Automated Process Control for the Beam Gas Curtain Vacuum System at CERN

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Abstract: The Beam Gas Curtain (BGC) system is a key diagnostic instrument for non-invasive proton beam profiling in the Large Hadron Collider (LHC), relying on precise and safe gas injection into the beam pipe. Initially operated via manual procedures through a supervisory control and data acquisition (SCADA) interface, BGC injections required expert users, were time consuming and vulnerable to human error. This paper presents the design and implementation of an automated gas injection control system, fully integrated within the LHC Vacuum Control System SCADA and using Vacuum Framework. The solution includes a finite state machine (FSM) deployed on a programmable logic controller (PLC), a new state-aware SCADA interface, and a comprehensive interlock strategy combining device-level and process-level safety. The system was extensively tested using simulations and staged commissioning, culminating in a successful deployment during the LHC Year-End Technical Stop (YETS) 2024/25. Automation has drastically simplified operations, increased reliability, and enhanced machine safety, requiring only two user actions to initiate an injection.

1 INTRODUCTION

The Beam Gas Curtain (BGC) is a promising diagnostic tool for the High-Luminosity upgrade of the LHC, providing non-invasive, high-resolution profiling of the proton beam. Installed at Point 4 of the LHC, it relies on the interaction between a supersonic gas jet and the particle beam to create fluorescence, enabling accurate 2D beam profile imaging (Salehilashkajani et al., 2022).

The BGC operates by expanding high-pressure gas through a specially designed nozzle (Tzoganis & Welsch, 2013) into what is known as the injection chamber, where the gas jet is shaped by a series of three skimmers. The gas curtain, which is tilted 45 degrees relative to the horizontal plane, then intersects the particle beam.

Finally, the curtain continues toward a dump chamber where the gas is evacuated and a last skimmer is used to not permit gas to reenter the interaction chamber (Sequeiro et al., 2024).

The BGC was initially installed in the LHC during YETS 2022/23 with dedicated vacuum equipment and a manually operated control system. This paper will describe the vacuum control system currently used for BGC operation, which has enabled automatic gas injection with only two user actions.

2 BGC LAYOUT AND CONTROLS

2.1 Vacuum Equipment

In Figure 1 we can see the layout of the BGC vacuum system. A core element is the set of five fixed pumping groups, each composed of a primary (PP1 to PP5) and a turbomolecular pump (TMP1 to TMP5). Three gate valves (VVGINJ, VVGDUMP and VVR4) have the important functionality of isolating the interaction chamber from the other chambers of the BGC instrument and from the dedicated pumping group. The injection line that supplies the BGC with gas houses three injection valves (VVA1, VVA2 and VVA3) used to start the gas injection. A primary pump (PPINJ) is used to pump the gas remaining in the nozzle after injections using the injection line. Pressure throughout the volumes and the pumping groups is monitored using piezoelectric (VGM0, VGM1, VGM2), Pirani (VGR1A, VGR1B, VGR2, VGR3, VGR4B, VGR5A and VGR5B) and Penning

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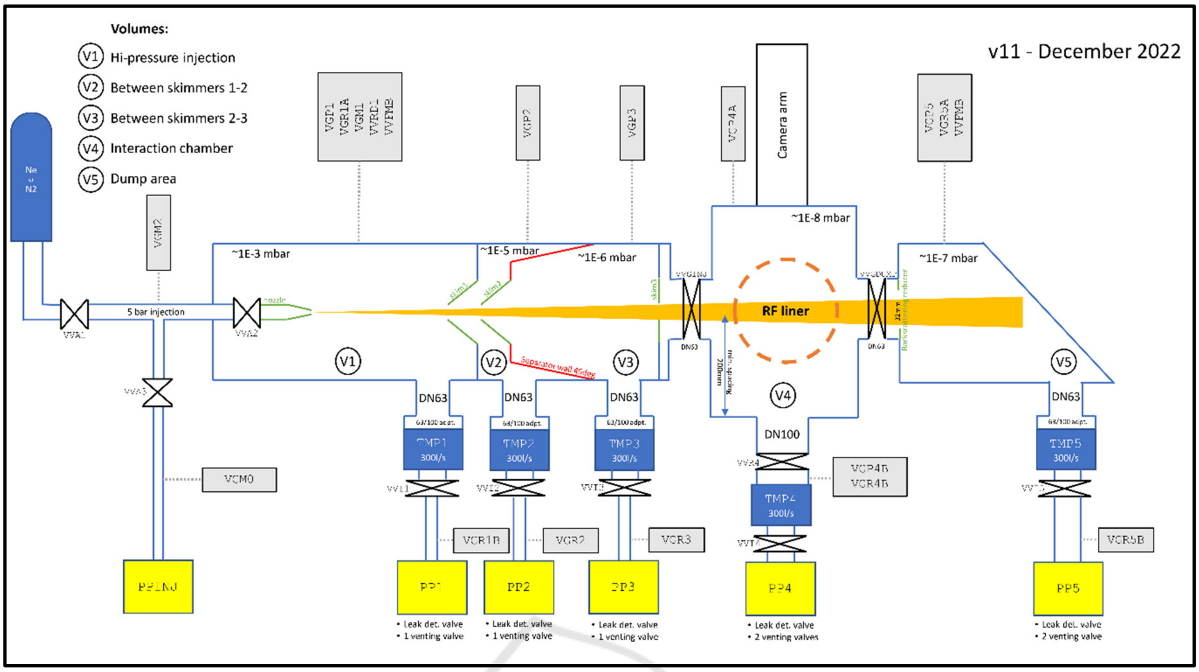

Figure 1: Layout of the BGC Vacuum System (Ady & Sequeiro, 2022).

(VGP1, VGP2, VGP3, VGP4A, VGP4B, VGP5) gauges. In addition, the injection line is equipped with two pressure transmitters (VGA1 and VGA2) to monitor the pressure of the gas to be injected.

2.2 Vacuum Framework

The control of the BGC equipment is implemented using the CERN Vacuum Framework, which consists of a library of baseline PLC functions implemented using structured text, common SCADA panels, control scripts and files, ORACLE databases to store device data, and vacCC, an application which allows users to modify vacuum devices via a web browser and which automatically generates SCADA and PLC configuration files (Rocha et al., 2019). The framework is essential to enable the configuration, maintenance and operation of the very large distributed vacuum control systems at CERN (Antoniotti et al., 2014). Each vacuum device in the framework is instantiated from what is known as a control type, within which everything needed to manage the equipment is defined.

Vacuum framework devices can be operated either in automatic or manual mode. When the equipment is in manual mode it can only receive manual commands from users operating the SCADA, whilst when in automatic mode the device is under the control of an automatic process in the PLC. Only operators with high enough permissions can swap devices between automatic and manual modes. Normal users can generally not manually operate a device which is being controlled by a process.

2.3 Control System

The control system developed for the BGC consists of six PLCs. Each of the five pumping groups is controlled by a dedicated PLC (Simatic S7-1200), as they are implemented using the standard solution for fixed vacuum pumping groups on the LHC developed at CERN (Ferreira et al., 2016). Finally, a sixth controller is used to handle the rest of the equipment as the main PLC of the BGC control system.

All Pirani and Penning gauges are managed by dedicated controllers (Pfeiffer TPG300), which interface with the PLCs through Profibus. The piezoelectric gauges are connected to a standard controller for LHC piezoelectric gauges developed at CERN (Chatzigeorgiou & Kuhn, 2024), from which the main PLC acquires pressure values through 0-10V signals.

Finally, the pressure transmitters, gate valves and injection valves are all controlled through the main PLC I/O (Zygaropoulos, 2022).

2.4 Machine Safety

Given that the BGC injects gas directly into the LHC beam pipe close to crucial and sensitive equipment such as the radio frequency cavities that accelerate the particle beam, machine safety must be a critical part of the control system design, both at the hardware and software levels.

2.4.1 Control Hardware Safety Considerations

At the hardware level, all PLCs and equipment controllers are connected to a UPS, meaning that if a power loss is experienced during gas injection, the injection and gate valves can still be operated and the pressure in the chambers can still be monitored.

Pumping group devices, though, are powered locally in the LHC tunnel to adhere to the standard LHC fixed pumping group control architecture (Ferreira et al., 2016) (as normally pumping groups are placed very distant from the control rack location and would experience too large a voltage drop), meaning that in the case of power loss, they are not connected to backup power (as UPS connections are not available in the LHC tunnel).

The standard hardware that controls vacuum pumping groups at CERN is designed to vent both the turbo-molecular and primary pump of a pumping group after a power loss using a charged capacitor (Zygaropoulos & Wickham, 2024).

The BGC is the only case in the LHC where the following two types of pumping group configurations are found: pumping groups without isolating valves, and a pumping group with a turbo-molecular pump equipped with a venting valve. These configurations have fewer intermediate valves directly controlled by the pumping group between the beam pipe and venting points.

It was decided, therefore, to remove the automatic venting functionality, as it is of the utmost importance to minimize any possible risk of venting the beam pipe.

The compressed air lines that supply the pumping group, injection and gate valves are provided with reservoirs. If there is a loss of both the compressed air and the reservoir, the gate valves will not close automatically as they are bistable, but the injection valves will close automatically, avoiding the risk of continued injection.

2.4.2 Device Interlocks

Software interlocks, called device interlocks in this context, are also used in this system to ensure the machine safety of the LHC. Device interlocks are separated in two categories:

- *Start interlocks*, which permit or not, a valve to open or a pumping group to start but will not close or stop them if open or running.
- *Full interlocks*, which do not allow a valve to open or a pumping group to start and will close or stop them if open or running.

Given the critical nature of the BGC, when operating the instrument manually, devices which have been interlocked must be manually reset through the SCADA after the underlying interlock condition has been cleared. This is required in order to re-acquire control of the equipment and resume normal operation.

Table 1: Start interlock conditions for each device.

Device	Start Interlock conditions
VVGINJ and VVGDUMP	• All pumping groups must be in nominal state • All Penning gauges must be on and not in error • Pressure thresholds on all Penning gauges
Pumping Group VVIs	• The pumping group Pirani gauge must be on and not in error • Pressure threshold on the pumping group Pirani gauge • VGR1A must be on and not in error • VGR1A pressure must be 50x greater than the pumping group Pirani gauge's
Pumping Group Processes	• Adjacent Gate and/or Injection valve/s closed, not in error and not in warning

The start interlocks listed in Table 1 serve several protective functions for the BGC. On VVGINJ and VVGDUMP, they ensure that these valves can only open when the injection and dump vacuum chambers are under nominal vacuum conditions. For the VVIs of the pumping groups, the interlocks prevent potential backflow of oil from the primary pumps into the BGC chambers or the LHC beam pipe by ensuring that the valves can only be opened when the pressure differential between the injection chamber and the primary pump volume is high enough. Finally, the interlocks associated with the pumping group processes ensure that these groups can only start pumping when the chamber they are connected to is properly isolated.

Table 2: Full interlock conditions for each device.

Device	Full Interlock conditions
VVGINJ and VVGDUMP	• All pumping groups must be in nominal state and not in error • All Penning gauges must be on and not in error (except VPG1, not on during injection) • Pressure thresholds on all Penning gauges (except VPG1)
Dump Pumping Group Turbo Venting Valve	• VVGDUMP closed, not in error and not in warning
VVA1	• VVA3 closed, not in error and not in warning
VVA3	• VVA1 closed, not in error and not in warning
PPINJ	• All injection valves not in error and not in warning

The full interlocks listed in Table 2 provide additional protection for the BGC system. On VVGINJ and VVGDUMP, they act on valve operation if pressures in the injection or dump chambers are too high, or if a pumping group fails, thereby safeguarding the beam vacuum. The full interlock on the turbo venting valve of the dump chamber pumping group ensures the beam pipe cannot be accidentally vented by venting the pumping group with VVGDUMP open. The full interlocks on VVA1 and VVA3 protect the neon gas bottle from being accidentally emptied through PPINJ. Finally, the protection on PPINJ itself blocks pumping from the injection line when faults are detected in one or more injection valves.

The statuses used in the interlock logic that need to be exchanged between the main and pumping group controllers (pump nominal and error status, the start interlock on the intermediate valve and the start interlock on the pumping process) are transmitted via hard-wired signals.

2.5 Operation and Limitations

Initially, when a gas injection was required, the BGC vacuum system was operated manually by sending separate commands to each device following a written procedure with great care, whilst also monitoring pressures and the status of the system as a whole. A schematic representation of the actions that users would have to follow to start an injection can be seen in Figure 2.

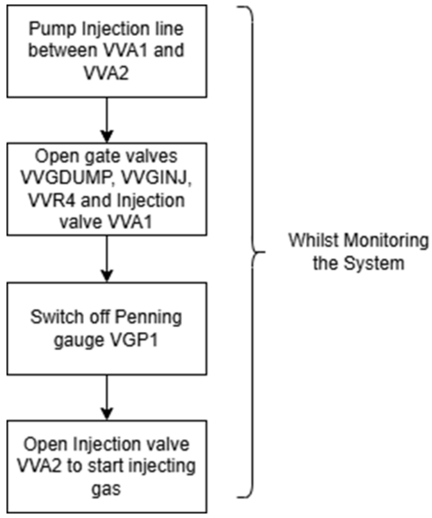

Figure 2: Manual actions needed for injection.

As a result, only expert users with a high level of familiarity with the system were allowed to start an injection.

The complicated nature of the procedure meant that the system was prone to human errors and that starting the injection took a lot of attention and work.

To make the whole process more reliable, efficient and accessible for new users, it was proposed to develop a system that could automatically handle the gas injection.

3 AUTOMATION OF THE GAS INJECTION

The objective of the automated control system is to execute the gas injection sequence described in Section 2.5, as well as returning the instrument to its initial stand-by state following an injection. In addition, the process must be able to recover from equipment failures and react to detected risks to the LHC beam pipe (such as detected high pressures), returning the instrument to the safest possible conditions. Furthermore, the control system must prioritise machine safety, ensure reliability and reduce operational time and user effort.

3.1 Implementation of the Automatic Injection Process

Process Control with Vacuum Framework is achieved by creating a new, instantiable, control type, which will take control of all required equipment instances according to the desired logic. The automated control logic is implemented as a finite state machine (FSM) in the main PLC. All BGC devices that are part of the automatic injection scope are forced to automatic mode and are sent automatic commands by the process.

The status of the instrument during the automatic injection is monitored by process interlocks (which will be described in a later section).

The FSM states correspond to the stages of the injection cycle and can be seen in Figure 3. The functions of these states are described below:

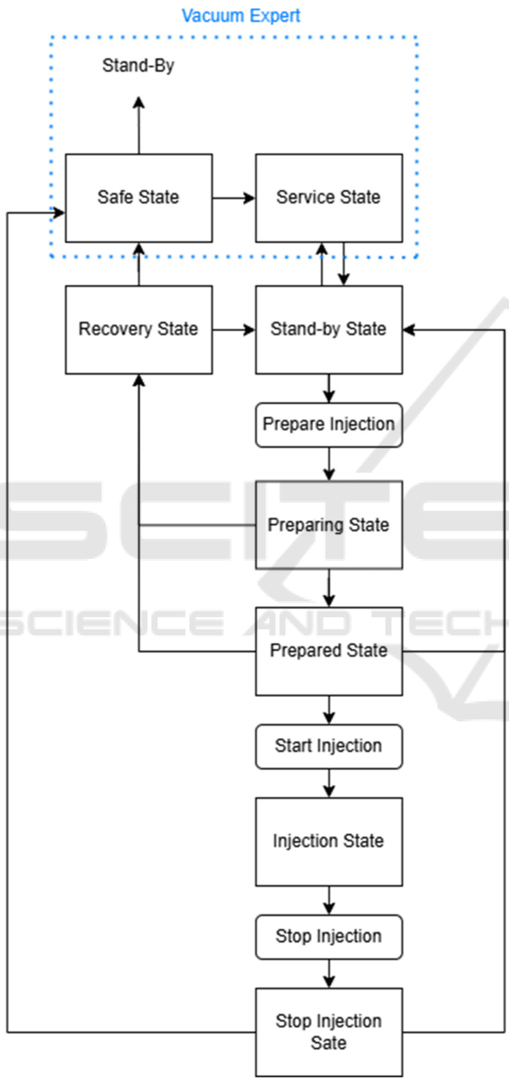

Figure 3: Automated injection FSM.

- *Stand-by*: Default operational state (when not injecting) where all valves are forced closed. Awaits a "Prepare" command to proceed.
- *Preparing*: Injection line is evacuated with PPINJ, gate valves are opened, Penning gauge VPG1 is turned off, VVA1 is opened.
- *Prepared*: System is ready for injection. If "Start Injection" command is not issued within 10 minutes, returns to Stand-by automatically through Recovery.
- *Injection*: VVA2 opens to inject the gas curtain. Stops on user command or automatically after 20 hours, transitioning to Stopping Injection. If process conditions are breached or an actuator failure is detected, also transitions to Stopping Injection.
- *Stopping Injection*: All valves close, injection line is pumped, VPG1 is reactivated. Returns to Stand-by if successful, or to Safe if the process conditions were breached or an actuator failure was detected.
- *Recovery*: Triggered if process conditions are breached or an actuator failure is detected during Preparing or Prepared. Actuators are driven to safe positions before moving to Safe.
- *Safe*: All actuators are forced to their safest state. Can only be exited by a vacuum expert. Default state on PLC startup.
- *Service*: Expert-only state for manual control and maintenance. No automatic commands are sent to the devices.

Whilst the injection is exclusively performed using the automatic process described above, experts also have the option to activate manual control through a specific command. This will allow them to individually set devices to manual mode and perform manual operations. Manual control is mostly used whilst the instrument is in the Service state for operations such as leak detections.

3.2 Process Interlocks and State-Based Safety

Failures or hazards during the automatic injection are detected by using process interlocks. Process interlocks are conditions applied to the states of the process. If the conditions are not met, the process will either not be able to start or will move from the current state to the Safe state in a controlled manner. As the vacuum levels and equipment states in the BGC chambers will differ based on the operational state of the instrument, different sets of process interlocks exist:

- *Start Process Interlocks*: act during the Stand-by state of the process and, if not satisfied, do not allow the process to move to the preparing state.

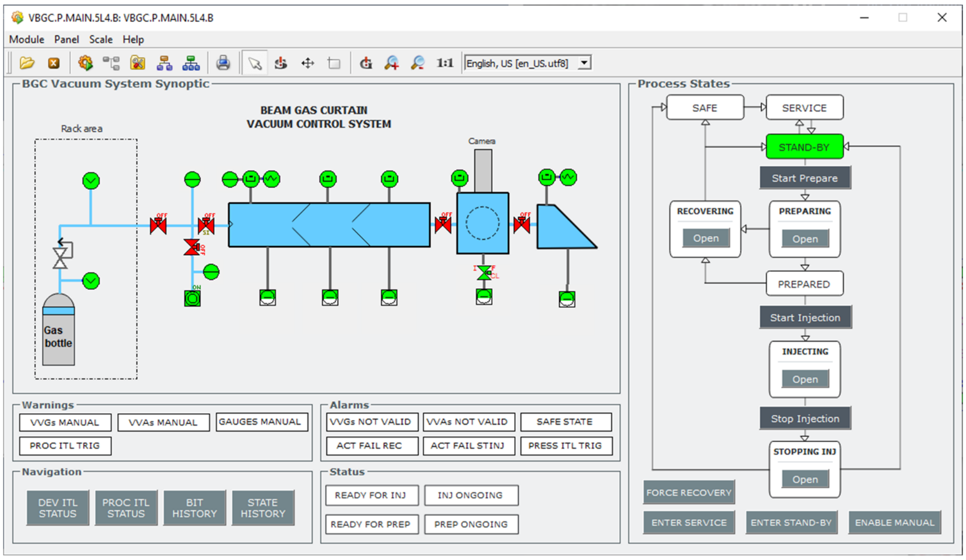

Figure 4: New BGC User Interface

- *Prepare Process Interlocks*: act during the Preparing and Prepared states and, if not satisfied, move the process to the Recovery state and then to the Safe state.
- *Injection Process Interlocks*: act during the Injecting state and if not satisfied, move the process to the Stopping Injection state and then to the Safe state.

The process interlocks are calculated based on a set of pressure values and device statuses.

The device interlocks described in section 2.4.2 are still active even during the automatic injection, protecting the integrity of the beam vacuum by acting on individual devices, whilst process interlocks protect the overall procedure.

3.3 New User Interface

For users to send the needed commands and to monitor the system in the context of the automatic injection, a new user interface was developed, which can be seen in Figure 4.

On the right side of the main panel, the FSM for the automatic injection can easily be monitored and commands can be sent, with only two button presses needed to start a gas injection. Some of the states shown in the “Process States” box on the SCADA main screen have internal steps that can be viewed in the detailed steps panels such as the one shown in Figure 5.

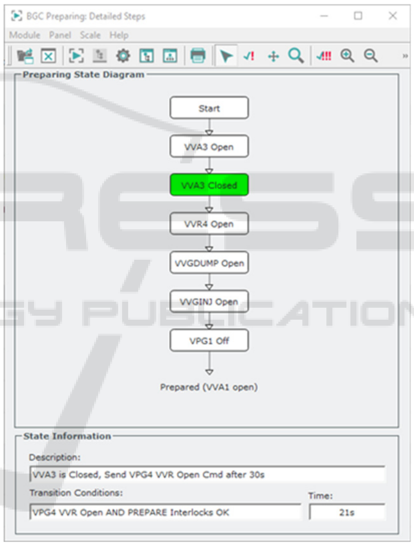

Figure 5: Preparing state detailed panel.

Various statuses, warnings and alarms are also visible on the UI. Particularly important are the alarms, which are configured to send an SMS notification to predetermined vacuum experts when triggered, so that action can be taken promptly.

Panels to monitor the status of both process (Figure 6) and device interlocks are also available and can be very useful for the users to better understand what may be blocking the gas injection.

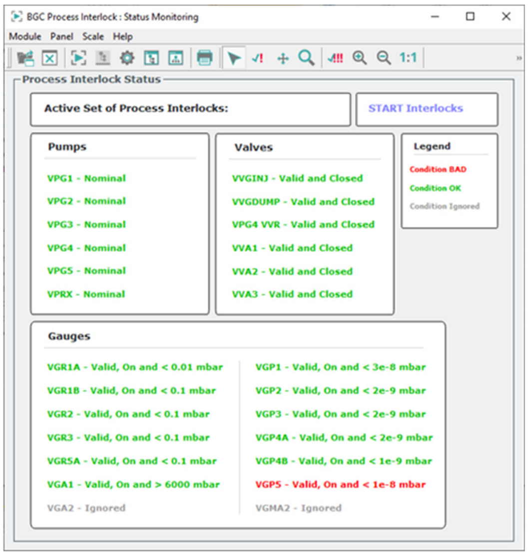

Figure 6: Process interlocks details panel.

3.4 Testing and Installation

A testing checklist was produced after identifying all potential failures and hazardous conditions the process needed to handle, as well as the general functionalities required for automatic injection.

The checklist was used to thoroughly test the full control chain by running the code on a virtual PLC using the Siemens PLCSim Advanced software (Siemens, 2022) connected to a local SCADA instance. All the controlled devices were simulated within the PLC by writing custom code.

The installation and commissioning of the new control process along with the newly developed control crate for the main PLC took place during YETS 2024/25 in three stages of commissioning:

1. *Device consistency across the whole control chain was ensured*, from SCADA to hardware, by individually actuating each device and monitoring its actual status on the field.
2. *All device interlocks were validated* by manually triggering each condition using simulators and jump wires, ensuring the control system responded correctly. These simulators mimicked the behaviour of real components (e.g., specific resistance for Penning gauges, relay actuation for valves) and were used throughout the testing process.
3. *The full functionality of the automatic injection was tested* in three stages:
   a. Process tests with simulators connected to all valves.
   b. Process tests with simulators connected to gate valves only (injecting gas only in the injection chamber).
   c. Process tests injecting directly in the LHC beam pipe with vacuum sector valves closed (Penning gauge pressures demonstrating a successful injection are shown in Figure 7).

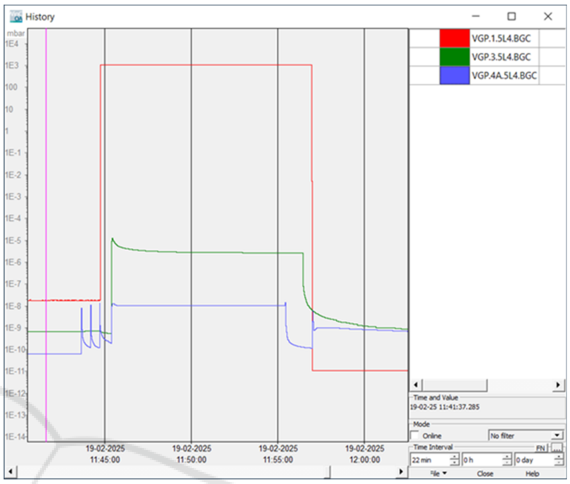

Figure 7: Penning gauge pressures during test injection in the LHC beam pipe (1E3 mbar value indicates the Penning gauge is off).

The different features introduced with the automated injection were tested by manually introducing failures and checking that the instrument recovered as expected. This was achieved by using simulators to trigger process interlocks such as high pressures in some of the gauges and incorrect valve positions or error statuses.

Commissioning reports documenting the results of all performed tests were produced, uploaded to CERN's internal repository, and are readily available for consultation (Cantu, 2025).

The new injection control system was successfully handed over for operations to the Beam Instrumentation group at CERN together with a user manual containing all necessary information (Cantu, 2024).

4 CONCLUSIONS

The development and deployment of the automated vacuum control system for the BGC marks a significant advancement in its safe and reliable operation. The initial manually operated system, while functional, was labour-intensive, prone to human error due to its complexity and difficult for new users to become familiarised with. By applying industrial automation principles, the injection process has been transformed into a robust, streamlined procedure requiring minimal user intervention.

The use of a PLC-based finite state machine, tightly integrated with CERN's Vacuum Framework and supervised via a purpose-built user interface, ensures consistent and reproducible operation. Device and process-level interlocks provide a dual layer of protection, safeguarding the accelerator infrastructure and the injection process itself. The thorough validation strategy, including simulated fault scenarios and staged commissioning, has demonstrated the system's capacity to handle operational anomalies gracefully and has been fully documented with commissioning and testing reports.

Following deployment during YETS 2024/25, the system was handed over to the Beam Instrumentation group for routine use. Users have reported that the system significantly reduces operational complexity, improves reliability and saves time. Positive feedback has highlighted the clarity of the user interface, the robustness of the automation, and the reduction in manual interventions required to perform an injection.

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