Remotely Controlled Gas System for High Repetition Rate Experiments

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Introduction

The Astra Gemini High Power Laser Facility, based at the Rutherford Appleton Laboratory, has a unique dual beam, Petawatt capability with a repetition rate of 20sec/pulse for use by the UK research community and their international collaborators. Several experiments in Gemini require gas targets of different species and pressures and a system that would allow remote control of gas parameters is a major requirement.

The goal was to develop and build a flexible fixed system that would allow multiple gasses and pressures to be controlled from the Target Area control room during shot runs. This would reduce the engineering staff overhead required and the impact caused by continuously requiring access to the bunker to change pressures and pipework. The system was designed to work with a wide range of flammable and inert gasses and mixtures.

Operation

The main control is achieved by a touchscreen which interactively allows the selection of the source gas bottle and pressures for the shot. In the background the pipework is vented, evacuated and filled by the required target gas. A hardwired safety system breaks in to override the PLC should a safety related event be triggered. Pressure values are displayed throughout the system to confirm the system is operating as expected. The target pressures and bottle pressures are recorded on-shot and stored with the shot meta-data. All pressures are also recorded continuously on a data logger to allow a full diagnostic capability.

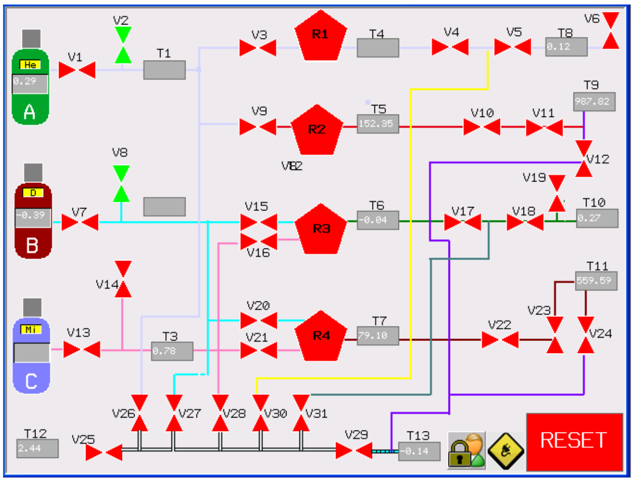


Figure 1-Main PLC control screen

Figure 1 shows the main control screen where areas are touch sensitive to provide control. Touching on a bottle spawns a window to allow the gas type to be selected. The selection is recorded on the logger and with the on-shot experimental data. The gas selection window is shown in Figure 2 and shows the list of the currently used gasses. Mixtures vary significantly and therefore specific mixes are agreed in advance. When a gas is selected the bottle on the main screen changes colour and the chemical symbol is displayed where possible to allow staff and visiting groups to easily see what is connected and quickly assess the hazards if necessary.

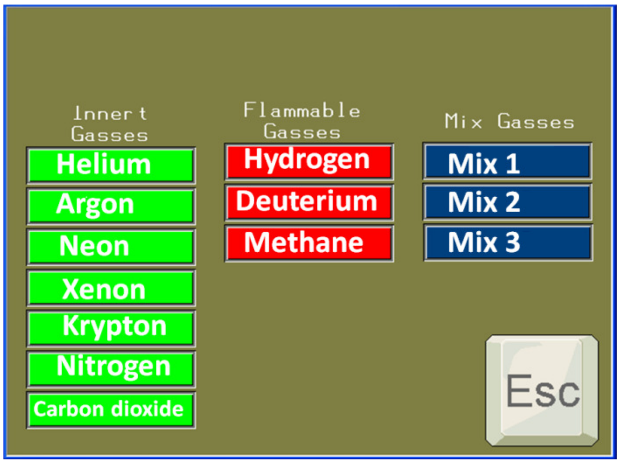


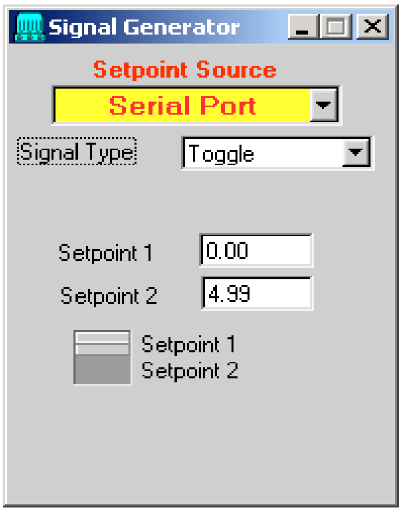
Figure 2-Gas selection window

Valves that are open change to green and those closed are shown in red. The gas remaining in the bottle and pressures throughout the system are displayed in the grey boxes. Control is through each of the pentagons and this spawns an appropriate window providing options. Figure 3 shows the window which is spawned to connect regulator 3 to one of two potential gas sources. Flags such as evacuating, purging etc. are displayed against the appropriate line such that is it obvious where the system is within the selected program.

Figure 3-Selecting the source bottle for regulator 3

The system is currently used conservatively below the maximum working pressure of the weakest components to provide headroom for pressure spikes caused when flow hits a dead end. Valves are opened in a methodical sequence to minimise the extent of any pressure spikes. Check valves are used in the supply pipes to prevent bottles being inadvertently cross-contaminated and on the exhausts to eliminate purity contamination caused by mixing with other gasses or air. Nitrogen is used to purge parts of the system diluting flammables being exhausted and diluting light gasses to improve pumping. Pressure relief valves are used throughout the system to protect gauges and transducers from over pressurisation and protect against regulator creep. Manual regulators are fitted to the bottles which limit the maximum sustained pressure available to the Target Area. This set-point is determined by the maximum working pressure of the weakest item in the chain or 100barg, whichever is lower.

The system currently allows for three bottles to be connected. There is provision for two 50L bottles outside and a smaller potentially more expensive bottle inside the Target Area (to minimise pipe lengths). There are four electronically controlled regulators, two high pressure 1-100barG and two low pressure 0-2barA. It is foreseeable that all four regulators could be used concurrently in an experiment and all bottles could be used.


Signal Generator

Setpoint Source: Serial Port

Signal Type: Toggle

Setpoint 1: 0.00

Setpoint 2: 4.99

Setpoint 1
Setpoint 2

Figure 4-Setting the target pressure

Figure 4 shows the window on the PC which controls the pressure set-point. The pressure is entered in barG or mbarA depending on the selected regulator and the toggle moved with the mouse. The change in pressure occurs in under a second.

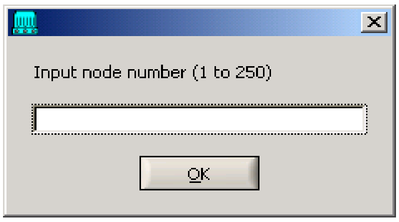

Input node number (1 to 250)

Figure 5-Selecting the regulator to change the pressure

Figure 5 shows the window to select the regulator to adjust. Only one regulator is adjusted at a time but all four can be active. The regulators are connected to the gas PC using RS485.

Many of the gasses used are flammable with very low explosive limits. The system is designed to close all the valves and open two exhaust valves should the gas alarms, emergency stop, or a multiple trip of the gas vacuum interlock be detected. Figure 6 shows a schematic of the gas independent vacuum switches where both must agree that the chamber is lower than 1mbarA for gas to be enabled. When at atmosphere the local line to the chamber is automatically vented to ensure staff are not potentially exposed to gas and allow for connections to made and broken. All the target gas solenoids are also disabled electrically as an additional safeguard and to assist with commissioning.

Figure 7 shows the hardware installed in the gas cupboards to control the local venting and delivery to the room. All the pneumatically controlled gas valves are normally closed for interchangeability and to reduce spares. Where a normally open valve is required this has been done using a normally open pilot valve. Future provision for other bottles has been installed. To prevent unwanted venting of the gas bottle mid control sequence the vent operation is delayed by a restrictor. All the hardware installed is intrinsically safe where possible to further minimise the likelihood of any ignition should a failure in any hardware occur.

Figure 8 shows a password protected mode which allows individual access to each of the 31 electronically controlled valves. All the safety interlocks are overridden in this mode and therefore approved access is limited to a small number of staff. This allows failures or problems to be investigated looking at individual sub-systems and full commissioning.

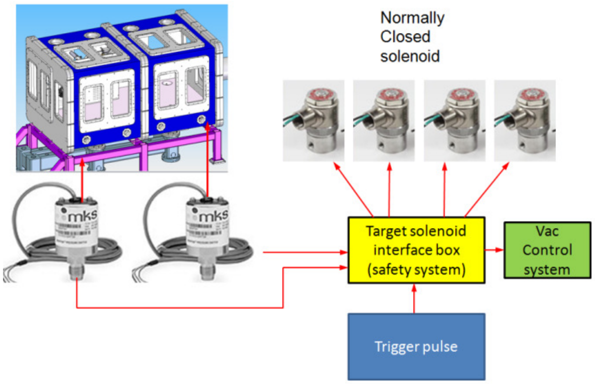


Figure 6-The Vacuum interlocks and their interfaces

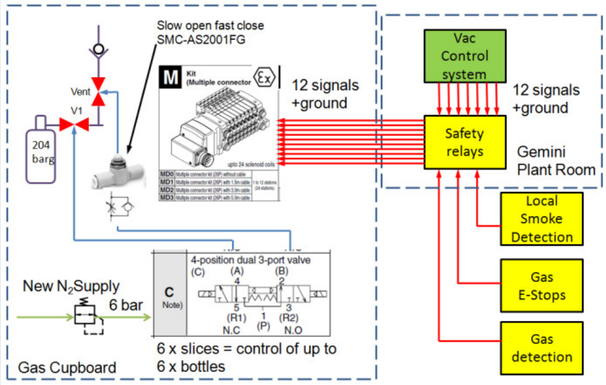


Figure 7-Valve control in the gas cupboard

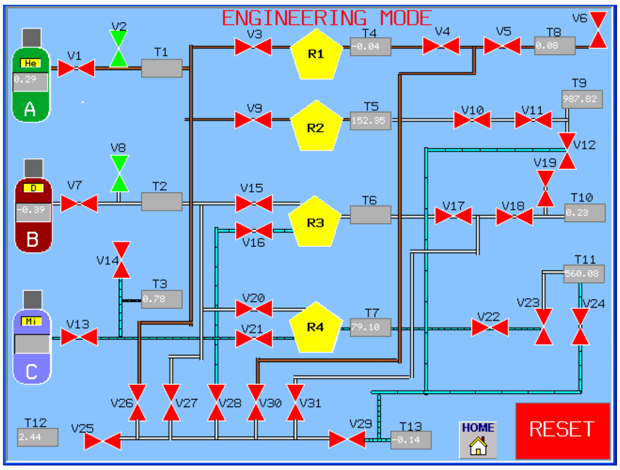


Figure 8-Engineering mode for debugging and testing

Conclusions

A flexible gas system is required to maximise the beam time on a high rep rate laser facility. A number of experiments have been fielded by the system and some improvements have already been made to remove inbuilt features of some hardware and increase some of the flexibility. The feedback has been positive from those using the system.

TAP Interaction Chamber vacuum upgrade

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Introduction

The Target Area Petawatt (TAP) is the leading high intensity area on the Vulcan Laser Facility. The Target Area is used primarily for plasma physics experiments for the academic community.

The vacuum system is attached to two main vacuum chambers referred to as the Compression Chamber and the Interaction Chamber. The Compression Chamber contains the last segment of the laser system and the Interaction Chamber is where the experiments are carried out. To meet experimental demand the inside of the Interaction Chamber is accessed several times per day to change targets and re-configure hardware. Unlike many vacuum chambers people regularly work inside this chamber, when it is at atmosphere, wearing full cleanroom overalls and face masks.

The Interaction Chamber is shown in Figure 1 and has an internal volume of 20m^3 and there is a 630mm diameter gate valve connecting the Interaction Chamber to the Compression Chamber (100m^3) next to it. The facility stipulate that this gate valve must not be opened until the interaction chamber is <1x10^{-3}mbar to minimise the likelihood of contamination of the compression chamber and optics. With the gate valve closed it is not possible to take laser shots. Some experiments require a better vacuum than 9x10^{-4} mbar impacting the shot rate significantly. Analysis was carried out to look at improving the pumping speed and thus reduce the cycle time between shots. This analysis focuses on a number of areas:

1. The effect on pumping speed when the Interaction Chamber has been open to the room air for extended periods.
2. The current system performance and limitations.
3. Potential performance gains.

The amount of experiment related hardware and its vacuum compatibility will have a major impact on pumping speed and for all the tests the internal hardware was consistent.

Hardware used for tests

All chamber vacuum data was captured using a MKS 974 gauge which utilises three independent sensors to provide accurate readings throughout the range from atmosphere to 10^{-8}mbar. The vacuum levels were recorded initially using the supplied MKS software with one data point every 30 seconds and more recently using a Measurement Systems DataWEB logger which interfaces to the gauge analogue out recording every 2 seconds. All environmental data was captured using a Swiftbase CM-Relay climate monitor with a temperature and humidity sensor located inside the vacuum chamber next to the last turning mirror in the chain.

Existing TAP vacuum infrastructure

Figure 1 shows a general overview of the pumping infrastructure in TAP. The chamber is roughed by 2 x 300m3/hr oil sealed rotary pumps which are supported by 2 x 1000m3/hr roots pumps. When roughed the control system seals off the roughing system and opens pendulum valves to allow the Oerlikon Leybold 2200l/s and 2800l/s turbo pumps to take over. The turbo pumps at this point are running at full speed and this change-over currently takes place at 9x10^{-2}mbar. The turbo pumps are quoted as being able to operate at the mbar level but require a significant backing pump to prevent the turbo from stalling. Currently both turbo pumps are backed by the same 100m3/hr pump. Tests had previously been carried out and with this backing pump the changeover is optimised at 9x10-2mbar due to the size of the chamber.

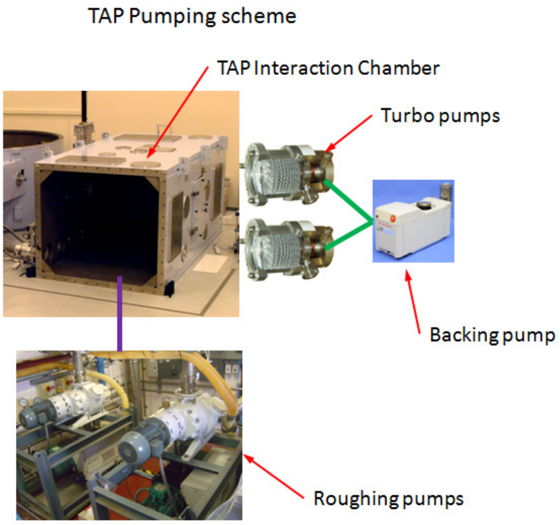

Figure 1 - TAP interaction chamber vacuum infrastructure

Figure 2 shows a standard pump down of this system where on average it takes 54minutes to reach a level that the 630mm gate valve can be opened for a shot. This was based on the chamber being open for a few hours and the chamber containing some standard experimental hardware. Figure 2 also shows the phases of pump down and relevant pumping technologies.

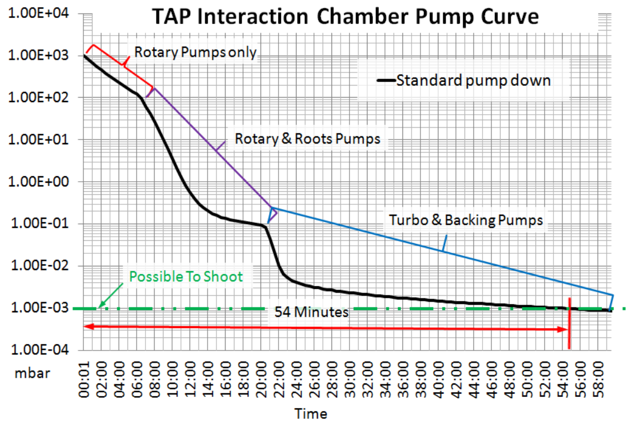

Figure 2 - Standard pump curve for the TAP Interaction Chamber

Dry Air Let-up

It is well documented that moisture affects the speed of pump down and chambers will attain a better vacuum faster if let-up to dry air or nitrogen. We have a dry air system where the specification of the air delivered is +3 dew point. In theory this would help fast turnaround but what we had not quantified was the effect of having the chamber open for extended periods to the room air which is not humidity controlled. With the chamber open moisture would be allowed back onto the dry surfaces and slow the pumping performance. The chamber was left in the same state throughout the test in that no additional hardware was added and it is expected that the surface cleanliness may have improved slightly throughout the test. Figure 3 shows the effect of having the doors open for a range of periods. The graph shows the longer the chamber is open to the room the longer it takes to get to the turbo pump trigger point. There is also a significant delay in opening the gate valve for shooting.

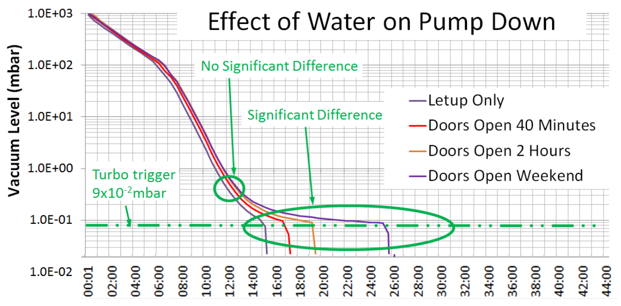

Figure 3 - Shows how leaving the chamber open to the room affects pumping speed

Figure 4 shows the temperature and humidity change both during and after a let-up without opening the chamber doors. The temperature of the air in the interaction chamber rose by 7°C during let-up and then cooled back down to ambient within about 20 minutes. It also shows the chamber as being drier than -40°C dew point (limitation of the sensor) whilst being pumped but rising to -12°C dew point during let-up before falling back to -18°C dew point as the moisture is absorbed by the chamber surfaces. The dry air stored for let-up utilises a refrigeration drier which achieves +3 dew point at best.

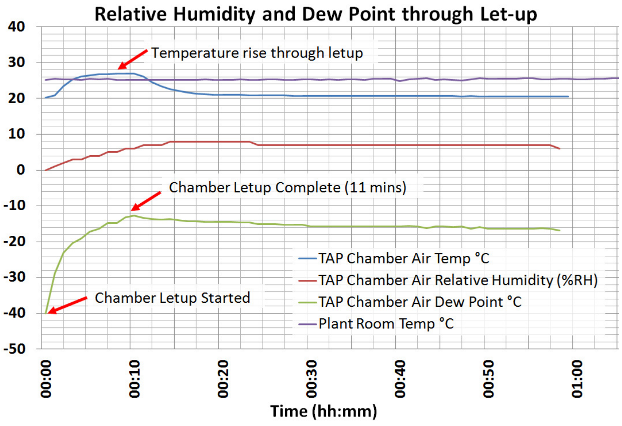

Figure 4 – Showing the effect of let-up on the Interaction chamber

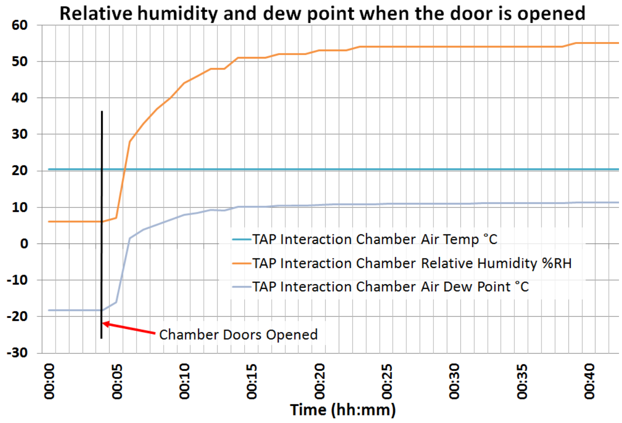

Figure 5 – shows how the relative humidity in the chamber changes when the door is opened.

Figure 5 shows that within five minutes there have been sufficient air changes that the relative humidity of the air in the chamber is close to matching the relative humidity of the entire room.

Potential Gains

From the data, drier air would be unlikely to deliver any gain when the major driver is the amount of time the chamber is open to the room air. But from Figure 3 large reductions in time could be realised by bringing in the turbo pumps earlier in the cycle. At a trigger point of 2.5x10-1mbar any delays caused by having the chamber open to the room for an extended period are negated. This is well within the operating window of the turbo pumps providing sufficient backing performance is available. This is shown more clearly in Figure 6.

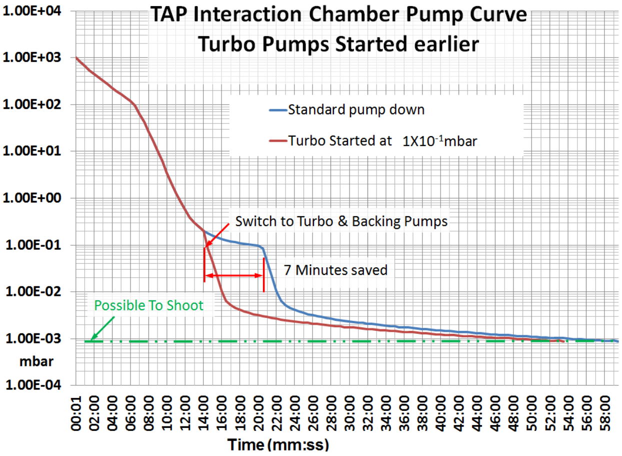

Figure 6-shows the saving in time by starting the turbo pumps at $1x10^{-1}$ rather than $9x10^{-2}$ mbar

Backing performance needed to bring the turbo pumps on earlier

To ascertain which vacuum pump from our standard stocked range would be most appropriate we replaced the 100m3/hr backing pump by a 600m3/hr variant (Edwards IGX 600) as a trial. This was connected to the turbo pumps with the minimum of pipe and as much of this at ISO100 as possible. The pump down was repeated slowly incrementing towards 2.5x10-1mbar whilst monitoring the rotor speed of the turbo pumps on the controller. Using the 600m3/hr vacuum pump the turbo pumps were just starting to register a slowing of the rotor speed at 2.5x10-1mbar but were showing full current draw for approx 30 seconds which was deemed acceptable by Oerlikon Leybold Vacuum.

There is currently insufficient space for the 600m3/hr vacuum pump as a permanent fitment in the target area but the roughing system was modified to assist the backing pumps through the initial phase. The roughing system would be operating at full speed during this phase of the pump down thus the headline pumping speed would be 2000m3/hr. The pipe work was modified to utilise the 100m3/hr backing pump permanently but use the roughing system to supplement the backing system for a short period allowing the turbo pumps to be switched to early. Although the tests were successful utilising the roughing system the turbo pump spindle speed did drop by a few Hz. The roughing system performed poorly compared to the IGX600 due to the distance from the Interaction Chamber to the roughing pumps in the Knudsen flow regime where pipe diameter is critical and ISO160 is small. Changing the ISO160 pipe work to ISO250 or larger is not viable due to the trench infrastructure and access around the bunker but alternative roughing systems have been investigated and explored.

Alternative roughing pumps

With the roughing pumps close to the end of their life and the desire to change to dry technology we evaluated the market to look for the best all-round replacement. A collaboration with Oerlikon Leybold was formed where options were analysed and a DRYVAC DVR 5000 S-I was trialled and subsequently purchased. This has a headline pumping figure of 3800m3/hr but it is heavily restricted by our pipe diameter.

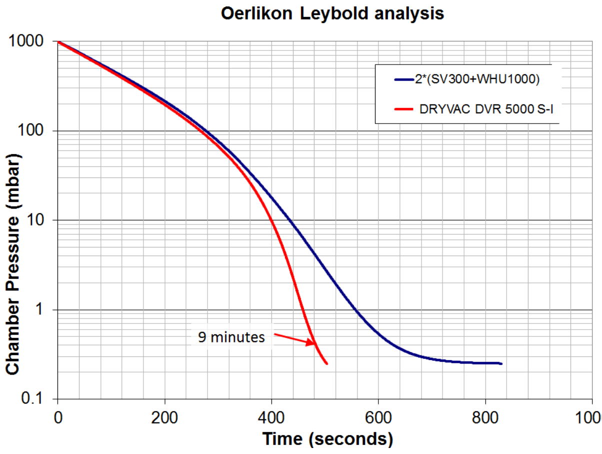

Figure 7 shows the predicted performance for the DryVAC against the performance of the existing hardware taking account the ISO160 pipework.

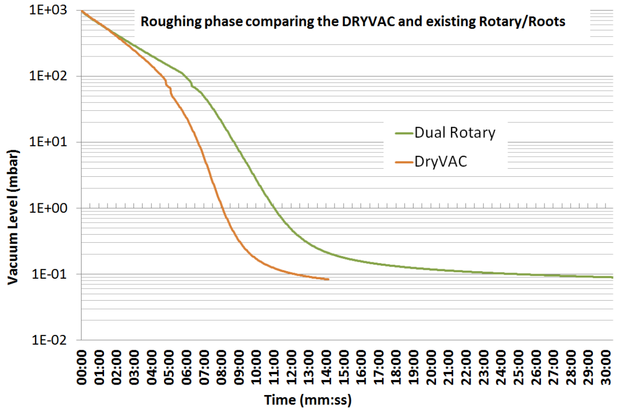

Figure 8 shows the actual performance of both vacuum pumps.

Comparing Figures 7 and 8 our analysis was broadly accurate and we will realise a significant saving in cycle time.

Both Figure 7 and Figure 8 suggest that when we get the DRYVAC DVR 5000 S-I running in the control system we will be able to get to Turbo level within 10 minutes regardless of its contents and the amount of time the door is open. This assumes that the DRYVAC DVR 5000 S-I has sufficient capacity to back the turbo pumps allowing them to be opened at $2.5x10^{-1}$ which from all the work so far is not unreasonable.

High vacuum performance

With improvements available in rough vacuum we looked harder at options to speed the high vacuum phase. This phase for us is dominated by water vapour and cryogenic vacuum pumps are a good solution for pumping water vapour. After research a SHI CP-16 cryogenic vacuum pump was sourced on a DN400 flange and a VAT DN400 pendulum valve to permit it to be isolated from the chamber.

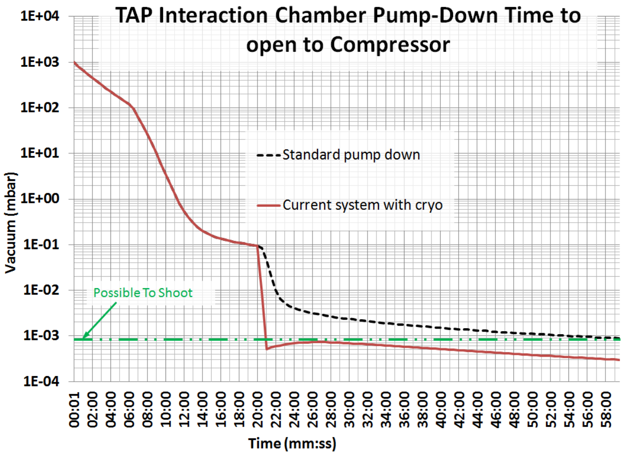

Figure 9 - Comparing the pump down with and without the cryogenic pump enabled.

Figure 9 shows the initial experimentation work with the cryogenic vacuum pump where a nearly decade of vacuum performance was seen instantly. This brings the minimum shooting window from about 54 minutes to 10-15 minutes depending on the roughing pumps. It also makes the use of MCP's and other diagnostics requiring a good vacuum more viable for experimental fitment without impacting shot rate significantly. Cryogenic pumps generate vibration which have the potential to impact experiments, but this was investigated separately [1] and found not to impact operations on TAP.

Actual performance during an experiment

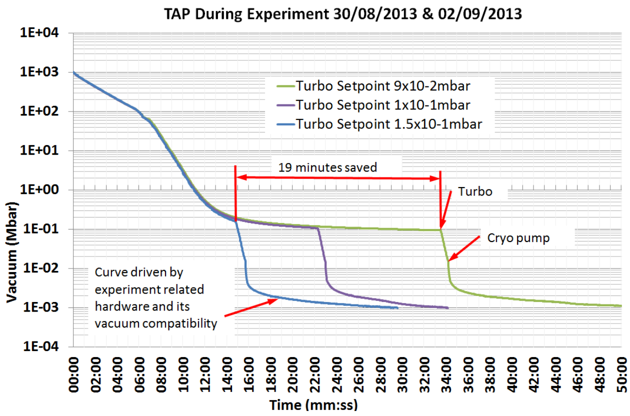

Figure 10 – showing data from the current TAP experiment

The Cryogenic pump and the valve to help the backing pumps are now fully integrated into the control system. The only remaining item is the integration of the DRYVAC DVR 5000 S-I roughing pump into the control system which is currently underway. Figure 10 shows plots from the 4th week of the TAP experiment as the final elements of the system were enabled. This particular experiment has required the use of much plastic inside the chamber. There is no data without the cryogenic pump but the effect from the pump is visible with the instant drop when engaged. The three curves show the impact of the turbo set point on a real experiment. The starting point of the cryogenic pump has been delayed to allow analysis to be carried out on the frequency of regenerations. This appears conservative given that a regeneration of the pump has not been required thus far.

Conclusions

The TAP vacuum system has been running successfully for over 10 years. Some of the existing vacuum hardware is nearing the end of its life and in need of replacement. Rather than replacing like for like we explored the marketplace for the most appropriate solution. Research showed that the recently installed Oerlikon Leybold turbo pumps had a wider operating window that could be exploited. Testing of opening times with increased backing was positive and significant steps were possible to significantly reduce the time taken to reach turbo level. With the addition of a single CP-16 cryogenic vacuum pump down time is further reduced significantly. With this brute force approach any pumping impact caused by leaving the vacuum chamber open to the room is negated. The choice and condition of materials installed in the chamber does still impact the performance below 3×10^{-3}mbar but there is scope to utilise more vacuum sensitive diagnostics without leaving the chamber to pump overnight. The only concern is that small leaks become undetectable until the cryogenic vacuum pump has reached its storage capacity for water or gas. The frequency for regenerations has yet to be fully explored but with the current settings we have nearly completed an experiment with regenerating. This suggests there is scope to start the cryogenic pump earlier. Further performance gains will be realised when the DRYVAC DVR 5000 S-I is fully implemented in the control system. There is also space on the Interaction where a 2nd Cryogenic Vacuum pump could be installed and this would further improve the pumping curve below 3×10^{-3}mbar.

Acknowledgements

Much of the analysis on the roughing pumps would not have been possible without close collaboration with Oerlikon Leybold and the loan of an early production DRYVAC DVR 5000 S-I. SHI Cryogenics also provided significant information and support in selecting and setting up the CP-16 cryogenic vacuum pump.

References

1. CLF annual report 2011/2012 article 78 - Cryogenic pump induced vibration in the TAP Interaction Chamber

2. CLF annual report 2000/2001 - Interaction Chamber for the Vulcan Petawatt Upgrade.