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# A COLD-BORE VACUUM SYSTEM DESIGN FOR POPAE*

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## Abstract

We have made a conceptual design of a cold-bore vacuum system for the Fermilab 1000 GeV x 1000 GeV colliding beam facility (POPAE). A double wall vacuum system is used between magnets and cryopumped molecular traps between the cold-bore and warm straight section regions. The beam-induced pressure rise phenomena has been taken into account as well as the liquid helium leak rate between the cold magnets and the vacuum bore. Since beam for POPAE will be injected at the desired energy, there are no heat loads from accelerated beam or eddy currents and the cold-bore system appears very attractive. This design is based on the best experimental evidence available today.

## Introduction

It is natural to consider a cold-bore vacuum system for storage rings constructed with superconducting magnets. The continuously-distributed cryopumping may result in reduced aperture requirements, an improved packing factor in the machine lattice, and lower costs than a conventional vacuum system. Since beam for POPAE will be injected at the desired energy, there is no need for acceleration, so there are no heat loads from the accelerated bunched beam or from eddy currents, and the cold-bore system is very attractive.

The vacuum requirements of proton storage rings are determined primarily by the need to (a) avoid the beam-induced pressure rise observed at the CERN ISR, (b) clear trapped electrons and negative ions, and (c) provide low enough pressure so that backgrounds from beam-gas interactions can be tolerated by the experiments.

To meet these requirements, the presently designed system will use 6-cm ID aluminum vacuum chambers, operating at 4.5°K in the curved sections and at room temperature in the long straight sections. There will be a pressure of $10^{-11}$ Torr in the interaction regions, while the cold-bore pressure will be $\lesssim 10^{-13}$ Torr and may drop even further as residual gas molecules condense on the surface. The entire residual gas load forms only a very small fraction of a monolayer even if completely absorbed. It should also be noted that the outgassing rate at 4.5°K is essentially zero. A cryopumped transition region between the warm and cold areas will reduce molecular transmission by a factor of about 200. All connections in the lattice region will be welded and flanges will be used only in the warm sections of the rings.

The design of the present system is based on the best experimental evidence available today and appears to be an attractive solution. Similar cold-bore vacuum systems are planned for both the Fermilab Energy Doubler/Saver and for the Lawrence Berkeley Laboratory ESCAR project. While neither of these machines presents vacuum requirements as stringent as those of POPAE, the research and development program at ESCAR[1] has been useful in the design of the cold-bore vacuum system for POPAE. However, further experimental work will be undertaken to test these concepts with components designed specifically for POPAE.

## Beam-Gas Background

In colliding-beam experiments, background events can come from the circulating beam interacting with the residual gas in the vacuum and/or from beam particles striking the walls. The latter can be controlled by collimation and scraping. To maintain a sufficiently low beam-gas background, it is necessary to reduce the density of residual gas molecules by several orders of magnitude from that of a conventional accelerator. The vacuum system is designed to produce a vacuum of $10^{-11}$ Torr in the interaction regions, a value typical of the ISR. A 5 A circulating current will yield about $10^4$ interactions/s in 100 m of $10^{-11}$ Torr, compared with $10^8$ beam-beam events for a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$. Since this background is easily measured by running one beam at a time, it will not be troublesome even at much lower luminosity.

## Beam Neutralization

Electrons and negative ions produced by ionization of the residual gas become trapped in a potential well created by the Coulomb field of the proton beam. The trapped ions provoke an electron-proton transverse instability and also partially neutralize the beam, shifting the betatron tune of the circulating protons. To eliminate these effects, a semi-cylindrical clearing electrode of approximately the same diameter as the beam pipe and 15 cm long is placed between every magnet. This electrode will operate at a potential of up to 15 kV, while the bore tube itself will form the ground electrode. This potential is sufficient to keep the tune shift to $\leq 10^{-3}$.

## Surface Treatment and Bake-out

Of major importance is the proper processing of materials which go into the vacuum system. Experimental results[2,3] show that the following steps lead to acceptable outgassing rates:

1) Chemically polish all materials
2) Bake to 150° C in a vacuum furnace at $10^{-6}$ Torr
3) Glow discharge in argon and oxygen
4) Bake-out after assembly at 150°

*In situ* bake-out will be accomplished by flowing hot gas through the magnets.

This treatment is expected to result in an outgassing rate at room temperature of $4 \times 10^{-14}$ Torr - $\ell$ cm$^{-2}$ s$^{-1}$ with a residual gas composition of 99% hydrogen. As the curved-lattice section is cooled to 4.5°K, the outgassing rate in the cold-bore section goes essentially to zero.

## Surface Phenomena

There have been numerous arguments for and against cold bore.[4-6] One of these is related to the beam-induced pressure rise, or "pressure bump phenomenon" observed at the CERN ISR. This effect is caused by residual gas ions being accelerated into the

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vacuum chamber wall by the electrostatic potential of the stored beam. This liberates adsorbed molecules and raises the chamber pressure, which in turn results in more ions being generated. At a critical current, $I_{crit}$, the effect runs away and leads to a local pressure bump which destroys the beam.

For the geometry of POPAE with a cold-bore vacuum system, the Fischer equation predicts[7,8]

$$\eta\ I_{crit} = 8 \times 10^4 \text{A}.$$

The desorption coefficient $\eta$ (number of atoms released per incident ion) depends on the mass and energy of the ionized residual gas atoms, as well as the surface conditions. In POPAE, the only important residual gas is expected to be hydrogen, and the beam-to-wall potential will be approximately 500 V, so the bombarding ions will be $\sim$ 0.5 keV protons.

Erents and McCracken[9] have studied the desorption of various gases condensed on a coppper surface at liquid-helium temperature. Using 5 and 20 keV protons, they showed that the desorption coefficient is independent of the thickness of surface coverage if the coverage is thicker than one monolayer ($\sim 3 \times 10^{15}$ molecules/cm$^2$), but decreases with thinner coverage. This trend was true for all gases studied. For hydrogen, which has the largest yield, they found that for a thickness of a few monolayers $\eta \approx 5 \times 10^4$ atoms/ion, while for coverage of one-tenth of a monolayer, $\eta \approx 400$ to 2000 atoms/ion, depending on the experimental conditions.

The authors have interpreted their results in terms of a thermal-spike model, although the model could not explain all aspects of the experimental results. According to the thermal-spike model, the incident proton will go through the thin layer of hydrogen, and most of its energy will be deposited in the metal substrate, generating a thermal spike in the substrate. From the energy-range relation and the range straggling of protons of a few keV in copper, one can calculate the radius of the thermal spike. The energy of the incident proton will be given partly to the lattice of the substrate and partly to the orbital electrons. Because the mean free path for electrons at these temperatures is very long, the energy transferred to the electrons will be dissipated over a large volume and only give a small temperature rise. Therefore, the model considers only energy given directly to the lattice by the incident proton.

For POPAE, with 0.5 keV protons on an aluminum substrate, the energy transferred to the lattice is 200 eV and the spike radius is 200 Å, compared with 420 eV and 210 Å for Erents and McCracken's experiment of 5 keV on copper. This suggests a factor of two less yield than for 5 keV protons on copper, $\eta \approx 200$ to 1000 for 0.1 monolayer of hydrogen

The expected coverage of adsorbed molecules on the cold sections of the POPAE vacuum chamber is a very small fraction ($\sim 10^{-6}$) of a monolayer. Even taking a very pessimistic set of values (0.1 monolayer of hydrogen and McCracken's larger value for $\eta$ without the factor-of-two improvement from lower ion energy) gives:

$$I_{crit} = 40 \text{ A}.$$

The true value will likely be considerably larger, and this effect should be negligible in the cold bore.

Experience at the CERN ISR shows that with care the warm sections of the machine should not encounter pressure-bump problems for beams of up to a few tens of amperes. In the transition section between warm and cold sections, where one expects high concentrations of condensed residual gas, the cryosorbing surface will be hidden behind baffles, and the beam-induced ions will not reach the condensed gas.

There has been some speculation that water vapor frozen on the chamber surface may release hydrogen molecules when bombarded by ions.[6] A study of hydrogen released from frozen water and hydrocarbons by ion bombardment shows the yield will be negligible in POPAE. As an example, we have considered a pessimistic case in which the surface is covered with a monolayer of ice. Ghormley and Stewart[10] have found that the number of hydrogen molecules released per 100 eV of energy deposited in ice is $G \lesssim 0.1$. Using this value and a dE/dx for 0.5 keV protons in water of 0.5 eV/Å, the expected hydrogen yield for a 5 A stored beam is 250 molecules cm$^{-2}$ s$^{-1}$ ($3 \times 10^{-6}$ monolayer per year if all of the released hydrogen should condense). The actual yield probably will be even less, because such a slow proton would lose most of its energy to excitation of orbital electrons rather than ionization of the water molecules.[11] Since the G-values of the hydrocarbons and water are comparable, a similar conclusion can be drawn for hydrocarbons. We therefore expect no significant release of hydrogen from ion bombardment.

## Mechanical Design of the Cold-Bore Region

In this region, care must be taken to avoid helium leaks into the ultrahigh vacuum system. As shown in Fig. 1, the bore tube in each magnet is a thick monolithic structure which extends sufficiently far into the transition region between magnets that there is no weld between the helium region and the inner vacuum system. For helium to leak into the ultrahigh vacuum, it must either penetrate the integral seamless aluminum structure or go through two welds separated by the insulating vacuum.

Since the insulating vacuum will be cryopumped by some 300 cm$^2$ of cryosorption material in each transition region, it is extremely unlikely that significant amounts of helium (or other gases) will penetrate into the ultrahigh vacuum.

Between magnets the inner tube containing the ultrahigh vacuum is formed by a stainless-steel tube and stainless-steel bellows, welded at each end to an Al-SS bonded transition piece. It contains a bellows shield to reduce the impedance seen by the beam, a ceramic insert for the clearing electrodes, and a welded can containing a baffled titanium sublimation pump. This unit will be prefabricated, then leak checked and temperature cycled between 150$^\circ$C and 4.5$^\circ$K. Only one aluminum weld per magnet will be required on the inner tube during field assembly.

A heat shield at 90$^\circ$K surrounds the outer vacuum so that between magnets the region both inside as well as outside the inner tube will be cryopumped. At 4.5$^\circ$K, there should be a completely negligible leak rate from outer to inner system through any component of the inner tube. Standard commercial components for the ultrahigh vacuum applications have quoted leak rates of less than $10^{-10}$ standard cm$^3$/s. The Al-SS transition pieces and the all-welded nature of the inner vacuum vessel should have leak rates no worse than this. Since we will operate the outer vacuum at a room-temperature pressure of $10^{-5}$ Torr, this gives a leak rate of $10^{-15}$ Torr- /s. Even if the 6 welds and Al-SS transition pieces were to each leak at this rate, we would still have a total leak of only $6 \times 10^{-15}$ Torr- /sec in each transition region. This amounts to less than $10^{-2}$ monolayer per year.

Since all components will be leak checked over several temperature cycles before installation, the possibility of troublesome leaks developing is minimal. Test assemblies will be used to optimize the welding technique in order to minimize the possibility of leaks from the aluminum weld made in the field.

If leaks do develop, they will be difficult to locate. Provisions will be made for connecting vacuum devices (such as gauges, leak detectors or gas analyzers), mounted on adapter tubes, into the vacuum system at the base of the titanium pump housing. After evacuation and the completion of tests, the adapter tubes can be severed and sealed off with a pinch-off tool, and the vacuum devices removed from the system without opening the bore tube to the atmosphere.

## Warm-to-Cold Transition and Interaction Region

To prevent significant molecular streaming from the $10^{-11}$ Torr warm-bore straight-section region into the cold-bore curved region, a cryosorption pumping section will be placed between the warm sector valve and the cold bore. A Monte Carlo study[12] of the transmissivity of a cylindrical pipe indicates that for a 6-cm ID bore tube and a sticking coefficient of 0.8, a 70-cm pumping region will reduce transmission by a factor of $4 \times 10^{-3}$ for an initial uniform gas distribution. For a cosine distribution, this becomes $6 \times 10^{-3}$. The tubular condensation cryopump[13] developed at CERN has a 70-cm pumping length and a limiting pressure in the $10^{-14}$ Torr range. It appears to be eminently suitable for our application, but if additional reduction in the transmission is required, a longer cryopump can be used. As an extreme example, a 6-m pumping region should reduce the transmission by another two orders of magnitude.

On the warm-bore side of the cryopump will be a sector valve, the roughing and turbo-molecular pumps, a second sector valve, and a fast-acting flapper valve capable of closing within 20 ms after a vacuum failure. The cold connections will be welded, while those at room temperature will be flanged. The warm-bore regions will be maintained at $10^{-11}$ Torr by pumping stations every 5 m.

## Pumpdown Procedure

Leak checking and assembly will proceed one sector (one-twelfth of the rings) at a time. After assembly, the sector will be roughed down to $10^{-3}$ Torr with the roughing and turbo-molecular pumps at each end. The insulating vacuum system surrounding the inner bore tube will also be roughed down. For *in situ* bake-out, helium gas at 150°C will be passed through the magnet system in place of the usual liquid helium. Pumping will continue from the ends during this time, and as the pressure near the pumps drops to the $10^{-5}$ Torr level, the closest sublimation pump will be activated. As the pressure drops along the length of the sector, succeeding pumps will be turned on and the pressure will drop to $10^{-7}$ Torr. Then the heat source will be turned off and cooldown to room temperature will occur. The anticipated outgassing rate is $4 \times 10^{-14}$ Torr $cm^{-2}$ $sec^{-1}$ at room temperature. Cooldown to 4.5°K could then start. The total residual gas load at $10^{-7}$ Torr is only $10^{-6}$ monolayers. As cooldown to 4.5°K starts, the outgassing rate becomes smaller and becomes essentially zero at 4.5°K.

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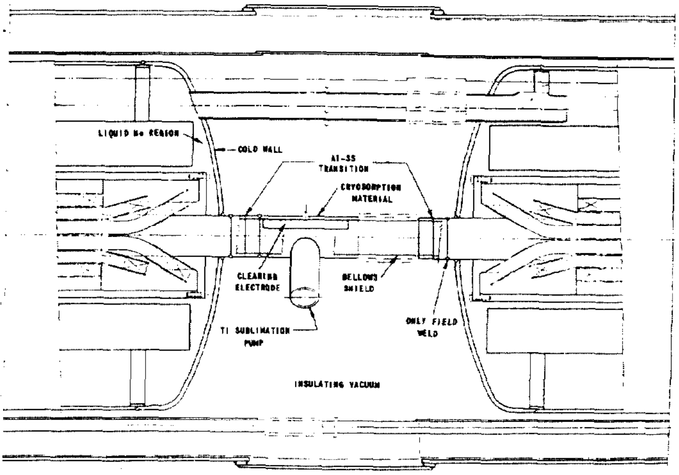

Fig. 1 Cold-bore transition assembly between magnets