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Informal Report

SOME REMARKS ON COLD BORE VACUUM SYSTEMS

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ABSTRACT

In storage rings employing superconducting magnets, the use of their cold bores as cryopumps looks at first very attractive. A possible design of a cold vacuum system is therefore discussed in some detail with its theoretical and practical limitations. The comparison with ISABELLE vacuum system reveals that in a large practical machine the warm approach is superior. Relative disadvantages of the cold and warm systems are summarized at the end of this report.

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Fig

I. INTRODUCTION

When considering a design of a storage ring using superconducting magnets, an approach of going cold all the way seems at first glance very attractive¹⁻³ i.e. why not utilize the cold bore of the superconducting magnets to get maximum aperture at minimum cost plus all the pumping speed almost free. Since such an opportunity does not present itself too often to the machine builder, we would like to consider in this report, a cold vacuum system design in some detail to see how many features⁴ could be utilized to:

- a) Simplify and improve the machine construction and operation,
- b) increase the circulating current (luminosity),
- c) lower the cost.

Then we will compare the cold design with the ISA warm vacuum system⁵ as presented in the ENL proposal.⁶

II. THEORETICAL LIMITATIONS

In order to accomplish the above, let us first review the limitations imposed on the circulating proton beam by the dimensions of the vacuum system represented by finite pumping speed, finite gas conductance, and cleanliness of the beam pipe. We will not treat here transverse and longitudinal instabilities due to the presence of metallic boundaries (aperture) and discontinuities of the surrounding vacuum chamber.

It is well-known that the most serious limitations on the circulating proton current in the ISR⁷ are the pressure bumps caused by gas release from

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1. P. Grant, BNL Informal Rept. 16843 (1972).
 2. J.P. Blewett and H. Hahn, Ed. "200 GeV Intersecting Storage Accelerators ISABELLE, A Preliminary Design Study", BNL 16716 (1972).
 3. J.R.J. Bennett, Rutherford High Energy Laboratory Rept. RL-74-024, EPIC/MC/42 (1974).
 4. J.W. Bittner and H.J. Halama, Proc. 2nd All Union Conf. on High Energy Accelerators, Moscow, p. 191 (1972).
 5. H.J. Halama, BNL Informal Rept. 17820 (1973).
 6. H. Hahn and M. Plotkin, Ed., "A Proposal for Construction of a Proton-Proton Accelerator Facility, ISABELLE", BNL Rept. 18891 (1974).
 7. E. Fischer, J. Vac. Sci. Technol. 9, 1203 (1972).

the chamber walls when they are bombarded by the residual gas molecules ionized by the stored beam. The equations describing the dynamic situation of the gas density distribution in the vacuum chamber and their solutions in terms of maximum current, I_{crit} which can be achieved, were discussed elsewhere.^{4,8-10} Assuming pumps with an infinite pumping speed between magnets and an ionization cross section $\sigma = 1.2 \times 10^{-18} \text{ cm}^2$ (Ref. 9) I_{crit} in amperes

$$\eta I_{crit} = \frac{1}{7.5} \left(\frac{\pi}{2} r \bar{v} s + \frac{10\pi^2 C}{h^2} \right) \quad (1)$$

where η = desorption coefficient,

r = radius of vacuum chamber in cm,

s = sticking factor,

C = conductance in m-liters/s,

h = distance between pump in m,

$\bar{v}$ = arithmetic mean velocity in cm/s.

Both C and $\bar{v}$ are functions of temperature T and mass number M according to¹¹

$$C = 0.038(2r)^3 \sqrt{\frac{T}{M}} \quad (2)$$

$$\bar{v} = 14551 \sqrt{\frac{T}{M}} \quad (3)$$

In a practical warm vacuum system ηI_{crit} will depend on the pumping speed between the magnets as depicted in Figs. 1 and 2. Here Fischer's solution⁹ is used to calculate ηI_{crit} of aperture diameter $2 < d < 8$ cm in a machine with two different magnet lengths and $s = 0$. Points (Δ) in Fig. 2 represent infinite pumping speed, Eq. (1).

It should be pointed out that $\eta = 2$ was measured at CERN⁹ with $I_{crit} = 19$ A. η depends on the surface condition of the chamber and on the energy of bombarding ions. Since the ion energy is determined by the circulating current, lower η 's are to be expected for lower circulating currents. In a warm vacuum system the readsorption is generally very small ($s \sim 0$) and the term

8. E. Fischer, private communication (1972).

9. E. Fischer and K. Zankel, CERN Rept. CERN-ISR-VA/73-52 (1973).

10. O. Grobner and R.S. Calder, IEEE Trans. Nucl. Sci. **NS-20**, 760 (1973).

11. G. Lewin, "Fundamentals of Vacuum Science and Technology", (Mc-Graw-Hill, New York, 1965).

FIG.1 CRITICAL CURRENT LIMIT

DISTANCE BETWEEN PUMPS=5 m

FIG.2 CRITICAL CURRENT LIMIT

$(\pi/2) r \bar{v}_s$ in Eq. (1) can be neglected. In any event, this system achieves reasonable currents by striving for clean walls through surface preparation and bakeouts to reduce η and by using many pumps and large conductance of the chamber.

On the other hand, in a cold bore the gas conductance decreases to about 12% of its room temperature value, and the sticking factor becomes 1 for gasses whose vapor pressure is less than the operating pressure. The term $(\pi/2) r \bar{v}_s$ then predominates giving

$$\eta I_{\text{crit}} = 4.7 \times 10^3 \text{ for mass 28.} \quad (4a)$$

The condition $s \rightarrow 1$ holds for hydrogen if the surface coverage is less than one monolayer only in which case

$$\eta I_{\text{crit}} = 1.8 \times 10^4. \quad (4b)$$

III. COLD VACUUM SYSTEM

We have seen in the previous chapter that a very high ηI_{crit} can be achieved in a cold bore if we deal with gasses other than helium and hydrogen. It might, however, be unrealistic to expect that He molecules are excluded from a chamber which is surrounded by liquid helium. We have to consider, therefore, a practical storage ring to see what gasses are likely to be encountered in the system due to possible vacuum leaks and constructional details.

We will arbitrarily exclude a machine² using a chamber thermally isolated from the cold magnets, since such a machine loses the advantage of larger aperture and requires a separate liquid helium loop as well as a complicated vacuum chamber, which significantly increases the cost, but permits bakeout with cold magnets.

Let us then consider, as an example, a machine similar to ISABELLE,⁶ namely 8 octants each about 160 m long and 8 straight sections > 100 m. The straight sections are operated at room temperature due to the accessibility dictated by the equipment used in them. They are isolated by a large capacity of differential pumping to minimize the condensation of gasses on the cold walls. In addition, 16 warm-to-cold transitions have to be provided to decrease the heat leak. The most efficient way to build the bending octants would be to eliminate all warm parts from them. In fact, the

inclusion of a warm section would increase the octant lengths, introduce heat leaks into a 4.2 K system, and require additional pumping, thus increasing the cost. Almost all pumping could be obtained by condensation on the cold surfaces, but a few cryosorption pumps should be included^{1,12} to pump He and H₂. They might also be necessary for the initial pumpdown.

The octant could be constructed in a similar way to ISABELLE,⁶ namely by welding and flanging the vacuum chamber together via a larger tube containing clearing electrodes, pick-up electrodes, bellows and other diagnostic equipment. Since there are no reliable gauges at 4.2 K, we would have to either develop one or use a modulated BA gauge connected through a tubulation at some higher temperature to reduce the heat leak.

After the assembly, the complete octant would be roughed out, leak checked and incorporated into a continuous dewar so that the chamber including the instrumentation can be brought to liquid helium temperatures. In this type of construction, no bake out is feasible and the walls of the beam pipe will initially be covered with a few monolayers of adsorbed gasses. The magnet cooldown cycle can now be started and the gasses will condense preferentially on cold spots. The sections between the magnets might never quite reach 4.2 K, since they are cooled by conduction from the magnets only, but are warmed by heat leaks due to wire connections to room temperature equipment and by beam induced currents. Any vacuum leak opening after the cooldown would be difficult to detect, and even if detected, it would require the warming up of the whole section to room temperature. Furthermore, the removal of a magnet or any change of diagnostic apparatus inside the chamber would require the same. In other words, the octant would be inaccessible.

The pressure and the gas composition in the chamber (predominantly helium and hydrogen) would, of course, depend on the adsorbed gasses present on the surface* as well as the leaks and the gas flow from warm surfaces. All the above effects are difficult to estimate at best, but one has to keep in mind that there are many welds, ceramic-to-metal feedthroughs, bellows, electrodes, etc. in the cold vacuum chamber. Many small leaks

* Bombarding ions may break-up adsorbed water and hydrocarbon molecules and liberate hydrogen.

12. H.J. Halama and J.R. Aggus, J. Vac. Sci. Technol. 11, 333 (1974) and to be published.

each below the detection sensitivity at room temperature are likely to be present and could constitute a substantial gas load. In addition, the vapor pressure of H_2 at 4.2 K is only $\sim 10^{-6}$ Torr after a few monolayers have been adsorbed which results in $s \rightarrow 0$ at the operating pressure. Taking into account the high desorption coefficients for H_2 and He measured by McCracken^{13,14} at cold surfaces ($\eta > 10^4$) and the presence of barely detectable leaks, a circulating current $I_{crit} < 1$ A could be expected according to Eq. (4).

Another important unanswered question is the desorption due to particles which are lost from the beam and strike either the chamber or the adsorbed layers at very small angles. In particular, during stacking where the loss rate might be high, a substantial temperature rise can occur locally due to the very low specific heat of metals at 4 K; for example, $C_p(Al) = 2.6 \times 10^{-4}$ as compared to $C_p(Al) = 0.9 \text{ J g}^{-1} \text{ }^\circ\text{K}^{-1}$ at 300°K . Another uncertainty is created by the high dielectric strength of frozen gasses,¹⁵ i.e. $\sim 1 \times 10^6 \text{ V/cm}$ for A, N_2 and O_2 . Charges collected on these films might break down the films and desorb large amounts of gas causing a pressure bump. The cryosorption on frozen CO_2 or A (Ref. 16) introduced into the chamber for the purpose of pumping could therefore be rather dangerous. Furthermore, H_2 adsorbed on a film of frozen argon¹⁴ has the same η as H_2 adsorbed on bare metals. Finally, we should note that the gas density n is inversely proportional to temperature T and that at a given pressure there are 70 times more molecules per unit volume at 4.2 K than at room temperature

$$P = nkT$$

One can, of course, design and assemble the machine in a different way; for instance, one can use a cryosorption pump between every magnet and cool them before the magnets are cooled or one can design a complicated chamber with even more complicated intermagnet sections. Such an approach, however, makes the vacuum system only more expensive without removing the most serious disadvantages of accessibility and exchangeability.

13. S.K. Erents and G.M. McCracken, J. Appl. Phys. 44, 3139 (1973).
14. S.K. Erents and G.M. McCracken, 5th Intern. Conf. on Atomic Collisions in Solids, Gatlinberg, Tenn. (1973) to be published.
15. K.N. Mathes, "Dielectric Properties of Cryogenic Liquids", IEEE Trans. Electrical Insulation, EI-2, No. 1 (1967).
16. E. Muller, Cryogenics 6, 242 (1966); J. Hengevoss J. Vac. Sci. Technol. 6, 58 (1969); A. Hunt, et al., Adv. in Cryogenic Engineering 8, 100 (1963).

IV. COMPARISON AND SUMMARY

Let us compare the system just described with the warm chamber approach⁶ where simple aluminum pipes are pumped by units (Fig. 3) between each magnet common to both rings. The bulk of the pumping is obtained by Ti-sublimation which is very economical. Magnet replacement or an addition of diagnostic equipment can be accomplished within 4 days including the bakeout. Consulting Figs. 1 and 2 reveals that critical current of 10 A can be maintained with $\eta > 2$ which compares favorably with $\eta = 2$ at 19 A at CERN.⁹ The details of the ISA vacuum system including its cost estimate can be found in Ref. 6.

Finally, it might be instructive to briefly summarize the relative shortcomings of both systems.

1. Disadvantages of warm bore

a) Smaller aperture for the same magnet bore due to thermal insulation. This loss in aperture might not, however, be so significant due to poor magnetic field in that location.

b) Larger heat leak into liquid helium system.

c) Higher gas diffusion from the bulk of metals.

d) Higher electrical resistivity of the chamber might increase resistive wall instabilities.

2. Disadvantages of cold bore

a) Electrons cannot be stored due to high synchrotron radiation.

b) Components in the octants are inaccessible.

c) Replacement of magnets or equipment within the octants might take a long time $\sim 3 - 4$ weeks, depending on cooldown characteristics of the magnets.

d) It is difficult to measure low pressure at low temperature.

e) Construction, assembly and leak checking are more difficult.

f) Greater probability of leaks exists due to large differential contraction and lower ductility of materials, such as feedthroughs.

g) Temperature dependent leaks are almost impossible to detect.

FIG.3 ISA PUMPING UNIT

h) As the gas coverage of the chamber increases due to the initial condensation during cooldown and due to the presence of tiny leaks, the equilibrium pressure increases and the pumping speed decreases.

i) Electrical breakdown of frozen gasses can cause gas bursts.

j) Even with $s = 1$, cryopumping is insufficient to cope with higher values of η (Ref. 13, 14).

k) In the case of bunched beam operation, beam induced heating W_H has to be removed at 4.2 K. Since $W_H \propto \sqrt{f} I^2$ the cooling of intermagnet section might be required if the frequency and average currents are high.^{3,5}

In spite of the above disadvantages, there are, however, certain types of lower average current machines which might be economically built using a cold bore. Such machines should have an absolute minimum of instrumentation in the bending and focusing sections to reduce the number of feedthroughs and joints. Clearing electrodes could possibly be eliminated and pressure bump problems lessened by bunched beam operation. In the case of a storage ring with a small diameter, the cold bore could also be feasible for the above reasons, but would in our opinion be less flexible and more expensive. At any rate, with the present lack of knowledge, there is always a large risk involved for uncertain gains.

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