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A VACUUM COLD BORE TEST SECTION AT THE CERN ISR

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Summary

A 2 m helium cooled vacuum test section has been inserted into the CERN ISR to investigate problems which could be encountered in future cold bore proton machines. The UHV bore is cooled from the helium bath via a variable pressure gas filled space which enables operation at any temperature between 2.5 K and ambient. Temperature and degree of surface contamination can be remotely controlled. First observations from nominally clean and from hydrogen contaminated surfaces operating at temperatures close to 4.2 K are presented.

1. Outline of the Problem

The continual advance in superconducting magnet technology makes it distinclty probable that any new large scale accelerator or storage ring project would employ, at least in part, this type of magnet. The cores of these magnets would operate at or near liquid helium temperature (4 K) and the designers of the magnet and vacuum systems are immediately confronted with a common problem - namely, whether to keep the vacuum chamber at or near ambient temperature as is normal in present day machines or whether to let it follow the temperature of the magnet core, i.e. the 'cold bore' alternative. At first sight, the cold-bore design looks advantageous for both parties: it allows a saving on thermal insulation thus permitting a smaller magnet aperture while at the same time reducing heat losses; it should, automatically, produce an ideal vacuum by virtue of reduced or zero outgassing rates and by converting the whole vacuum chamber into one large cryopump. A closer scrutiny, however, does not entirely favour the simple cold-bore option. It links the magnet and vacuum systems both physically and operationally in a way which often may not be convenient; it complicates and reduces bakeout possibilities of the vacuum chamber which may still be necessary; it may lead to the build-up of condensed gas layers (from the outgassing of other parts or from leaks) which could give rise to severe problems of gas release due to ion bombardment. This paper is concerned with an experimental investigation of these basic vacuum problems using the CERN ISR.

The analogous warm bore problem of beam induced pressure bumps has been extensively studied, and to a large extent successfully overcome, on the ISR at CERN[1]. In practice, the observed pressure P follows approximately the predicted relation $P = P_o/(1-I\sigma\eta/S_{eff}e)$ (1) where P_o is the initial pressure, I the beam current, σ the molecular ionisation cross-section, e the electronic charge and S_{eff} the effective pumping speed per unit length. Pressure instability occurs for $I \geqslant I_c (= S_{eff}e/\sigma\eta)$ and stability is extended towards higher currents either by increasing S_{eff} (more and/or bigger pumps) or, more elegantly, by various surface cleaning techniques which reduce the ion induced gas desorption yield η. Both alternatives are used successfully on the ISR[2]. Values of η typically start at $\simeq 30$ molecules/ion for unbaked vacuum chamber materials (e.g. stainless steel, titanium, aluminium, etc.) and fall to $\lesssim 4$ mol./ion after a normal in-situ vacuum bakeout of 300°C. Although this can be reduced further by bakeout at still higher temperatures, the most spectacular results are obtained using inert gas glow discharge cleaning which, even after exposure to air, yields desorption coefficients after rebaking of about zero or even slightly negative, i.e. more residual gas molecules are adsorbed as ions than secondary molecules are released (beam pumping).

In the CERN ISR, in which, for geometrical reasons, S_{eff} could be considered an approximate upper value for future storage rings with lumped pumping, the η ($\leqslant 4$) resulting from normal 300°C vacuum bakeout suffices for critical currents of approximately 30 Amps. From laboratory measurements it is known that the desorption from condensed layers of H_2 by H_2^+ ions of ~ 5 keV can approach 10^5 mol./ion and 10^3 mol./ion for N_2/N_2^+ [3,4]. Although the build-up of such substantial condensed layers should be an extremely slow process (or even for H_2 impossible) in the UHV of a storage ring, the situation is clearly critical unless these potentially large desorption coefficients are safely balanced by a large effective cryopumping speed. This may be estimated using equ. (1) in which the volume rate of removal of molecules by cryopumping per unit length replaces S_{eff}. The standard gas kinetic formulae give this as $\frac{1}{4}\pi D\bar{v}\alpha$, i.e. we have $P = P_o(1-4I\eta\sigma(\pi D\bar{v}\alpha e)^{-1})^{-1}$ ... (2) where D is the cold bore diameter, $\bar{v}$ the mean molecular velocity and α an effective sticking factor which might include further molecular/molecular desorption. Fig. 1 shows the parameter $(I_c/\alpha D)$, where the critical current is defined as $I_c = \pi D\alpha e\bar{v}(4\sigma\eta)^{-1}$, as a function of η for H_2 and N_2 for several values of $\bar{v}$ expressed in equivalent molecular temperatures or energies. Laboratory

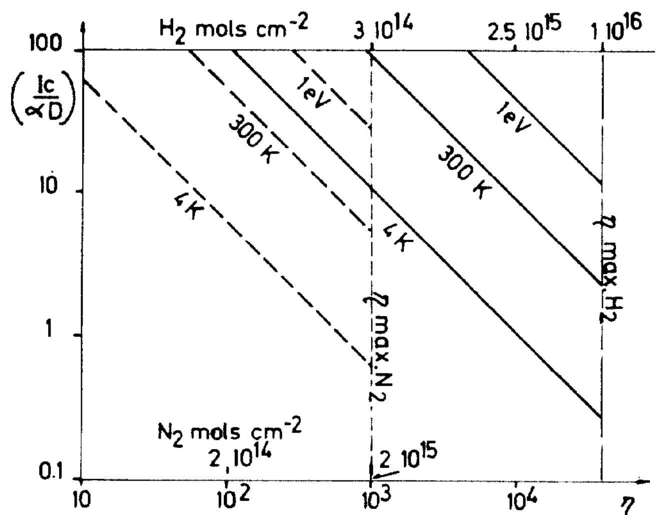

Fig. 1 $(I_c/\alpha D)$ Amp cm^{-1} as function of η (or surface coverage at a primary ion energy of 5 keV) for H_2 and N_2 at various desorption energies

measurements permit η, which passes a maximum of $4\cdot10^4$ mol./ion for H_2/H_2^+ and 1.10^3 for N_2/N_2^+ for primary ion energies of 5 keV, to be expressed as a function of the surface coverage θ. However, although η scales almost linearly with the primary ion energy the usefulness of these relations is still limited since neither α ($0<\alpha<1$) nor $\bar{v}$ is known. The sticking coefficient α is probably $\simeq 1$, especially if $\bar{v}$ corresponds to thermal energies, and it could be measured in the lab. By contrast, the mean desorption velocity is not easily measurable and, plausibly, it could range from values corresponding in energy to the 4 K surface to the eV range typical in sputtering. To overcome these difficulties and obtain an estimate of the compound parameter $\eta/\alpha\bar{v}$, to verify the validity of equ. (2) and to expose any unexpected limitation, an experimental cold bore test section has been constructed and used in the CERN ISR. Primarily the purpose is to permit a measurement of the equilibrium pressure P (and hence I_c) as a function of I for various initial conditions of surface contamination (η) and temperature. The available temperature span should be large to be able to investigate the various cold- or cool-bore variations which have been proposed. Finally, it should permit an interesting confirmation of pressure bump theory under ideal conditions of a one gas component system with constant η and surface conditions.

the normal machine aperture). These baffles transmit less than 10^{-3} of the incident ambient temperature radiation.

This cryostat offers the appreciable advantage in that the N_2 cooled shield and the cold bore do not have thermal contacts except via the necks and consequently there are no intermediate ill-defined temperature regions. To permit circulation of the image current across the corresponding gap the latter is bridged by 8 short metal wires. The temperature on the cold bore is measured by means of four gold + 0.07% iron versus chromel thermocouples. The electrons produced by the

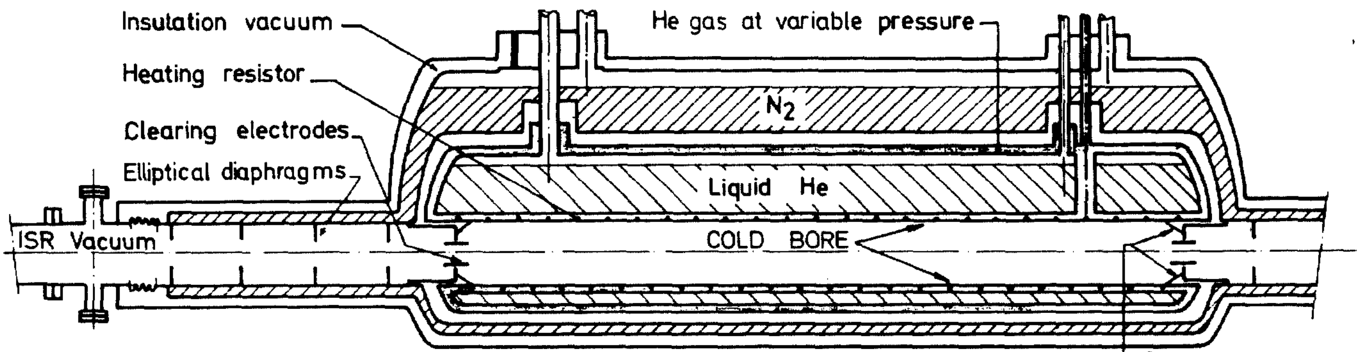

Fig. 2. Cold-Bore Cryostat - Schematic Outline.

2. Apparatus

2.1 Construction. The cold bore cryostat (see Fig. 1) consists of a central body (a horizontal cylinder of approximately 200 cm length and 60 cm diameter) to both ends of which a cylindrical extension (about 100 cm length and 30 cm diameter) is connected. This central body contains, concentrically, the liquid nitrogen and liquid helium vessels with capacities of 200 and 135 liters respectively. The vacuum between the room temperature outer wall and the N_2 vessel is independent of the main vacuum which is common to the helium vessel and the ISR. Eccentric and traversing longitudinally both vessels is a tubular passage through which the proton beam circulates during normal operation. All the walls of the He vessel are surrounded by a second concentric wall, the central cylinder of which is the experimental cold bore. These two concentric vessels are welded to each other at the two necks of the cryostat, and the volume which they enclose, communicating with the outside, can be filled with He gas at any desired pressure. The equilibrium temperature of the cold bore is therefore defined by the balance between the heating by infrared radiation absorption and cooling by gas conduction to the He vessel. To speed up temperature variations and also to help in stabilising the temperature, a thermocoax heating element is wrapped around the wall of the cold bore. Good thermal contact, as well as the required temperature homogeneity, are insured by a half mm thick copper layer electrolytically deposited on the cold bore after the mounting of the heating element. The operating temperature range is between 2 and 300 K. The liquid N_2 cooled shield, which surrounds completely this double central vessel, also extends in the side arms to protect the cold bore from infrared radiation emitted by room temperature walls. This radiation would not only increase the liquid helium losses, but would also desorb molecular H_2 from the cold bore surfaces and interfere with the ion induced desorption to be investigated[4]. The N_2 cooled extensions, 16 cm diameter and blackened along their full length of 70 cm, have therefore been provided with 5 elliptical diaphragms (with axis of 16 and 5 cm corresponding with

beam ionisation inside the cold bore are cleared by two pairs of electrodes at the two ends of this volume. The corresponding clearing current can also be used for monitoring possible pressure bumps, which could pass unnoticed from the outside due to the high sticking coefficient on the cold bore.

2.2 Vacuum and cryogenic performance. The ultimate pressure obtained in the laboratory after baking, using two adjacent sputter-ion and Ti-sublimation pumping stations (about 1500 ℓs^{-1} for N_2) is $\simeq 6\times10^{-12}$ torr with the cryostat at room temperature and 2×10^{-12} torr with the cold bore at 4.2 K. The consumption of liquid N_2 is 35 ℓ per day, thus providing an operating time between refills of 5 days. The consumption of liquid He is 6.7 ℓ per day, and the corresponding life time about 20 days. This consumption is unaffected by the level of liquid N_2. In contrast, it increases if the fraction of the He gas escaping from either of the two necks of the He vessel is below 25% of the total. The temperature of the cold bore is the same as that of the He bath (within 10^{-2} K) when the He pressure inside the double wall of the central vessel is not lower than 1 torr. For pressures below 10^{-3} torr, when the gas flow is molecular, the thermal conductivity is proportional and the temperature difference inversely proportional to the gas pressure in so far as the accommodation coefficient of the molecules to the walls does not change. In the present case a temperature difference of 4 K (i.e. 8 K on the cold bore) is obtained when the He pressure is about 1×10^{-4} torr.

Particular care has been put in defining the best procedure to be followed for obtaining known and homogeneous coverages of H_2 and N_2 gases on the surface of the cold bore. The standardised procedure is as follows: the gas is first injected at one extremity, resulting in a coverage decreasing very sharply towards the opposite end of the cold bore. The temperature is then raised high enough to yield a pressure in the cold bore region in the range of $\gtrsim 10^{-8}$ torr. At this pressure the gas spreads uniformly in a few minutes, the result being ensured by equal pressure readings on the two sides of the cold bore (when the temperature is first raised the pressure increases much more on the side of the injection). The temperature is then lowered quickly and the gas adsorbed again on the cold bore. The only difference of procedure when handling H_2 and N_2 is that in the latter case the baffles at the ends of the cold bore must be kept at a temperature not lower than 120 K during this operation to prevent them from pumping when the pressure is raised.

4. Experimental Observations in the ISR

When installed in the ISR the UHV performance of the cold bore was excellent - pressures measured on gauges close to each end were $\sim 1.10^{-11}$ torr after bakeout and $\sim 2.10^{-12}$ torr after cooling to 4 K. Performance in the presence of an ISR beam was less satisfactory, with persistent run-away pressure instabilities at about 16 A which curtailed the performance of the machine. It must be stressed that this behaviour was probably due to an unfortunate mechanical design in relation to electron clearing and nothing whatsoever to do with the operating temperature - the same limitation being observed equally at ambient temperature or 4 K. Nevertheless, this effect marred the measurement of any quantitative true cold bore effects and the following low temperature observations must be taken as essentially qualitative and provisional until they can be repeated after improving the electron clearing aspects of the installation.

At ambient temperature and 10^{-11} torr the behaviour of the cold bore installation was entirely normal up to $\sim$14 A. At this point unusually rapid and catastrophic pressure instabilities set in which carried the pressure virtually instantaneously into the 10^{-9} - 10^{-8} torr range. Such pressure bumps, with no warning of their onset, have not previously been seen on the ISR. The magnitude of this pressure run-away could be influenced in an erratic and rather uncontrollable manner by altering the potential on the clearing electrodes (see Fig. 2) or by placing an additional beam pulse on the injection orbit. These observations have led to the conclusion that the phenomenon is to be associated with gas release from the walls stimulated by electron and/or ion bombardment, the whole process being triggered and then maintained by the minimum current level of $\sim$14 A and its interaction with partially uncleared pockets of electrons trapped in between the diaphragms of the nitrogen cooled baffles.

Cooling the cold bore to 4.2 K (and radiation baffles to 77 K) gave a stable base pressure of 2.10^{-12} torr. Behaviour in the presence of an ISR beam was practically identical with that seen previously when operating at ambient temperature. A similar pressure run-away now occurred at $\sim$18 A; effects of clearing voltage and injected pulses remained as before. This close similarity supports the conclusion that the pressure instability was occurring in the baffles since the enormous cryopumping speed now available in the central cold bore at 4 K should have strongly modified any pressure bump in this region. By injecting slowly with a few pulses at a time it was possible to coax 23 A into the machine without exceeding the initial pressure bump of 10^{-9} torr at 18 A. This effect, already seen when operating at ambient temperature, is again in complete contrast to the normal ion induced pressure bumps frequently encountered on the ISR.

While at 4.2 K a large quantity, estimated as equivalent to several tens of monolayers, of H_2 was injected into the system. At this temperature the saturated vapour pressure is high ($\sim 10^{-6}$ torr) and the surface coverage equalises rapidly. The system temperature was then lowered to 2.5 K where the H_2 saturated vapour pressure is $\sim 10^{-13}$ torr. In practice, after exposure to 10^{-6} torr, the vacuum gauges take a considerable time to approach their equilibrium reading and the measurements reported here had to be made while the gauges were still reading in the 10^{-10} torr range. This is essentially a contamination effect in the part of the system at ambient temperature. In the central cold bore tube at 2.5 K with the heavy layer of condensed hydrogen the pressure should have rapidly reached the equilibrium value of $\sim 10^{-13}$ torr or rather, as is estimated from radiation effects, the value of $\sim 4.10^{-12}$ torr[5]. In this condition a beam of 15 A was stacked in the ISR without difficulty. Dumping this beam gave a barely discernible pressure drop ΔP of 1.10^{-11} and 3.10^{-12} torr on the gauges at each end of the cold bore. Applying equ. (2), which may be written as $I_c = I(1 + P_o/P)$, and using $P_o = 4.10^{-12}$, I = 15 A, one obtains the critical current I_c of 21 A or 34 A. These values should probably be regarded as lower limit estimates since other extraneous effects could be contributing to the observed ΔP. A second stack at 2.5 K provoked pressure run-away at 17 A. The behaviour appeared similar to both that at 4.2 K and that at ambient temperature, i.e. it was probably not in the central cold bore region. A third stack at 2.8 K (which raises the saturated vapour pressure P_o of H_2 to $\sim 1.10^{-10}$ torr) produced a pressure run-away at 15 A which, as previously, could be influenced by the potential on the clearing electrodes. Again, injecting slowly a few pulses at a time, it was possible to achieve a current of 24 A without exceeding a critical current but with an unstable pressure bump of $\sim 10^{-9}$ torr.

5. Conclusion

A 2 m long helium temperature cold bore (diameter 16 cm) has been installed and operated in the CERN ISR. In the most critical, although probably impracticable, situation for the operation of a cold bore vacuum system where the surface is saturated with several tens of monolayers of H_2, it was possible to stack a beam of 15 A with an extremely small pressure rise and 24 A at 10^{-9} torr without reaching the critical current. The first result suggests an extrapolated critical current in excess of 30 A. The second shows that it is at least as high as 24 A. A practical cold bore system should never reach this degree of contamination and, hence, should be at least as stable. The vacuum system, whether at ambient temperature or cold gave other vacuum problems apparently associated with electron clearing in the radiation baffles of the transition region between ambient and helium temperatures. This will be modified and experiments continued but one lesson to be drawn is that careful attention must be paid to the mechanical and geometrical aspects of these transitions.

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