BASIC DESIGN OF THE VACUUM SYSTEM FOR

400 GEV LSR WITH NORMAL MAGNETS

by

D. Blechschmidt

Geneva, 4th July 1975
1. INTRODUCTION

A recent report describes the skeleton design of the LSR with conventional magnets\textsuperscript{1)}. The present work is intended to provide more detailed information about the vacuum aspects that were briefly outlined therein.

It is obviously sufficient to solve the vacuum problem for the normal lattice, where the magnet filling factor is higher than in insertion regions. This report is therefore only concerned with the normal lattice using geometric parameters that were fixed during the 1974 CERN Autumn Study\textsuperscript{2)}. It is believed that the solution for the vacuum problem given in this paper may be straightforwardly applied to the rest of the machine.

2. BASIC DESIGN AIMS

Beam lifetime and stability depend very much on the average residual pressure in the beam chamber, but also on the surface condition of the chamber walls exposed to the proton beam. In order to obtain performance conditions that are at least as good as those of the ISR, the average pressure in the LSR must be less than $10^{-11}$ torr. Electron clearing should be even more efficient since magnets are longer in the LSR and also because the residual gas ionisation cross-section for 400 GeV/c protons is higher than at ISR energies.

A more stringent requirement, however, is to achieve a critical current that is safely above the design current of 7 A but at minimum magnet gap aperture. The proposed gap size in bending magnets\textsuperscript{3)} is $120 \times 78$ mm$^2$. It leaves just enough space for an elliptical beam chamber of $90 \times 60$ mm inner aperture besides the elements required for bakeout and cooling. The size of this aperture, together with the inaccessibility of the beam chamber within the long bending magnets practically excludes integrated pumping. Lumped pumping stations must therefore be installed at the shortest possible intervals.

Beam instabilities arising from the coupling impedance of bellows, tapers or similar cross-section variations of the beam chamber seriously impair the performance of a machine of LSR dimensions\textsuperscript{4)}. The
beam chamber must therefore be electrically smooth, with "underpants" 5) wherever cross-section changes are inevitable like in pumping stations. Such "underpants" are transparent vacuum-wise but do not impede the image charge current.

Furthermore, it is obvious that pumping stations must be as small as possible due to their large number. In order to minimise the length of short straight sections, a length of 400 mm has been allocated for the vacuum installation 2).

Finally, a maximum degree of periodicity has been aimed for to keep the design as simple as possible and the number of different components to be installed low.

3. PRESUPPOSITIONS AND DESIGN CONSTANTS

This chapter deals with some basic design assumptions which had to be made before beginning with the general layout.

3.1 Specific Thermal Outgassing

The LSR vacuum system will be made of special stainless steel (316 LN) as is used for the ISR. This appears to be the best at the present state of technology (see Chapter 5.1). Pretreatment in a vacuum furnace at 800 - 900°C and at a pressure of less than 10^{-5} torr results in an outgassing rate of about 2 \times 10^{-13} torr l/scm² 6). Lower rates may be obtained with smaller hydrogen partial pressures in the vacuum furnace 7).

The prevailing residual gas component in the ISR at static pressure is hydrogen, followed by gas of mass 28 (mainly CO, some N₂), 16 (mainly CH₄) and 44 (CO₂) 8). The composition of residual gas in a titanium system does not differ very much 6,9).

The specific thermal degassing of the walls of a very clean stainless steel system which is pumped for time t (s) but not yet
baked is given approximately by\textsuperscript{10}:

\[ Q \approx 2 \times 10^{-5}/t \text{ torr} \cdot \text{cm}^2 \]  

(1)

3.2 Ionisation Cross-section

The residual gas ionisation cross-section \( \sigma \) for protons at ISR energies has been calculated earlier\textsuperscript{11} using the Bethe formula and the constants measured by F. Rieke and W.P. Prepejchal\textsuperscript{12}. The results were later confirmed by measurements of clearing current and average pressure with coasting beams in the ISR\textsuperscript{13}. Since no measurements have so far been published for 400 GeV/c protons, the Bethe formula has been used again to obtain \( \sigma \) at LSR energies. Results are compiled in Table I. The ionisation cross-section in the LSR is about 1.3 times larger than for ISR energies.

3.3 Titanium Sublimation Pumping Speed

The pumping speed of a sublimation pump at very low pressures (p < \( 10^{-10} \) torr) is obtained from

\[ S = \frac{1}{4} \left( \frac{\text{SR}}{\pi M} \right)^{\frac{3}{2}} \left( \frac{1}{A_a} + \frac{1}{\alpha A_s} \right)^{-1} \]  

(2)

where the pump entrance aperture is denoted by \( A_a \) and the getter surface area by \( A_s \). \( M \) denotes the molecular weight of the gas to be pumped and \( R \) is the universal gas constant. Sticking probabilities \( \alpha \) for different residual gas molecules on Ti at 300\textdegree K are compiled in Table II, the most recent ones are those for \( \text{H}_2, \text{N}_2, \text{CO} \) and \( \text{O}_2 \). Values for \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) are less certain\textsuperscript{14}. Methane and rare gases are practically not pumped at all.

3.4 Ion Induced Molecular Desorption

In order to estimate the critical current in the LSR, the ion induced molecular desorption must be known. It can either be obtained from experience gained in the field, i.e. from ISR operation, or found in the laboratory. The first method yields \( \eta \approx 3.3 \) molecules per ion at the worst place,
arcs where the theory predicts $\eta I_c = 100 \text{ A}^{17}\). Values found under laboratory conditions are lower, typically between $\eta = 2$ to 3 molecules/ion$^{18}$) for stainless steel specimens and titanium specimens without glow discharge pretreatment. $H_2$ and CO constitute together, in approximately equal parts, more than 90% of all that is desorbed by ions of mass 28 ($N_2$).

These $\eta$-values must, however, be considered with some reservation because they depend on many parameters such as the ion energy (i.e. beam potential) or angle of incidence (electric field), and may not therefore be straightforwardly adapted to the LSR. Also, values found in the field should be taken into account rather than those obtained under clean conditions.

Glow discharge cleaning yields much smaller or even negative $\eta$-values$^{18}$) Increasing the bakeout temperature has a similar effect at high beam currents$^{19}$).

It is, however, the place with the highest $\eta$-value - even if only over a relatively short distance - which determines at what beam current the vacuum becomes unstable. It appears therefore reasonable to assume $\eta = 3$ molecules/ion as the design figure for a vacuum system which is so many kilometres long. This value, however, which still appears rather high, compensates for all other design assumptions which might turn out to be too optimistic in practice.

Nevertheless, all beam chambers should be glow-discharge cleaned with a dose of $10^{18}$ ions/cm$^2$ at least prior to installation and the bakeout temperature even higher than 350°C.

4. APERTURE CONSIDERATIONS

The minimum aperture is determined by the critical current $I_c$, the distance of vacuum stations $d$, and their pumping speed $S$, and the linear conductance $c$ of the beam pipe. A short theoretical evaluation (see Appendix) yields:

$$I_c \approx \frac{e \pi^2 c}{\eta \sigma (d + 4 \frac{c}{S})^2}$$

(3)
where e is the elementary charge. The relative error is less than 0.5 per cent for \( S > 12 \) c/d, which is already necessary from static pressure considerations\(^{16,20}\).

### 4.1 Application of Pumping Speed

The term \( c/S \) may be interpreted as an additional distance which separates the pumping stations. Increasing the pumping speed \( S \) yields a higher critical current if this distance is comparable with the physical separation of the stations. Beyond a certain value of the pumping speed \( S >> 12 \) c/d Equ. (3) becomes:

\[
I_c \approx 1.6 \times 10^{-17} \frac{c}{\eta \odot d^2} \text{ A}
\] (4)

where \( I_c \) is given in A, \( c \) in \( \text{km/s} \), \( \sigma \) in \( \text{cm}^2 \) and \( d \) in m. This is the situation for which the design should aim.

However, most of the pumping speed is provided by Ti-sublimation pumps which are almost entirely aperture limited. Since this aperture is related to the beam pipe cross-section for mechanical and geometrical reasons the question therefore arises as to whether the condition for Equ. (4) can in fact be realised for the range of beam pipe apertures in question.

We obtain from Equ. (2) for \( A_s \to \infty \) (purely aperture limited pump)

\[
S_\infty = \frac{1}{4} \left( \frac{8RT}{\pi M} \right)^{\frac{1}{3}} \pi b^2
\] (5)

where \( b \) denotes the half major axis of an (assumed) elliptical beam pipe. The beam pipe conductance per unit length is given by\(^{21}\):

\[
c = \frac{2\pi}{3} \left( \frac{8RT}{\pi M} \right)^{\frac{1}{3}} \sqrt{\frac{\pi}{a^2 b^2}} \frac{\sqrt{a^2 b^2}}{(a^2 + b^2)^{\frac{1}{2}}}
\] (6)

where \( a \) is the minor axis of the beam pipe. Hence from Equ. (5) and (6)

\[
\frac{c}{S_\infty} = \frac{8\sqrt{2}}{3} a \left\{ 1 + \left( \frac{b}{a} \right)^2 \right\}^{-\frac{1}{2}} < \frac{8}{3} a \ll d
\] (7)
In the LSR a is about two orders of magnitude smaller than the distance d between pumps. Hence, with a purely aperture limited pumping $S = S_\infty$, the approximation given in Eqn. (4) always applies. This can be achieved from the design point of view by making the pumping surface big enough ($A_s > A/a$) e.g., increasing $A_s$ artificially by designing an elliptical pump body.

### 4.2 Beam pipe conductance and stability limit

With Eqn. (6) and $b = \varepsilon a$, Eqn. (4) may be rewritten:

$$I_c \approx \frac{8e \pi \frac{5}{2} \sqrt{RT}}{3} \left[ \frac{1}{\sigma \eta \sqrt{M}} \sqrt{1 + \varepsilon^2} \right] \frac{a^3}{d^2} \varepsilon^2$$

(8)

The problem is now to fix the parameters such that $I_c > 10 \text{ A}$ even for the residual gas with the highest product $\sigma \eta \sqrt{M}$, where $\eta_p$ is the "partial" $\eta$, i.e. the fraction of residual gas ions released per any bombarding ion. These values are compiled in Table III using $\eta_p$ measured in the laboratory. It is obvious from this table that CO is far more dangerous than any other residual gas. Taking into account that even hydrogen may desorb CO we have $\sigma \eta \sqrt{M} = 2.4 \times 10^{-17} \text{ cm}^2$, with $\eta = 3$.

Hence with $a = 0.03 \text{ m}$, which is the maximum minor half axis of the beam pipe for a magnet gap height of 78 mm, we have

$$I_c \approx 135 \varepsilon^2 \frac{a^3}{\sqrt{1 + \varepsilon^2}} \frac{1}{d^2} \text{ A}$$

(9)

where $d$ is given in metres. Using an elliptical beam pipe of maximum aperture that just fits into the magnet gap we get $\varepsilon < 1.5$. For $I_c > 10 \text{ A}$, Eqn. (9) is satisfied with $d < 4.10 \text{ m}$. The magnet block length is 7.2 m; it must therefore be split in the middle and a sublimation pump be installed in the gap as was already proposed earlier$^{2,16}$. For a circular pipe $\varepsilon = 1$, $a = 3\text{cm}$ and $d = 4\text{m}$ the critical current becomes $I_C \approx 6\text{A}$, which is not acceptable.

Gas like Ar and CH$_4$ is not pumped by the Ti sublimation pumps; however, it is believed to be harmless with regard to pressure instabilities due to its even smaller sticking probability on stainless steel; sputter ion pumps may therefore be installed at bigger intervals$^{16,22}$. 
A cross-section view of the beam chamber in the gap of a bending magnet is shown in Figure 1. The bakeout equipment will be discussed later.

4.3 Beam Pipe Aperture in Quadrupoles

In order to retain the cross-section of 60 × 90 mm within the normal lattice the distance between opposite pole faces must be at least 93 mm, see Figure 2. If this is not feasible the consequences of a smaller aperture may be estimated from Eqn. (9) – assuming η = 3 ions/molecule. As has also been pointed out in previous sections, a further increase of the critical current by increased pumping speed is almost impossible. Since d > 4 m for quadrupoles too, η has to be less than 1.8 mol./ion to obtain a critical current of 10 A in a beam pipe of circular cross-section and 60 mm diameter.

However, even if η < 1.8 could be achieved by special provisions (such as the use of titanium or in situ glow discharge) some 450 transitions would be required to taper elliptical and circular beam chamber sections. The taper angle would be – for geometrical reasons – about 100 mrad. This design is considered not only to be hazardous from the aspect of beam stability since it turns the beam chamber into a gigantic bellows, but also increases the construction cost considerably.

5. LAYOUT OF THE VACUUM SYSTEM

This chapter covers the technological aspects of the vacuum system design. It is based on the previous considerations; furthermore, much emphasis has been put on aiming for a system of the highest possible periodicity and simplicity.

5.1 Beam Chamber Material

Aluminium, titanium and stainless steel have been considered as material for the chamber.

Aluminium is commonly used in electron accelerators and storage rings where pressures in the 10⁻⁹ torr range are either acceptable or inevitable due to synchrotron radiation. In the LSR, however, the vacuum system must be baked at temperatures which are beyond the tolerable limit
for aluminium, in order to achieve the required average pressure. Furthermore, its use reduces the vacuum aperture since an aluminium beam chamber must have much thicker walls than is necessary with stainless steel. The technological problems arising from the use of this material in the LSR rule out its possible advantages.

Titanium has a lower outgassing rate \(^{6,9}\) than stainless steel and yields \(n\)-values that are slightly lower after the same cleaning procedure\(^{18}\). The cost of a titanium vacuum system, however, will be approximately 30 - 40 per cent higher and the present state of technological experience is not yet sufficient to base the design of the LSR on this material\(^{16}\). It therefore appears more realistic to improve the pretreatment of stainless steel (lower \(H_2\) partial pressure in the vacuum furnace\(^{6,7}\), to reduce the carbon contamination on the surface, and to bake at a higher temperature\(^{19}\)).

A wall thickness of 2 mm is sufficient to prevent deformation of the chamber during bakeout up to far beyond 400°C.

5.2 Layout of UHV pumps

The layout of UHV pumping stations is chosen to provide at least 90 per cent of the critical current that can be achieved with infinite pumping speed \(S \to \infty\) see Equ. (3). This condition is satisfied with \(S > 74.4 \text{ c/d or } c/S < 0.11 \text{ m as can be easily verified from Equ. (3). The use of conductance limited sublimation pumps fulfils this requirement automatically for } a = 3 \text{ cm, see Equ. (7).}

For gases that are harmless with respect to beam induced pressure instability, however, only \(S > 12 \text{ c/d is necessary to obtain a low static base pressure most economically}^{16,20}\). These gas components are more volatile (Ar, CH\(_4\)) or less abundant (H\(_2\)O, CO\(_2\)) in a well baked system, but poorly removed by sublimation pumps. Because sputter ion pumps are expensive and bulky, they will therefore only be installed together with every second sublimation pump. The nominal pumping speed of sputter ion pumps (see Eqs. (5) and (6)), has to be at least twice the effective pumping speed needed for argon; hence \(S > 24 \text{ c/d for } M = 40, \text{i.e.} S_{\text{nom}} > 119 \text{ l/s.}

A schematic general layout of pumping stations within half a normal cell is sketched in Figure 3.
5.2.1 Main Pumping Stations

The main stations are installed at 8 metre intervals, i.e. there are four per half normal period on either side of the bending magnets. They comprise a 120 l/s sputter ion pump and a sublimation pump of 1700 l/s and 900 l/s for H₂ and CO respectively. Figure 4 is a cutaway drawing of a main station. The most important parameters of the titanium sublimation pumps are compiled in Table IV.

The sputter ion pumps are not only needed to remove gas that is not pumped by the sublimation pumps, but also for the pumpdown period after bakeout and during the conditioning of the sublimation pumps.

Two bellows (hydro-formed) compensate for the thermal expansion of the vacuum chamber during bakeout since the beam pipe has its fixed position at the centre of bending magnets and in the long straight section at the quadrupole end.

Sliding contacts, similar to RF plugs, provide the electrical connection between the beam pipe and the "underpants". They are made from titanium sheet metal and are pressed against the silver-plated ends of the beam chamber by a spiral spring. Another spring clip must be removed if the pumping station has to be exchanged, see Figure 4. A flange pair (Ø 200 mm) provides interchangeability of the main stations.

An electrostatic clearing electrode can be used simultaneously to measure the residual gas pressure with stacked beam. An ionisation pressure gauge provides this information at zero beam current. The aperture of the gauge pocket is closed by a grid to prevent extraction of electrons by the positive beam potential.

Wherever possible the use of flanges has been avoided for reasons of economy and reliability. Apart from the flanges needed to remove the pumping station as a whole, the weld-and-cut technique, as studied earlier ²⁴) and now used in some of the ISR bicones, has been adopted.
5.2.3 Auxiliary Pumping Stations

The additional sublimation pumps are installed midway between all main pumping stations, see Figure 3. For this purpose the bending magnet blocks are split by a slot of 200 mm in the centre. Four auxiliary stations are installed within half a normal lattice period. Their pumping speed is 1600 l/s for H₂ and 900 l/s for CO, see Table IV. A clearing electrode is mounted opposite the pump aperture. A cutaway drawing of these pumps is shown in Figure 5.

5.3 Electron Clearing

Electrostatic clearing electrodes are installed at 4 metre intervals. They are 116 mm long and 70 mm wide. Their shape is that of the beam pipe envelope of 60 × 90 mm elliptical cross-section.

Electric potential measurements on graphite paper yield an effective clearing length of at least 90 mm for a beam potential of over 1.4 kV and a clearing electrode potential of 6 kV. This is considered to be sufficient since the beam potential is less than 1.4 kV at 7 A²5).

Although the electrodes will be loaded by a shunt impedance externally, as in the ISR, to reduce coupling with higher RF modes, it might be necessary to do the same at the vacuum side. This problem has not yet been taken care of in the present design.

5.4 Sectorisation

The vacuum system of the ISR is divided into 24 sectors of an average length of approximately 70 m. The LSR will most likely be baked less frequently than the ISR - leaving aside insertion regions. Therefore, a LSR vacuum sector will extend over two normal lattice periods, which is about 124 m.
The sector valves are situated in the long straight sections next to the quadrupoles and need a space allocation of 200 mm in an axial direction.

5.5 Mechanical Pumping Stations

Four mechanical pumping stations are installed in each sector. They consist of a 100 – 150 l/s turbomolecular pump backed by a two-stage backing pump of about 20 m³/hour and a basic pressure of $5 \times 10^{-4}$ torr approximately. The layout of these stations is mainly determined by the requirement of short pump-down time, a low average pressure during bakeout and the necessity of a starting pressure of below $10^{-6}$ torr for all sputter ion pumps just at the end of the bakeout period.

The mechanical pumping stations are installed at the centre of every half normal cell, between the second and third bending magnet. They are connected to the UHV system by a short pipe ($\phi$ 60 mm) running into the neck of the sputter ion pump. The length of this pipe should be less than 50 cm. A roughing valve, which is bakeable and could be of a similar type as is used in the ISR, separates the station from the UHV system after bakeout.

5.6 Bakeout

The LSR vacuum system may be baked up to 400°C. Heater jackets are used wherever the vacuum system is freely accessible, and air cooling. Within the magnet gaps, (see Figure 1), however, heat is provided by two heater tapes (for reasons of redundancy) which are wound spirally on the beam chamber. The pipe with the tapes is wrapped in 5 mm special thermal insulation material ($k < 10^{-4}$ W/K°C) and clasped by two halves of a rectangular cooling box. This box is made from extruded aluminium and fits into the magnet gap of 78 × 120 mm². Cooling water streams along the four channels in the corners of this box.

The heat loss across this insulation is less than 300 W/m with the chamber at 400°C. A total flow rate of 0.6 l/sec per magnet keeps the temperature rise of the water below 1°C. Two independent water circuits protect the magnet coils from damage during bakeout.
6. **EXPECTED PERFORMANCE**

6.1 **Pumpdown**

Approximately ten minutes after the start of pumpdown, the backing pumps will have reached their base pressure and the turbomolecular pumps will be at full speed. About one hour later, and after leak detection, the bakeout can be initiated, since the pressure is below $10^{-5}$ torr. The bakeout time will be about 18 hours. Before the system is allowed to cool below 300°C, the sputter ion pumps will be started and the roughing valves closed. Some six hours later the system will be near ambient temperature. During the cooling down of the system the sublimation pumps have to be conditioned.

6.2 **Static Pressure Profile**

The average static true pressure in the LSR will be less than $8 \times 10^{-12}$ torr, taking into account a base pressure of pumping stations which is typically about $3 \times 10^{-12}$ torr. The maximum pressure between adjacent pump stations will be just about the design pressure of $1 \times 10^{-11}$ torr. Hydrogen is expected to be the major residual gas component (over 85 per cent).

With a circular beam chamber of 60 mm diameter in the quadrupoles but an elliptical cross-section elsewhere, the average static pressure will be $8 \times 10^{-12}$ torr and have a maximum at $1.2 \times 10^{-11}$ torr at the centre of the quadrupoles.

The static pressure profile is drawn in Figure 3.

6.3 **Stability Limit and Residual Gas Composition Near Vacuum Breakdown**

CO and H$_2$ are the most predominant kind of molecules that are desorbed by ions bombarding the walls of the vacuum chamber but CO is the most harmful one, see Table III. Whereas the presence of only hydrogen in the system would permit stacking a critical current of about 172 A, CO will cause a vacuum breakdown below $I_C = 9.8$ A. These figures are the
exact solution (for effective pumping speeds as quoted in Table IV and \( \eta = 3 \) molecules/ion) of the instability condition\(^{17} \) for different pumping speeds \( S_r \) (right) and \( S_L \) (left):

\[
\frac{S_r S_L - c^2 \omega_c^2}{c \omega_c (S_r + S_L)} \tan(\omega_c d) = 1,
\]

(10)

where \( \omega_c^2 = I_c \sigma \eta / e c \). Assuming a (rather high) thermal desorption rate of about \( 10^{-14} \) torr.l/s cm\(^2\) for CO, the average pressure at 8 A will still be \( 1 \times 10^{-11} \) torr with a maximum of \( 1.7 \times 10^{-11} \) torr between the pumps. Still over 50 per cent of the residual gas between the pumping stations will be hydrogen at 8 A beam current.

With a circular beam pipe aperture of 60 mm diameter, the average pressure at 5 A will be about \( 1.1 \times 10^{-11} \) torr with a maximum of \( 2.7 \times 10^{-11} \) torr at the quadrupole centre. The exact critical current is 5.7 A for \( \eta = 3 \).

These results have been obtained with a special computer programme\(^{26} \) that calculates pressure distributions with stacked beams based on a theoretical study in an earlier report\(^{17} \).
7. **APPENDIX**

The gas density distribution \( n(x) \) along the beam pipe is obtained from\(^{27}\)

\[
a + bn'(x) + cn''(x) = 0 \tag{A1}
\]

for the equilibrium case \( \partial n(x,t)/\partial t = 0 \). The apostrophe denotes differentiation with respect to \( x \).

Substituting

\[
K(x) \equiv n(x) + a/b \tag{A2}
\]

the differential equation is solved for

\[
K(x) = z \exp(i \omega x) , \tag{A3}
\]

where \( z \) is a complex number, and where

\[
\omega^2 = b/c \tag{A4}
\]

There is a pump of pumping speed \( \frac{1}{2}S \) at \( x = 0 \):

\[
cn'(o) = \frac{1}{2} Sn(o) , \tag{A5}
\]

and since there will be another pump with the same pumping speed at a distance \( d \)

\[
n'(d/2) = 0 \tag{A6}
\]

for symmetry reasons. Hence with the boundary conditions (A5) and (A6) \( z \) may be determined from Equ. (A3):

\[
(S - 2i \omega c)z = aS/b \\
i \exp(i \omega d/2)z = 0 . \tag{A7}
\]
The vacuum becomes unstable as n \to \infty, which is the case if \(|z| \to \infty\) for finite a/b (i.e. for b > 0 and finite gas density independent desorption or leak rate), with

\[
D = \begin{pmatrix} S & -2 \omega c \\ -\sin(\omega d/2) & \cos(\omega d/2) \end{pmatrix} \to 0,
\]

\(|z|\) goes to infinity according to Kramer's rule. This is satisfied for

\[
p \sin p = q \cos p
\]

where

\[
p = \omega_c d/2 \quad \text{ and } \quad q = S d/4 c \quad (A8)
\]

As we will see later, \(p \approx \pi/2\) for most practical cases; therefore with \(p = \frac{\pi}{2} - \varepsilon\) (where \(\varepsilon\) is small), we get from Eqn. (A8)

\[
\left(\frac{\pi}{2} - \varepsilon\right) \sin \left(\frac{\pi}{2} - \varepsilon\right) = q \cos \left(\frac{\pi}{2} - \varepsilon\right)
\]

or

\[
\left(\frac{\pi}{2} - \varepsilon\right) \cos \varepsilon = q \sin \varepsilon
\]

In a first approximation \(\cos \varepsilon \approx 1\) and \(\sin \varepsilon \approx \varepsilon\), hence from Eqn. (A9)

\[
p \approx \frac{\pi}{2} \cdot \frac{q}{q+1} \quad (A10)
\]

A second order approximation is obtained by substituting \(p\) in Eqn. (A8):

\[
\frac{\pi}{2} \cdot \frac{q}{q+1} \cdot \sin p = q \cos p,
\]

hence

\[
p \approx \arctan \left[ \frac{2(1+q)}{\pi} \right] \quad (A12)
\]

With \(b_c = \frac{\sigma n I}{e}\) and \(b_c = \omega_c^2 c\), where \(e, n,\) and \(\sigma\) are the elementary charge,
the ion molecule desorption probability and ionisation cross-section, we find from Equ. (A10)

\[ I_c \approx \frac{\pi^2 ec}{\eta \sigma \left( d + \frac{4 \xi}{S} \right)^2} \]  

(A13)

and

\[ I_c \approx \frac{4ec}{\eta \sigma d^2} \left\{ \arctan \left[ \frac{1 + \frac{Sd}{4C}}{\pi/2} \right] \right\}^2 \]  

(A14)

An expression similar to Equ. (A14) was already found earlier\(^{28}\).

The error made by approximation may be easily determined. Since in a tubular vacuum system with lumped pumping \( S \gg 12 \) c/d in order to achieve a low basic pressure most economically\(^{16,20}\), there will always be \( q > 3 \), in particular when the pumping speed has to be even much higher to avoid pressure instability. Hence from Equ. (A8) \( p \gg 1.19 \), and we get

\[ \left| \frac{I_c(A13) - I_c(A8)}{I_c(A8)} \right| \leq 8 \times 10^{-3} \]  

(A15)

for the first approximation, and

\[ \left| \frac{I_c(A14) - I_c(A8)}{I_c(A8)} \right| \leq 7 \times 10^{-3} \]  

(A16)

for the second.
8. ACKNOWLEDGEMENTS

The author would like to thank his colleagues from the ISR Vacuum Group for their great support and excellent collaboration. The results of helpful discussions are incorporated in this paper, in particular from R. Calder, E. Fischer, O. Gröbner, F. Le Normand, A. Mathewson, B. Monnier, H. Schuhbäck and W. Unterlerchner.

Valuable discussions with H.G. Hereward, K. Johnsen, B.W. Montague, W. Schnell and B. Zotter have helped to solve many problems beyond the field of vacuum physics.

C. Grünhagel has taken care of most of the technical minutiae and he also prepared the drawings. The electric potential measurements for clearing electrodes have been carried out by J-C. Billy.
REFERENCES

1. Report on 400 GeV LSR with normal magnets, to be published.


3. L. Resegotti, private communication as amendment to reference 2.


6. F. Le Normand, private communication.


8. C. Benvenuti and M. Hauer, private communication.


11. K. Hübner, private communication.


13. O. Gröbner, private communication.


18. A. Mathewson, private communication.


20. H. Winick, BNL 1973 Summer Study Report, p. 81


22. E. Fischer, private communication.


* All technical notes, performance reports, memoranda, etc. have been referred to as a private communication.
### TABLE I

Residual gas ionisation cross-section $\sigma$
for 400 GeV/c and 26 GeV/c protons in $10^{-18}$ cm$^2$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$(400 GeV)</th>
<th>$\sigma$(26 GeV)</th>
<th>$\sigma$(400)/$\sigma$(26)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>0.304</td>
<td>0.236</td>
<td>1.29</td>
</tr>
<tr>
<td>He</td>
<td>0.310</td>
<td>0.231</td>
<td>1.34</td>
</tr>
<tr>
<td>Ne</td>
<td>0.825</td>
<td>0.602</td>
<td>1.37</td>
</tr>
<tr>
<td>CO</td>
<td>1.495</td>
<td>1.150</td>
<td>1.30</td>
</tr>
<tr>
<td>N$_2$</td>
<td>1.507</td>
<td>1.116</td>
<td>1.35</td>
</tr>
<tr>
<td>Ar</td>
<td>1.617</td>
<td>1.244</td>
<td>1.30</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1.788</td>
<td>1.365</td>
<td>1.31</td>
</tr>
<tr>
<td>Kr</td>
<td>2.389</td>
<td>1.731</td>
<td>1.38</td>
</tr>
<tr>
<td>Xe</td>
<td>3.135</td>
<td>2.340</td>
<td>1.34</td>
</tr>
</tbody>
</table>

### TABLE II

Sticking probability for different
residual gas molecules on Ti at 300$^\circ$K$^{14,15}$

<table>
<thead>
<tr>
<th></th>
<th>H$_2$</th>
<th>N$_2$</th>
<th>CO</th>
<th>O$_2$</th>
<th>CO$_2$</th>
<th>H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.06</td>
<td>0.3</td>
<td>0.7</td>
<td>0.8</td>
<td>$\approx 0.8$</td>
<td>$\approx 0.2$</td>
</tr>
</tbody>
</table>
TABLE III

Product of $\sigma_n \sqrt{M}$ for different residual gas components with ionisation cross-section $\sigma$ (see Table I), partial $n_p$
(Ref. 18) and with molecular weight $M$

<table>
<thead>
<tr>
<th></th>
<th>$H_2$</th>
<th>$CH_4$</th>
<th>$H_2O, Ar$</th>
<th>CO</th>
<th>$CO_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 LN</td>
<td>3.7</td>
<td>-4.9</td>
<td>0</td>
<td>21.2</td>
<td>-37.1</td>
</tr>
<tr>
<td>Ti</td>
<td>2.5</td>
<td>-4.9</td>
<td>0</td>
<td>10.0</td>
<td>-41.1</td>
</tr>
</tbody>
</table>

Values are given in $10^{-18}$ cm$^2$
**TABLE IV**

**Parameters of Ti sublimation pumps**

<table>
<thead>
<tr>
<th></th>
<th>Main Station</th>
<th>Aux. Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump entrance surface area (cm²) $A_a$</td>
<td>110</td>
<td>95</td>
</tr>
<tr>
<td>Underpants &quot;open&quot; surface area (cm²)</td>
<td>320</td>
<td>-</td>
</tr>
<tr>
<td>Pumping surface area (cm²)</td>
<td>$\geq 1150$</td>
<td>$\geq 910$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\text{H}_2$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping speed at 300 K [L/s]</td>
<td>1670</td>
<td>1550</td>
<td></td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>900</td>
<td>930</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>890</td>
<td>940</td>
<td></td>
</tr>
<tr>
<td>$\text{N}_2$</td>
<td>790</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>840</td>
<td>940</td>
<td></td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>720</td>
<td>800</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\text{H}_2$</th>
<th>$\text{H}_2\text{O}$</th>
<th>CO</th>
<th>$\text{N}_2$</th>
<th>$\text{O}_2$</th>
<th>$\text{CO}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c/s$ [m]</td>
<td>0.11</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Assuming a usable amount of Ti of about 1 gr per pump and with figures quoted by D.J. Harrä\textsuperscript{23}) the autonomy of the pumps will be several years for the typical stainless steel specific outgassing rate of $2 \times 10^{-13}$ torr lit/s cm\textsuperscript{2}.
FIGURE CAPTIONS

Figure 1: Beam chamber cross-section in a magnet unit. 1. beam chamber (2 mm), 2. heater tapes (1 mm), 3. thermal insulation (5 mm), 4. cooling box (Al), 5. cooling water channels.

Figure 2: Cross-section of beam pipe in a quadrupole.

Figure 3: Layout of the vacuum system in half a normal lattice period, (approximately at scale). Pressure profiles are shown just before starting the sputter ion pumps, and at base pressure without beams.

Figure 4: Cutaway drawing of a main pump station; vertical longitudinal cut: top left; horizontal longitudinal cut: below; vertical transverse cut: top right. Details are shown for the sliding contacts (lower left corner and top centre). An additional flange connected to the beam pipe (dashed lines) is optional for beam observation or similar purposes. The connection pipe (dashed lines) for turbomolecular pumps is welded at the neck of the sputter ion pump. An optional tapered connection is shown in the centre below, together with the end piece of the cooling box.

Figure 5: Auxiliary pumping station with clearing electrode. The sublimation pump has an elliptical cross-section and its aperture is shielded electrically by thin wires (Ø 1 mm) welded at the chamber in axial direction.
FIG. 2

LSR Vacuum Chamber

Vacuum Cross Section in Quadrupole

CERN LAB. I

LSR-274-102-4

<table>
<thead>
<tr>
<th>Scale</th>
<th>C. Grünhagel</th>
<th>22.4.1975</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>
Vacuum Layout of a Half Normal Cell