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COMPARISON OF COLD AND WARM VACUUM SYSTEMS FOR INTERSECTING STORAGE RINGS*

H.J. Halama and J.C. Herrera
Brookhaven National Laboratory
Upton, New York 11973

Summary

In storage rings employing superconducting magnets, the use of a cold bore as a cryopump appears, at first glance, as simple and economical. Since the selection of a cold or warm vacuum system has far-reaching implications on the basic design, we consider each system in some detail. The theoretical and practical limitations imposed on the maximum beam current by the gas desorption from the chamber walls are discussed. A realistic design of a cold vacuum chamber is developed and then compared with the proposed warm ISABELLE vacuum system. The comparison shows that the warm approach is preferable.

I. Introduction

When considering the design of a storage ring using superconducting magnets, an approach utilizing the cold bore of the magnets as the vacuum chamber appears at first glance very attractive.[1-3] It provides maximum beam aperture for a given magnet, maximum circumferential packing factor, and free pumping in the cold sections. Since such an opportunity does not present itself very often to the machine builder, it is desirable to compare the design and construction of a vacuum system of the proposed ISABELLE with both a cold and a warm chamber. This comparison will be done considering the entire machine, where the design decisions are governed not only by the gas density but also by the requirements of beam stability, economy and ease of construction. Furthermore, the chamber must accommodate a sufficient number of pick-up electrodes to correct the equilibrium orbit which might be more critical with superconducting magnets. A high degree of clearing will require clearing electrodes even if the pressure is very low. Other diagnostic equipment must be provided for maximum utilization of the storage rings.

II. Theoretical Considerations

A. Operation Without Beam

It was shown at the CERN-ISR[4] that the average pressure in the vacuum chamber without the beam should be $\sim 1 \times 10^{-11}$ Torr. At this pressure, questions of beam lifetime, radiation background, beam neutralization by electrons and beam-gas instabilities are easily controlled. For a warm system, the average pressure in the beam tube is given by

$$P_{av} = P_o + 200\,\pi r L q \left(\frac{1}{S} + \frac{L}{12C}\right) \tag{1}$$

where P_o = base pressure of pump (Torr),
S = pumping speed ($\ell \cdot s^{-1}$),
L = distance between pumps $\sim$ magnet length (m)
q = outgassing rate (Torr $\ell \cdot s^{-1}$ cm^{-2}),
C = unit conductance $\sim r^3 \sqrt{T/M}$ ($\ell \cdot m \cdot s^{-1}$), and
r = radius of chamber (cm).

The requirement of 10^{-11} Torr is achieved by careful preparation of surfaces to reduce outgassing, ample pumping speed, and a compromise between the conductance and magnet length. Outgassing measurement using long aluminum tubes at BNL[5] have yielded an outgassing rate $q = 1\text{-}2 \times 10^{-14}$ Torr $1/s$ cm^2 which, for the proposed ISA,[6] would result in pressures below 1×10^{-11} Torr.

In a cold tube where the whole surface is cryopumping, the pressure will depend only on the presence of helium and hydrogen and, therefore, on the condition of the surface and the leaks which are hard to predict. For the same residual gas density, the equilibrium pressure in the cold tube must be 70 times lower than in a warm tube. Freedom of leaks and the possibility of leak checking in a cold vacuum system is absolutely essential Even though no cold machine exists, it seems reasonable that in a leak-free and clean chamber the required pressure of 3×10^{-13} Torr can be achieved.

B. Operation With Beam - Warm Chamber

It has been found at the CERN ISR that a much more stringent requirement on the vacuum system is introduced when the proton beam is injected into the chamber. The principal limit on the intensity of the beam is then set by the phenomenon known as the "pressure bump".[7] The circulating protons ionize the residual gas molecules and the electric field due to the beam then drives the ions into the chamber wall. These ions are neutralized and, depending on the surface condition of the chamber, may liberate (desorb) gas molecules from the surface. As the beam current is increased, the pressure rises rapidly. The limiting current (I_{crit} in ampere), derived by solving the gas continuity equation,[8,9] may be expressed for practical vacuum systems as

$$\eta I_{crit} = \frac{4\pi^2}{3} R \left(\frac{K}{1+K}\right)^2 \left[1 + \frac{\pi^2}{12}\frac{1}{(1+K)^3} - \frac{\pi^4}{80}\frac{1}{(1+K)^5}\right]^{-2}, \tag{2}$$

where η is the surface desorption coefficient (i.e. the number of molecules desorbed per impinging ion), $R = C/L^2$ and $K = SL/4C$. Figure 1 shows ηI_{crit} as a function of the parameters R and K. In these calculations, we have used the ionization cross section of $1.2 \times 10^{-18}\,cm^2$ corresponding to the heavier desorbed gases of CO and H_2O.[8,10] In order to compare the ISA and the ISR, we have indicated in this figure the point characteristic of the proposed warm ISA[6] as well as the successive

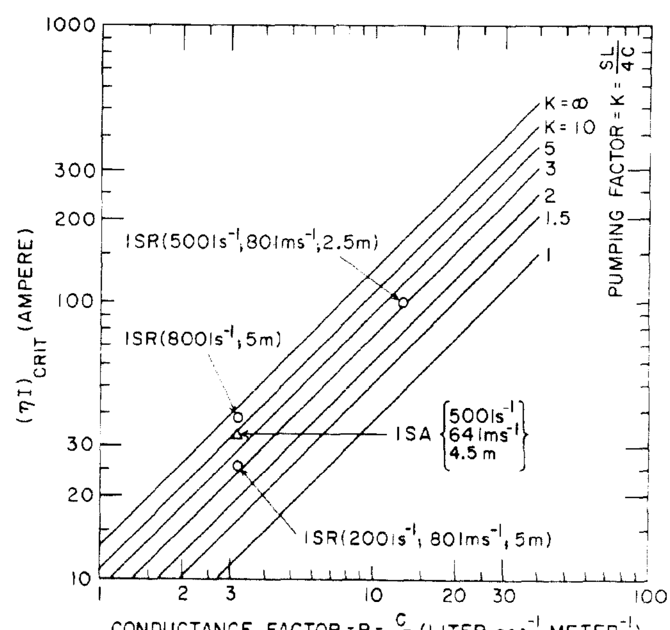

Fig. 1. Normalized ηI_{crit} curves.

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points through which the CERN ISR has passed as their limiting current has increased from 6 to approximately 30 A.

For a given chamber conductance and pumping speed, the rise in pressure accompanying an increasing current is essentially given by

$$\frac{P(I)}{P(0)} = \frac{8}{\pi^2} \frac{b_{crit}}{b} \left\{ \frac{1 - \cos[(\pi/2)\sqrt{b/b_{crit}}]}{\cos[(\pi/2)\sqrt{b/b_{crit}}]} \right\} \qquad (3)$$

In this equation, the parameter[8] b is

$$b = \eta\sigma(I/1.6 \times 10^{-19}).$$

Since the ionizing cross section (σ) can be considered essentially constant for a given proton energy and a given gas species, the value of b is primarily dependent on the current I. In addition, the desorption coefficient itself will depend on the current in a manner similar to the sputtering coefficient,[11] since the probability of ejecting an ion will be a function of the energy with which it strikes the wall. Figure 2 shows a graph of Eq. (3) when η is a constant and when it varies linearly with the current. It is expected that the behavior of the pressure bump with any given surface will initially follow the lower curve and then with increasing current approach the upper curve.

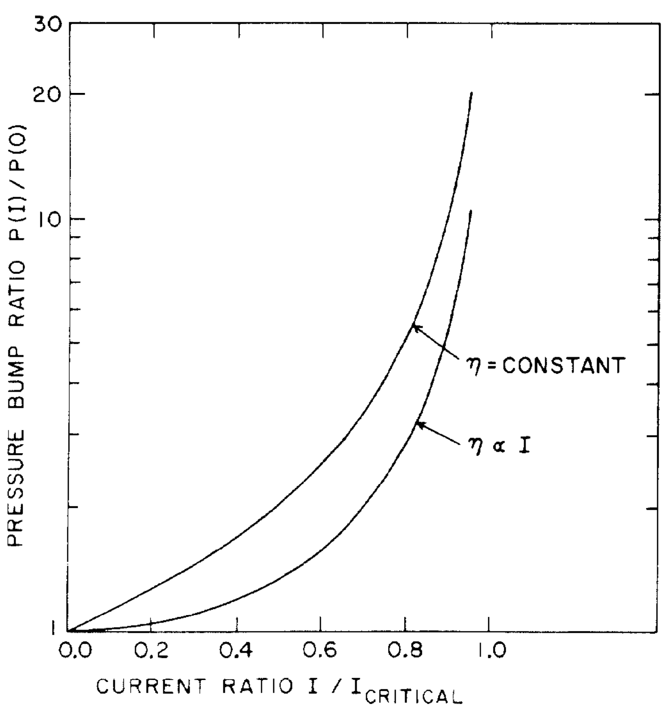

Fig. 2. Pressure bump ratio vs current ratio.

We have expressed Eq. (3) as a function of the coefficient b because the actual dependence on the current I is complicated. Not only does the η coefficient vary with the surface cleanliness and conditioning, but also the gas composition changes during the pressure bump. Thus, at the CERN ISR,[7] the composition of the residual gases changed from 90% H_2 to 40% CO, 40% H_2, 20% of H_2O and hydrocarbons. The heavier gases having larger η and σ are more effective in desorbing gases. The only measurement of the gas desorption coefficient at these energies has been done at the ISR.[4,12] The experiment[12] yielded values of η between 2 and 3 for I between 18 and 26 A for stainless steel which had been vacuum fired at 800 °C before installation. In contrast, a value of η = - 0.5 for I = 12 A was measured for stainless steel, which had been glow-discharged in argon and oxygen, thereby eliminating the carbon contamination from the surface.

Though the ion desorption model provides a good explanation of the pressure bump phenomenon, it is well to remember that other mechanisms, such as field emission from whisker[13] on the vacuum chamber or primary protons grazing the chamber may play a significant role in the initiation of the pressure bump at the high currents presently achieved at CERN.

C. Operation With Beam - Cold Chamber

In a chamber held at 4-5 °K the whole surface becomes a cryopump. The gas conductance decreases to about 12% of its room temperature value and the pumping between magnets becomes unnecessary. The expression for I_{crit} reduces to[9,14]

$$\eta\sigma I_{crit} = \frac{\pi}{2} r\bar{v}s \qquad (4)$$

where $\bar{v}$ = average velocity of desorbing molecules, and
s = sticking coefficient (probability that a molecule incident on the wall will stick).

The sticking factor approaches unity for all gases whose vapor pressure is less than the operating pressure and Eq. (4) gives

$$\eta I_{crit} = 4.7 \times 10^3 \text{ A, for mass 28 } (CO, N_2) \quad .$$

The value of the H_2 sticking coefficient depends on the surface coverage and since no data exist for T = 4.6 °K, it is difficult to calculate the behavior of a vacuum chamber working at this temperature.

If we assume $\sigma = 3 \times 10^{-19}$ cm^2 (extrapolated from 1 MeV measurements)[15] and s = 0.5, then $\eta I_{crit} = 3.6 \times 10^4$ A. The only data on desorption from cold surfaces were obtained by Erents and McCracken,[16] who used protons and electrons to bombard films of frozen N_2, H_2, Ar and He. They measured $\eta \sim 5 \times 10^4$ for H_2 and He, η between 10 - 100 for N_2 and Ar.

It can be concluded that if H_2 and He can be kept out of the chamber, I_{crit} of 100 A can be reached. The lack of sufficient data for hydrogen prevents us from giving a realistic estimate of I_{crit} if H_2 is present, but for the reasons given in Ref. 14, it could be as low as 1 A. The presence of He would, of course, be disastrous since the vapor pressure at the operating temperature is above one atmosphere.

Before one can plan on using a cold vacuum chamber, one should, therefore:

i) guarantee that the helium leaks are eliminated,
ii) decrease the surface coverage of H_2O and hydrocarbons by bakeout since these gases are broken up into free hydrogen[17] by ion bombardment,
iii) provide the possibility for leak checking when the system is cold, and
iv) minimize the gas flow from the warm into the cold sections.

Clearly all these requirements cannot be met by a vacuum system using the cold bore of superconducting magnets. Thus, it appears that the most interesting case[14] offering larger aperture and increased packing factor is excluded. Similar conclusions have been reached by Bittner and Grant[2] of BNL and Benvenuti[18] of CERN.

III. Practical Considerations

A. General Remarks

It is evident that some sort of a double wall vacuum chamber must be resorted to and in this section the most promising solution proposed by Benvenuti[18] will be compared with the present ISABELLE design.[6] A solution employing complicated structures inside the vacuum tube, such as suggested for ESCAR[19] or in Ref. 18, will not be considered since such structures would adversely effect an intense beam in a large storage ring. They might, however, be suitable in a small low current machine where the problem of resonances and chamber impedances are not so severe. Before we start the comparison, let us briefly enumerate other considerations which play an important role in the design of a vacuum system for intersecting storage rings.

1. Clearing Electrodes. The required ratio of trapped electrons to beam protons in the ISA is approximately 10^{-4}. The effective clearing of electrons depends on the ratio of the transverse electric field to the magnetic field. For a superconducting ring where the magnetic field ($\simeq$ 50 kG) is large while the electric field is small for a ribbon-like beam, it is expected that many clearing electrodes will be essential.

2. Pick-up Electrodes. In order to observe and correct the equilibrium orbit, it is desirable that at least four vertical and four horizontal pick-up electrodes per betatron wavelength be provided. This is particularly important in a superconducting ring where a large number of correcting windings have to be adjusted to accurately position a relatively wide beam.

3. Eddy Current and RF Heating. During the acceleration of the beam, the chamber must dissipate the power by RF induced currents and eddy currents.

4. Beam Loss. During the stacking process, a few spots around the machine may be hit by a substantial amount of protons.

5. Warm to Cold Transitions. Several parts of the machine must be at room temperature (experimental straight section, scrapers, beam dump, accelerating cavities, etc.).

B. Warm Vacuum System

ISABELLE[6] consists of eight focusing and bending octants 160-m long, which are separated by long straight sections. More than one-half of the circumference is devoted to straight sections. The 8-cm diameter aluminum chamber, having a conductance of 64 l•m/s, is kept at room temperature and is isolated from the cold magnets by 1-cm thick layer of insulation. This arrangement results in a heat leak of 0.4 W/m during operation and 2 W/m during a 200 °C bakeout. The chambers and bellows are welded together between magnets. To achieve the required clearing efficiency, a pair of clearing electrodes is mounted at each dipole. There are four vertical and horizontal pick-up electrodes per betatron wavelength. The chambers of both rings are evacuated by a common pump with an effective speed of 500 l/s at the chamber. Prior to installation, the chamber will be chemically polished and subsequently glow-discharged in argon and oxygen. This treatment yields an outgassing rate of 1×10^{-14} Torr l/s cm^2 after 200 °C bakeout. Hydrogen then comprises 99% of the residual gas. Unfortunately, the ion desorption coefficient for aluminum has not been measured. It is, however, encouraging that the manufacturing process of aluminum is cleaner than that of steel and the electron desorption coefficient measured is 2-3 times lower than that for stainless steel.[20] Consulting Fig. 1, we see that ηI_{crit} for ISABELLE is greater than 30 A and the design current of 10 A seems quite reasonable.

C. Cold Vacuum System

When the double wall system, similar to that described initially by Benvenuti[18] is adapted to ISABELLE,[6] one must bear in mind that at least a part of each straight section will have to be kept at room temperature. Furthermore, each octant will be divided into two parts ~ 80-m long which will be kept at 4.6 °K to accommodate a vacuum gauge and other equipment. This arrangement requires 32 warm to cold transitions per ring of undetermined length and complexity. Needless to say, these transitions present very dangerous areas for desorption and a small region having a few monolayers coverage will be sufficient to cause a pressure bump at higher currents.

Within the cold octants, the intermagnet sections would look somewhat as sketched in Fig. 3. The mechanical complexity is quite apparent. In addition, some means of an adequate bake-out must be provided. The bellows, B_1 and B_2, reduce heat leaks and compensate for mechanical expansion while B_3 and B_4 only serve to equalize the expansion (a 4.5-m tube will increase in length by 3.5 cm, when its temperature is rasied from 5 °K to 150 °C).

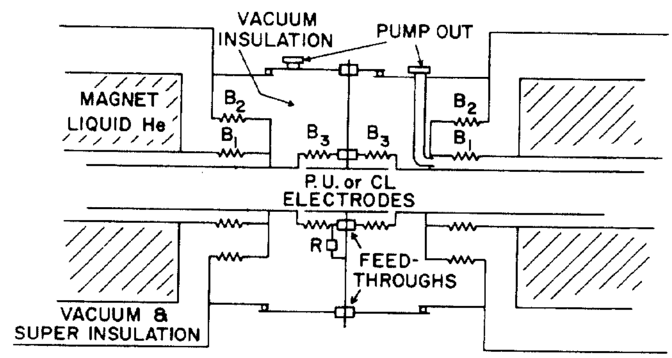

Fig. 3. Sectionalized double wall chamber (Ref. 18).

If the chamber is thermally isolated from the liquid helium, the eddy currents and the beam induced RF currents will cause a larger rise in temperature because of the low specific heat of metals. For instance, in ISABELLE, a 10 A beam, accelerated by a 200 kHz RF system to a final energy in two minutes would raise the temperature from 5 °K to 19 °K. Since the rise in temperature varies as $\sqrt{f}$, higher frequencies will increase the temperature accordingly.

With the arrangement shown in Fig. 3, the clearing and PU electrodes may never reach 4.5 °K due to the heat leak caused by the connections via a feedthrough to the equipment at room temperature. In addition, these clearing electrodes are bombarded by 10 keV electrons which are 10^5 times more effective[16] in desorbing the gases at 4.2 than at 20 °C.

IV. Discussion

From the above comparison, it is apparent that no general decision between cold and warm vacuum systems can be made. Rather, each individual machine must be considered in its own right. For example, any bunched beam operation during stacking, acceleration and storage, especially if the frequency is high, puts severe limitations on the cold chamber design. The storage of electrons in the same ring becomes impossible. Simplicity, ease of construction, and component accessibility are significant advantages of the warm approach. In addition, diagnostic instrumentation can be placed almost anywhere in the ring.

The cold chamber design, on the other hand, does reduce the cost of superinsulation, refrigeration and vacuum pumps. However, a large number of warm to cold transitions, with the accompanying heat leaks in the intermagnet regions, could easily cancel this gain.

One important advantage of a warm system, not mentioned previously, is the availability of a wealth of information gained at the ISR, in particular, that on surface preparation. An interesting example is the possibility[4] of using titanium as a chamber material and thereby converting the whole chamber into an ion pump.

Only systematic study and experiments can shed more light on the problems associated with cold vacuum chambers. As long as they are missing, the warm vacuum system proposed for ISABELLE seems the safest, simplest, and most economical approach.

Acknowledgments

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