ENGINEERING

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Abstract
The performance of a UHV system depends to a large extent on the effort spent in optimising the vacuum chamber as well as the components of the system. This chapter describes the design principles of a UHV system and its building blocks, joining methods, the combined action of flanges, gaskets and bolts, welding and weld preparation, valves, expansion bellows and bakeable vacuum systems.

1. DESIGN PRINCIPLES OF A UHV SYSTEM AND ITS BUILDING BLOCKS

1.1 Design criteria

In order to obtain the optimum performance at the lowest possible price it is useful to set up well-defined design criteria. Let us start with the *design pressure.* Obviously it does not pay to hunt for a pressure much better than this. On the other hand, it can be a real problem if the needed pressure is not at all achieved, or not achieved within reasonable time. Remember that it can be useful to have some margin to account for small problems. A 10^{-7} Pa vacuum system needs baking up to 150 ^{o}C, or, maybe, no baking at all if the outgassing is not too high and the pumps are large enough. On the other hand, 10^{-8} to 10^{-9} Pa needs baking to higher temperatures and requires that special precautions be taken to obtain sufficiently-low outgassing. The outgassing rate depends on the material properties, the surface treatment and cleaning procedures.

Let us define the needed *pump-down time*. A baked system will reach UHV conditions much faster than an unbaked system, although baking takes 24 to 36 h depending on the baking temperature. Accelerator vacuum systems with *circulating ion beams* as well as other UHV systems may have restrictions on *the rest-gas composition*. It is usually required to minimise the average mean square Z of the rest gas. Therefore one should use materials with low outgassing and try to minimise the effects of *gas loads* from process gas or gas-jet targets in the vacuum system.

The *operating temperature* of the UHV system is another important factor to be taken into account. A room temperature system is quite different from a cryogenic one. Systems operated at elevated temperature or with hot cathodes have much higher outgassing than room temperature systems.

Last but not least comes the overall *budget* which can be split up into *capital investment* (purchasing of the system) and o*perational costs*. The latter depends on the need for consumables and maintenance. It can be useful to include operational costs for 5 to 10 years when comparing for instance different pump alternatives.

1.2 Engineering formulae for vacuum systems

It is important to be aware of the conductance limitations for different shapes of vacuum chambers. Some examples for standard type tubes are given in Eqs. (1)–(3). For more complicated structures it is recommended to make Monte Carlo calculations (see Section 1.3).

The conductance, W [m^3/s] through an orifice is given by

$$W = 36.4A\sqrt{\frac{T}{M}} \tag{1}$$

where A [m^2] is the area of the orifice, T is the temperature [°K] and M is the molecular weight. This is usually calculated for nitrogen. The conductance for hydrogen is 2.8 times higher. Similarly, for a long cylindrical tube where r [m] is the diameter and L [m] is the length

$$W = 305\frac{r^3}{L}\sqrt{\frac{T}{M}} \ . \tag{2}$$

Finally, for a long elliptic-cross-section tube where a [m] and b [m] are the elliptic axes

$$W = 431\frac{a^2b^2}{L\sqrt{a^2+b^2}}\sqrt{\frac{T}{M}} \ . \tag{3}$$

The effective pumping speed, S_{eff} [l/s] for a pump with the nominal pumping speed S_{o} [l/s] connected to a vacuum chamber via a tube with conductane C [l/s] is given by

$$\frac{1}{S_{\mathrm{eff}}} = \frac{1}{S_{\mathrm{o}}} + \frac{1}{C} \ . \tag{4}$$

For large vacuum systems one uses either linear pumps or distributed (lumped) pumps as shown in Fig. 1.

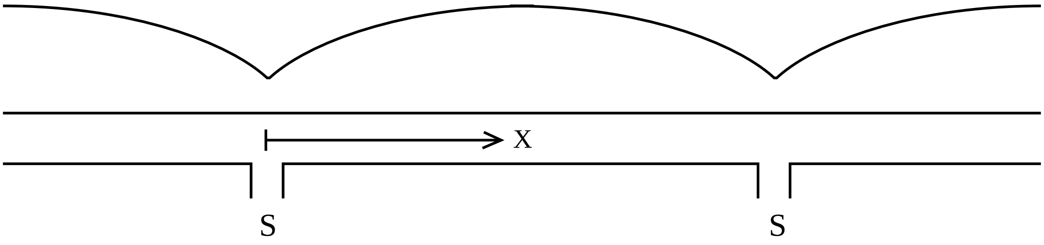

Fig. 1 Distributed pumps. Bottom: beamline with pumping ports. Top: pressure distribution in arbitrary units

Following a calculation by Gröbner [1] for the molecular flow regime we define: the distance between pumps L [m], the effective pumping speed S [l/s], the pressure P [mbar], the specific molecular conductance w [m l s^{-1}], the specific surface area A [cm^2 m^{-1}], the specific outgassing rate q [mbar l s^{-1}cm^{-2}], the gas flow Q [mbar l s^{-1}].

$$Q(x) = -w\frac{dP}{dx} \tag{5}$$

and

$$\frac{dQ}{dx} = Aq \tag{6}$$

give

$$w\frac{d^2p}{dx^2} = -Aq \ . \tag{7}$$

$$\left.\frac{dP}{dx}\right|_{x=L/2} = 0 \tag{8}$$

and

$$P\big|_{x=0} = \frac{AqL}{S} \tag{9}$$

give

$$P(x) = Aq\left(\frac{Lx - x^2}{w} + \frac{L}{S}\right) \tag{10}$$

From this can be calculated the maximum pressure

$$P_{\max} = Aq\left(\frac{L^2}{4w} + \frac{L}{S}\right) \tag{112}$$

and the average pressure

$$P_{av} = \frac{1}{L}\int_0^L P(x)dx = Aq\left(\frac{L^2}{6w} + \frac{L}{S}\right) . \tag{12}$$

1.3 Computer simulations

Properly done computer simulations prior to purchasing and manufacturing of a complicated vacuum system can save money as well as a lot trouble at a later stage. A few computer programs are available for vacuum system simulations. Finite-element calculations as well as Monte Carlo calculations have been developed by Pace and Poncet [2]. Monte Carlo calculations are recommended for conductance calculations of non regular structures, where simple formulas like (1)–(3) can not be used. Ziemann [3] has developed a program for vacuum system simulations using matrix multiplications in analogy with magnetic field calculations. There is a commercial program, VacSim™ [4], which also provides design and pumpdown data.

1.4 Materials

Having defined the criteria mentioned above one should be able to decide which vacuum chamber material to use. The options are usually only aluminium and stainless steel. Aluminium is preferred for systems with synchrotron radiation load. It requires a special welding technique. Most vacuum components are nowadays also available in aluminium [5]. Stainless steel products are however less expensive and are available from a large number of companies. The most common qualities 304, 304L, and 316L. 316LN or 304LN are often required for their high mechanical strength and low magnetic permeability, typically 1.005. For use in magnetic field a magnetic permeability less than 1.01 is usually required.

Vacuum firing is a very effective way to reduce outgassing of stainless steel. The material is heated quickly to 950 °C and remains at this temperature for 1–2 h at a pressure lower than 10^{-3} Pa. It is customary to vacuum fire the completed chamber with all flanges welded on. It is recommended to use 316LN or 304LN material in vacuum fired chambers.

Titanium is an alternative material which is not often used. It is more expensive than stainless steel and more difficult to weld. When also taking into account the working cost, a Ti chamber is about 20% more expensive than a stainless steel chamber. Beryllium is often required for thin windows etc. (see Section 2.3).

1.5 Construction

When constructing non-standard vacuum chambers it is important to make at least simple mechanical stability calculations. For very difficult structures it is recommended to perform calculations with finite-element codes like the ANSYS™ code. An example of such calculations for a thin window is given in Ref. [6]. Standard tolerances in construction drawings are often too high for certain applications. It is therefore necessary to indicate the needed tolerances, e.g. of flanges which should be aligned to the same axis etc. Some vacuum companies have simple construction programs available from their web site, of course only with part numbers for flanges etc from their own company.

1.6 Purchasing vacuum systems and vacuum components

When purchasing vacuum products it is useful to compare specifications from different manufacturers. If certain quantities are very important, ask for copies of test results of, for example, pumping capacities of H and He in a cryo pump, pumping speeds of noble gases in ion pumps, maximum magnetic field that a cryo pump or a turbo pump can accept etc. For large systems it is recommended to prepare a *call for tender* document, where the required performance of all equipment is specified. One can usually save money by placing the order split over different manufacturers, rather than requiring that one manufacturer delivers all items.

If you do not have your own workshop for the vacuum chamber manufacturing you can ask for quotations from the major vacuum companies as well as from many specialist companies and workshops. To make sure that you find competent firms ask, in your call for tender for vacuum chambers, for references to other customers who placed similar orders. If references cannot be given, be careful and insist on the production of test samples. Stipulate in the specification how welds should be done, if mechanical tolerances beyond the standard ones are necessary, what cleaning methods are allowed, to what standard the leak detection should be done at the company and/or after delivery. If the chamber will be subject to vacuum firing and/or baking, stipulate that it must be leak tight after these treatments.

2. TYPICAL BUILDING BLOCKS IN A UHV SYSTEM

2.1 Standard catalogue items

In this section the typical building blocks of a vacuum system are treated. Standard multipurpose *vacuum chambers* are available from most manufacturers. Such chambers can usually be used for auxiliary systems, while process chambers, beam line chambers and chambers for diagnostic devices etc of an accelerator usually have to be prepared specially.

Vacuum pumps and traps are treated specially in other chapters of these proceedings. Here we shall only, for the sake of completeness, give an overview of available types and their specific use. *Forepumps* are either one- or two-stage *rotary vane pumps* (with oil) or ***dry pumps*** (without oil) such as *membranes, Roots or sorption pumps.*

High vacuum pumps operate in the pressure range from 10^{-2} Pa and down. *Diffusion pumps* are often used in the high vacuum (HV) range, but should avoided in UHV. Turbo pumps can be used in high vacuum as well as UHV, provided that there is a drag stage which improves the compression ratio for hydrogen. *Cryopumps* and *sputter-ion pumps* are used in HV and UHV. Some typical ***pump combinations*** for the UHV range are: sputter-ion pumps and *titanium sublimation pumps* as well as sputter-ion pumps and *non-evaporable getter pumps*. *Liquid He cryopumps* have long been used for the lowest pressures.

The most common *vacuum gauges* are: Pirani gauges for the fore vacuum range, Penning or cold-cathode gauges in the HV range. Special cold-cathode gauges with triax coaxial cables can measure down to 10^{-9} Pa. Ionisation gauges work down to 10^{-11} Pa. It is still a challenge to make reliable pressure measurements in the XHV range. The extractor gauge is one alternative. *Rest-gas analysers* for UHV should be vacuum fired in order to have sufficiently low self-outgassing of hydrogen.

There is a wide range of standard *electrical feedthroughs* for current and voltage available on the market. For signals there are 50 Ω feedthroughs of many types such as BNC, N, SMA etc. These feedthroughs are expensive and require much space on the flange. For projects requiring many signal feedthroughs in a close-packed array there are 15 to 50 pin D-SUB contacts. These have been available from a couple of companies for several years. The product range includes internal bakeable cable contacts for Kapton-insulated cables. On the outside one can use cheap standard contacts and cables, provided that they can be demounted during bakeout.

In-vacuum cables for UHV are either ceramic-bead insulated with metal inner (and outer) conductor(s), Kapton-insulated metal conductor, or hermetically-sealed cables with stainless-steel outer and a central conductor inside an insulator. The Kapton cables are available as single conductors, coaxial cables with 20 to 50 Ω characteristic impedance, and thermocouple cables. There are also Kapton-insulated band cables with 25 parallel conductors.

Liquid feedthroughs are available for water etc. and liquid nitrogen. *Rotational* as well as *linear feedthroughs* for UHV are usually bellows sealed. The rack-and-pinion linear feedthrough and permanent-magnet-type manipulators are used for long strokes, e. g. for sample transfer etc. All types can be motorised. Some of the commercially available motors are rather weak and are also quite expensive, probably since very few are sold. It is therefore possible to save money by home-built motorised versions.

Standard *UHV fittings* include flanges, screws, bolts, elbows and T-pieces. The standard flange steel is usually 304, while 316LN is often required for accelerator vacuum systems. O*ptical windows* are available for different wavelength regimes: standard glass for 300-3000 nm, quartz for 230-4000 nm, sapphire for 150-5500 nm, and magnesium fluoride for 100-8000 nm. There are also radiation resistant windows. A shutter can be installed inside the window to protect it from evaporation onto the glass.

Bakeout equipment will be treated in Section 8. Since vacuum companies usually only provide heating jackets for valves and ion pumps it is necessary to go to special companies for heating tapes, heating jackets, metal heating collars, thermo elements, bakeout controllers etc. For large systems there is also a need for a computer control for the bakeout heaters. IR lamps are available as an alternative baking method, where the inside surface is heated. All areas may not see the same temperature however.

Computer controls for vacuum systems are not available from vacuum companies. See the chapter by D. Schmied in these proceedings.

2.2 Special parts for UHV systems, standard or non-standard items

It is recommended to use silver- or gold-plated screws in bakeable vacuum systems, since uncoated screws may seize after baking. For screws in a tapped hole it is recommended to drill a ventilation hole through the centre of the screw, see Fig. 1 in the chapter "The best laid schemes...".

There is a wide variety of insulator material which can be used in UHV systems. *Ceramics*, e.g. alumina are difficult to cut, but can be ordered specially from ceramics companies. Machinable ceramics, e.g. Macor (by Corning) or Shapal M-Soft (by Narasaki Sangyo Co) can be machined in a workshop. Other often used insulators are Vespel, PEEK and Kapton. It is recommended to make outgassing tests of such products since there are different grades. We have had problems with excessive outgassing in some deliveries.

2.3 Experimental equipment

There is a wide variety of evaporation sources, piezo-electric microbalances, surface analysis instruments etc. available from vacuum companies as well as from specialist companies.

In order to perform nuclear and particle physics experiments inside the UHV system of a storage ring, it is necessary to find detector materials, cables, connectors etc. which fulfil the UHV requirements. At the CELSIUS storage ring in Uppsala, Sweden a few groups are using germanium and silicon solid-state detectors as well as GSO scintillators with photo-diode readout. A report on scintillator materials for storage ring work is found in Ref. [7]. Progress reports on the CHICSi 10 µm +300 µm silicon barrel particle detector, which also includes GSO crystals are given in Refs. [8] and [9]. Microchannel plates are used for electron amplification in time-of-flight detectors for slow recoil fragments, Ref. [10]. For the latter project a ceramic thin-film circuit-board voltage divider was developed by Monolitsytem AB, Sweden. The resistors could be laser trimmed to high precision. We have vacuum tested such circuit boards with up to 19 layers.

We have tested outgassing of single- and double-sided Kapton circuit boards prepared by Xicon AB, Sweden. They were approved for use in the storage ring. Other types of Kapton multilayer circuit boards have not fulfilled our requirements.

Thin windows are needed for detection of particles (pions, protons, heavy ions) in air outside the vacuum chamber. The window should have high transparency

$$X_0 = \frac{t_{\text{eff}}}{L_R} \tag{14}$$

where t_{eff} is the effective thickness of the window, taking into account if the particle enters the window normal to the surface or at an angle. L_R [mm] is the radiation length. The most common materials are beryllium, carbon-fibre composites, aluminium and stainless steel. Their Youngs modulus E are 29000, 22000, 6000 and 19000 [daN/mm^2] and radiation length L_R 353, 188, 89 and 17.5 [mm], respectively.

Beryllium is the best material. It is however expensive and dangerous to manufacture and to handle. Composite carbon fibre is also quite expensive since it has to be made to special order. Aluminium and stainless steel are the more-easy-to manufacture alternatives. For security reasons it is important to set a high safety margin. For a 0.8 mm thick and 500 mm diameter aluminium window in the form of a sphere with the pressure from the outside of the sphere, a buckling pressure of 3 bar was calculated. An experiment showed that buckling occurred at 3.1 bar [6].

3. JOINING METHODS

A thorough description of joining methods is found in Refs. [11] and [12]. Seals can either be demountable (such as elastomer and metal seals), or permanent seals (such as glass, glues, brazing, soldering and welding). A combination of these methods is practised at Dubna Laboratory in Russia, where two thin radial lips are sealed by welding and opened again by a cutting tool looking like a can opener. This process can be repeated several times until the welding lips have disappeared.

Historically, permanent vacuum seals and entire vacuum systems were prepared by *glass* makers. Very little of this remains today, but glass-to-meal joints can still be found in vacuum catalogues. *Glues* can be used in UHV systems provided that the outgassing is not too high. It is recommended to perform outgassing tests. In this way one can be sure that the whole process including oven heat treatment works. There is a list of glues and their outgassing properties on the NASA home page. We have used the non-conductive, conductive and heat-conductive Epotek two-component glues with the heat treatment prescribed by the manufacturer.

Permanent seals are brazing and welding [TIG (Tungsten Inert Gas), plasma welding and laser welding]. Demountable seals are O-ring seals (used on the fore vacuum side only) and various types of metal seals (Al, In, Pb, Ag, Au and Cu, with different temperature ranges). Indium and Au are used in cryogenic systems. The most common metal gaskets are Cu (OFHC). OFHC (silver plated) is used in baked systems and OFS (0.1% Ag) is a harder gasket which keeps its hardness after multiple bakeouts. Other types are Helicoflex™ and alpha C-seal™. These are spring-loaded seals with an outer seal of Al or Cu, depending on the temperature range. The VAT-seal™ is used for rectangular shapes. Ferrofluidic seals are used for rotational axes, however not in the UHV range.

3.1 Flange types

Small flanges (ISO-KF) are used on the fore vacuum side with elastomer seals. With a spring-loaded seal like Helicoflex™ and special clamps it is possible to use this flange type also in UHV. The available nominal widths (inside diameters) are 10, 16, 20, 25, 40 and 50 mm. ISO-K (ISO-F) are used in high vacuum systems, but not in UHV with metal seals due to lack of sealing force. Available nominal widths are 63, 100, 160, 200, 250, 320, 400, 500, 630, 800 and 1000 mm.

The Conflat™ flange is the most widely used type for UHV systems. It is available in the following nominal widths: 16, 40, 63, 100, 160, 200 and 250 mm. A few companies deliver alternative dimensions like 75 and 125 mm etc. The standard steel is 304. For vacuum firing or mounting in magnetic fields 316LN should be used. Old 250 mm flanges may not fit each other since there were different numbers of screw holes and screw diameters etc.

The Wheeler Flange™ by Varian is an alternative for very large diameters. Special flanges of the small-flange type with a large clamp chain and Helicoflex™ seal were developed for the SPS ring at CERN, Ref. [13]. Enamel-coated versions offer a cheap alternative to ceramic electrical isolation of a beam tube, at low isolation voltage though. The Pyraflat flange™ by Thermionics is a possibility for square, rectangular or other odd-shapes. It has a Conflat type Cu gasket.

4. COMBINED ACTION OF FLANGES, GASKETS AND BOLTS

The elastic-plastic deformation of a flange seal is illustrated in Fig. 2. At low sealing force the deflection is elastic, while at high sealing force there is a plastic flow. At higher temperature the curve is shifted downwards and the plastic deflection is increased. It is important for a flange-seal system to have adequate spring-back resulting in a large enough sealing force. This depends on the slope of the elastic curve, and the unloading due to plastic flow of the system.

For Conflat seals it is recommended to use a torque wrench and increase the torque stepwise after completing a full turn, e. g. for NW16CF 1st turn 4 Nm and 2nd turn 6.5 Nm; for NW35CF 1st turn 5 Nm, 2nd turn 10 Nm, 3rd and 4th turn 15 Nm; for NW63-200CF 1st turn 10 Nm, 2nd turn 20 Nm, 3rd and 4th turn 30 Nm.

For best performance in very large accelerator systems like the CERN ISR machine it was found that the bolts must have adequate tensile strength and yield stress. Standard bolts have class 80 (800 N/mm^2) tensile strength and yield stress. It was found that class 100 (1000 N/mm^2) screws had many less failures. The bolts are Molykote treated for better performance when baking. The nuts are glass bead blasted and Molykote treated. Washers have special high hardness. In this way the ISR ring leak rate was only 0.06 %, i.e. 1 in 1700 flanges leaked per year.

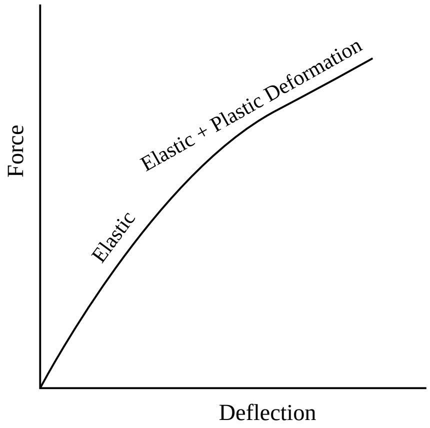

Fig. 2 Elastic and plastic deformation characteristic

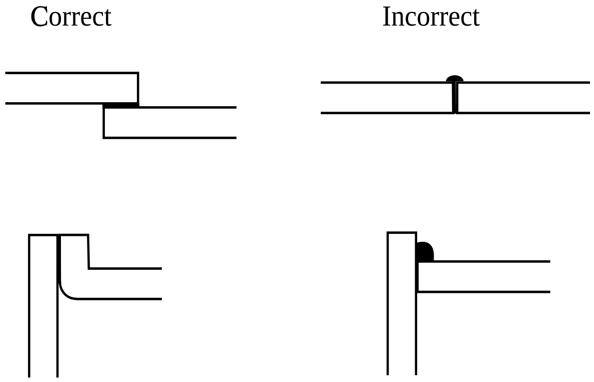

Fig. 3 Correct and incorrect brazing preparations

The outside diameter of a Conflat Cu gasket has a clearance of 0.1 mm to the flange. When the seal is partly tightened there is a radial force in the copper towards the flange. When the bolts are tightened more the seal hits the flange. When fully tightened there is a very high force back onto the sloping surface before the knife edge.

5. BRAZING AND BRAZING PREPARATIONS

Brazing involves a molten filler metal being drawn by capillary attraction into the space between closely adjacent surfaces. It is usually done in a hydrogen atmosphere in a dome open from below to prevent oxidation of the joints. In Fig. 3. are shown examples of correct and incorrect brazing preparations. Brazing can be done in several steps with fillers that melt at successively lower temperature.

6. WELDING AND WELD PREPARATION

Tungsten Inert Gas (TIG) welding is the most commonly used technique for welding vacuum components. Plasma welding is commonly used for welding thin material, e. g. bellows and thin windows. Laser welding is a new quite expensive technique which may be more used in the future. Explosion welding is used as an alternative for material which cannot be welded in any other way.

General guidelines for weld preparations:

- Cleanliness is a must.
- Use protective Ar gas, also from the outside.
- Use no filler. If necessary, use correct filler recommended and provided by the steel manufacturer.
- A vacuum chamber should always be welded from the inside. In preparing for welding it is often useful to spot weld (tack weld) from the outside to fix the structures to each other.

Examples of correct and incorrect welding preparations are shown in Fig. 4. Welding on both the inside and outside of a chamber means that the welds can not be leak detected properly. If the inside weld leaks there is a virtual leak. Some examples of welding lips for bellows are shown in Fig. 5.

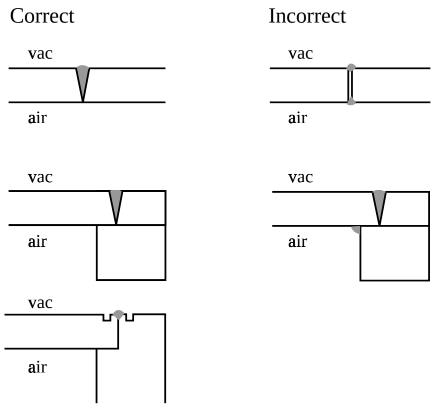

Fig. 4 Weld preparations

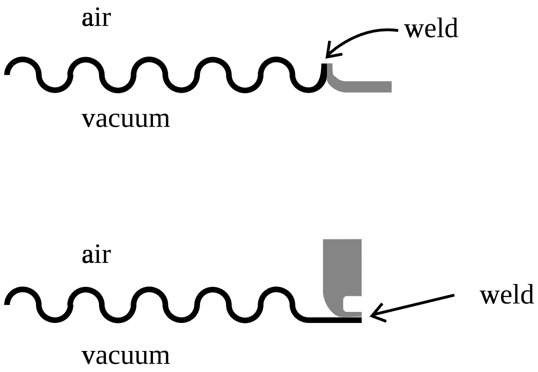

Fig. 5 Two examples of welding lips for bellows

Welding a thin window is quite delicate. The left part of Fig. 6 shows the welding preparation for a large-area, thin, stainless-steel window 450 mm ID. Welding is done from the outside. The structure to the right in Fig. 6 was used for windows from 100 to 250 mm diameter. The pieces are pressed together and are welded from the outside.

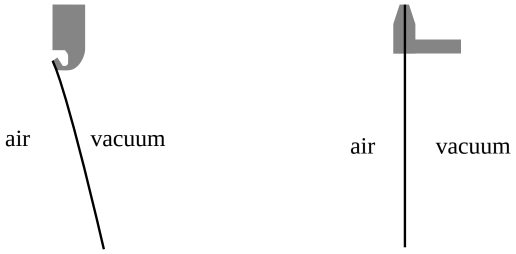

Fig. 6 Examples of thin-window welding

7. VALVES

Fore-vacuum and high-vacuum valves are usually O-ring sealed. These valves are made from aluminium or stainless steel. For UHV it is necessary to have all-metal valves. These are usually made from stainless steel. Aluminium all-metal valves are however also available. *Angle valves* and *straight through valves* are usually bellows sealed. When sealing a gate valve there is first a sideways movement of the sealing disc followed by a movement towards the seat.

Leak valves with sapphire crystal as a sealing surface are used for controlled inlet of gases into a UHV system e.g. or calibration of a rest-gas analyser. Calibration data on the size of the leak as a function of the number of turns should be supplied by the manufacturer.

Fast-closing valves are used for safety interlocks to protect vacuum systems from sudden pressure failures. There are leak-tight fast-closing valves and non-leak-tight fast-closing shutters. The latter type protects the system until an ordinary slow valve can be closed. The closing time is in the range 10 to 20 ms. A simple and very effective all-metal shutter is shown in Fig. 7. It has been used in the HV range, but can if made from stainless steel also be used for UHV.

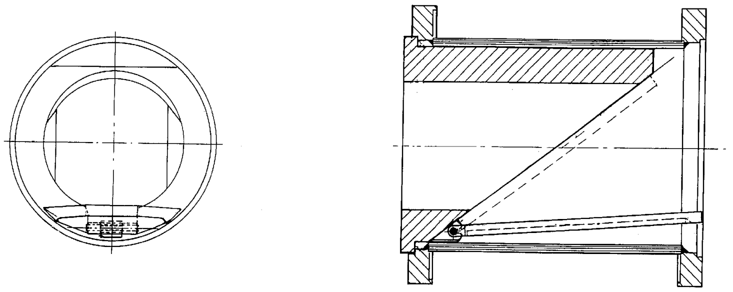

Fig. 7 A simple and very effective all-metal shutter constructed by O. Byström, TSL, Uppsala, Sweden

8. EXPANSION BELLOWS

The usual material for bellows is stainless steel of grades 304, 304L or 316L. Aluminium bellows are also available. Hydraulically-formed bellows have elongations of about 10%, while membrane (or diaphragm) bellows have much higher elongations, 50 to a few hundred %, depending on the type and inside and outside diameters of the membranes. For bellows which are used very frequently it is important to notice the maximum of strokes guaranteed by the manufacturer. The manufacturer can also tell how skew operation of the bellows reduces this number. Examples of welding lips for bellows are shown in Fig. 6. In many accelerators it is required that bellows assemblies have internal rf bridge shields.

9. BAKEABLE VACUUM SYSTEMS

All materials of a bakeable system must be compatible with the temperature cycling. There are at least 3 orders of magnitude difference in outgassing between baked and unbaked chamber material. Therefore, unbaked or low temperature baked parts will, even if their total area is only a few %, dominate the total outgassing. The most common bakeout cycles are 150 °C (to get rid of water vapour), 300 °C or 450 °C. The latter bakeout cycle can be applied to a system which is not vacuum fired in order to reduce the ougassing further. Air bakes at 400 °C have successfully been used for gravitational wave interferometer vacuum systems like LIGO. Here the stainless steel has been air baked prior to welding. A comparison outgassing and hydrogen content in air-baked and vacuum-fired stainless steel is found in Ref. [14]. Further studies, including large scale bakeout tests are going on [15].

9.1 Baking hardware

The standard types of heating tape are 150 and 300 W/m. There is a selection of standard lengths. The following simple formula can be useful to determine the length, L, of a heating tape for a vacuum chamber.

$$L = \frac{AJ}{2B} \tag{14}$$

where A is the total area of a tube, B is the width of the tape, J is a goodness factor, which is an estimate of the fraction of the chamber which can be wound with heating tape (roughly the length of the chamber which is not covered by flange collars or other obstructions. The distance between two turns should be the same as the tape width. Never cross tapes since this can cause a short circuit. Use double tapes in magnet chambers and other hard-to-access-chambers for fast replacement in case a tape breaks down.

For good heat contact with the vacuum chamber, braze the thermocouple end onto a 10 mm × 25 mm stainless steel piece. The non magnetic type E thermocouple is recommended for chambers placed in magnetic fields. In Fig. 8 is shown how to mount the thermocouple onto a chamber. Use Kapton tape or glass fibre tape to attach the beginning and the end of the heating tape on to the chamber. Mount two thermocouples on hard-to-access chambers, e.g. in magnets. In this way a spare is easily available if the thermocouple breaks down. Continue by winding the heating tape onto the vacuum chamber as shown in Fig. 8.

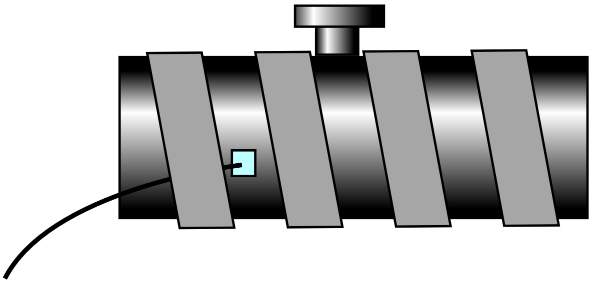

Fig. 8 Thermocouple and heating tape wound on a chamber

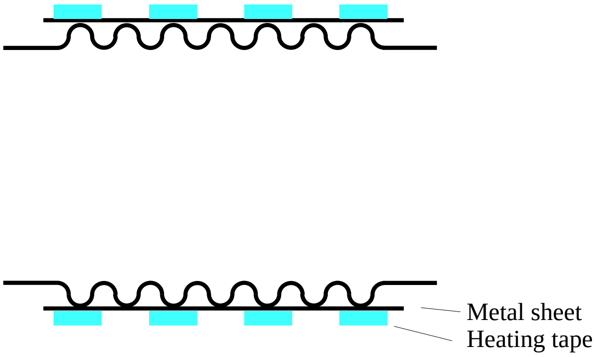

Fig. 9 Mounting of baking equipment for bellows. The outer insulation is not shown.

It is recommended to use as thick insulation as possible to reduce the power consumption. Insulation sheets can be bought from heating tape suppliers and from other companies. Use the following thickness guidelines: with 25 mm insulation the power needed for 300 °C and a bit beyond is 16 W/dm^2, for 15 mm 20 W/dm^2, for 10 mm 30 W/dm^2 and for 5 mm 45 W/dm^2. Seal the insulation on the outside by 5 cm-wide aluminium tape. For chambers where a very thin insulation is required it may be necessary to water cool a copper sheet outside the insulation to protect for example a magnet from being overheated.

Do not wind the heating tapes directly on bellows due to bad heat transfer and the risk of short circuiting. Instead, wind a thin (0.1 mm) stainless-steel sheet around the bellows and wind the heating tape on the outside as shown in Fig. 9.

Flanges can be baked by metal heating collars with the same width as the two flanges together. Use non magnetic heaters in magnetic fields. Soft heating jackets are also available for standard flanges. Bakeout jackets are commercially available for valves, ion pumps etc. For other chambers custom made bakeout jackets are an alternative to heating tape and insulation. This is also recommended where the bakeout equipment for space reasons must be demounted after bakeout.

Power controllers can be bought from many electrical companies. Make sure they are made for your thermocouple type. The controllers have usually the functions: ramp up, dwell time and ramp down. It is recommended not to ramp faster than 60 °C/h.

Large vacuum systems require more sophisticated bakeout controllers, which can handle 50 to 100 control circuits per baked sector of the vacuum system. A typical 300 °C bakeout cycle is given in Table 1.

Table 1
Bakeout cycle

Time (h)	Temp (°C)	Action
0	Amb.	Start baking. Max. 60 °C/h.
5	300	Stay at full temperature for 24 h.
28	300	Degas sublimation pump filaments at 20A for 1 h. Flash ion pumps 30s every 20 min (3–4 times).
29	300	Decrease temperature. Same time derivative. Residual gas analysers should stay at 300 °C for 2 h.
31	200	Degas ionisation gauge filaments. Degas sublimation pump filaments at 35A for 5 min.
32	150	Degas sublimation pump filaments at 40A for 2 min. Degas RGA 30 min (at 200 °C). Start ion pumps. Close turbo pump valve.
33	100	Run sublimation pump filament at 48A for 1 min to pump down.
35	Amb.	Bakeout finished.

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