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APPLICATIONS OF VACUUM TECHNOLOGY TO NOVEL ACCELERATOR PROBLEMS*

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Summary

Vacuum requirements for electron storage rings are most demanding to fulfill, due to the presence of gas desorption caused by large quantities of synchrotron radiation, the very limited area accessible for pumping ports, the need for 10^{-9} torr pressures in the ring, and for pressures a decade lower in the interaction regions. Design features of a wide variety of distributed ion sublimation pumps (DIP) developed at SLAC to meet these requirements will be discussed, as well as NEG (non-evaporable getter) pumps tested for use in the Large Electron Positron Collider at CERN. Application of DIP to much higher pressures in electron damping rings for the Stanford Linear Collider will be discussed.

Introduction

The first electron storage ring, assembled at Stanford University in 1963, employed stainless steel chambers and discrete ultra-high vacuum stations with oil diffusion pumping. Research probing failure to maintain the necessary 10^{-9} torr vacuum in the presence of stored beams dictated pumping with oil-free ion sublimation pumps, and produced a model[1] which predicted for the next 2 generations of storage rings (SPEAR-DORIS and PEP-PETRA) the synchrotron-radiation-induced desorption rates. Even though our subsequent research showed that aluminum chambers reduced radiation induced desorption by a factor ≈5 from stainless steel, it was clear from the quite limited chamber conductance that some kind of distributed pumping was necessary. Ion sublimation pump cells within the vacuum chambers in the bending magnets were chosen with enough discrete ion pumps around the ring to maintain vacuum in the absence of bending magnet fields (and beam). Use of DIP in magnetic fields whose primary function was to shape stored beam orbits led to research on pump behavior and empirical formulae for predicting speed as a function of pressure, applied voltage and magnetic field. The first such work available was a 1969 preprint[2] from Novosibirsk by Malev and Trachtenberg. This work received wider distribution when it was published, slightly modified, in Vacuum (1973)[3]. About a year later Hartwig and Kouptsidis published a more complete analysis[4], which caused Malev and Trachtenberg to modify their speed formula to be valid in the high magnetic field case[5]. I shall use the formalism of Hartwig and Kouptsidis[4] in the following discussion. In normal operation, ion pumps have two significant discharge modes, which differ in their potential profile in the cell. In the LMF-mode (low magnetic field) the space charge of an electron cloud extended over the entire cell volume deforms the potential profile. In the HMF-mode (high magnetic field) there is a field-free plasma region around the cell axis and a cloud of electrons forming a sheath adjacent to the anode. In a plot of discharge intensity I/P (or pump speed) vs magnetic field, the speed becomes non-zero at a specific ignition field B_i. Starting at B_i the speed rises linearly, merging tangentially with that given by Eq.(4) at $2B_i$. At a higher transition field B_{tr}, the discharge switches to HMF mode. For $B > B_{tr}$ the speed remains constant if the pressure is less than $\approx 10^{-7}$ torr, but falls somewhat if $p > 10^{-7}$ torr. A summary of the formulae of Hartwig and Kouptsidis[4] follows for convenient reference. Discharge ignition occurs for magnetic fields greater than:

$$B_i = 300/r_a \tag{1}$$

Transition to HMF-mode occurs at:

$$B_{tr} = \frac{7.63\sqrt{U_a}}{r_a P^{0.05}} \tag{2}$$

the nitrogen pumping speed of one cell:

(i)LMF-mode, $B_i \lesssim B \lesssim 2B_i$

$$S_1 = 6.27\text{x}10^{-5}\left(1-\frac{1.5\text{x}10^6 P}{1+4\text{x}10^6 P}\right)P^{0.2}\ell r_a^2 B_i(B-B_i) \tag{3}$$

(ii)LMF-mode, $2B_i \lesssim B \lesssim B_{tr}$,

$$S_1 = 1.56\text{x}10^{-5}\left(1-\frac{1.5\text{x}10^6 P}{1+4\text{x}10^6 P}\right)P^{0.2}\ell r_a^2 B^2 \tag{4}$$

(iii)HMF-mode, $B \gtrsim B_{tr}$

$$S_1 = 9.1\text{x}10^{-4}\left(1-\frac{1.5\text{x}10^6 P}{1+4\text{x}10^6 P}\right)P^{0.1}\ell U_a \tag{5}$$

$$\text{x}\left\{1-1.5\text{x}10^4[(B-B_{tr})r_a P]^{1/2}/U_a\right\}$$

Misalignment of the cell by θ with respect to the magnetic field reduces the electron cloud radius to:

$$r_{ae} = r_a \cos\theta - 0.5\ell_a \sin\theta \tag{6}$$

Where symbols and units are:

B = applied magnetic field in G
B_i = magnetic field at ignition point in G
B_{tr} = magnetic field at transition point in G
ℓ_a, ℓ = anode height, effective height of cell in cm
P = pressure in torr
r_a, r_{ae} = actual, effective cell radius in cm
S_1 = nitrogen pumping speed of 1 cell in ℓ/sec
U_a = anode voltage in V
θ = angle between anode axis and magnetic field direction

The pumping speed for an array of n cells is obtained by multiplying by n and taking account of the conductance of the gaps between the cell anodes and cathode plates, as is discussed in the source paper[4].

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Malev and Trachtenberg[3,5] provide a useful empirical formula for the minimum pressure to maintain the discharge (or pumping). In the same units as above:

$$P_{min} = 3.12\text{x}10^{3}U_{a}^{-1}\left(Br_{a}^{2} - \frac{0.9\text{x}10^{5}}{B}\right)^{-3} \qquad (7)$$

DIP for the Damping Ring

The application of DIP to UHV production in electron storage rings is well established. In the realization of the SLC (Stanford Linear Collider) electrons and positrons must be damped for 3 ms in auxiliary damping rings before final injection into the 2-mile linac. To achieve fast damping 20kG bending fields are required, while for small emittance 63kG/m focusing fields are necessary. The vacuum chamber cross section is shown in Fig. 1. Note that the outside dimensions are 67 mm x 19 mm. Although the base pressure is $<5 \times 10^{-9}$ torr and the operating pressure requirement with rated 13.1kW of synchrotron radiation power is only $\lesssim 10^{-7}$ torr, because of the small magnet bore and chamber conductance a DIP is required. The DIP pump was designed to produce a total speed of 7.3×10^{3} ℓ/s, and is combined with 20 discrete 20ℓ/sec ion pumps around the 34m circumference which act as holding pumps. The performance of the prototype (207-3mmϕ cells, $\ell_a = 5.7$ mm) is shown in Figs. 2-4. Fig. 2 gives the speed as a function of B, with B_i and B_{tr} (calculated from Eq.(1) and Eq.(2)) indicated. Since the test pressure is $<10^{-7}$ torr, the speed is constant for $B > B_{tr}$. Fig. 3 gives speed vs anode voltage for B = 20kG. (The solid curves were however calculated from Malev and Trachtenberg[3,5] by choice of the test engineer.) Fig. 4 shows the speed vs pressure behavior and demonstrates the predicted optimization at 10^{-7} torr as well as the expected fall off above that pressure. The damping ring is now complete and as of March 6, 1983 stored a beam of 0.6 mA at 950 Mev with a δp of 1×10^{-9} torr. The final specification is a circulating beam of 140 mA at 1.2 Gev with $p < 10^{-7}$ torr. From our experience, the ring will process and clean up by a factor of 10, so the measured figures project a very comfortable conformance with specifications. The total installed cost (including engineering and design) for the damping ring DIP was \$12/ℓ/s.

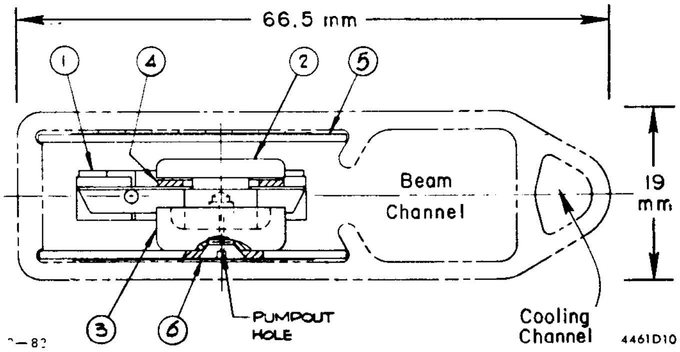

Fig. 1 Cross section of SLC damping ring vacuum chamber 1) 3 mm-dia. cylindrical anode, 2),3) insulators, 4) washer 5) titanium cathode, 6) screw

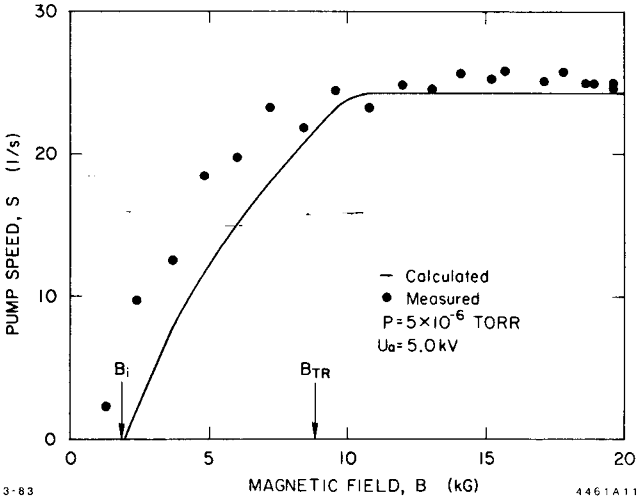

Fig. 2 Speed vs Magnetic Field for SLC DIP prototype

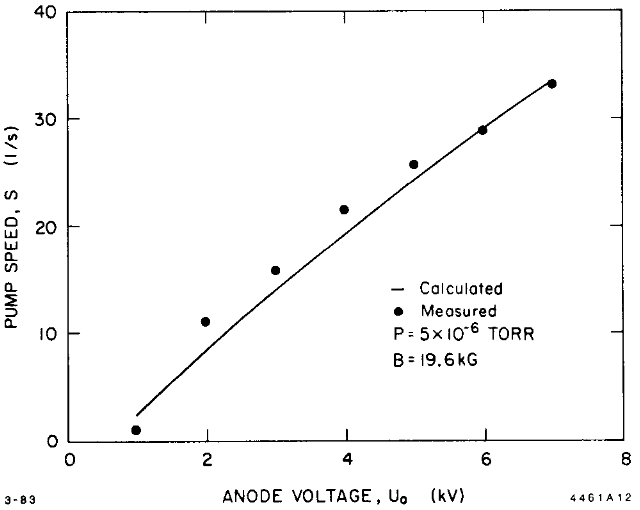

Fig. 3 Speed vs Anode Voltage for SLC DIP Prototype

DIP for Interaction Region

A major detector at PEP is the TPC (time projection chamber). In order to maintain interaction region pressures in the low 10^{-9} torr range or less, DIP pumps were designed to fit at each end of the chamber contained within the TPC, using the detector magnetic field. The pump, shown in Fig. 5 had a speed of about 350 ℓ/S, and was both tapered and fitted with a Be-Cu electrical shield to minimize higher-order-mode generation induced by the circulating beams. In pumps near the beam line, it is necessary to shadow the electrical feedthrough by some kind of defining aperture or shield. The two TPC pumps were engineered, designed, fabricated and installed for a total of 50K\$, or about \$70ℓ/S.

DIP for Use in Low Magnetic Fields

In an attempt to produce a DIP structure useable in LEP (which has a magnetic field at injection of only 200G), Laurent and Groebner[6] have studied DIP structures whose anodes are formed of layers (spaced a few mm apart) of perforated plates aligned and

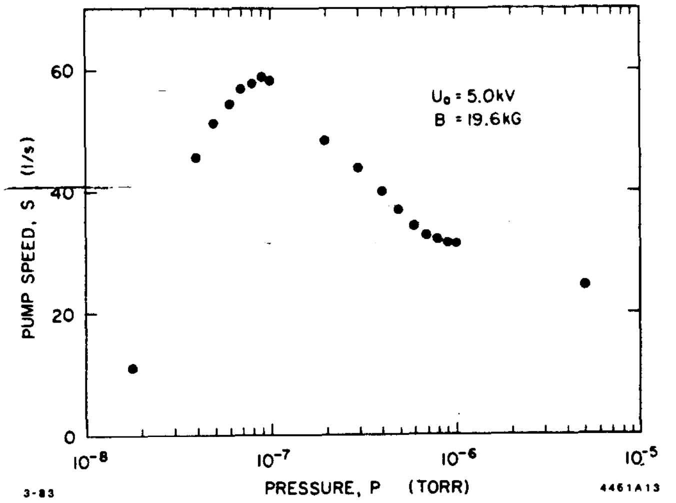

Fig. 4 Speed vs Pressure for SLC DIP Prototype

assembled to occupy the space of normal cylindrical anodes. Such a structure with a 3-cell wide, 5-layer anode showed higher conductance to the beam and a lower discharge ignition field B_i than those obtained for conventional cylindrical anodes. The latter property is presumably due to the relative freedom of lateral movement of the discharge within the layered anode structure compared to cylindrical structures, and might not be expected to persist to the same degree in a 1-cell wide structure. Subsequent tests by the same authors[7] confirmed this caveat. By using 50 mm ϕ cells, they were able to design a single row ion pump which worked in magnetic fields between 200 and 1200G, employing layered anodes. The linear pumping speed reached 150 ℓ/s-m, but was reduced by various operating conditions such as low bakeout temperature, saturation by pumped gas, or increased working temperature due to synchrotron radiation heating. The minimum $B_i \approx 200$G is dangerously close to the minimum LEP injection field, even with reduction of anode voltage to 2kV to maintain a discharge at these low magnetic fields, as suggested by Eq.(7).

NEG Pumps for LEP

As we have seen above, production of the required 3×10^{-9} torr vacuum in LEP, to be built in the proximity of CERN, poses unique problems which are very difficult if not impossible to solve with DIP technology. For this reason, C. Benvenuti of CERN has proposed, evaluated in the laboratory, and tested in operation at PETRA a linear NEG (non evaporable getter) pump. On the basis of these careful and successful tests[8], the decision has been taken to employ NEG pumps for distributed pumping on LEP. With permission of C. Benvenuti, some of his data is presented here.

The circumference of LEP is about 27 km, of which dipole magnets and multipole magnets comprise 24 km, divided by valves into 474 m-long sections, each consisting of 6 cells of 79 m length. In each cell there are 2 groups of 3 vacuum chambers (each 12 m long) inserted into the dipole magnets, and 2 short straight sections (total length 7 m) in the quadrupole and sextupole magnets. The dipole vacuum chamber is a straight aluminum alloy extrusion coated with a few mm of lead to absorb synchrotron radiation, and is shown in cross section in Fig. 6. Water cooling is used to carry away heat produced in the chamber, and periodic holes provide good conductance to the pump channel.

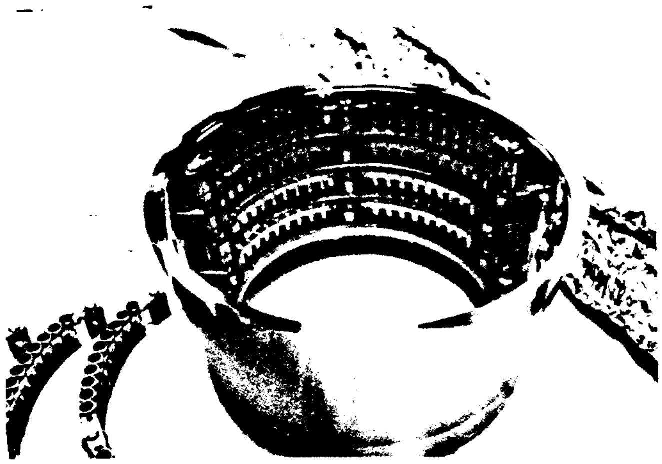

Fig. 5 Tapered DIP for Time Projection Chamber

A material which provides pumping action when introduced in bulk form into a vacuum system is called a non evaporable getter, in contrast to materials such as titanium which provide pumping only when sublimated. The NEG pumps form stable compounds with most active gases (O_2, N_2, H_2O, CO, CO_2...), while sorption of H_2 is thermally reversible. Noble gases and methane are not pumped. After air exposure, the surface of the NEG is saturated and pumping must be reestablished by activation; heating which diffuses the gas on the surface into the bulk of the getter and reduces in the NEG the level of H_2 when its dissociation pressure there exceeds the H_2 pressure in the vacuum system. If large quantities of active gases are to be pumped after activation, the getter temperature must be kept high enough to provide an adequate rate of diffusion of the stable compounds formed into the bulk of the getter and avoid surface saturation, or the NEG must be periodically heated for this purpose. The best known commercial getter is presently ST 101[9], a Zr-16%Al alloy bonded as a powder to a constantan ribbon. For this NEG, full activation requires 30 min. at 700°C or 1 day at 600°C. Pumping speeds of fresh surfaces are ≈1 ℓ/s-cm² for H_2 and CO over the temperature range 20°C to 400°C[10]. Up to 0.6 torr-ℓ/cm² can be sorbed for H_2 without embrittlement, and can therefore be reversibly desorbed by heating. Optimum operating temperature is 400°C for heavy gases at pressures $>10^{-7}$ torr, with lower temperatures required for lower pressures. H_2 can be pumped at 20°C for pressures below 10^{-8} torr. Tests for LEP employed 30 mm-wide ribbons which could be heated by direct current, and provided active surface area and pumping speed per meter of 500 cm² and 500 ℓ/s, respectively.

The ribbon was mounted by means of insulators spaced 30 cm apart to a rigid stainless steel frame which was slid into the pumping channel of the vacuum chamber of Fig. 6. This insulator spacing allowed expansion during activation to be accommodated with either vertical or horizontal mounting of the strip as shown in Fig. 7, and allowed reduction of the pumping channel from 64 mm (required for DIP) to 52 mm. Heating currents of 100A produced NEG temperatures of 700°C, while 50A gave 400°C, corresponding to power dissipations of 900 and 225 W/m, respectively. Although this power could easily be removed by water cooling, even the 50A current would perturb the stored LEP beam. The NEG must therefore be used at room temperature and intermittently heated when pumping speed becomes inadequate. Experimental results[8] show that only a few minutes at 400°C are required to effect restoration of speed; this process is referred to as "conditioning", and is distinct from 700°C activation, necessary only after air exposure.

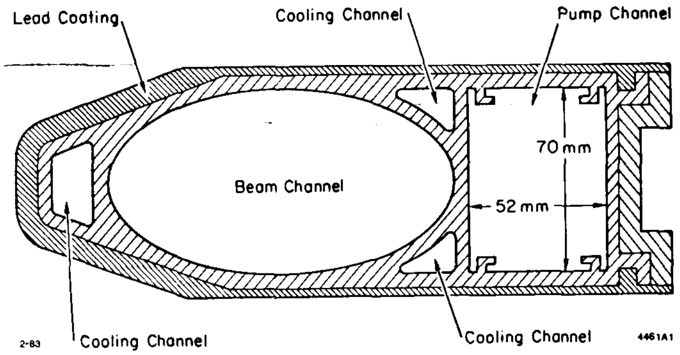

Fig. 6 Cross section of the LEP dipole vacuum chamber

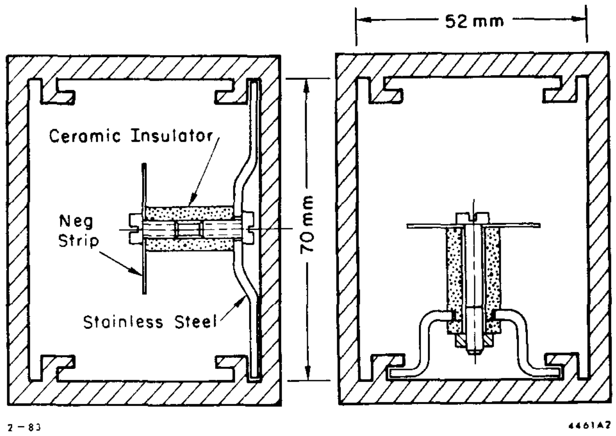

Fig. 7 Cross section of the pumping channel with NEG mounted horizontally or vertically

Variation of pumping speed vs pumped quantity, Q, was measured with a test dome for individual gases on freshly activated new NEG samples, and is shown in Fig. 8. The pumping speed for CO_2 (not shown) is close to that for CO. Pumping speed for H_2O has been measured by a different technique[8], and is about 250 ℓ/s-m. Only for the case of H_2 is there evidence of internal diffusion within the NEG affecting the speed as a function of rate, as is shown in Fig. 8.

Pumpdown and bakeout (120--150°C) cycles were carried out on a 7 m long LEP chamber with NEG installed, and are shown in Fig. 9. Here a 70 ℓ/s turbomolecular pump and a 30 ℓ/s ion pump were connected, with the turbo pump valved off immediately after NEG activation. The ultimate pressure is marginally affected between curve A (24 hour bake) and curve B (2 hour bake). Pressures of 10^{-10} torr were obtained within 8 hours for the latter case. For these curves H_2 comprised 80% of the total pressure after bake. Curve C repeats curve B, with the ion pump throttled to 0.3 ℓ/m-s. In this case, methane and water vapor show slightly higher partial pressures than H_2.

By comparing PETRA to LEP, Benvenuti concluded that for equal beam currents PETRA has about twice the photon flux per meter, with comparable spectral shapes (14 Gev PETRA vs 50 Gev LEP). He presents an equation derived from experience at PETRA for the dynamic degassing there:

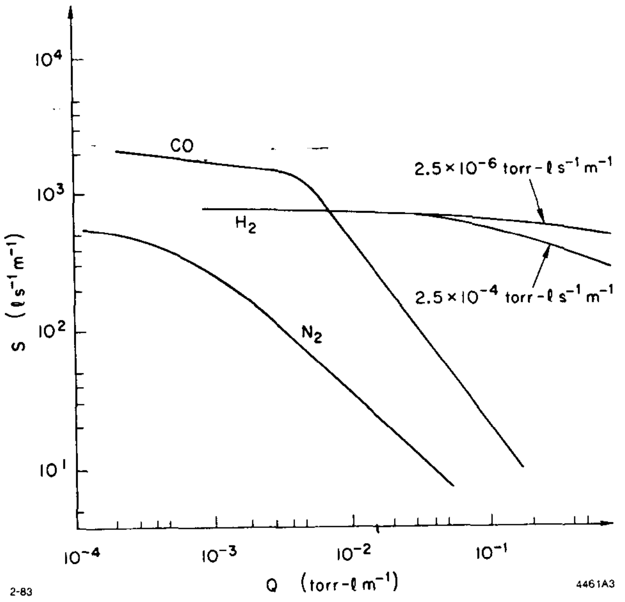

Fig. 8 Variation of NEG's pumping speed S at room temperature as a function of pumped quantities Q of gas. Both S and Q refer to 1 m of getter strip 30 mm wide. Spread from different samples is about 10%.

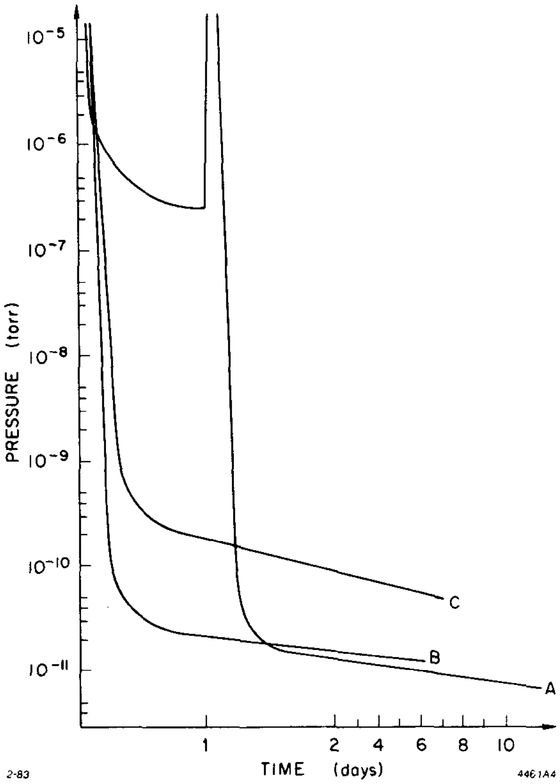

Fig. 9 Pumpdown curves for a LEP chamber 7 m long equipped with a linear NEG pump. The chamber is baked at 120--150°C for 24 h (curve A) or 2 h (curves B and C). For curve C the pumping speed of the SP and TMP are reduced, by interposed diaphragms, to 2.3 ℓ/s.

$$dP/dI = 6.7 \times 10^{-8} D^{-0.63}, \qquad (8)$$

where the term on the left is the pressure increase in ~~torr for~~ 1mA circulating beam, and D is the integrated beam current intensity (dose). A standard 7m PETRA chamber was replaced by a new one with 5.5m of NEG replacing the DIP in the bending magnets. The differential pressure vs dose to 10Ah is shown in Fig. 10 by the solid lines which show discontinuous drops at each of the 3 conditioning times. For comparison, the dashed curve I gives the pressure history of another new chamber pumped by DIP, while curve II is derived from Eq.(8). The experiment in PETRA is considered fully satisfactory for proving the feasibility of NEG pumping for LEP.

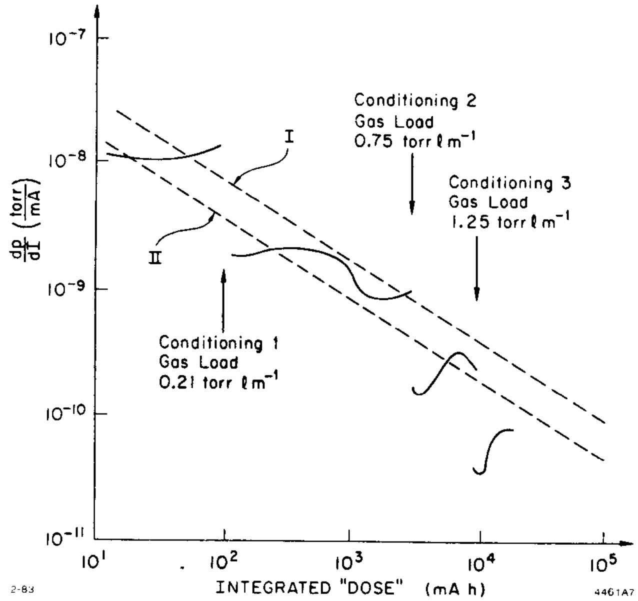

Fig. 10 Variation of the differential pressure rise as a function of the integrated beam dose for the NEG pumped chamber at PETRA (full line). Also shown (dotted lines) are the same variations for another new chamber pumped by ISP (I) and the reference curve (II) expressed by equation (8).

Benvenuti has also made experimental tests which show that the NEG, fitted with modest safety cutoffs, can survive accidental atmospheric exposure even at 700°C. Use of NEG also allows reduction of the numbers of turbopump stations and of discrete ion pumps, as well as the maximum current of the voltage supplies for the latter, because they can be started at 10^{-7} torr.

Acknowledgements

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