Ultrahigh vacuum gauges

Karl Jousten, PTB, Berlin

1. Introduction and history
2. Ion gauges with crossed EM fields
3. Ion gauges with emitting cathodes
4. Comparison between the ion gauge types
4. Accuracy and problems in applications
5. Summary

Introduction

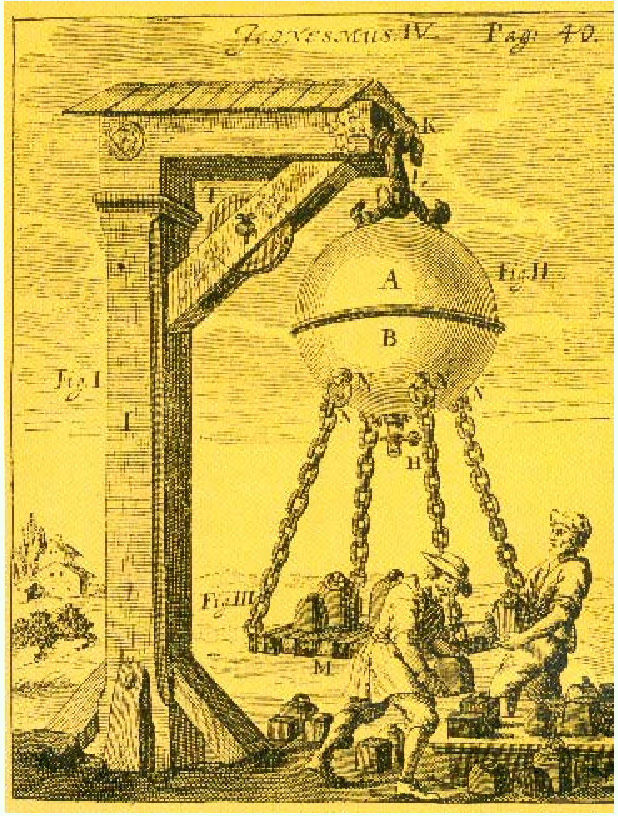
We have learned yesterday:

The definition of pressure *p* is

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

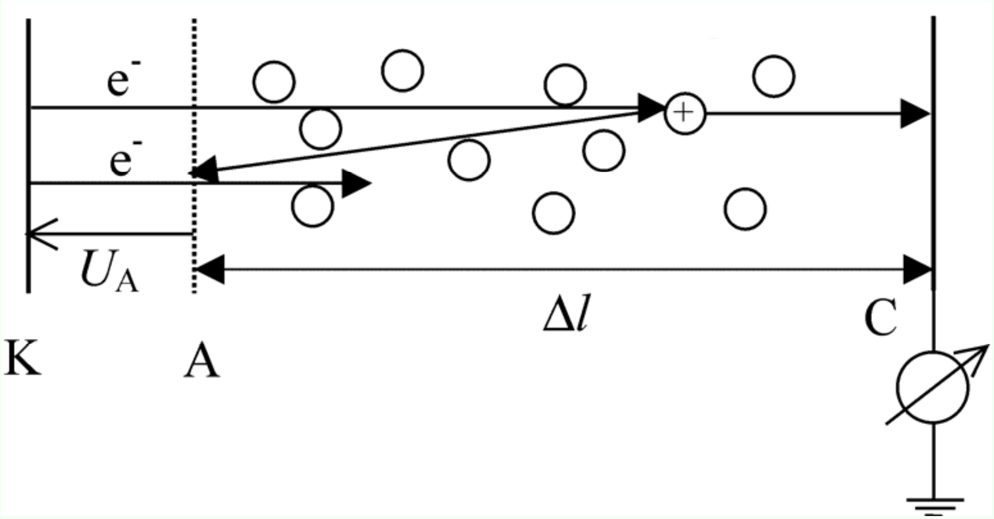
At 1E-7 Pa and *A*= 10 cm^2, it is *F*=1E-9 N.

Range of AF microscopes.

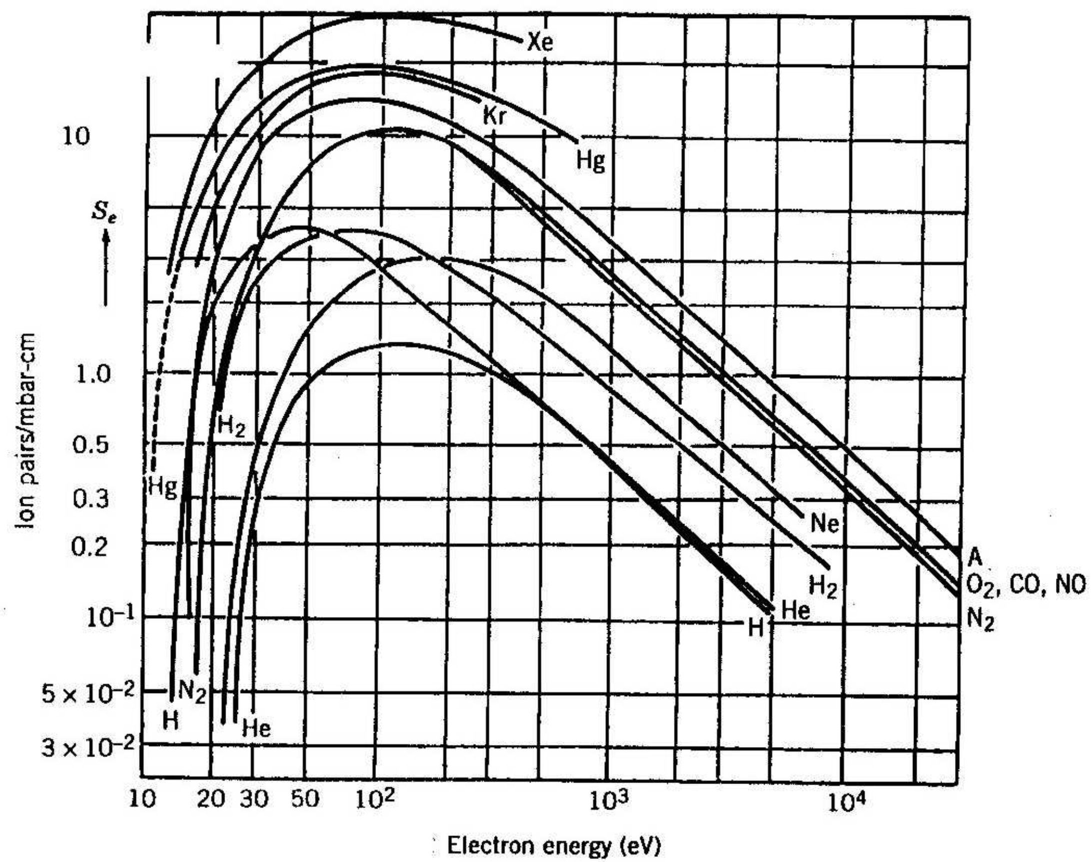


Measurement principle

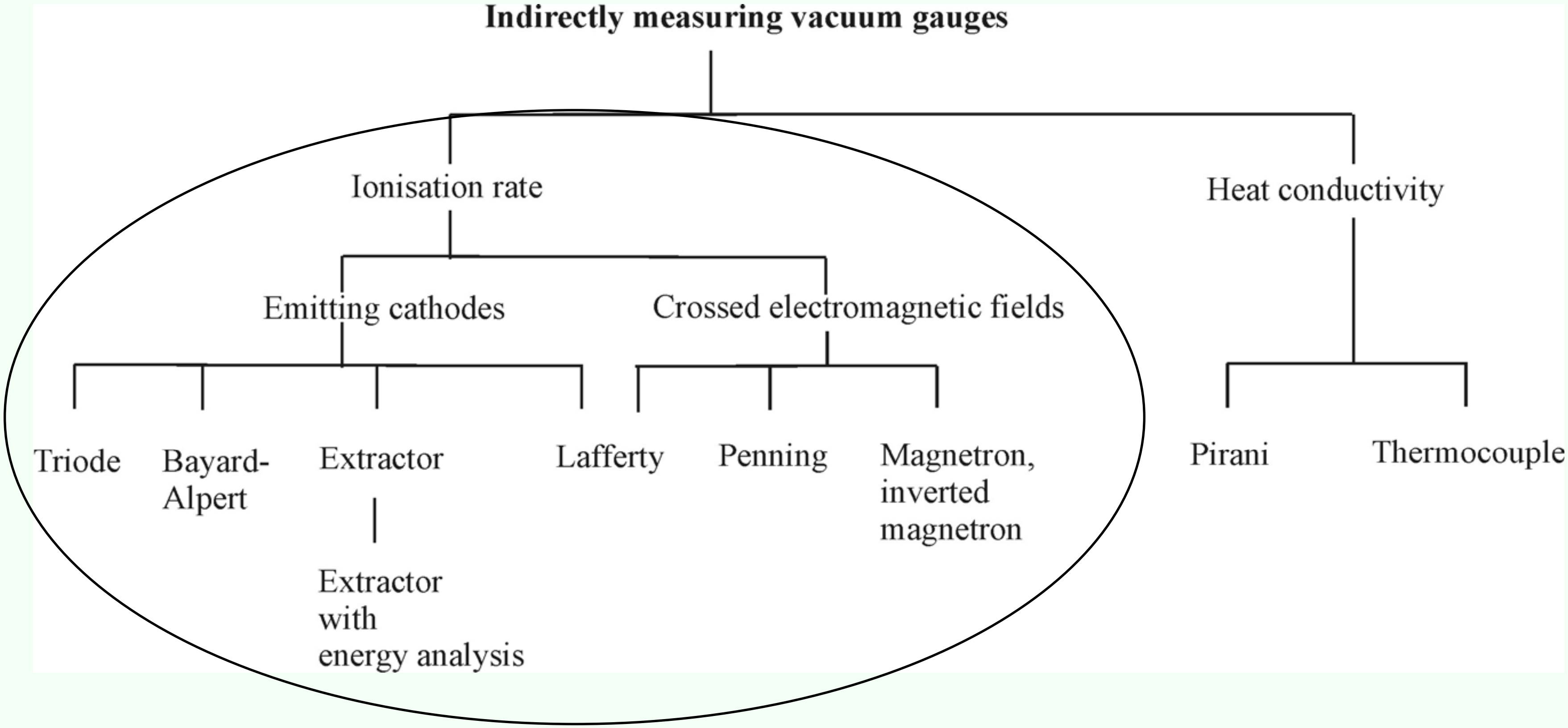
Ionisation

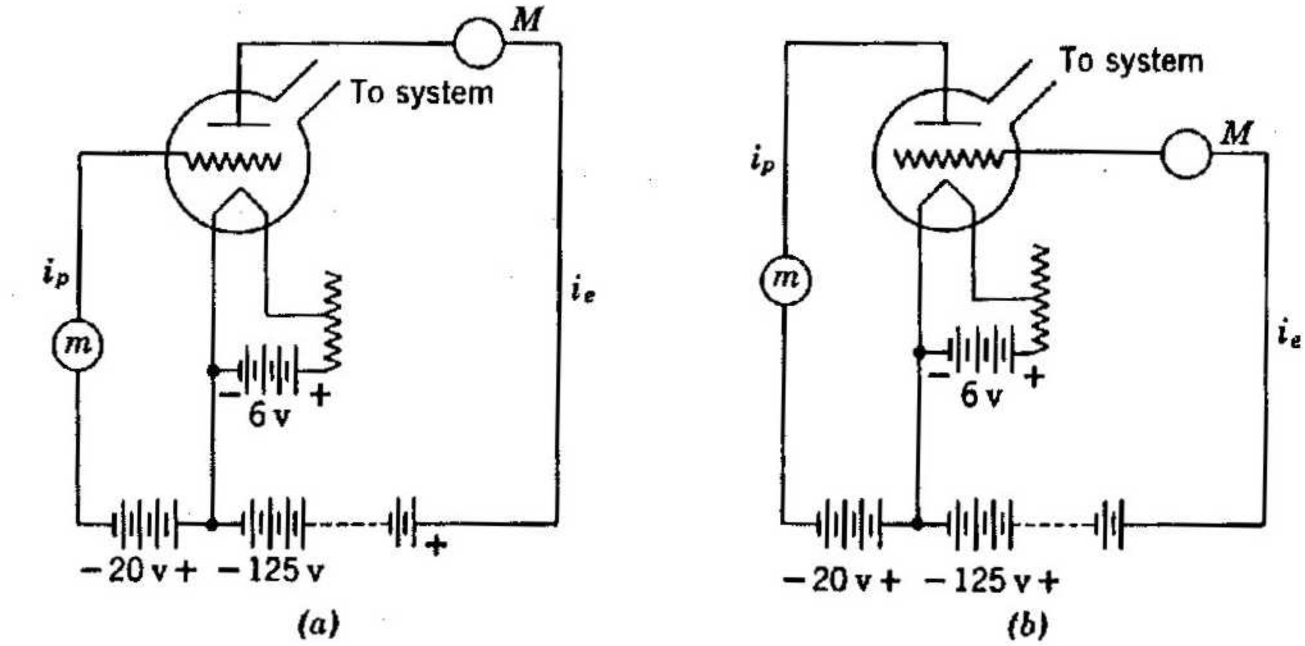


Ionisation probability of different gas species for electrons between 10 eV and 10 keV



Measurement principle



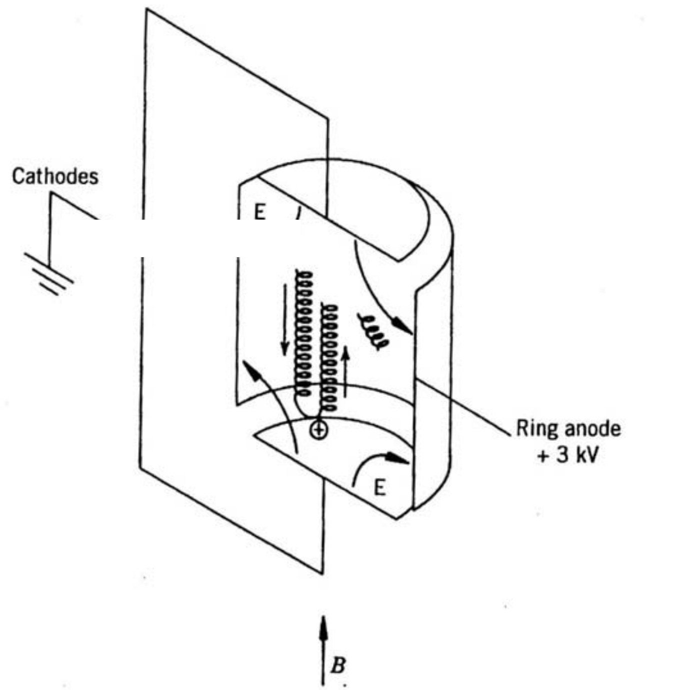


The historical triode gauge,

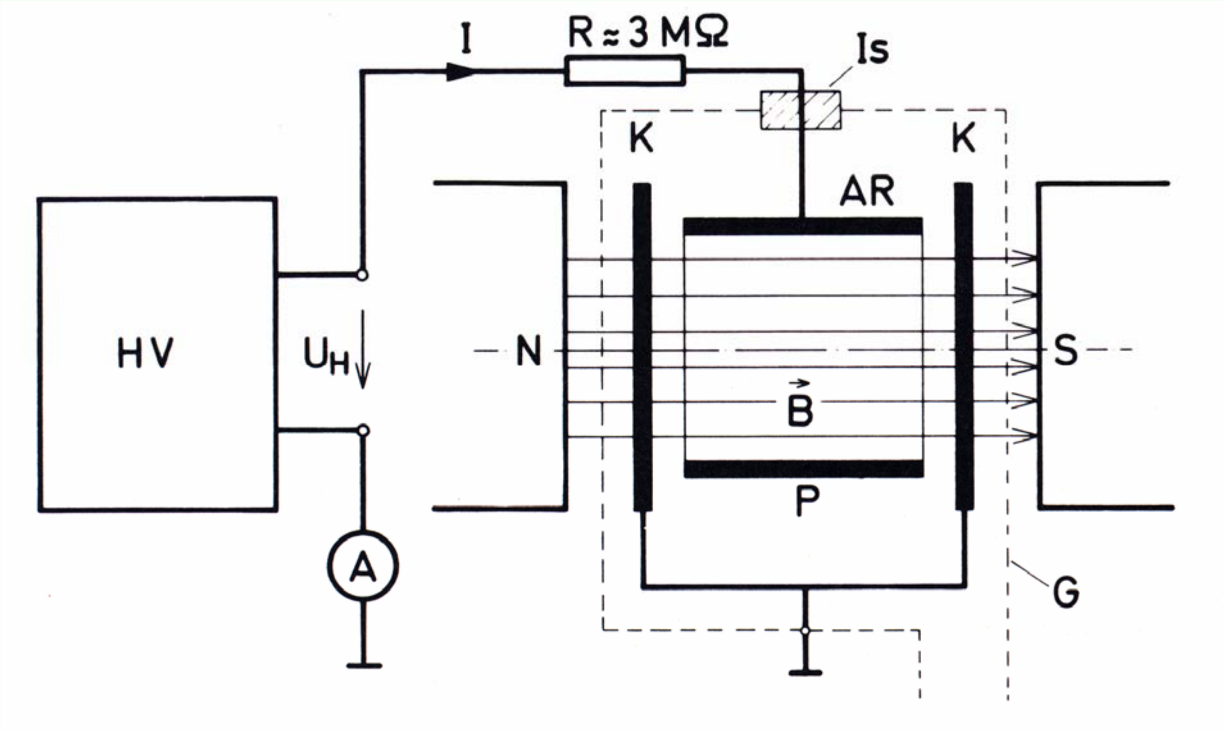
the „tube“.

The Penning gauge

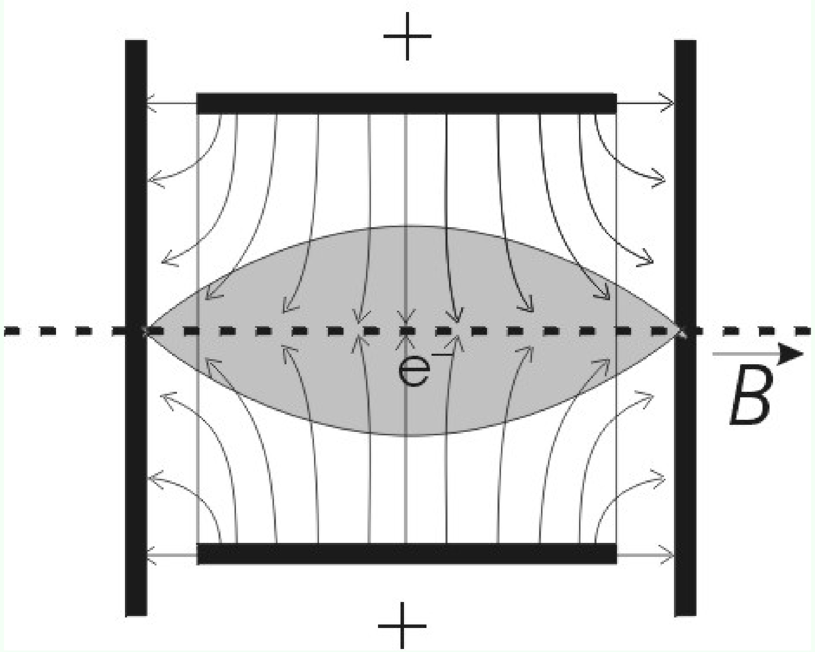
2nd generation 1949



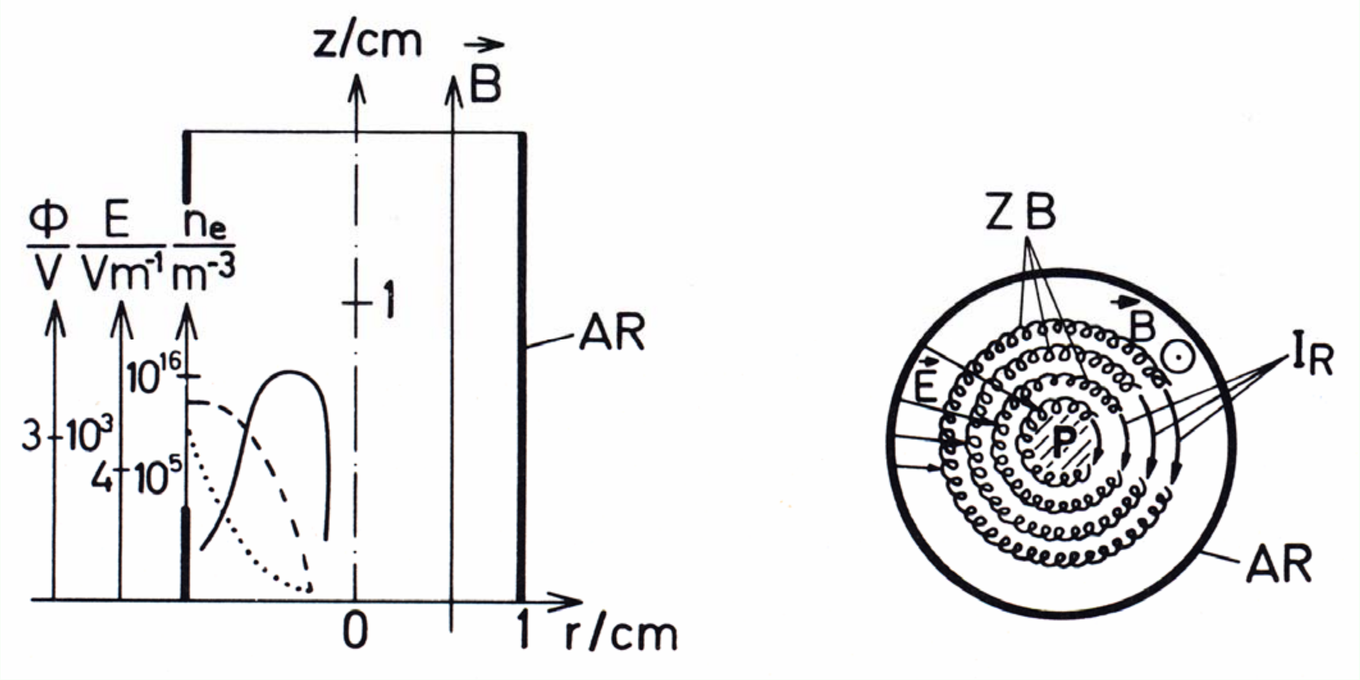
Electrode arrangement, fields, and trajectories in the Penning gauge.



Scheme of Penning gauge

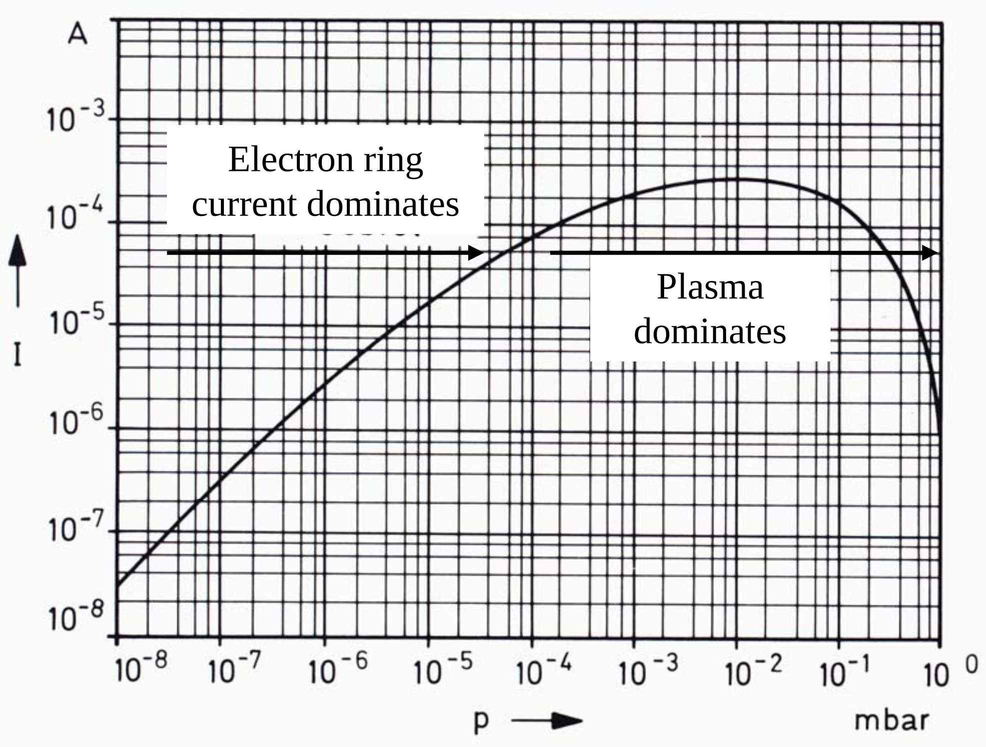


Directions of electrical field in Penning gauge



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

Crossed field gauges



Calibration curve of typical Penning gauge

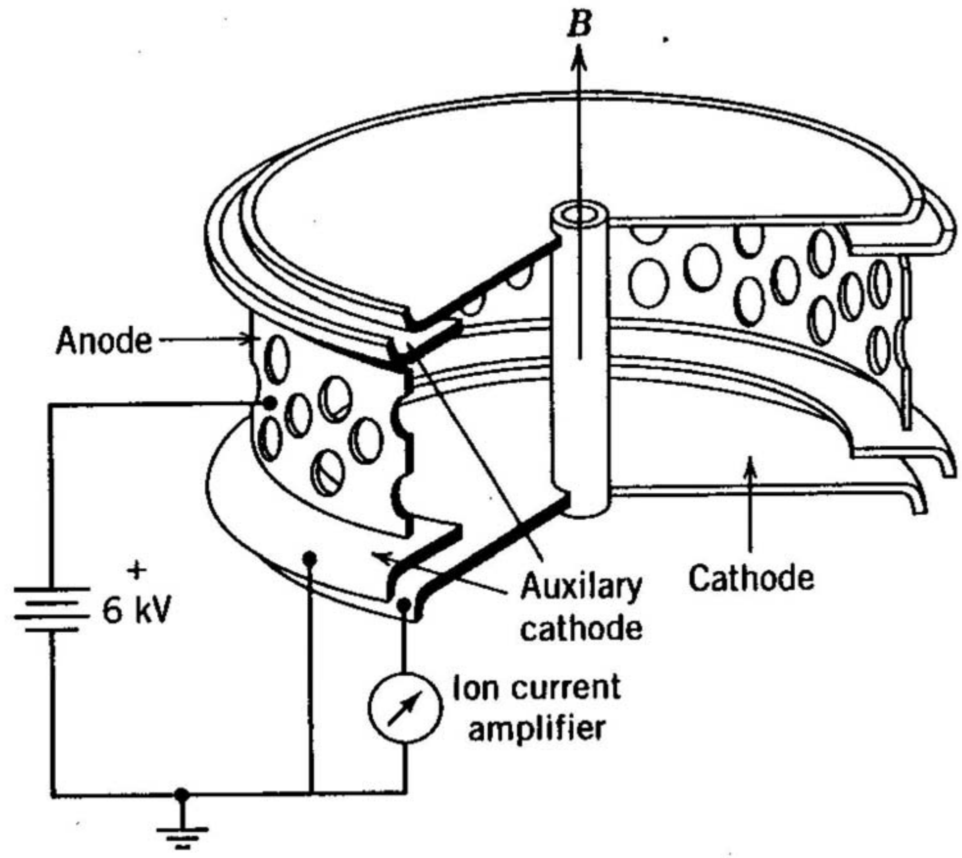
Crossed field gauges

Commercial

Penning gauge

Crossed field gauges

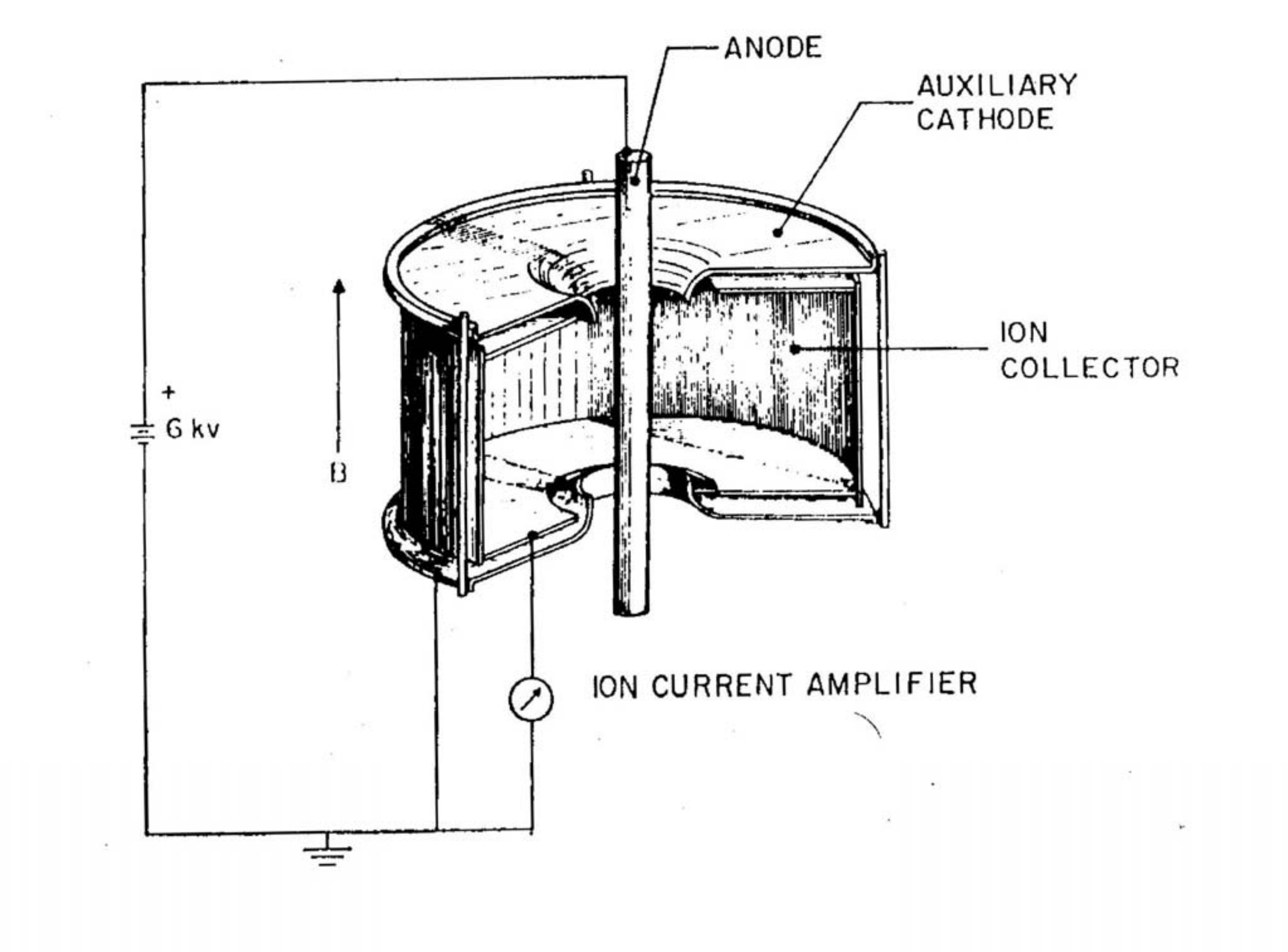
The Magnetron



Crossed field gauges

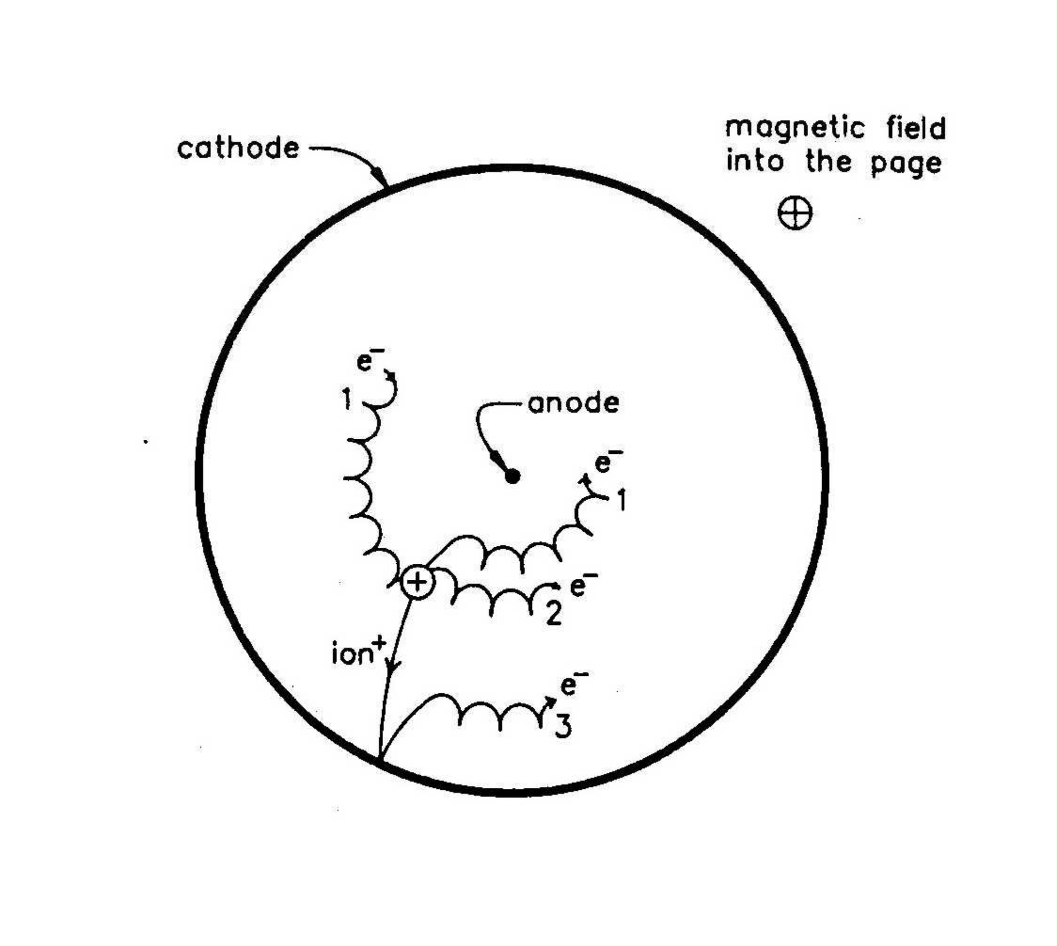
The inverted

Magnetron



Trajectories in

inverted magnetrons

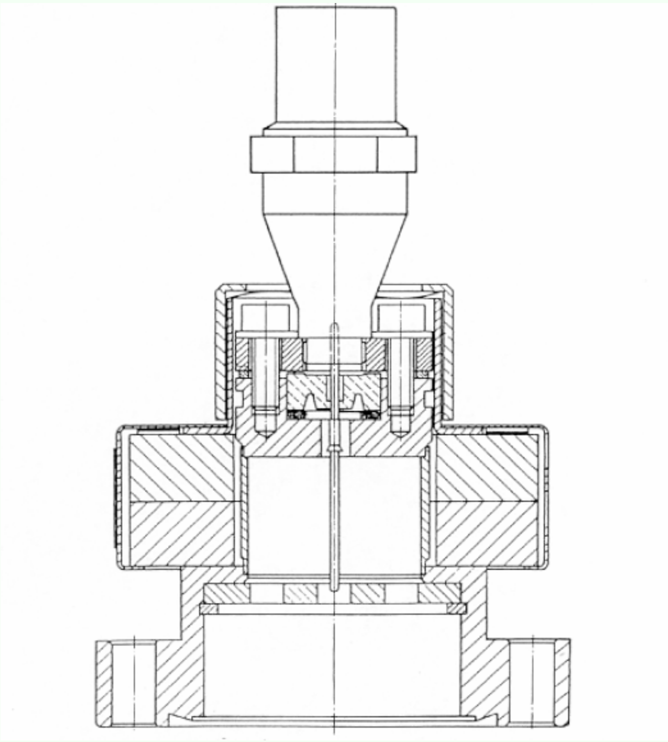


Crossed field gauges

Commercial

inverted magnetron

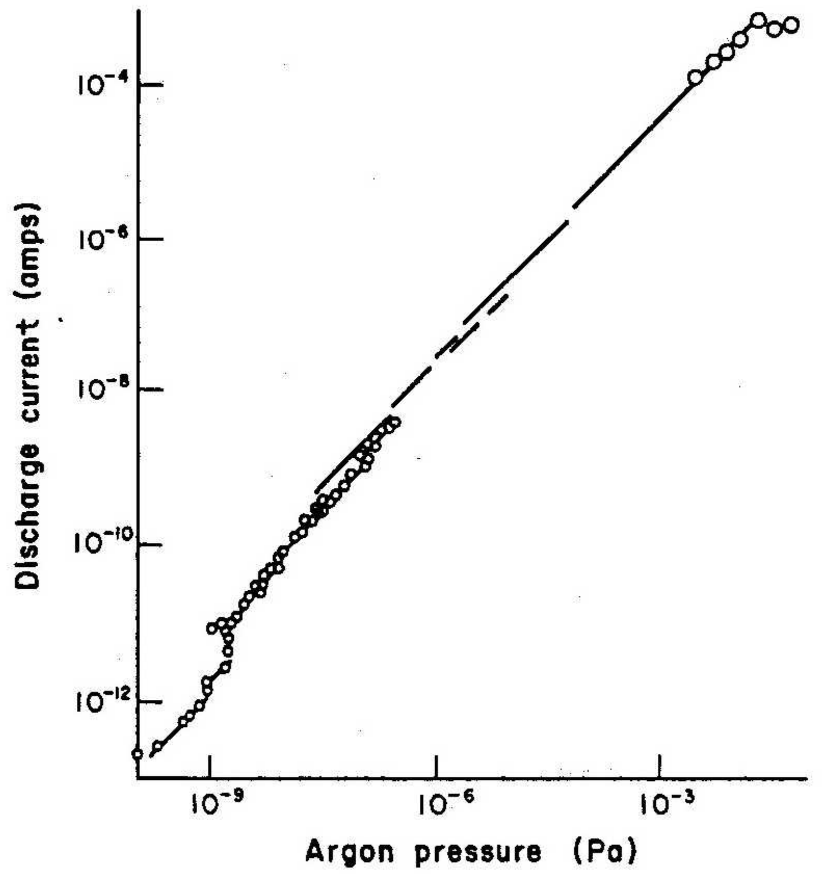
$$I^{+} = K \cdot p^{m}$$



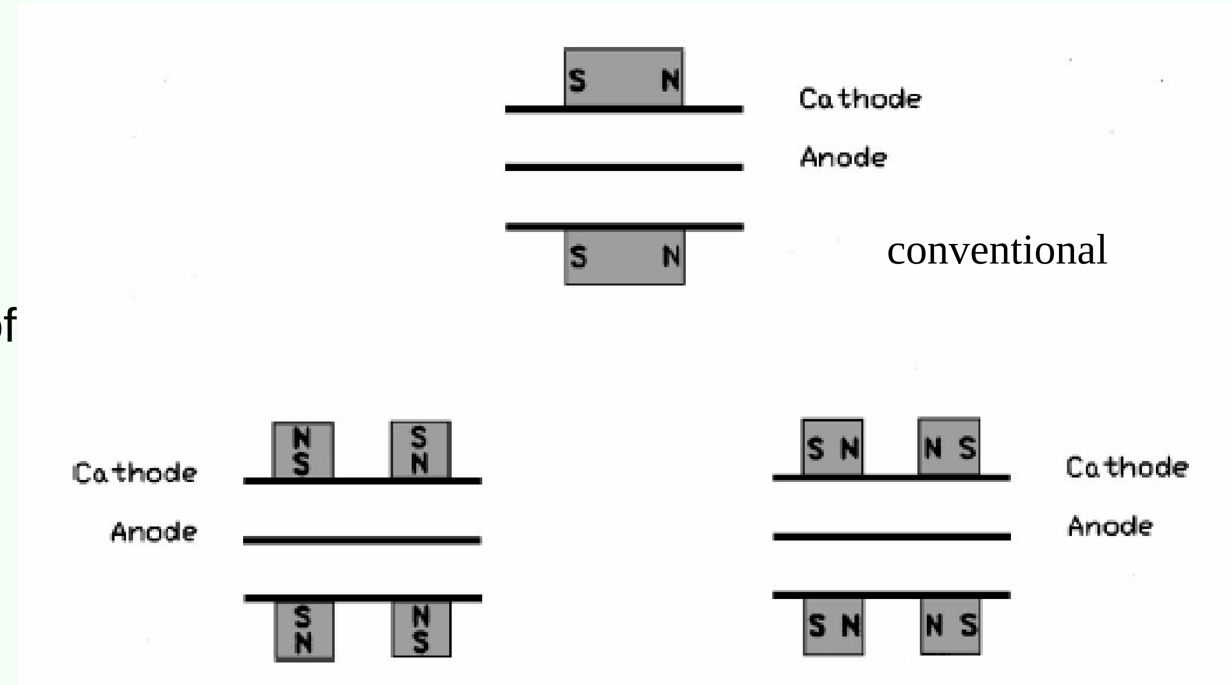
Penning gauge:

I vs *p*.

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



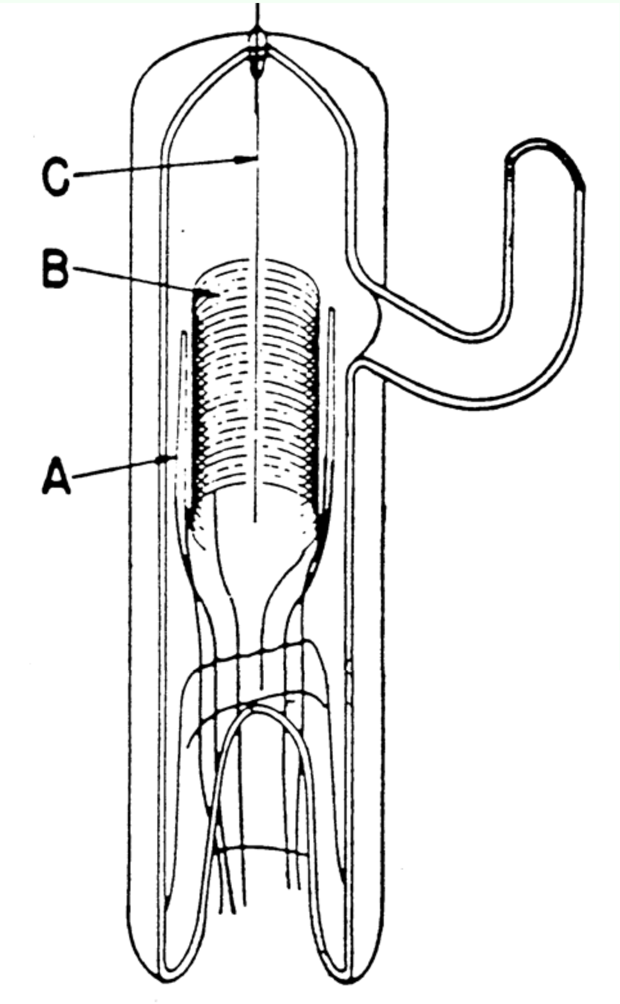
Reducing the magnetic field strength outside of the inverted magnetron



Lethbridge, Asl, 1993

Drubetsky, Taylor 1996

The original Bayard-Alpert gauge



Ion gauges with emitting cathodes

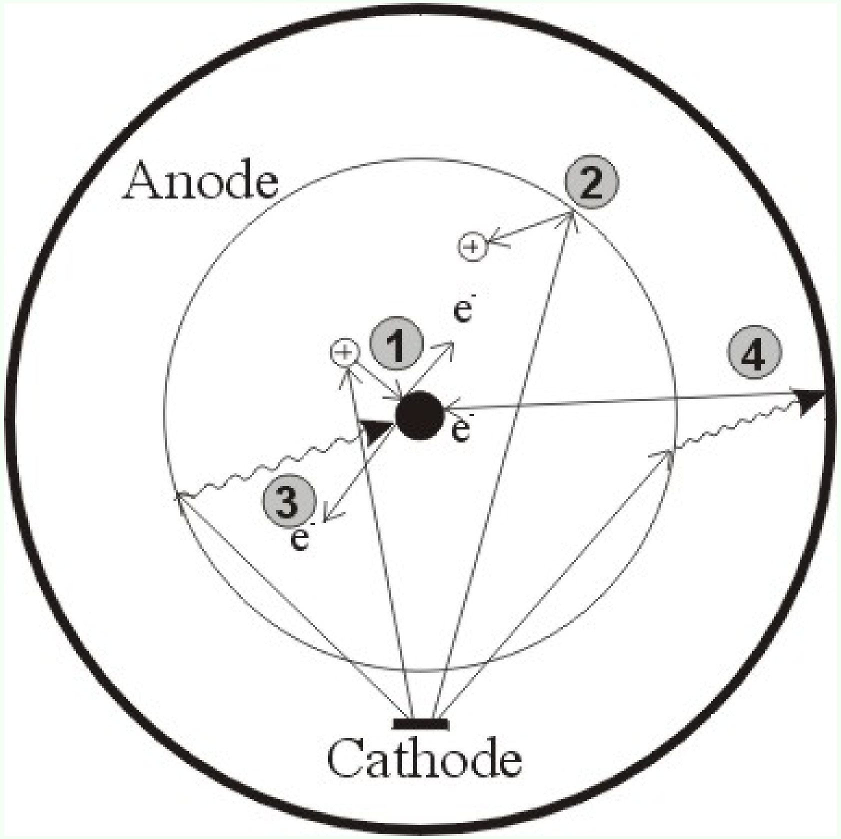
Effects in Bayard-Alpert gauges

1: The desired ionisation

2: Electron stimulated desorption

3: X-ray effect

4: Inverse X-ray effect



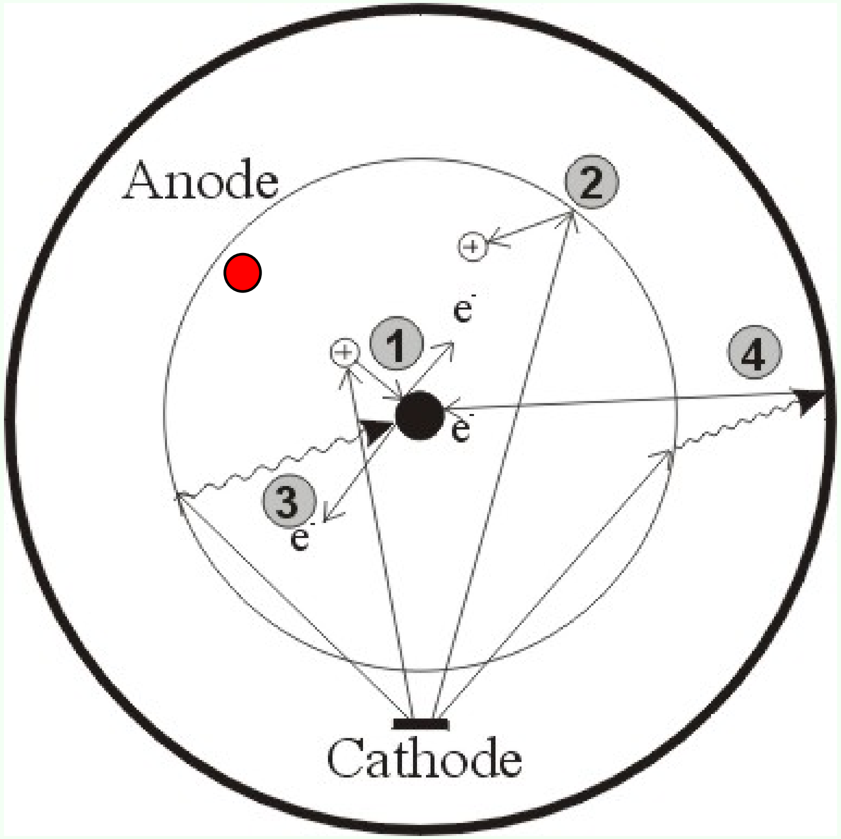
Approaches to measure lower pressure as with normal BA-gauge

1. Measure X-ray plus ESD current
2. Change geometry of the gauge to reduce residual current
3. Increase sensitivity (a) by geometry (b) by using electric or magnetic field

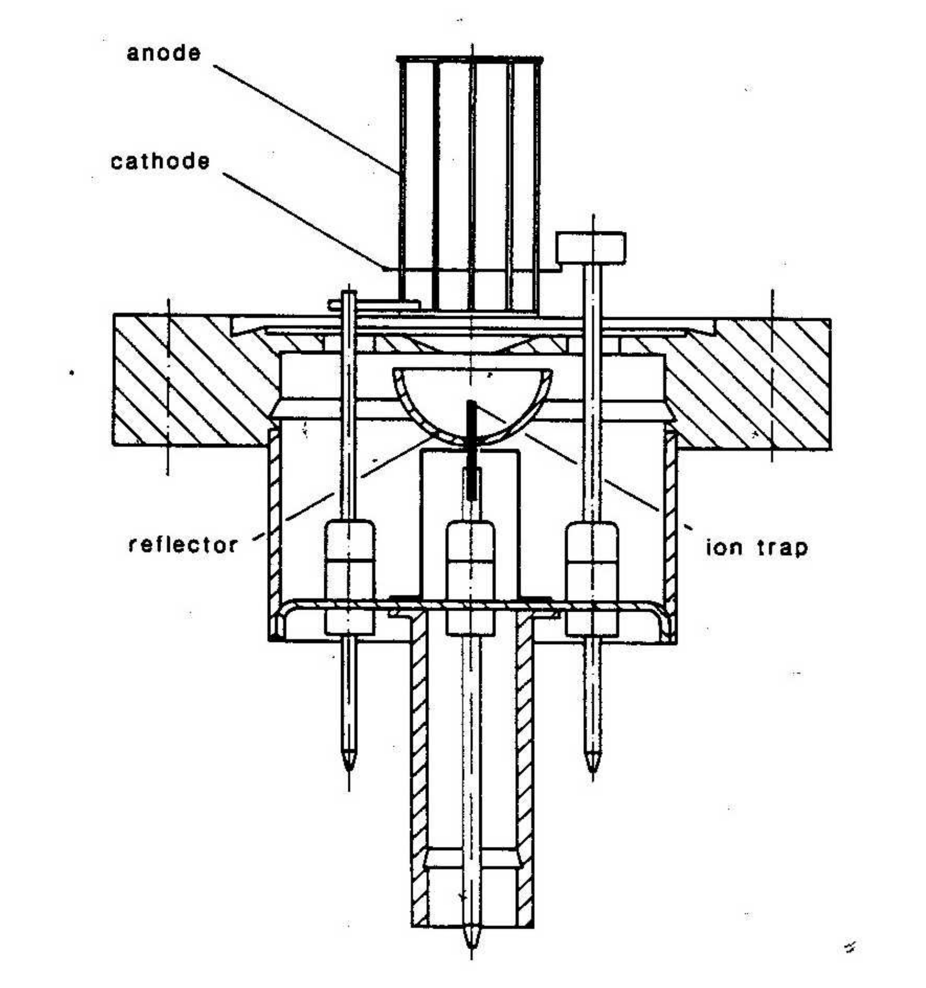
Ion gauges with emitting cathodes

- Modulator in Bayard-Alpert gauge (potential switched between grid and collector):

  Generated ions in space are modulated, secondary electrons and ESD ions are not modulated.

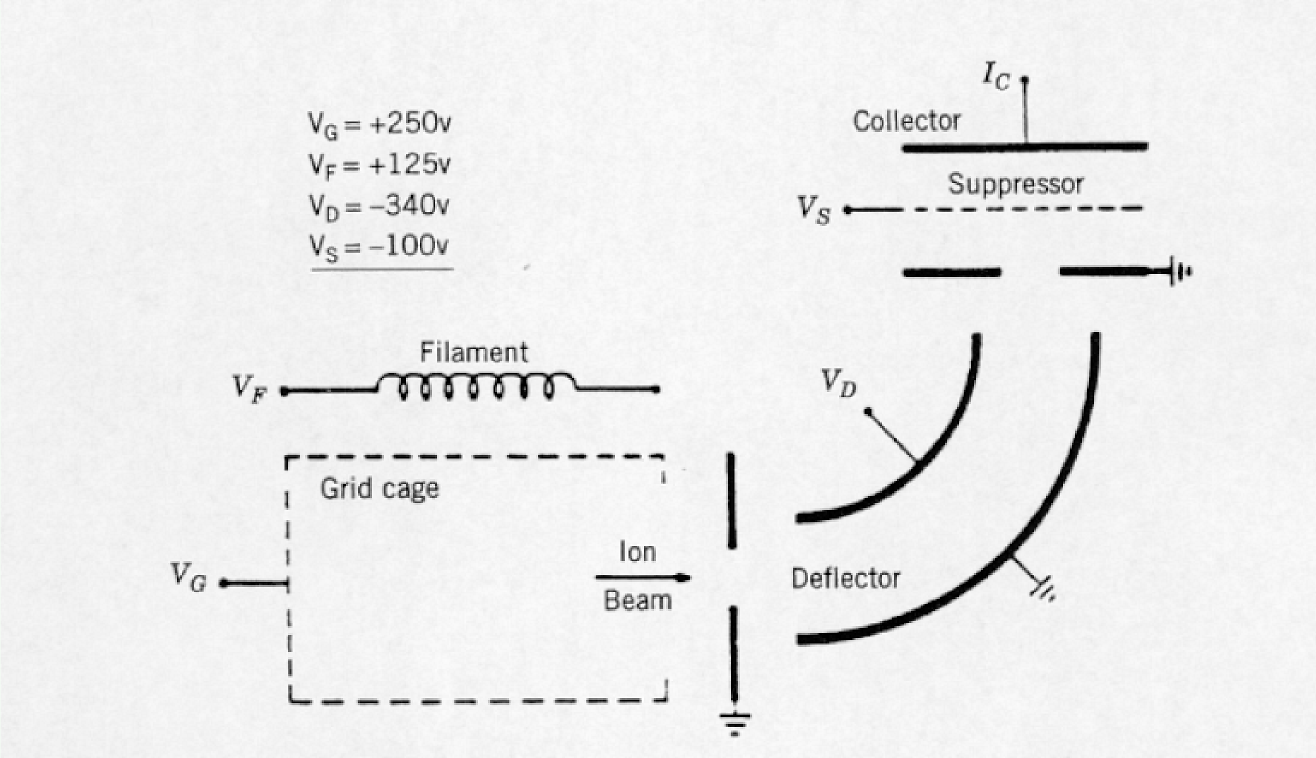


The extractor gauge



Ion gauges with emitting cathodes

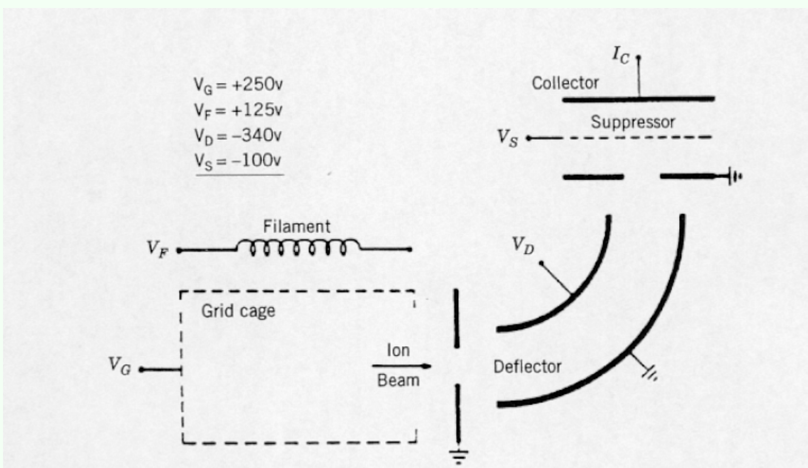
The Helmer gauge

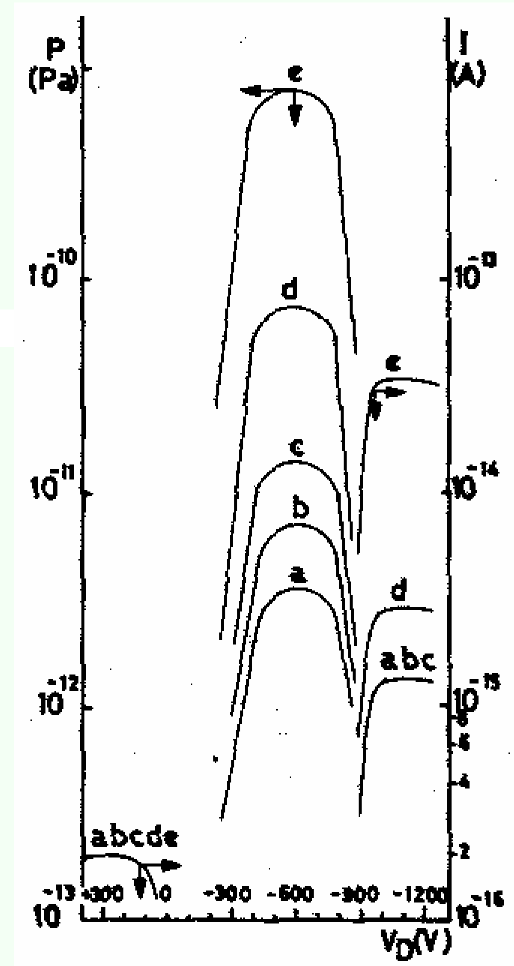


Ion gauges with emitting cathodes

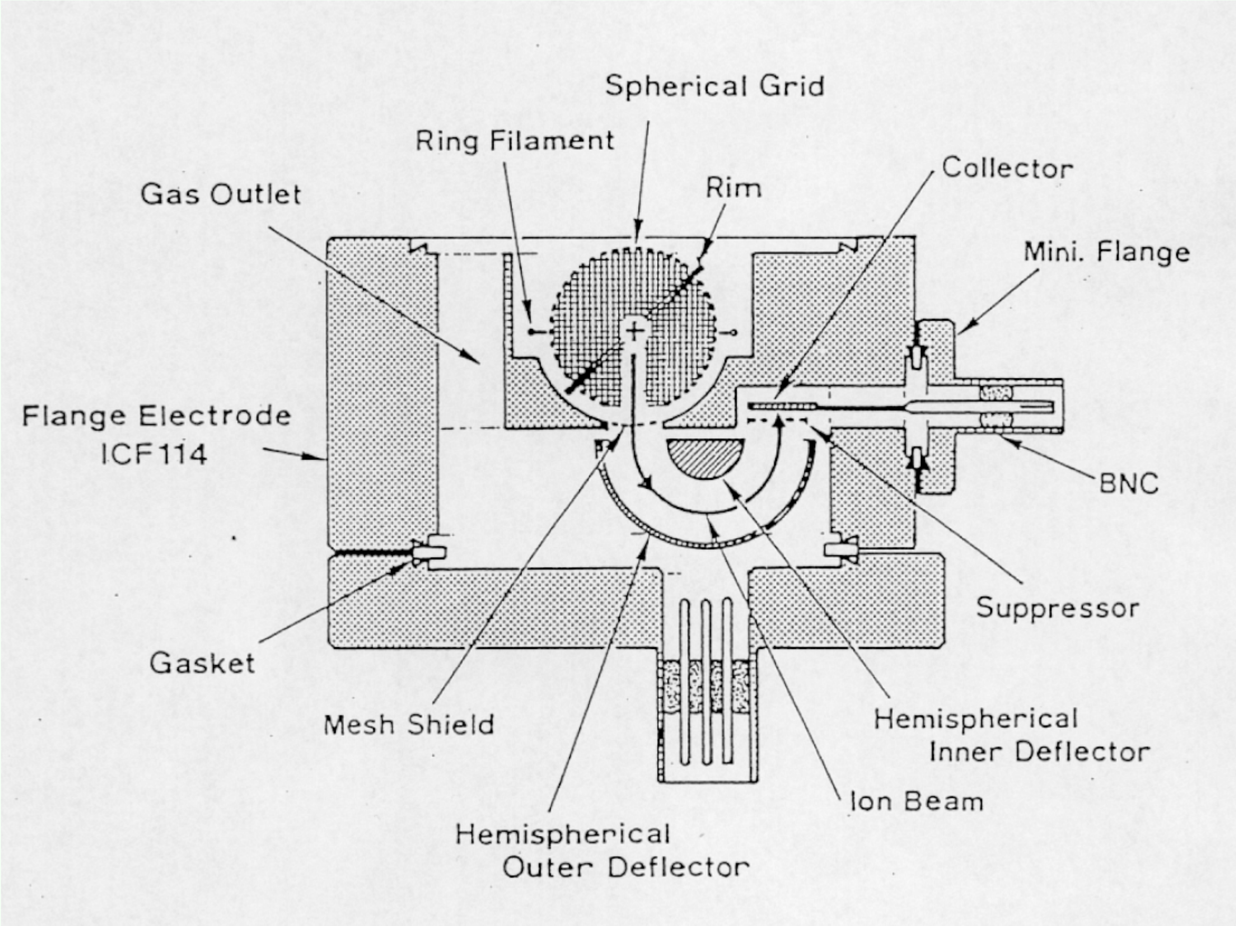
The Helmer gauge:

Benvenuti, Hauer, 1980





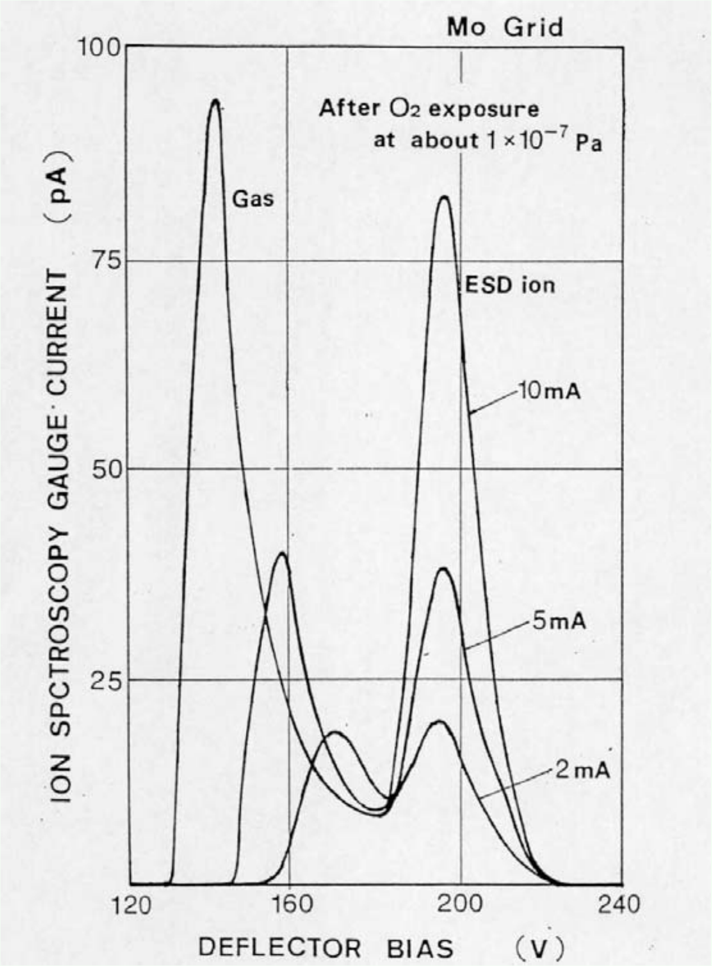
Ion gauges with emitting cathodes



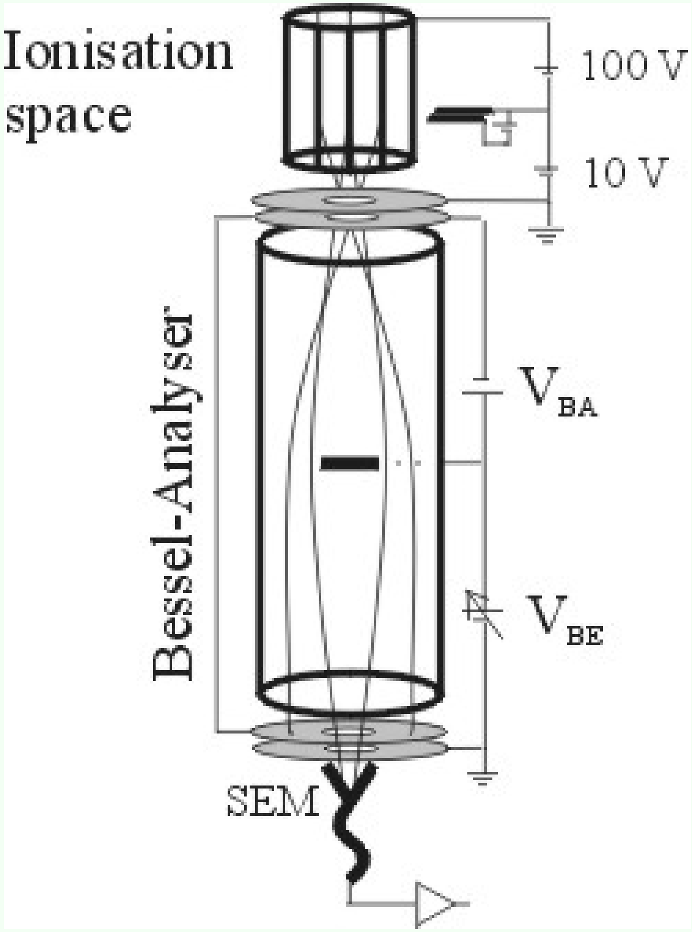
The ion spectroscopy gauge by Watanabe

Ion gauges with emitting cathodes

The energy spectrum in the ion spectroscopy gauge by Watanabe

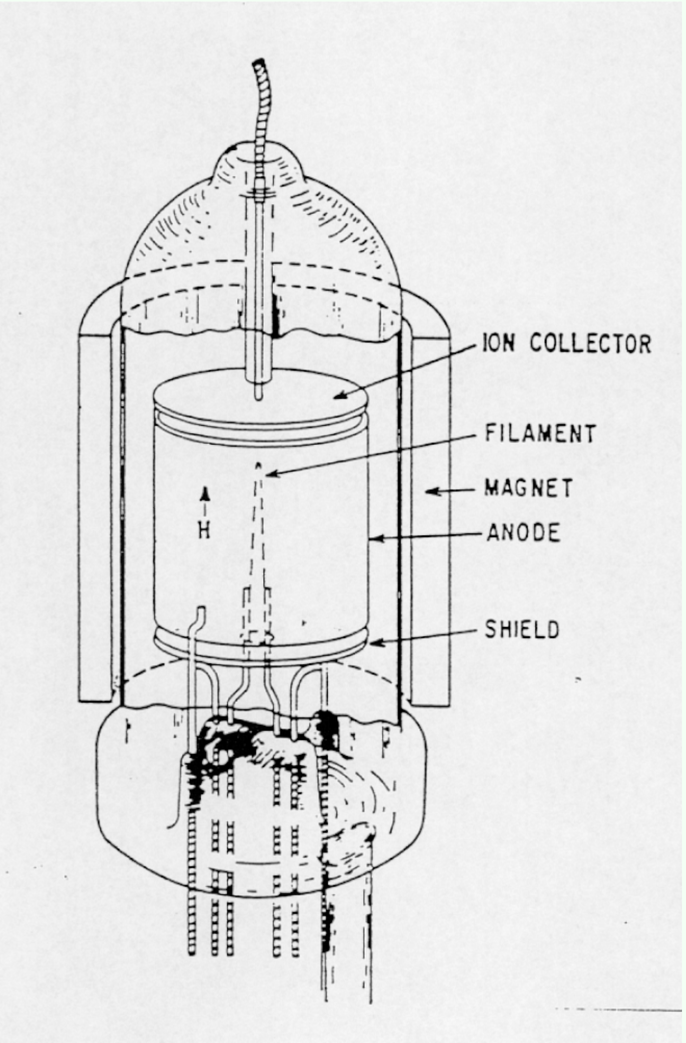


The AxTran gauge

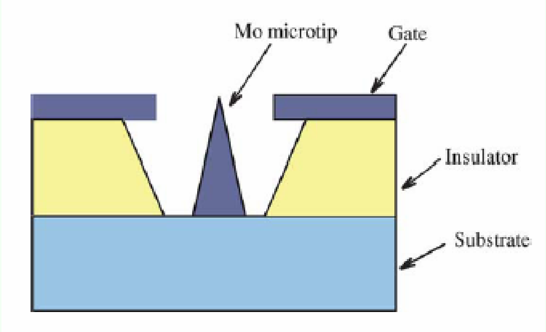


Ion gauges with emitting cathodes

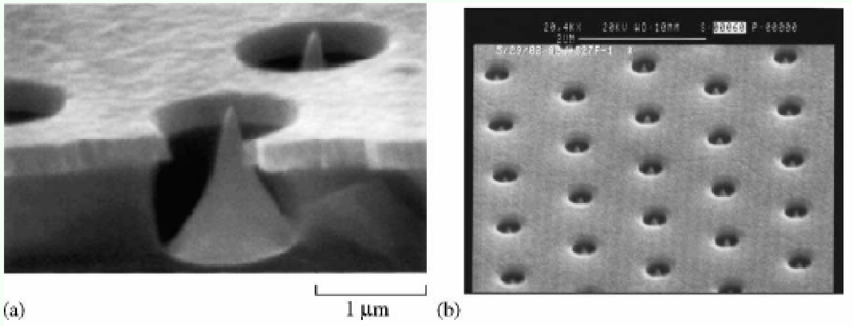
The Lafferty gauge



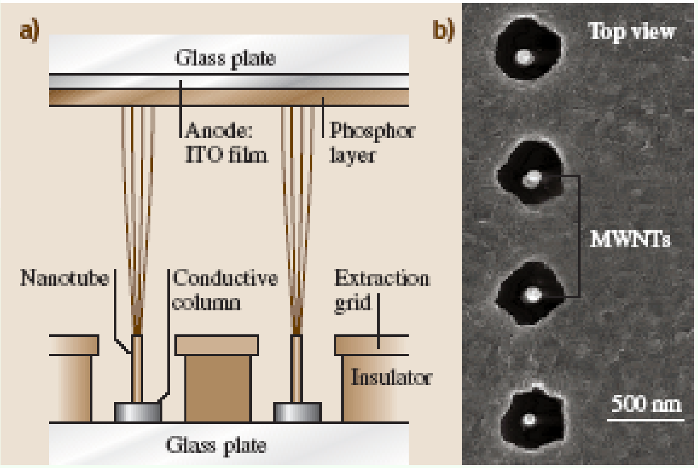
Spindt field emitters and carbon nanotubes as cold cathodes



Spindt cathode - basic structure



C. A. Spindt, SRI, Ca, USA



From Springer Handbook of Nanotechnology, ed. Bhushan, 2004.

Summary: Types of ionisation gauges

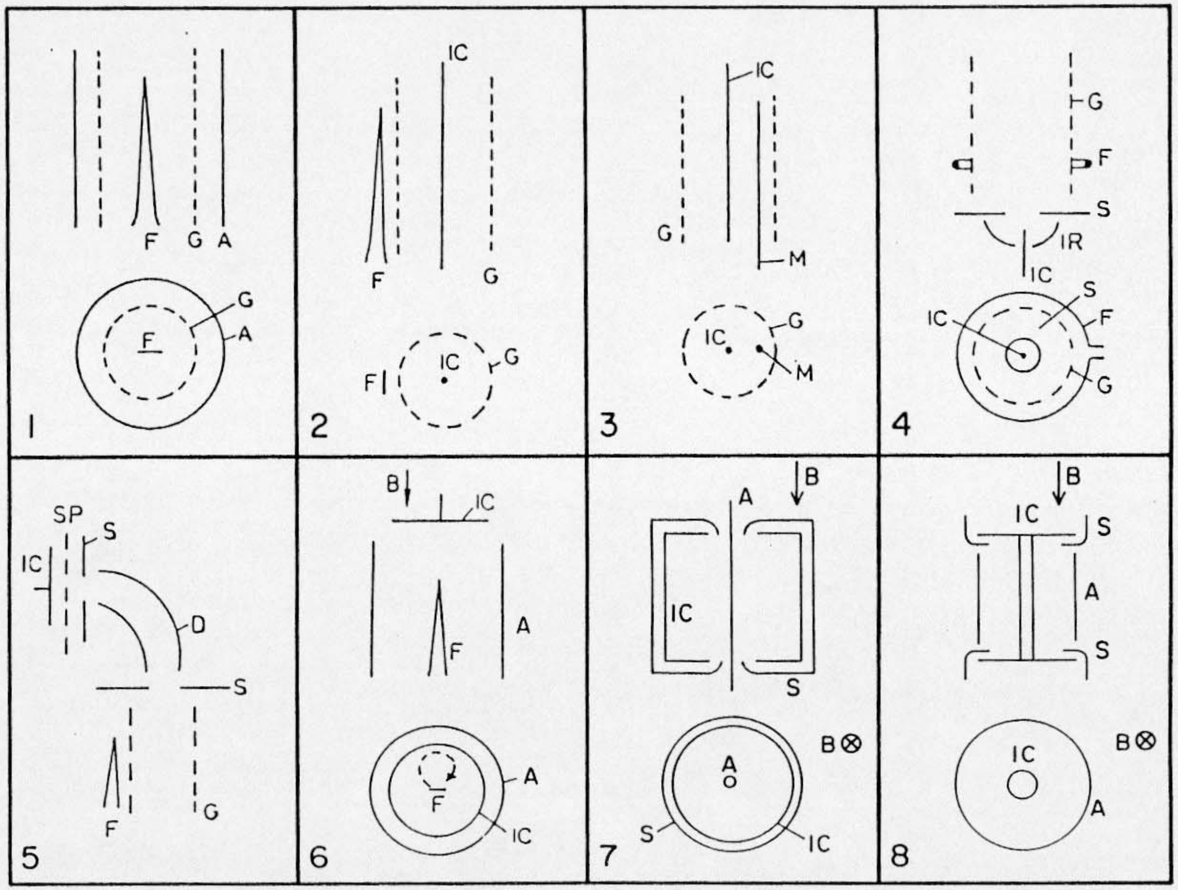
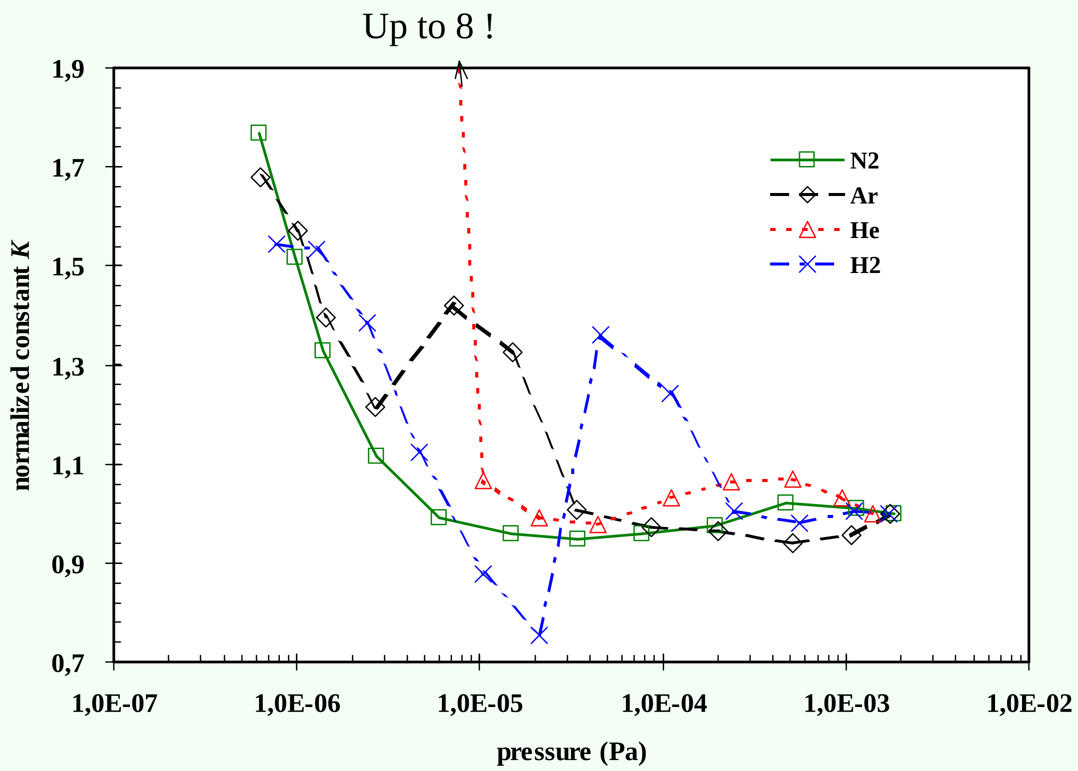


FIG. 5. Schematic diagrams of ionization gauges; (1) conventional gauge; (2) Bayard–Alpert gauge; (3) modulated Bayard–Alpert gauge; (4) extractor gauge; (5) bent-beam gauge; (6) hot-cathode magnetron; (7) inverted-magnetron gauge; (8) magnetron gauge. A–Anode, D–deflector, F–filament, G–grid, IC–ion collector, IR–ion reflector, M–modulator, S–shield, SP–suppressor.

Comparison of the types of ionisation gauges

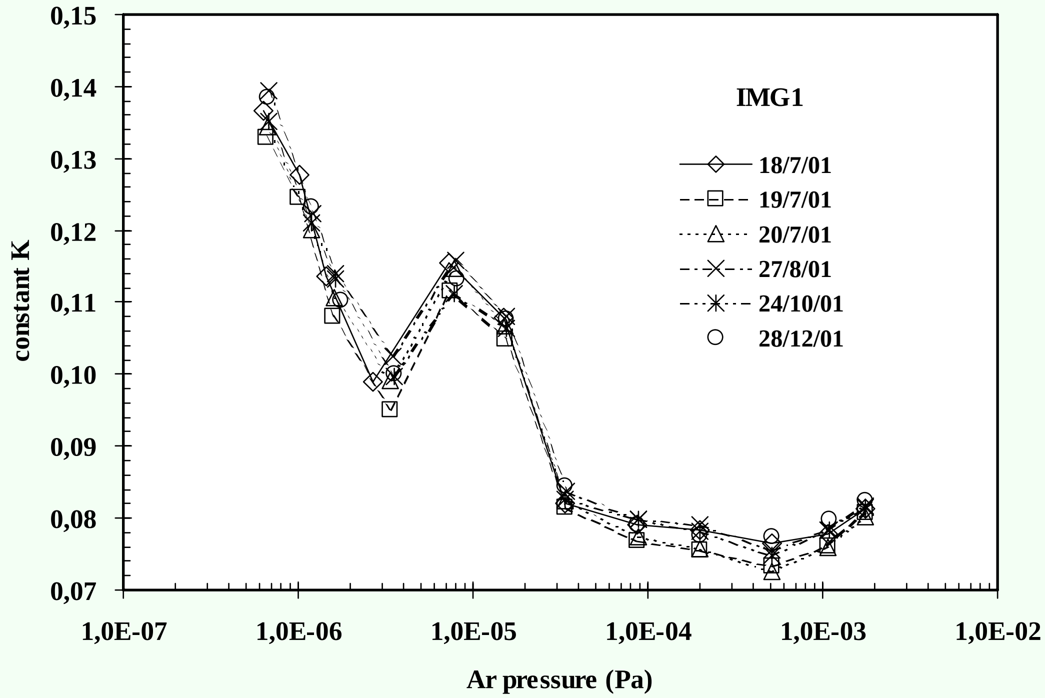
$$I = Kp^m$$

	m
H_2	1.15
He	1.30
N_2	1.17
Ar	1.17



Comparison of the types of ionisation gauges

$$I = Kp^m$$



Max. deviations in % from 1 st calibration within 6 months

	EXG	**BAG1**	**BAG2**	**IMG1**	**IMG2**
N_2	-2.5	-4.3	-3.2	-6.2	+5.9
Ar	-1.9	-3.8	+3.8	-2.4	+3.1
He	-5.9	-4.4	-3.6	+8.4	-5.0
H_2	+9.4	-1.9	-3.6	-1.0	-1.3

From D.Li, K. Jousten, Vacuum 70 (2003), 531...541.

Max. deviation limits in % from mean within 72 h operation (1E-4 Pa)

	EXG	**BAG1**	**BAG2**	**IMG1**	**IMG2**
N_2	-0.40…+0.31	-0.15…+0.20	-0.24…+0.51	-1.34…+1.51	-1.81…+0.58
Ar	-0.90…+1.52	-0.95…+0.56	-0.33…+0.29	-1.25…+2.31	-1.03…+1.21
He	-0.29…+0.43	-0.46…+0.42	-0.27…+0.30	-1.52…+2.53	-1.08…+0.77
H_2	-0.32…+0.39	-0.18…+0.33	-0.12…+0.36	-0.56…+0.58	-0.36…+0.21

From D.Li, K. Jousten, Vacuum 70 (2003), 531...541.

Outgassing rates in Pa L/s

EXG at 1.5mA	BAG1 at 4mA	BAG2 at 1mA	IMG1/IMG2
$2.4 \cdot 10^{-8}$	$8.1 \cdot 10^{-8}$	$3.0 \cdot 10^{-8}$	none

From D.Li, K. Jousten, Vacuum 70 (2003), 531...541.

Comparison of the types of ionisation gauges

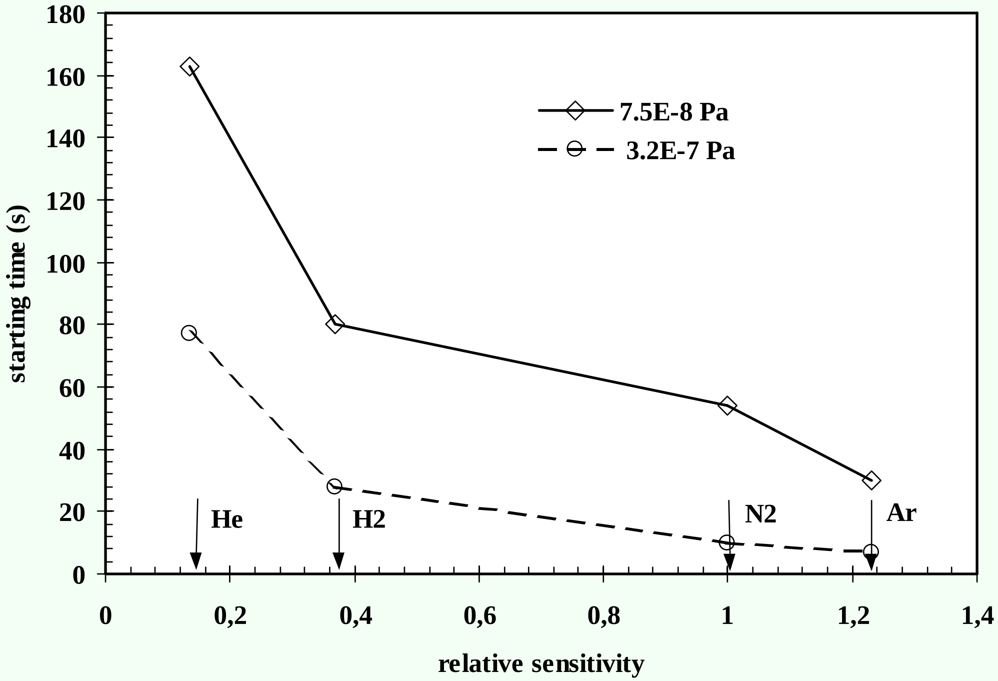
Pumping speeds in L/s

Gas	IMG1	IMG2	BAG1 at 4mA	BAG2 at 1mA	BAG2 at 10mA
N_2	0.045	0.065	0.019	-	0.045
Ar	0.2	0.21	0.067	0.037	0.23

From D.Li, K. Jousten, Vacuum 70 (2003), 531...541.

Comparison of the types of ionisation gauges

Ignition of inverted magnetrons



Problems special to accerators:

Radiation (Example: IG close to photon absorber)

Strong magnetic fields (shielding necessary)

RF radiation (Example: RF cavity -> shield)

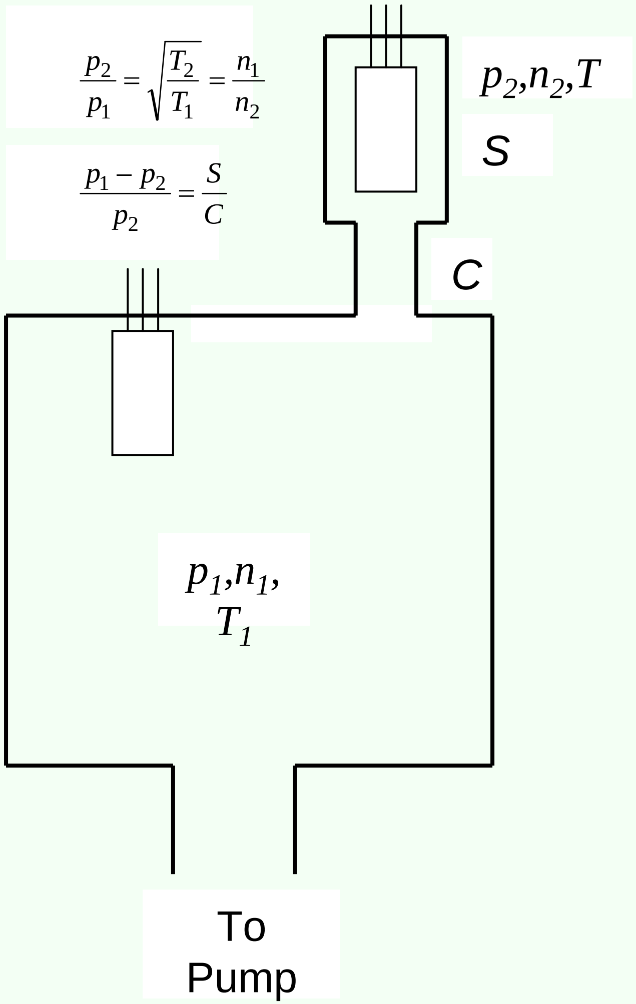
Problem: IG measures density, not pressure

Sealed-off chamber, cool it down.

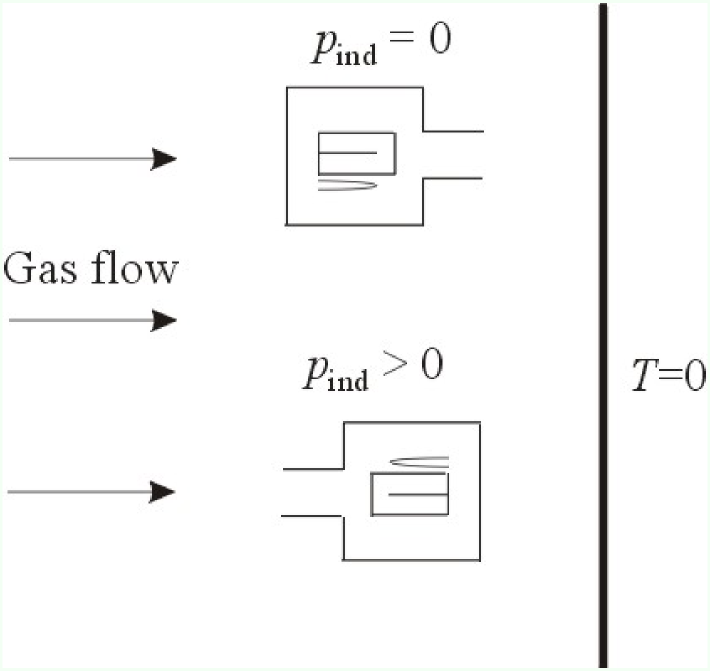
$$\frac{p_2}{p_1} = \frac{T_2}{T_1} = \frac{77}{300} = 0.257$$

But IG will have same reading!

The effects of tubulation, conductance, pumping speed, and thermal transpiration

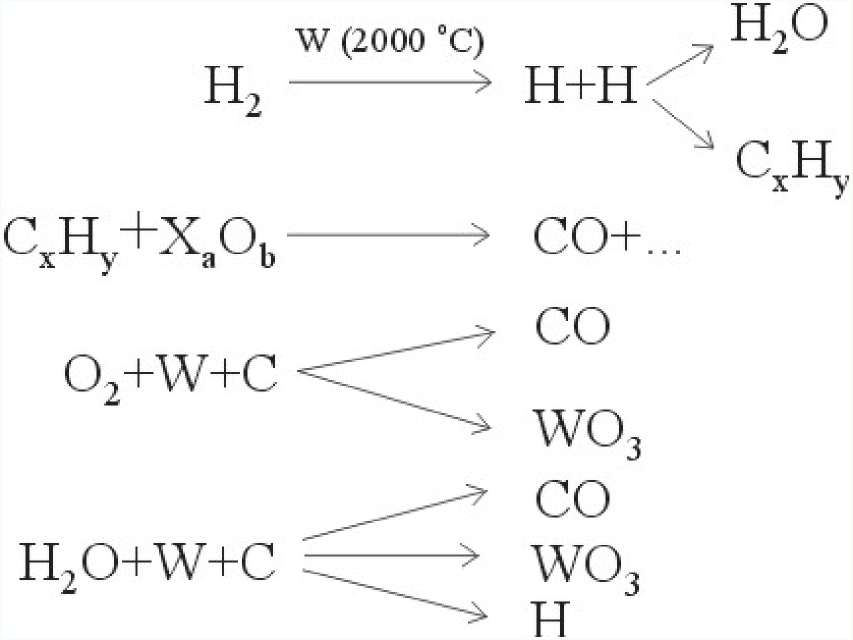


Orientation of a gauge



Problems with ion gauges

Effects on a hot cathode



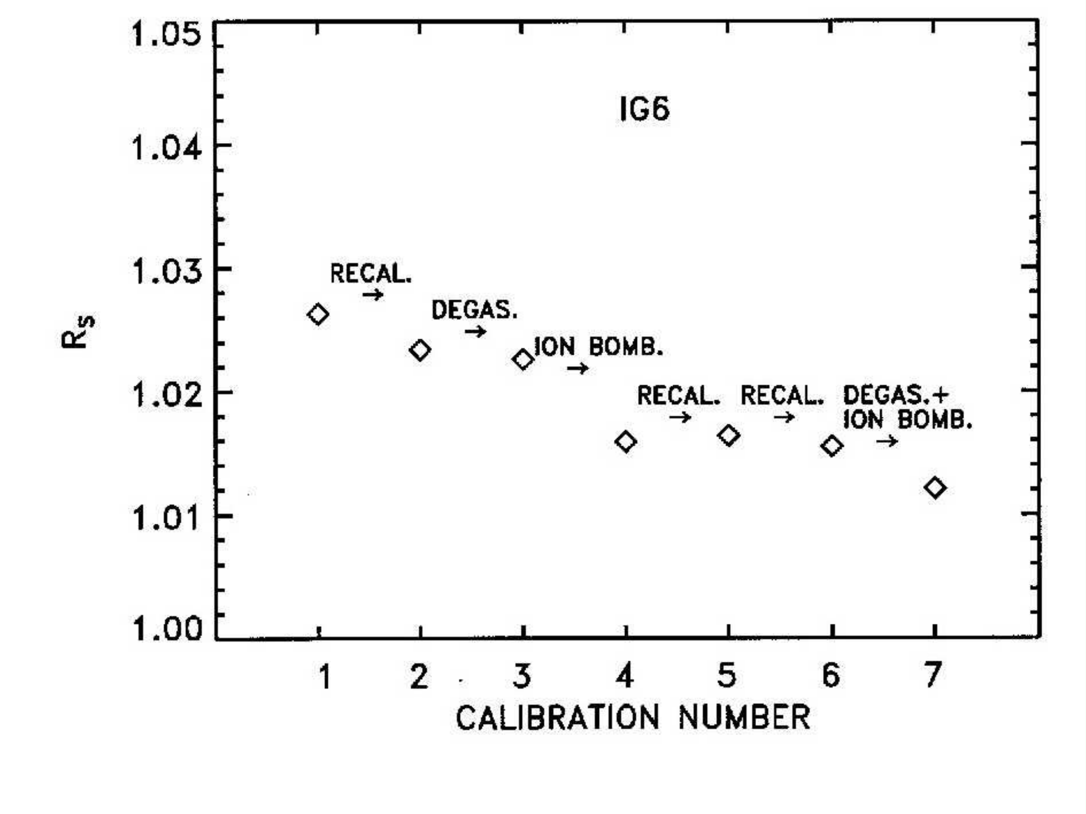
Gas species	$KF_i(N_2)$
N_2	1
He	7,24
Ne	4,55
Ar	0,85
Kr	0,59
Xe	0,41
H_2	2,49
O_2	1,07
Air	1,02
CO	0,97
CO_2	0,70
J	0,17
CH_4	0,71
C_2H_6	0,37
C_3H_8	0,22
CF_2Cl_2	0,36
Oil vapours	0,1

From „Wutz Handbuch Vakuumtechnik“, ed. K. Jousten, Vieweg, 2004.

Problems with ion gauges

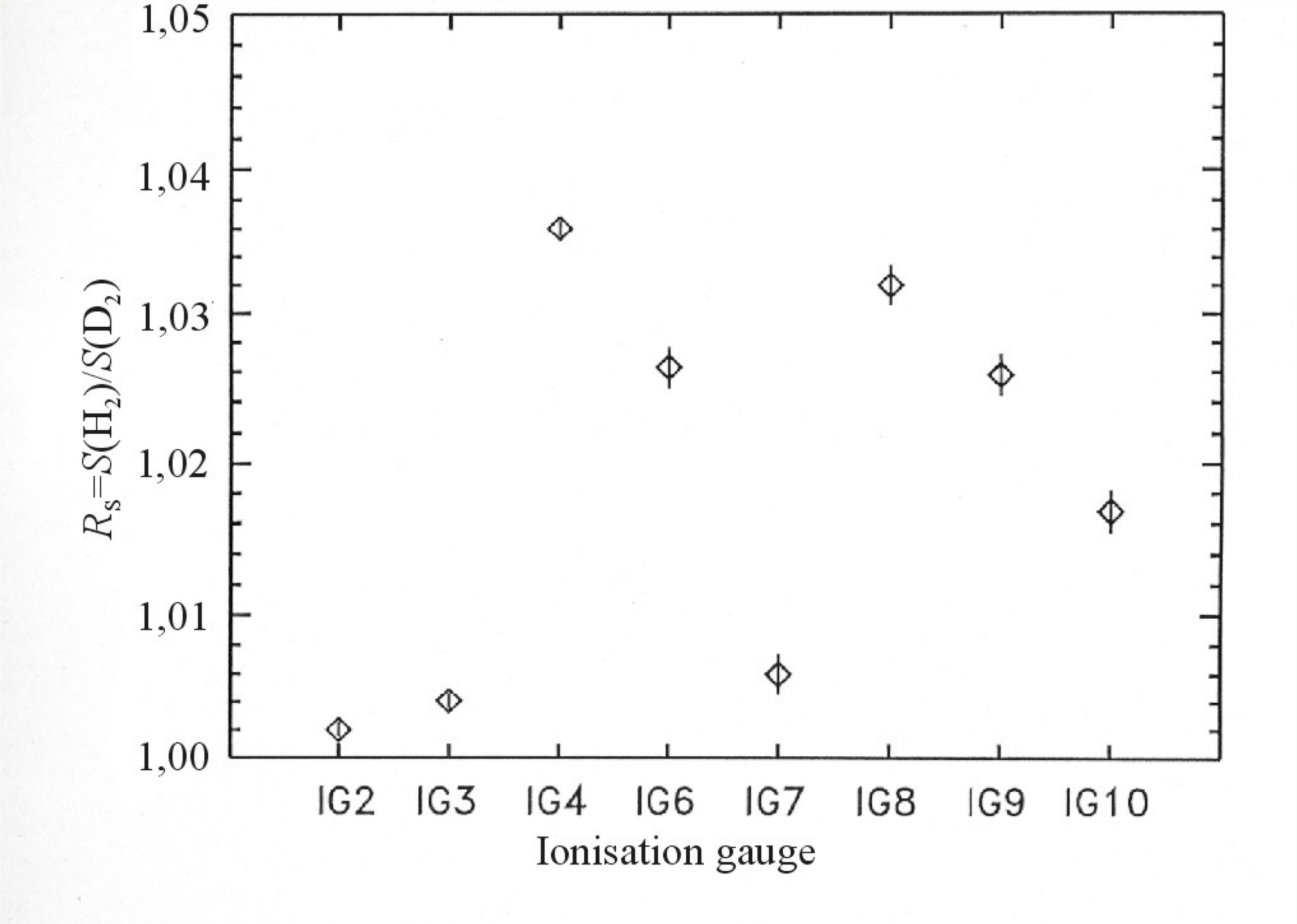
Sensitivity ratio R_S of hydrogen and deuterium

Effects on the collector after differnt treatments.



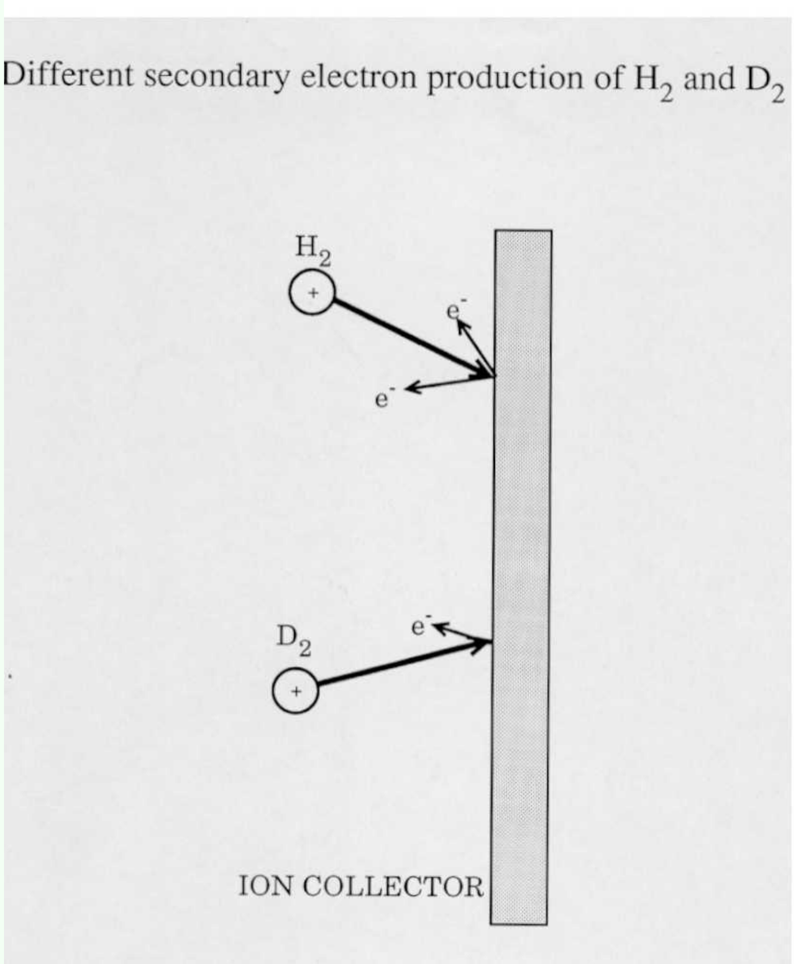
Sensitivity ratio R_S of hydrogen and deuterium

Effects on the collector for different gauges



Problems with ion gauges

Effects on the collector



Summary: Types of ionisation gauges

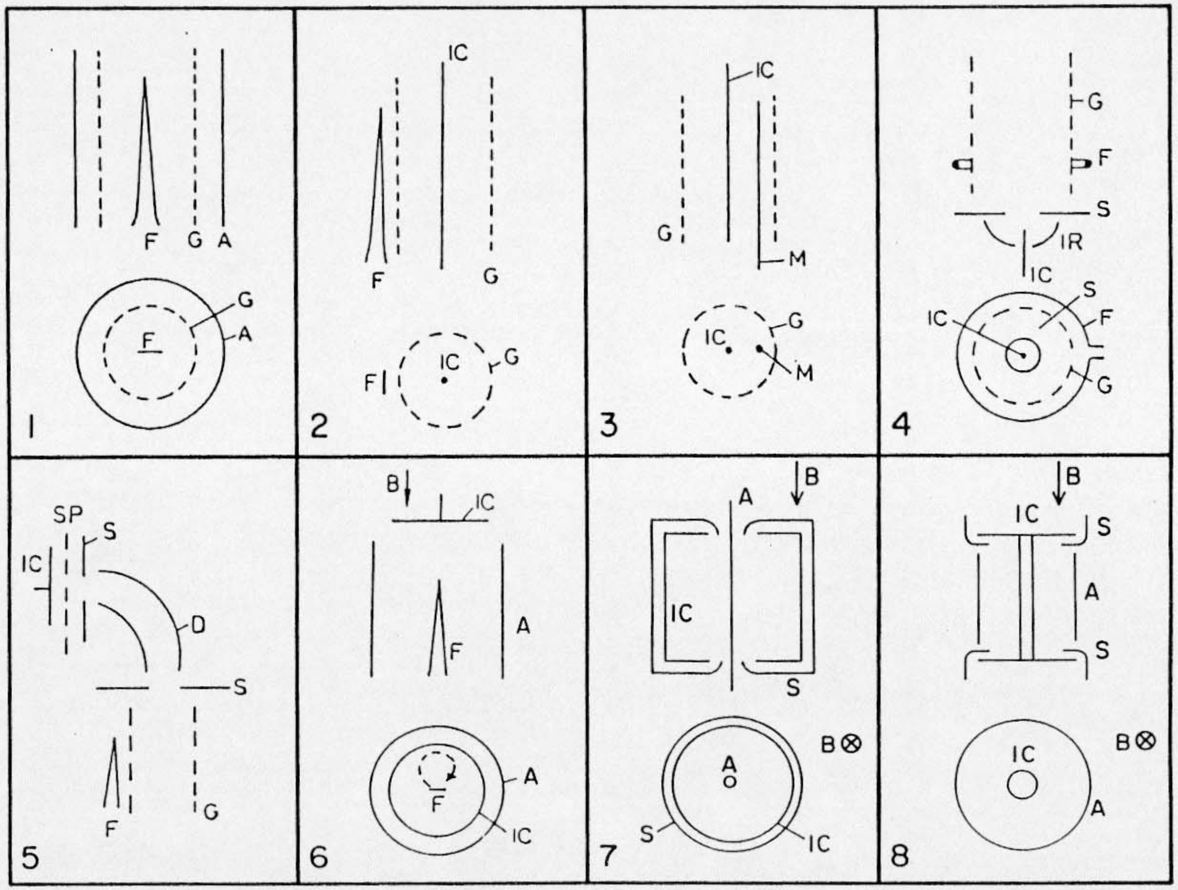


FIG. 5. Schematic diagrams of ionization gauges; (1) conventional gauge; (2) Bayard–Alpert gauge; (3) modulated Bayard–Alpert gauge; (4) extractor gauge; (5) bent-beam gauge; (6) hot-cathode magnetron; (7) inverted-magnetron gauge; (8) magnetron gauge. A–Anode, D–deflector, F–filament, G–grid, IC–ion collector, IR–ion reflector, M–modulator, S–shield, SP–suppressor.

Calibration constant of ECG

$$S = \frac{I^{+} - I^{+}_{res}}{I^{-}(p - p_{res})}$$

$$S = \frac{I^{+}}{I^{-} p}$$

Calibration of CFG

$$S = \frac{I^{+}}{p^{m}}$$

Calibration results often given by

Error of reading

$$e = \frac{p_{ind} - p_{cal}}{p_{cal}}$$

correction factor

$$CF = \frac{p_{cal}}{p_{ind}}$$

Reasons for inaccuracies

- Uncertainties due to calibration chain
- Uncertainties due to installation (or mistakes in installation)
- Uncertainties due to operation (surface layers, corrosion, dust, aging)
- Inaccuracies caused by gas mixture
- Uncertainties caused by the device itself

Uncertainties due to the vacuum gauge itself

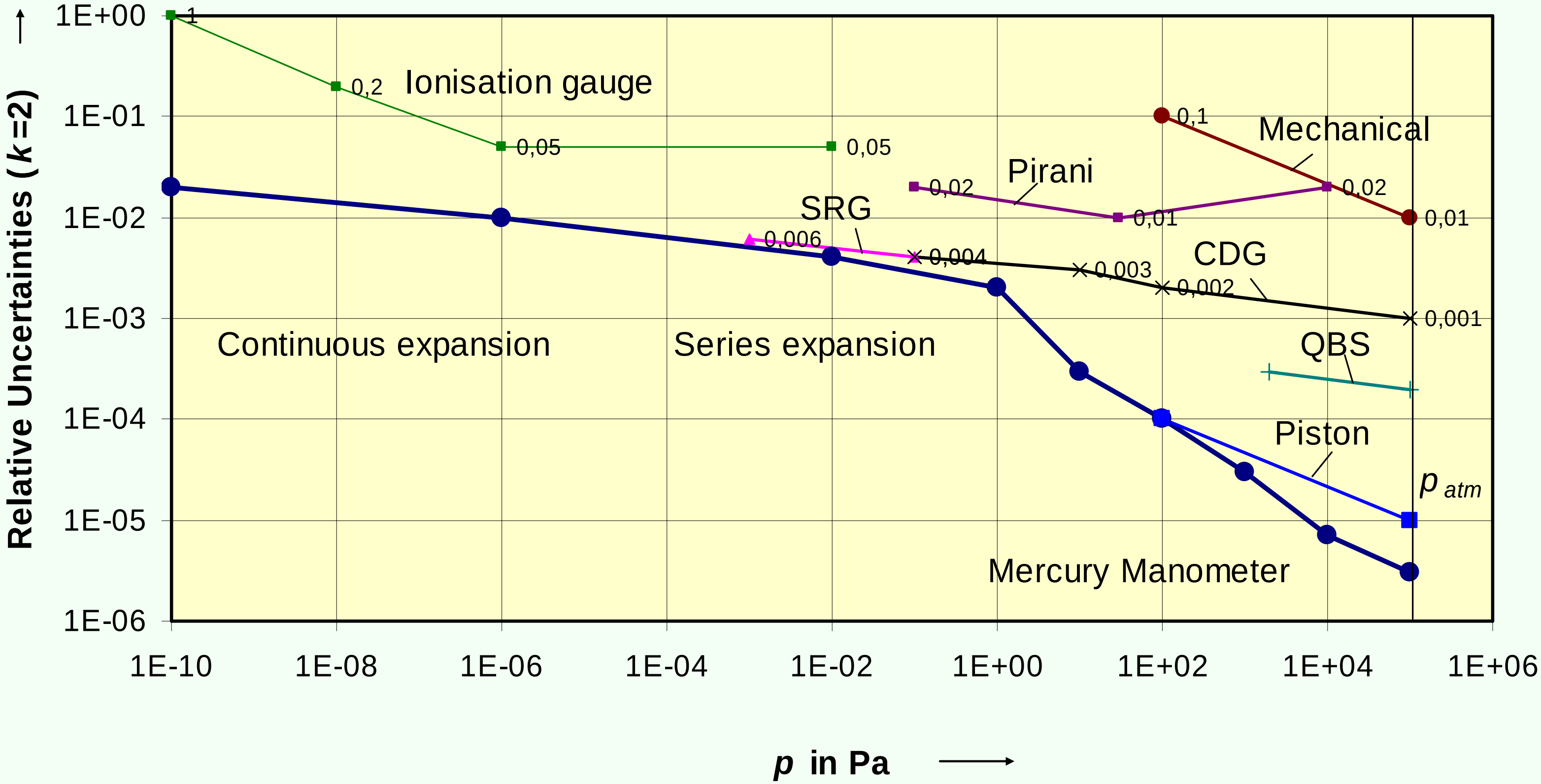
Offset due to X-ray, ESD, elcetronics, incomplete insulation
Offset instability (drift)
Resolution
Influences of environment (mainly temperature)
Non-Linearity
Integration time (scatter of data), repeatibility
Reproducibility (stability of calibration constant)
Hysteresis (ESD)
Prior usage, cleanliness

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 ...0.01		
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 % (error factor > 1) are possible.

Ultrahigh vacuum gauges

UHV gauges

We have discussed

Principle of ionization

Overview of types of ionization gauges

Crossed field gauges and emissive cathode gauges

Effects in emissive cathode gauges

Comparison between the types of ion gauges

Problems in applications

Accuracy and calibration

Thanks for listening !