Safe, secure & clean – routine shot operations in the ORION High Intensity Laser Facility

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Introduction & Background

Orion is a new national facility for plasma physics research in the UK. Combinations of long-pulse and short-pulse laser beams are used to simultaneously heat & compress miniature targets (millimetre sized samples of materials of interest to our scientific users) that are held under high-vacuum in a chamber approximately 4m in diameter. Sensitive diagnostic instruments placed on ports around the circumference of the target chamber are used to monitor the laser interaction with the target and provide scientists with data on the target material's performance in the plasma state. The facility footprint is approx. 100m by 60m and the facility extends to a height of around 30m. To preserve the sensitive optics used to process & deliver the beams, the laser is housed in a series of interconnected, and very large, class 10000 (ISO 7) clean rooms, known as "halls", in which the environment is maintained at 19 C (+/- 0.5 C) with a relative humidity of 48%. With the associated support laboratories and office areas, the facility extends over 3 working floors and a maintenance plenum above.

The facility is operated by AWE staff and will primarily be used by AWE scientists and their collaborating partners. However 15% of the facility beam-time in each operating year will be made available to UK Academia for physics research, which will involve experimenters accessing the facility who may be unfamiliar with our operational model and the specific hazards found in the facility.

The Orion project started in 2005 and progressed through Design, Construction & Installation to completion of Initial Commissioning at the end of 2010. Full facility commissioning was completed in March 2012 and the capability of all 12 beams, 10 long pulse (max. 5kJ at 351nm in 1ns) & 2 short pulse (max.1 petawatt at 1054nm in 0.5ps), has been demonstrated. The first "capability proving" experiment has given high confidence that we can achieve the desired plasma measurements at more than 500eV and twice solid density, and a full experimental schedule has been defined for the Operating Year commencing April 2013.

This paper looks at the hazards routinely present in the facility and describes the control measures employed (and where they have changed during the project journey from design through to operation) to maintain laser safety in this highly specialised environment. We will also describe the training programme we have implemented to support the transition from commissioning into routine experimental operations.

Summary of Main Hazards & Safety Systems Employed

Laser Light

Laser light is found in both the main "target laser" and in the "auxiliary lasers", e.g. alignment lasers, used to set up the system prior to a "target shot". The approach taken to protect against the target laser is to contain the light within light-tight halls, protected by a comprehensive interlock system, and exclude all personnel from these areas at shot time. For the auxiliary lasers, which must be propagated when personnel may be present in the halls for various pre-shot duties, the primary control measure is to contain any light above the MPE in beam tubes or enclosures. The complexity of containment is such that there remains a remote possibility that auxiliary laser light might escape an enclosure that has been accessed for maintenance so laser protective eyewear is always worn as an supplementary measure when auxiliary lasers are propagating.

Ionising Radiation

The interaction of the target laser beams with the target material causes an intense but short-lived burst of X-ray radiation and, with some target materials, the generation of neutrons. The radiation is contained within the target hall walls which are constructed of 1.5 metre thick concrete and personnel are excluded from the hall during and after the shot. Re-entry to the hall is only allowed when post-shot monitoring confirms it is safe to do so. The interlock system protects against unauthorised entry throughout the shot-cycle and, if challenged prevents the shot from being fired.

EMP

The interaction of the target laser beams with the target also results in an electromagnetic pulse (EMP) which may interfere with sensitive electronic devices, including medical devices such as heart pacemakers or personal infusion pumps. Accordingly the target hall walls are clad with a conductive shield to form a Faraday cage in which to contain the EMP and sensitive electronic equipment inside the hall is installed in EMP protective racks with filter connections to protect the input & output circuits. As previously mentioned, the hall is an interlock protected, exclusion zone at shot-time and as an ALARP measure, persons wearing electronic medical devices must completely leave the facility when the shot is fired.

HV & Stored Charge

Pulses of laser light for the main target laser are amplified in special laser amplifiers which are "pumped" using high voltage (HV) flash lamps. The flash lamps are triggered by HV electrical energy derived from large capacitor bank modules (CBM) that are charged up to 25kV. Such voltages and stored electrical energy are clearly lethal and this hazard is controlled by excluding personnel from the HV areas at all times the CBM are energised or charged and these areas remain an exclusion zone until the shot is fired or the charge is safely dumped by the automatic protection system. The use of individual personal access keys ensures that HV cannot be applied when persons are present in HV areas and a comprehensive interlock system guards against re-entry during the shot-cycle.

Conventional Hazards

The most significant conventional hazards in the facility arise from lifting operations and working at height. These are managed through the adoption of conventional workplace risk-assessment and the implementation of suitable control measures including PPE (hard-hats, safety lines & tethered tools) and work control procedures. Wherever possible, permanent access structures have been installed to provide a safe & secure platform for frequently accessed areas at-height. For areas where access is less frequent we use mobile elevating platforms or "cherry-pickers" which have posed some interesting training challenges for an operations team used to working with their feet firmly on the ground.

Safety Interlock System

The Main Safety Interlock System (SIS) protects personnel from main target laser hazards (e.g. ionising radiation and high voltage) by excluding personnel from the hazardous areas during shot firing. It also protects personnel from exceeding the maximum permissible exposure to auxiliary laser light.

The SIS consists of a mechanical trapped key subsystem to control the application of the high voltage (HV) pulsed power system used to charge the CBM & fire a target shot, and an electrical subsystem monitoring multiple door contacts and emergency stop buttons throughout the facility. These subsystems are diverse, separated and segregated to minimise the likelihood of common cause or common mode failure and either can disable the main target laser. The subsystems are sufficiently independent to allow multiplicative safety claims to be made using the subsystem reliability predictions. The systems are of high integrity and are designed to meet a Safety Integrity Level 2 (SIL2) safety system. The systems were designed such that they satisfied a number of Safety Functional Requirements (SFR) derived from the facility safety case.

The trapped key subsystem comprises multiple key exchanges throughout the facility and only when all the keys are in the key exchange can the respective control keys be removed and taken to the control room where they in turn are used to release further keys used to energise and ultimately fire the target laser. All persons entering a high-hazard area (i.e. the halls or HV pulsed power areas) are required to take a personal access key from the key exchange at the entrance and keep it with them all the while they are in the area. The act of taking a key ensures that the control key for that key exchange is locked-in and therefore cannot be taken to the control room to start the target laser sequence. The personal access key therefore becomes an individual "safety token" that will protect the holder from any possibility of exposure to the high hazards associated with the target laser.

During the commissioning a number of operating and documentation issues associated with the SIS were highlighted, including:

- Drawings did not fully represent the installed state of the system.
- Compromises made during installation might impact the SIL rating actually achieved.
- The design intent of the system was not being fully met in some areas. (SFRS not being completely satisfied).
- A number of wiring protection faults were also identified which increased the risk of fire.

The safety systems for Orion were designed several years ago and delivered through the installation phase of the project. Now we have had the opportunity to use these systems through the facility commissioning stages we have also identified a number of areas where improvements can be made to enhance both safety and operational efficiency – all of which are discussed below.

Improvements arising from System Review & Operational Experience

SIS Drawings Verification
A complete survey of the installed state of the SIS was undertaken and a set of configured drawings issued. This provides the baseline against which all future modifications can be assessed and developed.

SIS Wiring Review
From the configured drawings a review of the electrical safety of the system was undertaken. The review identified a number of potential electrical safety issues. Once identified the electrical system was shut down to allow remedial work.

SIS SIL compliance review
A review of the SIL compliance of the SIS was undertaken. The review identified that the actual implementation "as delivered" had been compromised through the installation of additional relays (not part of the design intent) to compensate for voltage drops discovered during setting to work. These relays were not part of the original design intent and by being of the "non-monitored" type, could result in unrevealed faults within the system. The review has resulted in a revised system design which fully meets the requirements of SIL 2.

To enable continued use of the system prior to the revised design being installed, an enhanced testing regime and several managerial controls were implemented; these allowed the SIL rating of the system to be maintained.

Installation of a Turnstile at TH Entrance
The principal safety system to protect an individual against the major hazards arising from a target shot is the SIS and the use of a personal access key (PAK). This approach is reliant on each person adhering to the procedure for taking a key and not just following someone else who may already have a key to enter a hazardous area. Analysis of human error probability has shown that performance in this area can be improved by the installation of an engineered measure to ensure that "1 key – 1 person" is enforced. We have therefore decided to install a turnstile at the entrance to the target hall (i.e. the area where all the hazards coalesce and present the biggest risk to operatives).

The turnstile will be installed in the pedestrian access labyrinth to the target hall and will be operated by a combination of a swipe-card (security/safety) and a personal access key (safety); the turnstile only operating when both have been used. The swipe card system will be programmed to ensure that only authorised persons are allowed to enter the hall and final activation by means of the personal access key (PAK) ensures each person entering has their individual key with them.

Key Monitoring
The act of taking a key ensures personal safety but to operate the target laser all

the keys must be returned and we have experienced some instances of individuals forgetting to replace their key in the key exchange on leaving the area and then leaving the facility taking their key with them, thus preventing the facility from operating at all. To try and prevent this happening too often we are therefore installing a “key monitoring” system at the exits, similar to the systems employed to prevent goods being removed from retail premises. A special key fob attached to the PAK will trigger a sensor and sound an alarm if someone should inadvertently try to leave the facility whilst retaining their key about their person.

Laser Interlock Partitioning
Our initial design for the SIS featured large interlinked laser protected areas which required all areas to be in the same state before lasers could be used in any individual area. Whilst totally safe this has proved inflexible and inefficient so we are partitioning the system to allow laser propagation in one area while high integrity shutters prevent propagation into an adjacent area, which can then be held at a lower state to allow more general work to take place.

At the same time we are taking the opportunity to modify the SIS logic controller to provide optional maintenance modes that will remove the need to apply temporary commissioning aids (i.e jumper leads or disconnections) currently used to disable certain areas of functionality during maintenance & testing.

SIS Operator Interface
Some complaints were received from the operators that they could get little information on the SIS status when an interlock violation occurred, which made the identification of the violation difficult to confirm. To improve on this, SIS status information is now made available via an interface to the facility Integrated Control System (ICS) and presented on the operator’s screen in the facility control room.

Viewing Gallery Windows
Orion is a high profile facility and subject to frequent VIP tours by persons visiting the AWE site. Aware of this requirement at the design stage we have included two viewing galleries overlooking the laser hall and target hall to showcase our technology and allow observation of pre-shot activities. Our original design included clear glass windows in the gallery with protective blinds to be pulled down as a supplementary measure when alignment lasers were propagating. The blinds being linked through the SIS to the laser propagation sequence.

The frequency of visits to Orion is such that the number of requests to raise the blinds in the viewing galleries was having a significant impact on operational efficiency. We have therefore decided to cover the clear glass windows with laser protective glass that will not require the blinds to be lowered during alignment operations. The blinds are still required to be lowered for target shots and the SIS logic controller has therefore been modified accordingly.

Laser Enclosures
In some parts of the system, large areas of laser curtain material have been used to provide a laser enclosure but we have found that where these require frequent opening for routine maintenance access the fit on replacement has been less than perfect. Accordingly we are embarking on a program of replacing large curtains with fixed panels where frequent removal and replacement is required. Curtains will be retained in areas where access is only infrequently required.

Use of Laser Goggles
The use of laser protective eyewear is a key element in our laser safety program and we have selected lasers to use in the facility such that a single type of goggles can be worn to protect against all wavelengths present in the main laser halls. However protection is only provided if the goggles are actually worn and we have had a few instances of persons attempting to enter the halls when lasers are propagating without putting on their goggles. Fortunately colleagues have noticed and alerted the “non-wearer” of the situation and no harm has been done.

We have therefore decided to implement an “engineered colleague” and placed a special warning sign at the entrance to the halls. In addition to a voice warning advising persons entering the hall to “wear goggles” we have introduced a coloured sign that becomes invisible to those wearing the correct goggles but which remains completely visible to those that have forgotten to put on their goggles; the message facing the non-goggle wearer is simply “Not Wearing Goggles!”.

Safety Information at the Point of Use
Although we have put considerable effort into engineering safety throughout the Orion facility, documentation in the form of Work Instructions, Risk Assessments and Hazard Information remains an important part of our overall safety program. Currency of information and availability at the point of use are vital if documentation is to be effective and the paper copies initially deployed are less than ideal, particularly in clean rooms. Accordingly, we are rolling out a series of safety information kiosks at key locations throughout the facility to replace the ring-binders full of paper copies currently used.

The safety information kiosks feature a touch screen interface with simple menu selection that can easily be used whilst wearing clean room clothing, including gloves & goggles, and are networked to a central content server providing all the up to date documentation. No log-on is required to access the screens so anyone working in the facility is able to read the up to date documentation at their place of work.

Alignment of Exposed Optics
Where it is necessary to open a beam enclosure for the purpose of optical alignment we have introduced a policy that, while the beam is exposed, nothing above a Class 2 Laser shall be used for the alignment activity. This ensures that any stray beams that might be reflected out of the open enclosure cannot harm other workers in the vicinity.

Protection from Falling Items
The Orion Target Hall features three levels of fixed work platform arranged around the target chamber to facilitate access to the final optics assemblies and diagnostic instruments arrayed around the circumference of the chamber. To ensure the air flow in this large clean room is maintained in accordance with the design parameters, the flooring used for the platforms features a slatted grid pattern for air to pass through. Although fastenings and tools generally used in the target hall are tethered, we have experienced a few incidents where small items have been dropped and fallen through the slatted flooring onto persons working below. To guard against further occurrences we have therefore introduced netting fixed to the underside of the floor and provide temporary mats to place on top of the floor for the duration of a task in the local work area.

Orion Training Programme

Orion was built & commissioned by a core team that developed & operated the previous generation of laser facility at AWE, the now retired Helen facility. This core team created initial procedures for operating Orion and learned how to operate the systems during the initial commissioning phase. In preparation for full operations, the knowledge that was gained during commissioning has been captured and forms the basis for the Orion Training Programme now being rolled out to an expanding operations team who will run the facility going forward.

Although similar in technology and general functionality to Helen, Orion is a completely new facility with new equipment, new ways of working and specific operations to carry out. A comprehensive training initiative was therefore required to ensure that all operational personnel are suitably prepared for work and, most importantly, that evidence of such training is available to our external regulators.

The first thing we did was to draw up an Orion Training Policy to set out our objectives for training the staff. Simply put, this stated that all personnel working on Orion will be trained as appropriate to the job or task requirements and their individual needs. The training records for Orion will be held in Oracle Learning Manager (OLM) within the AWE business system.

We then established a Training Steering Committee (TSC) to provide governance for the training development program. The TSC comprised a core team drawn from Orion management & system experts together with members of the wider training community across AWE. The remit of the TSC was to act as the authority responsible for ensuring that the training requirements are properly identified and then met by the development program, and to advise on best practice to be implemented. The training development activity was subject to scrutiny at a monthly TSC Meeting where progress was reported and help provided by the membership to analyse issues arising and define ways forward. A comprehensive set of metrics were developed to focus attention on specific issues arising.

Identifying Training Requirements
Our fundamental principle was that training would be defined based on a comprehensive training needs analysis, and a Training Development Manager was recruited to set up and implement the program, including:

Job or role analysis - Individual job descriptions and generic roles were analysed for training requirements and reviewed with relevant line managers to identify and agree the most appropriate training method.

Operational process & task analysis - General work processes and specific tasks, including Work Instructions where available, were analysed and reviewed with relevant line managers and Subject Matter Experts (SME) to identify and agree the most appropriate training method.

System & equipment documentation review - System or equipment Operation & Maintenance (O&M) manuals were analysed for training requirements and reviewed with relevant system owners and SMEs to identify and agree the most appropriate training method. Where O&M manuals were still in development, training requirements were identified by discussion with the designer or SME.

A training scope & status report was created to summarise the training curricula and courses to be developed across each of the different operational areas of the facility, including an action plan for each area.

Training Delivery
Training is delivered by the means most suitable to achieve the learning objectives. This may be through formal classroom delivery or through On the Job Training (OJT) with assessment or by keeping a Task Book. OJT is carried out on simpler tasks where the trainee can very quickly learn what is required and answer a series of questions on the key points of the system; the trainee can then be assessed as competent. A Task Book sets out a series of activities undertaken by the trainee to check their understanding of the system and demonstrate their competence by carrying out tasks under supervision for as many times as is necessary prior to being assessed as competent.

A staff training matrix was drawn up and gap analysis used to define training plans for each individual, which were then managed by the Line Manager concerned. Metrics to monitor the status of completed training recorded in OLM are presented at the monthly TSC Meeting and actions taken accordingly to maintain the desired progress.

Experimental Operations
Target shots conducted on Orion are grouped into experimental campaigns led by an experienced scientist. The facility is operated by trained Orion staff on behalf of the users but the lead scientist or "principal investigator" is a key member of the team during shot operations and is responsible for ensuring the correct setup and operation of the diagnostic instrumentation used to monitor the interaction of the laser with the target and thereby obtain the experiment results.

AWE scientists are trained and familiar with Orion operations & equipment and therefore integrate well with the build-up to an experimental campaign and the working arrangements with the daily shot-operations team. This process includes participation in the three readiness reviews that each campaign is subjected to at 6 months, 3 months and 1 month before the scheduled start date. At the Readiness Review Meeting each campaign is scrutinised for safety and compatibility with the laser capabilities being employed and a shot-plan is agreed for subsequent implementation.

When the facility is made available to the academic community for physics research it is unlikely the lead scientist will be as familiar with Orion as their AWE counterparts so we have decided to provide a trained AWE link-scientist or "co-investigator" for such campaigns who will manage the experiment through the readiness process and provide a scientific interface for the academics at shot-time.

Academic access will therefore generally be on an “eyes off hands off” basis with direct interaction through experienced AWE hands but where visiting academics can demonstrate training equivalent to AWE scientists & technicians then more “hands-on” access is possible.

Conclusions & What Next?

The completion of the commissioning phase marks the “end of the beginning” for the Orion journey. Much of the original design intent for the Orion safety systems and operational procedures remain today and have been enhanced by improvements made in the light of initial operational experience. Operations are heavily process-driven and training with formal records plays an important part in ensuring our team are demonstrably ready to exploit the facility to the full.

All of us at Orion are committed to continuous improvement and maintaining the facility as a leading example of world class laser safety. We intend to do this through frequent benchmarking against the best of similar facilities around the world and by participation at international safety events and operational workshops to inform an ongoing programme of facility development throughout the planned life of the facility over the next 25 years.