LOW COST VACUUM HARDWARE DEVELOPED FOR THE CERN PS BOOSTER

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Introduction

The CERN PS Booster (PSB) is a vertically stacked four-ring accelerator of 50 m mean diameter designed for accelerating 2.5 x 10^{12} protons per pulse per ring from 50 to 800 MeV. The distance between rings has been fixed at 0.360 m mainly through considerations of the RF accelerating system and the beam angles in the injection and recombination lines. The 157 m long circumference of the rings is divided into 16 periods, a typical period being shown schematically in Fig. 1.

The vacuum system

The various long straight-sections, L1, contain the injection and ejection equipment as well as acceleration, beam measuring and correction elements and vacuum manifolds interconnecting the four rings. The connecting vacuum pipes here are normally circular with an ID of 120 mm x 1.5 mm wall and are made from SST 316 LN. The only way vacuum connections between the various elements can be made is by sealed flanges. Welding of the four stacked pipes in situ instead of using sealed flanges was carefully considered but finally could not be realized. Firstly, the size of the welding equipment needed and the space actually available in the 4 stacked accelerator rings does not allow the welding process. Secondly, it must be considered that if a piece of equipment in one ring only breaks down and must be replaced it is usually necessary to break into all four rings to replace it necessitating the opening and reclosing of eight vacuum connections. If these vacuum connections are of the welded type such replacement of equipment may become quite inconvenient.

The bending magnets B1 and B2 each contain four 70 mm high gaps through which passes an elliptical 0.4 mm thick, corrugated vacuum chamber made from Inconel X 750 having horizontal/vertical inside axis of 132 and 62.5 mm respectively and a corrugation height of 3 mm. The coil design of the C-type bending magnet is such that the vacuum chamber becomes captive of the magnet and, therefore, cannot be replaced without removing the magnet necessitating a vacuum joint at the two ends. Again, welding up the connections could not be considered for the same already mentioned reasons.

Six of the straight-sections, L2 contain the four stacked vacuum sector valves dividing the ring into 6 vacuum sectors. These valves too must be flanged into the vacuum system.

The triplet containing a focusing QF1, defocusing QD and a second focusing QF2 quadrupole is treated as a subassembly mounted on a girder and transported as a unit. This does allow to place a single diamond shaped vacuum chamber (welded from 1.5 mm thick SST 316 LN sheet) having horizontal/vertical inside axis of 135 and 121 mm respectively through each of the four 120 mm gaps of the three quadrupoles reducing the number of needed vacuum joints between elements. Unfortunately it became later necessary to insert into the straight-section L3 a beam position monitor made from a 140 mm ID ceramic tube introducing two additional vacuum joints per period and ring. Around this pick-up electrode is mounted a multipole correction magnet and in the straight-section L4 there normally are horizontal and vertical correction dipoles which, however, can be assembled around the four stacked triplet chambers and thus do not necessitate additional joints.

The last straight-section L5 contains the same manifold as mentioned in L1. The four rings are interconnected through each one of these manifolds that is normally two times per period. The four rings of each vacuum sector are thus evacuated simultaneously by one or two (depending on the size of the sector) mechanical pump groups connected to selected manifolds. A mechanical pump group consists of a 70 ℓ/s turbomolecular pump backed by a 32 m^3/h vane type forepump. Furthermore each manifold is equipped with a 400 ℓ/s sputter ion pump and the necessary gauges for pressure measurements and interlock system. The design pressure is in the 10^{-8} Torr range.

It is seen that with the described design with all its space restrictions, a very large number of vacuum joints joining differently shaped vacuum chambers of similar sizes are required. The number and frequency of such joints is summarized in Table 1 :

Table 1

Segment	No of joints	length of vac. line m	average No. of joints/m
Inj.line	78	130	0.6
PSB ring	664	630	1.05
Transfer line	60	120	0.5
TOTAL	802	880	0.9

For economic reasons it was necessary to minimize the number of different joints and to take a very close look at all details. Furthermore, it was decided to use metallic joints only for reasons of durability (radiation damage), degassing and cleanliness. Other conditions to be fulfilled were :

a) quick installation and removal
b) extreme reliability for UHV
c) space allowed along beam axis for a joint including mounting clearance ≤ 40 mm
d) the radial space occupied by the joint should be the smallest feasible
e) 400 ring joints must be electrically insulated for reasons to be explained later.

The marriage of these conditions has been found in a pair of relatively narrow flanges having identical outer profiles but differently shaped holes for welding on the various pipes and a three jaw clamp with a single bolt for tightening in combination with a specially shaped seal disc made from soft aluminium. In the following the seal is first described followed by a description of the clamp and the special case of insulated joints having a relatively large dc resist-

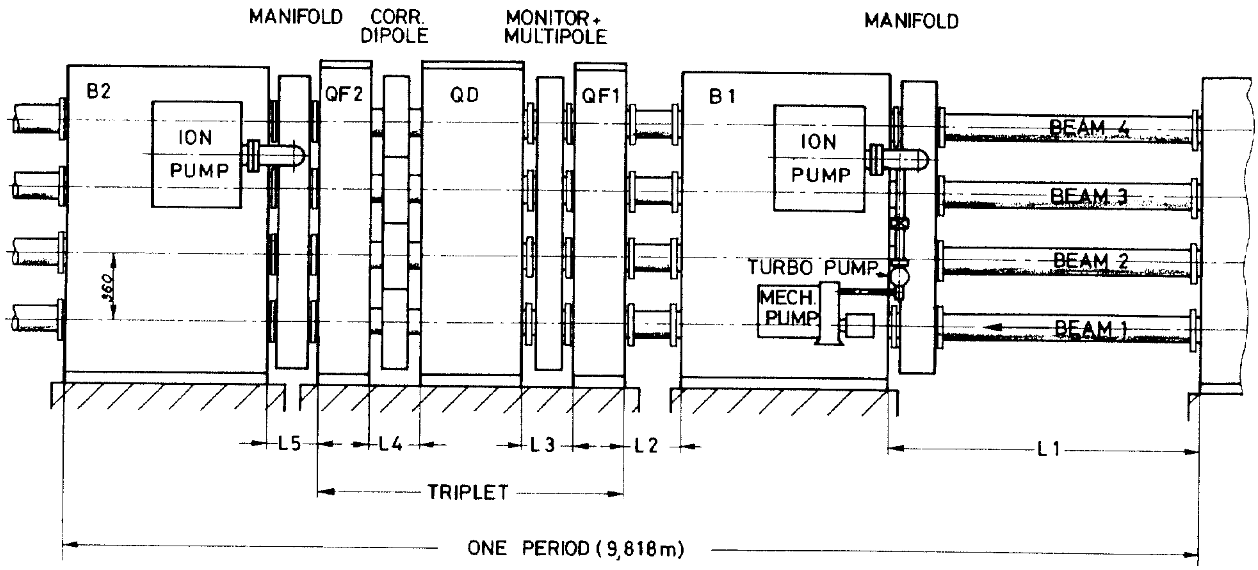


Fig. 1. The typical booster period.

ance but a low impedance at 8 MHz.

Development of a low cost metal seal

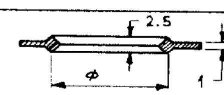
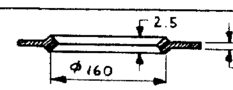
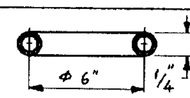
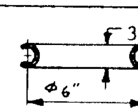
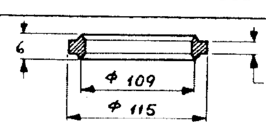
The goal was to find a metallic ultra high vacuum seal having a seal diameter of 160 mm and satisfying the following requirements :

a) low cost because of the large quantity involved,
b) high reliability, easy handling and application,
c) a small sealing force because of limited compression realizable with a simple flange clamp,
d) must be capable of providing a reliable UHV seal with an unevenly distributed sealing force around the circumference. This non-uniform distribution of the seal force is principally due to the friction characteristics of the flange and clamp assembly during the tightening process and mechanical and positioning tolerances,
e) must be capable of making a reliable UHV seal against vitreous ceramic coated flange surface.

As a result of these many requirements a study of all known, commercially available UHV seals having potential application, including some new CERN developments, was undertaken[1,2]. This study consisted in determining the minimum sealing force required, kgf/cm at which a reliable UHV seal was established, the amount of deformation of the seal and its ease of application in view of the four stacked rings and the little space available in the PSB. A test apparatus capable of taking this kind of data was built using a hydraulic car jack between two columns, two stainless steel plates with a surface finish of 0.8 μm, a load gauge and two dial indicators hooked up to a high sensitivity He leak detector. Tests were conducted on the seals shown in Table 2.

From the list of seals shown it is evident that the seal type A requires a wire holding frame while the seal types D,E and F require a holding frame plus

Table 2

Seal code	Manufacturer	Description of a seal
A	CERN Geneva	 Al wire hard (38 HV)
B1 B2	Leybold-Heraeus Hanau D	 Al disc soft (22 HV)
C1 C2	CERN/Heraeus Geneva	 Al disc half hard (38 HV) Al disc soft (22 HV)
D1 D2 D3	United Aircraft Prod.	 Indium coated SST O-ring
E	Pressure Science Inc. Beltsville, Maryland	 Indium coated Inconel X C-ring
F	CERN/ Calorstat Geneva	 SST Ω bellows modified and Indium coated
G	CERN Geneva	 Al ring half hard for rubber O-ring replacement

an accurately machined spacer or a flange groove limiting the deformation of the seal. These supplementary parts add substantially to the cost of the seal. The seals B and C can be used without any additional hardware while the aluminium knife edge seal type G was conceived to replace rubber O-rings in O-ring grooves of circular as well as any other shape e.g. elliptical.

The results of these tests are summarized in Table 3.

Table 3. Results of seal tests

Seal code	Cost per seal SF	Number of seals tested	Number of leaks	Number of times used	Min. force kgf/cm	δ* mm
A	-	10	0	1	73 - 125	-
B1	11	2	0	1	31 - 34	
B2	21	4	0	1	24 - 32	0.3 - 0.6
C1	CERN mfg.	4	0	1	42 - 45	0.3 - 0.6
C2	$\sim$8	1	0	1	42	0.3
D1	$\sim$200	3	3	1	up to 55	0.8
D2	$\sim$200	1	1	1	"	0.9
D3	$\sim$200	2	0	5	54	0.75
E	$\sim$200	2	0	10	$\sim$20	0.2 - 0.3
E		2	2	35	$\sim$20	0.2 - 0.3
E		1	1	8	$\sim$40	1.0
F	$\sim$20	2	0	1	<20	

*δ = S - d where S = seal thickness before compression and d = thickness at minimum compression at which seal is leak tight.

Discussion of results. The seals which could withstand the roughest handling and which were the least sensitive to the application of a non-uniform pressure over the seal periphery and give a reliable UHV seal were the types A,B,C and G. These are also the seals of lowest cost. For reasons of convenience and price the seal type C2 was chosen. This soft aluminium seal uses the same diamond profile as type B developed by Heraeus, but it has a non-standard seal diameter and instead of bolt holes it has a small rivet for hanging the seal into a notch milled into the flange. Concerning this diamond profile it was found that the minimum seal force needed to obtain a tight seal does not depend on the hardness of the seal (see Hertzian contact pressures) but rather on how well the knife edge has been formed. The measurements indicate that the knife edge of seal B was better executed than the one of seal C. The seals have the disadvantage of being non-reusable, however, in view of their low cost this is not considered a serious disadvantage.

The seal types D,E and F were found to be very delicate and extremely sensitive to the amount and uniformity of deformation to which they were subjected. The seals D1 and D2 (thin-walled O-rings) were found to be completely unsuitable for vacuum work , while the thick-walled O-ring seal D3, was good provided its deformation was kept about one half the recommended value in the catalogue. The seal type E gave unsatisfactory results when sealing against a ceramic coated flange, the coating having sort of an "orange skin" surface. These seals are also much more costly than the seals of the previous group and their potential reusability does not make them much more attractive. In this connection it is curious to note that the deformation recommended by the manufacturers, namely 20 per cent for O-rings as well as for C-rings to make a vacuum seal is much too large and as shown in Table 3 improved results are obtained when the deformations stay within the near elastic range. In fact it was possible to use two C-rings 35 times before they became leaky, note however that their deformation was consistently limited to 0.2 to 0.3 mm which is only 1/3 to 1/5 the value recommended by the manufacturer. Using a deformation of about 20% ($\sim$1 mm) another C ring could be used only eight times before it became leaky. Therefore,only under accurately controlled conditions of deformation and compression can these seals be successfully used more often than only once.

Description of the clamp

As already mentioned, the longitudinal space to be occupied by the seal assembly including mounting clearance and the space needed for the insertion of bolts, if any, was to be less than 40 mm. The simple solution of a bolted flange assembly would be possible only by reducing the flange thickness below the safe limit and, furthermore, because of the geometry, accessibility to some of the bolts would be rather limited. Moreover, the removal of a relatively large number of bolts per seal is time consuming and thus increases the radiation dose a technician may be subjected to while making repairs.

A more suitable, so called quick clamp connection was found in the form of a pair of conical flanges and a three jaw, hinged clamp using a single screw for tightening. The principle of such a clamp (usually made from pressed steel in two segments) is not new and has been successfully applied before to existing accelerators. The presently developed clamp and flange assembly is shown in Figs. 2 and 3. The seal surface of the flange is flat and smooth with a surface finish of 0.8 µm while the outside surface of the flange is inclined at an angle of 20 degrees. One flange of the pair has a milled notch which serves as a seal holder. The clamp has three segments which are cast from a high strength aluminium alloy. Each segment has a spring loaded centering button the spring force being selected in such a way that a radial flange centering force of nominally 30 kgf is obtained before the actual clamping process begins.

The clamping force is obtained by tightening the screw M12. Measurements of tightening torque versus axial force were made with a screw pitch of 1.75, a clamp angle of 20 degrees and molycote lubricated contact surfaces. The results of these measurements made on a tensile testing machine and by using a torque wrench are shown in Fig. 4.

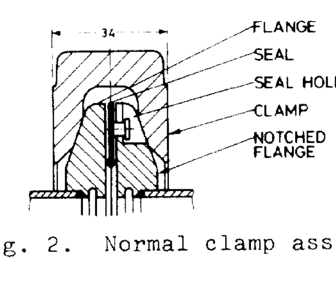


Fig. 2. Normal clamp assembly.

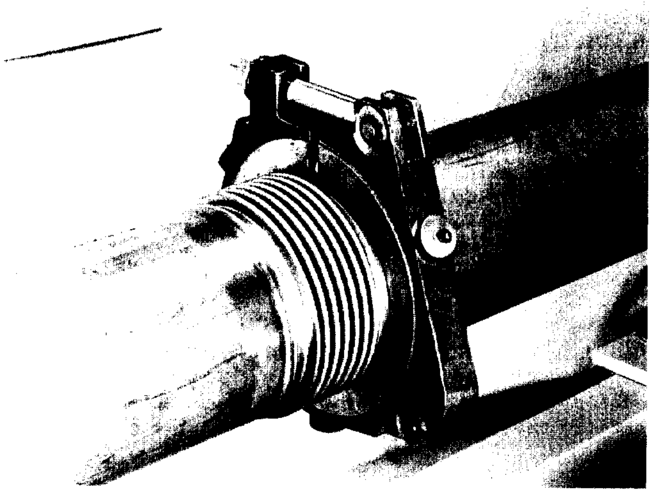


Fig. 3. Installed clamp.

Seal tests with the described flange and clamp combination and with the seal type C2 showed that the deformation of the seal is rather non-uniform around the circumference and that hence, the peripheral distribution of the axial force is also non-uniform as expected. Typical deformations δ_{min} and δ_{max} of a seal as a function of the tightening torque are shown in Table 4. δ_{min} is measured at a point on the seal opposite the clamp bolt while δ_{max} is measured opposite δ_{min}.

As shown in Table 4 a helium leak tight joint is obtained reliably at a screw torque of about 2 m kgf corresponding to an average seal force of about 100 kgf/cm, however a torque 3.5 to 4 mkgf is used for application to the PSB vacuum system. Clamp breakage can occur when the torque exceeds 9 mkgf.

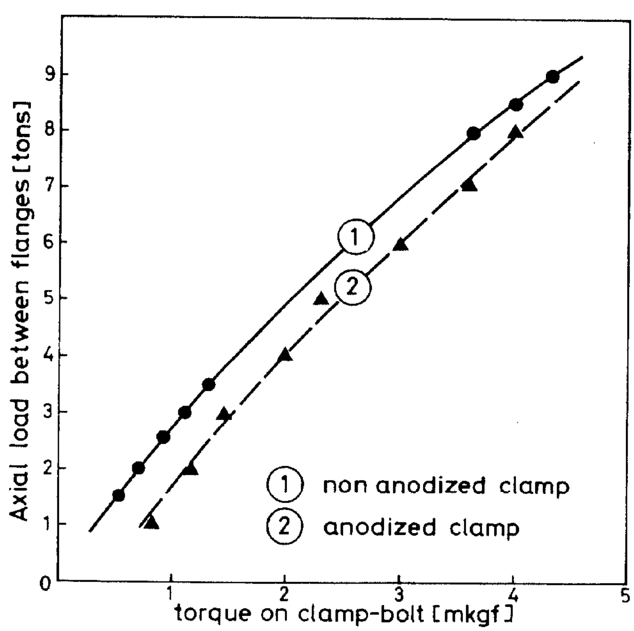


Fig. 4. Torque vs. axial load.

Table 4. Deformation of seal type C2

Seal No	Min. torque at which He tight mkgf	Final applied torque mkgf	Deformation δ_{min} mm	Deformation δ_{max} mm
1	< 2	-	0.06	0.46
2	< 2	2	0.07	0.47
3	< 2	3	0.15	0.69
4	< 2	4	0.26	0.88
5	< 2	5	0.38	0.94
6	< 2	6	0.68	1.06

The case of an insulated joint

A particular problem of insulated joints usually not encountered in ordinary accelerators exists in the PSB due to its four superposed beams. Taking the bending magnet as an example one sees that the four gaps have a common yoke and further, that the four vacuum chambers inside the gaps are connected to a common manifold on one side while on the other side they may be earthed through the tube supporting, or another structure. Thus, unless the vacuum joints are electrically insulated one would have loops between the four gaps as well as ground loops in which field disturbing induced currents may circulate[3]. Such an insulated vacuum joint should satisfy the following conditions :

1. Any loop currents occurring every cycle as well as any accidental ones occurring only in case of one earth fault of a vacuum chamber must be small enough not to disturb the magnetic field. Measurements performed on the prototype magnet and chamber suggest that the DC resistance of an insulated joint must be $R > 1\Omega$ in order to have an effect smaller than 10^{-5} on the magnetic field at injection[4].

2. The impedance seen by the RF current crossing an insulated joint should be $|Z| \leq 1\Omega$ at 8 MHz [5,6] and is estimated from RF acceleration voltage and cavity considerations and the number of insulated joints. No electrical resonances should occur up to rather high frequencies.

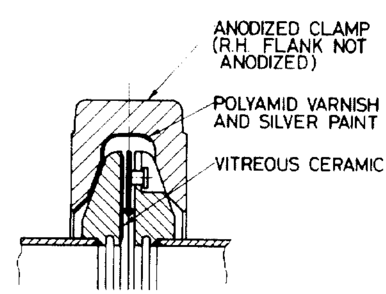


Fig. 5. Insulated clamp with RF by-pass.

3. For reasons of personal safety no metallic object, which can be touched, should be allowed to rise to a dangerous voltage in case of an earth fault of the main magnet circuit. Thus, the breakdown voltage of an insulated joint should be in the 20 to 50 volt range.

These requirements can be met by an insulated joint bypassed by a capacitive and/or resistive arrangement distributed along the periphery of the joint and connected through low inductance paths in order to avoid resonances. A rather elegant solution to this problem was possible because the clamps are cast from aluminium, which through partial anodization and application of a silver paint could produce the needed capacity of 20'000 pF or more bypassing the insulated joint. This is shown in Fig. 5.

A number of processes to obtain this "integrated" capacitor were tested[7], however, the following procedure is considered the most satisfactory one from the combined point of view of cost, reliability, ease of production and assembly.

A smooth, non-porous and shock resistant vitreous ceramic coating, 0.2 mm thick, (electrical breakdown > 2000 V dc) is applied to the sealing surface of one flange of a pair. Each clamp segment is hard anodized 50 to 60 μm thick to provide a thin, non-conductive layer. Anodization is prevented by masking on one of the 20 degree flanks of the clamp. Since it was found that the silver paint (Du Pont Air Dry Silver 4929) which was to be applied on top of the anodized surface of the other 20 degree flank (in order to provide an equipotential surface of known area) would sometimes short-circuit across the anodized layer through the always present pores in the hard anodize, it was necessary to seal this surface prior to silver painting with a radiation resistant, insulating varnish (Du Pont Pyre M.L. Varnish RK-692). The body of the clamp and the coating of silver separated by the layers of aluminium oxide and sealing varnish form a capacitor. Once a joint is assembled, this capacitor is automatically connected to the two flanges, through the conducting, mating surface on the one side and the silver painted, but insulated mating surface on the other side. Radial distribution of capacitance and low inductance connections are automatically provided.

With a 50 μm thick anodization the following results have been obtained :

$R > 5\ k\Omega$
$C \approx 33'000\ pF$
$|Z|$ = see Fig. 6
$V_B \approx 30\ V$

Too few clamps have been tested to provide significant statistics, but it is interesting to note that the observed spread of C is of the order of ± 10% while the values of R range over one order of magnitude or more. Fig. 6 shows the measured frequency dependence of the impedance of various insulated vacuum joint assemblies. The solid drawn line represents the results for a typical capacitive clamp while the dashed line gives the results of a normal, non-capacitive clamp with an external arrangement of 10 capacitors of 2000 pF each. The dash-dotted line represents the results of a normal, non-capacitive clamp without any additional RF bypassing.

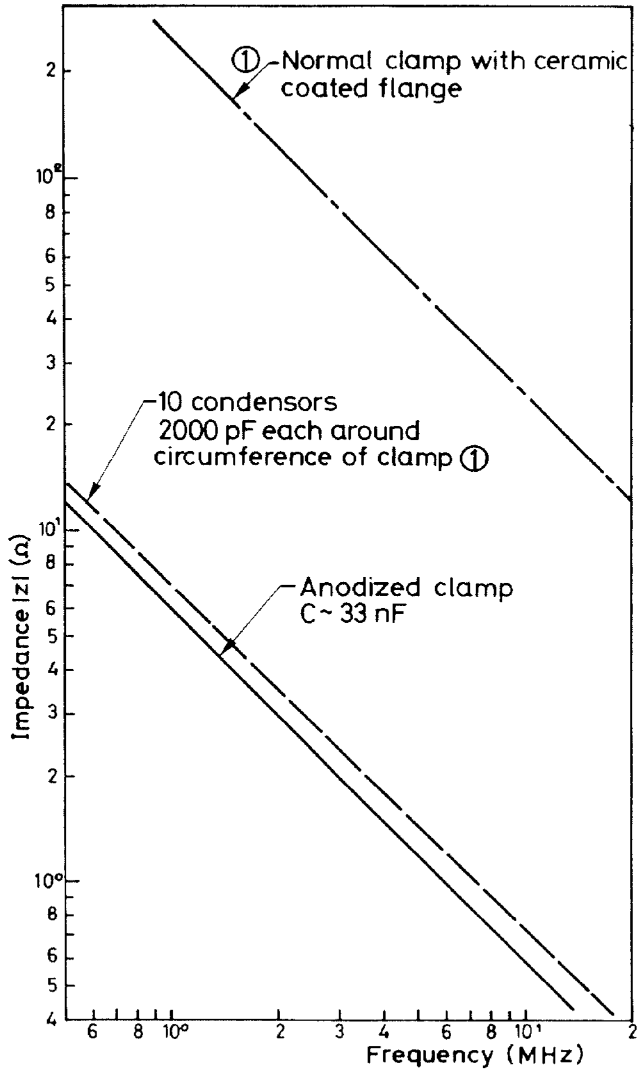


Fig. 6. Measurement of joint impedance.

References

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