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**NON-STANDARD VACUUM HARDWARE
FOR AN ACCELERATOR VACUUM SYSTEM**

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ABSTRACT

The metal sealed demountable joints of the LEP vacuum system have been proposed and designed in such a way that well-proven stainless steel components like pumps, valves, gauges or bellows could be joined without transition pieces onto the aluminium vacuum chambers. Important boundary conditions which were imposed by the operation parameters were corrosion and temperature resistance with the general demand for a high standard of reliability which had to be assured despite the considerable differential expansion caused by the dissimilar flange materials at elevated temperature. 2800 bellows compensate alignment tolerances and the length increase of the aluminium chambers during bake-outs. Their circular aperture would create 2800 cavities of an inadmissible transverse impedance. An inner screen has therefore been designed which provides a reliable electrical contact under all working conditions of LEP and which keeps the elliptical aperture of the beam path quasi-constant, such eliminating higher order mode losses, which would otherwise be induced by the passage of charged particles. The report describes the design and technology of these components and their performance in the ultra-high vacuum system of LEP.

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1. UHV joints with flanges of dissimilar metals

Already in an early stage of the feasibility study of the Large Electron Positron storage ring (LEP) ¹⁾, it appeared clearly that, with the size and the parameters of the proposed machine, considerable work on vacuum hardware would have to be done to meet the requirements. The boundary conditions were already defined along general lines which emerged from the need for :

- the application of ultra-high vacuum techniques with metal sealed joints
- water cooled, lead shielded vacuum chambers in aluminium of about 12 meter length for more than 90% of the 27 km circumference of the machine
- bake-outs to 150°C in the aluminium sections, bake-outs to 300°C around the experiments and in the stainless steel sections
- all of the components had to be resistant to synchrotron radiation and corrosion ²⁾.

General requirements such as above average reliability, simple design and reasonable cost were imposed because of the number of components involved, the size of the machine and its location in a deep underground tunnel. Furthermore, it was proposed to use proven stainless steel vacuum components like valves, gauges and pumps.

1.1 Principle ideas

In the design study it became apparent that there would have to be more than 15000 demountable joints in the ultra-high vacuum system of LEP. The demand for vacuum components in stainless steel connected to aluminium chambers raised questions about the type of the joint, their reliability and cost. In general, friction welding, brazing, roll-bonding, flat and concentric explosive bonding or "DEPI"-welding are the most common transition pieces from aluminium to stainless steel ^{3, 4, 5)}. In one case, Al-ConFlats with vacuum components out of aluminium have been developed ⁶⁾.

Transition pieces, in general, are susceptible to failures and their reliability depends, apart from their design, on a strict supervision of their production parameters. As a consequence they complicate a system and entail considerable cost.

In view of the size of the machine and the number of components involved, a flange joint was proposed ⁷⁾ which allowed a direct connection of stainless steel components to aluminium chambers. Its design was such that it could absorb the differential expansion between two flanges of dissimilar materials during the bake-out.

The new proposal profited from the experience gained during the improvement program on the UHV joints of the former ISR vacuum system whereby its design was chosen such as to satisfy the operational conditions of LEP.

1.2 The joint design

The gasket of the LEP vacuum joint is in a recess of the flange faces, as the gaskets of other UHV joints (Fig. 1).

The bolt forces of such designs pass firstly through the gasket until it is completely formed. Forces in excess pass through the flange/flange interface; the gasket is hence in the by-pass of the bolt forces (Fig. 2b).

A vacuum joint can be presented as an elastic assembly of five springs mounted in series (Fig. 3). Its common spring characteristic is :

$$\frac{1}{C} = \sum \frac{1}{C_i}$$

If one of these springs fails, the numerator of the developed expression becomes zero and the joint may fail.

It is evident that with the standardization of flange dimensions and the number of bolts per flange, the gasket remains the only free parameter and it has to be chosen carefully so that it does not become the weak link in the chain.

The sealing surfaces on the flanges are of a well-defined roughness in order to provide enough "friction" in case of differential expansion and shear, and to enhance the local pressure in the gasket-flange interface during the forming of the seal (see contact pressure of Hertz : $p_0 \sim \sqrt{F/r}$). The gasket is of the diamond-edge type, identical in shape to one which has been proposed once to replace organic seals in the Proton Synchrotron at CERN 8). This joint has proved to be reliable with flange pairs of dissimilar metals such that all flanges could be kept in the same material as the components to be joined.

The vacuum performance is described in paragraph 1.4, extensive tests on its elastic properties are summarized in a report 9).

1.3 Mechanical and physical properties

The material of the gasket has been adapted to the operating conditions of LEP with particular emphasis on :

- the thermal stability of the material up to 150°C
- corrosion resistance
- mechanical strength.

These requirements could be met with an aluminium alloy containing 0.5% magnesium. The magnesium atoms, occupying interstitial lattice places of the matrix, increase both the yield point and the recrystallization temperature of the material.

The essential properties of the four components of a joint are summarized in the following table :

Component	Flanges		Gasket	Bolts
Material properties	Stainless steel	Aluminium		
Material grade	AISI 304 L	Al Si Mg Mn	Al 99, 85 Mg 0.5	AISI 316
Material state	Quenched	Age-hardened	Cold-rolled	Cold-rolled
Yield strength daN • mm ⁻²	~ 20	~ 25	13	90
Hardness (HV)	140 - 160	> 100	45 - 50	> 350
Thermal expansion (K ⁻¹)	16.5 • 10 ⁻⁶	23 • 10 ⁻⁶	24 • 10 ⁻⁶	17 • 10 ⁻⁶
Young's modulus daN•mm ⁻²	20000	7000	6500	20000

Table 1 - Material properties of the joint components

1.4 The Field experience

Joints of this type have been successfully tested since 1978 and the final geometry of the flanges was frozen in 1985. Since 1986 to June 1989, more than 62000 gaskets, mainly for joints of 113 and 225 mm outer diameter, have been used in tests during the production of the vacuum components, during their acceptance tests at CERN and for the installation of the vacuum system in the tunnel.

As in all bolted systems where the forces are applied as point loads around the circumference of the flange, there exists the risk of wobbling between the two flange-planes during the tightening of the bolts. This means that instead of having the ideal situation of a steady increase of sealing force with gasket deformation, wobbling may cause a local drop of sealing force. In the extreme case, the forming of the seal is interrupted which may entail leaks.

Fortunately, these problems were very limited and disappeared completely after a running-in period. The joints behaved reliably during later stages of manufacturing and testing, and even exceptionally during the installation of the LEP vacuum system. Altogether, the following number of leaks of LEP-type joints have been recorded after bake-out and commissioning of the ultra-high vacuum system :

LEP-type joints	Installed	Leaks	Failure rate
225 mm o.d.	5569	3	$6 \cdot 10^{-4}$
113 mm o.d. on ion pumps	1330	12	$8 \cdot 10^{-3}$
113 mm o.d. remaining	6586	0	0
70 mm o.d.	1712	0	0

Table 2 - Failures on LEP-type joints

All but the smallest joints are sealed with the described aluminium gaskets. The joints of 70 mm o.d. are equipped with Helicoflex-type gaskets to provide extra elasticity to the design, in particular they have to compensate for the flow in the thread between the studs and the Aluminium block.

The high failure rate on ion-pump flanges was due to an unfortunate non-conformity to our specification. Two of the remaining three leaks on big joints were very close to or on stainless steel components baked at 300°C.

1.5 Cost comparison of the joints

In the following comparison the cost of LEP-type joints is set against that of ConFlats combined with Aluminium-to-steel transition pieces. In both cases five gaskets per joint are taken into account. The comparison is based on prices for large quantities as required during the construction period of LEP. With the most optimistic price for transition pieces of SF 100.-- per unit plus SF 50.-- for welding and individual testing, one finds a cost ratio of more than 1:3 for the two designs or for figures for LEP quantities :

2 mill. SF for LEP-type joints, as compared to 6.5 mill SF for ConFlat joints with transition pieces.

The above figures do not include costs of a more expensive chamber design or any extra cost which may arise from longer uncooled or unshielded chamber ends due to the transition pieces. More expensive transitions, as available on the market for more than SF 1000.-- per unit, would have increased the vacuum budget of the machine considerably.

2. RF-shielding of components in the beam-line

The maximum stored beam in LEP is expected to be limited by transverse mode-coupling, an effect which appears on abrupt cross-section changes of the vacuum chamber. Particles passing such places induce electromagnetic fields which can produce undesirable effects :

- the transverse field induced by the head of a bunch deflects particles at the tail of the same bunch

- the induced fields act on the charged particles in subsequent bunches leading to longitudinal and transverse instabilities
- higher order mode losses cause heat dissipation in the walls. The subsequent energy loss has to be compensated by additional RF-power.

All three effects lead to a beam loss and determine the maximum current of the beam.

In order to minimize these effects, aperture variations along the beam line have therefore to be avoided or bridged with metallic sleeves and electrical contacts such that the cross-section of the beam tube remains as constant as possible. The requirement for this so-called RF-sleeve is particularly stringent for the circular bellows which would create, when mounted between vacuum chambers of elliptical aperture, about 2800 cavities which sum to an unacceptable transverse impedance ^{10, 11}).

2.1 The parameters of the vacuum bellows

The vacuum bellows (Fig. 4) have to cope with a compression of about 37 mm during bake-out at 150°C. In addition, they have to allow some millimeters radial offset to compensate installation and alignment tolerances. Hence, the bellows have to meet as far as design, material and performance are concerned, the following specifications :

- hydroformed bellows of 0.15 mm wall thickness in the material quality AISI 316 L with a reduced level of non-metallic inclusions
- LEP type flanges of 225 mm outer diameter in quality 304 L
- nominal installation length of 168 mm
- longitudinal compression during bake-out of 37 mm
- radial offset to compensate for installation and alignment tolerances of 3 mm
- lifetime at bake-out temperature and with the specified offset: more than 250 cycles.

The sleeve which bridges the inner surface of the vacuum bellows has to:

- provide a smooth continuation of the aperture between the adjacent vacuum chambers while still taking up any alignment offset
- follow telescopically the compression of the bellows during bake-out
- provide reliable electrical contacts for wall currents
- have a well defined electrical resistance to limit eddy currents induced during the ramping of the magnets.

In addition the bellows had to be equipped with static inter-flange contacts in order to bridge the relatively deep gap of 5 mm width of the gasket groove in a joint.

2.2 Design of the bellows

The bellows were of the hydroformed type with 10 convolutions and 14 mm convolution height. Already during the qualification tests they had an excellent life time which was confirmed during the production period. Following a strict selection of the material and supervision of manufacturing steps, an average life time of 25000 cycles, measured on more than 30 bellows, was obtained. These tests were carried out under simulated LEP conditions, namely at 150°C, with 37 mm stroke and 3 mm radial offset between the two flanges.

The inner sleeves as used in other machines could not be accepted for LEP because of their high transverse impedance 10, 11). They would have caused, because of the large number of pieces involved, an unacceptable beam current limitation. A new telescopic sleeve has therefore been designed such that the approximately 2800 bellows are no longer a dominant factor for beam current limitations. In the design which was finally adopted, particular emphasis has been put on a smooth continuation of the elliptical beam chamber aperture 12).

The flexible part is made from 0.4 mm Cu-Be sheet metal with stamped-out contact fingers. They are silver coated and the contact force of 0.4 to 0.7 N per finger is applied by a coil spring placed around the circumference of the finger ends.

The rigid part of the sleeve is made out of 1 mm stainless steel sheet metal which provides the desired electrical resistance in order to limit eddy currents during ramping of the magnetic field.

The inter-flange contacts bridging the 5 mm gap of the gasket groove in a joint are of the same material as the finger contacts of the sleeve. Since they are static contacts, they are not silver coated.

Both the sliding and the static contacts as designed and manufactured for bellows have also been used elsewhere to shield other components in the beam line like valves or beam instrumentation equipment.

2.3 The vacuum performance of the bellows

In particular the residual total and partial degassing rates after bake-out, and the enhanced desorption during the 37 mm stroke have been tested on about 3% of the delivered bellows. A typical result of such a test is shown in Fig. 5.

The static outgassing after bake-out is about $5 \cdot 10^{-9}$ mbar l/s per bellows unit. The dynamic outgassing seems to be higher by a factor of 20 to 30. But, since the scraping process and the desorption of the sleeve occurs in LEP, a thousand times more slowly than in the laboratory tests, and because it takes place during bake-outs at a much higher pressure and pumping speed, it is imperceptible in the pressure reading of the machine.

3. Conclusion

The excellent results with joints during the LEP installation were obtained not only because of well prepared material but also due to competent installation teams. The achievement must be seen in the light of the difficult local conditions in the tunnel, the shortage of time due to a tight planning and the large number of components involved. The simple design of the joint increased the reliability considerably and reduced the cost of the vacuum system. The perfect electric shielding of the bellows and inter-flange gaps was obtained via a reliable and relatively simple system developed by a small but highly skilled team. In both cases there was an excellent collaboration with industry which manufactured on a large scale what we prepared as models.

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FIG.1
 LAY OUT OF LEP VACUUM JOINTS

Fig.2 Fundamental difference in joint designs:
 a) gasket in the main flow of the bolt force
 b) gasket in the by-pass of the bolt force

Fig.3 Schematic presentation of forces and deformations in a joint.

FIG.4 Standard bellows assembly

Fig.5 Vacuum performance of shielded bellows