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Vacuum technology — Vacuum gauges — Characteristics for a stable ionisation vacuum gauge

Technique du vide — Manomètres à vide — Caractéristiques des manomètres à ionisation stable

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This document was prepared by Technical Committee ISO/TC 112, *Vacuum technology*.

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Introduction

The ionisation vacuum gauge is the only type of vacuum gauge covering the full range of high and ultrahigh vacuum.[1] Important applications need better accuracy, reproducibility and known sensitivities for many gas species, properties which all current types of ionisation vacuum gauges lack. This document provides the characteristics for a stable ionisation vacuum gauge so that this gauge is accurate, robust and long-term stable, with known sensitivity for nitrogen and known relative sensitivity factors, and can be built by any experienced manufacturer of other ionisation vacuum gauges.

Vacuum technology — Vacuum gauges — Characteristics for a stable ionisation vacuum gauge

1 Scope

This document describes a special design of an ionisation vacuum gauge which has a well-defined ionising electron path length.[2] Due to the construction design, it leads to good measurement accuracy, long-term stability, as well as gauge independent and reproducible sensitivity for nitrogen and relative sensitivity factors[3][4]. It is designed for the measurement range of 10^{-6} Pa to 10^{-2} Pa.

This document describes only those dimensions and potentials of the gauge head which are relevant for the electron and ion trajectories. This document does not describe the electrical components necessary to operate the ionisation vacuum gauge in detail. The gauge head can be operated by voltage and power sources and ammeters commercially available, but also by a controller specially built for the purpose of the operation of this gauge head.

The ionisation vacuum gauge described in this document can be built by any experienced manufacturer of other ionisation vacuum gauges. It is not subject to intellectual property protection.

It is assumed for this document that the applicant is familiar with both the physics and principles of ionisation vacuum gauges as well as high and ultra-high vacuum technology in general.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN ISO 13920, *Welding - General tolerances for welded constructions - Dimensions for lengths and angles - Shape and position (ISO 13920:1996)*

ISO 2768-1, *General tolerances — Part 1: Tolerances for linear and angular dimensions without individual tolerance indications*

ISO 3669, *Vacuum technology — Dimensions of knife-edge flanges*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
Wehnelt electrode
Wehnelt
an electrode with cylindrical symmetry around the electron emitting cathode, mainly used for focusing of the electron beam

3.2
ionisation space
the space in which ions generated by collision of gas molecules with high energy electrons reach the ion collector by means of a suitable electrostatic field

3.3
Faraday cup
metal cup or other piece of metal designed to catch charged particles in vacuum

Note 1 to entry: In the ionisation vacuum gauge described in this document, the Faraday cup is designed to capture the electrons emitted from the cathode.

3.4
envelope
the metallic wall at zero (earth) potential surrounding the gauge head at least in its full length

3.5
electron transmission
the ratio of electron current measured at the Faraday cup divided by the electron current emitted from the cathode

4 Symbols and abbreviated terms

I	ion current at pressure p [A]
I_0	ion current at residual pressure p_0 [A]
I_e	electron emission current [A]
p	pressure [Pa]
p_0	residual pressure [Pa]
r_x	relative sensitivity factor as defined in ISO 27894
S	sensitivity (coefficient) [1/Pa]
S_{N2}	sensitivity for nitrogen [1/Pa]

5 General description of the design

5.1 Components

The ionisation vacuum gauge consists of the following functional parts:

a) electron emitting cathode,

b) Wehnelt electrode,

c) anode cage in two parts,

d) ion collector,

e) electron deflector,

f) Faraday cup,

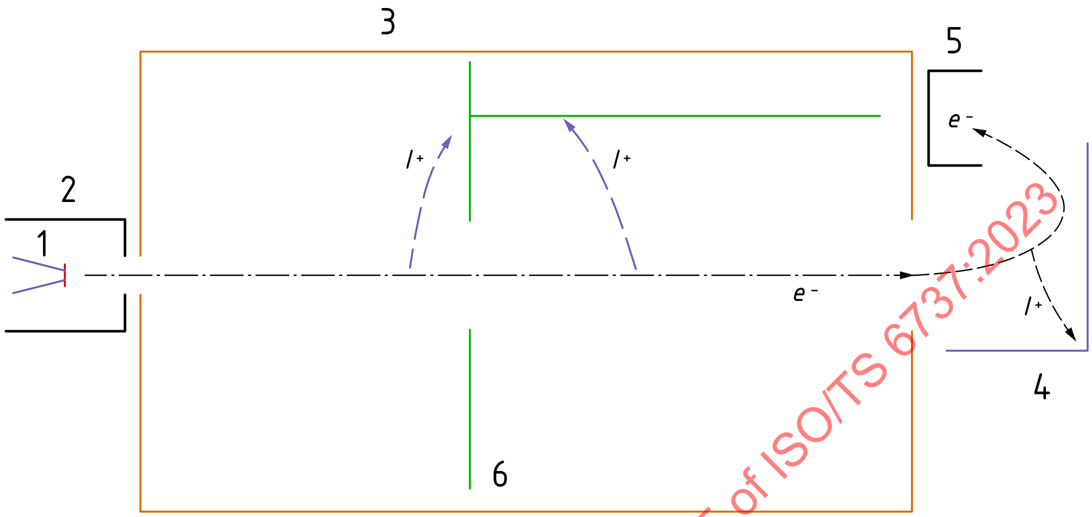
g) envelope.

The functional components a) to f) need to be exactly dimensioned.

In addition, the gauge needs electrical feedthroughs, wires, mounting parts and insulators. The gauge shall be mounted on a DN40CF or on a DN63CF flange according to ISO 3669 with corresponding tube sizes DN40 or DN63 as envelope (see 7.9).

5.2 Mode of operation

A schematic for the illustration of the operation of the gauge is shown in Figure 1, for a detailed drawing see Figure 2 in 7.2. For simplification, in Figure 1 the anode cage (3) has not been divided in two parts as in Figure 2 with (3a) and (3b) and the collector ring (6) in between (see also Figure 3) .



Key

1 cathode with emitter disk (red)
2 Wehnelt cylinder
3 anode cage
4 electron deflector
5 Faraday cup
6 ion collector
I^+ ion
e^- electron

Figure 1 — Simplified illustration of mode of operation (informative)

Electrons are emitted from the hot thermionic cathode (1 in Figure 1 and Figure 2), which is preferably an indirectly heated disk emitter on a potential of 50 V. The Wehnelt electrode (2 in Figure 1) surrounding the cathode has a lower potential and controls and focuses the electron beam into the opening of the anode cage at 250 V.

Note that in the future, it can be possible that the thermionic cathode can be replaced by a so-called cold field emission cathode. This cathode shall be long-term stable and provide an electron current of about 100 µA. In addition, it shall be ensured that the energy of the electrons along their path in the ionization space is not changed compared to the design with thermionic cathode.

Due to the penetration of the anode potential into that of the Wehnelt electrode the electrons can be extracted and accelerated into the inner part of the cylindrical anode cage. The first part of the anode cage (3a at 250 V, see Figure 2), the ion collector ring (0 V, 6 in Figure 1 and Figure 2) and the second remaining part of the anode cage (250 V, 3b in Figure 2) form an electrostatic lens which focuses the electron beam into the circular exit of the anode cage. Behind this exit the electron beam is deflected by the electron deflector electrode (45 V, 4 in Figure 1 and Figure 2) in a U-turn onto the capturing part of the Faraday cup (280 V, 5 in Figure 1 and Figure 2). When the electrons hit the Faraday cup, they will generate X-rays. By the U-turn, it is ensured that these X-rays have a very low probability to reach the ion collector or the anode where they would generate secondary electrons.

The ions generated by the electron beam inside the anode cage are accelerated towards the ion collector which consists of the mentioned ring and a rod reaching into the larger space of the anode cage. Ions generated behind the exit of the cage are accelerated towards the electron deflector electrode. The ionisation space is well defined in this design.

The measured ion current will be proportional to the gas density in contact with the electron beam, the ionisation probability of the gas molecules by the electron impacts along their path, the mean path length of the electrons inside the ionisation space and the electron current.

Due to the focused electron beam inside the anode cage, the electron current should not exceed 200 µA. Higher currents can cause non-linearities.

The mean electron path length is defined by the length of the anode cage and the potential inside it. Any changes of the emission points of the electrons on the cathode will not significantly change the path length. A replacement of the same cathode type will have an insignificant influence on the path length. Space charge effects of ions will also have an insignificant influence on the path length within the specified measurement range up to 0,01 Pa. Due to the well-defined electron path length, the nitrogen sensitivity and the relative sensitivity factors will not significantly vary from gauge to gauge except within the uncertainty due to variation of secondary electrons produced by the ion impingement on the collector.[3]

As for an ionisation vacuum gauge of the extractor type, in this gauge, X-rays have a low probability of reaching the ion collector. This ensures that the secondary electron current on the ion collector produced by X-rays is rather small. Such a current would be indistinguishable from the measured ion current.

Ions desorbed by electron impact in the Faraday cup will be attracted to the electron deflector and will not reach the ion collector. Electron stimulated desorption of neutrals, however, will contribute to the gas density in the gauge and therefore to the ion current.

6 Specifications of the ionisation vacuum gauge

6.1 General specifications and requirements for the gauge head

a) The electrons shall have a direct and well-defined path from their source, the cathode, through the ionisation space to the target, the Faraday cup. The path length shall not be increased by oscillations through the ionisation space, e.g. by a magnetic field.

b) The two parts of the anode cage, the ion collector ring and the Wehnelt electrode shall have a common cylindrical axis according to best possible practice. The center of the cathode shall be aligned to this axis.

c) The electron emitting cathode shall be surrounded by a Wehnelt electrode.

d) It is recommended that the cathode is an indirectly heated disk emitter to ensure well defined and stable starting points on equal potential of the electron trajectories over the emission area.

e) The shape, dimensions, position and potentials of the anode cage, Wehnelt electrode and electron emitting part of the cathode shall be such that the emitted electrons are accelerated parallel to or with a small maximum angle (typically < 5°) to the cylindrical axis described in b).

f) The two parts of the anode cage and the ion collector ring shall form an electrostatic lens for the electrons to focus them to the circular exit of the anode cage. The electron beam shall be focused in such a way that less than 5 % of the total electron current hits the anode cage. The collector electrode consists of a ring with a long rod reaching into the anode cage in the direction of the Faraday cup to efficiently collect ions from inside of the electron beam.

g) It is necessary that openings in the cylindrical anode cage allow a free exchange of molecules inside and outside of the cage so that there is no significant difference in gas density. This can be achieved by slotted holes or similar. It is, however, required that there is no significant potential penetration from the envelope into the anode cage.

h) The electron beam shall be captured by a Faraday cup located behind the exit of the anode cage. The area of impact of the electrons shall be located such that generated X-rays have no direct line of sight to the ion collector. This is achieved by a deflector electrode which directs the electron beam onto a suitable target spot of the Faraday cup.

i) The electrical insulation of the ion collector to the anode cage parts shall have a total resistance (surface and bulk) such that the leakage current across them contributes with less than 0,4 % to the measured ion current at 10^{-6} Pa of nitrogen.

NOTE 1 With dimensions and potentials described in Clause 7, at 30 µA emission current, the collector current amounts to 10 pA at 10^{-6} Pa of nitrogen, so that 0,4 % correspond to 40 fA. To achieve this, a guard electrode is helpful.

j) The attachment of the gauge electrodes shall be such that their positions against each other are not changed during a transport of the gauge. Also, the stiffness of the electrodes shall be such that their shape is not changed during transport. Before and after a test according to ISTA 2A:2011, the sensitivity for nitrogen near 1 mPa is to be reproduced within 2 % ($k = 2$ according to GUM: ISO/IEC Guide 98-1). The test should be performed 3 times or more.

NOTE 2 It is sufficient to perform the ISTA 2A:2011 test with a single gauge after development of a prototype by a manufacturer.

k) The envelope shall be a cylindrical tube as for UHV components and cover the full length of the gauge parts plus 10 mm in length in both directions. It is recommended to close the cylinder with a grid or similar as equipotential plane. It is recommended to attach two CF flanges at the ends of the envelope tube.

l) The whole gauge head shall withstand bake-out temperatures of at least 250 °C.

m) No ferromagnetic material should be used in the gauge head except for feedthroughs (see 7.8) and the envelope (see 7.9).

All the specifications above are met by the mandatory and recommended dimensions and potentials described in Clause 7.

6.2 Electrical equipment

The voltage output of the power supplies must supply voltages between 25 V and 300 V. The cathode, Wehnelt and deflector voltages shall be stable within ±0,2 V, anode and Faraday voltages within ±0,4 V.

The power supply for the heating current of the thermionic cathode shall be on high potential of 50 V and provide enough heating power for the cathode in use to provide an emission current of up to 200 µA.

It is recommended that the total emission current (on anode and Faraday cup) be either measured with a standard uncertainty of 0,3 % or controlled within a standard uncertainty of 0,3 %.

NOTE 1 Due to some misalignment or scattering, a small, but unwanted part of electrons can reach the anode. These electrons and secondary electrons can also ionise gas molecules and contribute to the ion current.

Also, it is recommended that the current from collector to ground is measured with a standard uncertainty of 0,3% in the range of nitrogen pressure from 10^{-6} Pa to 10^{-2} Pa.

NOTE 2 With dimensions and potentials described in 7, at 30 µA emission current, the collector current ranges from about 10 pA to 100 nA.

It is permissible to use current measuring instruments with higher uncertainties. To the extent of their higher uncertainties, this will increase the uncertainty of pressure measurement. If either or both currents are measured with a standard uncertainty of more than 2 %, the uncertainty of nitrogen sensitivity and relative gas sensitivity factors given in 8.1 is exceeded for some gas species and an individual calibration of the gauge can be necessary (see also 9.6).

Electrical feedthroughs, connectors and cables shall be applied:

— by which the range and the uncertainties of current measurements and

— by which the necessary power and potential requirements,

given in this document can be achieved.

7 Dimensions and potentials

7.1 General

The following dimensions and potentials meet the specifications given in 6.1 and are mandatory if not specified otherwise. Tolerances, gaps and angles where critical are given in Table 1. For all other dimensions machining tolerances of class "m" or "f" according to ISO 2768-1 shall be applied. Welding tolerances of class "B" and "F" according to EN ISO 13920 shall be applied. The total inner length from entrance plane of the electrons in the first part of the anode 3a (Figure 2) to exit plane of the second part of the anode 3b (Figure 2) shall be (50,0 ± 0,2) mm exact.

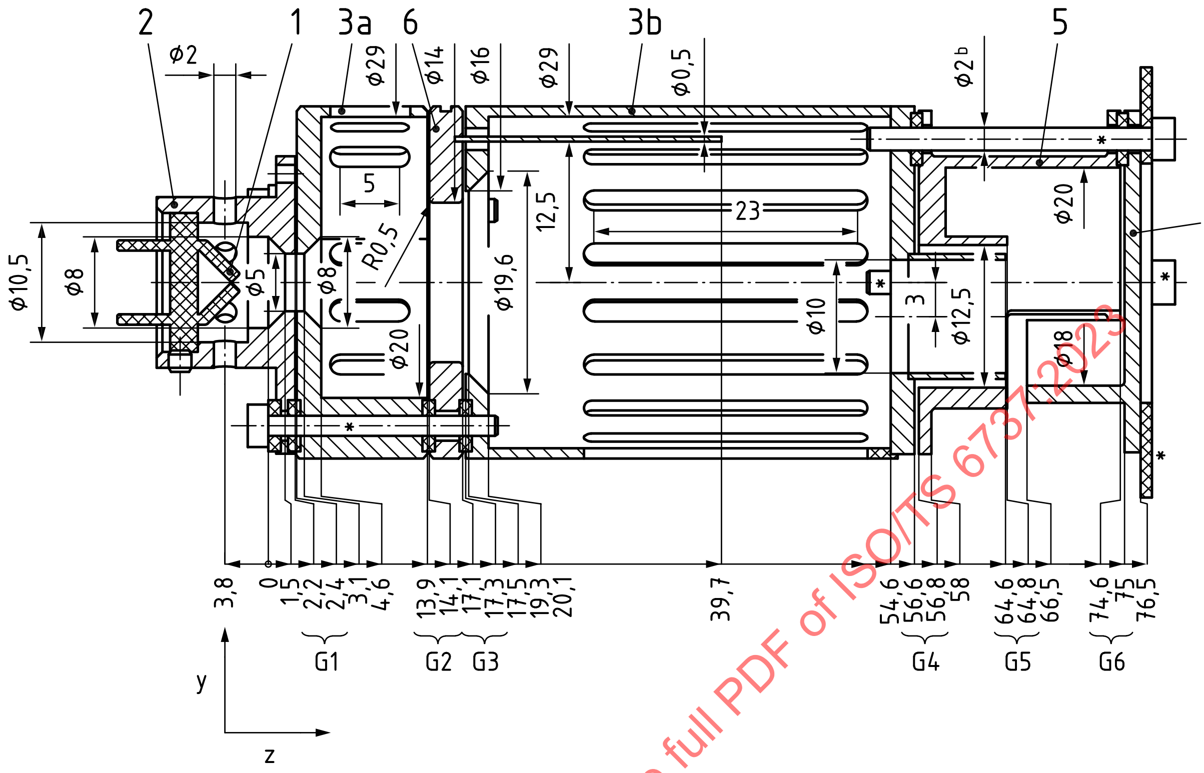
NOTE 1 In principle, other dimensions and potentials can also meet the specifications given in 6.1 and will also lead to a stable and robust ionisation vacuum gauge with known relative sensitivity factors. However, other dimensions and potentials will result in different sensitivities for nitrogen and possibly relative sensitivity factors, which would counteract the idea of this document, which is that all gauges manufactured according to this document should have the same sensitivity and relative sensitivity factors.

NOTE 2 The dimensions and potentials given were tested by gauges manufactured from two different companies[4].

The alignment of the different electrodes to a common axis and their distances are critical for the performance of the gauge. However, it is up to the manufacturer to decide how to ensure the distances and tolerances (Table 1). In this sense, the drawing of the gauge head of Figure 2 should be understood as a proposal.

NOTE 3 Table 1 gives some freedom for the gap sizes between the electrodes. Depending on the chosen gap sizes the length of the two anode parts shall be reduced or enlarged so that the total inner length from entrance plane (marked with 4,6 in Figure 2) of the electrons in 3a to exit plane (marked with 54,6 in Figure 2) in 3b of the anode is (50,0 ± 0,2) mm exact.

7.2 Dimensions and tolerances



Key

1	cathode
2	wehnelt
3a, 3b	anode in two parts
4	deflector
5	faraday cup
6	ion collector
G1, G2, G3, G4, G5, G6	gaps between electrodes
*	part not normative, but shown as example
∅ 2b	3 times, each 90 ° apart (not normative)

Figure 2 — Dimensions of gauge head in mm

NOTE The gap sizes (mostly 0,2 mm) shown in Figure 2 (side view of cut shown in Figure 3) are the ones used in the original simulation of the electron and ion trajectories in the gauge head. Some of these gap sizes are too small for a safe operation. Column 3 in Table 1 gives gap sizes which are both in agreement with safe operation (IEC 61010 series[5]) and which do not significantly alter the characteristics of the gauge.

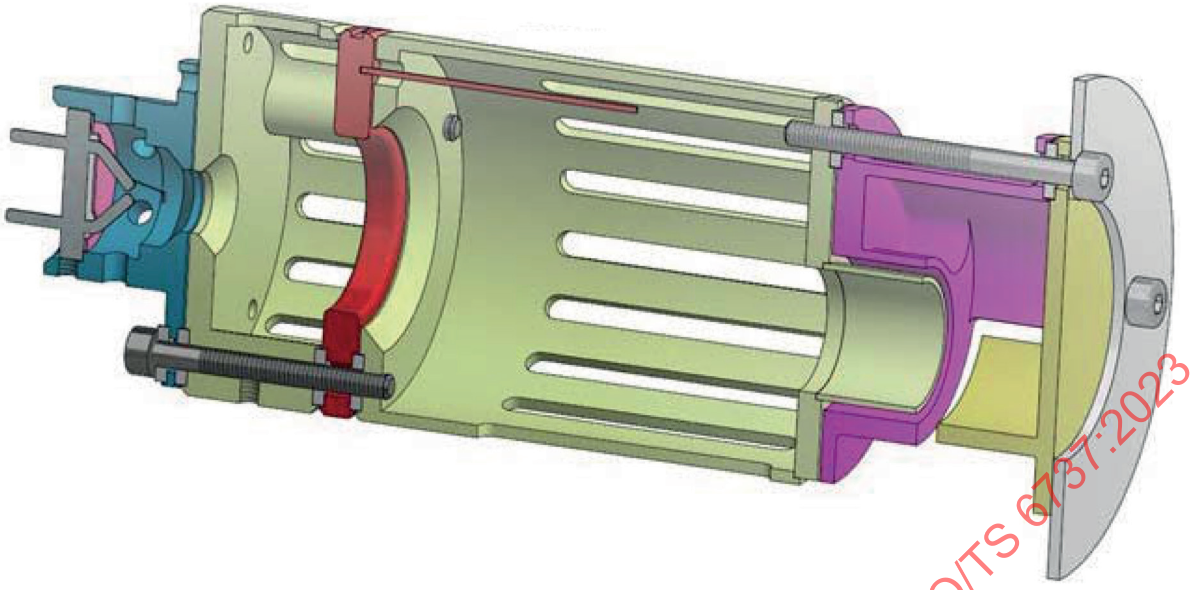


Figure 3 — Side view of cut from Figure 2.

The following tolerances shall be observed.

Table 1 — Tolerances of lengths and angles

Symbol or index number in Figure 2	Description	Gap distance, position, dimension or angle	Tolerance
G1	Gap between 2 (Wehnelt) and 3a (first anode cage part), 0,2 mm in Figure 2	0,3 mm	±0,1mm
G2	Gap between 3a (first anode cage part) and 6 (collector ring), 0,2 mm in Figure 2	0,45 mm	±0,25 mm
G3	Gap between 6 (collector ring) and 3b (second anode part 3b), 0,2 mm in Figure 2	0,45 mm	±0,25 mm
G4	Gap between 3b (second anode part) and 5 (Faraday cup), 0,2 mm in Figure 2	0,20 mm to 1,00 mm	The range given in the previous column shall not be exceeded.
G5	Other gap between 3b (second anode part) and 5 (Faraday cup), 0,2 mm in Figure 2	0,2 mm	+0,1 mm
G6	Gap between 5 (Faraday cup) and 4 (electron deflector), 0,4 mm in Figure 2	0,4 mm	±0,15 mm
Total length	Entrance plane of 3a, marked with 4,6 to exit plane of 3b, marked with 54,6	50 mm	±0,2 mm
1	Center of emitting area of cathode	Position see Figure 2	dx ±0,3 mm; dy±0,4 mm; dz±0,5 mm

Table 1 *(continued)*

Symbol or index number in Figure 2	Description	Gap distance, position, dimension or angle	Tolerance
1	Angle of emitter plane to Wehnelt and anode axis	0°	±20°
6	Collector ring	Position see Figure 2	dx ±0,2 mm; dy-0,25 mm+0,45 mm
6	Collector rod: diameter	0,5 mm	±0,06 mm
6	Collector rod : alignment to axis of anode part	0°	±4°

7.3 Potentials

The following potentials (Table 2) shall be applied for the gauge head described in 7.2. Allowed variations are specified in 6.2.

Table 2 — Potentials of the different electrodes

Index number in Figure 1 and Figure 2	Potential
1	50 V
2	28 V to 35 V
3a, 3b	250 V
4	45 V
5	280 V
6	0 V

7.4 Cathode

As electron emitters disc cathodes of tantalum or yttria coated Ir discs are recommended. The use of a U-shaped tungsten filament is also possible. The length of the emitting section of the filament must be chosen such that the emitting area is at the same place as for the disk emitter which is 2,4 mm (tolerance: see Table 1) from the entrance plane of the anode cage.

NOTE The electron emitter disc is mounted on an AEI base, one of standard bases of electron emitters in electron microscopes.

7.5 Anode cage

The two cylindrical anode cage parts, each with an inner diameter of 29 mm, shall exhibit an open area between 9,8 cm^2 and 11,0 cm^2 realized by slits of 2 mm width. There shall be made 14 to 18 equally spaced slits of a length of 7 mm in anode cylinder 3a (Figure 2), 17 slits of a length of 23 mm to 25 mm in 3b (Figure 2). No slit is allowed in the range of ±20° on the cycle radius around the axis of anode cylinder 3b, where the intersection of 3b with the plane through cylinder axis and ion collector rod is at 0°. Also, no slit is allowed in the range of ±20° on a cycle radius around the axis of 3a or 3b, where any metal rod (e.g. for support) outside of the anode cage is at 0° and at a potential different from the anode.

It is possible that other openings will give the same sensitivity for nitrogen and relative gas sensitivity factors. The openings near the collector rod are critical for the ion collection efficiency. The influence of the openings on the electron trajectories and their energy is less critical provided that the openings are not too large. The two effects, however, were not tested yet in detail, so that the openings as described in this section shall be used. The effect of the openings can be greatly reduced by stretching a fine metal mesh over the opening.

7.6 Gaps between electrodes

Several gaps are necessary for electrical insulation between the electrodes. Since the gaps G1, G2, G3 (Figure 2) are also part of electrostatic lenses, these are critical for the electron and ion trajectories. Also, the insulation of collector 6 for any leakage current from anode parts 3a or 3b is critical. G1 shall not exceed 0,4 mm (nominal value 0,2 mm), G2 and G3 shall not exceed 0,7 mm (nominal value 0,2 mm) when looking from the gauge axis. The manufacturer is free to decide how to design the gaps and electrical insulation outside of the inner diameter of the anode cage cylinders. The shape of the gaps or other measures shall protect any insulators (e.g. ceramics, glass) from being bombarded by ions or other particles. Consider i) in 6.1.

7.7 Electrode materials

All electrodes shall be made of materials compatible with UHV. No ferromagnetic material except of mu-metal for the envelope is allowed. Low carbon stainless steel (e.g. ANSI: 316L, DIN 17440: 1.4404) is recommended. Vacuum firing[6] of the parts before mounting them is recommended.

7.8 Electrical feedthroughs

All electrical feedthroughs shall be specified for the voltages and/or currents of the respective electrode and ensure compatibility with UHV. The feedthrough to the collector needs special care concerning shielding and isolation due to the low currents to be measured (pA and lower). Co- or triaxial feedthroughs are recommended for this electrode. In some feedthroughs Kovar™ 1), which is ferromagnetic, is used. If such a ferromagnetic material is used, care has to be taken not to expose it to a strong magnetic field. It has to be ensured that the magnetic field at the place of the electrode beam is not higher than specified in 7.10.

NOTE In the model gauge types[4] from two different manufacturers SMB or other sockets with Kovar™ were used for the collector feedthrough. This did not affect the performance of the gauge.

7.9 Surrounding tube (envelope) and flanges

The gauge shall be mounted on a DN40CF or on a DN63CF flange according to ISO 3669. The gauge head shall be surrounded by a DN40 or DN63 cylindrical tube (the inner diameter of the tube is 40 mm or 63 mm as a minimum) with a length exceeding the total length of all electrodes by at least 10 mm in both directions. DN63 gives more flexibility for mounting and electrical insulation of the electrodes and also higher gas conductance towards the chamber.

It is recommended that the part open to the vacuum system is protected by a grid. Metal sealing of flanges is required. It is recommended that the surrounding tube ensures a magnetic shielding effect (refer to 7.10). No ferromagnetic material except of mu-metal shall be used for the envelope.

7.10 Magnetic fields

It shall be ensured that any magnetic field inside the gauge does not reduce the electron transmission below 95 %. To this end, the magnetic field (including the Earth's magnetic field) perpendicular to the direction of the electron beam (anode cage cylinder axis) shall be less than 50 µT.

NOTE The requirement can be reached either by proper alignment of the gauge to the Earth's magnetic field or by using a µ-metal magnetic shield, and in addition by avoiding ferromagnetic materials in or near the gauge.

The electron path length shall not be significantly extended by a longitudinal magnetic field. To this end, any magnetic field in the direction of the anode cage cylinder axis shall not exceed 4 mT.

1) Kovar is a trademark of CRS Holdings inc.. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

8 Characteristics of the gauge (informative)

8.1 Sensitivity

The gauge described in Clause 7 operated with a tantalum disk cathode has a sensitivity S_{N2} = (0,289 ± 0,007) Pa^{-1} for nitrogen at 23 °C and k = 2. The variation (as expanded standard deviation) is the variation from gauge to gauge. The following relative sensitivity factors (Table 3) have been measured:

Table 3 — Relative sensitivity factors with uncertainties

x (gas species)	r_x
H_2	0,374 ± 0,015
He	0,176 ± 0,005
CH_4	1,385 ± 0,015
Ne	0,337 ± 0,015
H_2O	0,832 (uncertainty unknown)
N_2	1,000 (fixed)
CO	1,031 ± 0,003
O_2	0,964 ± 0,057
CO_2	1,433 ± 0,029
Ar	1,134 ± 0,013
Kr	1,532 ± 0,006
Xe	2,215 ± 0,078
$C_{12}H_{26}$	12,4 ± 0,6[a]

[a] Variation of a single gauge for repeated measurements.

NOTE Other kinds of cathodes and different heating powers can slightly change the sensitivity for nitrogen, but hardly affect relative sensitivity factors.

8.2 Linearity

In the range from 10^{-6} Pa to 10^{-2} Pa the non-linearity, equal to the variation of sensitivity, is within ±0,5 %.

8.3 Electron transmission efficiency

Electron transmission is typically 97 % to 99 %. A significant lower value indicates some misalignment, normally of the cathode, or a disturbing magnetic field. In addition, it was found that for misaligned cathodes there is a strong dependence of electron transmission on the Wehnelt potential between 15 V and 35 V, while there is no significant dependence in this range for well aligned cathodes.

8.4 Residual current and resolution

Under good conditions, a resolution of $2 \cdot 10^{-14}$ A can be expected at a measured minimum residual current of 1 pA. With an emission current of 33 µA and the sensitivity for nitrogen, the resolution pressure limit is $2 \cdot 10^{-9}$ Pa. The residual current of 1 pA corresponds to a pressure of $1 \cdot 10^{-7}$ Pa.

NOTE Resolution is defined as 3 times the standard deviation of current noise as in ISO 14291:2012, 2.2.6.

8.5 Repeatability

Repeatability of sensitivity was tested at 10^{-5} Pa for 10 measurements. Between each measurement a pump down to base pressure was performed. The standard deviation of sensitivity about the mean was 0,02 %.