Vacuum Gauge Calibration System in Pohang Accelerator Laboratory

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(Received September 16, 1994)

포항가속기 연구소의 진공게이지 교정시스템

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(1994년 9월 16일 접수)

Abstract − The vacuum gauge calibration system has been designed and established in Pohang Accelerator Laboratory (PAL). This system is characterized by a dynamic expansion method with a spinning rotor gauge as a transfer standard. This calibration system is used extensively for calibrating Bayard-Alpert (BA) nude ionization gauges as well as cold cathode gauges used in the storage ring vacuum system of Pohang Light Source (PLS). The pressure range for the calibration is between 10^{-4} and 10^{-9} Torr. This study covers design details and some of calibration results for several types of gauges: six BA nude ionization gauges, one extractor gauge, one high pressure gauge, and five cold cathode gauges.

요 약 − 포항가속기연구소에서 사용될 진공게이지 교정시스템이 설계 제작되었다. 이 교정시스템은 동적 교정 방법으로 설계 되었으며, transfer standard 로서 spinning rotor gauge 를 사용하였다. 포항가속기의 저장링에 사용될 모든 진공게이지는 이 교정시스템으로 교정을 하여 사용할 것이며, 주로 교정할 게이지로는 Bayard-Alpert (BA) nude ionization gauge 와 cold cathode gauge 등이 있다. 본 논문에서는 포항가속기의 진공게이지 교정시스템에 대해서 소개를 하였고, 현재까지 BA nude ionization gauge 6대, extractor gauge 1대, high pressure gauge 1대와 cold cathode gauge 5대를 10^{-4} 에서 10^{-4} Torr 범위내에서 교정하여 그 결과를 보였다.

1. Introduction

The 2 GeV storage ring of Pohang Light Source (PLS) has a circumference of about 280 meters, and is designed for an ultimate electron beam current of 400 mA. In spite of the high outgassing rate due to photon induced desorption the vacuum chamber should be maintained in ultra high vacuum (UHV) range, which is less than 5 nTorr in order for the electrons to have required beam lifetimes of more than 5 hours. The pressure in the storage ring will be monitored with 10 Bayard-Alpert (BA) nude ionization gauges and 40 cold cathode gauges (CCG). These gauges are used for monitoring the pressure distributions in the ring as well as for interlocking to other equipment on a probable emergency status. Since the accuracy of pressure measurements gives the correct analysis of the vacuum of the storage ring, especially during electron beam operation, all UHV gauges to be installed in the ring should be calibrated. Since it is well known that the dominant gases in the storage ring vacuum chambers are H_2

and N_2 or CO [1], the gauges are calibrated only for two gases, H_2 and N_2. Also, the UHV gauges in the ring will not be used in the vacuum range higher than 10^{-6} Torr, and the calibration range is from 1×10^{-6} Torr down to the lower pressure for UHV gauges. Most of gauges including their controllers are newly purchased, and their aging effect will be also investigated in the future. The spinning rotor gauge is used as a transfer standard, and the ball is calibrated by the primary standard in Deutscher Kalibrierdienst (DKD) to reduce its own uncertainties.

2. Vacuum Gauge Calibration System

2.1. Principle

The PLS gauge calibration system is designed to meet so called the dynamic expansion method with a spinning rotor gauge as a transfer standard [2,3]. The gauge head under calibration and a spinning rotor gauge as a pressure standard are attached to the calibration chamber and subject to a steady pressure generated by balancing the rate of flow of calibration gas into the chamber against the rate of removal of gas. Such a system is illustrated in Fig. 1. The calibration chamber is composed of three right cylindrical chambers, and the ports to the calibration chamber are arranged around the periphery of the calibration chamber in the symmetrical eight locations. If there is a gas throughput Q into the chamber 1, the gas flow from the chamber 1 across the orifice C_1 and C_2 to the pumping system is expressed as

$$Q = C_1(P_1 - P_2) = C_2(P_2 - P_3) = SP_3 \tag{1}$$

This gives

$$S = C_1 \left(\frac{P_1}{P_2} - 1 \right) \frac{P_2}{P_3} = C_2 \left(\frac{P_2}{P_3} - 1 \right) \tag{2}$$

Assuming that the pumping speed S of the system is constant, the ratios of P_1/P_2 and P_2/P_3 become clearly constant from eq. (2). Consequently, if we measure P_1, the pressure of the chamber 1, and the ratio of P_1/P_2 with a constant pumping speed, we can calculate P_2, the pressure of the chamber 2. Since the spinning rotor gauge is used for the

range of pressure $10^{-2} \sim 10^{-6}$ Torr, it cannot be used as a direct transfer standard in the range less than about 10^{-6} Torr. However, if we measure the ratio of P_1/P_2 at the end of increasing pressure where two spinning rotor gauges can be measured and compared simultaneously, the pressure of the chamber 2 can be calculated stepwise by both the ratio and the measurement of P_1 from the relation of

$$P_2 = \alpha \, P_1 \tag{3}$$

where α is the pressure ratio determined at the end of increasing pressure.

2.2. Calibration Chamber

As shown in Fig. 1, the gauge calibration chamber in PLS is composed of three cylindrical chambers. The chamber 1 is both for the gas inlet and for the upper range of calibration ($10^{-6} \sim 10^{-2}$ Torr), the chamber 2 for the range of $10^{-9} \sim 10^{-7}$ Torr, and the chamber 3 both for another gas inlet and for the range less than 10^{-9} Torr. At this time, the calibration in the chamber 3 has not been performed. The gauge calibration chamber is designed so that a pressure uniformity as well as a stability can be achieved in the chamber, and each chamber has eight gauge ports in the symmetrical locations.
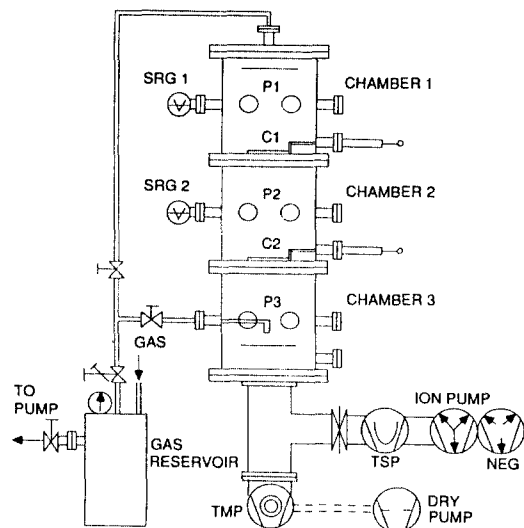

Fig. 1. Vacuum gauge calibration system in PLS vacuum group.

The orifice C_1 between the chambers 1 and 2 is restricted by a small orifice in a movable orifice plate, whose diameter is 1 mm. This orifice makes the pressure difference between the chambers 1 and 2 more than 2 orders, but less than 3 orders. The orifice C_2 between the chambers 2 and 3 is the same kind of movable orifice as the orifice C_1 and its diameter is 17 mm. Since the orifice area of C_2 is small compared with the chamber surface area, the pressure gradients in the chamber 2 can be kept small, and they can be minimized by locating the gauges properly. On the other hand, the orifice opening must be large enough so that there is adequate pumping speed to limit the background pressure during calibration. The baffles are placed near the gas inlet tube in order for incoming gas molecules to experience a number of collisions before entering into a gauge because the gas inlet is not in a molecular flow regime. The regulated flow of calibration gas is usually valved directly into the chamber 1, but it can be valved directly in the chamber 3 if a good pressure uniformity is required. The calibration chamber is 34 cm high 27 cm in diameter, which is composed of a cylindrical chamber with 13-1/4″ o.d. conflat flanges, and eight 2-3/4″ o.d. conflat flanges are available in each chamber so that various gauges can be mounted on the chamber at the same time. Since the pumping speed through the orifice is inadequate for initial pumping down and clean up of the system, the orifice can be placed over or raised over above a larger hole in a stainless steel plate. The orifice can be raised or lowered by a simple linear motion feedthrough. The conductance can be quite large in the raised position, and it will be limited by the drilled hole and a leakage between the plate and the bottom of the chamber in the lowered position. It is only necessary that this conductance be stable during calibrations, and need not be known nor even reproducible when the orifice plate is raised and lowered repeatedly [3]. The orifice is contained in a plate that seals into a GaIn-filled groove located in the central wall. For the GaIn to form a seal when the orifice plate is lowered, it remains in the liquid phase in the room temperature. Although GaIn does not give a vacuum-tight seal to the orifice plate,

it will be enough to reduce large leaks that may exist in the orifice plate. The vapor pressure of GaIn is quite low at the room temperature, and there is no evidence of GaIn vapor in the chamber [4]. The calibration system is baked with electric heating tapes that encloses the chambers including gauge ports. The chambers maintained at a uniform temperature of 250℃ for two days.

2.3. Vacuum Pumps

As the gauge calibration system requires a clean, oil-free vacuums, a stable pumping speed, and a vibration free pump, a 520 l/s Balzers turbo molecular pump (TMP) operated by a magnetic levitation is installed as a principal high vacuum pump. As an UHV pump, only a Balzers titanium sublimation pump (TSP) with an intrinsic pumping speed of about 1100 l/s for nitrogen was originally operated. But the hydrogen gas is so dominated in the base pressure with a factor of 2 orders higher than the next highest one. Thus, a combination pump which is composed of a 60 l/s Varian sputter ion pump with two lumped non-evaporable getter (NEG) with a measured effective pumping speed of about 270 l/s for nitrogen is installed additionally to the pumping system. A 7.5 l/s Alkatel dry pump is also used for backing, and it does not contaminate the vacuum system even without any traps. Since the dry pump generates vibrations, forelines should be flexible and anchored so that vibrations are not transmitted to the calibration system. Although pumps other than the TMP do not have a very stable pumping speed, the effective pumping speed can be optimized by the limited conductance of the orifice C_2 that is less than 27 l/s for the nitrogen at 27℃. As a result, a small change in the pumping speed caused by the TSP and combination pump does not affect significantly the effective pumping speed through the orifice C_1.

2.4. Gas Inlet Lines

The gas inlet lines are made of stainless steel tube of 1/4″ diameter. The tube following the variable leak valve is welded on a conflat flange to meet the UHV leak rate while the tube between the variable leak valve and the gas tank is sealed with

Swagelok fittings. The inlet gas is charged in a gas reservoir whose volume is 9 liters, and all metal variable leak valve fed from it, where the leak valve is controlled by a stepping motor which is interfaced with a personal computer. The gas reservoir including inlet lines are evacuated by a small turbo molecular pump, and baked at about 150℃ by electric heating tapes and then backfilled with the calibration gas up to an appropriate pressure after isolating the pumping system from the gas reservoir.

2.5. Calibration Procedure

A personal computer is interfaced with a stepping motor and gauge controllers. The stepping motor is operated by pulses generated by the computer, and the interface protocol of controllers is selected among RS 232, RS 422, and IEEE-488 communications depending on the type of interfacing available in the controller under calibration. During the initial pumping and the bakeout, the orifices C_1 and C_2 are remained at the raised position. After the base pressure reaching around 7×10^{-11} Torr in the chamber 3, the spinning rotor gauge starts to operate to measure the residual drag, so called offset value at "zero" pressure which is a magnetically induced, pressure-independent slowing of the ball. After a careful determination of this offset, orifices C_1 and C_2 can be lowered manually. At equilibrium, the pressures in the chambers 1,2, and 3 indicate equivalent nitrogen pressures of about 5×10^{-8}, 5×10^{-10}, and 7×10^{-11} Torr, respectively, and then gauges can be calibrated by entering the gas through the variable leak valve. The residual gases in the chamber 2 are continuously monitored by a residual gas analyzer (RGA). The calibration starts with the lowest limit of the calibration range after entering the calibration gas sufficiently, and is carried out by increasing the pressure stepwise. The variable leak valve is controlled in such a way that the sequence of steps permits the generation of at least three or four pressure points for each decade. When the pressure approaches at the upper end of the pressure range, the pressure ratio P_1/P_2 is determined by two spinning rotor gauges which are placed in the chambers 1 and 2. After determining the pressure ratio, the calibration is then carried out by

decreasing the pressure stepwise in order to investigate the hysteresis of gauges. During this calibration procedure, gauges in the range between 10^{-2} and 10^{-6} Torr can be calibrated in the chamber 1 directly to the SRG 1, and the calibration in the range between 10^{-7} and 10^{-9} Torr can be obtained from the measurement of SRG 1 divided by the pressure ratio. The DKD calibrated ball has its own uncertainty of 2.8% in the range of 10^{-6} Torr, and the uncertainty due to the change of the pumping speed through the orifice C_2 is approximately 1%. Thus, the pressure P_1 in the chamber 1 has its uncertainty of less than 3.8%, and the pressure P_2 in the chamber 2 has 9.4%. Since temperature variation and mechanical vibration can result in a very unstable offset value of a SRG, which is a very crucial factor determining the performance of a SRG, the calibration system requires to be maintained under uniform ambient temperature as well as to be free of vibration.

3. Calibration Result

Several types of gauges are calibrated for nitrogen and hydrogen gases, and the types of gauges with controllers are presented in the Table 1. There are five Bayard-Alpert (BA) nude ionization gauges with 1 mA emission current, five cold cathode gauges (CCG), and one extractor gauge (EXT). These are calibrated for the pressure range of $10^{-7} \sim 10^{-9}$ Torr for hydrogen and nitrogen gases. For the calibration range of $10^{-4} \sim 10^{-7}$ Torr for two gases, there are two gauges: one high pressure gauge (HPG) and one BA nude ionization gauge having its emission current of 0.1 mA. The ratio of the controller reading to the true pressure measured by the spinning rotor gauge is also shown in Table 1. [5]. This ratio is defined as a sensitivity which is the slope in the graph of the controller reading vs. the true pressure. As shown in Table 1, the measured hydrogen sensitivities for six BA nude ionization gauges are in the range between 0.362 and 0.412 relatively to the nitrogen sensitivity, while the ones for five cold cathode gauges are between 0.344 and 0.371 relatively to the nitrogen sensitivity. It is also observed that the hydrogen sensitivities

Table 1. Sensitivity and hysteresis measurements of various gauges for N_2 and H_2

		BA-1	BA-2	BA-3	BA-4	BA-5	EXT	CCG-1
H_2	Up	0.3997	0.2793	0.2930	0.2927	0.3870	0.5103	0.4600
	Down	0.3975	0.2712	0.2913	0.2913	0.3825	0.5074	0.4704
	Dev.	0.276	1.471	0.291	0.240	0.585	0.285	−1.118
	Rel.	0.397	0.382	0.362	0.398	0.412	0.456	0.369
N_2	Up	1.0070	0.7182	0.8045	0.7294	0.9311	1.0546	1.2590
	Down	1.0016	0.7214	0.8113	0.7370	0.9387	1.0616	1.2600
	Dev.	0.269	−0.222	−0.421	−0.518	−0.406	−0.331	−0.040
	Rel.	1	1	1	1	1	1	1

		CCG-2	CCG-3	CCG-4	CCG-5	HPG	BA-6
H_2	Up	0.4773	0.4462	0.5053	0.4340	0.3875	0.2977
	Down.	0.4858	0.4534	0.5120	0.4399	0.3844	0.2956
	Dev.	−0.883	−0.800	−0.659	−0.675	0.402	0.354
	Rel.	0.344	0.346	0.366	0.371	0.437	0.381
N_2	Up	1.4007	1.3014	1.3948	1.1734	0.8796	0.7768
	Down	1.4006	1.2986	1.3856	1.1849	0.8867	0.7791
	Dev.	0.004	0.108	0.331	−0.475	−0.402	−0.147
	Rel.	1	1	1	1	1	1

Up; Sensitivity measured while increasing pressure
Down; Sensitivity measured while decreasing pressure
Dev; (Up-Down)/(Up+Down)×100 (%)
Rel; Relative sensitivity to N_2 sensityvity
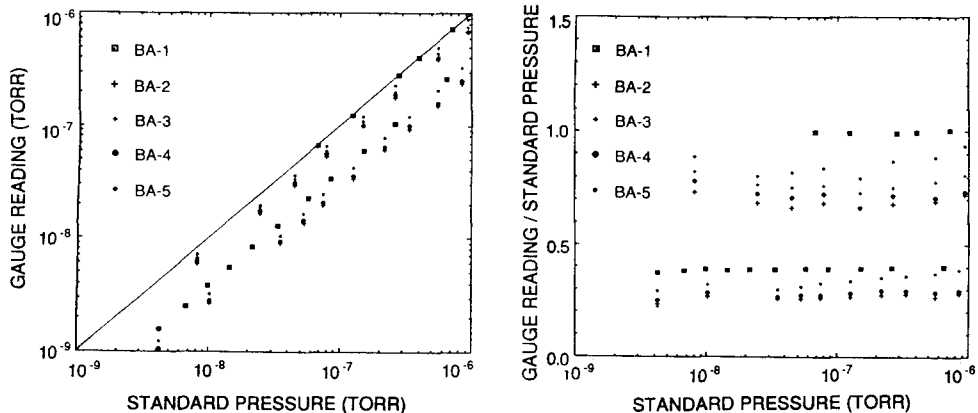
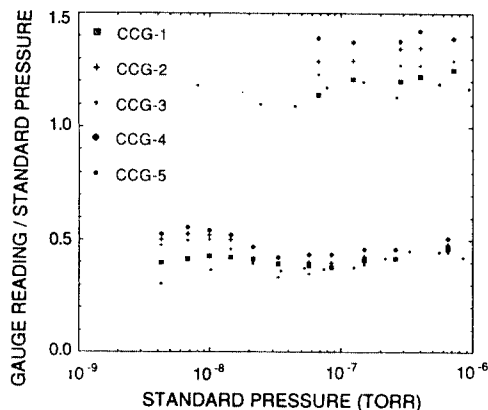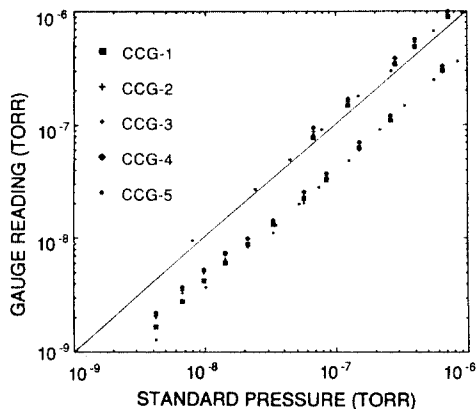**Fig. 2.** (a) Plot of BA ion gauge readings vs. standard pressure.
(b) Plot of sensitivities for BA ion gauges vs. standard pressure.

for the high pressure gauge and the extractor gauge have relatively higher values. The calibration results of five BA gauges are plotted in Fig. 2(a) and (b). The upper group in the figures indicates the results for N_2 gas and the lower group for H_2 gas. Since the controller reading is set to the nitrogen gas, the measured data for the nitrogen gas is expected to scatter around the diagonal line with a slope
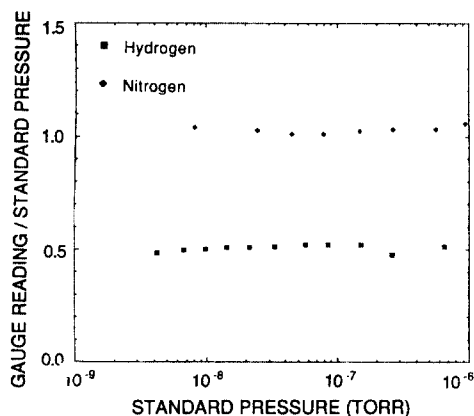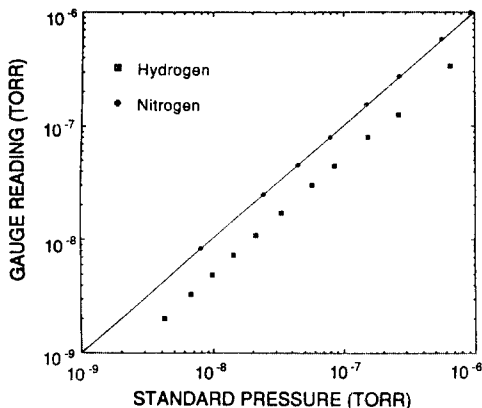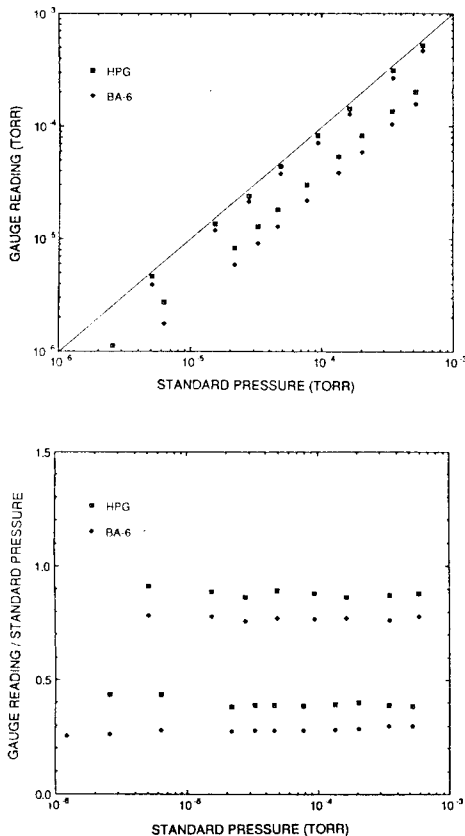
Fig. 3. (a) Plot of extractor gauge readings vs. standard
pressure.
(b) Plot of sensitivities for extractor gauge vs.
standard pressure.

Fig. 4. (a) Plot of cold cathode gauge readings vs. stan-
dard pressure.
(b) Plot of sensitivities for cold cathode gauges
vs. standard pressure.

one indicated by solid line in Fig. 2(a). In the case
of BAs, the data are scattered below the solid line
which means that the controller reading is slightly
lower than the true pressure. The scattered sensiti-
vities for the BAs are shown in Fig. 2(b). Among
the five BAs, only BA-1's is different from those
of four other controllers, and BA-1 and 3 have tung-
sten filaments while others have thoria coated iri-
dium filaments. The results of BA-1 measured by
the controller different from the others is quite sta-
ble in sensitivity, but the other four results are fluc-
tuating. The results of the extractor gauge are
shown in Fig. 3(a) and (b). In Fig. 3(a), the calibra-
tion results for N_2 are scattered along the solid line.
This means that the measured gauge reading is al-

most identical with the standard pressure for nitro-
gen. For the scattered sensitivities in Fig. 3(b), the
results seem to be stable but not better than BA-
1 in Fig. 2(b). The calibration results for the cold
cathode gauges are shown in Fig. 4(a) and (b). Un-
like BA ionization gauges, cold cathode gauges seem
to have a tendency to read slightly higher pressure
than the standard pressure. The sensitivities of the
cold cathode gauges show worse scattering than
those of BA gauges, and very rapid changes are
observed below about the middle of 10^{-8} Torr. Fig.
5(a) and (b) show the results of one high pressure
gauge and one BA ionization gauge of 0.1 mA emis-
sion current.

Fig. 5. (a) Plot of high vacuum gauge readings vs. standard pressure.
(b) Plot of sensitivites for high vacuum gauges vs. standard pressure.

4. Summary

Several types of gauges including their controllers are calibrated in the vacuum gauge calibration system newly designed in vacuum group of PLS. This system is characterized by a dynamic expansion system with a spinning rotor gauge as a transfer standard. The vacuum range of $10^{-2} \sim 10^{-6}$ Torr and $10^{-7} \sim 10^{-9}$ Torr can be calibrated within uncertainties of about 4% and 10%, respectively. Five Bayard-Alpert nude ionization gauges with two types of controllers and two types of filaments have been calibrated, and the results depend significantly on the type of controller as well as gauge itself under calibration. The sensitivities are linear to within ± 1% for the best case and ± 8% for the worst case for

nitrogen gas, while ± 3% for the best case and ± 13 % for the worst case for hydrogen gas. Also, five cold cathode gauges have been calibrated, and their linearity seems to be more unstable than that of BA nude ionization gauges, and it is observed to be ± 11% for the best case and ± 20% for the worst case for hydrogen gas. This kind of large deviation in the sensitivity for the cold cathode gauges is caused by a rapid change under the middle range of 10^{-8} Torr, as shown in Fig. 4(b).

5. Future Work

In this report, we have not performed successive calibrations for the same gauges with the identical situation, but it must be done later to see whether the uncertainties of the calibration system meet the error limit we prescribed above, that is, 4% for the vacuum range of $10^{-2} \sim 10^{-6}$ Torr, and 10% for the vacuum range of $10^{-7} \sim 10^{-9}$ Torr. The uniformity of the pressure distribution at different gauge ports should be checked later by calibrating the same gauge head at different gauge ports and by examining the resulting scatter of sensitivities. We will calibrate a number of vacuum gauges to be used in the storage ring, and then will check periodically the performance of the gauges over periods of several months. Finally, we will strive for the lower calibration range through the calibration chamber 3 in which its base pressure is 7×10^{-11} Torr, although the uncertainties will be a little larger than those of the chamber 2.

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