ATLAS Level-1 Calorimeter Trigger

FOX (Fex Optics eXchange)

Project Specification

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Prepared by: Yuri Ermoline, Murrough Landon, Philippe Laurens, Reinhard Schwienhorst

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14

TABLE OF CONTENTS

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 Fiber Optics eXchange (FOX). Alternate names are “fiber 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.

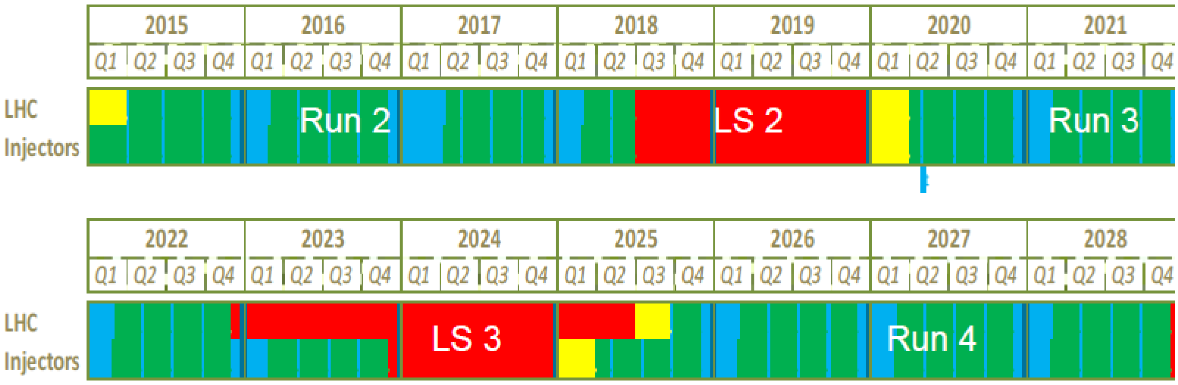


Figure 1: LHC Shutdown and Run Schedule.

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 1 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] L1Calo Phase-I gFEX Specification (not yet available) https://twiki.cern.ch/twiki/bin/view/Atlas/LevelOneCaloUpgradeModules

[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 fiber-optic exchange (FOX) that routes the optical signals via fibers 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 fiber 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-1 upgrade, and will operate during Run 3. Part of the FOX will be replaced in the Phase 2 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 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, fibers and splitters.

The input and output specification for the full Phase 1 L1Calo system is also detailed.

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

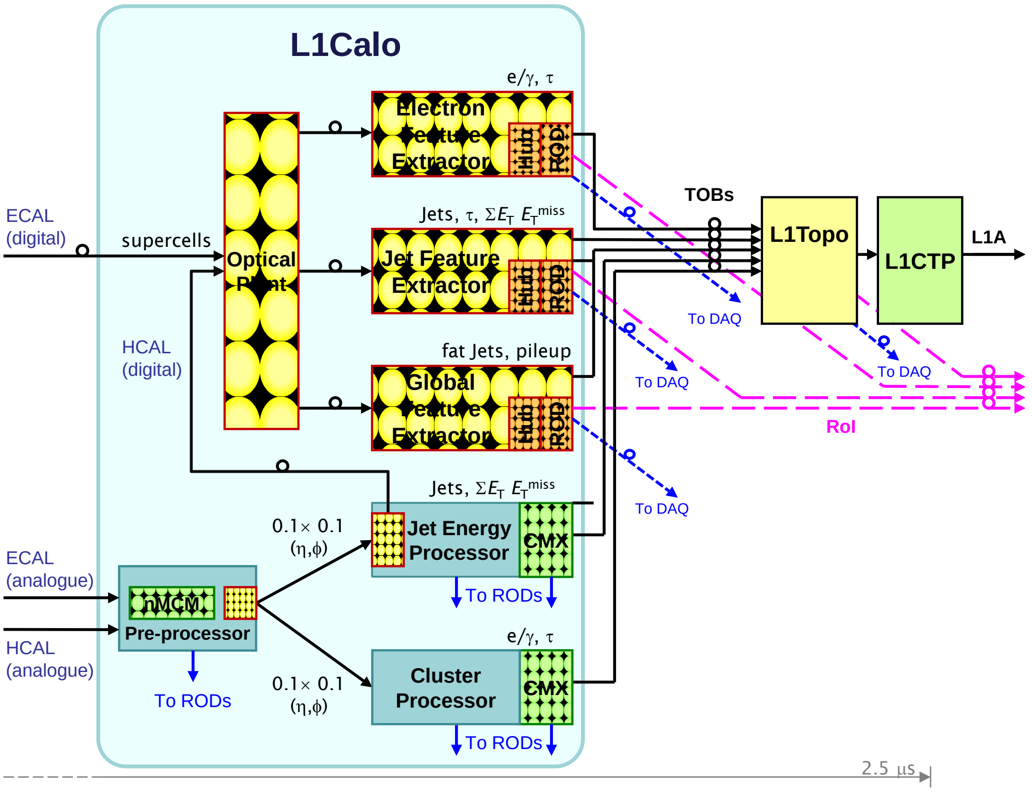


Figure 2: The L1Calo system in Run 3. ***Components installed during LS2 are shown in yellow/orange***

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

- the Pre-processor, which 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 jFEX modules, and Hub modules with ROD daughter cards. 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 fibers (for the FEX subsystems), see document [1.2] . From the hadronic calorimeters, only analogue signals are received (see document [1.3]). These are digitised on the Pre-processor, transmitted electrically to the JEP, and then transmitted optically to the FEX subsystems, see document [1.4] . Initially at least, the eFEX and jFEX subsystems will operate in parallel with the CP and JEP subsystems. Once the performance of the FEX subsystems has been validated, the CP subsystem will be removed, and the JEP used only to provide hadronic data to the FEX subsystems.

The optical signals from the JEP 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 fiber bundles, changing the mapping from that employed by the LDPS and JEP electronics to that required by the FEX subsystems. Second, it provides any additional fan-out 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. 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.

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 Pre-processor, 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.

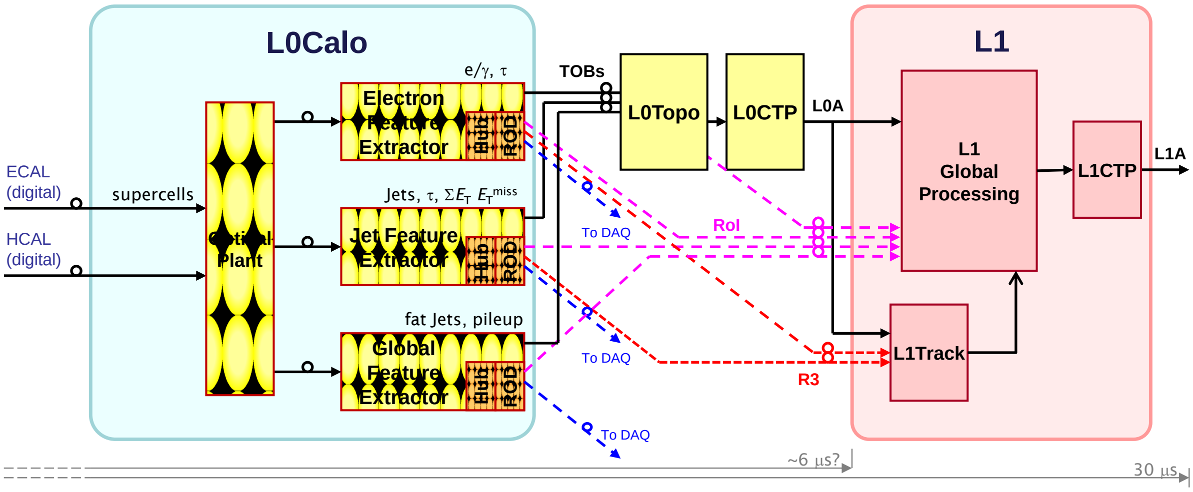


Figure 4: The L0/L1Calo system in Run 4. The new Level-1 system is shown in red and pink. Other modules (yellow /orange) are adapted from the previous system to form the new L0Calo.

1.4 FOX – OVERVIEW

The FOX system is an integral part of the L1Calo Phase 1 upgrade. Its primary function is to receive the signal fibers from the LAr and Tile calorimeters, to redistribute them to the individual FEX cards (mapping), as well as to duplicate certain signal fibers as required by the FEX algorithms. An overview of the FOX connectivity is shown in Figure 5.

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 fibers by destination. The three output module sets are eFox, jFox and gFox, which provide the final fiber ribbon by fiber ribbon mapping and provide fiber duplication as required. The LAr and JEP transmitters provide most of the signal duplication. Details about the fiber count and mapping are presented in Chapter **Error! Reference source not found.**.

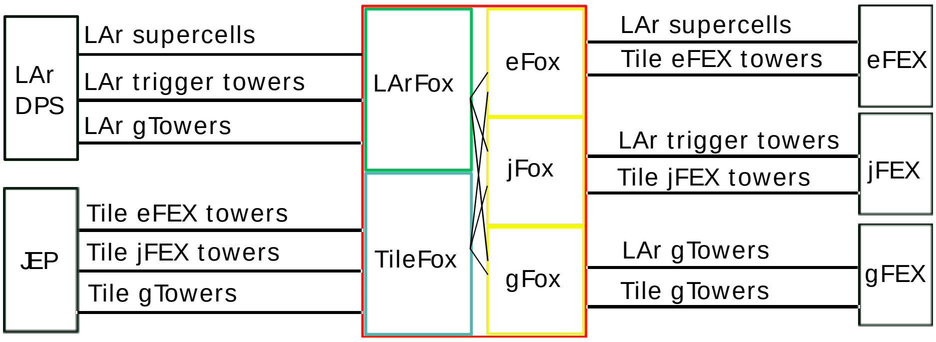


Figure 5: Overview of optical plant connections.

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 supercells 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 fibers which are organized into four ribbons of 12 fibers each. One of these fibers will contain gTower information, 4 to 8 will contain trigger tower information, 24 to 32 fibers will contain supercell information, and the rest are spares.

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

- 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 he 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.

Each eFEX module receives three cables of four ribbons with 12 fibers, i.e. the eFEX has three input connectors, each for 48 fibers [1.5] . Each jFEX module receives four cables of six ribbons with 12 fibers, i.e. the jFEX has four input connectors, each for 72 fibers [1.6] . The gFEX module also receives four cables of six ribbons with 12 fibers, i.e. the gFEX also has four input connectors, each for 72 fibers [1.7] .

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

1.5 FOX - FUNCTIONALITY

The FOX will map each of the input fibers to a specific FEX destination. It will also provide passive duplication (optical splitting) of some of the fibers, as required for corners and special regions. Signals arrive at the FOX via 48-fiber cables, organized as 4 ribbons of 12 fibers each. They arrive at the LArFOX or TileFOX, each a set of modules arranged by calorimeter geometry. The fiber cables plug into the FOX through a MPO connector. From the inputs, fibers are routed to a mapping module, which redistributes the signals to output connectors, which are multi-fiber MPO connectors with varying number of fibers. Short fiber-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 fibers to the appropriate output connector.

For fibers that require passive splitting, a fiber 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.

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.

1.7 SCHEDULE

The schedule for design and construction of the FOX centers on the integration tests at CERN and the decision on the final fiber 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

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 1 where the Tile towers will still be processed by the existing L1Calo preprocessor and for phase 2 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 LAr DPS 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 fibers 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 supercell to the LDPS. Each of those 10 supercells per tower needs to be sent to the eFEX. However the jFEX only needs the Et sum from all 10 supercells, ie one quantity per tower and the gFEX will receive just one Et sum from a 0.2*0.2 area of four trigger towers. Thus for the EM layer the bulk of the output fibers are sent to the eFEX.

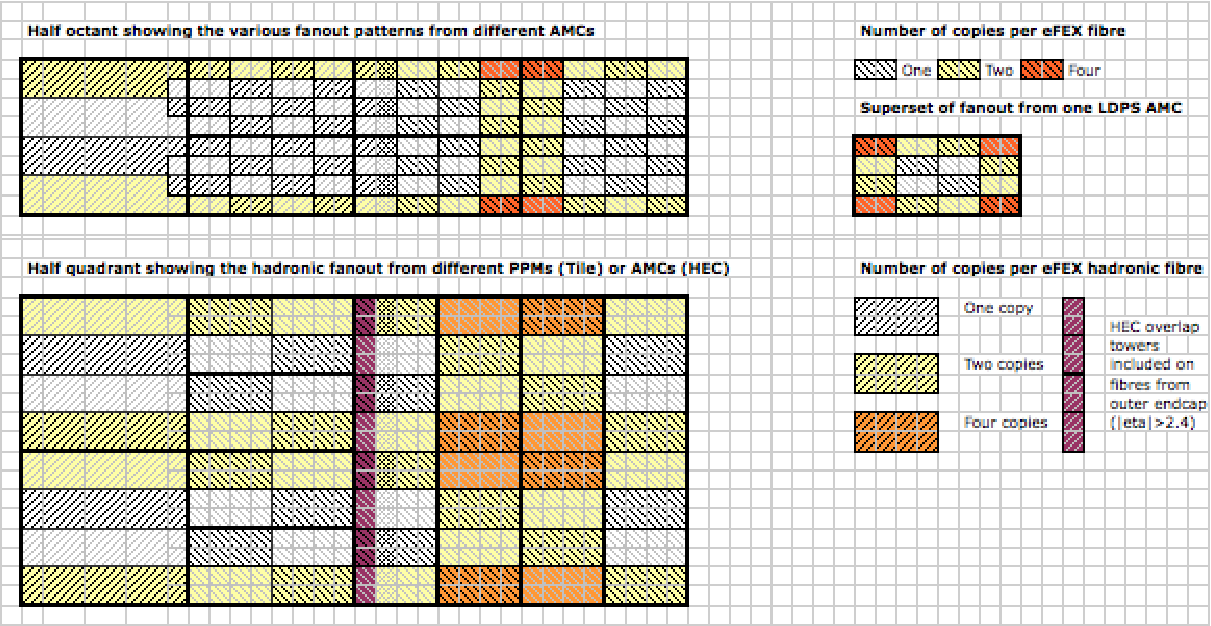


Figure 6: AMC fiber coverage and fanout requirements.

At the baseline link speed of 6.4 Gbit/s the intention is that each fiber to the eFEX will carry the 20 supercells from two adjacent towers in eta, ie each fiber will cover 0.2*0.1 in eta*phi. To provide a reasonable number of bits per supercell 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 fiber will still carry the same 20 supercells but there would be no need for the BCMUX scheme. In either case each AMC will have 16 different 0.2*0.1 fibers though the fanout requirements of the eFEX architecture mean that some of these fibers need to be sent with multiple copies at source.

For the jFEX each fiber 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 fibers 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 fibers per AMC in total. The gFEX only needs a single fiber from the whole 0.8*0.4 AMC area independent of the link speed.

The diagrams in Figure 6 indicate the coverage and fanout requirements (number of copies) of eFEX and jFEX fibers from each AMC and 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 fibers required from each AMC.

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

2.1.1.2 LArHEC

The granularity of the HEC is much lower than the EM calorimeter. Each input channel of the DPS 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 fiber the same as the jFEX fibers 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 fibers 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 fibers covering the forward region. The jFEX needs three copies and the overlap region is sent on separate fibers. 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 combine 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 1 (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 fibers covering 0.4*0.2 (at low speed) or 0.4*0.4 (at high speed). However the gFEX fibers will each cover 0.4*0.8 instead of 0.8*0.4 from the LDPS.

After the phase 2 upgrade (Run 4) the Tile front end electronics will be replaced and the FEXes will then receive the Tile towers from new Tile RODs. These will each cover 1.6*0.4 in eta*phi.

This change in geometry will switch the gFEX fibers 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 fiber counts

Table 1 shows the numbers of fibers from each part of the calorimeter at the baseline 6.4 Gbit/s link speed. It indicates those “direct” fibers needing no additional fanout and those which must be fanned out after the DPS 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 2 will have a more favourable geometry and all modules have the same number of output fibers.

Table 1: Number of fibers from each part of the calorimeter for a baseline link speed of 6.4Gbit/s.

Calo Region vs N.Fibers 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/ROD	*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	4	3?	2	2
Direct/AMC	38	33	8	19	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	2434	1056	432		108?	768	1408
Total fanouts	0	0	336		0	320	0
Total from AMCs	2434	1056	768		108?	1088	1408
Total to FEXes	2434	1056	1104		108?	1408	1408

FIXME ADD TABLE FOR HIGH SPEED LINKS

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 addition ring of towers taking the total coverage to 2.0*1.0 in the centre of the EM layer and rather larger at the endcaps. The coverage of each hadronic fiber 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 fibers is used to provide each 0.2*1.0 area in eta with 2 unused fibers per group. In the hadronic layer each full group of 12 fibers will cover 0.8*1.2 at the low link speed baseline, though the same area could in principle be covered by only six fibers in the high speed option but the alignment in phi may result in eight fibers 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.

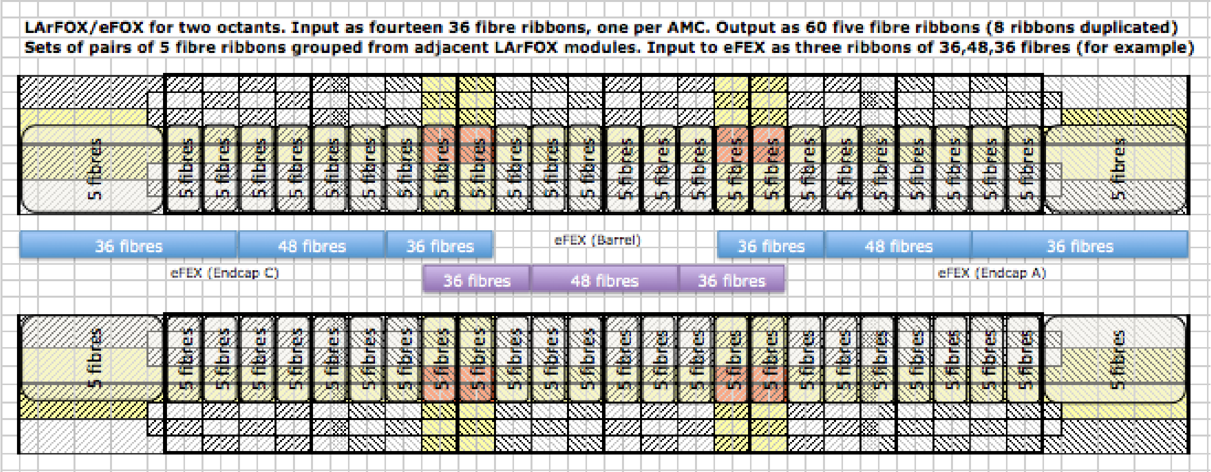


Figure 7: LArFOX fiber mapping to eFEX.

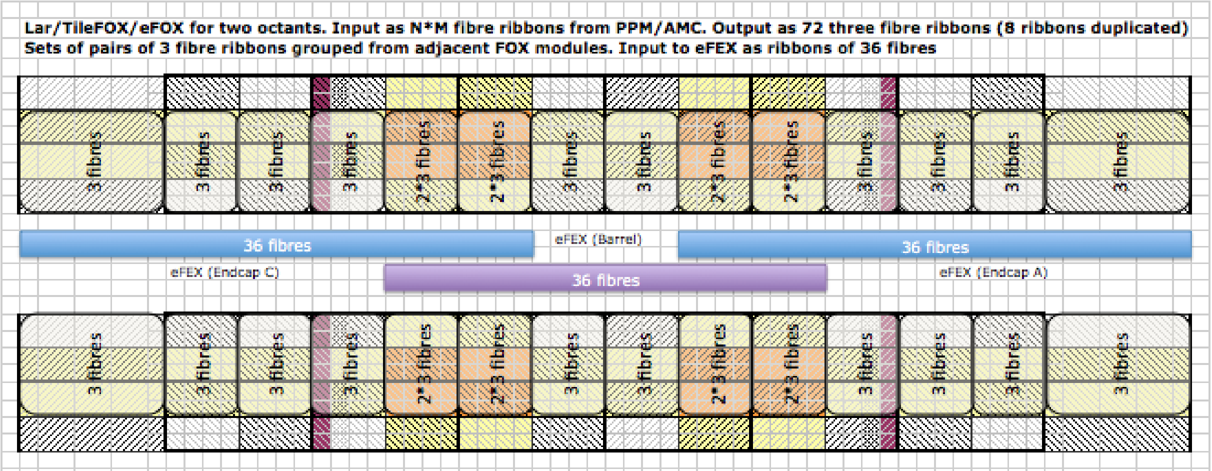


Figure 8: LArFOX and TileFOX fiber mapping.

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 fiber covers 0.2*0.4 in eta*phi (cf 0.4*0.2 for eFEX) and three copies of each fiber are required. This is the worst case for the mappings and use of HEC DPS outputs.

In particular to provide enough outputs from the suggested special crate DPS (forward EM + HEC) the fibers 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.

FIXME LAYOUT OF FIBERS TO BE DONE

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 fibers from each of the EM and hadronic layers. The challenge for the FOX is that these fibers must be collected one per AMC.

FIXME LAYOUT OF FIBERS TO BE DONE

2.3 OPEN QUESTIONS

This section has outlined the current ideas for mappings between the LAr DPS and the FEXes including the Tile outputs from PPMs in phase 1 or new Tile RODs in phase 2. 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 fibers 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

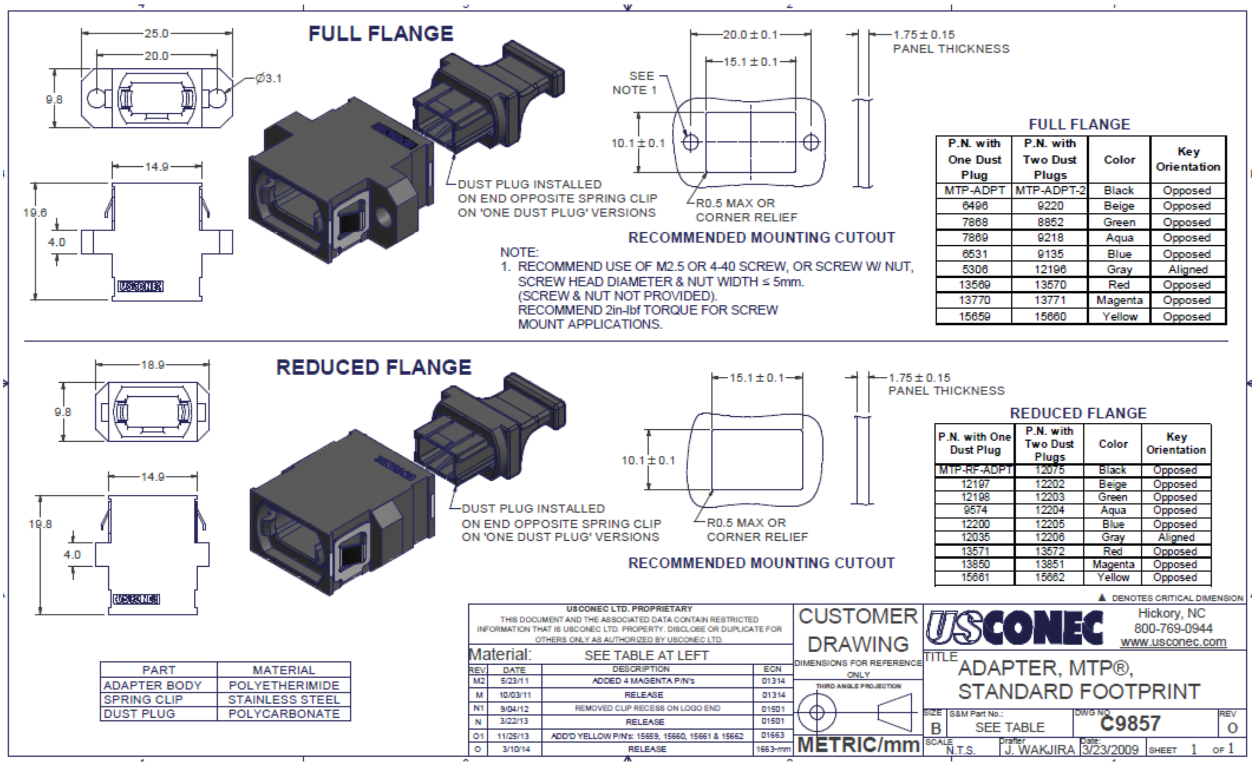
The FOX optical chain contain necessary components to connect, split (if needed) and map the optical outputs of calorimeter electronics (ECAL and HCAL) to the optical inputs of different FEX modules. The optical outputs and inputs connectors are parallel Multi-fiber Push-On/Pull-Off (MPO) connectors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

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

The outputs of the FOX are also 12 fibers MPO connectors. The eFEX module uses 48 fibers MPO connectors and the jFEX and the gFEX modules use 72 fibers MPO connectors. Therefore there may be the break-out cables (48 to 4x12 and 72 to 6x12 fibers) between the FOX output 12 fibers MPO connectors and FEX’es 48 and 72 fibers 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 fibers pressed together. The multiple fibers terminated at the MPO connector are arranged in rows of twelve fibers 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

TITLE ADAPTER, MTP®, STANDARD FOOTPRINT
SIZE B
S&M Part No.: SEE TABLE
DWG NO. C9857
REV O
SCALE N.T.S.
Drafter J. WAKJIRA
Date: 3/23/2009
SHEET 1 OF 1

Figure x: 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 fiber ribbons of 12 fibers will have female version of the MPO connector.

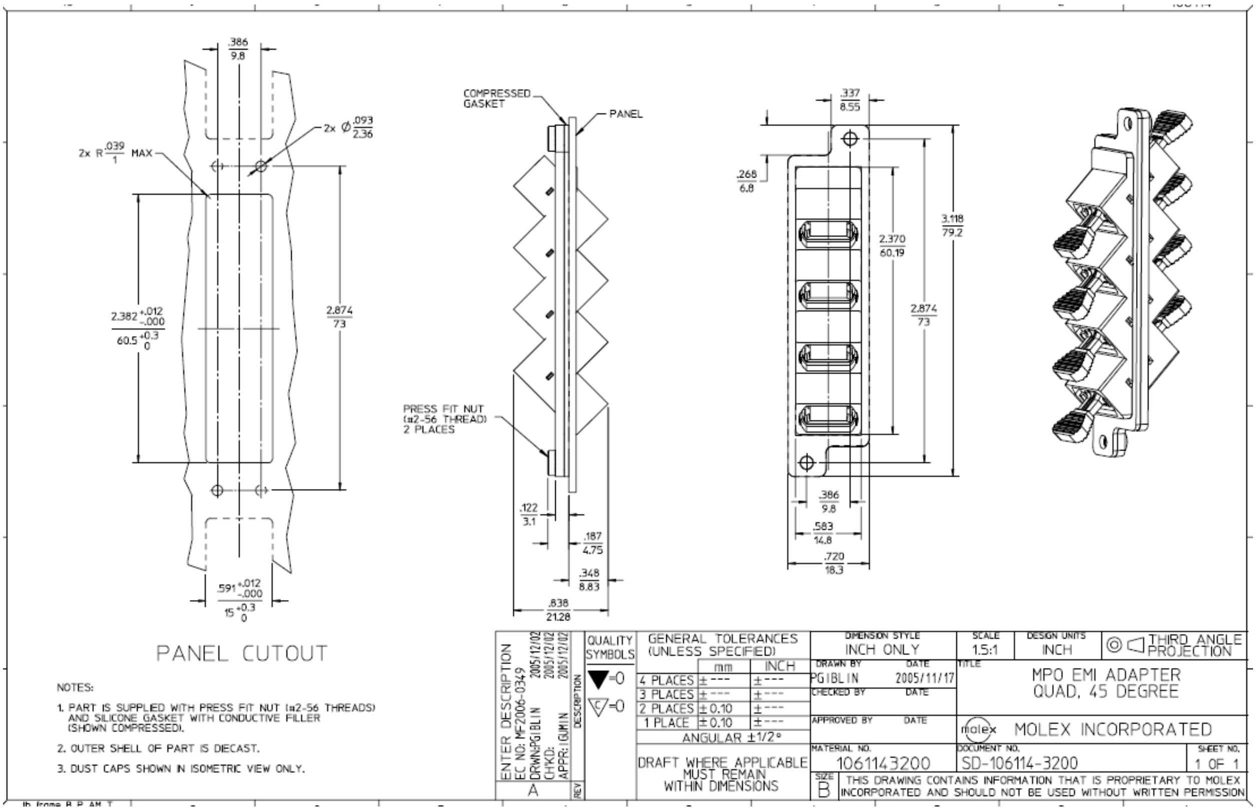


Figure x: Quad MPO/MPT adapters.

3.2 FIBERS MAPPING

3.2.1 Mapping at the input and output

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

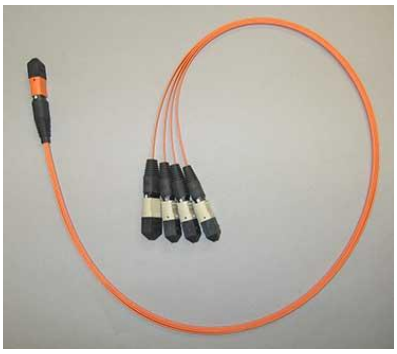


Figure x: 48 to 4x12 MPT custom cable assembly.

3.2.2 Mapping by connectors

The FOX will map each of the input fibers to a specific FEX destination. In order to achieve this, the input and output parallel fiber ribbons of 12 fibers break out in individual fibers with MPO harness cable, and then individual connectorized fibers are connected to each other using couplers:

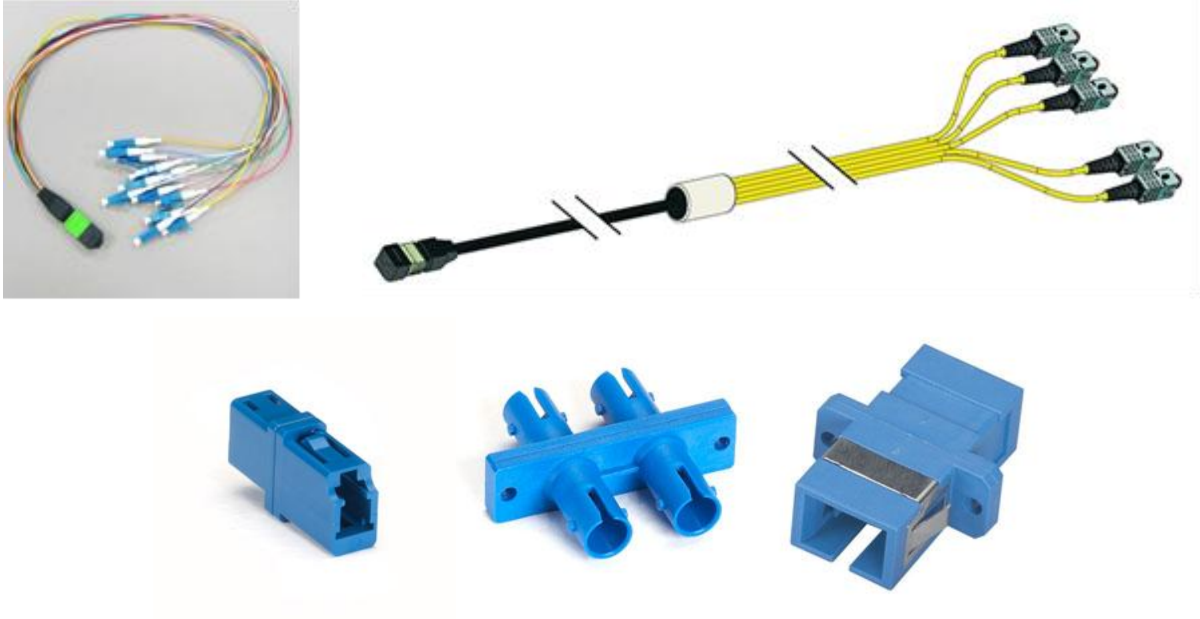


Figure x: MPO harness and connector couplers (LC, ST, SC).

This way of mapping is very flexible and allow 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 fibers by connectors and couplers, fusion splicing may be used. The splicing process includes stripping the fiber 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.

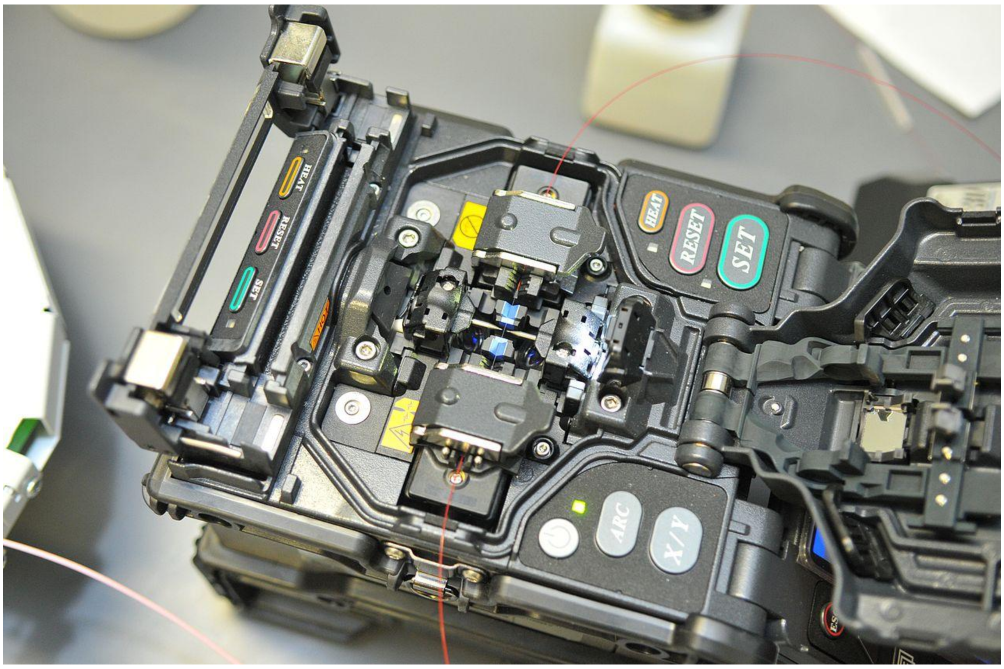


Figure x: Fusion splicing.

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.

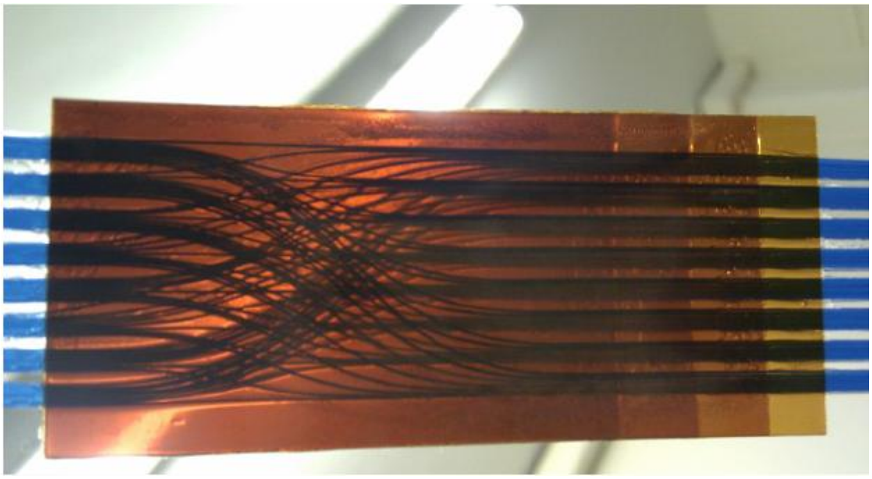


Figure x: Fiber mapping.

3.3 FIBER PASSIVE SPLITTING

For the fibers 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 fibers 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 below:

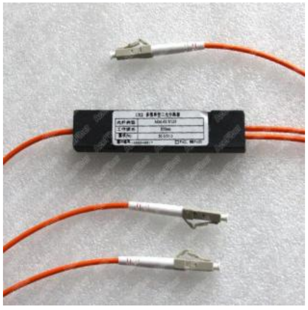


Figure x: Fiber passive splitter.

http://www.acefiber.com/1x2-lc-to-lc-splitter-50125-multimode-850-20mm-p-183067.html

1x2 LC to LC Splitter 50/125 Multimode 850 2.0mm - 1x2 LC/PC to LC/PC Splitter/Fiber Splitter/FBT Splitter/Coupler 50/125 Multimode Even split ratio, 2.0mm 1 m input, 1 m output, wavelength: 850 nm.

3.4 FIBER ACTIVE SPLITTING

For the fibers 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.

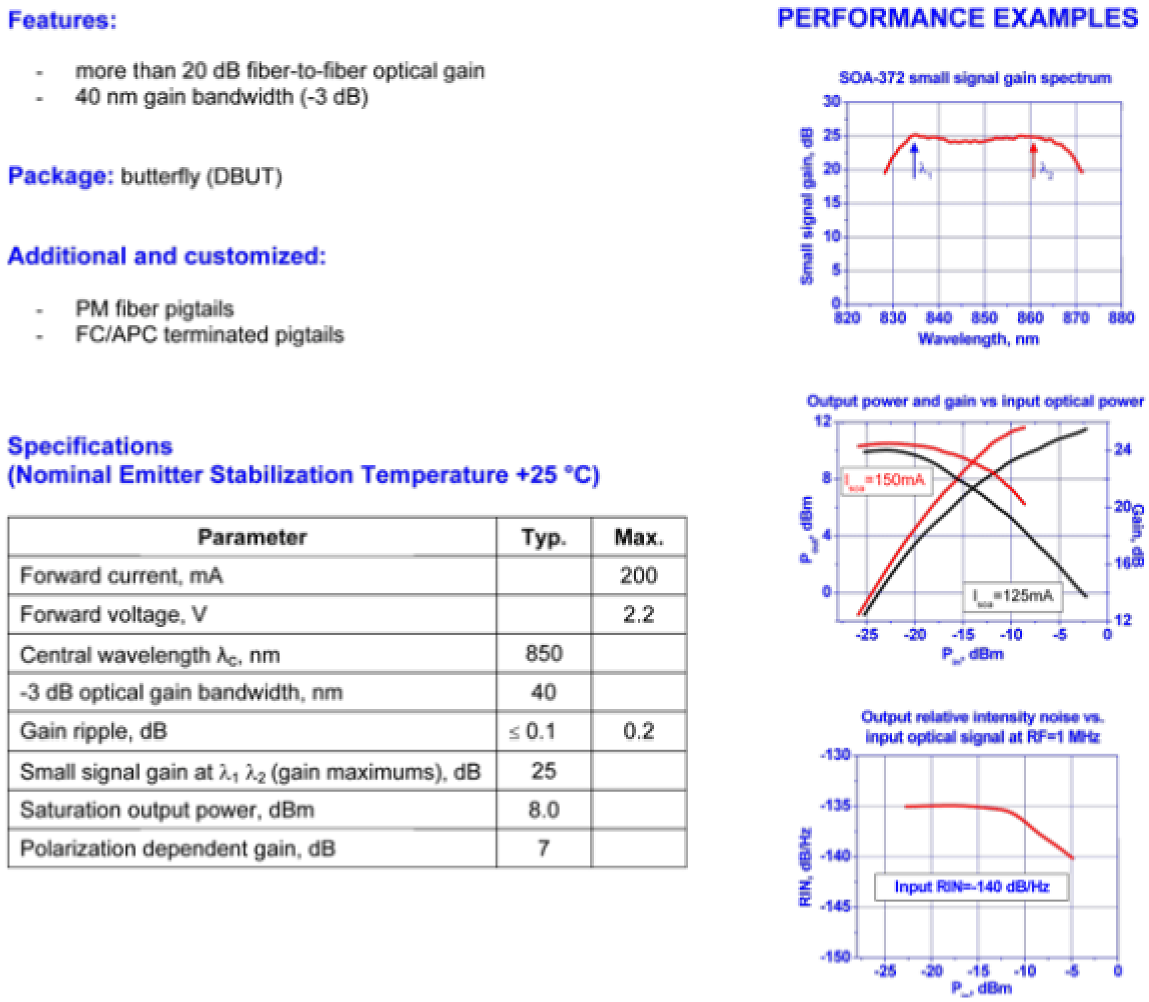
3.4.1 Electrical signal fan out at the source

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.

3.4.2 Optical amplification

The optical signal can be amplified before the passive splitters on order to rise 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: http://www.qphotonics.com/Semiconductor-optical-amplifier-850nm.html

- SUPERLUM Diodes
- Traveling-wave MQW design
- CW or pulsed operation
- PM or SM pigtails
- Low chip-to-fiber 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

The SOA has a fiber-to-fiber 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:

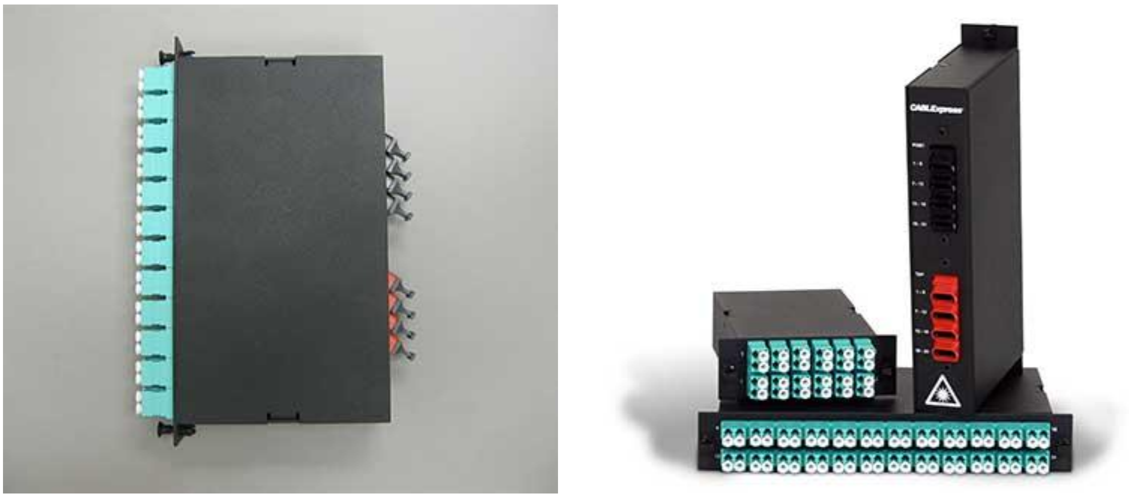


Figure x: LC to MTP Modules.

Figure x: 4U 192 Port / 384 Fiber 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 for all the input and output fibers of the FOX system.

4.1 DEMONSTRATOR GOALS

The demonstrator stage for the FOX system has two main goals. The first goal is the study of the light path between the transmitter miniPODs of the Liquid Argon or Tile Detector Front-Ends and the receiver miniPODs of the Feature Extractor modules of l1calo. The second goal is a study of the mechanical components required to build an overall physical plant providing the required management and mapping of all the fibers with its installation in USA15.

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

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-fiber MTP/MPO connector (detector side) and the output side as a 48-fiber (eFEX side) or 72-fiber MPO/MTP connector (jFEX and gFEX side).

It is expected that all the source, sink and intermediate components located upstream, downstream and within the FOX system all follow the convention that fiber patch cables have female MPO/MTP connector on both ends and that modules (Front-Ends, FEXs, FOX) have MPO/MTP connectors equipped with male alignment pins.

The type of fiber to be used in FOX is defined by two things: the miniPOD laser transmitters which are operating 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 multimode OM3 (or better) fibers with a 50 micron core and 125 micron cladding.

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

This test environment forms a convenient setup 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 pursued for the final FOX system. Any mechanical components used in this setup are chosen mainly for ease of testing and the 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 a measurement of the connection quality that is representative of that link and these source and sink.

The optical demonstrator must be transportable and usable with other prototypes as they become available at their home institution or at CERN when appropriate.

4.2.2 Mechanical Demonstrator

This is the set of test assemblies used to evaluate and choose the combination of commercial (or custom made where necessary) mechanical components appropriate to build the full FOX system. An important and pressing outcome from the demonstrator phase 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 in advance.

As shown in Figure 5 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 support the required fiber 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 can be explored if rack space in USA15 becomes a limitation but such measuer 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 phase 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.

A few channels of this final form of the mechanical demonstrator will be equipped with a representative set of the optical components that were separately qualified with the optical demonstrator for a demonstration of their mechanical integration.

4.3 EXPLORATIVE STUDIES

Two additional technologies are also explored and evaluated as options or backup solutions, especially for the case simple passive splitters are determined not to be sufficient.

4.3.1 Fiber fusing

Connecting two segments of optical fibers is most simply done through optical connectors on each end of the fibers (e.g. LC or SC connectors for individual fibers) 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. The light power loss depends on several factors including the cleanliness of the polished faces and the fine alignment of the two fiber 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.

Commercial equipment can also be purchased to fuse fibers 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 predictable at about 0.1 dB.

The information available about fiber fusers describes a fairly slow but straightforward process. The operator must cut, strip and prepare two clean bare fiber 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 fibers which can easily penetrate the skin and the operator must be attentive to the safe disposal of all fiber scraps.

One downside in fusing fibers in the FOX system is in the loss of modularity and flexibility. How desirable a saving of about one dB will be to the 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 process 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. This 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 fiber fusing will be used, this explorative study is meant to prepare for such possibility.

4.3.2 Light amplification

It is expected that channel splitting will be required in some channels of the FOX system. It is expected that only one-to-two light splitting will be required and that passive light splitters will be sufficient in all cases. There is however yet no certainty that this will be the case, and should one-to-four channel splitting be required, it is already clear that passive splitting would not be sufficient. The FOX system would need to use active splitting (i.e. with light amplification or signal regeneration) would be required.

This explorative study is a continuation of the effort already started in surveying what solutions might be commercially available.

850 nm multimode communications at 10 Gbps happens to also be one of the technologies used for short range connections in Ethernet communication. Ethernet fiber link duplication also happens to be important in certain Ethernet switching contexts. It 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 more fatal problem was identified after pursuing the specification details with one vendor related to the encoding of the data stream, namely that l1calo uses 8b/10b encoding which incompatible with the 64b/66b encoding used in the optical Ethernet protocol. Proprietary firmware would need to be modified while no clear path forward was proposed from that particular vendor.

Discrete components for light amplification at 850 nm should also be explored and more importantly tested 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 is found to be practical in the context of a FOX system, it can be tested with the optical demonstrator 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 fiber. The tester is first calibrated (zeroed) using two fixed fibers before inserting the section of light path to be measured. The additional power loss detected 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 however no different than the power loss for the modulated power. This insertion loss measurement is also the quantity to be used in modulated power budget calculations.

Insertion loss measurements are the main quantitative measurement used to compare different components to be evaluated with the optical demonstrator. The 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 fiber. This is the optical equivalent to an electronic time domain reflectometer. An OTDR injects a series of optical pulses into one end of the fiber under test and detects the light reflected by any discontinuity (a step loss) or glass media scattering (a propagation loss) within the fiber. The time delay of the reflection is converted and displayed as a distance into the fiber. Unlike the power meter method which needs physical access to both ends of the fiber 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 connections (hundreds or thousands of meters or even tens of kilometers of single mode fiber) 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 FOX system.

4.4.3 Bit error rate 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 fiber and a detector receiving this signal at the other end of the fiber. The BERT simply consists in the bit level comparison of the recovered data pattern to the known input pattern and the counting of the number of mistakes.

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 in the overall 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 form the link quality measurements for the evaluation of individual channels in 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 fiber. This type of tool could be useful for optimizint 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 are not within the control of the FOX system. 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 channel quality measurement while bit-error tests will also be used to show proper operation.

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 fiber patch cables and components with and 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 both 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 will 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 perform differently than channels without light splitting.

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

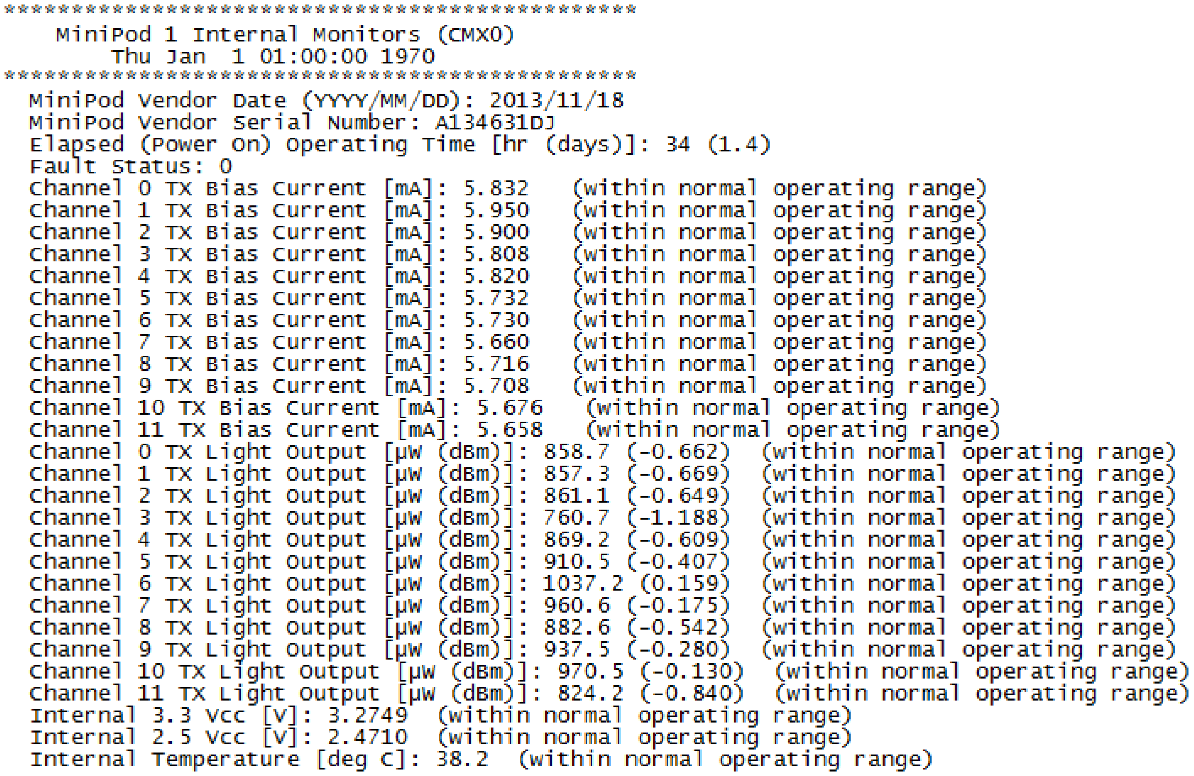
4.5.3 MiniPOD Light Level Monitoring

Transmitter and receiver miniPODs host a number of internal registers accessible through a Two Wire Serial interface (TWS). These control and status registers include monitoring information about the amount of light measured by the device itself to be either transmitted or received. These internal measurements are specified with a rather fine granularity of 0.1microW (-30 dBm) but with a tolerance of only +/- 3 dB. This coarse tolerance prevents using these monitoring values as a direct quantitative measurement. During CMX production module testing the values returned have been found to be stable over repeating queries (an example of the data currently retrieved is shown in Figure 9 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 could 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 a problem.

More than optical power could 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.

How much a systematic and system-wide collection of such monitoring information would be valuable over time to ATLAS is not clear. Access to the information from all MiniPODs would first need to be designed into the hardware and firmware of all the Phase I modules installed in USA15 and the DCS system would need to plan for the collection and low rate recording of this data.



```
***********************************************
    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 9: example of MiniPOD information captured by current CMX software and firmware.