Vacuum Gauges I

Karl Jousten, *Section Vacuum Metrology, PTB, Berlin*

1. Measurement of vacuum pressures and the calibration chain

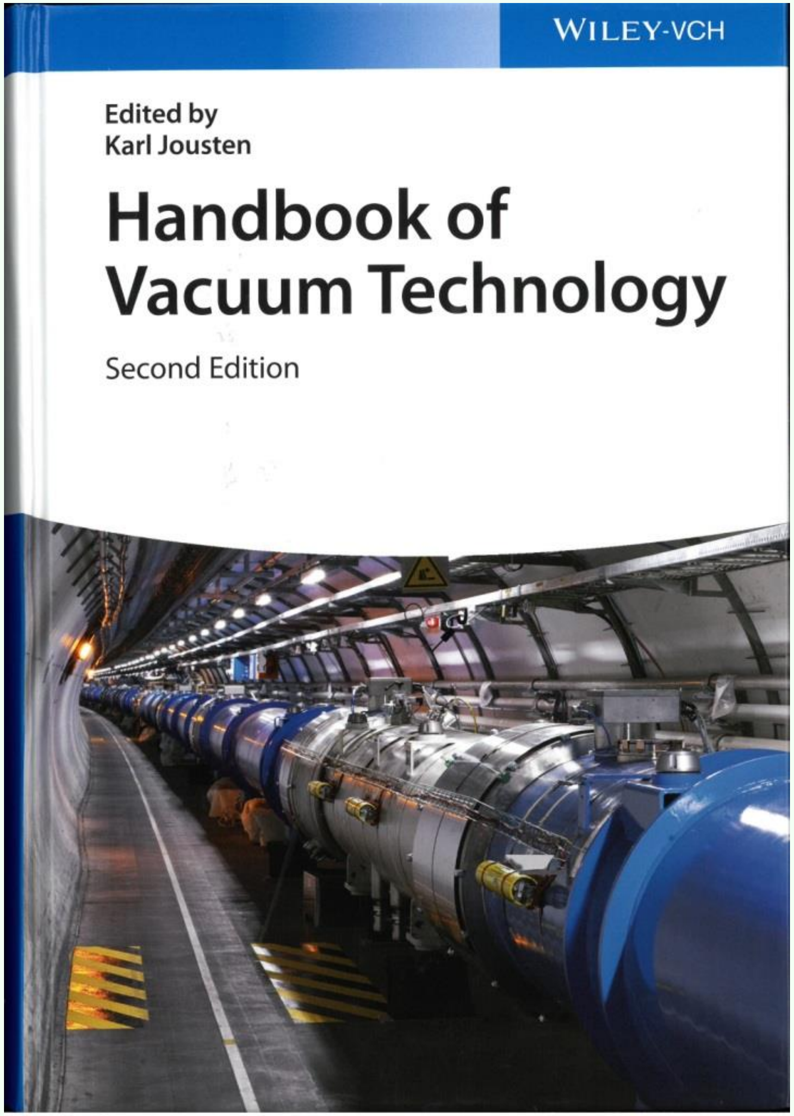
2. Overview of measurement principles and gauge types

3. Crossed field gauges („cold cathode“ gauges)

4. Accuracy of vacuum gauges

PTB, Siemens-Building, Berlin-Charlottenburg

References



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CERN Accelerator School 2006
"Vacuum in Accelerators"
CERN-2007-003
Chapters "Gauges for fine and high vacuum" pp. 65 and „UHV gauges" pp.145

The measurement process

Any physical quantity is a product of a **number and** a **unit**

$$Q = \{Q\}\, x\, [Q]$$ e.g.: D = 39.8 mm or $p = 4.7 \times 10^{-5}$ Pa

Each measurement process is a comparison between the physical quantity and the unit.

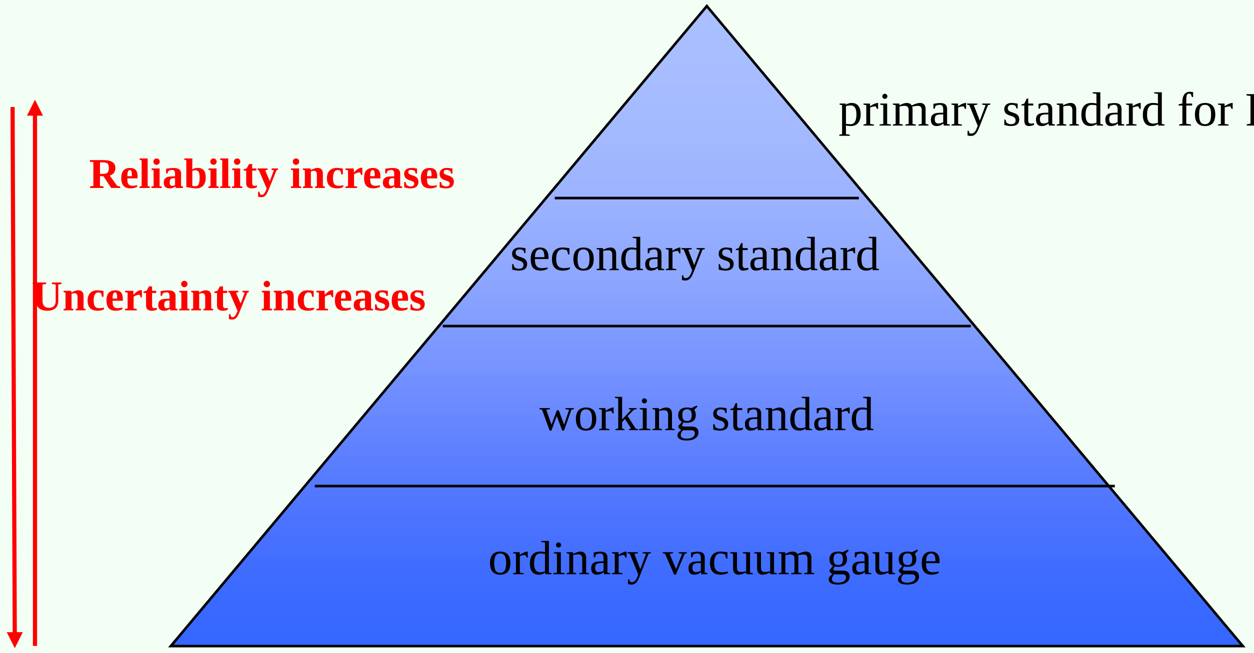
The unit is provided by a calibration.

SI Unit for pressure : 1 [Pa] = [N] $[m]^{-2}$ = [kg] $[m]^{-1}$ $[s]^{-2}$

1 [Pa] = 10^{-2} [mbar]

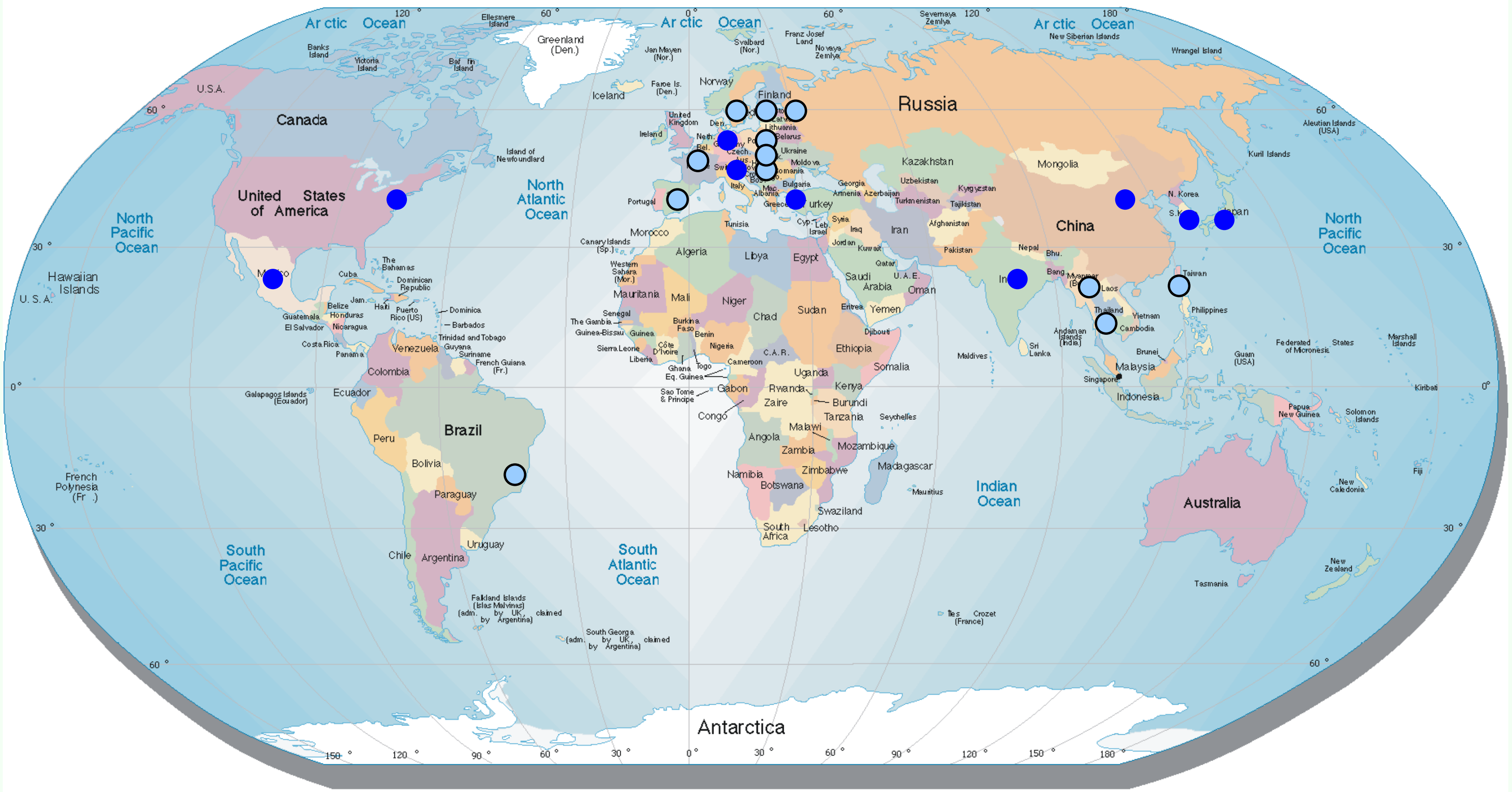
“Torr” and “micron” were related to the height of the mercury column and are obsolete.

The calibration chain



Traceability and primary standards

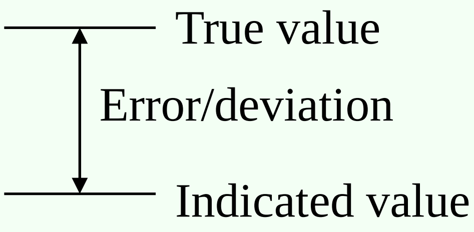
● Fully developed primary standards ○ partly developed standards



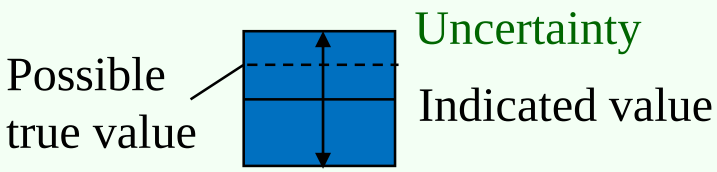
©1994 Magellan Geographix[SM] Santa Barbara, CA (800) 929-4MAP Robinson Projection

Error and uncertainty

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

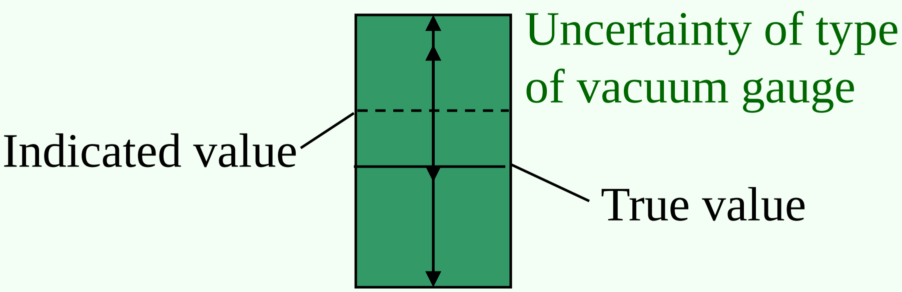


Uncertainty: The possible ***range*** by which a reading ***may*** not reflect the true value defined by the SI units.

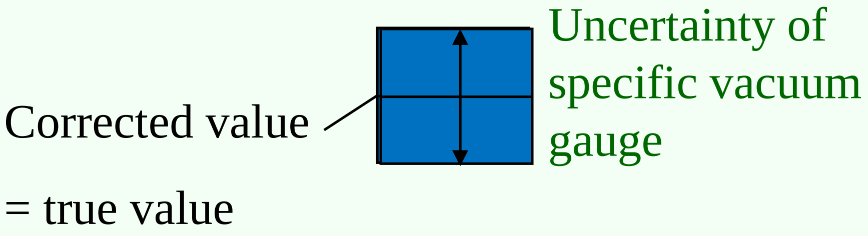


Error and uncertainty

Measurement uncertainty of a type of gauge: Must include error of reading and uncertainty!



Measurement uncertainty of a specific gauge: Error of reading is known from calibration certificate and can be corrected!



Accuracy and uncertainty

International Vocabulary of Metology (VIM)

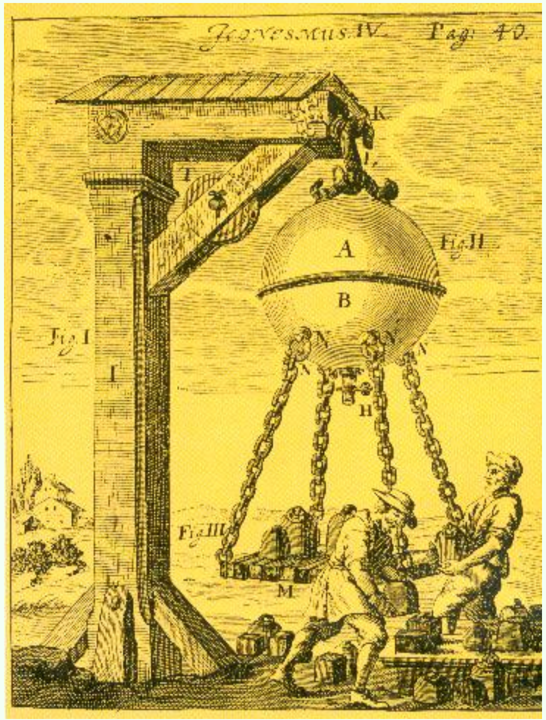
Uncertainty: The possible ***range*** by which a reading ***may*** not reflect the true value defined by the SI units.

Accuracy: closeness of agreement between a measured quantity value and a true quantity value of a measurand

NOTE 1 The concept ‘measurement accuracy’ is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error or uncertainty.

Equations for realization and measurement

Wide spread definition of pressure *p*:



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

Mass

Length

Time

More suitable for vacuum (at 10^{-7} Pa and A= 10 cm^2, it is F=10^{-9} N, range of AF microscopes):

$$p = nkT$$

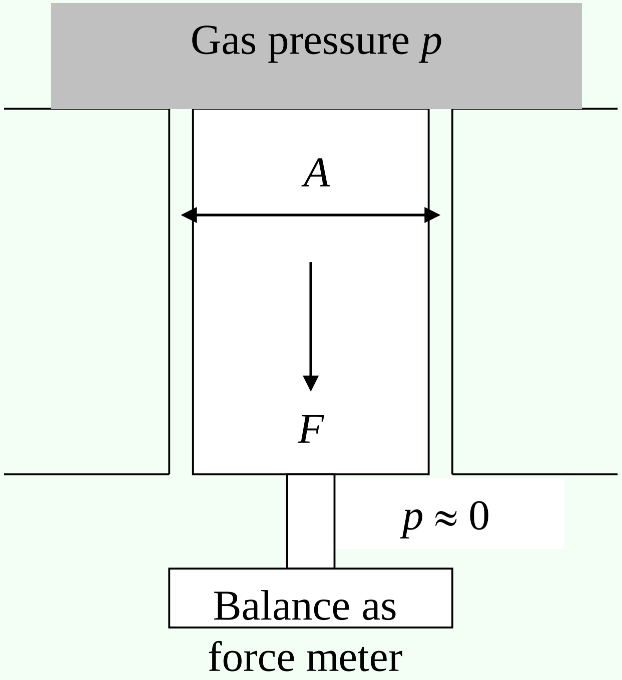
Access to optical methods (absorption, refractive index)

Primary standards under development!

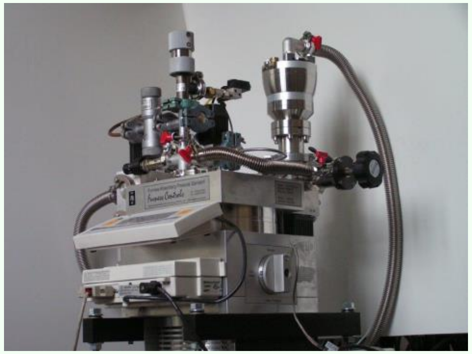
Measurement of vacuum pressure

Piston gauge or pressure balance:

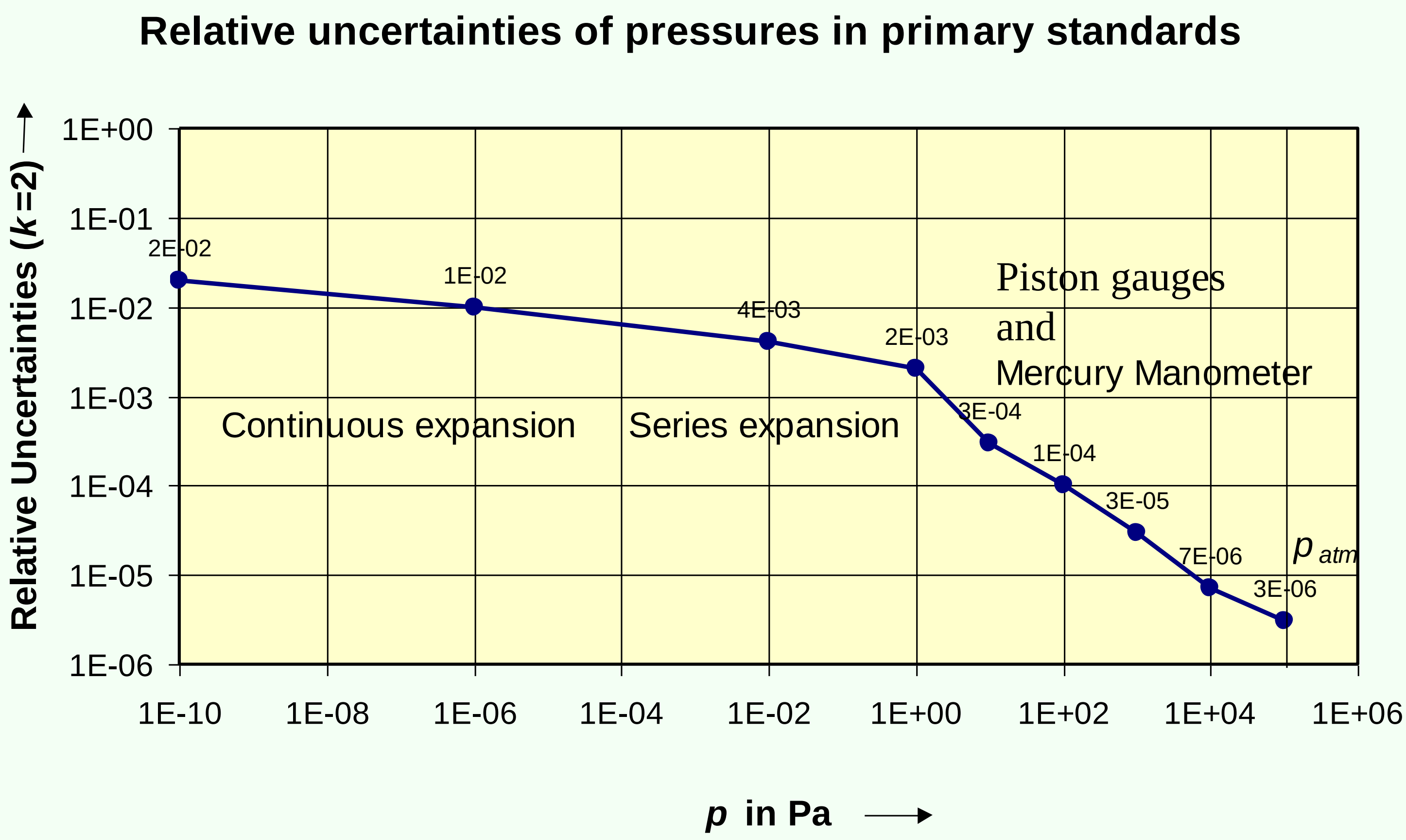
$$p = \frac{F}{A}$$



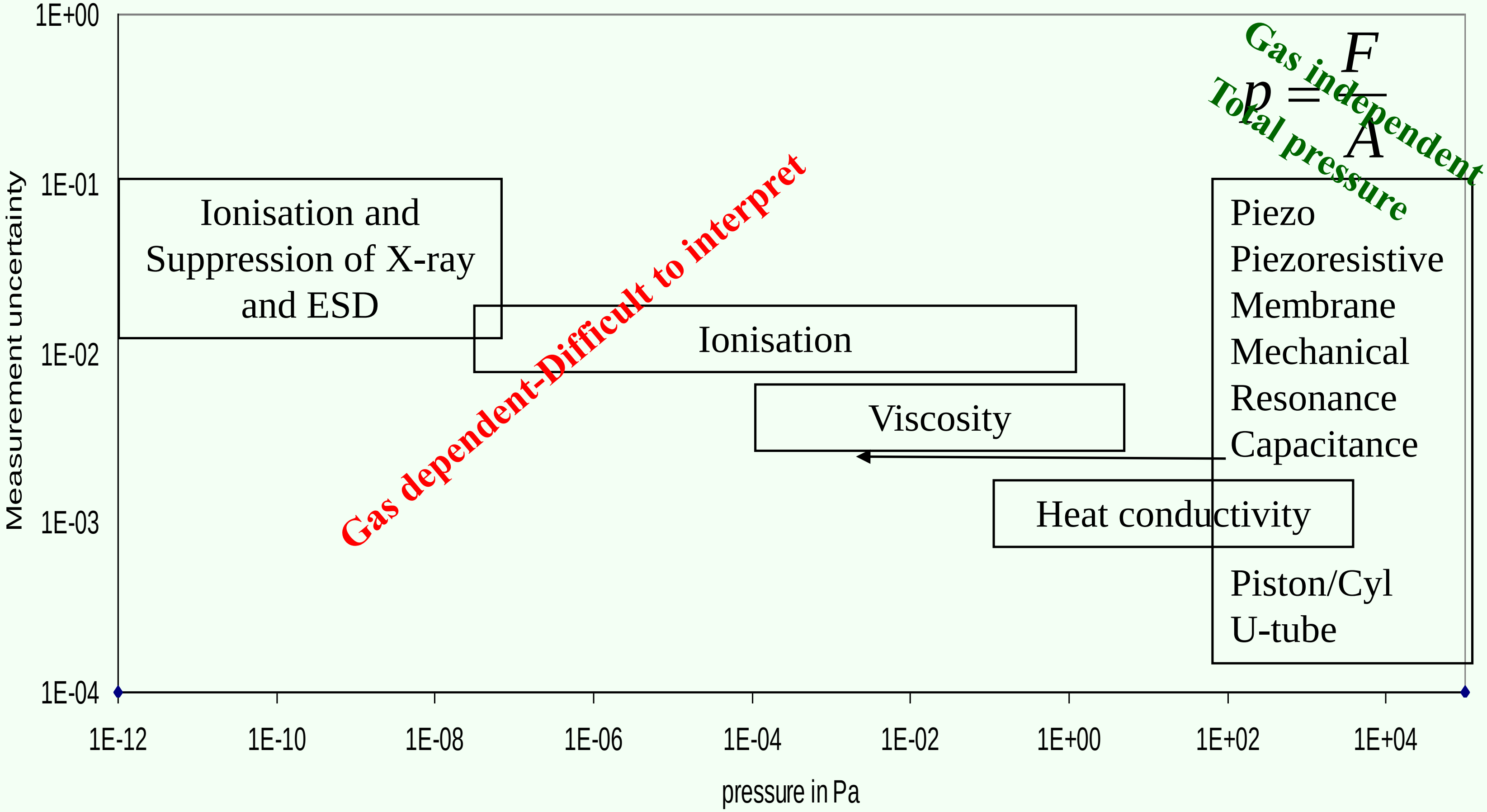
This is a traceable instrument usable as primary standard



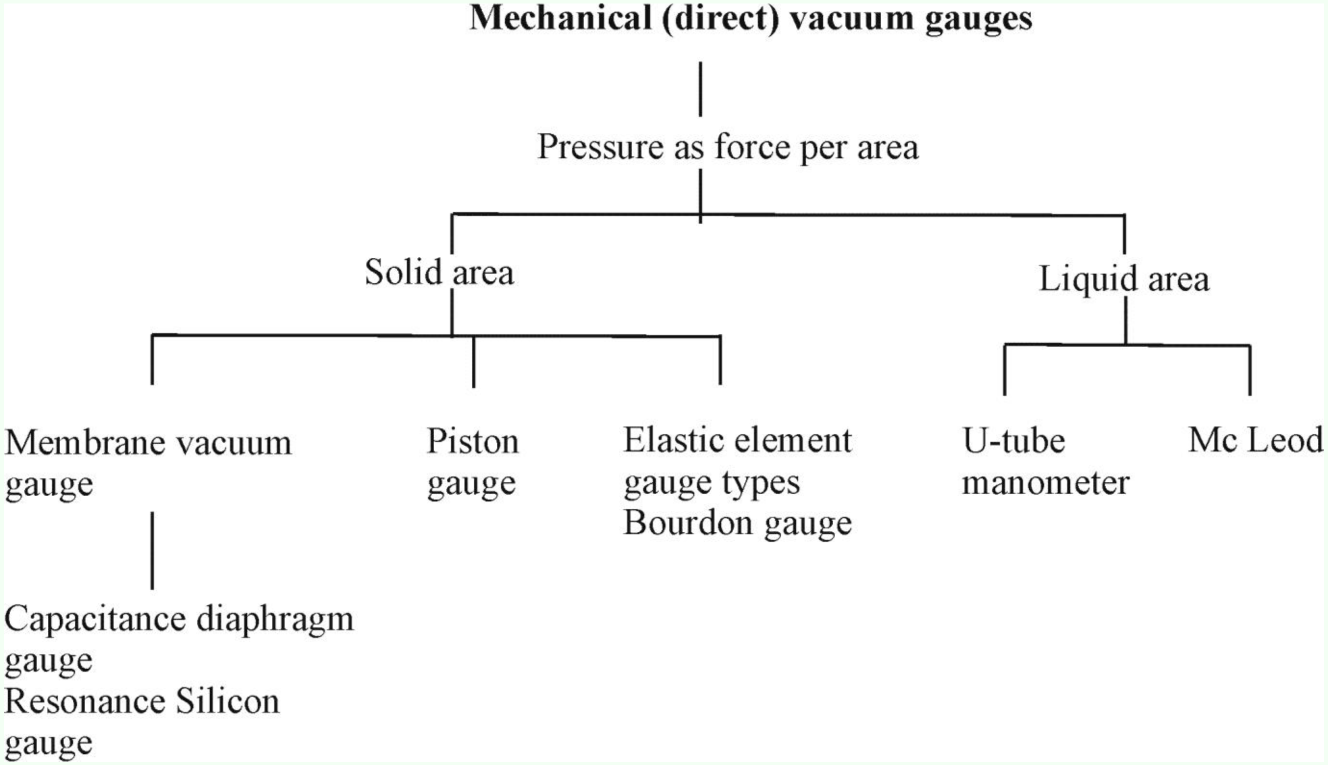
Best accuracy available



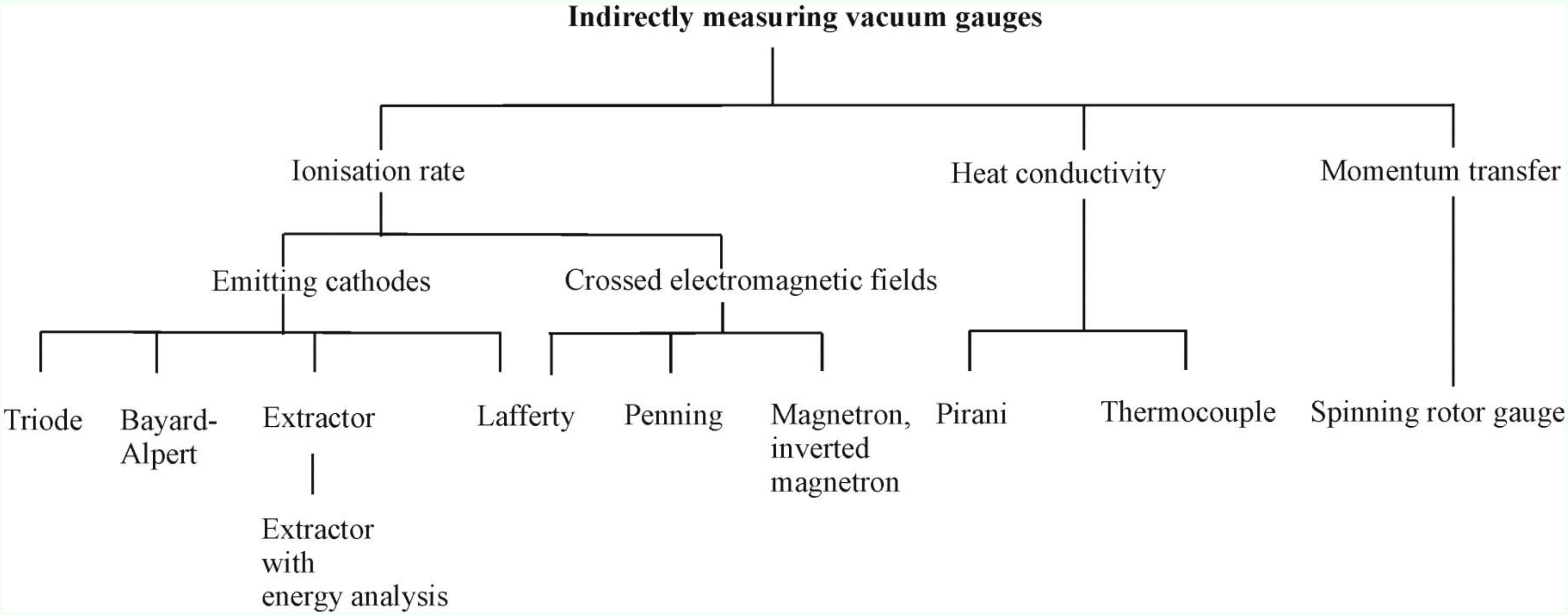
Measurement principles and gauges



Measurement principles and gauges



Measurement principles and gauges



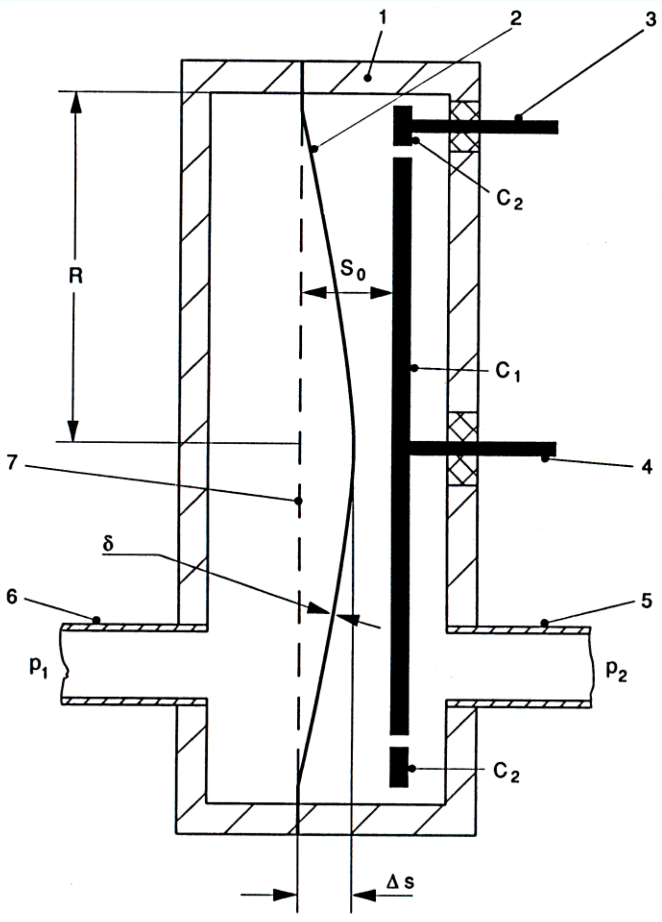
Capacitance diaphragm gauge

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

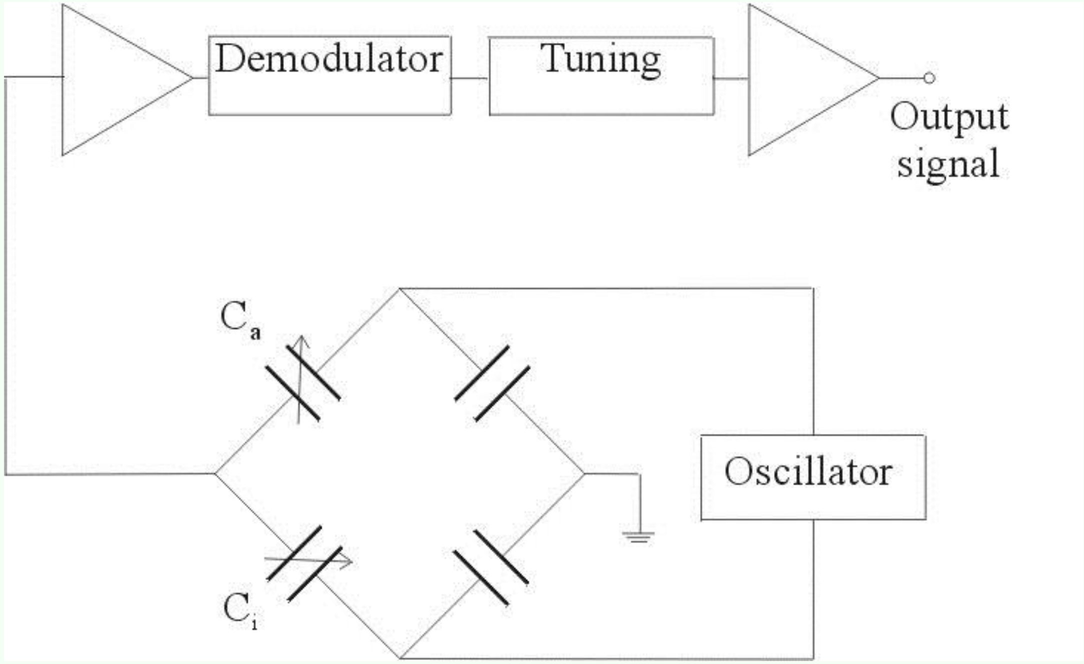
Two improve zero stability:
2 capacitors plus thermostated housing

Sensitivity of deflection: 0.4 nm!

Measurtement range with different types of fullscale:
1 mPa … 100 kPa



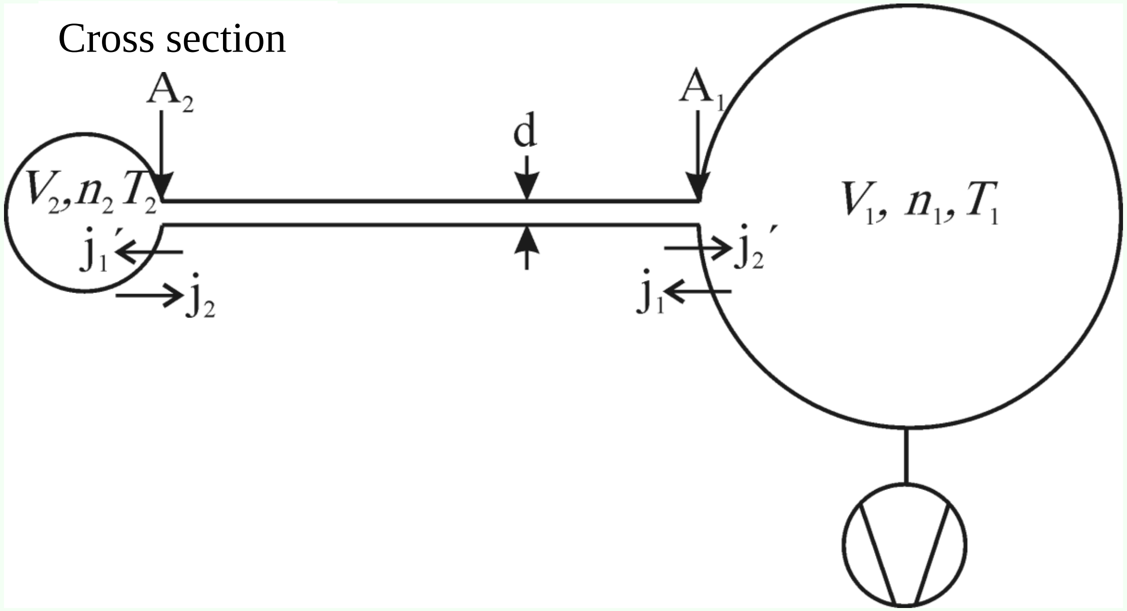
Electrical block diagram of a type of capacitance diaphragm gauge (MKS)



Bridge amplitude: proportional to pressure

Phase: Direction

Thermal transpiration effect



$$n_1 c_1 = n_2 c_2$$

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

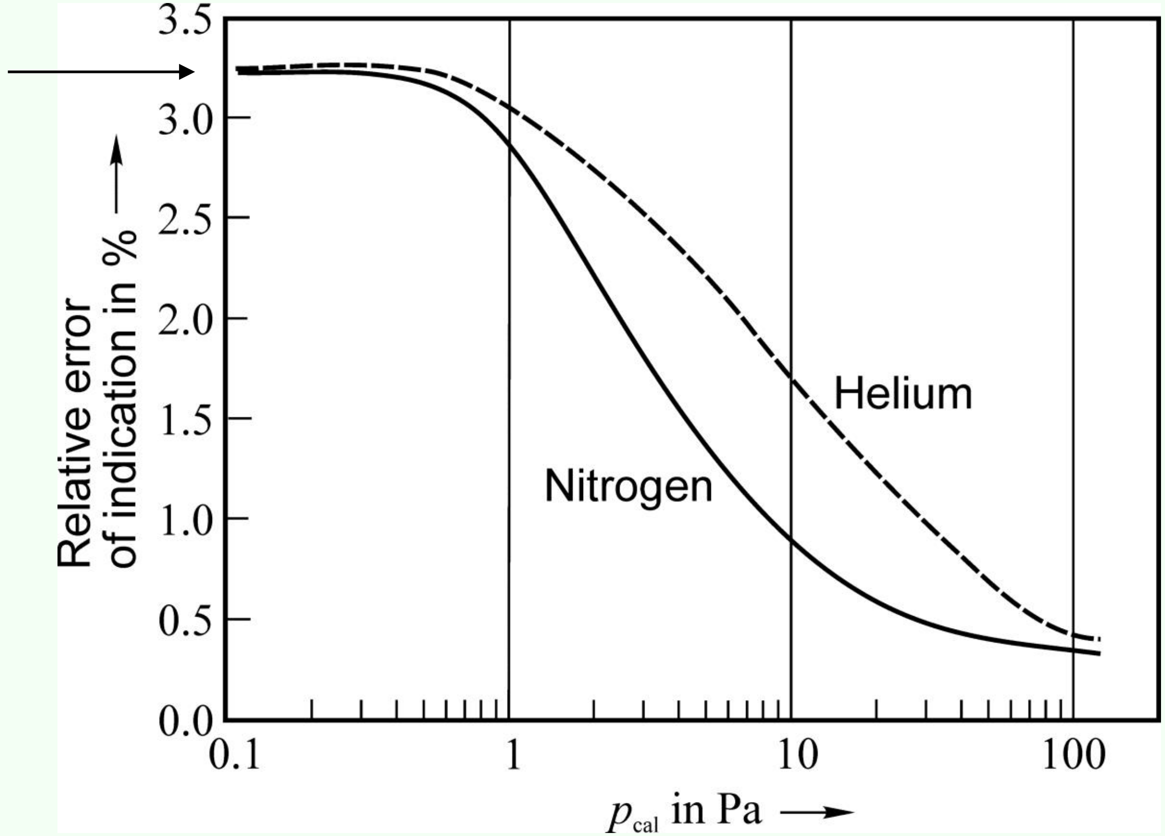
$$\frac{p_2}{p_1} = \sqrt{\frac{T_2}{T_1}}$$

Measurement principles and gauges

Thermal transpiration effect

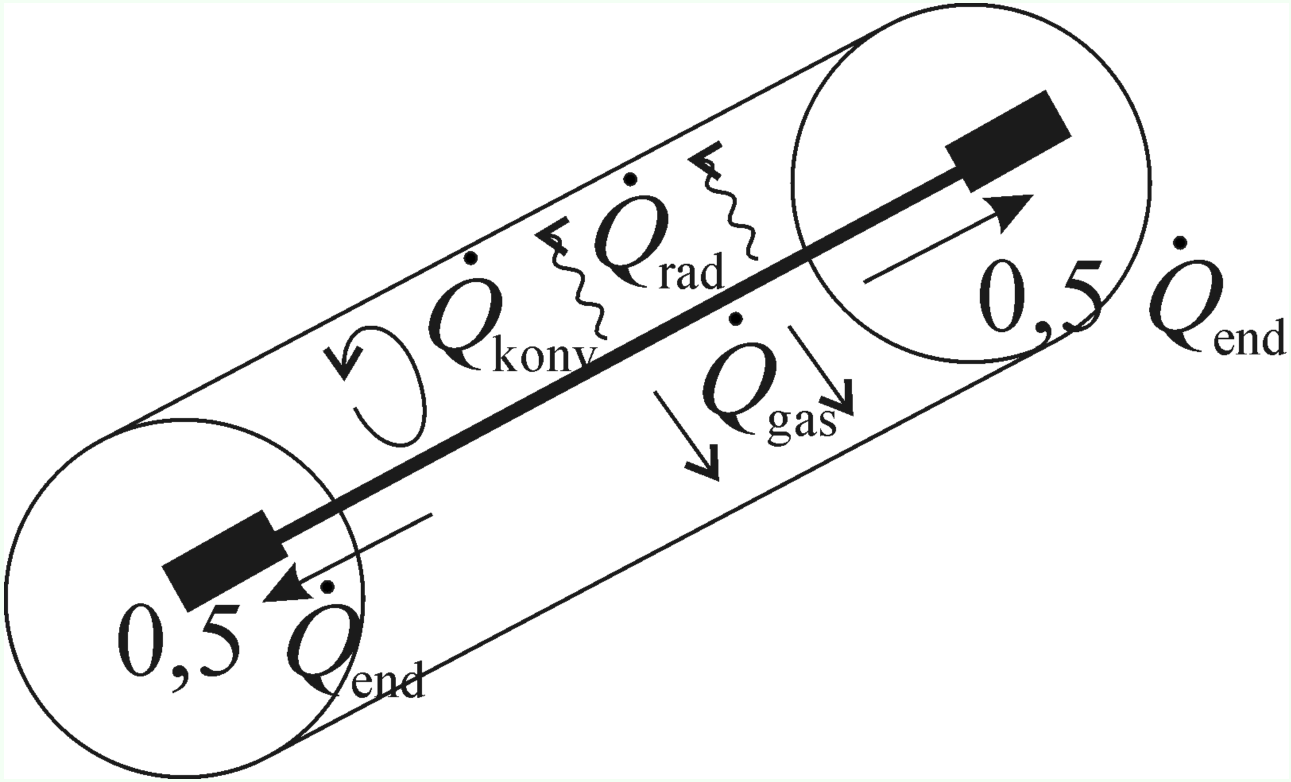
$$\sqrt{\frac{318}{296}} = 1.036$$

$$Kn := \frac{\lambda}{d}$$

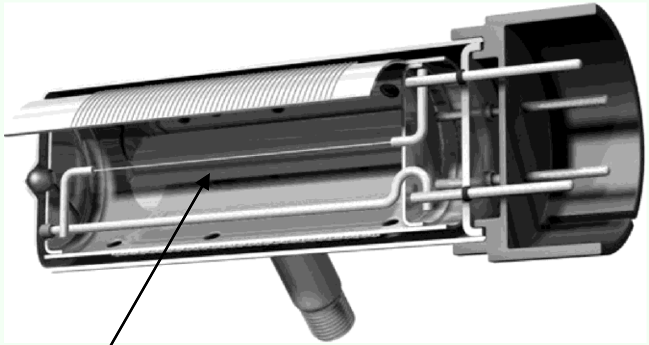


Calibration curve by PTB for two gases

Heat conductivity through a gas: Pirani gauge

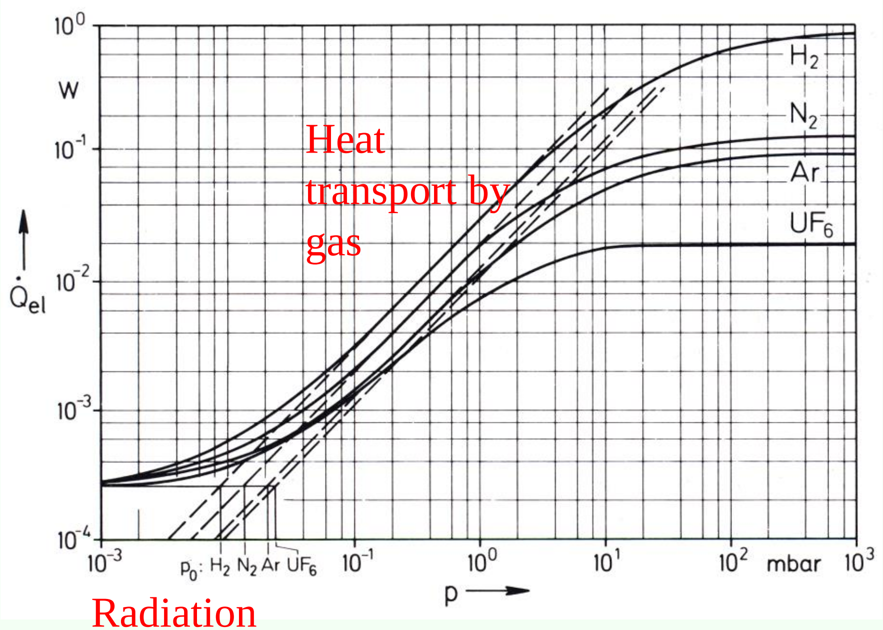


Pirani gauge



Wire: typically tungsten, $d \approx 10$ µm, 80 °C … 100 °C

convection



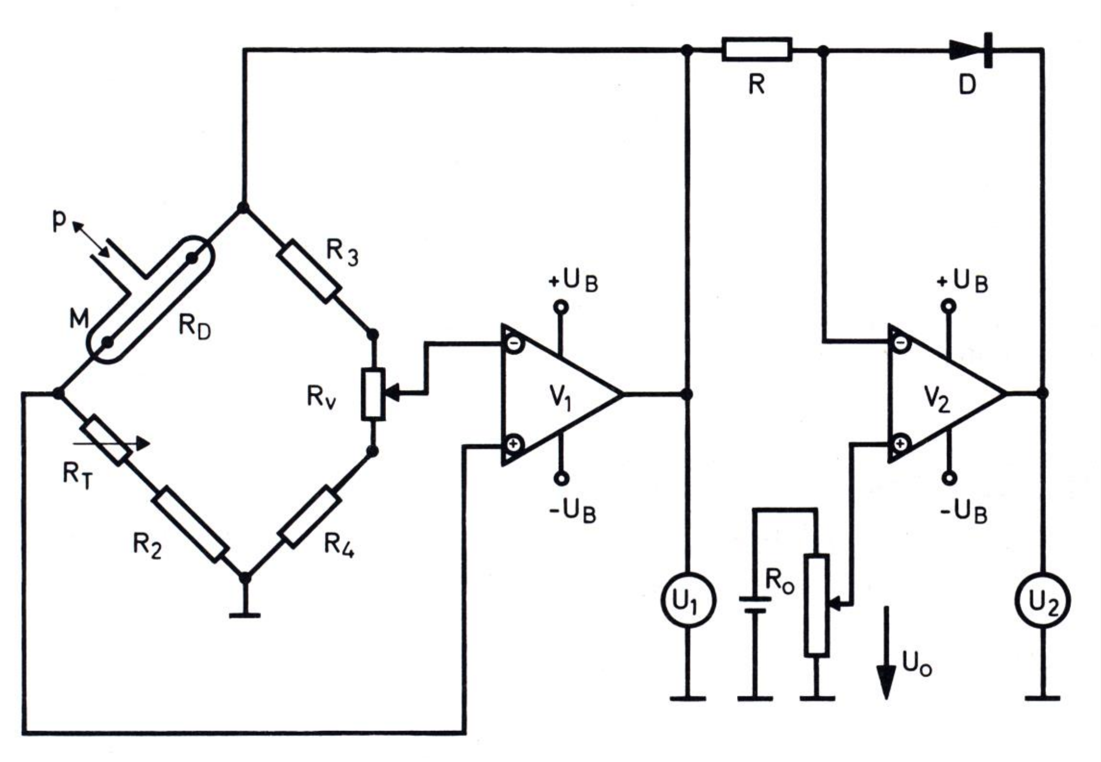
Heat transport by gas

Radiation and conduction

Electrical circuit for Pirani gauge

Constant temperature

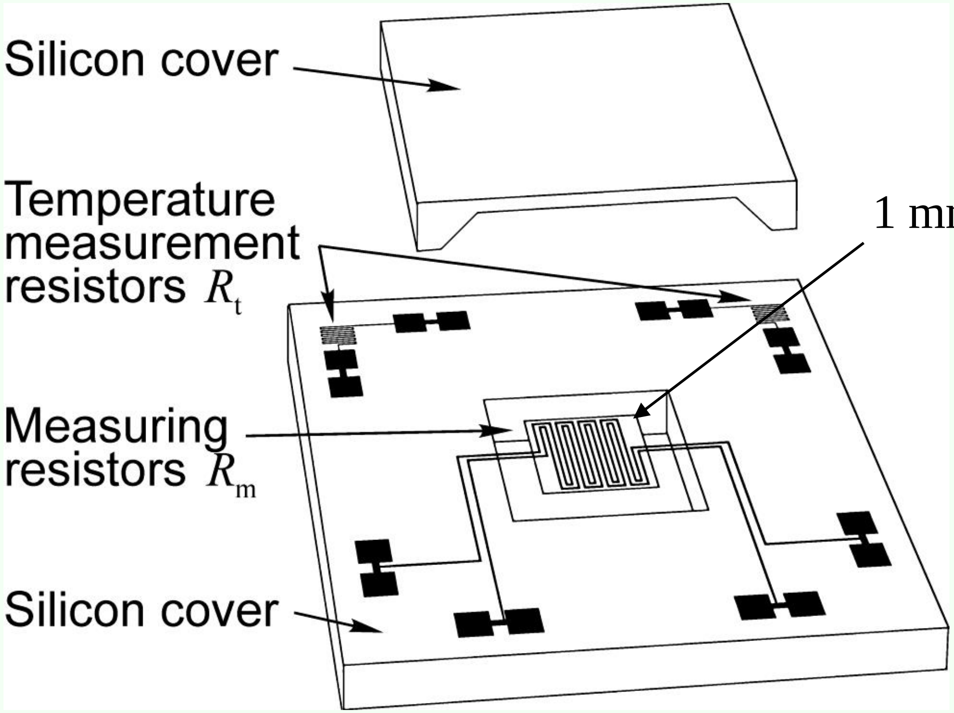
Measure the power needed

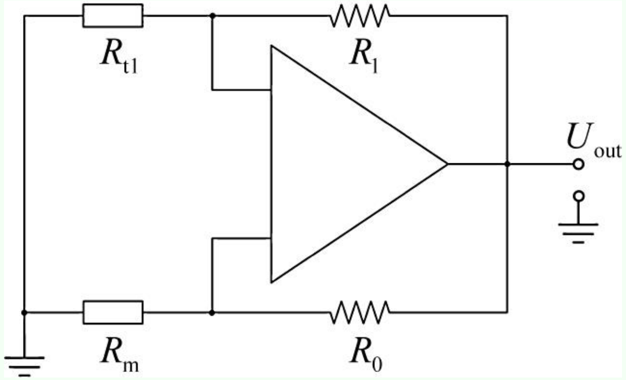


Mikro Pirani (MEMS manufactured)

Heated sheet 60°C

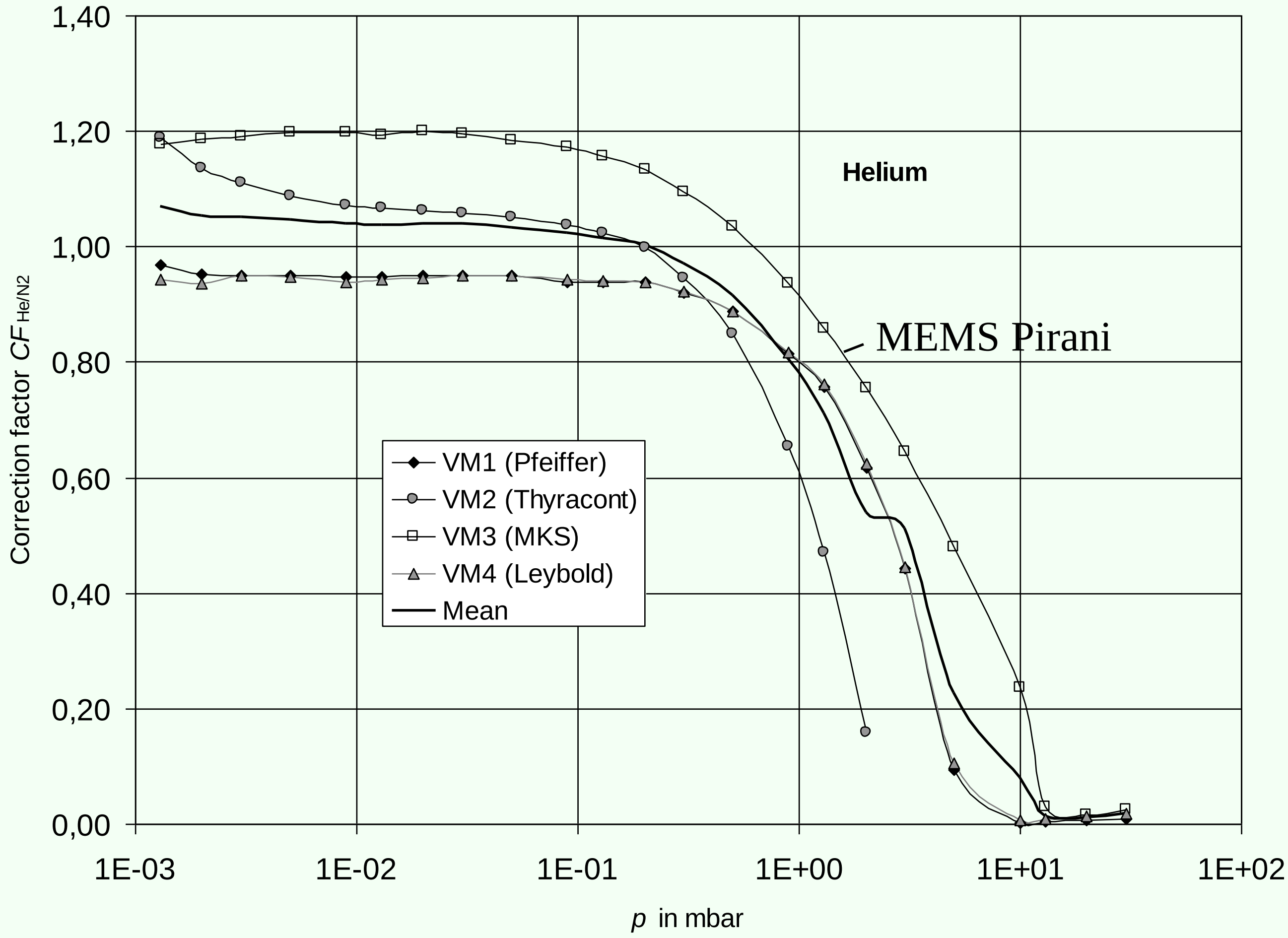
MEMS: higher Knudsen number, no convection





Measurement principles and gauges

Correction factor for helium for 4 different Pirani gauges

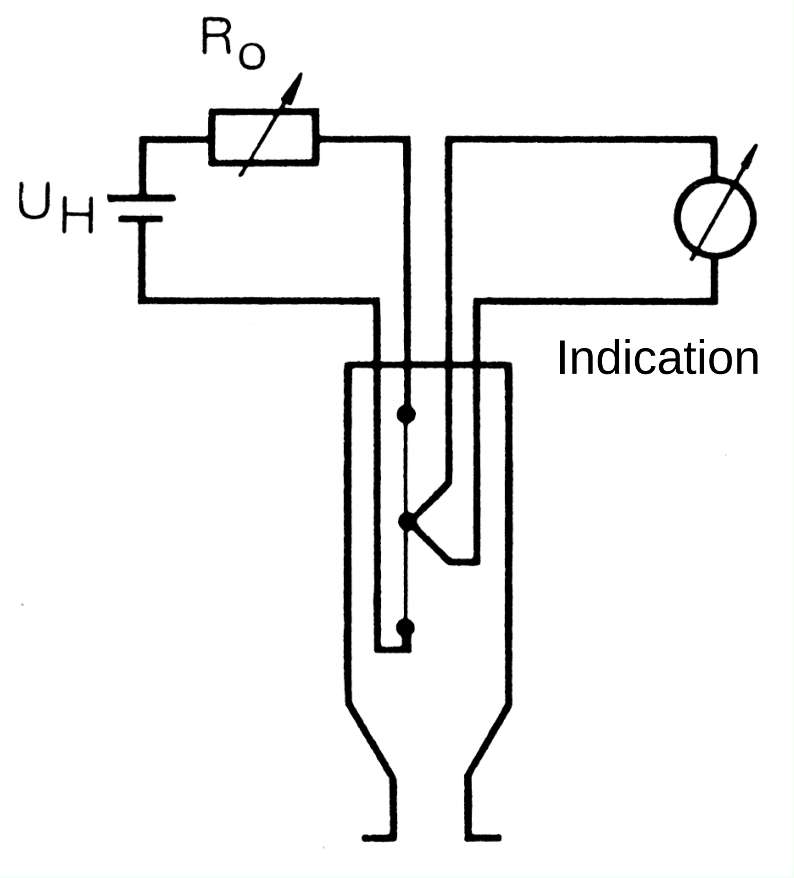


Experimental standard deviations of repeat calibrations for 4 different Pirani gauges at various pressures

#	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

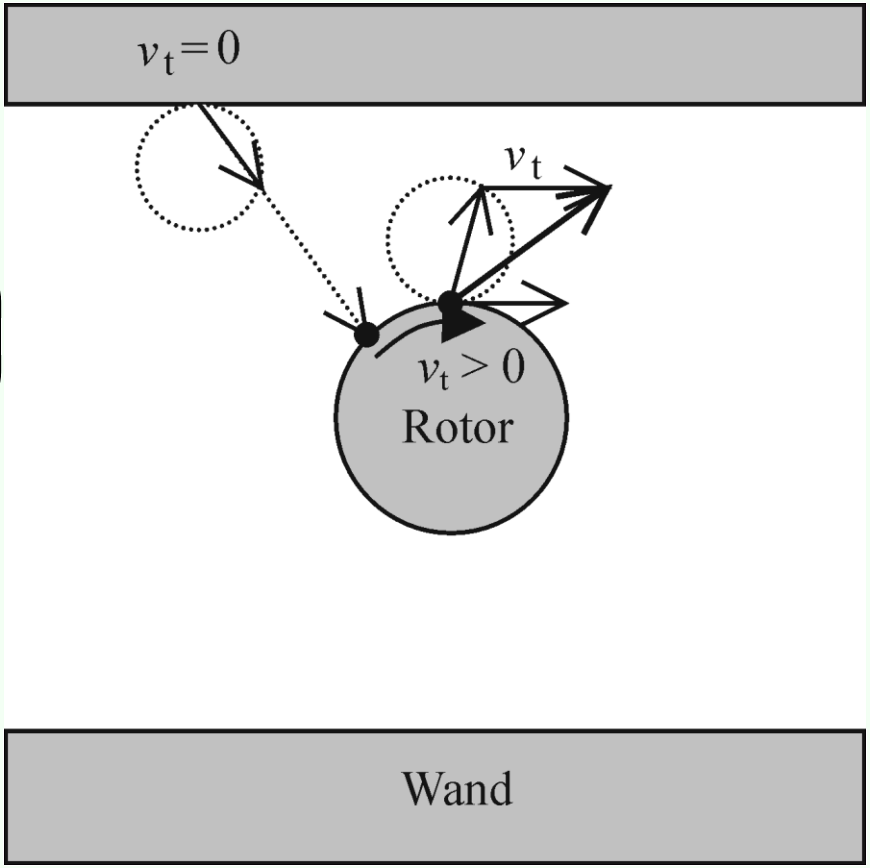
This partly excellent repeatability must not fake that this is an accurate instrument (gas dependence, non-linearity, temperature dependence, …)

Thermocouple gauge



Viscosity: The spinning rotor gauge

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



Measurement principles and gauges

Spinning rotor gauge

1 rotor

2 thimble

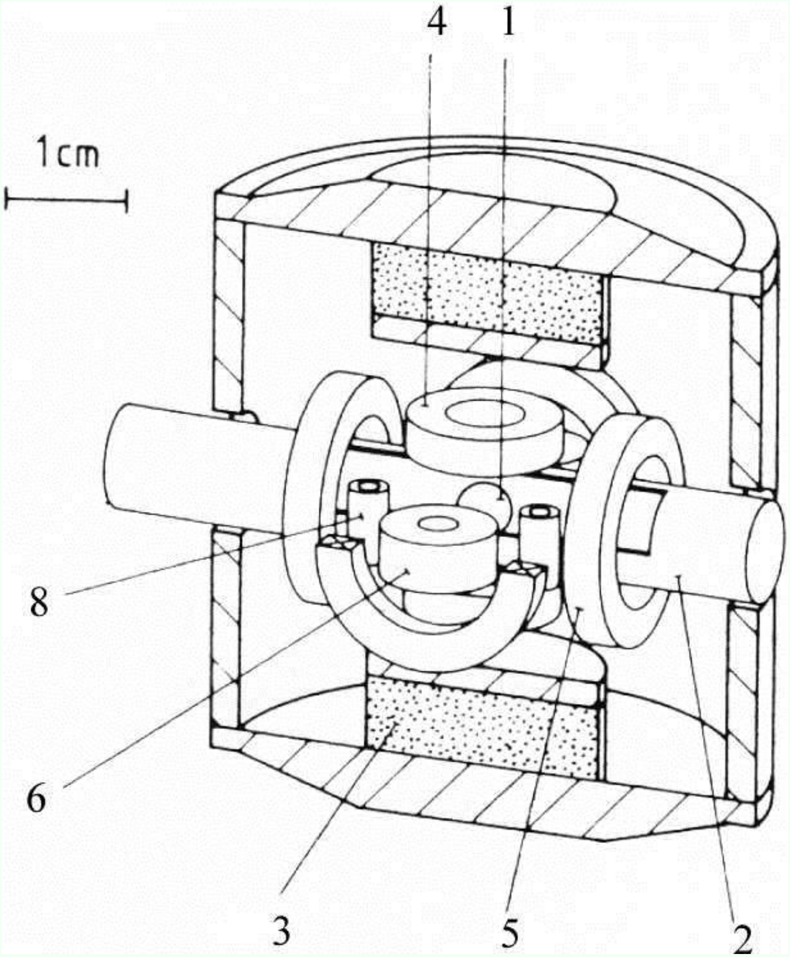
3 magnet

4 coils (vertical stabilization)

5 driving coils

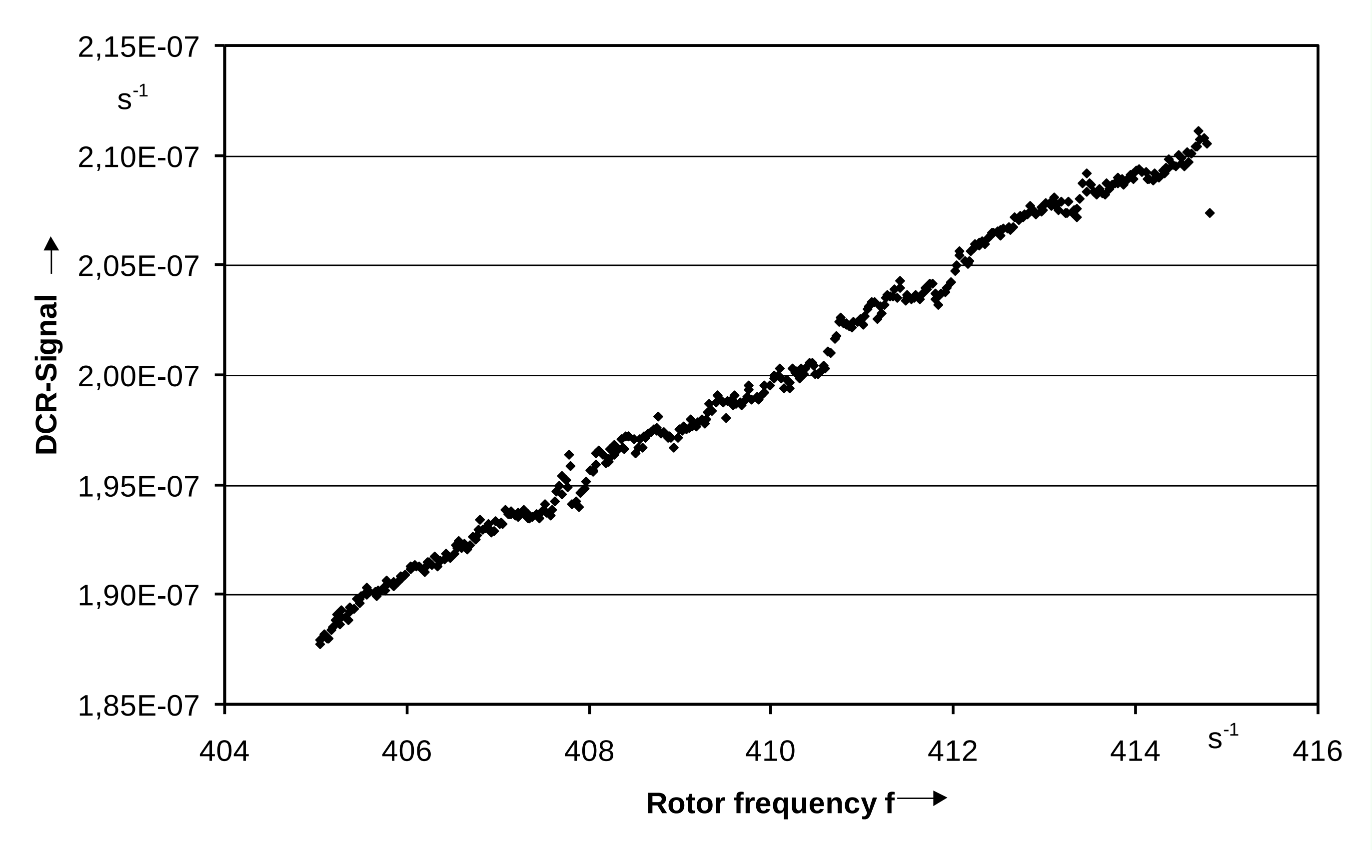
6 pick-up coils

8 coils (horizontal stabilization)



Spinning rotor gauge

Residual drag vs. frequency of rotor



Sprinning rotor gauge

No gas consumption (e.g. by ionization)

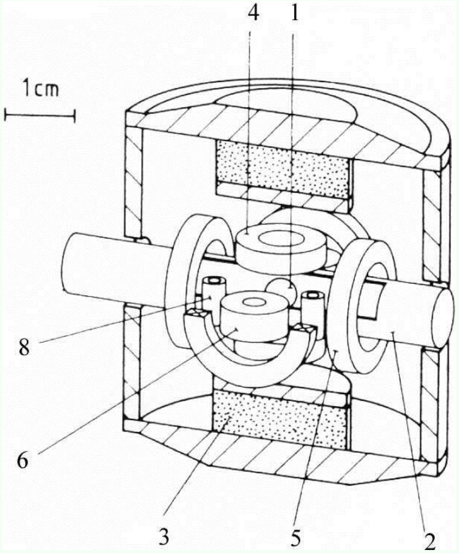
No dissociation (hot cathode)

Low outgassing rate

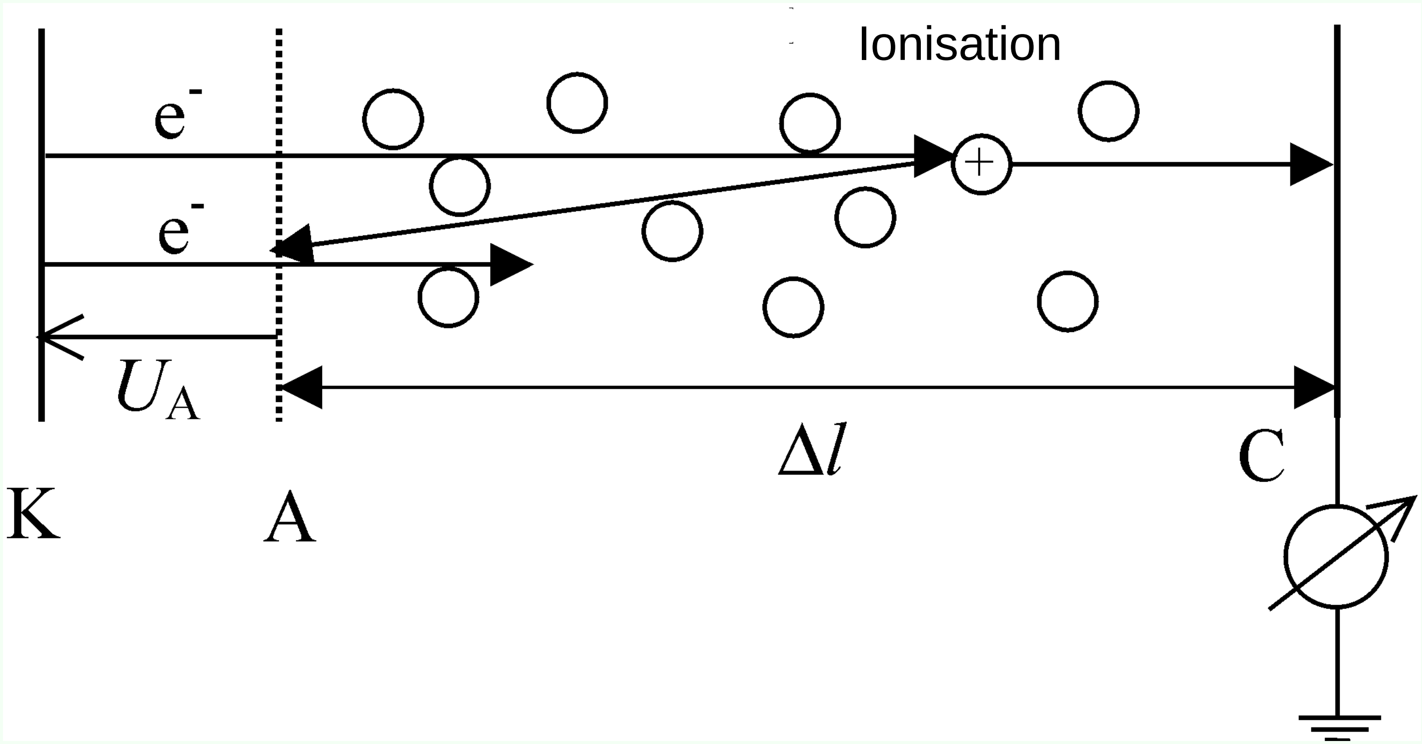
Predictable reading

High accuracy

High long-term stability

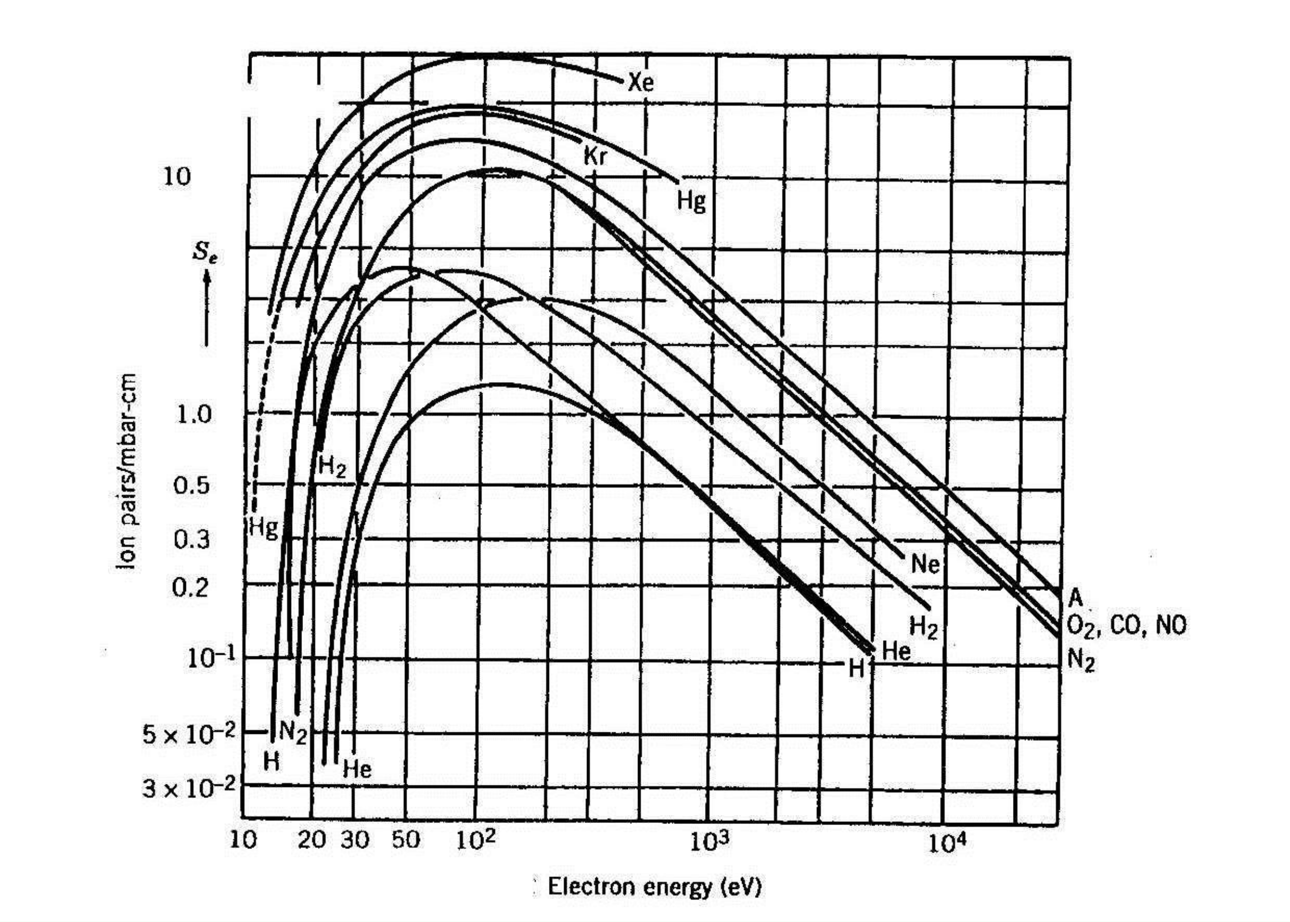


Measurement principles



Measurement principles

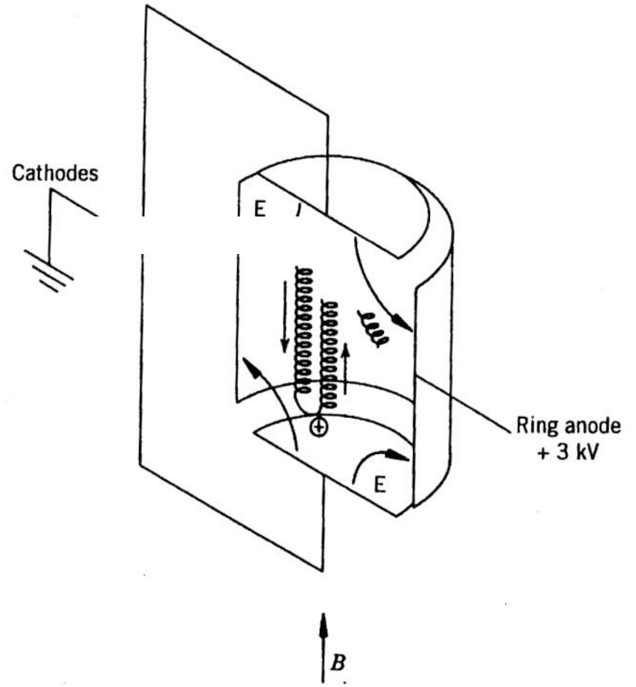
Ionisation probability of different gas species for electrons between 10 eV and 10 keV



Crossed field gauges

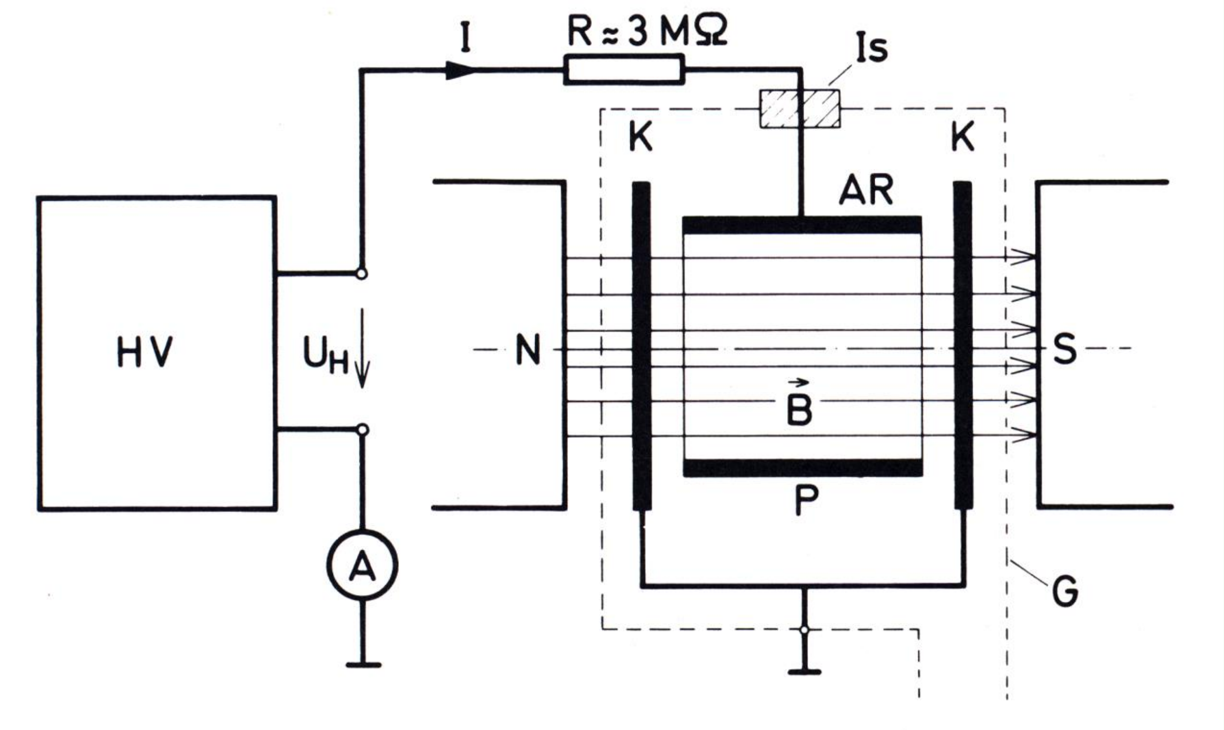
The Penning gauge

2nd generation 1949



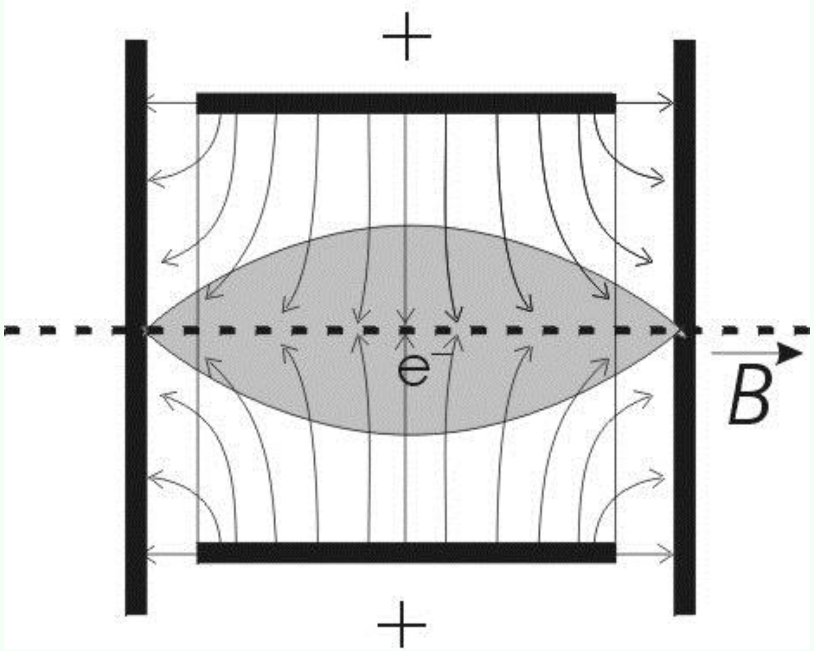
Electrode arrangement, fields, and trajectories in the Penning gauge.

Crossed field gauges



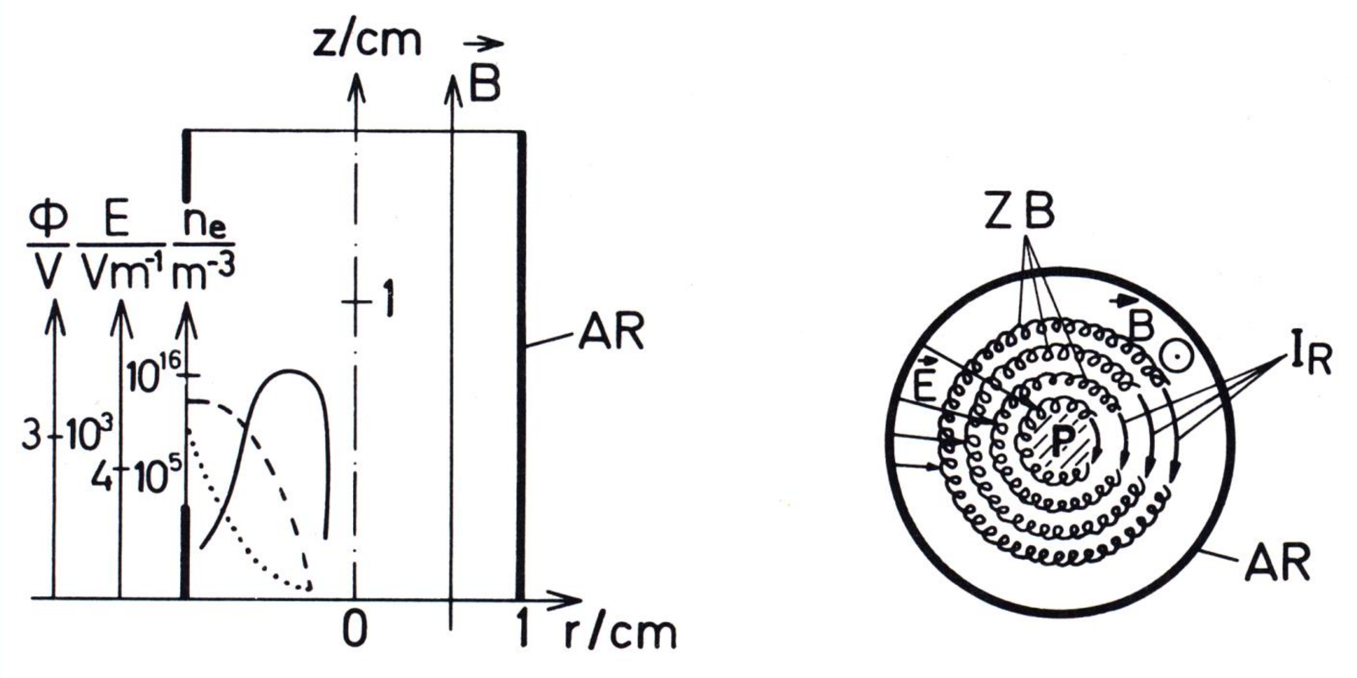
Scheme of Penning gauge

Crossed field gauges



Directions of electrical field in Penning gauge

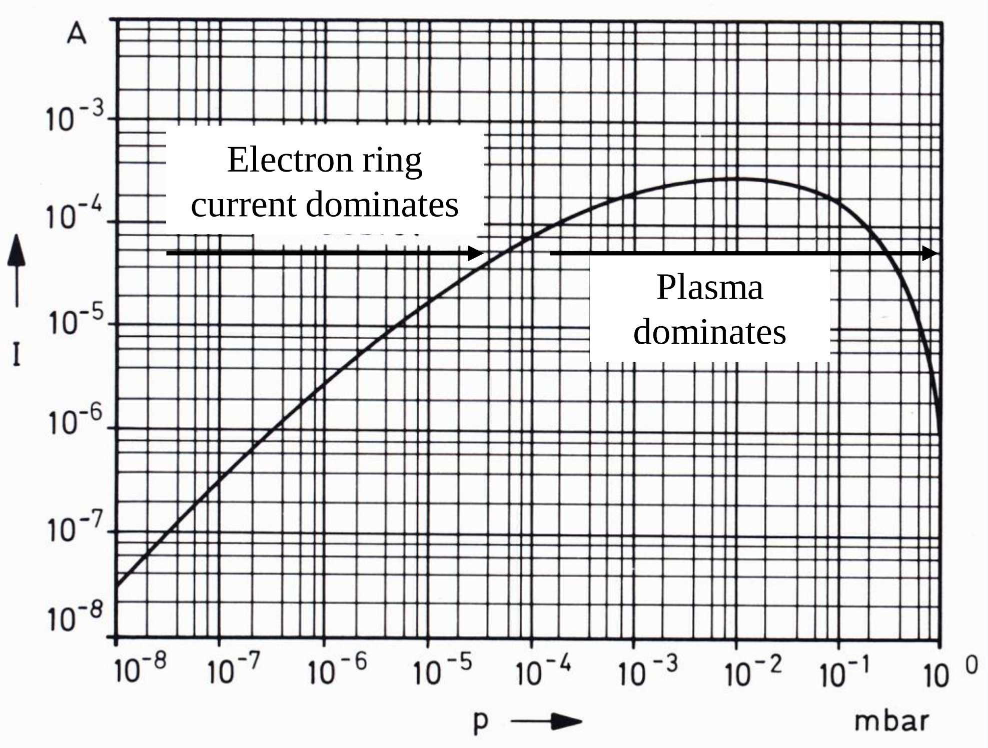
Crossed field gauges



Field strength, potential, electron densities (left) and electron trajectories (right) in typical Penning gauge

Crossed field gauges

$$I^+ = K \cdot p^m$$



Calibration curve of typical Penning gauge

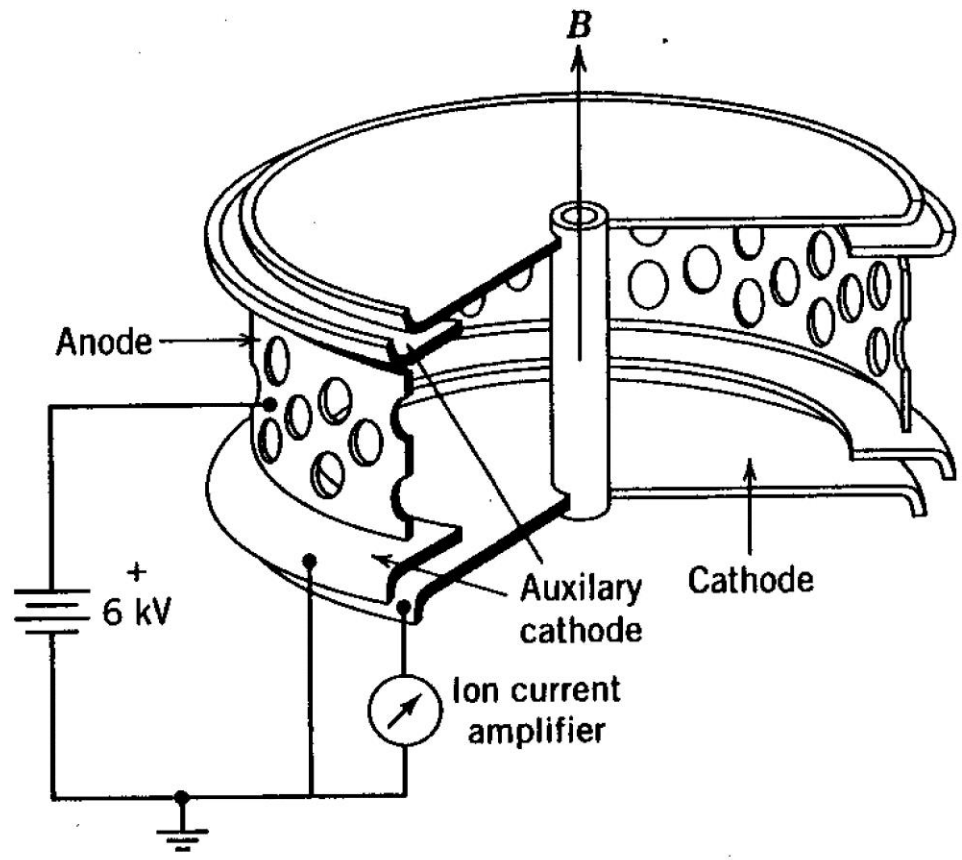
Crossed field gauges

Commercial

Penning gauge

Crossed field gauges

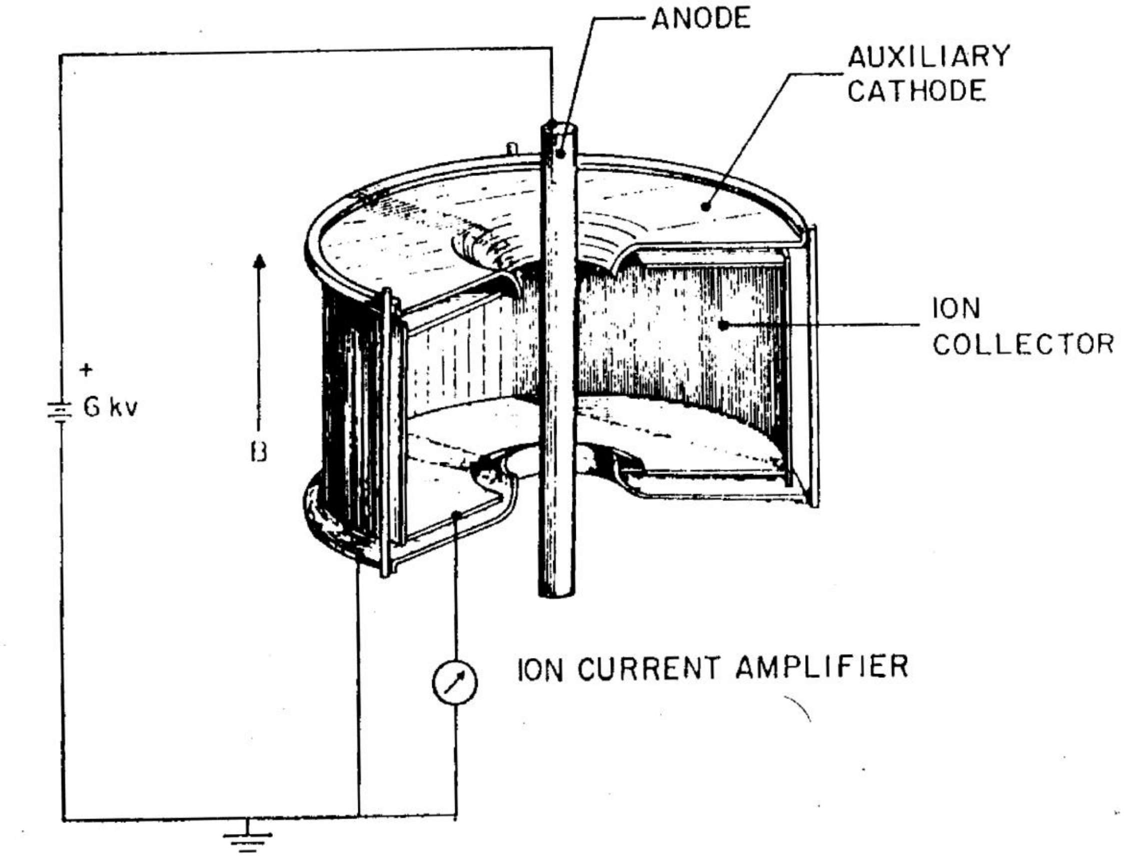
The Magnetron



Crossed field gauges

The inverted

Magnetron

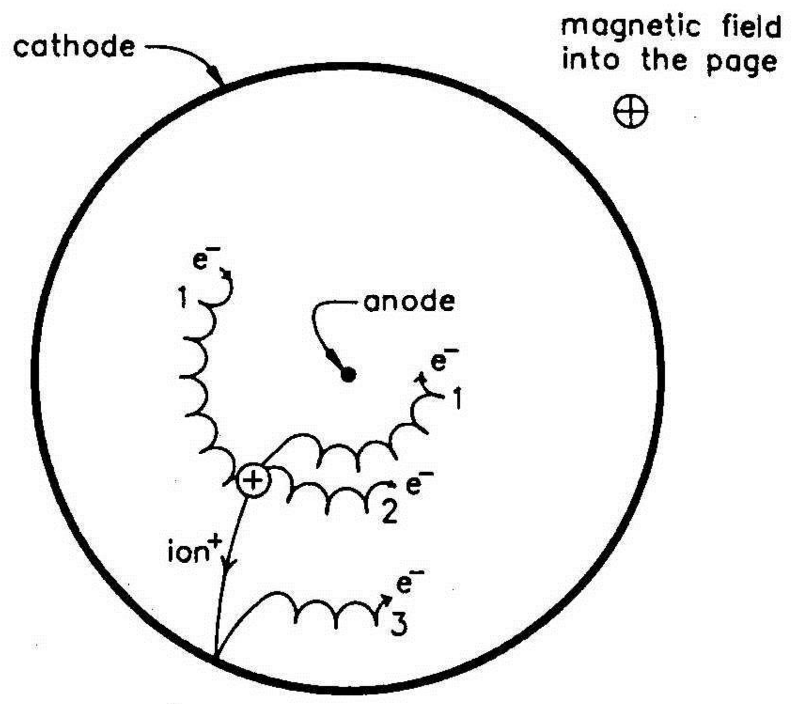


Crossed field gauges

Trajectories in

inverted magnetrons

$$I^{+} = K \cdot p^{m}$$

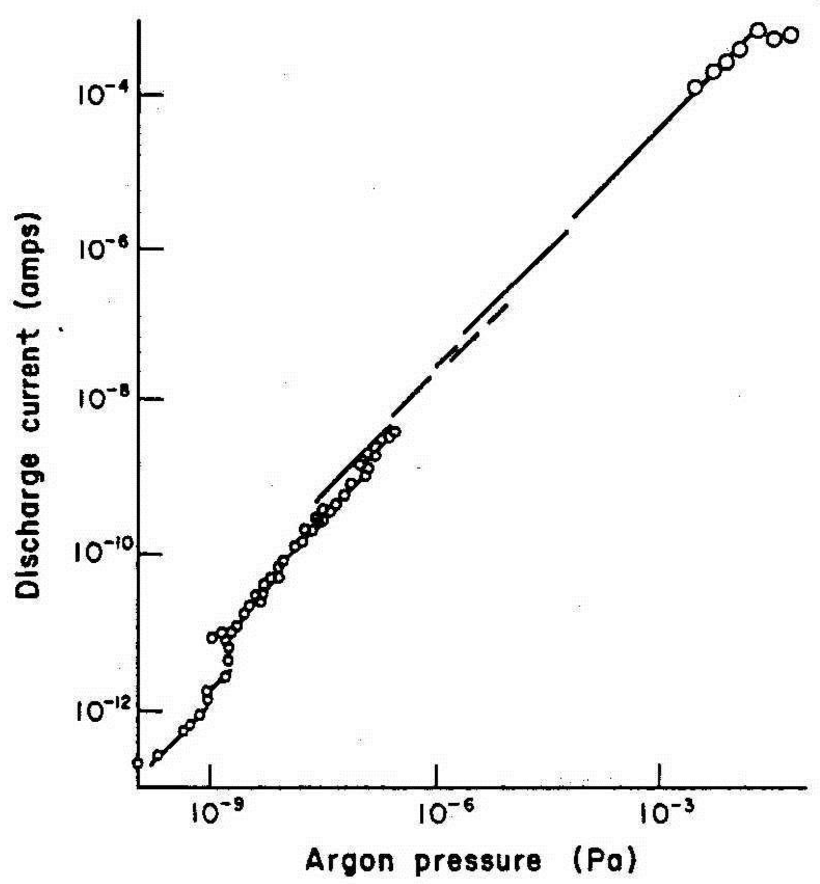


Crossed field gauges

Penning gauge:

I vs *p*.

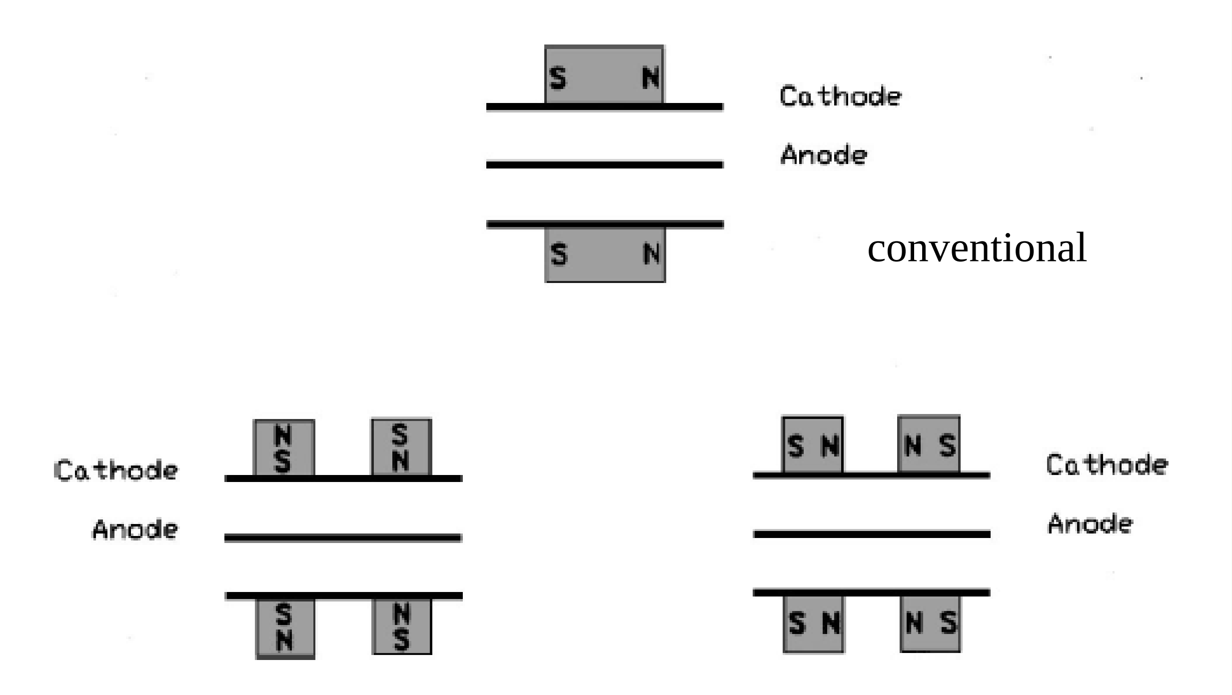
$$I^+ = K \cdot p^m$$



W.J. Lange, J.H. Singleton and D.P. Eriksen, JVST 3 (1966), 338

Crossed field gauges

Reducing the magnetic field strength outside of the inverted magnetron



Lethbridge, Asl, 1993

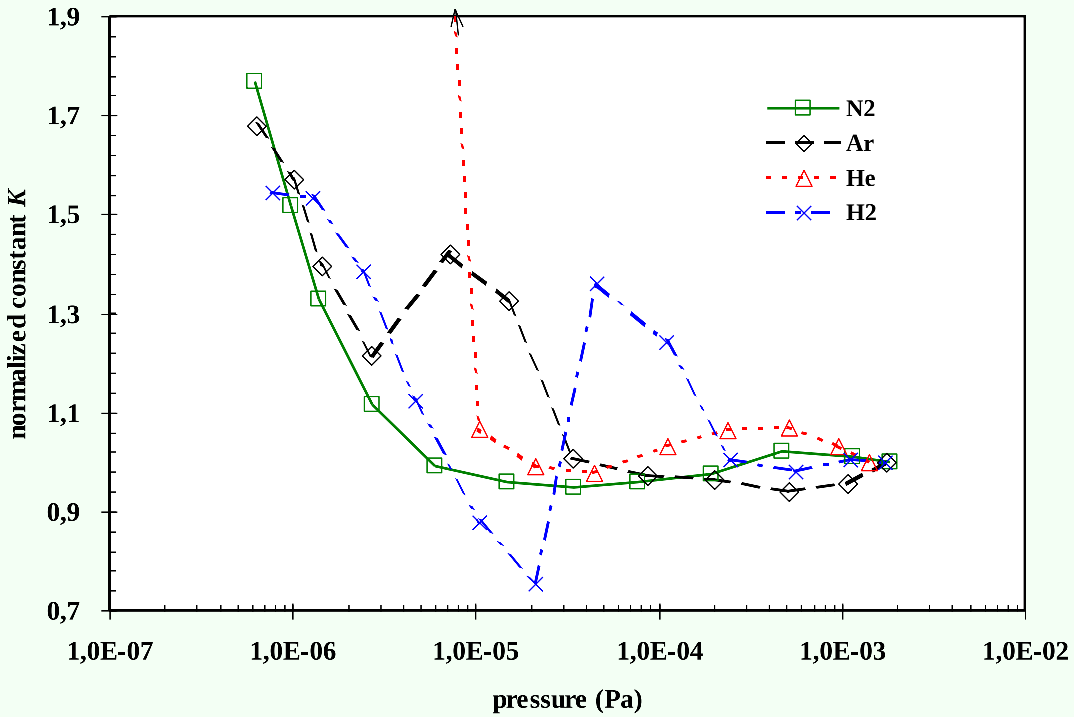
Drubetsky, Taylor 1996

Crossed field gauges

$$I = Kp^m$$

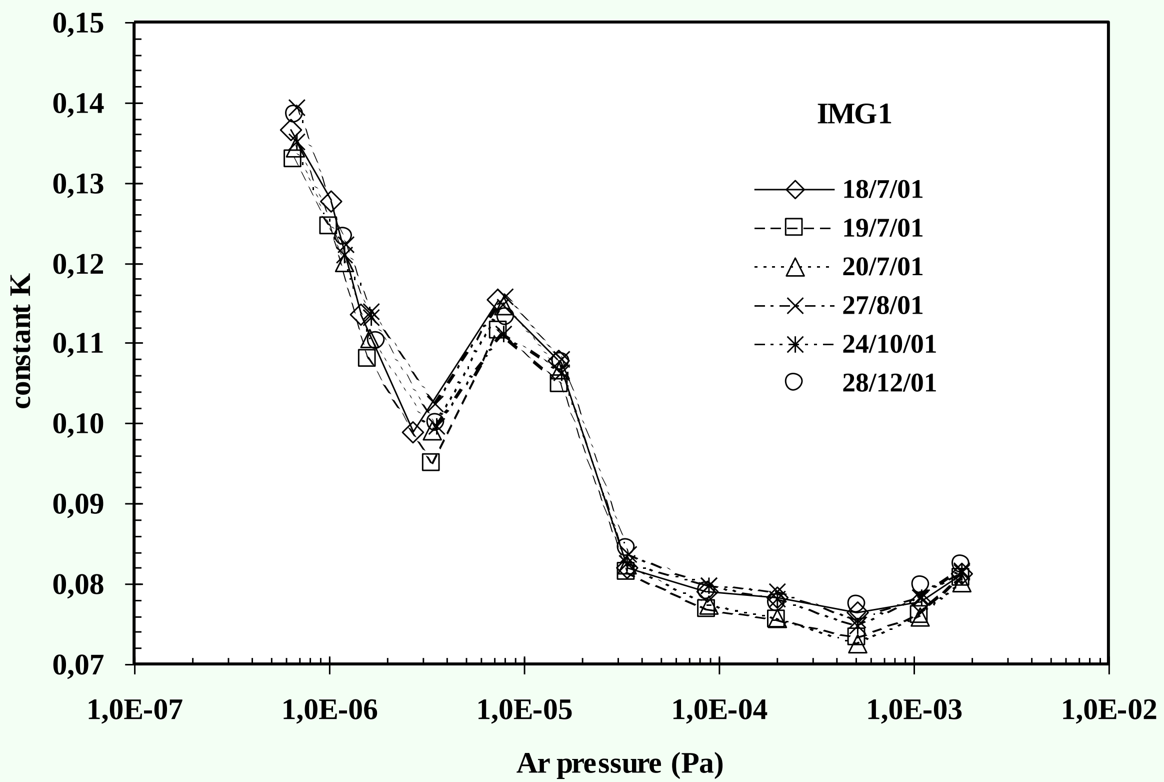
	m
H_2	1.15
He	1.30
N_2	1.17
Ar	1.17

Up to 8 !



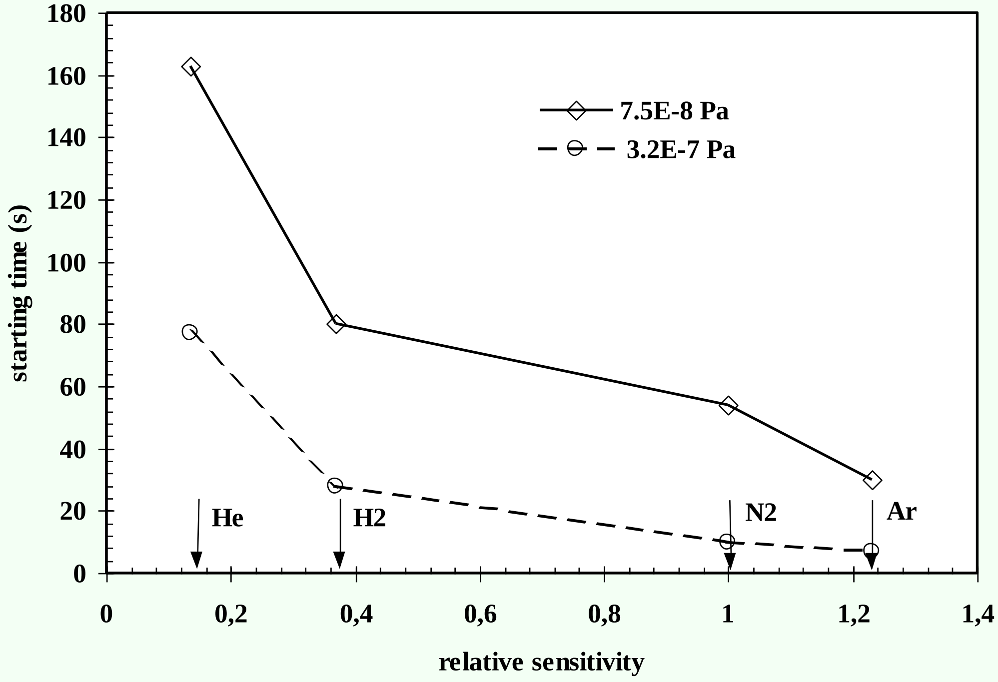
Crossed field gauges

Stability of *K* rather good



Crossed field gauges

Ignition of inverted magnetrons



Comparison ionization gauge types

Criterion	Crossed fields (“cold cathode”)	Emitting (“hot”) cathode
Pumping speed	high	low
Accuracy, stability	moderate	good
Size, mechanical stability	good	moderate
Sensitivity towards outside magnetic field	low	high
Outside magnetic field	yes	no
Susceptibility to contamination	high	moderate
Start-up problems	occur	none
X-ray limit	none	10^{-10} Pa to 10^{-6} Pa
Electron stimulated desorption	negligible	Dependent on gas species
Price	low	high

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

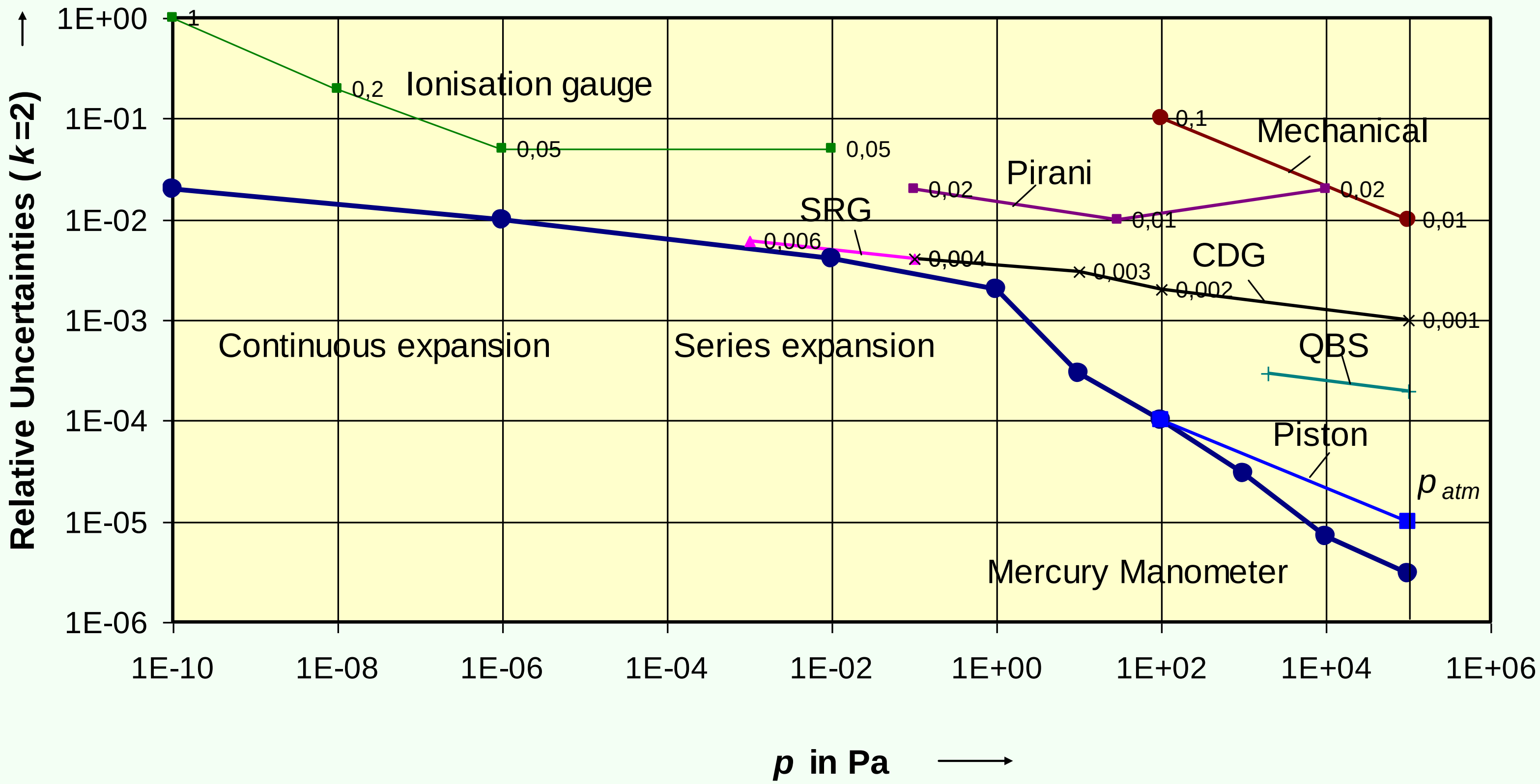
General	Examples
Offset measurement	residual drag in SRG, zeroing of Pirani gauge, X-ray- and ESD-effect for ion gauges
Offset instability (drift)	Offset drifts with environmental temperature (Piroutte effect in SRG), bridge is no more balanced with time
Resolution	Number of digits shown
Influences of 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	$10 \ldots 10^{5}$		$10^{2} \ldots 10^{5}$	$10^{-4} \ldots 10^{-5}$
Quartz-Bourdon-manometer	$10^{3} \ldots 10^{5}$		$10^{3} \ldots 10^{5}$	$3 \times 10^{-4} \ldots 2 \times 10^{-4}$
Resonance silicon gauges	$10 \ldots 10^{5}$	0.003... 0.0005	$100 \ldots 10^{5}$	$2 \times 10^{-4} \ldots 5 \times 10^{-5}$
Mechanical vacuum gauge	$10^{2} \ldots 10^{5}$	0.1 ...0.01		
Membrane vacuum gauge	$10^{2} \ldots 10^{5}$	0.1 ...0.01		
Piezo	$10^{2} \ldots 10^{5}$	1 ...0.003		
Thermocouple gauge	$10^{-1} \ldots 10^{2}$	1... 0.3		
Pirani gauges	$10^{-1} \ldots 10^{4}$	1 ... 0.1	1 ... 100	0.02 ... 0.01
Capacitance diaphragm gauges	$10^{-4} \ldots 10^{5}$	0.1... 0.003	$10^{-1} \ldots 10^{5}$	0.006... 0.001
Spinning rotor gauges	$10^{-5} \ldots 10$	0.1 ... 0.007	$10^{-3} \ldots 10^{-1}$	0.006...0.004
Penning gauges	$10^{-7} \ldots 1$	0.5 ... 0.2	$10^{-5} \ldots 1$	0.3...0.1
Magnetron gauges	$10^{-8} \ldots 1$	1 ...0.1	$10^{-6} \ldots 1$	0.1...0.02
Ionisation gauges (Emission cathodes)	$10^{-10} \ldots 10^{-2}$	1...0.05	$10^{-8} \ldots 10^{-2}$	0.2...0.02

How accurate are vacuum gauges ?



Lowest relative uncertainties for vacuum gauges and primary standards

Errors > 100 % are possible.

Todays commercial gauges

Either

Gauge head + controller

or

Active gauges or
transmitter (all in one)

or

Digital gauges (digital
output via interface)

Disclaimer: Just example, no recommendation of these products

Vacuum Gauges I

We have discussed:

- Metrological system - primary standards-calibration chain
- Measurement principles and gauges
- Crossed field gauges
- Sources of uncertainties with values from 0.001% up to 100% or factor