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CHARACTERISTICS OF THE ISABELLE VACUUM SYSTEM*

J.R. Aggus, D. Edwards, Jr., H.J. Halama and J.C. Herrera
Brookhaven National Laboratory
Upton, New York 11973

SUMMARY

We discuss the complete vacuum system of ISABELLE, emphasizing those design characteristics dictated by high vacuum, the avoidance of beam current loss, and the reduction of background. The experimental and theoretical justifications for our current choices are presented.

I. INTRODUCTION

The vacuum system for the Intersecting Storage and Acceleration Ring, ISABELLE, represents a large extrapolation from the presently operating CERN ISR system. It is, therefore, important that the basic design be simple, reliable, and yet inexpensive. Since the ISABELLE machine must store protons for many hours at a luminosity of $10^{33}cm^{-2}s^{-1}$ with little background radiation, it is also necessary that the direct beam-gas collisions be small and that the susceptibility of the beam to possible instabilities be minimized. In this paper we shall, therefore, discuss the engineering aspects of the complete ISABELLE vacuum system, the pertinent prototype tests that have been performed to date, and the extent to which the residual gas may be expected to influence the circulating proton beam.

II. ENGINEERING CONSIDERATIONS

From the mechanical point of view, the ISABELLE vacuum system consists of a circular stainless steel tube (8 cm i.d., wall thickness 1 mm, approximately 5.2 km in length) passing through the center of the dipole and quadrupole magnets of the two storage rings. Within this vacuum chamber the pressure of the residual gas, which is mainly hydrogen, will be maintained at a value of 3×10^{-11} Torr by a series of pumping stations. A sketch of a typical module of the overall system is illustrated in Fig. 1, while the details of the pumping station are given in Fig. 2. Following initial roughing with the turbomolecular and sorption pumps, the system is brought to, and sustained at, the operating pressure by a titanium sublimation and a VacIon pump. Recent tests conducted on the ISABELLE

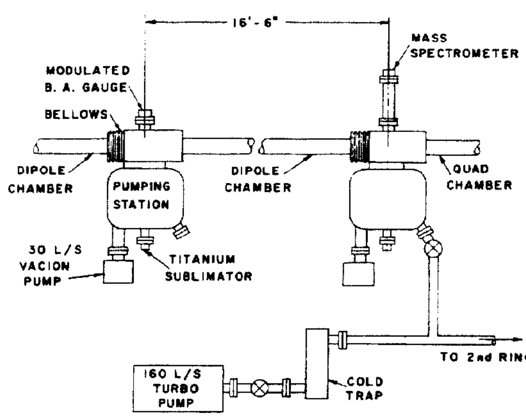

Fig. 1. Typical module of the ISABELLE Vacuum System.

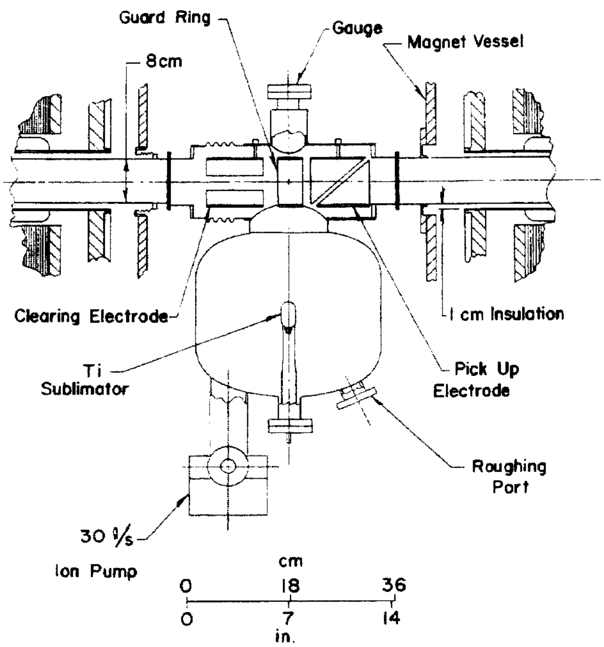

Fig. 2. Details of the Pumping Station.

half cell have indicated that this pumping arrangement is practical and efficient. Two of the stations joined by aluminum tubes (2 for the dipoles and 1 for the quadrupole) were assembled to form the ISABELLE half-cell vacuum system (Fig. 3). After an initial bakeout

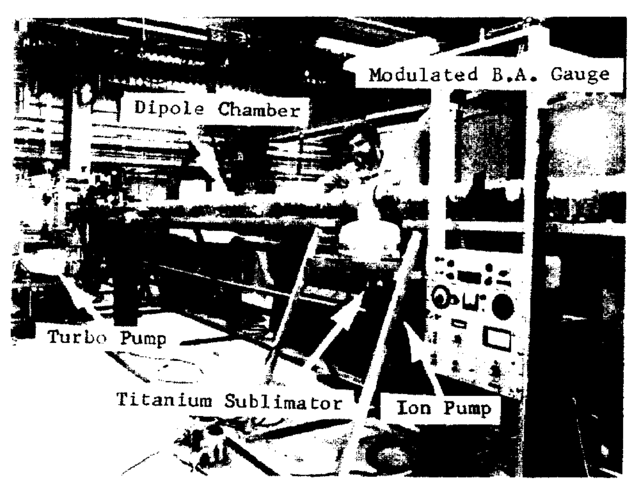

Fig. 3. Prototype Half-Cell Vacuum System.

(200°C for the Al tubes and 300°C for the stainless pumping stations) and a titanium flash, a pressure of less than 1×10^{-11} Torr was measured by a modulated Bayard Alpert gauge. In Fig. 4 we present the actual curve for the system which reached a final equilibrium pressure of $\sim 6 \times 10^{-12}$ Torr in 14 days. A Helmer gauge mounted at the end of the beam tube showed that

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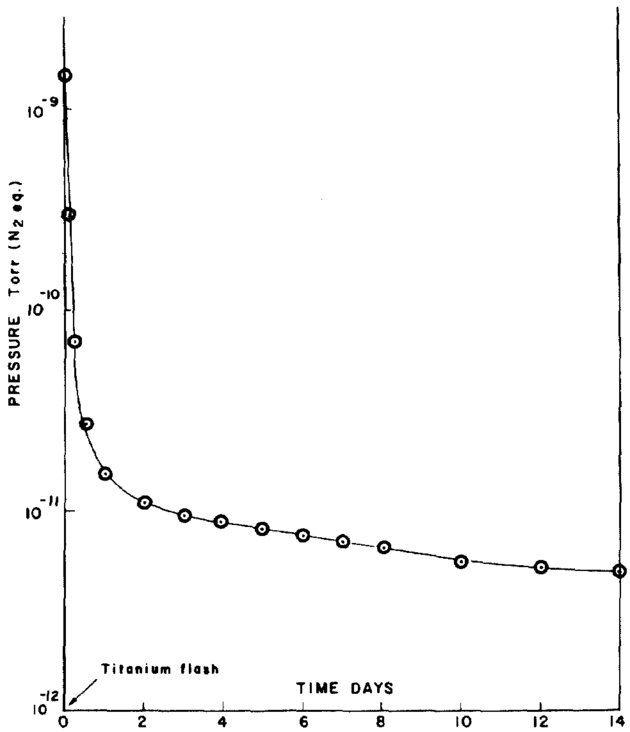

Fig. 4. Pump-Down Curve for the Half-Cell Vacuum Envelope.

the outgassing rate of about 1×10^{-13} Torr ℓ $s^{-1}cm^{-2}$ had been attained.[1] It will have been noticed that these tests were carried out for chambers constructed of aluminum, which in view of its excellent vacuum properties[2] and relative low cost, had been initially chosen for the ISABELLE vacuum chamber material. However, preliminary experiments[3] on the CERN ISR have now cast some doubt as to whether the use of an aluminum chamber is consistent with a high intensity proton beam in a storage ring. The present ISABELLE design specifying an all stainless system at room temperature, consequently, represents a conservative approach. An experimental setup, similar to that just described for the half cell, has been assembled with stainless tubes and detailed measurements on it will soon be carried out.

Since the bakeout of the vacuum chamber must be done in place while the superconducting magnets of ISABELLE must be maintained at liquid helium temperatures, it is necessary that the chamber be surrounded by a good heat insulating barrier. Accordingly, tests on cryogenic insulation have been made to determine both the type and the method of application of such insulation. Measurements performed on a 1 m long test setup have demonstrated[4] that a combination of NRC-2 superinsulation and one layer of fiberglass mat permitted a heat leak into the LHe system of 0.45 W/m when the chamber was at room temperature. During a 200°C bakeout the heat load rose to 1.5 W/m. Thus, for the 4¼ m ISABELLE magnet, the heat load would be 2 W during normal machine operation and 6.3 W during bakeout. Subsequent tests on a 4¼ m magnet (MK IV) have, to date, confirmed the value given for room temperature. It is planned to perform further experiments for an insulation employing aluminized Kapton which can be heated to above 300°C.

In Table I we have listed the principal vacuum components comprising the ISABELLE vacuum system.

Table I. Main Vacuum Components

Component	Characteristic	Total Number
Ion Pump	30 ℓ/sec^{-1}	792
Titanium Sublimation Pump	~ 2000 ℓ/sec^{-1}; H_2 ~ 1000 ℓ/sec^{-1}; CO	1092
Roughing Station	Turbomolecular 160 ℓ/sec^{-1} Sorption Pump	12 24
Vacuum Gauge	Bayard Alpert 10^{-4} to 10^{-11} Torr	244
Clearing and Vacuum Electrode	Stainless Plates ± 5 kV/Plate < 10^{-11} Torr	1008
Spectrometer	Quadrupole Mass. Spec.	16
Ring Isolation Valves	All Metal/Pneumatic - Automatic	60

III. BEAM DECAY AND BACKGROUND

Some idea of the vacuum requirements in a storage ring can be had by comparing the beam loss due to beam-beam nuclear collisions (which are the desired interactions) and that due to the beam gas nuclear collisions (which are the background interactions). Thus, if we consider the ISABELLE when it is running at a maximum luminosity of $L = 1 \times 10^{33} cm^{-2}\ s^{-1}$ and a beam current of $I = 10$ A (a total number of protons per ring of $N_p = 5.5 \times 10^{14}$), and if we assume that the total proton-proton cross section is $\sigma_T = 40 \times 10^{-27} cm^2$, we obtain a decay rate due to the collision of the beams at the six intersections expressed by

$$\left[\frac{-1}{I} \frac{dI}{dt} \right]_{BB} = \frac{6L\sigma_T}{N_p}. \qquad (1)$$

or numerically, 26×10^{-6}/min. On the other hand, for the beam-gas collisions which occur around the entire circumference of the machine, one has the relationship

$$\left[\frac{-1}{I} \frac{dI}{dt} \right]_{BG} = n\sigma_T c \qquad (2)$$

where n is the number of hydrogen atoms per cm^3 of gas and c the velocity of light. A gas pressure of 3×10^{-11} Torr corresponds to $n = 2 \times 10^6$ atoms/cm^3, and the resultant decay rate is 0.14×10^{-6}/min.

Another measure of the "goodness of the vacuum" in a storage ring is the rate of growth in the rms size (directly related to the emittance) of the beam due to multiple Coulomb scattering in the residual gas. A convenient expression for this growth has been recently derived[5] and we quote the result:

$$\left[\frac{1}{\sigma_V} \frac{d\sigma_V}{dt} \right]_{MC} = (0.031)\ \beta_V \left(\frac{\pi}{E_V} \right) \frac{P}{\gamma} \qquad (3)$$

where σ_V is the rms vertical size, β_V the average beta function in meters, E_V the normalized vertical emittance in rad m, γ the proton energy in rest mass units, and P the residual gas pressure in Torr. The appropriate values for ISABELLE at injection energy are $\gamma = 30$, $\beta_V = 18.5$ m, $E_V = 20\ \pi\ 10^{-6}$ rad m. Equation (3) now yields a rate of growth for the vertical size of 1.7×10^{-6}/min. If we choose a 1% change in this size as an upper limit, that is, $d\sigma_V/\sigma_V = 0.01$, we derive a lifetime of 100 hours. Thus multiple scattering will not be a significant effect for the storage rings.

An estimate of the number of particles produced by beam-gas collisions in the experimental straight section is also of importance. Corresponding to a length of gas ℓ (cm), we have a rate of interaction

$$N = n\ell\sigma_T \frac{I}{e}.$$

Here the new symbol is the electronic charge, e. For an insertion length of 40 m in the ISABELLE machine and a beam current of 10 A, we then calculate a beam-gas (hadron-hadron) interaction rate for the two beams equal to $4 \times 10^4 s^{-1}$, or a value about 1000 times less than the primary beam-beam interaction rate ($40 \times 10^6 s^{-1}$). Since for the relevant center-of-mass energies (20 GeV for the proton incident in the stationary gas nuclei, 400 GeV for the proton-proton collisions), the particle multiplicity[6] due to beam-gas collisions is about ¼ of that due to beam-beam collision, the effective ratio of the number of particles produced by true collision events to that produced by background events is, therefore, 4000 to 1.

IV. PRESSURE BUMP INSTABILITY

This vacuum instability was discovered[7] at the CERN ISR and has probably been the most serious limitation on maximum beam current. Qualitatively, the effect is caused by ionized gas molecules which are propelled by the electric field of the beam, strike the vacuum chamber wall, and thereby liberate adsorbed molecules in sufficient quantity to increase the gas pressure. At a certain value of beam current, I_{crit}, this pressure increase leads, avalanche-like, to a local pressure peak and to the destruction of the beam. A quantitative analysis, specifically related to the ISABELLE vacuum system, has already been published.[2] The theory predicts a product $\eta I_{crit} \leq 30$ A, where the surface desorption coefficient η (defined as the net number of molecules desorbed per incident ion) is a characteristic of the chamber wall and depends upon the surface preparation and bakeout temperature used for the material, as well as upon the mass and energy of the bombarding ions. In ISABELLE, though the residual gas will be mainly hydrogen, the onset of the pressure bump will manifest itself by a rise in the pressure of CO.[7] It is to be expected that, for a beam to wall potential of 2 kV, the desorption coefficient will be less than 3, and, therefore, that the beam current limit will be greater than 10 A. A recent measurement[8] of η, performed at BNL, has been encouraging. This experiment was made on a sample of stainless steel tube (4 in. o.d. and 15 in. length) which had been prepared as follows: 1) degreasing, 2) chemical cleaning, oxide removal, and passivation,[9] 3) Argon glow discharge, 4) exposure to atmosphere, and 5) bakeout in place at 200°C. After such a sample treatment, the number of CO molecules released into the gas phase per incident 1 keV argon ion was found to be $\simeq 0.9$, corresponding to an η value of ≈ -0.1. Such negative values, indicative of a net pumping by the chamber wall, have also been observed at the CERN ISR.[10,11] Accordingly, this measurement would argue for the use of a 200°C bakeout as sufficient for the ISABELLE vacuum system. These early tests are being followed by more extensive studies.

V. ELECTRON CLEARING

When the circulating protons pass through the residual gas, they not only produce positive ions but also free electrons. In contrast to the ions which are driven toward the wall by the radial electric field diverging from the beam, the electrons instead tend to be captured within the positive proton beam. To reduce the resulting neutralization of the coasting beam, the ISABELLE machine will have 1008 pairs of clearing electrodes distributed at regular intervals around the circumference of each ring. The various physical mechanisms which cause the electrons to drift longitudinally along the beam toward the location of the clearing electrodes have been discussed in some detail in Ref. 12. The average ratio of trapped electrons to circulating protons is therein shown to be 1 to 2×10^{-4} at full beam current. For this degree of neutralization the changes in betatron tunes of an unbunched beam can be determined. Thus at injection one obtains[13] a net space-charge vertical tune depression of 0.009, while at 200 GeV one obtains a value of 1×10^{-3}. The corresponding horizontal tune changes are respectively - 0.007 and 1×10^{-3}. The accompanying tune variation across the beam, from center to edge, is about 10% of the central depression. These net betatron tune value changes are small and can be compensated for by proper adjustment of the tune and chromaticity corrections of the lattice.[14]

The presence of trapped electrons in the beam can also give rise to a coherent motion of the protons, coupled to the electrons oscillating in the potential well of the beam. This "e-p instability" has been observed at the CERN ISR[15,16] and also at the LBL Bevatron.[17] Though difficult to calculate, the degree of neutralization at which this instability can start is very much dependent on the spread in frequencies of the oscillating electrons.[18] The ISABELLE has characteristically large variations in beam size as a function of azimuthal position. Since this results in a large spread of electron frequencies, the onset of the e-p instability is inhibited at a neutralization of 10^{-4}.

VI. DISCUSSION

In the previous sections we have thought of the vacuum chamber as essentially a uniform tube. However, in the insertion regions of the machine this will surely not be the case. At these locations the experimental physics requirements will undoubtedly dictate that there be special chamber configurations with special pumping provisions. These large changes in chamber diameters may necessitate some local clearing electrodes in order to eliminate the possibility of "electron traps." In addition such cavity-like structures call for further consideration and study, since they may possibly result in rf beam instabilities.

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