacuum gauges

Todays commercial gauges

Pirani gauge

Old classical gauges:

Gauge head + controller

Today: Active gauges or transmitter (all in one)

or

Digital gauges (digital output via interface)

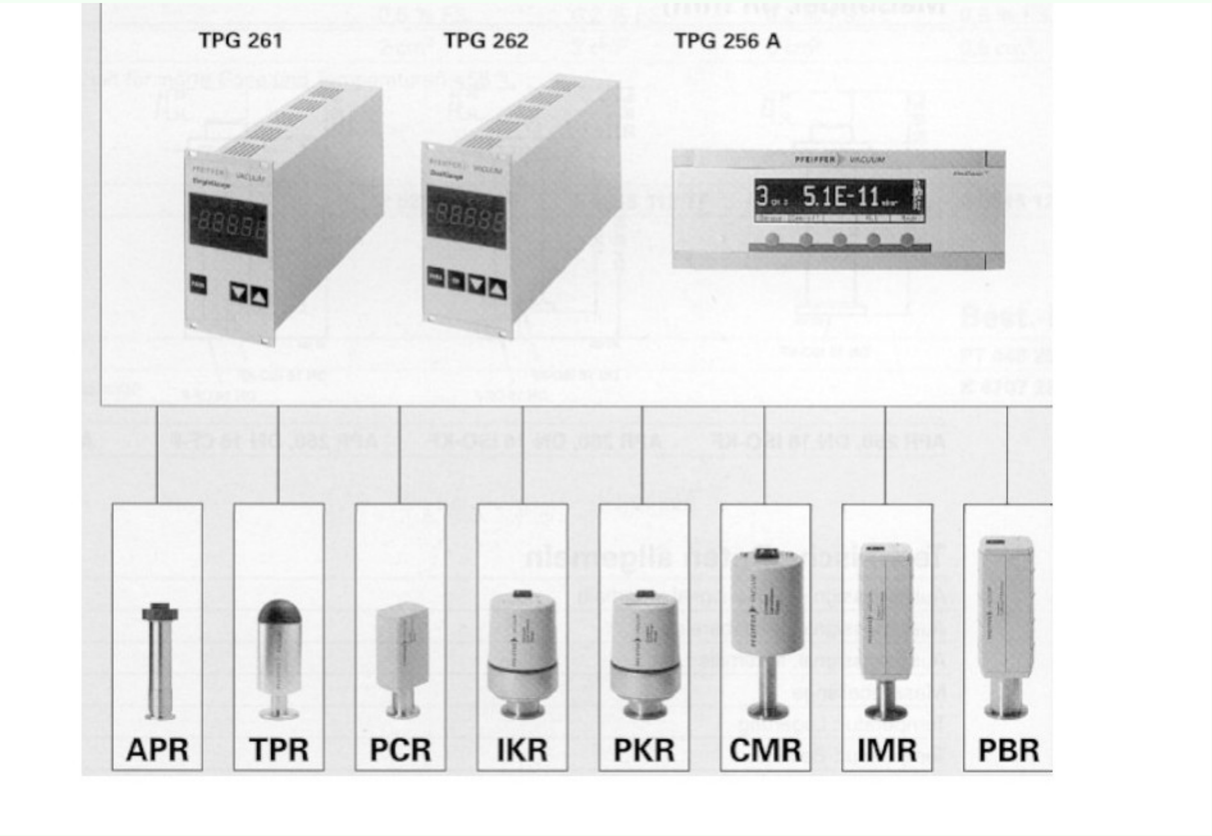
Todays commercial gauges

Transmitter gauge plus

Profibus Converter

Todays commercial gauges

Commercial „active“ Line vacuum gauges



Fine and high vacuum gauges

We have discussed:

Metrological system - primary standards- calibration chain

Measurement principles and gauges

Direct, indirect measuring gauges

Sources of uncertainties with

values from 0.001% up to 100% or factor

Thanks for listening !