Working Document on Laser Safety for ATLAS

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Executive Summary

Purpose

The purpose of this document is to describe the control measures proposed by ATLAS to ensure compliance with the IEC laser safety standards and the local CERN laser safety rules.

Scope

In its final form, this document is expected to cover all of the optical fibre systems that are connected to the detector, linking it to various services located in the adjacent technical services cavern (USA-15), or in the surface buildings.

Status

This is currently a working document, which is undergoing regular revision as new engineering data from various sub-systems becomes available. However, the core sections on laser safety are now stable, as are the majority of the sub-sections dealing with the SCT front-end links and alignment system. The architecture of the LArg calorimeter front-end links is not yet mature, so several options are presented. Therefore, the precise details of the LArg links may be subject to change. For the purposes of laser safety, these two sub-systems will be treated as 'prototypes' for the remaining sub-systems, which are not expected to raise any significant new laser safety issues. Feedback is welcomed.

Main Conclusions

Each part of every sub-system has been (or will be) classified according to IEC 825-1 and 2.

The vast majority of the fibre optical installation will come under hazard levels 1, 3A and k x 3A. This currently includes all of the optical fibres linking the detector in UX-15 to the outside world (whether in the form of individual fibres, ribbon fibres or cables). Besides mechanical protection, labelling and normal good engineering practice, no special precautions will be required for these sub-systems.

The main exceptions to this will be the insides of the on-detector patch panels and ROD crates, where ribbon fibre MT connectors will be used, and the small number of power delivery fibres for the SCT alignment system. These parts of the fibre installation will fall into hazard level 3B. They will therefore require more stringent control measures to eliminate the possibility of accidental exposure to laser radiation in excess of the accessible emission limit for class 3A. This will be achieved by the use of fail-safe, automatic power reduction systems for the patch panels and crates, combined with additional mechanical protection, where appropriate. Sense fibres will be incorporated into the cable construction for the SCT alignment power delivery fibres. A fail-safe mechanical shutter will block the lasers coupling into these fibres whenever the low power sense signal is lost.

In addition, the SCT alignment system will utilise several class 4 lasers confined to a small light-proof, restricted access room in the surface buildings. This room will fully comply with the additional requirements for a class 4 laser controlled area.

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1 Introduction

The purpose of this document is to describe the laser safety measures proposed by ATLAS to ensure compliance with the IEC laser safety standards[1] and the local CERN laser safety rules [2].

In its final form, the scope of this document is expected to include all of the optical fibre systems that are connected to the detector, linking it to various services located in the adjacent technical services cavern (USA-15), or in the surface buildings.

This is a working document, which will be revised as new engineering data from various sub-systems becomes available. However, the core sections on general laser safety and the classification of laser hazards are stable.

The current version of this document covers the SCT and LArg sub-detectors in detail. For the purposes of laser safety, these two sub-systems will be treated as 'prototypes' for the remaining sub-systems, which are not expected to raise any significant new laser safety issues. The front-end data links proposed for the Pixel sub-detector will be very similar to the SCT links described here. Other sub-detectors at larger radii will either follow the general features of the LArg calorimeter installation or they may choose to use 'off the shelf' class 1 systems.

In the case of the SCT, the architectures of the front-end data links and alignment system are well developed, so that specific control measures can be proposed. The scenario described here is very unlikely to change.

However, the architecture of the LArg calorimeter front-end links is not yet mature, so several options are presented. Therefore, the details of the LArg links may be subject to change. However, from a laser safety perspective, the approach described here is likely to be very similar to the final design.

ATLAS will use approximately 22,000 fibre-optic links to transfer data between the on-detector front-end electronics and the associated off-detector electronics, which will be situated either in USA-15 or in the surface buildings. The SCT alignment system will utilise around 1,600 optical fibres to link equipment in USA-15 to the detector. In addition, several other sub-systems will utilise smaller numbers of fibres. A number of these are not yet fully defined, but will follow the basic approach set down in this document.

The data links will use Vertical Cavity Surface Emitting Laser diodes (VCSELs) operating at 850 nm, coupled into multi-mode optical fibres terminated with PIN-diode receivers. Every sub-detector will have VCSELs mounted on-detector for data readout. Some sub-detectors (notably the SCT and Pixels) will have bi-directional links, with additional VCSELs located in USA-15 to distribute clock and control signals to the on-detector electronics. Full details of the link specifications can be found in ATLAS-ELEC-001 [3].

The SCT alignment system will use a technique known as Frequency Scanned Interferometry (FSI) to make remote, high precision, length measurements of approximately 800 fixed path interferometers mounted on the detector, via optical fibres. Each measurement channel will have a pair of single-mode fibres, linking the interferometer to its associated equipment located in a rack in USA-15. FSI will use tuneable lasers operating at 830±10 nm.

The remainder of this document is arranged as follows: Section 2 contains more detailed descriptions of the various optical fibre installations. Section 3 introduces the basic principles of laser safety, with emphasis on those issues relevant to ATLAS. The potential laser hazards are then identified for each sub-system in Section 4, where they are also classified in accordance with the IEC laser safety standards. Section 5 discusses the control of potential laser hazards in general, and Section 6 describes in detail the measures proposed to control these hazards, in accordance with the guidance and recommendations contained in the IEC laser safety standards, CERN Safety Instruction 22 and other relevant safety documents.

2 Proposed Optical Fibre Installations

2.1 Common Features

2.1.1 Introduction

There are many aspects of the proposed optical fibre installation which will be common to all sub-systems. Although the internal light-guiding properties of the fibres will be different for each sub-system, they will all have the same external dimensions and other physical properties. They can therefore be grouped together into ribbons and cables in the same way. Some of the sub-systems (particularly sub-detectors at large radii) may decide to use individual optical fibres. However, the majority will be using multi-fibre ribbons, together with commercial MT series ribbon-fibre connectors.

It will be shown later that the vast majority of the fibre installation will fall into one or two laser hazard categories. It is therefore appropriate to apply a common approach when considering laser safety.

2.1.2 Ribbon Fibres

All of the optical fibres proposed for use in ATLAS have an outside diameter of 125 µm for the glass cladding and a nominal overall diameter of 250 µm for the acrylate buffer. These are industry standard dimensions, which allow the fibres to be 'ribbonised' using 'off-the-shelf' processes. Figure 2.1 shows a cross-sectional view of the 12-way ribbon produced by Fujikura for the SCT data links. Other manufacturers' ribbonising processes give rise to similar, if not identical, dimensions.

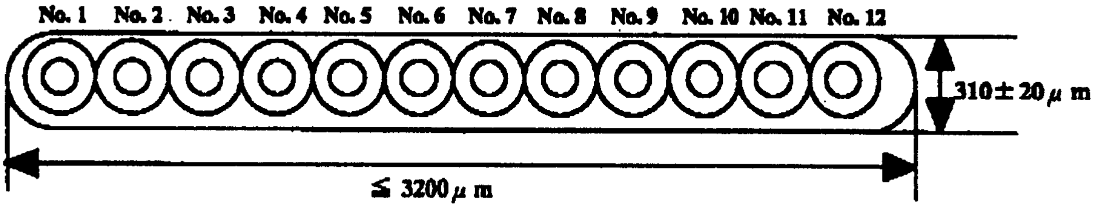

Figure 2.1 **Cross-sectional view of a Fujikura 12-fibre ribbon**

2.1.3 Multi-ribbon Cables

In order to satisfy laser safety and reliability requirements, it will be necessary to provide mechanical protection to the ribbon fibres. The most efficient way of achieving this, in terms of minimising the total cross-sectional area of the services, will be to combine groups of ribbons together into common protective jackets, thus forming 'multi-ribbon cables'. Other advantages to be gained by using these multi-ribbon cables include faster and easier installation, with less risk of damage to the fibres.

It is proposed that the majority of the cables will each contain 96 fibres, in the form of eight 12-way ribbons. This may vary slightly for the FSI system, but the overall dimensions of the cable will be the same. The cables will have a ruggedized and fire retardant outer jacket. They will also contain longitudinal strength members to limit the maximum strain that can be applied to the fibres during installation into conduits, ducts and trunking etc.

A candidate 96-fibre cable designed by Ericsson Cables is described in Appendix A. Samples of this cable have satisfactorily completed mechanical testing to IEC 794-2, as required by the IEC laser safety standards (see Section 6.1.3 of this document).

These cables will run from the patch panels adjacent to the various sub-detectors directly to the electronics racks located in USA-15, or on the surface. The SCT, Pixel and barrel section LArg cables will be routed along the outer surface of the tile calorimeter and out through the muon system at approximately z = 0. The cables from the end-cap LArg calorimeter will be laid into flexible cable guides to facilitate the movement of the end-cap detectors during access periods.

All of the cables will then be run into the main cable trays, through the cable galleries linking the detector cavern (UX-15) to USA-15 and thence to the electronics racks.

2.1.4 Ribbon Fibre Connectors

It is proposed to use MT series ribbon connectors at all patch panels where interconnections between ribbon fibres will be required. They will also be used in some sub-systems to connect ribbon fibres directly to VCSEL and PIN-diode arrays.

These connectors provide reliable high performance interconnects for between 4 and 12 fibres in a minimum footprint. Two main versions will probably be utilized in ATLAS; bare MT connectors, which will be used for the SCT and Pixel sub-detectors where the available space will be extremely limited and packing densities will be high, and MTP/MPO ruggedized connectors, which may be utilized for the outlying detectors, where space will be less critical. Both forms are illustrated in Figure 2.2 and described below.

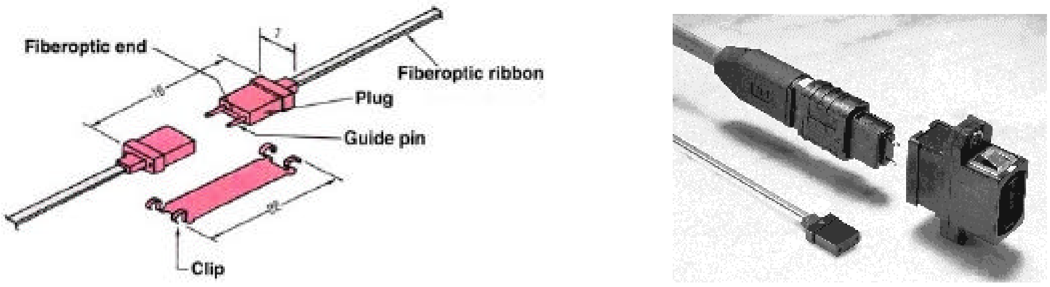

Figure 2.2 **Drawing of a bare MT connector (left), and photograph of bare MT and MTP connectors (right, courtesy of Molex Inc.)**

All MT series connectors utilize the same precision moulded NTT compatible ferrule, illustrated in Figure 2.3.

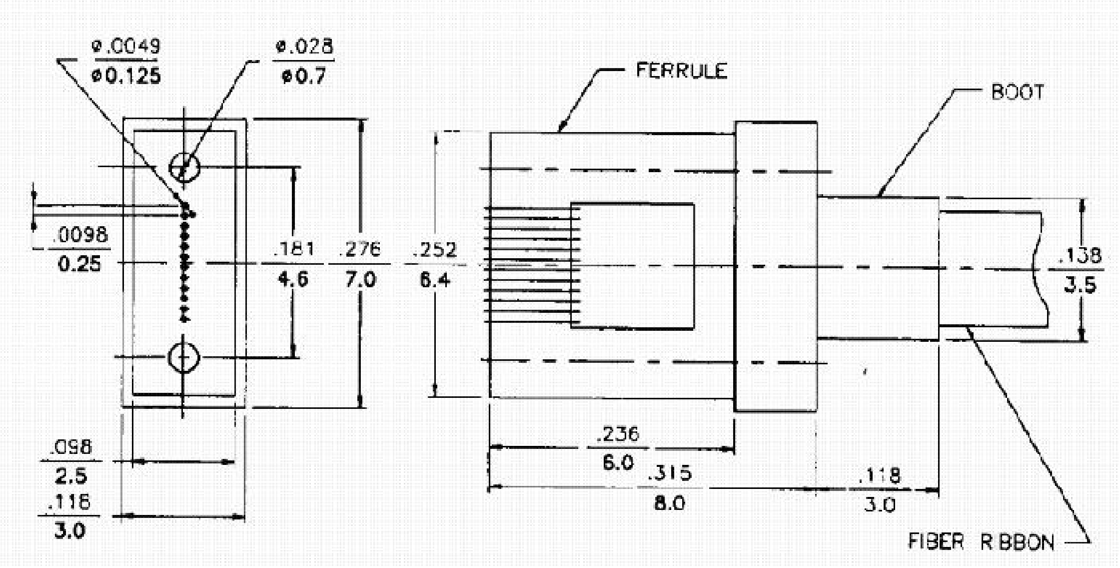

Figure 2.3 **NTT compatible MT connector ferrule (courtesy of Molex Inc.)**

Alignment between mating ferrules is accomplished using two precision guide pins that are pre-installed in a designated male connector. Two corresponding holes in the female connector locate the pins providing repeatable core to core alignment of the fibres. The two ferrules are normally kept in the mated condition with the aid of a spring clip (but see below). Back reflections for single mode fibres are minimised by angle polishing to eight degrees.

One problem with standard bare MT connectors is that they utilize a metallic spring to hold the two mating ferrules together. This spring is expensive and easily lost. Plastic versions do not provide adequate pressure to ensure proper contact between the ferrules. One proposed solution to these problems is a device which will replace the spring clip with a plastic surround which will encase the ferrules, as indicated in Figure 2.4. In addition, this would provide some mechanical support for the ribbon fibres and would also allow them to be stacked, enabling large numbers of ribbons to be connected in the minimum space. This device is presently under development by ATLAS. Another possible solution is being actively considered by an optical fibre manufacturer.

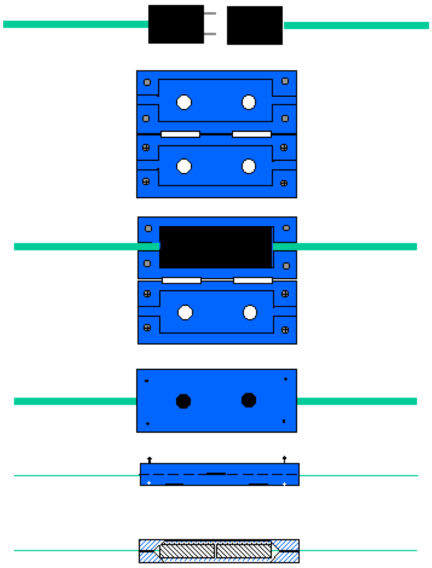

Figure 2.4 **A proposed plastic housing for MT connectors**

The MTP/MPO ruggedized assemblies utilize the same MT ferrules and package them in a push-pull keyed connector housing for quick and easy connection using the MTP adapter. Guide pins in the male connector maintain alignment with holes in the female connector while the adapter retains the connectors in the mated position. Fanouts from MTP connectors to single fibre leads fitted with industry standard SC, FC, and ST connectors are available commercially.

2.2 The SCT

2.2.1 Front-End Data Links

Figure 2.5 is a schematic representation of the SCT data links. These links will be bi-directional, with VCSELs both on the detector and in USA-15. Each detector module will be associated with a pair of up-links (for data readout) and a single down-link (for clock and control data). A more detailed description of the proposed link architecture can be found in a recent conference paper [4].

Mounted on the super-structure of the detector, adjacent to each module, will be a pair of VCSELs and a single PIN-diode. These will be contained in a so-called ‘opto-package’, a light-tight, pig-tailed package (that is, one in which the fibres are permanently coupled to the VCSELs and PIN-diode). In total there will be 4,088 of these opto-packages. The typical fibre-coupled power will be 300 – 500 μW for each of these on-detector VCSELs, with a maximum of 2 mW, even under foreseeable fault conditions. The latest detailed specifications for the opto-packages can be found in the SCT document 'Opto-Package Specifications'[5].

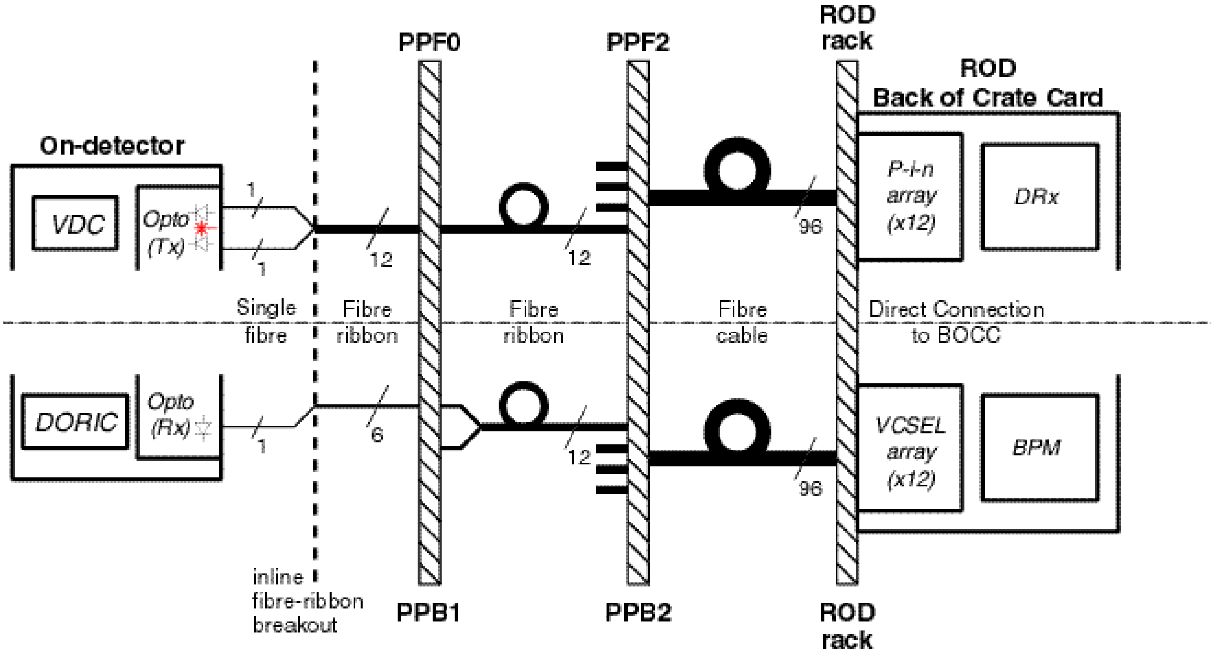

Figure 2.5 **A schematic representation of the SCT optical data links**

The VCSEL fibre pig-tails will be grouped into 12-way ribbons and the PIN-Diode pig-tails grouped into 6-way ribbons inside the SCT thermal shield. Before exiting the thermal shield, these ribbons will be grouped into a small number of larger bundles. The final routing from this point is still under development and the latest version can be found in the SCT document 'Fibre routing for SCT Optical links'[6].

However, in the current design, the 6-way ribbons will be paired up at patch panels PPB1 (for the barrel) and PPF0 (for the forward) close to the SCT and still inside the bore of the LArg cryostat. These patch panels will consist of bare MT-12 connectors, mounted in stacks of the proposed plastic clips described in Section 2.1.4.

Once they leave the thermal enclosures, the bundles of ribbons will be routed in protective plastic ducts to the enclosed patch panels at PP2, near to the outer edge of the calorimeter. Whilst inside the bore of the cryostat these ducts will not be fully enclosed. However, once they pass onto the cryostat end plates they will be fitted with close fitting lids. At PP2 all of the fibre ribbons will be connected to the multi-ribbon cables, in groups of eight, via bare MT-12 connectors.

The cables will lead directly from PP2 to the off-detector Read-Out Driver (ROD) racks housed in USA-15, following the route described in Section 2.1.3. Here they will pass inside the racks, at the rear, where the individual ribbons will be separated out and connected to the electronics modules via bare MT-12 connectors. The VCSELs and PIN-diodes in the ROD crates will most probably be in the form of 12-way arrays, which will mate directly with these MT connectors.

There will be a total of 4,088 VCSELs in the ROD crates and the absolute maximum output power will be 3 mW per VCSEL, with a beam divergence of 15 ° (full width). The typical fibre-coupled power will be 1 mW, with a maximum of 3 mW, even under foreseeable fault conditions. The latest detailed specifications for the VCSEL arrays can be found in the manufacturer's data sheet[7].

The fibre for the SCT data links will be a custom, radiation hard, step-index multi-mode (SIMM) fibre, with a pure silica core of 50µm diameter, and a fluorine spike-doped cladding. It will have a numerical aperture (NA) of 0.2 ± 0.02.

The Pixel links will be similar to the SCT links, except that they will convert from the radiation hard SIMM fibre to a standard, radiation tolerant graded index multi-mode (GIMM) fibre at PP2. This will have a Ge-doped core of 50 µm diameter, with a numerical aperture (NA) of 0.2 ± 0.015.

2.2.2 Alignment System

Figure 2.6 is a schematic representation of the SCT alignment system. This will be based around a technique known as Frequency Scanned Interferometry (FSI) to make remote, high precision, length measurements of approximately 800 fixed path interferometers mounted on the detector, via optical fibres. Each measurement channel will have a pair of single-mode fibres, linking the interferometer to its associated equipment located in a rack in USA-15. The ‘transmit’ fibre will be illuminated by 830±10 nm tuneable laser radiation via a ‘splitter tree’, and the ‘receive’ fibre will be terminated by an Avalanche Photo-Diode (APD) detector.

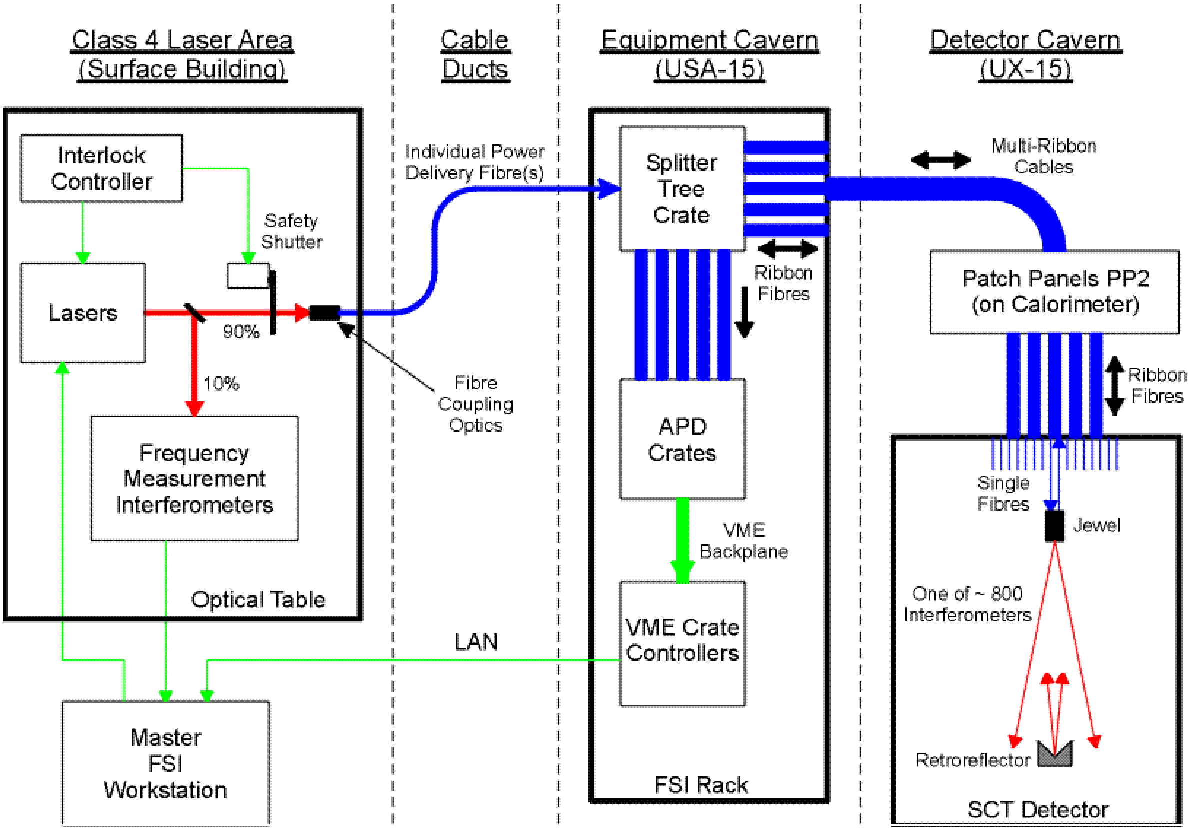

Figure 2.6 A schematic representation of the SCT alignment system

The interferometer fibre pig-tails will be grouped into ribbons inside the SCT thermal shield. The exact grouping is still to be decided, but will probably be between 6 and 12 ways. Before exiting the thermal shield, the ribbons will be grouped into a small number of larger bundles, in the same way as for the data link fibres. Once they leave the thermal enclosure, these bundles will be routed in the same protective plastic ducts as the data link fibres, to the same enclosed patch panels at PP2. At these patch panels the ribbons will be connected, probably in groups of eight, to the multi-ribbon cables, via bare MT connectors.

The cables will lead directly to the FSI rack housing the off-detector 'splitter tree' and receiver crates located in USA-15, probably adjacent to the ROD crates, following the route described in Section 2.1.3. Here they will pass inside the rack, at the rear, where the individual ribbons will be separated out and connected to the electronics modules via MT connectors.

The actual lasers will be a pair of high power devices, probably titanium:sapphire ring lasers pumped by intra-cavity frequency doubled, diode pumped Nd:YVO_4 lasers. These will be located in a controlled access room in the surface buildings, together with a series of precision interferometers which provide the frequency (and hence, length) standards. There will be a small number of special, high power 'delivery' fibres coupling the lasers to the input of the splitter tree (located underground, in USA-15). These will have a maximum fibre coupled power of 500 mW per fibre. However, the power level in the transmit fibres for the individual channels (after the splitter tree) will be a maximum of approximately 2 mW (probably significantly lower than this). The light levels in the receive fibres will be below 1 nW, which is negligible from a laser safety perspective.

The fibre for the FSI system between the splitter tree/APDs and the on-detector interferometers will be a custom, radiation hard, single-mode (SM) fibre, with a pure silica core of approximately 6 μm diameter, and a fluorine spike-doped cladding. It will have a numerical aperture (NA) of 0.1 ± 0.01 and a cut-off wavelength of 760 ± 40 nm. This gives a mode field diameter (MFD) of order 7 μm at 830 nm. A standard, non-radiation hard, polarisation maintaining fibre, with a matched MFD, will be used for the power delivery fibres which will link the lasers on the surface to the input of the splitter tree.

2.3 The LArg Calorimeter

A schematic representation of the LArg calorimeter front-end links is shown in Figure 2.7. These links will be unidirectional, with VCSELs only present on the front-end electronics boards.

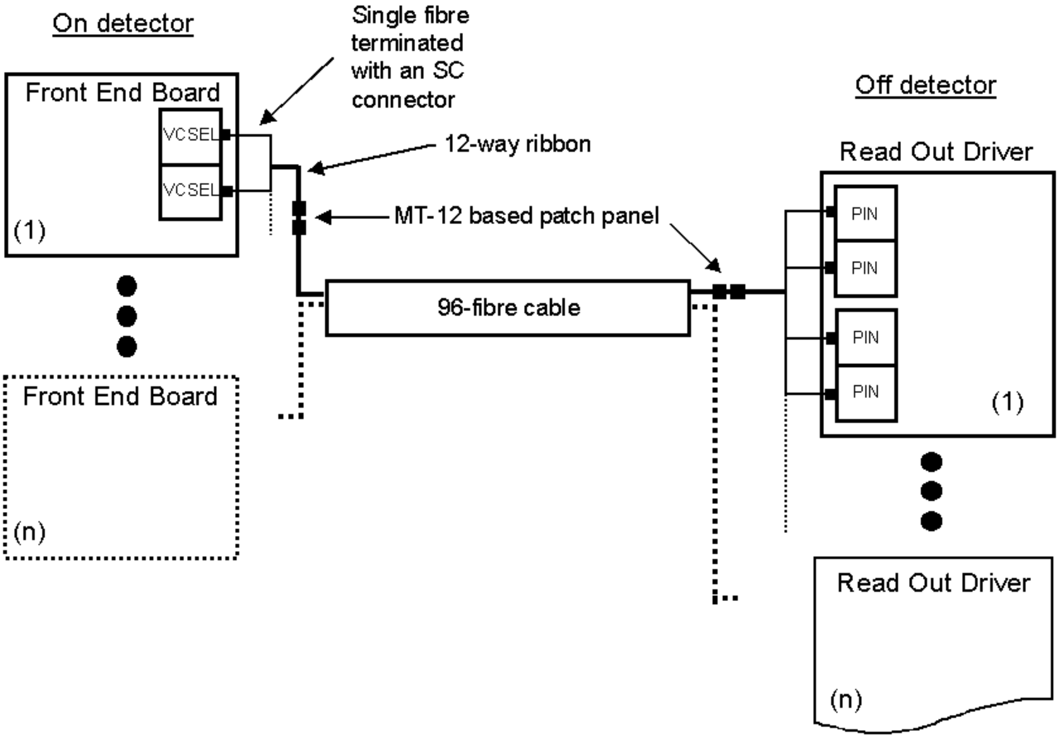

Figure 2.7 A schematic representation of the Liquid Argon Calorimeter data links

The front-end electronics of the LArg calorimeter will be located on large circuit boards grouped into crates, which will be attached to the outside of the calorimeter cryostat. There will be 16 crates at each end of the barrel cryostat, corresponding to 896 electronics boards. Access to these crates and boards will only be possible during maintenance and test periods after the endcap detectors have been retracted. There will be a further 13 crates secured to the outside of each endcap cryostat, corresponding to 628 electronics boards. Access to these crates and boards will also only be possible during maintenance and test periods after the endcap toroids have been retracted.

The current baseline architecture for the LArg calorimeter links has two VCSELs located on each front-end electronics board. Each VCSEL will be coupled to a single fibre via a commercial connector (e.g. ST or SC), and then grouped into 12-way ribbons. Groups of eight ribbons will either be formed directly into multi-ribbon cables or via MT-12 connectors at small patch panels attached to the detector infra-structure in the vicinity of the electronics crates (as shown in Figure 2.8) or outside the muon system.

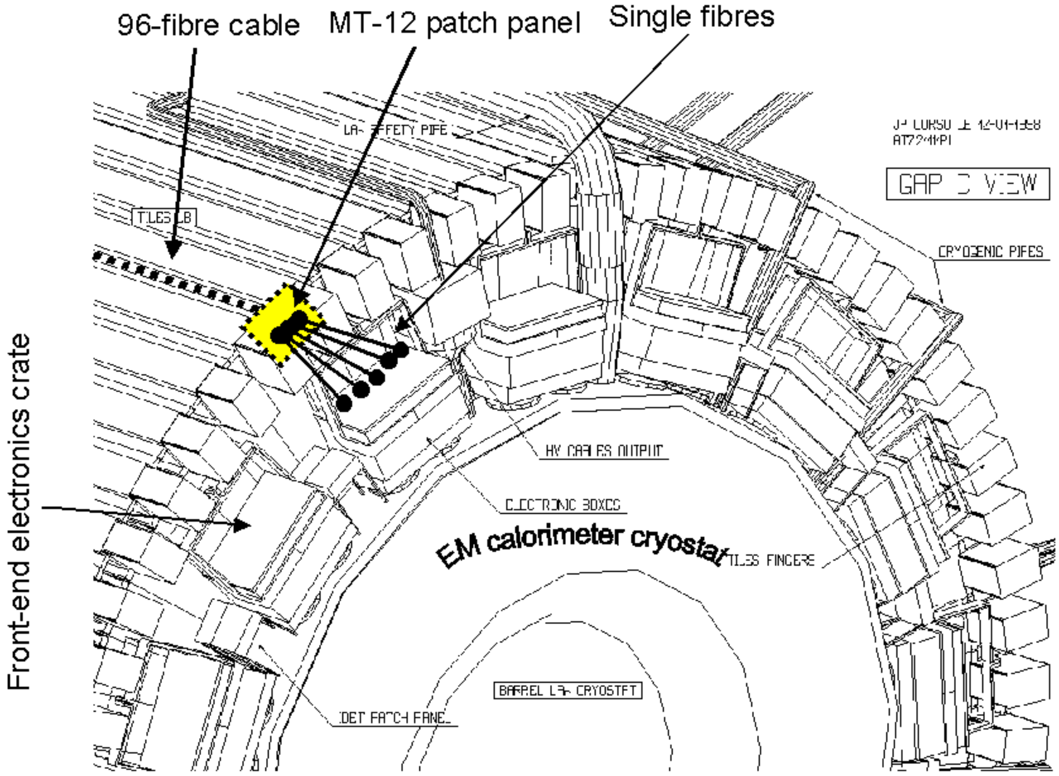

Figure 2.8 A general view of the end face of the LArg calorimeter cryostat, showing the front-end electronics crates, possible patch panel location and routing of the optical fibres

The cables will be routed directly to the ROD crates situated in USA-15 along the route detailed in Section 2.1.3. Connections to the PIN-diodes in the ROD crates will be made with commercial ST or SC connectors.

It should be noted that the design for the LArg links is not yet frozen and is subject to change. However, it is unlikely that there will be more than two VCSELs per Front-end Board. The basic design approach is described in more detail in the Liquid Argon Calorimeter, Technical Design Report [8], although this is not completely current.

Independent of the final link implementation chosen, the VCSELs will be driven by electronics which will ensure an absolute maximum output power of 3 mW, even under foreseeable fault conditions. The beam divergence will be 15 ° (full width) and the fibre coupled power will not exceed 3mW.

The fibre for the LArg links will be a standard, radiation tolerant (GIMM) fibre, with a Ge-doped core of 50 µm diameter, and a numerical aperture (NA) of 0.2 ± 0.015.

3 Laser Safety

3.1 General Approach

There are two IEC standards which cover laser safety: IEC 825-1, 'Safety of laser products Part 1: *Equipment classification, requirements and user's guide*' which applies to laser sources; and IEC 825-2, 'Safety of laser products Part 2: *Safety of optical fibre communication systems*' which extends the guidance offered in IEC 825-1 to cover optical fibre communication systems.

The essential difference between these two standards is that the former is aimed at self-contained laser products, in which the hazards are under effective local control, whereas the latter deals with extended systems, in which the laser sources can be separated by a significant distance from the potential hazards. The precautions required to minimise the risk of exposure to hazardous laser radiation in an extended system will clearly be different from those required for a more conventional laser source, which would normally be under local operator control.

The approach to laser safety adopted in this document is based on the recommendations of these IEC standards. It involves two distinct stages:

(i) Identification and classification of all potential laser hazards;

(ii) Implementation of appropriate control measures for each potential hazard, so as to prevent exposure, or to reduce it to a safe level.

The first stage is discussed in the remainder of Section 3 and Section 4. The second stage is described in Sections 5 and 6 of this document.

Section 3.2 describes the basic approach to the classification of laser hazards and Section 3.3 discusses the potential hazards that will be encountered in ATLAS. Section 4 lists the actual classifications for ATLAS, sub-system by sub-system.

Methods to limit exposure to laser radiation can be divided into three categories:

(i) Engineering controls;

(ii) Administrative controls;

(iii) Provision of personal protective equipment.

In this document, these control measures have been applied in a hierarchical way, as explicitly recommended in the UK universities 'Yellow Book' on laser safety[9] (Sections 1.2.3 – 1.2.7), which is a primary reference quoted in CERN Safety Instruction 22. Thus engineering controls (such as enclosures, interlocks and shutters) are proposed where-ever reasonably practicable. In cases where such engineering controls will not be appropriate, then administrative controls are proposed. The use of personal protective equipment (PPE) is considered a last resort and is not proposed anywhere in this document, except for certain initial 'alignment procedures' with the high power FSI lasers (which will take place in an enclosed, 'laser controlled area', with access restricted to qualified and trained personnel only).

Section 5 discusses some general points in relation to controlling the potential laser hazards that will be encountered in ATLAS and Section 6 describes the proposed control measures in detail.

These control measures closely follow the advice and guidance given in the IEC standards, together with additional guidance given in CERN Safety Instruction 22.

3.2 Classification of Laser Hazards

In order to establish the potential seriousness of exposure to laser radiation, every system containing a laser(s) must be classified in accordance with the IEC standards. There are six laser classes defined in IEC 825-1 and summarised in Appendix B of this document. IEC 825-2 extends this classification scheme to cover the potential laser hazards from optical fibre communication systems. It specifies six 'hazard levels', which are closely related to the six laser classes.

It is important to clearly understand the reasons for having a separate standard (IEC825-2) to deal with optical fibre systems. This is covered in Annex A of that document, which is reproduced in full as Appendix C of this document and summarised in the next few paragraphs.

Under normal operating conditions an optical fibre communication system would be safe because the optical radiation is totally enclosed. Indeed, it could be argued that a rigorous interpretation of IEC 825-1 would give a class 1 allocation to all such systems. However, this would clearly not accurately reflect the potential hazard.

The potential hazard depends both on the likelihood of the protective housing being breached (eg at a disconnected fibre connector or a broken cable) and the nature of the optical radiation that might subsequently become accessible. Also, because of the extended nature of these systems, the hazard may occur at a considerable distance from the source.

The precautions required to minimise the hazard will therefore be different from those applicable to more conventional laser sources, which are normally under effective local operator control. These precautions may also vary from one location to another, even within a single system.

Each accessible location in an optical fibre communication system will be assigned a 'hazard level', using criteria similar to those used for the classification of lasers in IEC 825-1, based not on directly accessible radiation, but on radiation that could become accessible under reasonably foreseeable circumstances[*] (eg as a result of cable damage or routine maintenance or testing).

To classify a laser system according to IEC 825-1 requires the knowledge of four basic system parameters:

(i) The wavelength, λ (in particular, whether the radiation is visible);

(ii) The emission duration, t, and whether the laser is cw, pulsed or modulated;

(iii) The visual angle subtended by the apparent source at the eye of an observer, α (in particular, whether the source is point like or extended);

(iv) The amount of accessible radiation.

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[*] A 'reasonably foreseeable event' is defined in IEC 825-2 Clause 3.19 as follows:

"An event the occurrence of which under given circumstances can be predicted fairly accurately, and the occurrence probability or frequency of which is not low or very low.

Examples of reasonably foreseeable events might include the following: fibre cable break, optical connector disconnection, operator error or inattention to safe working practices.

Reckless use or use for completely inappropriate purposes is not to be considered as a reasonably foreseeable event."

Each of the six laser classes is defined by specifying an Accessible Emission Limit (AEL) in terms of the wavelength, emission duration and angular size of the source. This AEL is the maximum permitted level of accessible radiation for that particular laser class. The AELs are expressed in terms of radiant energy (J) or radiant power (W) and/or radiant exposure (Jm^{-2}) or irradiance (Wm^{-2}), and are tabulated in IEC 825-1, Tables 1 to 4.

As noted above, the six 'hazard levels' for optical fibre systems defined in IEC 825-2 are closely related to the laser classes defined in IEC 825-1. Thus, 'hazard level 3A' in IEC 825-2 is defined by applying the AEL for 'class 3A' in IEC 825-1. However, there is one special case; hazard level k times 3A (k x 3A).

Hazard level k x 3A only applies in the wavelength range 400 nm to 4,000 nm, and represents a limited extension of hazard level 3A into what would normally be hazard level 3B (in a similar way to Class 3B* - see Appendix B). This was introduced to more realistically reflect the true hazard associated with viewing optical fibre components. It allows for increased power levels in optical communication systems without increasing the risk of ocular damage under reasonably foreseeable circumstances.

Hazard level k x 3A is important here because the control measures required for 3B are much more stringent than those required for 3A and k x 3A (the boundary between 3A and 3B effectively marks the point between low powered, essentially safe, and high powered, potentially dangerous, lasers).

3.3 Classification of ATLAS laser systems

3.3.1 Introduction

This section summarizes those parts of the IEC standards that are relevant to the laser systems that will be used in ATLAS.

Some of the optical fibre systems for the outlying detectors (not currently included in this document) are likely to be commercial 'off the shelf' systems, which come under hazard level 1. These will not be discussed further here, as they are considered to be inherently safe.

All of the systems described in this document will operate in the near infra-red, at wavelengths between 820 and 850 nm, or at 1310 nm. There will thus be no aversion responses (such as the blink reflex) to protect the eye in case of accidental exposure. As a consequence, hazard level 2 will not be applicable to ATLAS.

The power that will be coupled into all of the ATLAS fibre systems will fall below the AEL for class 3B (500 mW [*]) so hazard level 4 will not be applicable to any of the fibres. [Note: the lasers for the FSI system (on the surface) will probably be class 4, but no more than 500 mW will be coupled into a single optical fibre.]

The relevant hazard levels are thus 3A, k x 3A and 3B. The AELs for class 3A are defined in IEC825-1, Table 3. For each wavelength range there are two limits, a radiant energy or power limit (in J or W) and a radiant exposure or irradiance limit (in Jm^{-2} or Wm^{-2}). The more restrictive of the two must be used. In the former case, the radiant energy or power is to be integrated over a 50 mm[†] diameter circular aperture, whilst in the latter case, the radiant exposure or irradiance is the maximum averaged over a 7 mm[‡] diameter circular aperture (to represent the pupil of a human eye). Both measurements are to be performed at a minimum distance of 100mm[§] from the apparent source, which is equal to the shortest accommodation distance for the human eye.

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[*] For $t > 0.25$ s and wavelengths between 315 nm and 1 mm. See IEC825-1, Table 4 for other cases.

[†] For $\alpha \leqslant 1.5$ mrad and wavelengths between 400 nm and 1400 nm. See IEC825-1, Table 01 for other cases.

[‡] For eye exposure and wavelengths between 400 nm and 1400 nm. See IEC825-1, Table 7 for other cases.

[§] For $\alpha \leqslant 1.5$ mrad and wavelengths between 400 nm and 1400 nm. See IEC825-1, Clause 8.2(c) and Table 01 for other cases.

According to IEC 825-1 Clause 9.3(e), for all wavelengths greater than 700nm and where intentional long term viewing is not inherent in the design of the system, it is permissible to use a reduced time base of 100 s to calculate the AELs for hazard levels 1 and 3A. This is the situation that is relevant to ATLAS. Therefore, unless otherwise stated, $t = 100$ s has been used in all of the calculations in this document.

Clause 3.8 of IEC 825-2 states; "… For purposes of the k x 3A hazard level evaluation, the class 3A AEL table is used and the minimum measurement distance shall be increased to 250 mm from the apparent source and the time base used shall be 10 s provided longer viewing durations are not reasonably foreseeable".

For wavelengths in the range 700 nm to 1400 nm, this reduction in the time base for k x 3A from 100 s to 10 s translates directly into an increase in the AEL by a factor of $10^{0.25} = 1.778$[*]. Clearly, the increase in measurement distance can only result in a less stringent upper limit for the power of the source, compared to hazard level 3A, if the laser radiation is diverging. However, this is usually the case for optical fibre systems, where typical sources are radiation emerging from a bare fibre end or an uncollimated semiconductor laser.

It is important to note that the factor k varies from one system to another, depending on the precise radiation pattern and should not be calculated directly. The radiation patterns of different types of laser diode and optical fibres can vary significantly. A single mode fibre will usually emit a less divergent beam, and thus exceed the k x 3A threshold at a lower power, than a multi-mode fibre at the same wavelength.

Over the wavelength range 400 nm to 1400 nm, the class 3A AELs refer to the parameter $C_6(\alpha)$. The angular size of the source, α determines the size of the image on the retina. Thus the purpose of $C_6(\alpha)$ is to allow extended sources to be dealt with correctly. Over the range of interest for ATLAS, $C_6(\alpha)$ is defined as follows[†]:

$$C_6(\alpha) = 1 \qquad \text{for} \quad \alpha \leqslant \alpha_{min}$$

$$C_6(\alpha) = \alpha / \alpha_{min} \qquad \text{for} \quad \alpha_{min} < \alpha \leqslant \alpha_{max}$$

with $\alpha_{min} = 11$ mrad, for $t \geqslant 10$ s[‡] and $\alpha_{max} = 100$ mrad.

The condition $\alpha \leqslant \alpha_{min}$ is easily satisfied for 'point like' sources such as single fibres or lasers, but not necessarily for VCSEL arrays or ribbon fibres (see next section).

In the following sections, the classification of the hazard levels for the VCSELs and fibres are based on information supplied by manufacturers and the calculations in Appendix D of this document, which follow the procedures set out in the IEC standards.

3.3.2 Ribbon Fibre Issues

According to Clauses D.5.4 and D.5.5 in Annex D of IEC825-2, a ribbon fibre must be treated as a single extended source when the ends are polished or cleaved. In these cases the radiation patterns of the individual fibres overlap and must be treated as additive. This is the situation that applies to an MT connector, in which case the AEL applies to the whole ribbon. The maximum power per fibre is determined by dividing the AEL equally between all of the fibres in the ribbon.

However, it has been shown by extensive measurements that a broken ribbon fibre can be treated as a bundle of independent fibres with random alignments. In this case the radiation patterns of the individual fibres do not overlap and need not be treated as additive. Therefore, the AEL can be applied to each fibre individually.

Thus, the maximum power per fibre for hazard levels 3A and k x 3A are significantly reduced wherever there are MT connectors, as in a patch panel. A similar argument also applies to the arrays of VCSELs used in the SCT ROD crates.

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[*] See IEC825-1, Table 3.

[†] See IEC825-1, Notes to Tables 1 to 4.

[‡] See IEC825-1, Clause 9.3(d) for other emission durations.

Because ribbon fibres and VCSEL arrays subtend an angle, $\alpha \geqslant 1.5$ mrad, they can be treated as extended sources when calculating the relevant AELs. Thus $C_6(\alpha) \neq 1$ and the aperture diameter for the radiant power or energy measurement changes in accordance with Table 01 in IEC 825-1. These rather lengthy calculations are reproduced in Appendix D of this document.

A simple and conservative approach would be to divide the AEL for a single fibre or VCSEL by the total number of fibres in the ribbon or VCSELs in the array. However, this is overly pessimistic.

3.3.3 820 nm to 850 nm Systems

In order to calculate the AELs for classes 1 and 3A in the wavelength range 700 nm to 1050 nm, it is necessary to evaluate the parameter $C_4(\lambda)$, defined as follows[*]:

$$C_4(\lambda) = 10^{(\lambda - 700)/500}$$

with λ, expressed in nm. C_4 varies from 1.738 at 820 nm to 1.995 at 850 nm.

The relevant[†] class 1 AEL is defined in IEC 825-1, Table 1 as;

$$7 \times 10^{-4}\, t^{0.75}\, C_4(\lambda)\, C_6(\alpha)\ \text{J}$$

For $C_6 = 1$, this is equivalent to a radiant power of **0.38 mW** at 820 nm, or **0.44 mW** at 850 nm.

The relevant[‡] class 3A AEL is defined in IEC825-1, Table 3 as the more restrictive of;

$$3.5 \times 10^{-3}\, t^{0.75}\, C_4(\lambda)\, C_6(\alpha)\ \text{J} \qquad \text{or} \qquad 18 \times t^{0.75}\, C_4(\lambda)\, C_6(\alpha)\ \text{Jm}^{-2}$$

In the former case, the radiant energy is to be integrated over a 50 mm[§] diameter circular aperture, whilst in the latter case, the radiant exposure is the maximum averaged over a 7 mm diameter circular aperture. Both measurements are to be performed at a minimum distance of 100mm from the apparent source.

For $C_6 = 1$ and $\lambda = 820$ nm these conditions are equivalent to **1.9 mW** and **9.9 Wm^{-2}** respectively, whilst for 850 nm, the corresponding numbers are **2.2 mW** and **11.4 Wm^{-2}**.

Some examples of the maximum power limits for hazard levels 1 to 3B in an optical fibre are given in Table D.1 of IEC825-2. For an NA = 0.18, MM fibre at 850 nm, this gives a maximum power of 2.2 mW for hazard level 3A and 6.6 mW for k x 3A. Both of these limits are derived from the radiant energy condition, which is more restrictive in these cases. An NA of 0.18 is equal to the lower limit for the MM fibres used in the SCT and LArg front-end data links. Details of maximum power limit calculations for SM fibres at 830 nm are given in Appendix D of this document.

3.3.4 1310 nm Systems

[Note: this section has been included to accommodate possible future links at 1310 nm. It is not currently relevant.]

In order to calculate the AELs for Classes 1 and 3A in the wavelength range 1050 nm to 1400 nm, it is necessary to evaluate the parameter $C_7(\lambda)$, which is equal to 8 for wavelengths between 1200 nm and 1400 nm[**].

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[*] See IEC825-1, Notes to Tables 1 to 4.

[†] For 1.8×10^{-5} s < t < 10^3 s.

[‡] For 1.8×10^{-5} s < t < 10^3 s.

[§] For $\alpha \leqslant 1.5$ mrad only, see Appendix D of this document for ribbon fibre calculations.

[**] See IEC825-1, Notes to Tables 1 to 4 for other wavelengths.

The relevant[*] Class 1 AEL is defined in IEC 825-1, Table 1 as;

$$3.5 \times 10^{-3}\, t^{0.75}\, C_6(\alpha)\, C_7(\lambda)\ \mathrm{J}$$

For $C_6 = 1$, this is equivalent to a radiant power of **8.85 mW**.

The relevant[†] class 3A AEL is defined in IEC825-1, Table 3 as the more restrictive of;

$$1.8 \times 10^{-2}\, t^{0.75}\, C_6(\alpha)\, C_7(\lambda)\ \mathrm{J} \qquad \text{or} \qquad 90 \times t^{0.75}\, C_6(\alpha)\, C_7(\lambda)\ \mathrm{Jm^{-2}}$$

In the former case, the radiant energy is to be integrated over a 50 mm[‡] diameter circular aperture, whilst in the latter case, the radiant exposure is the maximum averaged over a 7 mm diameter circular aperture. Both measurements are to be performed at a minimum distance of 100mm from the apparent source.

For $C_6 = 1$, these conditions are equivalent to **46 mW** and **230 Wm^{-2}** respectively.

Some examples of the maximum power limits for hazard levels 1 to 3B in an optical fibre are given in Table D.1 of IEC825-2. For a fibre which is SM[§] at 1310 nm[**], this gives a maximum power of 24 mW for hazard level 3A and 83 mW for k x 3A. The former limit is derived from the radiant exposure condition and the latter from the radiant energy condition.

3.3.5 Summary

The accessible emission limits at wavelengths relevant to ATLAS are summarized in Table 3.1. The AELs in this table have been calculated for an emission duration of t = 100 s and point-like sources with $\alpha \leqslant \alpha_{min}$.

λ / nm	AEL class 1	AEL class 3A	AEL class 3B
820	0.38 mW	1.9 mW and 9.9 Wm^{-2}	500 mW
850	0.44 mW	2.2 mW and 11.4 Wm^{-2}	500 mW
1310	8.85 mW	46 mW and 230 Wm^{-2}	500 mW

Table 3.1 Summary of relevant AELs at ATLAS wavelengths

4 Classification of Potential Laser Hazards in ATLAS

4.1 Introduction

IEC 825-2, Clause D.5.7 (a) states: “The assessment of hazard levels shall always consider worst case conditions, including reasonably foreseeable fault conditions… .” Therefore, the following assumptions have been made throughout this document:

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[*] For 5×10^{-5} s < t < 10^3 s.

[†] For 5×10^{-5} s < t < 10^3 s.

[‡] For $\alpha \leqslant 1.5$ mrad only, see Appendix D of this document for ribbon fibre calculations.

[§] Mode field diameter of 11 µm.

[**] Calculated at 1270 nm, the lower wavelength limit of the “1300 nm telecommunications window”.

(i) Fibre attenuation has been neglected;

(ii) All laser sources have been assumed to be cw;

(iii) The maximum possible power has been assumed for laser sources, including under reasonably foreseeable fault conditions in the associated driver electronics.

The hazard level assessments given in this section represent the 'basic' potential hazard. That is, they have been calculated in the absence of any form of control measure to reduce the potential hazard to a 'safe' level. Because hazard level 3B and above will not be permitted in the majority of ATLAS locations (see Section 5.2), engineering and/or administrative control measures will have to implemented in order to reduce the potential hazard to k x 3A or below. These control measures are described in Section 6.

4.2 The SCT

4.2.1 Front-End Data Links

The SCT front-end data links will operate at a wavelength of 850 nm, and use MMSI fibre with NA = 0.2 ± 0.02. The worst case corresponds to NA = 0.18, so the values referred to in Section 3.3.3 (from Table D.1 of IEC 825-2) apply.

The maximum power limits for individual fibres and broken or damaged ribbons or cables are therefore 2.2 mW and 6.6 mW for hazard levels 3A and k x 3A respectively.

The full calculations for ribbon fibre connectors are reproduced in Appendix D. They show that for MT-12 connectors, the maximum power limits per fibre are *0.68 mW* and *2.5 mW* for hazard levels 3A and k x 3A respectively. [**Note, these numbers are currently being checked. They will not increase – but they are likely to decrease. The most conservative limits would be 0.18 mW and 0.55 mW for hazard levels 3A and k x 3A respectively.**]

The maximum fibre coupled power will be 3 mW. Thus, hazard level k x 3A will be appropriate for individual fibres and broken or damaged ribbons or cables. However, hazard level 3B will be appropriate for MT connectors, and hence for the inside of patch panels.

The on detector VCSELs are pigtailed and hence the radiation is not directly accessible.

The VCSELs in the ROD crates will be in the form of linear arrays of 12, with a pitch of 250 µm to match the ribbon fibres. They must therefore be treated as extended sources. The full calculations are reproduced in Appendix D, and show that hazard level 3B will be appropriate.

Thus all fibres, ribbons and multi-ribbon cables will be hazard level k x 3A and the inside of all patch panels and ROD crates will be hazard level 3B.

4.2.2 Alignment System

The alignment system will operate over the wavelength range 830 ± 10 nm, and use SM fibre with NA = 0.10 ± 0.01 and a MFD of 7µm. The calculations applicable to this fibre are reproduced in Appendix D, both for an individual fibre and a ribbon fibre connector.

The maximum power limits for individual fibres and broken or damaged ribbons or cables are 0.9 mW and 3.4 mW for hazard levels 3A and k x 3A respectively.

The maximum power limits per fibre for MT-8 and MT-12 connectors are **? mW and **? mW for hazard levels 3A and k x 3A respectively.

The maximum fibre coupled power will be 2 mW for individual channels. Thus, hazard level k x 3A will be appropriate for individual fibres and broken or damaged ribbons or cables. However, hazard level 3B will be appropriate for MT connectors, and hence the inside of patch panels and the splitter tree crate.

The worst case hazard from the on-detector interferometers will be exactly equivalent to individual bare fibre ends. Therefore, the limits for single fibres will apply and hazard level k x 3A will be appropriate. These interferometers will be located inside the thermal shield, and hence will only be accessible during assembly and testing.

The power delivery fibres (from the surface to the splitter tree crate) will be run at a maximum of 500 mW per fibre. They will therefore fall into hazard level 3B.

The laser systems in the surface buildings will be over 500mW and will thus be class 4.

4.2.3 SCT Summary

To allow the appropriate control measures to be incorporated into the detailed mechanical and electrical design of the SCT and its associated services, a complete set of working laser hazard level assessments is required.

It is therefore proposed to use the following set of ‘basic’ hazard level assessments (i.e. in the absence of further control measures) for this detailed design phase:

(i) hazard level **k x 3A** for all of the fibres and ribbons within the SCT thermal enclosure and all of the multi-ribbon cables linking the SCT to its associated electronics crates in USA-15;

(ii) hazard level **3B** for the inside of all SCT patch panels, ROD crates and FSI splitter-tree crate;

(iii) hazard level **3B** for the FSI power delivery fibres, which connect the splitter-tree crate in USA-15 to the lasers in the surface buildings;

(iv) hazard level **4** for the FSI laser system in the surface buildings.

4.3 The LArg Calorimeter

The LArg front-end data links will operate at a wavelength of 850 nm, and use MMGI fibre with NA = 0.2 ± 0.015. Taking a worst case of NA = 0.18, the values referred to in Section 3.3.3 (from Table D.1 of IEC 825-2) therefore apply.

Thus, the maximum power limits for individual fibres and broken or damaged ribbons or cables are therefore 2.2 mW and 6.6 mW for hazard levels 3A and k x 3A respectively.

The full calculations for ribbon fibre connectors are reproduced in Appendix D. They show that for MT-12 connectors, the maximum power limits per fibre are *0.68 mW* and *2.5 mW* for hazard levels 3A and k x 3A respectively. [**Note, these numbers are currently being checked. They will not increase – but they are likely to decrease. The most conservative limits would be 0.18 mW and 0.55 mW for hazard levels 3A and k x 3A respectively.**]

The on-detector VCSELs will have an angular divergence of 15 ° (full width). The calculation in Appendix D shows that this is equivalent to NA = 0.16, and that the maximum power limits for hazard levels 3A and k x 3A are 2.2 mW and 5.7 mW respectively.

The maximum fibre coupled power will be 3 mW. Thus, hazard level k x 3A will be appropriate for individual fibres and broken or damaged ribbons or cables. However, hazard level 3B will be appropriate for MT connectors, and hence for the inside of patch panels.

The individual on-detector VCSELs will have a maximum output power of 3 mW and will therefore be hazard level k x 3A.

To allow the appropriate control measures to be incorporated into the detailed mechanical and electrical design of the LArg calorimeter and its associated services, a complete set of working laser hazard level assessments is required. It is therefore proposed to use the following set of 'basic' laser hazard level assessments (i.e. in the absence of further control measures) for this detailed design phase:

(i) hazard level **k x 3A** for individual fibres, ribbon fibres, multi-ribbon cables, ST/SC connectors and individual VCSELs;

(ii) hazard level **3B** for the inside of patch panels containing MT connectors.

5 Control of Laser Hazards

5.1 'Location Type' and Access Restrictions

The specific control measures required for any particular hazard level will depend on the type of location (eg domestic, industrial, etc.). In effect, this means whether or not access controls on personnel are implemented, together with the degree of competence in laser safety of those personnel who do have access.

Therefore, before proceeding to the details of the proposed control measures, it is necessary to establish the 'location type' of the various locations within ATLAS which contain potential laser hazards, in accordance with the IEC standards.

IEC 825-2 defines three location types in Clauses 3.13 to 3.15, as follows:

> ***location with controlled access:*** A location where access to the protective housing (enclosure) is controlled and is accessible only to authorized persons who have received adequate training in laser safety and servicing of the system involved. Examples include optical cable ducts and switching centres.
>
> ***location with restricted access:*** A location where access to the protective housing (enclosure) is restricted and not open to the public. Examples include industrial and commercial premises.
>
> ***location with unrestricted access:*** A location where access to the protective housing (enclosure) is unrestricted. Examples include domestic premises and those open to the public.

IEC 825-2 also gives some typical examples of such locations in Clause D.3.1.

IEC 825-1, Clause 3.37 contains the following definition:

> ***laser controlled area:*** An area where the occupancy and activity of those within is subject to control and supervision for the purpose of protection from radiation hazards.

From a laser safety perspective, most of ATLAS (including the majority of the surface buildings, UX-15 and USA-15) would appear to fall into the second category, a 'location with restricted access'.

The only exceptions to this would appear to be the FSI laser room on the surface (which must be defined as a 'laser controlled area' due to the presence of class 4 laser systems) and the ***inside*** of cable ducts, patch panels and electronics racks (which are classed as 'locations with controlled access' in Clause D.3.1(a) of IEC825-2).

5.2 Engineering Requirements

Clause 4.5.2 of IEC 825-2 states that: "Optical fibre communication systems operating in restricted locations shall have a hazard level of 1, 2, 3A or k x 3A."

The patch panels and ROD/FSI crates would therefore appear to be situated in a 'location with restricted access', in which accessible laser radiation of hazard level 3B (or above) is not permitted.

In order to satisfy the requirements of IEC825-2, it will therefore be necessary to ensure that accessible laser radiation from the patch panels and crates is reduced to hazard level k x 3A (or below). Under normal operation, this will be achieved by totally enclosing the relevant parts. However, during access for testing or maintenance, this will require the use of additional engineering controls, such as Automatic Power Reduction (APR), and/or administrative controls to ensure that the relevant sub-system(s) cannot become energised when personnel are working inside the patch panels or ROD/FSI crates.

The use of engineering controls is the approach recommended by the IEC standards and the UK Universities 'Yellow Book' on laser safety, a primary reference quoted in CERN Safety Instruction 22.

Automatic Power Reduction (APR) is discussed in the next section and appropriate working practices during maintenance and testing are discussed in Section 5.5.

The engineering controls required by Clause 4 of IEC 825-2 are summarized in Annex B of that document, which has been reproduced in full as Appendix E of this document.

In addition to the requirement for labelling (which applies for hazard levels 2 and above, in all locations) there are additional engineering requirements which apply to hazard level k x 3A in a restricted location. These are as follows:

(i) Additional mechanical protection for cables;

(ii) The use of a tool to mate or de-mate connectors wherever the maximum accessible emission from a connector could exceed hazard level 3A.

The implementation of these engineering requirements is discussed in Section 6 of this document.

5.3 Automatic Power Reduction

Clause 4.1.4 of IEC 825-2 states that: "Automatic power reduction may be used to control the hazard level." However, Clause D.5.3 emphasises that "Automatic power reduction **should not** take the place of good work practices and proper servicing and maintenance. Also, the reliability of the APR mechanism shall be taken into account when assessing the hazard level."

The application of APR for restricted (and unrestricted) locations is discussed in IEC 825-2, Clause D.5.3.4, which states: "… designers shall be aware of the restrictions in Annex B (Appendix E of this document) regarding restricted and unrestricted environments, and incorporate APR into any system that has the potential to expose humans to laser or LED power of class 3B (class 3A in unrestricted) and above in these respective environments. Appropriate reliability precautions shall be taken when designing this power down system."

Thus, APR would appear to be mandatory for those patch panels and electronics crates located in a restricted area, and in which the hazard level would otherwise be 3B. This includes all locations where MT ribbon connectors will be utilised in ATLAS.

The timing requirements for an APR system to react are discussed in Clause 4.4.3 of IEC 825-2, which states: "The speed of power reduction required to obtain a specific hazard level can be determined form the AEL tables in IEC 825-1." In practice, this means that the laser power in a high power system must be reduced more rapidly than that in a lower power system. Thus the APR must be more rapid in the case of the FSI power delivery fibres than for the MT connectors in the patch panels and electronics crates.

However, this reaction time is to be determined from the moment that the potential hazard becomes accessible. In the case of the disconnection of a fibre connector, for example, Clause D.5.3.2 of IEC 825-2 states: "A possible and likely assumption that could be made is that human accessibility to the energized fibre would not occur until one second after the disconnection."

As a result, the time derived from the AEL tables in IEC 825-1 can be increased by 1 s for this case. Clearly, the APR reaction time can be increased still further if the interlock system is operated immediately that the enclosure cover is removed (for example, by a micro-switch). This timing requirement is considered separately in detail for each part of each sub-system in Section 6 of this document.

An alternative form of APR that could be utilised for a connectorized system, such as ATLAS, would be to incorporate shuttered connectors. These are discussed in Clause D.5.3.2 of IEC 825-2, where it is made clear that the shutters would have to operate within the time restrictions discussed above and satisfy the reliability requirements outlined in Clause D.6 of IEC 825-2. This is not likely to be practical at the higher 3B power levels used by, for example, the FSI delivery fibres, but it may be possible in the lower range of hazard level 3B powers.

Unfortunately, suitable shuttered MT connectors do not appear to be commercially available. They would anyway be much too large and massive for use at the SCT patch panels located within the actual detector. However, if they could be developed, or were to become available commercially, they could be utilized in some locations, such as the LArg patch panels and the electronics crates in USA-15.

Single fibre shuttered connectors are available commercially and may therefore represent a viable solution for those sub-systems which will be using individual fibre connectors, such as ST or SC connectors, at the lower end of hazard level 3B (or k x 3A in an unrestricted location, or to avoid the requirement for a tool with k x 3A in a restricted location).

5.4 Assembly, Installation, Maintenance and Testing

Different operational laser safety arrangements will need to be applied during the assembly and installation phases of ATLAS. These will vary from one sub-detector to another and are described in detail in the corresponding parts of Section 6.

However, there will clearly be a number of operations which will involve testing at various times during the assembly and installation phases. Therefore, some general points which are relevant will be discussed in this section, which is primarily concerned with maintenance and testing.

The following, self-explanatory paragraphs contain excerpts from Section 5 of IEC 825-2, which provides guidance for maintenance and testing operations and are clearly relevant to the performance of these operations for at least some of the optical fibre sub-systems within ATLAS.

Clause 5.1.1 states: "…Wherever possible, diagnostic tests should be carried out in such a way so as not to increase the hazard level at any location. It may be necessary to have administrative controls which in some cases may involve a permit to work system. When connecting test equipment, due regard should be taken to establishing actual power levels introduced into the system in assessing the hazard."

Clause 5.1.2 states: "There shall be clearly defined conditions under which automatic power reduction facilities may be overridden."

Clause 5.1.4 states: "Wherever reasonably practical, servicing, maintenance and repair should be carried out with no power propagating in the fibre, otherwise the system should be operated at the lowest power consistent with the need ."

Clause 5.2.1.2 states: “Before working on any optical fibre cable or system, staff should check the operational status and hazard level. In the case of systems that are installed and activated, this will be indicated by the appropriate hazard warning labels. During installation, these may not yet have been provided and, in their absence, precautions appropriate to the classification of any test equipment containing optical sources connected to the fibre should be used.”

Clause 5.2.1.3 states: “During installation or testing of an optical fibre cable or network, only test equipment of laser class 1, 2 or 3A should be used. If, in a particular instance, it is essential to use test equipment of a higher class, the accessible fibre ends and connectors at all locations should be secured and labelled with the appropriate hazard level before testing proceeds.”

Clause 5.2.1.4 states: “Entry points to controlled areas with a hazard level k x 3A and above shall have a sign indicating:

- the warning label according to figure 14 in IEC 825-1 and the hazard level number incorporated in the explanatory label according to figure 15 of IEC 825-1;
- a sign limiting access to authorized persons only and explaining the existence of a potential hazard.”

Clause 5.2.2.1 states: “Only staff who have attended an optical fibre safety training course should be permitted to work on optical fibre systems in a location with hazard levels k x 3A and 3B.”

Clause 5.2.2.3 states: “ Where possible, optical transmission or test equipment should be shut down, or put into a low power state or disconnected before any work is done on exposed fibres, connectors etc. In that case, unintentional switching on should be prevented by a remote control switch or another suitable method. The status of the line (power on or off) should be clearly indicated.”

Clause 5.2.2.4 states: “Staff should ensure that optical fibre communication systems and test equipment in locations with a hazard level k x 3A or 3B are properly operated and controlled so as to protect unauthorized personnel.”

And finally Clause 5.2.3 states: “ The employer of staff installing or maintaining optical fibre communication systems should establish and maintain an adequate programme for the control of hazards. Safety and training programmes should be instituted for staff working on fibres or communication systems with a hazard level of k x 3A or 3B. …”

Some of these requirements may have an impact on the engineering design, for example, the requirement for remote control switching of sources in Clause 5.2.2.3. Others will require suitable administrative controls to be implemented, for example permits to work, overriding of APR systems and labelling etc.

5.5 Working Practices and Training Requirements

It will clearly be necessary for ATLAS to define an appropriate set of working practices for personnel working on the various optical fibre systems. A suggested set of working practices are outlined in Clause D.7 of IEC 825-2, which is reproduced here as Appendix F.

As noted in the previous section, only staff who have attended an optical fibre safety training course should be permitted to work on optical fibre systems in a location with hazard levels k x 3A or 3B.

Since much of the ATLAS fibre installation will be hazard level k x 3A or above, it will be necessary for ATLAS to arrange a training programme (probably in conjunction with TIS) to ensure that all personnel who will be working on, or in the vicinity of, these parts of the fibre installation will be adequately trained and competent to do so.

In addition to general instruction in laser safety, this training must include specific instruction in the particular hazards and working practices for the sub-system(s) that the personnel will be working on.

6 Control Measures Proposed for ATLAS

6.1 Common Control Measures

6.1.1 Individual Optical Fibres

The vast majority of individual optical fibres will fall into or below hazard level k x 3A. The only exception to this will be the FSI power delivery fibres, which will be hazard level 3B. These 3B fibres are discussed separately below.

The following control measures will be implemented for all single optical fibre cables, as appropriate to their location and hazard level:

All single optical fibre cables:

Will carry appropriate markings to distinguish them from other services, such as electricity[*].

All single optical fibre cables not installed in a controlled location:

(i) Will have mechanical characteristics of not less than those required by IEC 794-2[†];

(ii) With a hazard level in excess of 3A, will have 'further and adequate mechanical protection', in addition to the requirements of IEC 794-2[‡];

(iii) In which connectors will be accessible in an unrestricted location, will require the use of a tool to disconnect them, if hazard level 1 can be exceeded[§];

(iv) In which connectors will be accessible in a restricted location, will require the use of a tool to disconnect them, if hazard level 3A can be exceeded[**].

All single optical fibre cables not enclosed within a patch panel or electronics crate:

All connectors will be labelled in accordance with the requirements of Clause 4.2.2 of IEC 825-2, if hazard level 1 can be exceeded.

Note that the labelling requirements for patch panels and electronics crates is dealt with in Section 6.1.4.

The precise details of the implementation of these engineering requirements will vary slightly from one sub-system to another. They are therefore described in detail in Section 6.

Because they represent a greater potential hazard, the 3B fibres will require additional engineering control measures. These fibres will be routed in cable galleries, from the surface buildings to USA-15, with 'restricted' access (or even possibly 'unrestricted' access) where accessible 3B radiation is prohibited. Therefore APR will be required to reduce the hazard level to k x 3A or lower.

In addition to the control measures described above, the following extra control measures will be implemented for the 3B fibres:

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[*] Clause 4.2.1 of IEC 825-2.
[†] Clause 4.1.2.1 of IEC 825-2.
[‡] Clause 4.1.2.2 of IEC 825-2.
[§] Clause 4.1.3.1 of IEC 825-2.
[**] Clause 4.1.3.2 of IEC 825-2.

(i) When inside the enclosure of a patch panel or electronics rack, the fibres will be run in miniature flexible stainless steel conduit;

(ii) When not in a controlled area or inside the enclosure of a patch panel or electronics rack, the cables will be fully enclosed along their entire length, within conduits, ducts or trunking;

(iii) Any such conduits, ducts or trunking will be manufactured from either metal or an impact resistant plastic and will require the use of a tool to remove any covers;

(iv) Appropriate laser warning labels will be attached to the outside of all such conduits, ducts and trunking at intervals of approximately 1 m, wherever they are accessible;

(v) A fail-safe APR system which will shut down the high power input to the fibre whenever the integrity of the cable is breached;

(vi) No other services, such as electricity, will share these conduits, ducts or trunking, except low voltage interlock cables which form part of the APR system.

The APR system will utilize a separate low power (hazard level 1) ‘sense’ fibre incorporated into the cable construction for each 3B fibre, which will continuously monitor the continuity of the cable. The high powered input will be blocked with a fail-safe mechanical shutter whenever this sense signal is lost. The full details of this APR system are described in Section 6.2.

6.1.2 Individual Ribbon Fibres

This section is limited to a discussion of the engineering requirements for individual ribbon fibres only. The MT connectors are covered in Section 6.1.4.

For the purposes of assessing the potential hazard due to damaged or broken fibre ribbons, all of the individual ribbon fibres fall into or below hazard level k x 3A.

Individual ribbon fibres do not meet the mechanical requirements of IEC 794-2. Therefore they must be installed in a controlled location[*].

The places where individual ribbon fibres will be installed include the inside of patch panels and the rear of the ROD/FSI electronics racks, together with the run from the SCT detector to the patch panels at PP2.

The patch panels and electronics racks will be fully enclosed and will either be fitted with APR or administrative controls wherever they would be accessible.

The bundles of ribbon fibres linking the SCT to the patch panels at PP2 will be inside the bore of the LArg cryostat for the first part of their route, where they will be inaccessible during normal operation. They will be protected by an APR system whenever they become accessible during installation and the very infrequent ‘long’ detector access periods.

As they leave the bore and radially cross the end faces of the LArg cryostat, these ribbon fibres will be installed in either non-magnetic metal or impact resistant plastic trunking, which will require the use of a tool to remove the covers and which will be labelled with appropriate laser warning labels at intervals of approximately 1 m. Here they will be inaccessible during normal operation, but will become accessible during the more frequent ‘short’ detector access periods, when they will protected by either APR or administrative controls. See Section 6.2 for further details.

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[*] Clause 4.1.2.1 of IEC 825-2.

6.1.3 Multi-ribbon Cables

This section is limited to a discussion of the engineering requirements for multi-ribbon cables only. The MT connectors are covered Section 6.1.4.

For the purposes of assessing the potential hazard due to damaged or broken fibre ribbons, all of the cables running between the detector patch panels and the electronics racks fall into or below hazard level k x 3A. It will therefore be possible to use a common approach to control the potential laser hazard due to these cables.

The following hazard control measures will be implemented for all multi-ribbon cables:

(i) All multi-ribbon cables will carry appropriate markings to distinguish them from other services, such as electricity[*].

(ii) All multi-ribbon cables will be constructed so as to comply with mechanical characteristics not less than those required by IEC 794-2[†].

(iii) To satisfy the additional engineering requirements for hazard level k x 3A, all multi-ribbon cables will be fully enclosed along their entire length, either within conduits, ducts or trunking, or within the enclosures of the patch panels or electronics racks[‡].

(iv) Any such conduits, ducts or trunking will be manufactured from either a non-magnetic metal or an impact resistant plastic and will require the use of a tool to remove any covers.

(v) Appropriate laser warning labels will be attached to the outside of all such conduits, ducts and trunking and other enclosures containing the multi-ribbon cables at intervals of approximately 1 m, wherever they are accessible.

(vi) No other services, such as electricity, will share these conduits, ducts or trunking, except (possibly) low voltage interlock cables which form part of the APR systems.

6.1.4 Patch Panels and Off-detector Electronics Crates

The following engineering control measures will be implemented for all patch panels and electronics racks containing optical fibres in excess of hazard level 1:

(i) Patch panels or electronics racks will be fully enclosed with secure, light tight covers, which will require a tool to remove.

(ii) Appropriate laser safety labels will be fixed to both the outside and inside of the enclosure[§]. The labels on the inside will be fixed in such a way that they will be clearly visible during maintenance or testing.

All patch panels and electronics crates containing individual fibre connectors with hazard level k x 3A will either utilize shuttered connectors or the connectors will require a tool to disconnect[**].

All patch panels and electronics crates containing MT connectors or VCSEL arrays would be hazard level 3B if no additional controls were implemented. Even though they will be fully enclosed during normal operation, access will be required for maintenance and testing. However, hazard level 3B is not permitted in a restricted

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[*] Clause 4.2.1 of IEC 825-2.

[†] Clause 4.1.2.1 of IEC 825-2.

[‡] Clause 4.1.2.2 of IEC 825-2.

[§] Clause 4.2.3 of IEC 825-2.

[**] Clause 4.1.3.2 of IEC 825-2.

location[*]. Additional engineering and/or administrative controls will therefore be required. Because MT connectors do not require a tool for disconnection, these controls must ensure that any accessible radiation falls into hazard level 3A or below[†].

Hence, in addition to the above requirements for mechanical protection and labelling, APR will be implemented for all patch panels and electronics crates containing MT connectors, or other hazard level 3B sources (such as the FSI power delivery fibres).

It will be impractical to provide interlocks for individual connectors, therefore a single APR system will be implemented for each enclosure, which will ensure that all laser sources that could generate accessible radiation above hazard level k x 3A within the enclosure will be disabled whenever the cover to any part of the enclosure is removed. There will be clearly visible local indicators fitted to the inside of the enclosure which will confirm that the lasers have been disabled[‡].

All APR systems will be hard-wired and designed to be fail-safe. They will be completely independent of the Detector Control System (DCS) and any other slow control computers, although their current status may be monitored by the DCS. They will either be implemented using low power optical links (hazard level 1) or low voltage electrical signals. The former may be necessary in order to maintain electrical isolation between the various different locations.

Because unintended operation of the APR system will cause serious disruption to ATLAS data taking, a tool will be required to remove any covers. For the same reason, the APR system will need to be very reliable. Note that some parts of the system will be located in the main detector cavern (UX-15) and will therefore not be readily accessible. These parts will also need to be radiation tolerant.

Should the interlock itself fail, there will need to be an administrative procedure to over-ride the interlock system. This will require a competent person in authority (such as a shift leader) to sign an authorization allowing the interlocks to be over-ridden whilst data taking proceeds. A further authorization will be required from the same person before access to the inside of any such enclosure can take place.

It is intended that these administrative controls will only be used in an emergency. The temporary authorization to over-ride the APR system will have to be re-validated regularly (for example, at every shift changeover) until the fault in the APR system has been rectified.

6.2 Specific Control Measures for the SCT

6.2.1 During Normal Operation and Routine Maintenance

The patch panels at PP2 and the ROD and FSI splitter tree racks will be protected in accordance with the requirements described in Section 6.1.4, above. The APR system at PP2 will disable all of the appropriate VCSELs and FSI lasers whenever any of the covers are removed. The APR systems at the electronics racks will disable either the FSI lasers (if the FSI splitter tree crate) or the VCSELs (in the case of the ROD crates).

There will be key operated over-rides to the APR systems, with appropriate administrative controls, as described in Section 6.1.4.

The VCSELs will be disabled by inhibiting the appropriate power supplies, whilst the FSI lasers will be disabled by the use of mechanical shutters in the laser controlled area in the surface buildings.

During normal detector operation the end cap calorimeter cryostats will be in place and it will be impossible to obtain access beyond PP2.

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[*] Clause 4.5.2 of IEC 825-2.

[†] Clause 4.1.3.2 of IEC 825-2.

[‡] Clause 5.2.2.3 of IEC 825-2.

During the ‘short’ detector access periods (of order 10 days) these cryostats will be retracted, giving access to the end faces of the barrel cryostat. At this stage, it will not be possible to gain access inside the Inner Detector region, and SCT will remain totally enclosed by its (light-tight) thermal shields.

However, all of the SCT fibres will run across the end faces of the barrel cryostat, where they will be in the form of bare ribbons and so will have to be protected from accidental damage, as described in Section 6.1.2. The exact design for the SCT services in this region has not yet been finalised. Note that, during detector access periods, scaffolding will be erected across these end faces to facilitate access to, for example, the LArg front-end electronics crates. These operations would clearly give rise to a significant risk of damage to unprotected fibres and it will be essential to keep the SCT readout and alignment systems running during these access periods.

During the ‘long’ detector access periods (of order 5 months), access to the Inner Detector itself may be required. In this region the bare fibre ribbons will be run either along the bore of the cryostat, for the barrel services, or on the ‘squirrel cage’ which will support the forward services. No access will be possible to either whilst the outer TRT wheels are in their normal position. Therefore, a hard-wired interlock will be provided, which will prevent all of the VCSELs and alignment lasers from being operated when either of these outer TRT wheels has been removed.

If it is necessary to test the SCT links or alignment system when either of these wheels has been removed, then the area around the ends of the cryostat will be designated ‘locations with controlled access’. There will be appropriate warning signs and only suitably trained and qualified personnel will be allowed access. There will be a key system provided to over-ride this interlock, together with illuminated warning signs and cut-off switches, positioned just outside of the controlled areas. Only suitably trained and qualified personnel will be permitted to use the over-ride key, with the appropriate authorization from an appropriate authority (for example, the SCT shift leader).

[*This section is still under construction! Specific FSI control measures for power delivery fibre(s) and surface lasers.

Class 4 lasers in a light-tight, laser controlled area. Access restricted to trained and qualified personnel only. Illuminated warning signs over door. Appropriate protective eye-ware available for initial alignment purposes (multiple wavelengths present – green and NIR). All lasers to be registered with CERN. All usual class 4 laser hazard control measures, including; horizontal beams only, beam stops for all unwanted specular reflections, safety screens around optical table etc.

Remotely controlled, fail-safe beam shutter to shut off all optical fibre(s) leaving this area. Shutter operated either by crate or patch panel interlocks, or by failure of low-power ‘sense’ fibre loop incorporated into the cable construction of each of the ‘FSI power delivery fibre(s)’. Key operated over-ride – only to be used with written authorization from competent authority (SCT shift leader?). Warning signs and status indicators in splitter tree crate and in laser room for power delivery fibres.*]

6.2.2 During Assembly and Installation

[*This section is still under construction!

A similar safety system will be designed for the assembly of the SCT in the surface building at CERN.*]

6.3 Specific Control Measures for the LArg Calorimeter

6.3.1 During Normal Operation and Routine Maintenance

The VCSELs mounted on the front-end electronics boards will protrude through the front panel of the crates but will only be accessible during detector access periods, when the end cap toriods have been retracted. As the VCSELs will be hazard level k x 3A, they will be clearly labelled and fitted with commercial shuttered SC or ST connectors (or an equivalent).

The VCSELs will be connected to individual optical fibres and groups of 12 fibres formed into ribbons. It is not yet decided if the ribbons will be run directly into multi-ribbon cables (see Section 2.1.3) or if an intermediate patch panel based around MT-12 connectors will be used. In either case, the fibres or ribbons will be sheathed and reinforced with aramid yarn to meet the requirements of IEC 794-2. Individual fibres and ribbons attract a k x 3A hazard level and no special precautions are needed beyond additional mechanical protection, which will probably take the form of miniature flexible stainless steel conduit. The presence of a patch-panel based around MT-12 connectors would constitute a class 3B laser hazard and the APR measures required are discussed below.

Once lead off the detector, the multi-ribbon cable bundles will enter the rear of the ROD crates enclosed in trunking. Access to this area of the ROD crates would be restricted through the use of secure covers and laser warning signs. Fibres split from fibre ribbons will either be routed to PIN-diode receivers on individual ROD cards directly (requiring no additional safety precautions) or via MT-12 based patch panels located inside the secured region of the crate. The presence of MT-12 based patch panels will be dealt with as follows. The patch panels will be robustly covered, suitably labelled and require a tool to remove the front panel. The presence of MT-12 connectors means that a 3B hazard level is relevant and so some form of APR is required. One of three possible solutions will be used. The exact choice of solution depends on design choices in other parts of LArg electronics system which are currently not mature. The choices are:

(i) A dedicated, hard-wired interlock from the patch-panel cover to the front-end electronics boards which can turn off the VCSEL emitters when the patch panel cover is removed. Access to a single ROD crate would require that VCSELs on all front-end boards connected to that ROD crate be turned off, as shown in Figure 6.1.

(ii) The MT connector system would be provided with mechanical shutters so that it is impossible to be exposed to laser light whilst plugging or unplugging connectors from the patch panel. As such connectors do not exist commercially, some form of development would be required.

(iii) The LArg links could be operated in a reduced power mode so that the maximum fibre coupled power per VCSEL is engineered to be below 0.18mW (0.55mW) to fall within the 3A (k x 3A) hazard level for the MT connector.

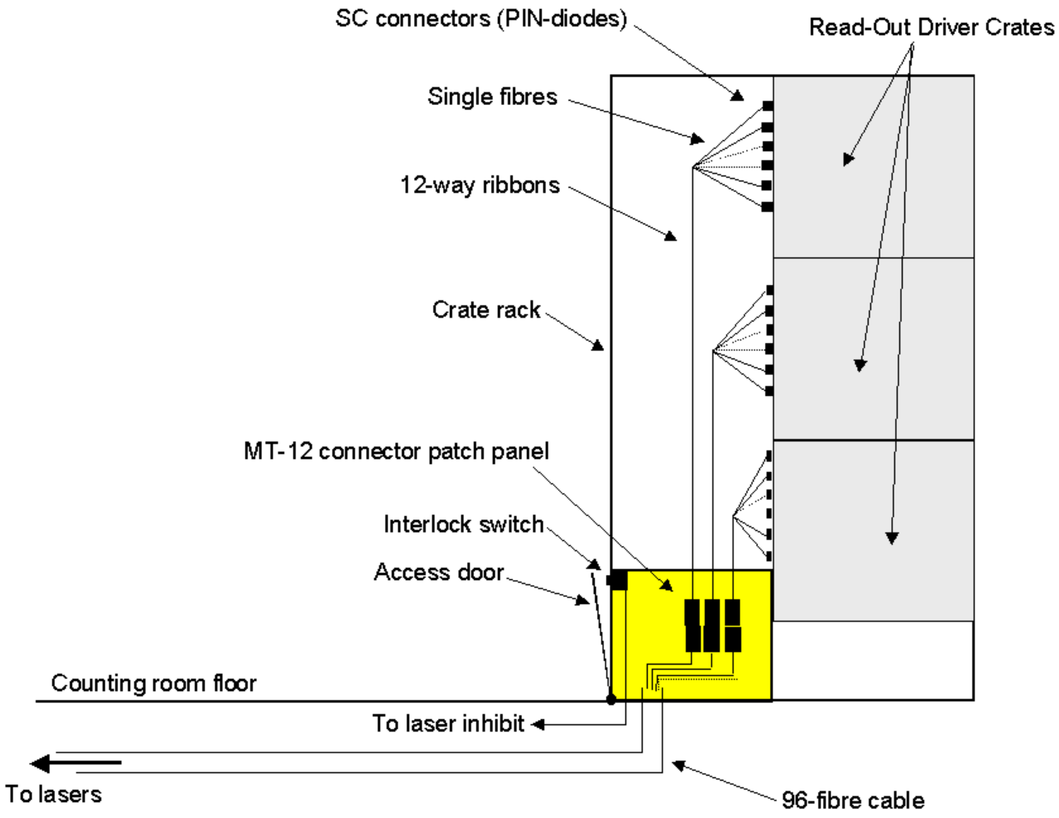


Figure 6.1 A possible patch panel and interlock arrangement at the rear of a LArg ROD rack

6.3.2 During Assembly and Installation

[*This section is still under construction!

A similar safety system will be designed for the assembly of the LArg at CERN.*]

7 Appendices

Appendix A

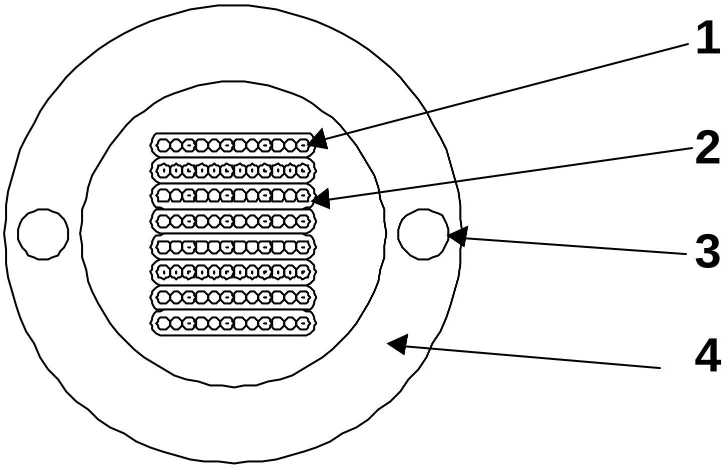
Please Note: **The information contained in this appendix is proprietary.** It should not be communicated to people outside of the ATLAS collaboration without permission (contact: Mark Pearce).

ERICSSON *CABLE PROPERTIES*

Temperature range, operation:	-20 to +70 °C	
Temperature range, handling:	-10 to +40 °C	
Tensile force, permanent:	80 N	maximum
Pulling force, during installation:	800 N	maximum
Bend radius, permanent and during installation:	8 cm	minimum
Crush resistance:	500 N	maximum
Cable net weight:	75 kg/km	
Overall diameter:	9.5 mm	

This cable has recently been subjected to, and successfully passed, full mechanical testing to IEC 794-2.

Cross Section



Construction		Dimensions
1.	Acrylate coated fibres	0.25 mm diameter
2.	12-Fibre ribbon	3200 x 310 µm
3.	FRP-rod	1.0 mm diameter
4.	Sheath: Polyethylene, flame retardant	9.5 mm diameter

Appendix B

LASER Safety Classification Scheme According to IEC 825-1

The laser safety classification scheme defined in IEC 825-1 is summarized in Table 7.1, based on Table 1 in the UK Universities 'Yellow Book' on laser safety.

Class 1	Safe	*either* very low power, so 'inherently safe' *or* totally enclosed, so 'safe by engineering design'
Class 2	Low power Visible only	Protected by natural aversion responses (eg blinking). Simple control measures are sufficient.
Class 3A	Low-medium power	Hazard from direct viewing of beam with optical aids. This must be controlled.
Class 3B*	Low-medium power Visible only	As for class 3A, but slight hazard from direct viewing of beam. This must be controlled.
Class 3B**	Medium power	Hazard from direct viewing & from specular reflections. More detailed control measures are necessary.
Class 4	High power	Not only hazard from direct viewing & from specular reflections, but possible hazard from diffuse reflections. Use requires extreme caution.

Table 7.1 Summary of laser classification scheme

Note: the terminology 3B* and 3B** is not used explicitly in IEC 825-1, although it appears implicitly in the form of several references to "five times the AEL for class 2 in the wavelength range from 400 nm to 700 nm". It is however used explicitly in the UK Universities 'Yellow Book' on laser safety, and is included here as it is thought to be helpful.

Appendix C

Annex A (informative), reproduced from IEC 825-2.

Rationale

The safety of laser products, equipment classification, requirements and user's guide are covered by IEC 825-1. This part is primarily aimed at self-contained products which are under effective local control. An optical fibre communication system would be safe under normal operating conditions because the optical radiation is totally enclosed under intended operation. However, because of the extended nature of these systems (where optical power, under certain conditions, may be accessible many kilometres from the optical source), the precautions to minimize the hazard will be different from more conventional laser sources which are normally under local operator control. (It should be noted that many optical fibre communication systems contain LEDs, which are included within the scope of IEC 825-1).

The potential hazard of an optical fibre communication system depends on the likelihood of the protective housing being breached (e.g. a disconnected fibre connector or a broken cable) and the nature of the optical radiation that might subsequently become accessible. Engineering requirements and user precautions that are required to minimize the hazard are specified in this part of IEC 825.

Each accessible location within an optical fibre communication system is allocated, by the system operating organization or his delegate, a hazard level which gives a guide as to the potential hazard if optical radiation becomes accessible. These hazard levels are described as hazard levels 1 to 4 in a similar fashion as the classification procedure described in IEC 825-1. In addition, a distinction is made between the higher and lower power ranges within the 3B class (see later in this annex for further explanation).

Where operating organizations subcontract parts of a system to installers or manufacturers of subsystems, the duties of all parties concerned should be clearly regulated in an agreement.

In summary, the primary differences between IEC 825-1 and this part 2 are as follows:

- a whole optical fibre communication system will not be classified in the same way as required by IEC 825-1. This is because, under intended operation, the optical radiation is totally enclosed, and it can be argued that a rigorous interpretation of IEC 825-1 would give a class 1 allocation to all systems, which may not reflect accurately the potential hazard. However, if the emitter can be operated separately, it must be classified according to IEC 825-1;

- each accessible location in the extended enclosed optical transmission system will be designated a hazard level, based on similar procedures as those for classification in IEC 825-1, but based not on accessible radiation but on radiation that could become accessible under reasonably foreseeable circumstances (e.g. a fibre cable break, a disconnected fibre connector etc.);

- the nature of the safety precautions required for any particular hazard level will depend on the type of location, i.e. domestic premises, industrial areas where there would be limited access and switching centres where there would be controlled access. For example, it is specified that in the home, a disconnected fibre connector should only be able to emit radiation corresponding to class 1, whilst in controlled areas it could be higher;

- The k x 3A hazard level was introduced to more realistically reflect the true hazard associated with viewing optical fibre components. The longer measurement distance reflects more common behavioural practices. The shorter time base reflects the fact that it is not normal human behaviour to fixate on a small spot for extended periods of time. Hence, the k x 3A level allows for increased power levels in optical fibre systems without increasing the risk of ocular damage under reasonably foreseeable circumstances. The value of 'k' should not be calculated. The designation is only used to indicate that the hazard level k x 3A is higher than that of hazard level 3A.

Appendix D

Maximum Power Calculations

1. *Single Mode Fibre for FSI system*

The specifications for the SM fibre that will be used in the SCT alignment system are given in Section 2.2.2, and are as follows:

$$NA = 0.10 \pm 0.01,\ \ l_c = 760 \pm 40nm \text{ and } \ l = 830 \pm 10nm.$$

Gaussian Beam Approximation:

According to Marcuse,[10] a Gaussian beam is a very good approximation to the irradiance pattern emitted from the cleaved or polished end of a SM fibre. For a such a beam propagating in free space, the irradiance, E at the point (R,z), where R is the radius from the optical axis and z the distance from the beam waist along the optical axis, is given by [11]

$$E(R,z) = \frac{2P_0}{pw^2(z)}\exp\left(-\frac{2R^2}{w^2(z)}\right) \qquad \textbf{(1)}$$

P_0 is the total power in the beam and the locus of the $1/e^2$ points is given by

$$w^2(z) = w_0^2\left(1+\left(\frac{lz}{pw_0^2}\right)^2\right) \qquad \textbf{(2)}$$

l is the wavelength and $2w_0$ is the diameter at the beam waist. In this case, $2w_0$ is also equal to the mode field diameter (MFD) of the fundamental LP_{01} mode propagating in the fibre. In the far field, Equation **(2)** can be approximated by

$$w(z) = \frac{lz}{pw_0} \qquad \textbf{(3)}$$

Substituting this into **(1)** gives

$$E(R,z) = \frac{2pP_0w_0^2}{l^2z^2}\exp\left(-2\left(\frac{pw_0R}{lz}\right)^2\right) \qquad \textbf{(4)}$$

In safety calculations it is usual to express this as a function of the beam diameter, $d = 2R$, and the diameter at the $1/e$ points, d_{63} (which contains 63% of the total power).

Thus

$$E(d,z)=\frac{4P_0}{pd_{63}^2}\exp\left(-\left(\frac{d}{d_{63}}\right)^2\right) \qquad \textbf{(5)}$$

and

$$d_{63}=\frac{\sqrt{2}\,lz}{pw_0} \qquad \textbf{(6)}$$

According to Marcuse, the MFD of the fundamental Gaussian mode propagating in the fibre is given by

$$2w_0=2a\left(0.65+\frac{1.619}{V^{3/2}}+\frac{2.879}{V^6}\right) \qquad \textbf{(7)}$$

$2a$ is the core diameter of the fibre and V is the so called 'normalized frequency' or 'V number', given by

$$V=\frac{2paNA}{l} \qquad \textbf{(8)}$$

At cut-off

$$V_c=\frac{2paNA}{l_c}=2.405 \qquad \textbf{(9)}$$

and so

$$V=2.405.\left(\frac{l_c}{l}\right) \qquad \textbf{(10)}$$

Therefore **(7)** can be rewritten in the form

$$2w_0=\frac{Vl}{pNA}\left(0.65+\frac{1.619}{V^{3/2}}+\frac{2.879}{V^6}\right) \qquad \textbf{(11)}$$

Using the nominal values of $NA=0.10$, $l_c=760nm$ and $l=830nm$, gives

$$V^{nom}=2.20 \qquad \text{and} \qquad 2w_0^{nom}=6.82mm$$

Clearly, from a safety perspective, the worst case occurs when the irradiance, $E(d,z)$ is maximized. This corresponds to the minimum value for d_{63}. From Equation **(6)** it can be seen that, at a fixed distance z, this occurs when w_0/l is maximized. From Equation **(11)**

$$\frac{w_0}{l}=\frac{V}{2pNA}\left(0.65+\frac{1.619}{V^{3/2}}+\frac{2.879}{V^6}\right) \qquad \textbf{(12)}$$

For a given NA, this expression passes through a minimum around $V=2.0$ and increases towards cut-off at $V=V_c=2.405$. Thus, in the region of interest, the worst case will occur when V is maximized. Taking $l_c=800nm$, $l=820nm$ and $NA=0.09$, and substituting into Equations **(10)** and **(11)** gives

$$V^{wc}=2.35 \qquad \text{and} \qquad 2w_0^{wc}=7.61mm$$

Thus, in the worst case, Equation **(6)** gives

$$d_{63}^{wc} = 0.0970.z \tag{13}$$

Power passing through an aperture:

According to Equation (3) on p89 of IEC 825-1, the fraction of power, h_a that passes through a circular aperture of diameter d_a is given by

$$h_a = 1 - \exp\left(-\left(\frac{d_a}{d_{63}} \right)^2 \right) \tag{14}$$

Hazard level 3A:

At a distance $z = 100mm$, **(13)** gives $d_{63}^{wc}(100mm) = 9.70mm$. For $t = 100s$, $l = 820nm$ and $a \le a_{\min}$, Table 3.1 gives the class 3A AELs as $P_{3A}^1 = 1.9mW$ for the maximum radiant power condition and $E_{3A}^2 = 9.9Wm^{-2}$ for the maximum irradiance condition. The latter can be converted to an equivalent power by multiplying by the area of the measurement aperture. Thus

$$P_{3A}^2 = \frac{pd_a^2}{4}.E_{3A}^2 \tag{15}$$

For $d_a = 7mm$, this gives $P_{3A}^2 = 0.381mW$.

Using Equation **(14)**, the fraction of power passing through the $50mm$ aperture, $h_{50} = 1.000$. Therefore, the maximum radiant power condition gives

$$P_{0,\max}^1 = \frac{P_{3A}^1}{h_{50}} = 1.9mW$$

The fraction of power passing through the $7mm$ aperture, $h_7 = 0.406$. Therefore, the maximum irradiance condition gives

$$P_{0,\max}^2 = \frac{P_{3A}^2}{h_7} = 0.94mW$$

The latter is the more restrictive condition, so the maximum power for hazard level 3A is 0.94 mW .

Hazard level k x 3A:

At a distance $z = 250mm$, Equation **(13)** gives $d_{63}^{wc}(250mm) = 24.3mm$. For $t = 10s$, $l = 820nm$ and $a \le a_{\min}$, the class 3A AELs given in Table 3.1 must be multiplied by the factor $10^{0.25} = 1.778$. Thus $P_{3A}^1 = 3.38mW$ for the maximum radiant power condition and $E_{3A}^2 = 17.6Wm^{-2}$ for the maximum irradiance condition. Converting the latter to an equivalent power using Equation **(15)** with $d_a = 7mm$, gives $P_{3A}^2 = 0.677mW$.

The fraction of power passing through the $50mm$ aperture, $h_{50} = 0.986$. Therefore, the maximum radiant power condition gives

$$P^1_{0,\max} = \frac{P^1_{3A}}{h_{50}} = 3.4mW$$

The fraction of power passing through the $7mm$ aperture, $h_7 = 0.080$. Therefore, the maximum irradiance condition gives

$$P^2_{0,\max} = \frac{P^2_{3A}}{h_7} = 8.5mW$$

The former is the more restrictive condition, so the maximum power for hazard level k x 3A is 3.4mW .

2. *Single VCSEL*

In order to calculate the maximum power for each hazard level, it is necessary to assume an angular distribution for the light emitted by a VCSEL. A Gaussian distribution will correspond to the worst case and so this ha been assumed for the following calculations.

According to the manufacturer's data sheet, the divergence, f_{fw} measured to the $1/e^2$ points is $15°$ (full width). The $1/e^2$ points contain 86% of the total power. Therefore, at a distance z, the diameter at the $1/e^2$ points, d_{86} is given by

$$d_{86} = 2z\sin\left(\frac{f_{fw}}{2}\right) \approx zf_{fw} \qquad \textbf{(16)}$$

where the small angle approximation has been used. From Equation **(5),** $d_{86}/d_{68} = \sqrt{2}$, therefore

$$d_{63} = \frac{zf_{fw}}{\sqrt{2}} \qquad \textbf{(17)}$$

Equation (1) on p88 of IEC 825-1 gives the following expression for d_{63} in terms of NA,

$$d_{63} = \frac{zf_{fw}}{\sqrt{2}} \approx \frac{2zNA}{1.7} \qquad \textbf{(18)}$$

Therefore

$$NA \approx \left(\frac{1.7}{2\sqrt{2}}\right) f_{fw} \qquad \textbf{(19)}$$

For $f_{fw} = 15°$, Equations **(17)** and **(19)** give

$$d_{63} = 0.185.z \qquad \textbf{(20)}$$

and

$$NA = 0.16$$

Hazard level 3A:

At a distance $z = 100mm$, Equation **(20)** gives $d_{63}^{wc}(100mm) = 18.5mm$. For $t = 100s$, $l = 850nm$ and $a \le a_{\min}$, Table 3.1 gives the class 3A AELs as $P_{3A}^{1} = 2.2mW$ for the maximum radiant power condition and $E_{3A}^{2} = 11.4Wm^{-2}$ for the maximum irradiance condition. Converting the latter to an equivalent power using Equation **(15)** with $d_a = 7mm$, gives $P_{3A}^{2} = 0.439mW$.

Using Equation **(14)**, the fraction of power passing through the $50mm$ aperture, $h_{50} = 0.999$. Therefore, the maximum radiant power condition gives

$$P_{0,\max}^{1} = \frac{P_{3A}^{1}}{h_{50}} = 2.2mW$$

The fraction of power passing through the $7mm$ aperture, $h_7 = 0.133$. Therefore, the maximum irradiance condition gives

$$P_{0,\max}^{2} = \frac{P_{3A}^{2}}{h_7} = 3.3mW$$

The former is the more restrictive condition, so the maximum power for hazard level 3A is $2.2\ \mathrm{mW}$.

Hazard level k x 3A:

At a distance $z = 250mm$, Equation **(20)** gives $d_{63}^{wc}(250mm) = 46.3mm$. For $t = 10s$, $l = 850nm$ and $a \le a_{\min}$, the class 3A AELs given in Table 3.1 must be multiplied by the factor $10^{0.25} = 1.778$. Thus $P_{3A}^{1} = 3.9mW$ for the maximum radiant power condition and $E_{3A}^{2} = 20.3Wm^{-2}$ for the maximum irradiance condition. Converting the latter to an equivalent power using Equation **(15)** with $d_a = 7mm$, gives $P_{3A}^{2} = 0.780mW$.

The fraction of power passing through the $50mm$ aperture, $h_{50} = 0.688$. Therefore, the maximum radiant power condition gives

$$P_{0,\max}^{1} = \frac{P_{3A}^{1}}{h_{50}} = 5.7mW$$

The fraction of power passing through the $7mm$ aperture is $h_7 = 0.023$. Therefore, the maximum irradiance condition gives

$$P_{0,\max}^{2} = \frac{P_{3A}^{2}}{h_7} = 34.5mW$$

The former is the more restrictive condition, so the maximum power for hazard level k x 3A is $5.7\mathrm{mW}$.

3. Multi-mode Ribbon Fibre

4. Single Mode Ribbon Fibre

Appendix E

Annex B (normative), reproduced from IEC 825-2

Summary of engineering requirements at locations in an optical fibre communication system

Hazard level	Location type		
	Unrestricted	Restricted	Controlled
1	No requirements	No requirements	No requirements
2	Labelling And Class 1 from connector or connector requires tool	Labelling	Labelling
3A	Labelling And Class 1 from connector or connector requires tool	Labelling	Labelling
k x 3A	Not permitted	Labelling And Protected cable Class 3A from connector or connector requires tool	Labelling
3B	Not permitted	Not permitted	Labelling And k times 3A from connector or connector requires tool
4	Not permitted	Not permitted	Not permitted

Table 7.2 Summary of engineering requirements reproduced from Annex B of IEC 825-2

Appendix F

[**Details from IEC 825-2, Annex D Section 7 to go here.**]

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[1] 'Safety of laser products Part 1: *Equipment classification, requirements and user's guide*', (IEC 825-1) and 'Safety of laser products Part 2: *Safety of optical fibre communication systems*', (IEC 825-2); International Electrotechnical Commission (IEC).

[2] 'Rules for the Safe User of Lasers at CERN'; TIS Division, CERN Safety Instruction/IS-22 (January 1994).

[3] 'ATLAS Front-end Read-out Link Requirements'; J.D.Dowell and M.Pearce; ATLAS-ELEC-001 (July 1998). This document is currently available at the following web address: http://preprints.cern.ch/cgi-bin/setlink?base=atlnot&categ=Note&id=elec-98-001

[4] 'Development of Radiation –hard VCSEL/PIN-diode Optical Links for the ATLAS SCT'; D.G. Charlton *et al.;* presented at the 4th workshop on LHC Electronics, Rome, September 1998. This document is currently available at the following web address: http://www-pnp.physics.ox.ac.uk/~weidberg/LEB98_weidberg.ps

[5] 'Opto-package Specification (draft 25/10/99)'; This document is currently available at the following web address: http://www-pnp.physics.ox.ac.uk/~weidberg/optopackage_specs.pdf

[6] 'Fibre routing for SCT Optical Links'; J. Troska. This document is in preparation, but is currently available at the following web address: http://www-pnp.physics.ox.ac.uk/~weidberg/fibre_routing.pdf

[7] 'Mitel Product Information Sheet, 12L485 VCSEL Array'; This document is currently available at the following web address: http://www.cern.ch/Atlas/GROUPS/INNER_DETECTOR/sctnew/Electronics/links/arrays/mitel_VCSEL_12channel.pdf

[8] ATLAS Liquid Argon Calorimeter Technical Design Report, CERN/LHCC 96-41 (December 1996).

[9] 'Safety in Universities: Notes of Guidance. Part 2:1 Lasers'; W.T.Baker *et al.;* ISBN 0948890 19 7 (October 1992).

[10] 'Loss Analysis of Single-Mode Fiber Splices'; D. Marcuse; The Bell System Technical Journal **56** 703 (1977).

[11] *For example:* 'Optical methods in Modern Communications'; A. Yariv; Oxford University Press, 5th Ed. ISBN 0-19-510626-1 (1997).