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CRYOGENIC DESIGN OF THE STOCHASTIC COOLING PICK-UPS FOR THE CERN ANTIPROTON COLLECTOR (ACOL)

by

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ABSTRACT

Stochastic cooling, a technique of prime importance for obtaining antiproton beams usable at high-energy colliders, requires wide-band and low-noise signal acquisition and processing. For this purpose, the CERN Antiproton Collector (ACOL), presently under construction, is equipped with six beam pick-up stations operating at cryogenic temperatures. Each station consists of a high-vacuum vessel housing two mobile arrays of pick-up electrodes, cooled to about 100 K by radiation to a surrounding thermal shield, and two preamplifiers kept below 20 K. Refrigeration is provided by a pair of two-stage Gifford-McMahon helium cryogenerators, thermally linked to the preamplifiers and to the thermal shield. The cryogenerators also cool activated charcoal cryopanels, in order to maintain a residual pressure in the vessel below 10^{-8} mbar. The choice of such cryogenic options is dictated by performance (steady-state and cool-down), simplicity of operation and maintenance, and high reliability.

INTRODUCTION

The fruitful use of intense antiproton beams for high-energy physics has been made possible by the invention of beam condensation techniques, and especially of stochastic cooling[1,2], which has been extensively applied to the CERN antiproton source, the Antiproton Accumulator (AA)[3]. The present accumulation rate is expected to increase by an order of magnitude after the commissioning of a second ring, the Antiproton Collector (ACOL)[4,5], which will surround the AA (Fig. 1). One of the main functions of ACOL is the fast shrinking or "cooling" of the beam transverse dimensions[6]. The cooling is obtained by observation and correction of microfluctuations in the beam structure which induce ultra-low level signals in the pick-ups. Such weak signals can only emerge from the thermal noise if the pick-ups are operated at cryogenic temperatures (Table 1).

Table 1. Characteristics of ACOL Stochastic Cooling System

Noise temperature	60	K	Beam signal	2.3	pW
Bandwidth	1 to 3	GHz	Thermal noise	1.6	pW
Output power	2.6	kW	Electronic gain	148	dB

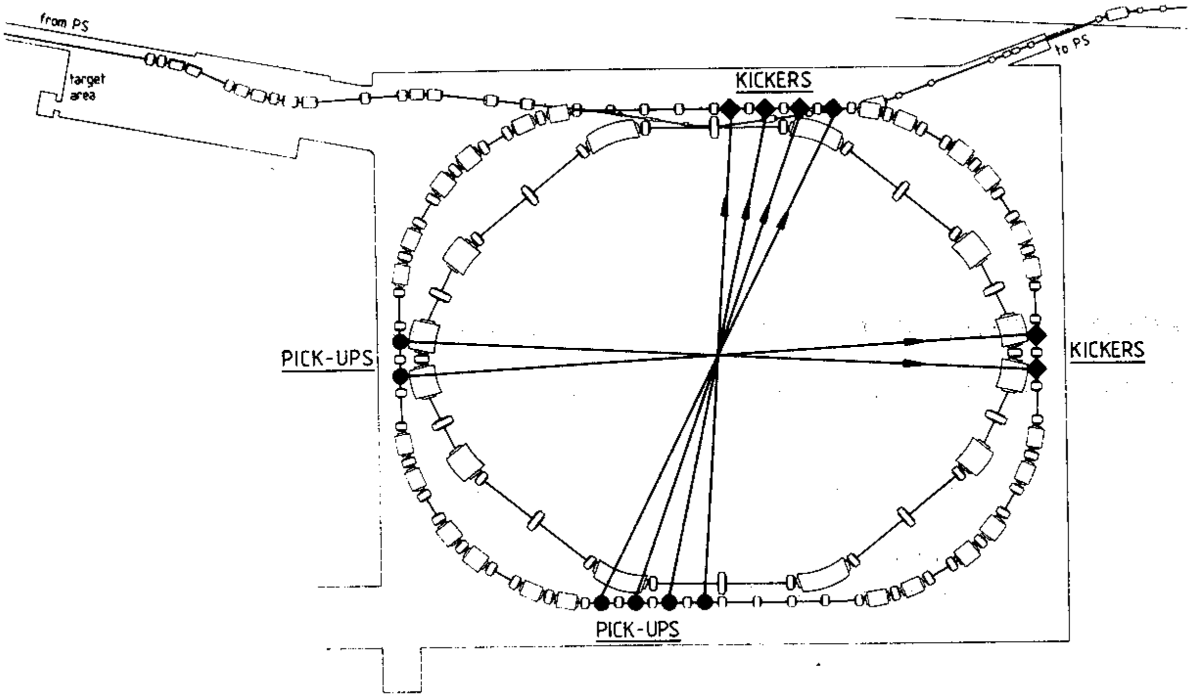

Fig. 1. Layout of AA and ACOL showing ACOL stochastic cooling system.

THERMAL NOISE SOURCES

The pick-up electrodes are composed of directional couplers arranged in rows above, below and on each side of the beam. All couplers in a row are connected to a two-way combiner board; one way terminates on the characteristic impedance of the line, a 50 Ω resistor; in the other way, all signals are summed up in power before being amplified in a very low-noise preamplifier. The noise temperatures result from resistive losses in the combiner and from the finite temperature of the resistors and preamplifiers. Resistive losses are kept low by maintaining the pick-up electrodes at about 100 K. As for the preamplifiers, it is intended to use gallium arsenide field-effect transistors (Ga As FET), the noise temperature of which also decreases with operating temperature. For this application, preamplifiers and termination resistors have to be cooled to less than 40 K: a design value of 20 K has been chosen.

DESIGN OF PICK-UP STATIONS

Each pick-up station (Fig. 2) consists of a cylindrical high-vacuum vessel, 0.5 m in diameter, 2.3 m in length, made of AISI 304L stainless steel, housing two mobile arrays of pick-up electrodes supported by two 2.2 m long aluminium alloy beams facing each other inside the vessel. In order to maintain a sufficient signal level, the electrode-supporting beams translate by about 45 mm each in order to follow the decrease in transverse dimensions of the particle beam envelope during the stochastic cooling process (about 1 s). This translation is achieved by means of two rigid AISI 304 actuating shafts supporting and accurately positioning (± 0.1 mm) the beams, via linear guides and an electrical actuator mounted outside the vessel. Each mobile assembly represents a mass of 25 kg aluminium alloy (beam) and 3 kg alumina (combiner boards).

Cryogenics

The design temperature of 100 K appears sufficient to permit the two electrode-supporting beams, which have an effective radiating area of

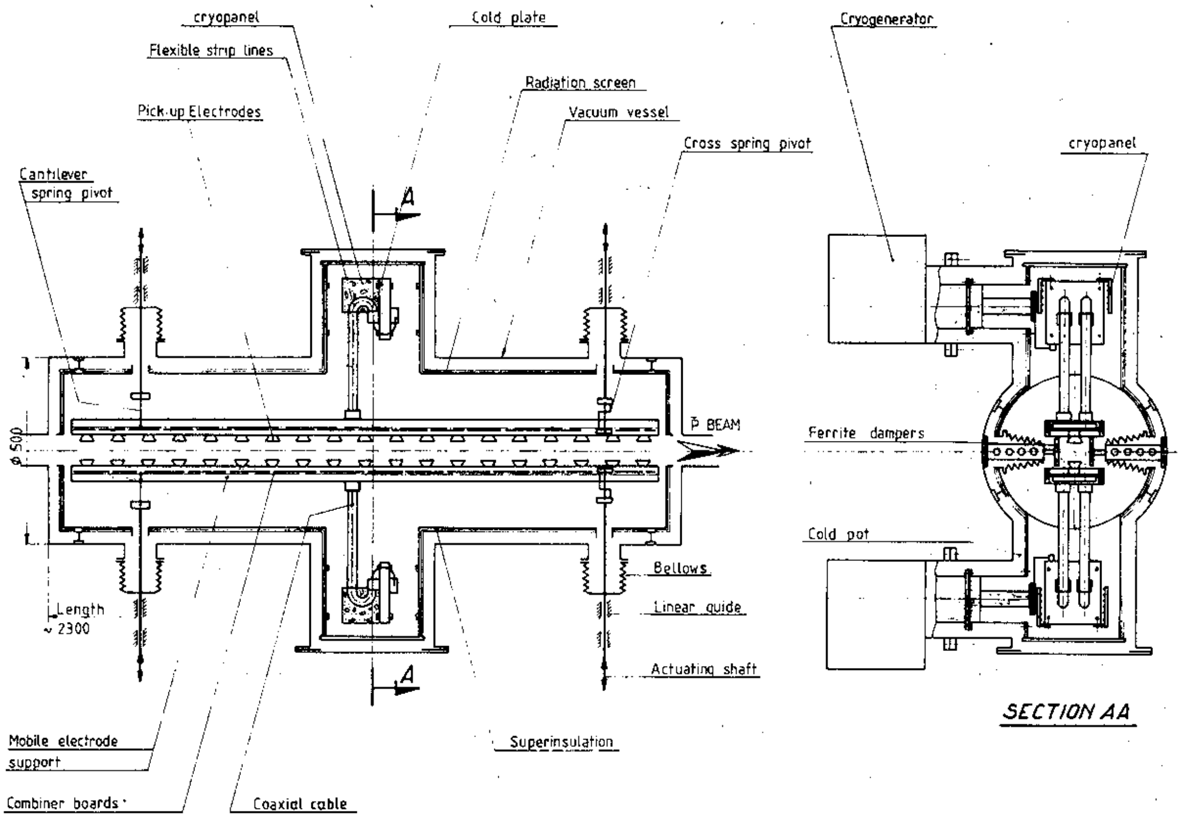

Fig. 2. Schematic cross-sections of ACOL cryogenic pick-up

about 1 m^2 each, to be cooled by radiation to a fixed thermal shield surrounding them. This solution, which avoids transfer of cryogen to the mobile assemblies and therefore leads to a simpler design, is however strongly dependent on the emissivities of the shield and beam surfaces. Emissivities in excess of 0.9 can be obtained reproducibly on technical material by coating them with silicon black paint[7], yielding a surface finish compatible with high vacuum. The mobile beams as well as the inner surface of the shield are coated with such a paint, while its outer surface is wrapped with aluminized Mylar superinsulation, a material which has been shown[8,9] to be compatible with residual pressures of less than 10^{-8} mbar, such as required for the circulating particles.

In order to reach about 100 K by radiative cooling under the above conditions, the steady-state heat load on each beam must not exceed 4 to 5 W. Thus, conductive heat inleak along the actuating shafts is limited by supporting the beams via slender cross-spring and cantilever-spring pivots made of Ti 6Al 4V alloy, a solution which guarantees rigid support and accommodates longitudinal thermal contractions. The other major source of heat inleak to the beams is radiation from the ambient temperature environment through the 100 × 50 mm^2 rectangular windows which allow for the passage of particles at each end of the thermal shield. The breakdown of the estimated primary heat load (80 - 100 K)is given in Table 2.

The preamplifiers and termination resistors have maximum dimensions of about 0.1 m, which permits to confine the low-temperature cryogenics to "cold pots" of small volume, and hence limit the refrigeration requirement at 20 K, in particular by thermal shielding of the cold pots and bridging of supports and output coaxial lines at the 100 K level. An estimate of the secondary heat load (20 K) also appears in Table 2. In all cases, the internal power dissipation in the 100 K and 20 K components is negligible with respect to heat inleaks from higher temperature environment.

Table 2. Estimated Heat Loads (W) of ACOL Cryogenic Pick-ups.

	Shield		Beam
- Primary heat load (80 - 100 K):	Shield		Beam
Conduction along supports	3.2		3.6
Transmission through superinsulation	6.0		---
Radiation from beam windows	2.6		0.7
	11.8		4.3
Total per pick-up station		20.4	
- Secondary heat load (20 K):			
Radiation from shield		0.02	
Conduction along input lines		0.04	
Conduction along output cable		0.13	
Conduction along supports		0.36	
Total per cold pot		0.55	
Total per pick-up station		1.10	

The staging of temperature levels, and the relative proportions of their corresponding refrigeration loads appear to be well matched to the performance of currently available two-stage, Gifford-McMahon cycle cryogenerators. This type of machine has already demonstrated its adequacy to such an application during tests conducted in cryoelectronic devices for AA[3]. Two such cryogenerators, each capable of delivering 50 W at 80 K and 2.5 W at 18 K, have their first stages thermally bridged to the thermal shield of each pick-up station, while their second stages cool copper plates supporting the preamplifiers and termination resistors.

The expected cool-down performance of the system can be assessed from the thermal model of Fig. 3: the shield and beam temperatures are well coupled at the beginning of cool-down due to efficient radiation, while the cryogenerators, which extract heat from the shield through conductive paths, cool down much faster. As the limit temperatures are approached, the shield and cryogenerator temperatures come closer, while the beams do not cool much lower than 100 K due to the drop in radiation efficiency. The steady-state temperature of 100 K is practically reached in 48 h. Such a period does not appear as dead time for operation of ACOL, since it is masked by a pump-down of comparable duration.

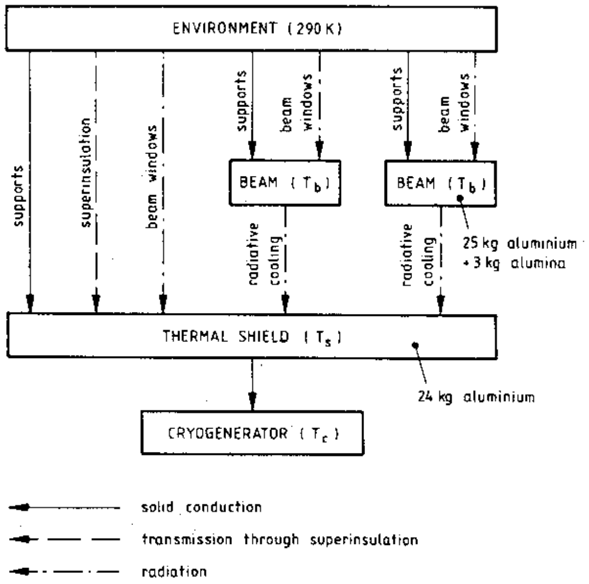

Fig. 3. Thermal model of pick-up.

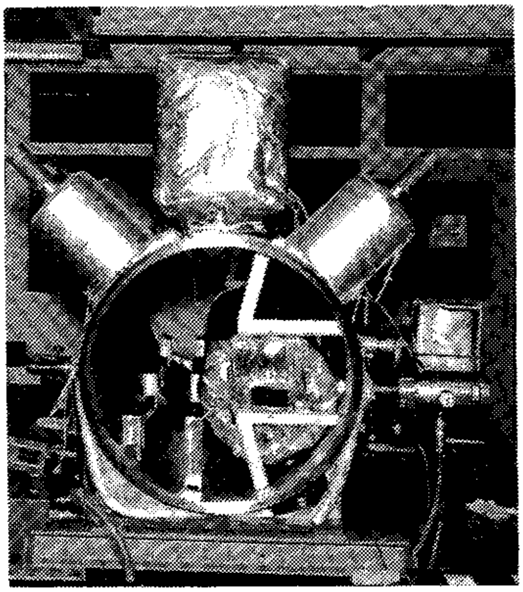

Fig. 4. Pick-up model set-up.

Vacuum

Beam lifetime requirements[4] impose a residual pressure of less than 10^{-8} mbar, which can normally be obtained with pumps of low pressure limit and large pumping speed (thousands of l s^{-1}) for H_2 and H_2O. Ample pumping speed and capacity for H_2O is provided free of charge by the thermal shield cooled below 100 K, whereas charcoal-bonded panels cooled at 20 K can easily take care of H_2. Such cryopanels, designed to provide more than 1500 l s^{-1} pumping speed for H_2, are fitted in the cold pots and thermally linked to the second stage of the cryogenerators. Thermal baffling of these cryopanels is performed by the thermal shield of the pick-up station. In addition, a small 60 l s^{-1} sputter ion pump of the triode type, which is also used as a pressure gauge, takes care of residual He, a gas not pumped by the cryopanels, and provides some back-up in case of failure of the cryosystem. Roughing is classically done with turbomolecular-mechanical pumping stations, down to a pressure of about 10^{-5} mbar at which the cryogenerators are switched on. This prevents the cryopanels from adsorbing large quantities of gas, thus preserving their full capacity at the low-pressure limit, and permits rapid pump-down in less than 24 hours.

MODEL TESTS

In order to assess the validity of the above design, tests were performed on a pick-up vessel model shown in Fig. 4. A 2 mm-thick cylindrical copper shield, wrapped with 30 layers of aluminized Mylar superinsulation, and suspended inside the vacuum vessel, surrounds a 10.5 kg aluminium alloy beam. The inner surface of the shield and the aluminium beam are coated with silicon black paint[7] of high emissivity. Two Leybold-Heraeus RG580 cryogenerators, fed by RW5 compressors, are mounted horizontally at the ends of the vessel; their first stages are thermally linked to the thermal shield, while a total of 300 cm^2 of charcoal-bonded cryopanels are mounted on their second stages. Instrumentation includes platinum resistor thermometers, total and partial pressure gauges and a 60 l s^{-1} triode sputter ion pump. The beam is also equipped with electrical heaters providing adjustable heat load.

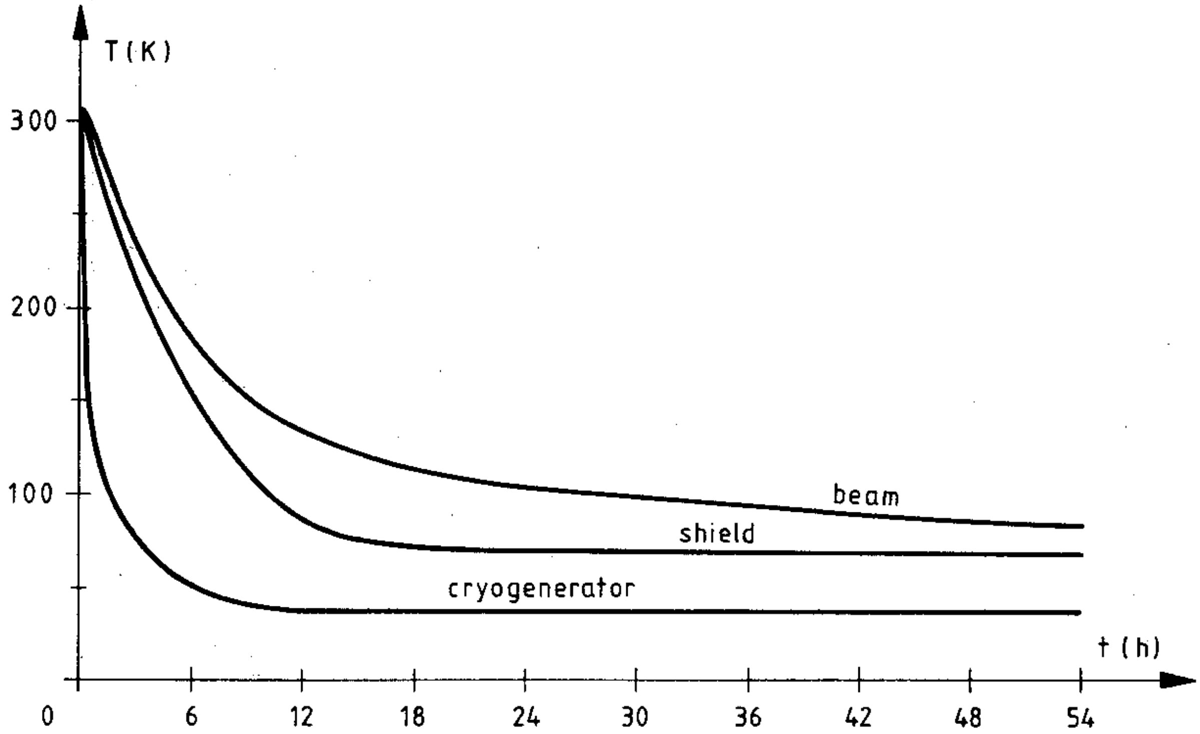

Fig. 5. Typical cool-down of pick-up model.

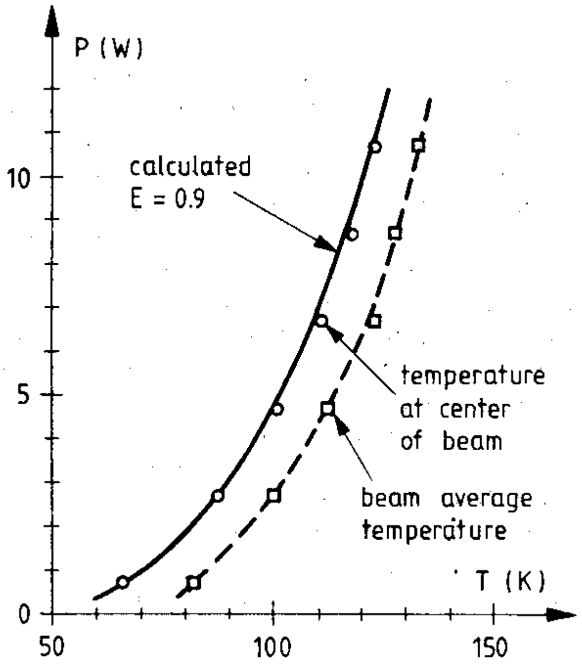

Fig. 6. Steady-state performance of radiative-cooled beam.

Typical measured cool-down curves (Fig. 5) show good agreement with the predictions of the thermal model. However, they reveal excessive thermal impedance between cryogenerators and thermal shield, where contact will have to be improved.

Efficient radiative cooling of the beam is illustrated by the steady-state characteristics of Fig. 6, in accordance with design calculations.

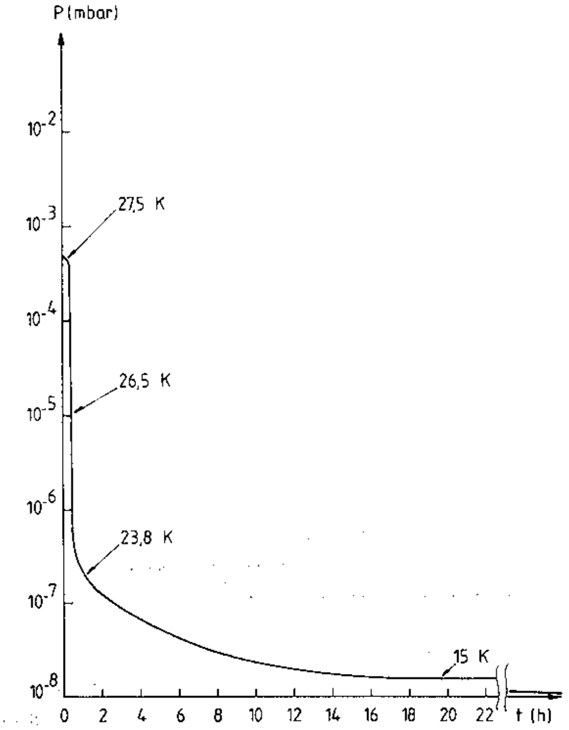

Fig.7. Typical pump-down of pick-up model.

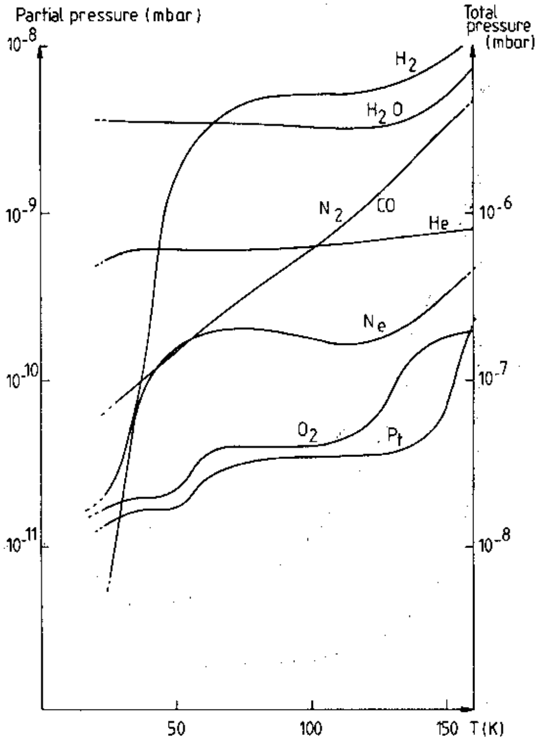

Fig. 8. Total and partial pressures vs. cryopanel temperature.

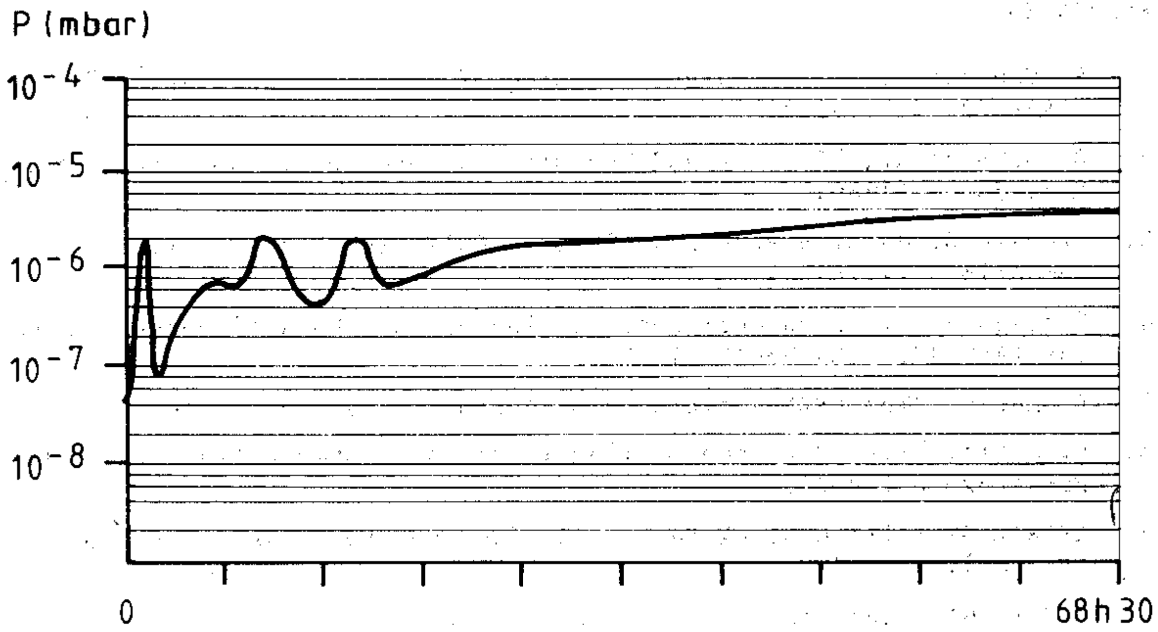

Fig. 9. Evolution of pressure after stop of cryogenerators.

The load on the pumping system results primarily from outgassing of the 300 m^2 aluminized Mylar, followed by that of 6 m^2 blackened copper and aluminium surfaces and 6 m^2 stainless steel. The overall outgassing rate has been estimated at 3×10^{-4} mbar l s^{-1} (room temperature) and 1.5×10^{-5} mbar l s^{-1} (cryogenic) after 100 h of pumping. A typical pump-down curve is given in Fig. 7: the cryogenerators are switched on at time zero, after the vessel has been roughed down to 10^{-5} mbar. The sudden pressure drop within the first 15 minutes occurs when the cryopanels reach 30 to 20 K, a temperature range in which common gases (Ar, N_2, CH_4, O_2) exhibit a sharp decrease in vapour pressure.

Gas injection tests have shown a pumping speed for H_2 of more than 3000 l s^{-1} at a pressure of 10^{-8} mbar. A limit pressure below 10^{-8} mbar is reproducibly reached in less than 100 hours, the amount of pumped gas being low with respect to potential cryosurface coverage. Typical composition of the residual gas as a function of temperature (Fig. 8) shows mainly water vapour remaining in the cold system.

In case of cryogenerator failure, runaway tests show that acceptable temperatures are maintained for several hours. After a rapid initial pressure peak due to release of H_2 from the cryopanels, pumping speed is renewed, probably due to gas remplacement phenomena (Fig. 9). In the long run, the small sputter ion pump prevents catastrophic vacuum failure.

FUTURE OUTLOOK

The exacting requirements of cryogenic refrigeration of electronics located inside the beam vacuum of antiproton storage rings appear particularly well matched by the performance and reliability of currently available cryogenerators. A complete cryogenic system comprising 16 such cryogenerators has been designed for ACOL: installation and first tests are due by the end of 1986, and operation will start in early 1987.

ACKNOWLEDGEMENTS

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