ORGANISATION EUROPEENE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

GENEVE, SUISSE
GENEVA, SWITZERLAND

CMS Tracker Optical Links

Quality Assurance Manual

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K. Gill, J. Troska, F. Vasey[†]
CERN

[†] Contact: francois.vasey@cern.ch

1 Introduction

This document reviews the procedures implemented to ensure the quality of the CMS tracker optical links. It explains how we intend to qualify products and validate production batches, while remaining in-step with the tight assembly schedule of the CMS Tracker. It gives the quantities to be ordered as well at the number of samples to be reserved for qualification and validation of the production batches. The production flow and scheduling is described, along with the testing systems required. Finally, it discusses the various means to archive results and documents in databases, reports and technical notes.

Beyond this document, we believe the quality of the CMS-tracker optical link will be driven by the thoroughness of the technical investigations, by the commitment of the personnel that have developed it and will commission it, and by the good relationship with the industrial partners manufacturing the components.

Document history:

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2 System description

A block diagram representing the CMS Tracker readout and control systems is shown in Figure 1.

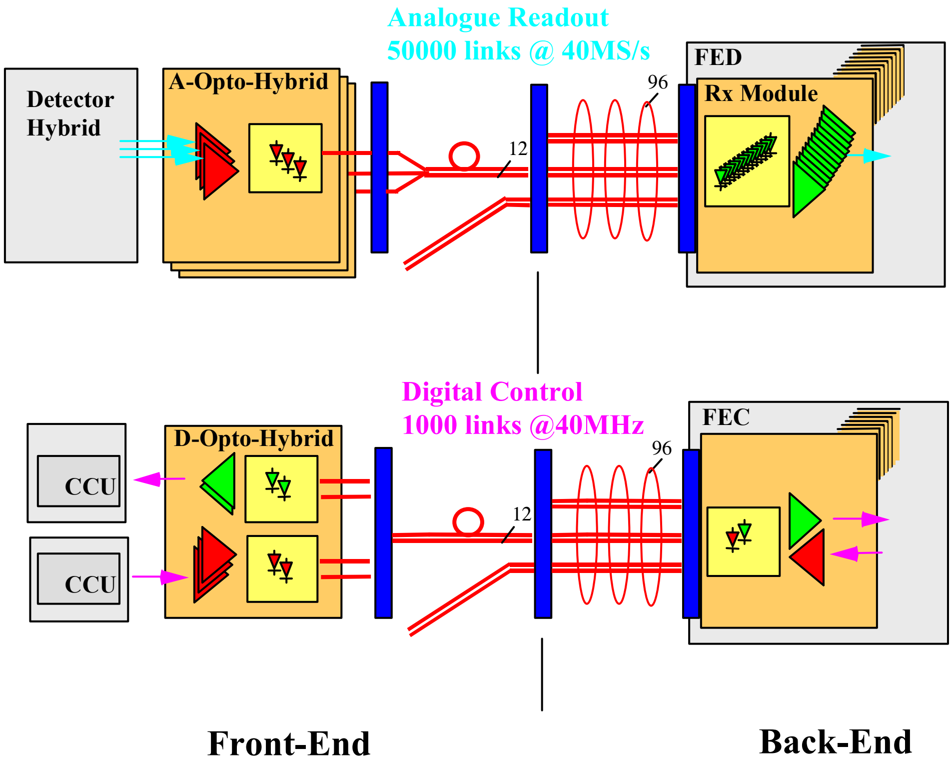


Figure 1: CMS-Tracker read-out and control system

The ~40000 uni-directional analogue links used to read data out of the CMS tracker are based on edge-emitting laser transmitters and pin photodiode receivers operating at a wavelength of 1310nm. In every single-mode fibre, data from 256 detector channels are time-multiplexed at a rate of 40MSamples/s. The individual fibres originating from the transmitters are fanned-in, first to a 12-way ribbon, and then to an 8-ribbon cable carrying 96 fibres away from the detector to the counting room, via two patch-panels.

The ~1000 bi-directional digital links used for control and timing distribution are based on almost identical components as the analogue readout system, but with a different modularity. The transceiver hybrids placed inside the detector include radiation resistant photodiodes and discriminating amplifiers (which are not needed in the readout system), whereas the transceiver modules located in the counting room are based on standard commercial components.

All system components situated inside the detector volume (lasers, photodiodes, fibres and connectors) must be radiation resistant and non-magnetic, as well as conforming to the functional specifications of the system.

3 Description of components and assemblies

The architecture of the analogue readout system is schematically shown in Figure 2. The digital control link architecture is expected to be very similar, but the final details of its implementation remain to be defined.

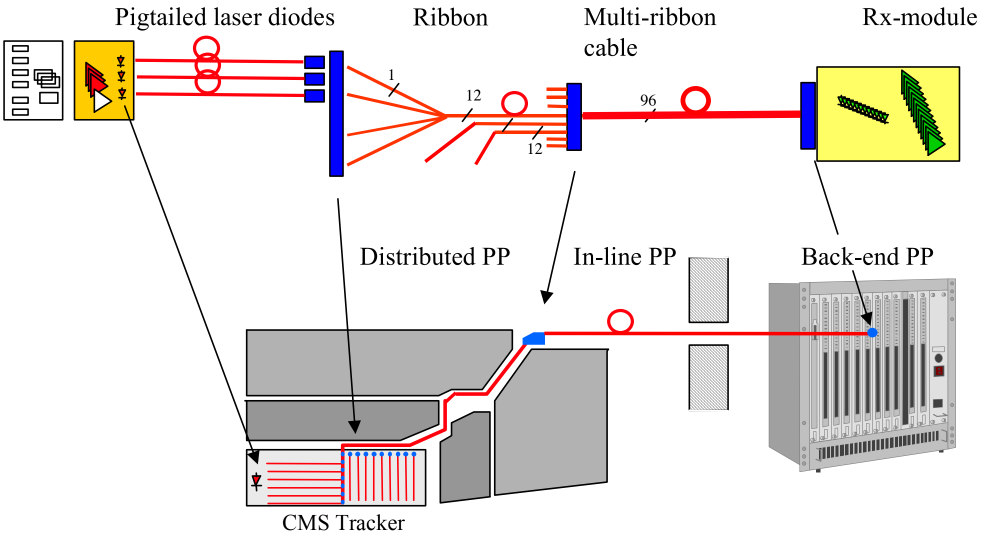


Figure 2: Optical link architecture. Analogue read-out system shown as example.

By its very nature, the optical link is a distributed system connecting front-end to back-end electronics. The optical signals are routed over typically 60m to 90m of single mode optical fibre, via three optical patch-panels.

These three optical patch panels define three regions of the system with different requirements and constraints (environment, size, modularity, etc.). The selected optical link components must thus be optimally adapted to their specific location and its particular set of requirements, while guaranteeing compatibility with the neighbouring components.

The distributed patch-panel is based on single-fibre MU connectors. It is positioned at the edge of the mechanical structures carrying the detector modules (rods for the barrel, petals for the forward) and allows easy testing and maintenance of the optical front-end components at the rod/petal level. Also, the use of single-fibre connectors allows optimising the 12-fibre ribbon usage with full flexibility, since fibres originating from different hybrids can be conveniently connected to a common ribbon. Replacement or re-routing of individual channels is also possible at this point.

The in-line patch panel is located between the CMS magnet cryostat and the HCAL end-cap. It is partitioned into cassettes, each housing 480 optical connections based on 40x12-channel MT ferrules. A small amount of ribbon slack (~10cm) can be compensated for in the cassette, and limited space is available if a faulty connector needs to be repaired or a ribbon needs to be fusion spliced. No repair or re-routing at the *individual* channel level can be envisaged however.

The back-end patch panel is the front-panel of the FED (or FEC) crate where the optical-cable connectors are directly plugged into Rx (or TRx) module receptacles.

Different assemblies must be built and procured for the different parts of the system. Table 1 relates the basic components that have been selected for their good functional and environmental properties, and the assembled devices that will be procured from industry.

Table 1: Optical link components and assemblies (excluding opto-hybrids)

Components ⇒	Laser diode chip	SM buffered fibre	12-way SM ruggedized ribbon	96-way dense multi-ribbon cable	1-way connector	12-way connector	Pin diode chip	Rx ASIC
Assemblies ⇓								
Laser Transmitter	◆	◆			◆			
Pin Diode Receiver		◆			◆		◆	
Terminated Fibre Ribbon			**1x◆**		**12x◆**	**1x◆**		
Terminated Multi-Ribbon Cable				◆		**16x◆**		
A-Rx-Module						◆	**12x◆ (array)**	◆

Each assembly is described below, numbered in a way compatible with the specification documents described in section 4.

2. Opto-Hybrids carry the active opto-electronic components situated at the front-end. In the new tracker layout adopted in the spring of 2000, the use of front-end detector hybrids with only 4 or 6 APVs is foreseen. This corresponds to either 2 or 3 lasers to read-out these hybrids. Accordingly, analogue opto-hybrids with a base-modularity of 3 lasers have been designed. They are populated with only 2 lasers in cases where 4 APVs need to be read-out. Digital opto-hybrids carry two laser transmitters and two pin-diode receivers, with associated electronics. Pigtailed laser diode transmitters and pin photodiode receivers consist of individual semiconductor chips assembled on ceramic or Si-submounts, coupled to single mode optical fibres and terminated with small form-factor connectors of type MU (1.25mm ferrule). These assemblies will be delivered pre-tested to the opto-hybrid assembly centres.
3. The ribbon cable consists of one, 12-fibre ribbon protected by aramide yarn and sheathed with polyethylene. It is terminated on one end with a 12-fibre connector based on a MT ferrule; on its other end (laser transmitter pigtail side), each ribbon is fanned-out to 12 individual fibres and terminated with a compact and simplified version of the MU connector.
4. The multi-ribbon cable is a rugged, halogen-free flame-retardant assembly running outside the detector to the counting room. Its high density (less than 1cm diameter for 96 fibres) and flexibility (8cm bending radius) are compatible with the CMS routing constraints. It is terminated at both ends with eight, 12-fibre connectors. Both ribbon-stack and multi-ribbon cables are delivered pre-terminated and pre-tested by industry.
5. Whereas the laser transmitters and cables are used both for the analogue and digital links, the 12-channel Rx module is specific to the analogue read-out system and adapted to the size requirements of the Front End Driver

boards (FED). It consists of a 12-channel pin-photodiode array coupled to a 12-fibre connector. A custom designed, 12-channel analogue current amplifier array directly converts the photocurrents into levels compatible with the 10-bit ADCs in the FED. The receiver modules are delivered to the FED assembly centres pre-tested by industry, ready to be surface mounted.

4 Specifications

All assemblies described in section 3 above, as well as some of the components to be purchased from industry are uniquely described by a set of specifications stored in the EDMS database. The list of available specifications is shown below:

Analogue Readout

- Part 1. Analogue Readout System
- Part 2. Analogue Opto-Hybrid
  - 2.1. Laser Driver
  - 2.2. Laser Transmitter
    - *2.2.1. Terminated Pigtail*
      - *2.2.1.1. Buffered fibre*
  - 2.3. Analogue Optohybrid Substrate
    - *2.3.1. Tracker Inner Barrel*
    - *2.3.2. Tracker Inner Disks*
    - *2.3.3. Tracker Outer Barrel*
    - *2.3.4. Tracker End Cap*
    - *2.3.5. Pixel Barrel*
    - *2.3.6. Pixel End Cap*
- Part 3. Terminated Fibre Ribbon
  - 3.1. Ruggedized Ribbon
- Part 4. Terminated Multi-Ribbon Cable
  - 4.1. Dense Multi-Ribbon Cable
- Part 5. Analogue Opto-receiver Module
  - 5.1. Analogue Receiving Amplifier
- Part 6. Distributed Patch Panel
  - 6.1. MU-SR Adaptor
- Part 7. In-line Patch Panel
- Part 8. Back-end Patch Panel

Digital Control

- Part 1. Digital Control System
- Part 2. Digital Opto-Hybrid
  - 2.1. Laser Driver
  - 2.2. Laser Transmitter
    - *2.2.1. Terminated Pigtail*
      - *2.2.1.1. Buffered fibre*
  - 2.3. Digital Receiving Amplifier
  - 2.4. Pin Diode Receiver
    - *2.2.1. Terminated Pigtail*
      - *2.2.1.1. Buffered fibre*
  - 2.5. Digital Optohybrid Substrate
- Part 3. Terminated Fibre Ribbon
  - 3.1. Ruggedized Ribbon
- Part 4. Terminated Multi-Ribbon Cable
  - 4.1. Dense Multi-Ribbon Cable
- Part 5. Digital Opto-Transceiver Module
- Part 6. Distributed Patch Panel
  - 6.1. MU-SR Adaptor
- Part 7. In-line Patch Panel
- Part 8. Back-end Patch Panel

5 Responsibilities

The responsibility for specifying, qualifying, producing, testing and delivering the optical link components to CMS is shared among CERN, the CMS institutes in charge of the procurement of specific items and the manufacturers of these items. In some cases, CERN is also the CMS institute in charge of procurement. The hierarchy and partition of responsibility is:

1) CERN	Project management, Specification and overall Quality Assurance.
2) CMS Institute in charge	Qualification and Delivery of component performing within specifications, Management of interaction with manufacturer, Quality Assurance.
3) Manufacturer	Production and 100% test of components, Quality Assurance.

The flow of information follows a top-to-bottom and bottom-to-top path without bypassing the middle party.

The detailed partition of responsibilities is outlined in Table 2 and Table 3 below:

Table 2: Distribution of responsibilities for the analogue optical link

Item	Specification	CMS Institute in charge	Manufacturer
1. Analogue Readout System	CERN-CME	CERN-CME	N/A
2. Analogue Opto-Hybrid	CERN-CME	INFN-PERUGIA HEPHY-WIEN	
2.1. Laser Driver	CERN-CME	CERN-MIC	IBM
2.2. Laser Transmitter	CERN-CME	CERN-CME	
2.2.1. Terminated Pigtail	CERN-CME	CERN-CME	
2.2.1.1. Buffered fibre	CERN-CME	CERN-CME	ERICSSON
2.3. Analogue Optohybrid Substrate			
2.3.1. Tracker Inner Barrel	INFN-PERUGIA	INFN-PERUGIA	
2.3.2. Tracker Inner Disks	INFN-PERUGIA	INFN-PERUGIA	
2.3.3. Tracker Outer Barrel	HEPHY-WIEN	HEPHY-WIEN	
2.3.4. Tracker End Cap	HEPHY-WIEN	HEPHY-WIEN	
2.3.5. Pixel Barrel			
2.3.6. Pixel End Cap			
3. Terminated Fibre Ribbon	CERN-CME	CERN-CME	
3.1. Ruggedized Ribbon	CERN-CME	CERN-CME	ERICSSON
4. Terminated Multi-Ribbon Cable	CERN-CME	CERN-CME	
4.1. Dense Multi-Ribbon Cable	CERN-CME	CERN-CME	ERICSSON
5. Analogue Opto-receiver Module	CERN-CME	CERN-CME	
5.1. Analogue Receiving Amplifier	CERN-CME	CERN-CME	
6. Distributed Patch Panel	CERN-CME	CERN-CME	
6.1. MU-SR Adaptor	CERN-CME	CERN-CME	
7. In-line Patch Panel	CERN-CME	CERN-CME	
8. Back-end Patch Panel	CERN-CME	CERN-CME	

Table 3: Distribution of responsibilities for the digital optical link

Item	**Specification**	**CMS Institute in charge**	**Manufacturer**
1. Digital Control System	CERN-CME	CERN-CME	N/A
2. Digital Opto-Hybrid	CERN-CME	HEPHY-WIEN (?)	
2.1. Laser Driver	CERN-CME	CERN-MIC	IBM
2.2. Laser Transmitter	CERN-CME	CERN-CME	
2.2.1. Terminated Pigtail	CERN-CME	CERN-CME	
2.2.1.1. Buffered fibre	CERN-CME	CERN-CME	ERICSSON
2.3. Digital Receiving Amplifier	CERN-CME	CERN-MIC	IBM
2.4. Pin Diode Receiver	CERN-CME	CERN-CME	
2.2.1. Terminated Pigtail	CERN-CME	CERN-CME	
2.2.1.1. Buffered fibre	CERN-CME	CERN-CME	ERICSSON
2.5. Digital Optohybrid Substrate	HEPHY-WIEN	HEPHY-WIEN (?)	
3. Terminated Fibre Ribbon	CERN-CME	CERN-CME	
3.1. Ruggedized Ribbon	CERN-CME	CERN-CME	ERICSSON
4. Terminated Multi-Ribbon Cable	CERN-CME	CERN-CME	
4.1. Dense Multi-Ribbon Cable	CERN-CME	CERN-CME	ERICSSON
5. Digital Opto-Transceiver Module	CERN-CME	HEPHY-WIEN	
6. Distributed Patch Panel	CERN-CME	CERN-CME	
6.1. MU-SR Adaptor	CERN-CME	CERN-CME	
7. In-line Patch Panel	CERN-CME	CERN-CME	
8. Back-end Patch Panel	CERN-CME	CERN-CME	

6 Assembly flow and quantities

The various assemblies composing the optical link have been described in section 3. Figure 3 bellow illustrates the sequence envisaged to build the link, referenced to the Tracker major assembly steps. Table 4 lists the quantities to be purchased and the contingency.

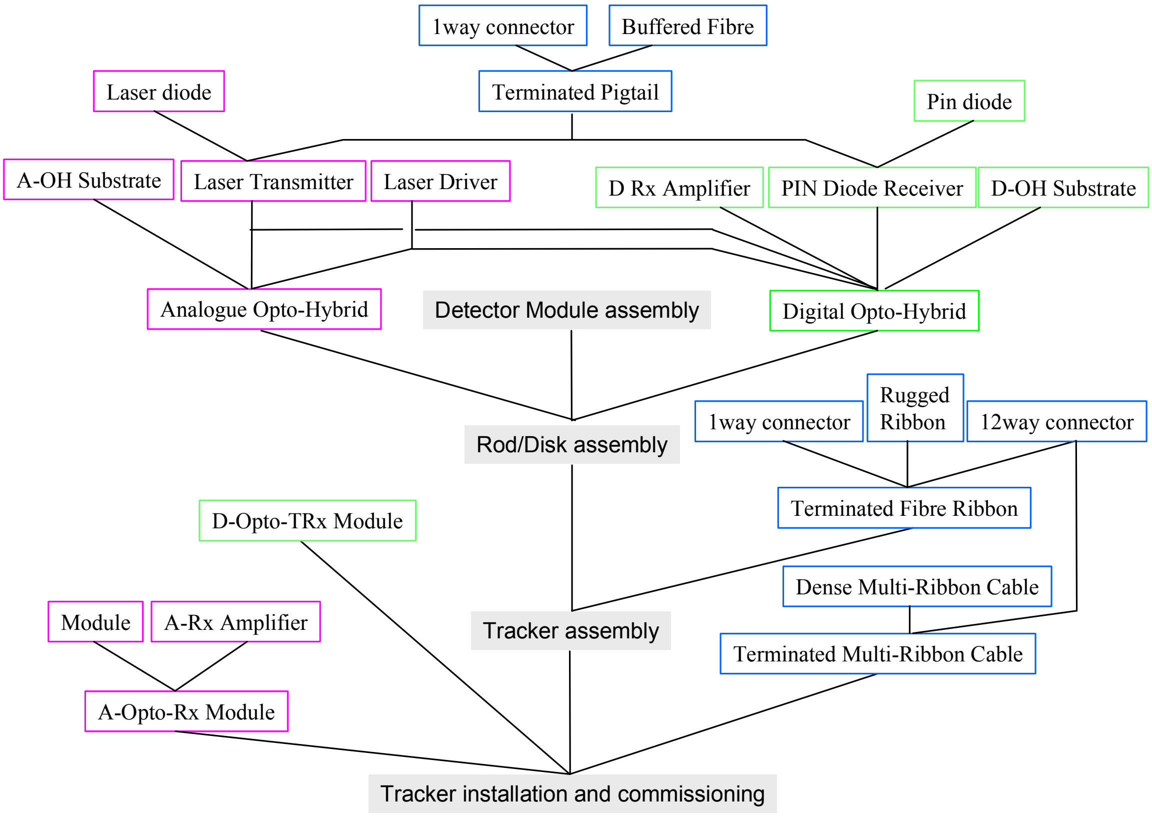


Figure 3: Optical link components assembly flow, in relationship with tracker assembly

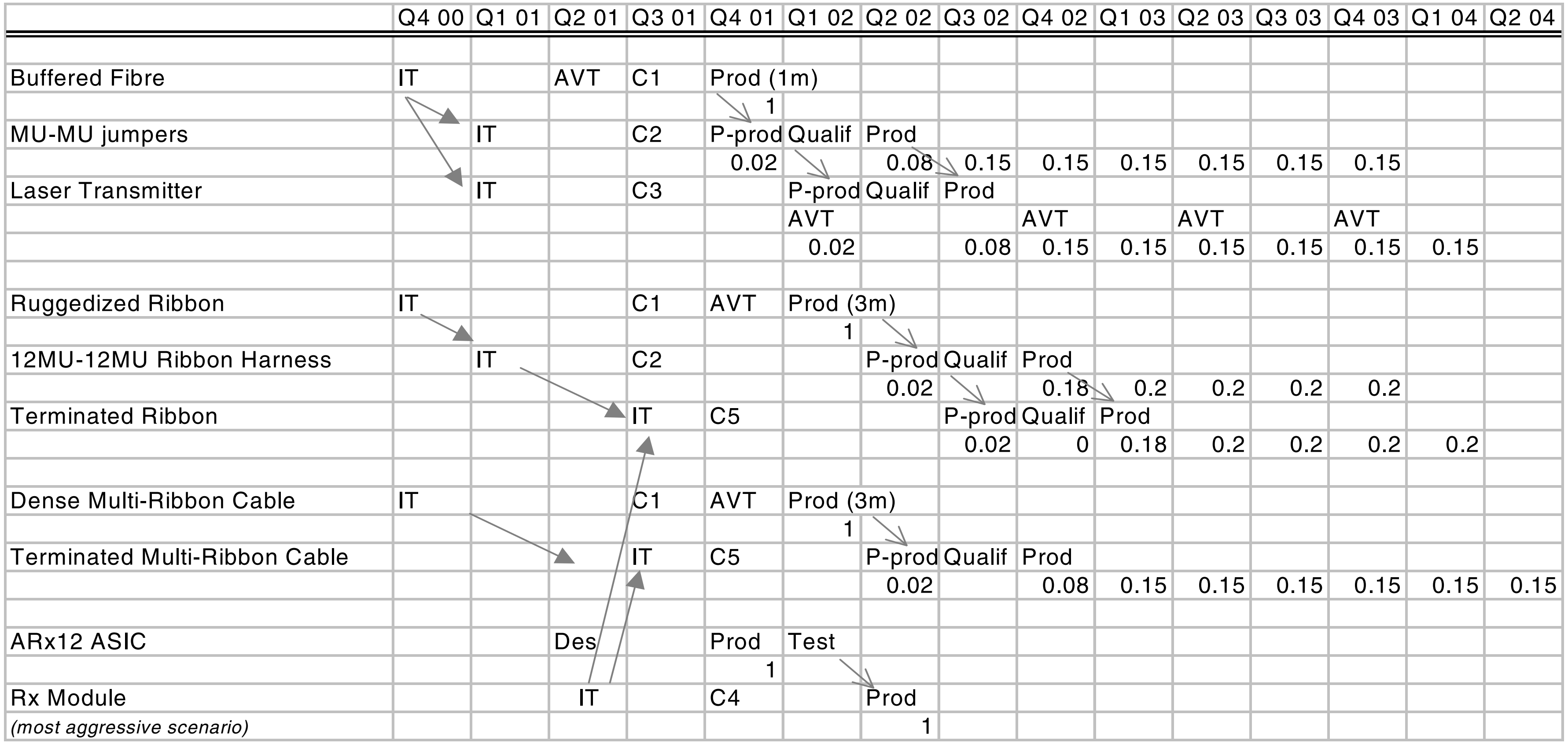
Table 4: Quantities to be ordered and contingency

	Total Quantity	**Including Contingency**			
Component	Quantity	Spares	Assembly yield	Dark fibre	Excess length
Buffered Fibre	50 km	10%	90% (connector assembly)	N/A	10%
Terminated Pigtail	50000	10%	100%	N/A	N/A
Laser Transmitter	50000	10%	90% (opto-hybrid assembly)	N/A	N/A
Pin Diode Receiver	500	10%	90% (opto-hybrid assembly)	N/A	N/A
Laser Driver	19000	10%	90% (opto-hybrid assembly)	N/A	N/A
Analogue Optohybrid Substrate	19000	10%	90% (opto-hybrid assembly)	N/A	N/A
D Rx Amplifier	250	10%	90% (opto-hybrid assembly)	N/A	N/A
Digital Optohybrid Substrate	250	10%	90% (opto-hybrid assembly)	N/A	N/A
Ruggedized Ribbon	30km	10%	90% (connector assembly)	10%	30%
Terminated Fibre Ribbon	4400	10%	100%	10%	N/A
Dense Multi-Ribbon Cable	45km	10%	90% (connector assembly)	15%	10%
Terminated Multi-Ribbon Cable	570	10%	100%	15%	N/A
A-Opto-Rx Module	4500	10%	95% (FED assembly)	20%	N/A
A-Rx Amplifier	5000	10%	95% (Module assembly)	20%	N/A

7 Schedule

Figure 4 shows the planed production schedule. Quantities are expressed as fraction of the total supply. Quantities to be delivered will be revised quarterly, allowing to compensate for reasonable fluctuations in the production chain, and to minimize the associated risk.

The precision of this schedule is driven by the time of contract-placement for each item to be purchased, and by the contractual terms and conditions agreed with the manufacturers. It should be considered as preliminary until all contracts have been placed.



	Q4 00	Q1 01	Q2 01	Q3 01	Q4 01	Q1 02	Q2 02	Q3 02	Q4 02	Q1 03	Q2 03	Q3 03	Q4 03	Q1 04	Q2 04
Buffered Fibre	IT		AVT	C1	Prod (1m)										
					1										
MU-MU jumpers		IT		C2	P-prod	Qualif	Prod								
					0.02		0.08	0.15	0.15	0.15	0.15	0.15	0.15		
Laser Transmitter		IT		C3		P-prod	Qualif	Prod							
						AVT			AVT		AVT		AVT		
						0.02		0.08	0.15	0.15	0.15	0.15	0.15	0.15	
Ruggedized Ribbon	IT			C1	AVT	Prod (3m)									
						1									
12MU-12MU Ribbon Harness		IT		C2			P-prod	Qualif	Prod						
							0.02		0.18	0.2	0.2	0.2	0.2		
Terminated Ribbon				IT	C5			P-prod	Qualif	Prod					
								0.02	0	0.18	0.2	0.2	0.2	0.2	
Dense Multi-Ribbon Cable	IT			C1	AVT	Prod (3m)									
						1									
Terminated Multi-Ribbon Cable				IT	C5		P-prod	Qualif	Prod						
							0.02		0.08	0.15	0.15	0.15	0.15	0.15	0.15
ARx12 ASIC			Des		Prod	Test									
					1										
Rx Module			IT		C4		Prod								
(most aggressive scenario)							1								

Legend:	IT	Invitation to Tender	Prod	Production
	C	Contract	P-prod	Pre-Production
	AVT	Advance Validation Test	Qualif	Qualification

Figure 4: Preliminary production schedule for optical-link components

8 Quality assurance procedures

From the development of the first prototypes to large-scale production, a wide range of quality assurance procedures has been implemented, as shown in Figure 5. Whereas a large fraction of the results obtained during the development phase of the optical link project were documented in reports, technical notes and scientific publications, the first formal step in the quality assurance procedure started with the technical qualification of suppliers in the framework of CERN market surveys.

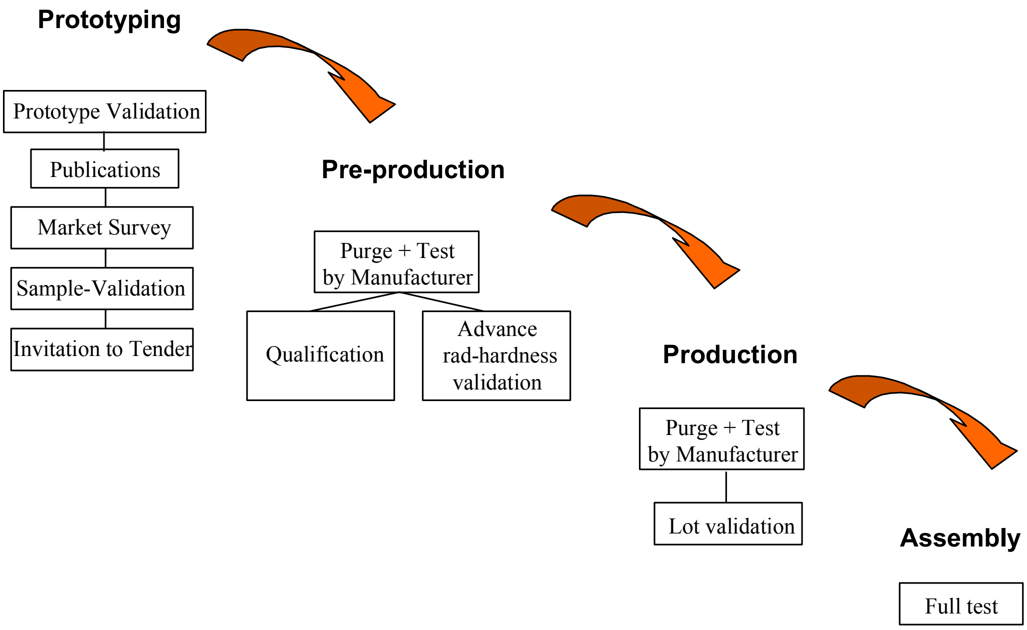


Figure 5: Quality assurance procedures during various project phases

Market surveys for semiconductor lasers (MS2690) and optical connectors (MS2691) were issued in 1999. Market surveys for optical fibre, ribbon and cable (MS2811) as well as for receiver modules (MS2810) were issued in 2000. In all cases, evaluation samples were requested from the companies interested in tendering, and subjected to a sample validation procedure described in more detail in section 8.1. Based on the results of this sample-validation procedure, manufacturers were qualified (or not), and invited to tender for the production of the components or assemblies.

The CMS tracker will require ~50000 optical links to operate its analogue readout and digital control systems. The tens of prototypes evaluated during the feasibility phase and market survey tests give confidence that specifications will be met by the final system. This quantity is however clearly insufficient to assure quality during production, and a full qualification phase must be envisaged. However, as industrial products evolve on a much shorter time-scale than the LHC project, a meaningful qualification can only start once specifications are frozen and orders have been placed.

The pre-production batch will form the basis for the qualification of the manufacturing process. In the case of the front-end components, the pre-series will need to be built from wafers and fibre-preforms validated for radiation hardness. These advance validation tests are required since the optical link components are based on commercial off the shelf products (COTS), sold with no radiation hardness guarantee whatsoever. Advance validation prevents building assemblies that could be rejected later due to poor radiation hardness of one of the components. Validated wafers and fibre pre-forms will be stored and subsequently used throughout the production period. Advance radiation-hardness and product qualification tests are described in sections 8.2 and 8.3 respectively.

Once the processes will have been qualified, full-scale production will start in industry, and products will be delivered pre-tested by the manufacturers. Only a fraction (typ. 5%) of these deliveries will be re-tested at CERN on a lot-by-lot basis, to monitor the stability of the process. The lot-validation (also referred to as lot acceptance) procedure is presented in more detail in section 8.4.

8.1 Sample validation

Evaluation samples sent to CERN in the framework of market surveys are validated according to the procedure sketched in Figure 6. In the semiconductor laser case (MS2690), the irradiation consists of both gamma and neutron tests, while in the connector (MS2691) and fibre/cable (MS2811) cases it consists only of gamma tests. No CERN-specific environmental tests (B-field or Irradiation) are performed on the Rx modules (MS2810), which will be operated in the counting room, away from the radiation and magnetic field.

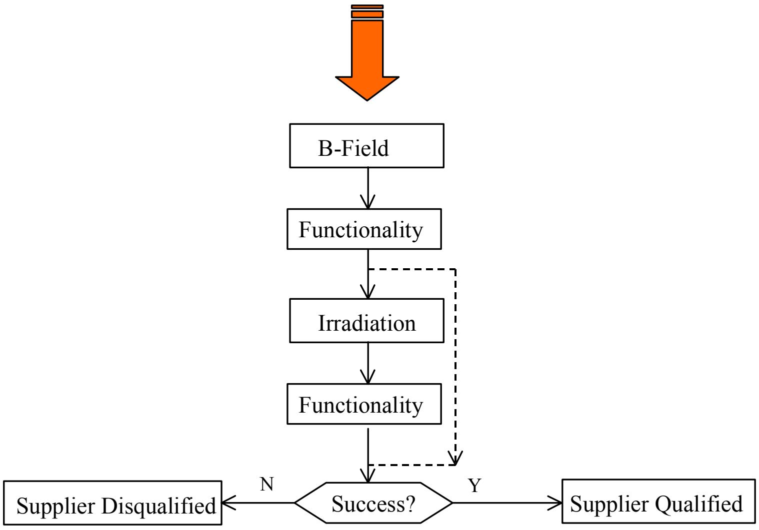


Figure 6: Flow chart of the Sample-Validation procedure.

Results of Sample-Validation tests are archived in confidential reports, with one copy sent to the manufacturer for information.

8.2 Advance radiation hardness validation

Devices delivered to CERN during the pre-production phase will have already been qualified for market-readiness by the manufacturers. They will be delivered pre-tested and, in the case of active components, purged. However, none of the COTS components are guaranteed to be radiation resistant and additional environmental tests are necessary to confirm their full compliance to the CMS-Tracker specification. In order to avoid rejecting assembled devices because of non-compliance of one of their components, an advance radiation hardness validation procedure is foreseen for laser die and naked fibre. No device assembly is allowed to proceed until samples of laser wafers and naked fibre lots have passed the advance validation test.

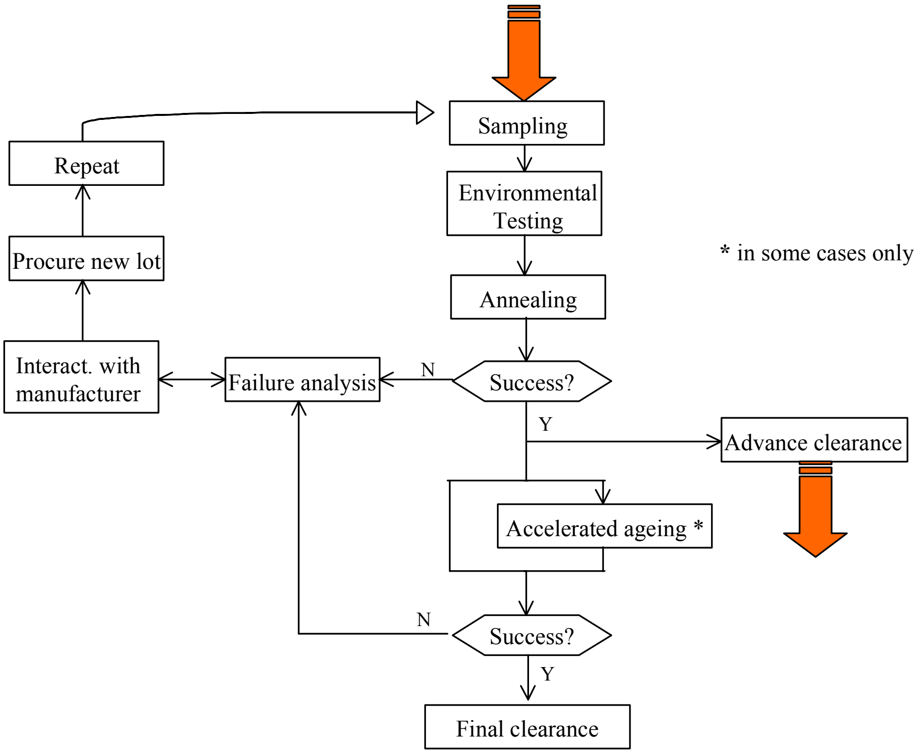


Figure 7: Flow chart of the advance radiation hardness validation procedure.

Results of advance radiation hardness validation tests are archived in the EDMS database, with one copy sent to the manufacturer for information.

8.3 Qualification

Qualification of pre-production will involve rigorous testing of devices sampled from the pre-production delivery in order to qualify the devices and manufacturing processes in preparation for full production. This includes evaluating the compliance of the components and assemblies to their specifications whilst, or following, exposure to conditions representative of the Tracker environment. Accelerated ageing can also be part of the pre-production qualification. In some cases, qualification tests may progress in parallel with advance validation tests.

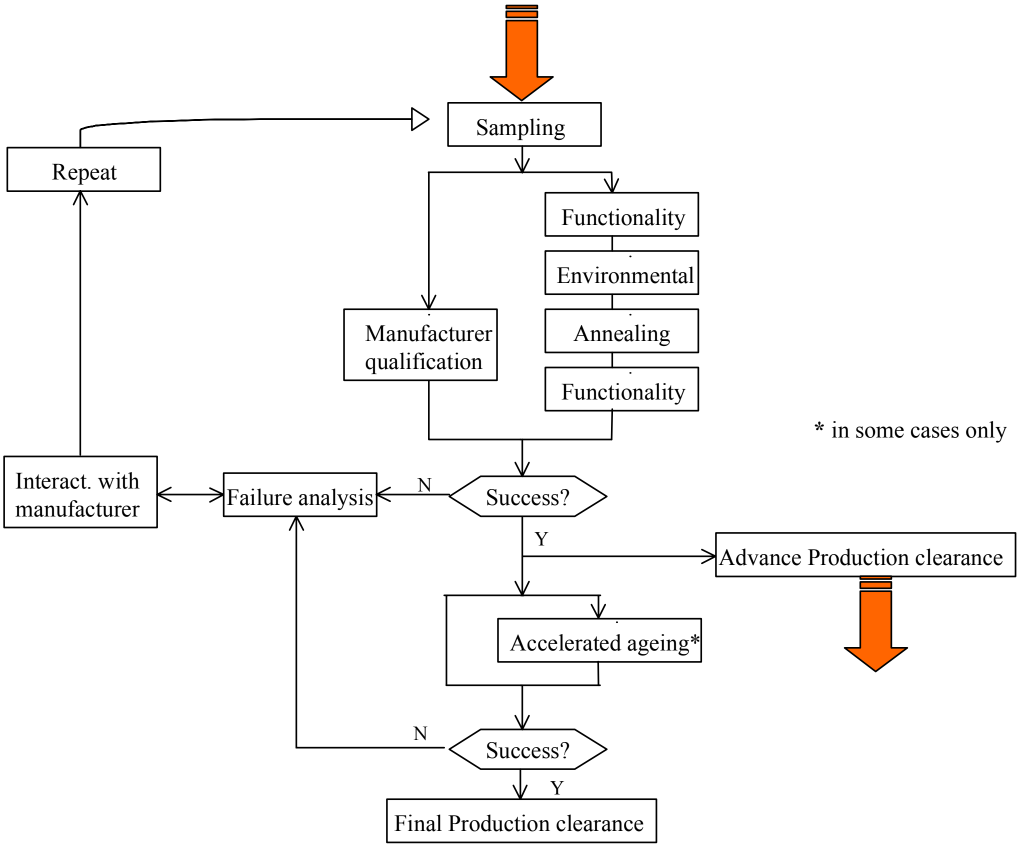


Figure 8: Flow chart of the pre-production qualification procedure.

Results of pre-production qualification tests are archived in the EDMS database, with one copy sent to the manufacturer for information.

8.4 Lot validation

Once pre-production components and assemblies have been fully qualified, production can be launched. Lot validation involves sample testing of every delivered batch, and has as outcome the acceptance or rejection of the tested lot.

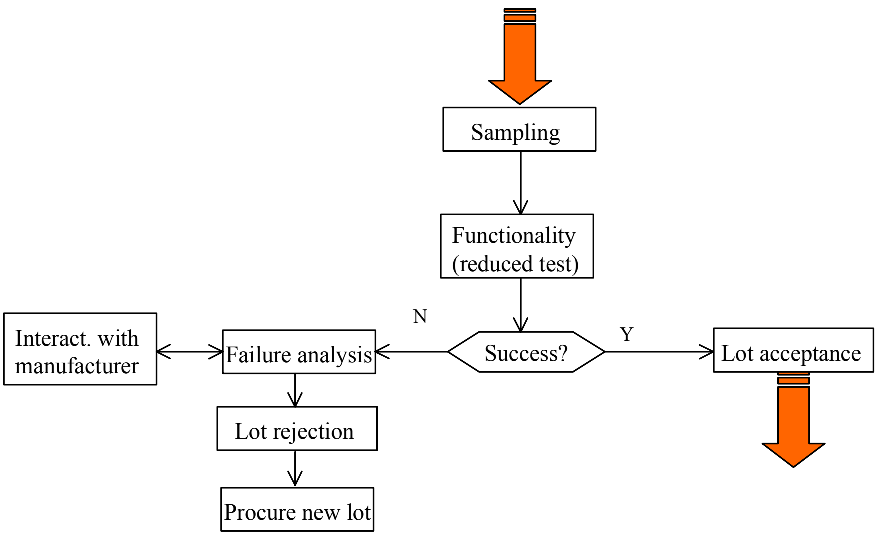


Figure 9: Flow chart of the lot validation procedure.

Results of lot validation tests are archived in the EDMS database, one exemplar is sent to the manufacturer for information.

9 Quality Assurance programme

Responsibility for ensuring that the quality assurance procedures outlined in this document are carried out is shared among the project stakeholders who are CERN, the CMS institute in charge of the procurement of a specific item and the manufacturer of the item (as stated in section 5 above). The partition of responsibility in the context of the Quality Assurance programme is outlined below:

CERN — Specifications, Test Procedures and Acceptance Criteria, Test System definition and implementation
CMS Institute in Charge — Management of interaction with Manufacturer. Qualification and Lot Validation. Test System Implementation
Manufacturer — 100% Production test, assuring delivery of functional components

Given this hierarchy the flow of information between the stakeholders should follow the same top-to-bottom path without bypassing the middle party. In this way all the stakeholders should feel comfortable about obtaining pertinent information from their nearest neighbour in the hierarchy, which will inevitably lead to more efficient handling of problems and straightforward quality assurance. The same information path should be used for requests to change aspects of the quality assurance standards and methods. This is demonstrated graphically in Figure 10:

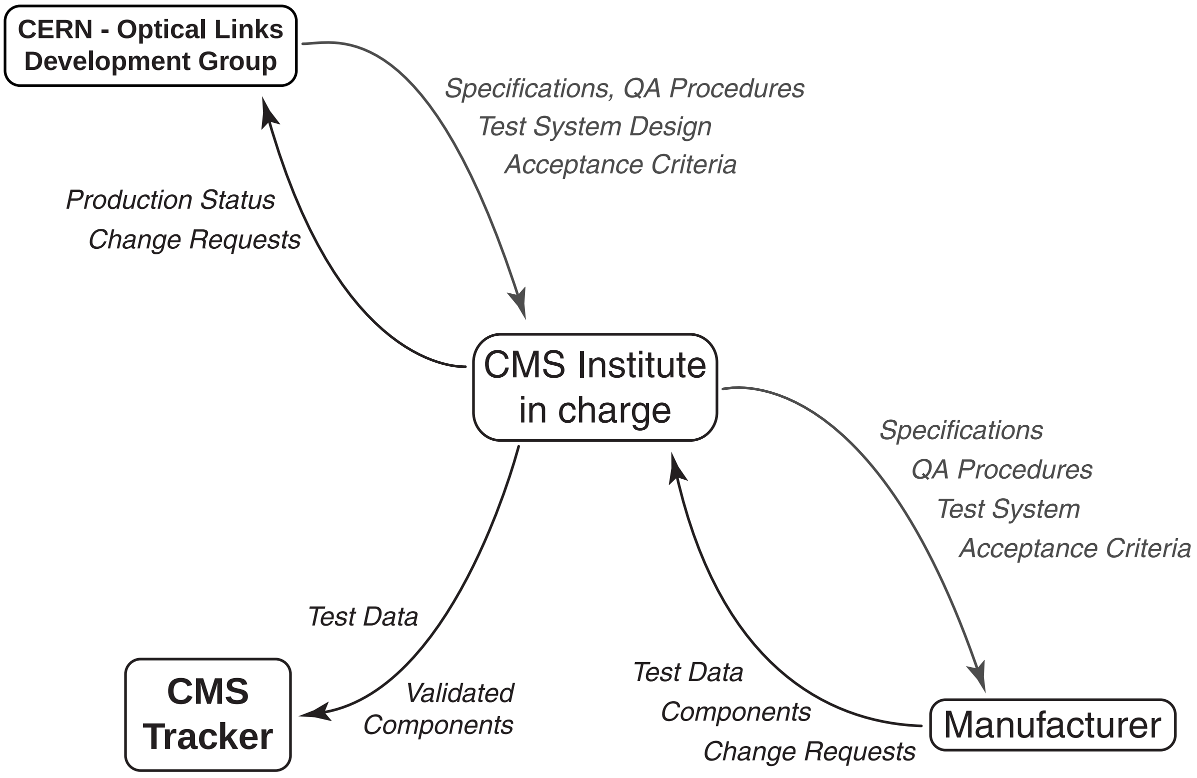


Figure 10: Information flow between project stakeholders

The numbers of devices making up the pre-production and production quantities are given in Table 5. This table also shows the qualification sample sizes as well as the projected number of lots that make up the full production quantity and the number of devices available for the lot validation steps.

Table 5: Preliminary pre-production and production quantities and timescales for optical link components

Item	**CMS Institute in charge**	**Total Production**[*]	**Pre-Production**		**Production**			
			Total	*Qualification Samples*	*Number per lot*	*Number per lot validation*	*Number of lots*	*Total production time*
Analogue Optohybrid (TIB)[†]	INFN	3100	*2%* 80	*25%* 20	TBD	TBD	TBD	TBD
Analogue Optohybrid (TID)[†]	INFN	900						
Analogue Optohybrid (TOB)[‡]	HEPHY	5800	*1.5%* 90	*30%* 30	TBD	TBD	TBD	TBD
Analogue Optohybrid (TEC)[§]	HEPHY	7100	*1.5%* 105	*30%* 30	TBD	TBD	TBD	TBD
Laser Driver[**]	MIC	19000	n/a	n/a	19000	TBD	1	n/a
Laser Transmitter	CME	50000	*2%* 1000	*10%* 100	*max. 15%* 7500	*1%* max. 75	7	*7 Quarters* 21 months
Terminated Pigtail	CME	50000	*2%* 1000	*20%* 200	*max. 15%* 7500	*1%* max. 75	7	*7 Quarters* 21 months
Buffered Fibre	CME	50km	n/a	n/a	50km	500m	1	n/a
Terminated Fibre Ribbon	CME	4400	*2%* 90	*22%* 20	*max. 20%* 860	*1%* max. 10	5	*5 Quarters* 15 months
Ruggedized Ribbon	CME	30km	n/a	n/a	30km	200m	1	n/a
Terminated Multi-Ribbon Cable	CME	570	*2%* 10	*50%* 5	*max. 15%* 85	*2%* 2	7	*7 Quarters* 21 months
Dense Multi-Ribbon Cable	CME	45km	n/a	n/a	45km	100m	1	n/a
Analogue Opto-receiver Module	CME	4500	*2.5%* 100	*20%* 20	4500	*1%* 45	1	n/a
Analogue Receiving Amplifier	CME	5000	*2.5%* 100	↑↑	5000	n/a	1	n/a
Distributed Patch Panel	CME	n/a	n/a	n/a	n/a	n/a	n/a	n/a
MU-SR Adaptor	CME	4400	n/a	n/a	4400	*1%* 44	1	n/a
In-line Patch Panel	CME	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Back-end Patch Panel	CME	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Pin Diode Receiver	CME	500	n/a	n/a	500	*2%* 10	1	n/a

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[*] Including Spares and Contingency

[†] There are 4 types of Analogue Optohybrid for the inner tracker, they are considered as one here but pre-production should consist of samples of all types.

[‡] There are 2 types of Analogue Optohybrid for the TOB, they are considered as one here but pre-production should consist of samples of all types.

[§] There are 2 types of Analogue Optohybrid for the TEC, they are considered as one here but pre-production should consist of samples of all types.

[**] Pre-production for the ASICs will be Engineering runs carried out before the full production run, so are not included in the table.

Item	**CMS Institute in charge**	**Total Production***	**Pre-Production**		**Production**			
			Total	*Qualification Samples*	*Number per lot*	*Number per lot validation*	*Number of lots*	*Total production time*
Digital Receiver**	MIC	250	n/a	n/a	250	TBD	1	n/a
Digital Optohybrid	HEPHY(?)	400	*5%* 20	*100%* 20	TBD	TBD – 1-2%	TBD	TBD
Digital Opto-transceiver Module	HEPHY(?)	800	n/a	n/a	800	*1%* 10	1	n/a

9.1 Functionality test requirements

The purpose of this section is to define the requirements for functional tests of optical links components at all stages of qualification and production so as to ensure the adequate functionality upon installation of the Tracker system. This is particularly important in view of the fact that, during production, components will not be able to be tested in their final link environment since front-end and back-end components will be manufactured (and tested) separately. Our goal is therefore to define test methods that will give us the utmost confidence that full optical links will function as specified when the system is commissioned.

After definition of the concepts used in the following sub-sections the implementation of the test requirements will be outlined. There then follows an overview of how the functionality testing of different components of the optical link will be carried out.

9.1.1 Concepts

Production and the associated functionality testing proceed in three phases for most of the components of the optical links:

1. Pre-production – manufacturing test (100% of components tested) plus qualification
2. Production – manufacturing test plus lot validation
3. Integration – high-level test suites

Successful qualification of the pre-production quantity is a requirement before continuing with full production. In some instances – where the item in question is a pure COTS device and the total quantity is small – the pre-production step is skipped in favour of receiving only one shipment of the entire production.

As stated in section 8, the manufacturing test is carried out by the item manufacturer on every item before delivery to CMS to ensure 100% compliance with the key specifications tested at this stage. Qualification is carried out on the pre-production lot and tests the compliance of the item with all of the specifications. Data from the two test suites applied to the pre-production lot may be used to fine-tune the acceptance criteria (that will be based upon the specifications) for the production and lot validation test of the production lots. Lot validation is carried out for each lot received during production and will be very similar if not identical to the qualification tests. Which specifications are tested during lot validation will be finalised based upon qualification test data.

During integration of the different manufactured items into the overall CMS Tracker system further testing will be carried out that will culminate in the commissioning of the full system. This system-level testing will be carried out in a small number of adequately equipped institutes.

9.1.2 Implementation

With the breakdown of the testing into three parts as described above, it is envisaged to use three types of test system to carry out the optical link functionality testing:

1. Manufacturing test – system easily operated by manufacturing staff on the manufacturer's premises, consisting of equipment that the manufacturer already owns and operates.

2. Optical Link Test System – standalone compact test system for use by manufacturers of items who are not already equipped to carry out the required testing. Will be designed by CERN for use by manufacturers.
3. Qualification and Lot Validation – building upon the optical link test system but incorporating further laboratory test equipment to enable more detailed testing to be carried out by test engineers at the CMS institute in charge of the procurement of a particular item.
4. Integration test – electrical-to-optical and optical-to-electrical conversion modules used in the manufacturing test system will be supplied to the integration test system designers for incorporation into their systems.

It should be noted that in many instances the manufacturer of a particular component is already well equipped to carry out the production testing and in these cases the CERN production test system will not be used. However, the manufacturers of items that are no longer true COTS will not in general be equipped with the necessary test equipment and will require the standalone optical link test system.

Manufacturers of these other components (AOH, DOH, FED and FEC) who do not have the required testing capability available in-house will require a standalone test system that is therefore being designed by CERN to meet their testing needs. The test system will be standalone and not require a large amount of additional hardware for the test sequences to be carried out. Its schematic design is shown in Figure 11 – the basis of the system is a PXI chassis with a controller host CPU and several electronic modules for signal generation and evaluation. The only instrument required in addition to this system will be a GPIB-controlled power supply. Interaction with the user is via the on-board screen – a keyboard and mouse can be attached if required although using mouse only is possible with the built-in pointing device.

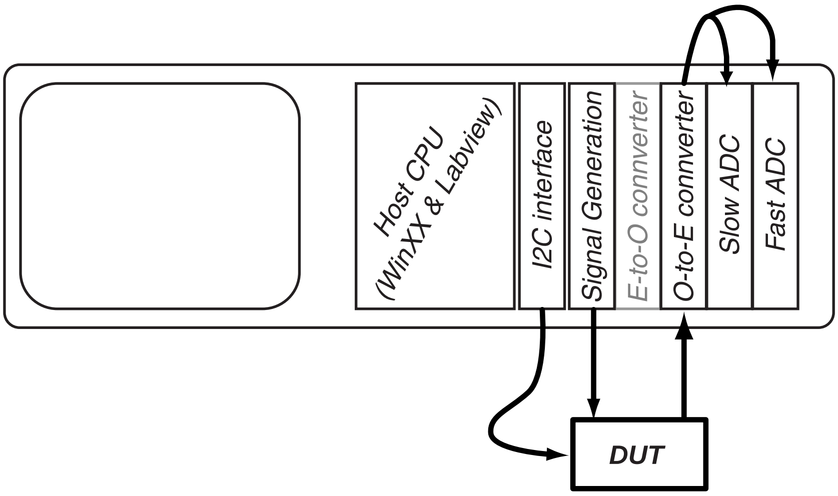

Figure 11: Schematic showing example use of standalone test system for optohybrid production testing. The E-to-O converter is used for testing receiver components.

The test routines will be written in LabVIEW and will be heavily based upon existing evaluation methods as used throughout the optical link development phases. The goal is to produce software that requires minimal input from the test personnel. Total testing times remain to be determined once detailed test procedures are finalised.

Upon delivery of tested optical link components to CMS further testing will be carried out as larger and larger sub-assemblies are integrated to form the CMS Tracker system. While test systems have already been conceived to carry out this testing, it is the responsibility of the CERN optical link development group to supply interface modules that allow testing of the embedded optical link components. These electrical-optical or optical-electrical interfaces will be the same ones as used within the optical link test, qualification and lot validation systems. A further responsibility of the CERN optical link development group is to advise the tracker test system designers as to the procedures required to test the functionality of the embedded optical link components so that they may implement them within their existing test framework.

The details of which specifications will be tested are given in Specification Documents and (where these exist) Tender Documents.

9.1.3 Functionality test systems

As there are four testing scenarios described above the maximum number of different test systems for a given item is thus four. It is desirable to have as much commonality as possible between systems that are specific to the optical link (i.e. not the manufacturer's own test systems) to minimise the development and maintenance/support effort for test systems. Table 6 outlines the testing systems that will be used for the different components for the different tests of the optical links and thus which items require the development of dedicated systems.

Table 6: Use of the different types of functionality testing systems foreseen for optical link components at different stages during production. Integration tests are only carried out on items not already embedded into others. The key is shown below the table.

Item	**Manufacturing Test**	**Qualification**	**Lot Validation**	**Integration Test**	**Comments**
Analogue Optohybrid	2	3	3	4	
Laser Transmitter	1	3	3	n/a	
Laser Driver	n/a	3	3	n/a	100% Testing of ASICs to be carried out after packaging using system TBD under the responsibility of CERN-MIC
Terminated Pigtail	1	3	3	n/a	
Buffered Fibre	1	3	3	n/a	
Terminated Fibre Ribbon	1	3	3	3	
Ruggedized Ribbon	1	3	3	n/a	
Terminated Multi-Ribbon Cable	1	3	3	3	
Dense Multi-Ribbon Cable	1	3	3	n/a	
Analogue Opto-receiver Module	1	3	3	4	Support will be given to the manufacturer to adapt their existing digital test systems to meet our requirements
Analogue Receiving Amplifier	1	3	3	n/a	
Patch Panels	1	3	3	3	
Digital Optohybrid	2	3	3	4	
Digital Receiving Amplifier	n/a	3	3	n/a	100% Testing of ASICs to be carried out after packaging using system TBD under the responsibility of CERN-MIC
Pin Diode Receiver	1	3	3	n/a	
Digital Opto-transceiver Module	1	3	3	4	

Key: 1 Manufacturer's own test system
2 Standalone test system developed by CERN
3 Laboratory instrument suite (can include standalone system)
4 Interface modules

9.2 Environmental test requirements

In this section the Tracker operating environment, in particular the radiation field, is summarized briefly. Simulation of the Tracker radiation environment for validation testing is then described, explaining the choice of radiation sources for testing and discussing the general use of accelerated testing. The main effects of radiation damage on the link components are then described and the specific procedures for individual optical link parts are outlined.

9.2.1 CMS Tracker environment

The devices located in the Tracker will be exposed to a harsh radiation environment and access to the Tracker will be very limited once the experiment is running. Replacement of any failed components inside the Tracker is therefore considered to be practically impossible and devices in the Tracker must be qualified, in advance of production, for radiation resistance and reliability in terms of their ability to operate for 10 years in this environment.

The radiation damage effects are of primary importance and the procedures given in this section focus mainly on this type of environmental validation. The Tracker will also operate at a nominal temperature of -10°C and in a 4T magnetic field. The atmosphere will be constantly flushed, dry nitrogen. In terms of the thermal and magnetic constraints, all the devices are specified to operate above -20°C and they have all been screened to ensure that they are non-magnetic. Tests have already confirmed that the link performance is not affected by the magnetic field, at least up to 4T[9.1].

The radiation environment is described in detail elsewhere[9.2]. It is dominated by a hadron (and gamma) spectrum centred at ~100MeV, in addition to spallation neutrons with energies ~1MeV. Over a ten-year lifetime, assuming an integrated luminosity of $5\text{x}10^5\text{pb}^{-1}$, total doses will be up to 100kGy and particle fluences will be up $2\text{x}10^{14}/\text{cm}^2$ for the components located closest to the beam. Uncertainties in the particle fluences and doses mean that a safety factor of 1.5 should be applied in the inner tracker and 2 in the outer tracker.

9.2.2 Laboratory simulation of the Tracker environment

In order to validate components for radiation hardness within the production schedule we must carry out accelerated tests. For radiation effects testing this means using only a limited number of radiation sources and fluxes or dose rates in excess of those expected in the Tracker. Accelerated testing also applies to measurements of annealing and wearout where these effects can be thermally enhanced. In all the validation tests the effects expected over the lifetime of the components are then determined by extrapolation of the results from the accelerated tests to the conditions expected at a given location in the tracker.

We assume that the radiation damage effects from different incident particles (or from particles of different energy) are identical at the basic level of the creation and annealing of defects for a given damage mechanism, i.e. ionization, displacement, or SEE. Under this assumption all validation for a given component, can be made with just one type of radiation source to test each mechanism. We therefore propose to use photon sources for ionization damage tests, neutron sources for displacement damage tests and proton sources for SEE tests.

9.2.2.a Ionization damage

In the case of ionization damage testing, cobalt-60 gamma sources are the most suitable for irradiation of fibres and packaged devices, since the photons are penetrating and strong sources are available. X-ray sources are then the most suitable for tests of unpackaged chips. Gamma and X-ray sources that have already been used in earlier validation studies, and are intended for use in pre-production qualification and advance validation, are summarized in Table 7.

Accumulated effects are characterized in terms of the total dose received, which is measured using standard techniques, e.g. PAD dosimeters or by pre-calibrating the radiation source. The scaling of the damage data to that expected inside the CMS tracker can then be made by extrapolating (whilst taking into account annealing effects) to the doses given for the various parts of the Tracker.

Table 7: Suitable gamma irradiation facilities for ionization damage tests

Source	Type	Dose rate	Particularities
UC Louvain-La-Neuve	Cobalt-60 (rods in air)	up to ~1kGy/hr	In-situ measurements possible. Small volume with high dose rate. Large volume with low dose rate.
SCK-CEN, Mol (RITA)	Cobalt-60 (rods in water pool)	~2kGy/hr	In-situ measurements possible. Small, fixed volume with uniform and high dose rate

9.2.2.b Displacement damage

For displacement damage, the effects are often compared with reference to the non-ionizing energy loss (NIEL) of a given particle in a given material. The number of defects created in the irradiated material is hypothesized to be proportional to the NIEL, which is also a function of the incident particle energy. Many calculations have been made of NIEL in common semiconductor materials such as silicon and gallium arsenide. However, in the case of the lasers and photodiodes used in the Tracker optical links, where displacement is the dominant mechanism of radiation damage, reliable non-ionizing energy loss (NIEL) calculations have not yet been made. This is primarily because these components have complex internal structures, containing very thin layers of compound material: InGaAsP and InP in the lasers and InGaAs on an InP substrate in the photodiodes. Given that it is also not yet known exactly where the most important radiation damage occurs in the device, or the precise characteristics of the main defects, it is therefore not yet possible to predict the susceptibility of these types of lasers and photodiodes using NIEL calculations alone.

An experimental approach was therefore adopted in order to determine how to proceed with displacement damage validation tests for lasers and photodiodes. An extensive series of radiation damage measurements, on many types of candidate laser and photodiode samples, has been made using a variety of radiation sources that resemble, when taken as a whole, the CMS Tracker radiation environment. The sources included 24GeV protons, 330MeV pions, 20MeV, 6MeV and 0.8MeV neutrons[9.3] and irradiation was made using fluences typical of the worst-case expected in the Tracker. Based on a detailed comparison of the damage and annealing data, the relative damage factors of each of the various sources, for each type and brand of component, have been calculated.

We have selected neutron sources for the validation tests concerning displacement damage since these are the most readily available and are also convenient to use. Facilities that have already been used in the earlier studies, and are intended for use in validation tests, are summarized in Table 8. The damage will be measured for a given fluence and then using the damage factors, whilst taking into account any annealing effects, the damage expected for components at any given position in the tracker can be determined by extrapolation. It should be emphasised that, since the fluxes used can be several orders of magnitude greater than that in the Tracker, careful measurement of any annealing is also very important in order to make a robust extrapolation to the effects of long-term operation.

Table 8:Suitable neutron irradiation facilities for displacement damage tests

Source	Type	Neutron energy	Neutron flux	Particularities
UC Louvain-La-Neuve (CRC T2 beam)	Divergent neutron beam from deuterons incident on a beryllium target	Mean energy of 20MeV from 40MeV deuterons	up to 3×10^{10}n/cm^2/s	In-situ measurements possible. Cooling is possible. Small volume available for high flux irradiation.
CEA Valduc (PROSPERO)	Reactor	Mean energy of 0.8MeV	up to 4×10^{10}n/cm^2/s	In-situ measurements possible. Cooling is possible. Large volume available, with lower flux.

9.2.2.c Single Event Effects

Single-event-effects (SEE) due to the passage of individual particles through sensitive volumes of a given device are usually compared in terms of ionizing energy loss in the sensitive volume, using linear energy transfer (LET). SEE cross-sections measured under test conditions, using a calibrated radiation source, can then be scaled in order to predict error and upset rates inside the Tracker, based on the relative ionization of the test source and the particles expected in the Tracker. A proton beam facility, suitable for SEE testing is summarized in Table 9.

Table 9:Irradiation facility for SEE tests

Source	Particle type	Energy	flux
UC Louvain-La-Neuve	Proton beam	Up to 60MeV	up to 4×10^8n/cm^2/s

9.2.3 Radiation damage effects in the optical link components

In this section the most important damage effects are summarized in order to place the following test procedures into context. The descriptions of the effects are based on the measurements made in earlier validation testing of prototypes and other candidate components being considered for use in the CMS Tracker optical links.

9.2.3.a Laser

Lasers are used throughout the tracker volume in both the analogue and digital link systems and these devices are considered to be the most sensitive element in terms of radiation damage.

Displacement damage can cause significant degradation in the device performance, through an increase in threshold current (and forward voltage) and a decrease in output efficiency[9.3]. The linearity and noise characteristics may also change, following any adjustments of the operating parameters of laser driver chip to compensate for the laser degradation.

The displacement damage effects at the level of the laser diode (threshold increase and efficiency loss) are believed to be correlated and due to the build-up of the same types of defect in the device, either in or around the active volume. These defects, as yet unidentified, act to reduce the carrier lifetime in the device, which subsequently causes the observed degradation.

The radiation damage effects mentioned anneal significantly after irradiation, and this recovery has to be correctly taken into account when considering the long-term radiation damage effects in devices operated inside the Tracker.

The lasers being considered are normally insensitive to gamma damage for doses up to 150kGy[9.3,9.4]. SEE is also negligible as the active volume is extremely small and because there is a high current density through the forward-biased laser diode junction.

9.2.3.b Optical fibre

The same type of 9/125/250 single-mode Ge-doped optical fibre will be used throughout the analogue and digital optical link systems. This fibre will be in the final form of 1-way buffered pigtails, 12-way ribbon in a ruggedized sheath, or 8x12way ribbons in a ruggedized cable.

The fibre situated in the Tracker volume will be the most exposed to radiation, with the dominant effect expected to be the radiation-induced attenuation[9.3,9.4]. This is caused by defects, or 'colour centres', introduced primarily by ionization damage into the glass core that act to absorb and/or scatter the light being transmitted in the fibre.

Displacement damage is negligible at the levels of fluence inside the Tracker[9.3], and SEE is expected to be unimportant.

It should be noted that only a short length (~10m) of each fibre channel will actually be exposed to significant amounts of radiation in and around the Tracker. Beneficial annealing is also expected to reduce the overall accumulation of damage[9.3,9.4].

9.2.3.c Optical connectors

The same types of optical connectors are used in both the analogue and digital link systems, with the components situated in the distributed patch-panels within the Tracker being the most exposed to radiation. The connectors in the in-line patch panel are also exposed to radiation, but at a much lower rate.

According to previous validation studies, none of the connector types are degraded by radiation damage in terms of their insertion (or return) loss and mechanical functionality, for the levels of dose and fluence expected inside the Tracker[9.3,9.4].

9.2.3.d Photodiodes

The photodiodes that are exposed to radiation are those that are used in the digital receivers located in the Tracker.

Displacement damage degrades the photodiode performance, through an increase in the leakage current and a decrease in detection efficiency, due to the build up of defects that introduce generation-recombination and trapping centres in the semiconductor band-gap[9.3]. For InGaAs photodiodes the damage to the leakage current anneals slowly whereas the damage to the responsivity does not anneal significantly.

Ionization damage is negligible in comparison to displacement damage for the levels of dose and fluence inside the Tracker[9.3].

SEE in the form of single-event-upset (SEU) can be generated by direct ionization, or secondary ionization from a nuclear recoil. This can cause bit-errors in a digital optical link, with the bit-error-rate (BER) being dependent upon the active volume of the photodiode, the data-rate and amplitude, and the receiver bandwidth[9.3]. More optical power in the signal leads to fewer upsets and in principle the BER can therefore be reduced to an acceptable level by simply launching more optical power into the link.

9.2.3.e Electronic chips

The analogue laser driver, digital laser driver and digital receiver circuits, are all fabricated using deep sub-micron 0.25µm technology and radiation tolerant design practices. As such, they are expected to be radiation resistant to the dose and fluence levels of the CMS Tracker, as well as being resistant to latch-up. The rate of SEE in terms of bit-errors in the control interfaces is to be measured, though these parts of the circuit are protected by majority voting in order to avoid bit-upsets.

9.2.3.f Optohybrids

Radiation effects have yet to be measured for the optohybrid substrates and no significant damage is expected. Radiation tests of populated prototype optohybrids are foreseen. These will be specified and carried out in collaboration with the CMS groups responsible for optohybrid production.

9.2.4 *Specific environmental test procedures for optical link components*

In general, for the radiation resistance validation, 'worst-case' testing is performed, using doses and fluences equivalent to the maximum expected for the links used in the Tracker. The uncertainties in the radiation environment simulation require that a safety factor SF=1.5 should be included when qualifying Inner Tracker components (and SF=2 for Outer Tracker components). For total dose tests, devices are therefore be exposed to up to ~150kGy ionizing dose and for displacement damage tests, devices are irradiated to the equivalent of ~3×10^{14}(300MeV/c pions)/cm^2.

Table 10 summarises the pre-production qualification and advance validation procedures for the various analogue and digital link components respectively. An outline of the procedures is given in this section, with the individual procedures detailed in separate test protocol documents[9.5].

In both the analogue and digital link environmental testing program, there will be a significant overlap between the pre-production and advance validation testing of laser diodes and fibres. The irradiation step in the pre-production qualification can therefore be omitted if the corresponding advance validation is passed successfully. Similarly, the irradiation steps in the qualification of the populated hybrids can also be abbreviated, following successful tests of the individual components.

A summary report shall be prepared following each test that includes the intended objectives of the test, details of samples, test set-up, irradiation parameters, effects, discussion, and conclusion including statement of conformity of the tested samples. Manufacturers will receive copies of reports, which will be archived in a database of quality assurance tests for the optical links along with the actual test data.

Table 10: Summary of environmental tests to be performed on optical link components

Optical link element	**Link system**	**Pre-production qualification**[*]	**Advance validation**
Laser diode chip	Analogue and Digital	-	total dose, fluence and annealing[†] accelerated ageing
Laser transmitter	Analogue and Digital	magnetic field	-
Laser driver	Analogue and Digital	total dose and annealing accelerated ageing SEE	-
Optohybrid substrate	Analogue and Digital	*to be decided*	*to be decided*
Analogue transmitter hybrid	Analogue	total dose, fluence and annealing SEE magnetic field accelerated ageing	-
PIN photodiode receiver	Digital	magnetic field	total dose, fluence and annealing accelerated ageing
Digital receiver amplifier	Digital	total dose and annealing accelerated ageing SEE	-
Digital optohybrid	Digital	total dose, fluence and annealing SEE magnetic field accelerated ageing	-
Optical fibre	Analogue and Digital	-	total dose and annealing
Buffered fibre	Analogue and Digital	total dose	-
Optical fibre ribbon	Analogue and Digital	total dose	-
Ruggedized ribbon	Analogue and Digital	total dose	-
Dense multi-ribbon cable	Analogue and Digital	total dose	-
Optical connectors	Analogue and Digital	total dose magnetic field	-

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[*] Some tests on pigtailed assemblies and populated hybrids may be omitted based on successful validation of sub-components.

[†] Ideally these devices should be housed in pigtailed packages, but not necessarily using the final fibre or connector.

9.2.4.a Lasers

9.2.4.a.i Radiation damage and annealing

Radiation resistance tests of lasers for both analogue and digital links will be done in advance validation steps, where a number of devices will be tested from each wafer, in advance of the final production of packaged devices from the given wafer. This means that any wafers that are not sufficiently radiation resistant can be identified and excluded without wasted effort on the part of the manufacturer. It should be noted that the candidate devices have already passed the validation tests within the Market Survey and therefore the chance of wafer-rejection is small.

A sample group of 20 devices is required to validate a given wafer for radiation resistance. These samples should be packaged in the final form to facilitate mounting and testing. The lasers will be irradiated under bias, with gamma rays and then neutrons, up to the worst-case doses and fluences taking into account the damage factors of the sources used relative to the Tracker radiation spectrum. Both gamma and neutron irradiations will be made at room temperature with in-situ monitoring of the laser L-I and V-I characteristics at periodic intervals before, during and after irradiation. The rates of degradation and annealing of the threshold current and output efficiency can therefore be determined.

Acceptance criteria for pre-production qualification and advance validation are such that 90% of the lasers should remain within all the operating specifications for the system, under the worst-cases of radiation damage exposure, throughout the full 10year lifetime of the links. The results of the damage and annealing tests will be extrapolated to the conditions of damage and annealing expected in the Tracker, in order to determine whether the acceptance criteria have been satisfied. Should a tested sample group of lasers fail these acceptance criteria, the corresponding wafer will be 'down-graded' and used at a location in the Tracker where the fluence and dose will be sufficiently low. If the down-grading step is not possible, for example because of unavailability of suitable locations in the Tracker system, then a new lot of devices will be procured from a different wafer, following discussion with the manufacturer.

9.2.4.a.ii Ageing

For each advance validation test of a given wafer 20 irradiated lasers, in addition to 10 unirradiated lasers, will be passed through an accelerated ageing step. The devices will be operated at 80°C for at least 1000 hours to determine the rate of long-term wearout degradation. The inclusion of both irradiated and unirradiated samples allows a control of any possible degradation mechanisms that are due to radiation damage.

In-situ monitoring will be used to make measurements of the laser L-I and V-I characteristics at periodic intervals during the ageing test. In between measurement cycles, the lasers will be biased at 60mA. This represents the maximum current available with the final laser driver.

Wearout and random failure mechanisms are assumed to be temperature dependent, being thermally activated following the Arrhenius law. In any case where the activation energies for wearout failure and random failure of the lasers are not known, values of 0.4eV and 0.35eV respectively will be assumed, following Bellcore recommendations[9.6].

Device failures are defined such that a laser fails to function according to the system operating specifications, either failing during the test, or having characteristics that are outside the specifications following extrapolation of the ageing data to the full 10year lifetime of the links.

Any failure will be analysed post-mortem, in order to establish the cause of failure. Only failures that are intrinsic to the device-under-test will be counted in the statistics of the test. For example, failure of wire-bonds to the test-board will not be counted.

Acceptance criteria for the ageing tests of pre-production and advance validation components are such that 90% of the lasers should remain within the system operating specifications, following ageing equivalent to the full 10year lifetime of the links. If a batch is found to be unsuitable for use in the Tracker the appropriate lot will be rejected, and a new lot procured, following discussion with the manufacturer.

9.2.4.a.iii Magnetic Field

Unirradiated laser samples will be exposed to magnetic fields up to 4T in each of the 3 perpendicular axes. The laser L-I characteristics will be measured in-situ to determine whether the performance of the device is degraded by the field. These samples do not need to be in their final packaged form since the test is aimed at their operating characteristics. If the device operating characteristics, e.g. threshold current, are modified significantly by the applied field then an additional margin for these effects will be included in the acceptance criteria for radiation damage and ageing.

Unirradiated devices from the pre-production batch, in their final packaged form will be exposed to a strong magnetic field (~0.1T). If the device is found to be magnetic then this type of laser will be excluded.

9.2.4.b Optical fibre, ribbon cable and multi-ribbon cable

Bare optical fibre samples from each preform will be tested by advance validation to ensure that it is suitable for use in the CMS Tracker, before it is integrated into the final production. The same type of bare fibre is used in all parts of the links: the buffered fibre for pigtails and ribbonized fibre for the ruggedized 12-way cables and the 96-way cables.

Two 100m long samples of optical fibre per preform will be irradiated with gamma rays and neutrons up to the maximum dose and fluence expected inside the Tracker. In-situ measurements of the radiation-induced attenuation in the fibre and the subsequent annealing will be performed in these tests. The acceptance criterion for the preforms tested in the advance validation is that the loss will be no more than 50dB/km (i.e. 0.5dB over 10m inside the Tracker).

Samples from the pre-production delivery of buffered fibre for pigtails, 12-way fibre ribbon, single-ribbon cable and multi-ribbon cable will be irradiated with gamma rays up to the maximum dose expected inside the Tracker. Measurements of bending-induced losses and mechanical robustness, e.g. strip-force will be made before and after irradiation. There should be no significant degradation in these characteristics following irradiation, otherwise the corresponding lot of fibre, ribbon, or cable will be rejected. Visual inspection will also be carried out after irradiation to check for discolouration of the fibre jacket or cable sheath.

9.2.4.c Optical connectors

Samples of the pre-production deliveries of connectorized fibre (in the form of patch-cords) will be tested for magnetic susceptibility and radiation resistance. The connectors will be exposed to a strong magnetic field (~0.1T) and any connector type found to be magnetic will be excluded.

The radiation resistance will be measured in terms of return-loss and insertion-loss before and after irradiation. The acceptance criteria are such that all connectors from a given batch must perform within the target specifications before and after irradiation.

9.2.4.d Photodiodes

9.2.4.d.i Radiation damage and annealing

Radiation resistance tests of photodiodes will be done as part of an advance validation, where a number of devices will be tested from a given wafer, in advance of the final production of packaged devices from the wafer. A sample group of 20 irradiated devices is required to validate a given wafer. The devices should be packaged in the final form to facilitate mounting and testing.

The photodiodes will be irradiated under bias, with gamma rays and then neutrons, up to the worst-case doses and fluences taking into account the damage factors of the sources used relative to the Tracker radiation spectrum. Both the gamma and neutron irradiations will be made at room temperature with in-situ monitoring of the photodiode leakage and response characteristics made at periodic intervals before, during and after irradiation. The rates of degradation and annealing can therefore be determined.

Acceptance criteria for radiation resistance are such that 90% of the photodiodes should remain within all the operating specifications for the system, under the worst-cases of radiation damage exposure, throughout the full 10year lifetime of the digital links. The results of the damage and annealing tests will be extrapolated to the conditions of damage and annealing expected in the Tracker, in order to determine whether the acceptance criteria have been satisfied. Should a tested sample group of photodiodes fail these acceptance criteria, the corresponding wafer will be rejected and a new lot procured from a different wafer, following discussion with the manufacturer.

9.2.4.d.ii Ageing

20 irradiated and 10 unirradiated photodiodes will be passed through an accelerated ageing step as part of the advance validation. The devices will be operated at 80°C for at least 1000 hours to determine the rate of long-term wearout degradation. The inclusion of both irradiated and unirradiated samples allows a control of any possible degradation mechanisms that are due to radiation damage.

In-situ monitoring will be used to make measurements of the photodiode leakage and response characteristics at periodic intervals during the ageing test. The photodiodes will be biased constantly at -2.5V.

Wearout and random failure mechanisms are assumed to be temperature dependent, being thermally activated following the Arrhenius law. In any case where the activation energies for wearout failure and random failure of the photodiodes are not known, values of 0.55eV and 0.35eV respectively will be assumed. The value for the wearout activation energy is the worst-case value found in similar tests, and the random failure figure is taken from Bellcore recommendations[9.3,9.6].

Device failures are defined such that a photodiode fails to function according to the system operating specifications, either failing during the test, or having characteristics that are outside the specifications following extrapolation of the ageing data to the full 10year lifetime of the links.

Any failure will be analysed post-mortem, in order to establish the cause of failure. Only failures that are intrinsic to the device-under-test will be counted in the statistics of the test. For example, failure of wire-bonds to the test-board will not be counted.

Acceptance criteria for the ageing tests of pre-production and advance validation components are such that 95% of the photodiodes should remain within the system operating specifications, following ageing equivalent to the full 10year lifetime of the links. If a batch is found to be unsuitable for use in the Tracker the appropriate lot will be rejected, and a new lot procured, following discussion with the manufacturer.

9.2.4.d.iii Magnetic Field

Unirradiated photodiodes in their final packaged form will be exposed to magnetic fields up to 4T, in each of the 3 perpendicular axes. The photodiode characteristics will be measured in-situ to determine whether the performance of the device is degraded by the field. If the device is found to be magnetic then this type of photodiode will be excluded.

If the device operating characteristics are modified significantly by the applied field then an additional margin for these effects will be included in the acceptance criteria for radiation damage and ageing.

9.2.4.e Electronics chips

The laser driver and digital receiver chips will be tested in accordance with the other tests of the Tracker electronics chips.

9.2.4.f Hybrids

The tests of the hybrids will be defined in more detail in collaboration with the CMS Groups in charge of optohybrid production. Clearly the optohybrids should enable the specified link performance to be met throughout the lifetime of the Tracker. The optohybrids should be qualified in irradiation and accelerated ageing tests to prove their long-term reliability. These should include ionization and displacement radiation damage tests, thermal cycling to simulate the temperature changes possible inside the Tracker, or during storage and transport, and mechanical shock and vibration tests to simulate the stresses than can occur during handling and transport.

9.3 Storage and handling

Storage and handling conditions will be determined in common agreement with the manufacturers. In all cases, appropriate handling and storage conditions will be adopted so as to minimize the risk of damaging or degrading components.

9.4 References

[9.1] Magnetic field test data report currently in preparation. Data from tests up to 2.4T published in CMS Note 2000-40.

[9.2] Tracker Technical Design Report. CERN LHCC 98-6, 1998.

[9.3] List of publications of radiation damage tests carried out within the framework of the CMS Tracker Optical Links Project (1996-2000), available at:
http://cms-tk-opto.web.cern.ch/cms-tk-opto/rad_pubs.html

[9.4] Market Survey Data. (Confidential).

[9.5] Test protocols in preparation.

[9.6] Bellcore Specification GR-2903-CORE "Fiber Optic Data Links Reliability Qualification and Lot-to-Lot Controls", 1995.

10 Component traceability

All optical link components will be labelled or marked so as to allow their unambiguous identification during testing, installation and maintenance inside the CMS Tracker. Figure 12 and Table 11 describe the type of identifier foreseen for each component. Label numbers will be stored in the database and linked to manufacturer, test and assembly-position data. An estimated quantity of 100000 labels will be required to identify all optical components. The labelling system to be used shall be common to the whole Tracker but is as yet undefined. Manufacturers will not be forced to use this system, but will be asked to attach the labels if applicable. A look-up table will cross-reference CMS-Tracker and Manufacturer serial numbers.

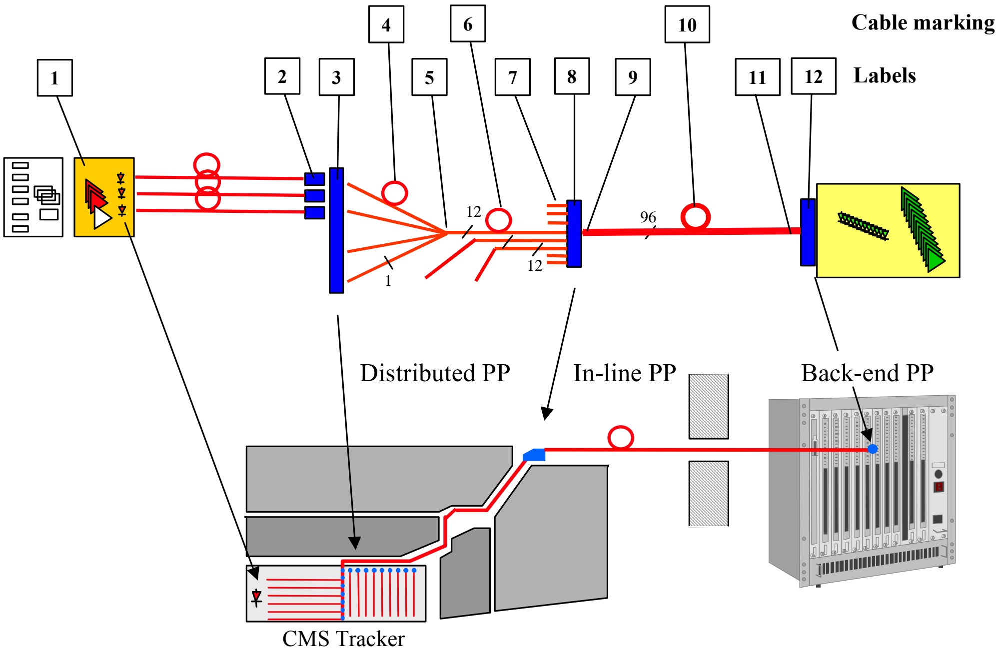

Figure 12: Distribution of labels along the optical read-out chain

Table 11: Labelling concept for optical link components

#	**Component**	**Identifier type**
1	Opto-Hybrid	Coded label glued on PCB.
2	Laser Transmitter Pigtail	Coded label attached to buffered fibre at connector end.
3	MU-Adaptor Shell	Coded label glued on 12-MU adaptor.
4	Single fibre section of 12-way ruggedized ribbon	Buffered fibre colour (12 colour Bellcore code) or rings numbered 1 to 12.
5	Furcation Element of 12-way ruggedized ribbon	Coded label glued on body of furcation element.
6	12-way ruggedized ribbon	Manufacturer code and ribbon length to spool start (in m.) is ink-jet printed on ribbon jacket during manufacture, every 1m. Every terminated ribbon section thus has a unique start and end-length, stored in the database.
7	Multi-way connector end of 12-way ruggedized ribbon	Coded label attached to ruggedized ribbon at connector end.
8	Multi-way connector adaptor shell	Coded label glued on Multi-way connector adaptor shell.
9	Multi-way connector end of multi-ribbon cable	Coded label attached to multi-ribbon cable at connector end.
10	Multi-ribbon cable	Manufacturer code and ribbon length to spool start (in m.) is ink-jet printed on cable sheath during manufacture, every 1m. Every terminated cable section thus has a unique start and end-length, stored in the database. Each one of the 8 ribbons in the cable is individually identifiable. Each fibre in the ribbon is individually coloured (12 colour Bellcore code).
11	Multi-way connector end of multi-ribbon cable	Coded label attached to multi-ribbon cable at connector end.
12	FED front-panel	Coded label glued on FED front-panel. Each of the 8 connector slots on FED is numbered from 1 to 8.

11 Maintenance

Even though the optical link has been designed for high robustness and reliability, wear-out and random failures cannot be excluded during the lifetime of the CMS Tracker. Maintenance will be possible at the level of the opto-hybrid, of the cabling network and of the receiver modules, as highlighted in Table 12 below:

Table 12: Maintenance scenarios for optical link components

Failing component	Action	Rework Scenario(s)
Laser Transmitter	Exchange opto-hybrid.	No rework possible due to glued fibre-clamp. If the failing laser is on a 3-laser analogue opto-hybrid, recycling of the hybrid is possible by transforming it into a 2-laser opto-hybrid.
Pin Diode	Exchange opto-hybrid.	No rework possible due to glued fibre-clamp.
Laser Driver Digital Receiving Amp	Exchange opto-hybrid.	Replace packaged electronics.
Terminated Pigtail	Exchange opto-hybrid.	Fusion splice fibre or new connector.
Opto-hybrid	Exchange opto-hybrid.	Replace passive component, or discard hybrid.
Terminated Fibre Ribbon	If it is a connector break, splice new connector in situ. If it is a ribbon break, exchange or add new Ribbon Cable if possible. If not, splice ribbon or new connector in situ. If not possible, permanently re-route faulty fibre-channels at distributed patch-panel.	
Terminated Multi-Ribbon cable	If it is a connector break, splice new connector in situ. If it is a ribbon break, permanently re-route faulty ribbon at in-line patch-panel. If it is a cable break during installation, pull new cable. If it is a cable break during operation, splice repair if possible.	
Opto-Receiver Module Opto-Transceiver Module	Exchange FED	Replace faulty Module on FED. No rework at module level.

12 Laser safety

12.1 Overview

The laser safety requirements and recommendations in this Section are taken from the current international standards IEC 60825-1 (1998-01) and IEC 60825-2 (2000-05) concerning safety of laser products and safety of optical fibre communication systems respectively. Laser safety is broadly categorized in terms of the potential optical power level that is accessible under reasonably foreseeable circumstances, and the wavelength of the radiation. The information provided here focuses on safety requirements relating to the CMS Tracker analogue and digital optical link systems operating at 1310nm wavelength. The requirements outlined in this Section therefore do not necessarily apply to other optical link or laser systems within CMS or elsewhere.

The hazard classification is determined for the system and its components based on a comparison of the worst-case possible exposure with the maximum permitted exposure (MPE) limits for a given class. Class 1 is considered as eye-safe and Class 3A denotes a laser that represents a low-level hazard. Class kx3A is specifically related to fibre-optic systems that have greater accessible optical power than that allowed in Class 3A but do not present a risk sufficient to be classified as Class 3B.* (Class 2 is related to visible wavelengths and is not applicable in the CMS Tracker system.)

The specific safety requirements that arise from the hazard classification are then outlined. These include the necessary warning signs and labels, the need for controlled access to the locations housing the optical link system and the testing laboratories, and the requirements of training of users and other personnel having access to the system and its components.

12.2 Hazard classification

12.2.1 Lasers

The 1310nm lasers that will be mounted inside the Tracker, as delivered in a package pigtailed with single-mode fibre, are individually Class 3A since they are capable of high optical power output when driven with a sufficiently strong current source.

In practice, when powered through the CMS Tracker optohybrids, the maximum drive current is 65mA (d.c. bias offset, i.e. 100% duty cycle). The power emitted from the fibre can therefore be no more than 3.25mW given the maximum specified laser efficiency of 50µW/mA.

The lasers are therefore designated as Class 1 components when operated in the CMS optical links, or when driven on test-benches using the laser driver ASIC on the optohybrid or current sources limited to 150mA.

12.2.2 Complete optical link system

Figure 13 summarises the hazard classification of the optical link system. All completely connected, unbroken optical links are nominally Class 1, since the optical power is completely contained, and the system poses no risk of exposure to

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* In Class kx3A 'k' is not a calculable constant.

users. However the hazard classification now must also take into account the potential exposure to laser radiation that can occur if a connection is opened, or if a fibre is broken, whilst the system is energized.

Within the CMS Tracker optical links there are two types of optical interfaces that are potentially accessible to users during the development, testing, operation, and maintenance of the optical links. These are the single way connections with MU connectors and 12-way ribbon connections with MT connectors. In addition there is always a risk that an energized single fibre, 12-way fibre ribbon, or 96-way multi-ribbon cable could be broken, thus exposing personnel to laser radiation. These conditions are considered now in greater detail.

In the worst case of opening a single-way MU-connection whilst the attached laser is being driven at the maximum current of 65mA, the maximum optical power emitted from the open fibre is ~3.25mW which is within Class 1 limits at 1310nm.

In the worst case of opening an MT connector there could be 12 fibres transmitting 3.25mW each. The densely packed fibres in the ribbon are considered to behave as a single extended optical source and the maximum power output of 39mW at 1310nm warrants classification as Class kx3A.

In the case of the multi-ribbon cable, the individual ribbons have their own separate MT connection therefore the hazard classification of kx3A also applies to the terminated multi-ribbon cable.

In the case of a broken single-way fibre the radiation exposure risk is the same as for opening an MU-connection, which is Class 1 in the CMS Tracker optical link system. In the case of a broken ribbon it is considered within the IEC Standards that this presents no greater risk than a broken single fibre, and this event therefore presents a Class 1 hazard. The same applies to a broken multi-ribbon cable where the risk is the same as a single-fibre channel, i.e. Class 1.

However it should be noted that in the case of a cleaved fibre ribbon, for example during splicing of a ribbon as part of a maintenance action, this situation presents the same risk as the opening of an MT-connector, i.e. Class kx3A in this system.

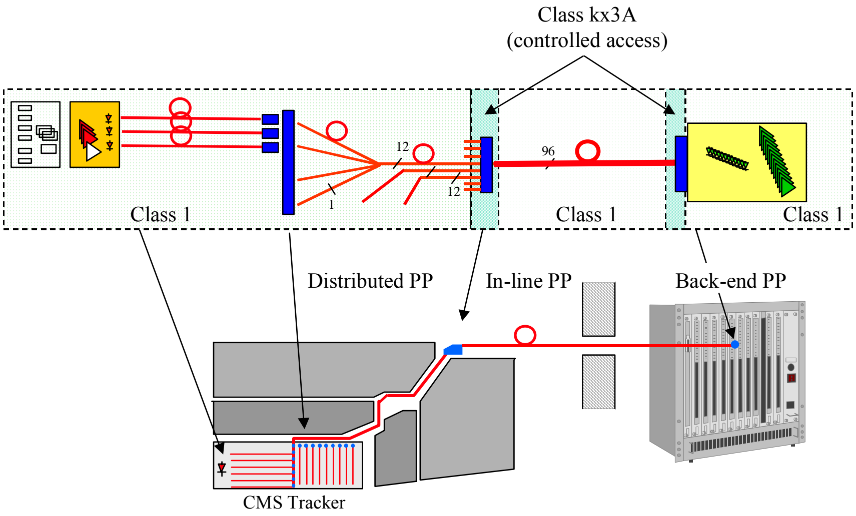

Figure 13: Optical link hazard classification

12.3 Safety requirements

12.3.1 Labelling of hardware

The IEC Standards state exactly where and which type of labels must be used throughout a fibre optic system. These recommendations must be followed within the CMS Tracker optical link system to minimize any risk to users.

12.3.1.a MU-Terminated laser assemblies and laser test-benches

The lasers, as delivered packaged on silicon submounts with their fibre pigtail and MU-connector, must be labelled Class 3A on the container. This is because the devices are capable of emitting a hazardous level of optical power when used with a strong enough current source.

Within the CMS Tracker optical link system the individual laser diodes do not present a risk greater than Class 1, therefore the lasers, their fibre pigtails, and the MU-connectors do not need to be labelled individually. The distributed patch-panels inside the Tracker, where the lasers are optically connected, must be marked with a Class 1 label to indicate that laser equipment is present that does not present a hazard in excess of Class 1.

Test-benches that power the lasers using the Tracker optohybrids must also be labelled as Class 1 hazards. In the unlikely event that these lasers are driven using a much stronger current sources (>150mA) the test-bench must be labelled Class 3A.

12.3.1.b Fibres, ribbons, optical cables, connectors and patch-panels

The single channel fibres, 12 channel ribbons, 12 channel ribbon cable, and 96 channel multi-ribbon cable in this system do not have to be labelled individually, since they do not present a hazard exceeding Class 1.

The accessible locations that present a potential hazard in excess of Class 1 are those patch-panels that house the 12 channel MT-connectorized fibre ribbon junctions. The single-way MU-connectors inside the Tracker do not need to be labelled as the hazard does not exceed Class 1. However, as mentioned in the previous paragraph the distributed patch panels should be marked with a Class 1 label. For the 12-way MT connectors in the final system the individual connectors do not require a warning label, since the accessible locations are limited to the various patch-panels. All of the patch panels containing 12-way optical connections must be labelled as Class kx3A, along with a description of the hazard.

For the in-line patch panels in the HCAL crack the patch-panel housing must have a Class kx3A label, and a hazard description label, that remain clearly visible even when the patch panel is opened. In the case of the receivers on the FEDs and FECs in the counting room, the crates, or racks, should have a protective cover that is clearly labelled as a Class kx3A, along with a warning label explaining the nature of the hazard. These labels must also be clearly visible when this cover is open. Access to the FEDs and FECs will only be granted to authorized personnel who have followed the appropriate laser safety training.

12.3.2 Access limitations to areas housing laser and optical links systems

The use of systems with hazard Class kx3A dictates that these operating environments must have limited access in order to protect all personnel from any potential risks. Of the three types of location outlined in the IEC Standards: Unrestricted, Restricted and Controlled, the locations housing the CMS Tracker optical link system where the hazard is Class kx3A must be designated as Controlled Areas. The 'location' referred to as a Controlled Area is a flexible term. It can be an area equivalent to an entire room or laboratory for example, or a part of a room, or simply the object containing the optical components, e.g. a closed patch-panel housing, or an electronics rack with a door or cover.

The IEC Standards demand that Controlled Areas must satisfy the following requirements:

- The location is marked as being of access only to authorized personnel
- The location is marked clearly with signs warning of the access conditions, at the entry and within the area, giving the hazard class and the nature of the hazard.
- The location is supervised by a trained person, or team of people, identified with the responsibility for checking that the rules for access, and safety recommendations for the use of the laser systems, are followed.
- All of the hazardous objects within the Controlled Area are labelled correctly.
- Appropriate eye-protection must be available.

The locations that are considered to be Controlled Areas within the final CMS Tracker optical link systems are:

- The patch-panel housing for the in-line patch panel situated in the HCAL crack (Class kx3A)
- the crates containing the FEDs (Class kx3A)
- the crates containing the FECs (Class kx3A if fibre-ribbon is used).

In contrast all the cable routing trays and ducts containing the optical fibres that are part of the CMS Tracker optical link systems, in the form of single-way, ribbon, or multi-ribbon cables, are all Class 1 and do not present any particular access restrictions. Clearly, from the point of view of minimizing all risks during installation of CMS, the optical cable ducts between the experiment and counting room should all be labelled as containing optical fibres, and all the cables should be handled only by appropriately trained personnel.

Ducts containing the CMS Tracker optical link channels that are accessible to any CMS personnel should be labelled "CMS Tracker Optical Links. Class 1". If the ducts contain fibre channels that are not part of the Tracker optical links, but are part of other systems, then the labelling must reflect the appropriate hazard class and provide specific details of the hazard.

Where maintenance of the optical links within the CMS Tracker system at any of the MT-connector patch-panels is being carried out, the area around the object being maintained will be temporarily designated as a Controlled Area. The boundary to this area will be defined as being that containing a laser radiation hazard in excess of Class 1 under reasonably foreseeable conditions. Access to this area will be limited by the appropriate use of temporary signs.

In the laboratories developing, testing or using the optical link system (with either analogue or digital links) the appropriate access controls must also be applied. In locations where the lasers are tested on the CMS Tracker opto-hybrids, or with current sources less than 150mA, such that the hazard is never in excess of Class 1, there are no special access requirements. It is assumed that, in any case, these work-places are considered as Restricted Areas, with no unsupervised access to the public, where laser operators have also received the appropriate training.

In laboratories containing test-benches for the CMS Tracker optical link system that use *ribbonized* optical fibre cables there must be Class kx3A access conditions. In this case the laboratory must be designated as a Controlled Area, unless the stronger requirements for down-rating to a Restricted Area are fulfilled. There must also be Class kx3A warning signs attached to the test-bench and Class kx3A labels on each optical connection and the connector housing, unless a patch-panel is being tested. In this latter case only the patch-panel must be labelled as Class kx3A.

12.3.3 Laser safety training

Laser safety should be an integral part of the training for CMS personnel in order to prepare them for encounters with the numerous optical radiation environments that exist within CMS.

The IEC Standards referenced at the start of this chapter contain all appropriate general safety recommendations. These or similar laser safety guidelines must be available for reference in all laboratories and locations housing optical link systems. However, adherence to these guidelines alone does not represent an acceptable substitute to proper Laser Safety training.

Laser Safety training must be sufficient to allow for the minimization of all risks associated with the given class of hazard that is accessible. In the case of the CMS Tracker optical links the worst-case hazards are Class kx3A, which defines the minimum training requirement for all link users, who have access to the hardware. In the final system, as well as in the testing laboratories, the personnel who are responsible for access to the Controlled Areas must have the right to request proof of sufficient Laser Safety training from all personnel who wish to access these locations.

The responsibility for ensuring adequate Laser Safety training of users lies fundamentally with the users themselves and with their immediate supervisors. Training courses are widely available and it is not the responsibility of the CMS Tracker optical link development team to train users in Laser Safety, or to accompany untrained users in Controlled

Areas. The optical link development team will also not be responsible for any accidents that occur through inappropriate use of the optical links or their component parts.

13 Documentation

In terms of quality assurance, the documentation related to all the parts of the project must be complete, sufficient and available to all the relevant groups involved.

During the earlier phases of optical link development the project www pages (on http://cms-tk-opto.web.cern.ch/cms-tk-opto/) have been used extensively as a means of disseminating specifications, reports, notes and user manuals. All prototype components that have been delivered to date are traceable through a www interface to a private database that also contains the manufacturer data-sheets.

In preparation for full production, the project now uses EDMS and the CMS Tracker Database that is under development. EDMS is used as an archive for the link specifications, outlined in Section 5. All batch requests, test reports, and acceptance documents related to the pre-production and production will also be archived in EDMS, as well as being made available to the appropriate manufacturers. Component datasheets, test-data and traceability data will be archived in the CMS Tracker database.