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Pressure Measurements in the SPS Vacuum System

B. Angerth, G. Gontero, H. Wahl

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SUMMARY

Since it was first made operational, in 1976, the vacuum system of the 400 GeV proton accelerator (SPS) has been gradually developed to produce lower pressures, in order to meet the requirements of proton-antiproton collider operation which began in 1981.

The vacuum measurement equipment installed originally was designed to cope with pressures down to 10^{-8} mbar. For collider operation this limit had to be lowered to below 10^{-9} mbar.

Studies of the cold cathode gauges and the sputter-ion pumps which are used to monitor the pressures in the SPS vacuum system showed that, by improving the read-out systems, the gauges could be used to measure pressures as low as 10^{-10} mbar and useful pressures estimates, to about the same level, could also be made with the sputter-ion pumps, under certain conditions

When the SPS vacuum system was pumped for periods of several months it reached an average pressure in the mid 10^{-10} mbar range.

1. Introduction

CERN has been operating its 400 GeV Super Proton Synchrotron (SPS) since 1976. Built originally to meet the requirements of a proton accelerator the basic SPS vacuum system produced 3×10^{-7} mbar after 24 hours of pumping.

For proton-antiproton collider operation, which started in 1981 as a complement to the SPS accelerator operation, the ring vacuum system had to be upgraded. The new specification stipulated an average pressure of 3×10^{-9} mbar to be reached within 10 days after a venting to air.

Although the SPS vacuum system is of an "all-metal" construction bakeout cannot be used to rapidly reduce the gas desorption, except in the two proton-antiproton experimental areas which cover less than 5% of the ring circumference.

The vacuum improvement programme mainly consisted in doubling the number of sputter-ion pumps in the normal machine periods and in adding a titanium sublimation pump to every sputter-ion pump all around the ring. In parallel with the improvement of the pumping system the vacuum gauges also had to be upgraded to be able to cope with the new operating pressures. This was achieved by introducing new control units for some of the gauges.

The design pressure in the upgraded system was reached within the specified time. Thereafter the pressure continued to fall slowly and entered well into the 10^{-10} mbar range after some months of pumping⁽¹⁾. This was a very useful feature notably because it allowed a rapid return to the specified average pressure after venting of limited areas of the system. The pressure measurement facilities incorporated in the SPS, in the form of the gauges and also the sputter-ion pump current measuring circuits, were not designed to cope with this situation. This paper which reviews the pressure measurements made in the SPS vacuum system therefore puts particular emphasis on the efforts made, with essentially the existing equipment, to estimate pressures down to about 10^{-10} mbar.

2. Description of the SPS vacuum system

The SPS vacuum system has an overall length of about ten km; seven km for the ring system and nearly 3 km for the beam transfer lines. As the vacuum improvement effort was only required in the ring vacuum system, the subject of the beam transfer lines will not be treated here.

The normal SPS machine periods, housing the main bending and focussing magnets, cover nearly 80% of the ring circumference. The remaining part is occupied by six long straight sections containing the equipment for beam injection, acceleration and extraction, as well as the two proton-antiproton collider experiments. The whole ring system is divided by valves into 61 sectors which vary in length from a few meters in the long straight sections to over 400m in the normal periods. Each sector is fully independent from the point of view of vacuum production.

The vacuum pump layout in the normal periods was mainly determined by the magnet lattice as the pumps had to be fitted in the intermagnet gaps. In the upgraded vacuum system sputter-ion pumps of 30 l/s pumping speed are placed about every 6.5 m along the beam channel and a titanium sublimation pump is inserted in the short pipe which connects the sputter-ion pump to the system. Details of the standard pump layout in the gap between two main magnets are given in Fig. 1.

In the long straight sections which contains the special equipment and its associated important gas loads, 400 l/s sputter-ion pumps in combination with sublimation pumps are installed.

Rough pumping in the SPS is obtained by turbomolecular pumping stations.

Each sector of the vacuum system has one so-called "central pair" vacuum gauge (a Pirani and a cold cathode gauge mounted on a common manifold), placed roughly in the middle of each sector and allowing pressure measurements from atmospheric pressure down to below 10^{-9} mbar. The sectors in the long straight sections are usually equipped with additional gauges. Each roughing station is also equipped with a vacuum gauge pair, using the same gauge heads as those chosen for the beam channel. They are, in this case, connected to control units with a low pressure measuring limit of only 10^{-8} mbar.

All control units for pumps, gauges and valves are installed in six surface buildings equally spaced around the accelerator ring. They are operated by local general purpose computers which are in turn connected to the central control computers in the main control room of the SPS.

3. Equipment for pressure measurements

3.1 Introduction

The two-gauge heads in the vacuum gauge pairs used generally in the SPS are powered by a combined control unit. There are in total 85 such sets which have been adapted to monitor the pressure in the ring beam channel.

In the normal periods of the machine, the distance between adjacent gauge heads can be up to 200 m. The limited number of gauges installed in these parts of the machine, coupled with the conductance limitation of the vacuum system, makes it important to obtain complementary pressure readings via the 30 l/s sputter-ion pumps.

As there is no space available in the normal periods for gauge ports in the beam channel, the gauge heads are mounted behind the sputter-ion and sublimation pumps as shown in Fig. 1. The problem of measuring the pressure in the beam channel itself is overcome by multiplying the pressure readings of the gauges as well as those of the pumps by a correction factor. In early pumping tests in the lab and in the SPS, this factor was found to have a value of about 3.

In the long straight sections vacuum measurements are more straightforward. Each of the special systems in these areas form a short vacuum sector to which has been allocated at least one, and in most cases more, vacuum gauges which directly read the pressures in the beam channel. Therefore the sputter-ion pumps are not needed here for pressure measurements. Furthermore, in the proton-antiproton experimental zones, each sector is also equipped with a hot cathode gauge and a residual gas analyser.

In the normal periods only one residual gas analyser was installed. It monitors the typical gas composition in the unbaked regions of the vacuum system.

All pressures in the SPS are expressed in nitrogen equivalent gauge readings. In a few cases the true total pressure was also given as well as the nitrogen equivalent pressure for multiple Coulomb scattering of the SPS beam particles by the residual gas.

The hot cathode gauges and the residual gas analysers were all checked in the laboratory against calibrated total pressure reference gauges before being used in the SPS vacuum system. Samples from each delivery batch of normal gauge pairs were checked before installation. The control units of these gauges undergo maintenance and adjustment yearly.

3.2 Test system for gauges and residual gas analysers

Figure 2 shows the simple test system used for low pressure gauges and for residual gas analysers. A gas inlet system is placed below the test volume. The complete system is bakeable to 300°C and can produce limit pressures around 10^{-11} mbar. For routine checks the system is used unbaked and can rapidly produce pressures around 10^{-9} mbar.

The reference gauge is a calibrated hot cathode gauge of the extractor type with a measuring limit below 10^{-11} mbar (type IM51C, calibrated by Leybold-Heraeus). As a complement to this gauge, a spinning rotor gauge (type SRG-1, calibrated by MKS Corporation) was added, and is used in the range from 10^{-6} to 10^{-4} mbar.

Residual gas analysers were only subjected to some simple checks in the narrow pressure range from 10^{-7} to 10^{-6} mbar, using pure gases or gas mixtures of known composition.

A second, commercially available, test facility was used for the pressure range from 10^{-6} mbar up to atmospheric pressure (Balzers type PSK-100). This system was equipped with a membrane reference vacuum gauge with a measuring range from 10^{-4} mbar to 1 mbar (type Baratron, calibrated by MKS). Gas injection directly into the test volume or via a differential pumping system allows comparisons between 10^{-6} mbar and 1 mbar. For measurements between 1 mbar and atmospheric pressure a McLeod gauge and a U-tube gauge were added.

3.3 The high/low pressure vacuum gauge pair

The range from atmospheric pressure down to 5×10^{-4} mbar is covered by a Pirani gauge of the Balzers TPR 015 type. The extension of the range of this gauge to atmospheric pressure is very useful, especially during pump-downs in big systems although no precise vacuum measurements are required in this range. An indication that the pressure falls continuously is sufficient to show that the roughing pumps work well and that no "hole" was left open in the system. The gauge heads are not temperature compensated, as the temperature variations in the tunnel amount to only a few °C. Corrections for a cable length of up to 800 m can be made in the control unit.

The low pressure range, covered by a cold cathode gauge of the type Balzers IKR 020, extends from 2×10^{-3} mbar to 2×10^{-10} mbar. The lower end of the range corresponds to a limit which was set in the control unit and which was considered by the manufacturer to correspond to the optimum for the majority of applications. In clean vacuum systems, operating most of the time at low pressures, the gauge could actually be used below 2×10^{-10} mbar. The practical limit for the SPS vacuum system is at present under study.

The gauge electrode system is coaxial with the anode in the centre. The electrode configuration prevents field emission currents from entering the measuring circuit and also facilitates ignition at low pressures, although with some delay. This delay is of little importance as the gauges are switched on at high pressures during the pump down and thereafter operate continuously. The gauge head is connected to the power supply via a low noise triaxial cable. Figure 3 shows the measuring circuit. This circuit ensures full performance of the gauge for cable lengths of up to 800 m. Figure 4 shows a comparison in the lab between the reference gauges and the cold cathode gauge, connected to its control unit by a 5m long cable and by a 510 m long cable.

Automatic switching from the high to the low pressure gauge takes place around 10^{-3} mbar. This feature almost completely avoids damage to the cold cathode gauge head from exposure to very high pressures during operation. Furthermore, above 10^{-5} mbar the discharge current in the gauge head is kept constant and the variation of the voltage over the gauge electrodes as a function of pressure is used for the measurements. This allows, at least in clean systems, operation of the gauge at 10^{-4} mbar for about 200 hours. Nevertheless, we find that prolonged operation at pressures above 10^{-5} mbar should be avoided in order to preserve full performance down to the lowest pressures. The pump downs in the SPS are practically always rapid enough to easily fulfil this requirement.

The control units are connected via their digital outputs to the SPS computers for remote pressure readings in the SPS main control room.

3.4 Hot cathode gauge

The sectors of the SPS vacuum system which house the proton- antiproton collider experiments and where pressures of about 10^{-10} mbar must be rapidly produced through bakeout are, in addition to the normal gauges, equipped with hot filament gauges of the extractor type (IM51C, Leybold- Heraeus). A few such gauges are also used in the unbaked regions of the vacuum system for comparison with the cold cathode gauges.

The measuring limit of the hot filament gauges is below 10^{-11} mbar. They are equipped with Thoria coated Iridium filaments which notably give low power dissipation in the gauges. This was, of course, found to be an advantage in the unbaked regions of the SPS vacuum system. The control units are mounted outside the SPS ring, as in the case for the basic gauges and the cable lengths are limited to 200 m.

3.5 Residual gas analysers

In the SPS, residual gas analysers are used for checks of the gas composition in the proton-antiproton collision zones as well as to permit estimates of the true total pressure and, more important, the equivalent pressure for multiple Coulomb scattering in the unbaked regions of the ring. Five residual gas analysers are permanently installed in the SPS ring during proton-antiproton collider operation. The analysers are of the quadrupole type with a secondary electron multiplier. (Quadrupac 200 Leybold-Heraeus). They have a mass range from 1 to 200 AMU and a quoted partial pressure detection limit of 1×10^{-13} mbar. The control units were installed about 3 m from the analyser heads. The output signals were brought out from the SPS tunnel via 100 m long cables. So far, only a limited number of remote control features have been installed. The instruments are left scanning continuously during operation of the SPS.

Neither the residual gas analysers nor the hot cathode gauges can at present be monitored from the main control room. Analog read-outs are available locally in the equipment buildings.

3.6 Sputter-ion pumps

The sputter-ion pumps in the normal periods are of the diode type with a nominal pumping speed of 30 l/s. They were in particular designed to withstand the expected high gas loads and frequent pump downs in connection with intense proton accelerator operation. The pumps are powered over coaxial H.V. cables up to 800 m long. Figure 5 shows the powering scheme in the normal periods. This scheme was introduced in 1979 when the upgrading of the SPS vacuum system called for a doubling of the pumps in the normal periods. It was then decided not to install additional power supplies. In each group of 12 pumps (6 "old" and 6 "new") there are 4 individually powered pumps and 1 set of 2 pumps as well as 1 set of 6 pumps, each powered by a common supply. The individually powered pumps and the set of 2 pumps assure rapid starting at pressures around 10^{-4} mbar, whereas the sets of 6 pumps come into action at pressures below 10^{-5} mbar in order to boost the low pressure pumping.

The pump power supplies are normally operated from the main control room via the SPS control computers. The remote current readout system has a detection limit which corresponds to about 10^{-8} mbar (Fig. 6).

Below pressures of 10^{-8} mbar, the parasitic currents in sputter-ion pumps or in their power circuits are frequently comparable to the currents drawn by the discharge in the pump, and the currents in the power circuits can therefore hardly be relied on for pressure measurements. In the SPS this limitation is usually aggravated by noise pick-up from the magnet systems when these are operated in a pulsed mode (accelerator operation). Also, prolonged running of the pumps at high pressure naturally favours the development of stray currents in the pumps. The latter type of operation can largely be avoided in the SPS because the sputter-ion pumps are started at quite low pressures. Furthermore, they rather seldom need to operate for a long time in the presence of big gas loads from leaks etc. When the magnets are not pulsing, the 30 l/s sputter-ion pumps in the SPS can therefore in most cases be used in a straightforward way for pressure measurements down to 10^{-9} mbar.

Therefore, measurements with a detection limit of about 10^{-9} mbar can be made directly on the pump power supplies in the equipment buildings as a complement to the remote readings. For this, simple control boxes for manual control are temporarily fitted to the power supplies. It is thus practically excluded that any significant local pressure rise, due to leaks etc. will remain undetected. Major leaks are rapidly detected and rather precisely located with the help of the remote read-out system, as illustrated by Fig. 7.

At pressures below 10^{-9} mbar, leakage and noise in the power circuit in addition to the stray currents in the pumps themselves, make current measurements with simple instruments difficult in all modes of the SPS operation. It was observed, however, that by making many measurements of the pump currents in rapid succession and then calculating the average reading, the effect of the part of the stray signals which fluctuates with time could be considerably reduced. With the help of microprocessor controlled instruments, blocs of about 1000 measurements are made in a few minutes. Each bloc of measurements is stored on a magnetic disc for detailed analysis in the lab. Figure 8 shows a plot of the raw data from such a series of measurements as well as a printout of the resulting average pump current. This method made it possible, under the operating conditions prevailing in the SPS during collider operation and after correction for certain DC stray currents, to estimate pressures down to about 10^{-10} mbar with the help of the sputter-ion pumps.

DC stray currents in a single pump can usually be eliminated by comparison with the currents drawn by adjacent pumps. A leak which causes a significant pressure "bump" in the beam channel will influence more than one pump. A high current drawn by a single pump will therefore as a rule not be taken into account, but steps will be taken to understand the cause of the anomaly and one will try to cure it as soon as access is granted to the SPS, in order to keep the number of pumps with this type of fault, low. In most cases a short exposure to a voltage which is higher than the normal 7 kV applied to the 30 l/s pumps was enough to reduce sharply this type of parasitic currents ("Hi-potting").

Another type of DC stray current was observed when the sputter ion pumps were used for pressure measurements below 10^{-9} mbar. The origin of this current is not fully understood at present. It appears to be produced in the power supply itself and in the basic cabling to the SPS tunnel. The local cabling in the tunnel, used to feed 2 or 6 pumps in parallel, does not contribute to the effect which, for an individually powered pump, typically produces an equivalent pressure reading of 4×10^{-10} mbar. In a set of several power circuits measured the spread in these parasitic readings was quite small. As the local cabling does not add to this effect it follows that in a group of 6 pumps powered in parallel the average parasitic pressure reading per pump amounts to only about 7×10^{-11} mbar.

4. Results.

Table 1 summarizes the gauge readings in the SPS vacuum system in May 1983 for each of the sextants into which the SPS is subdivided. Also indicated in the table are the lengths of the sectors to which a given pressure refers. The pressures for the Long Straight Sections which house the proton-antiproton experiments (LSS4 and LSS5) are those measured by the hot cathode gauges.

From these values an average pressure of 7×10^{-10} mbar for the 7 km long ring vacuum system was calculated. This pressure represents an upper limit as the gauges in 18 of the 24 sectors in the normal periods had reached their low pressure limit of 2×10^{-10} mbar. Subsequent measurements in a few normal period sectors, with a series of modified gauge control units which gave the corresponding gauges a detection limit of 1×10^{-10} mbar, demonstrated that the system pressures actually continue to fall below the normal low pressure limit of 2×10^{-10} mbar.

Additional lab tests in which cold cathode gauges with modified control units were compared with the extractor type reference gauge, confirmed that the cold cathode gauge could now be used down to 1×10^{-10} mbar as shown in Figure 4.

During the first pumping tests, in 1978, in preparation for the upgrading of the SPS vacuum system, a residual gas analyser was installed for a few months in the normal periods. The spectrum obtained at that time showed a water content of the order of 35%. This spectrum was used until quite recently to calculate the true total pressure and the nitrogen equivalent pressure for multiple Coulomb scattering. Early 1983, a residual gas analyser was again installed in the normal periods. The corresponding vacuum sector was as far as possible protected by dry nitrogen during the brief venting needed for the installation of this instrument. Figure 9 shows a residual gas analysis made with this new analyser after two months of pumping. The water content in the spectrum is now much lower than that found earlier. This result was to some extent expected because of the observed very slow saturation rate of the sublimation pumps under limit pressure conditions which suggested that residual gas components other than hydrogen had very low partial pressures.

In order to check the observed value for the partial pressure of water in the ring, a parallel test was made in the lab, using standard SPS chambers, pumps and measuring systems. A limit pressure of 5×10^{-10} mbar was reached in this case, with the same low water content in the residual gas spectrum as was found in the ring.

Using the gas composition of Fig. 9, the average total true pressure in the ring vacuum system could be estimated to be 1.5×10^{-9} mbar, and the nitrogen equivalent pressure for multiple Coulomb scattering 1.4×10^{-10} mbar, on the basis of the average nitrogen equivalent gauge reading of 7.10^{-10} mbar from Table 1.

A series of measurements using the microprocessor controlled measuring system mentioned earlier, were made late in 1982 on the sputter-ion pumps in a long sector in the normal periods as part of a first attempt to measure pressures below 10^{-9} mbar with the sputter-ion pumps.

These measurements covered 70 pumps powered from 33 control units and indicated pressures around 10^{-10} mbar in many of the pumps. More detailed studies of the pump pressures in four sectors in the normal periods were made a few months later on 39 pumps powered by 12 control units. These pumps were located in a region of the SPS which was largely different from that covered by the previous study. In the new study, two of the power supplies powered 2 pumps each, five supplies powered 6 pumps and five supplies were connected to single pumps. The groups of 6 pumps always included the central pair vacuum gauge of the sector concerned. All the gauges had a reading limit of 1×10^{-10} mbar. It was found that the groups of 6 pumps systematically showed the lowest average pressure per pump. This can be explained by the fact that the groups of 6 pumps hardly see high pressure operation as they are started only after the other pumps have brought down the pressure to below 10^{-5} mbar. By a short "Hi-potting" treatment to the individually powered pumps, they could also be made to show the same low current as the pumps powered in groups of six. There still remained a difference between pumps powered in groups of 6 pumps and individually powered pumps, due to the parasitic current in the power circuits as discussed in chapter 3. It is necessary to take this effect into account when using the pumps for pressure measurements in the 10^{-10} mbar range.

It follows that relatively good average pressure estimates can be made with pumps powered in groups of 6 down to about 1×10^{-10} mbar. Individually powered pumps can of course also be used for low pressure measurements. For the lowest pressures, Hi-potting will, however, be required from time to time and the parasitic DC current in the power circuit has to be measured separately for each pump circuit. In practice only the sets of 6 pumps need to be monitored to check that the pressure indicated by the central pair gauge is representative for a whole sector.

Table 2 summarizes the pressures recently sampled in seven long sectors in the normal periods. These pressures were measured by gauges with a fixed pressure limit of 1×10^{-10} mbar. In 4 of these sectors, pressures were in addition measured by the sputter-ion pumps. In one case the comparison was possible with a hot cathode gauge mounted directly in the beam channel.

These measurements gave an average pressure in the beam channel of 3.5×10^{-10} mbar. There is good reason to believe that this value should be used in Table 1 for all the 18 sectors where the normal gauge reading limit of 2×10^{-10} mbar had been reached. This would bring the pressure in the 7 km long ring vacuum system from 7×10^{-10} mbar to about 5×10^{-10} mbar nitrogen equivalent gauge reading. Corresponding reductions in the true total pressure and in the nitrogen equivalent pressure for multiple Coulomb scattering should also be expected.

CONCLUSION

The SPS vacuum system produced pressures well below the design pressure after some months of pumping. This feature not only reduced the effect of beam gas interaction but also offered a very rapid return to the specified average pressure after venting of limited parts of the system.

Investigations of the cold cathode gauges installed to monitor the total pressure in the ring showed that these could be relied on at least down to 10^{-10} mbar under the operating conditions prevailing in the SPS. Furthermore, the 30 l/s sputter-ion pumps which are used in most of the ring and which constitute a necessary complement to the gauges for the detection of any local pressure variations, could be used for pressure estimates to nearly 10^{-10} mbar.

Reference:

- 1) B. Angerth, R.B. Flockhart, G. Kouba, H. Wahl
IEEC Trans. Nuclear Science, Vol. NS-30, No 4, p. 2790.

Fig.1

TEST SYSTEM FOR GAUGES AND GAS ANALYSERS

Fig. 2 .

MEASURING CIRCUIT OF COLD CATHODE GAUGE

Fig. 3

GAUGE COMPARISONS

POWERING SCHEME FOR SPUTTER-ION PUMPS

- SET OF 6 PUMPS
- SET OF 2 PUMPS
- SINGLE PUMPS

Fig. 5

Remote reading of sputter ion pumps
at limit pressure

SPS VACUUM : 20101 - TS 2 - TO 21301

.16-09-83

Fig. 6

Remote reading of sputter ion pumps in presence of leaks

SPS VACUUM\TS3+

1977-06-10-21:07:56

Fig. 7

PMP POS.

Fig. 8

Average of all 800 measurements $2.678E-07$

Standard deviation $3.488E-07$

Average of the 658 measurements within ± 1 S.D. $2.629E-07$

TABLE 1
PRESSURE IN THE BEAM CHANNEL
 (mbar $\times 10^{10}$)

Sextant N°	Normal Periods		Long Straight sections	Normal Periods	
	384 m	~104 m	~114 m	~102 m	448 m
1	< 6	9	20	6	6
2	< 6	< 6	7	6	< 6
3	< 6	9	20	20	< 6
4	9	< 6	2	< 6	< 6
5	< 6	< 6	1	< 6	< 6
6	< 6	< 6	7	< 6	< 6

TABLE 2

Sector N°	Pump or gauge N°	Gauge reading (mbar x 10 ¹⁰)	Pump pressure (mbar x 10 ¹⁰)	N° of pumps	Corrected pressure for beam channel position (mbar x 10 ¹⁰)
16	20060	1.9			5.7
21	20620		1	6	3
	20660	1.4			4.2
	20680		1 *	1	3
22	21340		1	6	3
	21540	1			3
26	22820		1	6	3
	22920		1	1	3
	22940	1			3
	22960		1 *	1	3
31	30502	3.7 **			3.7
36	32560		1.5	2	4.5
	32580		1	6	3
	32601		1.5	1	4.5
	32801		2	2	6
	32820		1	6	3
	32840		2	1	6
52	51602	4.5 **			4.5
average in beam channel					3.5

* after "Hi-potting"

** gauge mounted directly in beam channel position