Abstract. The Steady-state Superconducting Tokamak (SST-1) is an indigenously built medium sized fusion device at IPR designed for plasma duration of 1000 seconds. It consists of two large vacuum chambers – Vacuum Vessel (16 m$^3$) and Cryostat (39 m$^3$) which will be pumped to UHV and HV pressures respectively using a set of turbo molecular pumps, Cryo-pumps and Roots pumps. The total as well as the partial pressure measurement in these chambers will be carried out using a set of Pirani gauges, Bayard Alpert type gauges, Capacitance manometers and Residual Gas Analyzers (RGA). A reliable and accurate pressure measurement is essential for successful operation of SST-1 machine. For this purpose a gauge calibration system is set up in SST-1 Vacuum laboratory based on Spinning Rotor Gauge which can measure absolute pressure in the range $1.0 \text{ mbar}$ to $1.0 \times 10^{-7} \text{ mbar}$. This system is designed to calibrate up to five gauges simultaneously for different gases in different operating pressure ranges of the gauges. This paper discusses the experimental set-up and the procedure adopted for the calibration of such vacuum gauges.

1. Introduction
Vacuum System is one of the main subsystems of SST-1 tokamak [1, 2] and it consists of (i) Vacuum vessel, (ii) Cryostat (iii) Pumping system and (iv) Gas feed system. Vacuum vessel is the main chamber which will be pumped down to $< 1.0 \times 10^{-8} \text{ mbar}$ while the cryostat is a high vacuum chamber with the base pressure $< 1.0 \times 10^{-5} \text{ mbar}$. Plasma discharge will be carried out in vacuum vessel while the cryostat encloses magnet system and radiation shields. The pumping system comprising of Roots pumps, Turbo-molecular pumps and Cryo-pumps will be used for evacuating these two main vacuum chambers. Total pressure measurement will be done using a set of Convectron gauges, Capacitance manometers (CM) and B. A. gauges while the partial pressure will be measured using Residual Gas Mass Analyzers (RGA). Gas feed system will be used during plasma operation for the pre-filling of vessel at required gas pressure, density build up phase and during wall conditioning.

Vacuum gauges mounted on SST-1 will play a passive role because the entire pumping system and vacuum DATA acquisition will be remotely operated using PXI based system which has both the software and hardware interlocks for any un-eventual failures. All the feedback control like pumps operation, gate valves interlock and will be based on the gauges reading. Also the gas feed and density control completely depends on the gauges reading. In either case, the accuracy in the pressure...
measurement is very important to achieve the desired results in SST-1 experiments. Hence all the pressure gauges must be calibrated in their respective measuring ranges before mounting into SST-1. Also the ageing effect and contamination of the gauges lead to a change in the gauge sensitivity, therefore periodic calibration of the gauges must be carried out with a reference gauge. For this purpose a Spinning rotor gauge (SRG) calibration system has been set-up.

2. Calibration Methods
Pressure measuring instruments are classified as the primary and the secondary gauges. Primary gauges measure pressure simply by the direct application of the definition of pressure as a force acting on a surface. On the other hand, the secondary gauges measure pressure indirectly by exploiting a gas property that depends on pressure. The secondary gauges therefore require to be calibrated against a primary standard. Additionally the sensitivity of the secondary gauge depends upon the type of gas and therefore they must be calibrated for a specific gas. Due to advancement in technologies, nowadays secondary gauges are available in a wider range from atmospheric pressure (1013 mbar) to less than $10^{-10}$ mbar. Still not a single gauge can measure the entire ranges with considerable accuracy and one has to use a combination of secondary gauges to cover the complete pressure range.

The calibration process must be carried out in the entire measurement range of the vacuum gauges since many times the gauges exhibit non-linearity in their response with pressure. Thus, ideally a primary gauge is required in the entire measurement range of the gauges for the calibration purpose. In case where primary gauge is not available, an appropriate vacuum must be created in the calibration chamber in a primary way using basic gas laws. A brief overview of the calibration processes in different pressure ranges is given below.

2.1. Direct comparison with a primary gauge
It is the comparison of a gauge reading with a primary gauge where both the gauges are mounted to a calibration chamber and are exposed to the gas at identical gas densities or pressures. The primary gauges available for this type of calibration are mainly the liquid column manometers. The pressure in a liquid column is given by the well-known formula

$$ P = \rho g_1 \Delta h + p_r $$

(1)

where $\rho$ is the density of the liquid used (kg m$^{-3}$),
$g_1$ is the local acceleration due to gravity (m s$^{-2}$),
$\Delta h$ is the level difference in the two columns of the U tube and
$p_r$ is the residual pressure in the reference side.

McLeod gauge belongs to this category. Despite its wide use, McLeod gauge is now considered to be obsolete because of its complicated operation and the numerous uncertainty sources involved which cannot always be analysed exhaustively or reduced. The major limitations of the McLeod gauges and liquid manometers are the accurate measurement of the liquid level.

2.2. Static/dynamic expansion systems (below $10^{-3}$ mbar)
For pressures lower than $10^{-3}$ mbar, the primary gauges are not available. In such case, the gauge can be mounted on a special calibration chamber in which an accurately known pressure has been established by applying the gas laws. Such calibration systems are essentially of two types, i.e. (i) Static expansion systems and (ii) Dynamic expansion systems.

In case of static expansion systems, gas at known pressure high enough to be measured by a primary instrument is expanded from a volume into a larger one, both volume values being determined with primary methods. If the temperature and number density are constant, the pressure value is obtained by applying Boyle’s law (PV = constant).
In the dynamic expansion method, the pure gas whose flow rate $Q$ is to measure is caused to flow through a known conductance $C$ separating the measurement and the pumping chambers. The pressure for such case is represented as

$$p = \frac{Q}{C \left(1 - \frac{1}{r}\right)}$$  \hspace{1cm} (2)$$

where $r$ is the ratio between the pressure values in the calibration and pumping volumes.

This formula is applicable only if the temperature of the entire system is constant. The gas flow rate can be determined in different ways but the most widely used method is the constant pressure method [3-7].

### 2.3. High Accuracy Gauge

Another popular method of vacuum gauge calibration is to use a high accuracy gauge such as Spinning Rotor Gauge (SRG) which offers $< 1\%$ calibration accuracy over an extended range of $1.0 \text{ mbar}$ to $1.0 \times 10^{-7} \text{ mbar}$. The gauge calibration system described in this paper is based on this method.

### 3. The Spinning Rotor Gauge

The spinning rotor gauge is based on the principle of momentum transfer. It can measure the pressures in the range from $1.0 \text{ mbar}$ to $1.0 \times 10^{-7} \text{ mbar}$. A small steel sphere ($\phi = 4.5 \text{ mm}$) is axially suspended in vacuum inside a metal tube by means of a permanent magnet as shown in figure 1. The magnetic forces balance the weight of the sphere. A series of electromagnets stabilize the position of unstable equilibrium. The sphere is accelerated to a working frequency of $340 \text{ Hz}$ by two pairs of guiding coils. The guiding field is then stopped and the rotational frequency of the sphere will vary depending upon the number of collisions of the residual gas molecules against the sphere surface.

![Figure 1. Schematic of spinning-rotor gauge.](image)

The rotational frequency is measured using inductive coils and the rate of its decrement is then converted to pressure using the formula given as

$$p = \frac{\pi v^* a \rho \sigma}{10 \omega} = \left(\frac{\pi v^* a \rho}{10 \sigma}\right) \times \left(\frac{t_n - t_{n-1}}{t_n \times t_{n-1}}\right)$$  \hspace{1cm} (3)$$

where $v^* = \frac{RT}{\sqrt{2\pi M}}$ is the mean molecular velocity,
\( M \) is the average molar mass of the gas,
\( \sigma \) is the sphere diameter,
\( \rho \) is the density of the gas and
\( \sigma \) is the viscosity coefficient or the momentum transfer coefficient.

Thus the pressure is given by

\[
P = \left( \frac{K}{\sigma} \right) \times \left( \frac{t_n - t_{n-1}}{t_n \times t_{n-1}} \right) - ofs
\]

with \( K = \frac{\text{mmHg}}{\text{mbar}} \) which must be calculated for each type of gas and sphere at the operating temperature. The factor \( \sigma \) can only be measured which varies between 0 (for an ideal smooth surface) to 1.27 (for a very rough surface), depending on the mass of the gas used. The term ‘ofs’ refers to the residual magnetization [3]. Offset value of an SRG must be determined every time the gauge is switched on.

4. Experimental Set-up

A schematic of the calibration set-up is shown in the figure 2. The calibration chamber is fabricated using SS 304L material in a spherical form of diameter \( \phi = 30 \text{ cm} \). Six (06) numbers of DN 63 CF ports are provided symmetrically around the circumference of this chamber with a dimensional accuracy of 0.01 mm. An MKS make SRG is connected to one of these ports while five different gauges under calibration can be mounted on the remaining ports. The pumping port is provided at the bottom of the system and is connected to a Varian make 500 l/s Sputter ion pump. The initial roughing of the system to a base pressure < 5.0 \( \times 10^{-5} \) mbar is achieved using a 500 l/s Pfeiffer make portable turbo-molecular pump. Further pumping down to a pressure < 1.0 \( \times 10^{-7} \) mbar is achieved using the ion pump with 5 hours of baking at 150 °C and long duration of pumping of about 8 hours. A Varian make sapphire gas feed valve is provided on the top of the chamber to maintain the desired pressure in the chamber with a specified gas with respect to which the secondary gauge has to be calibrated.

![Figure 2. Schematic diagram of the calibration set-up.](image)
5. Calibration Procedure and Results

The entire system is leak tested in vacuum mode using a Mass Spectrometer Leak Detector (MSLD) and is found to be leak tight below $1.0 \times 10^{-9}$ mbar l/s. With net pumping speed of 100 l/s inside the chamber and considering the out-gassing rate of the electro-polished stainless steel material to be $1.0 \times 10^{-10}$ mbar l/s/cm$^2$ [8], the system pressure is expected below $1.0 \times 10^{-7}$ mbar. After achieving the system pressure $< 1.0 \times 10^{-7}$ mbar, SRG offset value is measured and stored in the control unit. Nitrogen gas of 99.95 % purity is fed into the chamber using the leak valve and a desired pressure is maintained in the system.

RGA scans of the system for its background and with nitrogen gas feed are shown in the figure 3 and figure 4 respectively. It can be seen that the partial pressure of nitrogen (base peak at 28 amu, secondary peak at 14 amu) is at least one decade more than the remaining gas components. Once the required pressure is stabilised, the readings of the gauge and the SRG are noted and the calibration factor is determined. This process is carried out in the entire pressure range of the gauge to be calibrated and the calibration curve is plotted. The calibration factor is determined for different pressure ranges and the correction factor is incorporated directly into the Data acquisition program.

![Figure 3](image3.png)  
**Figure 3.** RGA scan after baking and 24 hours pumping.

![Figure 4](image4.png)  
**Figure 4.** RGA scan with Nitrogen gas feed.

The calibration of a B.A. gauge with measuring range from $1.0 \times 10^{-10}$ mbar to 1000 mbar and a Capacitance manometer with measuring range from $1.0 \times 10^{-5}$ mbar to 0.1 mbar is carried out simultaneously. The calibration plot for these two gauges is shown in the figure 5. The capacitance manometer readings show a good match with the SRG reading in the range of 0.1 mbar to $1.0 \times 10^{-4}$ mbar with percentage error less than 5 % whereas in the range from $1.0 \times 10^{-4}$ mbar to $1.0 \times 10^{-5}$ mbar this error increases up to 25 %. This could be due to the offset correction in the two gauges which becomes significant in this range as it is of the same order as the actual pressure value in this range.

In the case of B. A. gauge the error is within ± 10 % in the measurement range from $1.0 \times 10^{-7}$ mbar to $1.0 \times 10^{-3}$ mbar whereas in the range of $1.0 \times 10^{-3}$ mbar to 0.1 mbar, this error increases up to 30 %. The reason for this could be due to the measurement principle of thermal conductivity of the gas where inaccuracy increases due to the various types of thermal losses such as the lead loss at the filament ends. The percentage error of both of these gauges at different pressure ranges is tabulated in the table 1.
Again the calibration process is repeated for Hydrogen gas of 99.9995% purity. The calibration curve B. A. Gauge is shown in the figure 6. In normal condition the sensitivity of the B. A. Gauge is set for nitrogen gas. However, since the ionisation cross-section for Hydrogen gas is different from Nitrogen gas, an appropriate correction factor is applied to obtain the Hydrogen gas equivalent pressure.

6. Conclusion
An SRG based vacuum gauge calibration system has been commissioned and is in the operation for the calibration of five numbers of different gauges at a time in the range of 1.0 mbar to 1.0 × 10⁻⁷ mbar for different gases.

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