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# COLD BORE EXPERIMENTS AT CERN ISR

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## Summary

At the beginning of 1978 a new cryostat was installed in the ISR to study the vacuum behaviour of a cold chamber in presence of intense proton beams. The cryostat permits cooling 1.3 m of the elliptical standard ISR vacuum chamber to any temperature in the range from 2.3 K to ≃ 200 K. The connection of the 'Cold Bore' to room temperature regions is made via elliptical bellows without baffles for thermal radiation. Proton beams of intensities up to 40 A were circulating inside the Cold Bore in different experimental conditions for times of the order of 24 h. In one experiment about 10 monolayers of $H_2$ were condensed at 2.3 K to produce the situation which, according to theoretical estimates, should provide the highest chance of observing a beam induced pressure rise. In another experiment, the Cold Bore was exposed to air and subsequently pumped and cooled without baking, to simulate the case of a cold unbaked machine. Under all conditions the vacuum remained perfectly stable. Although experiments are still in progress, the available results indicate that the vacuum of a cold bore machine would be stable to above 40 A in the ISR geometry.

## 1. Introduction

An important decision to be taken when designing superconducting Proton Storage Rings is whether the vacuum chamber should be maintained at room temperature or cooled down with magnets. A cold bore machine would present many peculiar features, both with respect to design and operation. A few of these features are attractive, others are more of an inconvenience. Advantages and disadvantages have been discussed by many authors and recently summarised[1]. Besides practical implications a necessary condition to be fulfilled is that of the vacuum stability. Circulating protons result in ion bombardment of the vacuum chamber by ionising residual gas molecules and accelerating the ions so produced to the surrounding walls. Depending on surface conditions, gas release may lead to unstable pressure rises when not balanced by an adequate pumping speed. A cold bore solution appears particularly promising in this respect since the vacuum chamber itself becomes a cryopump. However, the pumping action of the walls may lead to large gas coverages and consequently to large ion induced desorption.

By equating the rates of degassing and wall pumping and in absence of lumped pumping stations, it can be derived[1] that the pressure runs away when the current of the circulating proton beam exceeds a critical value defined as $I_c = \pi D\ \alpha e \bar{v}\ (4\sigma\eta)^{-1}$ (1). In this equation $\pi D$ is the perimeter of the vacuum chamber, $\alpha$ the sticking probability and $\bar{v}$ the average speed of the desorbed molecules, e the electron charge, $\sigma$ the ionisation cross-section of the gas molecules and $\eta$ the yield of ion induced gas desorption. The various parameters of equ. (1) will be discussed together with the experimental results in section 3. Among them, only $\bar{v}$ is completely unknown, and difficult to measure in laboratory experiments.

To obtain information on this quantity, to check the validity of the physical model leading to equ. (1) and directly observe the vacuum behaviour of a cold bore chamber, a specially designed cryostat was installed in the ISR during January 1976. The cryostat and the measurements carried out in the following year are described in detail in reference 1. Unfortunately, these experiments were spoilt by unexplained pressure spikes which appeared almost independently of the experimental conditions (bore warm or cold, with or without condensed gas layers), at circulating current intensities between 14 and 18 A. The pressure spikes were not produced by the classical ion desorption mechanism and not relevant to our study. The cryostat disturbed ISR operation and no simple way of curing it was found. The decision was then taken to construct a new cryostat of simpler design, which was installed in the ISR during January 1978.

## 2. New cryostat (Fig. 1)

The cold bore vacuum chamber is 1300 mm long and of elliptical cross-section (160 × 54 mm). This chamber is connected to the ISR vacuum system by elliptical bellows (182 × 70 mm) about 300 mm long. Cooling is provided by LHe contained in a horizontal cylindrical vessel of 450 mm diameter and 200 litres capacity. The He vessel is protected against room temperature thermal radiation by a shield cooled by the boil-off of He gas. Both the He vessel and the shield are immersed in the same vacuum which is independent of the main vacuum of the ISR. Bakeout at 300°C is achieved by 4 resistors located in the liquid He vessel.

### 2.1 Cold Bore Chamber in the ISR

In the absence of thermal radiation shields at the entrances of the cold chamber, a very large heat input is to be expected. Mainly to reduce the latter, elliptical cross-section was preferred to the circular section of the previous cryostat. This choice provides other advantages. First, the cryostat can be made shorter because the importance of the end effects during vacuum stability experiments depends on the ratio of the length to the equivalent diameter of the cold chamber. Furthermore, a smaller perimeter results in lower values of $I_c$ (equ. (1)). This feature is important because it provides a higher chance of observing pressure rises - the key for interpreting the behaviour of the cold bore. To minimize the risk of unwanted pressure instabilities during physics runs, the cold bore chamber was argon discharge cleaned according to the standard ISR procedure[2]. In the final installation, at each end of the cryostat, a pumping station (Ti sublimation and sputter ion pump) was connected via a large aperture valve. These valves are closed when gases are injected and during vacuum stability runs, to better approach the situation of a cold bore machine without lumped pumping. As in the previous installation, the electrons produced by the beam ionisation inside the cold bore are cleared by two pairs of electrodes at the two ends of this volume.

### 2.2 Vacuum and cryogenic performance

The cryostat can be heated from 20 to 300°C in 8 hours by means of the internal resistors. After standard bakeout in the ISR (24 h at 300°C) a pressure of about $2 \times 10^{-12}$ torr is obtained at room temperature. Upon cooling to LHe temperature the pressure is about $10^{-12}$ torr. For cooling a LHe bath method was chosen for many reasons. The bath insures temperature homogeneity and stability, provides a precise temperature indication and makes the stabilisation of temperatures below 4.2 K much easier. This last feature is of practical importance because the operating temperature of the magnets in a superconducting machine could range between 2.5 and 4 K. The boil-off is 9.3 ± 0.2 litres of liquid per hour. This corresponds to a total heat load of about 6.5 W, of which 4.5 W due to room temperature radiation enter-

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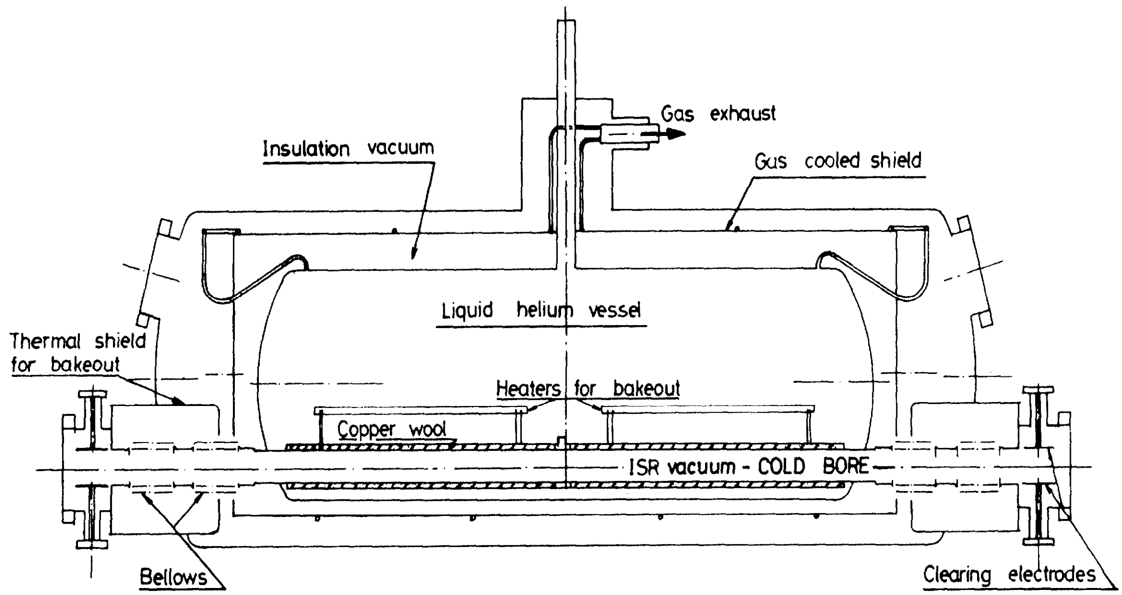
Fig. 1 The new cryostat




ing from the end apertures and 2 W to thermal conduction along the elliptical bellows. The cold escaping gas circulates in a pipe welded to the thermal shield. The latter is silver-plated outside and reaches, at equilibrium, temperatures ranging from 30 to 50 K at its various points. The losses due to thermal radiation produced by this shield and absorbed by the outer wall of the He vessel are negligible.

Liquid He is transferred from a 500 litre storage dewar which is filled during shutdown periods and is normally located close to the cryostat in the ISR tunnel. A transfer line permanently connects the cryostat to the storage dewar and the cooling can be carried out and controlled from outside the tunnel. The endurance for ISR experiments is ≈ 20 h for a single LHe transfer and about twice as much if the full capacity of the 500 ℓ storage dewar is used in subsequent transfers. Cooling of the cryostat from room temperature and filling with LHe requires about 3 hours. This operation is carried out by means of a special transfer line in which a heating element is brazed on the He pipe. The heater permits one to vaporize the liquid helium during transfer and to heat up the resulting gas to any desired temperature in the range 4 - 200 K. The helium is introduced in the helium vessel at the central point of the cold bore chamber, circulates between the ISR and a protection chamber (across the copper wool, see Figure 1) and is then exhausted via the shield. This transfer line was designed to permit stabilization of the cold bore at temperatures above the range covered by LHe. Such higher temperatures are required to get a reasonably uniform coverage of the cold chamber when gases heavier than $H_2$ are injected[1].

## 3. Experiments in the ISR

Beams of intensities higher than 30 A did not induce any pressure rise with the cryostat kept at room temperature. On the contrary, when valving off the two nearest pumping stations, an appreciable pressure decrease was noticed at high currents. This effect, usually referred to as beam pumping, is observed in many other places of the ISR after argon discharge cleaning. It implies negative $\eta$ values, i.e. more impinging ions are trapped than gas molecules released, and becomes observable only in presence of low pumping speeds. For this reason subsequent cooling with liquid helium did not produce any noticeable effect. For the same $\eta$ value, cooling increases the pumping speed and consequently $I_c$ by many orders of magnitude (see equ. (1)). In other experiments the value of $\eta$ was enhanced by covering the cold bore with condensed gases ($H_2$ and $N_2$) or by simply omitting bakeout.

### 3.1 Condensed hydrogen

The most critical stability conditions might be obtained when a few monolayers of $H_2$ are condensed on the cold chamber. Among the gases which are commonly present inside UHV systems, condensed $H_2$ shows the highest values of $\eta$, which increases almost linearly with surface coverage and reaches a flat top value of about $5 \times 10^4$ at $10^{16}$ molecules/cm$^2$ for incident proton energies of 5 keV or higher[3 4]. Below 5 keV the flat top value can be expressed as $\eta = 10^4$ E (2) where E is the energy of the incident protons in keV[4]. For gases heavier than $H_2$ much lower yields were measured. For instance, $\eta = 10^3$ for condensed $N_2$ (coverage from 3 to $10 \times 10^{15}$ molecules/cm$^2$) bombarded by $N_2$ ions with energy above 5 keV[4]. Although not representative of a possible situation in a real machine (where the $H_2$ load would be too small), this experiment was performed hoping to obtain $I_c$ in a well defined surface coverage situation. After filling the cryostat with LHe, hydrogen was injected at one end of the cold chamber, for a total amount corresponding to a uniform coverage of $\approx 3 \times 10^{16}$ molecules/cm$^2$ or ≈ 10 monolayers. At the end of the injection, the same pressure of $3 \times 10^{-6}$ torr was obtained on both sides of the cryostat, showing that saturation was achieved on the whole length of the bore. The temperature of the cryostat was then reduced by pumping over the liquid helium bath from 4.2 to 2.3 K. Previous experiments carried out in the laboratory showed that at this temperature the $H_2$ saturation pressure reaches the low $10^{-10}$ torr range and then levels off due to desorption by thermal radiation[5] entering the cryostat from the ends. Upon reaching a pressure of $\approx 2 \times 10^{-10}$ torr the ISR sector valves were opened and a proton beam injected into the machine. A slight pressure increase was observed at 6 A and the increases became more pronounced with higher beam current. At constant currents the pressure recovered at a rate which also increased with the beam intensity. At 35 A the pressure went through a maximum of about $6 \times 10^{-10}$ torr on both sides of the cold bore and then kept decreasing even when the current was raised to 36 A. All pressure variations were predominantly $H_2$ (more than 95%). The maximum current obtained was 36 A and the beam was kept for 6 h. During this time the pressure decreased continuously and finally reached a value of $1 \times 10^{-10}$ torr, i.e. lower than before circulating a beam. When the beam was dumped, its intensity was 33 A. Dumping produced a pressure decrease of $1.5 \times 10^{-11}$ torr.

Interpretation of these results is difficult. Taking $r = 5.7$ cm, $\sigma = 2.3 \times 10^{-19}$ cm$^2$, and assuming that the energy of the ions up to intensities of the order of 30 A is 1 keV per 10 A and that the desorbed molecules have the temperature of the cold chamber (2.3 K) and consequently that $\alpha = 1$, from equ. (1) and (3) follows $I_c = 10$ A. This value could be compatible with the observed pressure increase at 6 A. On the other hand, if the molecular temperature is 300 K (at which $\alpha \simeq 0.7$) the same equations give $I_c = 28$ A. This value could be considered as an upper limit because it would imply that about 50% of the energy of the impinging ions is used to desorb $H_2$ molecules. However, the simple theory on which these estimates are based does not readily explain the pressure decay at constant beam current. This decay indicates a decrease of desorption yield which, we believe, might be produced by $H_2$ rearrangement consequent to non-uniform ion bombardment on the perimeter of the vacuum chamber. The observed decay times are compatible at these pressures with the rearrangement of the relatively small quantities of $H_2$ condensed on the cold bore. To clarify this point we plan to repeat the experiment with larger $H_2$ coverage to render the effect of rearrangement small during the test.

### 3.2 Condensed $N_2$

A quantity of $N_2$ corresponding to an homogeneous coverage of $6 \times 10^{16}$ molecules cm$^2$ (or about 20 monolayers) was injected with cold bore at $\simeq 15$ K. This layer is thicker on the injection side, where the gas first impinges on cold surfaces. In the present case a coverage of the order of 100 monolayers is estimated at the entrance of the cold bore. After gas injection the layer was frozen by cooling to 4.2 K and the cryostat filled with LHe. After opening the ISR sector valves, a beam of 31 A was stacked with perfectly stable vacuum. At that time (the two nearest pumping stations were valved off), the pressures were $3 \times 10^{-11}$ torr at the injection side and $3 \times 10^{-12}$ torr at the other extreme of the cold bore. An important pressure spike appeared suddenly (pressure to $10^{-8}$ torr) and from this moment the spikes accompanied the experiment in spite of reduced beam currents and different beams stacked. The observed pressure spikes are clearly not produced by ion induced desorption. In ion induced pressure bumps, the pressure does not increase so suddenly and quickly, and it does not recover at constant beam current. Furthermore, beam dumping should result in a pressure decrease which was not observed in this experiment. Here the pressure spikes seem to be produced rather by electrical charging of the $N_2$ layer. The frequency of the spikes is in first approximation proportional to the rate of ion production inside the cold bore (beam intensity $\times$ pressure). A reasonable hypothesis is to assume that an electrical breakdown is produced when the electric field across the condensed $N_2$ layer reaches a critical value. The breakdown would result in local heating and gas desorption. Further experiments are needed to confirm this hypothesis. Although interesting from a basic point of view, the observed phenomenum does not present a real danger for cold bore machines. Even if assuming that such a machine can be operated in presence of a leak yielding locally a pressure of $10^{-9}$ torr, many years would be required to reach a coverage as in this situation.

### 3.3 Unbaked Cold Bore

For this experiment the cold bore ISR sector was exposed to air for one hour and then pumped and baked (300°C, 24 h) with exception of the cold bore chamber. The latter was kept at room temperature by circulating cold helium gas in the cryostat, and progressively cooled at the end of the baking cycle to about 90 K. Various beams of intensities ranging between 30 and 40 A were circulating for approximately 24 h, while the temperature of the cold bore was stabilized at various levels between 130 K and 4.2 K. The pressure was perfectly stable during the experiment and as low as $3 \times 10^{-12}$ torr at 4.2 K. In one case, when the cold bore was at 130 K and the beam (36 A) was dumped, an appreciable beam pumping for CO was noticed.

The main conclusion which can be derived from this experiment is that high intensity beams can safely circulate inside glow discharge cleaned unbaked chambers cooled to below 130 K. However, only at liquid helium temperatures is enough pumping speed provided for all gases by the cold chamber so as not to need some additional pumping. At liquid helium temperatures the safety margin for dynamic pressure stability is so large that the conclusions of the experiment can easily be extended to unbaked, undischarged chambers. Laboratory measurements[6] show that $\eta$ does not exceed 10 for these latter surfaces while values up to $10^4$ were shown to be tolerable by the experiment with condensed $H_2$. The transition regions between warm and cold chambers appear to be stable even in the most critical and unusual situation where they link baked and unbaked surfaces. Finally, the experiment shows that extremely low vacua can be achieved even if a vacuum system is only partially baked.

## Conclusions

Although many basic aspects of beam induced gas desorption from cold surfaces still need to be better clarified, we believe that the reported experimental evidence proves the feasibility of cold bore, unbaked Proton Storage Rings. To strengthen this conclusion we plan to run the ISR with this test section cold and unbaked for a period of about 3 weeks.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