Nitrogen Usage and Nitrogen Generation

Contact *steve.blake@stfc.ac.uk*

Stephen Blake

Central Laser Facility, STFC, Rutherford Appleton Laboratory,
HSIC, Didcot, Oxfordshire, OX11 0QX, UK

Robert Taylor

Activ Air Automation Ltd, Belmont House, Kimpton Road,
Sutton Surrey, SM39TE www.activ-air.co.uk

Introduction

Nitrogen is used throughout the CLF as a reliable supply of compressed gas to operate laser shutters, purge laser cavities and purge vacuum pumps. We carried out a review to evaluate our current usage and investigated Nitrogen generation hardware with a view to implementing it should it be more cost effective in the long run.

Why do we need to use Nitrogen?

Much of the hardware is purged with Nitrogen to ensure any flammable gasses are diluted well below the lower explosive limit. Laser amplifiers, optics and targets are constantly purged to ensure an oxygen depleted atmosphere. Historically a pipe work infrastructure was fed from a Nitrogen evaporator connected to a cryogenic storage vessel and the Nitrogen provided an extremely low particulate, oil free and highly reliable supply for laser shutters and sliding mirror assemblies. This provided excellent hardware reliability and low maintenance.

What has changed to make generation an option?

Oil free compressor technology has improved recently with the development of screw and scroll compressors. Pressure Swing Absorption (PSA) Nitrogen generators are also more commonplace, utilising molecular sieves, filters, valves and a control system to generate high quality Nitrogen. Oil free compressed air can be generated by non lubricated Piston compressors, Screw compressors, Scroll compressors or by employing a significant number of oil filters to prevent the oil reaching the product. The advent of water lubricated screw compressors has opened up a significant alternative source of oil free compressed air at a more affordable level.

In the past connecting millions of pounds of optics, amplifiers and sensitive systems to an oil lubricated compressor with a number of oil filters in the system would have posed a major risk that was easily mitigated by the installation of a liquid Nitrogen tank and evaporator.

With our need for large quantities of Nitrogen gas and not liquid Nitrogen, additional processing is being carried out on the product that is not necessarily required. Although the liquid is 99.9999% pure Nitrogen, we believe 99% Nitrogen is sufficient for our processes. High quality compressed air is required to letup vacuum vessels therefore both systems could be combined in the same area.

What is our usage?

In order to determine any possible saving it is important to quantify the past, current and future usage. The past usage can be calculated by analysing the quantity of liquid purchased per month. Figure 1 shows the liquid consumed per month over a two year period and looks at how the facility has changed in that period.

Averaging the liquid usage from figure 1 340LPM (Litres Per Minute) was used whilst the Lasers for Science Facility was located in R1. Very roughly and ignoring other factors usage dropped to about 226LPM after the LSF relocated to the Research Complex at Harwell.

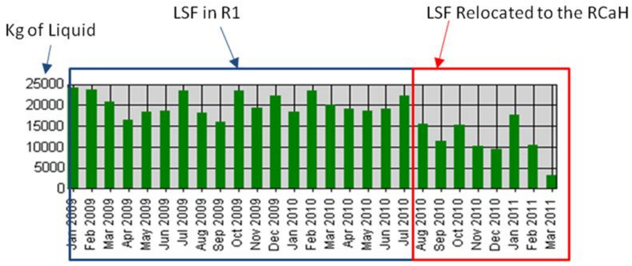

Figure 1- showing the liquid consumed over the last 2 years.

In an attempt to confirm the usage a SMC high gas flow switch (PF2A7H type) was installed on the main supply pipe from the tank. Figure 2 shows a trace confirming the background to be around 220LPM. The spikes relate to three simulated Vulcan shots and high demand from another area which ramped down at about 18:35.

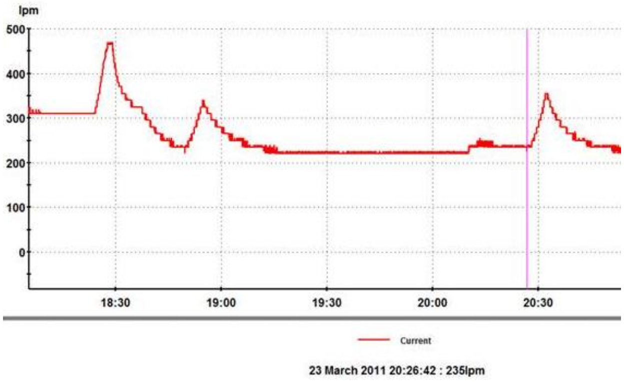

Figure 2- a trace of the Nitrogen usage on the 23rd March 2011.

Figure 3 shows a longer trace taken over three days starting on the 7th June 2011. Again the background is stable at about 220LPM and a higher demand spike relates to an increased demand in target areas or clean rooms.

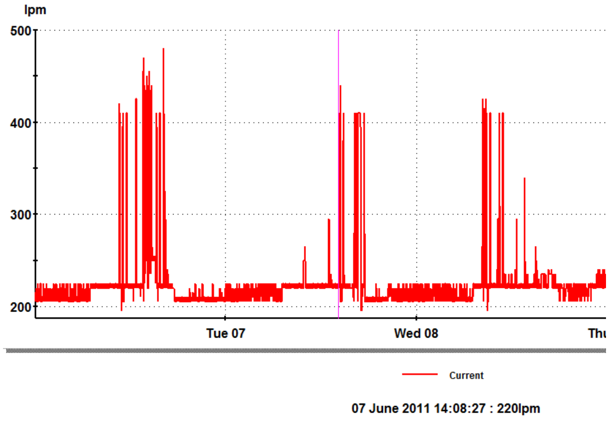

Figure 3 showing the nitrogen usage over three days.

Unless other large sections of the CLF are relocated or shutdown demand will again increase as more vacuum pumps and laser systems are commissioned as areas continue to add complexity and develop. It is important that any new system can support an increased demand.

Nitrogen Generation

To generate Nitrogen a number of components need to be in place. A compressor is required to supply the compressed air, an air receiver is required as a buffer to smooth out the peaks, a nitrogen generator removes the oxygen and finally an air receiver buffers the processed Nitrogen for use. Each one of these steps has a number of options and these are explained below.

Compressors

There are three main compressor technologies that are fully oil free. These are Piston, Scroll or Screw compressors.

In order to generate 400LPM of Nitrogen the compressor would need to deliver about 1200LPM of air. Piston pumps could be utilised but they are generally bulky and a significant source of vibration which could impact the operation of the facility. Scroll compressors could be employed, but their maximum size is limited and a large number would be required (7-8). Trying to get all the scroll compressors to function together as a team would impact the reliability; increase the complexity and ultimately increase the operating costs. Screw compressors would offer the best compromise for reliability, servicing and footprint. One manufacturer Almig offer a variable speed water injected screw pump at the required capacity and an example is shown in figure 4. The components identified are as follows:

1. Stainless steel single stage compressor
2. IP55 rated 3-phase electric motor
3. Refrigerant drier to dry air and supply water to compressor.
4. Stainless steel cyclonic separator to aid air drying.
5. Direct drive transmission system
6. Power supply hardware
7. HMI screen

Figure 4- showing the Almig water injected screw compressor

Nitrogen generator

There are two main technologies to convert compressed air to Nitrogen.

1. Membrane based technology that has a maximum purity of 99%.
2. Pressure swing adsorption (PSA) which allows generation to higher purities up to 99.9999%.

Both can be adjusted to achieve any level up to the maximum. The major factor in purity is the amount of compressed air consumed. For example with PSA 2/3 of the compressed air is exhausted to get to 99% purity. More than 3/4 of the compressed air would be exhausted to get to 99.9%. Therefore the compressor size required gets exponentially larger for each increase in purity required.

The membrane technology is generally cheaper but requires a significant desiccant drier and annual replacement of the membrane increasing the maintenance costs and downtime, negating the initial cost benefit. The PSA generator by SysAdvance shown in figure 5 does not require a desiccant drier and the PSA medium requires replacement every five years. This reduces maintenance costs and intervention significantly, making the unit more cost effective in the long run.

Figure 5- showing the SysAdvance Nitrogen Generator

Accumulators

Good quality accumulators are manufactured to comply with BS5169 and EN286-1. They are generally manufactured to order and would be constructed from a standard domed ends with a range of heights to fit the volumetric requirements. The ends would be manufactured to a range of standard diameters allowing significant scope for size and volume. An example of an air receiver is shown in figure 6.

With the supply air from the screw compressor at 10bar gauge the output pressure of the nitrogen generator would be at 8 bar gauge. Nitrogen at 7 bar gauge is distributed around the facility so any stored nitrogen would only represent 1 x the volume of the accumulator. For example at 250LPM a 3 cubic metre vessel would only last 12 minutes without a Nitrogen supply before the pressure dropped below 7bar. This would not provide a worthwhile buffer should there be a significant additional demand or hardware failure. To improve the stored volume a higher pressure receiver could be specified and a booster pump to increase the pressure to 30 bar gauge. In this example the stored volume would be 23 x 3 = 69 cubic metres. Again assuming a drain of 250LPM the system could fulfil demand for approx 4.5 hours.

This booster pump would increase the real estate required, the cost and increase the complexity and potential for single point failure.

Figure 6- showing an example of an air receiver.

Redundancy

The liquid Nitrogen system runs 24/7 and any proposed alternative would need to have the same reliability. Servicing, maintenance and failure management would need to be considered to achieve this. The safest system would be 100% redundancy as shown in figure 7 where a single compressor and Nitrogen generator would be able to meet the normal demand. This also has capacity to cope with an extreme peak demand where the fixed compressor would take over as the main supply and the variable would top up.

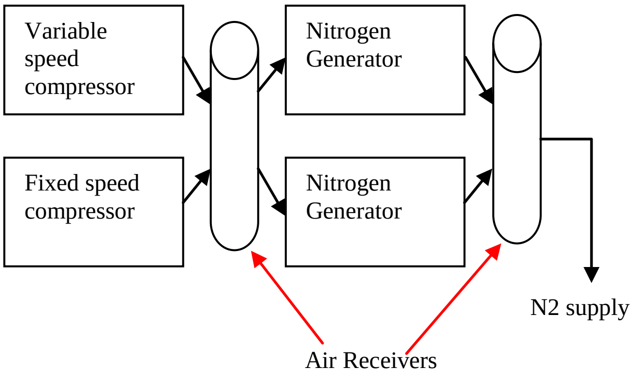

Figure 7- showing a system with redundancy.

Advantages/Disadvantages

Liquid Nitrogen will always naturally want to boil off, and the only time there would be no gas would be if the liquid was not delivered. Boil off nitrogen will always be extremely dry and pure as any impurities would lead to complications in the tank. However due to environmental levies and the need to liquefy, transport and store the liquid this will always be an expensive option in the long term.

Nitrogen generation introduces susceptibility to power failure and mechanical breakdown. Insufficient investment in hardware can impact the maximum gas available. Replacing underspecified compressors or generators with larger capacity versions would be incredibly expensive. Adding sufficient redundant hardware to attempt to match the reliability of the boil off system will require a significant capital investment. With a well specified system it is expected that after 3-4 years the hardware would pay for itself.

Installation

Figure 8 shows the redundant system could be installed in the TAP plant room providing compressed air to let-up the vacuum chambers and supply the Nitrogen generators. Space for the accumulators and vacuum pumps has also been allocated.

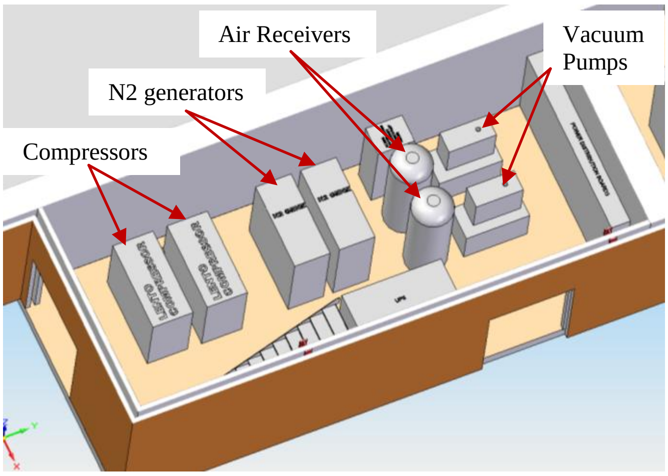

Figure 8- showing the TAP plant room with the redundant system described in figure 7.

Conclusions

Nitrogen generation is a viable alternative to using liquid Nitrogen boil off for the CLF. Significant initial investment would be required to fund the compressors, generators and accumulators with an estimated breakeven point after three to four years. Two main options are proposed:

1. Dual compressor and generator scheme as depicted in Figure 7.
2. Single compressor, single generator and a high pressure booster pump/accumulator combination.

Option 1 provides the most reliability and flexibility. Option 2 would be lower cost but maintenance windows would be limited to a few hours at most and complete failure of any system would lead to downtime.

Acknowledgements

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Environmental and Equipment Monitoring

Contact *steve.blake@stfc.ac.uk*

Stephen Blake

Central Laser Facility, STFC, Rutherford Appleton Laboratory,
HSIC, Didcot, Oxfordshire, OX11 0QX, UK

Introduction

Monitoring of the mechanical hardware and mechanical services throughout the Central Laser Facility has been limited. Failure of plant has been apparent when working back from the effect rather than being aware of the cause. An example is a vacuum failure in TAP caused by overheating of the room water cooling circuit, but the primary failure was the air conditioning plant providing cooling to the room water circuit. In many instances failure of hardware happened over a period of days or weeks where performance slowly deteriorated. With the minimum of funding these could be identified early and resolved without impact to the programme.

Specification

We were looking for a cost efficient solution that could monitor temperatures, vacuum level, relay set-points, water flow and gas pressure. When a pre-determined event occurred the system should send emails or SMS messages identifying the error and be easily interrogated to look at long term trends. It should be possible for anyone to access but the main settings should be password protected. It needed to be a simple solution that could be installed in every area but each area owner would only be interested in their hardware being monitored.

Potential Solutions

Both ISIS and RAL Space employ sophisticated systems offering a wide range of sensor options with a highly customisable data display. This flexibility not only requires significant financial investment in the hardware but also the software front end. Much of what we wanted to monitor would be standard for high end server rooms and this is a highly competitive marketplace where a number of commercial solutions were available. The most flexible and cost effective was the climate monitor range from Swiftbase[1]. This had previously been reviewed and was highly recommended by the PC Pro[2] magazine.

Implementation

The project started in TAP as this area could gain the most in terms of monitoring. Not only does the mechanical hardware require reliable cooling water but the room temperature affects the beam alignment and experimental weeks can be lost if the compression chamber vacuum level rises to more than 1mbar.

The climate monitor was located in the vacuum rack in the control room and a loom constructed to allow the following to be monitored:

1. Vacuum pump water temperatures in the Target Area and Plant Room.
2. Plant Room and Target Area room temperatures.
3. Interaction Chamber and Compression Chamber vacuum level.
4. Nitrogen gas circuit pressure.

Hardware

Climate Monitors

The monitors are a rack mounted unit 1U in height and the data can be accessed from any computer via the hosted web page. We have deployed three different variants (figures 1-3) but settled on the CM-16 and CM relay for future installations. The CM-2 offers additional sensors that are not beneficial in our rack environment.

Figure 1- The CM-2 offers up to sixteen 1-Wire sensors with three analogue ports and an airflow sensor, a sound sensor and a light sensor.

Figure 2- The CM-16 offers up to sixteen 1-Wire sensors with three analogue ports.

Figure 3- The CM relay offers up to sixteen 1-Wire sensors with six analogue ports and three relays for controlling external hardware.

Room Sensor:

The room sensor from Swiftbase (figure 4) allows the room temperature and relative humidity to be monitored with a reading logged every minute. This employs the Maxim DS18B20[3] and the Honeywell HIH-3610[4] series humidity sensor. Since we are looking at relative temperatures the accuracy limitations on the Maxim chip are not a concern and the relative humidity monitoring is unlikely to be used for controlling hardware meaning that the +/-2%RH is not critical.

Figure 4 - showing the room temperature and humidity sensor with a RJ11 connector.

Water Temperature

Modifying the Swiftbase temperature sensor to fit on the water circuit would lead to a cumbersome package and thus we have purchased the sensor directly from a distributor. This has been wired to a low cost 3-pin plug and bonded to a standard nut. Experimentation has shown thermal lag as being minimal and the package although not elegant (see figure 5) has been functional.

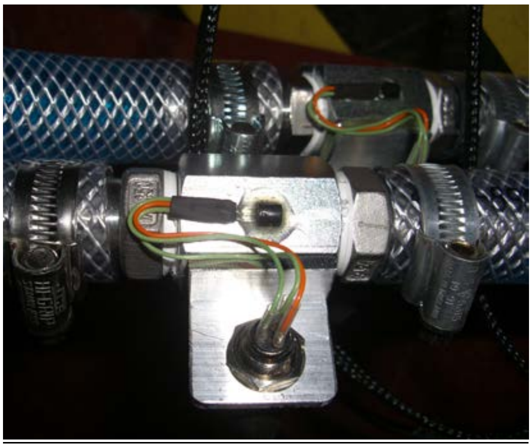


Figure 5- DS18B20 sensors bonded to stainless steel nuts within the supply and return pipe work for the vacuum pumps.

Water Flow Sensor

We have installed and tested a SMC PF3W water flow switch shown in figure 6. We connected the 1-5V output to the analogue input on the climate monitor and although the climate monitor does not currently permit the legend on the scale to be altered it's still possible to identify a level for the trip and compare historical flows.

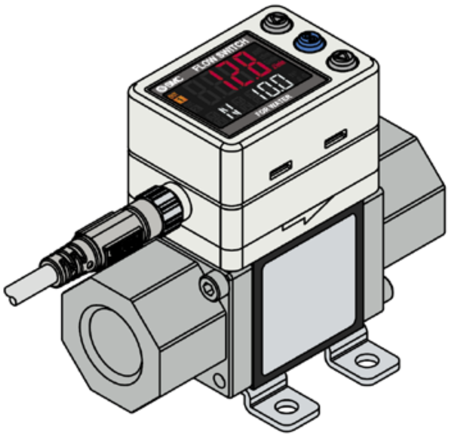


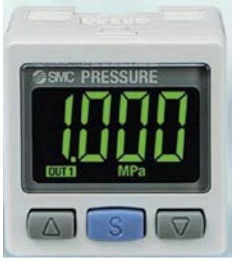
Figure 6 – showing the PF3W SMC water flow switch used to monitor the water flow.

Vacuum Gauge

We utilised a MKS 974[5] wide range vacuum gauge to provide the output to the monitor. This is shown in figure 7. Connecting the log linear output through a voltage divider circuit the voltage was modified to register between 0-5V. Although it's not possible to read an actual vacuum value it can be used to identify problems comparing the current pump down curve to a known curve. Again an appropriate alert level can be set for warnings, the current vacuum status of the chamber can be seen from any computer and the number of vacuum cycles per day can be confirmed.

Figure 7- showing the MKS 974 vacuum gauge.

Pressure Gauge



We have selected a SMC pressure switch from the same family as the water flow switch. This is shown in figure 8. Although we have yet to install and test its functionality, the installation method would be identical to the water flow switch shown in figure 6.

Figure 8- SMC ISE30A pressure switch.

Historical Data Backup

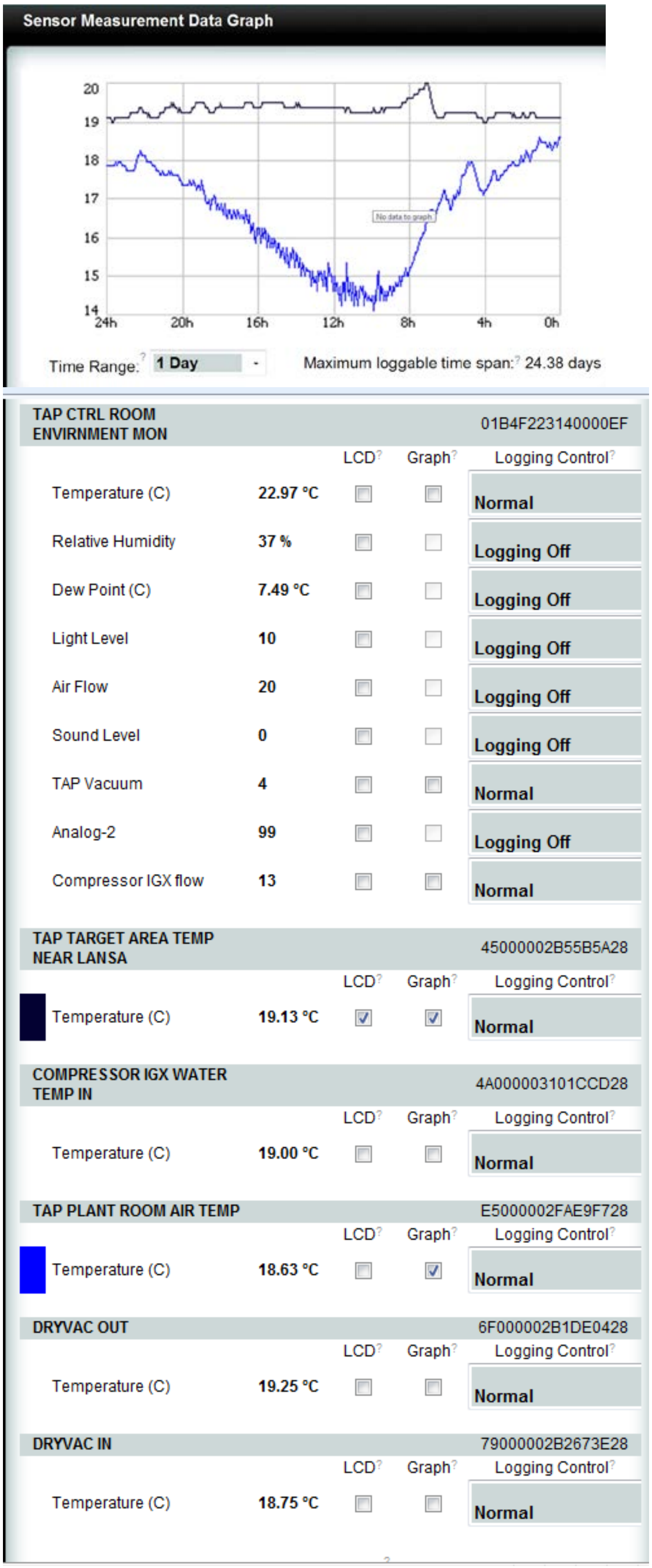
Each climate monitor has a small flash memory chip onboard to record the data. Depending on the number of sensors being recorded this could store several months of data down to several weeks. There is an option to download the datafile in CSV format and we have automated the download to capture the datafile each Sunday. The batch file is set to run using task scheduler (included in Microsoft Windows XP and Windows 7) interrogating the status of each IP address and then using the free utility wget.exe downloads the CSV file to a network share.

Graphical Interface

The graphical interface is accessed by typing the IP address into a web browser. The main menu area is shown in figure 9 where the sensors tab lists and displays a graph for each sensor independently. The Alarms tab allows limits to be set and email address to be selected. The Logging tab provides the most comprehensive method of comparing the data and the method of selecting the data to be recorded. The Display tab allows each sensor to be renamed to be more meaningful. The Config tab is where passwords, IP addresses, and server details are specified.

Figure 9 -showing the main menu area

Figure 10 shows the logging screen for TAP where the Target Area and Plant Room temperatures are displayed for a 24 hour period. The sensors are listed on the left and the logging status on the right shows normal for those that are stored.



Time Range: 1 Day

Maximum loggable time span: 24.38 days

TAP CTRL ROOM ENVIRNMENT MON	01B4F223140000EF	LCD	Graph	Logging Control
Temperature (C)	22.97 °C	☐	☐	Normal
Relative Humidity	37 %	☐	☐	Logging Off
Dew Point (C)	7.49 °C	☐	☐	Logging Off
Light Level	10	☐	☐	Logging Off
Air Flow	20	☐	☐	Logging Off
Sound Level	0	☐	☐	Logging Off
TAP Vacuum	4	☐	☐	Normal
Analog-2	99	☐	☐	Logging Off
Compressor IGX flow	13	☐	☐	Normal

TAP TARGET AREA TEMP NEAR LANSA	45000002B55B5A28	LCD	Graph	Logging Control
Temperature (C)	19.13 °C	☑	☑	Normal

COMPRESSOR IGX WATER TEMP IN	4A000003101CCD28	LCD	Graph	Logging Control
Temperature (C)	19.00 °C	☐	☐	Normal

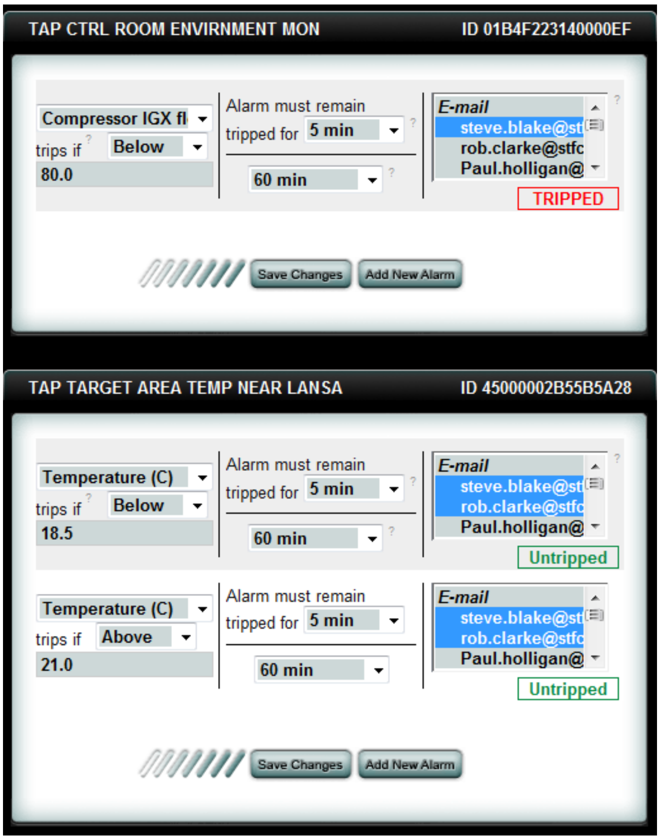
TAP PLANT ROOM AIR TEMP	E5000002FAE9F728	LCD	Graph	Logging Control
Temperature (C)	18.63 °C	☐	☑	Normal

DRYVAC OUT	6F000002B1DE0428	LCD	Graph	Logging Control
Temperature (C)	19.25 °C	☐	☐	Normal

DRYVAC IN	79000002B2673E28	LCD	Graph	Logging Control
Temperature (C)	18.75 °C	☐	☐	Normal

Figure 10 showing the logging screen for TAP

Figure 11 shows part of the alarms screen where three different alarms are set. Up to five email addresses can be stored to be used in any of the alarms. The top part of the figure shows the analogue input level set to 80% equating to a signal of 4V. Therefore if the flow meter registered a voltage below 4V for 5 minutes the alarm would be tripped and all selected email addresses would be sent a message. The next panel is specifically against one sensor whereby the room limits are set and email addresses are selected. Multiple levels and corresponding e-mail addresses can be set for each sensor.


TAP CTRL ROOM ENVIRNMENT MON ID 01B4F223140000EF

Compressor IGX fl
trips if Below
80.0
Alarm must remain tripped for 5 min
60 min
E-mail
steve.blake@st
rob.clarke@stfc
Paul.holligan@
TRIPPED

TAP TARGET AREA TEMP NEAR LANSA ID 45000002B55B5A28

Temperature (C)
trips if Below
18.5
Alarm must remain tripped for 5 min
60 min
E-mail
steve.blake@st
rob.clarke@stfc
Paul.holligan@
Untripped

Temperature (C)
trips if Above
21.0
Alarm must remain tripped for 5 min
60 min
E-mail
steve.blake@st
rob.clarke@stfc
Paul.holligan@
Untripped

Figure 11 – showing the alarms page on the TAP monitor

Conclusions

An environmental monitoring solution is being rolled out across the CLF to improve the overall reliability of the facility. A solution aimed at computer server rooms has provided an off the shelf, low cost and quick to implement solution. Long term logged data is already available for some areas. A number of events on the air conditioning plant have already been identified early and resolved.

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Motion Control System Development

Contact *Paul.Holligan@stfc.ac.uk*

P Holligan, D Rathbone, J Suarez-Merchan, A Zayyani

Central Laser Facility, STFC, Rutherford Appleton Laboratory,
Chilton, Didcot, OX11 0QX

Introduction

Motion control is an essential component of the laser system and a major contributing factor to the successful operation of the facility. With much of the beam propagation under vacuum, it is essential that beam pointing adjustments can be made remotely, and with pulse characteristics and experimental success sometimes reliant on sub micron accuracy, attention must be given to both the mechanical design of the optical stages and the motors, encoders and other feedback devices used to ensure these control parameters are achievable. A generic motion control system will satisfy the motion control requirements of both the laser and target areas.

No commercial software solution was available to satisfy the need to use a variety of different motion controllers supplied by a number of manufacturers which was required to be easily reconfigurable with changing technologies and reconfigured for each experiment. An in house solution needed to utilise existing hardware whilst allowing the evolution of both motion controllers and the equipment under control.

Existing Hardware

There was a large amount of motion control equipment already in existence throughout the Central Laser Facility and a vast amount of knowledge surrounding its functionality and support. An attempt to standardize has focused on recommendations for mount design, integration of limits and encoders, and compatibility of motors all based on experience gained using similar systems.

Parker 6k Series[1] motion controllers have been used where possible with alternatives considered in cases where specific motion controllers are required for certain drives. Universal stepper drives and servo amplifiers have been used to allow versatility in experimental set up, but this brings additional problems relating to tuning and other drive parameters.

Quadrature (A+, B+, Index), rotary shaft and linear encoders are used along with Sony Magnescales[2] which offer excellent robustness and immunity to EMP which is a major consideration.

Software

The main software was written using Microsoft Visual Studio 2010. The source code using VB.Net is highly documented and uses a "Class" and "Form" structure. Each class is designed to be easily identified as to its control function within the whole program and the key software objective is modularity so that new classes can be added or deleted as hardware changes. All versions of the software are backed up using Subversion[3].

The user interface is designed to be intuitive with simple touch control and the user can move drives, targets and stages in a number of ways:

- Simple touch left or right
- Slider control in absolute values
- One touch for +/- 1µm or 1mm
- Numeric touchpad for absolute or relative values

The PC uses two screens, one lower screen as touch entry and upper screen as visual data which even allows the user to see a CAD model or photograph of the stage under control.

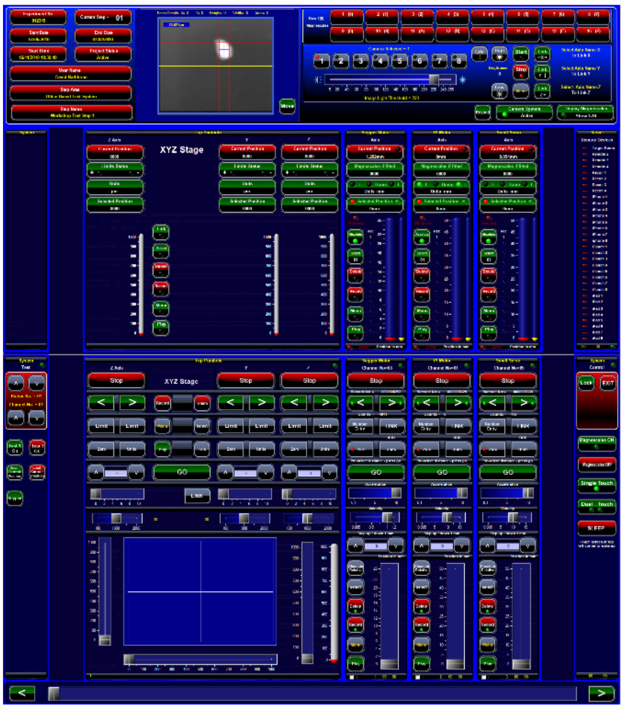

Figure 1. Two 21" touch screens are mounted together to allow intuitive user interaction and visual representation of the system.

Key to the systems performance is the database where explicit information needed to control the drive is held. The database system has its own PC user interface "Drive and Stage editor". Any PC on the network can access the database and add new experimental setups or stage and drive information along with new users etc.

The software can also be used in the planning stages of an experiment as a planning tool or to track assets where stages are used throughout the facility.

Figure 2 shows a screen shot of the PC Planning Tool which allows users to search, edit, delete or add different aspects to the drive system. This interface allows an engineer to find the maximum travel on a linear motor or the pin out for a connector on an encoder.

Further forms act as front ends to the Microsoft Access 2007[4] database engine which stores information ranging from user access rights to the IP and MAC address of motion controllers. Motor or stage information is also stored in a database and barcodes are used to easily identify equipment and reduce the set up time for an experiment. When a user scans the barcode of a stage all of the PID, maximum travel, encoder data and limit information is associated with the relevant channel. This is also a very useful way of tracking faulty stages as a simple tick box highlights the health of the stage.

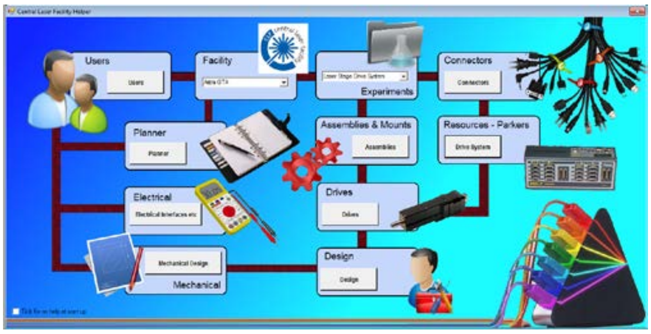

Figure 2 shows the Drive System Planning Tool where users can access and input data.

System Architecture

Central to the system is the server/master PC which is an Intel core i7[5] system with 8 GB DDR3 memory and a powerful 1 GB Nvidia GeForce graphics card. The PC runs Windows 7 Proffessional 64 bit operating system and has been selected for its multithreading ability. The server/master has to poll all of the motion controllers, remote devices and its own touch screens. This can run as a standalone system or additional slave PC's or 802.11G/N wireless hand held devices can be added for control in additional locations.

A web server is currently being developed to allow any mobile or remote device to provide control options, with screen resolutions optimised for iPad and iPhone devices. This maintains the philosophy of future proofing by not being device specific and allowing continuous development with technological advancements.

Implementation

The full system is currently operational in the Gemini Target Area with plans to upgrade current systems in Gemini LA3, Vulcan TAW and TAP in the next 12 months. Ongoing improvements will be made and additional motion controllers are continually being added.

Conclusions

Motion control and software reliability were causing serious problems and affecting experimental efficiency and success. With no commercial solution available it was clear that an in house solution utilising professional development techniques and tools would be the most effective route to take. The feedback received from users and staff confirms the success of the project.

Acknowledgements

The authors would like to acknowledge the ESG staff and facility users who have contributed to the requirements and functionality of the software as well as assisting with many hours of set up and functional testing.

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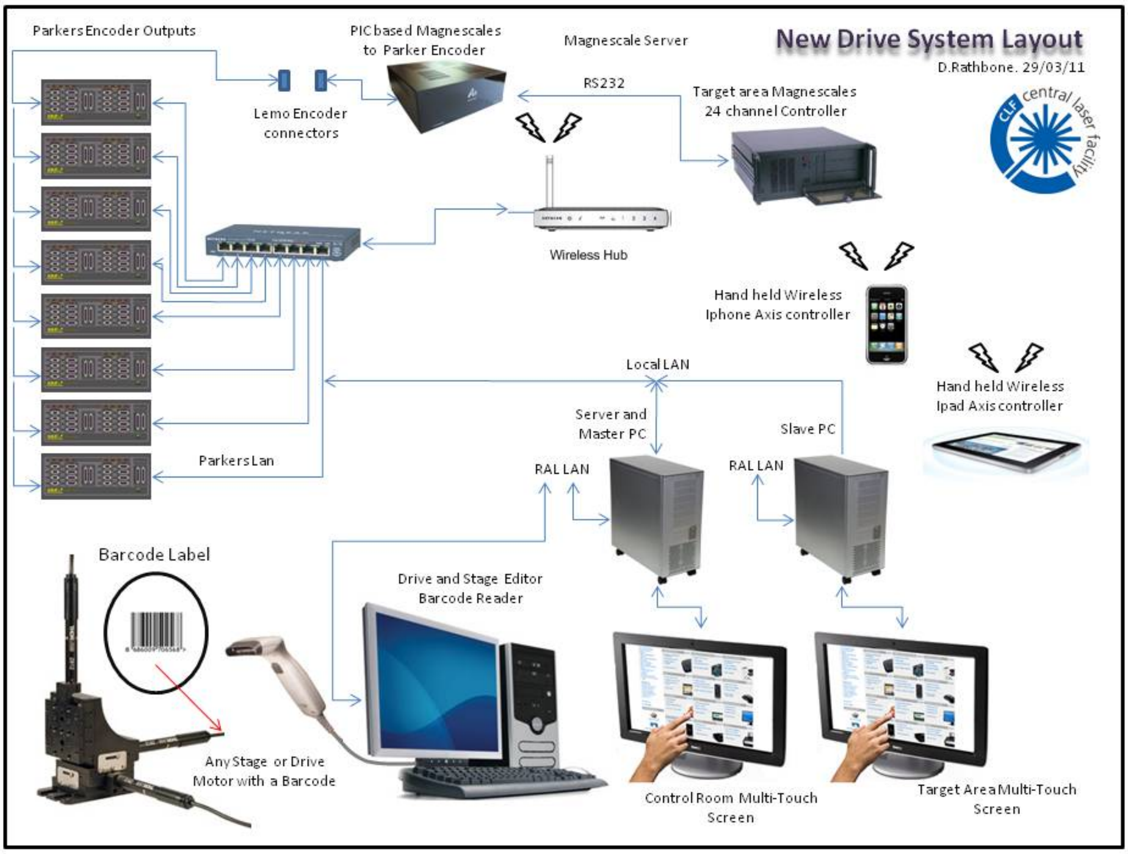

Figure 3 shows the architecture of a typical system

Pulsed Power Developments

Contact *Paul.Holligan@stfc.ac.uk*

P Holligan, Luis S. Caballero Bendixsen, M R Pitts, C Sawyer

Central Laser Facility, STFC, Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX

Introduction

The Vulcan Laser Facility and proposed 10PW upgrade utilise disc amplifiers which rely on flash lamp pumping technology[1-3]. An electrical discharge is driven through a gas producing an arc, and the radiation produced in the discharge is then used to pump the active amplifier medium (i.e. Nd: glass) achieving the population inversion required for lasing. A high voltage/current pulse is delivered by a Pulsed Power System (PPS) to create the electric discharge.

The existing Vulcan pulsed power system is too large for the proposed 10PW building, so a more compact pulsed power system needed to be designed to fit in the proposed building footprint. The existing ignitron configuration was bulky and offered scope for a reduction in size by utilising a more modern design.

Pulsed Power System

The PPS is required to deliver a high current/voltage pulse to the Xenon flashlamps and Faraday rotator coils of the laser system. Load matching is critical in the design of the system, and particularly difficult as the flashlamp has a time dependant impedance which is very high (>MΩ) when the pulse arrives, falling to mΩ as the electrical discharge dominates the reaction. The radiation output of the flashlamps is required to match the absorption spectrum of the amplifier medium, Nd:glass, which is λ ~[350 - 900 nm] this overlaps with the radiation spectrum of Xenon (Xe) FL λ ~ [250-1000nm] when a discharge current density of 5 kA/cm^2 drives the discharge.

The Faraday rotator consists of a disk of FR5 glass with a Verdet constant of 0.07 min/Oe.cm at a wavelength of 1053 nm [5], surrounded by a coil with an inductance of L=200 μH. When an oscillating current pulse with peak current of 15 kA is delivered to the coil it induces magnetic field B~15kGauss. This magnetic field changes the properties of the FR5 glass causing an incident laser beam polarization to be rotated 45°.

A simplified circuit diagram of a flashlamp circuit is shown in Figure 1. The circuit consists of a capacitor charging unit, a capacitor bank, and inductor and a high voltage switch. The PPS and flashlamp are located in different areas and are connected via a coaxial cable. The distance of coaxial cable must be kept to a minimum as there are losses associated with the coaxial cable which are typically 5 dB/100m at a frequency of 100MHz. Table 1 shows a summary of the requirements for each flashlamp pair.

Amplifier	Single FL Length (mm)	Working Voltage (kV)	Stored Energy (kJ)
150/208 mm	1100	20	50
108 mm	1240	20	45

Table 1. Amplifier requirements and operating parameters

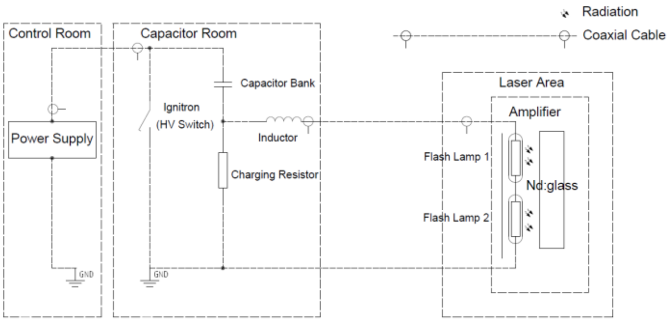

Figure 1. Simplified circuit diagram of flashlamp circuit

Ignitron Switches

The high voltage switching mechanism used on the Vulcan laser system consists of two ignitrons connected in series and gives a maximum standoff voltage of 50kV[4], as shown in Figure 2. Ignitrons are used as they are reliable, robust and require very little maintenance. Their drawback is size and the need to be both heated and water cooled to maintain a temperature differential between electrodes. In addition to the size and space implications of using two ignitron units, the extra connections increase parasitical inductance, which may affect the circuit characteristics.

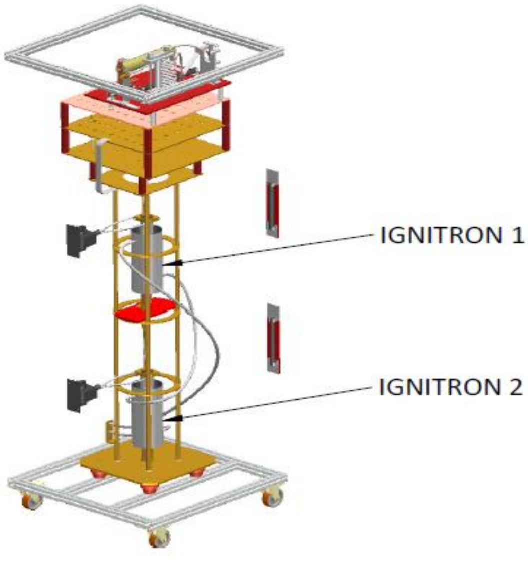

Figure 2. Ignitron cabinet

In order to meet the space requirements of the proposed 10PW capacitor room footprint there was a requirement to redesign the PFN's, capacitor banks and ignitron cabinets. This also offered the ability to replace older technology with newer technology and improve reliability and maintainability.

It was found that the NL7703EHV[5] ignitron matched the electrical characteristics of the existing series pair of ignitrons and occupied about a third of the volume when comparing with a single ignitron currently in use. These characteristics allow the ignitron to be located nearer to the capacitor bank reducing the amount of cabling, hence having a more compact design.

PFN Boards

By relocating the PFN board to the front of the capacitor bank and mounting the ignitron on a board a more compact design is achieved when compared to the existing configuration. These two changes are shown in figure 5 where the capacitor banks are shown on the right hand side, the PFN boards are shown on the left hand side and the ignitron boards are displayed in the centre.

Each amplifier circuit consists of four capacitor banks with four or five capacitors in parallel depending on which type of amplifier it is driving, four PFN boards in front of the capacitors and a single ignitron board. Therefore three amplifier circuits are located on each rack.

The Faraday boards were also redesigned to incorporate the select relays, dumping circuit and ignitron all on one front mounted board.

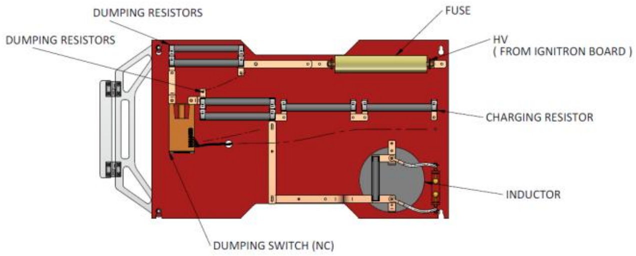

Figure 3. PFN board

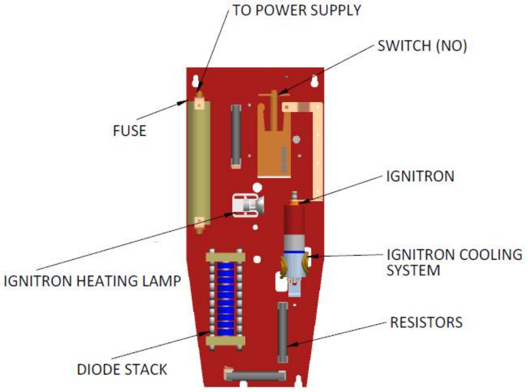

Figure 4. Ignitron board

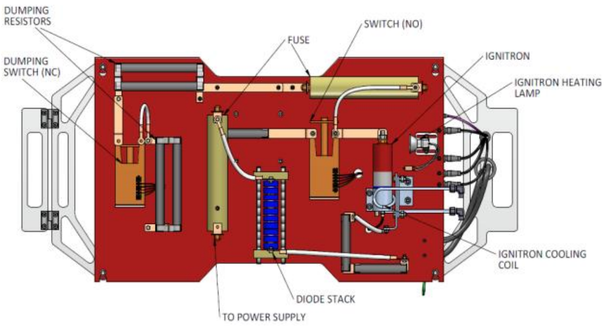

Figure 5. Faraday/Ignitron board

Conclusions

The new PFN board and ignitron board design is very compact which considerably reduces the footprint of the pulsed power system. The modular nature of the design allows for easy removal of a single component, a board or capacitor bank, resulting in a reduced turnaround time following component failure. The layout of the components also increases the visibility of the PFN and ignitron components, which aids inspection, testing and preventative maintenance.

Both circuits have been designed to maintain as many features as possible to keep to a minimum equipment variety and to manufacture or use standard parts where possible, reducing costs and assembly time.

The new PFN and ignitron board design has been successfully constructed and tested on the pulsed power test facility, with one whole amplifier circuit now available for functional and soak testing of flashlamps.

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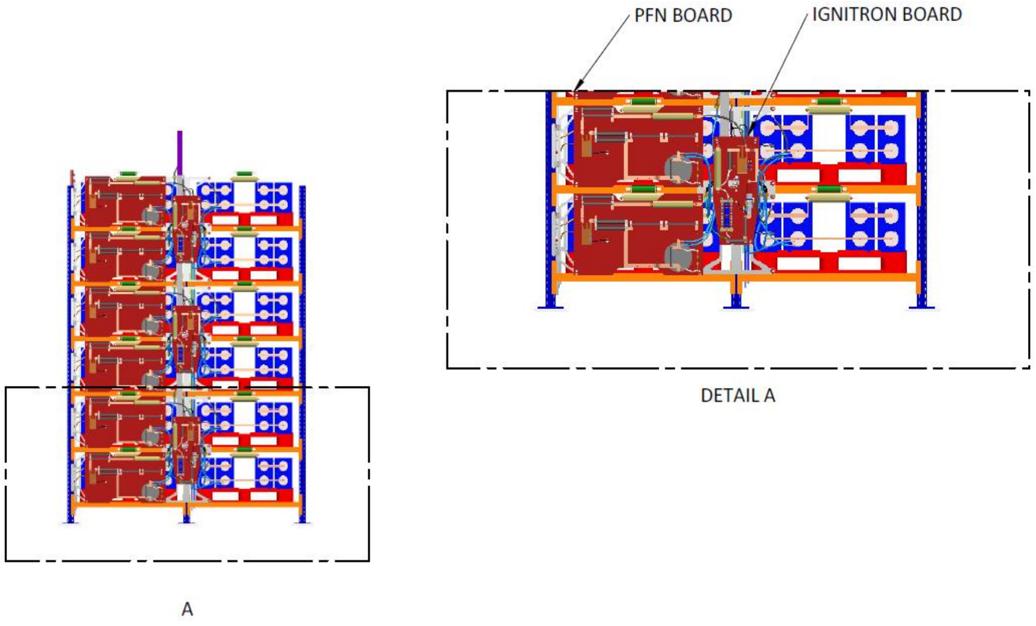

Figure 6. Amplifier circuit rack

Flash lamp Test Facility Pulsed Power and Control Upgrade

Contact *Paul.Holligan@stfc.ac.uk*

P Holligan, Luis S. Caballero Bendixsen, M R Pitts, C Sawyer, A Zayyani

Central Laser Facility, STFC, Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX

Introduction

The flash lamp test facility is used to test flash lamp pumped disc amplifiers before they are put in to operation on the Vulcan Laser system. It also serves as a test bed for pulsed power components as the hardware is identical to that used on the main facility.

In order to test the technology chosen for the Vulcan 10PW upgrade, one whole amplifier circuit was changed to incorporate the new ignitron and PFN design, leaving one amplifier circuit in the original configuration for testing and support of Vulcan components. To automate the testing of flash lamps and any pulsed power components, the control software has been upgraded to allow continuous firing and recording of data.

Flash Lamp Test Facility

The existing flash lamp test facility housed two amplifier drive circuits in order to test 108mm, 150mm and 208mm amplifiers and associated flash lamps. Each circuit consisted of a capacitor charging unit, four pallets of capacitors, PFN boards and ignitron cabinet. This area needed to be reconfigured to include the new compact circuit which has been designed for the 10PW upgrade project. This will then provide a test bed for the equipment before installation, and has allowed the technology to be proven to reduce risk to the project.

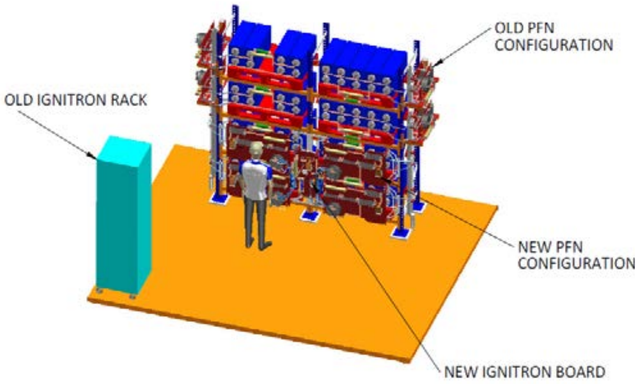

Figure 1. New Test Facility Circuit Configuration

The room layout needed to be modified so the racking could be changed to accept the new style PFN and ignitron board. Additional floor space was also required so the 10PW design Faraday driver circuit could be tested.

Test Facility	No. of Circuits	Working Voltage (kV)	Charging Time (s)	No. of Capacitors
108 mm	1	15-25	< 50	16
150/208 mm	1	15-25	< 50	20
Faraday rotator	1	5-10	< 50	4

Table 1. Test Facility Requirements

Control Software

It is essential that the charging, firing and shorting of the capacitor bank is automated to ensure the safe operation of the system, and also to allow remote selection and control from outside of the test area.

The existing control software had been written in Delphi and provided automated charging and firing of capacitors in to flash lamps or dummy loads. Testing of flash lamps required multiple lamp discharges, all performed consecutively with waveform data saved to disc for future reference. This required an operator to be present for the whole testing cycle which could last for a number of days if multiple lamps, half shells and amplifiers required testing.

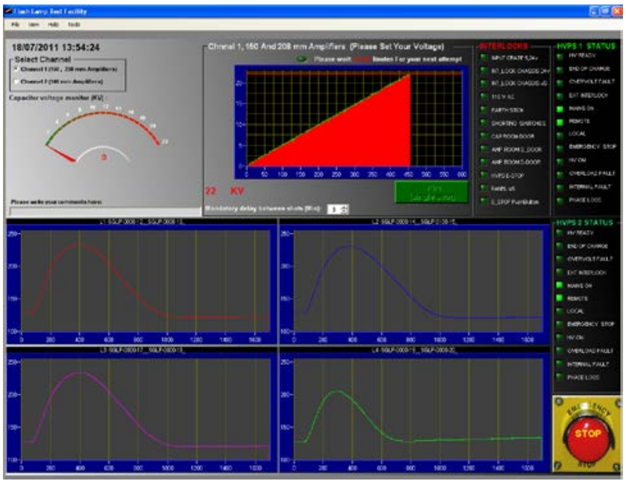

Figure 2. Control Software GUI

The control software was rewritten in VB.Net to incorporate automated testing of flash lamps, half shells, amplifiers and pulsed power components as well as providing additional manual control of components. This enables new equipment to be tested individually at reduced energy before automated testing begins.

Control Hardware

A vast amount of digital and analogue I/O is required to control and monitor all of the parameters of the pulsed power system. The capacitor chargers alone each require selection, voltage setting, command to charge and interlock connections along with a number of diagnostic signals which communicate the health of the unit. There are also a large number of HV relays, shorting switches and dump relays, all of which require control and monitoring to ensure the status of the system is known at all times. The firing of the system uses fibre optic delay generators to propagate and synchronise the firing of individual circuits.

The existing Camac control crate was used which also maintained compatibility with the Vulcan facility. The Camac crate houses digital and analogue I/O, as well as fibre optic output units for ignitron triggering.

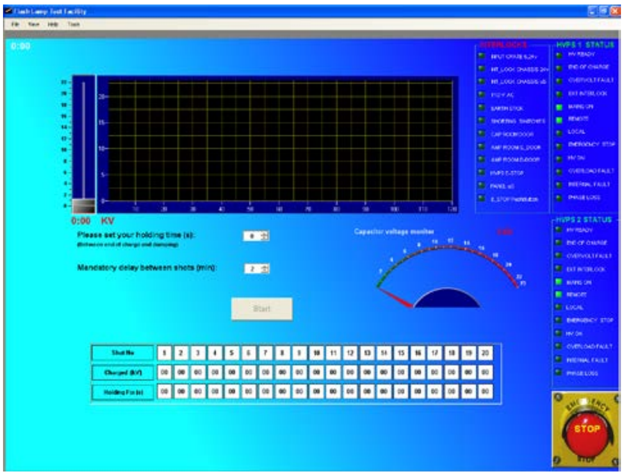

Figure 3. Component Test Screen

Testing

The existing and 10PW design circuits were tested and compared in order to determine which changes were beneficial to the Pulsed Power System and where design changes may be required. This included the testing and commissioning of the software where a number of user requests were incorporated to improve data storage and retrieval.

There were a number of layout changes which were identified to improve the installation and maintenance of the system that included the redesign of brackets and mounts, but the testing of the new PFN board and ignitron were extremely successful and proved the technology for future use. The Faraday circuit has yet to be tested but is based on the same technology as the full amplifier circuit.

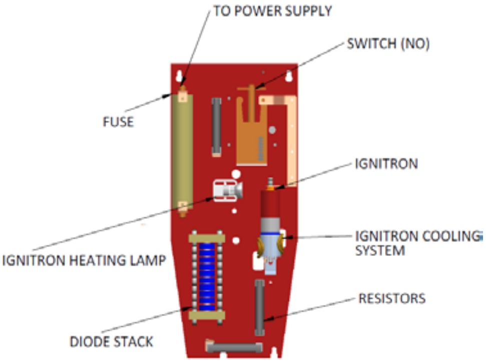

Figure 4. Ignitron board

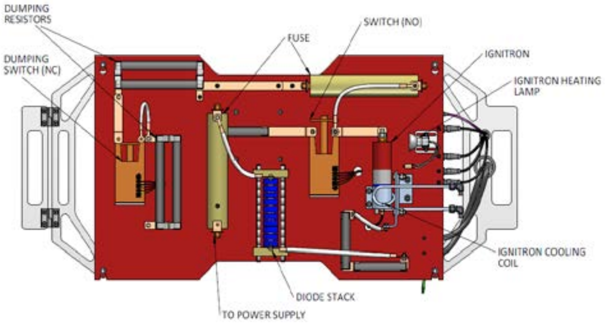

Figure 5. Faraday/Ignitron board

Conclusions

The test facility provides an invaluable tool for testing flash lamps and pulse power components before inclusion on the main facility, as well as providing working spares in case of a failure. The redesign has allowed confirmation of new technology and also provided an opportunity to automate processes which were labour intensive, freeing up much needed resource.

Research Complex Laser Interlock System

Contact *chris.john@stfc.ac.uk*

C John, A Tylee, D Robinson, P Holligan, T Roper, N Symcox

Central Laser Facility, STFC, Rutherford Appleton Laboratory,
Chilton, Didcot, OX11 0QX

Introduction

The development of the Research Complex at Harwell (RCaH) in R92, is set to provide a multi-disciplinary research facility that will attract world-class research and world-class scientists.

In order for the Lasers for Science Facility (LSF) to successfully occupy lab space in RCaH, a multi-room laser interlock and control system was required for safe laser operation.

This report highlights the design challenges and solutions employed to implement them.

Laser Interlock Safety

The LSF occupies three areas or clusters within RCaH incorporating 15 laser rooms, they are:

- FBI – Functional Biosystems Imaging known as Octopus
- ULTRA - Molecular Structure and Dynamics **MSD**
- Analytical Services - R&D labs

Laser interlock systems have been developed and used throughout the Central Laser Facility (CLF) for many years, but a new approach was employed in dealing with the FBI cluster as its requirements posed new design challenges.

RCaH System

The Lasers in this cluster are primarily transferred in fibre optics enabling ease of set up and operation with minimum of optical loss. This uniquely provides multiple laser combinations with no alignment issues.

The transfer and coupling of lasers between rooms was particularly challenging and required the design of a special coupling enclosure to maintain optical and electrical interlock continuity. (*Patent pending)* to ensure safe operation.

The operation of the FBI (Octopus) laboratory consist of five laser laboratories that can operate independently or link from the central source hub which is G 36.

Each laser lab has the capability of bringing on laser hazards and controlling the propagated hazards when coupled to the target rooms.

If the room is deemed to be unsafe or a fault is detected in one particular room this will trip all laser hazards present in that room but not affect lasers in the other rooms allowing the system to function with some independency.

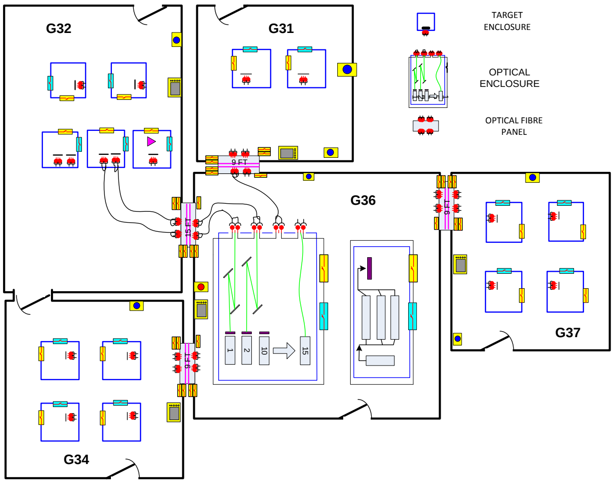

Figure 1 Operational layout of Octopus area

There is an optical enclosure situated in G36 with the provision for 20 source lasers. There are also mini electrical shutters in this optical enclosure for beam isolation and control. The lasers from inside the optical enclosure propagate to the target rooms G-31, G-32, G-34, and G-37 via a unique manufactured optical fibre and cabling combination with plugs and sockets.

Safety issues associated with optical Fibre lasers

The laser beam transmits inside the fibre optic. One of the major hazards associated in using optical fibres is the means of detecting when the fibre has been damaged. The result can cause laser beam exposure in the surrounding room to go undetected.

A combination of electrical wiring active interrogation now allow these connections and fibres to be electrically interlocked.

This solution provides the means of detecting faults and also preventing accidental or unauthorised individuals disconnecting fibres with the likelihood of shinning it into their eyes.

Due to the operational losses that occur in the coupling of optical fibre’s transferred lasers, the traditional pneumatic wall shutters can not be used between the rooms. Figure 2 shows the special Optical Fibre Panel designed to provide electrical and optical connection. This also provides physical entrapment of the optical fibre laser hazard.

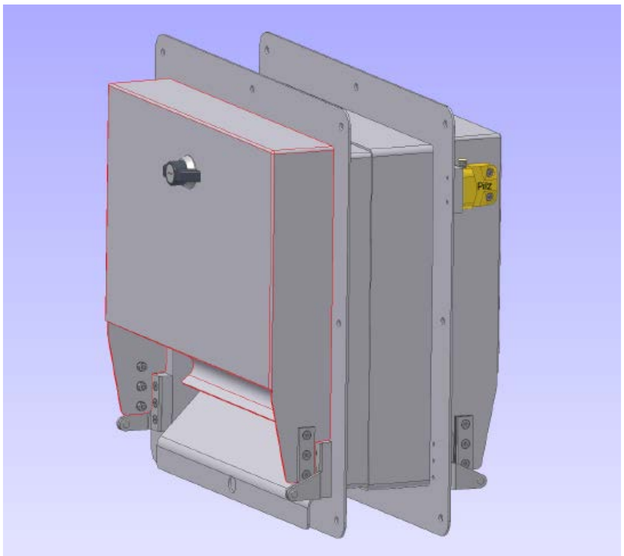

Figure 2 Optical Fibre Panel that sits between the rooms

A new feature of the interlock system is the incorporation of the safe handling of the optical fibre lasers. Requiring request and acknowledgment routines to allow overriding of optical panels

A further feature of the Fibre Optical panel is the Independence Plate which provides the means of sealing the Optical Fibre Panels between rooms which prevents any lasers being connected. When in place the Independence plate provides total isolation from the source and the respective target rooms.

All the functions of theses Optical Fibre Panel are electrically monitored and form part of the integrated interlock system.

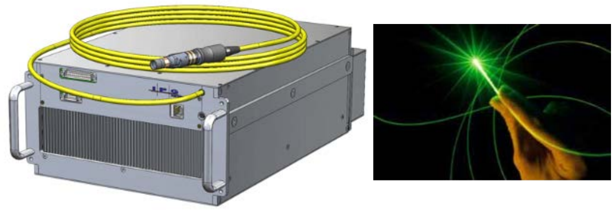

Figure 3 Shows the issue with fibre lasers which can be easily waved in free space due to the flexibility in the cable

The Ultra cluster of rooms consists of main source lasers, a transfer area and up to four target rooms.

The unique flexibility of this laser system allows multiple experiments to take place from selectable single sources into separate target room. This maximizes the capability without compromising the safety.

The transfer and isolation of the laser beams are controlled with the conventional pneumatic wall shutter between rooms and electrical shutters at the source points.

The electrical integrity of the interlock system monitors the operational safety of all the rooms

The four R&D Labs are configured operationally as stand alone, singular rooms primarily for the support of FBI and Ultra. The interlock system installed has the facility to link these rooms for future expansion.

Move To (Human Machine Interface) HMI

Another improvement is the move from the hardwired laser control box formerly used in the LSF to a modern reconfigurable HMI operator interface for bringing lasers on and off.

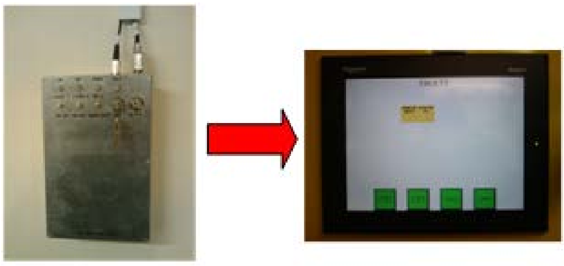

Figure 4 Shows the Former hardwired control panel and new HMI control panel

The former panel had a fixed architecture which did not allow for flexibility when an additional laser needed to be installed..

The Touch screen offers high quality graphic options which will give the operators a realistic view of the laser system. The HMI can also replace all the push buttons which can be programmed via a laptop without the need for switching the interlock system off.

Another benefit of this system is the means of diagnosis and fault finding which the previous system did not offer. Faults and trips can be logged instantly, providing information as to the cause of a room trip or activation of hazard conditions. This reduces fault finding time which in turn reduces overall system downtime.

Move from Din connectors to Terminal in the Panel Design

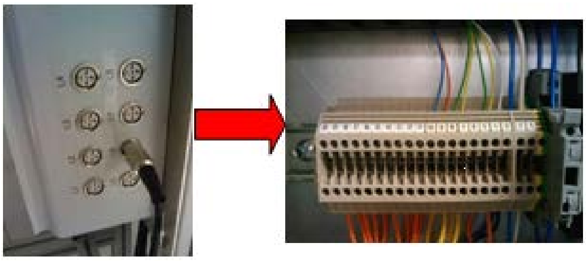

Figure 5 shows the former din connectors replaced by terminals

The connectors have been replaced by screw terminals. Terminals are cheaper than connectors and allows for faster connections to be made as you eliminate the need for time consuming soldering of wires. It also allows for greater flexibility for carrying out requested changes to the interlock system from the users.

Status lights

Introduction of information warning lights similar to the traffic light colour scheme. This informs the user if there has been an unauthorized access in the laser area, and the status of corresponding linking rooms.

Figure 6 Light indicators

Conclusions

These new developments have been successfully implemented in the RCaH which is now in operation.

The improvement in safety as well as in laser operation has been aided by the drive of the team in improving the system and providing the users with a user friendly system as well as confidence in the safety of the system.

Another move saw the move from the previously used Proteus CAD tool to industry used AutoCAD Electrical 2010 for electrical design.

The benefit has been in capturing all the electrical schematics drawings, cables, and bill of materials which provides a well documented structure for future modifications or fault finding.

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Development of the Laser Interlock System within the CLF

Contact *chris.john@stfc.ac.uk*

C John, D Robinson, P Holligan, A Tylee, T Roper

Central Laser Facility, STFC, Rutherford Appleton Laboratory,
Chilton, Didcot, OX11 0QX

Introduction

The aim of this report is to draw the readers' attention to laser safety within the CLF and the steps taken by the Electrical Engineering Section to improve interlock safety and design procedures.

As well as the moral obligation to avoid harming anyone, there are laws set in place that require machines to be safe, thereby avoiding accidents.

The Flixborough incident in June 1974, which resulted in 28 deaths focused the UK public and media attention on the importance of safety of equipment controlling hazardous processes. The cause of the disaster was found to be related to a simple mechanical failure.

In terms of laser systems, if the control system were to fail with power remaining on to all outputs, this would cause the connected lasers to remain permanently switched on. An unknowing user for example could walk into a room with a high possibility of eye damage from exposed laser hazards present in the room.

The human eye is the part of the human body that is most sensitive to light and can most easily be damaged by lasers if ever contact is made as a result of direct exposure or from reflected beams. This can result in permanent visual impairment. The power of laser beams, particularly pulsed power lasers, can be so high that not only the main beam but also weak reflections and diffusely scattered radiation can be hazardous.

Figure 1 Laser warning signs

Hazards can also occur when the skin is exposed to high power laser beams which can cause very painful burns. Photo-chemical burns can also occur from ultraviolet laser beams.

Laser Interlock Safety

Any assembly of devices designed to protect people from hazards or injuries that could arise from the use of the machine can be considered to be a "*Machinery safety system*".

The goal has been for the provision of an interlock system for the control and safety functioning of hazardous lasers that are used within the CLF.

The idea is to avoid the possibility that a malfunction or electrical defect in the basic system controls can at the same time override or corrupt the safety controls. This failure, singly or in combination with other failures/errors, could lead injury.

Safety Compliance

The interlock systems are designed in accordance with the international standard IEC 61508 which outlines basic functional safety best practices to follow. The use of interlocks is also a requirement of the *"Safety of laser products"* IEC 60825-1 standard for all Class 4 and most Class 3B lasers whatever the application, and this is usually enforced by Health and Safety Executive and local authority inspectors. This is also a requirement according to the STFC SHE Safety code No: 22 Working with Lasers.

SIL stands for Safety integrity Level, and is a measure of the safety systems performance. In other words the effectiveness of the interlock system is described in terms of "the probability it will fail to perform its required function when it is called upon to do so". This is its Probability of Failure on Demand (PFD). *'how likely is the equipment under control to fail and if it does fail, what is the outcome?'*

The higher the SIL Level, the greater the impact of a failure and the lower the failure rate that is acceptable. The target SIL level for the CLF interlock systems is SIL 2.

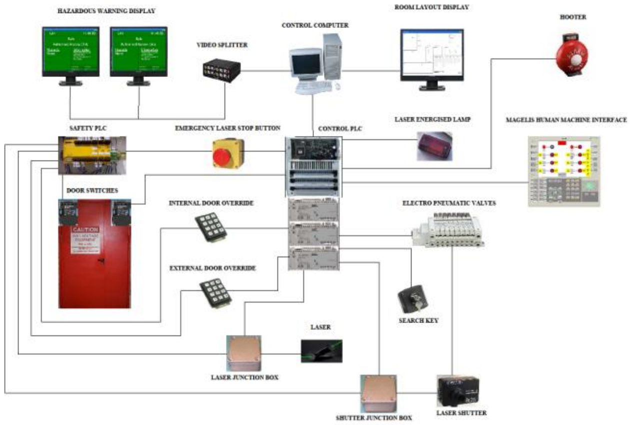

Figure 2 Architecture of the interlock system

Interlock Developments

The first step in any safety- related project is to identify the hazards and to consider the level of the risks they present.

The objective is to reduce the risk from the unacceptable to at least the tolerable. If we cannot take away the hazards, then we will have to reduce the risks, buy designing safety systems that will have a low probability of failure when required to perform its safety functions.

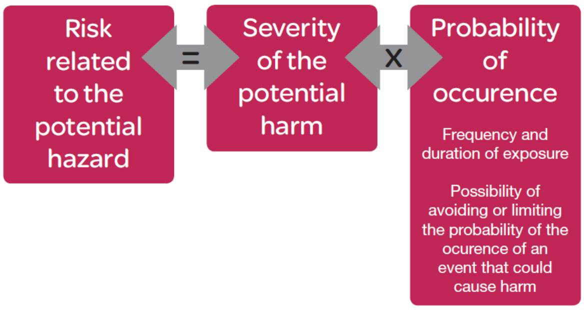

Figure 3 Calculation of the probability of I

For 20 years the interlock system was implemented in TTL logic and this proved to be difficult to change and expand as the laser system evolved. Then followed the PC based system in 1999 based around I/O cards.

Both system would have failed to comply with the IEC 61508 standard as they had no room for fault tolerance and configurability.

PLC – Relay System

The old Interlock system used in the R1 Lasers for Science Facility labs was split into two parts. The control system and the safety system.

1. A laser control system using a standard PLC from Schneider electric which controls the lasers, opening shutters, enclosures etc.
2. And a separate safety system using standard relays and timer relays to perform the safety logic functions.

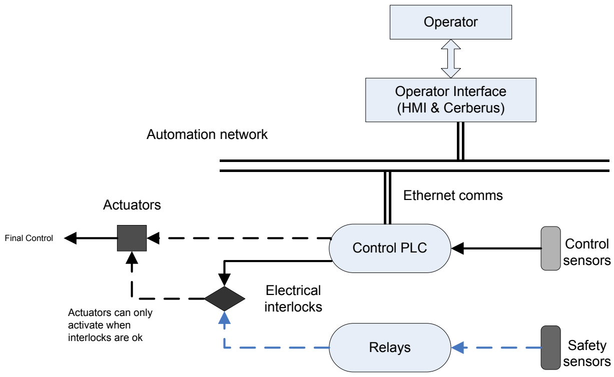

Figure 4 PLC – Relay system block diagram

Both control system and safety system performed the safety function, where both relays from the safety and the control has to be made before any laser could be turned on. This provided the system with redundancy whereby if one system fails the other system would prevent lasers coming on, provided both systems do not fail at the same time.

For example if contact 1 of a door is stuck in the closed position, when the door is opened the protection remains through contact 2 and will drop out the command, thereby tripping the lasers.

Fault detection is also achieved at start-up and by comparison of the status of the parallel channels of the input and output devices as well as the logic.

The issue with this system is the outputs to the lasers are based around the use of standard relays to perform the safety function. One of the problems with relays is that the contacts can stick or weld when subjected to large arc currents or voltages. Material loss on the contacts occurs dues to splattering of the molten and boiling metal as contacts bounce on make.

In terms of safety of the laser; this method can prove to be catastrophic as a weld in the contacts would leave the lasers permanently switched on irrespective of the room being tripped or an emergency stop button being activated. There is no means of diagnosis and detecting a welded relay contact.

The other issue occurs in terms of development changes that can occur to large complex systems which has been hardwired via relay based logic. The effort and time required to modify a built system can prove costly as compared to having a software based tools for configuration and management of the logic.

Other problems faced with relay safety system:

- Fixed architecture which means little flexibility in control logic changes which frequently occurs in the scientific disciplines.
- It is much easier to download a program than build another panel.
- Changes to relay logic requires the system to be taken offline. Changes in a PLC can often be made online with no downtime.
- Relays are not as fast as their PLC counterparts.
- No means of data collection and communication of information.

This system does not achieve the required safety integrity target of SIL 2.

PLC – Pilz System

After review of the interlock system by an outside independent assessor [3] it was decided to replace the relay based safety system with a safety PLC instead.

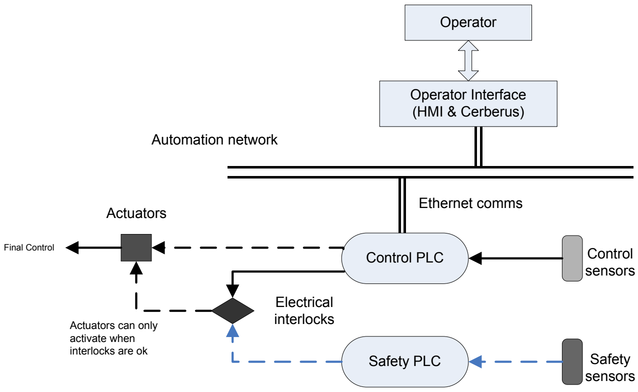

Figure 5 PLC – Pilz system block diagram

One of the questions that arose was "*why not use a general purpose PLC for safety functions instead of a safety PLC?*"

Although general PLCs are lower in cost and easier to use they are not designed for safety applications.

- They have limited redundancy.
- Limited failsafe characteristics.

A standard PLC has only one microprocessor to executes the program, RAM for making calculations, a Flash area which stores the program, ports for communications and I/O to detect and control the machine. In contrast, a safety PLC has redundant microprocessors, Flash and RAM that are continuously monitored by a watchdog circuit and a synchronous detection circuit.

Standard PLC inputs provide no internal equipments for testing the functionality of the input circuitry. By contrast, Safety PLCs have an internal ‘output’ circuit associated with each input for the purpose of ‘exercising’ the input circuitry. Inputs are driven both high and low for very short cycles during runtime to verify their functionality.

If a failure is detected at either of the internal two safety switches in Safety PLC, due to switch or microprocessor failure, or at the test point downstream from the output driver, the operating system of a safety PLC will acknowledge system failure automatically. At that time, a safety PLC will default to a known state on its own, facilitating an orderly equipment shutdown.

The new interlock systems in Vulcan consists of:

1. A laser control system still using a standard PLC from Schneider electric which controls the operation of lasers, opening shutters, enclosures etc.
2. And a separate safety system using a certified safety PLC from Pilz to perform the safety logic. PSS 3047-3.

Although this system performs the intended safety functions and has been successful, it still does not achieve the required safety integrity target of SIL 2.

The misconception was aided by the complexity in the IEC61508 standard, where is was presumed that by simply using a SIL2 rated safety PLC guarantees you a SIL2 system which is not the case.

It is incorrect to call a particular device “SIL 1” or “SIL 2”. For example, it is common to call the Pilz safety switch a “SIL 2” device. This is inaccurate because the entire control loop must be taken into account. Technically, it is accurate to say a device is “*suitable for use within a given SIL 2 environment*”.

PLC – Pilz System with improvements

Although the interlock system designed and built for the LSF in the research complex (R92) has a similar architecture to that in Vulcan, changes have been made to improve the overall safety capabilities. The control and safety function have been separated, with the Schneider PLC performing the control functions and the Pilz handling all the safety. The new improvements to the interlock system include:

- Utilising the capabilities of the Pilz PSS 3047-3 for self checking of wiring faults which can go undetected in previous systems using test pulses. The system now periodically checks for short circuits which can be responsible for nuisance trips to the lasers connected to the system.

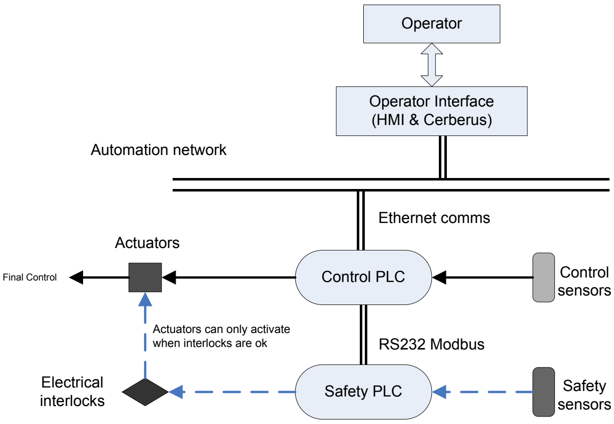

Figure 6 PLC – Pilz with improvements system block diagram

- The safety PLC Pilz has two sections split into the
    1. Standard section (ST) and the
    2. Failsafe section (FS).

Where the ST is the non-safety related section of the PSS. The FS is where all your safety logic should be written as this section has been approved if in the event of a fault the system will shut down to a safe state.

- In the previous interlock system the safety logic software is written in the (ST) section of the Pilz instead of the (FS) section.
- The safety PLC handles all the safety function and transfers status information to the control PLC via RS232 Modbus.

Utilising a password lock system which prevents anyone from altering or making permitted changes to the software.

Conclusions

This constant commitment along with the safe practices and procedures has ensured no laser related casualties within the CLF. The new interlock system satisfies the requirements for a SIL 2 system, providing diagnostics, redundancy and fault tolerance level 1.

Possible future expansions, could include the use of safety relays to replace the current normal relays being used. This would provide the capabilities for self checking and diagnostics in the event of a relay contact welding.

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5. Pilz, *Guide to Programmable Safety Systems, Vol.2, IDC Safety Instrumentation.*
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Vulcan TAW vacuum system under experimental loading conditions

Contact *steve.blake@stfc.ac.uk*

D. A. Neely, S. P. Blake, R. Clarke, P. A. Rice and A. Cox
Central Laser Facility, STFC, Rutherford Appleton Laboratory,
HSIC, Didcot, Oxford. OX11 0QX, UK

Introduction

Laser Plasma experiments routinely require a fast pump down of the vacuum chamber to give the maximum number of shots possible during the experimental run. This report aims to investigate the influence of several factors on the pump down time of the Target area west (TAW) chamber as well as potential improvements. An important element is to identify the experimental hardware having the greatest effect on pump down time and determine if this could be reduced.
The design performance [1] for the TAW system is:

- Ultimate vacuum 1x10^{-5}mbar.
- Time from atmosphere to reach 5x10^{-3}mbar 20mins.
- Expected operating cycle's 6/day.

During a typical experiment the chamber is routinely opened between cycles to adjust and install equipment, detectors and targets. It has previously been observed that the TAW chamber achieves a faster pump down time if it has been through one or more cycles without being opened to the surroundings. This effect is attributed to outgassing. Outgassing is where gas molecules and more commonly water molecules are desorbed from the surfaces of the chamber contents and the chamber itself. This is further discussed in *Vulcan TAW Upgrade-Vacuum System Design* [1]. To account for this during the tests, the chamber was left open to the surroundings for a minimum of 30 minutes after each let up. The system let up used a new dry air system which raised the vacuum vessel from 10^{-5} mbar to atmospheric in approximately 5 minutes.

TAW Pump down under different loading conditions.

The effect of loading the chamber was investigated during three separate pump down tests, (1) an empty chamber, (2) with the cabling system only and (3) with a full range of experimental equipment. During each pump down, the chamber was pumped for a period of 1 hour, recording the pressure every minute.
Unsurprisingly, the quickest pump down time happens when the chamber is empty, achieving a pressure of 5x10^{-5} mbar after an hour.

In any laser plasma experiment an extensive array of cabling is required to provide drive and feedback from all the motorised hardware. It was expected that the additional surface area of the armoured cabling and the potential for trapped air would have a high outgassing rate slowing the pump down. Looking at figure 1 the impact of the cables is insignificant in comparison to the impact from the experimental hardware. The most obvious effect is from 2x10^{-1} – 8x10^{-2} mbar, just before the system switches across to the turbo pumps. The roughing pumps are approaching their ultimate vacuum level and losing pumping speed while the outgassing rate is increasing.

TAW pump down with Inverter fitted

A roots pump can generally be up to 4 times the pumping speed of the backing pump. The backing pump is 250m^3/hr and therefore the 500m^3/hr roots pump is half the size it could be. Some models of roots pump can be frequency doubled using an inverter to increase the overall throughput by about 80%. An inverter set to 100Hz was installed in the system and figure 2 shows the impact this had when pumping the same experimental hardware.

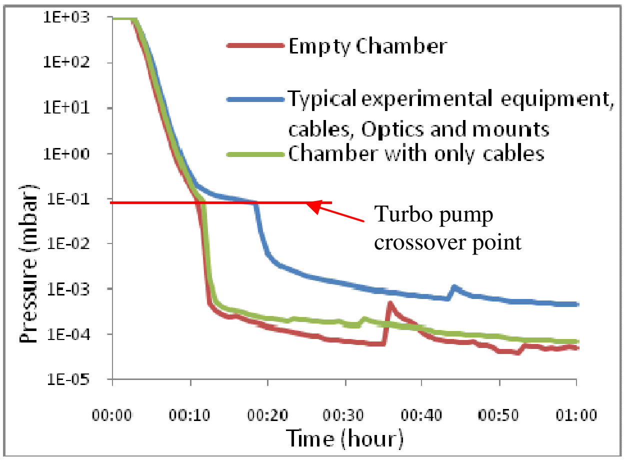

Figure 1 – TAW pump down cycle under different loading conditions.

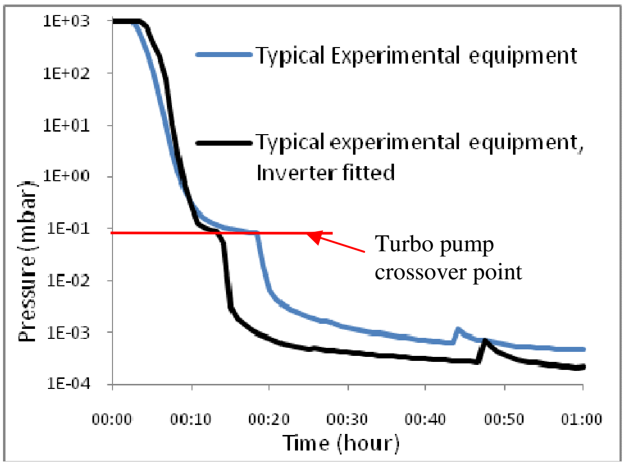

Figure 2 – Comparison of TAW chamber vacuum pumping with and without inverter with experimental equipment.

At the beginning of the pump down cycle, the inverter actually seems to slightly impede the system, slowing the pump down rate. However, this does not cause an overall increase to the pump down time, as below 100 mbar, the inverter pump down rate is now much greater than the original system. With the inverter present, the rate of pumping is maintained until the point where it switches to the turbo pumps and about 4 minutes is saved.

TAW Pump down further equipment investigation with Inverter fitted.

As the previous sections have shown, it is the combined optics and mounts which have the greatest effect on the pump down time. Therefore, it was decided to go further and investigate which part in particular of the optics and mounts was causing the delay to the pump down time.

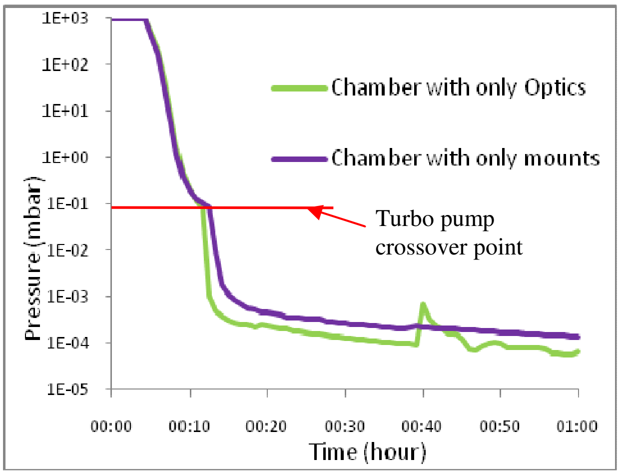

Figure 3 – TAW vacuum chamber pump down comparison with optics and mounts.

From figure 3 the mirror mounts have the greatest effect on the pumping rate. This is attributed to the mounts having a large surface area, some anodised components and the potential for fingerprints from handling.

Anomalous Pressure Spike

Most of the pumping curves show an unexpected pressure spike at pressures in the range 10^{-3} – 10^{-4} mbar. Interestingly, each spike occurs at a different pressure and with varying magnitudes. These spikes are expected to be caused be either outgassing or the release of a trapped volume and will require further experimentation to fully understand its cause.

Conclusion

With the full suite of experimental hardware in the interaction chamber the pump down time to reach $5x10^{-3}$ was outside specification. The graphs confirmed one area to target was the roughing stage. The roots pump being undersize presented an opportunity to look at the impact of speed doubling it utilising an inverter at 100Hz. This proved to be extremely successful. With the inverter present, the system meets the specification, reaching a vacuum level of $5x10^{-3}$ in less than 20 minutes achieving $2x10^{-4}$ mbar in an hour. This will easily reach the target of at least 6 cycles a day.

Cleanliness of the experimental hardware would be an obvious way of improving the pump down time further however the long term costs of achieving this would not be economically viable and focus would be better placed on an improvement to the vacuum pumping capacity.

Further work

Shortly after the testing the manufacturer of the roots pump revised their recommendation for the inverter frequency from 100Hz to 60Hz which is expected to have reduced most of the gain. The impact of this change needs to be evaluated. Another method of achieving the same gain would be to replace the $500m^3$/hr roots pump with a $1000m^3$/hr roots pump. Taking the cost of this change into account it may be more financially sound to invest in another 2200l/s turbo pump or possibly a cryogenic pump.

A cryogenic vacuum pump was tested successfully on TAP and Gemini and a further test of this pump is planned for TAW. Based on previous tests in the other areas the impact in pumping speed would be significant but some chamber designs have been susceptible to vibration from the reciprocating piston and pulsing pipe work making the pump unusable. Further investigation is planned.

References

1. S. P. Blake, CLF Annual Report, 246-248 (2008-2009)