



# ATLAS Level-1 Calorimeter Trigger FOX (Fex Optics eXchange)

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## Project Specification

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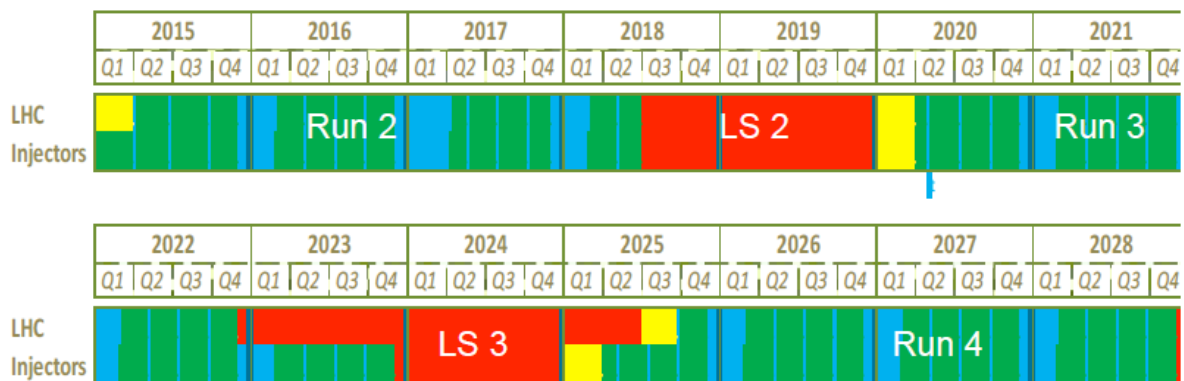
74 **1. INTRODUCTION**

75 **1.1. CONVENTIONS**

76 The following conventions are used in this document:

- 77 • The term “FOX” is used to refer to the Phase-I L1Calo Optical Plant – Fex Optics eXchange or  
78 Fiber Optics eXchange (FOX). Alternate names are “fiber plant” or “optical plant” or “FEX  
79 optical plant”.
- 80 • eFEX – electron Feature EXtractor.
- 81 • jFEX – jet Feature EXtractor.
- 82 • gFEX – global Feature EXtractor.

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



85 **Figure 1: LHC Shutdown and Run Schedule.**

86

87 **1.2. RELATED PROJECTS**

- 88 [1.1] ATLAS TDAQ System Phase-I Upgrade Technical Design Report, CERN-LHCC-2013-018,  
89 <http://cds.cern.ch/record/1602235>
- 90 [1.2] ATLAS Liquid Argon Phase 1 Technical Design Report, CERN-LHCC-2013-017,  
91 <https://cds.cern.ch/record/1602230>
- 92 [1.3] ATLAS Tile Calorimeter, [http://atlas.web.cern.ch/Atlas/SUB\\_DETECTORS/TILE/](http://atlas.web.cern.ch/Atlas/SUB_DETECTORS/TILE/)
- 93 [1.4] ATLAS L1Calo Jet-PPM LCD Daughterboard (nLCD)
- 94 [1.5] Electromagnetic Feature Extractor (eFEX) Prototype (v0.2), 6 February 2014,  
95 [https://twiki.cern.ch/twiki/pub/Atlas/LevelOneCaloUpgradeModules/eFEX\\_spec\\_v0.2.pdf](https://twiki.cern.ch/twiki/pub/Atlas/LevelOneCaloUpgradeModules/eFEX_spec_v0.2.pdf)
- 96 [1.6] Jet Feature Extractor (jFEX) Prototype (v0.2), 14 July 2014,  
97 [http://www.staff.uni-mainz.de/rave/jFEX\\_PDR/jFEX\\_spec\\_v0.2.pdf](http://www.staff.uni-mainz.de/rave/jFEX_PDR/jFEX_spec_v0.2.pdf)
- 98 [1.7] Global Feature Extractor (gFEX) Prototype (v0.3), 16 October 2014,  
99 <https://edms.cern.ch/file/1425502/1/gFEX.pdf>
- 100 [1.8] High-Speed Demonstrator (v1.5), 18 July 2011,  
101 <https://twiki.cern.ch/twiki/bin/view/Atlas/LevelOneCaloUpgradeModules>
- 102 [1.9] FEX Test Module (FTM) (v0.0), 18 July 2014,  
103 [http://epweb2.ph.bham.ac.uk/user/staley/ATLAS\\_Phase1/FTM\\_Spec.pdf](http://epweb2.ph.bham.ac.uk/user/staley/ATLAS_Phase1/FTM_Spec.pdf)

104 **1.3. L1CALO TRIGGER PHASE-I UPGRADE**

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

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

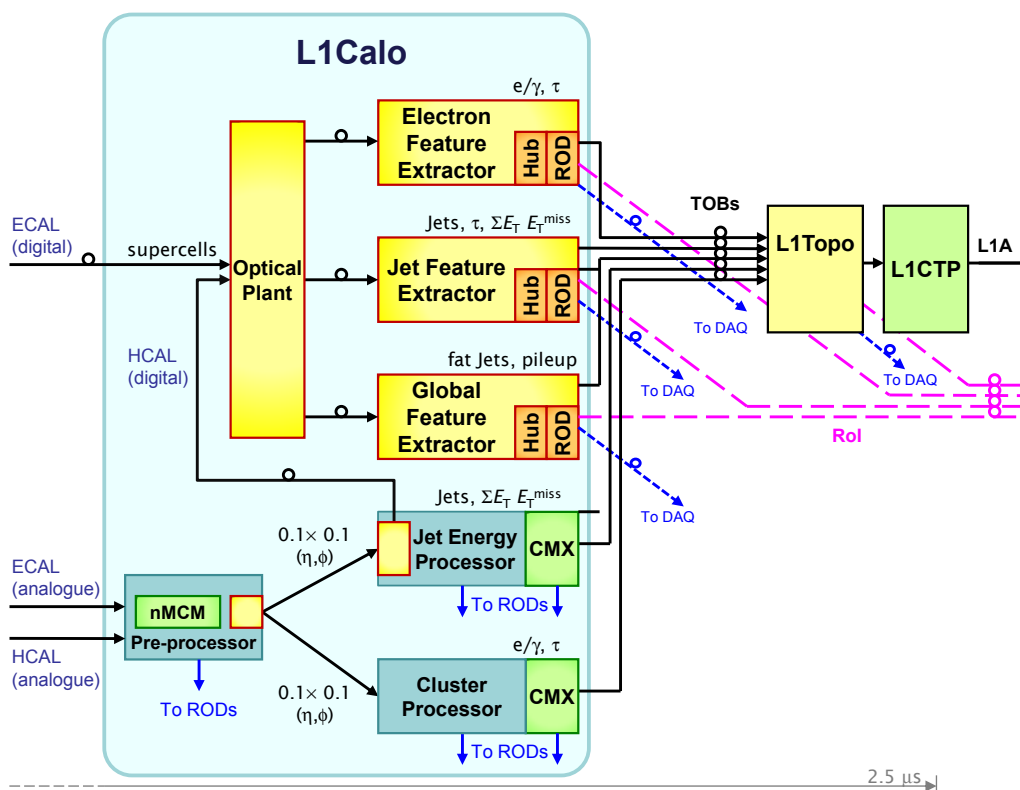
116 This document is the specifications of the FOX inputs and outputs, as well as of the prototype FOX,  
 117 the demonstrator, which will be used for optical transmission tests and for integration testing together  
 118 with other modules at CERN. The demonstrator is intended to exhibit the transmission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

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

### 122 1.3.1. Overview of the L1Calo System in Phase-I (Run 3)

123 In Run 3, L1Calo contains three subsystems that are already installed prior to LS2, as shown in Figure  
 124 2 (see document [1.1]):

125



126

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

128

- 129 • the Pre-processor, which receives shaped analogue pulses from the ATLAS calorimeters, digitises  
 130 and synchronises them, identifies the bunch-crossing from which each pulse originated, scales the

131 digital values to yield transverse energy ( $E_T$ ), and prepares and transmits the data to the following  
132 processor stages;

- 133 • the Cluster Processor (CP) subsystem (comprising Cluster Processing Modules (CPMs) and
- 134 Common Merger Extended Modules (CMXs)) which identifies isolated  $e/\gamma$  and  $\tau$  candidates;
- 135 • the Jet/Energy Processor (JEP) subsystem (comprising Jet-Energy Modules (JEMs) and Common
- 136 Merger Extended Modules (CMXs)) which identifies energetic jets and computes various local
- 137 energy sums.

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

- 140 • the electromagnetic Feature Extractor eFEX subsystem, documented in [1.5] , comprising eFEX
- 141 modules and FEX-Hub modules, the latter carrying Readout Driver (ROD) daughter cards. The
- 142 eFEX subsystem identifies isolated  $e/\gamma$  and  $\tau$  candidates, using data of finer granularity than is
- 143 available to the CP subsystem;
- 144 • the jet Feature Extractor (jFEX) subsystem, documented in [1.6] , comprising jFEX modules, and
- 145 Hub modules with ROD daughter cards. The jFEX subsystem identifies energetic jets and
- 146 computes various local energy sums, using data of finer granularity than that available to the JEP
- 147 subsystem.
- 148 • the global Feature Extractor (gFEX) subsystem, documented in [1.7] , comprising jFEX modules,
- 149 and Hub modules with ROD daughter cards. The gFEX subsystem identifies calorimeter trigger
- 150 features requiring the complete calorimeter data.

151 In Run 3, the Liquid Argon Calorimeter provides L1Calo both with analogue signals (for the CP and  
152 JEP subsystems) and with digitised data via optical fibers (for the FEX subsystems), see document  
153 [1.2] . From the hadronic calorimeters, only analogue signals are received (see document [1.3] ). These  
154 are either digitised on the Pre-processor, transmitted electrically to the JEP, and then transmitted  
155 optically to the FEX subsystems, or converted to optical signals on a Pre-processor daughter board,  
156 see document [1.4] . Initially at least, the eFEX and jFEX subsystems will operate in parallel with the  
157 CP and JEP subsystems. Once the performance of the FEX subsystems has been validated, the CP  
158 subsystem will be removed, and the JEP will be either used only to provide hadronic data to the FEX  
159 subsystems or it will also be removed.

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

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

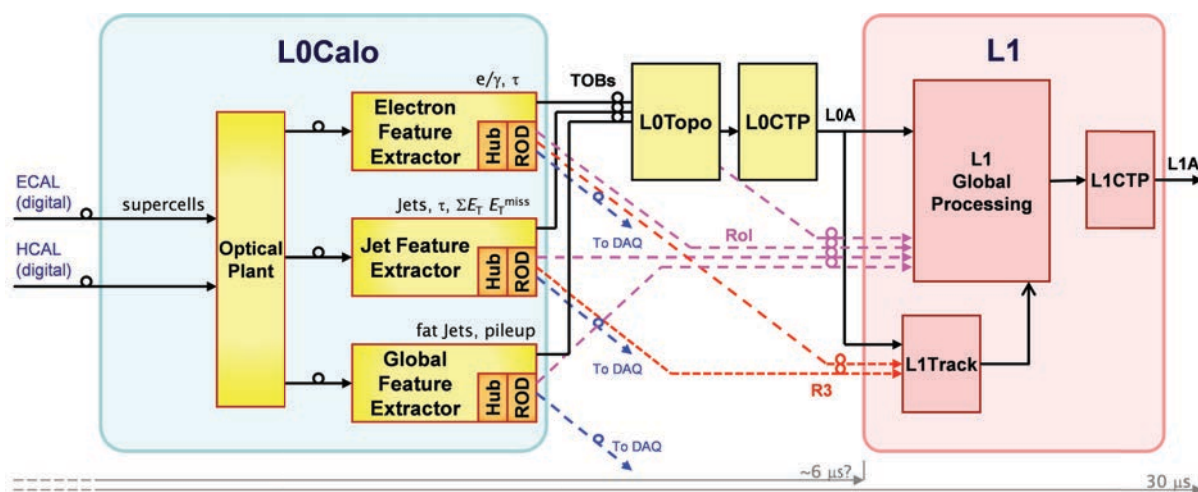
170 The eFEX, jFEX, gFEX and L1Topo subsystems comply with the ATCA standard. The eFEX  
171 subsystem comprises two shelves each of 12 eFEX modules. The jFEX subsystem comprises a single  
172 ATCA shelf holding 7 jFEX modules. The gFEX subsystem comprises a single ATCA shelf holding a  
173 single gFEX module. The L1Topo subsystem comprises a single ATCA shelf housing up to four  
174 L1Topo modules, each of which receives a copy of all data from all FEX modules. All L1Calo  
175 processing modules produce Region of Interest (RoI) and DAQ readout on receipt of a Level-1 Accept  
176 signal from the CTP. RoI information is sent both to the High-Level Trigger (HLT) and the DAQ  
177 system, while the DAQ data goes only to the DAQ system. In the FEX and L1Topo subsystems, these  
178 data are transmitted by each FEX or L1Topo module via the shelf backplane to two Hub modules  
179 (with the gFEX a possible exception). Each of these buffers the data and passes a copy to their ROD  
180 daughter board. The RODs perform the processing needed to select and transmit the RoI and DAQ

181 data in the appropriate formats; it is likely that the required tasks will be partitioned between the two  
182 RODs. Additionally, the Hub modules provide distribution and switching of the TTC signals and  
183 control and monitoring networks.

184 **1.3.2. Overview of the L1Calo System in Phase-II (Run 4)**

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

196



197

198 **Figure 3: The L0/L1Calo system in Run 4. The new Level-1 system is shown in red and pink. Other**  
199 **modules (yellow /orange) are adapted from the previous system to form the new L0Calo.**

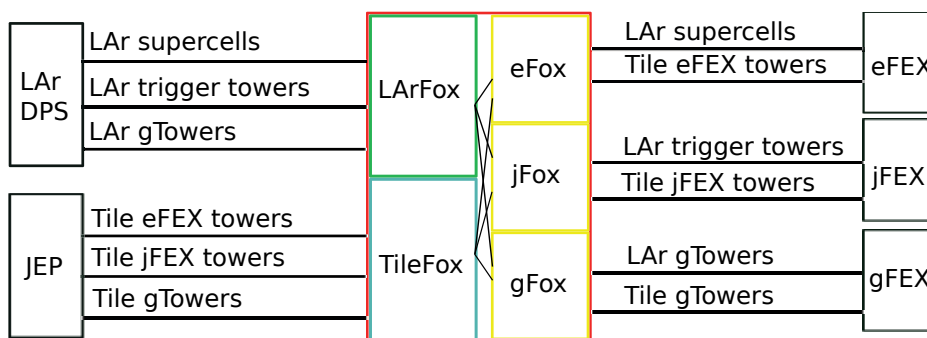
200

201 **1.4. FOX – OVERVIEW**

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

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





211

212

**Figure 4: Overview of optical plant connections.**

213

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

- 216 • LAr supercells, with fine-grained electromagnetic calorimeter information. Each calorimeter  
217 trigger tower of size  $0.1 \times 0.1$  in  $\eta \times \phi$  is subdivided into ten supercells in order to be able to  
218 create better isolation variables for electrons, photons and taus.
- 219 • LAr jet trigger towers, with a granularity of  $0.1 \times 0.1$  in  $\eta \times \phi$ .
- 220 • LAr gTowers, with granularity of  $0.2 \times 0.2$  in  $\eta \times \phi$ .

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

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

- 225 • Tile trigger towers with a granularity of  $0.1 \times 0.1$  for the eFEX.
- 226 • Tile trigger towers with a granularity of  $0.1 \times 0.1$  for the jFEX. These might contain the same  
227 information as the eFEX trigger towers, but don't necessarily have to.
- 228 • Tile gTowers with a granularity of  $0.2 \times 0.2$  for the gFEX.

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

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

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

239

## 240 1.5. FOX - FUNCTIONALITY

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

246 which redistributes the signals to output connectors, which are multi-fiber MPO connectors with  
247 varying number of fibers. Short fiber-optic patch cables connect these input modules to the output  
248 modules. Each of the eFOX, jFOX and gFOX contain output modules. In the eFOX and jFOX case,  
249 each module provides mapping and passive optical splitting. The gFOX simply routes fibers to the  
250 appropriate output connector.

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

254

## 255 **1.6. FUTURE USE CASES**

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

260

261

## 262 **2. FOX INPUT AND OUTPUT SPECIFICATION**

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

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

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

272

### 273 **2.1. TRANSMITTERS (FOX INPUTS)**

#### 274 **2.1.1. LAr DPS transmitters**

275 The trigger information from the entire LAr calorimeter to the three FEX systems will be sent by the  
276 LAr Digital Processor System (LDPS). The LDPS is a set of about 30 ATCA modules called LAr  
277 Digital Processor Blades (LDPBs) housed in three ATCA shelves (crates). Each LDPB acts as a  
278 carrier board for four mezzanine cards (AMCs) each of which has a single FPGA with 48 output  
279 optical links providing data to the FEXes. There are therefore 192 output fibers per LDPB and over  
280 5500 from the whole LDPS system.

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

##### 284 **2.1.1.1. LAr EM**

285 Over most of the EM calorimeter every  $0.1*0.1$  trigger tower will send one presampler, four front  
286 layer, four middle layer and one back layer supercell to the LDPS. Each of those 10 supercells per  
287 tower needs to be sent to the eFEX. However the jFEX only needs the Et sum from all 10 supercells,  
288 ie one quantity per tower and the gFEX will receive just one Et sum from a  $0.2*0.2$  area of four trigger  
289 towers. Thus for the EM layer the bulk of the output fibers are sent to the eFEX.

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

297 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  
298 towers from a  $0.4*0.4$  area at the higher link speeds. This mapping implies four or two separate fibers  
299 with low or high speed links. However the jFEX fanout requirements may change with the link speed,  
300 needing a minimum of two copies at low links speed but three copies at the higher link speed making  
301 eight or six output fibers per AMC in total. The gFEX only needs a single fiber from the whole  
302  $0.8*0.4$  AMC area independent of the link speed.

303 The diagrams in Figure 5 indicate the coverage and fanout requirements (number of copies) of eFEX  
304 and jFEX fibers from each AMC at low and high link speeds. The jFEX requirements are uniform  
305 across the AMC but change with link speed whereas the eFEX requirements are independent of link  
306 speed but are more complex with additional copies required at the edges and corners. The eFEX  
307 fanout pattern also varies with the  $\eta$  and  $\phi$  location of the AMC both in the central region and in

308 the outer endcaps. However there is a single superset pattern that covers all possible locations. This  
 309 would allow a single firmware version in the AMC with the FOX connecting only those fibers  
 310 required from each AMC.

311



312

313

**Figure 5: AMC fiber coverage and eFEX fanout requirements at 6.4 Gbit/s.**

314

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

317 **2.1.1.2. LAr HEC**

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

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

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

335 **2.1.1.3. LAr FCAL**

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

339 **2.1.2. Tile transmitters**

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

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

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

349 **2.1.3. Summary of fiber counts**

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

359 Table 2 shows the same fiber counts for the higher link speed options. The counts are the same for the  
360 eFEX EM layer and gFEX fibers, but the eFEX hadronic layer and all jFEX fibers are halved as each  
361 fiber carries twice the number of towers. At 10 Gbit/s there is no need for any passive optical splitting.  
362 Part of the optimisation to achieve this involves shifting the coverage of each eFEX module by 0.2 in  
363  $\phi$  which means that, unlike the baseline option, alternate Tile sRODs need to provide additional  
364 fibers, though still fewer than at 6.4 Gbit/s. The sROD will need to have three minipods for output to  
365 L1Calo.

366

367 **Table 1: Number of fibers from each part of the calorimeter for a baseline link speed of 6.4**  
368 **Gbit/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			
<i>N.AMC/PPM/ROD</i>	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	2434	1056	416		108	768	1408
Total fanouts	0	0	336		0	320	0

Total from AMCs	2434	1056	752	108	1088	1408
Total to FEXes	2434	1056	1088	108	1408	1408

369

370 **Table 2: Number of fibers from each part of the calorimeter for a baseline link speed of ~10**  
371 **Gbit/s.**

372

Calo Region vs N.Fibers to FEXes at ~10 Gbit/s	EM Barrel	EM Endcap	Special Crate		FCAL	Tile (PPM) min/max	Tile (sROD) min/max
			EM Fwd	HEC			
<i>N.AMC/PPM/ROD</i>	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	2434	1056	720		76	736	736
Total fanouts	0	0	0		0	0	0
Total from AMCs	2434	1056	0		76	736	736
Total to FEXes	2434	1056	720		76	736	736

373

374

375 **2.2. RECEIVERS (FOX OUTPUTS)**

376 **2.2.1. eFEX**

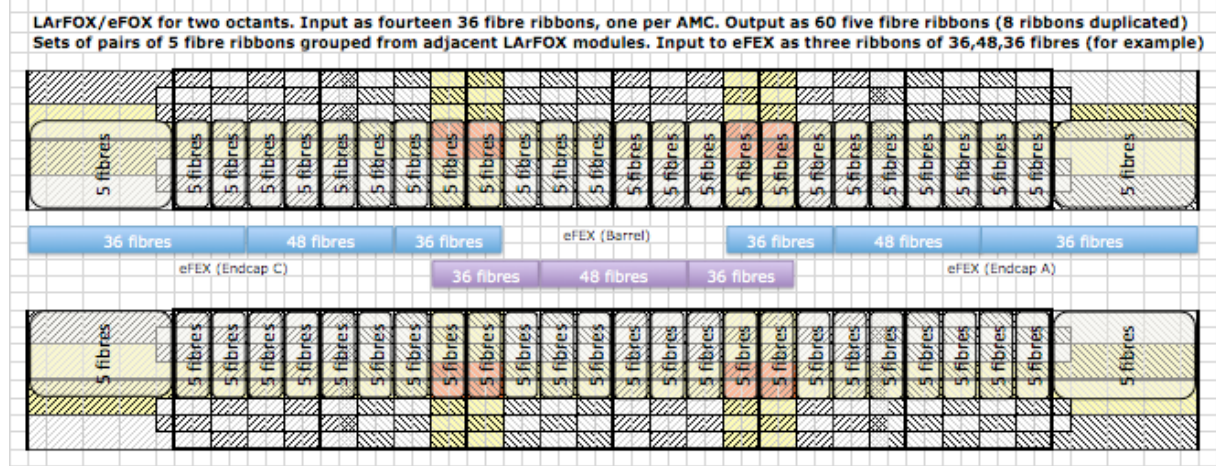
377 Each eFEX module handles a core area of roughly 1.6\*0.8 in eta\*phi but the trigger algorithms require  
378 an addition ring of towers taking the total coverage to 2.0\*1.0 in the centre of the EM layer and rather  
379 larger at the endcaps. The coverage of each hadronic fiber does not neatly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

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

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

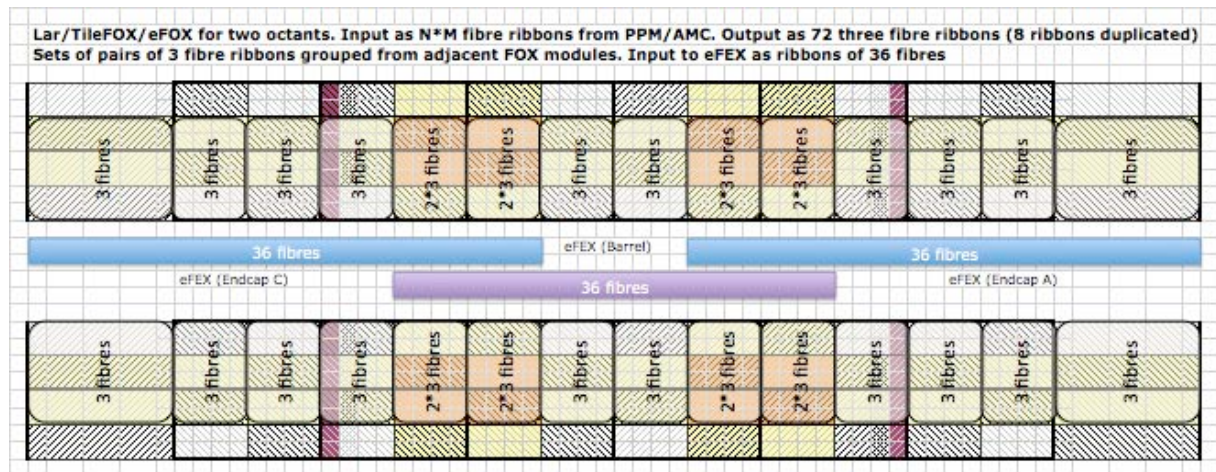
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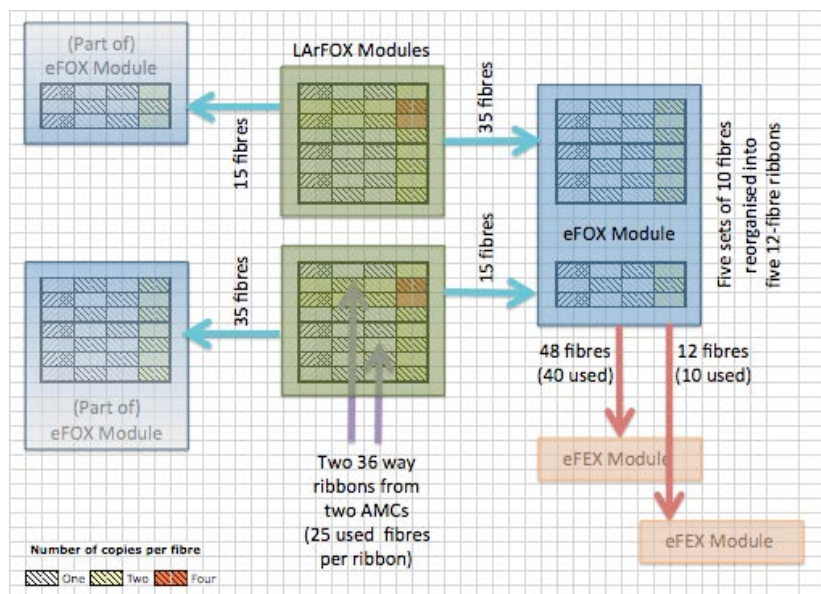
392  
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394

Figure 6: LArFOX fiber mapping to eFEX at 6.4 Gbit/s.



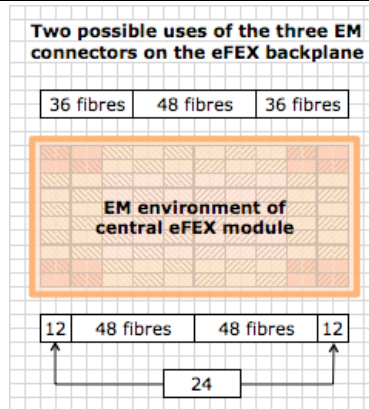
395  
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397

Figure 7: LArFOX and TileFOX fiber mapping at 6.4 Gbit/s.



398  
399

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



400

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

403

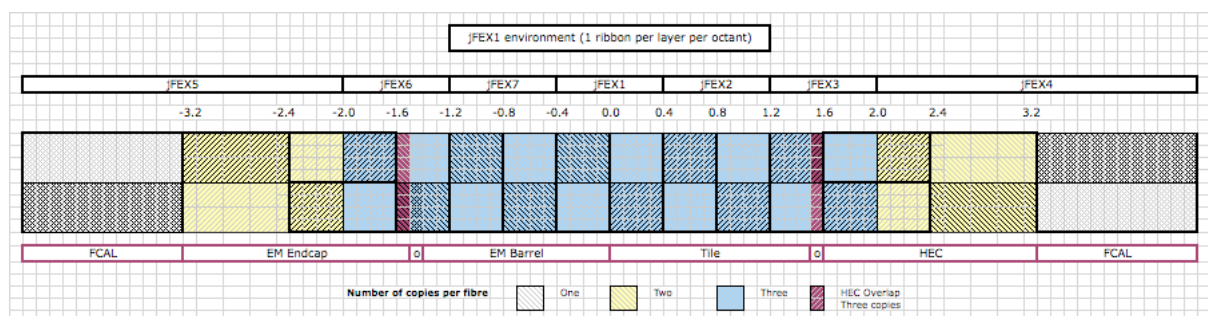
404 **2.2.2. jFEX**

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

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

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

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



420

421 **Figure 10: Number of fanout copies of each jFEX fiber at ~10 Gbit/s.**

422

423 **2.2.3. gFEX**

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



427 **2.3. OPEN QUESTIONS**

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

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

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

440

441 **3. COMPONENTS OF OPTICAL CHAIN**

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

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

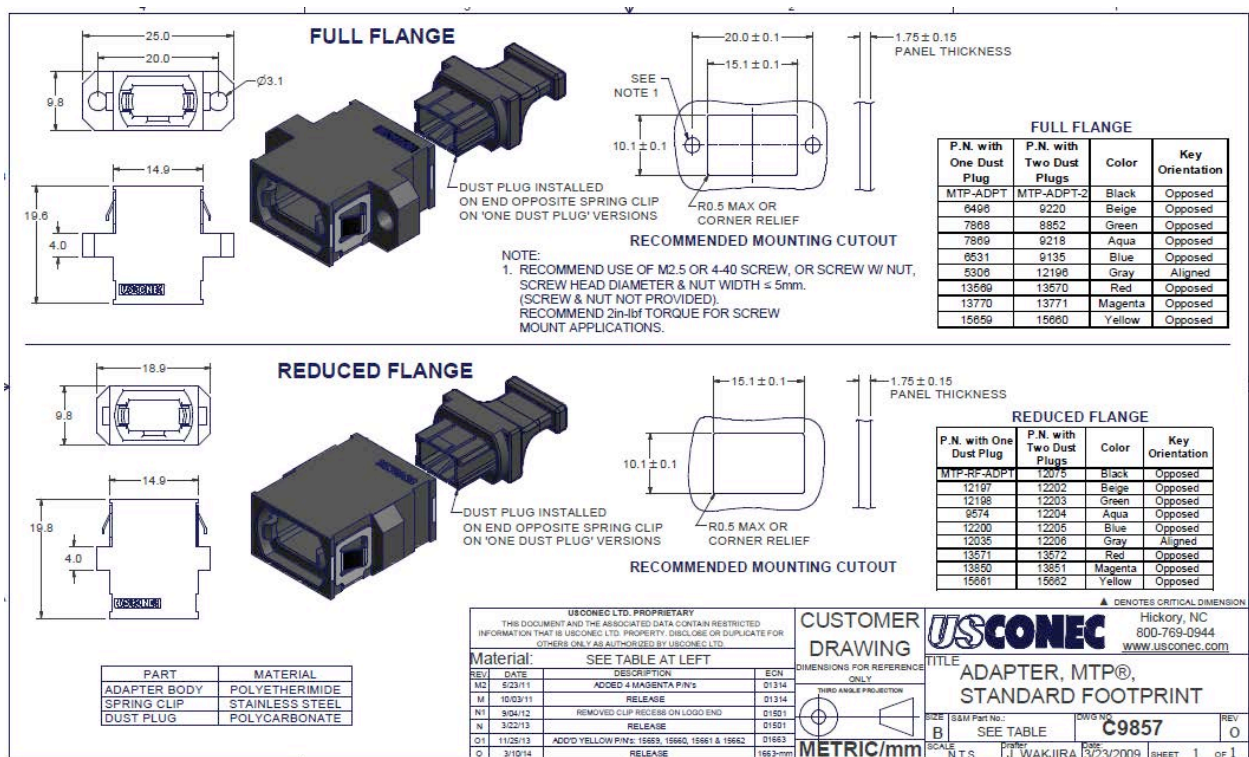
449 The outputs of the FOX are also 12 fibers MPO connectors. The eFEX module uses 48 fibers MPO  
450 connectors and the jFEX and the gFEX modules use 72 fibers MPO connectors. Therefore there may  
451 be the break-out cables (48 to 4x12 and 72 to 6x12 fibers) between the FOX output 12 fibers MPO 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

453

454 **3.1. INPUT ADAPTERS FOR MPO/MPT CONNECTORS**

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

459



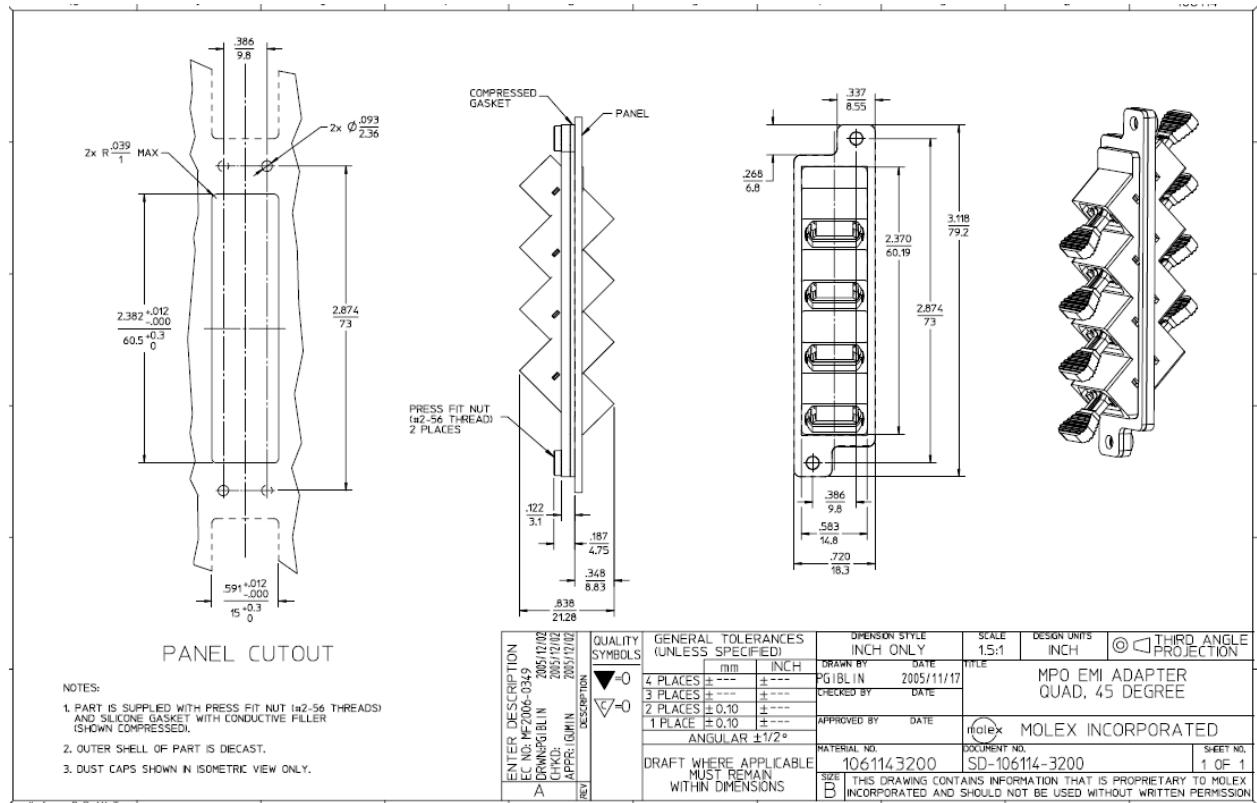
460

461 **Figure 11: Individual MPO/MPT adapter.**

462

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

465 Input MPO connectors of the FOX will be male version (with guide pins). The parallel fiber ribbons of  
466 12 fibers will have female version of the MPO connector.



467  
468  
469

Figure 12: Quad MPO/MPT adapters.

470 **3.2. FIBERS MAPPING**

471 **3.2.1. Mapping at the input and output**

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



476  
477

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

478 **3.2.2. Mapping by connectors**

479 The FOX will map each of the input fibers to a specific FEX destination. In order to achieve this, the  
480 input and output parallel fiber ribbons of 12 fibers break out in individual fibers with MPO harness  
481 cable. Connecting two segments of optical fibers is most simply done through optical connectors on  
482 each end of the fibers (e.g. LC or SC connectors for individual fibers) and a barrel connector to mate

483 the two connectors. The amount of light lost in the connection is expected to be in the range of 0.25 to  
 484 0.5 dB, with a value range depending on different expectations about what might be typical versus  
 485 what should be used in conservative calculations (see Appendix Appendix A). The light power loss  
 486 depends on several factors including the cleanliness of the polished faces and the fine alignment of the  
 487 two fiber cores, but even with perfect alignment some light reflection and power loss is always  
 488 present. The advantage of having connectors and using modular components (e.g. for splitters) comes  
 489 from the convenience of assembly and maintenance of the full system.

490



491

492

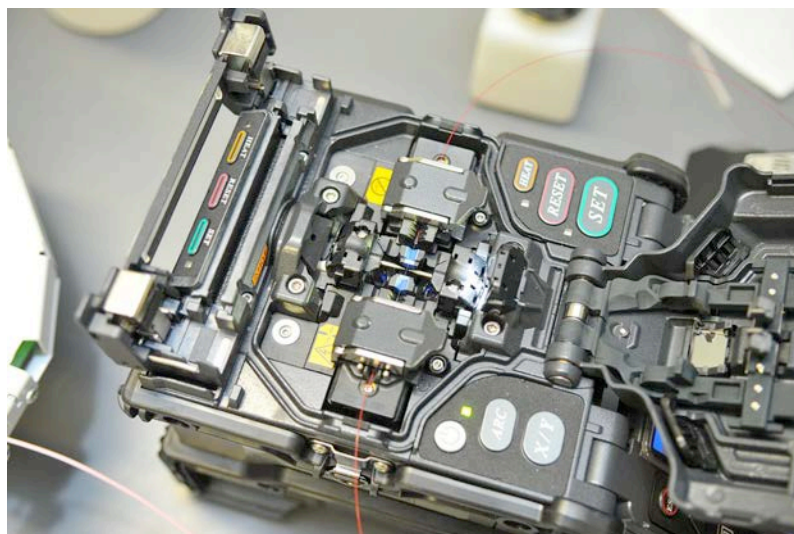
493 **Figure 14: MPO harness and connector couplers (LC, ST, SC).**

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

496 **3.2.3. Mapping by fusion splicing**

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

502



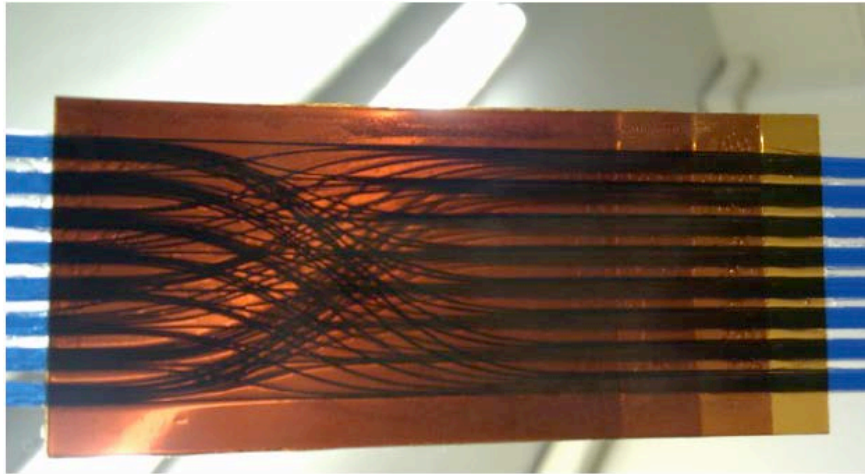
503

504

**Figure 15: Fusion splicing.**

505 **3.2.4. Mapping by custom mapping module**

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



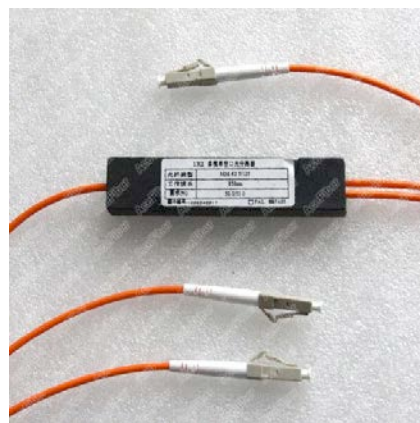
509  
510 **Figure 16: Fiber mapping.**

511

512 **3.3. FIBER PASSIVE SPLITTING**

513 For the fibers that go to two destinations and therefore require passive splitting, a passive optical  
514 splitter with the even split ration (50/50) can be used. The splitter may be connected to the  
515 input/output fibers by connectors (see 3.2.2), which create addition insertion loss, or by fusion splicing  
516 (see 3.2.3). Example of connectorized passive splitter is shown in Figure 17:

517



518  
519 **Figure 17: Fiber passive splitter.**

520 It contains LC connectors on both ends and use multimode fiber of 850 nm wavelength. The split ratio  
521 is even. 1 m input and output cables.

522

523 **3.4. FIBER ACTIVE SPLITTING**

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



527 **3.4.1. Electrical signal fan out at the source**

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

533 **3.4.2. Optical amplification**

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

537

- 538 • SUPERLUM Diodes
- 539 • Traveling-wave MQW design
- 540 • CW or pulsed operation
- 541 • PM or SM pigtails
- 542 • Low chip-to-fiber coupling loss
- 543 • Built-in thermistor and TEC
- 544 • Hermetic butterfly package or DIL package
- 545 • Optional FC/APC connectors



**Features:**

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

**Package:** butterfly (DBUT)

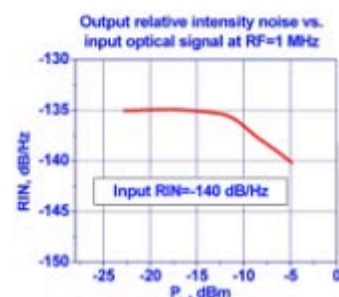
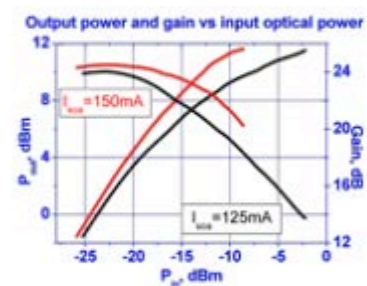
**Additional and customized:**

- 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 $\lambda_c$ , nm	850	
-3 dB optical gain bandwidth, nm	40	
Gain ripple, dB	$\leq 0.1$	0.2
Small signal gain at $\lambda_1, \lambda_2$ (gain maximums), dB	25	
Saturation output power, dBm	8.0	
Polarization dependent gain, dB	7	

**PERFORMANCE EXAMPLES**



546

547

**Figure 18: Optical amplifier.**

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

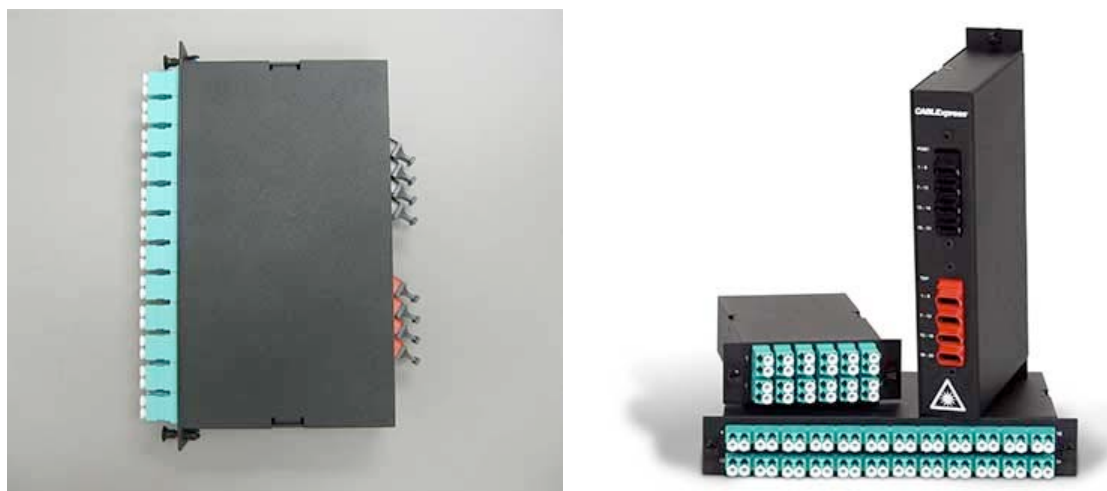
551

### 552 3.5. MECHANICS

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

557 Commercial customized housing and available from a number of manufacturers:

558



559

560

**Figure 19: LC to MTP Modules.**

561



562

563

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

564

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

567

## 568 **4. DEMONSTRATOR(S)**

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

572

### 573 **4.1. DEMONSTRATOR GOALS**

574 The initial study phase for the FOX system has two main goals. The first goal is the study of the light  
575 path between the transmitter MiniPODs of the Liquid Argon or Tile Detector Front-Ends and the  
576 receiver MiniPODs of the Feature Extractor modules of l1calo. The second goal is a study of the  
577 mechanical building blocks necessary to construct an overall physical plant providing the required  
578 management and mapping of all the fibers and its installation in USA15.

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

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

585

### 586 **4.2. DEMONSTRATOR COMPONENTS**

#### 587 **4.2.1. Optical Demonstrator**

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

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

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

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

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

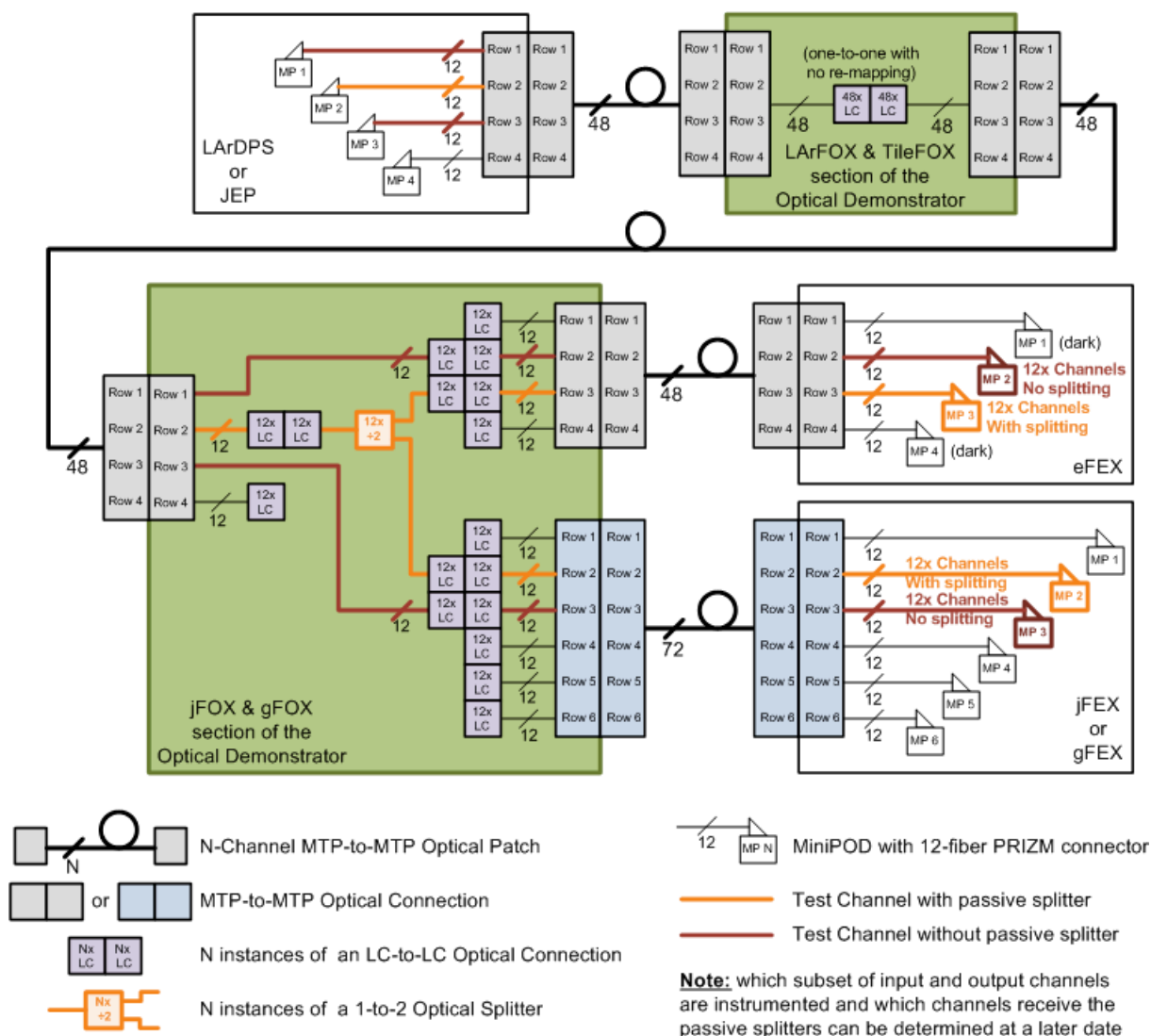
610 The optical demonstrator is usable in isolation, i.e. with hand-held test equipment using continuous or  
611 pulsed light sources and light meters to measure and compare the insertion loss of different  
612 configurations. It can also be connected to a modulated light transmitter and a light detector  
613 (preferably MiniPODs) to simulate a l1calo data stream at 6.4 Gbps (or other speed) and provide an



614 empirical measurement of the connection quality that is representative of that link and that set of  
615 source and sink.

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

624



625

626

Figure 21: Draft diagram of the FOX Optical Demonstrator.

627

#### 628 4.2.2. Mechanical Demonstrator

629 The mechanical demonstrator study consists of one or several test assemblies used to evaluate and  
630 choose a combination of commercial (and custom made where necessary) mechanical components  
631 appropriate to build the full FOX system. An important and pressing outcome from the demonstrator

632 phase of the FOX system is to determine the physical size of the FOX module so that the required  
633 space in USA15 can be properly understood and planned for in advance.

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

638 The existing infrastructure in USA15 expects the FOX sub-modules to be mounted in a 19-inch rack  
639 rail environment. Mounting some passive FOX module(s) outside of the rack enclosures could be  
640 explored if rack space in USA15 becomes a limitation but such measure will hopefully not be  
641 necessary.

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

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

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

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

656

### 657 **4.3. EXPLORATIVE STUDIES**

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

#### 661 **4.3.1. Fiber fusing**

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

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

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

676 The goal of this explorative study is to evaluate how easy or challenging this fusing procedure really  
677 is. We will also understand how long each fused connection might take in the context of building the

678 final FOX system. This study will thus determine how feasible it would be to fuse some of the  
679 connections in a fraction of the FOX channels, namely those requiring the use of light splitters. The  
680 feasibility will of course also depend on how many channels would need to receive this treatment (tens  
681 or hundreds versus thousands). While it may be too early to predict if fiber fusing will be needed, this  
682 explorative study is meant to prepare for such possibility.

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

#### 685 **4.3.2. Light amplification**

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

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

694 Optical 850 nm multimode communication at 10 Gbps is one of the technologies used for short range  
695 connections in Ethernet communication. Ethernet fiber link duplication also happens to be desired in  
696 certain Ethernet switching contexts. This is used to provide a copy of all internet traffic for the  
697 purpose of flow monitoring and for intrusion detection. Commercial devices accomplishing such flow  
698 duplication are called “taps”. There would be important issues related to cost and space per channel,  
699 but a basic problem was also identified after discussing the details of the specification with one  
700 vendor. Ethernet protocol uses a different encoding scheme for the data stream and the 8b/10b  
701 encoding scheme used in L1Calo is incompatible with the 64b/66b encoding used with the 10Gb  
702 Ethernet protocol. Proprietary firmware in these commercial products would need to be modified for  
703 8b/10b encoding while no clear path forward was proposed by that particular vendor. Moreover, the  
704 embedded FPGA implementation for 64b/66b isn’t fixed latency, and doesn’t detect errors at the  
705 required tick/channel granularity.

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

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

711

### 712 **4.4. MEASUREMENT TOOLS**

#### 713 **4.4.1. Optical power meter**

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

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

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

#### 726 **4.4.2. Reflectometer (OTDR)**

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

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

#### 739 **4.4.3. Bit error ratio tester (BERT)**

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

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

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

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

#### 754 **4.4.4. Optical oscilloscope**

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

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

764

### 765 **4.5. TEST PROCEDURE**

#### 766 **4.5.1. Insertion loss measurements**

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

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

#### 773 **4.5.2. Bit error test**

774 For all initial data transmission tests the optical demonstrator will use one of the existing 11calo CMX  
775 modules equipped with a “Topo FPGA”, i.e. with all its transmitting and receiving MiniPODs. The  
776 optical demonstrator can later be used with the prototype versions of the upstream and downstream  
777 modules, as they become available.

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

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

790 One limitation of using a CMX card is that its Virtex 6 FPGAs can only test a transmission speed up to  
791 6.4 Gbps. Testing MiniPOD transmission at higher speeds will need to be performed with prototypes  
792 modules being built for the Phase-I upgrade (assuming higher line rates will indeed be used).

#### 793 **4.5.3. MiniPOD Light Level Monitoring**

794 **Transmitter and receiver MiniPODs host a number of internal registers accessible through a**  
795 **Two Wire Serial interface (TWS). These control and status registers include monitoring**  
796 **information about the amount of light either transmitted or received as measured by the device**  
797 **itself. These internal measurements are specified per channel with a rather fine granularity of**  
798 **0.1microW (-30 dBm) but with a tolerance of only +/- 3 dB. This coarse tolerance prevents using**  
799 **these monitoring values as a direct quantitative measurement. During CMX production**  
800 **module testing the values returned have been found to be stable over repeating queries (an**  
801 **example of the data currently retrieved is shown in Figure 22: Example of MiniPOD information**  
802 **captured by current CMX software and firmware.**

803  
804 below). These measurements will thus be included in the testing of the FOX optical demonstrator and  
805 will be compared to and calibrated against the insertion loss measurements obtained with other test  
806 equipment.

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

813 More than optical power could also be tracked by querying the MiniPODs, including manufacturing  
814 date, serial number and operating time. Case temperature and electrical measurements are also

815 available. Faults and Alarms on optical, electrical or temperature measurements can also be  
816 monitored.

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

822

```
*****  
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)
```

823

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

825

826

827 **5. NOTES**

828 **5.1. REQUIREMENTS**

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

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

834

835 **5.2. SCHEDULE**

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

838

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

839

840 The optical demonstrator will be designed and assembled in time for the integration testing in Fall  
841 2015. The demonstrator will continue to be available for future tests at CERN as well as at institutions  
842 responsible for L1Calo Phase-I components.

843

844

845 **APPENDIX A. OVERVIEW OF FIBER OPTIC TECHNOLOGY, SIMPLIFIED AND**  
846 **APPLIED TO THE MINIPOD ENVIRONMENT.**

847 **APPENDIX A.A. OPTICAL FIBER**

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

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

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

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

867

868 **APPENDIX A.B. PROPAGATION SPEED**

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

871

872 **APPENDIX A.C. SERIAL ENCODING**

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

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

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

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



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

898

## 899 **APPENDIX A.D. TRANSMITTED POWER**

900 The amount of light emitted by a Laser is measured in units of dBm. This unit is related to the the  
901 Decibel (dB). The decibel is a dimension-less logarithmic unit used to characterize the ratio of two  
902 quantities. The ratio of two power values expressed in dB is defined as

$$903 \text{PowerRatio (dB)} = 10 \log (\text{power1}/\text{power2})$$

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

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

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

$$912 \text{AbsolutePower (dBm)} = 10 \log (\text{Power}/1 \text{ mW})$$

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

915

## 916 **APPENDIX A.E. MODULATED POWER**

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

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

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

926

## 927 **APPENDIX A.F. POWER ATTENUATION**

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

933 Typical sources of attenuation (power loss) are:

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

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

949

## 950 **APPENDIX A.G. POWER BUDGET**

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

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

957

## 958 **APPENDIX A.H. DISPERSION**

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

968