

ULTRAHIGH VACUUM SYSTEM OF THE HEAVY ION TRANSPORT LINE AT BROOKHAVEN*

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Summary

Heavy ions with an energy up to 8 MeV/A for S^{+16} and 1 MeV/A for Au^{+34} from the 16 MV Tandem will be injected into the AGS for further acceleration to ≤ 15 GeV/A. A 600-meter beam transport line between the Tandem and the AGS has been designed and is under construction. This paper describes the design of the vacuum system of this transport line and the performance of the prototype vacuum sectors.

Introduction

The Brookhaven AGS is an alternating gradient synchrotron, 807 m in circumference, which accelerates approximately 10^{13} protons per pulse to 30 GeV for particle physics experiments. The 16 MV Tandem Van de Graaff accelerates heavy ions up to ^{238}U to several MeV/A for nuclear physics research. Using the Tandem as an injector for the AGS, fully stripped heavy ions up to $M=32$ (sulfur) can be accelerated to 15 GeV/A. With the addition of a booster between the Tandem and the AGS in the near future, heavy ions such as gold ($M=200$) can be accelerated to 30 Z/A GeV/A. A 600 m heavy ion transport line¹ (HITL) is under construction, which will connect the Tandem facility to the AGS or, with further extension, to the booster. To minimize the beam loss due to charge exchange between heavy ions and residual gas molecules, average pressure of 10^{-9} Torr in the transport line is necessary, especially for the partially stripped heaviest ions (i.e., 1 MeV/A Au^{+34}). To achieve this pressure with minimum cost, an ultra-high vacuum system pumped by the combination of small ion pumps and linearly distributed non-evaporable getter (NEG) strips² has been designed and is under construction. The details of this vacuum system, as well as the performance of the prototypes of various length (3 m to 30 m), are presented here.

The Vacuum Requirement

The HITL¹ will transport, from the Tandem, fully stripped light ions (up to S^{+16} with $\beta=0.12$) to the AGS ring for injection, or alternatively will carry partially stripped heavier ions (i.e., Au^{+34} with $\beta=0.046$) to the to-be-built AGS booster for acceleration and stripping before injection into the AGS ring for further acceleration.

The requirements for the residual gas density in the vacuum pipes are determined by three major factors: (a) nuclear scattering of the ions by residual gas atoms; (b) charge exchange through collisions between ions and residual gas molecules; and (c) the pressure bump effect in which the beam ionizes residual gas molecules which are then accelerated to the wall by the beam-wall potential, more gas molecules will be liberated from the wall due to this ion bombardment. The nuclear scattering cross section, $\sigma_{NS} \sim 4 \times 10^{-25} A^{2/3} \beta^{-2} \text{ cm}^2$ in nitrogen,³ is small even for low- β heavy ions ($7 \times 10^{-21} \text{ cm}^2$ for 1

MeV/A Au^{+34} and 3×10^{-22} for 8 MeV/A S^{+16}), and the resultant emittance growth should be negligible. At the projected 10^8 - 10^{10} ions per pulse the beam-wall potential is only a few volts⁴ and the desorption yield by the bombardment of eV ions will be insignificant. No pressure bump phenomenon is expected.

The vacuum requirement will be dominated by charge exchange between ions and residual gas molecules. Electron loss and capture cross sections in nitrogen can be estimated by the following formulae,^{3,5} for $\beta > 0.01$:

$$\alpha_L \sim 9 \times 10^{-19} q^{-2/5} \beta^{-2} \text{ cm}^2$$

$$\sigma_C \sim 3 \times 10^{-28} q^{5/2} \beta^{-7} \text{ cm}^2.$$

The total cross sections ($\alpha_T = \alpha_L + \sigma_C$) for 8 MeV/A S^{+16} and 1 MeV/A Au^{+34} will be $1 \times 10^{-18} \text{ cm}^2$ and $4 \times 10^{-15} \text{ cm}^2$, respectively,^{5,6} which are in fair agreement with the measured ones.⁷ The beam loss due to charge exchange can be calculated by

$$d \ln D = -n \alpha_T dx.$$

Here $1-D$ is the fraction of beam loss after distance $x(\text{cm})$, n number of molecules/ cm^3 . α_T is constant for HITL, and

$$1-D = 1 - e^{-n \alpha_T x} = 1 - e^{-3.5 \times 10^{16} P \alpha_T x}$$

with P the N_2 equivalent pressure in Torr. For fully stripped light ions such as 8 MeV/A S^{+16} , the beam loss due to charge exchange will be a mere 0.025% even at a pressure of 1×10^{-7} Torr. However, to have a 10% beam loss for 1 MeV/A Au^{+34} , the vacuum has to be $< 1 \times 10^{-8}$ Torr. Of course, the beam loss will be smaller if hydrogen is the main residual gas, which has a α_T about one decade lower than nitrogen.

The HITL Vacuum System

To achieve a vacuum of 10^{-9} Torr, low thermal outgassing of the vacuum wall and high linear pumping speed are required. Outgassing rates of $< 1 \times 10^{-11}$ Torr. $\ell/\text{s} \cdot \text{cm}^2$ (or 3×10^{-8} Torr. $\ell/\text{s} \cdot \text{m}$ for pipes of 3 or 4" diameter) for Al and SS can be achieved by in-situ bakeout at 100-150°C. To provide linear speed of approximately 10 $\ell/\text{s} \cdot \text{m}$, two different pumping approaches can be taken; (1) using the conventional lumped pump system (sputter ion pump with or without titanium sublimator) distributed along the line; or (2) using linearly distributed NEG strips² together with small ion pumps. The average pressure inside the beam pipe with lumped pumps is a function of linear conductance of the pipe, the pumping speed of the pumps, and distance between pumps. Ion pumps of approximately 200 ℓ/s , spaced every ten meters or less will be needed to achieve 10^{-9} Torr.⁷ When linearly distributed NEG strips and small ion pumps are used, the pumping speed is no longer conductance limited and average pressure of 10^{-10} Torr can be easily obtained.

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The vacuum system of the HITL uses the combination of 20 ℓ/s diode ion pumps, every 37 meters and NEG strips lined along the length of the vacuum pipes. Any materials which pump gases in vacuum without sublimation can be called non-evaporable getter or NEG. The NEG used here is called St 707 developed by SAES Getters, Inc. It is a Zr-V-Fe alloy deposited on a constantan support strip 0.2 mm thick and 3 cm wide. This NEG has been proven suitable for ultra-high vacuum systems.² After activation at 400-500°C in vacuum, pumping speed of > 100 $\ell/s \cdot m$ and capacity of 1 Torr $\cdot\ell/m$ for active gases are available. This capacity, at a pressure of 10^{-9} Torr, represents several months of operation before saturation and reactivation. Activation is done by resistive heating of the constantan support strip. A current of 70 A and 700 watts/m power will be required to maintain the NEG at 400°C. The NEG strip also serves as the heat source during in-situ bake-out.

To incorporate NEG strips into the synchrotron, the size of the vacuum chambers and the magnet pole gap have to be larger, which will drastically increase the cost of magnets. No limitations of this type exist in HITL. The maximum vertical and horizontal beam excursions for all the heavy ions from the Tandem are about one inch.^{1,8} The NEG strips with insulators will have a vertical dimension of < 1" and can comfortably fit inside a pipe of ≥ 3 " diameter.

The 650 meter HITL is divided into 18 vacuum sectors of various lengths. A typical vacuum sector of 73 m in length is shown schematically in Figure 1(a). It consists of eight vacuum pipes with NEG strips installed, two 20 ℓ/s diode ion pumps, several ion gauges and one beam diagnostic box. The diode ion pumps remove the small amount (< 1%) inert gases such as Ar and CH₄, which are not pumped by NEG. Figure 2(a) shows the cross sectional view and Figure 2(b) the uncaptured version of NEG strip with support and insulators inside the pipe. The thermal expansion of the NEG strips during bakeout and activation is absorbed by two copper braids at each end of the pipe as shown in Figure 2(c).

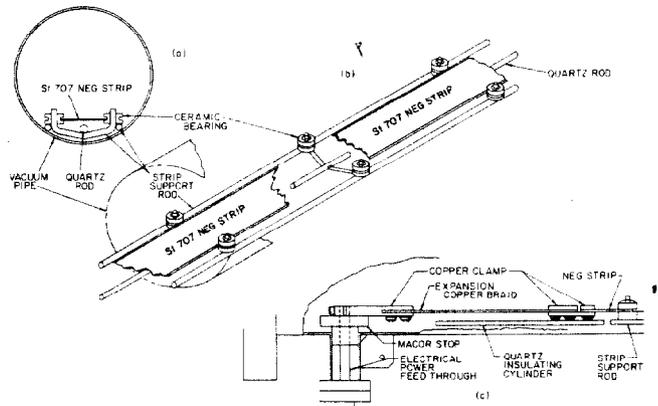


Figure 2 - The vacuum pipe with NEG strip installed (a) cross sectional view; (b) the uncaptured version; and (c) the side view around the feedthrough.

The monitoring and control of the HITL vacuum system will be passive through hardwired interlock and/or microprocessor terminals as shown schematically in Figure 3. The Granville-Phillips 303 vacuum process controller is located in the tunnel to monitor the vacuum through convection gauges and ion gauges. The process control channel outputs (with pressure setpoints) of the 303 are used to interlock ion pump power supplies and sector valve modules through hardwiring. The same functions are also available through RS232 interface to microprocessor terminals at the control houses. The status of the whole vacuum system is available through either the terminals or the video display at each local station.

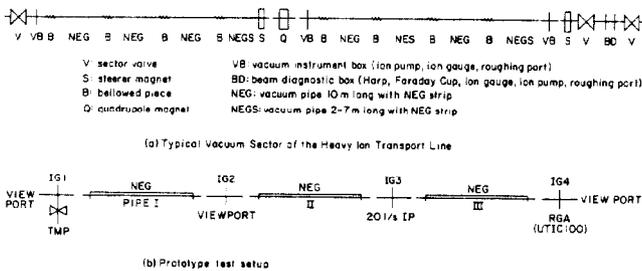


Figure 1

The startup of each vacuum sector will be done manually. After roughing down with portable turbo-molecular pump stations to 10^{-5} Torr range, the pipe will be baked by heating NEG strips at < 300°C (50Å), little activation of NEG will occur at this temperature. Activation at 400°C (70 A) is maintained for 30 minutes, then the ion pumps are turned on and the turbo stations valved off. Within 24 hours the sector pressure will be in the 10^{-10} Torr range.

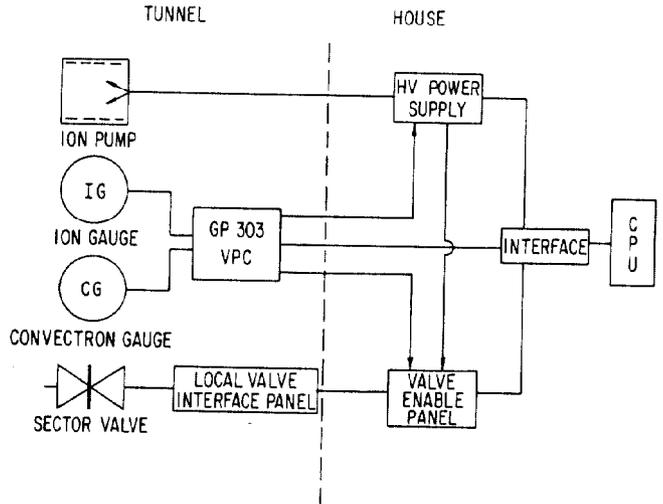


Figure 3 - The HITL vacuum control system.

Performance of Prototype Vacuum Sectors

To test the performance of the NEG strips and to give guidance in the design and operation of the HITL vacuum system, prototype vacuum sectors with a length of 3 m, 10 m, 20 m and 30 m were assembled and operated for six months. Figure 1(b) shows the setup of the 30 m long sector. Several ion gauges, one 20 ℓ/s ion pump and an UTI C100 residual gas analyzer (RGA)

were installed at vacuum boxes located between the 10 m long NEG containing vacuum pipes. The vacuum sectors were baked to approximately 150°C for approximately 16 hours using heating tapes on boxes and 50 A current through NEG strips. After activation at 400°C (70 A) for 30 minutes, a pressure of 10^{-10} Torr was achieved within one day. The pumpdown curves in Figure 4 show the pressure distribution along the vacuum pipes. The pressure at the middle of the NEG strip² is shown by curve 4(a). Curve 4(b) represents the range of pressure distribution at the instrument boxes which have larger ratio of surface area to pumping speed. The residual gas composition at the box is shown in Figure 5(a). Besides hydrogen and carbon monoxide which are common in ultra-high vacuum systems, a small amount of methane which is non-gettable by NEG was also present. The effect of these inert gases on the vacuum system was studied by turning off ion pumps. The pressure stabilized at approximately 4×10^{-9} Torr after three days as shown by the peak of curve 4(b). The RGA spectrum (Figure 5(b)) indicates that most of the increase is due to methane and argon. In a separate test, three months after the ion pump was turned off, the pressure remained at low 10^{-7} Torr range. In reality, these inert gases will be removed by the next ion pumps 30 m away and no interruption of vacuum operation is expected due to ion pump failure and/or power failure.

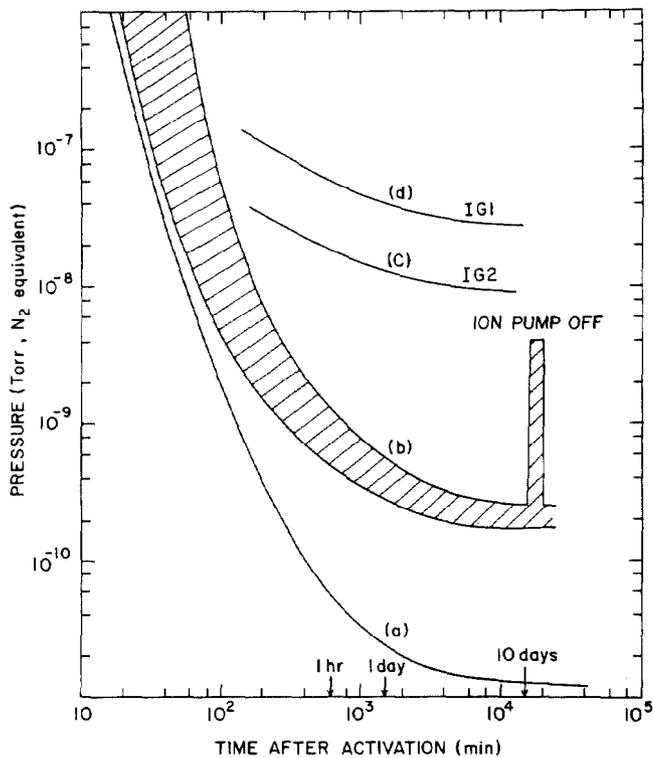


Figure 4 - Pumpdown curves of the prototype vacuum sectors.

The pressure of the AGS ring and the Tandem near the HITL will be at high 10^{-8} Torr range. The effect of operating NEG near this high pressure zone was studied by creating an artificial pressure zone near the NEG strips. Vacuum boxes at IG1 and IG2 and the pipe I were not baked and NEG I was not activated. The pressure distributions at IG1, IG2 and IG3 are shown by curves 4(c), 4(d), and 4(b), respectively.

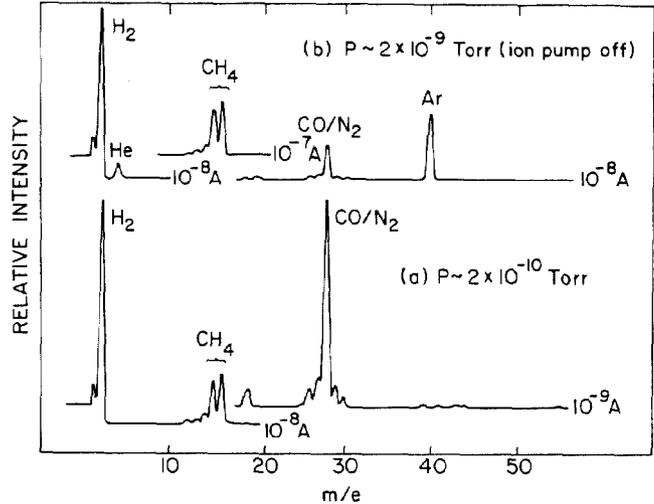


Figure 5 - Spectra taken by residual gas analyzer (a) with ion pump on; and (b) with ion pump off.

No pressure increase at IG3 was observed, suggesting the effectiveness of differential pumping by the NEG strips alone. The average pressure of the first 10 m NEG strip facing the 10^{-8} Torr pressure zone is estimated to be 10^{-9} Torr and frequent activation (i.e., < 1 month) is not required.

Conclusions

The HITL vacuum system using the linearly distributed NEG strips as the main pump will achieve ultra-high vacuum, though only very high vacuum (10^{-9} Torr) is required even for partially stripped heavy ions. This vacuum system offers simplicity in operation (low power requirement, little maintenance), rapid pumpdown (10^{-10} Torr in one day), and low construction costs (pumping system < \$200/m) and can be applied to other beam transport lines where high vacuum or ultra-high vacuum is required.

References

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