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**Pressure Measurements in the AGS Booster
Ultra-High Vacuum System***

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ABSTRACT

An average pressure of mid 10^{-11} Torr has been achieved and maintained in the AGS Booster ring vacuum system during its first year of operation. This ultra-high vacuum system is monitored through remote controlled Bayard-Alpert Gauges (BAGs). The characteristics of the pressure measurements with BAGs over the long cable lengths (up to 200 m) and under various accelerator operating conditions will be described. Two types of noise in the pressure readouts have been identified; the electromagnetic interference (EMI) associated with the acceleration cycles of the Booster

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and the environment noise associated with the temperature of the collector cables. The magnitude of the noise pickup depends on the routing of the collector cables and reaches the equivalent pressure of low 10^{-9} Torr.

I. INTRODUCTION

The AGS Booster at Brookhaven, located between the existing 200 MeV Linac, the Tandem Van de Graaff and the Alternating Gradient Synchrotron (AGS), is a small synchrotron for the acceleration of protons and heavy ions. The machine was commissioned in 1991 and has been running for high energy physics programs in the past year. It has accelerated protons from 200 MeV to 1.2 GeV, silicone (Si^{+8}) from 7 MeV/amu to 400 MeV/amu and gold (Au^{+33}) from 1 MeV/amu to 267 MeV/amu. It is the acceleration of Au^{+33} which puts the most stringent requirements on the vacuum system of the 200 m Booster ring. The partially stripped, low $\beta (= v/c)$, very heavy ions will exchange electrons with the residual gas molecules, which changes the magnetic rigidity of the heavy ions and causes immediate beam loss. The charge exchange cross sections of Au^{+33} with residual gas molecules is in the order of 10^{-15} cm^2 at injection energy of 1 MeV/amu[1]. At the design vacuum of $3 \cdot 10^{-11}$ Torr (90% H_2 and 10% CO), the integrated beam loss during acceleration cycles is less than one percent. At a vacuum of $3 \cdot 10^{-10}$ Torr (10% H_2 and 90% N_2), the beam loss for Au^{+33} is calculated[1] to be over 30%.

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The ring vacuum system was in-situ baked at 200-250°C in the spring of 1991. Average vacuum of mid 10^{-11} Torr was achieved after this initial bake. Bayard-Alpert type ionization gauges (BAGs) are used to monitor this ultra-high vacuum system. Due to the presence of high levels of background radiation, all vacuum instrumentation is located several hundred meters away in the equipment building. In this paper, the hardware and instrumentation of the vacuum system will be described briefly. Detailed information on the design and performance of the BAGs and their controllers will then be given. A study of the sources and magnitude of the noise pickup in the BAG system will be presented.

II. DESCRIPTION OF VACUUM SYSTEMS

The design of Booster vacuum system can be found in Ref. 2. The Booster ring, with a circumference of 200 m, has 48 halfcells. A typical halfcell chamber is 4.2 m long, made mostly of Inconel 625 and consists of chambers for dipole, quadrupole, pick-up electrodes, sextupole, bellows and a transition with ports connecting to pumps, gauges and roughing valve. The 12 "missing dipoles" house the accelerating cavities, kickers and other beam components. The vacuum chambers and the beam components are mounted with thermocouples and custom heating jackets. They were designed to be in-situ bakeable to 300°C. To this date, each vacuum sector was baked to 250°C with a computer controlled bakeout system. After roughing and insitu bake, the ring vacuum was achieved with the combination of fifty-five titanium sublimation pumps and fifty 20 l/sec sputter ion pumps.

Vacuum instrumentation for the Booster includes power supplies for ion pumps and titanium pumps, controllers for vacuum gauges and valves, and the computer system. Shielded cables, up to 200 m in length are routed from the equipment building, through outdoor cable trays to the hardware in the Booster tunnel. The status, readbacks and control of the instruments are also accessible from front panels as well as from Apollo nodes linked through an RS232 or IEEE488 interface. General purpose programs such as 'spreadsheet' and 'logread' are running on the Apollo for live display and for reviewing the logged data. Typical vacuum readbacks from 'logread' are shown in Fig. 1.

III. PRESSURE MEASUREMENTS WITH BAGs

A. Description of the BAG System

A total of 45 BAGs are distributed around the Booster ring. These BAGs have a collector of 0.05 mm diameter. The sensitivities and equivalent x-ray limits of some of these BAGs were measured to be $\approx 20 \text{ Torr}^{-1}$ and $\approx 4 \times 10^{-12} \text{ Torr}$, respectively for nitrogen[3]. Vacuum down to high 10^{-12} Torr can be measured with these BAGs. The BAGs were mounted at the transition of the half-cell chambers or at the center of the beam component housings. Factoring in the linear conductance[4] of the chamber, the average pressure in the halfcell chambers is approximately 1.3 times that of the BAG reading. The pressure of the halfcell chambers turns out to be insignificant in measuring the average ring pressure. The BAG readings at some beam components are one or two decades

higher than those of the halfcell chambers and become the dominant part of the average pressure.

Commercial digital vacuum process controllers (VPCs) are used to power and read the BAGs. The VPCs convert the measured collector current into pressure readings based on the user programmed sensitivity and emission values. The integration time of the VPCs is 0.66 sec for vacuum below 1×10^{-9} Torr. The pressure readings are displayed on the front panel of VPCs and sent via RS232 interface to Apollo nodes for processing. Through process control channels, the BAGs also provide interlocks for sector valves and beam components.

At low 10^{-11} Torr vacuum, the collector current of the BAGs is only a few picoamperes. Electrical noise pickup over the long cable runs masks the collector current and results in erratic pressure readings. The most prominent source of noise in accelerator is the electro-magnetic interference (EMI) from pulsing magnets, power supplies and accelerating cavities. Tests of noise pickup over long cable runs in the AGS ring were carried out in 1989. Among several different types of shielded coaxial cables tested, Belden 9311 coax[5] was selected. This coaxial cable features 100% shield coverage, a foil/braid outer shield, and a polyethylene dielectric. The cable capacitance is 26 pf/ft. The microphonics of this cable, at AGS operating conditions, was measured[4] to be approximately $\pm 30\%$ at mid 10^{-11} Torr and was

acceptable for Booster vacuum monitoring. In these tests, the collector cables were routed through indoor cable trays into the AGS tunnel. In the Booster, the cables are routed through outdoor cable trays into the tunnel. The magnitude of the noise pickup in the Booster is much higher than that observed in the original tests.

B. The Performance of the BAG Systems

During the operation of Booster, oscillations in some BAG readouts ranges from sub 1×10^{-11} Torr to low 10^{-9} Torr. These oscillations make measurements of average ring pressure difficult, if not impossible. A study was initiated to identify the sources of this excessive noise pickup. However, due to the lack of dedicated machine study time and accessibility to hardware in the tunnel, only limited results have been obtained so far as summarized below.

1. Observation of Oscillation through VPCs and Apollo

Typical logged BAG data plotted by 'logread' program is shown in Fig. 1. In these plots, readings below 1×10^{-11} Torr are rounded to 1×10^{-11} Torr; and values of 1×10^{-12} Torr are assigned when the BAG filament is off. The 8-hour daytime-averaged BAG readings are shown in (a) and (b); live readings over one-hour period are plotted in (c) and (d); and the readings of individual BAGs over a 24-hour period are given in (e) and (f). Both (a) and (c) were taken on a cloudy day. Plots (b) and (d) were recorded on sunny

days with the Booster in operation. Data in (e) and (f) was recorded with daytime sunny conditions.

From this data, it is evident that exposure to sunlight increases the average pressure substantially. After the observation of the differences in average pressure with and without exposure to sunlight, the readouts of individual BAGs were examined. Most of BAGs showed substantial irregular oscillations. The magnitude of oscillations varied among the BAGs and increased when exposed to sunlight and when the Booster was in operation. Typical oscillations of individual BAGs over a 24-hour period (Fig. 1(e) and 1(f)) show magnitude of one or two decades higher for day time than for night time. This sunlight related oscillation is bipolar as evident in Fig. 1(e).

Comparison of the BAG readings with the cable routings indicates a close correlation between the magnitude of oscillations and the length of outdoor cable run. BAGs located closer to magnets and beam components also showed higher levels of noise pickup. To distinguish the noise contribution from these different sources, three BAGs were selected for further studies. Analog gauge controllers were used in these studies and the observation is described in the next section.

2. Study of Selected BAGs with Analog Gauge Controllers

Three BAGs identified by their halfcell names as B7, E4 and F2 were selected. The vacuum levels at these three locations were measured locally to be less than 2×10^{-11} Torr. The peak stray magnetic field at F2 is estimated to be approximately 100 Gauss while those at B7 and E4 are less than 10 Gauss. The study of F2 gives the maximum level of the collector current induced by the ramping magnetic field. The F2 was connected to an analog gauge controller located at the gauge tube in the Booster tunnel. The output of the controller was analyzed outside the tunnel with a digital scope. In the cases of B7 and E4, the magnetic field induced collector current[5] is small comparing with other signals. The cable routings for B7 and E4 are different from each other, B7 has a short outdoor run and a long in-the-tunnel run while E4 has over 100 m outdoor run and 10 m in-the tunnel run. Studying the oscillations of their readings allows us to identify the contribution from machine EMI and from the solar effect. These two BAGs were powered by analog gauge controllers located in the equipment building. The outputs of the controllers were monitored using chart recorders with 100 mV equivalent to either 1×10^{-9} Torr or 1×10^{-10} Torr depending on the setting of the electrometers on the controllers.

The output signals of F2 BAG during the acceleration of gold and proton are shown in Fig. 2(a) and 2(b), respectively. During gold acceleration, the Booster magnets ramped for 1.2 sec over the

3.2-sec AGS supercycle. The 35 millivolt pulses in Fig. 2(a) have periods of ~ 1.2 sec corresponding to the current induced by the main magnet pulses. During the proton run, the Booster main magnets ramped five times of 100 msec each for protons and one pseudo cycle for heavy ions. The 6 millivolt pulses with ~ 100 msec width in Fig. 2(b) correspond to the noise generated by the main magnets during proton cycles. The 4 millivolt pulse corresponds to noise from the pseudo heavy ion cycle. These types of noise pickup with short periods cancel within themselves when VPCs are used due to the 0.66 sec integration time in the VPCs.

The magnitude and frequency of the oscillations in the output of B7 and E4 vary with the weather and machine conditions. They are much noisier in the day time (Fig 3). These weather related oscillations are bipolar and are usually less than 100 mV (equivalent to pressure of $1 \cdot 10^{-9}$ Torr) for E4 and less than 10 mV for B7. Very large amplitude pulses are occasionally observed. These are probably caused by the malfunctions such as arcing or corona in beam component power supplies and their cables. More studies are needed to identify the sources.

Faster scans of B7 and E4 signals show that the magnetic field generated pulses are riding on top of the weather generated oscillations. Typical outputs are shown in Fig. 4 with (a) and (b) recorded on a sunny day, and (c) on a cloudy day. The magnetic field generated pulses in both B7 and E4 are less than 20 mV

(equivalent to $2 \cdot 10^{-11}$ Torr) and are independent of weather conditions. The magnitude of oscillations of E4 is equivalent to a pressure in the mid 10^{-10} Torr range, while that of B7 is $5 \cdot 10^{-11}$ Torr on a sunny day and less on a cloudy day. This is consistent with the fact that E4 has a long outdoor cable run while B7 a short outdoor cable run.

CONCLUSION

The Booster ultra-high vacuum system relies on Bayard-Alpert gauges to monitor its pressure during machine operation. These BAGs are connected through long cables to gauge controllers. The noise pickup along the cables of some BAGs has made accurate pressure measurement difficult. The noise pickup on a few BAGs has been examined in detail and the present results indicate:

(1). There are three major sources of noise in Booster BAG system: weather conditions; main magnet pulsing; and malfunctioning of beam components.

(2). The weather induced noise is bipolar, increases in the day and drops off in the night, and is much higher during sunny days. The period of noise is irregular and on the order of minutes. The BAGs with longer outdoor cable runs have much higher noise equivalent to pressure of mid 10^{-10} Torr. Solar heating of the coaxial cables and their subsequent flexing in the cable tray seems to generate the electrical signals

(3). The noise induced by magnet pulsing is regular and has magnitude equivalent to pressure of low 10^{-11} Torr. The frequency of this noise is high enough that it cancels over the long averaging period of the digital gauge controller.

(4). The very large oscillations observed in some BAG outputs are thought to be caused by the malfunctioning beam components. More studies are planned in the near future to identify the exact sources.

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FIGURE CAPTIONS

Fig. 1. The Booster BAG readouts plotted by the 'logread' program with (a) and (b) the 8-hour time average readings; (c) and (d) the live plots over one-hour period; and (e) and (f) 24-hour plots of some selected BAGs which show the wider oscillations during the daytime(right side of the plots).

Fig. 2. The voltage output of F2 BAG with the analog gauge controller located in the Booster tunnel (a) during the acceleration of gold and (b) during the acceleration of protons.

Fig. 3. The output signals of B7 and E4 BAGs over 18-hour period. The horizontal axis gives the hour of the day.

Fig. 4. The output signals of B7 and E4 BAGs over 20-minute period with (a) and (b) taken on a sunny day and (c) on a cloudy day.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

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