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TECHNICAL NOTE

SASE3 Gas Attenuator Device PLC Interlock System

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Raúl Villanueva Guerrero
for the Vacuum group
at European XFEL

European X-Ray Free-Electron Laser Facility GmbH
Holzkoppel 4
22869 Schenefeld
Germany

Distribution

European XFEL

Instrumentation Department

Harald Sinn

Vacuum group

Martin Dommach, Michaela Petrich

Electronic and Electrical Engineering group

Patrick Gessler, Nerea Jardón

Controls Group

Christopher Youngman, Valerii Bondar

SCS Instrument

Andreas Scherz

SQS Instrument

Michael Meyer

CC:

Photon Run Coordination Team

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Abstract

The European XFEL SASE3 undulator beamline instrumental end-stations make use of a gas-based device to control the transmitted intensity of the free-electron laser (FEL) photon beam. This device is specifically designed to provide the required level of attenuation without compromising the general stability of the ultrahigh vacuum (UHV) conditions of the surrounding beamline vacuum sections.

The device is envisioned to work without any physical separation (i.e. windows or thin membranes), which imposes, apart from a challenging conceptual design, a strict set of operation conditions. Additionally, and due to the diverse subsystems involved in its correct operation, a certain degree of process automation has been implemented to the highest level of use simplicity.

The goal was to provide a valuable tool with a minimum learning effort for the end user, assuming very little or no previous knowledge on these types of devices. For this reason, an integral approach between the overlaying SCADA system at the European XFEL, known as “Karabo”, where the process automation is developed, and the underlying PLC scheme, has been subjected to multiple iterations to achieve the optimal system control stability and performance.

This Technical Note gives a general description of the most relevant aspects that characterize the control of the gas attenuator device. In particular, it is especially focused on the safety interlock implementation and the implications that it imposes on the operative characteristics of the device.

A particular effort has been also made to provide a clear view on the interaction among devices and the relevant signals flows. This has been extensively supported by the inclusion of graphical material that enables an easier understanding of the general control structure.

Motivation

This Technical Note is intended to facilitate the understanding of the subjacent control structure that defines the operation of the SASE3 beamline gas attenuator device. It shows all the relevant information as simply as possible in order to allow easy access to aspects that are more advanced that the simple operation of the instrument.

In particular, since the involved vacuum sectors are quite demanding in terms of safety requirements, one of the main goals of this document is to enable a starting point for troubleshooting in case of issues related to the two main aspects where the device should perform with the highest reliability:

- Injection of inert gas in subatmospheric pressure levels for the downstream intensity control of the transmitted photon beam
- Conservation of a windowless UHV interface with the rest of the UHV sectors of the beam transport system

A very important caveat is that the shown information is not to be used to modify any of the existing control parameters that are not explicitly available in the provided SCADA system graphical user interface (GUI). Any unauthorized and/or not communicated[1] alteration should be prevented. In this sense, the author of this document rejects any responsibility for its misuse.

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[1] *At the time of writing, the request for any modification should be addressed to the X-Ray Operations group leader for authorization after proper discussion at the Operation Board. After that, its implementation can be evaluated and, if the results are positive, the implementation can be executed by the device management group (i.e. the Vacuum group).*

Contents

1 European XFEL SASE3 photon beamline [7]

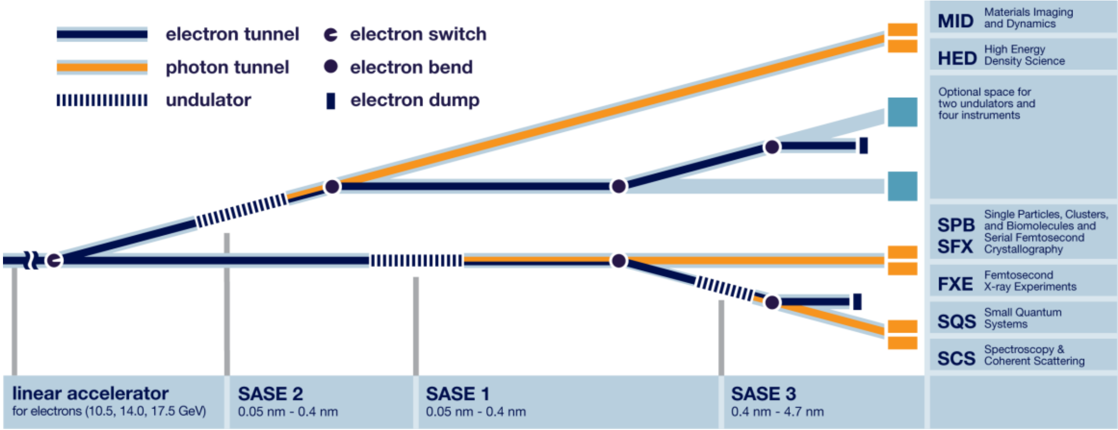
The European XFEL is a free-electron laser (FEL) facility outside Hamburg, Germany. A 1 700 m long, pulsed, superconducting linear accelerator (LINAC) accelerates the electron bunches up to 17.5 GeV [2]. At the end of the LINAC, the individual electron bunches are selectively distributed in the three undulator arrays (SASE1, SASE2, and SASE3).

Hundreds of meters of magnetic structures allow the X-ray radiation production through the self-amplified spontaneous emission (SASE) process. Due to the superconducting technology, the X-ray pulses are produced in powerful bursts, where many thousands of X-ray pulses of milijoule power and femtosecond duration are produced in less than a millisecond [3]. The goal of the photon transport system is to deliver the photon beam from the undulators to the experiments and to preserve its unique characteristics of transversal coherence and short pulse length. The photon transport system, like the rest of the facility, is located underground in up to 1 km long tunnels. The transport system has also to separate the FEL beam from its highly energetic background radiation, adequate the beam size to a usable size, and, accordingly to the experimental needs, limit the bandwidth by the use of monochromating devices.

The European XFEL photon system distribution is sketched in Figure 1.

Meanwhile, SASE1 and SASE2 are designed for production and transport of hard X-ray radiation and SASE3 is devoted to the soft X-ray wavelength range produced by the use of 21 undulators. These are 5 m long and with 68 mm magnetic period.

***Figure 1**: Layout of the European XFEL facility*



The superconducting LINAC can deliver electron bunches at 10.5, 12, 14, and 17.5 GeV. For each electron energy value, the undulator array generates a different wavelength with a narrow bandwidth distribution. Figure 2 summarizes these ranges for all the SASEs, and Figure 3 offers a more detailed view for the specific case of SASE3 beamline.

***Figure 2:** Dependence of the FEL photon beam energy on the machine electron energy configurations*

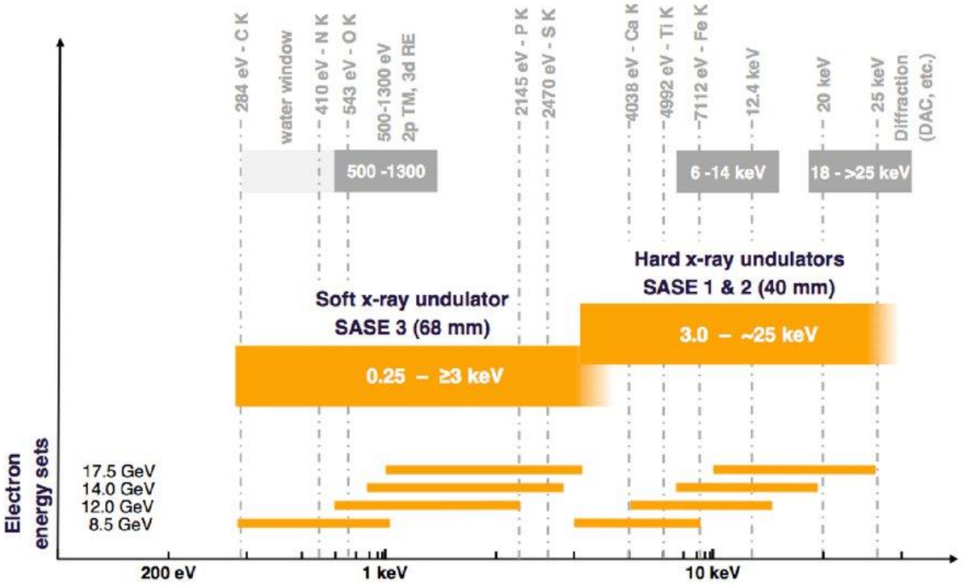
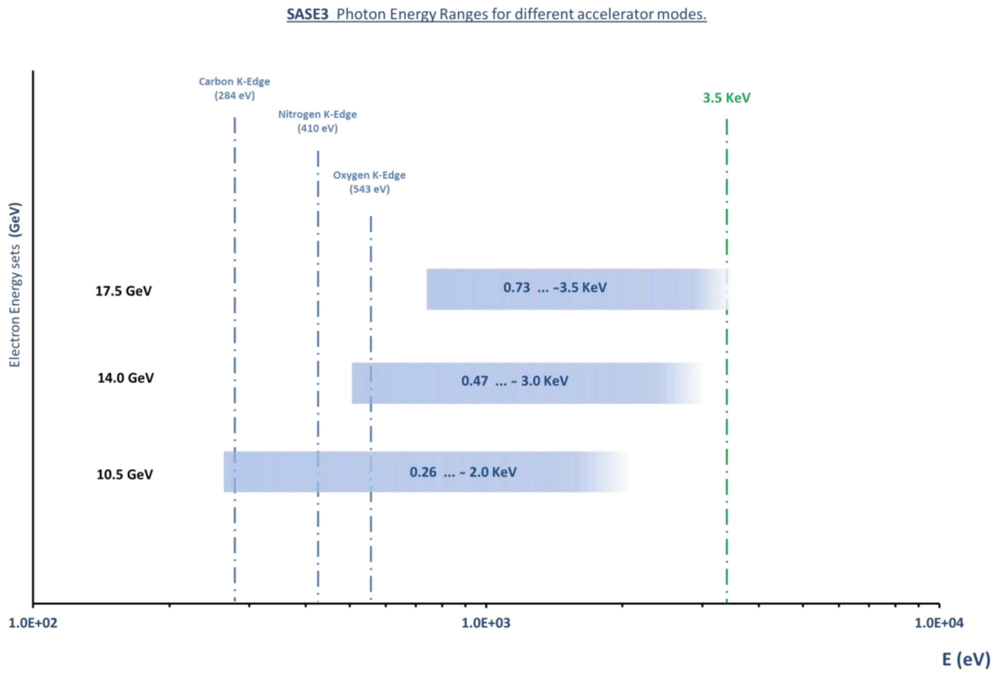


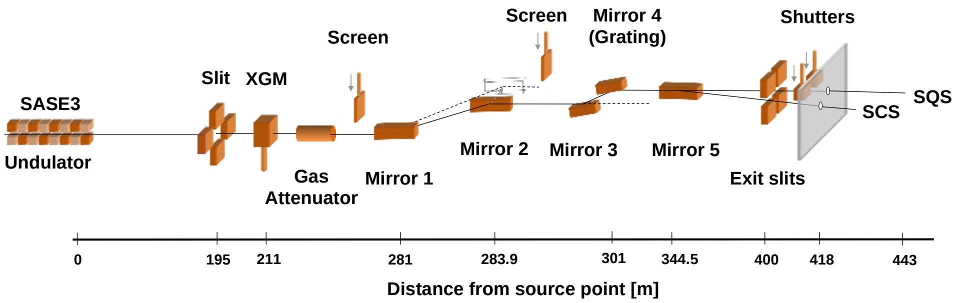
Figure 3: *SASE3 beamline photon energy ranges depending on accelerator electron energy configurations*



1.1 SASE3 outline and general description [4], [5]

The SASE3 basic outline is presented in Figure 4. It corresponds with the distribution of components in the XTD10 tunnel.

Figure 4: *SASE3 beamline basic layout*



NOTE: Not shown in the picture, but still existing in the tunnel, is another relevant diagnostics device downstream from the gas attenuator: the micro-channel plate (MCP) detector. In particular, given the lack of a second X-ray gas monitor (XGM) right after the gas attenuator, it is the single diagnostic device still in the tunnel can be used in correlation studies together with the upstream XGM.

Here one can find (from left to right) the following items:

1. SASE3 undulator arrays (FEL light source origin)
2. Synchrotron radiation aperture (SRA) slit system
3. XGM (gas-based intensity and position diagnostics device)
4. Gas attenuator for intensity tuning of the FEL photon beam
5. Set of pop-In monitor screens for “invasive” beam position control and shape diagnostics
6. Offset mirrors (M1 and M2) for background radiation elimination
7. Monochromating systems (M3 and M4)
8. Distribution mirror (M5) towards the instruments
9. Exit slits of each instrument branch
10. SCS and SQS safety shutters at the end of the beamline

1.2 Operational parameters

In Table 1, a summary of the most relevant parameters of SASE3 beamline are presented. Of particular interest for the gas attenuator design is the photon energy range, which determines, together with the gas species and the effective attenuation length, the required density (and hence, gas pressure for a given temperature) in order to provide at each time the required attenuation of the beam transmitted flux.

Table 1: *Most relevant operational parameters set of the European XFEL SASE3 beamline*

Photon energy	250–3000 *eV*
Wavelength	4.8–0.4 *nm*
Pulse energy	0.2–11 *mJ*
Peak power	50–120 *GW*
Average power	3–300 *W*
Pulse width	2–100 *fs*
Coherence time	0.3–1.8 *fs*
Photons per pulse	$0.1\text{–}2 \cdot 10^{14}$
Repetition rate	10 *Hz*
Pulses per train	up to 2700

2 The instrument

2.1 General description

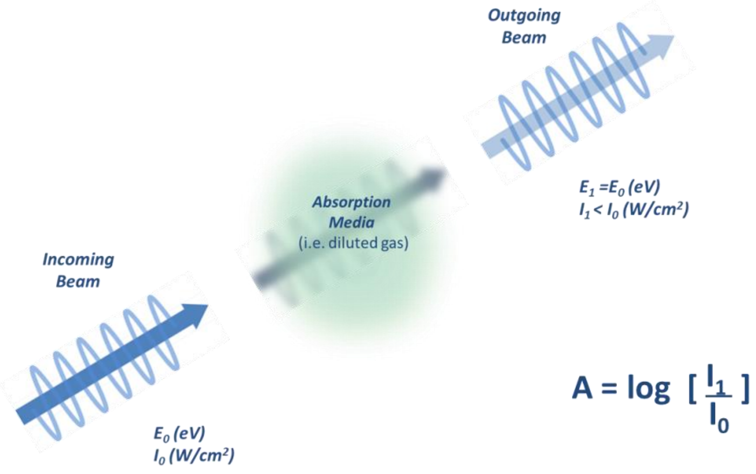
The gas attenuator device responds to the need of controlling the transmitted maximum pulse energy of the FEL beam, securing by first principles, the following aspects:

- Providing a progressive and continuous variation of the photon flux intensity
- Avoiding optical aberrations and/or wavefront distortions
- Overcoming the damage threshold issue that solid materials suffer from

As the absorbing media is a dilute gas, in principle a higher isotropic behaviour in the interaction zone can be achieved once a macroscopic steady state has been reached.

The system can benefit from different gas species selection, extending and adapting the capabilities to a wider range of experimental scenarios without further equipment modifications.

Figure 5: *Scheme of the first order photoabsorption process working principle*



In general, this is achieved by making use of a first order approximation of the Beer-Lambert law, which fairly describes the overall process as it can be appreciated in Figure 5:

$$I = I_0 \cdot e^{-\mu\rho d}$$

where ***I_0*** is the initial beam intensity, ***I*** is the intensity after the overall photoabsorption process, ***μ*** is the mass absorption coefficient (which depends on the material and the interacting photon energy), ***ρ*** represents the material density (for gases it will be dependent of pressure and temperature), and ***d*** represents the effective total attenuation path length [1,6].

A summary of the design features of the gas attenuator device is shown in Table 2.

Table 2: *Operational features of SASE3 gas attenuator device*

Photon energy range	250–3500 *eV*	—
Controllable transmission range	$1{\cdot}10^{-12}$%–100%	Depending on actual combination, photon wavelength, gas species, and pressure
Reference transmission	0.1%	Available for any combination of the above mentioned parameters
Pressure limit in the active gas cell	35 mbar	N2 equivalent
Minimum controllable pressure during injection	$1{\cdot}10^{-3}$ mbar	Defined by the minimum controllable flow of the MFC system and the first aperture of the differential pumping system
Default gas	N2	Permanent supply
Optional gases (on demand)	Ar, Ne, Kr, Xe	Pre-installed supply lines ready for connection with local or remote source
Configurable gas system	Yes	-
Gas analysis system	Yes	QMS plus analysis UHV chamber
Variable clear aperture	Yes	Discrete, 20, 12, and 6 mm.
Integration with photon diagnostic devices	Yes	See [9], [10]

2.2 Beamline vacuum sector(s)

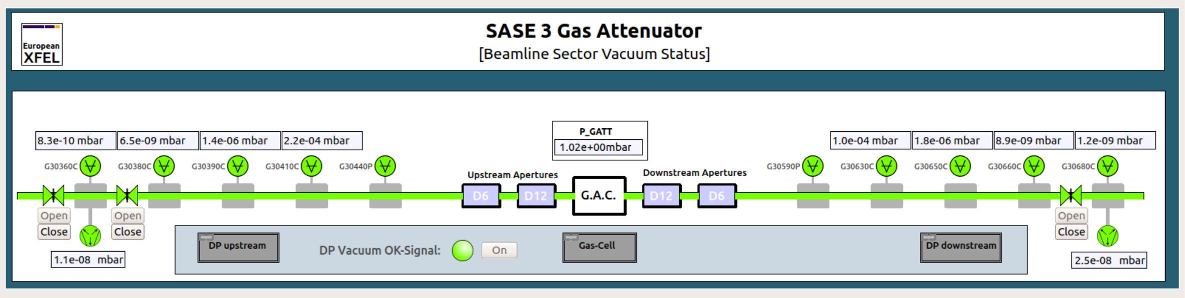
The SASE3 gas attenuator device in operation in the XTD10 tunnel of the European XFEL was conceived as a self-consistent conceptual project that includes three main parts:

1. Active gas cell and the gas management and injection system.
2. Necessary differential pumping modules.
3. So-called transition pipeline to both the immediately surrounding vacuum sectors, which is always ended with a reference chamber equipped with a 300 liter ion pump, and a set of full-range vacuum sensors.

Seen from the pressure profile that would be generated when it is under operation, the gas attenuator will introduce a symmetry feature that alters the directional order of a conventional vacuum beam transport system; that is the reason elements 2 and 3 appear symmetrically duplicated.

This particularity can be immediately acknowledged in **Figure 6**.

Figure 6: *Capture from the European XFEL Control GUI (Karabo) where the general pressure profile of the Gas Attenuator is shown when operating at 1 mbar in the Active Gas Cell.*



Because the system needs to be integrated within the standard definition of a beamline vacuum sector[2], it spans into a number of three, the first two from upstream (VS30040) to upstream (VS30050), fully consistent with the initial

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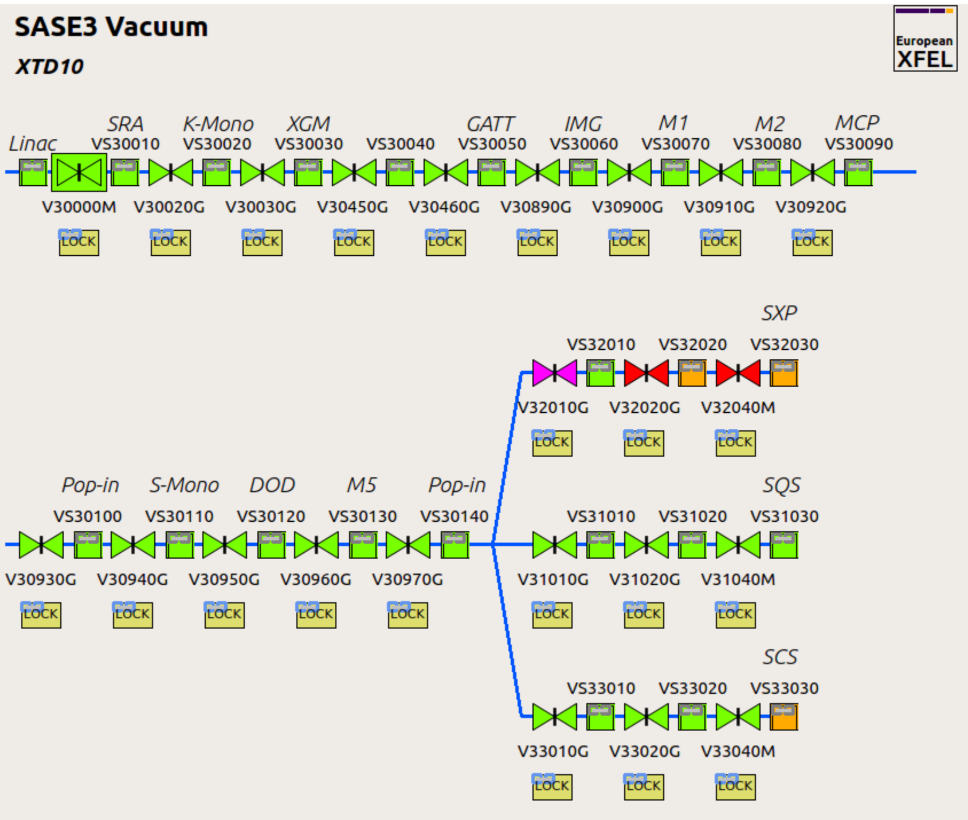
[2] *A standard beamline vacuum sector is defined in the European XFEL as a vacuum subsystem that is equipped with a least a vacuum pump and allows its isolation from the surrounding elements with two inline gate valves.*

concept design, and the last one downstream, being shared with another element of the beamline instrumentation (VS30060). This is depicted in

Figure **7**.

***Figure 7:** General outline of the SASE3 beamline vacuum control system (taken from Karabo)*



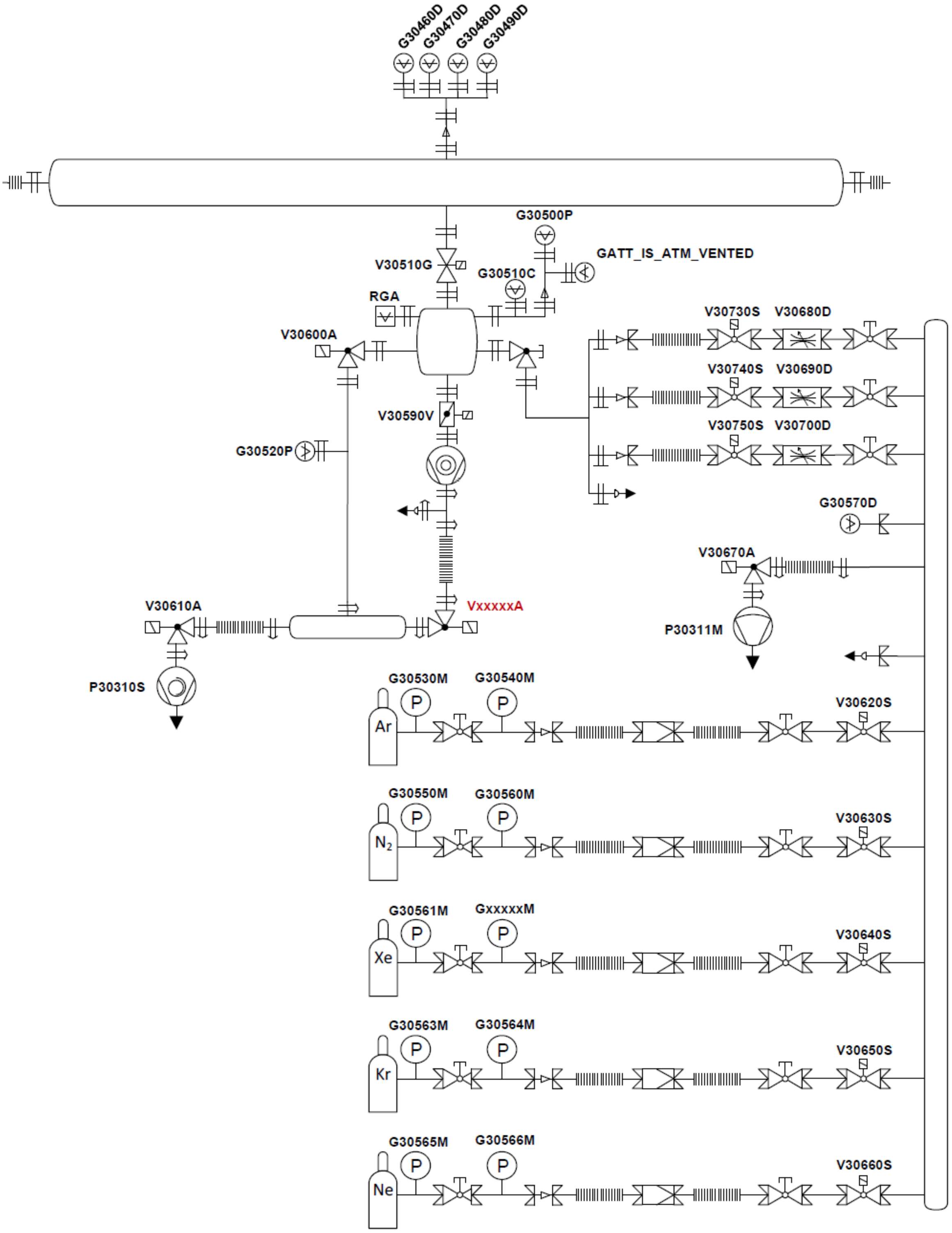
2.3 Gas injection system

The gas injection system is also known as the central gas injection (CGI) module, and its main tasks are:

1. Fine-tune the necessary gas flow to achieve the required attenuation
2. Precisely measure the pressure in the absorption cell
3. Enable the eligibility of up to five gases
4. Enable the purity evaluation of the injected gas
5. Enable a fast evacuation of the remaining gas when is not needed
6. Maintain UHV average conditions in case no gas is injected

The piping and instrumentation diagram (P&ID) of the existing system is shown in Figure 8.

Figure 8: *P&ID schematic of the gas attenuator injection system*



Also an actual view of the installed equipment is shown in Figure 9 and Figure **10**. In Figure 11, the conceptual pressure and flow control loop is also shown.

Figure 9: General view of the CGI module

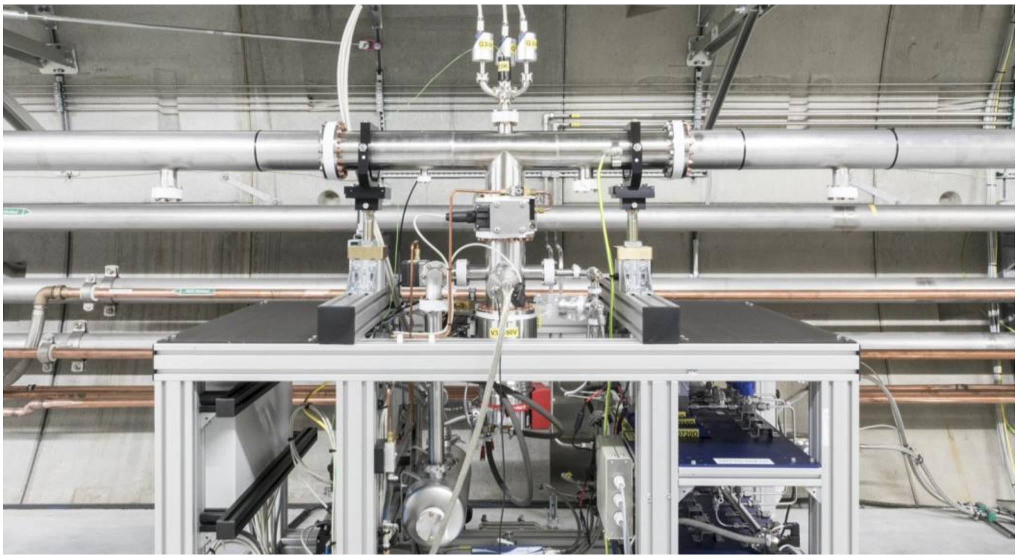
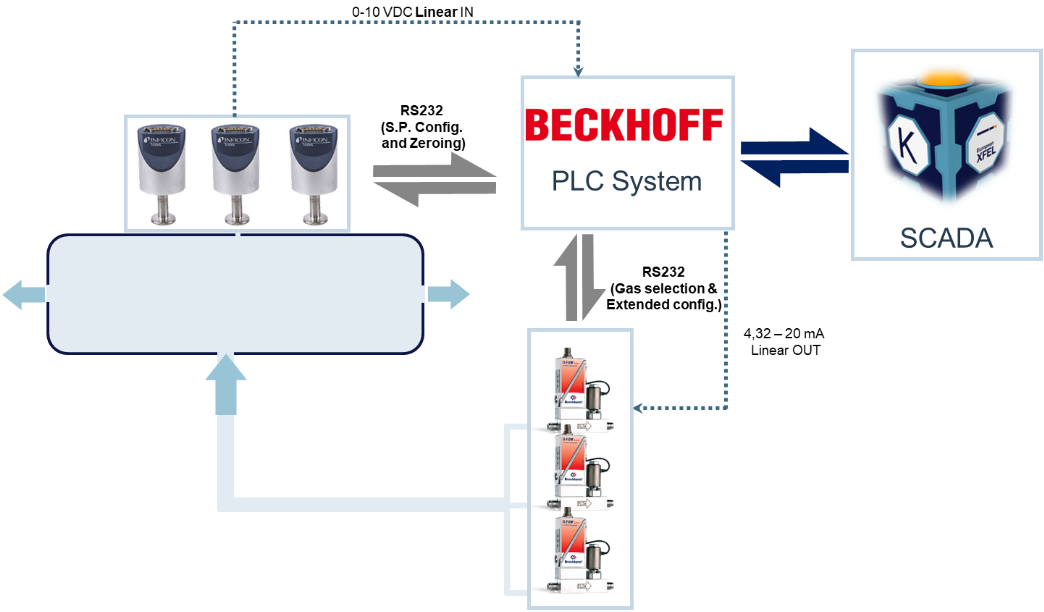


Figure 10: *Detail view of the CGI high purity gas manifold*

Figure 11: Conceptual scheme of the flow and pressure control system



2.4 Gas pumping system

Since the system is connected without any solid separation from the rest of the beamline, it has to also provide a dramatic pressure reduction (up to nine orders of magnitude) that can only be achieved in a progressive way. This has been implemented by means of a differential pumping scheme. It comprises up to four pumping stages and a system of discrete flow restrictors that can be inserted accordingly to the actual beam size in order to keep the specific gas flow under a safe limit [8].

As previously mentioned, this pumping system will appear twice in a mirror-like fashion, as can be seen in Figure 12 and Figure 13, respectively.

***Figure 12:** Upstream differential pumping system of the gas attenuator*

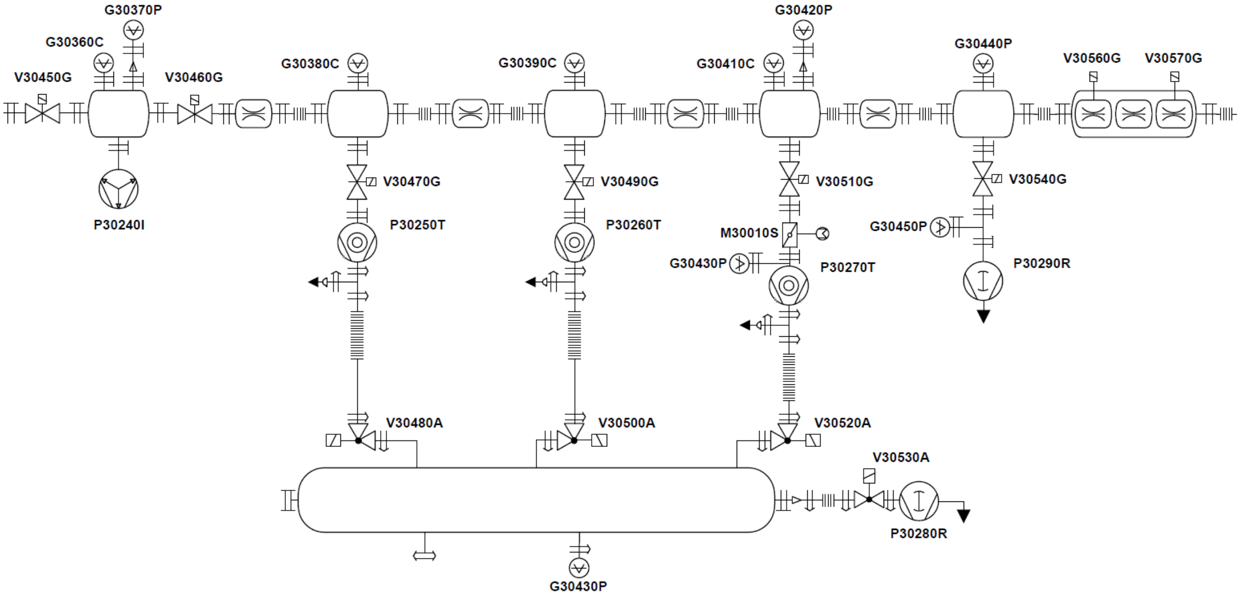


***Figure 13:** Downstream differential pumping system of the gas attenuator*

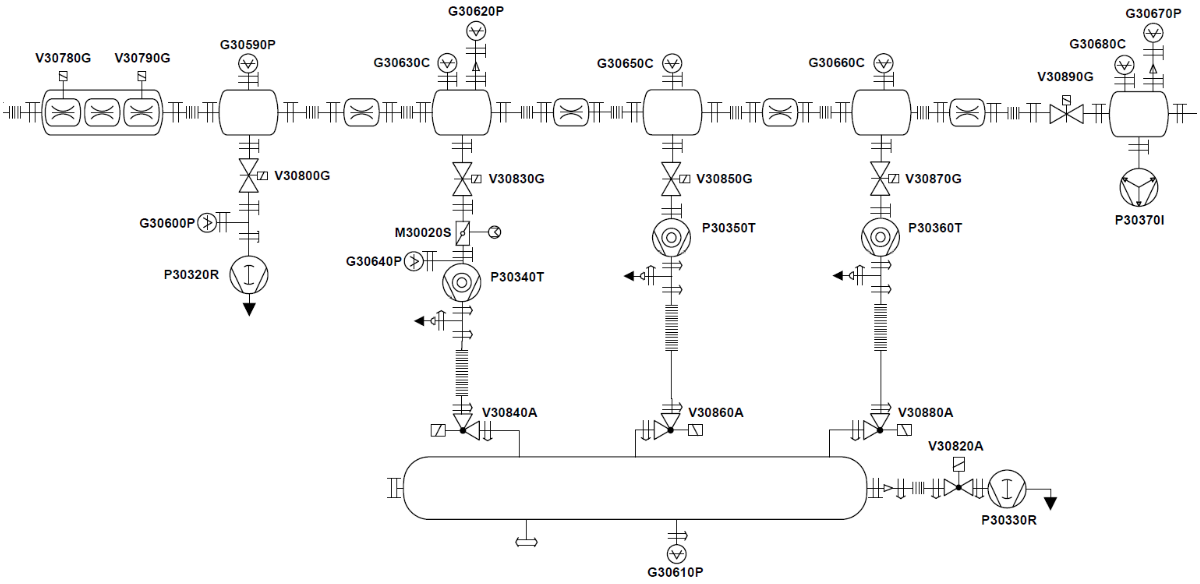


Figure 14 shows an actual view of the installed equipment in the XTD10 tunnel. In particular, the complete differential pumping module installed upstream the active gas cell.

Figure 14: *Current tunnel installation of the gas attenuator upstream differential system*

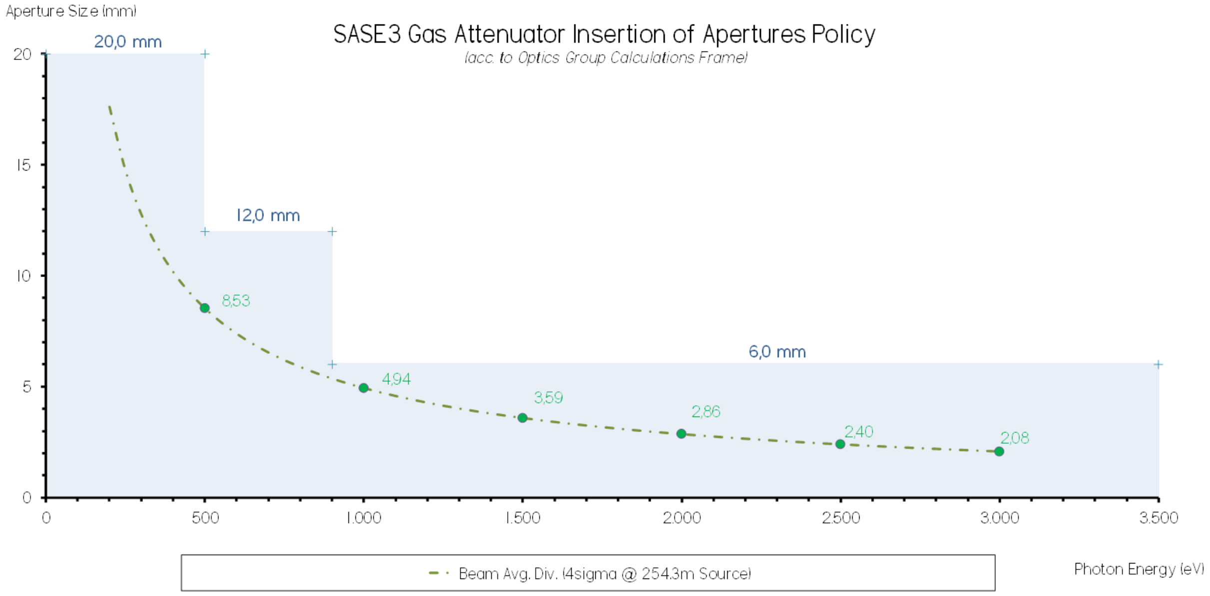
2.5 Clear aperture requirements

One of the key design aspects was enabling a large enough clear aperture for the beam passage for the whole photon energy operating range of the SASE3 beamline instruments.

In particular, the presence of 10 static apertures, in addition to four more that can be inserted simultaneously posed a challenge that required keen attention and a thoughtful estimation of all the mechanical tolerances necessary to define the discrete values of those four (two pairs of two different sizes).

In Figure 15, the calculated beam size (4σ) value variation along the photon energy range of the beamline is presented. The required values of 12 mm above 500 eV and 6 mm above 900 eV were agreed as a convenient compromise between the prevention of blockage of the beam passage and the necessary increase in the active gas pressure to provide the required attenuation level, still without compromising the stability of the vacuum pumping system due to excessive gas flow.

Figure 15: *Calculated FEL average beam size (in mm) dependence with the photon energy (in eV). The discrete 20, 12, and 6 mm aperture values are shown simultaneously.*



In Figure 16, it is shown the calculated gas flow variation that would be generated to maintain constant three orders of magnitude attenuation (0.1% transmission) for any photon energy that can be provided by the SASE3 undulators array.

Figure 16: *Gas flow variation over the whole SASE photon energy range when using the variable aperture system at a constant 0.1% transmission value*

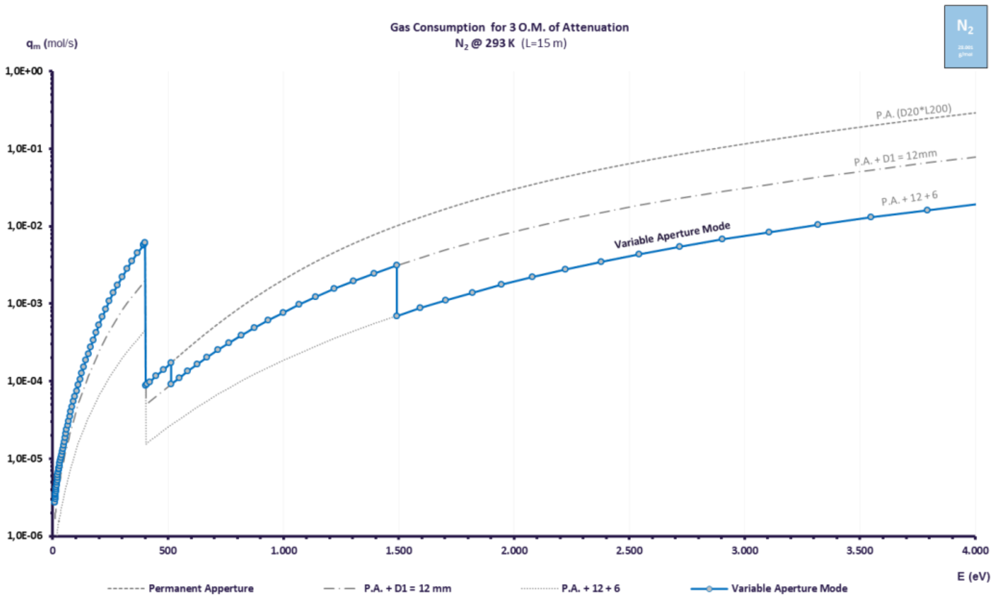


Figure 17 and Figure 18 show the different solutions developed in the system for both static and “dynamic” aperture system.

Figure 17: *Static 20 mm in vacuum aperture*

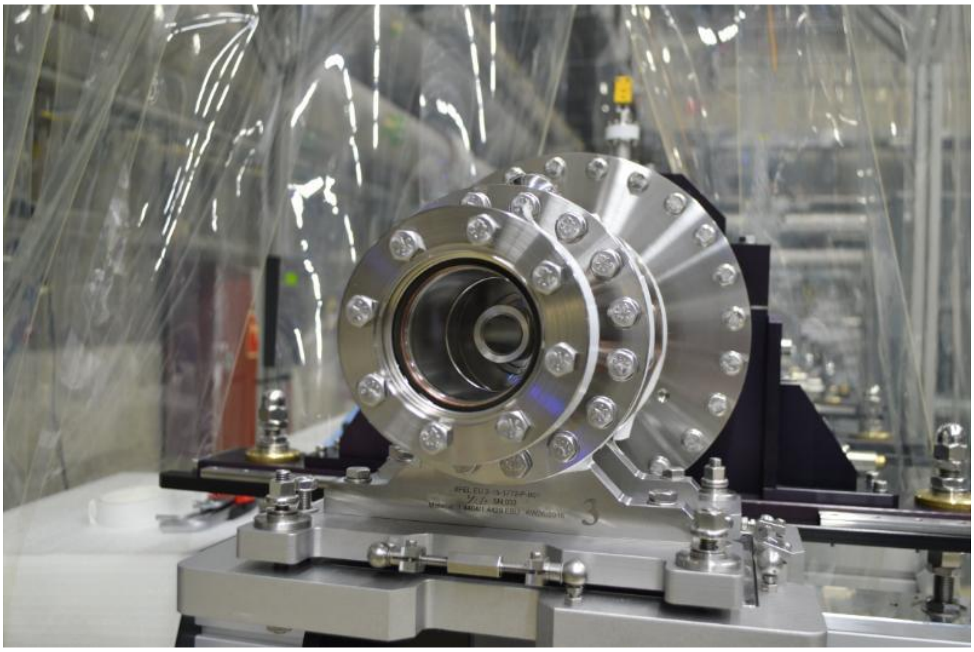
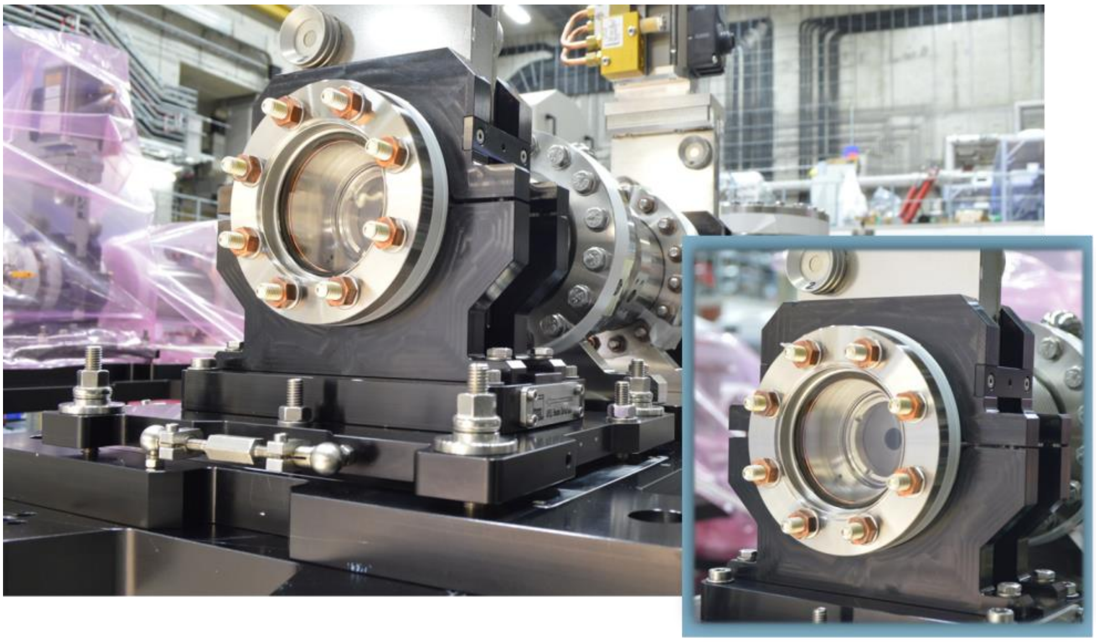


Figure 18: *“Dynamic” discrete aperture system*



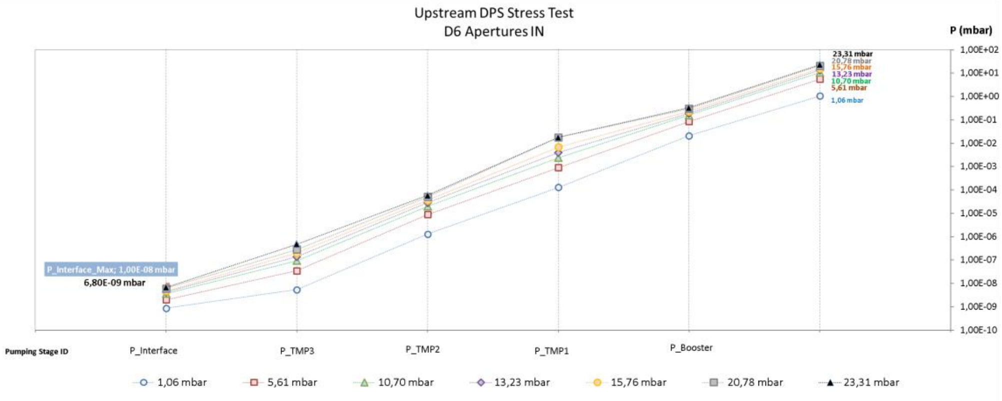
3 Operational constraints

3.1 Actual performance

After the commissioning phase that took place during the first quarter of 2018, it was clearly confirmed that the parameter dataset regarding the operation space of the component, established back in 2012, was achieved without major issues (see table 2). Since then, the almost 24/7 routine operation of the equipment has permitted a long term evaluation of the stability of all subsystems. The main conclusion drawn is that, in order to make the system work seamlessly, special attention must be paid to a careful definition of the logic signal flow. The developed schema(s) should serve to prevent the appearance of operation scenarios where instabilities derived from the demand of high gas flow in comparison with any other conventional vacuum sector may end up in a major incident.

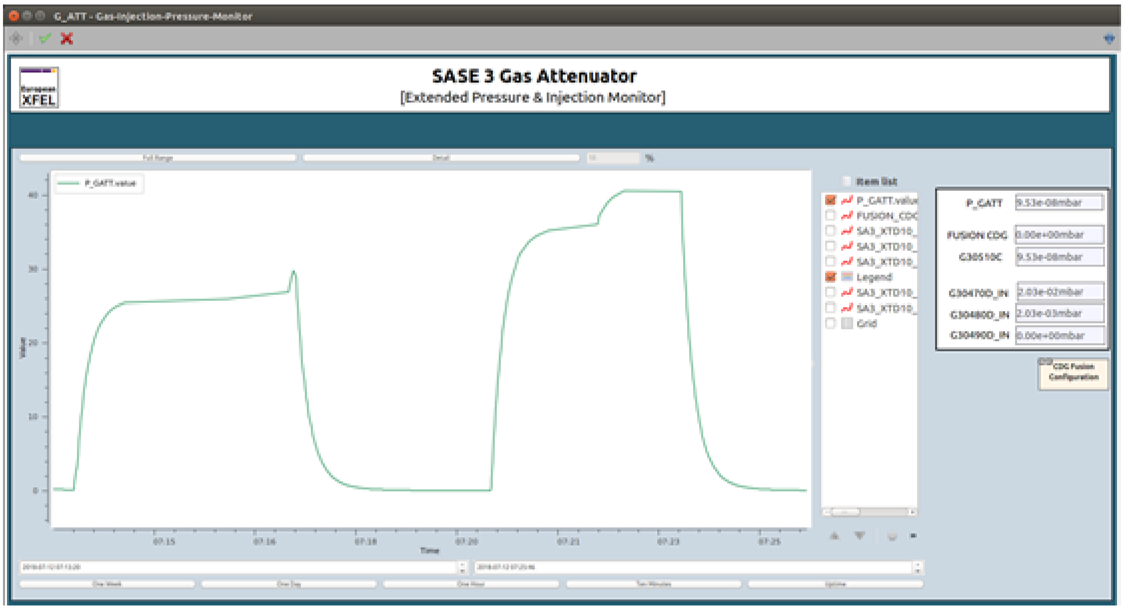
As an example, Figure 19 shows an extract of the results obtained with the stress tests campaign during the device commissioning phase. Notice here that the system fulfils the maximum pressure readout at the interface chamber for a pressure in the cell up to 23 mbar of N_2.

Figure 19: *Pressure profile on the upstream DPS under the stress test done during the device commissioning period*



Also, it is shown in Figure 20 that the measurement done at the active gas cell system at a pressure of up to 40 mbar of N_2 was achieved for a brief period. This was one of the first experimental qualifications of the capacities of the designed device:

Figure 20: *Stress cycle of the gas attenuator (captured from Karabo GUI)*

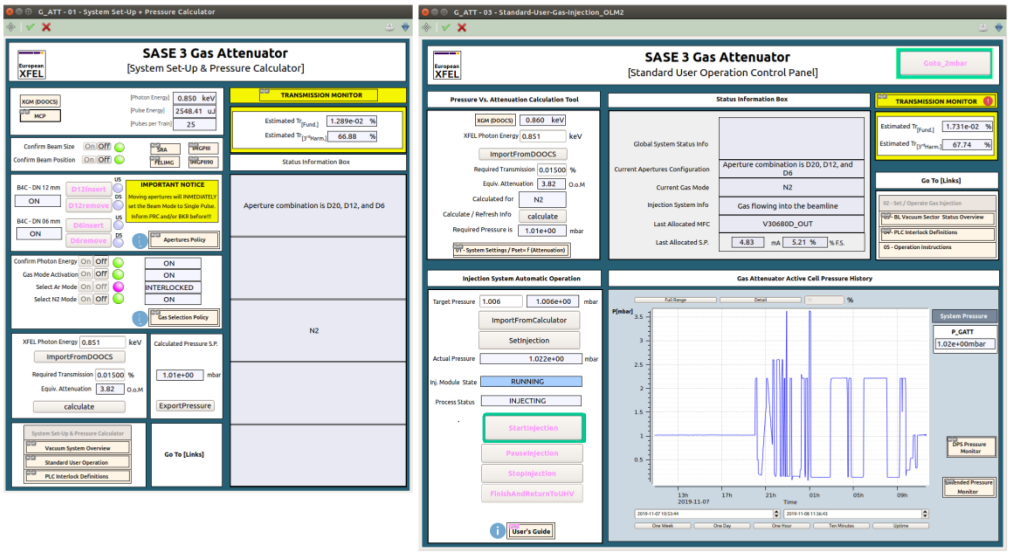


P_GATT 9.53e-08mbar
FUSION CDG 0.00e+00mbar
G30510C 9.53e-08mbar
G30470D_IN 2.03e-02mbar
G30480D_IN 2.03e-03mbar
G30490D_IN 0.00e+00mbar

3.2 Operability for non-experts

Beyond the technical aspects that represented the core of the design requirements, ease of use for end users was also considered a key element. The observation of this principle was kept from the very beginning and, once the system was technically commissioned, most of the efforts regarding controls were oriented to the development of an interface in which users would not need to act directly on the internal equipment in order to produce the required system response. In Figure 21, a capture of a current version of the Karabo screen is shown.

Figure 21: *Standard user operation GUI (Karabo) for the gas attenuator*



[Photon Energy] 0.850 keV
[Pulse Energy] 2548.41 uJ
[Pulses per Train] 25
Estimated Tr[Fund.] 1.289e-02 %
Estimated Tr[3rd Harm.] 66.88 %
Confirm Beam Size On Off
Confirm Beam Position On Off
B4C - DN 12 mm ON
B4C - DN 06 mm ON
IMPORTANT NOTICE: Moving apertures will INMEDIATELY set the Beam Mode to Single Pulse. Inform PRC and/or BKR before!!!
Aperture combination is D20, D12, and D6
Confirm Photon Energy On Off ON
Gas Mode Activation On Off ON
Select Ar Mode On Off INTERLOCKED
Select N2 Mode On Off ON
N2
XFEL Photon Energy 0.851 keV
Required Transmission 0.01500 %
Equiv. Attenuation 3.82 O.o.M
Calculated Pressure S.P. 1.01e+00 mbar

XGM (DOOCS) 0.860 keV
XFEL Photon Energy 0.851 keV
Required Transmission 0.01500 %
Equiv. Attenuation 3.82 O.o.M
Calculated for N2
Calculate / Refresh Info calculate
Required Pressure is 1.01e+00 mbar
Global System Status Info
Current Apertures Configuration: Aperture combination is D20, D12, and D6
Current Gas Mode: N2
Injection System Info: Gas flowing into the beamline
Last Allocated MFC: V30680D_OUT
Last Allocated S.P.: 4.83 mA 5.21 % %F.S.
Estimated Tr[Fund.] 1.731e-02 %
Estimated Tr[3rd Harm.] 67.74 %
Target Pressure 1.006 1.006e+00 mbar
Actual Pressure 1.022e+00 mbar
Inj. Module State RUNNING
Process Status INJECTING
P_GATT 1.02e+00mbar

Users just need to choose the required aperture size and the gas of interest among those available, and then input the specific transmission factor that is wanted. After that, only a single action is additionally required: to confirm the change of conditions in order to start the action. It is then that the state machine developed within the SCADA system takes over, initiating all the automatic sequences on the involved pieces of instrumentation, to finally obtain the desired system response.

To achieve this state of sophistication, a refinement of the interlock definition according to the previous explorations done during the commissioning phase was crucial.

This allowed the proper sequencing of the actions, as well as the vetoing of any other, depending on whether one or more required signals are or are not fulfilling the defined logic anymore. For more information about the use of the device, Ref. [11] and [12] are highly recommended.

3.3 Beamline vacuum system integrity

When taking into account the considerations depicted in Sections 3.1, “Actual performance”, and Section 3.2, “Operability for non-experts”, the definition of the interlock system should, at least, be considered to be highly effective in preventing any situation that could compromise the stability of the vacuum system. In particular, and from the point of view of the operation of the facility, an excessive pressure level at the interfacing vacuum sectors should be avoided at any time. This would trigger the so-called “*beam vacuum interlock*” signal that, at a final consequence, would close the shutter and eventually remove the beam permission for the north branch tunnels.

4 Gas attenuator safe operation concept

This chapter addresses the description of each of the main aspects that have been explicitly implemented as part of the safety interlock definitions. The goal is to provide a consistent operation of the gas attenuator instrument in all the possible scenarios. It includes not only operational restrictions but the necessary procedures to "anchor" the system to a safe state in case of undesired circumstances.

In general, the "gas attenuator safe operation concept" aims to limit the propagation of any issue or incident to a higher level of problems that could

- Compromise the continuous operation of the facility
- Prevent the mitigation of the issue in a reasonable short time

Up to five items were found to require particular attention regarding the scope of safe operation[3] of this particular instrument:

1. Defining a maximum gas pressure limit at the adjacent vacuum sector windowless interfaces
2. Securing and monitoring the integrity of the required vacuum pumping subsystems
3. Preventing any excessive gas flow conditions that could compromise items 1 and 2.
4. Protecting the mechanical components that could be exposed to the direct beam
5. Integrating within the SASE3 instrument photon beam shutter protection concept

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[3] In this document, the use of the "safe operation" concept is included without explicit reference to any of the formal definitions regarding the general facility protection systems, Machine Protection System (MPS) or Equipment Protection System (EPS). However, the general principles of both are indeed considered implicitly across all the development and, indeed, they have been proved to work consistently with those mentioned above, not only during the commissioning phase but also since then in the routine operation of the instrument.

4.1 Pressure limit at the vacuum sector interfaces

As an intrinsic part of the European XFEL photon beam transport vacuum system, the gas attenuator must fulfil some maximum allowable pressure condition at its interfaces with the adjacent sectors that secures a stable operation of the beam transport system. At the same time, it must also prevent that an excessive gas flow reaches upstream of its location, in such way as to not only compromise the proper operation of the instrumentation located there but also reach parts of the electron beam vacuum system.

In general, a 5×10^{-6} mbar (N_2 equivalent[4]) is defined as the usual trip point value for the conventional vacuum sector (usually equipped with ion getter pumps). This value is obviously far below the minimum required in the active gas cell of the gas attenuator for its specifications[5]. However, this value can be applied without further discussion right after the differential pumping sectors since they are dimensioned to provide an ultimate pressure below 1×10^{-7} mbar for any operation condition of the gas attenuator.

Based on this principle, and to add more reliability to the system, the overall definition relays in a redundant definition in which, if any of the two interfacing vacuum chambers reach a value above 5×10^{-6} mbar, this will be considered enough to assume that the system is out of normal operation and hence it should generate a consistent signal. This signal can then be integrated into the general vacuum interlock PLC system to produce the expected protective action.

Additionally, and with the goal to increase the system reliability against false triggers (i.e. gauge electronic spikes), the concept has been extended to the immediately adjacent pressure sensor towards the centre of the gas attenuator. Since these would be already be part of the last stage of each of

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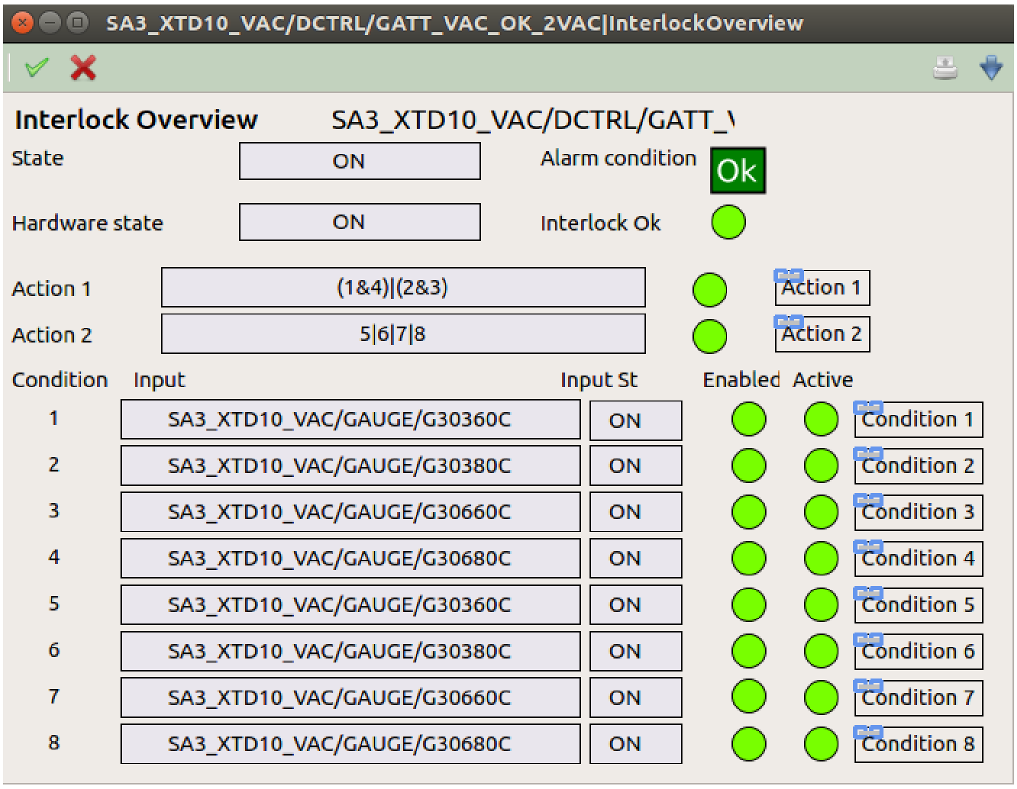
[4] From now on, if not stated otherwise, all the vacuum pressure values are defined as N_2 equivalent for convenience.

[5] As shown in Table 2, the gas attenuator can regulate pressure values down the 10^{-3} mbar range.

the mirror-like differential pumping sectors, a more restringing value of 5 x 10^{-5} mbar as a maximum trip point was proven to combine a still conservative approach with enough margin to detect real pressure rise incidents. This can be summarized as shown in the following GUI capture.

Figure 22: *Interlock overview scene for the variable “GATT_VAC_OK_2VAC”*



SA3_XTD10_VAC/DCTRL/GATT_VAC_OK_2VAC|InterlockOverview

Interlock Overview SA3_XTD10_VAC/DCTRL/GATT_\

State: ON

Alarm condition: Ok

Hardware state: ON

Interlock Ok: ●

Action 1: (1&4)|(2&3) ● Action 1

Action 2: 5|6|7|8 ● Action 2

Condition	Input	Input St	Enabled	Active	
1	SA3_XTD10_VAC/GAUGE/G30360C	ON	●	●	Condition 1
2	SA3_XTD10_VAC/GAUGE/G30380C	ON	●	●	Condition 2
3	SA3_XTD10_VAC/GAUGE/G30660C	ON	●	●	Condition 3
4	SA3_XTD10_VAC/GAUGE/G30680C	ON	●	●	Condition 4
5	SA3_XTD10_VAC/GAUGE/G30360C	ON	●	●	Condition 5
6	SA3_XTD10_VAC/GAUGE/G30380C	ON	●	●	Condition 6
7	SA3_XTD10_VAC/GAUGE/G30660C	ON	●	●	Condition 7
8	SA3_XTD10_VAC/GAUGE/G30680C	ON	●	●	Condition 8

Here one can also appreciate an extended set of conditions beyond what has been indicated until now. This corresponds to a general approach, also in use for the rest of the vacuum sectors, where not only the immediate change of the condition is considered but also a “long term” sustaining of the original issue. This second approach is summarized in the logic for the “Action 2” through the application of the so called “Filter Time”.

This parameter can be adjusted at the PLC level and allows the modification of the signal dwell period beyond the characteristic 10 ms cycle time in order to be considered within the PLC framework as a real change in the physical system. In this particular case, the conditions 5, 6, 7, and 8 make use of a Filter Time equal to 5000 ms. In the current version this signal has been declared as “SA3_XTD10_VAC/DCTRL/GATT_VAC_OK_2VAC”, and it has a physical digital output terminal associated with it[6].

4.2 Integrity of the vacuum pumping systems

When considering the vacuum equipment installed as part of the gas attenuator instrument, three main aspects must be considered:

1. The vacuum generation equipment has to be able to deal with a large gas flow when the process gases are introduced in the active gas cell.
2. It has to deliver the progressive pressure reduction in order to achieve a pressure below the previously indicated maximum allowable values at each vacuum sector interface.
3. It is capable of providing UHV conditions across the whole instrument if no attenuation is required.

In general, and as described previously, this could bring to up to 9 orders of magnitude pressure difference across the different chamber system of the instrument, and therefore make explicit the need that the many subsystems work as one.

This is particularly relevant for cases number 1 and 2 (gas is injected in the active gas cell). For the second case, is not critical since in case of a multi-device failure, its effect will be propagating from the single item until eventually the conditions explained in Section 4.1, “Pressure limit at the vacuum sector ”, will cease, hence raising the interlock condition and the predefined system response.

Either way, it was decided to generate a single signal that continuously monitors not only pumps, but any relevant piece of instrumentation that in

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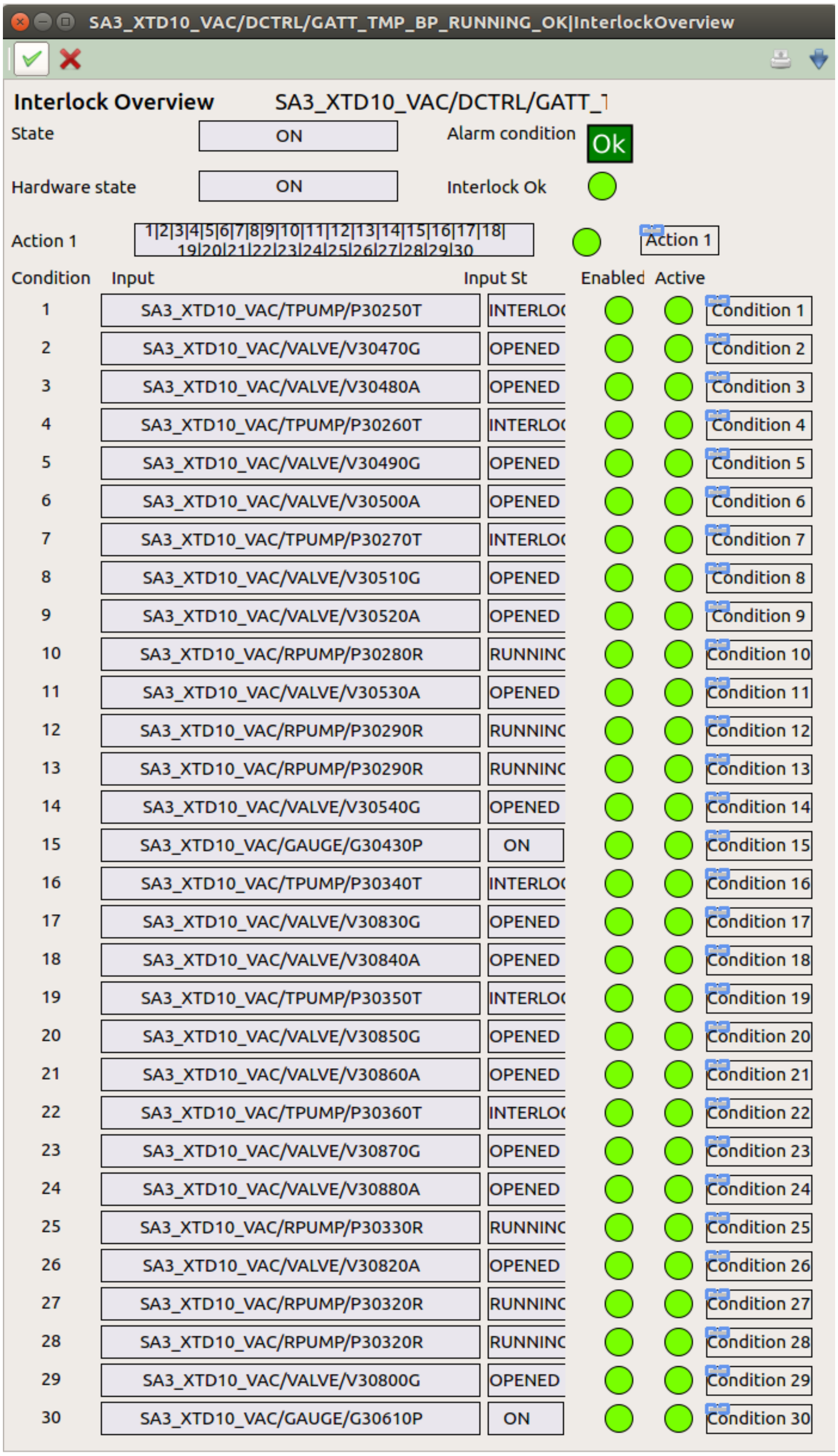
[6] NOTE: for all the signals declared as part of the Gas Attenuator Interlock system, a physical terminal has been associated, even if there is not a physical device connected to it. In general, this is part of a general policy in order to facilitate in case of need a direct wired connection (“hardwiring”) to transfer that information to any other PLC system without using the so called “inter-loop” communication.

case of not being working properly (i.e. a valve is closed when it should not) will be explicitly acknowledged.

This is shown in Figure 23. The logic is rather simple, as can be seen there, where it can be summarized as, if any of the 30 conditions is not fulfilled, the signal “SA3_XTD10_VAC/DCTRL/GATT_TMP_BP_RUNNING_OK”, will be set to a positive logic value of “0” (or logic “OFF”).

The output of this digital output can then be fed again as an input to the interlock system to trigger any other action (for more information, see Section 5.3, “Pumping system integrity ”, Section 5.5, “Permission for operation with gas ”, and Section 5.7, “Automation of the pump purge gas exchange ”).

***Figure 23:** Interlock overview scene for the variable “GATT_TMP_BP_RUNNING_OK”.*



SA3_XTD10_VAC/DCTRL/GATT_TMP_BP_RUNNING_OK|InterlockOverview

Interlock Overview SA3_XTD10_VAC/DCTRL/GATT_T

State: ON

Alarm condition: Ok

Hardware state: ON

Interlock Ok: ●

Action 1: 1|2|3|4|5|6|7|8|9|10|11|12|13|14|15|16|17|18|19|20|21|22|23|24|25|26|27|28|29|30 ● Action 1

Condition	Input	Input St	Enabled	Active	
1	SA3_XTD10_VAC/TPUMP/P30250T	INTERLOC	●	●	Condition 1
2	SA3_XTD10_VAC/VALVE/V30470G	OPENED	●	●	Condition 2
3	SA3_XTD10_VAC/VALVE/V30480A	OPENED	●	●	Condition 3
4	SA3_XTD10_VAC/TPUMP/P30260T	INTERLOC	●	●	Condition 4
5	SA3_XTD10_VAC/VALVE/V30490G	OPENED	●	●	Condition 5
6	SA3_XTD10_VAC/VALVE/V30500A	OPENED	●	●	Condition 6
7	SA3_XTD10_VAC/TPUMP/P30270T	INTERLOC	●	●	Condition 7
8	SA3_XTD10_VAC/VALVE/V30510G	OPENED	●	●	Condition 8
9	SA3_XTD10_VAC/VALVE/V30520A	OPENED	●	●	Condition 9
10	SA3_XTD10_VAC/RPUMP/P30280R	RUNNING	●	●	Condition 10
11	SA3_XTD10_VAC/VALVE/V30530A	OPENED	●	●	Condition 11
12	SA3_XTD10_VAC/RPUMP/P30290R	RUNNING	●	●	Condition 12
13	SA3_XTD10_VAC/RPUMP/P30290R	RUNNING	●	●	Condition 13
14	SA3_XTD10_VAC/VALVE/V30540G	OPENED	●	●	Condition 14
15	SA3_XTD10_VAC/GAUGE/G30430P	ON	●	●	Condition 15
16	SA3_XTD10_VAC/TPUMP/P30340T	INTERLOC	●	●	Condition 16
17	SA3_XTD10_VAC/VALVE/V30830G	OPENED	●	●	Condition 17
18	SA3_XTD10_VAC/VALVE/V30840A	OPENED	●	●	Condition 18
19	SA3_XTD10_VAC/TPUMP/P30350T	INTERLOC	●	●	Condition 19
20	SA3_XTD10_VAC/VALVE/V30850G	OPENED	●	●	Condition 20
21	SA3_XTD10_VAC/VALVE/V30860A	OPENED	●	●	Condition 21
22	SA3_XTD10_VAC/TPUMP/P30360T	INTERLOC	●	●	Condition 22
23	SA3_XTD10_VAC/VALVE/V30870G	OPENED	●	●	Condition 23
24	SA3_XTD10_VAC/VALVE/V30880A	OPENED	●	●	Condition 24
25	SA3_XTD10_VAC/RPUMP/P30330R	RUNNING	●	●	Condition 25
26	SA3_XTD10_VAC/VALVE/V30820A	OPENED	●	●	Condition 26
27	SA3_XTD10_VAC/RPUMP/P30320R	RUNNING	●	●	Condition 27
28	SA3_XTD10_VAC/RPUMP/P30320R	RUNNING	●	●	Condition 28
29	SA3_XTD10_VAC/VALVE/V30800G	OPENED	●	●	Condition 29
30	SA3_XTD10_VAC/GAUGE/G30610P	ON	●	●	Condition 30

4.3 Avoidance of excessive gas flow scenarios

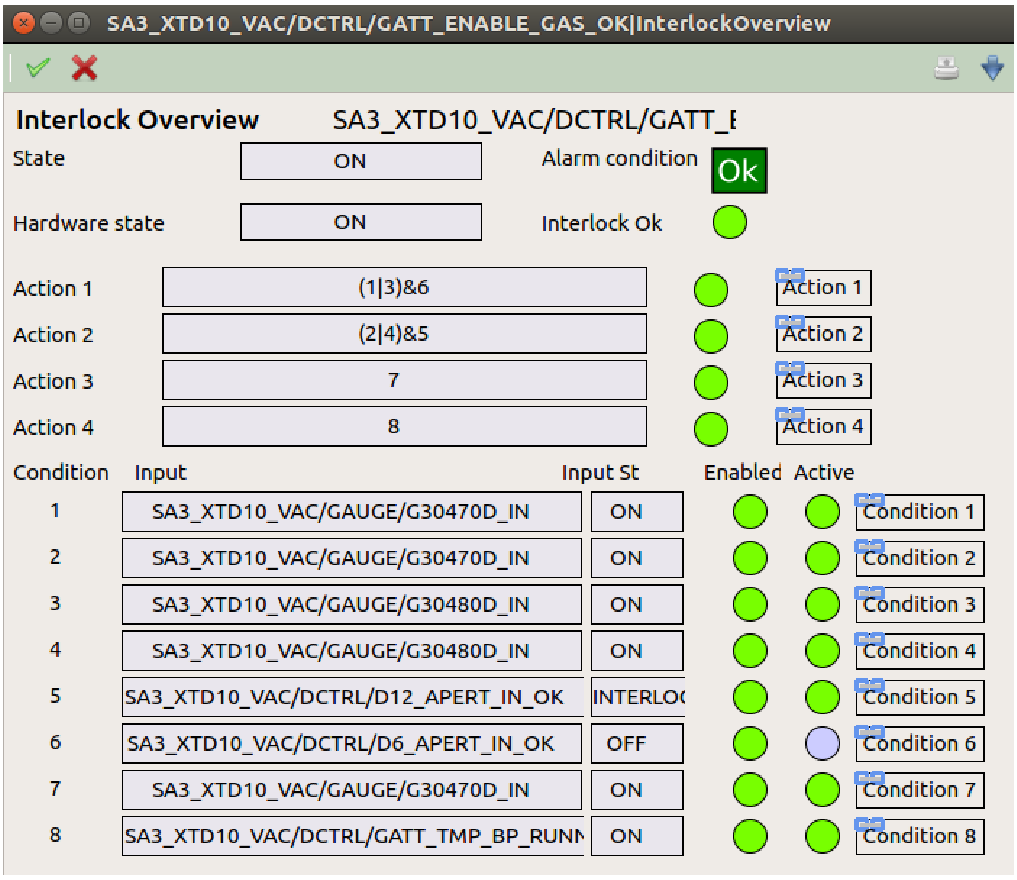
As a direct consequence of the parameter space that was requested during the design phase of the instrument, there are scenarios where the gas flow rate could be extraordinarily large for a conventional vacuum system.

In particular, the combination of the required large optical apertures (up to 20 mm)—providing a relatively large attenuation factor when using a gas whose nearest absorption edge (optimal attenuation efficiency) is far from the actual FEL beam wavelength, and therefore requiring higher pressure levels—could lead to excessive stress for the vacuum pumping system. As a consequence, an abrupt failure is not desired and must be prevented. To do it, valuable information was extracted during the commissioning phase, where multiple stress tests were performed.

After a careful evaluation, the technical conclusions were consolidated in a strict combination of required aperture size and maximum allowable pressure in the active gas cell. Those values were also checked against the required clear aperture and the 0.1% transmission (three orders of magnitude) threshold stated as available at any photon energy, confirming the feasibility of the required instrument performance. The current allowed gas pressure and flow limiting aperture size is shown in Table 3 in Section 4.4, “Insertion/removal of flow-limiting discrete ”.

In Figure 24, the respective implementation of the interlock variable “SA3_XTD10_VAC/DCTRL/GATT_ENABLE_GAS_OK” is shown. Here it can be appreciated the two group of components involved in its definition: pressure sensors (G30470D, G30480D and G30490D) as well as internal PLC signals that multiplex the position indication of the respective two end switches involved for each pair of apertures (“D12_APERT_IN_OK” and “D6_APERT_IN_OK”).

Figure 24: *Interlock overview scene for the variable “GATT_ENABLE_GAS_OK”*



SA3_XTD10_VAC/DCTRL/GATT_ENABLE_GAS_OK|InterlockOverview

Interlock Overview SA3_XTD10_VAC/DCTRL/GATT_E

State	ON	Alarm condition	Ok
Hardware state	ON	Interlock Ok	●

Action 1	(1|3)&6	●	Action 1
Action 2	(2|4)&5	●	Action 2
Action 3	7	●	Action 3
Action 4	8	●	Action 4

Condition	Input	Input St	Enabled	Active	
1	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	●	●	Condition 1
2	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	●	●	Condition 2
3	SA3_XTD10_VAC/GAUGE/G30480D_IN	ON	●	●	Condition 3
4	SA3_XTD10_VAC/GAUGE/G30480D_IN	ON	●	●	Condition 4
5	SA3_XTD10_VAC/DCTRL/D12_APERT_IN_OK	INTERLO	●	●	Condition 5
6	SA3_XTD10_VAC/DCTRL/D6_APERT_IN_OK	OFF	●	○	Condition 6
7	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	●	●	Condition 7
8	SA3_XTD10_VAC/DCTRL/GATT_TMP_BP_RUN	ON	●	●	Condition 8

4.4 Insertion/removal of flow-limiting discrete apertures

Another relevant aspect of the regular operation of the gas attenuator is the need to change between the different sizes of clear aperture available. In particular the rule of selection for this purpose has been summarized in Table **3**.

Table 3: *Summary of the allowed aperture size – pressure in the active cell for the gas attenuator.*

FEL photon energy	**4σ larger nominal[7] beam size**	**Usable aperture size**	**Maximum N_2 pressure in the active gas cell**
$E_{ph} \leq 500$ eV	4σ ≤ 8.5 mm	20, 12, or 6 mm	≤ 0.5 mbar
$500 < E_{ph} \leq 900$ eV	5.8 ≤ 4σ ≤ 8.5 mm	12 or 6 mm	≤ 2.0 mbar
$E_{ph} \geq 900$ eV	4σ ≤ 5.8 mm	only 6 mm	≤ 15[8] mbar

Where, in order to cope with the technical requirement exposed in Section 4.3, “Avoidance of excessive gas flow ”, the current pressure limit (only for Nitrogen) is also shown for each scenario.

Considering the mechanical design of the insertion device, (based on a standard gate valve for each of the two pairs of apertures, respectively 6 a 12 nominal diameter[9]), it is important to prevent that the beam hits anything else but the area where the boron carbide (B4C) aperture disk is installed.

This means that, when they are moving either in or out from the beam, ideally no pulse should illuminate them. For that purpose, the variable “SA3_XTD10_VAC/DCTRL/GATT_APER_OK_2EPS” has been implemented.

It picks up a simple concept:

“*if there is a single aperture actuator (valve) not fully positioned, either completely inserted (“Closed”) or completely removed (“Opened”) from the beam path, the above mentioned variable will be set to a value of “0*”.

Because the associated Digital Output terminal to this signal is hardwired to a Digital Input terminal from the EPS PLC loop existing in an adjacent crate, the

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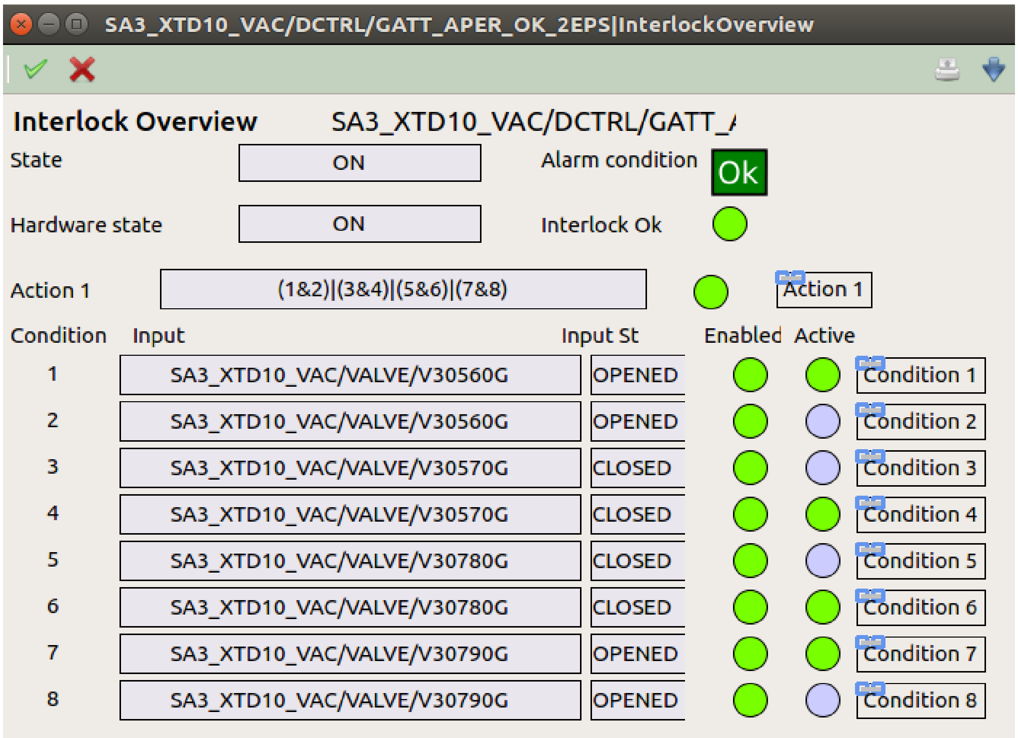
[7] All the cases have been explored and quantified thoroughly and all fulfil the required clear aperture required for the beam passage, confirming that the 4σ nominal estimation has indeed some upper margin. That is indeed the reason to have the 6 mm aperture as condition to operate the system with pressure higher than 2.5 mbar when the E_{ph} is above 900 mm, despite the nominal estimation would should a smaller clearance margin.

[8] System has been tested up to 35 mbar. Higher values approaching this maximum will be evaluated progressively and enabled if needed.

[9] The 20 mm apertures are indeed of the “static” type: they are in-vacuum short tubes and represent the default reference for clear aperture of the complete vacuum sector.

signal will be directly transmitted as an input to the accelerator safety system. Once there, and depending on the current status of the interlock definition (different from the one here explained) a specific action can be triggered. For instance, it could force the accelerator to single pulse mode until the value is automatically set back to “1” once the aperture(s) are back to their respective engaged positions.

Figure 25: *Interlock overview scene for the variable “GATT_APER_OK_2EPS”*



SA3_XTD10_VAC/DCTRL/GATT_APER_OK_2EPS|InterlockOverview

Interlock Overview SA3_XTD10_VAC/DCTRL/GATT_

State: ON

Alarm condition: Ok

Hardware state: ON

Interlock Ok: ●

Action 1: (1&2)|(3&4)|(5&6)|(7&8) ● Action 1

Condition	Input	Input St	Enabled	Active	
1	SA3_XTD10_VAC/VALVE/V30560G	OPENED	●	●	Condition 1
2	SA3_XTD10_VAC/VALVE/V30560G	OPENED	●	○	Condition 2
3	SA3_XTD10_VAC/VALVE/V30570G	CLOSED	●	○	Condition 3
4	SA3_XTD10_VAC/VALVE/V30570G	CLOSED	●	●	Condition 4
5	SA3_XTD10_VAC/VALVE/V30780G	CLOSED	●	○	Condition 5
6	SA3_XTD10_VAC/VALVE/V30780G	CLOSED	●	●	Condition 6
7	SA3_XTD10_VAC/VALVE/V30790G	OPENED	●	●	Condition 7
8	SA3_XTD10_VAC/VALVE/V30790G	OPENED	●	○	Condition 8

4.5 Integration with SASE3 instrument shutter operation

The robustness and reliability of the gas attenuator device has been also brought under long-term testing conditions during almost two years due to an unexpected operation requirement. In particular, after the SASE3 beamline commissioning phase, it was clear that the beam shutter safety concept would be compromised under specific conditions of beam power and focusing.

This situation led to a revision of the different devices initially involved and the overall safety concept for this particular beamline. The implementation and certification process of the new safety system is to be finished by the first quarter of 2020. In order to continue the scientific program of both instruments SQS and SCS during this period, an interim solution was approved and brought under successful operation. In particular, the underlying idea was to prevent illuminating any of the instrument beam shutters if the FEL beam was not extremely attenuated. For that, the gas attenuator was working on a 24/7 mode either being used within its initial scope or in a “passive” mode of attenuation (with a constant 2 mbar pressure setpoint of Nitrogen) when the beam was not in use in any of the instrument hutches.

For more information, the concept for this temporary solution can be found in Ref. [13].

5 Interlock system synoptic maps

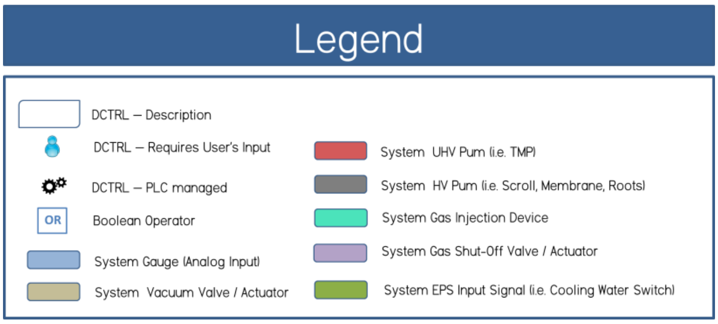
This chapter consolidates the understanding of the actual interlock implementation. A graphical representation of the logic dataflow has been chosen as the most adequate method to achieve this purpose.

Since the system has evolved almost naturally towards a situation where multiple interactions among those signals take place, the presentation has been split in different sections in which each of them is grouped as a consistent entity:

- Section 5.1, "Individual device status control and protection"
- Section 5.2, "Vacuum sector interlock"
- Section 5.3, "Pumping system integrity control"
- Section 5.4, "Safe insertion of dynamic apertures"
- Section 5.5, "Permission for operation with gas injection"
- Section 5.6, "Management of the gas supply manifold"
- Section 5.7, "Automation of the pump purge gas exchange process"
- Section 5.8, "Operation of the mass spectrometer"

Due to the size of some of the produced schemes, it is highly recommended to obtain the high-resolution version of them. This is available in the appendix to this document. The legend for the different symbols and colours used in the synoptic maps is shown in Figure 26.

***Figure 26:** Legend for the gas attenuator interlock maps*



5.1 Individual device status control and protection

Despite the complex appearance of Figure 27, the reader can quickly see the interaction and information flow between the different devices involved. Also, an indication of the current values that trigger a given action for each of them is included. The most relevant aspects are succinctly explained below.

5.1.1 Turbo pumps

In terms of status control for the turbomolecular pumps available in the gas attenuator, the principles of surveillance are:

- The pump controller is not in error.
- The pump is running above a given rotation speed threshold that keeps a reasonable compression ratio for gases heavier than 20 amu.

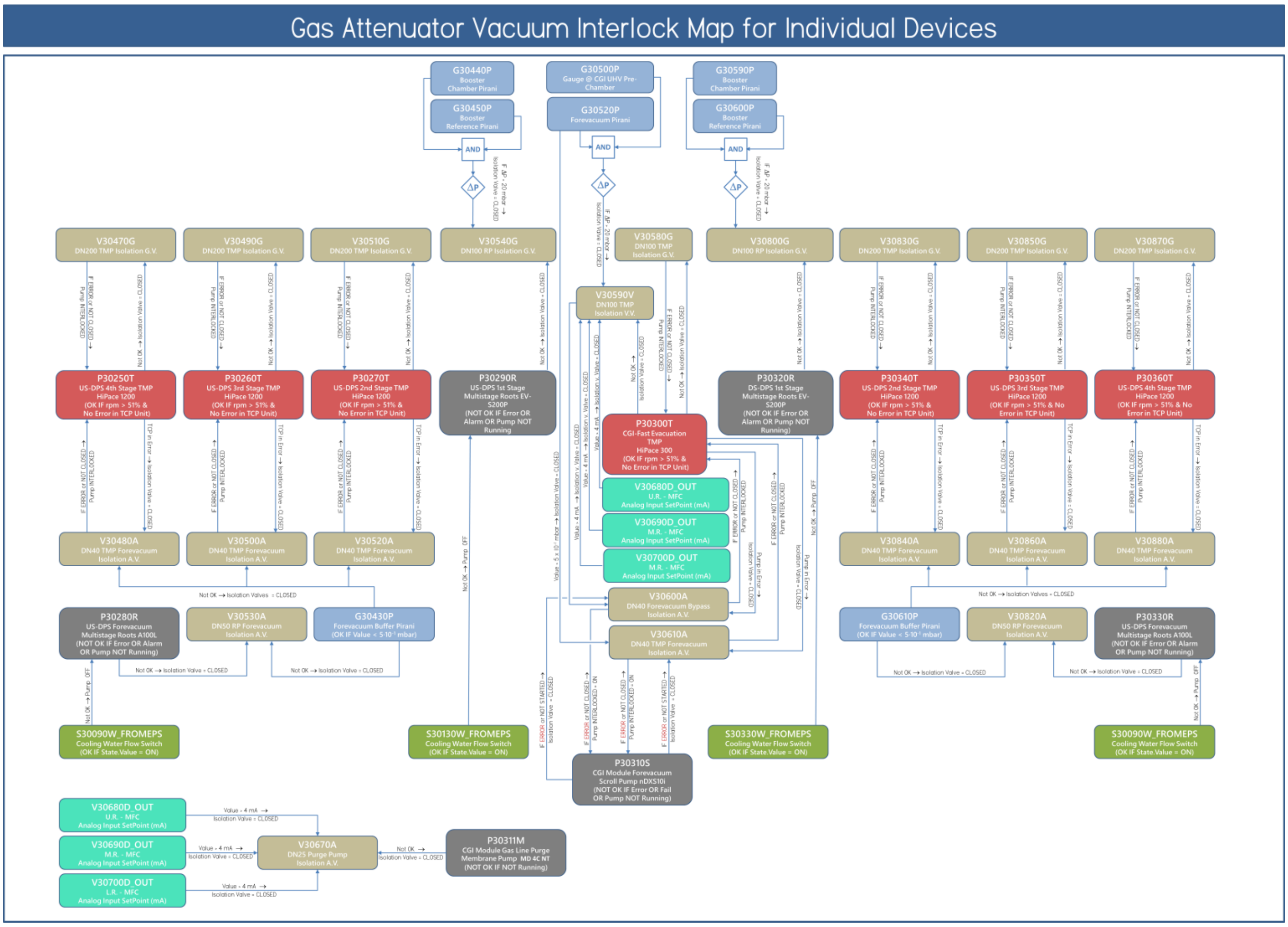
If any of these conditions cease to be true for a particular device unit, the action to be triggered would be its complete isolation from the rest of the vacuum system by means of the corresponding UHV gate valve at the beamline side and high vacuum (HV) angle valve at the forevacuum side.

The operator may try to troubleshoot and solve the issue. If successful, the system can be brought to normal operation status: the error status is acknowledged and set back, the pump is usually returned to full rotational speed condition, and then the isolation valves can be reopened.

Otherwise, it would be expected that the pump should be decommissioned, the control device disabled and the pump, once it has been isolated, vented with dry nitrogen in order to prevent the potential migration of oil vapors towards de UHV side.

Although not shown, the remote venting of the pump can only be enabled if the pumps is fully isolated (i.e. all the surrounding valves are closed).

Figure 27: *Interlock map overview for individual devices*



All the turbomolecular pumps installed in the gas attenuator are equipped with a solenoid-controlled venting valve and an active connection to the N_2 supply system (5.0 purity grade) by means of a conditioning manifold that delivers the inert gas at a nominal reduced pressure of 0.2 bar(g) and prevents any migration of oil vapour and/or particles towards the main line.

5.1.2 Vacuum valves

As shown for the turbomolecular pumps, most of the involved vacuum valves are intrinsically connected to the status of this particular vacuum pumping equipment. In particular, they will close automatically if their associated pump is in error, not running, or running below a given minimum speed threshold.

For some others, i.e. those related to the forevacuum side, one could find two main cases:

- Angle valves that follow up only the default “normal” status of their associated pump operation: pump is running and without any error.
- Angle valves that prevent that an excessive forevacuum pressure may reach the associated turbopumps.

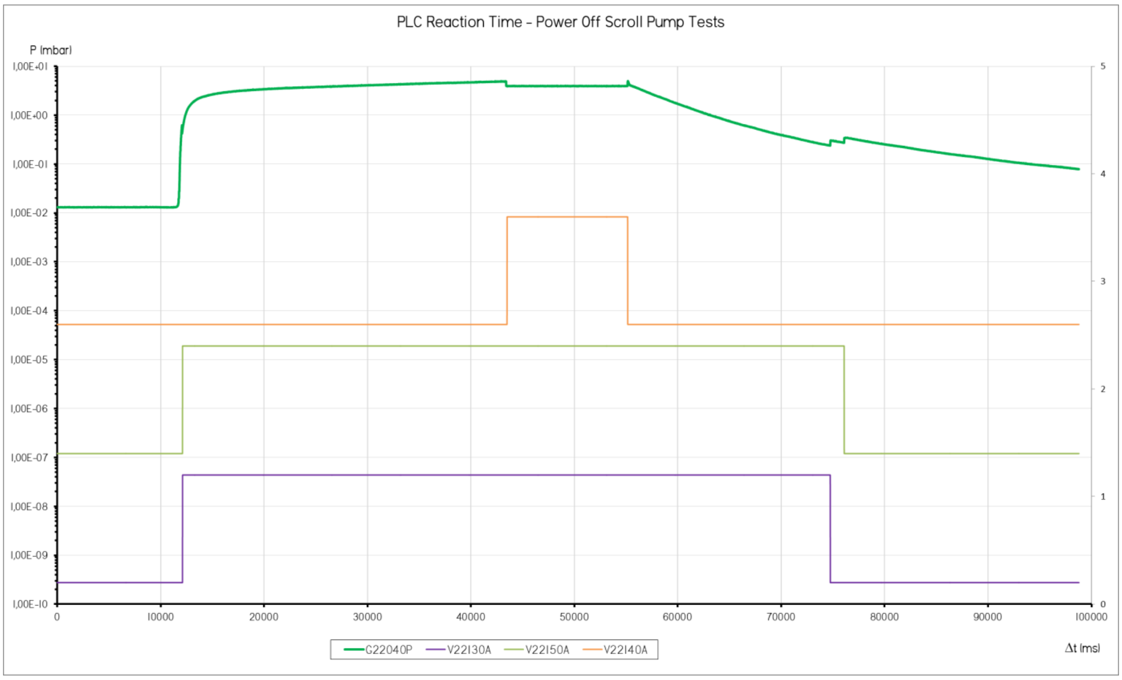
This second case includes extreme cases as a sudden inrush of gas that has been proven to work in such way that, with the current definition, the issue does not escalate and affect the beamline vacuum UHV.

A capture of one of the many tests done where a scroll pump power line was abruptly disconnected is shown in Figure 22. In this particular case, it is well known that, if this happens, the pre-compressed gas within the pump body will lead to an equilibrium pressure in the order of 10–20 mbar. Based on this fact, the test consisted in proving that with a 0.5 mbar setpoint to trigger the closure of the respective isolation valves below each turbomolecular pump, the pressure wave will neither affect the operation of the pumps nor lead to any major disturbance (i.e. due to ballistic propagation of a shockwave through the blades of the pump) in the UHV side of the system.

Another specific case is that one that could affect the isolation valve of the necessary large gas-flow–capable pumps installed in the corresponding first stages of both upstream and downstream differential pumping subsystems. Since these valves are UHV gate valves, their operation is subjected to a strict limitation on pressure difference across their two sides. This limit is 20 mbar and is constantly monitored by a pair of vacuum gauges, whose analog outputs are computed by the PLC and compared against the above-mentioned setpoint, preventing their actuation if is this condition is not fulfilled.

Finally, it is also worth mentioning the applied definition for the protection of the specific turbomolecular pump located in the middle of the active gas cell. Apart from the previously explained conditions, this particular item is also isolated from the UHV beamline anytime one of the gas flow regulating devices (in this case, a mass flow controller) is actuated. The reason for this is to prevent overloading it when gas is injected during the normal operation mode of the device, while keeping the pump at full speed to minimize the evacuation time when a “transparent” mode in the active gas cell is required. As shown in the P&ID representation (see Figure 8), this is achieved using a specific valve manifold configuration where the CGI module offers different paths depending on the gas flow requirements (injection or evacuation).

Figure 28: *Record of the power-off test from the control PLC data logger*



5.1.3 Forevacuum pumps

When considering those pumps whose main purpose is to generate the necessary forevacuum pressure levels for the correct operation of UHV-type pumps, the interlock scheme is relatively simple but effective. As stated in Section 5.1.2, “Vacuum valves”, there is always a HV vacuum valve above them. Besides the conditions for those valves’ operation explained earlier, the status of this pump is always monitored by the PLC system.

Depending on the pump requirements for normal operation (i.e. air- or water-cooled, etc.), it is considered that the pump is out of normal status when

- There is no power
- Pump is in error
- Pump is in alarm

- Pump is not running
- There is no cooling water flowing

In the gas attenuator, only two types of rough vacuum pumps are used: scroll and multistage roots (without a boosting stage). The first type is air-cooled; the second requires a supply of cooling water. It is only for this second case that the last condition is applicable.

Since all these conditions are monitored using digital signals, only pump models with this type of communication interface and with status output are used as part of any of the fore-vacuum systems present in the gas attenuator.

5.1.4 Multi-stage root booster pumps

Together with those rough pumping solutions used as part of the fore-vacuum systems, the gas attenuator implements two high-flow capacity–boosting pumps (water-cooled) in each of the corresponding first stages of the differential pumping systems.

These elements are critical to fulfil the highly demanding flow specifications of the device, in particular for some specific cases of required pressure and beam clear aperture. Therefore, their operation in normal conditions is carefully observed.

Since they are connected directly to the beamline, they must be properly isolated from it when

- There is no power
- Pump is in error
- Pump is in alarm
- Pump is not running
- There is no cooling water flowing.

In any of these cases, the system will prevent the opening of their corresponding isolation valves.

5.1.5 Cooling water

In the gas attenuator, the cooling water infrastructure is used for the refrigeration of

- Turbomolecular pumps
- Root pumps

The interface between the general installation and the point of use is implemented by means of custom-made distribution manifolds. Each of them is adapted to the needs of a specific subsystem.

In any case, the all share the following features:

- Temperature monitoring of the cooling water inlet (common for all the devices connected to a single manifold)
- Temperature monitoring of the cooling water outlet for each individual device
- Minimum flow detection for each individual device
- Valve manifold for operation of each individual circuit branch

In general, all the devices in use also monitor their own temperature status, and some of them also detect that the minimum water flow is present, raising an alarm/error flag if the limits for normal operation are exceed / not achieved, respectively.

However, it was decided to add independent monitoring redundancy that allows the anticipation of excessive thermal stress. Again, a conservative approach has been used, and the control system reacts immediately if the cooling water flow switches are triggered when the flow value is below the minimum setpoint.

Regarding to the temperature sensors, they are not directly used as interlock signals, but in general they provide the necessary information for further investigation in case of malfunction of the cooling system.

5.1.6 Gas supply lines vacuum module

In order to operate the system in optimal conditions, the implementation of a vacuum subsystem devoted to the conditioning of the gas supply lines was considered.

This system makes it possible to

- Maintain the cleanliness of the gas delivery lines
- Proceed with the necessary gas species exchange

It is technically implemented by means of a membrane pump, an HV angle valve, and the necessary manifold for the array of high-purity gas valves.

In general, the system is robust enough to handle any situation of malfunctioning, and the physical integrity for overpressure scenarios is secured by means of passive elements (i.e. using burst discs). However, the situation where the path between the gas supply lines and the mass flow controllers is not fully isolated from the pump during normal injection procedures could lead to a situation where the required conditions for the whole device may not be achieved.

For this reason, if any of the mass flow controllers (all of them normally closed) is set to a value different from passive (input current different from 0 mA), it leads to the automatic closure of the pump isolation valve. On the other hand, and following the same approach already seen for the fore-vacuum pump, if the existing membrane pump is not running or is in error, the valve remains closed.

More details about the way that this system operation is controlled are provided in Section 5.5, “Permission for operation with gas ”, Section 5.6, “Management of the gas supply ”, and Section 5.7, “Automation of the pump purge gas exchange ”.

5.2 Vacuum sector interlock

Like any other beamline vacuum sectors, those in which a module of the gas attenuator device is present have to interact harmonically with the general vacuum system interlock concept.

In general terms, a beamline vacuum sector is comprised of at least the following elements:

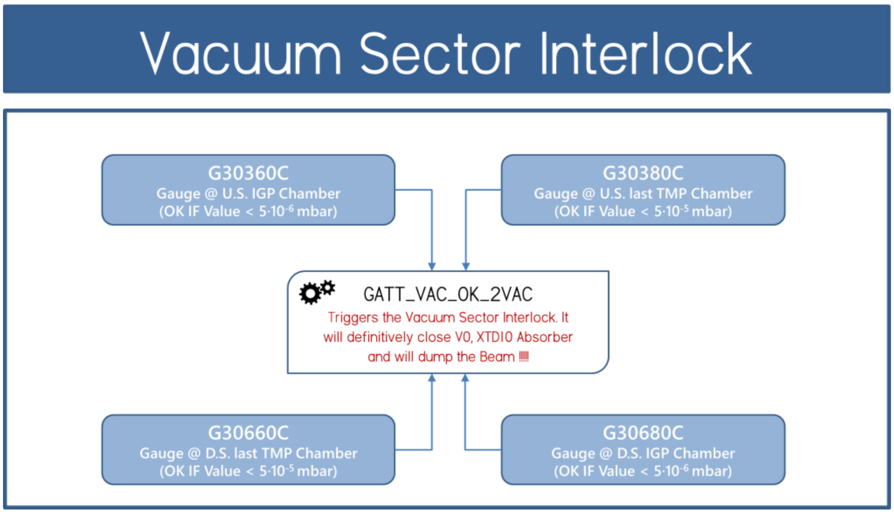
- One vacuum chamber
- One vacuum pump
- Two isolation UHV inline gate valves

The explanation of the overall vacuum system logic exceeds the scope of this document. In any case, it is sufficient to mention that each vacuum sector should provide a signal about its status (i.e. "*Vacuum OK*" signal), indicating whether it is running under the expected performance conditions.

For the case of the gas attenuator, the signal "GATT_VAC_OK_2VAC" is the one that plays this role. Due to the complexity and size of this device control system, it is implemented in a different PLC machine from the one used for the rest of the SASE3 vacuum control system. Therefore this signal is transferred to the latter via hardwiring and is received as "GATT_VAC_OK" to then be used as any other vacuum sector status signal.

As shown in Figure 29, the physical conditions that control the ON/OFF status value of "GATT_VAC_OK_2VAC" are based on the pressure readouts of some of the multiple gauges present in the gas attenuator beamline modules. In particular, it makes use of those installed in the last chamber on each of the differential pumping modules, together with the gauges available on each ion getter pump chamber on the device side.

***Figure 29**: Interlock logic map for the “GATT_VAC_OK_2VAC”*

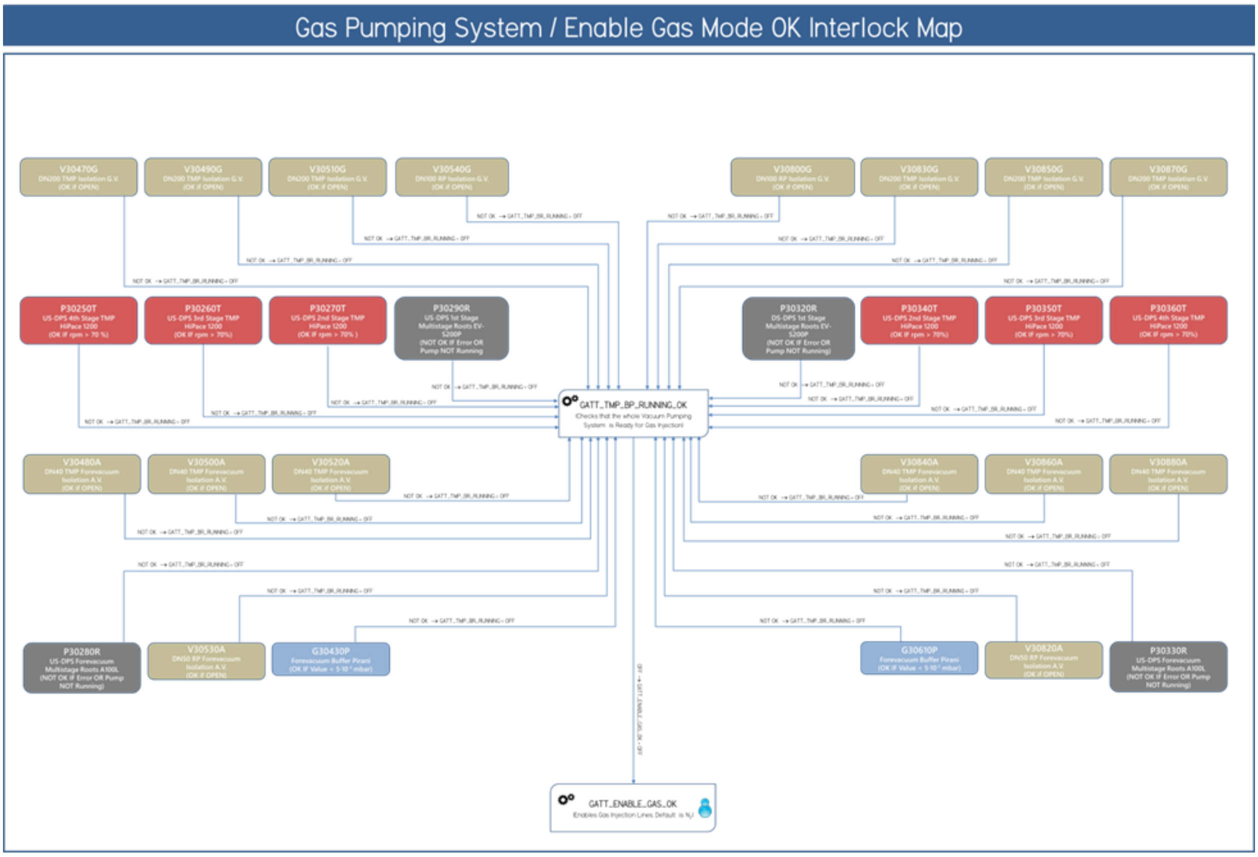


In order to choose the most adequate pressure thresholds, a thorough commissioning of the system was done in a way that allows the most demanding operating scenarios for the pumping system without compromising the expected vacuum performance integrity at the surrounding beamlines. The details are explained in Section 4.1, “Pressure limit at the vacuum sector ”.

5.3 Pumping system integrity control

Figure 30 shows the general scheme of information flow to determine the status of the vacuum pumping system. It can be clearly seen that the signal “GATT_TMP_BP_RUNNING_OK” surveys every valve and pump required for sustaining the operation of the device for instance when gas is injected.

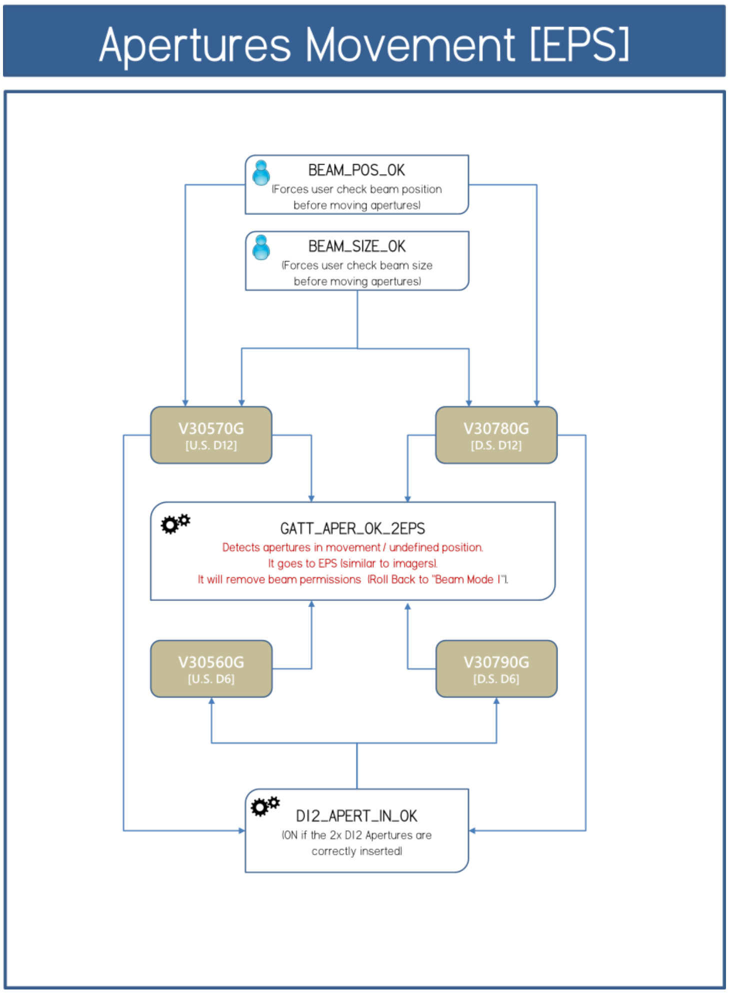
***Figure 30:** Interlock logic map for the “GATT_TMP_BP_RUNNING_OK” signal*



5.4 Safe insertion of dynamic apertures

As explained in Section 4.4, “Insertion/removal of flow-limiting discrete apertures”, the insertion and removal of the flow limiting B4C apertures is also monitored to prevent their illumination with the FEL beam and therefore beam damage during the execution of these operations. **Figure 31** summarizes this concept.

__Figure 31:__ Interlock logic map for the "GATT_APER_OK_2EPS" signal



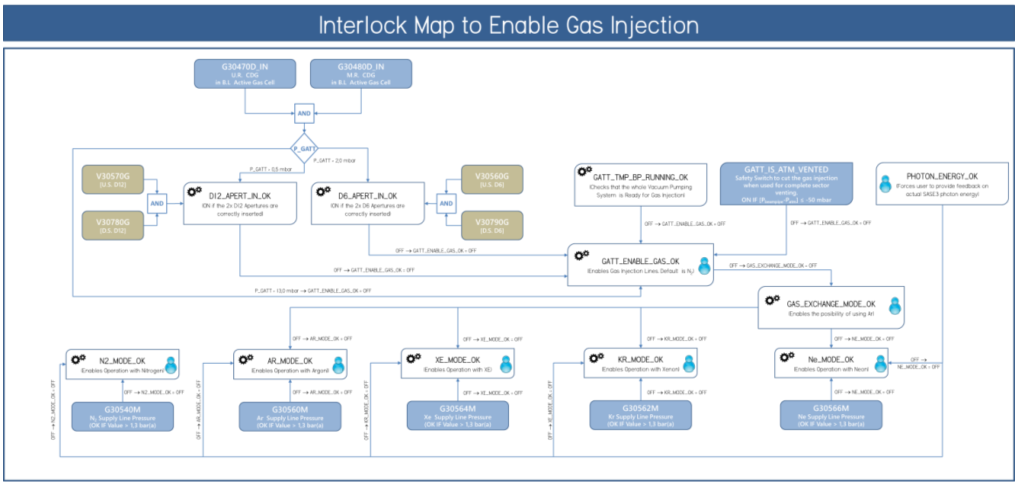
5.5 Permission for operation with gas injection

In general, the gas attenuator operation is foreseen in two normal scenarios:

1. "Transparent" mode, where no gas injection is needed
2. "Active" mode, where a given pressure of an available gas is required to provide some specific transmission reduction for the FEL beam

Meanwhile, the first case can be identified as a reduction of the whole device to a conventional beamline vacuum sector, whose main function is to sustain similar UHV pressure levels as the rest of the surrounding sectors; it is the second case that requires an additional set of conditions to run safely and robustly. This is shown in Figure 32.

Figure 32: *Interlock logic map for the "GATT_ENABLE_GAS_OK" variable*



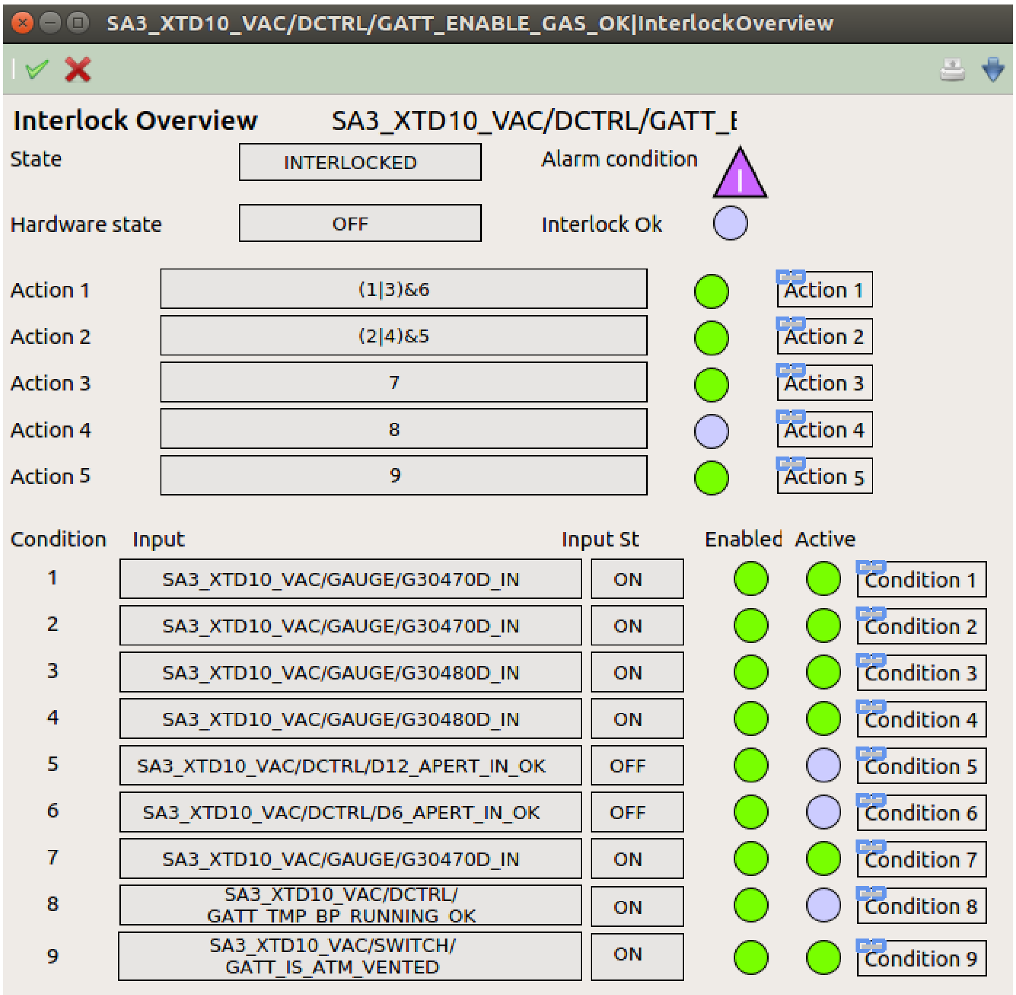
The input arrows on the signal "GATT_ENABLE_GAS_OK" are set to OFF if either of the following conditions is present:

- The vacuum pumping system is not fully operational.
- A forbidden combination of pressure and clear aperture is met (excessive gas flow).

Additionally, and to prevent overpressure when using the gas injection system to vent the sector (i.e. for upgrade and maintenance work), if the sector is already vented above 950 mbar, the permission to inject gas will be also removed.

The current status of the implemented interlock is as shown in Figure 33.

Figure 33: *Interlock overview scene for the variable "GATT_VAC_OK_2VAC"*



SA3_XTD10_VAC/DCTRL/GATT_ENABLE_GAS_OK|InterlockOverview

Interlock Overview SA3_XTD10_VAC/DCTRL/GATT_E

State: INTERLOCKED

Alarm condition

Hardware state: OFF

Interlock Ok: ○

Action 1	(1|3)&6	🟢	Action 1
Action 2	(2|4)&5	🟢	Action 2
Action 3	7	🟢	Action 3
Action 4	8	○	Action 4
Action 5	9	🟢	Action 5

Condition	Input	Input St	Enabled	Active	
1	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	🟢	🟢	Condition 1
2	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	🟢	🟢	Condition 2
3	SA3_XTD10_VAC/GAUGE/G30480D_IN	ON	🟢	🟢	Condition 3
4	SA3_XTD10_VAC/GAUGE/G30480D_IN	ON	🟢	🟢	Condition 4
5	SA3_XTD10_VAC/DCTRL/D12_APERT_IN_OK	OFF	🟢	○	Condition 5
6	SA3_XTD10_VAC/DCTRL/D6_APERT_IN_OK	OFF	🟢	○	Condition 6
7	SA3_XTD10_VAC/GAUGE/G30470D_IN	ON	🟢	🟢	Condition 7
8	SA3_XTD10_VAC/DCTRL/ GATT_TMP_BP_RUNNING_OK	ON	🟢	○	Condition 8
9	SA3_XTD10_VAC/SWITCH/ GATT_IS_ATM_VENTED	ON	🟢	🟢	Condition 9

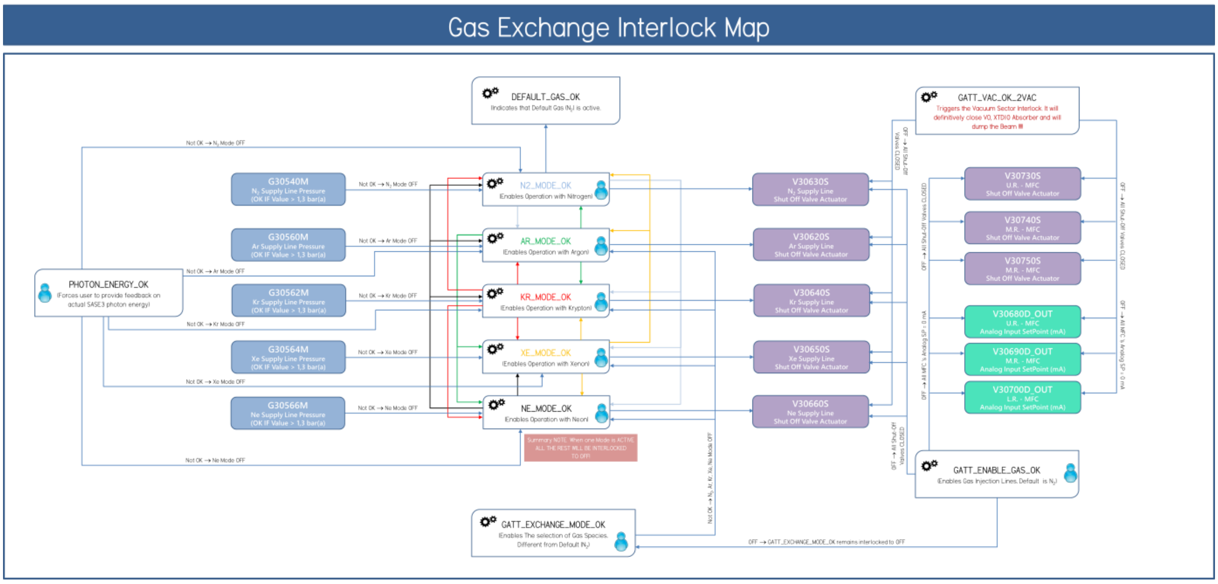
In this example, it can be seen that the gas injection is not allowed because the signal "GATT_TMP_BP_RUNNING_OK" is OFF (which is true since the two booster pumps were not running at the moment the screenshot was taken).

5.6 Management of the gas supply manifold

One of the most versatile features of the gas attenuator device is the possibility to choose among up to five different gas species to be injected, accordingly to the experimental requirements and suitability.

In order to prevent unwanted uncontrolled mixtures and to enable a clear set of automation procedures, the interlock scheme shown in Figure 34 has been implemented. In this particular case, the concept is oriented not only towards safety issues, but towards enhancing the operation stability of the system.

Figure 34: *Interlock logic map for gas supply manifold management*



In particular, the following main ideas are embedded:

1 To prevent uncontrolled gas mixtures in the mass flow controllers fore-line

2 To signal the lack of availability of a given gas species and, as a consequence, vetoing the activation of that particular gas mode

3 To make explicit the user intervention on a particular gas selection among those available

4 To secure that, prior to the initiation of any gas injection procedure, the vacuum system is running under normal conditions

5 Generating a signal for the default gas mode (N_2)

Based on these principles, the following scenarios are foreseen:

1 If a gas species is chosen, the other four are blocked and cannot be selected.

2 If the reduced line pressure of a gas species is below a threshold that could compromise the proper operation of the mass flow controllers, this particular gas mode is disabled.

3 Once a given gas mode/modes is/are disabled, their respective line shut-off valves are kept closed.

4 If the vacuum system status signal is OFF, all the shut-off valves of the manifold (gas line and MFCs) are locked in the CLOSED position.

5 Any gas other than Nitrogen requires the explicit activation of the "GATT_EXCHANGE_MODE_OK" signal, available only if "GATT_ENABLE_GAS_OK" is also ON.

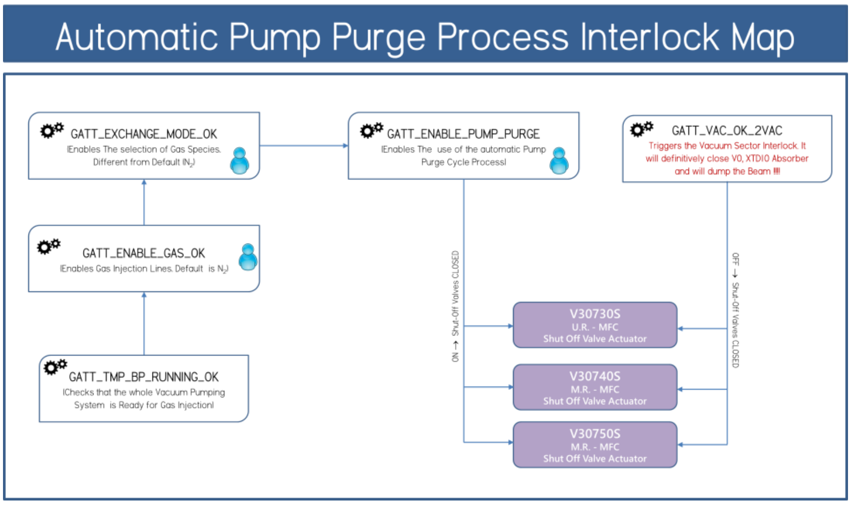
5.7 Automation of the pump purge gas exchange process

In order to secure the required gas purity when a change in the gas species is needed, a convenient pump purge process is mandatory.

During the development and implementation of the concept for the automation of these procedures, the need to make sure that a direct bypass between the gas line and the beamline vacuum system was detected. In particular, this could be the case when forcing the mass flow controllers to be fully open to facilitate the "rinsing" process with the new gas species to be used later.

For this reason the signal "GATT_ENABLE_PUMP_PURGE" was introduced as part of the safety interlock for the gas attenuator. If it is disabled, the automation procedures are vetoed. On the other hand, when it is set to ON, it immediately forces to CLOSED all the isolation shut-off valves between the outlets of each of the MFCs and the beamline vacuum system.

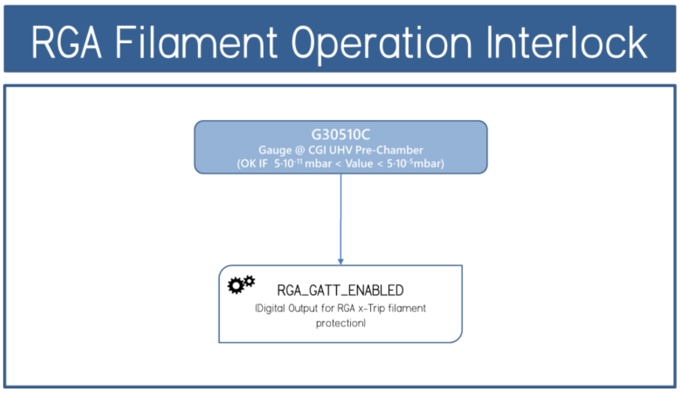
Figure 35: *Interlock logic ,ap for the automation of the pump–purge process (i.e. automatic gas exchange).*



5.8 Operation of the mass spectrometer

To prevent the destruction of the QMS filaments, a conventional protection concept has been implemented. In particular, when using the inverted magnetron gauge available in the same vacuum chamber, two thresholds are used to control the status of the “RGA_GATT_ENABLED” signal, as shown in Figure 36. Meanwhile, the upper value indicates the maximum tolerable operation pressure, and the lower value takes care of preventing the operation in a potential situation of malfunction of the pressure sensor.

Figure 36: *Interlock logic map for the protection of the QMS filaments*



A Reference material

The following reference material is posted online:

- **Complete P&ID schematic**

  Integrated version of the P&ID schematic.

- **Interlock maps**

  High-resolution version of the interlock maps shown in this document.

- **Interlock definition file**

  Up-to-date interlock definition running in the gas attenuator control PLC machine.

- **Device component list**

  Complete list of devices integrated for the gas attenuator.

B Abbreviations and acronyms

QMS	quadrupole mass spectrometer
RGA	residual gas analyzer
UHV	ultrahigh vacuum
HV	high vacuum
PLC	programmable logic controller
MFC	mass flow controller
LINAC	linear accelerator
SCADA	supervisory control and data acquisition
GUI	graphical user interface
SASE	self-amplified spontaneous emission
CGI	central gas injection module
P&ID	process & instrumentation diagram
GATT	gas attenuator
DPS	differential pumping system
XFEL	X-ray free-electron laser

C References

[1] C.T. Chantler et al.: “Detailed Tabulation of Atomic Form Factors, Photoelectric Absorption and Scattering Cross Section, and Mass Attenuation Coefficients for Z = 1-92 from E = 1-10 eV to E = 0.4-1.0 MeV”. NIST, Physical Measurement Laboratory. United States of America (2005)

[2] M. Altarelli et al.: *“*XFEL: The European X-Ray Free-Electron Laser - Technical Design Report*”.* DESY, Hamburg, Germany (2006)
doi:10.3204/DESY_06-097

[3] E.A. Schneidmiller et al.: “Photon beam properties at the European XFEL”. European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany (2011)
doi:10.3204/DESY11-152

[4] H. Sinn et al.: “Conceptual Design Report: X-Ray Optics and Beam Transport”. European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany (2011)
doi:10.3204/XFEL.EU/TR-2011-002

[5] H. Sinn et al.: “Technical Design Report: X-Ray Optics and Beam Transport”. European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany (2012)
doi:10.3204/XFEL.EU/TR-2012-006

[6] R. Villanueva: “The Gas Attenuator Instrument for SASE3 Soft X-Ray Beamline at the European XFEL”. European XFEL Users’ Meeting, Hamburg, Germany, (2014)

[7] La Civita et al.: “SASE3: soft x-ray beamline at European XFEL”. SPIE Optical Engineering + Applications, San Diego, United States of America (2014)
doi:10.1117/12.2061693

[8] R. Villanueva et al.: “Noble gases flow management in the European XFEL project UHV photon transport beamlines”. 9th Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation. MEDSI 2016., Barcelona, Spain (2016)

[9] R. Villanueva: “Intensity Tuning of X-Ray Laser Photon Pulses with Rarefied Gases: The SASE3 Beamline Gas Attenuator at the European XFEL Facility”. 15th European Vacuum Conference, Geneva, Switzerland (2018)

[10] R. Villanueva et al.: “Joint Operation of SASE3 Beamline Gas Attenuator and Diagnostic Intensity Monitors at the European XFEL Facility”. PhotonDiag 2018 - Workshop on FEL Photon Diagnostics, Instrumentation, and Beamlines Design, Hamburg, Germany (2018)

[11] R. Villanueva: “Quick Guide to Manual Operation of SASE3 Gas Attenuator Device”. European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany (2018). Internal documentation.

[12] R. Villanueva: “Standard Operation of SASE3 Gas Attenuator”. European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany (2018). Internal documentation.

[13] H. Sinn: “Update Radiation Safety Interlock for SASE3”. Internal Communication (2019)

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