Modular Control and DAQ of an electron beam test stand

Jay Sardesai
Supervised by Sameed Muhammed
SY-BI-XEI section, CERN

Abstract
Removal of SOx and NOx gases can be achieved in a single-step process using Electron Beam Flue Gas Treatment. This requires a window between the electron gun and the beam-gas interaction area. The Novel Electron Window Test Stand was constructed to test the suitability of these windows with regard to attenuation and deflection. In this summer student project, a modular control and DAQ system was developed for the test stand. In addition, the window must withstand a pressure difference of 1 bar; pressure testing was conducted to narrow the list of possible window designs.

Keywords
CERN summer student report; Control; Data Acquisition; LabVIEW.

Contents

1 Introduction

1.1 UTMOST CLEEN

Ongoing diversification of the maritime fuel mix presents a novel challenge; to meet climate goals, NOx and SOx pollution must be reduced, but ideally with one method. Electron Beam Flue Gas Treatment (EBFGT) is one promising solution, as it will remove both pollutants in a single-step process, regardless of the fuel type. High efficiencies can be achieved, with up to 98% SO2 and 82% NOx removed in one step [1]. Some challenges remain, however, as the beam setup must be compact enough to be mounted on a ship, have a low energy consumption, and be sufficiently durable.

The CERN knowledge transfer project UTMOST CLEEN aims to create such a beam setup. The planned setup of this beam is as shown below in Figure 1: An electron gun produces and accelerates electrons under ultra-high vacuum, using a high voltage supply (100kV, 1.0mA). These pass through an ultra-thin window, into the beam-gas interaction zone, where free radicals are formed, that react with the pollutant particles, producing harmless byproducts such as ammonium sulfate and ammonium nitrate. These are useful to the agricultural industry and can be sold as fertiliser.

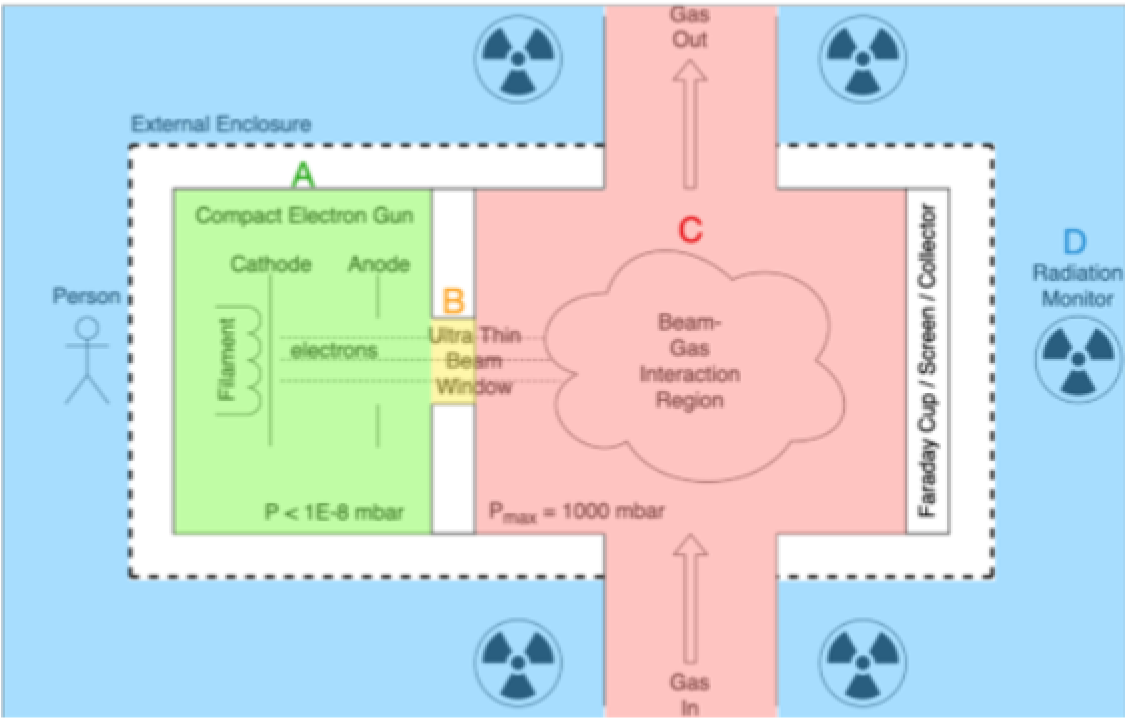


Figure 1: The planned UTMOST CLEEN desulfurization apparatus

1.2 Windows

The ultra-thin window is subject to several constraints: electron beam attenuation, deflection and heating of the window must be minimized, and the window must not crack under the difference in pressure. A preliminary investigation, involving simulations in ANSYS, was conducted by Abhishek Ganesh (formerly of SY-BI-ML) to find the ideal beam power, window size, and window material [2]. From these findings, a set of windows of differing sizes and materials were made, and subjected to pressure failure testing.

1.3 NEWTS apparatus

In addition, the Novel Electron Window Test Stand (NEWTS) was assembled, to measure the attenuation and deflection of the beam as it passes through the window [3]. A modular control and DAQ system was assembled, and the modules associated with the Electron Gun and Chopper are detailed below in part 3.

The NEWTS consists of four sections, each of which contains multiple parts which must be controlled separately. The test stand will be used to measure the attenuation and deflection of an electron beam by Ultra-Thin Membrane Windows mounted in the diagnostic station.

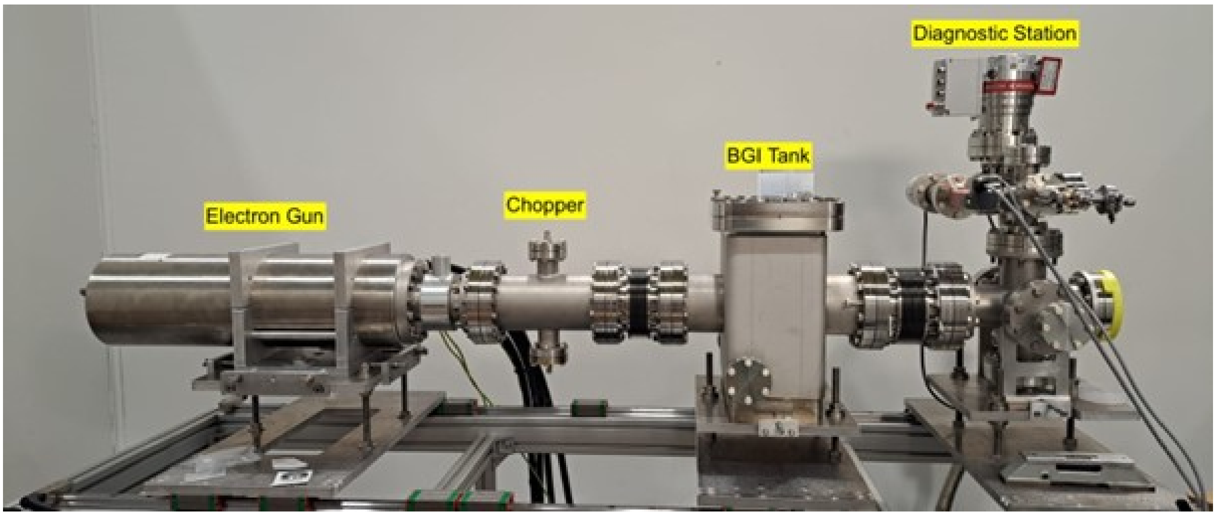


Figure 2: The Novel Electron Window Test Stand (NEWTS)

The electron gun can generate a high-power electron beam of up to 100keV, with a power of 100W and current of 1.0 mA. To generate the beam, a voltage is applied across the cathode filament by the Gun supply (in this case a Staib Instruments Electron Source Power Supply), causing emission of electrons. This is then accelerated towards the anode by a potential difference applied by a second external power supply, the Glassman WR series High Voltage.

Figure 3: The Electron Source Power Supply (middle) and Glassman WR series HV supply (lower)

In addition, the beam can be deflected in the X and Y direction by magnets located at the end of the gun, the voltage for which is controlled again by the Gun supply. The focus and grid for the beam (controlling the dispersion) are also located in the Gun, and controlled by the Gun supply.

The beam then travels through the beam-gas interaction task (not used for this experiment), before striking the Ultra-Thin Membrane Window in the Diagnostic Station. The beam is attenuated and deflected to some extent. The remaining electrons accumulate on the Faraday cup, to measure the transmitted beam current, while the YAG screen and camera measure the beam profile. A half-section view of the NEWTS is shown below:

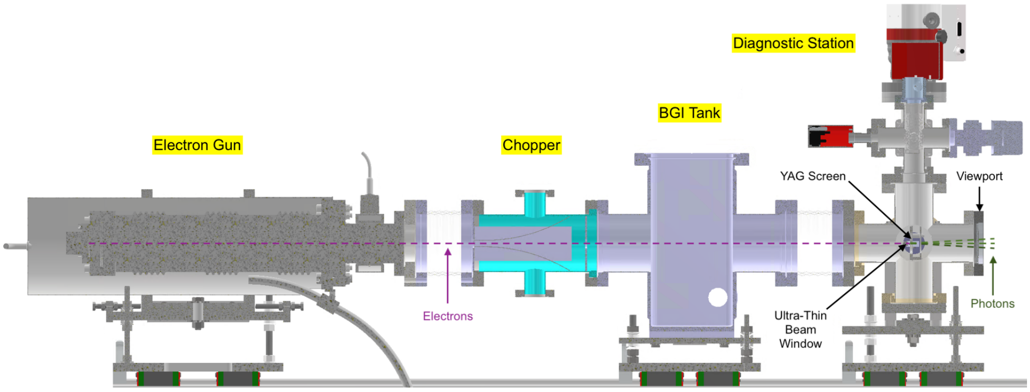


Figure 4: Half-section view of the NEWTS

2 Modular Control and DAQ

2.1 Environment

Due to the modular nature of the test stand, LabVIEW was used to write the control and DAQ programs. LabVIEW is a graphical programming environment that is well-suited for adding and communicating with multiple instruments. In addition, it is very modular and allows the creation of sub-VIs that can be called within the main VI (Virtual Instrument, similar to a function). As such, it is well suited for controlling the modular test stand. An example of what the main VI would look like for the control and DAQ of the NEWTS is shown below in Figure 5.

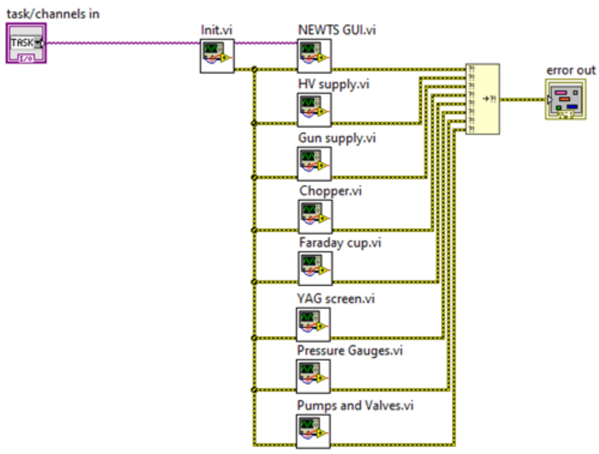


Figure 5: GUI

Due to the size of the project, and the need to deliver a working control system, the work was divided between the SY-BI-XEI and BE-CEM-MTA. Below is the work I've done on the GUI, HV supply control, and Gun supply control. It can be found on GitLab[1]. The work done by BE-CEM-MTA includes control and DAQ for the diagnostic station and the camera, and can also be found on Gitlab[2].

2.2 NI modules used

The test stand, as detailed above, consists of several instruments, which can be controlled separately, by analog and digital outputs. Also important is the need to acquire data from these instruments, so analog and digital inputs are needed. It was decided to use National Instruments (NI) modules, within a NI compactRIO chassis, to provide the inputs and outputs. This is important, as the high voltage power supplies can not be safely controlled by connecting directly to a PC.

The following modules were used for control:

NI modules used in control		
Module Name	Module Type	Use
NI 9264	Analog Output	Set analog values
NI 9205	Analog Input	Read analog values
NI 9403	Digital Input/Output	Set/Read 5V TTL values
NI 9401	Digital Input/Output	Set/Read 5V TTL values for fast triggering and interlock
NI 9475	24V Relay Digital Output	Set 0-24V digital output for relay control

2.3 GUI

First, the GUI (Graphical User Interface). This needed to have the controls for all parts of the test stand. In addition, all the readings, from the pressure gauges, pumps, and set values of the voltages also need to be displayed. It was decided to display all the read values on the corresponding part of the stand on the diagram, as shown below in Figure 6. Furthermore, to increase readability, each section of the NEWTS has a separate tab for controls and read values.

2.4 High Voltage supply

Second, the HV supply control. For this VI, the following functions were needed: Set the output voltage and current on the HV supply (voltage should be ramped to set value), read and display the set values of the HV supply, enable/disable the high voltage supply, and set the interlock status. The hardware used for this was an NI 9264 analog output module to set voltage, current and interlock status, NI 9205 analog input module to read the set values, and NI 9401 Digital Input/Output module to enable/disable, using the output function.

To allow this VI to be used separately, the front panel has buttons to allow each value to be set independently (as seen in Figure 7). A challenge when implementing this was that the NI compactRIO hardware does not support the events structure in LabVIEW. As such, a notifier was used instead to transmit the commands to a case structure.

[1] https://gitlab.cern.ch/rade/clients/sy-bi-xei/newts-sy-bi-xei

[2] https://gitlab.cern.ch/rade/clients/sy-bi-xei/newts.git

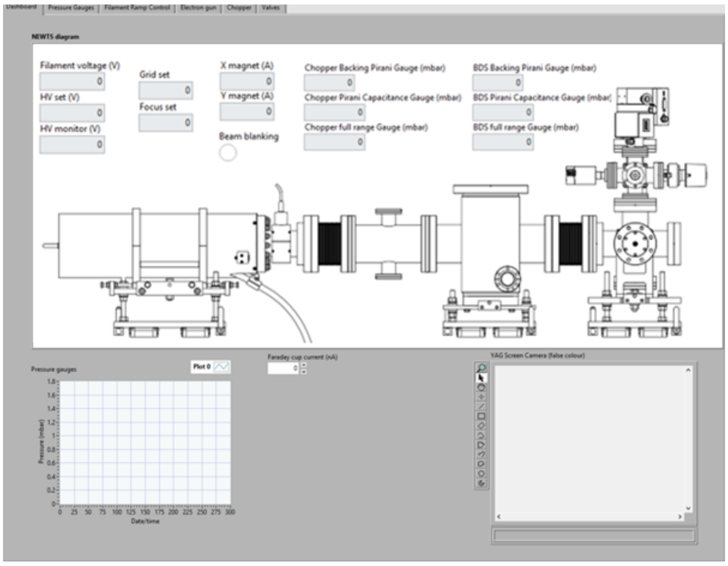


Figure 6: GUI

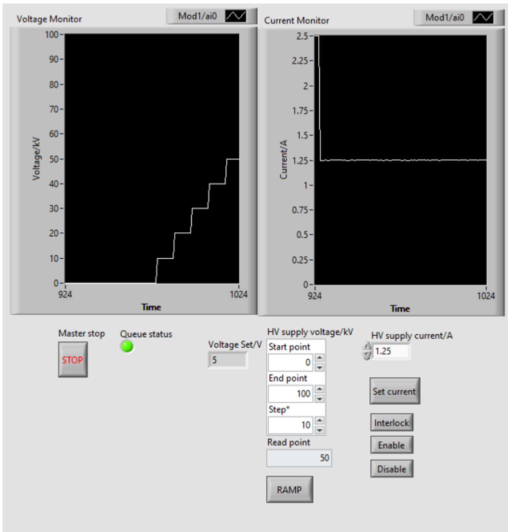


Figure 7: High voltage supply GUI

2.5 Gun Supply

Next, the gun supply control. Similar functions were required for this program, as the filament voltage should be set and ramped at the press of a button. The electron gun focus and grid voltage, as well as the voltages across the X and Y deflection magnets in the chopper, are all set with a second button, and the remote control with a third (see Figure 8). Notifiers were used similarly for this program.

3 Mechanical testing

The filament of the electron gun is under ultra-high vacuum (<1E-8mbar), while the beam-gas interaction region is at 1000mbar. Therefore, the regions must be separated by a window, that can both withstand the difference in pressure and allow the electron beam to pass through with limited attenuation and deflection. This establishes a lower and upper constraint on beam thickness (too thick, and attenuation is too high, too thin, and the window will fail under pressure). Therefore, it was necessary to test windows of different materials, thicknesses and sizes, to see which would be suitable for the test stand.

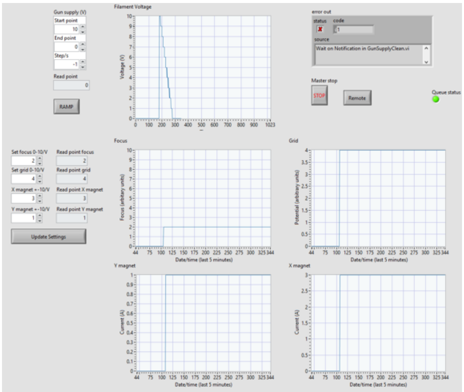


Figure 8: Gun supply control GUI

Figure 9: Round 1 of pressure testing, indicating failure (red), success (green), not fabricated (grey)

Aperture/thickness	100nm	200nm
1mmx1mm	(red)	(grey)
1.5mmx1.5mm	(grey)	(green)

(a) Uncoated silicon windows

Aperture/thickness	100nm	200nm
1mmx1mm	(red)	(grey)
1.5mmx1.5mm	(green)	(red)

(b) Uncoated silicon carbide windows

Aperture/thickness	30nm	50nm	100nm	200nm
1mmx1mm	(red)	(red)	(red)	(grey)
1.5mmx1.5mm	(grey)	(grey)	(red)	(red)

(c) Uncoated silicon-rich nitride windows

Aperture/thickness	30nm	100nm	200nm
1mmx1mm	(green)	(green)	(red)
1.5mmx1.5mm	(grey)	(red)	(red)

(d) Uncoated silicon nitride windows

The materials of choice were silicon (Si), silicon-rich nitride (SiRN), silicon nitride (Si3N4) and silicon carbide (SiC). 46 square windows were fabricated by an external manufacturer, Silson, of varying sizes, and thicknesses. Half of these windows were also coated in a 100nm layer of aluminium. This is to increase the thermal conductivity of the window, and hence the rate at which heat dissipates, as the absorption of the beam heats the window.

The Novel Electron Window Test Stand (NEWTS) was created to test the rate of attenuation and deflection of the beam, but for pressure differential testing, a new setup was created. The windows were epoxied to a KF-25 blank flange (shown below), and clamped to the end of a tube, separated from a pump by a series of valves. This allowed the pressure to be gradually lowered inside the pump, until the window broke, or the tube pressure reached high vacuum.

3.1 First round of testing

In the first round of pressure testing, conducted in July, 16 window types were used, all of which were without the aluminium coating. The results are displayed below on page 9 in Table 1:

Unfortunately, there were issues with attaching the frame to the mount. If too much epoxy is applied, or the frame is pressed too hard when placed on the mount, the epoxy can spread over the window or the central hole. This increases the strength of the window, preventing weak windows from failing. Conversely, pressing too little may mean that a seal isn't formed, so a high vacuum can't be formed on the pump side of the window, and the window appears to have broken. This can also happen if a

Table 1: Complete list of windows fabricated

Window	Material	Frame	Frame Thickness	Aperture	Thickness	Coating
1	Si	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	100nm	None
2	Si	5.0mm x 5.0mm	200nm	1.5 mm x 1.5 mm	200nm	None
3	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	30nm	None
4	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	50nm	None
5	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	100nm	None
6	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	200nm	None
7	SiRN	5.0mm x 5.0mm	200nm	1.5 mm x 1.5 mm	100nm	None
8	SiRN	5.0mm x 5.0mm	200nm	1.5 mm x 1.5 mm	200nm	None
9	SiRN	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	100nm	None
10	SiRN	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	200nm	None
11	SiRN	5.0mm x 5.0mm	200nm	2.5mm x 2.5mm	100nm	None
12	SiRN	5.0mm x 5.0mm	200nm	3.0mm x 3.0mm	200nm	None
13	SiC	5.0mm x 5.0mm	381nm	1.0mm x 1.0mm	100nm	None
14	SiC	5.0mm x 5.0mm	381nm	1.5mm x 1.5mm	100nm	None
15	SiC	5.0mm x 5.0mm	381nm	1.5mm x 1.5mm	200nm	None
16	SiC	5.0mm x 5.0mm	381nm	2.0mm x 2.0mm	100nm	None
17	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	30nm	None
18	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	None
19	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	None
20	Si3N4	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	100nm	None
21	Si3N4	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	200nm	None
22	Si3N4	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	100nm	None
23	Si3N4	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	200nm	None
24	Si	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	Aluminium
25	Si	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	200nm	Aluminium
26	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	30nm	Aluminium
27	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	50nm	Aluminium
28	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	Aluminium
29	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	Aluminium
30	SiRN	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	100nm	Aluminium
31	SiRN	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	200nm	Aluminium
32	SiRN	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	100nm	Aluminium
33	SiRN	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	200nm	Aluminium
34	SiRN	5.0mm x 5.0mm	200nm	2.5mm x 2.5mm	100nm	Aluminium
35	SiRN	5.0mm x 5.0mm	200nm	3.0mm x 3.0mm	200nm	Aluminium
36	SiC	5.0mm x 5.0mm	381nm	1.0mm x 1.0mm	100nm	Aluminium
37	SiC	5.0mm x 5.0mm	381nm	1.5mm x 1.5mm	100nm	Aluminium
38	SiC	5.0mm x 5.0mm	381nm	1.5mm x 1.5mm	200nm	Aluminium
39	SiC	5.0mm x 5.0mm	381nm	2.0mm x 2.0mm	100nm	Aluminium
40	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	30nm	Aluminium
41	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	Aluminium
42	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	Aluminium
43	Si3N4	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	100nm	Aluminium
44	Si3N4	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	200nm	Aluminium
45	Si3N4	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	100nm	Aluminium
46	Si3N4	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	200nm	Aluminium

Figure 10: Round 2 of pressure testing, uncoated windows, indicating failure (red), success (green), not fabricated (grey)

Aperture/thickness	100nm	200nm
1mmx1mm	red	grey
1.5mmx1.5mm	grey	red

(a) Uncoated silicon windows

Aperture/thickness	100nm	200nm
1mmx1mm	red	grey
1.5mmx1.5mm	red	red
2mmx2mm	red	grey

(b) Uncoated silicon carbide windows

Aperture/thickness	30nm	50nm	100nm	200nm
1mmx1mm	red	green	green	grey
1.5mmx1.5mm	grey	grey	red	green
2mmx2mm	grey	grey	red	red
2.5mmx2.5mm	grey	grey	red	grey
3mmx3mm	grey	grey	grey	red

(c) Uncoated silicon-rich nitride windows

Aperture/thickness	30nm	100nm	200nm
1mmx1mm	red	green	green
1.5mmx1.5mm	grey	red	red
2mmx2mm	grey	red	red

(d) Uncoated silicon nitride windows

sharp object is used to press on the frame, cracking the window. This may explain the confusing and inconclusive results of Fig 9a through Fig 9d.

3.2 Second round of testing

To avoid the issues discussed above, the following changes were made to the method: Less epoxy was used, especially for large windows, and a cotton bud was used to press the frame into the glue, making a better seal. For the second round, all 46 window types were tested, both those with an aluminium coating and those without.

3.3 Windows without aluminium coating

For the windows without an aluminium coating, the results are in line with predictions. All of the silicon carbide and silicon windows have broken, and only select windows of 1.0mm to 1.5mm in length have remained intact, with thicker windows fairing better.

3.4 Windows with an aluminium coating

The results, however, are not as promising for the aluminium-coated windows. Firstly, it is surprising to see that the 2.5mm and 3.0mm side length silicon-rich nitride windows did not fail, but the 1.5mm and 2.0mm windows did. A similar discrepancy is present for the silicon nitride windows.

It is not possible to check the windows once glued for excess epoxy, as the aluminium coating is opaque. Therefore, some defective glueing may have caused the issues, by accidentally strengthening the larger windows (the frame is smaller for the larger windows).

The results do, however, provide a clear indication of which windows should be subject to further pressure testing:

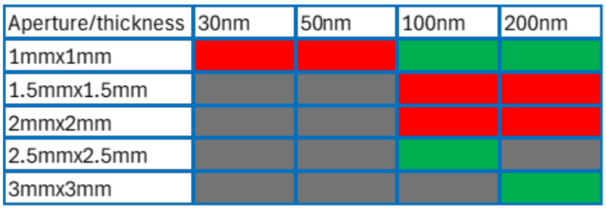
3.5 Fatigue testing control

The window will, over its lifetime, be repeatedly subject to changing pressures as the air is pumped out for high vacuum. As such, it is important to conduct fatigue testing on all windows which withstood the

Figure 11: Round 2 of pressure testing, aluminium coated, indicating failure (red), success (green), not fabricated (grey)

(a) Uncoated silicon windows

(b) Uncoated silicon carbide windows



(c) Uncoated silicon-rich nitride windows

(d) Uncoated silicon nitride windows

Table 2: Windows for fatigue testing

Window	**Material**	**Frame**	**Frame Thickness**	**Aperture**	**Thickness**	**Coating**
4	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	50nm	None
5	SiRN	5.0mm x 5.0mm	200nm	1.0 mm x 1.0 mm	100nm	None
8	SiRN	5.0mm x 5.0mm	200nm	1.5 mm x 1.5 mm	200nm	None
18	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	None
19	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	None
28	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	100nm	Aluminium
29	SiRN	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	Aluminium
34	SiRN	5.0mm x 5.0mm	200nm	2.5mm x 2.5mm	100nm	Aluminium
35	SiRN	5.0mm x 5.0mm	200nm	3.0mm x 3.0mm	200nm	Aluminium
36	SiC	5.0mm x 5.0mm	381nm	1.0mm x 1.0mm	100nm	Aluminium
42	Si3N4	5.0mm x 5.0mm	200nm	1.0mm x 1.0mm	200nm	Aluminium
44	Si3N4	5.0mm x 5.0mm	200nm	1.5mm x 1.5mm	200nm	Aluminium
45	Si3N4	5.0mm x 5.0mm	200nm	2.0mm x 2.0mm	100nm	Aluminium

simple pressure differential test in 4.2. This process can be automated by using two electropneumatic valves, such as the DN-16 ISO-KF HV angle valve [4]. For fatigue testing, the valves should be operated as follows:

1. 2 seconds: Valve 1 open, Valve 2 closed
2. 28 seconds: Valve 2 open, Valve 1 closed

The valves are operated with a 24V digital input, so the NI 9403 module was chosen, with an external 24V power supply. Using LabVIEW, a program to create the above sequence of digital outputs was made, and will be used to test the windows. The testing setup is shown below in Figure 12. The front panel of the valve control VI, and the oscilloscope reading from the digital outputs is also shown below, in Figure 13 and 14 respectively

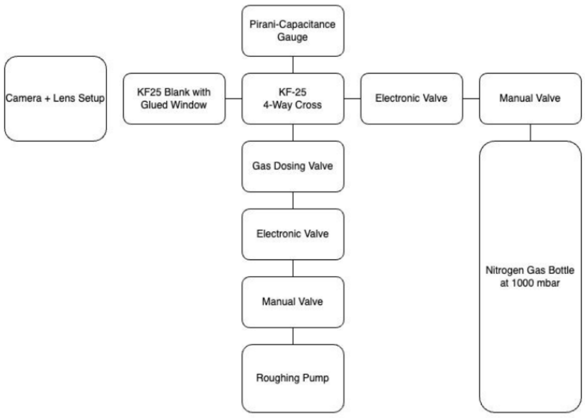


Figure 12: Fatigue testing setup

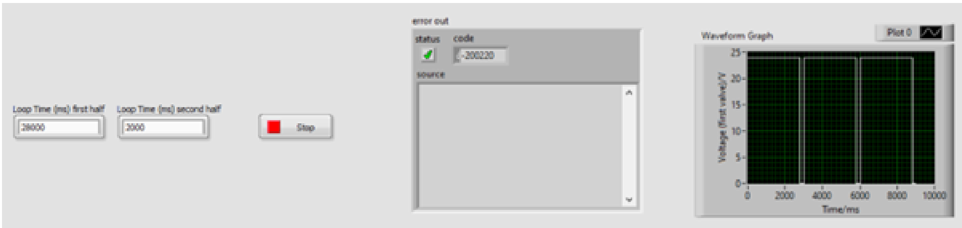


Figure 13: Valve Control VI front panel

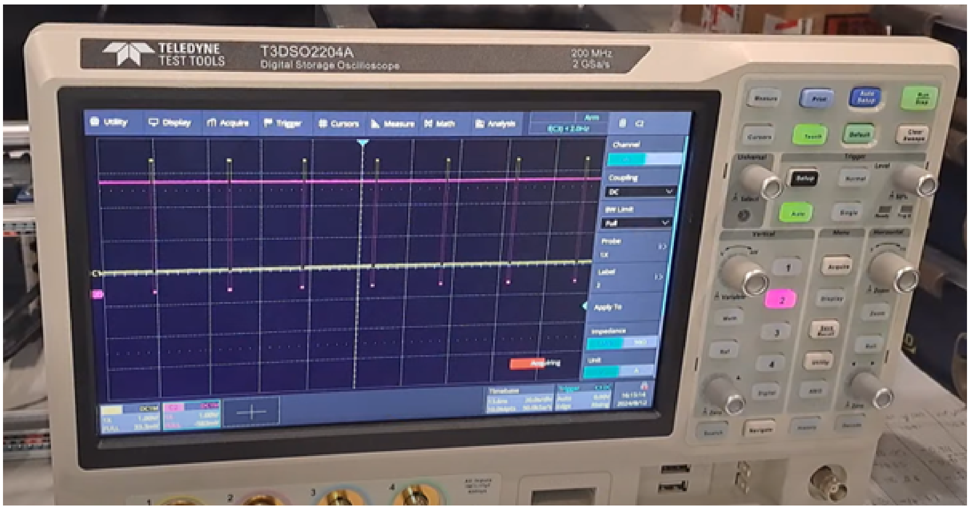


Figure 14: Oscilloscope reading for the digital outputs from the valve program

4 Conclusions

In summary, parts of a modular control and DAQ system were developed, for the power supplies of the NEWTS apparatus which supply the electron gun and chopper. In addition, pressure differential testing of Ultra-Thin Membrane windows was conducted, both of those with and without an aluminium coating.

The next steps for this project are, first, to connect the NI compactRIO with cabling to the NEWTS apparatus and test the controls for the electron gun and chopper. Secondly, the control VIs should be added to the main program, such that they are controllable from the GUI. Finally, pressure fatigue testing of the windows will be carried out, to ensure that the chosen window can withstand repeated loading.

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First, I would like to thank my supervisor, Sameed Muhammed, for his constant guidance and support over this summer, and leadership of the UTMOST CLEEN project. In addition, I'd like to thank Abhishek Ganesh, the technical student who worked before me on this project, and without whom my research would not have been possible. I'm also really grateful to my section, SY-BI-XEI, and the friends I made at CERN, for being so supportive and welcoming. Last, but not least, I'd like to thank my family for encouraging me to take this opportunity.

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[4] https://www.vatvalve.com/series/high-vacuum-angle-valve/26424-KA41