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Informal Report

VACUUM SYSTEMS FOR STORAGE RINGS

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Abstract

A discussion of vacuum systems for intersecting storage rings using both superconducting and conventional magnets is presented. It is shown that a circulating current $I > 15$ A can be achieved in a 7-cm-diameter vacuum chamber pumped every 3 m by 200-300 liter/sec pumps. A very economical and effective vacuum system can be built in narrow-gap, room-temperature magnets by utilizing distributed titanium sublimation pumping. Finally, pertinent experiments to study cryosorption, outgassing and desorption due to ion bombardment are outlined.

I. Introduction

A very important consideration in the design of vacuum systems for high circulating current storage rings appears to be the gas release from the walls of the vacuum chamber which are bombarded by residual gas molecules ionized by the beam.^{1,2} To achieve high currents one must produce clean and smooth surfaces and provide sufficient gas conductance and pumping speed. Thus the value of the stored beam at the CERN ISR has been increasing steadily due to longer and higher temperature bake-out and the addition of titanium sublimation pumps.^{1,2} As of now the pressure in the ISR is in the low 10^{-11} Torr range³ and the highest current achieved is 18.7 A.⁴

In a previous paper⁵ a 7-cm vacuum chamber operating at room temperature was chosen for the Intersecting Storage Accelerators (ISA). Due to high gas desorption from cold surfaces as reported by McCracken⁶ an approach⁷ using a vacuum chamber at 4.2 K was rejected.

In the present note we will discuss the design of vacuum systems for storage accelerators using both superconducting and normal magnets. We will use Fischer's results^{2,8} to calculate the maximum circulating current I_{crit} before the onset of pressure bump instability according to

$$\sqrt{b/C} \tan(\sqrt{b/C} L) < S/C ,$$

where

$$b = 7.5 (\eta I_{\text{crit}} - ks)$$

η = desorption coefficient

s = sticking coefficient

k = constant which depends on mass and temperature of desorbed gas and cross section of beam pipe

C = conductance

$2S$ = pumping speed

$2L$ = distance between pumps.

Finally, we will briefly describe the experiments which are being set up to gain more understanding of cryosorption, use of aluminum in high vacuum, and gas desorption.

II. Cold ISABELLE

In this section we will discuss the presently studied machine which uses a beam tube with 7-cm inner diameter and 2-mm wall thickness. It is operated at room temperature and is thermally insulated from superconducting magnets with 10-cm cold bore.

1. Pressure bumps

To estimate the maximum current due to pressure bump instability,⁸ we have plotted ηI_{crit} in Figs. 1 and 2 for various pumping speeds and conductances. The gas conductance of a long pipe is given by⁹

$$C = 3.8 \times 10^{-2} \left(\frac{T}{M} \right)^{\frac{1}{2}} d^3 \quad \text{m} \cdot \text{liters/sec} ,$$

where

T = temperature in $^{\circ}\text{K}$

M = molecular mass

d = diameter in centimeters.

For 1-m-long pipe at room temperature (293 K).

$C_{28} = 42$ liters/sec (N_2 , CO),

$C_{18} = 52.5$ liters/sec (H_2O),

$C_4 = 111$ liters/sec (He),

$C_2 = 158$ liters/sec (H_2).

In the ISR stainless-steel chamber the residual gas composition changes¹ from 95% H₂ under normal operation to 40% H₂, 40% CO, and 20% H₂O during pressure bumps. In an aluminum chamber water would probably be the main component.

Consulting Figs. 1 and 2 and letting $s = 0$ we obtain ηI_{crit} of 40-50 when the chamber is pumped at 3-m intervals by 300 liter/sec pumps. Increasing the pumping speed above 300 liters/sec yields only a small increase in I_{crit} due to the limiting conductance of the 7-cm chamber. An additional gain might be realized in a very clean system held at high vacuum for long periods of time where the sticking factor $s > 0$. But even if $s = 0$, a gas desorption coefficient $\eta = 3$ can be tolerated with a 15 A circulating beam. Recently CERN reached 18.7 A indicating $\eta < 2$.

There are, however, two substantial differences between ISR and ISA vacuum systems:

a) The chamber is constructed of aluminum and the gas release due to ion bombardment is unknown. It is believed, however that Al should be better¹⁰ than stainless steel.

b) Ion energy will be higher in the ISA due to bunched beam operation.

2. Ion energy

We consider for simplicity the radial motion of an ionized atom of residual hydrogen gas, produced at the edge of the circulating proton beam ($r = r_0$) with no initial velocity, and accelerated to an energy V electron volts at the chamber wall ($r_1 = 3.5 \times 10^{-2}$ m).

In the case of a uniform unbunched beam, the ion will receive an energy corresponding to the electric potential difference between the beam and the wall

$$V = \int_{r_0}^{r_1} \frac{\lambda}{2\pi\epsilon_0 r} dr = \frac{\lambda}{2\pi\epsilon_0} \ln \frac{r_1}{r_0} ,$$

where λ = linear charge density = I/c . If $I = 10$ A, $r_0 = 5 \times 10^{-3}$ m, $r_1 = 3.5 \times 10^{-2}$ m, then such an ion will receive an energy of 1.168 keV.

In the event that the beam is bunched,¹¹ the equation of motion of this ion is more complicated because λ is a function of time. In the extreme limit, when the effect of the bunch on the ion is that of an "impulse" (i.e., the distance traveled is negligible when the force is acting), an upper limit on the ion energy can be found.

The velocity acquired by the ion is

$$\Delta v = \frac{e}{m} \int E \cdot dt = \frac{e}{m} \frac{1}{2\pi\epsilon_0 r} \int_0^{\Delta T} \lambda dt ,$$

where $\lambda = I/c(T/\Delta T)$ and $T = 1/f =$ time interval between bunch centers, and ΔT , the effective length of time for a bunch to pass by the ion. Then:

$$\Delta v = \frac{e}{m} \frac{1}{2\pi\epsilon_0 r} \frac{I}{cf} .$$

The change in velocity under the impulse assumption is independent of the bunch width. The resulting velocity using values in the previous case is 2.55×10^6 m/sec corresponding to an ion energy of about 33.9 keV.

In more practical intermediate cases, a simple computer program was written which assumed each bunch in the circulating beam had a cosine "squared" distribution. The field was considered uniform for a small element of time (10^{-3} of an rf period) at the end of which the velocity, position and a new field were computed. The process was continued until the ion reached the chamber wall. Some of the results are shown in the following table:

l , Total Bunch
Length (m)

Energy of H^+ Ion at Wall Formed
at Various Positions Along Bunch (keV)

	0	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{3}{4}l$
∞			1.18	
54	2.12	2.53	2.08	0.81
27	4.45	4.83	3.12	1.26
13.5	8.42	7.90	4.31	4.15
7.96	12.1	11.6	5.65	5.76
3.36	16.9	15.8	6.90	6.90
1.68	21.7	20.5	8.29	7.90
Impulse			34.0	

If we assume a bunching factor of 3, i.e., $\ell = 27$ m and $I = 15$ A, the table indicates that an ion under the initial conditions stated here may have a final energy of about 7.5 keV instead of a corresponding value of about 1.8 keV in the unbunched case. These values will of course be influenced by the initial values of the ion energy and position.

3. Beam heating

Since the ISA beam is bunched at 4.5 MHz it will induce a current J in the vacuum chamber walls and dissipate power according to

$$P = \frac{1}{2} R_s |J|^2 ,$$

where R_s = surface impedance = $\sqrt{\pi f \mu_0 \rho}$. Taking again the average circulating current of 15 A, bunch length of 120 rf degrees and a cosine squared charge distribution, we obtain a total power dissipation $P = 2.6$ W/m of the beam tube (ρ for Al = $2.7 \times 10^{-8} \Omega \cdot m$). This power has to be removed, preferably at the end of each magnet, in order not to reduce the space occupied by super-insulation which thermally isolates cold magnets from the warm beam pipe. If the cooling coils are placed at 3-m intervals the proposed Al tube with 2-mm wall thickness will have a parabolic temperature distribution with a maximum $T_{\max} = T_0 + 29^\circ C$ at a point midway between the coils (T_0 = coolant temperature).

4. Eddy currents

During the acceleration, the rising magnetic field will induce eddy currents in the chamber walls which in turn will give rise to additional magnetic field (ΔB , ΔG) in the magnet aperture¹² and additional heating of the walls (ΔW).

Assuming

Maximum dipole field $B = 40$ kG

Maximum quadrupole field $G = 10$ kG/cm

acceleration time = 120 sec

the eddy currents will induce

$\Delta B = 0.6$ G in the dipoles

$\Delta G = 7.5 \times 10^{-2}$ G/cm in the quadrupoles.

The dissipation is significant only in the tube inside the dipole where $\Delta W = 120$ mW/m.

5. Mechanical design

The basic mechanical unit is a dewar which contains three 3-m dipoles and one quadrupole. A minimum of 38 cm are required between the magnets' inner dewars to accommodate a pump, a pair of clearing electrodes, cooling coils, and a vacuum gauge. The pump selected must be able to handle He which suggests either a sputter-ion or a cryosorption pump. The latter would be ideal since they require neither high voltage nor magnetic field and have larger pumping speed per given volume. But the experiments described in Sec. IV have to be completed before a choice can be made.

The vacuum chamber will be insulated by 1 cm superinsulation in order to reduce the heat leak to the magnets at 4.5 K to 0.2 W/m during operation and to 3 W/m during a 600 K bake-out. In aluminum, a lower temperature, 150-200°C, will be used, resulting in a lower heat leak. The chamber will be welded wherever possible. The unavoidable flanges will be machined from explosively bonded Al to stainless steel manufactured by DuPont & Co. to produce stainless to stainless flanges. This material was found virtually leak-free at SPEAR.

Even though the layout is still rather sketchy, for the purpose of lattice and circumference calculations we should allow about 55 cm between magnetic centers inside the dewar and about 120 cm between the dewars.

III. Warm ISABELLE

We will briefly consider a vacuum system using a rectangular chamber in a conventional window-frame magnet. For economical reasons the height of the magnet aperture should be made small while the width can be increased within reason to enhance the pumping speed. Using a magnet with a 4-cm gap the height of the vacuum chamber could vary between 2.5 and 3 cm to accommodate insulation and heating element for bake-out purposes.

The gas conductance of a rectangular duct is given by¹³

$$C = 9.7 \times 10^{-2} \frac{a^2 b^2}{a+b} \left(\frac{T}{M} \right)^{\frac{1}{2}} \text{ m} \cdot \text{liters/sec} .$$

Taking $a = 10$ and $b = 2.5$ cm, we obtain for a 1-m-long duct at 293 K

$$C_{28} = 15.7 \text{ liters/sec (N}_2\text{CO)}$$

$$C_{18} = 19.6 \text{ liters/sec (H}_2\text{O)}$$

$$C_2 = 58.7 \text{ liters/sec (H}_2) .$$

1000

A

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 $(\eta I_{crit} - 3.9 \times 10^3 \text{ s})$ $C = 16 \text{ m} \cdot \text{liters/sec}$

10 cm

2.5 cm

 $M = 28 \text{ N}_2$ $T = 293 \text{ K}$

100

10

Pumping speed

250 liters/sec

50 liters/sec

Figure 3

Critical current in a rectangular chamber.

Distance between pumps

1

2

3

4

5

m

It is obvious from Fig. 3 that the chamber should be pumped at intervals < 2 m in order to store reasonable circulating current (~ 15 A) which would make such short magnets rather uneconomical. Since we would like to use long magnets (~ 6 m) other solutions such as distributed pumping must be adopted. SPEAR¹⁴ employs distributed sputter-ion pumps for a vacuum in the 10^{-8} to 10^{-9} Torr range. The magnetic field is provided by the ring magnets. Besides the rather complicated structure and the requirement of high voltage, the pumping speed of these pumps decreases by a factor of 2 to 3 in the 10^{-11} Torr range, making them less suitable for our design. Titanium sublimation on the other hand presents a possibility of a cheap vacuum system with ample pumping to the 10^{-11} Torr range all along the chamber. The cross section of the proposed chamber shown in Fig. 4 uses two Ti-Mo rods located in the smaller side ducts.

Figure 4. Cross section of the chamber.

During the bake-out the chamber will be pumped by 250 liter/sec sputter-ion pumps between the magnets (6 m apart). After the bake-out $P_{\max}$ of 2×10^{-9} Torr occurs in the middle of the magnet if an outgassing rate of 10^{-12} Torr liters/sec cm^2 and gas conductance for N_2 are assumed. In fact the pressure will be lower since most of the residual gas will be H_2 . When Ti rods are heated and Ti deposited on the walls the pressure will drop to the 10^{-11} Torr range. The resulting pumping speed S_0 per 1 cm length of chamber shown in Fig. 4 is given in Table I.

TABLE I. Pumping speed per centimeter of chamber length due to two Ti-Mo rods.

Gas	H_2	N_2	O_2	CO	CO_2	H_2O	CH_4	A	He
S_0 liters/sec	60	90	—180—			60	0	0	0
S_{eff} liters/sec	18	6	6	7	5	8	0	0	0

Since we want to prevent the Deposition of Ti on the areas to be bombarded by ionized residual gas molecules we limit the aperture to 3 mm (Fig. 4) which decreases the pumping speed to S_{eff} in Table I. Ti-Mo rods similar to those commonly used in sublimation cartridges¹⁵ yield over 0.1 g of Ti per centimeter of length which provides 1.8 Torr-liter of pumping. A monolayer of Ti can be deposited either at preset intervals or whenever the pressure increases above the 10^{-11} Torr range. This represents several weeks if an outgassing rate of 10^{-12} Torr liter/sec cm^2 is assumed. Non-getterable gases will be pumped by sputter-ion pumps between the magnets. Under normal conditions the rods should last indefinitely but even if a new Ti film of a few monolayers had to be deposited every day the rods would last at least 10 years.

It is clear from the above discussion that the proposed chamber combined with Ti pumping can provide a very economical and effective vacuum system. It has to satisfy, however, the criteria imposed by space charge and instabilities.

When comparing the circular and rectangular chambers treated in this report the following differences should be mentioned:

- a) In a rectangular chamber the magnetic field generated by eddy currents during acceleration contains higher order terms.
- b) The heat produced in the vacuum chamber walls by the bunched beam is dissipated by the magnets at room temperature.
- c) Energy gained by the residual gas ions will depend on their position and can be calculated by Eq. (3) in Ref. 16, p. 85. Assuming an unbunched, uniform beam of 15 A with radius $r = 2.5$ mm and 5 mm, the maximum energy gain by the ion will be 1.7 and 1.0 keV respectively. A similar correction as in Sec. II has to be applied if the beam is bunched.

IV. Experiments

The design of the vacuum systems presented in the preceding chapters used aluminum for a beam pipe and cryosorption pumping. It must be stressed, however, that several assumptions and extrapolations have been made and experimental work is necessary to show that they were justified. In the three following sections we will therefore outline the experiments which will yield the required information.

1. Cryosorption

In the cold ISABELLE ample amounts of liquid He are available at 4.5 K and the molecular sieve will be operated between 4.5 and 5.5 K. An apparatus is presently being assembled to measure adsorption isotherms and pumping speeds of He and H₂ in the range of 10^{-11} to 10^{-6} Torr for sieve temperatures of 3-5 K. A commercially available pump containing 30 g of Linde 5A-30 adsorbent bonded to a stainless-steel panel with an area of $\sim 220 \text{ cm}^2$ is used.

2. Surface preparation

Spectrometric studies of outgassing in commercially available Al and Cu pipes will be carried out as a function of the following surface treatments:

- a) electro and chemical polishing
- b) bake-out temperature
- c) vacuum outgassing up to 400°C
- d) glow discharge cleaning.

Since the Al flanges are unreliable for a system requiring a bake-out, stainless steel to Al brazing will also be investigated. The results from the above experiments will determine the surface preparation of the vacuum chamber before it is assembled and installed in the ring.

3. Ion bombardment

The most important property of the beam pipe for storage ring application is a low gas desorption due to ion bombardment. Ionized molecules in an energy range 1-10 keV of gases commonly found in high vacuum will be used to bombard Al and Cu samples of various surface treatments. ISR stainless steel and clean tungsten will be used for comparison. This experiment will be done in cooperation with Y.Y. Chu and L. Friedman from Chemistry using their isotope separator as an ion source. The gas desorption will be measured by a fast scanning mass spectrometer. Finally, McCracken's experiments on desorption from cold surfaces⁶ will be repeated.

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