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DEVELOPMENT OF A FIELD EMITTER-BASED EXTRACTOR GAUGE FOR THE OPERATION IN CRYOGENIC VACUUM ENVIRONMENTS

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Abstract

This paper presents an investigation of a CNT emitter-based extractor gauge which is designed for pressure reading in cryogenic ultra-high vacuum systems. The results show that the modified gauge works well in both room temperature and cryogenic vacuum environments. Furthermore, it could be demonstrated that the modified gauge responds much more sensitive to small pressure fluctuations in cryogenic environments than the same gauge type having a hot-filament cathode.

INTRODUCTION

The pressure measurement in cryogenic vacuum systems has always been considered as a metrological problem which is not completely solved yet. Generally, UHV and XHV pressures are generated in cryogenic vacuum environments. Except some special measuring methods exclusively applicable in particle accelerators, such low pressures can only be measured by ion gauges. Whilst cold-cathode gauges seem to work unreliably at cryogenic temperatures, hot-filament gauges, however, are able to operate even at liquid helium (LHe) temperatures and provide meaningful pressure readings [1, 2]. Unfortunately, the operation of the thermionic cathode causes an unwanted heat load into the cryogenic system. This extra heat load needs to be compensated by additional cooling power. Moreover, the thermal radiation emitted from the thermionic cathode leads to a local pressure rise due to thermal-induced desorption. The thermal field generated by the hot filament also disturbs the thermal equilibrium of the local cryogenic gas atmosphere whose pressure is to be measured. All these disadvantages make the use of conventional hot-cathode ion gauges in cryogenic environments problematic. Consequently, hot cathode gauges are often avoided in low temperature vacuum systems, although its use would be beneficial and mandatory, e.g. for monitoring of dynamic vacuum instabilities or leak detection.

In order to realize a reliable pressure measuring device for cryogenic vacuum systems we decided to substitute the heat-generating hot filament of a commercially available ion gauge by a ‘cold’ electron emitter whose electron release mechanism is based on field emission. Compared to traditional thermionic cathodes, the dissipation power of a field emitter is substantially lower. Recently, some successful work and approaches on field emitter-based extractor gauges have already been published [3]. So far, however, there were no studies and experiences on the use and operating performance of a field emitter-based ion gauge under cryogenic vacuum conditions.

OPERATION PRINCIPLES OF IONISATION GAUGES

Ion gauges do not measure the pressure p, but, in fact, the residual gas density n. Their operation principle is generally known: Free electrons generated by a cathode are accelerated towards a cage-like, positively biased anode. On their path through the gas the electrons reach kinetic energies sufficient to ionize residual gas molecules. The generated ions are attracted by a grounded collector electrode. The ion current measured on this collector is directly proportional to the residual gas density in a wide vacuum range and provides the measuring signal. It can be expressed as:

$$I_+ = I_- \sigma n l \,, \tag{1}$$

where I_+ and I_- are the ion and anode current, respectively, σ is the ionization cross section of the gas, l is the total length of the electron trajectory through the gas and n represents the gas density.

As in most cases the pressure is of more practical interest, the measured residual gas density can be converted to the pressure p by use of the ideal gas law $p = nk_\mathrm{B}T$ (where k_B is the Boltzmann constant and T is the gas temperature). Thus, it follows

$$p = \frac{I_+ k_\mathrm{B} T}{I_- \sigma l} = \frac{I_+}{S(T) I_-} \,. \tag{2}$$

The parameter $S(T) = \sigma l / k_\mathrm{B}T$ represents the gauge sensitivity and depends on gauge type, gas composition as well as gas temperature. This temperature dependence [4, 5] is of crucial importance when an ion gauge is used in atmospheres where the gas temperature deviates from the gas temperature during calibration.

The linear relationship between p and I_+ is used as basis for pressure reading. However, the measuring range is restricted due to different physical effects causing an upper and lower measuring limit. Pressure independent residual currents produced as a result of the X-ray effect and electron stimulated desorption (ESD) are responsible for the lower measuring limit. Further information can be found in literature [6].

GAUGE DESIGN

The gauge used for our experiments was an extractor gauge of IE514 type which is capable to read pressures down to 10^{-12} mbar, which corresponds to a pressure limit of $1.4 \cdot 10^{-14}$ mbar at LHe temperatures. Its ring-shaped thermionic filament was replaced by a commercially available field emission cathode (FEC) of carbon nanotube-type (CNT) (Xintek, XTC-T01-SSC-C2.5x2.5), with an integrated extraction micro-grid. The FEC was arranged directly above the anode grid of the gauge. Its circular emissive area

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of $A = 0.049\,\mathrm{cm}^2$ was embedded in a cylindrical stainless steel housing. With an extraction grid voltage of $V_G \approx 750\,\mathrm{V}$ it provided a total emission current of $I_{em} \approx 150\,\mu\mathrm{A}$. However, the anode current, I_-, was substantially lower, about $50 \pm 5\,\mu\mathrm{A}$. Between the CNT cathode housing and the anode grid an additional deceleration electrode in form of a thin aperture was positioned. The ion current, I_+, was measured by a Keithley electrometer of 6514 type, whereas the electron currents, I_{em} and I_-, were measured using sensitive ammeters. The design of the field emitter-based gauge (FEG) and its electrical operating circuit are shown in Fig. 1.

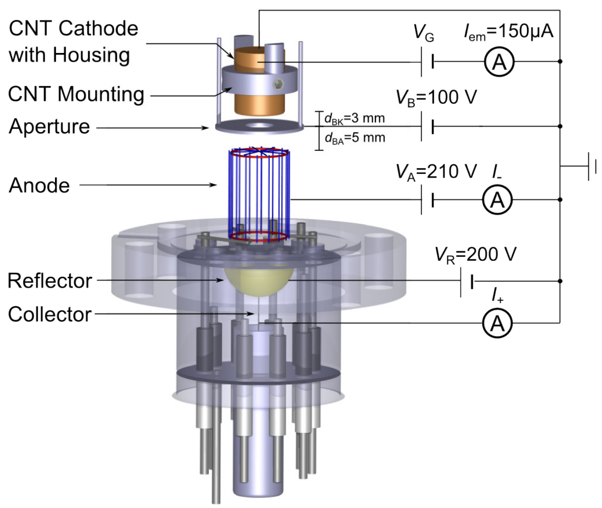

Figure 1: Setup of the modified extractor gauge (FEG) and its electrical operating circuit. Setup details are described in the text.

SETUP AND EXPERIMENTS

The first experimental study aimed to define the optimum operating parameters of the FEG. The operating voltages (V_G extraction grid voltage, V_A anode voltage, V_B aperture voltage, and V_R reflector voltage) and the distances between cathode housing, deceleration aperture, and anode cage (d_{BA} and d_{BK}) were optimized in order to operate the gauge with a high sensitivity. The optimized gauge parameters are given in Fig. 1.

In order to analyze its measuring performance, the FEG ion current response on pressure changes was studied for three different gas species, namely H_2, N_2, and He. These measurements have been carried out under room temperature conditions using a standardized vacuum system suitable for gauge calibration according to ISO 3567 [7]. A calibrated conventional hot-cathode extractor gauge (HCG) was used for the pressure measurement. Each test gas was injected from a base pressure of $p = 2 \cdot 10^{-10}$ mbar to a maximum pressure of $p = 1 \cdot 10^{-5}$ mbar (N_2-equivalent). The results are shown in Fig. 2. As expected, in all three test gas atmospheres the FEG ion current was linear dependent to the pressure, measured by the HCG, in a pressure range between 10^{-8} and 10^{-5} mbar (N_2-equivalent). Unfortunately, due to the low anode current, a poor signal-to-noise ratio was observed at $p < 10^{-8}$ mbar.

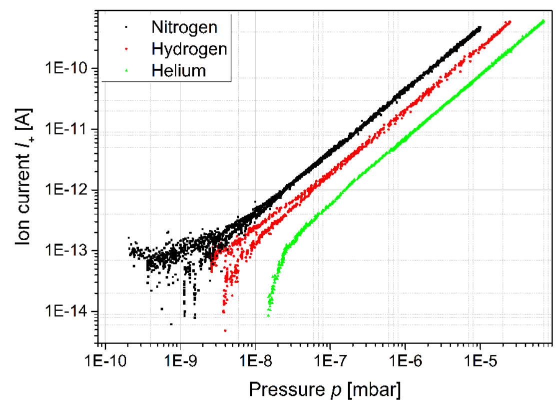

Figure 2: Characteristic of the FEG for three different test gases at a chamber temperature of $T = 293$ K.

The next experimental study involved the measuring behavior of the FEG in a cryogenic vacuum atmosphere. For that reason, the FEG was mounted to a 6-way reducer cross chamber (DN160-40 CF). The chamber was equipped with a LHe cooling circuit brazed onto the outer chamber wall. Again a HCG was used for the pressure reading. The heat load generated by the hot filament of the HCG was transferred by copper bands, which were wrapped around the gauge conduit and connected to the LHe supply line. Once the chamber was inserted into a cryostat, it was pumped by a turbo molecular pump, valved off and cooled down. When reaching a stable chamber temperature of about $T \approx 6$ K, the HCG read an ultimate pressure of $p = 10^{-11}$ mbar. As the gas temperature inside the cold chamber was not known exactly, the pressure values given here are therefore room temperature- (rt) and N_2-equivalent.

First, the FEC emission performance under cryogenic conditions was investigated. The emission current as a function of the extraction grid voltage, V_G, was nearly independent from the gas temperature. In a second run, both the long-term emission stability of the cathode and the ion current behaviour of the FEG at a stable pressure were studied. In order to investigate if re-adsorption occurs on the CNT surface, the measurement was interrupted for 22.5 hours after four hours of gauge operation. Adsorption at the FEC can lead to a work function change and therefore to an altered emission performance [8, 9]. After the interruption, the experiment was continued for 41 hours. Figure 3 shows the electron and ion current as a function of the operation time. As shown in this figure, the anode current remained relatively constant over the entire time. Even the measurement interruption did not affect the emission performance of the FEC. In contrast, however, the ion current decreased steeply in the first hours of operation and converged to a relative stable value of $I_+ = 2 \cdot 10^{-13}$ A. This typical ion current time profile can be explained by the ESD effect on the anode. It is caused by the

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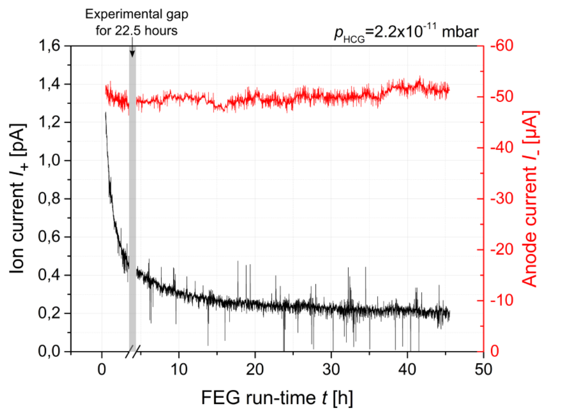

Figure 3: Time dependence of ion current I_+ and anode current I_- at cryogenic temperatures.

ionization of gas molecules adsorbed on the anode surface by impinging electrons. The formed ions are captured by the ion collector and contribute to the measuring signal as a pressure-independent stray current. This effect also plays an important role at room temperature and depends on the operation time.

After measuring the time profile, the LHe mass flow through the cooling tubes was reduced in order to warm up the chamber moderately. As a result, slight pressure fluctuations inside the cold chamber due to thermal-induced desorption were generated. The temperature-dependent responses of both gauges were recorded and are shown in Fig. 4. The results show that only the FEG responded highly sen-

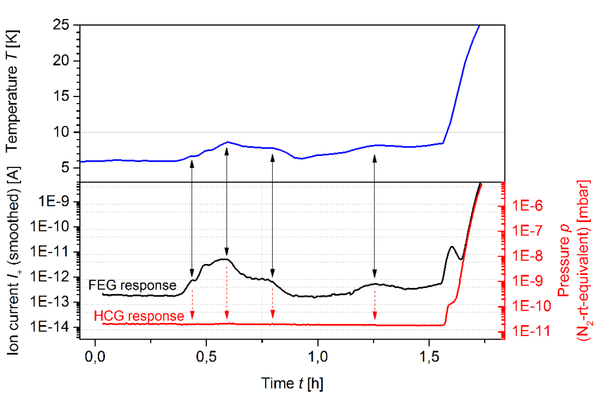

Figure 4: The responses of FEG and HCG on thermal-induced pressure fluctuations at cryogenic temperatures.

sitive to the thermal-triggered pressure fluctuations, whereas the HCG measurement was not affected at all. This implies that the FEG is considerablly more sensitive to pressure changes in a cryogenic vacuum environment than the HCG.

For the next experiment the setup was slightly modified and a sophisticated gas inlet system was added in order to inject hydrogen into the cooled chamber from room temperature side. Since hydrogen has a relatively high saturation vapor pressure ($p_S > 10^{-3}$ mbar at 6 K), it was suitable for FEG characteristic measurement within a cryogenic environment. The I_+ vs. p-characteristic is shown in Fig. 5. The tested field emitter-based gauge showed a linear relationship between ion current and pressure in the range between $p = 5 \cdot 10^{-9}$ and $1 \cdot 10^{-5}$ mbar.

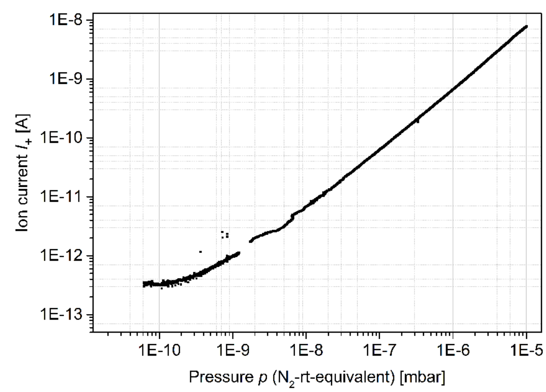

Figure 5: Ion current as a function of pressure at a chamber temperature of 6 K.

SUMMARY AND CONCLUSION

The application of a newly developed CNT emitter-based extractor gauge for pressure measurements at cryogenic vacuum environment has been investigated. Although the gauge sensitivity varied across the measurements, the results clearly demonstrate that the FEC-based extractor gauge works reliably not only under room temperature, but also under cryogenic vacuum conditions and provides meaningful pressure readings. As expected, the I_+ vs. p relation is linear even at low temperatures. Additionally, the FEG shows a fast response to small pressure changes in a cryogenic vacuum environment, unlike the hot filament-based extractor gauge. The results presented suggest that field emission-based extractor gauges may solve the problems of pressure measurement in cryogenic environments.

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