ATLAS

EDMS Number:

EDMS Id:

ATLAS Level-1 Calorimeter Trigger

FOX (Fex Optics eXchange)

Project Specification

Document Version: Draft 1.02

Document Date: 3 June 2015

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Document Change Record

Version	Issue	Date	Comment
0	0	15 August 2014	Initial document layout
0	1	15 October 2014	Contribution from Reinhard to Chapter 1
0	2	17 October 2014	Contribution from Yuri to Chapter 3 (not complete)
0	3	30 October 2014	Contribution from Yuri to Chapter 3 (completed)
0	4	31 October 2014	Contribution from Murrough to Chapter 2
0	5	03 November 2014	Contribution from Murrough to Chapter 2 (updated)
0	6	03 November 2014	Contribution from Philippe to Chapter 4 (not complete) Contribution from Reinhard to Chapter 1 (updated)
0	7	03 November 2014	Contribution from Philippe to Chapter 4 (updated)
0	8	03 November 2014	Miscellaneous minor updates
0	9	03 November 2014	Miscellaneous minor updates
0	10	09 November 2014	Updates from Yuri
0	11	10 November 2014	Updated from Reinhard and Murrough
0	12	10 November 2014	Add Appendix, update Demonstrator, add diagram
0	13	11 November 2014	Miscellaneous minor updates
0	14	11 November 2014	Miscellaneous minor updates
1	2	3 June 2015	Implemented review comments

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1. INTRODUCTION

1.1. CONVENTIONS

The following conventions are used in this document:

- The term “FOX” is used to refer to the Phase-I L1Calo Optical Plant – Fex Optics eXchange or Fibre Optics eXchange (FOX). Alternate names are “fibre plant” or “optical plant” or “FEX optical plant”.
- eFEX – electron Feature EXtractor.
- jFEX – jet Feature EXtractor.
- gFEX – global Feature EXtractor.

Figure 1 explains the timeline for Atlas running and shutdowns: Phase-I upgrades will be installed before the end of long shutdown LS 2; Phase-II upgrades will be installed before the end of LS 3.

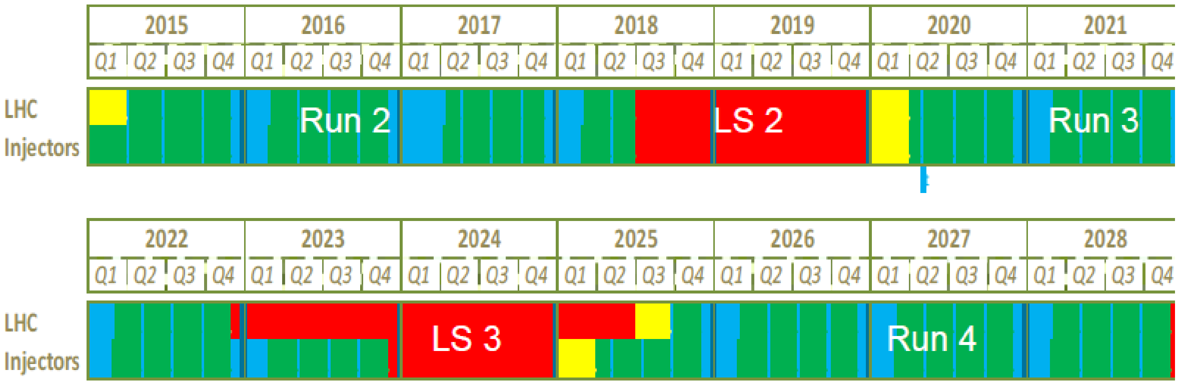


Figure 1: LHC Shutdown and Run Schedule.

1.2. RELATED PROJECTS

[1.1] ATLAS TDAQ System Phase-I Upgrade Technical Design Report, CERN-LHCC-2013-018, http://cds.cern.ch/record/1602235

[1.2] ATLAS Liquid Argon Phase-I Technical Design Report, CERN-LHCC-2013-017, https://cds.cern.ch/record/1602230

[1.3] ATLAS Tile Calorimeter, http://atlas.web.cern.ch/Atlas/SUB_DETECTORS/TILE/

[1.4] ATLAS L1Calo Jet-PPM LCD Daughterboard (nLCD)

[1.5] Electromagnetic Feature Extractor (eFEX) Prototype (v0.2), 6 February 2014, https://twiki.cern.ch/twiki/pub/Atlas/LevelOneCaloUpgradeModules/eFEX_spec_v0.2.pdf

[1.6] Jet Feature Extractor (jFEX) Prototype (v0.2), 14 July 2014, http://www.staff.uni-mainz.de/rave/jFEX_PDR/jFEX_spec_v0.2.pdf

[1.7] Global Feature Extractor (gFEX) Prototype (v0.3), 16 October 2014, https://edms.cern.ch/file/1425502/1/gFEX.pdf

[1.8] High-Speed Demonstrator (v1.5), 18 July 2011, https://twiki.cern.ch/twiki/bin/view/Atlas/LevelOneCaloUpgradeModules

[1.9] FEX Test Module (FTM) (v0.0), 18 July 2014, http://epweb2.ph.bham.ac.uk/user/staley/ATLAS_Phase1/FTM_Spec.pdf

1.3. L1CALO TRIGGER PHASE-I UPGRADE

This document describes the fibre-optic exchange (FOX) that routes the optical signals via fibres from the Liquid Argon (LAr) and Tile calorimeters to the feature extractor (FEX) modules of the ATLAS Level 1 calorimeter trigger system (L1Calo). The upgraded L1Calo system provides the increased discriminatory power necessary to maintain the ATLAS trigger efficiency as the LHC luminosity is increased beyond that for which ATLAS was originally designed. The FOX maps each LAr and Tile output fibre to the corresponding L1Calo FEX input and it provides the required signal duplication.

The FOX will be installed in L1Calo during the long shutdown LS2, as part of the Phase-I upgrade, and will operate during Run 3. Part of the FOX will be replaced in the Phase-II upgrades during LS3 to account for updated inputs from the Tile calorimeter. Other parts will remain unchanged and the FOX will operate during Run 4, at which time it will form part of L0Calo. The following sections provide overviews of L1Calo in Run 3 and L0Calo in Run 4.

This document is the specifications of the FOX inputs and outputs, as well as of the prototype FOX, the demonstrator, which will be used for optical transmission tests and for integration testing together with other modules at CERN. The demonstrator is intended to exhibit the transmission properties of the production FOX, including connectors, fibres and splitters.

The FOX components and testing equipment are also described. Appendix A contains definitions as well as the optical power calculation.

1.3.1. Overview of the L1Calo System in Phase-I (Run 3)

In Run 3, L1Calo contains three subsystems that are already installed prior to LS2, as shown in Figure 2 (see document [1.1]):

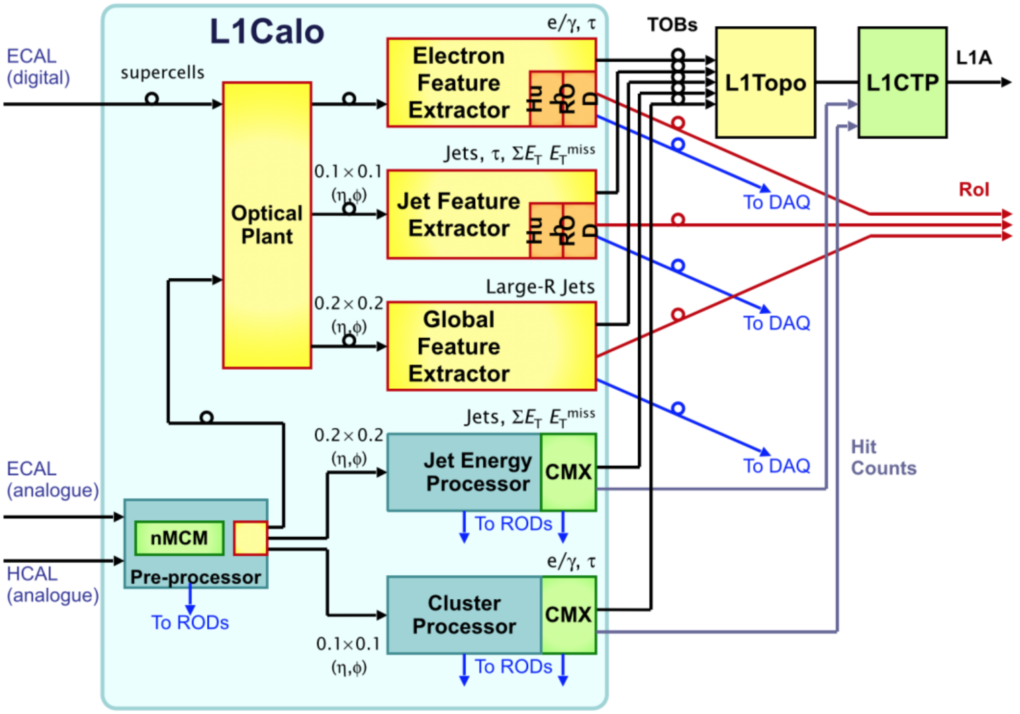


Figure 2: The L1Calo system in Run 3. ***Components installed during LS2 are shown in yellow/orange.***

- the PreProcessor (PPr) subsystem, comprising PreProcessor Modules (PPMs), receives shaped analogue pulses from the ATLAS calorimeters, digitises and synchronises them, identifies the bunch-crossing from which each pulse originated, scales the digital values to yield transverse energy (E_T), and prepares and transmits the data to the following processor stages;

- the Cluster Processor (CP) subsystem (comprising Cluster Processing Modules (CPMs) and Common Merger Extended Modules (CMXs)) which identifies isolated e/γ and τ candidates;
- the Jet/Energy Processor (JEP) subsystem (comprising Jet-Energy Modules (JEMs) and Common Merger Extended Modules (CMXs)) which identifies energetic jets and computes various local energy sums.

Additionally, L1Calo contains the following three subsystems installed as part of the Phase-I upgrade in LS2:

- the electromagnetic Feature Extractor eFEX subsystem, documented in [1.5] , comprising eFEX modules and FEX-Hub modules, the latter carrying Readout Driver (ROD) daughter cards. The eFEX subsystem identifies isolated e/γ and τ candidates, using data of finer granularity than is available to the CP subsystem;
- the jet Feature Extractor (jFEX) subsystem, documented in [1.6] , comprising jFEX modules, and Hub modules with ROD daughter cards. The jFEX subsystem identifies energetic jets and computes various local energy sums, using data of finer granularity than that available to the JEP subsystem.
- the global Feature Extractor (gFEX) subsystem, documented in [1.7] , comprising a single gFEX module. The gFEX subsystem identifies calorimeter trigger features requiring the complete calorimeter data.

In Run 3, the Liquid Argon Calorimeter provides L1Calo both with analogue signals (for the CP and JEP subsystems) and with digitised data via optical fibres (for the FEX subsystems), see document [1.2] . From the hadronic calorimeters, only analogue signals are received (see document [1.3]). The currently preferred option is that these are digitised on the PreProcessor and converted to optical signals on a PreProcessor daughter board, and then transmitted optically to the FEX subsystems Another possibility under consideration is to transmit optical signals from a JEP daughter card [1.4] . Initially at least, the FEX subsystems will operate in parallel with the CP and JEP subsystems. Once the performance of the FEX subsystems has been validated and once they are not needed anymore, the CP and JEP subsystems will be removed.

The optical signals from the PPM and LDPS electronics are sent to the FEX subsystems via an optical plant, the FOX. This performs two functions. First, it separates and reforms the fibre bundles, changing the mapping from that employed by the LDPS and PPM electronics to that required by the FEX subsystems. Second, it provides any additional fanout of the signals necessary to map them into the FEX modules where this cannot be provided by the calorimeter electronics.

The outputs of the FEX subsystems (plus CP and JEP) comprise Trigger Objects (TOBs): data structures which describe the location and characteristics of candidate trigger objects. The TOBs are transmitted optically to the Level-1 Topological Processor (L1Topo), which merges them over the system and executes topological algorithms, the results of which are transmitted to the Level-1 Central Trigger Processor (CTP).

The eFEX, jFEX, gFEX and L1Topo subsystems comply with the ATCA standard. The eFEX subsystem comprises two shelves each of 12 eFEX modules. The jFEX subsystem comprises a single ATCA shelf holding 7 jFEX modules at high link speed and up to ten at lower link speeds. The gFEX subsystem comprises a single ATCA shelf holding a single gFEX module. The L1Topo subsystem comprises a single ATCA shelf housing up to four L1Topo modules, each of which receives a copy of all data from all FEX modules. All L1Calo processing modules produce Region of Interest (RoI) and DAQ readout on receipt of a Level-1 Accept signal from the CTP. RoI information is sent both to the High-Level Trigger (HLT) and the DAQ system, while the DAQ data goes only to the DAQ system. In the FEX and L1Topo subsystems, these data are transmitted by each FEX or L1Topo module via the shelf backplane to two Hub modules (with the gFEX a possible exception). Each of these buffers the data and passes a copy to their ROD daughter board. The RODs perform the processing needed to select and transmit the RoI and DAQ data in the appropriate formats; it is likely that the required tasks will be partitioned between the two RODs. Additionally, the Hub modules provide distribution and switching of the TTC signals and control and monitoring networks.

1.3.2. Overview of the L1Calo System in Phase-II (Run 4)

The Phase-II upgrade will be installed in ATLAS during LS3. At this point, substantial changes will be made to the trigger electronics. All calorimeter input to L1Calo from the electromagnetic and hadronic calorimeters will migrate to digital format, the structure of the hardware trigger will change to consist of two levels, and a Level-1 Track Trigger (L1Track) will be introduced and will require TOB seeding. The PreProcessor, CP and JEP subsystems will be removed, and the FEX subsystems, with modified firmware, will be relabelled to form the L0Calo system in a two stage (Level-0/Level-1) real-time trigger, as shown in Figure 3. Hence, the FOX as well as the FEX subsystems must be designed to meet both the Phase-I and Phase-II upgrade requirements. The main additional requirements are to provide real-time TOB data to L1Track, and to accept Phase-II timing and control signals including Level-0 Accept (L0A) and Level-1 Accept. Additional calorimeter trigger processing will be provided by a new L1Calo trigger stage.

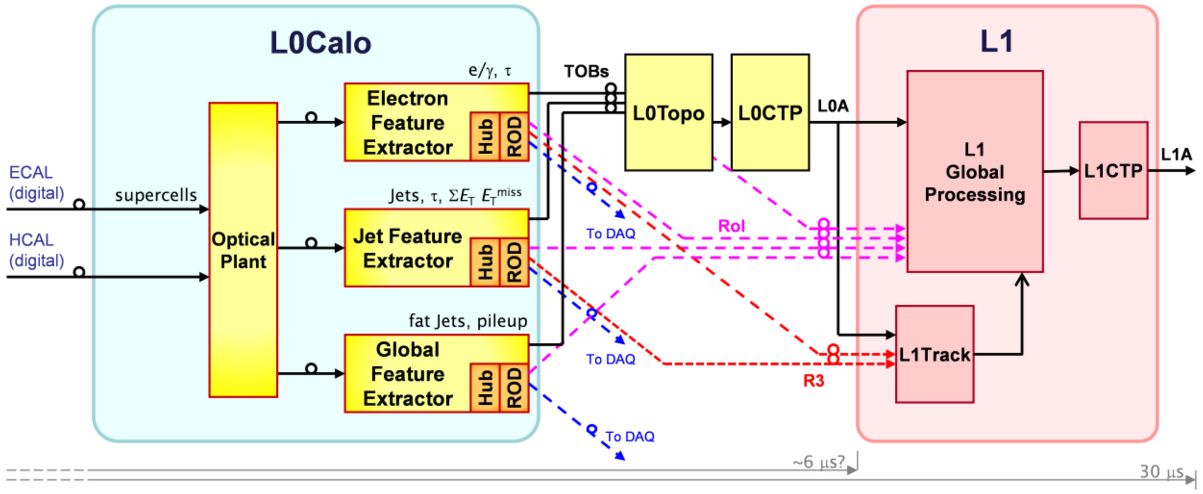


Figure 3: The L0/L1Calo system in Run 4. The new Level-1 system is shown in red and pink. Other modules (yellow /orange) are adapted from the previous system to form the new L0Calo. R3 is the Regional Readout Request sent to the track trigger to initiate the readout of a small region of the tracker.

1.4. FOX – OVERVIEW

The FOX system is an integral part of the L1Calo Phase-I upgrade. Its primary function is to receive the signal fibres from the LAr and Tile calorimeters, to redistribute them to the individual FEX cards (mapping), as well as to duplicate certain signal fibres as required by the FEX algorithms. An overview of the FOX connectivity is shown in Figure 4.

The FOX is schematically separated into five sets of modules by mapping functionality. The two input module sets are the LArFox and the TileFox which organize the fibres by destination. The three output module sets are eFox, jFox and gFox, which provide the final fibre ribbon by fibre ribbon mapping and provide fibre duplication as required. The LAr and PPM transmitters provide most of the signal duplication. Details about the fibre count and mapping are presented in Chapter 2.

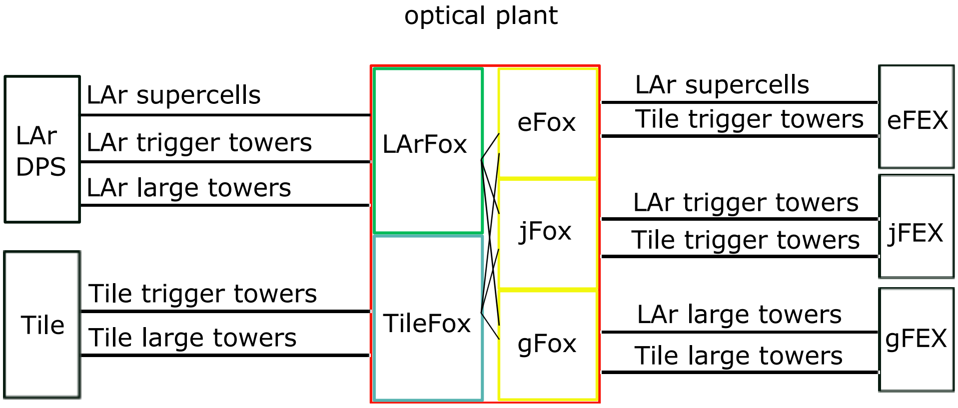


Figure 4: Overview of optical plant connections.

The LArFox receives three types of signals from the AMC cards, the LDPS system of the LAr calorimeter:

- LAr supercells, with fine-grained electromagnetic calorimeter information. Each calorimeter trigger tower of size 0.1x0.1 in ηxφ is subdivided into ten sums (supercells in layers 1 and 2 of the LAr calorimeter and sums of the presampler and layer 3) in order to be able to create better isolation variables for electrons, photons and taus.
- LAr jet trigger towers, with a granularity of 0.1x0.1 in ηxφ.
- LAr gTowers, with granularity of 0.2x0.2 in ηxφ.

This information is received in groups of 48 fibres which are organized into four ribbons of 12 fibres each. One of these fibres will contain gTower information, 4 to 8 will contain trigger tower information, 24 to 32 fibres will contain supercell information, and the rest are spares.

The FOX also receives three types of hadronic calorimeter signals from the Tile PPMs:

- Tile trigger towers with a granularity of 0.1x0.1 for the eFEX.
- Tile trigger towers with a granularity of 0.1x01 for the jFEX. These might contain the same information as the eFEX trigger towers, but don’t necessarily have to.
- Tile gTowers with a granularity of 0.2x0.2 for the gFEX.

Trigger towers sent to eFEX and jFEX have the same granularity and principally contain the same information. However, since the needs of the eFEX and the jFEX are different, they are treated distinctly here.

Table 1: Number of fibres per connector and number of connectors per FEX module for a link speed of 10 Gbit/s.

Counts at 6.4 Gbit/s	eFEX	jFEX	gFEX
Fibres per connector	48	72	72
Connectors per module	4	4	4
Number of modules	24	7	1

The number of fibres per connector, connectors per module and the total number of modules are shown in Table 1 for the eFEX [1.5] , jFEX [1.6] and gFEX [1.7] . Not all fibres in each connector are used. For the jFEX, the number of modules depends somewhat on coverage of each module and on the link speed and fibre content and might be reduced at 10 Gbit/s or increased at 6.4 Gbit/s.

The optical fibres themselves are multimode (OM4) with a nominal wavelength of 850nm. They are connected through Multi-fibre Push-On/Pull-Off (MPO) connectors.

1.5. FOX - FUNCTIONALITY

The FOX will map each of the input fibres to a specific FEX destination. It will also provide passive duplication (optical splitting) of some of the fibres, as required for corners and special regions. Signals arrive at the FOX via 48-fibre cables, organized as 4 ribbons of 12 fibres each. They arrive at the LArFOX or TileFOX, each a set of modules arranged by calorimeter geometry. The fibre cables plug into the FOX through a MPO connector. From the inputs, fibres are routed to a mapping module, which redistributes the signals to output connectors, which are multi-fibre MPO connectors with varying number of fibres. Short fibre-optic patch cables connect these input modules to the output modules. Each of the eFOX, jFOX and gFOX contain output modules. In the eFOX and jFOX case, each module provides mapping and passive optical splitting. The gFOX simply routes fibres to the appropriate output connector. The output of the FOX are fibre ribbons that plug into an MTP–CPI connectors in zone 3 of the RTM of the FEX crates, and these connectors make a direct optical connection to the FEX modules. The RTM provides mechanical support for the fibre bundles.

The FOX is a passive device only and has no power requirements. There is a possibility that active duplication of some signals is required. If yes, then the active duplication module has modest power requirements, the details will depend on the number of fibres that require active duplication.

For fibres that require passive splitting, a fibre is spliced and fused (or connected through a single ST connector) to a passive optical splitter, with the second output of the splitter going to a new destination.

Spare FOX components will be available. This includes spare fibres, connectors, mapping modules, splitters. Individual broken fibres can in some circumstances be mended through fibre fusing.

1.6. FUTURE USE CASES

The FOX will continue to be used in the L1Calo and L0Calo trigger systems through Run 4. The LAr inputs as well as the FEX modules will remain unchanged, but the inputs from the Tile calorimeter will change. Thus, the TileFOX will need to be replaced by new mapping modules and the other parts can remain unchanged.

2. FOX INPUT AND OUTPUT SPECIFICATION

This section describes the required mappings from LAr and Tile electronics to the inputs of the eFEX, jFEX and gFEX. The descriptions are focussed on the requirements for the baseline link speed of 6.4 Gbit/s with notes on the changes for the higher link speed options.

The first two subsections deal respectively with the organisation of the outputs from LAr and Tile calorimeters. For LAr there are different mappings from EM barrel, endcaps, HEC and FCAL. For Tile there is a different mapping for Phase-I where the Tile towers will still be processed by the existing L1Calo PreProcessor and for Phase-II when the Tile towers will be sent from new Tile electronics.

The remaining subsections cover the organisation of the inputs to the three FEX systems.

2.1. TRANSMITTERS (FOX INPUTS)

2.1.1. LDPS transmitters

The trigger information from the entire LAr calorimeter to the three FEX systems will be sent by the LAr Digital Processor System (LDPS). The LDPS is a set of about 30 ATCA modules called LAr Digital Processor Blades (LDPBs) housed in three ATCA shelves (crates). Each LDPB acts as a carrier board for four mezzanine cards (AMCs) each of which has a single FPGA with 48 output optical links providing data to the FEXes. There are therefore 192 output fibres per LDPB and over 5500 from the whole LDPS system.

The eta*phi coverage of each AMC FPGA is 0.8*0.4 in the central part of the EM calorimeter, however this is larger in the outer endcaps where the granularity changes. The hadronic endcaps (HEC) and forward calorimeter (FCAL) have other granularities which are described separately.

2.1.1.1. LAr EM

Over most of the EM calorimeter every 0.1*0.1 trigger tower will send one presampler, four front layer, four middle layer and one back layer sum to the LDPS. Each of those 10 sums per tower needs to be sent to the eFEX. However the jFEX only needs the E_T sum from all ten, i.e. one quantity per tower. The gFEX will receive just one E_T sum from a 0.2*0.2 area of four trigger towers. Thus for the EM layer the bulk of the output fibres are sent to the eFEX.

At the baseline link speed of 6.4 Gbit/s the intention is that each fibre to the eFEX will carry the 20 sums from two adjacent towers in eta, i.e. each fibre will cover 0.2*0.1 in eta*phi. To provide a reasonable number of bits per sum, this option requires the use of a digital filter using peak finder and the bunch crossing multiplexing scheme (BCMUX). At higher links speeds of around 10 Gbit/s each fibre will still carry the same 20 sums but there would be no need for the BCMUX scheme. In either case each AMC will have 16 different 0.2*0.1 fibres though the fanout requirements of the eFEX architecture mean that some of these fibres need to be sent with multiple copies at source.

For the jFEX each fibre would carry eight towers from a 0.4*0.2 area at 6.4 Gbit/s but could carry 16 towers from a 0.4*0.4 area at the higher link speeds. This mapping implies four or two separate fibres with low or high speed links. However the jFEX fanout requirements may change with the link speed, needing a minimum of two copies at low links speed but three copies at the higher link speed making eight or six output fibres per AMC in total. The gFEX only needs a single fibre from the whole 0.8*0.4 AMC area independent of the link speed.

The diagrams in Figure 5 indicate the coverage and fanout requirements (number of copies) of eFEX and jFEX fibres from each AMC at low and high link speeds. The jFEX requirements are uniform across the AMC but change with link speed whereas the eFEX requirements are independent of link speed but are more complex with additional copies required at the edges and corners. The eFEX fanout pattern also varies with the eta and phi location of the AMC both in the central region and in the outer endcaps. However there is a single superset pattern that covers all possible locations. This would allow a single firmware version in the AMC with the FOX connecting only those fibres required from each AMC.

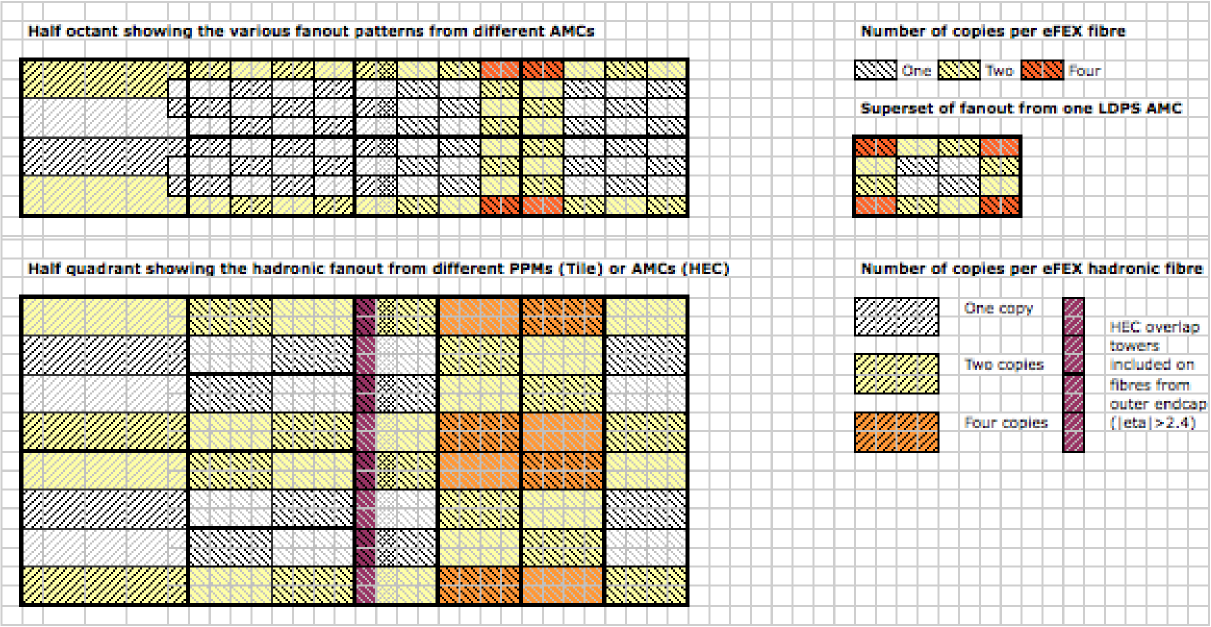


Figure 5: AMC fibre coverage and eFEX fanout requirements at 6.4 Gbit/s. Each square box corresponds to one trigger tower covering 0.1*0.1 in eta*phi. Each rectangular box corresponds to one fiber.

Although the structure of the eFEX EM fanout pattern is independent of link speed, optimisation of the fanout for the hadronic fibres to eFEX would suggest shifting the whole EM pattern by 0.2 in phi.

2.1.1.2. LAr HEC

The granularity of the HEC is much lower than the EM calorimeter. Each input channel of the LDPS is a single trigger tower of 0.1*0.1 for the inner region (|eta|<2.5) and mostly 0.2*0.2 in the outer endcaps. In contrast to the EM layer, both the eFEX and jFEX receive identical information with the coverage of each fibre the same as the jFEX fibres from the EM layer. Since the jFEX needs three copies at the higher link speed, the majority of the HEC LDPS outputs will be to jFEX with fewer to eFEX. The eta*phi coverage of the AMCs for the HEC is larger and so the gFEX will receive four fibres from each AMC.

The HEC contribution in the HEC/Tile overlap region (1.5<|eta|<1.6) is awkward and is handled differently for each FEX. The eFEX only needs one copy so the overlap towers are included on fibres covering the forward region. The jFEX needs three copies and the overlap region is sent on separate fibres. For the gFEX it is assumed that the overlap towers are summed into the neighbouring gTowers which will therefore cover 1.5<|eta|<1.8.

Given the very different fanout requirements from the EM and hadronic layers, a possible optimisation of the system is to process signals from both HEC and the outer EM endcaps in a single LDPS AMC covering an octant in phi on C or A sides. The HEC extends from 1.5<|eta|<3.2 and the outer EM endcap towers in this AMC would cover 2.4<|eta|<3.2. This is the scheme which will be described here though alternative schemes are possible.

2.1.1.3. LAr FCAL

The FCAL has a completely different granularity and geometry than the rest of the LAr calorimeter with two separate hadronic layers in addition to the EM layer. It is assumed that the eFEX will not need any input from the FCAL so the FCAL information is only sent to jFEX and gFEX.

2.1.2. Tile transmitters

In Phase-I (Run 3) the Tile towers will be sent to the FEXes from the existing L1Calo PreProcessor modules (PPMs) via new rear transition cards. Each PPM covers 0.4*1.6 in eta*phi so the geometry is different from that of the LDPS AMC in the same eta region. This has no effect on the eFEX or jFEX as they receive fibres covering 0.4*0.2 (at low speed) or 0.4*0.4 (at high speed). However the gFEX fibres will each cover 0.4*0.8 instead of 0.8*0.4 from the LDPS.

After the Phase-II upgrade (Run 4) the Tile front end electronics will be replaced and the FEXes will then receive the Tile towers from new Tile sRODs. These will each cover 1.6*0.4 in eta*phi.

This change in geometry will switch the gFEX fibres to have the same geometry as from the EM layer. The gFEX firmware will need to be updated with a new mapping at that point.

2.1.3. Summary of fibre counts

Table 2 shows the numbers of fibres from each part of the calorimeter at the baseline 6.4 Gbit/s link speed. It indicates those “direct” fibres needing no additional fanout and those which must be fanned out after the LDPS via 1:2 optical splitters. In the table, the EM Barrel AMCs cover |eta|<1.6, the EM Endcap AMCs cover the standard 1.6<|eta|<2.4 region and the AMCs handling the special crate include the forward EM region with |eta|>2.4. Due the corners in the eFEX design half the Tile PPMs need 1:2 fanout with the other half not needing any further fanout. The two cases are shown as min/max in the table and the numbers assume the PPM rear transition card will have three minipods. Any fewer would require 1:3 or 1:4 fanout. The Tile sROD in Phase-II will have a more favourable geometry and all modules have the same number of output fibres at 6.4 Gbit/s.

Table 3 shows the same fibre counts for the higher link speed options. The counts are the same for the eFEX EM layer and gFEX fibres, but the eFEX hadronic layer and all jFEX fibres are halved as each fibre carries twice the number of towers. At 10 Gbit/s there is no need for any passive optical splitting. Part of the optimisation to achieve this involves shifting the coverage of each eFEX module by 0.2 in phi which means that, unlike the baseline option, alternate Tile sRODs need to provide additional fibres, though still fewer than at 6.4 Gbit/s. The sROD will need to have three minipods for output to L1Calo.

Table 2: Number of fibres from each part of the calorimeter for a baseline link speed of 6.4 Gbit/s. Two adjacent towers are multiplexed using BCMXU on a single fibre to eFEX.

Calo Region vs N.Fibres to FEXes at 6.4 Gbit/s	EM Barrel	EM Endcap	Special Crate		FCAL	Tile (PPM) min/max	Tile (sROD)
			EM Fwd	HEC			
N.AMC/PPM/sROD	*64*	*32*	*16*		*4*	*32*	*32*
eFEX (direct)	25	20	6	6	0	12/0	18
eFEX (via 1:2 f/o)	0	0	2	6	0	0/12	0?
eFEX (after f/o)	0	0	4	12	0	0/24	0?
jFEX (direct)	12	12	0	9	24	16	24
jFEX (via 1:2 f/o)	0	0	2	11	0	4	0?
jFEX (after f/o)	0	0	4	22	0	8	0?
gFEX (direct)	1	1	2	3	3	2	2
Direct/AMC	38	33	8	18	27	30/18	44
To Fanout/AMC	0	0	4	17	0	4/16	0
After Fanout/AMC	0	0	8	34	0	8/32	0
Total direct	2432	1056	416		108	960/576	1408
Total fanouts	0	0	336		0	128/512	0

Total from AMCs	2432	1056	752	108	1088	1408
Total to FEXes	2432	1056	1088	108	1216/1600	1408

Table 3: Number of fibres from each part of the calorimeter for a baseline link speed of ~10 Gbit/s. No multiplexing is required.

Calo Region vs N.Fibres to FEXes at ~10 Gbit/s	EM Barrel	EM Endcap	Special Crate		FCAL	Tile (PPM) min/max	Tile (sROD) min/max
			EM Fwd	HEC			
N.AMC/PPM/sROD	*64*	*32*	*16*		*4*	*32*	*32*
eFEX (direct)	25	20	10	9	0	6/12	6/12
eFEX (via 1:2 f/o)	0	0	0	0	0	0	0
eFEX (after f/o)	0	0	0	0	0	0	0
jFEX (direct)	12	12	4	17	16	12	12
jFEX (via 1:2 f/o)	0	0	0	0	0	0	0
jFEX (after f/o)	0	0	0	0	0	0	0
gFEX (direct)	1	1	2	3	3	2	2
Direct/AMC	38	33	16	29	19	20/26	20/26
To Fanout/AMC	0	0	0	0	0	0	0
After Fanout/AMC	0	0	0	0	0	0	0
Total direct	2432	1056	720		76	640/832	640/832
Total fanouts	0	0	0		0	0	0
Total from AMCs	2432	1056	720		76	640/832	640/832
Total to FEXes	2432	1056	720		76	640/832	640/832

2.2. RECEIVERS (FOX OUTPUTS)

2.2.1. eFEX

Each eFEX module handles a core area of roughly 1.6*0.8 in eta*phi but the trigger algorithms require an additional ring of towers taking the total coverage to 2.0*1.0 in the centre of the EM layer and a rather larger area at the endcaps. The coverage of each hadronic fibre does not neatly fit the same area so the effective coverage of the hadronic layer will be 2.4*1.2.

The eFEX inputs will be arranged such that a group of 12 EM fibres is used to provide each 0.2*1.0 area in eta with 2 unused fibres per group. The exact allocation depends on the complex routing of the eFEX and is yet to be decided). In the hadronic layer each full group of 12 fibres will cover 0.8*1.2 at the low link speed baseline, though the same area could in principle be covered by only six fibres in the high speed option but the alignment in phi may result in eight fibres being used. Realigning the system to optimise the high speed hadronic inputs would imply a phi shift of 0.2 of the EM fanout pattern.

Figure 6 and Figure 7 show the groupings output fibres to eFEX for one octant across the whole eta space. Figure 8 and Figure 9 show a possible implementation of LArFOX and eFOX modules for the EM layer fibres to eFEX at 10 Gbit/s where, instead of two sets of five fibres, the optimal arrangement is sets of three and seven fibres.

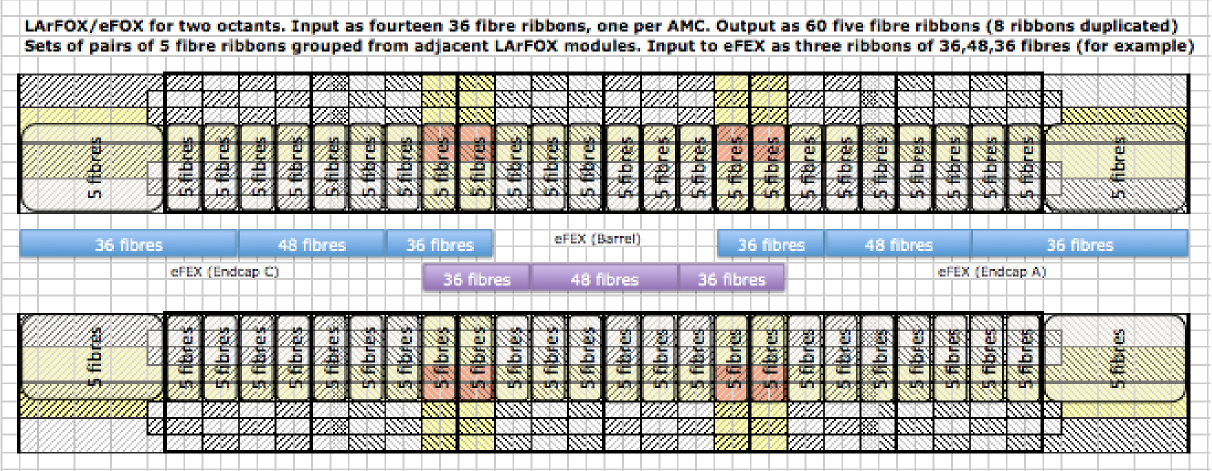


Figure 6: LArFOX fibre mapping to eFEX at 6.4 Gbit/s. Each square box corresponds to one trigger tower covering 0.1*0.1 in eta*phi. Each rectangular box corresponds to one fiber.

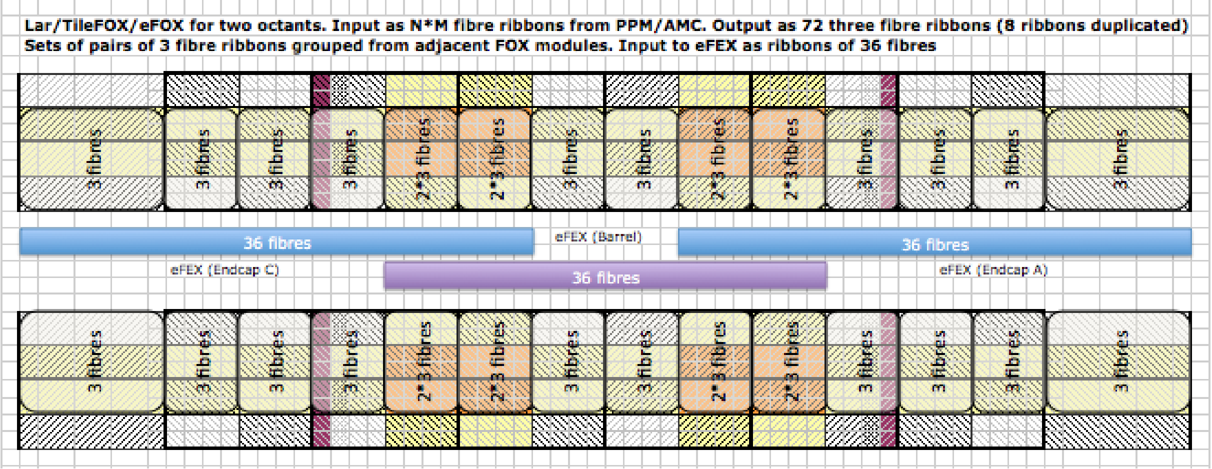


Figure 7: LArFOX and TileFOX fibre mapping at 6.4 Gbit/s. Each square box corresponds to one trigger tower covering 0.1*0.1 in eta*phi. Each rectangular box corresponds to one fiber.

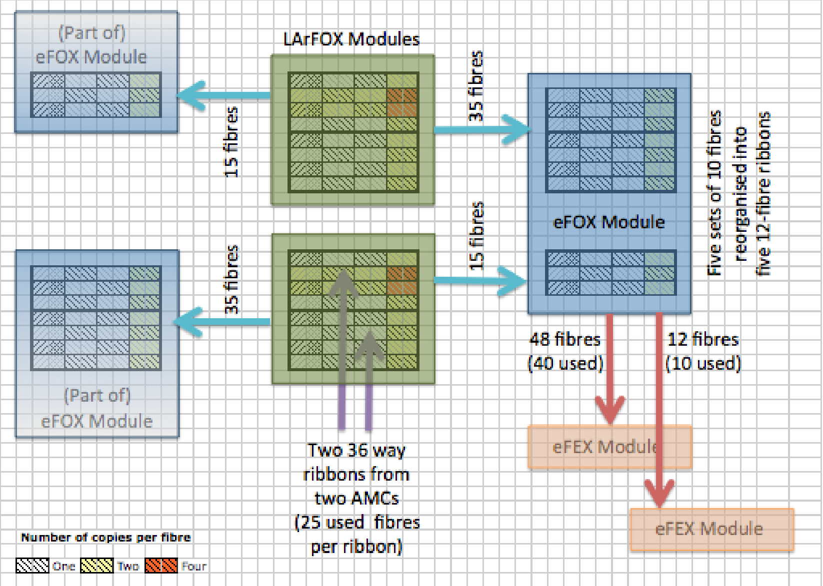


Figure 8: Possible organisation of central EM LArFOX and eFOX modules.

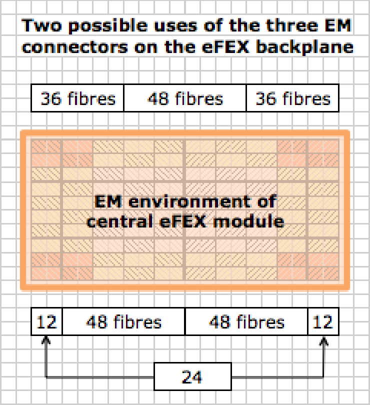


Figure 9: Two possible arrangements of input ribbons to eFEX which are convenient for the FOX modularity – but which may not exactly correspond to the current eFEX proposals.

2.2.2. jFEX

In the baseline jFEX design each jFEX module covers a complete ring in phi for a slice of eta. The core eta coverage of each jFEX module is 0.8 but the extended environment stretches an additional 0.4 each side in the original 6.4 Gbit/s design and 0.8 each side in the high speed design. This requires input of 1.6 or 2.4 in eta respectively.

A recent proposal has suggested an alternative design at the baseline link speed with a core coverage of 0.6 in eta with 0.6 each side with a total eta requirement per module of 1.8. In this scheme each fibre covers 0.2*0.4 in eta*phi (cf 0.4*0.2 for eFEX) and three copies of each fibre are required. This is the worst case for the mappings and use of HEC LDPS outputs.

In particular to provide enough outputs from the suggested special crate LDPS (forward EM + HEC) the fibres covering the region 2.4<|eta|<3.2 need to carry signals from 12 towers instead of 8. This could be done by reducing the number of bits per tower or by summing some low granularity or both.

The mapping for the high speed jFEX option is easier. The number of fanout copies at source of each fibre is shown in Figure 10 with the boundaries of each jFEX module. One 12 fibre ribbon provides the environment for one octant of one layer in the central region. The required LArFOX/TileFOX and jFOX module organisation is still to be worked out.

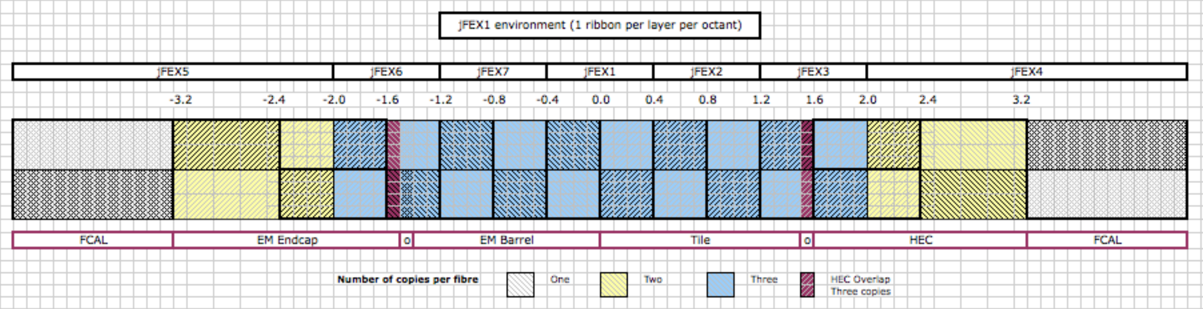


Figure 10: Number of fanout copies of each jFEX fibre at ~10 Gbit/s. Each square box corresponds to one trigger tower covering 0.1*0.1 in eta*phi. Each rectangular box corresponds to one fiber.

2.2.3. gFEX

The single gFEX module covers the entire eta-phi space without any need for fanout. Each FPGA covers roughly 1.6 in eta (more at the endcaps) and receives 32 fibres from each of the EM and hadronic layers. The challenge for the FOX is that these fibres must be collected one per AMC.

2.3. OPEN QUESTIONS

This section has outlined the current ideas for mappings between the LDPS and the FEXes including the Tile outputs from PPMs in Phase-I or new Tile sRODs in Phase-II. This is still preliminary and there are several open questions.

The main unknown is the link speed to be used. This choice has a large impact on the number of hadronic fibres and their mapping and also affects the EM mapping due to a reoptimisation of the layout.

Another question to be resolved is how and where to handle the different mappings on A and C sides. In the detector the mappings are either rotated (EM, Tile) or reflected (HEC?) between the two sides. The trigger algorithms expect to operate on an eta-phi space with translational symmetry – at least within a given FPGA. In the original L1Calo system all input towers were remapped into a single eta-phi space at the PPM inputs. However the FEXes have separate modules or FPGAs for A and C sides and it might be useful to keep the rotational symmetry to minimise the number of remappings.

3. COMPONENTS OF OPTICAL CHAIN

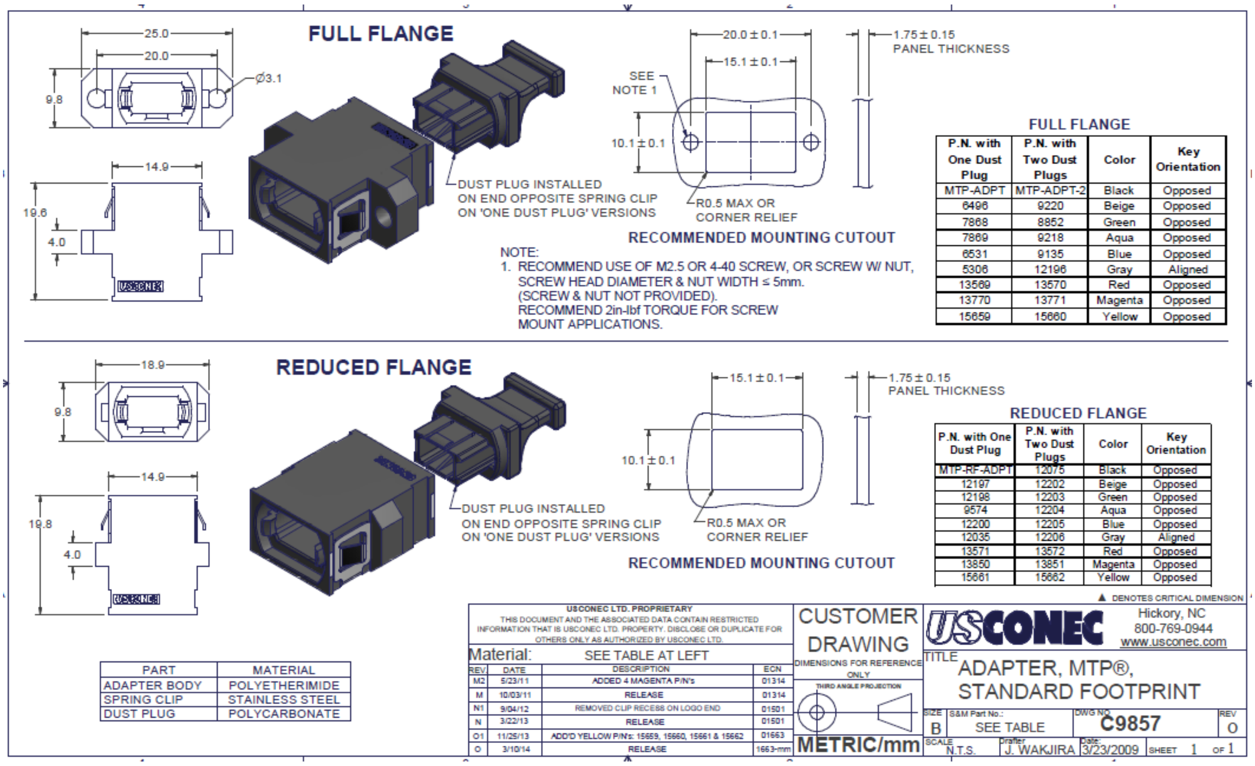
The FOX optical chain contains necessary components to connect, split (if needed) and map the optical outputs of calorimeter electronics (ECAL and HCAL) to the optical inputs of different FEX modules. The optical outputs and inputs connectors are parallel Multi-fibre Push-On/Pull-Off (MPO) connectors (or MTP which is inter-changeable).

The information from the calorimeter electronics is received in groups of 48 fibres which are organized into four ribbons of 12 fibres each (parallel fibre cables). Therefore, the inputs to the FOX are 12 fibres MPO connectors.

The outputs of the FOX are also 12 fibres MPO connectors. The eFEX module uses 48 fibres MPO connectors and the jFEX and the gFEX modules use 72 fibres MPO connectors. Therefore there may be the break-out cables (48 to 4x12 and 72 to 6x12 fibres) between the FOX output 12 fibres MPO connectors and FEX'es 48 and 72 fibres connectors.

3.1. INPUT ADAPTERS FOR MPO/MPT CONNECTORS

MPO connectors come in female and male versions, differentiated by the absence or presence of guide pins. MPO connectors have springs inside to keep the fibres pressed together. The multiple fibres terminated at the MPO connector are arranged in rows of twelve fibres each. Two MPO connectors can be connected together with a bulkhead mating adapter (feedthrough) to hold them in place.



NOTE:
1. RECOMMEND USE OF M2.5 OR 4-40 SCREW, OR SCREW W/ NUT, SCREW HEAD DIAMETER & NUT WIDTH ≤ 5mm. (SCREW & NUT NOT PROVIDED). RECOMMEND 2in-lbf TORQUE FOR SCREW MOUNT APPLICATIONS.

FULL FLANGE

P.N. with One Dust Plug	P.N. with Two Dust Plugs	Color	Key Orientation
MTP-ADPT	MTP-ADPT-2	Black	Opposed
6496	9220	Beige	Opposed
7868	8852	Green	Opposed
7869	9218	Aqua	Opposed
6531	9135	Blue	Opposed
5306	12196	Gray	Aligned
13569	13570	Red	Opposed
13770	13771	Magenta	Opposed
15659	15660	Yellow	Opposed

REDUCED FLANGE

P.N. with One Dust Plug	P.N. with Two Dust Plugs	Color	Key Orientation
MTP-RF-ADPT	12075	Black	Opposed
12197	12202	Beige	Opposed
12198	12203	Green	Opposed
9574	12204	Aqua	Opposed
12200	12205	Blue	Opposed
12035	12206	Gray	Aligned
13571	13572	Red	Opposed
13850	13851	Magenta	Opposed
15661	15662	Yellow	Opposed

PART	MATERIAL
ADAPTER BODY	POLYETHERIMIDE
SPRING CLIP	STAINLESS STEEL
DUST PLUG	POLYCARBONATE

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Material: SEE TABLE AT LEFT

REV.	DATE	DESCRIPTION	ECN
M2	5/23/11	ADDED 4 MAGENTA P/N's	01314
M	10/03/11	RELEASE	01314
N1	9/04/12	REMOVED CLIP RECESS ON LOGO END	01501
N	3/22/13	RELEASE	01501
O1	11/25/13	ADD'D YELLOW P/N's: 15659, 15660, 15661 & 15662	01663
O	3/10/14	RELEASE	1663-mm

Figure 11: Individual MPO/MPT adapter.

Depending on FOX implementation, denser packing of the adapters for the input and output MPO connectors may be required. In this case quad adapters may be used (see below).

Input MPO connectors of the FOX will be male version (with guide pins). The parallel fibre ribbons of 12 fibres will have female version of the MPO connector.

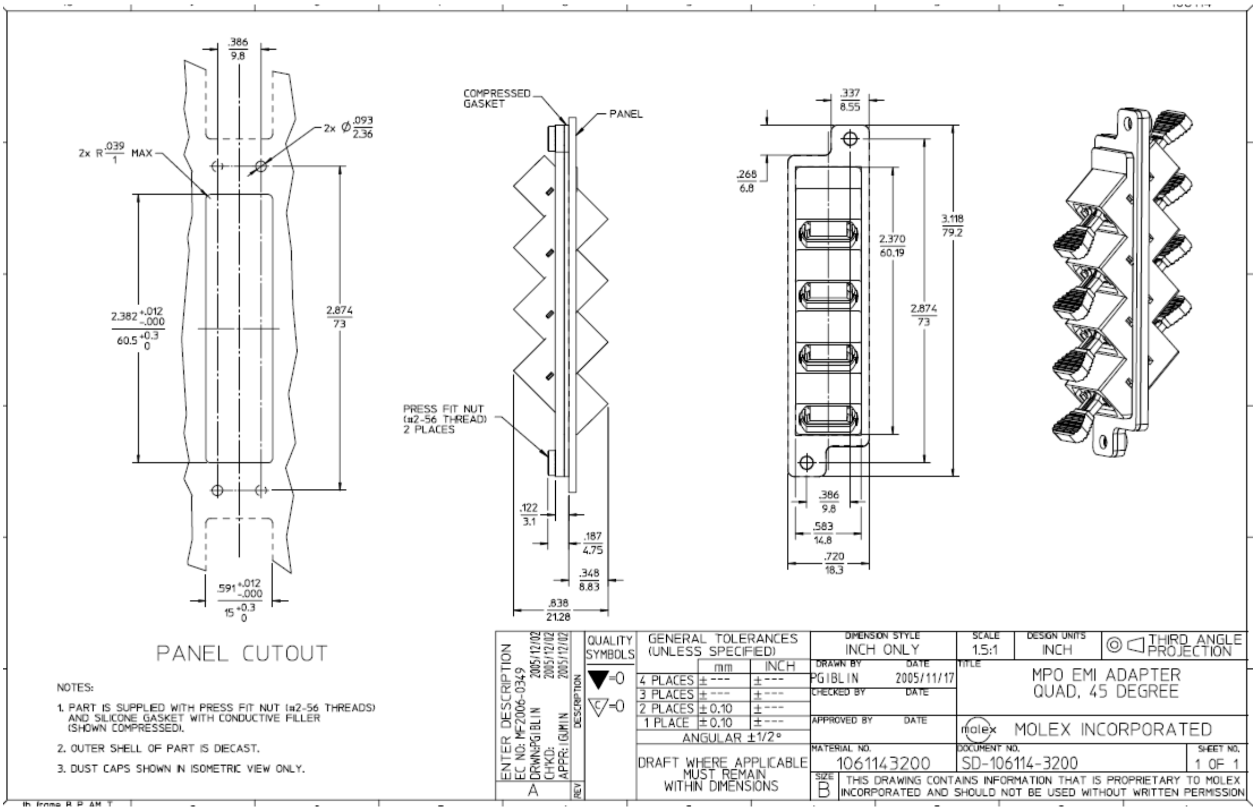


Figure 12: Quad MPO/MPT adapters.

3.2. FIBRES MAPPING

3.2.1. Mapping at the input and output

The information from the calorimeter electronics is received in groups of 48 fibres which are broken out into four ribbons of 12 fibres each (parallel fibre cables). It is assumed, that these 48 fibres can be split into 12-fibre ribbons with any desired mapping with custom cable assembly. This first stage of mapping shall be defined *a priori* and can be changed by replacing the cable assembly.

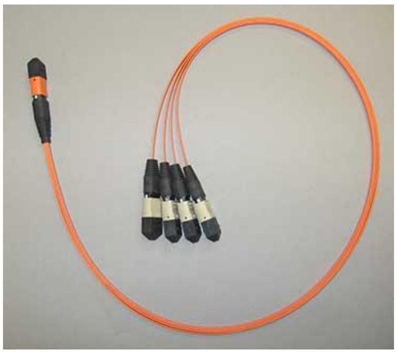


Figure 13: 48 to 4x12 MPT custom cable assembly.

3.2.2. Mapping by connectors

The FOX will map each of the input fibres to a specific FEX destination. In order to achieve this, the input and output parallel fibre ribbons of 12 fibres break out in individual fibres with MPO harness cable. Connecting two segments of optical fibres is most simply done through optical connectors on each end of the fibres (e.g. LC or SC connectors for individual fibres) and a barrel connector to mate the two connectors. The amount of light lost in the connection is expected to be in the range of 0.25 to 0.5 dB, with a value range depending on different expectations about what might be typical versus what should be used in conservative calculations (see Appendix Appendix A). The light power loss depends on several factors including the cleanliness of the polished faces and the fine alignment of the two fibre cores, but even with perfect alignment some light reflection and power loss is always present. The advantage of having connectors and using modular components (e.g. for splitters) comes from the convenience of assembly and maintenance of the full system.

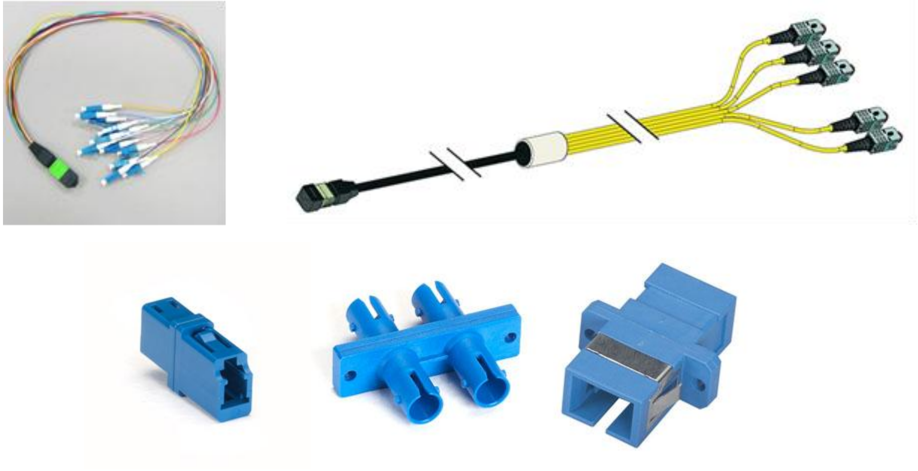


Figure 14: MPO harness and connector couplers (LC, ST, SC).

This way of mapping is very flexible and allows for quick modification. However, with a big number of connections it may occupy a lot of space.

3.2.3. Mapping by fusion splicing

Instead of connecting fibres by connectors and couplers, fusion splicing may be used (see also 4.3.1). The splicing process includes stripping the fibre by removing all protective coating, cleaning, cleaving, fusing and protecting either by recoating or with a splice protector. Advantages of fusion splicing are higher reliability, lower insertion and return losses than with connectors. However, fusion-splicing machines are rather expensive and this method may be difficult to use in-situ.

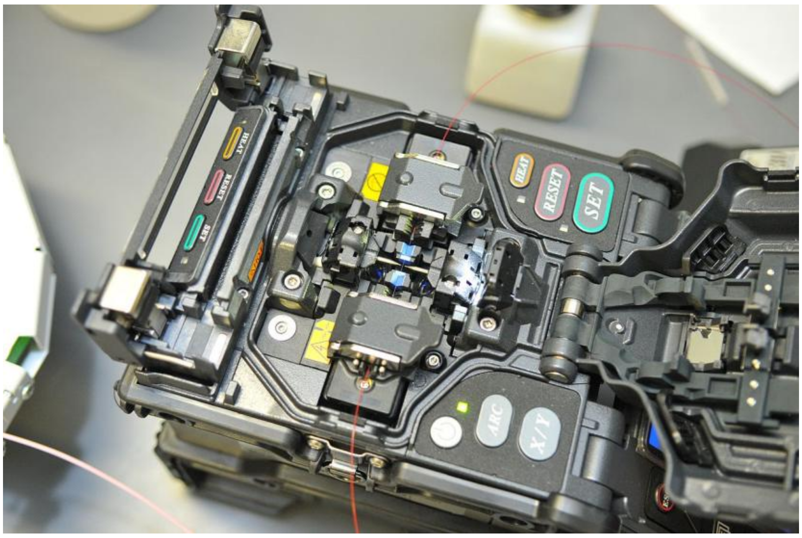


Figure 15: Fusion splicing.

3.2.4. Mapping by custom mapping module

In a case the mapping is defined a priori and will not change, a custom build commercial mapping module, which redistributes the input signals to output connectors, can be manufactured. This way of mapping is however is not flexible and doesn’t allow for further modifications.

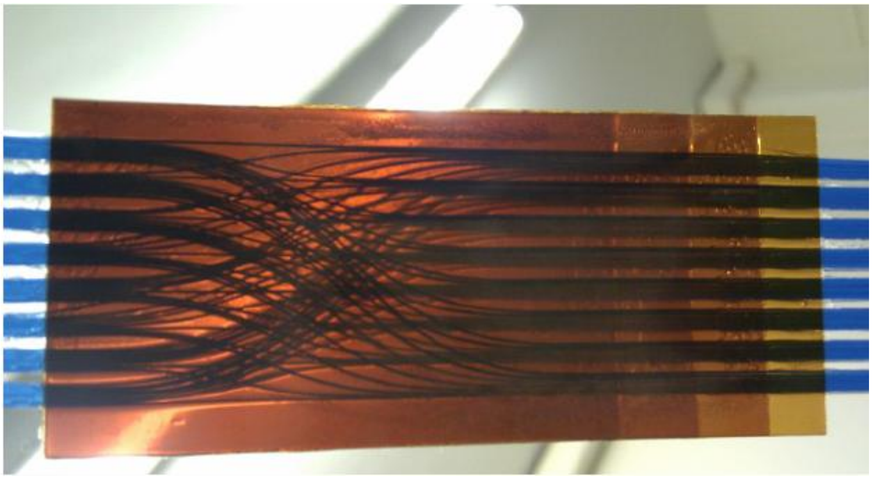


Figure 16: Fibre mapping.

3.3. FIBRE PASSIVE SPLITTING

For the fibres that go to two destinations and therefore require passive splitting, a passive optical splitter with the even split ration (50/50) can be used. The splitter may be connected to the input/output fibres by connectors (see 3.2.2), which create addition insertion loss, or by fusion splicing (see 3.2.3). Example of connectorized passive splitter is shown in Figure 17. It contains LC connectors on both ends and use multimode fibre of 850 nm wavelength. The split ratio is even. 1 m input and output cables.

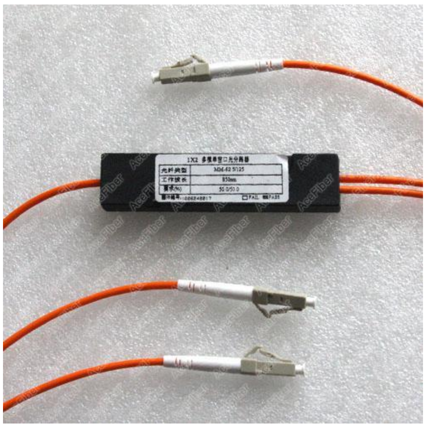


Figure 17: Fibre passive splitter.

3.4. FIBRE ACTIVE SPLITTING

For the fibres that go to more than two destinations, a passive optical splitter may not work due to the high losses and another way of the optical signal distribution shall be used. This can achieved in different way and in different places, therefore a total cost shall be estimated before making a decision.

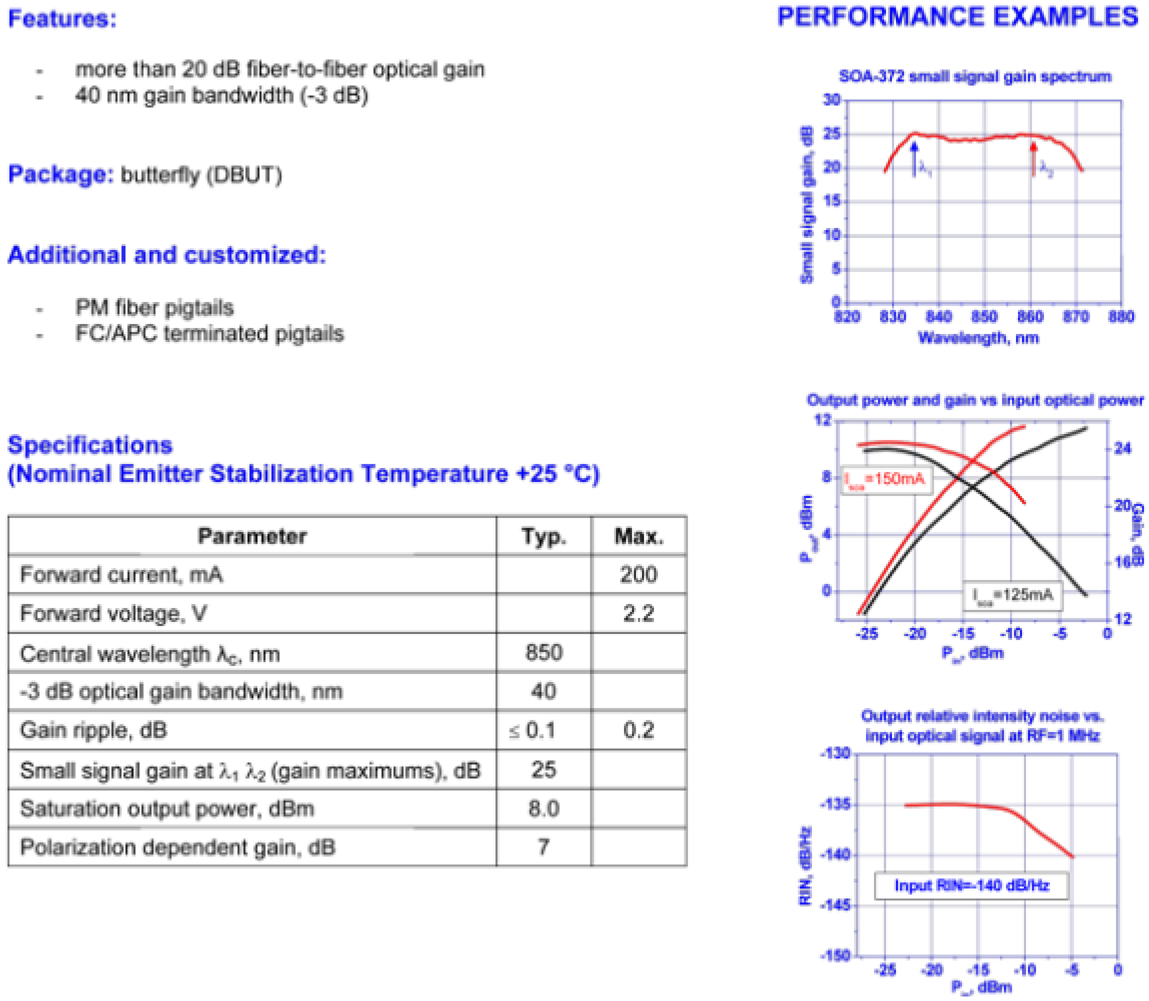
3.4.1. Electrical signal fan out at the source

The electrical fan out of the signals before electrical to optical conversion and optical transmission can be implemented in ECAL and HCAL transmitters. This way of signal duplications may increase the number and the cost of transmitters and the number of input connectors to the FOX. However, signal duplication at source is preferred since it provides the highest quality signals at the destination, particularly if the copies are driven by separate FPGA pins.

3.4.2. Optical amplification

The optical signal can be amplified before the passive splitters on order to raise the optical power budget. In this case 1 to 4 (and more) passive splitting may be achieved. An example of the commercial Semiconductor Optical Amplifier (SOA) @ 850nm, QSOA-372 is shown below:

- SUPERLUM Diodes
- Traveling-wave MQW design
- CW or pulsed operation
- PM or SM pigtails
- Low chip-to-fibre coupling loss
- Built-in thermistor and TEC
- Hermetic butterfly package or DIL package
- Optional FC/APC connectors



Features:

- more than 20 dB fiber-to-fiber optical gain
- 40 nm gain bandwidth (-3 dB)

Package: butterfly (DBUT)

Additional and customized:

- PM fiber pigtails
- FC/APC terminated pigtails

Specifications
(Nominal Emitter Stabilization Temperature +25 °C)

Parameter	Typ.	Max.
Forward current, mA		200
Forward voltage, V		2.2
Central wavelength λ_C, nm	850	
-3 dB optical gain bandwidth, nm	40	
Gain ripple, dB	≤ 0.1	0.2
Small signal gain at λ_1 λ_2 (gain maximums), dB	25	
Saturation output power, dBm	8.0	
Polarization dependent gain, dB	7	

PERFORMANCE EXAMPLES

Figure 18: Optical amplifier.

The SOA has a fibre-to-fibre optical gain of more than 20dB, which is, however, much more than needed (something on the order of 6dB for a 1:3 split plus insertion losses). So an extra passive splitter or an attenuator is needed to work with it. Also SOA needs s simple PCB and power.

3.5. MECHANICS

A mechanical arrangement of the individual components of the FOX optical chain is defined by the demonstrator layout and implementation. For the initial measurements, the components may be assembled on the optical test bench on the table. However, for the integration tests with other components of the L1Calo, some housing for the individual components will need.

Commercial customized housing and available from a number of manufacturers:

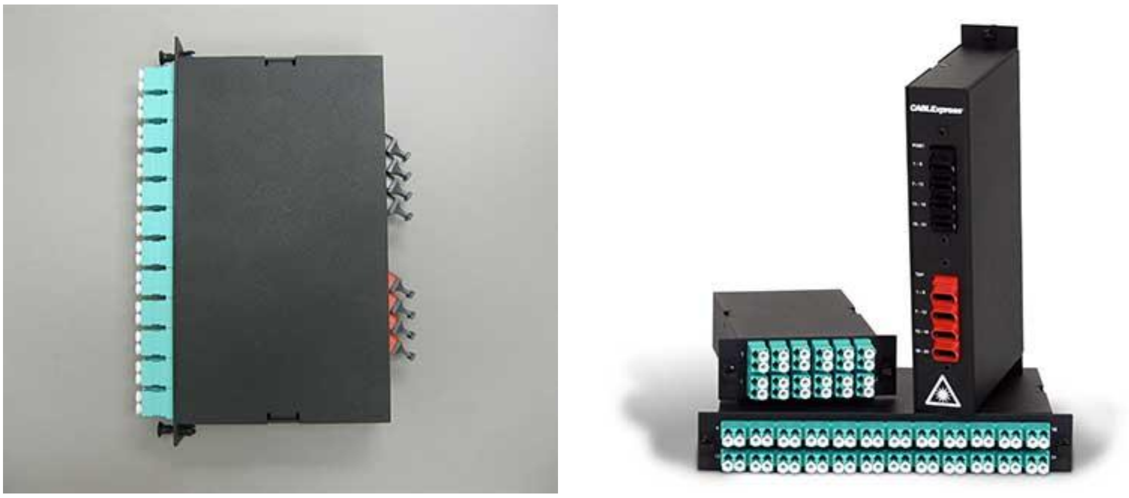


Figure 19: LC to MTP Modules.

Figure 20: 4U 192 Port / 384 Fibre LC Pass Thru Enclosure.

The final implementation and design of the demonstrator’s housing will be specified during the demonstrator design according to the integration tests requirements.

4. DEMONSTRATOR(S)

This section focuses on studies preparing for the practical implementation of a FOX system. These hardware studies are conducted in parallel to the ongoing work defining the details of the total count and internal mapping of the input and output fibres of the FOX system.

4.1. DEMONSTRATOR GOALS

The initial study period for the FOX system has two main goals. The first goal is the study of the light path between the transmitter MicroPODs of the Liquid Argon or Tile Detector Front-Ends and the receiver MiniPODs of the Feature Extractor modules of L1Calo, as well as to provide a prototype for system evaluation in the link tests in 2015. The second goal is a study of the mechanical building blocks necessary to construct an overall physical plant providing the required management and mapping of all the fibres and its installation in USA15.

These two aspects are largely independent and, to a large extent, can be studied separately.

These studies will provide a better understanding of light distribution as it applies specifically to FOX and accumulate the knowledge needed to support the design of the final system. The outcome of these studies will also include the manufacturing of physical demonstrators to be used as FOX prototypes during integration testing in 2015 along with the prototypes of the modules upstream and downstream from the FOX system.

4.2. DEMONSTRATOR COMPONENTS

4.2.1. Optical Demonstrator

This is the test setup used to study the light path between transmitting and receiving MiniPODs. The input side is defined as a 48-fibre MTP/MPO connector (LAr and TileCal side) and the output side as a 48-fibre (eFEX side) or 72-fibre MPO/MTP connector (jFEX and gFEX side).

The type of fibre to be used in FOX is defined by two things: the MiniPOD laser transmitters which are operating in multimode at 850 nm and the “pigtail” cables used on the source and sink modules (trademarked as “VersaBeam” or “PRIZM Light Turn”). The demonstrator and the FOX system are thus defined to use the same multimode OM3 (or better) fibres with a 50 micron core and 125 micron cladding.

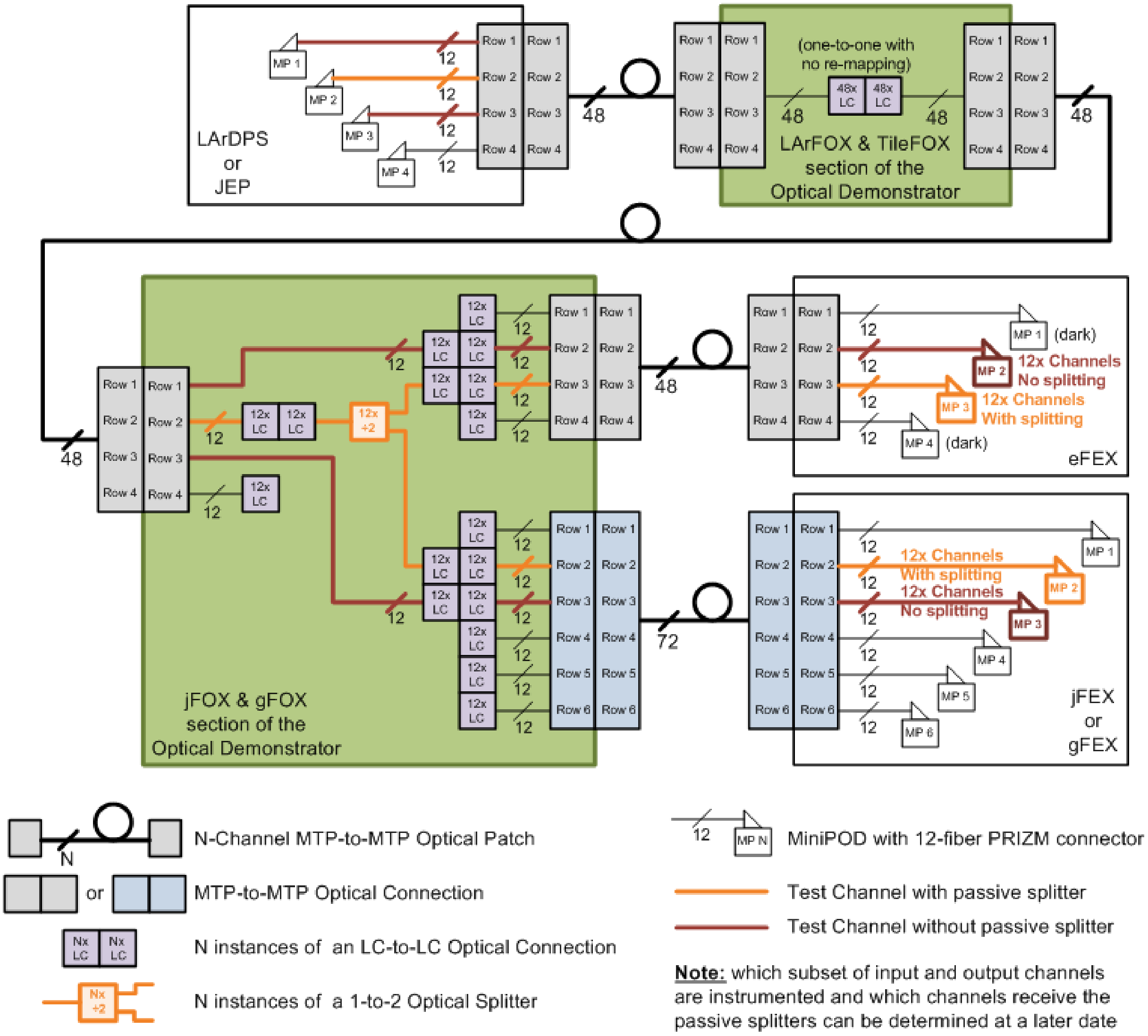
It is expected that all the source, sink and intermediate components located upstream, downstream and within the FOX system all follow the convention that fibre patch cables are fitted with female MPO/MTP connector on both ends and that all modules (LAr and TileCal modules, FEXs, FOX) use MPO/MTP connectors equipped with male alignment pins.

The optical demonstrator for the FOX system forms a full model of the light path between the detector front-ends and the FEXs, including the patch cables connecting the FOX modules to the upstream and downstream modules. The optical demonstrator thus includes patch cables of a representative length, barrel connectors identical to what will be used at the inputs and outputs to the FOX modules, and several “octopus” cables appropriate for arbitrary mapping at each stage.

This test environment forms a study platform where optical components from different manufacturers, different types of internal connectors, different passive splitters, and fixed attenuators can be inserted, tested and measured. The mechanical assembly of this optical test environment does not try to follow the mechanical choices studied separately for building the final FOX system. Any mechanical components used in this setup are chosen primarily for ease of testing and portability of the setup.

The optical demonstrator is usable in isolation, i.e. with hand-held test equipment using continuous or pulsed light sources and light meters to measure and compare the insertion loss of different configurations. It can also be connected to a modulated light transmitter and a light detector (preferably MiniPODs) to simulate a L1Calo data stream at 6.4 Gbps (or other speed) and provide an empirical measurement of the connection quality that is representative of that link and that set of source and sink.

One optical demonstrator will be made available, presumably at CERN, for integration testing with prototypes of the upstream and downstream modules as they become available. This Optical demonstrator will include instances of all types of light paths that will be present in the final system, including sets of channels with passive splitters and sets with no splitters. This will be available both on a 48-fibre connector for an eFEX and on a 72-fibre connector for a jFEX or gFEX. The exact details of the number of instrumented channels and their location can be discussed and adjusted at a later date, but an initial diagram of the optical demonstrator is shown in Figure 21 which assumes the natural quantum of test channels to be 12.



Note: which subset of input and output channels are instrumented and which channels receive the passive splitters can be determined at a later date

Figure 21: Draft diagram of the FOX Optical Demonstrator.

4.2.2. Mechanical Demonstrator

The mechanical demonstrator study consists of one or several test assemblies used to evaluate and choose a combination of commercial (and custom made where necessary) mechanical components appropriate to build the full FOX system. An important and pressing outcome from the demonstrator time period of the FOX system is to determine the physical size of the FOX module so that the required space in USA15 can be properly understood and planned for in advance.

As shown in Figure 4 the FOX system is designed to be modular. The input and output sides of the FOX system need to provide the MPO/MTP connectors for the patch cables connections to the upstream and downstream modules. The FOX sub-modules need to internally support the required fibre mapping and light splitting where necessary.

The existing infrastructure in USA15 expects the FOX sub-modules to be mounted in a19-inch rack rail environment. Mounting some passive FOX module(s) outside of the rack enclosures could be explored if rack space in USA15 becomes a limitation but such measure will hopefully not be necessary.

The criteria to be used in searching for and evaluating solutions are:

- Compactness to minimize the rack space required in USA15
- Modularity with separate sub-modules for each input and output types to help with construction, installation and future upgrades
- Component accessibility to ease construction, diagnostics and any repair

Several options may be found sufficiently attractive to be explored during this time period of the FOX design. At least one option will be pushed to become a physical demonstrator. This mechanical prototype must represent a coverage deemed sufficient to demonstrate and support the mechanical design of the full system. This mechanical demonstrator may be tested for a “dry fit” in USA15 during a shutdown period even if no suitable inputs and outputs are available at the time.

The mechanical demonstrator is not intended to be used as the main tool for testing light distribution. A few channels of the final mechanical demonstrator will however be equipped with a representative set of the optical components separately qualified with the optical demonstrator in order to illustrate their mechanical integration.

4.3. EXPLORATIVE STUDIES

Two additional technologies are also explored and evaluated as options or backup solutions. The use of these technologies might be required if the light loss through modular passive splitters is determined to be unmanageable.

4.3.1. Fibre fusing

Connecting two segments of optical fibres is most simply done through optical connectors at the end of each fibre and a barrel adapter (cf. 3.2.2). An alternative is to use commercial equipment and fuse the fibres end to end. With a good fuser machine and a careful fuser operator, the light loss through a fused optical connection is expected to be fairly well controlled at or below 0.1 dB which is less than the 0.25 to 0.5 dB lost through connector pairs.

The information available about fusion splicing equipment describes a fairly slow but straightforward process. The operator must cut, strip and prepare two clean bare fibre ends. The machine presents two fine lateral views to adjust the alignment of the two ends before fusing. Care must be taken while handling the sharp bare fibres which can easily penetrate the skin and the operator must be attentive to the safe disposal of all fibre scraps.

One downside in fusing fibres in the FOX system is in the loss of modularity and flexibility. Replacing three pairs of connectors along a path using a light splitter with three fused connections would constitute a saving of about 0.5 dB. How important (or sufficient) such a saving will be to the overall FOX system will be understood from the results of the optical demonstrator studies.

The goal of this explorative study is to evaluate how easy or challenging this fusing procedure really is. We will also understand how long each fused connection might take in the context of building the final FOX system. This study will thus determine how feasible it would be to fuse some of the connections in a fraction of the FOX channels, namely those requiring the use of light splitters. The feasibility will of course also depend on how many channels would need to receive this treatment (tens or hundreds versus thousands). While it may be too early to predict if fibre fusing will be needed, this explorative study is meant to prepare for such possibility.

Should fibre fusing proved to be an attractive option for FOX, the optical demonstrator will incorporate a set of test channels with fused connections replacing the LC-to-LC connections.

4.3.2. Light amplification

It is expected that channel splitting will be required in some of the channels in the FOX system. It is expected that only one-to-two channel splitting will be required and that passive light splitters will be sufficient in all cases. There is however no certainty yet that this will be the case. Should one-to-four channel splitting be required, passive splitting would not be possible as the inherent loss in each channel would be too great. The FOX system would need to use active splitting (i.e. provide light amplification before passive splitting or some form of signal decoding and signal regeneration).

An effort had already been started in surveying what solutions might be commercially available and this explorative study is a continuation of that effort.

Optical 850 nm multimode communication at 10 Gbps is one of the technologies used for short range connections in Ethernet communication. Ethernet fibre link duplication also happens to be desired in certain Ethernet switching contexts. This is used to provide a copy of all internet traffic for the purpose of flow monitoring and for intrusion detection. Commercial devices accomplishing such flow duplication are called “taps”. There would be important issues related to cost and space per channel, but a basic problem was also identified after discussing the details of the specification with one vendor. Ethernet protocol uses a different encoding scheme for the data stream and the 8b/10b encoding scheme used in L1Calo is incompatible with the 64b/66b encoding used with the 10Gb Ethernet protocol. The 64b/66b encoding can’t be used in the L1Calo system, as the FPGA implementation doesn’t have a fixed latency and doesn’t detect errors at the required tick/channel granularity. Proprietary firmware in these commercial products would need to be modified for 8b/10b encoding while no clear path forward was proposed by that particular vendor. Moreover, the embedded FPGA implementation for 64b/66b isn’t fixed latency, and doesn’t detect errors at the required tick/channel granularity.

Discrete components for light amplification at 850 nm should also be explored and tested if found appropriate for use in the context of MiniPOD to MiniPOD communication.

This study will continue to search for and evaluate commercial products in the form of pre-packaged solutions and discrete components. If some viable solutions are found to be practical in the context of a FOX system, they will be tested with the optical test platform.

4.4. MEASUREMENT TOOLS

4.4.1. Optical power meter

An optical power meter is used in conjunction with a stable light source to measure the amount of light transmitted through a fibre. The tester is first calibrated (zeroed) using two fixed fibres before inserting the section of light path to be measured. The additional power loss measured is called the insertion loss for the tested section.

A simple power meter measures the average light power as opposed to the modulated light power which carries the information of the data stream. The quantity measured is the light power ratio or power loss expressed in dB between input and output. Because it is a ratio, the power loss measured for the average power is no different than the power loss for the modulated power. This insertion loss measurement is also the quantity used in modulated power budget calculations.

Insertion loss measurements are the main quantitative measurement used to compare the different components being evaluated with the optical demonstrator. A power meter can also be used to diagnose and locate poor connections or wiring mistakes.

4.4.2. Reflectometer (OTDR)

An optical time-domain reflectometer (OTDR) can also be used to characterize an optical fibre. This is the optical equivalent to an electronic time domain reflectometer. An OTDR injects a series of optical pulses into one end of the fibre under test and detects the light reflected by any discontinuity (a step loss) or glass media scattering (a propagation loss) within the fibre. The time delay of the reflection is converted and displayed as a distance into the fibre. Connectors are seen as steps (called events) on the display. Unlike the power meter method which needs physical access to both ends of the fibre being tested, the OTDR makes its measurements from one end only.

Another theoretical advantage of an OTDR instrument is that it should be able to display and characterize each optical connector along the optical path. These instruments are mostly used in diagnosing long single mode connections (hundreds or thousands of meters or even tens of kilometers of single mode fibre) and we will need to determine how well it can perform for discriminating among the multiple connections likely separated by less than a meter within the multimode FOX system.

4.4.3. Bit error ratio tester (BERT)

A Bit Error Rate or Bit Error Ratio Test (BERT) requires a light source sending an encoded signal with a known pseudo-random data pattern at one end of the fibre and a detector receiving this signal at the other end of the fibre. The test output simply consists of the bit level comparison of the recovered data pattern to the known input pattern and the counting of the number of mistakes detected.

Test equipment manufacturers sell dedicated BERT source and measurement instruments, but this type of equipment would not provide a meaningful qualification of the FOX system.

A BERT measurement is not only dependent on the quality of the light path (FOX) but also critically dependent on the characteristics of the transmitter and receiver used for the test. The FOX system is meant to be used with MiniPOD devices and any meaningful BERT measurement should thus be using these devices, and preferably those from the modules used in the final system. The firmware design environment suite for the Xilinx FPGAs used in these ATLAS modules conveniently supports such BERT measurements with minimal effort.

Xilinx BERT measurements will provide the link quality measurements for the evaluation of the components chosen for the FOX system.

4.4.4. Optical oscilloscope

An optical sampling oscilloscope is a complex and expensive tool that can display the modulated light power received at the end of a fibre. This type of tool could be useful for optimizing the parameters available in a MiniPOD transmitter and the configuration of an FPGA MGT channel. The tuning of these parameters depends on the particular implementation details of the source modules and is not within the control of the FOX design effort. Such qualitative measurements are not considered to be within the scope of the FOX project.

The main figure of optical merit for the FOX system is understood to be in the minimization of light loss. Insertion loss will be the primary quality measurement of each individual while bit-error tests will be used to quantify the reliability of each type of light path.

4.5. TEST PROCEDURE

4.5.1. Insertion loss measurements

The optical demonstrator is used to determine the insertion loss of the light path through a typical channel of the FOX system, i.e. through a series of fibre patch cables and components, with or without a light splitter.

This insertion loss is measured with a power meter or OTDR instrument. This loss is then compared to the power budget for a MiniPOD to MiniPOD connection calculated using their guaranteed specification. This comparison will determine how much theoretical power margin is left.

4.5.2. Bit error test

For all initial data transmission tests the optical demonstrator will use one of the existing L1Calo CMX modules equipped with a "Topo FPGA", i.e. with all its transmitting and receiving MiniPODs. The optical demonstrator can later be used with the prototype versions of the upstream and downstream modules, as they become available.

A CMX module and Xilinx BERT firmware plus the Xilinx ChipScope interface can be used to generate and capture a 6.4 Gbps data stream for BERT measurements. These measurements provide an estimate of the minimum time (if no error is detected over the observation period) or an average time (if errors are detected) between transmission errors. An acceptable limit needs to be specified for the overall FOX system and for individual FOX channel, while keeping in mind that channels with light splitting will naturally show different limits than channels without light splitting.

If an insertion loss measurement and a datasheet can provide a theoretical calculation of the power margin available, a bit error test is an empirical verification of the existence of such margin. The cushion of this power margin can be probed using the optical demonstrator. In addition to checking for a zero or low bit error rate with a representative light path configuration, we can also insert light attenuators of known increasing power loss ratio until the bit error rate becomes significant. This empirical measurement can then be compared to the calculated value.

One limitation of using a CMX card is that its Virtex 6 FPGAs can only test a transmission speed up to 6.4 Gbps. Testing MiniPOD transmission at higher speeds will need to be performed with prototypes modules being built for the Phase-I upgrade (assuming higher line rates will indeed be used).

4.5.3. MiniPOD Light Level Monitoring

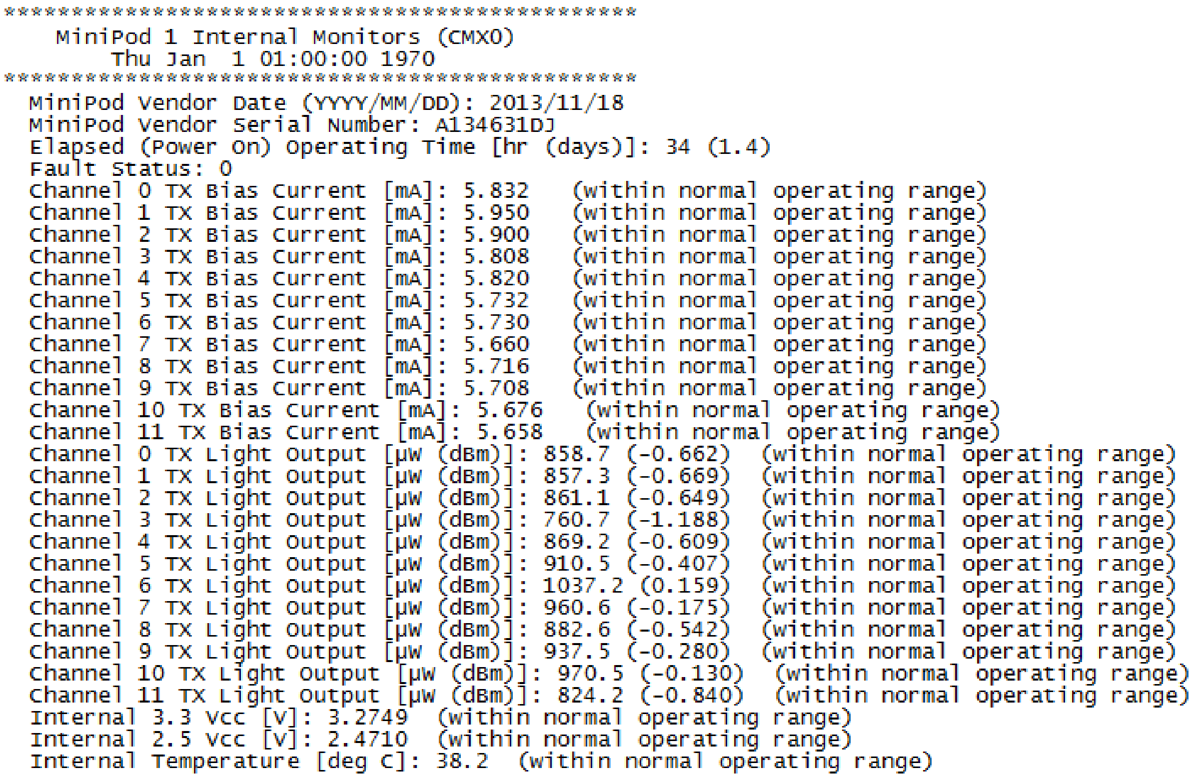
Transmitter and receiver MiniPODs host a number of internal registers accessible through a Serial interface (TWS). These control and status registers include monitoring information amount of light either transmitted or received as measured by the device itself. These internal measurements are specified per channel with a rather fine granularity of 0.1microW (-30 dBm) with a tolerance of only +/- 3 dB. This coarse tolerance prevents using these monitoring values direct quantitative measurement. During CMX production module testing the values returned been found to be stable over repeating queries (an example of the data currently retrieved is shown in Figure 22: Example of MiniPOD information captured by current CMX software and firmware.

below). These measurements will thus be included in the testing of the FOX optical demonstrator and will be compared to and calibrated against the insertion loss measurements obtained with other test equipment.

Such measurements could also prove to be valuable if they were to become part of the ATLAS monitoring information continuously recorded over a long period of time. Any short term degradation could help diagnose and locate channel transmission problems. The aging characteristics of MiniPOD devices are not currently understood. Any long term trend could help predict and plan for the replacement of MiniPOD components during extended shutdown periods, should aging become an issue.

More than optical power could also be tracked by querying the MiniPODs, including manufacturing date, serial number and operating time. Case temperature and electrical measurements are also available. Faults and Alarms on optical, electrical or temperature measurements can also be monitored.

The degree to which a systematic and system-wide collection of such monitoring information might be valuable to ATLAS can only be understood once it has been carried out. The FOX team recommends that access to the information from all MiniPODs be made available by the hardware and firmware of all Phase-I modules installed in USA15 and that the DCS system start planning for the low rate collection and recording of this type of monitoring data from all MiniPODs.



```
***********************************************
    MiniPod 1 Internal Monitors (CMX0)
        Thu Jan  1 01:00:00 1970
***********************************************
  MiniPod Vendor Date (YYYY/MM/DD): 2013/11/18
  MiniPod Vendor Serial Number: A134631DJ
  Elapsed (Power On) Operating Time [hr (days)]: 34 (1.4)
  Fault Status: 0
  Channel 0 TX Bias Current [mA]: 5.832   (within normal operating range)
  Channel 1 TX Bias Current [mA]: 5.950   (within normal operating range)
  Channel 2 TX Bias Current [mA]: 5.900   (within normal operating range)
  Channel 3 TX Bias Current [mA]: 5.808   (within normal operating range)
  Channel 4 TX Bias Current [mA]: 5.820   (within normal operating range)
  Channel 5 TX Bias Current [mA]: 5.732   (within normal operating range)
  Channel 6 TX Bias Current [mA]: 5.730   (within normal operating range)
  Channel 7 TX Bias Current [mA]: 5.660   (within normal operating range)
  Channel 8 TX Bias Current [mA]: 5.716   (within normal operating range)
  Channel 9 TX Bias Current [mA]: 5.708   (within normal operating range)
  Channel 10 TX Bias Current [mA]: 5.676   (within normal operating range)
  Channel 11 TX Bias Current [mA]: 5.658   (within normal operating range)
  Channel 0 TX Light Output [µW (dBm)]: 858.7 (-0.662)  (within normal operating range)
  Channel 1 TX Light Output [µW (dBm)]: 857.3 (-0.669)  (within normal operating range)
  Channel 2 TX Light Output [µW (dBm)]: 861.1 (-0.649)  (within normal operating range)
  Channel 3 TX Light Output [µW (dBm)]: 760.7 (-1.188)  (within normal operating range)
  Channel 4 TX Light Output [µW (dBm)]: 869.2 (-0.609)  (within normal operating range)
  Channel 5 TX Light Output [µW (dBm)]: 910.5 (-0.407)  (within normal operating range)
  Channel 6 TX Light Output [µW (dBm)]: 1037.2 (0.159)  (within normal operating range)
  Channel 7 TX Light Output [µW (dBm)]: 960.6 (-0.175)  (within normal operating range)
  Channel 8 TX Light Output [µW (dBm)]: 882.6 (-0.542)  (within normal operating range)
  Channel 9 TX Light Output [µW (dBm)]: 937.5 (-0.280)  (within normal operating range)
  Channel 10 TX Light Output [µW (dBm)]: 970.5 (-0.130)  (within normal operating range)
  Channel 11 TX Light Output [µW (dBm)]: 824.2 (-0.840)  (within normal operating range)
  Internal 3.3 Vcc [V]: 3.2749  (within normal operating range)
  Internal 2.5 Vcc [V]: 2.4710  (within normal operating range)
  Internal Temperature [deg C]: 38.2  (within normal operating range)
```

Figure 22: Example of MiniPOD information captured by current CMX software and firmware.

5. NOTES

5.1. REQUIREMENTS

In order to test and monitor the performance and stability of the FOX, reading the transmitted optical power and the received optical power is necessary. This information should be accessible in the prototype LDSP and FEX boards as well for the transmitters and receivers of the final system.

The mapping and link speed of the connections needs to be finalized before the FOX design can start, including an agreement on the handling of the mappings on the A and C sides.

5.2. SCHEDULE

The schedule for design and construction of the FOX centers on the integration tests at CERN and the decision on the final fibre link speed. The schedule is shown below:

Demonstrator	PDR	Nov 2014
	Demonstrator design complete	May 2015
	Demonstrator assembly complete	Aug 2015
	Technology decision (link speed, mapping)	April 2016
Production FOX	Production readiness review	Nov 2016
	FOX ready to install	Jan 2018

The optical demonstrator will be designed and assembled in time for the integration testing in Fall 2015. The demonstrator will continue to be available for future tests at CERN as well as at institutions responsible for L1Calo Phase-I components.

APPENDIX A. OVERVIEW OF FIBRE OPTIC TECHNOLOGY, SIMPLIFIED AND APPLIED TO THE MINIPOD ENVIRONMENT.

APPENDIX A.A. OPTICAL FIBRE

An optical fibre is a long thin glass rod surrounded by a protective plastic coating. This glass rod is made of two concentric glass sections with different refraction coefficients: the inner part (the core) and an outer part (the cladding).

Optical fibres are used to carry light from a light source (transmitter) to a light detector (receiver). The light is injected into the core at one end of the fibre and travels down the length of the core, being guided by internal reflection at the boundary between core and cladding.

A MiniPOD transmitter uses a row of twelve Vertical-Cavity Surface Emitting Laser (VCSEL) and a MiniPOD receiver uses a row of twelve PIN diodes (the PIN acronym comes from the use of P-type, Intrinsic, and N-type semiconductor regions). A 12-fibre ribbon is plugged into the top of a MiniPOD using a PRIZM (trademarked) connector providing the 90 degree coupling between the twelve vertically emitting lasers or receiving PIN diodes and the horizontally-exiting 12-fibre flat ribbon cable.

The MiniPODs operate with infrared light at a wavelength of 850nm. The type of fibre used with the MiniPODs is called multimode fibre with a 50 micrometer core and 125 micrometer cladding. This wavelength and this type of fibre are suited for short range connections as it is cheaper and simplifies the source and connector requirements but suffers from higher attenuation and dispersion than the alternative, called single mode fibre, used in long range connections. This type of fibre is used for short range links in commercial networking equipment, and the same type of 12-fibre ribbons is used with 40 Gb and 100 Gb Ethernet equipment.

APPENDIX A.B. PROPAGATION SPEED

The typical index of refraction in the fibre core is around 1.5 which translates to a light propagation speed through a fibre being about 2/3 of the speed of light in a vacuum.

APPENDIX A.C. SERIAL ENCODING

Data transmission is performed by modulating the amount of light sent through the fibre. The data payload is first serialized into a stream of ones and zeroes.

For the receiving side of a serial link to always be able to decode the data stream, it must be able to remain time-synchronized with the sending side. This means that the sending side must guarantee that there are enough state changes over time within the transmitted signal. More specifically the serialized stream must avoid long sequences of repeating ones or repeating zeroes, and guarantee a minimum spacing between transitions from one to zero or vice versa. This allows the receiving side to recover the clock used by the sending side.

The user data could of course contain any sequence of zeroes or ones and must thus be re-encoded during that serialization process. This re-encoding is performed by breaking down the user data into segments and re-encoding each segment. The encoding format used by L1Calo is called 8b/10b where every byte (8 bits) is translated into 10 bits of serial data, while guaranteeing that there can never be more than five 0s or 1s in a row. The re-encoding also sets a limit on the difference between the average number of zeroes and ones over defined periods of time. This means that there is no accumulating DC-component in the data transmission which helps on the electrical side of the sending and receiving modules.

Another popular encoding format which is used in ethernet fibre networks is 64b/66b where 4 bytes are translated at a time with a resulting lower overhead but higher latency for the recovered data.

This 64b/66b encoding format is not deterministic with respect to DC-balance and minimum transition rate characteristics, and has other flaws preventing its use in L1Calo. At the link speeds considered (i.e. 6.4 and 9.6 Gbps), the number of bits transmitted per crossing (respectively 160 and 240 bits) is not a multiple of 66 (nor 64) and this mismatch would not allow flagging channel transmission errors at the desired granularity of one bunch tick. These two encoding formats are not compatible which means that we simply cannot use any commercial networking equipment that depends on a 64b/66b encoding format.

APPENDIX A.D. TRANSMITTED POWER

The amount of light emitted by a Laser is measured in units of dBm. This unit is related to the the

Decibel (dB). The decibel is a dimension-less logarithmic unit used to characterize the ratio of two quantities. The ratio of two power values expressed in dB is defined as

PowerRatio (dB) = 10 log (power1/power2)

The ratio of the power of the light entering a point on the fibre to the power exiting another point along the fibre is measured in dB. Given that photons can only get lost along the way, the ratio will be less than one and the logarithm will be negative, i.e. a negative number in dB units. The absolute value of this number is often used to refer to the power loss through the fibre.

For example, a loss of 5% corresponds to about -0.2 dB and a factor two loss to about -3 dB. Conversely an attenuation of -1dB corresponds to a 21% loss and -10dB to 90%.

To specify an absolute light power level instead of a power ratio, the measurement is simply referenced to a light power of 1 milliwatt (mW), and expressed as "dBm" with the definition:

AbsolutePower (dBm) = 10 log (Power/1 mW)

This means that a power level of 1 milliwatt is expressed as 0 dBm, 1 microwatt as -30 dBm, and 1 nanowatt as -60 dBm.

APPENDIX A.E. MODULATED POWER

The serially encoded data stream is used to modulate the light emitted by the transmitter (e.g. the laser from a MiniPOD transmitter). This is not a full modulation as the laser light cannot be completely extinguished when a zero is being transmitted. The depth of this modulation is called the Optical Modulation Amplitude (OMA)

For reference, the lasers used in the CMX card have a minimum average optical light power (Po AVE) of -7.6 dBm with a minimum OMA of -5.6 dB.

It is the light power in the OMA that transports the information of the data stream. The receiving side needs to receive enough average power to be detectable by the PIN diodes, but also enough modulated power to be able to detect and reconstruct the stream of encoded zeroes and ones.

APPENDIX A.F. POWER ATTENUATION

The light power is attenuated while travelling through the optical fibre and the connectors. Both the average and modulated light power suffer the same attenuation ratio. It is thus sufficient to measure one to know the other. It is easier to use a continuous test source and measure an average power loss sustained through some segment of light fibre path to obtain the modulated power loss through that same path.

Typical sources of attenuation (power loss) are:

- Absorption and scattering inside the fibre: this contribution is fairly small for the short lengths involved in FOX (~3dB/km).

- Connector: this will be an important contribution in the FOX system as we could have as many as seven connections added to MiniPOD to MiniPOD links. Estimates vary from a conservative calculation using a 0.5dB loss per connector to estimates representing typical connections or optimistic views being as low as 0.25 dB per connection. This is an important contribution that the optical demonstrator will help measure and understand for this particular application.
- Fusion splice: a fused splice is expected to give a loss in the range of 0.05 to 0.1dB
- Passive splitter: the amount of input light is split in two equal halves for an expected loss of about 3.5 dB through each branch.
- Dust: any contamination present at the end of a fibre in any of the connections will be translated into a power loss. Much care will need to be taken in the assembly, installation, and maintenance of the system. A particle of dust floating in the air and invisible to the naked eye can easily be as big as the diameter of the fibre core.

APPENDIX A.G. POWER BUDGET

The power budget for a particular communication link composed of a modulated light transmitter and light receiver is defined as the difference (expressed as a ratio in dB) between the minimum OMA power guaranteed to be emitted by the transmitter and the minimum OMA power guaranteed to be detectable by the receiver.

The power budget of a link describes the maximum amount of light attenuation through that link before communication may be lost due to insufficient OMA at the receiving end.

APPENDIX A.H. DISPERSION

Another factor affecting communication through a fibre link is a distortion of the signal by dispersion in the fibre. Several factors contribute to dispersion, including modal dispersion. Modal (or multimode) dispersion accounts for the existence of several possible paths with different lengths through the fibre core as the light may be entering the fibre at different angles and continue reflecting at the boundary between core and cladding at different angles. These different possible paths in a multimode fibre spread the width of a light pulse as it travels down the fibre. There are additional sources contributing to dispersion. Dispersion is sometimes included in power budget calculations as a transmission penalty specified by the manufacturer, i.e. expressed as an attenuation loss equivalence specified in dB.