ATLAS Note

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Fibre Optic Exchange (FOX) Documentation

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This document details the design, internal mapping, and construction, of the Fibre Optic Exchange (FOX) system, as part of the ATLAS Liquid Argon Calorimeter Phase-I Upgrade.

Contents

1 Introduction **3**

2 Geometrical Coverage **3**
- 2.1 Naming Conventions 3
- 2.2 LATOME and TREX Types 3
- 2.3 FEX Modules 6
  - 2.3.1 eFEX 6
  - 2.3.2 jFEX 6
  - 2.3.3 gFEX 7
- 2.4 Fibre Usage 7

3 Mapping **11**
- 3.1 Overview 11
- 3.2 LArFOX A & C 11
- 3.3 LArFOX B & D 11
- 3.4 TileFOX E & F 11
- 3.5 FOX Box Interconnections 11

4 Hardware, Ribbons, Mapping Modules, and Connectors **19**
- 4.1 FOX Boxes 19
- 4.2 Ribbon Types and Numeration 30
- 4.3 Ribbon Mappings 34
- 4.4 Connectors 39

5 FOX Demonstrator **42**
- 5.1 Light loss tests 42
- 5.2 System tests with prototype source and sinks 43

6 FOX Assembly and Handling Procedures **44**

7 Timeline and Testing Procedures **44**

8 Conclusion **44**

Auxiliary material **46**

1 Introduction

This document describes the Fibre Optic Exchange (FOX) system for the Phase-I upgrade, which takes the fibres from the LAr and TREX frontend and connects them to the L1 Feature Extractor (FEX) modules, including any required mapping between the two.

The LAr calorimeter upgrade is described in detail in the ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report [1]. The current building block of the LAr calorimeter readout at trigger level is based on the so-called "Trigger Tower". Trigger Towers (TT) are formed of the sum of energies deposited in cells across longitudinal layers in an area of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$[1]. During the phase-I upgrade the LAr trigger readout granularity will be increased and the new building block is called "Super Cell". Super Cells (SC) have different sizes depending on the detector area. For the purposes of the FOX design, only the η-ϕ coordinates of these building blocks are important, so TT and SC will be used interchangeably.

The geometrical coverage of the detector and various relevant modules are described in Sec. 2, followed by details about the mapping in different regions of the detector in Sec. 3. The hardware description, as well as details for the ribbons, mapping modules, and connectors, is described in Sec. 4, followed by the FOX assembly as well as handling procedure presented in Sec. 6. Finally, the timeline and testing procedures are presented in Sec. 7, followed by general conclusions in Sec. 8.

2 Geometrical Coverage

2.1 Naming Conventions

This section describes the TT in different areas of the LAr calorimeter. The geometries of the LAr calorimeter are described in the original LAr TDR [2], where Fig. 10-3, 10-4 and 10-5 summarise the individual cells and the TT in the EMB, EMEC and the HEC, respectively.

The EMB, EMEC and HEC calorimeters are divided into 8 analogous parts called octants. A quadrant covers the positive or the negative η area with $\Delta\phi = \frac{2\pi}{4}$. The first quadrant starts at $\phi = 0$. The TT naming convention is of the form $I_\eta L_\phi$ where I_η is a number representing the η position of the TT while L_ϕ represents the ϕ position. The mapping between I_η (L_ϕ) and the $\Delta\eta$ ($\Delta\phi$) ranges depends on the detector area. The I_η indices are summarised in Tab. 1 while the L_ϕ indices are summarised in Tab. 2.

2.2 LATOME and TREX Types

The LAr Trigger Processing Mezzanines (LATOMEs) boards, also known as AMCs (Advanced Mezzanine Cards) form the bulk of the output fibres from the backend electronics (BEE) that have to connect to the FOX, as well as a smaller number of Tile Rear Extension (TREX) modules. This section describes the geometric coverage of the LATOMEs and TREX modules, as well as their fibre labelling, as sent from the BEE. Detailed information about LATOMEs can be found in Ref. [1], and TREXs in Ref. [3].

[1] the trigger tower size is different in some specific area of the detector especially in the forward regions

I_η	EMB	TREX	EMEC	HEC	FCAL
1	0.0-0.1	0.0-0.1	1.4-1.5	-	3.2-3.6
2	0.1-0.2	0.1-0.2	1.5-1.6	1.5-1.6	3.6-4.0
3	0.2-0.3	0.2-0.3	1.6-1.7	1.6-1.7	4.0-4.4
4	0.3-0.4	0.3-0.4	1.7-1.8	1.7-1.8	4.4-4.9
5	0.4-0.5	0.4-0.5	1.8-1.9	1.8-1.9	-
6	0.5-0.6	0.5-0.6	1.9-2.0	1.9-2.0	-
7	0.6-0.7	0.6-0.7	2.0-2.1	2.0-2.1	-
8	0.7-0.8	0.7-0.8	2.1-2.2	2.1-2.2	-
9	0.8-0.9	0.8-0.9	2.2-2.3	2.2-2.3	-
10	0.9-1.0	0.9-1.0	2.3-2.4	2.3-2.4	-
11	1.0-1.1	1.0-1.1	2.4-2.5	2.4-2.5	-
12	1.1-1.2	1.1-1.2	2.5-2.7	2.5-2.7	-
13	1.2-1.3	1.2-1.3	2.7-2.9	2.7-2.9	-
14	1.3-1.4	1.3-1.4	2.9-3.1	2.9-3.1	-
15	1.4-1.5	1.4-1.5	3.1-3.2	3.1-3.2	-

Table 1: I_η indices and the corresponding $|\eta|$ ranges for the various LAr calorimeters. The same indices are used for positive and negative values of η.

L_ϕ	EMB and EMEC(I_η<12)	EMEC($I_\eta \geq$12)	HEC(I_η<12)	HEC($I_\eta \geq$12)	FCAL
A	0.000-0.098	0.000-0.196	0.000-0.098	0.000-0.196	0.000-0.393
B	0.098-0.196	0.196-0.393	0.098-0.196	0.196-0.393	0.393-0.785
C	0.196-0.295	0.393-0.589	0.196-0.295	0.393-0.589	0.785-1.178
D	0.295-0.393	0.589-0.785	0.295-0.393	0.589-0.785	1.178-1.570
E	0.393-0.491	0.785-0.982	0.393-0.491	0.785-0.982	1.570-1.963
F	0.491-0.589	0.982-1.178	0.491-0.589	0.982-1.178	1.963-2.356
G	0.589-0.687	1.178-1.374	0.589-0.687	1.178-1.374	2.356-2.748
H	0.687-0.785	1.374-1.570	0.687-0.785	1.374-1.570	2.748-3.140
I	0.785-0.884	-	0.785-0.884	-	3.140-3.533
J	0.884-0.982	-	0.884-0.982	-	3.533-3.926
K	0.982-1.080	-	0.982-1.080	-	3.926-4.318
L	1.080-1.178	-	1.080-1.178	-	4.318-4.710
M	1.178-1.276	-	1.178-1.276	-	4.710-5.103
N	1.276-1.374	-	1.276-1.374	-	5.103-5.496
O	1.374-1.473	-	1.374-1.473	-	5.496-5.888
P	1.473-1.570	-	1.473-1.570	-	5.888-6.280

Table 2: L_ϕ indices and the corresponding Φ ranges for the various LAr calorimeters. One quadrant is represented for the EMB,EMEC and HEC; The other quadrant have the same structure. The full Φ range is presented for the FCAL.

There is only one type of TREX module, which is used in the central hadronic region ($0 < |\eta| < 1.6$), and covers $\Delta\Phi = 1.570$. There are 8 TREX modules in one quadrant. One can distinguish 5 types of LATOME boards depending on their geometrical coverage and their connection to the LAr Trigger Digitiser Boards (LTDBs), as well as the FEX modules after passing through the FOX:

- EMB: This type of LATOME board is used in the central region of the EMB ($0 < |\eta| < 0.8$). It covers $\Delta\Phi = 0.393$ starting at $\Phi = 0$. There are 4 LATOME boards of this type in one quadrant.
- EMB/EMEC: This type of LATOME board is used in the EM region with $0.8 < |\eta| < 1.6$. and $\Delta\Phi = 0.393$ starting at $\Phi = 0$. There are 4 LATOME boards of this type in one quadrant.
- EMEC: This type of LATOME board is used in the central region of the EMEC ($1.6 < |\eta| < 2.4$). It covers $\Delta\Phi = 0.393$ starting at $\Phi = 0$. There are 4 LATOME boards of this type in one quadrant.
- EMEC/HEC: This type of LATOME board is used in the forward region of the EMEC ($2.4 < |\eta| < 3.2$) and the full η range of the HEC in one quadrant. It covers $\Delta\Phi = 0.785$ starting at $\Phi = 0$. There are 2 LATOME boards of this type in one quadrant.
- FCAL1: This type of LATOME board is used to readout the electromagnetic FCAL (first layer) over the full Φ range. There is one LATOME of this type in each endcap.
- FCAL2: This type of LATOME board is used to readout the hadronic FCAL (second and third layers) over the full Φ range. There is one LATOME of this type in each endcap.

The different types of LATOME boards are summarised in Tab. 3.

LATOME type	Detector	$\Delta\Phi$	$\|\eta\|$	towers $\eta - \phi$	# SCS	# LATOME boards
EMB	EMB	0.393	0-0.8	8x4	320	32
EMB/EMEC	EMB,EMEC	0.393	0.8-1.6	8x4	320	32
EMEC	EMEC	0.393	1.6-2.4	8x4	312	32
EMEC/HEC	EMEC	0.785	2.4-3.2	8x8	80	16
	HEC		1.5-3.2	17x8	96	
FCAL1	FCAL Layer 1	6.280	3.1-4.9	18x16	192	2
FCAL2	FCAL Layers 2&3	6.280	3.2-4.9	18x16	192	2

Table 3: Coverage and number of the various LATOME board types.

2.3 FEX Modules

This section summarises the coverage of the different FEX modules, as well as the number of modules for each of the FEXs as summarised in Tab. 4.

FEX type	Total Number	MTP Connections per FEX
eFEX	24	4 x 48-way
jFEX	6	4 x 72-way
gFEX	1	6 x 48-way

Table 4: Number of each FEX type, as well as connections to each FEX.

2.3.1 eFEX

The eFEX system receives trigger tower information from the LAr and Tile calorimeter. There are three eFEX modules per octant in ϕ, for a total of 24 eFEX modules. The connection to each eFEX is made via four 48-way MTP connectors. Each of these four connectors has a specific purpose and are named A-D. connector A sends the left-half of the central fibre coverage for that module, while connector B sends the right-half of the central fibre coverage for that module. For the other two connectors: connector C sends the overlap fibres for that module, and connector D sends all of the hadronic fibres, while connectors A-C only send EM fibres. Duplicate or "copies" are needed wherever the modules overlap. Fig. 1 summarises the geometrical layout of the eFEX in one octant.

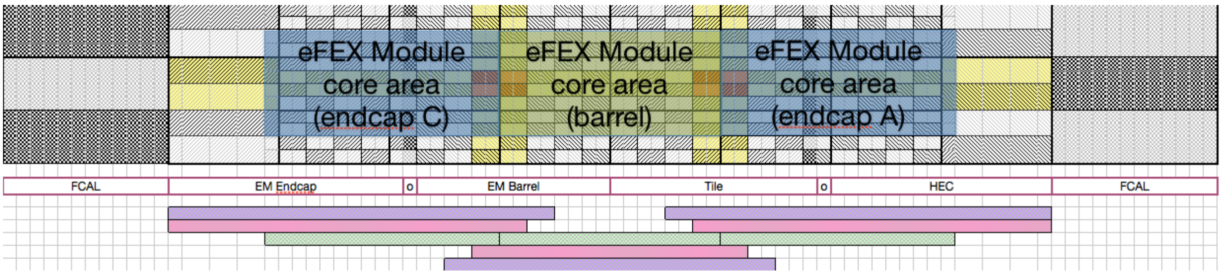


Figure 1: eFEX module geometrical coverage.

2.3.2 jFEX

The jFEX system also receives trigger tower information from the LAr and Tile calorimeter. There are six jFEX modules in total, and the connection to each jFEX is made via four 72-way MTP connectors. Each of these connectors covers a single quadrant in ϕ. 3 fibre duplicates are needed up to $|\eta| < 1.6$, followed by 2 duplicates for $1.6 < |\eta| < 2.0$, and one duplicate for $|\eta| > 2.0$, while no duplicates are needed in the FCAL. Fig. 2 summarises the geometrical layout of the jFEXin one quadrant.

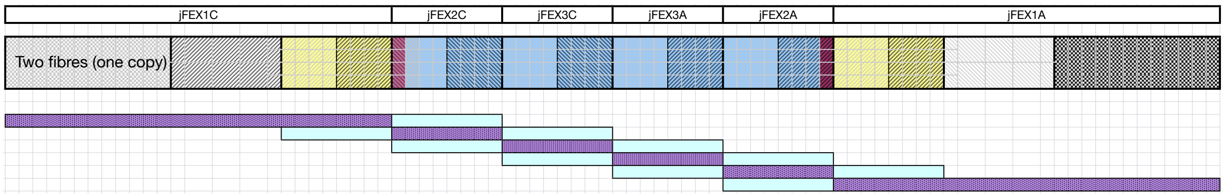


Figure 2: jFEX module geometrical coverage.

2.3.3 gFEX

The gFEX system receives information from the full calorimeter in a single module. The connection to the gFEX is made via six 48-way MTP connectors. Each of these connectors cover a different region in $\eta - \phi$, and are named gFEX1-gFEX6. The connectors gFEX1 and gFEX2 send the EM fibres for -2.4 $< \eta <$ 0.0, and 0.0 $< \eta <$ 2.4, respectively. The connectors gFEX3 and gFEX4 send Hadronic fibres for -2.5 $< \eta <$ 0.0, and 0.0 $< \eta <$ 2.5, respectively. The last two connectors, gFEX5 and gFEX6 send EM, Hadronic, and FCAL fibres for $\eta <$ -2.5 and $\eta >$ 2.5, respectively. No duplicates are needed, but the FOX will provide a 100% copy for redundancy reasons as this is feasible for gFEX. The geometrical center of energy deposits is needed in the central region of the EM calorimeter ($|\eta| <$ 2.4). Fig. 3 summarises the geometrical layout of the gFEX in one octant.

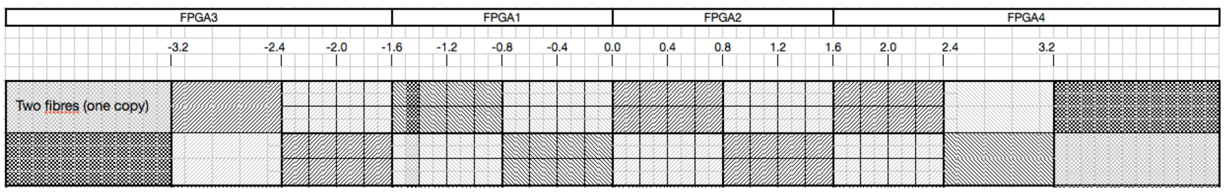


Figure 3: gFEX module geometrical coverage.

2.4 Fibre Usage

The LATOME boards will send individual SC information to the eFEX modules and summed TT information to the jFEX and gFEX modules. In the central region of the detector ($|\eta| <$ 2.5) TTs of size[2] 0.1×0.1 are sent to the jFEXwhile large TT of size 0.2×0.2 are sent to the gFEX. The EMEC and HEC have coarse granularity in the forward region; in this region TT of size 0.2×0.2 are sent to both the jFEX and gFEX. In some regions of the detector, TTs of size 0.1×0.2 in $\eta \times \Phi$ are sent to the gFEX as detailed below. In the FCAL individual SCs are sent to the jFEX while TTs are built and sent to the gFEX.

[2] an approximate size for the TTs is used. For example the $\Delta\Phi$ coverage for one TT in the central region is 0.098 (see Tab. 2) but it is rounded to 0.1 for simplicity.

The FEX modules geometrical coverage is described in Figs. 1, 2, and 3. Channels at the edges of the FEX modules are also sent to the adjacent modules as explained in Sec. 3. The fibers containing channels at these edges are duplicated and sent to different FEX modules. To reduce the number of output fibers the channels at the edges are grouped together when possible. A summary of the number of output fibers per LATOME type and FEX type is shown in Tab. 5 and explained in what follows.

	Number of Fibers (Unique)				Channels per Fiber		
LATOME type	eFEX	jFEX	gFEX	all	eFEX	jFEX	gFEX
EMB_0	30(16)	6(2)	1	37(19)	20	16	8
EMB_1	20(16)	6(2)	1	27(19)	20	16	8
$EMB/EMEC_0$	30(16)	6(2)	1	37(19)	20	16	8
$EMB/EMEC_1$	20(16)	6(2)	1	27(19)	20	16	8
$EMEC_0$	24(16)	5(2)	1	30(19)	18-20	16	8
$EMEC_1$	16(16)	5(2)	1	22(19)	18-20	16	8
EMEC/HEC	15(10)	21(9)	4	40(23)	16-20	8-16	14-16
FCAL1	16	16	5	37	12	12	16
FCAL2	16	16	4	36	12	12	16

Table 5: Output fiber count and content for each of the LATOME types.

The first eFEX module starts at $\Phi = 0.196$ and not at $\Phi = 0$. This shift of two Φ "bins" allows to reduce the number of fibers to be duplicated in the forward region of the detector with a coarse Φ granularity. Thus the LATOME and eFEX module edges are not aligned in the Φ direction; the number of duplicated fibers depends on the Φ position for the EMB, EMB/EMEC and the EMEC LATOME boards. LATOME boards starting at $\Phi = 0$ (labeled by the suffix $TYPE_0$) will have more duplicates than the ones starting at $\Phi = 0.393$ (labeled by the suffix $TYPE_1$) and this alternating pattern is repeated at larger Φ values as described in Fig. 4. Fig. 4 also represents the content of different output fibers. Each output fiber contain SCs from two adjacent TTs in the η direction. In the forward region of the EM calorimeter (covered by the EMEC/HEC board) one fiber contains all SCs over the full η range ($2.4 < \eta < 3.2$) range for $\Delta\Phi = 0.196$. There is three unique eFEX output fibers in $\Delta\Phi = 0.393$ for the full η range in the HEC. The three fibers cover $1.5 < |\eta| < 1.6 + 2.4 < |\eta| < 3.2$, $1.6 < |\eta| < 2.0$ and $2.0 < |\eta| < 2.4$ respectively with 16 channels each. While not currently needed, eFEX fibres are also provided from the FCAL.

The jFEX module coverage is described in Sec. 3. Three copies of each channel is needed up to $|\eta| < 2$. Two copies are needed in the region $2 < |\eta| < 3.2$. Only one copy is needed in the FCAL. Fig. 5 describes the distribution of the TTs on the different fibers. In the central region ($|\eta| < 2.4$), 16 towers corresponding to the region $\eta \times \Phi = 0.4 \times 0.4$ are sent on one fiber. The only exception is the HEC region with $1.5 < |eta| < 1.6$; in this region 8 TTs covering $\Delta\Phi = 0.785$ are sent in one fiber. In the forward region ($2.4 < |\eta| < 3.2$), the 12 TTs corresponding to $\Delta\Phi = 0.393$ are sent on one fiber. In the FCAL 12 TTs corresponding to one Φ "bin" are sent on one fiber. In this case the TTs in the second and third layer corresponding to the same Φ range are grouped in one fiber.

The full calorimeter is covered by one gFEX module and thus the fiber duplication is not needed. For the EMB, EMB/EMEC and EMEC LATOME boards only one gFEX fibre is needed containing 8 gTowers each corresponding to the region $\eta \times \Phi = 0.2 \times 0.2$. For the EMEC/HEC LATOME the size of the gFEX towers depends on the region: It is $\eta \times \Phi = 0.1 \times 0.2$ for the regions $2.4 < |\eta| < 2.5$ and $3.1 < |\eta| < 3.2$ in the EM calorimeter and the regions $1.5 < |\eta| < 1.6$, $2.4 < |\eta| < 2.5$ and $3.1 < |\eta| < 3.2$ in the HEC.

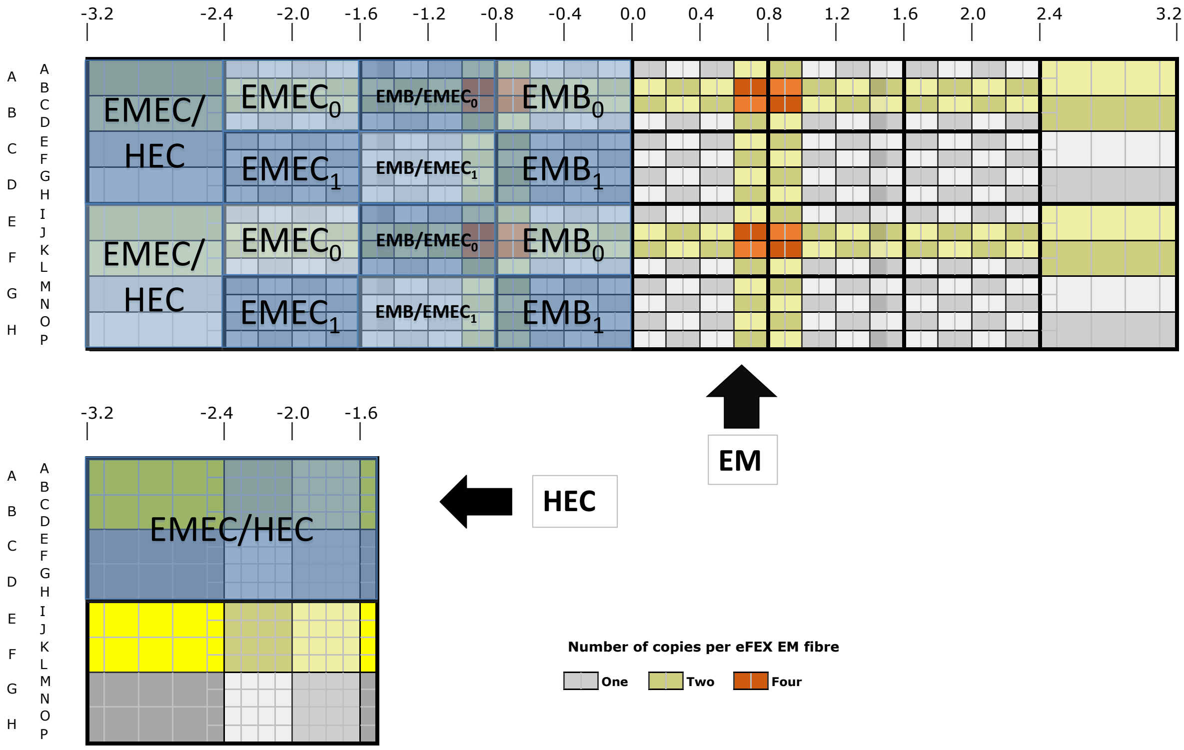


Figure 4: Representation of the eFEX fiber content for the EM and HEC calorimeters. The different colors represent the number of duplicates. Individual fiber content can be identified by different color shades. The geometrical coverage of the LATOME boards is also shown. Only part of the LATOME coverage is shown for clarity.

Otherwise the gTower size is $\eta \times \Phi = 0.2 \times 0.2$ as used in the central region. The TT size in the FCAL is under discussion.

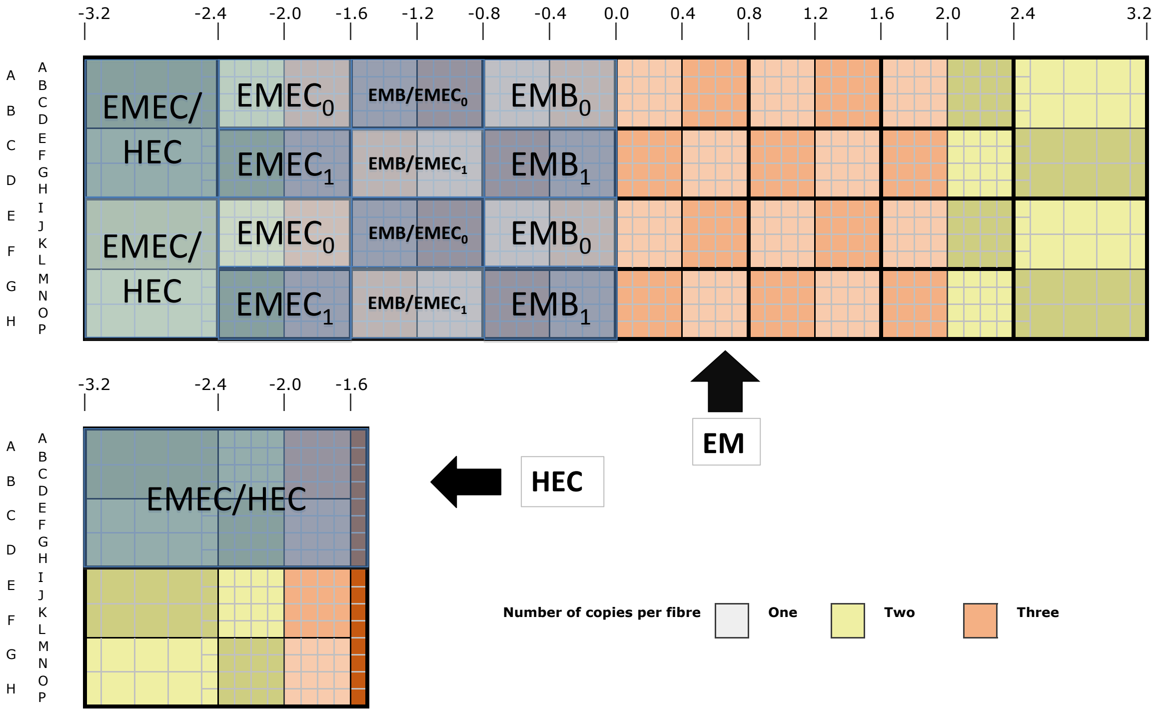


Figure 5: Representation of the jFEX fiber content for the EM and HEC calorimeters. The different colors represent the number of duplicates. Individual fiber content can be identified by different color shades. The geometrical coverage of the LATOME boards is also shown. Only part of the LATOME coverage is shown for clarity.

3 Mapping

3.1 Overview

This section provides the details for the mapping of the fibres from the LATOMEs/TREXs to the FEXs, through the FOX. Fig. 6 provides an overview of the FOX system, which consists of 6 separate parts - called "FOX boxes". Each FOX box has a different, but in some cases similar, internal layout. The FOX boxes called "LArFOX A" and "LArFOX C" deal with the EM and Had inputs from $|\eta| > 2.4$ and $|\eta| < 0.8$, going to the eFEX on the A-side and C-side of the detector, respectively. The FOX boxes named "LArFOX B" and "LArFOX D", then cover the EM and Had inputs from $0.8 < |\eta| < 1.6$, and $1.6 < |\eta|$ 2.4, respectively, going to the eFEX. Finally, the FOX boxes called "TileFOX E" and "TileFOX F" deal with the EM and Had inputs from across the detector coverage that need to go to the jFEX modules, and gFEX module. Where the other boxes cover all of ϕ in two η slices, these last two boxes cover all of η for half of the ϕ coverage each. Additionally, it should be noted that some of the FOX boxes provide through-put cables to another FOX box, to collect fibres efficiently before eventually being output to a FEX module. Fig. 7 shows an overview of which EM and Had LATOMEs/TREXs first enter into which FOX boxes. Table 6 provides an overview of the number of MTP connections in each connection plane for each box. Note that in most of the boxes, internal intermediate planes named "first" and "second" are needed for subsequent stages of mapping, which were designed to result in an optimal mapping with common ribbon types where possible.

Table 6: Number of MTP connections for each connection plane of the various FOX boxes.

Type	LArFOX B	LArFOX D	LArFOX A/C	TileFOX E/F	Total
Front	48	48	38	32	236
Internal 1	32	32	24	56	224
Internal 2	32	-	26	13	110
Back	24	28	38	18	164
Total	136	108	126	119	734

3.2 LArFOX A & C

3.3 LArFOX B & D

3.4 TileFOX E & F

3.5 FOX Box Interconnections

This section details the connections between the FOX boxes, and the connections from the FOX boxes to the FEXs. Fig. 12 shows the interconnections between the different FOX boxes. It should be noted that to optimise ribbon fibre usage, while minimising the number of connection interfaces, there are some instances of outputs being merged outside of the box. For instance, on the front panel of LArFOX A and LArFOX C, there are two sets of 4 outputs, which are combined into 2 outputs for the input to the front

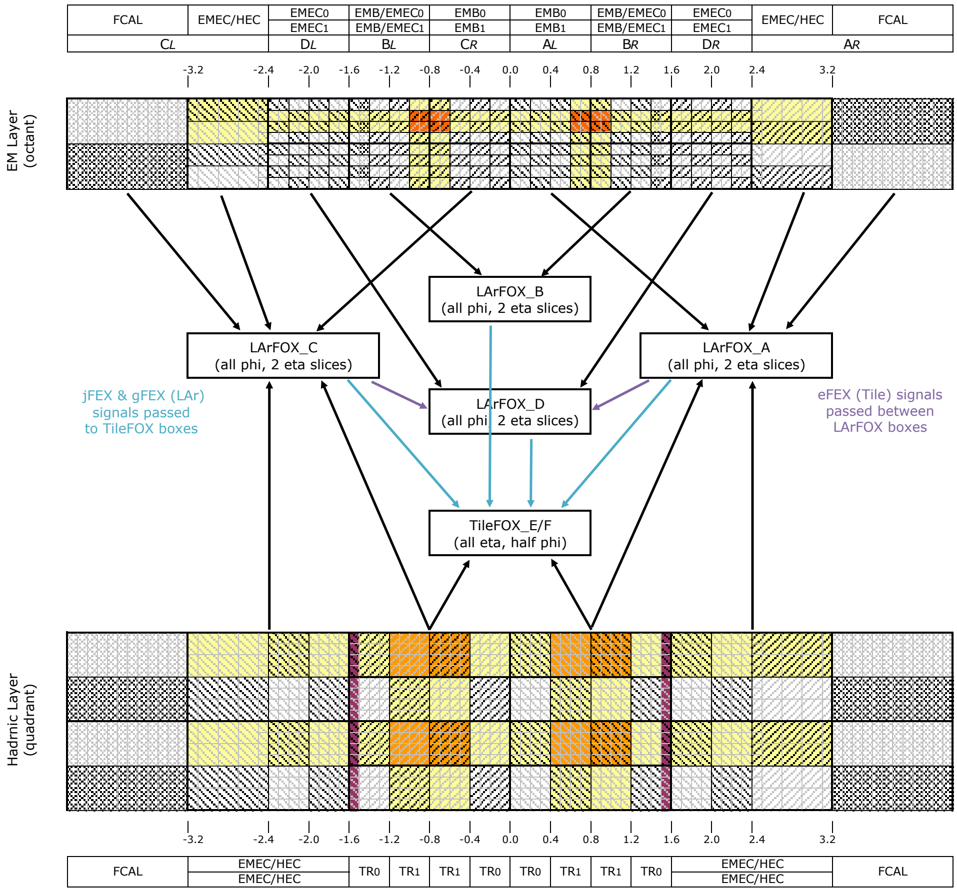
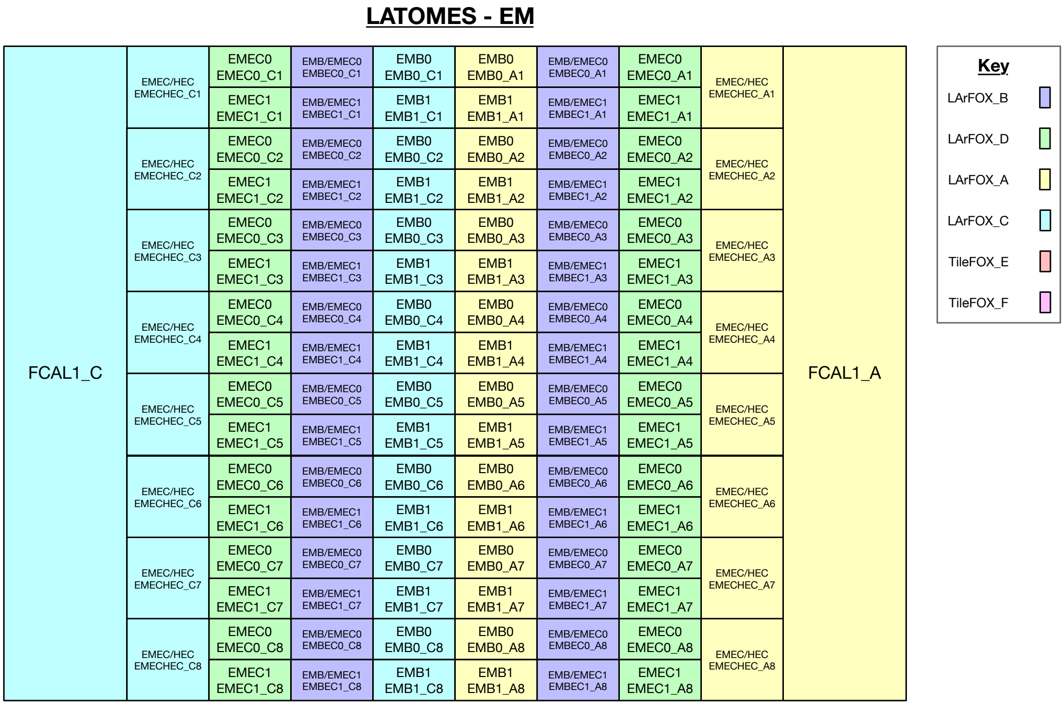


Figure 6: Overview of the FOX system, split into each of the separate components - called "FOX boxes".

panel of TileFOX E and TileFOX F. This is achieved via a 2 x 24-way to 1 x 48-way connector cable. This is also the case for the front panel of LArFOX B and LArFOX D, as input to the front panel of TileFOX E and TileFOX F. The same merging is also used to combine multiple sets of 24-way outputs from TileFOX E and TileFOX F, to the gFEX. This is because the gFEX expects a 48-way input, but needs inputs from both ϕ halves. Thus 24-way outputs are sent from each of the TileFOX boxes, and combined via a 2 x 24-way to 1 x 48-way connector, before connecting to the gFEX.



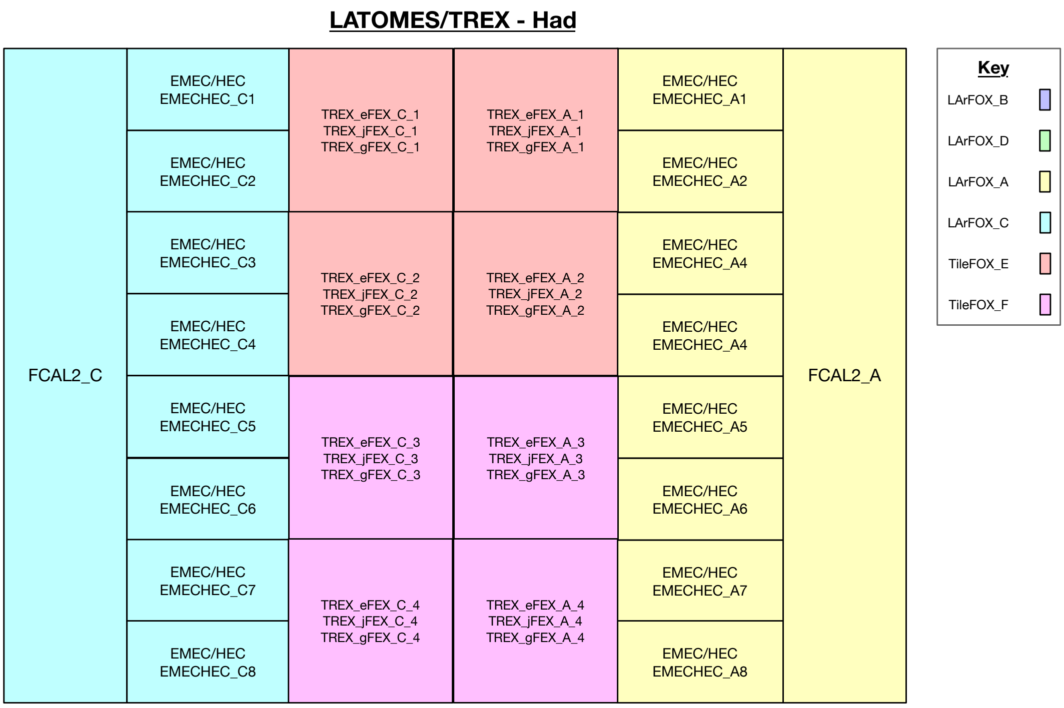


Figure 7: Overview of which LATOMEs/TREXsenter first into which FOX boxes.

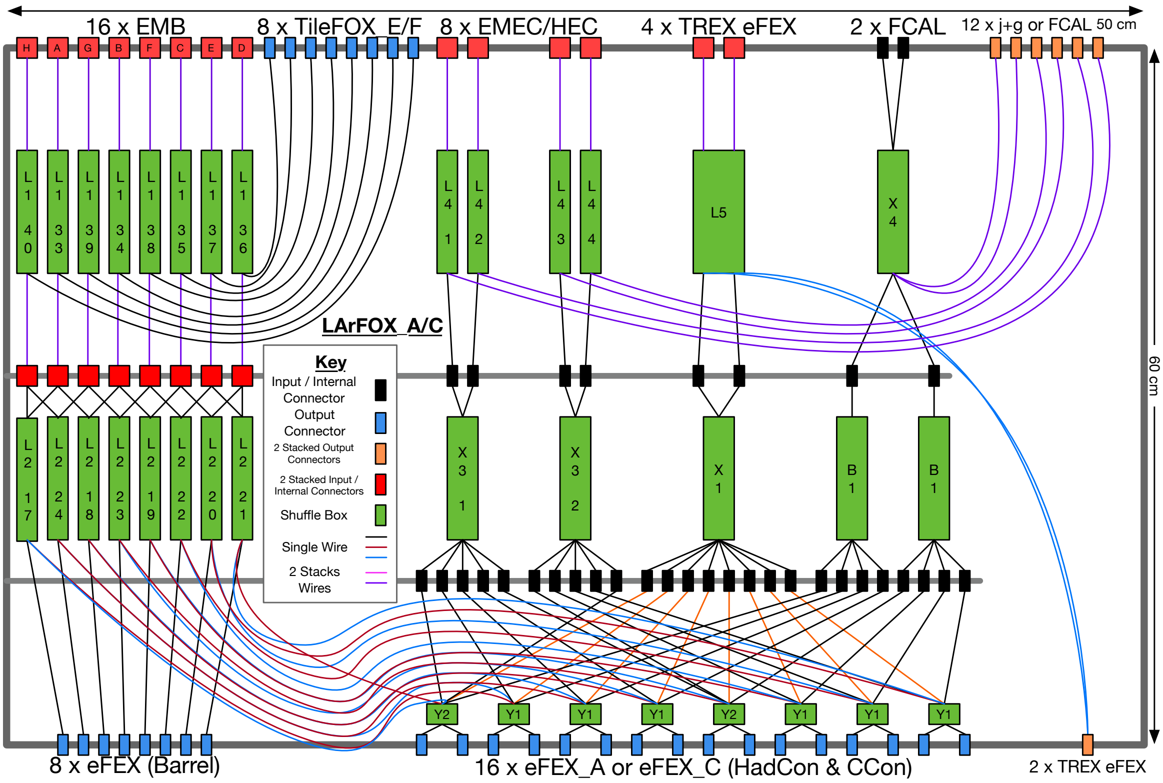


Figure 8: Schematic for the LArFOX A and LArFOX C.

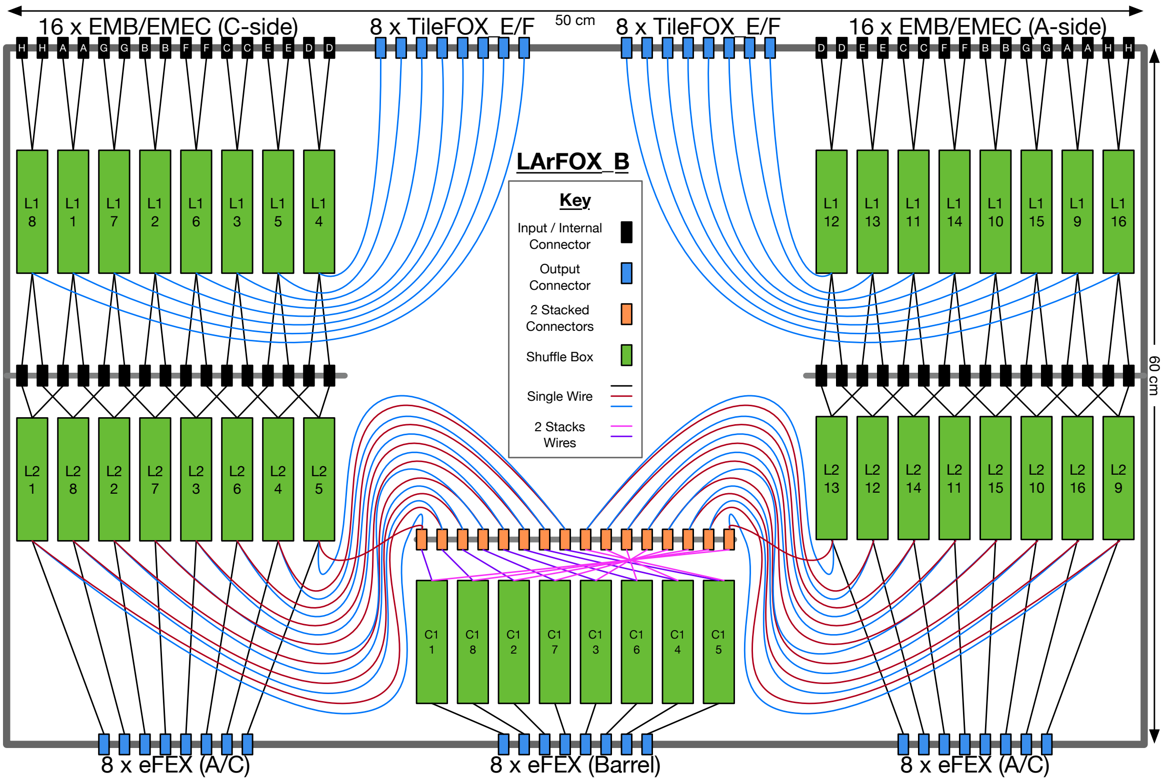


Figure 9: Schematic for the LArFOX B.

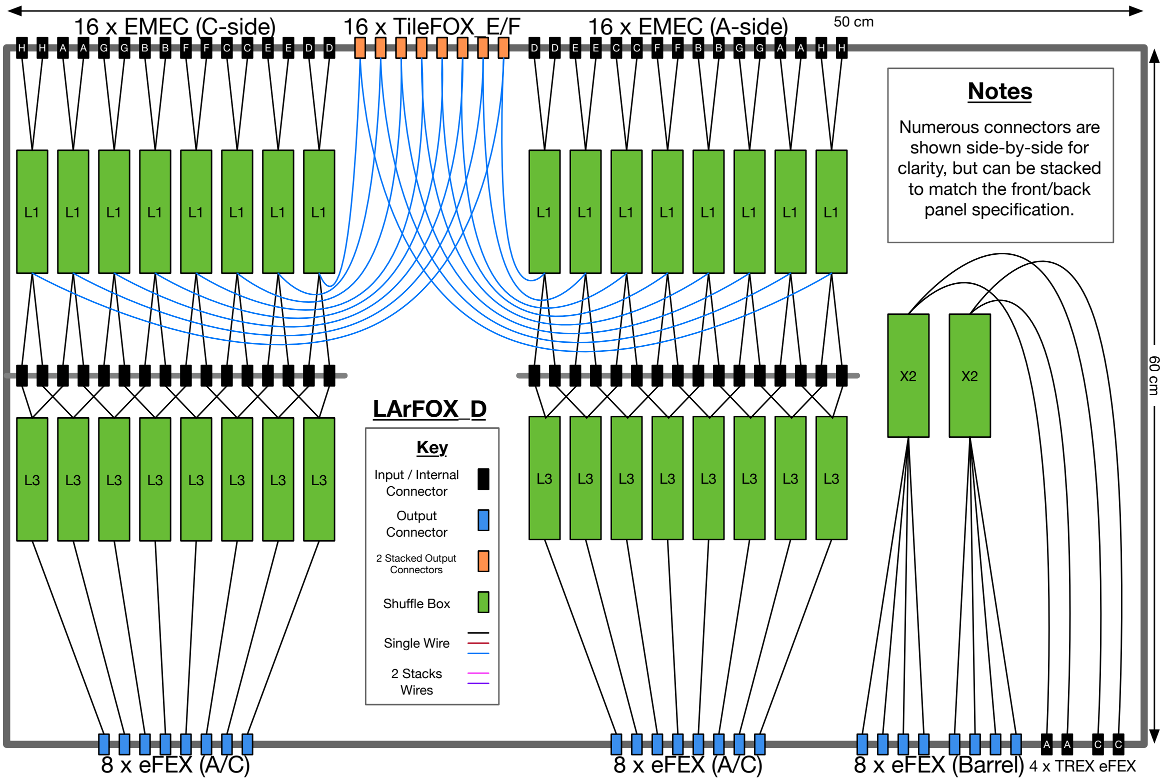


Figure 10: Schematic for the LArFOX D.

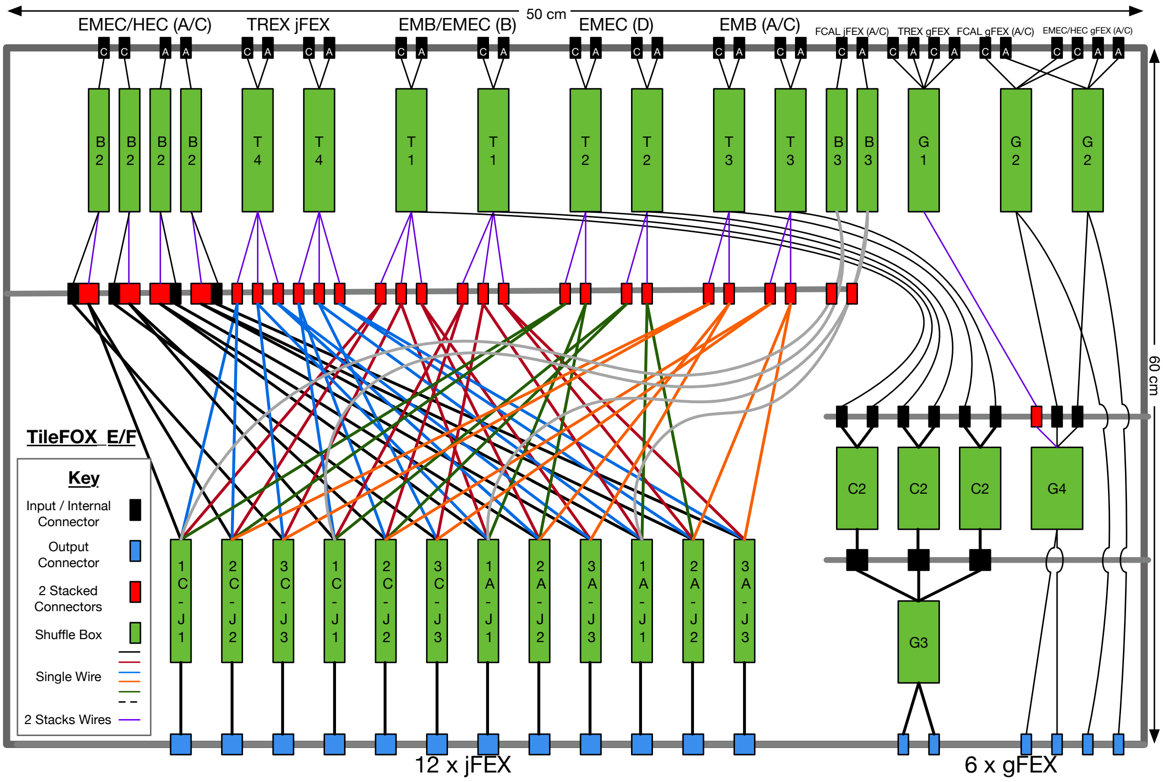


Figure 11: Schematic for the TileFOX E and TileFOX F.

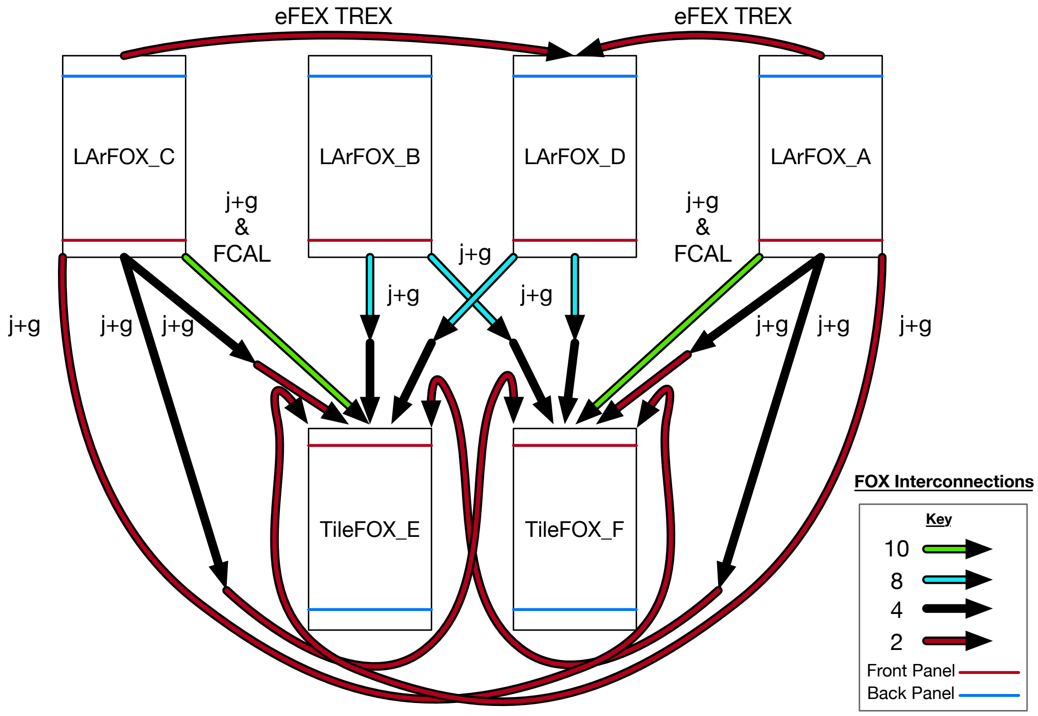


Figure 12: Interconnections between the different FOX boxes.

4 Hardware, Ribbons, Mapping Modules, and Connectors

4.1 FOX Boxes

This section describes the FOX box construction, and includes details about the dimensions, as well as the layout of the front and back panels of each. The physical mechanical components are explained below, as well as the technical details and the physical implementation of the FOX boxes.

As they relate to the physical implementation, the important points are:

- The large-scale global mapping of the overall FOX system between the front-end electronics and the FEX systems, is broken down into 6 medium size logical mapping sections, the FOX boxes.
- The mapping existing within each FOX box is further broken down into small-size mapping sections, the shuffle modules. There is a manageable total count of shuffle modules and a limited number of module types.
- Each shuffle module type is specified by its input and output connectors along with the mapping of input fibre to output fibre.
- The logical layout described above calls for up to 3 physical layers of shuffle modules inside each FOX box.

The vendor we selected, Sylex, is using small plastic shuffle boxes to hold and protect the mapping area of the shuffle modules, as shown in Figure 13. The FOX box enclosures need to contain and protect these fairly fragile shuffle modules, as well as support all input, output and internal MTP optical connections between optical cables and provide internal cable management. We chose the LArFOX B box (see Figure 9) to design our prototype box. The intention was to choose a FOX box type which was neither the most complex nor the simplest nor the densest and which would include all the difficulties and challenges present in any of the other box types. We are using the LArFOX B details for our prototype while we expect the resulting design to also be the final production version of the LArFOX B box. We further expect that the other FOX boxes will be very similar, possibly with small variations, while differing only in panel connectors location and lettering.

Chassis

Each FOX box is specified as a "19 inch" rack-mount "2U" chassis, 60 cm deep. The 19 inch format is imposed by the rack system in USA15. The "2U" height (3.5 inch or 44.45 mm) is a compromise allowing sufficient front panel space to support all needed MTP connectors and internal depth for manual assembly and maintenance while limiting the overall vertical rack space necessary to house all six FOX boxes. The 60 cm depth is a compromise between maximizing the usable internal volume for connecting 3 layers of shuffle boxes while still preserving enough space in the back of the rack for the management of bundles of optical cables coming from the detector electronics, bundles of cables going to the FEX crates and smaller bundles of cables interconnecting the 6 FOX boxes.

We are purchasing commercial empty chassis which we will customize in the Machine Shop of the Physics and Astronomy department of Michigan State University. The supplier we have tentatively selected for its custom size catalog choices is Par-Metal [4, 5]. We plan to mill holes in the front and back panels for the input and output MTP barrel adapters 14. We may ultimately decide to replace the stock thinner

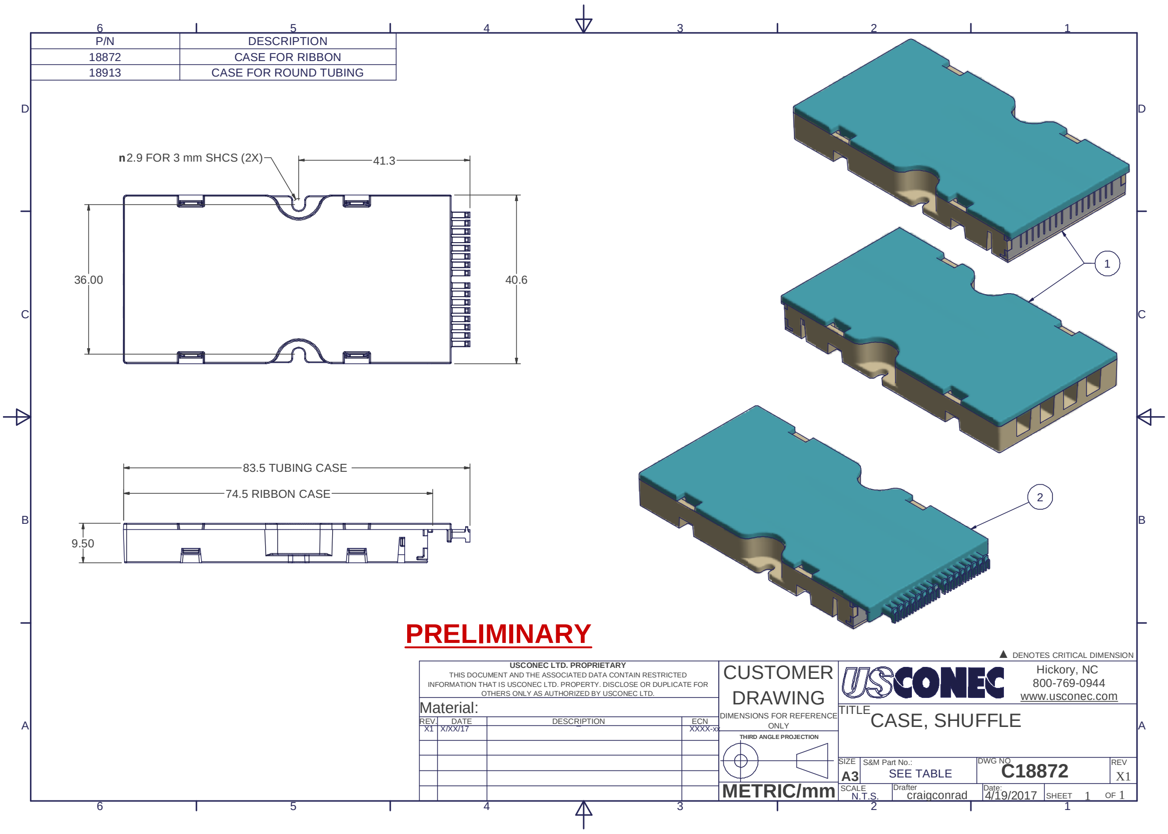


Figure 13: Plastic shuffle box produced by Sylex.

steel back panel with a thicker aluminum plate. We plan to paint the case and anodize the front panel. We also intend to add silkscreen lettering for the identification of each FOX box type and each connector location. MSU will also design and manufacture some custom components described below to hold the shuffle boxes and assist with internal cable management. These internal components will be affixed to the bottom plate of the FOX box chassis.

Shuffle Mapping Module Characteristics

The shuffle mapping modules are composed of 3 sections, as shown in Figure 15. The middle section is the plastic shuffle box itself which holds and protects the fragile fibers being mapped from one set of connectors to another set of connectors. One side of the shuffle modules has shorter cables made of one, two, four or six 12-fiber ribbons terminated by a 12-, 24-, 48-, or 72-fiber MTP connector. These cables are comparatively stiffer. In particular they do not bend laterally with respect to the plane of the ribbons. Optical fibres in general are very fragile and this side of the module is the most constraining. It will need to drive some of the implementation choices. We call this the Ribbon side (or R side) of the shuffle modules. Please note that the ribbon side of a module may be used as the input or output side of a given

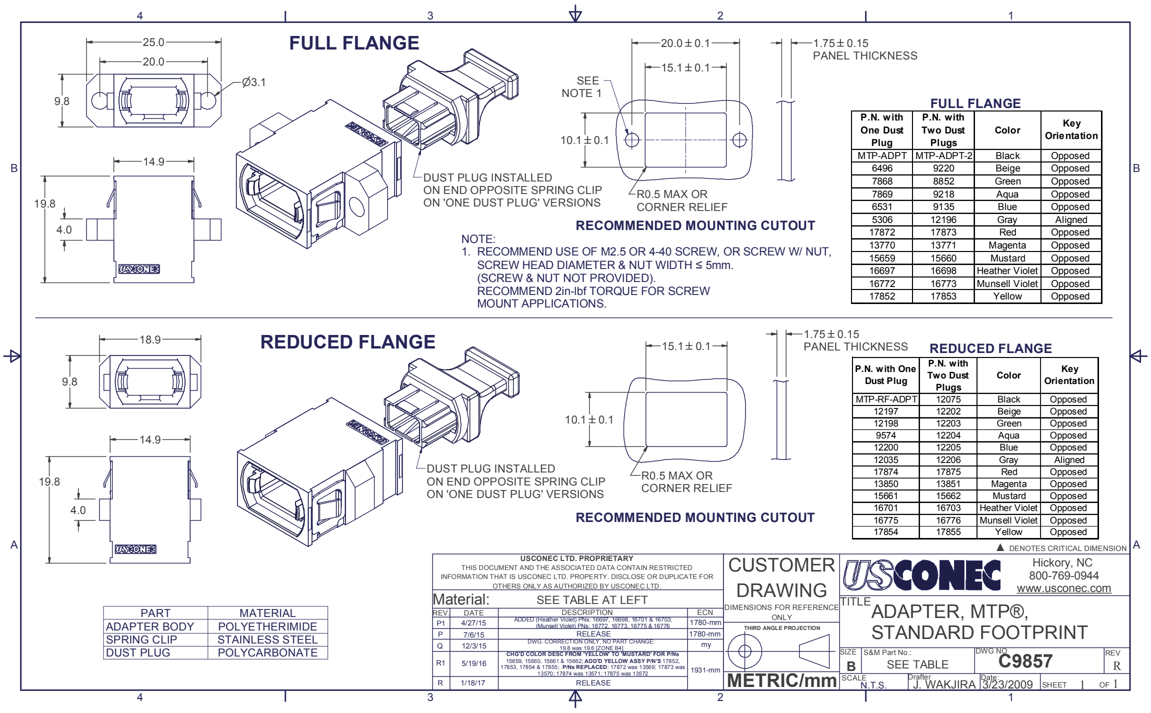


Figure 14: Sylex MTP connector footprint. All MTP connectors are Key-Up to Key-Down.

shuffle module within a FOX box, i.e. the input or output from the point of view of the photons traveling inside the 50 micron fibre cores. The other cable side of the shuffle modules has longer round cables with twelve, twenty-four, or forty-eight individual fibers covered with a protective over-tube stretching from the shuffle box to the terminating 12-, 24- or 48-fiber MTP connector. These cables are comparatively very flexible and can be easily routed to their destination without significant constraints. We call this the over-tubed side (or T side) of the shuffle modules. The over-tubed side of a module may be the input or output side of the shuffle module with respect to the FOX boxes and from the point of view of the photons. All of the shuffle boxes used MTP connectors that are Key-Up to Key-Down.

Rake Holders for Shuffle Boxes

The shuffle boxes and all inter-connections need to be held in place for mechanical protection and to help during assembly, shipping and servicing of the FOX boxes. Each row of shuffle boxes will be held in place with a pair of custom-designed parts we call “rakes”, as shown in Figure 16. These rakes are made from thermoplastic stock material of the type sold under the trade name Derlin. One of these rakes will be attached to the bottom of the box chassis. A row of shuffle boxes will be held vertically in the

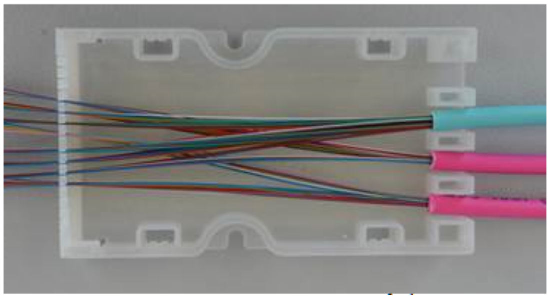


Figure 15: Sylex shuffle photograph.

grooves of the bottom rake and a second rake will be placed over the top and attached to the bottom rake at both ends. This will provide sufficient lateral and vertical spatial control of the row of shuffle boxes. If longitudinal control proves necessary, we will either make use of the grooves and notches present in the shuffle boxes or mill a perpendicular groove along the length of the rake and insert a rubbery strip for control by friction. The pitch of these rakes (the distance between shuffle boxes, center to center) is a critical design parameter as it control the density of shuffle boxes and drives the pitch of the front and back panel MTP connector placement. As described above, the ribbon side of the shuffle box is not very flexible and it is thus preferable to line up the shuffle box lateral placement with the lateral placement of the holes for the front panel MTP connectors.

The width of a front panel hole for an MTP connector is larger than the thickness of a shuffle box. Sufficient front panel material must also be allowed between neighboring holes to preserve the physical strength of the panel. Placing all MTP connectors side by side, with sufficient spacing, to hold 16 shuffle modules side by side as in the intended layout for LArFOX B would easily consume the whole front panel width. This would leave no room for the additional connectors needed on the front panel.

Reducing this rake and front panel pitch requires finding a workaround to leave sufficient material between neighboring panel holes. We also need to keep each set of shuffle module ribbon connector holes on the same vertical axis to prevent lateral ribbon cable bending. The solution consists in raising and lowering every other set of front panel holes for form a staggered pattern. This adds no additional stress to the ribbon cables as this is in the plane these cable can more easily bend.

The final pitch parameter was chosen to allow for 24 notches along the length of the rake. Up to 24 shuffle boxes could be held in one row, side by side. This means that the ribbon side connectors from all the layer of shuffle boxes nearest the front panel occupies only about two thirds of the front panel space. This leaves about one third of the front panel for all other necessary connectors. This particular choice of pitch helps further with two other aspects described below. A 3D rendering of the proposed front panel is presented in Figure 17.

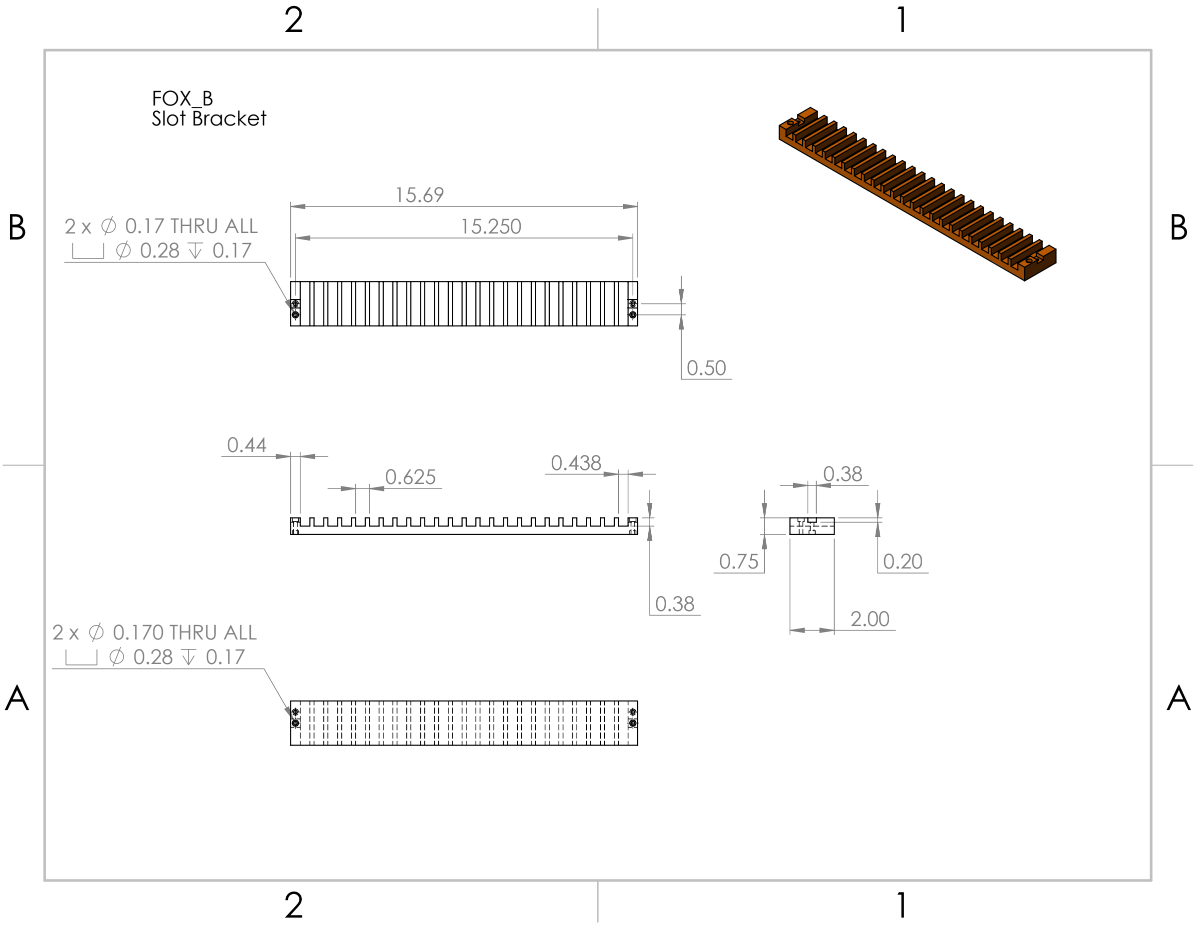


Figure 16: 3D rendering of the proposed shuffle box “rake”. Measurements are in inches.

Longitudinal Positioning of the Shuffle Layers

For the shuffle boxes positioned near the input or output side of the FOX box (iėthe first and the last layer) the ribbon side of the shuffle module will be connected to the front or back panel. The first and last layer or row of shuffle boxes will thus be positioned at a common appropriate distance from the front and back panels. This distance needs to allow a human hand to plug and unplug the cables on the internal side of the panel. This distance needs to allow sufficient cable bending to allow this connection and disconnection without damaging the fibres. At this time it is not totally clear if we should minimize the ribbon side length or lengthened it enough to allow one loop of the flat ribbon bundle. The criteria we use are minimizing the distance from the shuffle box to the front panel and minimizing the risk of damage while assembling and servicing the modules in the box. An isometric view of LArFOX B is provided in Figure 18.

The middle row of shuffle boxes cannot be placed in the middle of the FOX box chassis. This would not provide enough distance for connecting the cables from one row to the next as this needs to happen twice, once between the first and second row and again between second and third row. Instead we will position the middle row of shuffle boxes very close to the third row. This leaves sufficient space for cable management between the first and the second row. The connection between the second row and the third

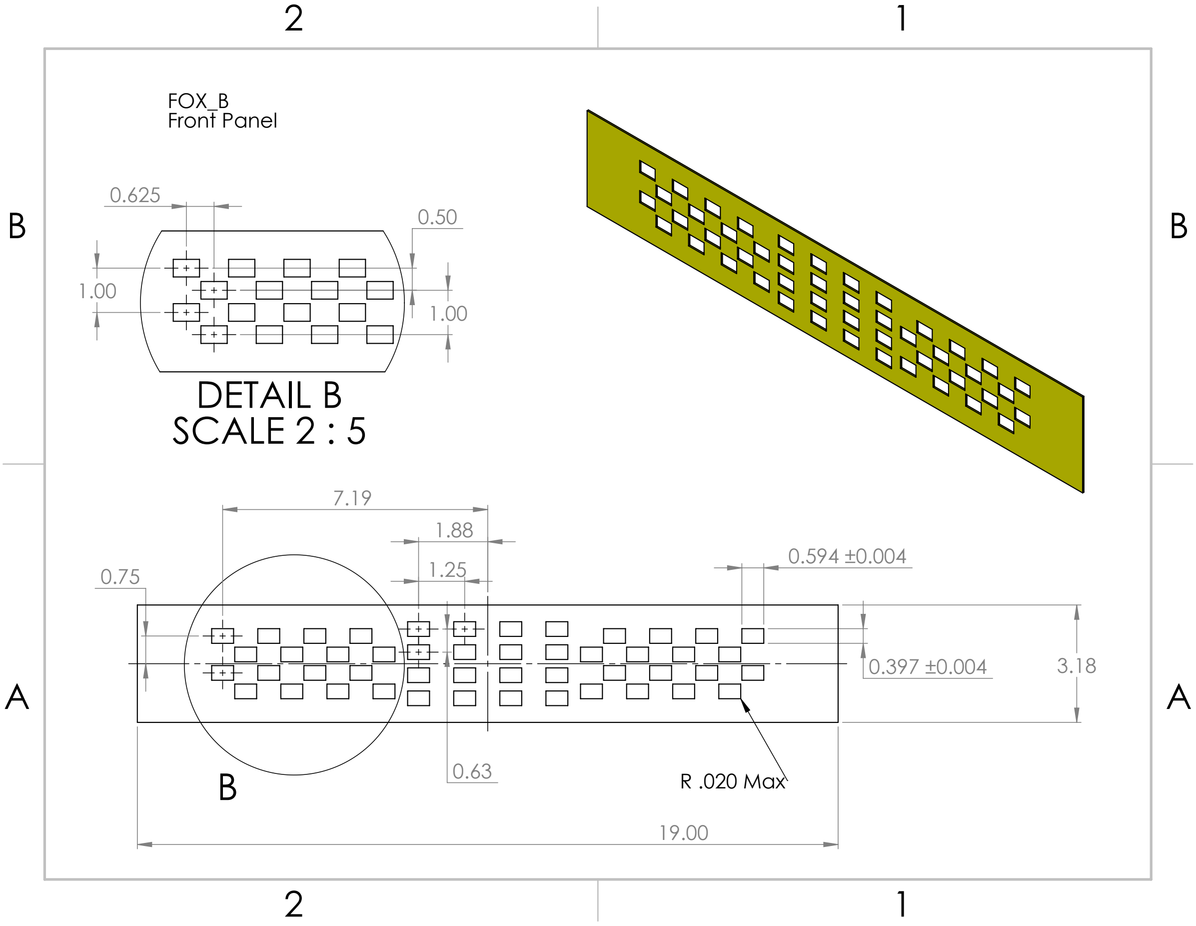


Figure 17: 3D rendering of the proposed LArFOX B front panel. Measurements are in inches.

row would firs seem impossible, but it is made possible by two factors.

The first enabling factor is the total count of 24 notches present on each rake while only 16 shuffle boxes are present in the second row and 8 shuffle boxes in the third row as show in LArFOX B figure XYZ. We place the group of shuffle boxes from the third row between the two groups of 8 shuffle boxes from the second row, just like in the logical diagrams. This means that no shuffle box from the second row is directly in front of or inline with a shuffle box from the third row. There is thus no interference between input and output fibers from the second and third row.

The second factor allowing the last two rows to be placed near each other is that the pitch of the rake holder leaves sufficient space between neighboring shuffle boxes for several over-tubed cables to be routed between neighboring shuffle boxes. The over-tubed cables out of the second row have enough room and no interference from the third row to loop back and squeeze laterally between their respective neighboring shuffle boxes and also vertically between the top and bottom rake holder components. The output of the second row can then loop again to meet and connect to the over-tubed side of the third row of shuffle boxes.

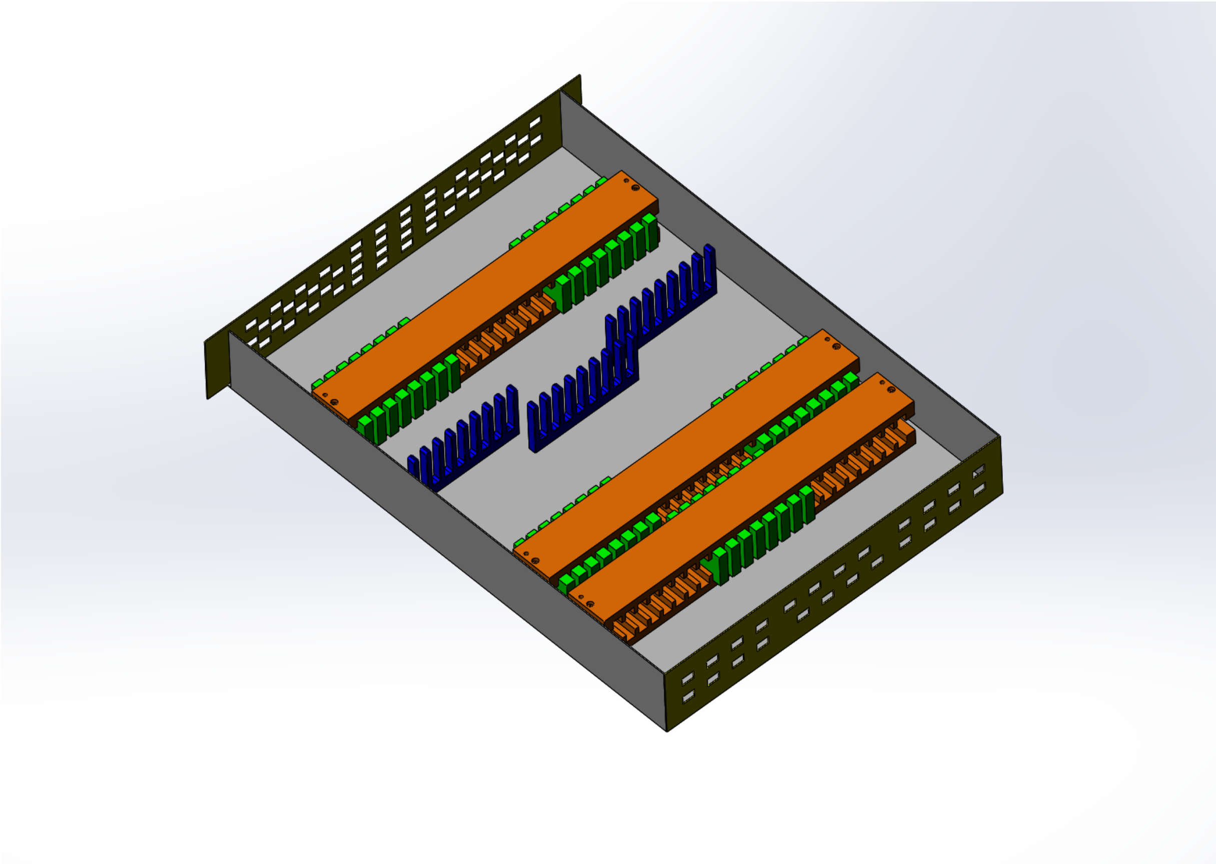


Figure 18: Isometric view of the proposed LArFOX B.

Comb Plates for Cable Management

The initial and most natural idea was to create internal patch panels, complete with holes and MTP barrel connectors. Such internal panels would bring a number of downsides. There are more connectors between internal layers than panel connectors which would thus require a lot of surface area and interfere with the path of other cables. Needing to plug and unplug connectors through these internal panels would require allowing physical space on both sides of the inner panels for hand and finger access and potential stress on the cables. Internal intermediate panels were thus deemed too cumbersome, too constraining, and would have increased the chances of damage during assembly or later servicing. The only perceived advantage would have been related to cable management with labeling on the panels, while any lettering would have been hard to read once fully assembled. The FOX boxes can certainly benefit from mechanical assistance and internal cable management, but this is primarily a concern for cable ordering during assembly and holding cable in place during shipment.

Instead of panels, we are designing and manufacture comb plates to attach to the bottom of the FOX boxes, as shown in Figure 19. The length of these coarsely toothed comb plates (finger-like) will be about one third of the width of the box. These plates will be positioned strategically to keep the cables internally ordered. All connector ends of all modules will be labeled by the manufacturer according to each type of mapping module. We can add our own additional identification labels with individual module numbering.

We can also use barrel connectors of different colors, and also label the barrel connectors themselves as needed.

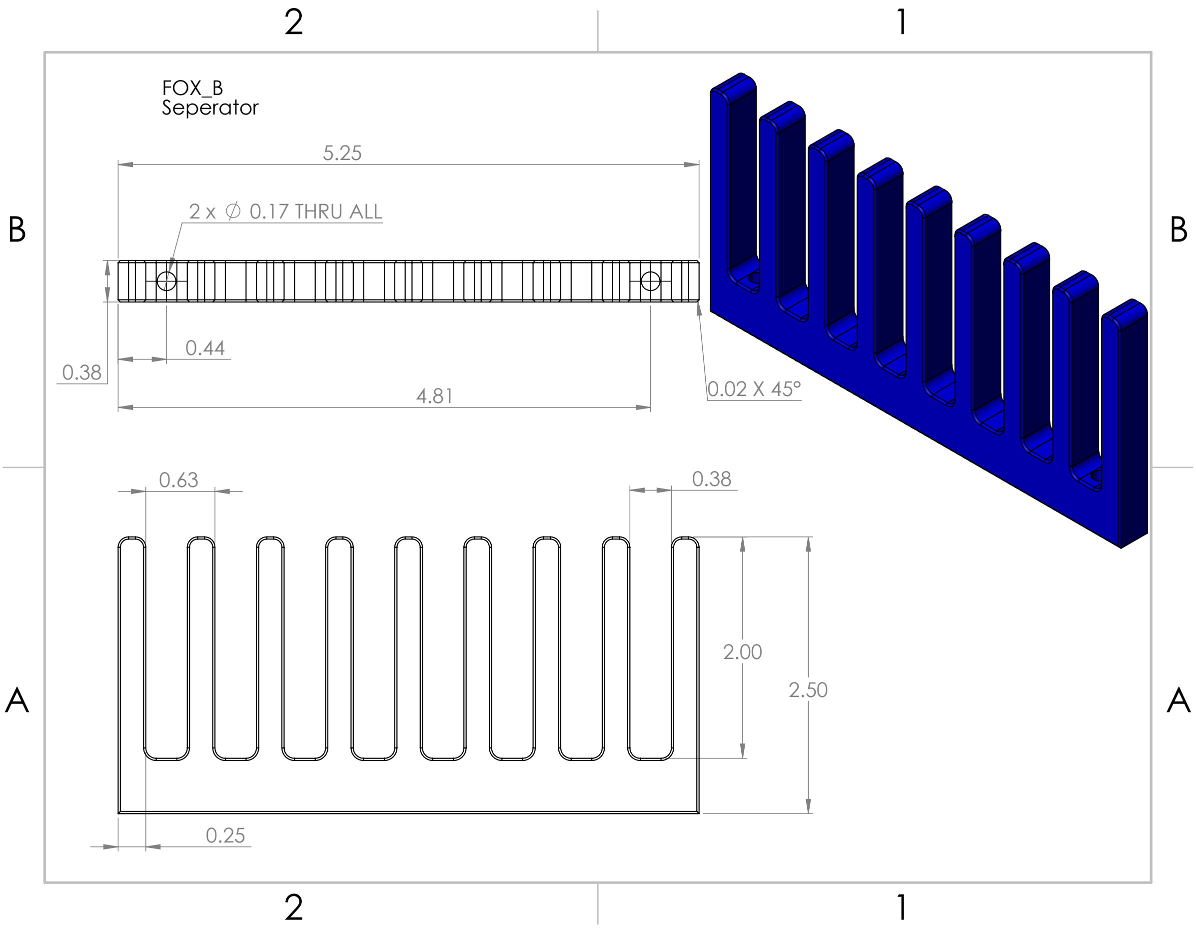


Figure 19: Schematic of cable management within the FOX boxes, which uses coarsely toothed comb plates. Measurements are in inches.

Current Status and Plans

- Have produced a set of mechanical drawings describing the rake holders and comb plates as well as their anticipated position inside the LArFOX B box chassis (see: https://web.pa.msu.edu/hep/atlas/l1calo/fox/hardw
- Have ordered one unfinished 2U chassis from Par-Metal. Will closely examine this first bare chassis and confirm it can form a suitable basis for FOX boxes.
- Will then make make any needed adjustments to the drawings. The MSU Machine Shop will produce one full set of internal rake and comb components.
- Currently have 4 samples of shuffle modules from Sylex (2 at MSU and 2 at CERN) which will be used to test and optimize the position of the rakes and combs inside the box before we commit to the position of their mounting holes through the bottom of the box.

- Are also planning on obtaining another 10 non-functional shuffle module samples to help with envisioning an planning for the total volume and local density of over-tubed cables and connectors inside the box. We will request a few variations in the length of the ribbon side of the shuffle modules. This will help with finalizing the parameters for the eventual final PO to Sylex.
- Will also use this intermediate step to verify or possibly adjust the location of the connector holes in the front and back panels. We will then produce one set of front and back panels for the LArFOX B.

By the time the above is complete, we will have produced one FOX box prototype. This prototype will also be a near final LArFOX B enclosure, missing only its surface finishing and lettering. This will be and empty enclosure, waiting for the installation and interconnection of actual shuffle modules. We should also have ordered and received a subset of optically correct shuffle assemblies which we can install in this prototype. We can verify the correct mapping of all fibres through these individual modules and through a total of three layers of shuffle modules. Ordering and assembling such small but representative subset of shuffle modules will verify that we have accounted for all implementation details and pitfalls, like the unavoidable fibre swapping through each MTP connections. This intermediate step will maximize chances of an error-free final shuffle box purchase order. It will also let us measure the total insertion loss through three layers of shuffle modules for a representative set of channels.

Other FOX Boxes

In parallel while finalizing and producing the LArFOX B box prototype we will also prepare drawings for the layout of the other FOX boxes. We expect that the rake and comb plate design can apply to all FOX boxes. We expect that the location of the rake and comb plates will also be common among all FOX boxes, but this needs to be closely studied. The commonality in front and back panels layouts to simplify and limit the number of different panel layouts will also be studied. The lettering can be tailored to each panel while the hole locations will hopefully be common to more than one FOX box type.

Logical view

This sections lays out the front and back panel connections in a logical way, while the previous section gave the specific details on what the final hardware will look like.

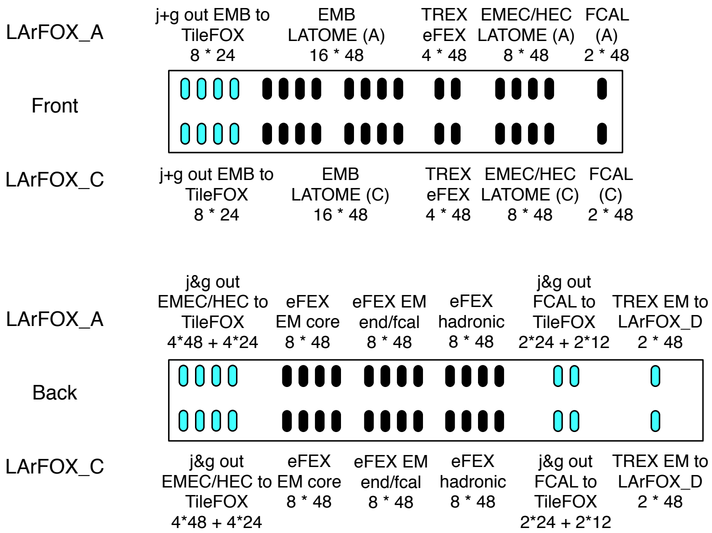


Figure 20: Front and back panel layout for LArFOX A and LArFOX C.

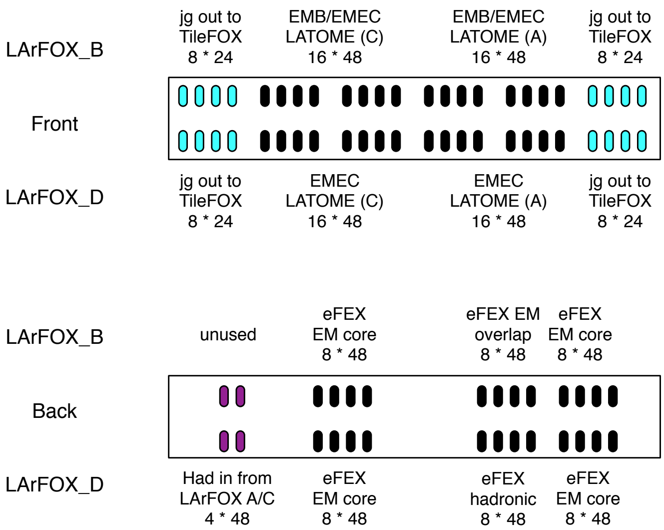


Figure 21: Front and back panel layout for LArFOX B and LArFOX D.

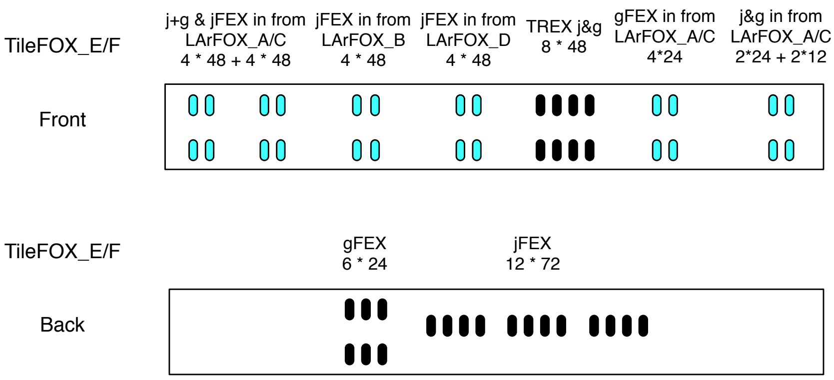


Figure 22: Front and back panel layout for LArFOX E and LArFOX F.

4.2 Ribbon Types and Numeration

This section describes the different types of ribbon/assembly and counts the number of them used in each FOX box to give a total count for the whole FOX system.

There are a total of 27 types of assembly. Figures 23 and 24 provide the name of each assembly type, together with the number of input and output connectors, and the MTP connector type for each. Table 7 then provides the number of each ribbon type in each FOX box, and the total of each assembly type for the FOX system. The total number of assemblies overall is 212.

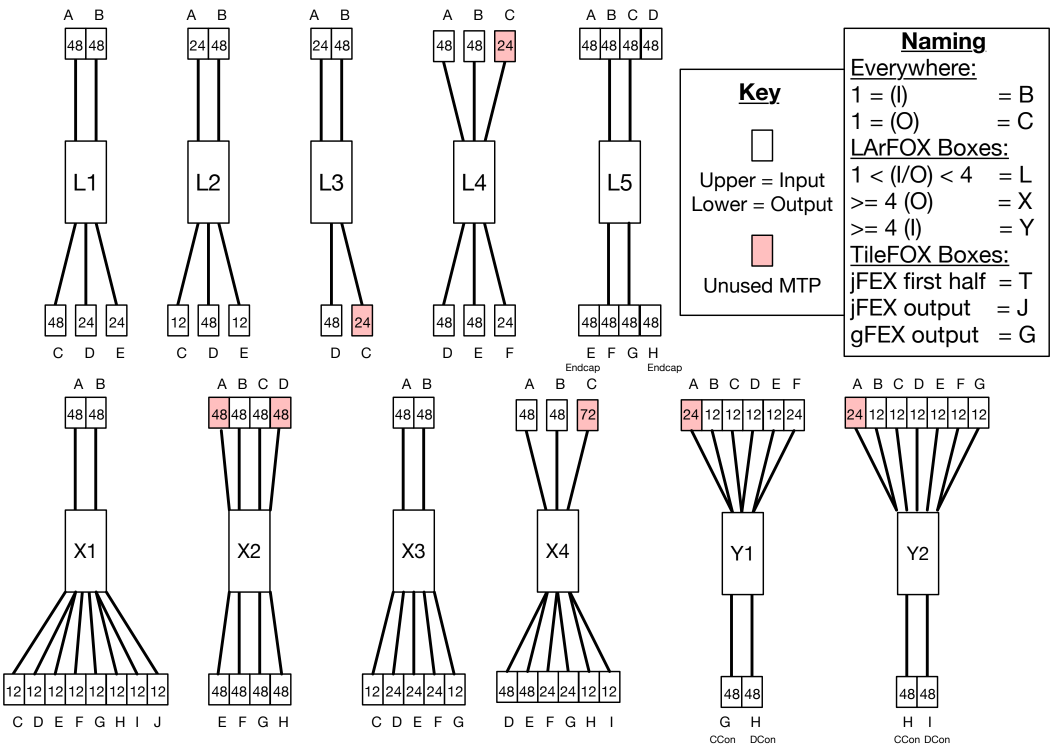


Figure 23: Assembly types part one.

The purpose of each assembly type is describe below, while the next section describes the precise fibre-by-fibre mapping of each ribbon, and the final output fibre order sent to the FEXs.

- L1-Type: Take EMB0 and EMB1, separates out 7+3, and j+g from e.
- L2-Type: Takes L1-Type, organises from rows to columns, and outputs to FEX. Overlaps go to C1-type.
- L3-Type: Similar to L2-Type, but with no overlaps. Output to eFEX C (ACon) or eFEX A (BCon).
- L4-Type: Splits out EMEC/HEC inputs into eFEX, jFEX, gFEX separately.

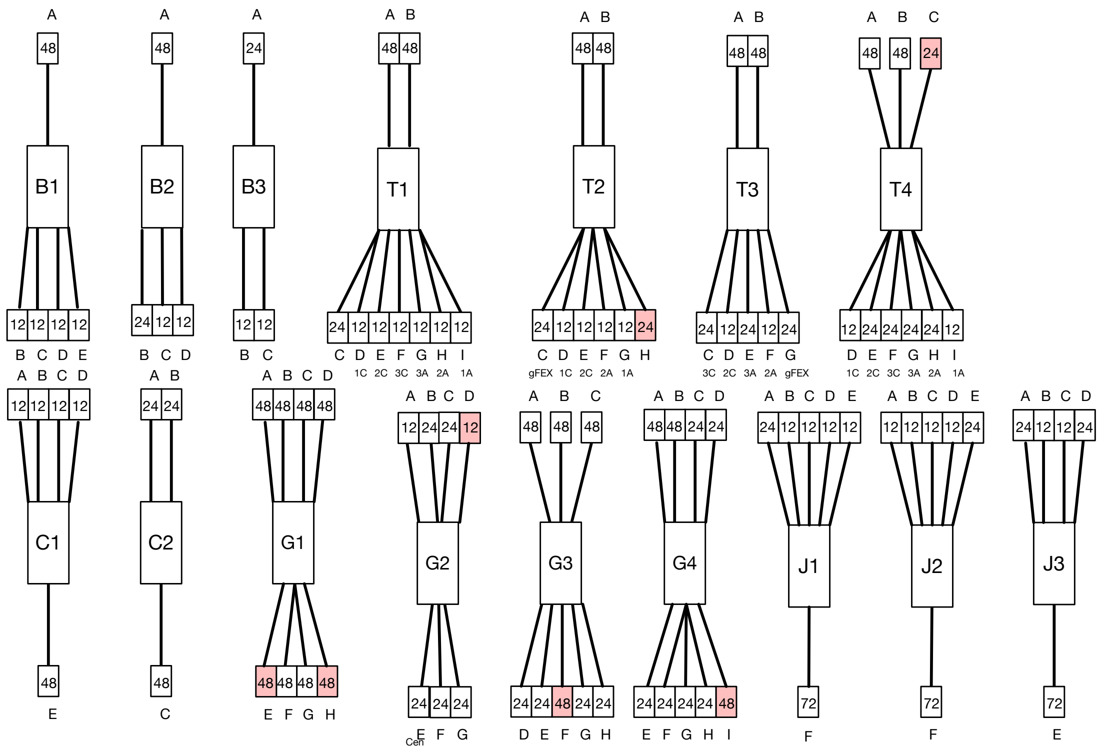


Figure 24: Assembly types part two.

- L5-Type: Split TREX eFEX inputs into Barrel and Endcap FEX outputs. Read off in columns: 2,1,2,1,noneX6, or 2,1,2,1,2,1,2,1. Includes wrap around for barrel (4 complete FEXes for each output to LArFOX D). Output connectors have to be flipped depending on A or C side.
- C1-Type: Takes overlaps for Barrel eFEX, simply brings them together and outputs to FEX.
- C2-Type: Takes gFEX from EMB/EMEC, EMB, EMEC. Each input always has the same pattern, even though they are from different sources. Ribbon simply splits them into all original, then all spare, then all none fibres. It does also make sure that all C-side are next to each other, followed by all A-side, within each group.
- X1-Type: Takes TREX eFEX Endcap fibres, and splits them into outputs to 8 FEXs on one side (C or A). This ribbon includes the wrap around in Phi.
- X2-Type: Input TREX eFEX for Barrel from LArFOX A/C, combines into eFEX barrel outputs (HadCon / DCon). First and last input legs take the empty half from the 4 outputs. Each ribbon feeds 4 complete FEXs (including wrap around) covering all eta and half phi.
- X3-Type: Takes EMEC/HEC inputs from half phi on one side (A or C), and splits them into 4 FEX outputs (fed into next ribbon, to collect other fibres on that output).
- X4-Type: Take FCAL1 and FCAL2 inputs, split them into two phi halves for eFEX, jFEX, gFEX.

Table 7: Numeration of the various assembly types throughout each FOX box and for the overall FOX system. There are a total of 27 assembly types, and 212 assemblies overall.

Type	LArFOX B	LArFOX D	LArFOX A+C	TileFOX E+F	Total
L1	16	16	16	-	48
L2	16	-	-	-	16
L3	-	16	16	-	32
L4	-	-	8	-	8
L5	-	-	2	-	2
X1	-	-	2	-	2
X2	-	2	-	-	2
X3	-	-	4	-	4
X4	-	-	2	-	2
Y1	-	-	12	-	12
Y2	-	-	4	-	4
B1	-	-	4	-	4
B2	-	-	-	8	8
B3	-	-	-	4	4
C1	8	-	-	-	8
C2	-	-	-	6	6
T1	-	-	-	4	4
T2	-	-	-	4	4
T3	-	-	-	4	4
T4	-	-	-	4	4
G1	-	-	-	2	2
G2	-	-	-	4	4
G3	-	-	-	2	2
G4	-	-	-	2	2
J1	-	-	-	8	8
J2	-	-	-	8	8
J3	-	-	-	8	8

- B1-Type: Takes FCAL1 and FCAL2 inputs and spreads to 4 FEXes (half phi, on one side). EM and Had inputs are split out later.
- B2-Type: Takes EMEC/HEC input for jFEX from LArFOX A/C and splits out into the different jFEX outputs.
- B3-Type: Takes FCAL input from LArFOX A/C and outputs to ribbons that feed the A or C side outer jFEXs, two quadrants each ribbon.
- T1-Type: Takes EMB/EMEC jFEX+gFEX from LArFOX B which includes A and C side, splits off gFEX, and also splits to all 6 jFEX outputs for one quadrant. “Nones” might be a bit awkwardly placed currently.
- T2-Type: Takes EMEC jFEX+gFEX from LArFOX D which includes A and C side, splits off gFEX, and also splits to the outer 4 jFEX outputs for one quadrant. “Nones” might be a bit awkwardly

placed currently.

- T3-Type: Takes EMB jFEX+gFEX from LArFOX A/C which includes A and C side, splits off gFEX, and also splits to the inner 4 jFEX outputs for one quadrant. “Nones” might be a bit awkwardly placed currently.
- T4-Type: Takes TREX jFEX inputs and splits them into all jFEX outputs for one quadrant.
- G1-Type: Takes TREX gFEX inputs and splits them into the two central gFEX outputs for half phi. “Nones” could be optimised further.
- G2-Type: Takes gFEX inputs from FCAL and EMEC/HEC and splits them into the central and outer gFEX outputs for half phi, plus spare outputs. 5 EM fibres from each FCAL side: 1 per quadrant + 1 for $3.1 < |eta| < 3.2$ across all phi. Can keep symmetric by sending an extra none on the other side.
- G3-Type: Takes gFEX inputs from EMB/EMEC, EMB, EMEC, after each having already been arranged into: all original, all spare, all none fibres, due to the C2 type. Passes to gFEX connectors for EM central.
- G4-Type: Takes gFEX inputs from TREX and EMEC/HEC to combine for the specific central hadronic output to gFEX.
- Y1-Type: Takes all eFEX inputs up until now, and splits them into Connector D and C types for Endcap A or C eFEXs. Currently read in columns of eta, from outer to inner detector. Also read as 3+7 in those columns.
- Y2-Type: Modified Y1-Type, to take 2 x 12 way overlap inputs from X3, instead of 1 x 24 way.
- J3-Type: Takes all central jFEX fibres for one quadrant, and outputs to jFEX. EM giving in rows, Had giving in columns per octant.
- J2-Type: Takes all middle jFEX fibres for one quadrant, and outputs to jFEX. EM giving in rows, Had giving in columns per octant.
- J1-Type: Takes all outer jFEX fibres for one quadrant, and outputs to jFEX. EM giving in rows, Had giving in columns per octant.

4.3 Ribbon Mappings

This section describes the ribbon mapping and also gives the final output order of the fibres as they leave the FOX system and are input into the respective FEXs. The fibre-by-fibre mapping for each ribbon type can be found from Ref. [6]. Following the definition of the FEX input connectors in Table 4, Figure 25 details the fibre output order for the various eFEXs, while Figures 26, 27, and 28 provides the same for the jFEXs and Figure 29 for the gFEX.

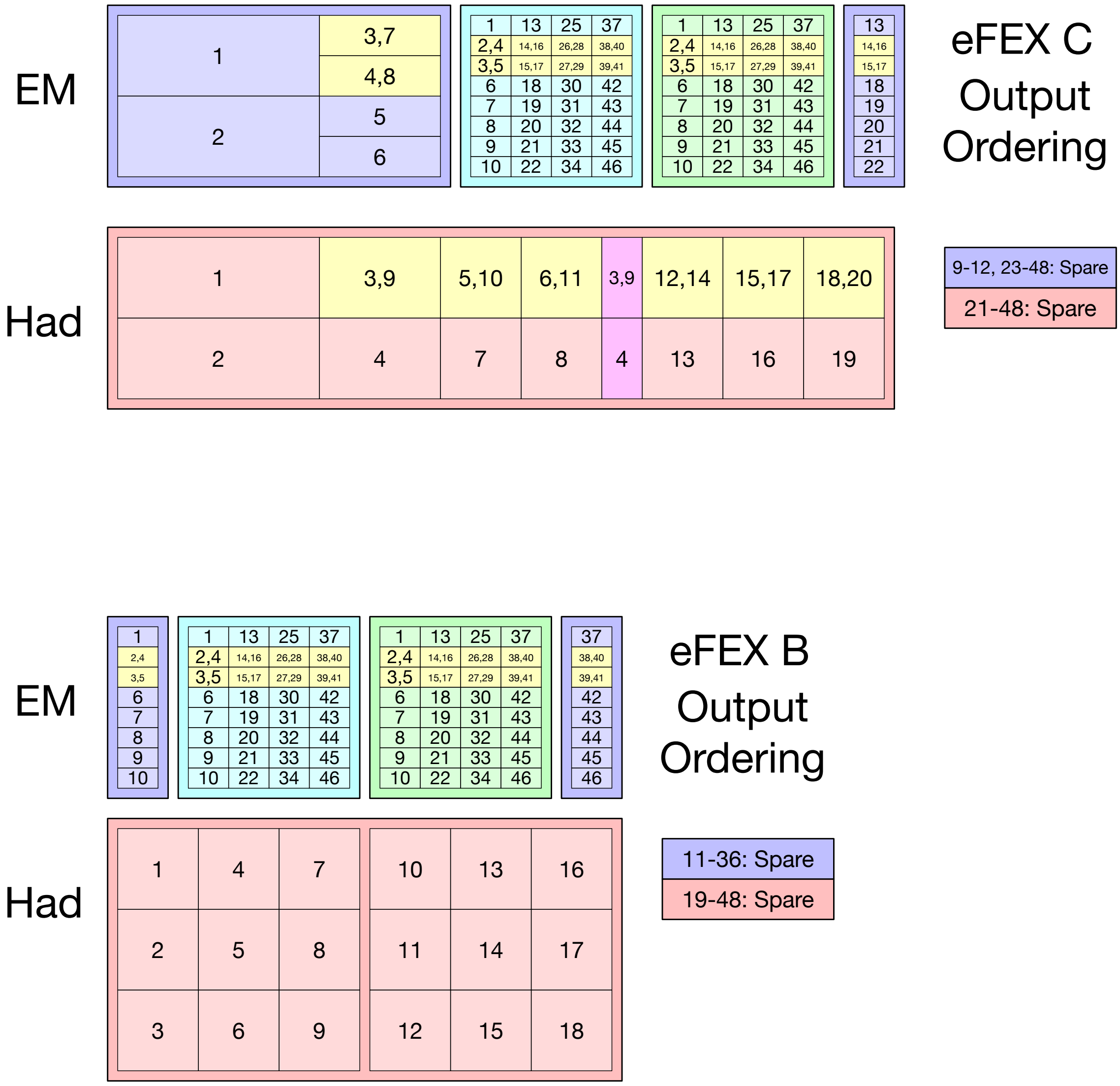


Figure 25: Fibre order of the output from the FOX system to the different eFEX connectors.

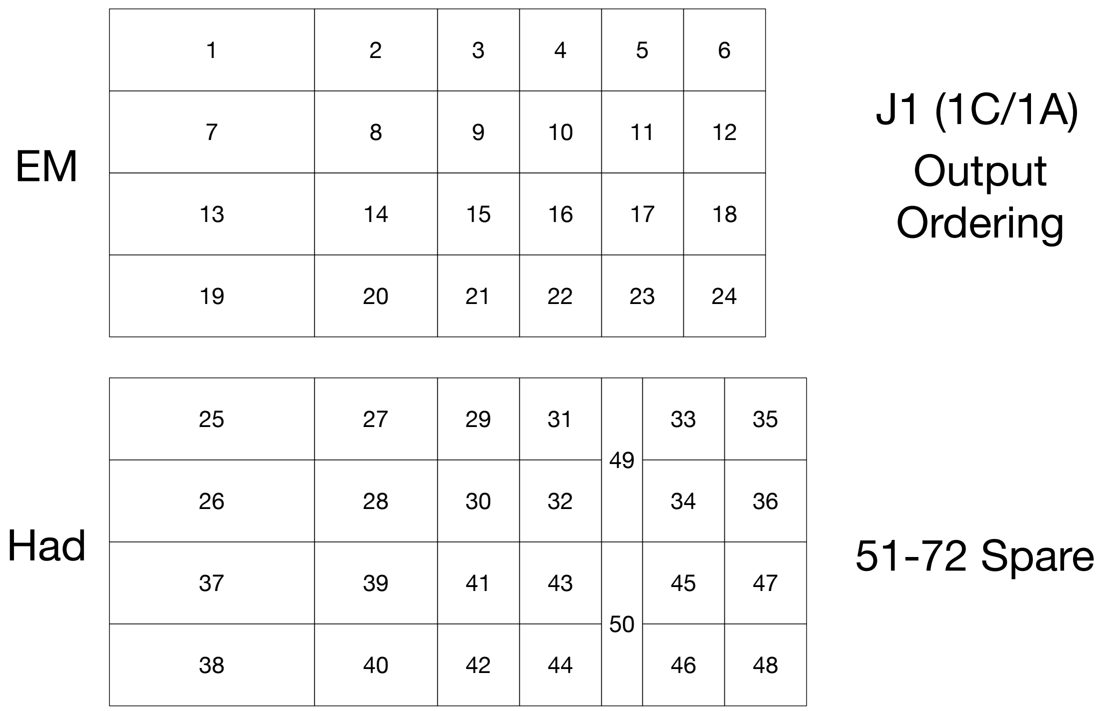


Figure 26: Fibre order of the output from the FOX system to the different jFEX connectors.

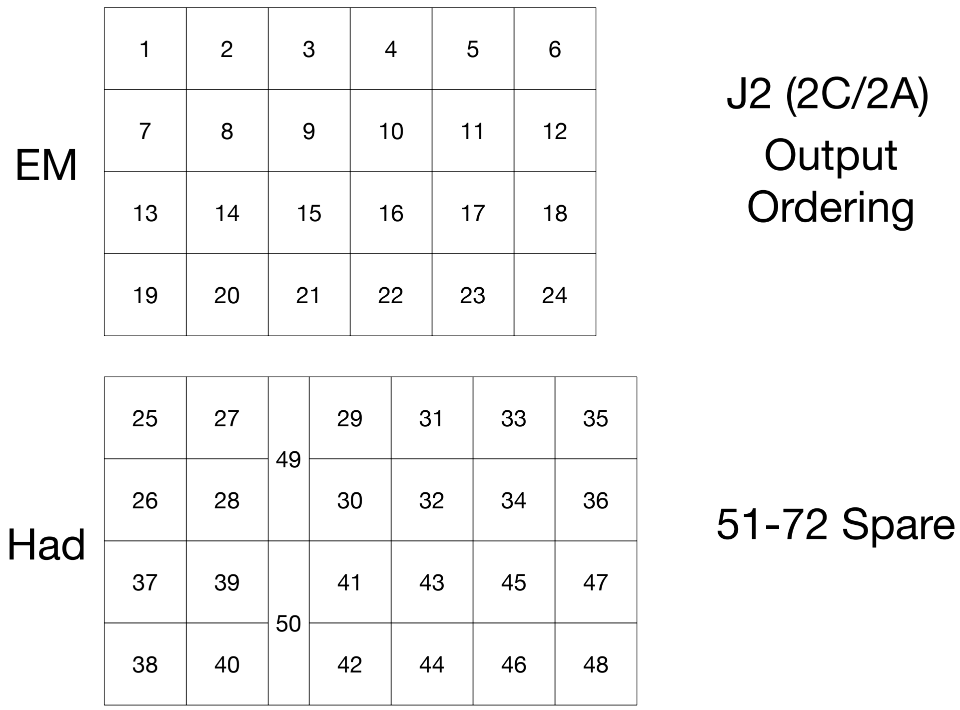


Figure 27: Fibre order of the output from the FOX system to the different jFEX connectors.

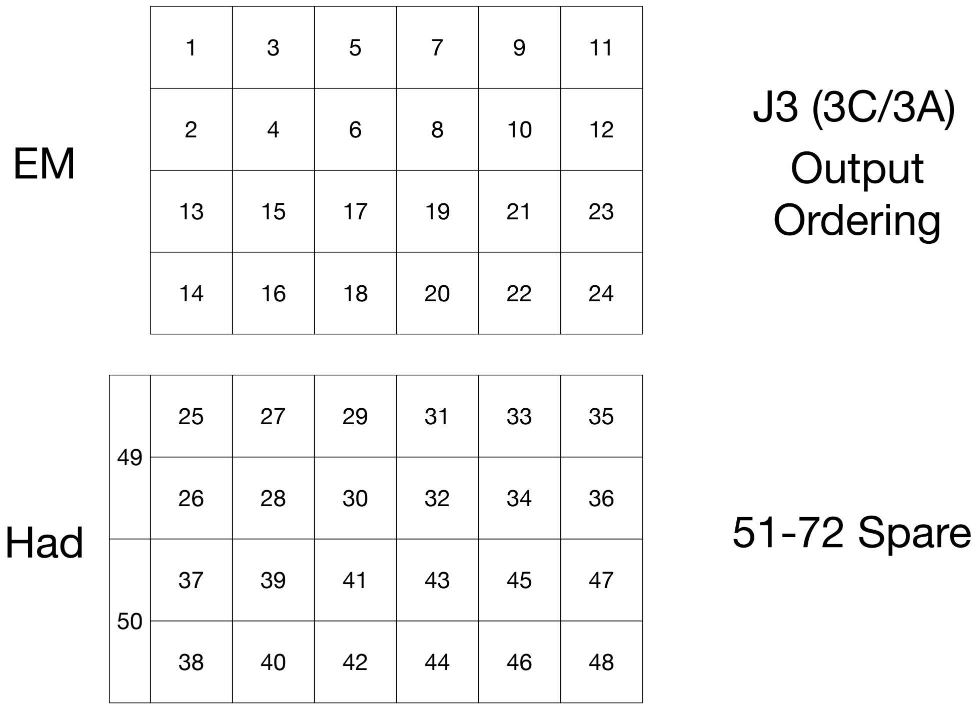


Figure 28: Fibre order of the output from the FOX system to the different jFEX connectors.

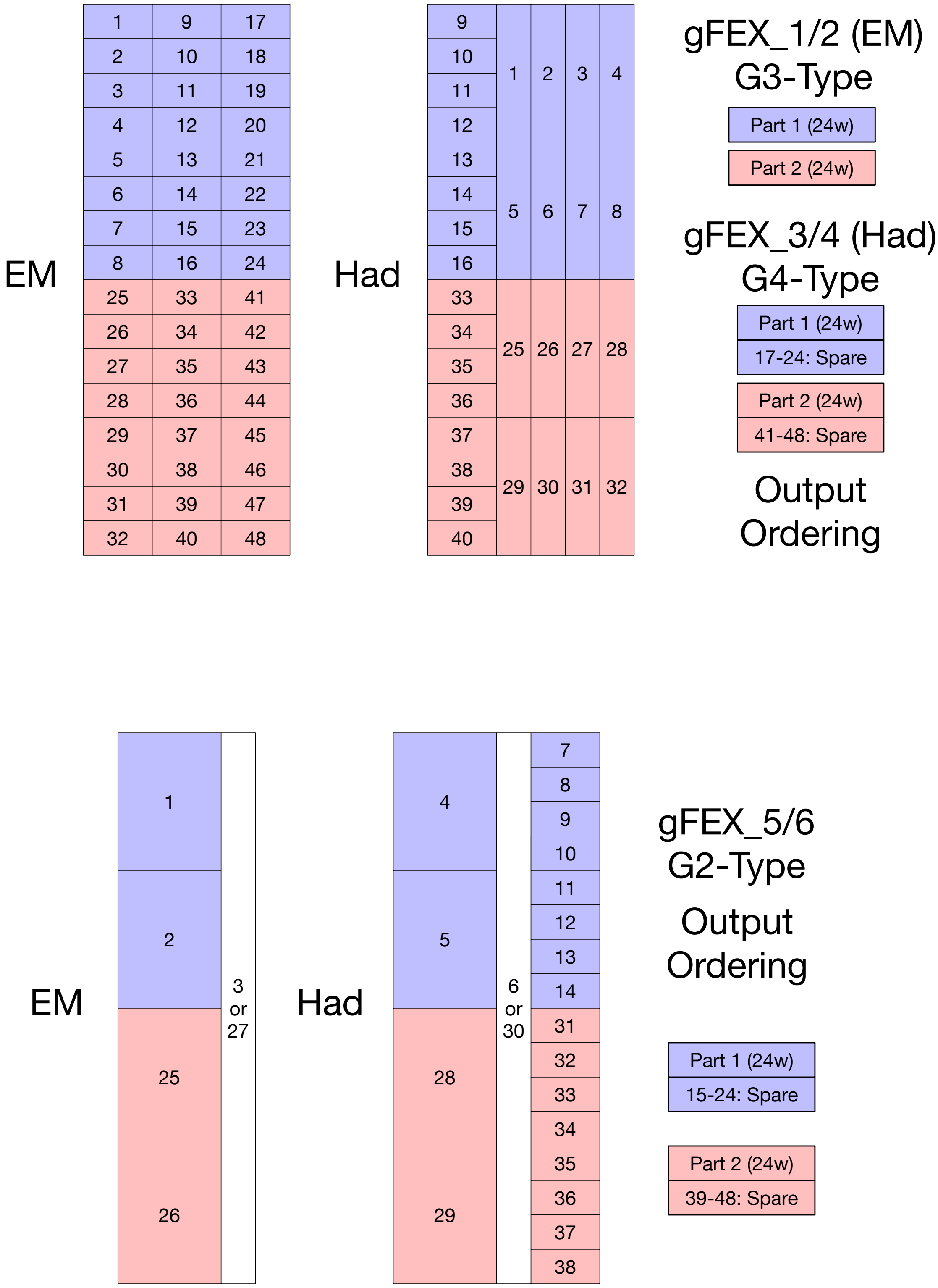


Figure 29: Fibre order of the output from the FOX system to the different gFEX connectors.

4.4 Connectors

This section presents the layout of the different FEX connectors, in terms of detector coverage.

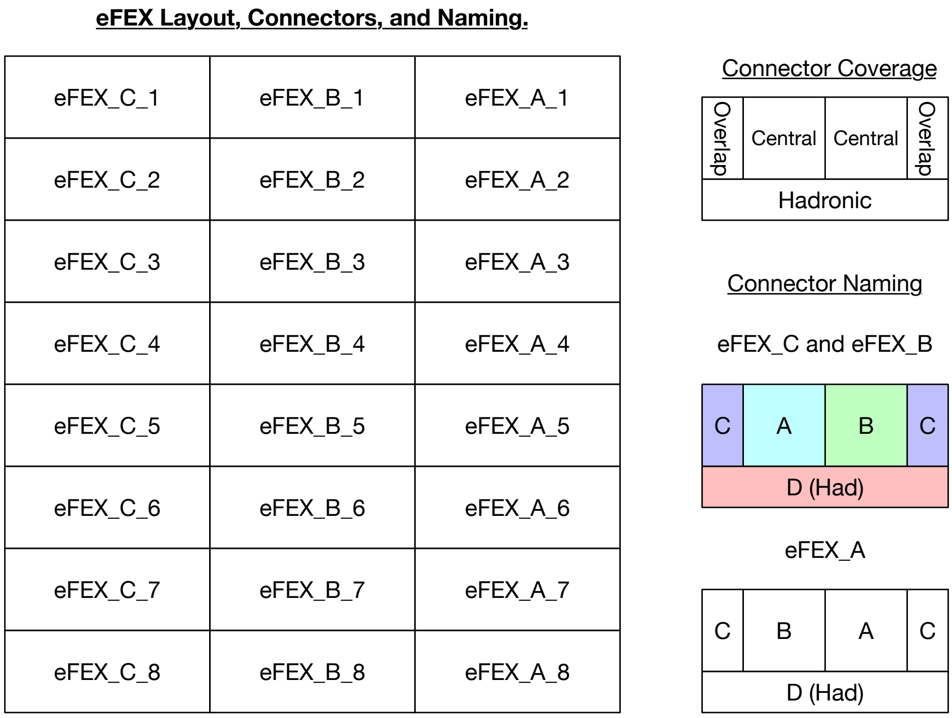


Figure 30: eFEX connector layout.

jFEX Layout, Connectors, and Naming.

jFEX_1C Con1	jFEX_2C Con1	jFEX_3C Con1	jFEX_3A Con1	jFEX_2A Con1	jFEX_1A Con1
jFEX_1C Con2	jFEX_2C Con2	jFEX_3C Con2	jFEX_3A Con2	jFEX_2A Con2	jFEX_1A Con2
jFEX_1C Con3	jFEX_2C Con3	jFEX_3C Con3	jFEX_3A Con3	jFEX_2A Con3	jFEX_1A Con3
jFEX_1C Con4	jFEX_2C Con4	jFEX_3C Con4	jFEX_3A Con4	jFEX_2A Con4	jFEX_1A Con4

Figure 31: jFEX connector layout.

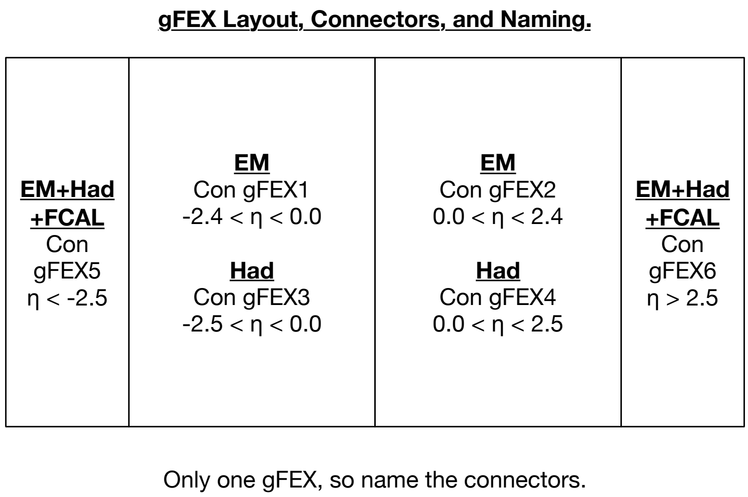


Figure 32: gFEX connector layout.

5 FOX Demonstrator

Many configurations of light loss have been tested with MiniPOD transmitters and receivers on the CMX board, both at Michigan State University (for individual connectors and cables) and at CERN (with the FOX demonstrator). The FOX demonstrator is the prototype FOX that has been used for prototype-integration tests with LAr cards and the different FEX modules, as well as for light loss tests. Figure 33 shows a picture of the demonstrator at CERN, as well as a diagram of the setup. The source in this example is a CMX with 12 fibers, but connections with 48 input fibers as well as with 48 or 72 output fibers were also tested. The breakout cables provide the possibility for mapping, while the number of MTP connectors is representative of the final system. Additional elements such as attenuators and additional MTP cables can also be added.

The tests with the CMX board run at a link speed of 6.4 G, while tests with the LAr LATOME use 11.2 G and those with the FTM 11.2 G and 12.8 G. The light loss characteristics do not depend on the link speed.

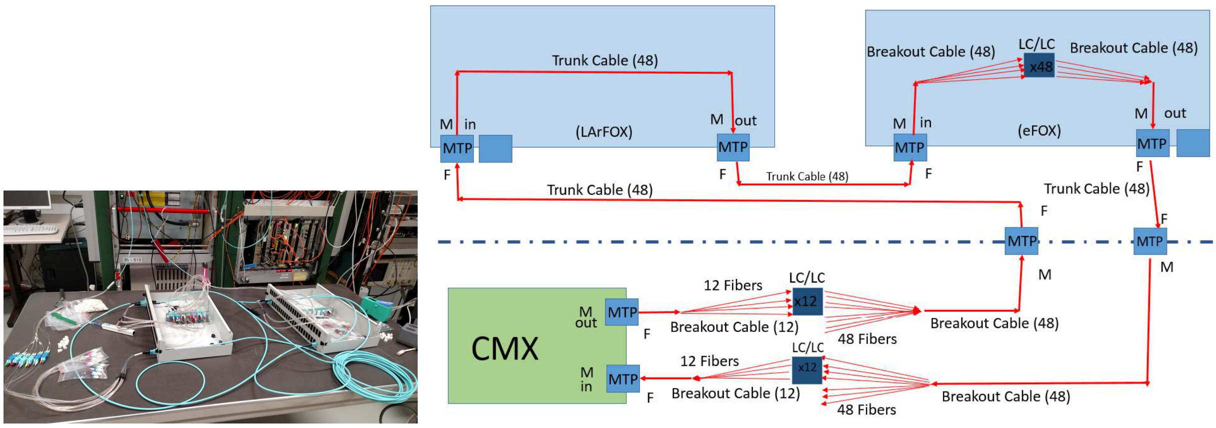


Figure 33: (Left) Picture of the FOX demonstrator boxes and the test stand at CERN, (right) diagram of the optical connections in the demonstrator.

5.1 Light loss tests

Optical power tests and measurements of the light loss through the FOX have been done with the MiniPODs on the CMX board, with prototype LATOME, FTM and FEX cards, and with a FLUKE optical power meter (SimpliFiber Pro, which includes both a DC source and an optical power meter). The results are consistent with each other, though the FLUKE meter consistently shows a light loss about 1 dB larger than the tests with MiniPODs. This is likely due to the connector type in the FLUKE, since this value is found not to change with changes in the setup, it stays at a difference of about 1 dB even when additional cables and connectors are added.

In tests at MSU, the light loss in individual fibers for MTP cables and combinations of connectors have been tested, including 24, 48 and 72-fiber connectors. Variations in receiver optical power are small, the optical power budget at the receiver end is relatively stable. The following light loss and variations of optical power have been observed:

- 0.2 dB to 0.4 dB for disconnecting and reconnecting MTP connectors, including with intermediate cleaning.
- 0.2 dB for a temperature increase from 36.4 to 38.2 degrees Celsius.
- 0.9 dB variation between different MiniPod receiver channels.
- 3 dB light loss for an optical splitter, though this is not used in the final system.

The light loss of the MTP connectors is nominally around 0.2 to 0.3 dB for MTP elite connector, but tests have shown that it is typically smaller, and 0.3 dB per connector is the extreme. In one test, the light loss for a setup with LATOME and gFEX for 8 MTP connectors and 3 LC connectors gave 3.5 dB as the extreme and 1 dB as the typical light loss. For a normal MTP connector, attenuation could be as high as 0.65 dB (compared to 0.3 dB for the MTP elite connector).

Bit error rate (BER) tests with variable attenuation reveal that channel synchronization is lost and regained and the BER rate becomes unacceptable around an attenuation of 8-10 dB. This test was done both with the MiniPods on the CMX and with the FTM-jFEX setup. There is a difference of about 2 dB between attenuation for which the MiniPODs on the CMX lose sync and regain sync. In a further study, the BER was measured as a function of light loss. The slope is approximately linear on a log-BER vs light loss plot, with a BER of about 10^{-15} per fiber reached at between 8 dB and 10 dB, and a BER of about 10^{-15} per fiber reached at an attenuation of about 10^{-10}.

5.2 System tests with prototype source and sinks

The FOX demonstrator was also tested in a setup with the jFEX prototype and the LATOME or FTM providing inputs, as shown in Figure 34 [7–9]. The setup of 48 channels was run at 11.2 G. In this setup, two FOX demonstrator boxes together with interconnects and internal mapping were used. The BER of this setup was better than 10^{-16} for the complete setup. The light loss through this system was measured to be 0.5 to 1 dB with the MiniPods and 1-2 dB with the Fluke meter.

In the test with the gFEX [7], the open area of the eye diagram was also found to be sufficiently large at all link speeds. In the test with the eFEX [8], the open area of the eye diagram was found to decrease by about 20% when increasing the link speed from 6.4 G to 12.8 G. These tests also showed that proper connector handling is important, all the way from transmitter to receiver.

In an additional test with the jFEX and the FTM [9], the signal rate was increased to 12.8 G and 60 input links were used, and again the total BER was better than 10^{-16}. And in another test with the jFEX, additional attenuators were added (5 db each). With one attenuator (5 dB additional attenuation), the system still passed tests, only with two attenuators (10 dB additional attenuation) did errors appear.

In summary of the light loss tests, the typical light loss was found to be about 1 db, though nominal light loss is 0.25 dB per connector, or about 2-3 dB expected total. The optical power available was confirmed to be 8-10 dB. Attention needs to be paid to fiber and connector handling in order to avoid deteriorating the connectors which might lead to failed connections for individual or groups of fibers in a connections.

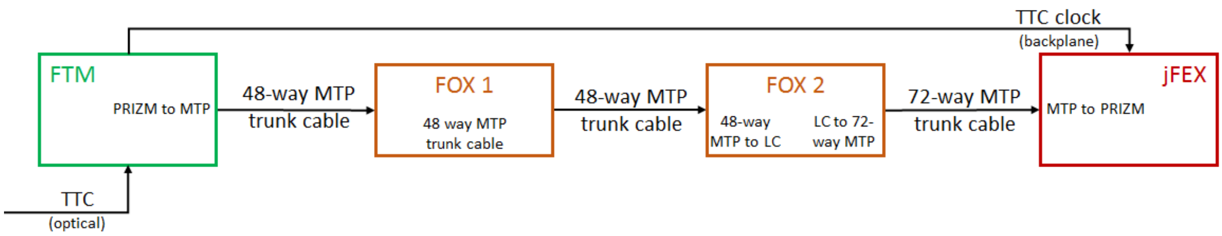


Figure 34: Setup to test the FOX demonstrator with the jFEX. The first element (providing the optical signal) was either a FTM as shown or a LATOME. In both cases, 48 fibers on a trunk MTP cable were connected.

6 FOX Assembly and Handling Procedures

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7 Timeline and Testing Procedures

This section describes the timeline and planned testing procedures.

- Mid-October: Initial Cost Estimate for Full system from Sylex.
- Early November: First metal box (LArFOX B) produced at MSU. L1Calo Review, to get approval to order subset of assemblies for physical tests.
- December: All metal boxes produced at MSU (LArFOX A/C, LArFOX D, TileFOX E/F). Narrow pass through for all boxes arrives at MSU, i.e. an adequate subset (and spares) of assemblies to test mapping and light loss tests.
- End of January: Assembly and Tests done at MSU (as described above).
- February: Show results in L1Calo Meeting / PRR, and seek approval to order all remaining components from Sylex.
- March-April: Components arrive at CERN.
- April-May: Assembly and testing at CERN, i.e. octopus cables connected to test all mapping paths, some light loss tests of the whole system, possibly even connection to some real latome and FEXs on the surface for full test. At this point, official task completed.
- Afterwards: Provide "7th" box for Surface Test Facility to use, containing a simple set of ribbons that go from a Latome to a variety of FEXs.
- Fall-Back time allowed in the schedule: 3 months.

8 Conclusion

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References

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Auxiliary material

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