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EXPERIMENTAL VALIDATION OF THE USE OF COLD CATHODE GAUGE INSIDE THE CRYOMODULE INSULATION VACUUM*

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Abstract

The Proton Improvement Plan - II (PIP-II) project is underway at Fermilab with an international collaboration involving CEA in the development and testing of 650 MHz cryomodules. The risk analysis related to cryomodule operation proposed to add a vacuum gauge on the power coupler to prevent the untimely rupture of its ceramic. Due to the advanced design of the cryomodules, the gauge needs to be integrated inside the insulation vacuum to reduce the impact of this new modification. The lack of experience feedback on a similar operating condition requires an experimental validation before the implementation. This article details the experimental tests carried out before the approval of this solution.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex [2]. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules [3, 4], equipped with 650 MHz Superconducting (SC) cavities are used. The same Power Coupler (PC) design was adapted for both cryomodules. In total, sixteen unit of them these PC will be need for the Linac. They each have a single ceramic window located inside the cryomodule vacuum tank, see Fig. 1.

The former design versions of the 650 MHz PC are not equipped with vacuum gauges (VG). However, recent risk analysis has raised the great impact of a PC ceramic failure, during operation, on the cryomodule and consequently on the Linac ability to produce the beam. Even if this problem is unlikely if all the precaution are taken, a high number of PCs and an operation during several years increase the probability to have this incident. Experience has shown that many of these incidents are reported [5-7] and are generally difficult to analyse without appropriate diagnostics. Ceramic degradation could be gradual due to some initially unseen weaknesses such as ceramic cracks and brazing problems, or due to many years of operation. But, it can also be instantaneous in case of a fail of the protection system, or of late detection of a strong event generating an important electron discharge.

In addition to insuring drastic quality control of the PC before its operation on the cryomodule, several strategies can be adopted from the design stage to reduce the risks of a PC window failure:

- Use double window design: it is expensive and complicates the design
- Use an existing well known design (even over designed): it is not always possible and may generate other design complications for the cryomodule.
- Use different types of diagnostics on PC: it may add integration complication and certainly increases the equipment's cost.

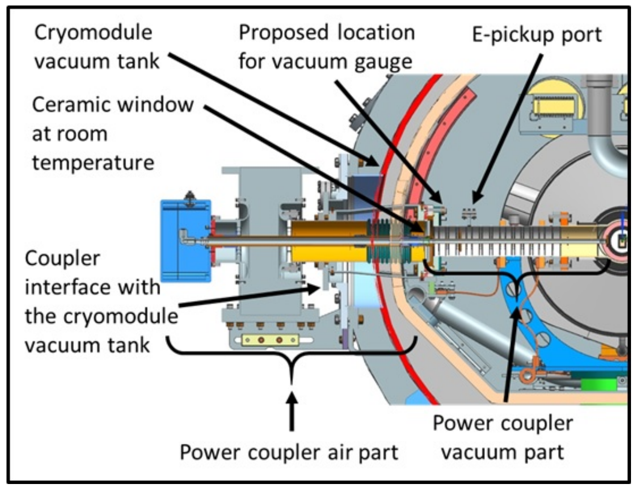

Figure 1: 650 MHz Power Coupler assembled on the HB650 cryomodule. This design version have not a vacuum gauge.

With the design of the 650 MHz PC almost complete, the natural strategy to adopt is to add a new diagnostic. In our case, the solution we propose was to add to the existing e-pickup a VG. This diagnostic, allows to trigger of a protection interlock in case of strong vacuum event in order to limit its impact. It is also the most efficient way to guarantee an early detection of window tightness issues. This allows to limit the degradation by adapting the operation conditions and to plan for a maintenance action. Without vacuum gauge on PC, it is difficult to detect the leak in operation because of the cryopumping induced by cavities. When the VG is not used on the PC, the beginning of the cavity performances degradation may be a sign of a tightness problem. This observation is not immediate, does not give the possibility to have a precise estimation of the magnitude of the leak and may not allow to designate the leaky coupler.

In the case of the 650 MHz PC, the implementation of the proposed solution (adding a VG) wasn't straightforward. This is because the advanced design of the HB650 cryomodule and the corresponding PC does not allow trivial use of the VG outside the vacuum tank (see Fig. 1). The use of the VG inside insulating vacuum seems to be the optimal option. Nevertheless, this configuration is not common for VGs generally used for these applications.

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Discussions with PC experts from DESY, KEK, CERN and Fermilab did not reveal any experience feedback on this practice.

This paper will explain the validation process performed at CEA to demonstrate the feasibility of this solution.

OPERATION CONDITIONS

The PC vacuum gauge will be used in the cryomodule under the following conditions:

1. Operation at room temperature (RT) and under atmospheric pressure during the RF conditioning of the PC: this corresponds to the standard operation of the VG.
2. Then operation at RT but while pumping the vacuum tank down to approximately 5 10^{-5} mbar: here is the first deviation from the standard operation of the VG.
3. And finally the operation in cold cryomodule where the pressure in the insulating vacuum reaches less than 5 10^{-7} mbar: the cryogenic temperatures are the additional difficulty to overcome.

CHOICE OF THE VACUUM GAUGE

The Proposed Vacuum Gauge

The chosen gauge is a Cold Cathode Ionization Measurement gauge using the inverted magnetron principle. It has remote electronics, which allows a high radiation resistance (10^7 Gy). This VG is commonly used on accelerator applications and on PCs. Initially, the baseline model was IKR 070. The alternative model was the IKR 060. Both are PFEIFFER® products (Fig. 2). They have almost the same design. The main difference is the use of a triaxial cable for IKR 070 instead of the coaxial cable used for IKR 060. Triaxial cable allows the measurement of lower currents and hence lower pressure levels potentially down to 10^{-11} mbar compared to the 10^{-10} mbar measurement limit for the IKR 060.

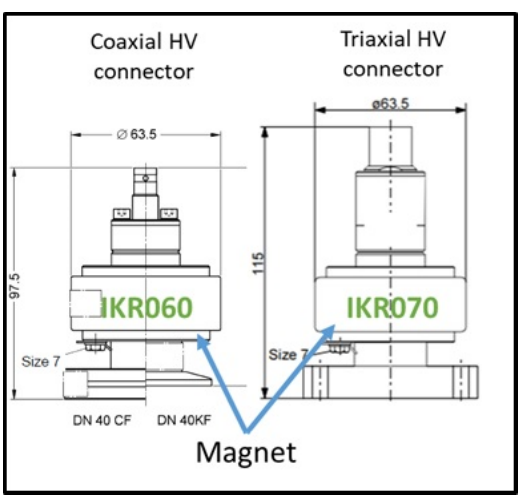

Figure 2: Vacuum gauges choice

These performances can be influenced by the choice of the measurement card or the length of the cable. But generally measurements down to 5 10^{-9} mbar pressure are possible for both models. This sensitivity is sufficient to detect small vacuum degradation when it takes place.

Adapting the Choice to the Operating Conditions

The proposed solution need to be adapted to the operation conditions listed above.

First, the recommended operating temperature of the chosen gauge is between 5 °C and 80 °C. As a consequence, it need to be preserved from too low temperatures when the cryomodule is cold. This problem do not have significant impact on the cryomodule design. In fact, the gauge port to be added on PC should be as close as possible from the RF window, which is actually operating at room temperature and will be equipped with heaters and copper straps to keep it warm during the cold operation. The same solution could be applied to the VG, if needed.

Second, each VG is equipped with a permanent magnet. This is not compatible with superconducting operation. Consequently, a magnetic shielding will be added to protect SC cavities from magnetic field and prevent the magnetization of the cryomodule components.

Third, the activation of the cold cathode gauges requires a polarisation voltage of 3.3 kV. This represents a risk of electron discharge during the vacuum pumping as predicted by Paschen's law. This empirical law predicts the voltage initiating discharge between two electrodes as a function of the product of the gas pressure and the gap distance between the electrodes. This behavior can be dependent on the local conditions.

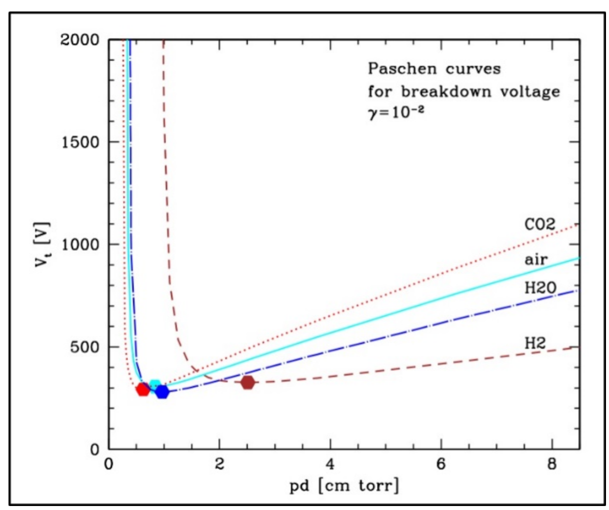

Figure 3: Paschen's law curve [8]: V_t [V]is the breakdown voltage, p [torr] is the gas pressure, and d [cm] is the distance between electrodes.

The general layout of the curve obtained from this law (see Fig. 3) suggests that during the pumping down an electric discharge is likely to occur in the VG connector for certain pressure range. This will alter the vacuum measurements as they are based on current measurements. When

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lower pressure levels are reached the discharge vanishes. This suggest that the operating procedure should automatically disable the VGs high voltage bias for a while during the cryomodule vacuum tank pumping. This operation has no consequence on the protection role fulfilled by the VG as the RF will be naturally switched off during that period. However, we need to define the pressure allowing to enable the VGs again without creating discharges.

Finally, the integration of the VG under vacuum requires vacuum tight feedthrough with the appropriate connectors to relate the IKR gauge to the controller (outside the cryomodule). The feedthrough needed for the coaxial high voltage (HV) IKR 060 connector was available. However, it was not possible to procure the feedthrough adapted to the triaxial IKR 070 connector without ordering large series of them. We then decided to perform the experimental test with the IKR 060 gauge. Given the great similarity of the gauges, experimental results will be generally applicable for the IKR070.

EXPERIMENTAL SET-UP

Objective of the Experiment

Our objective is to check the following performances:

- The VG measurement consistency: by comparing the IKR060 gauge measurement values during operation under atmospheric pressure with the measurements performed under 'insulation' vacuum.
- The VG thermal stability: by verifying that operation under vacuum does not increase the gauge temperature due to the lack of convective heat transfer.
- The VG operation reliability: by observing the behavior consistency during relatively long continuous operation under vacuum.

Description of the Experimental Set-up

To check the VG performances listed above, a test stand have been built, see Fig. 4.

The principle of this experimental set-up is to test the VG under configuration conditions similar to those of the cryomodule. All the tests are carried out at RT because we have proposed a solution to keep the gauge warm during cold operation of the cryomodule. However, we monitor the tested gauge temperature to see if the suppression of the convective heat transfer due to vacuum has an influence on its behavior.

The experiment reproduces the insulation vacuum chamber, where the tested VG "G1" (IKR 060) is placed, and the PC vacuum volume to be measured by the same VG. A reference VG "G5" (IKR 070) is used to measure simultaneously the PC vacuum and is linked to the same controller TPG300. The two VGs are assembled on the opposite ports of a symmetrical T-shaped tube where the pumped gas flows through the third port (Fig. 4). This avoids measurement discrepancies due to tube conductance differences.

The insulation vacuum is measured by the VG G3 and the "PC vacuum" is measured by G1 and G5 gauges. Details on these gauges are given in Fig. 4. G2 and G4 measurements are not presented in this paper.

For temperature monitoring, one thermocouple is connected to the G1 VG flange and another thermocouple is connected to the air side of the set-up to measure the RT.

A dosing valve is used to create a controlled leak in order to vary the pressure inside the "PC vacuum" by introducing pure nitrogen.

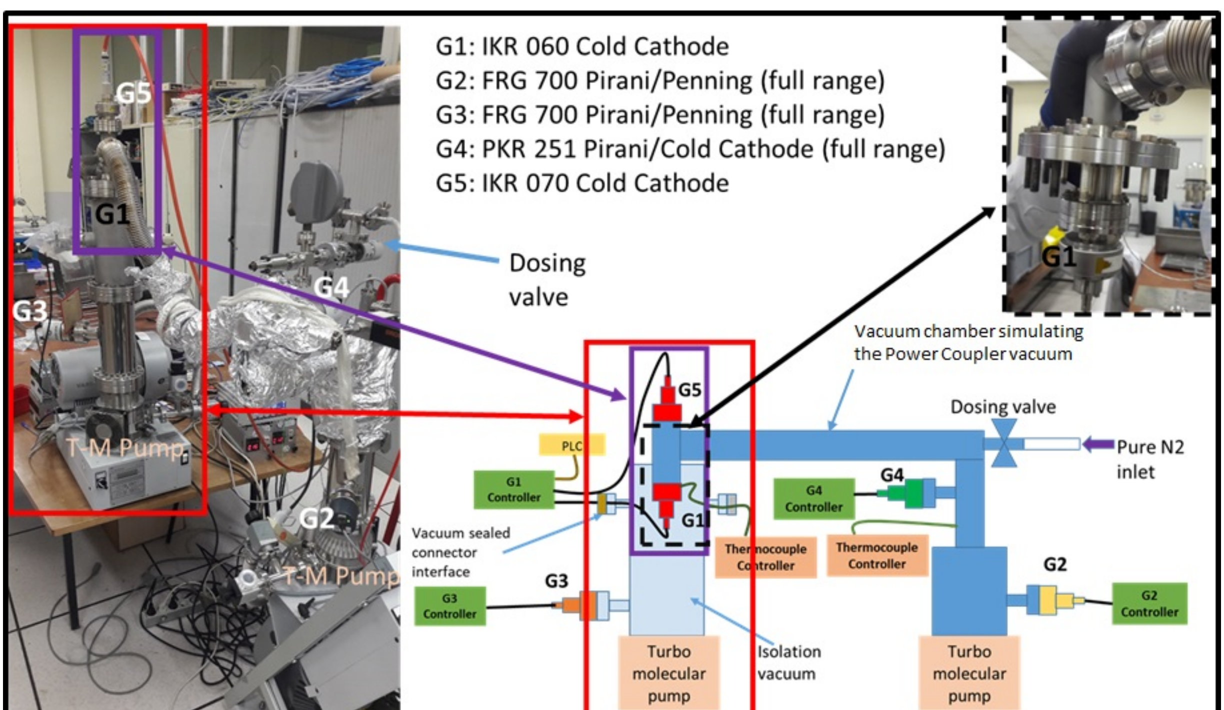

Figure 4: Experimental set-up.

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TEST RESULTS

Measurements Consistency

We started by pumping the "PC volume" while having the insulation volume at atmospheric pressure. Figure 5 (blue zone), shows that very similar measurements are given by G1 and G5 during pressure drop, as expected. Afterward, G1 is disabled to start the pumping down of the insulation volume. This aims to avoid discharges in the HV connector as explained previously. When insulation volume pressure becomes relatively low (<10^{-5} mbar) and G1 is enabled again, we find that G1 and G5 measurements are still consistent (peach colored zone in Fig. 5). In order to test the dynamic behavior, we increased the pressure inside the "PC vacuum" chamber by using the dosing valve. We can clearly see from Fig. 5 that the dynamic behavior of G1 and G5 are very similar and the measured values are almost the same.

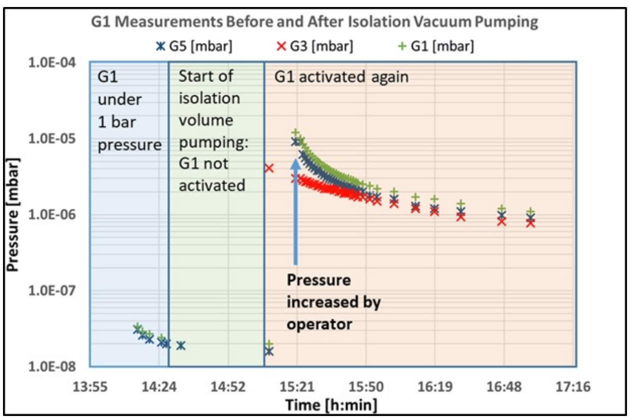

Figure 5: Measurement consistency test: G1, G5 and G3 are respectively the tested gauge, the reference gauge, and the insulation vacuum measurement gauge.

Thermal Stability

For the thermal stability test, initial conditions (Fig. 6) blue zone) were:

- Insulation vacuum pressure is stable and equivalent to the expected pressure in the cryomodule vacuum tank during operation (~10^{-7} mbar)
- Temperature on the G1 is stable and consistent with the RT. In our case, it was all the time 2°C higher.
- The "PC vacuum" is at 3.10^{-7} mbar. This value is high comparing to what is expected during operation but could be reached during the cavity and the PC RF processing.

Increasing pressure in the "PC vacuum" volume will enhance the current measured by G1 and give better chance to record potential heating of this VG. For that reason, the "PC vacuum" pressure was increased up to more than 10^{-5} mbar. This is probably at least an order magnitude higher that the tolerated pressure in PC during cold operation. After two hours of operation in that condition, the dosing valve was closed to again and pressure dropped to less than 10^{-7} mbar.

Figure 6, shows about 5 hours of recorded data representing the three stages of the experiment detailed above. There was a unique variation of 1 °C recorded on G1. This increase was correlated with a similar ambient temperature increase. The temperature stood stable several hours later even after the pressure decrease.

Based on these experimental results, we believe that there will be no overheating issue during the operation of the VG inside a pumped cryomodule vacuum tank.

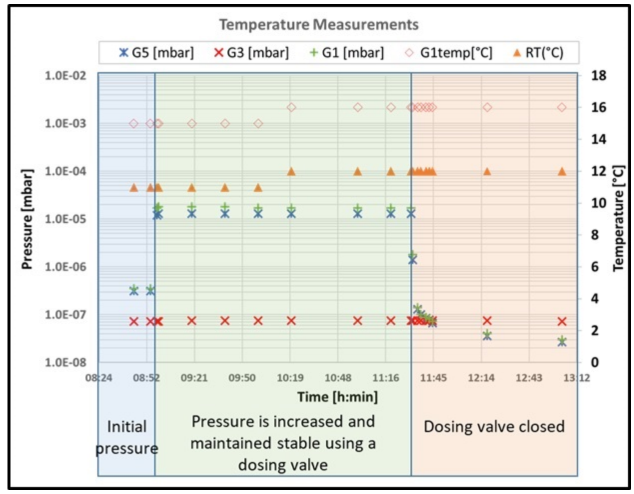

Figure 6: Measurement of the tested gauge temperature during operation under vacuum.

Reliability in "Long" Operation

The following test aims to check whether the behavior of G1 operating under vacuum is stable during a relatively long time. Figure 7, shows data recorded for 842 hours, where the insulating vacuum was pumped continuously. The interruption of recordings between 600h and 835h is not due to technical problems but to the fact that the recordings where manual and that the experiment was too long to make a daily follow-up for all the period. At the end of this test, the pressure was increased from 10^{-8} mbar to 10^{-6} mbar to recheck the dynamic behavior of G1. All the records show good operations stability of G1 for almost 35 days of continuous operation. This is considered as a good indication of the reliability of the chosen gauge in described operation conditions.

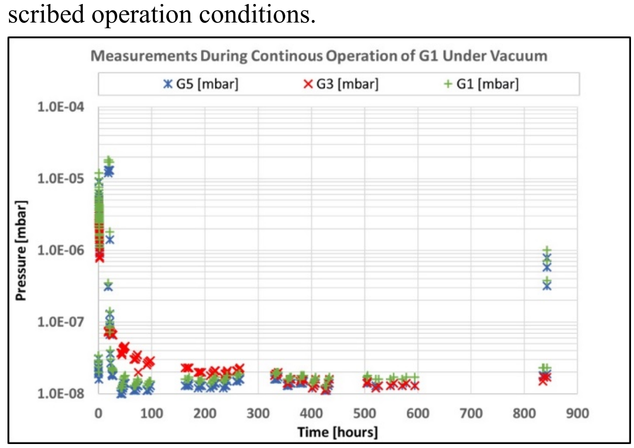

Figure 7: Long operation test.

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Again, the behaviors of G1 and G5 were almost identical. In addition, the relative measurement error of G1, considering that G5 gives the true pressure, was estimated during the long operation test for a stable pressure around 10^{-8} mbar. The error was between 15% and 30%. This demonstrates a good measurement accuracy of G1 during this test.

Complementary Tests

Complementary tests have been performed to give additional information.

We tried to experimentally determine the pressure likely to cause discharges in the connector, as predicted by the Paschen's Law. To do this, we just need to keep G1 activated when starting the pumping of the insulating vacuum volume. The pressure measured initially by G1 was 3 10^{-7} mbar. When pressure measured by G3 goes down to 10 mbar, G1 measures very fluctuating pressures going up to saturation. When G3 reaches 10^{-1} mbar G1 measurements become stable and we find back the initial pressure. This behavior is no longer reproduced at any pressure measured down to 2.2 10^{-7} mbar by G3. This behavior is confirmed several times by pumping and venting of the insulation volume. However, it is necessary to take some margin concerning the pressure range corresponding to the discharges because the accuracy of G3 is probably not very high between 10 mbar and 10^{-1} mbar.

A second test aimed to verify the impact of using the feedthrough on the measurement results. For that the test was performed with G1 placed in atmospheric pressure and measuring a stable pressure of 1.9 10^{-7} mbar without using the feedthrough. Then, this component was inserted in measurement chain. This had no influence measurement result.

CONCLUSION

Using a vacuum gauge on the PIP-II 650MHz Power Coupler requires to integrate this diagnostic inside the insulation vacuum of the cryomodule. This uncommon configuration required several experimental validation tests. A test bench was built to perform the tests. Results obtained with IKR 060 cold cathode gauge were sufficiently conclusive to accept this solution for the PIP-II 650 MHz HB650 prototype cryomodule.

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