Reliability of fibre-optic data links in the CMS experiment

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CERN EP/CME-OE

Outline

- Projects overview: CERN Optical links for CMS (*)
- Reliability issues
- Philosophy to maximize reliability
  - Reliability assurance
- Reliability testing of components and system
  - Environmental (radiation damage) and standard reliability testing
  - COTS issues

(*) Not including TTC-specific or CMS/DAQ link systems

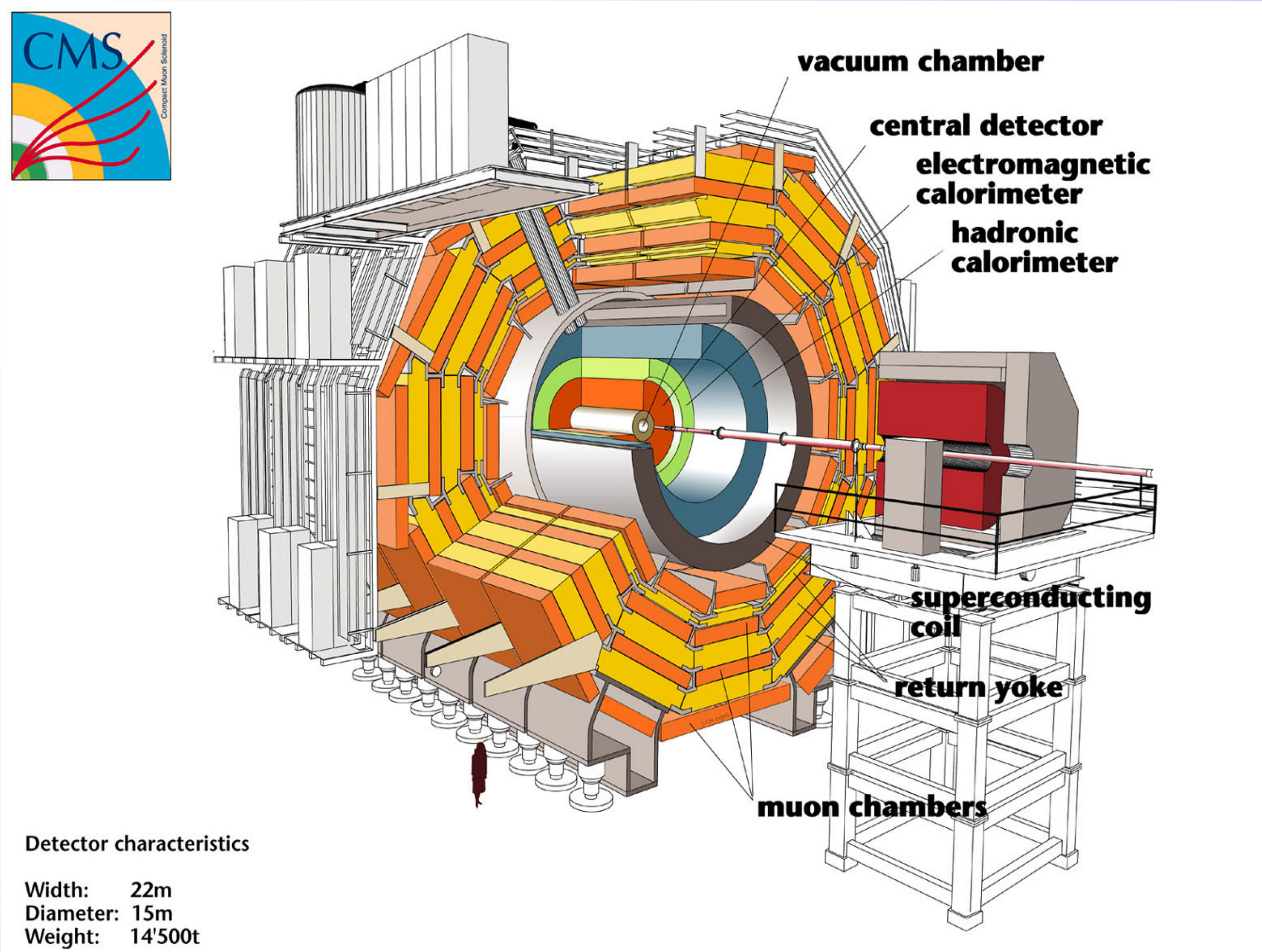
COTS = Commercial Off-the-shelf

Optical link team

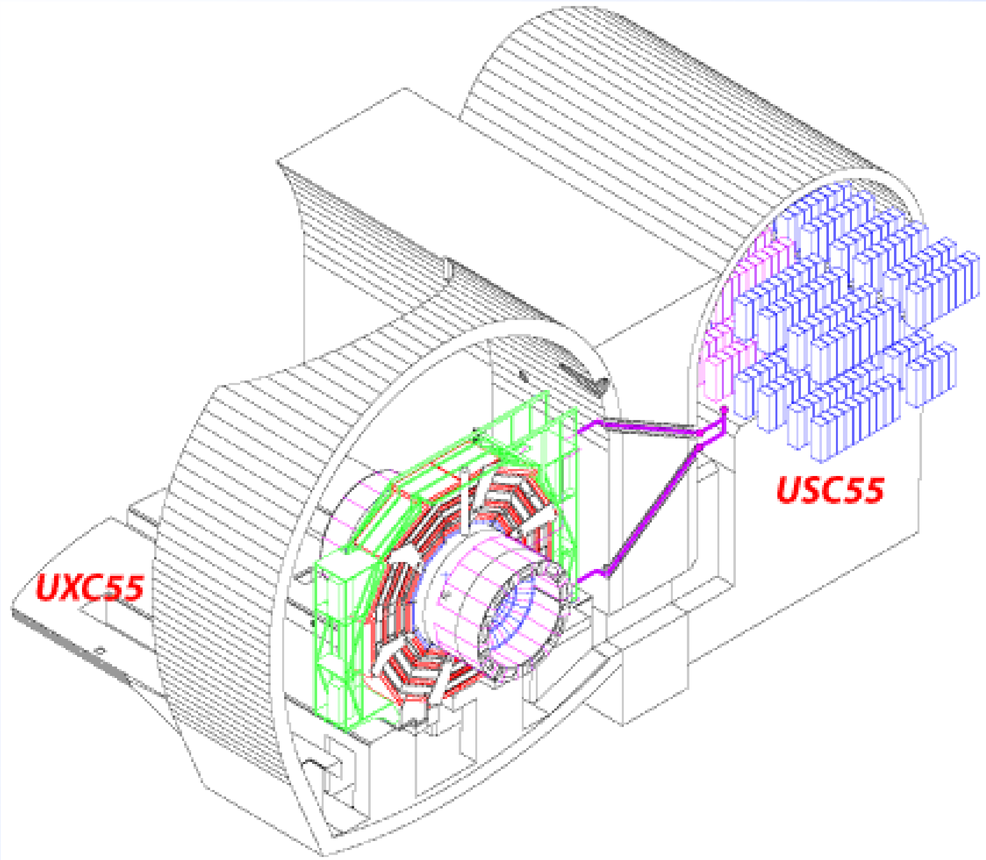
- CERN team
  - Overall CMS link projects manager: Francois Vasey
  - QA (reliability) + Control link project manager: Karl Gill
  - QA (analogue links): Jan Troska
  - Technical support+Integration: Robert Grabit, Christophe Sigaud
  - Digital links (test+development): Etam Noah
  - ECAL links (test+development): Guy Dewhirst
  - QA testing (radiation damage+reliability): Raquel Macias
  - QA testing (functionality): Guilia Papotti

- In collaboration with:
  - CERN/MIC (ASICs+control system)
  - Vienna (optohybrids)
  - Perugia (optohybrids)
  - Minnesota (ECAL links)
  - Imperial College/RAL (Tracker FED)

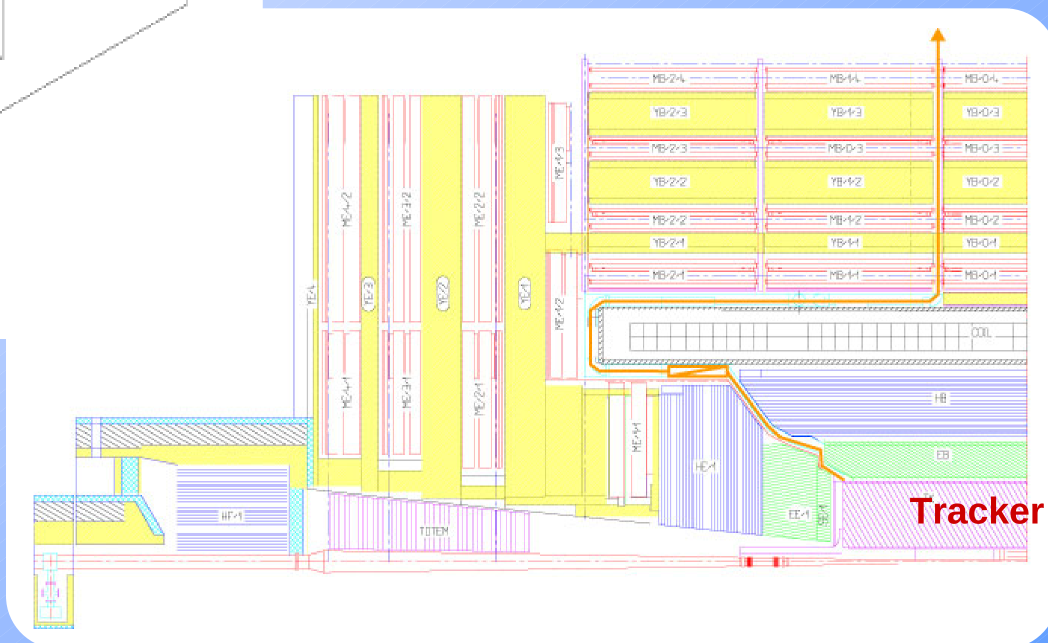
CMS


CMS
Compact Muon Solenoid
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

Optical link for CMS readout/control

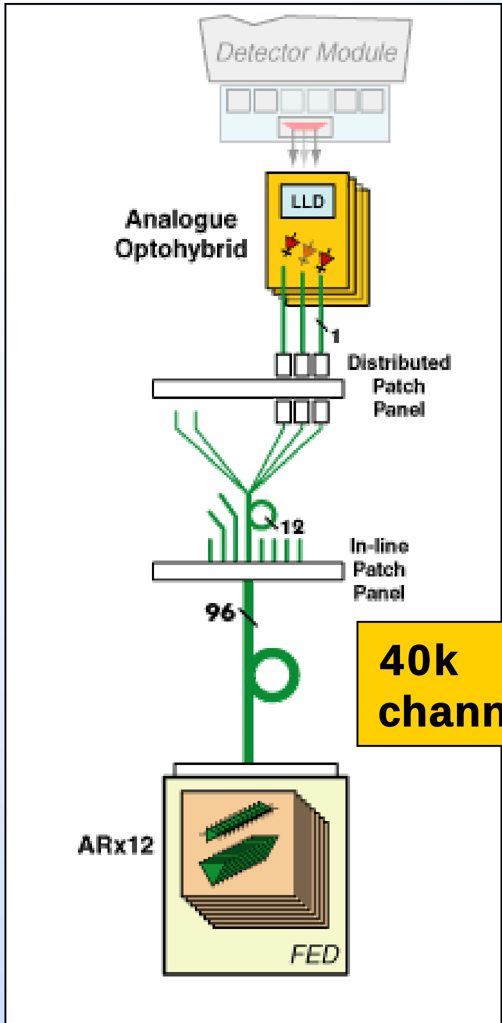


- E.g. optical links for Tracker



Optical links for CMS readout/control

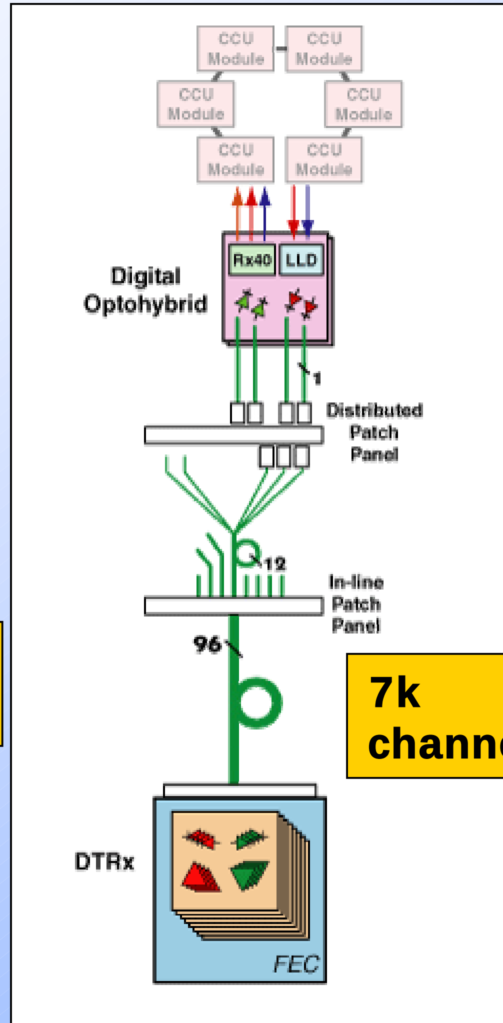
Tracker analogue readout links



40k channels

CERN/Vienna/Perugia/IC/RAL

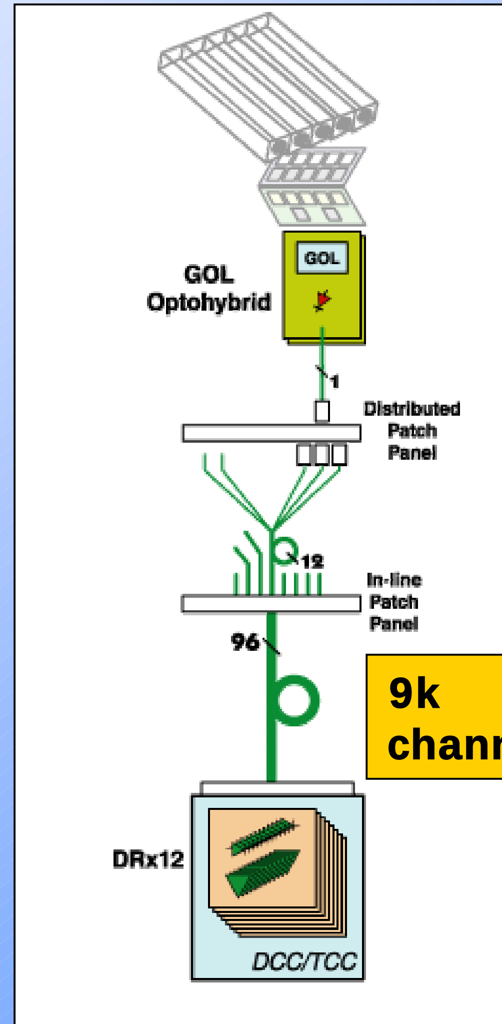
Digital control links



7k channels

CERN

ECAL digital readout links



9k channels

CERN/Minnesota

Reliability

- Adopted a simple definition for our practical uses:
  - Reliability = Probability of surviving for the required lifetime in the given environment
    - 'surviving' = system still capable of operating within spec
      - (even if components degraded/radiation-damaged)
- Also related issues ('RAMS')
  - Availability
  - Maintainability
  - Safety
  - Good "RAMS" = dependability

Ref: CERN Reliability and Safety training course, 2002.

CMS links 'RAMS'

- Target 100% reliability (and availability) of final system
- Zero maintenance possible/envisaged at front-end once inside CMS
    - Integrate only known good and known reliable components
        - Qualification
        - Lot Acceptance
        - Advance validation
        - Integration (system) tests
- Maintainability
    - Can replace back-end parts rapidly
        - Accessible in counting room
- Safety

  Final system: Class 1, with no (IEC) requirements other than labelling

  Halogen free, flame-resistant, low-smoke parts (CERN rule)

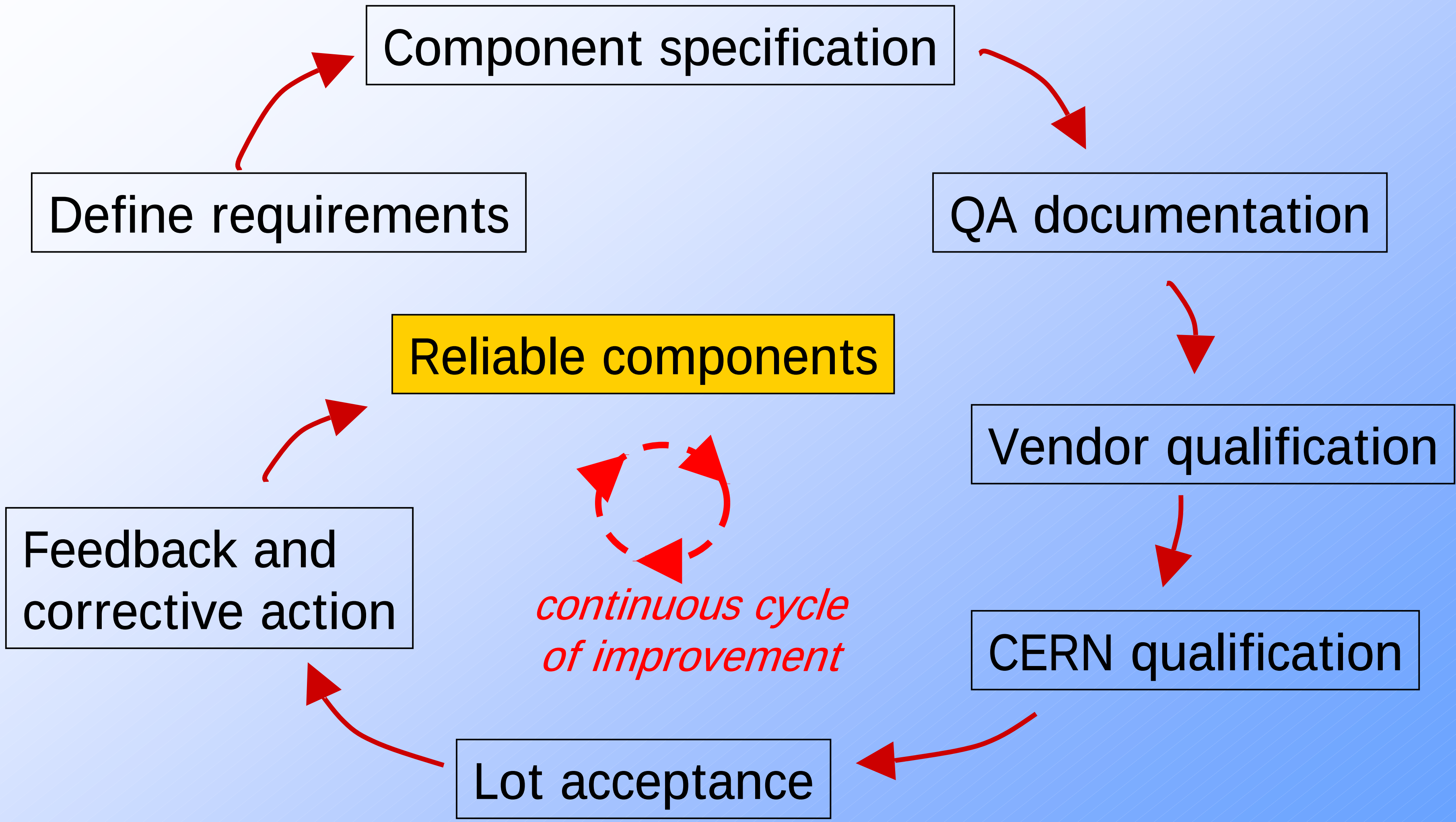
Reliability issues for CMS optical links

- Many issues impact reliability in this project
  - Some very different to telecoms (*) fairly typical, (****) unheard of!

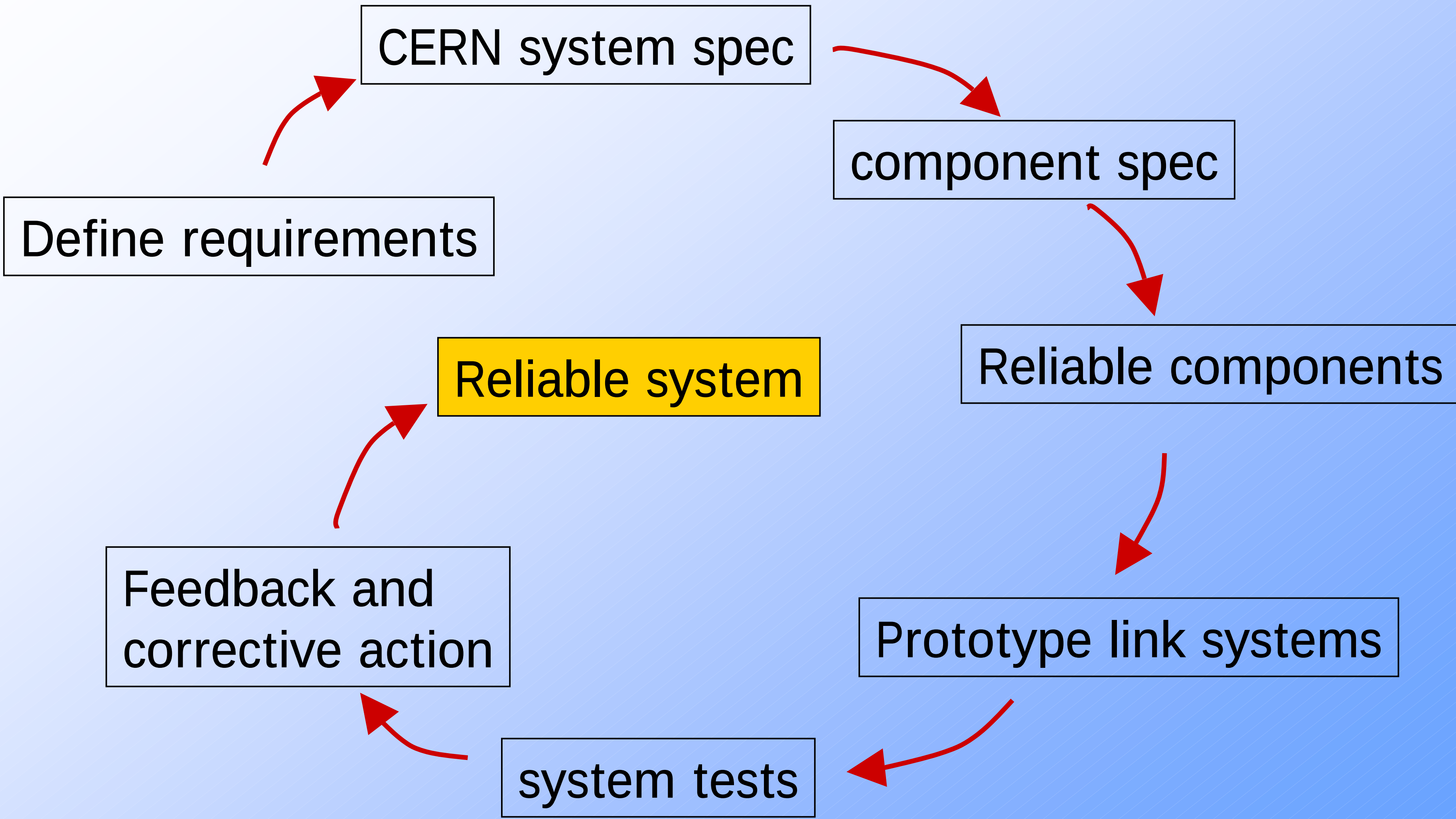
  - Complexity of system
    - Inaccessibility (*)
    - Radiation (****)
    - Quantity of components (***)
    - Integration involving many groups (***)
  - Complexity of production
    - Novel components (*)
    - COTs and COTs-based parts (*/***)
    - Multi-supplier chain for most parts (***)
  - Long project lifetime
    - 10 year span of development to commissioning (****)
    - 10 year operational lifetime (*)

- Similar projects, good contacts established (via RADECS, NSREC, SPIE conf's)
  - NASA (NEPP program, JPL), ITER (SCK-CEN, Be)

Component Reliability Assurance

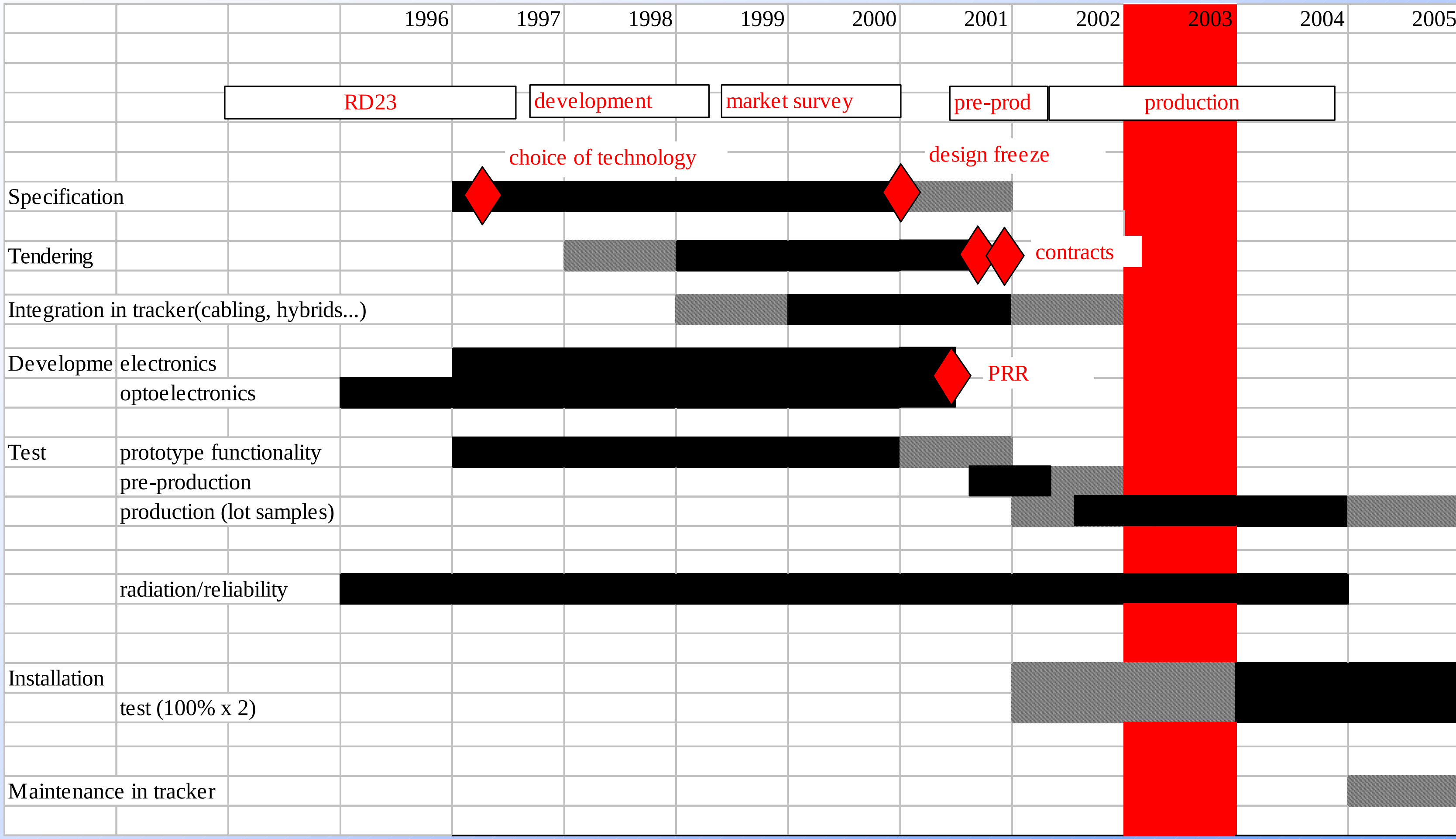


System Reliability Assurance



Timescales

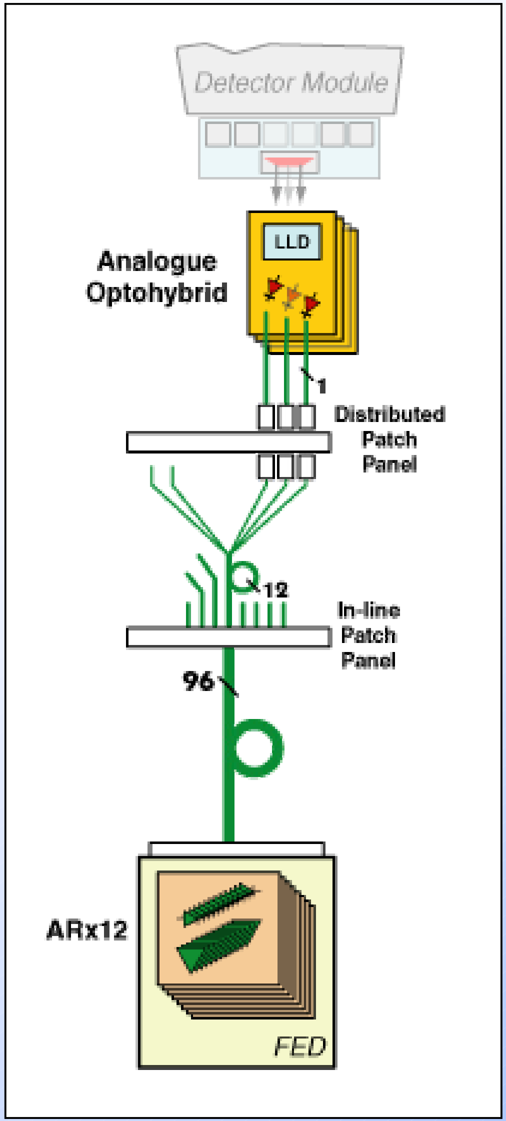
e.g. analogue link project: the most advanced.



QA/RA longest part of project. Still a lot of work to do.....

Optical link system requirements and implementation

Functionality Requirements



Focusing on CMS/Tracker analogue readout link system

Readout ~10 million silicon strips at 40Msamples/s

~40k optical link channels

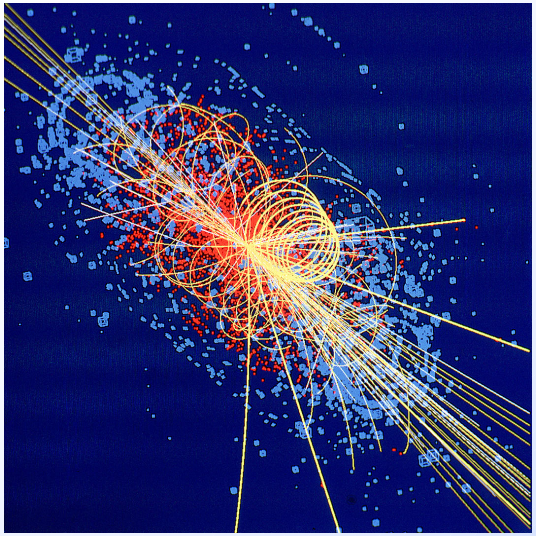
256:1 time-multiplexing

Linearity	1-2%
Dynamic Range	7-8 bits
Settling Time	<20ns
Gain	0.8 (3 MIP, 75K e- signal)

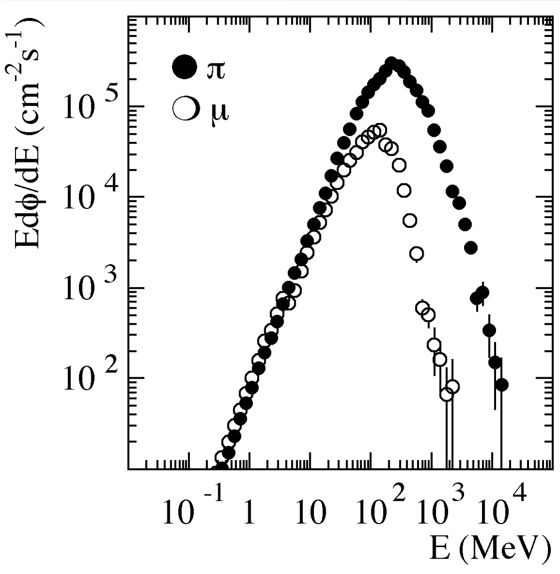
Requirements: environment factors

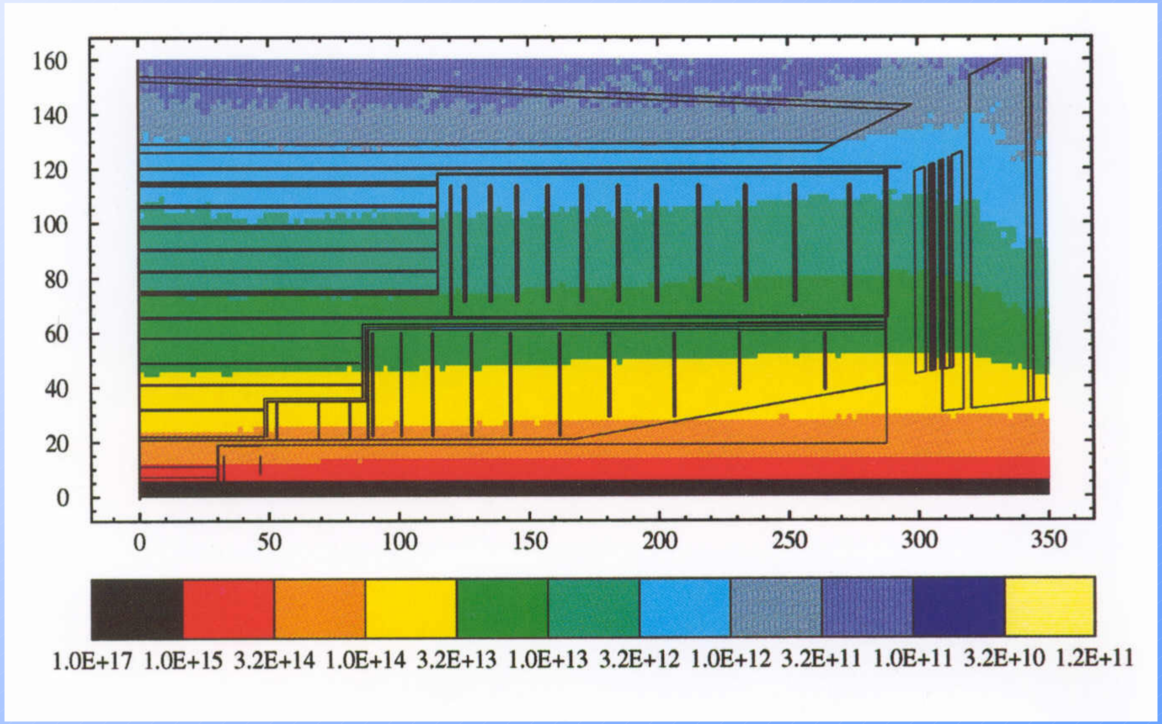
- Temperatures
  - TK –10°C, ECAL 10° to 30°C (fairly standard for telecoms)
- Magnetic field
  - 4T
- Small volume available
  - Compact packages, dense connection arrays, minimal mass
- Inaccessibility and lifetime
  - inside Tracker and ECAL practically inaccessible for maintenance
  - ten year lifetime
- Last but not least..... radiation environment

Requirements: radiation environment



- High Energy 7+7TeV
- High rate
  - Large radiation field
    - mainly pions (few hundred MeV) in Tracker





Charged hadron fluence (/cm^2 over ~10yrs)
(M. Huhtinen)

Implementation: Specifications

- e.g. analogue link main performance specs
  - evolved/iterated during development phase
  - frozen before production

Spec	System	A-OH	Rx-module
INL (2MIP)	1% typ.	1.5% max	0.5%
S_pNR (6MIP)	48dB typ.	46 dB min	60dB
Bandwidth	70 MHz	90 MHz min	100 MHz

↓ many other parameters specified, see www

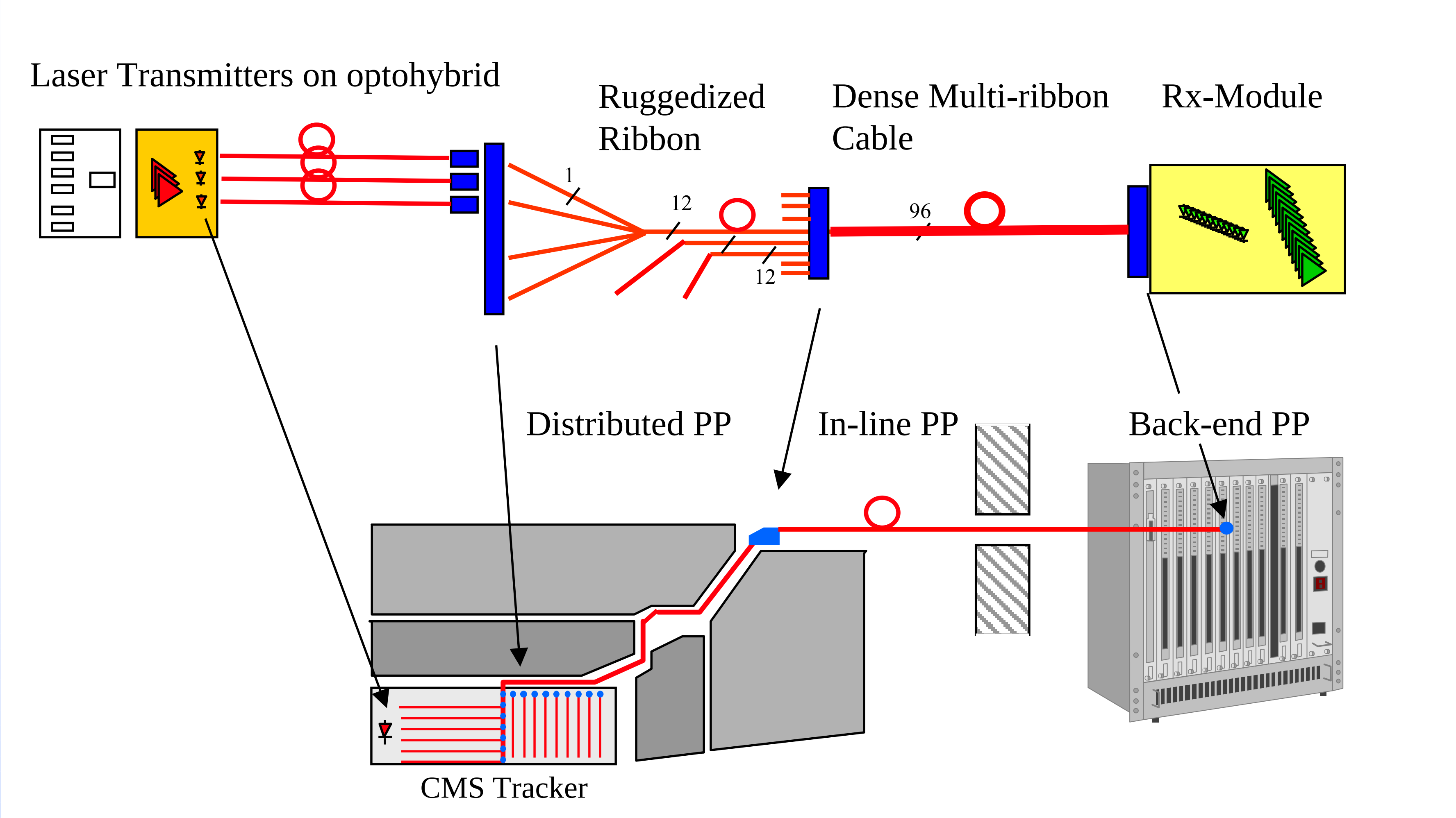
Implementation: Technology choice (1996)

- Developed analogue link system first (most links + most difficult)

Requirement	Technology choice
Linearity	Edge emitting Laser
Dynamic Range	Single mode System, 1310nm wavelength
Settling Time	Fast electronics (BiCMOS or CMOS-Subμ)
Gain	10bit ADC with equalization
Magnetic Field	Non-magnetic connectors and packages
Radiation	Extensive qualification of COTS-based components
Density	Semi-customized laser package Fibre ribbon & array connectors Customized multi-ribbon cable Semi-customized Rx-module

- Control link and ECAL readout developed later using many of same parts

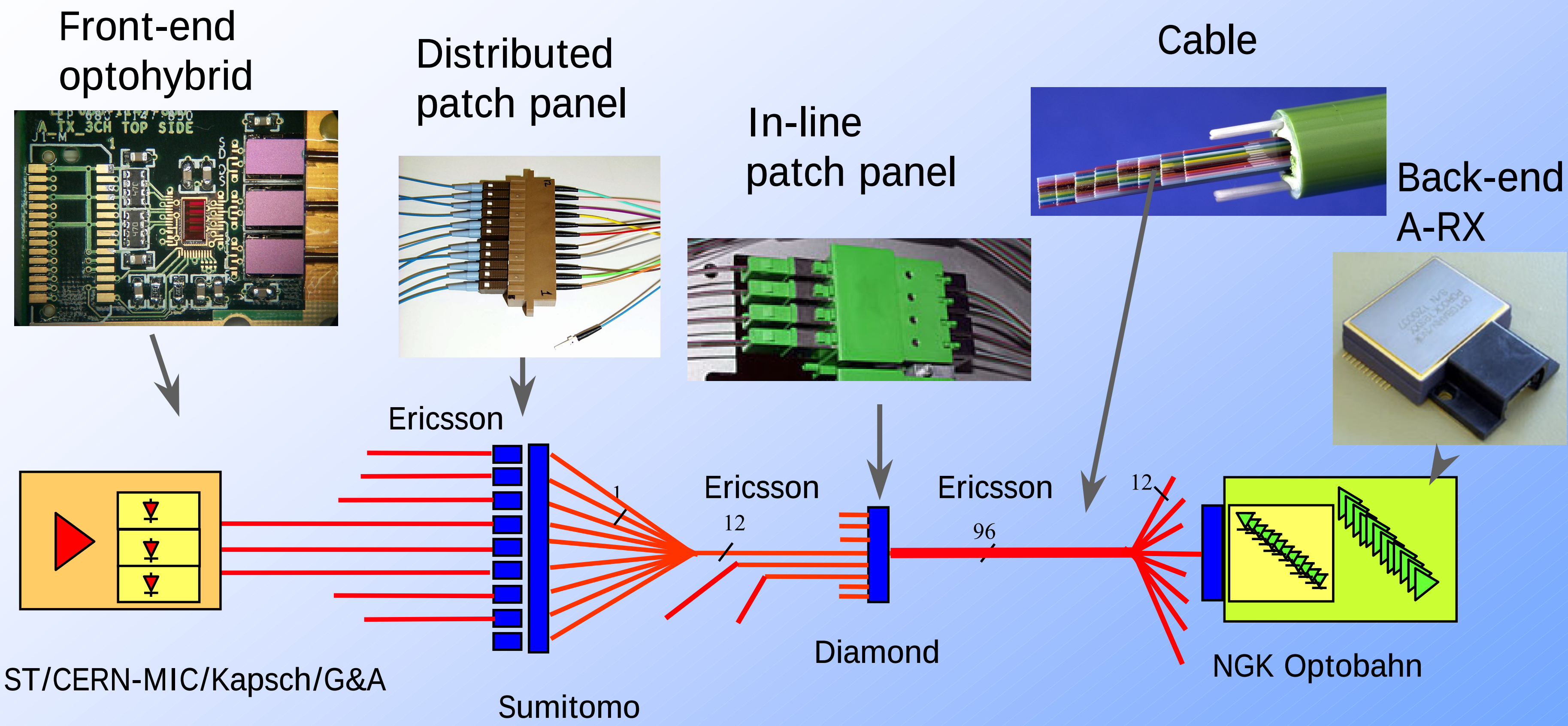
Implementation: Architecture (1996)



Tracker analogue readout link

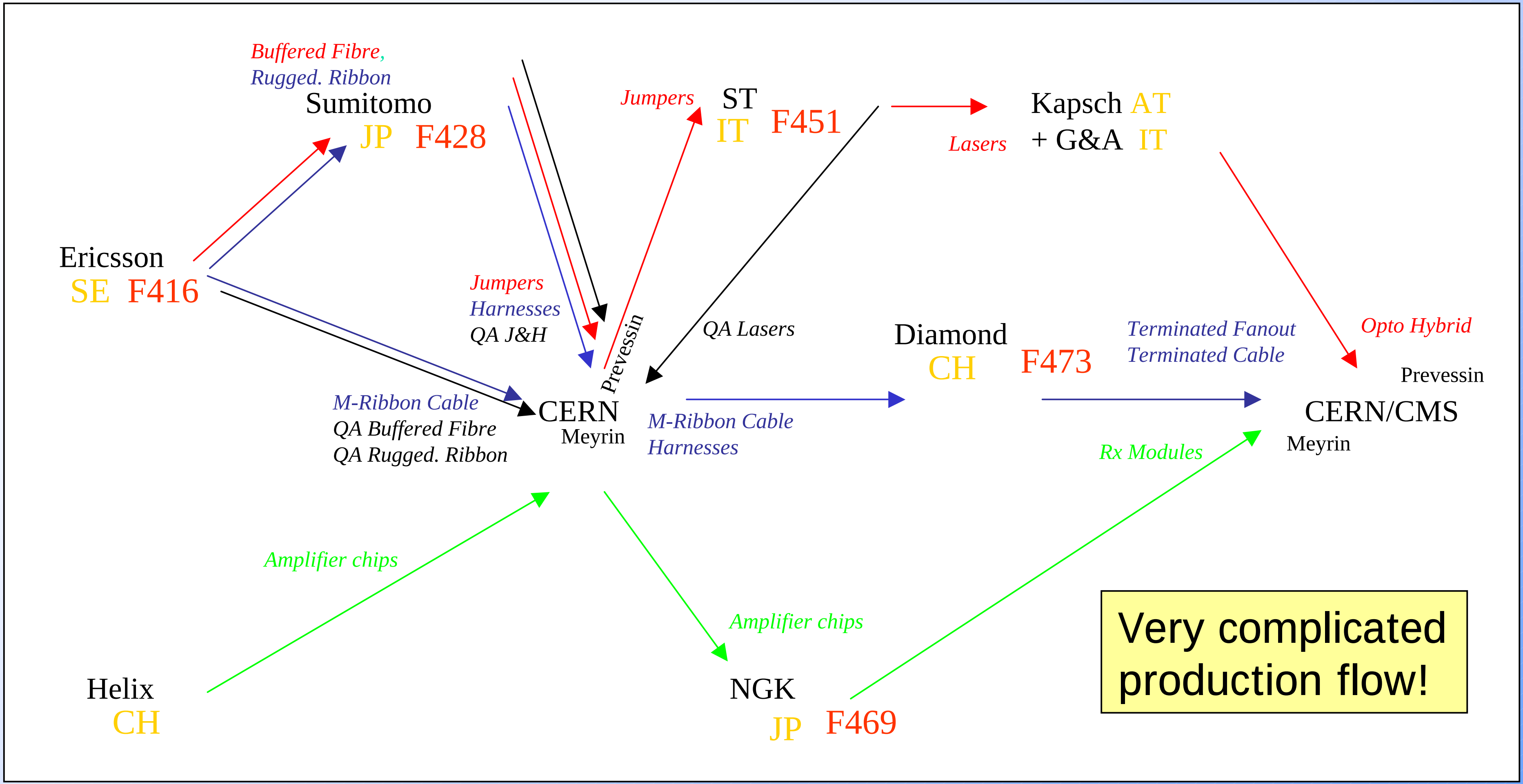
(Original RD23 link: reflective modulator at front-end, elegant but expensive/risky)

Implementation: Components (2000-02)



- Many COTS/COTS-based parts (e.g. analogue links)
  - Each component also has own CERN specification
- Long procurement process
  - CERN Market-Survey/Tendering

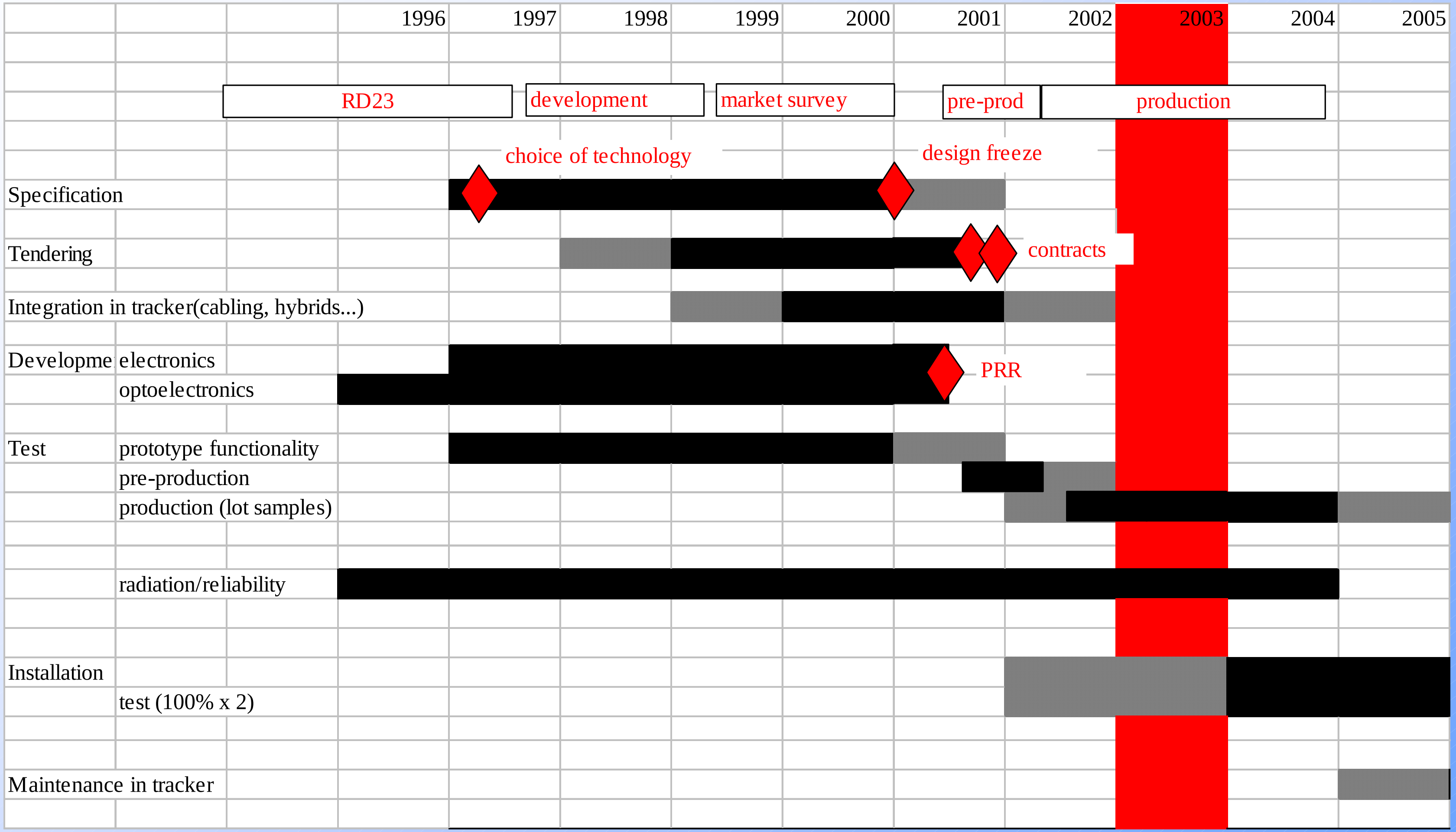
Implementation: logistics (2001 -)



- CERN in (unusual?) position of being both a customer and a supplier

Timescales

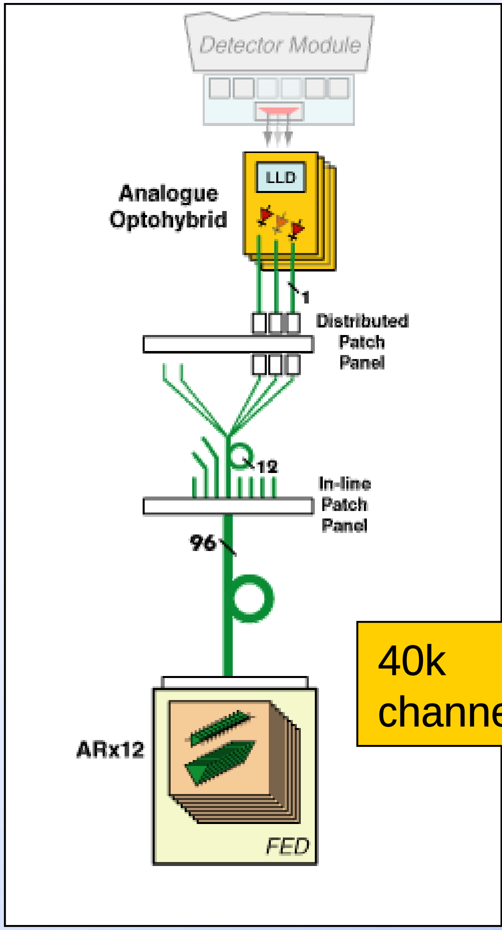
e.g. analogue link project: the most advanced.



QA/RA longest part of project. Still a lot of work to do.....

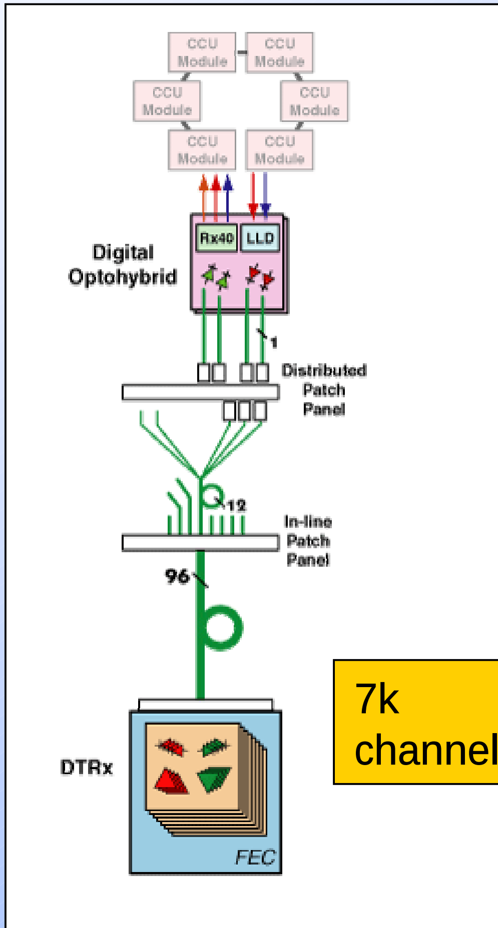
Other link systems

Tracker analogue readout links



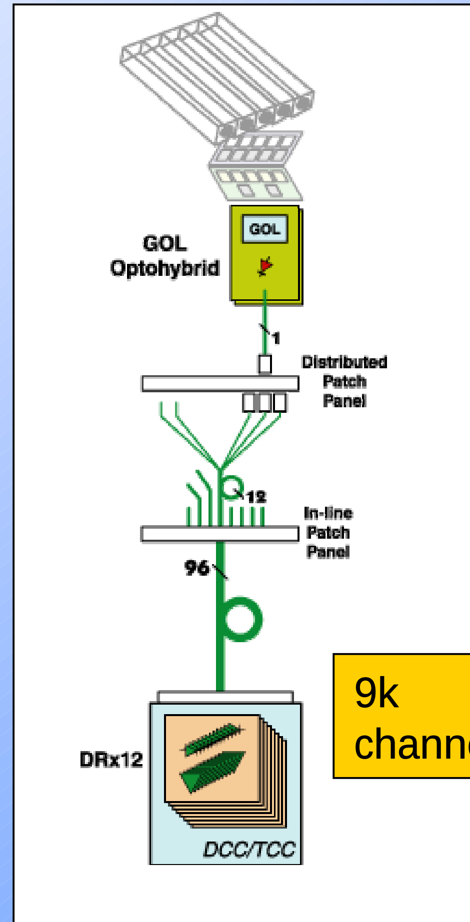
40k channels

Digital control links



7k channels

ECAL digital readout links



9k channels

- Philosophy to re-use bulk of analogue link parts for other smaller systems
- Optimizes effort, reduces overall costs, development/qualification time/effort

Reliability testing

Reliability Testing Goals

- Several important objectives
  - Validate various COTS parts for use in CMS
    - Disqualify weak candidate components (in Market Survey before Tender)
    - Understand and quantify damage/degradation effects
  - Refine the system and component specifications
    - Design-in damage mitigation
  - Validate test methods and define (pre)production test-procedures
  - Improve the production processes where possible

Reliability Testing overview (1996 - present)

- Environment
  - Irradiation [lasers, photodiodes, optohybrids, fibre, connectors, cables]
  - B-field [lasers (Vienna)], photodiodes and connectors]
  - Temperature [lasers, optohybrids (Perugia and Vienna)]

- Other accelerated stress-aging tests
  - High-T storage, thermal cycles [lasers, photodiodes, fibre, cables]
  - Strength [fibres, cables, lasers]
  - Mating cycles [connectors]

- Also manufacturer's own tests
  - Internal qualification
  - Lot tests
  - Assistance with CERN QA

Use of industry reliability standards

- Bellcore Reliability Standard GR 468
  - "Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment"
  - Other standards used include US-MIL 883, IPC
- Standards provide framework for manufacturers, vendors, suppliers and customers to discuss actions related to reliability of parts
  - e.g. definition of test procedures

MIL 883, US Department of Defense Microcircuits

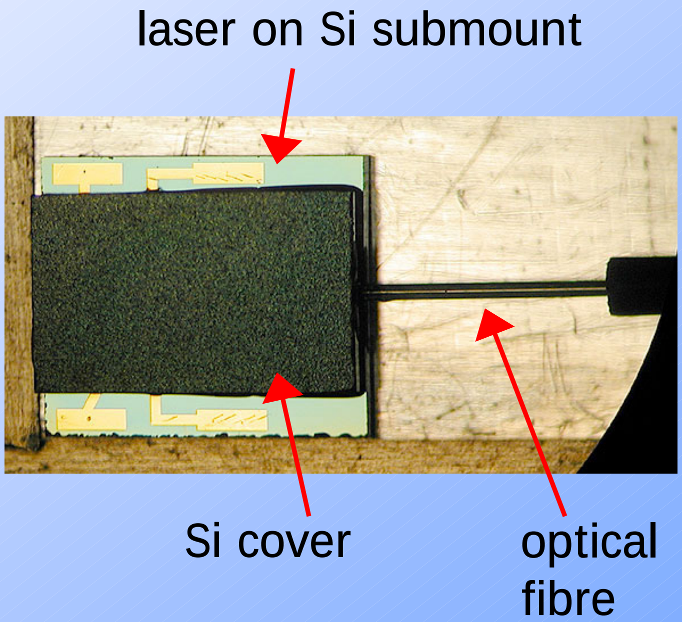
IPC 'Association Connecting Electronics Industries'

Limitations of standards/COTS for LHC

- Telecoms vendors typically qualify products to Bellcore standard
  - CERN/LHC very special application
    - Unusual environment in particular, requires own
      - reliability specs
      - test-procedures
      - acceptance criteria
  - We want to use COTS to avoid custom development
    - cannot expect manufacturers to 'upscreen' COTS products or re-qualify
      - CERN must
        - validate prototypes prior to Tender
        - qualify pre-production batches before final production
        - advance validate COTS sub-components
- A lot of work and heavy testing program
    - costs some money (So far <<NASA NEPP $10million/yr)
    - No choice – few rad-hard qualified parts available
    - Also, any custom parts would have to be qualified too!

COTS issues (example of laser)

- Laser in 'mini-pill' package
  - Part of COTS transmitter product
  - Normally inside a rugged DIL package



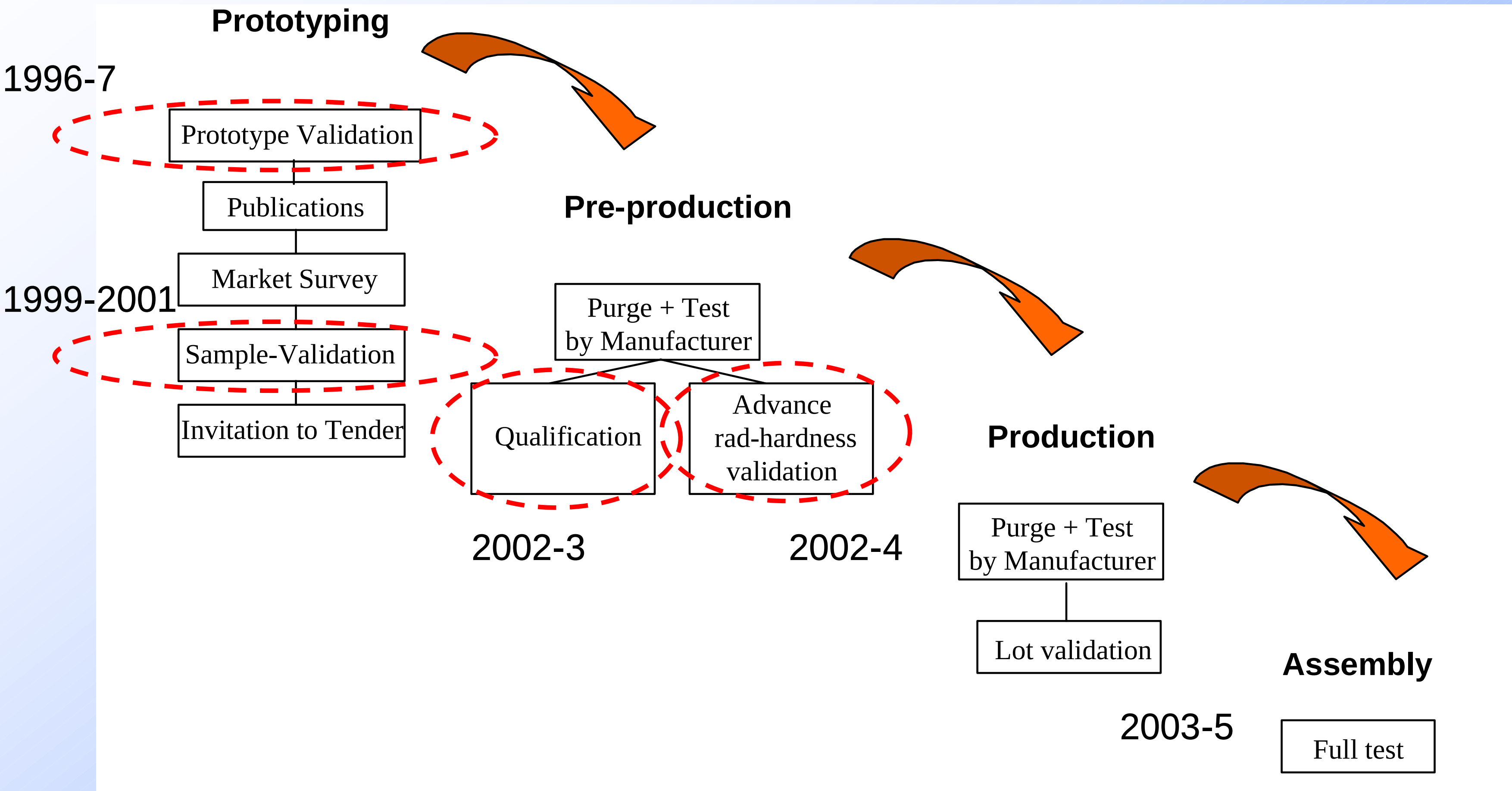
- Radiation hardness validated by CERN
  - resources not infinite:
    - incomplete understanding of the damage effects
    - no guarantee of radiation hardness of future batches

- Need to avoid (big) problem of having to reject fully assembled laser transmitters
  - ~200% added value
  - also avoid delays, possible disputes.....

- Use Advance valdiation test (AVT) procedure

Project QA overview

Will look at some reliability test data from various points in QA:



Dates for lasers

Accelerated test philosophy

- Forced to make accelerated tests due to limited time/resources available

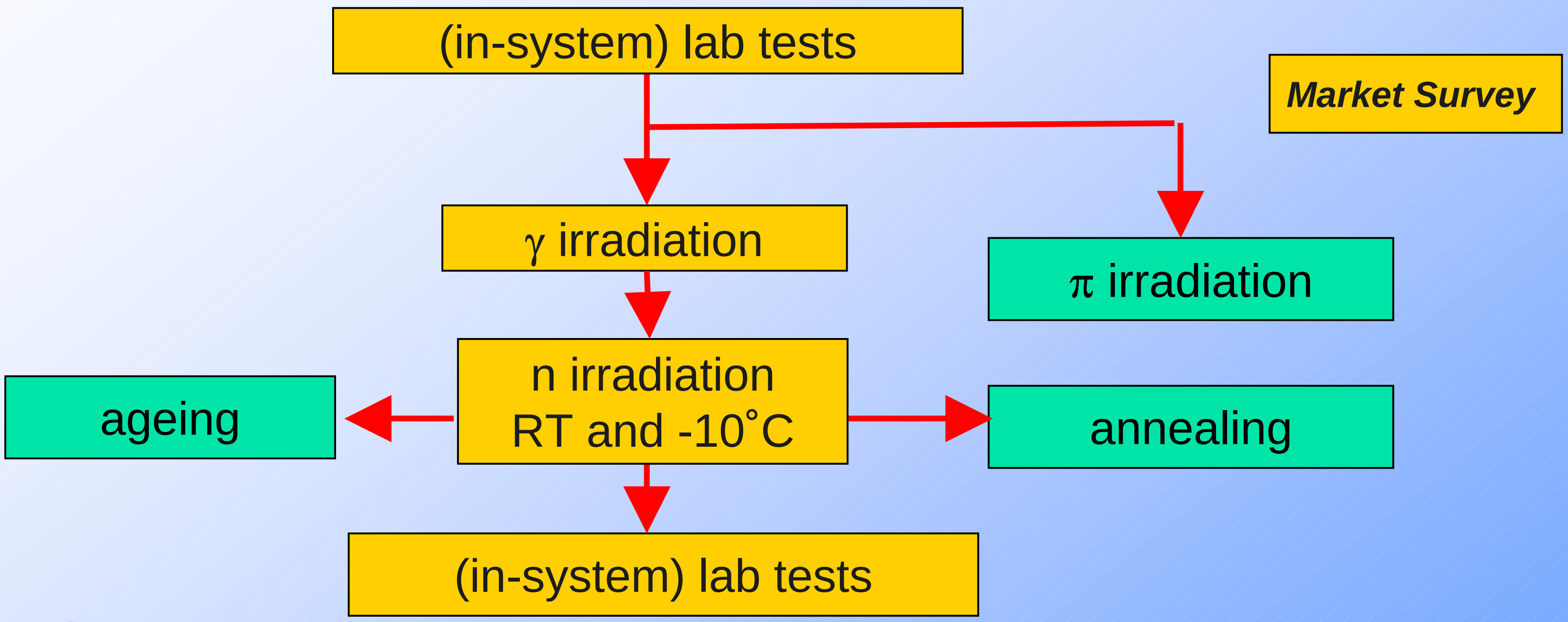
  - E.g. test 'worst-case' radiation exposure
    - also other acceleration factors: temperature, electrical bias
    - different particle types in CMS spectrum

  - in-situ measurements
    - maximum information on effects <u>and</u> rates of change
    - Post-test comparisons easy:
      - different radiation sources
      - different manufacturers
      - different operating conditions

- Idea to extrapolate from accelerated tests to CMS conditions
  - Calculate expected degradation
  - Refine test procedures for production QA

Environmental testing

- e.g. validation tests on lasers (1999-2001)

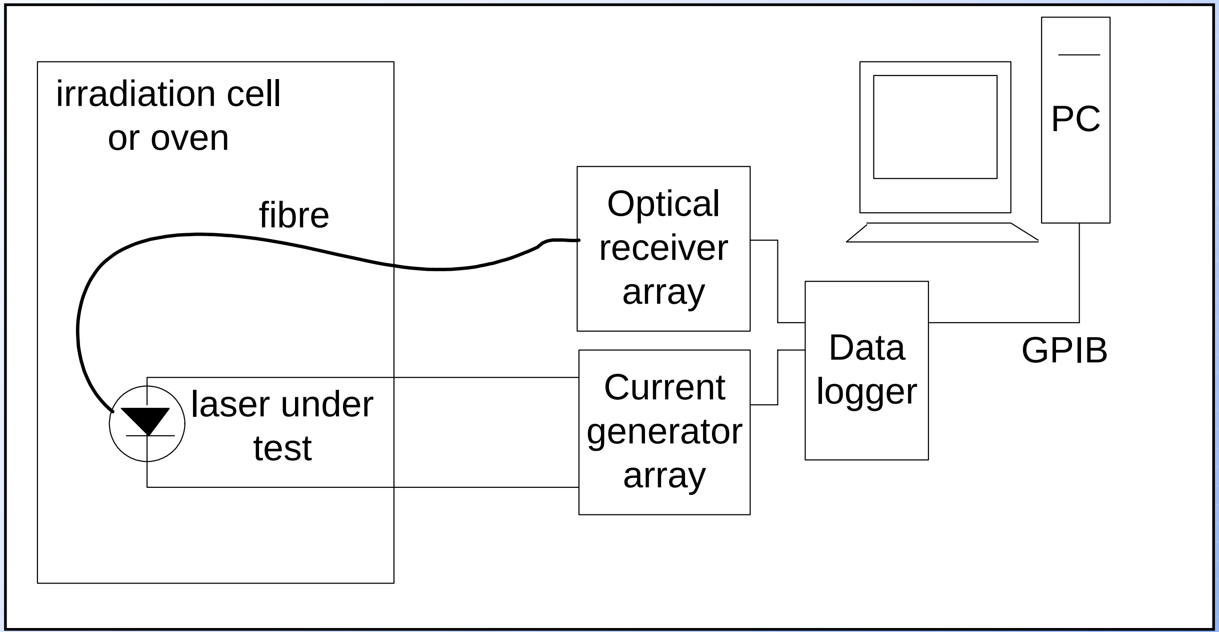


- Measured
  - Damage: different sources, different T, bias
  - Annealing rates, acceleration factors
  - Wearout

- 24 laser samples used in total, Ref: Gill et al, SPIE 2002

Irradiation test system

- Measurement setup (lasers)

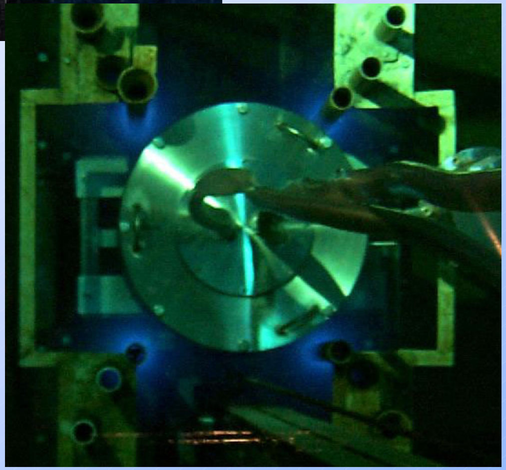


- In-situ measurements allows confident extrapolation/comparison
  - Avoid before/after tests unless damage kinetics understood
  - Few changes to test-procedure since 1997 for consistency

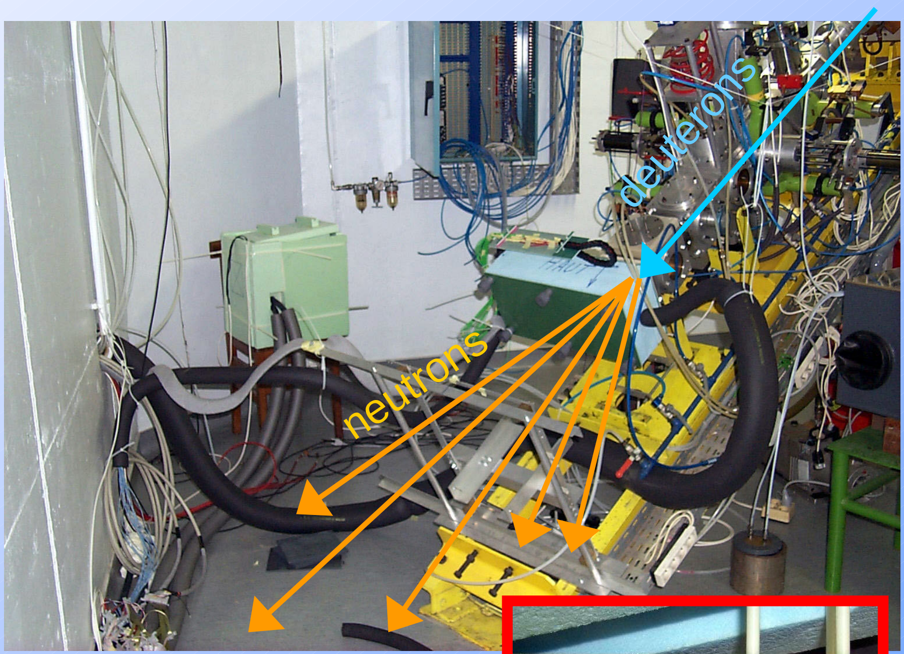
- Very similar system used for fibre and photodiodes

Irradiation at SCK-CEN and UCL

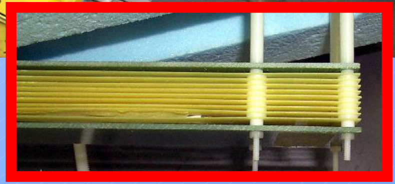
SCK-CEN Co-60 γ
2kGy/hr
underwater



UCL ~20MeV neutrons
flux ~ $5x10^{10}$n/cm^2/s



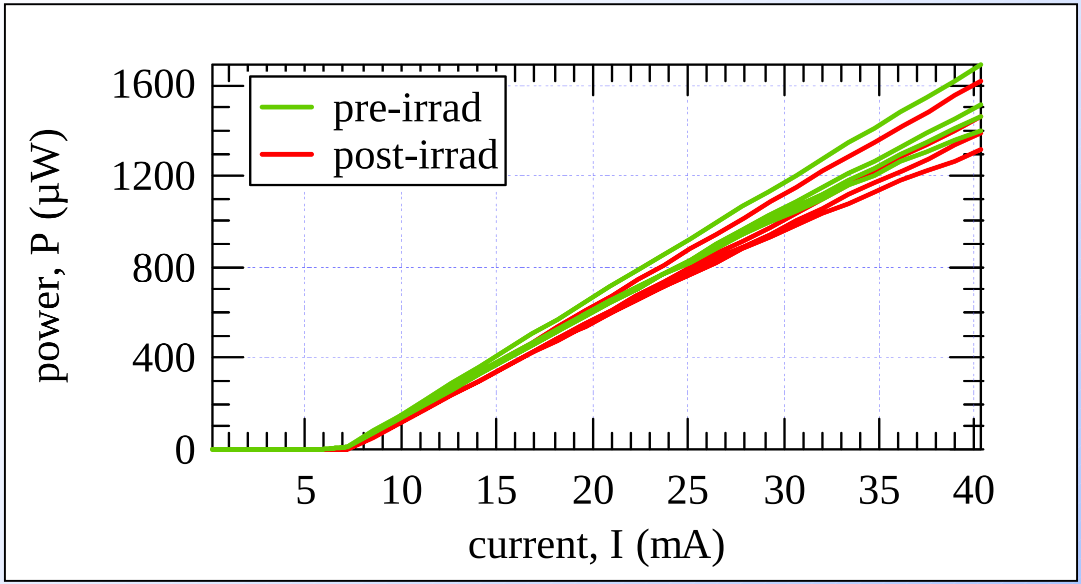
Samples stacked inside cold box (-10°C)



Interested to use these sources?
Please contact me

Ionization damage – typical laser data

- Laser L-I characteristics

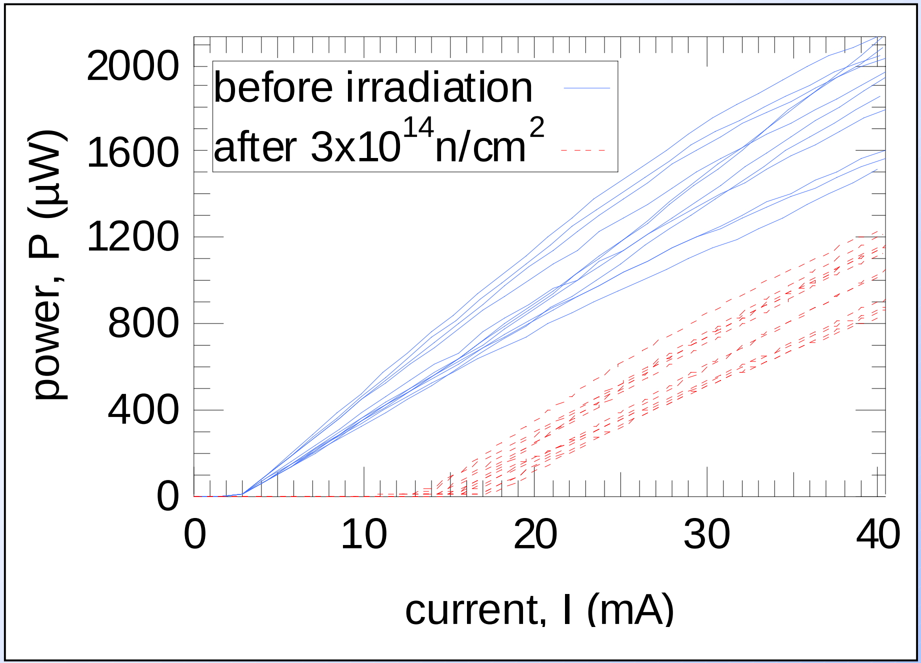


- Before/after 100kGy (10Mrad)
- Threshold current (laser turn-on) unchanged
- Efficiency (laser power output per unti current) unchanged

- No significant damage caused by total ionising dose (TID)
- Same conclusion for <u>all</u> laser diodes tested
  - Can have some loss of output light if lenses included in package
    - No lenses in CERN lasers

Displacement (bulk) damage

- Laser L-I before/after $3x10^{14}n/cm^2$

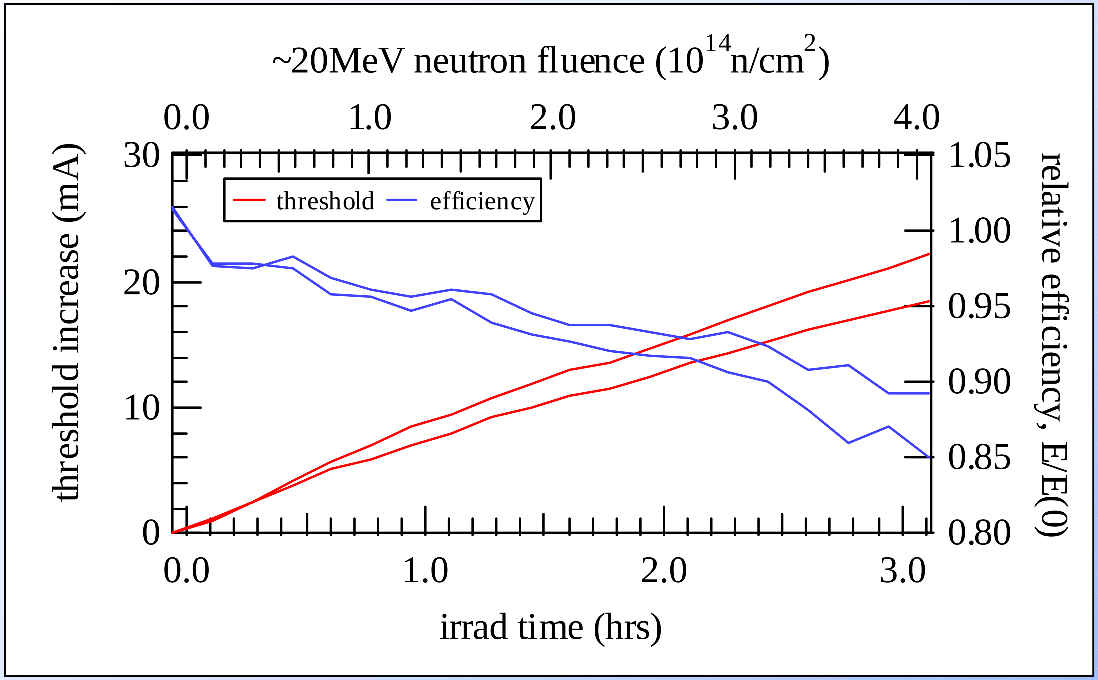


- ~20MeV neutrons
- (CRC, Louvain la Neuve, BE)
- Temp -13°C

- Laser threshold I_{thr} increases efficiency E decreases

Damage vs neutron fluence

- Laser threshold I_{thr} and efficiency E always approximately linear with fluence

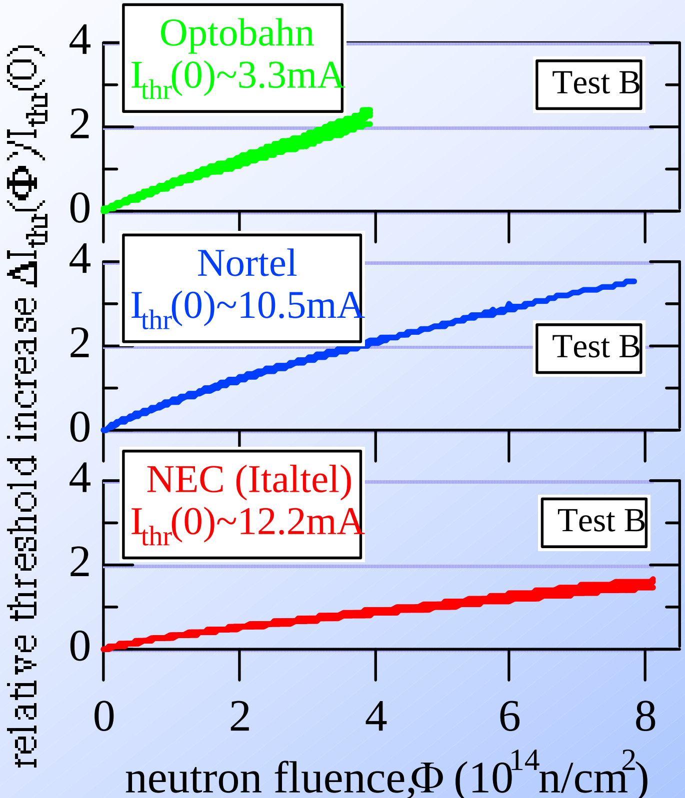


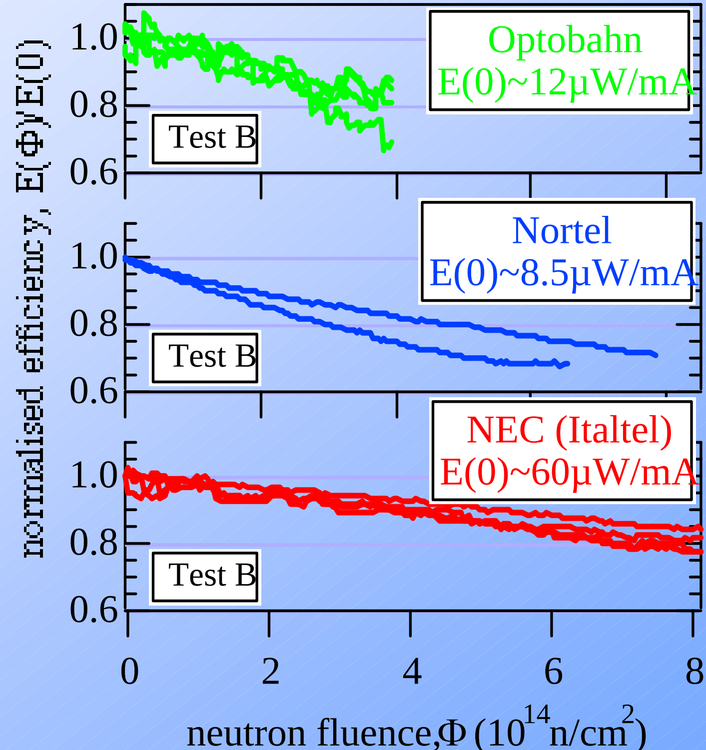
- ~20MeV neutrons (UCL)
- Temp 20°C

- Damage 'roll-off' due to annealing during irradiation period
- Threshold change proportional to initial value

Other laser suppliers

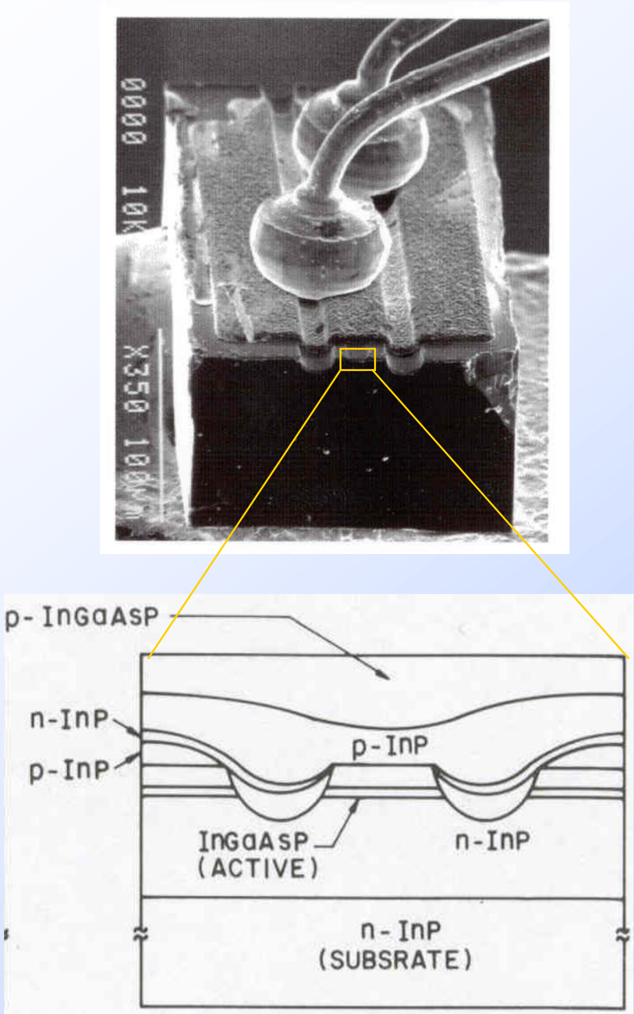
- I_{thr} and Eff vs neutron fluence

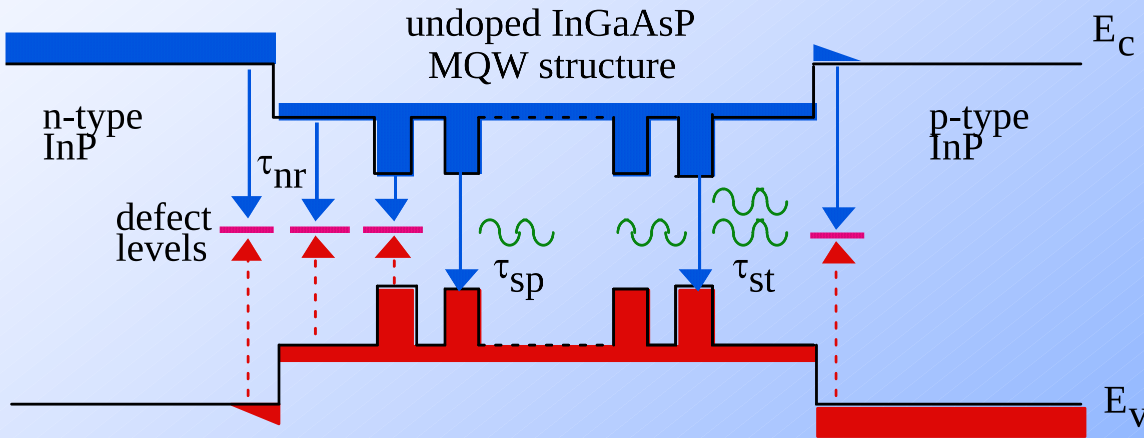




- Normalised effects similar in <u>all lasers tested</u> (ref: Gill et al, LEB 1998)

Qualitative damage model





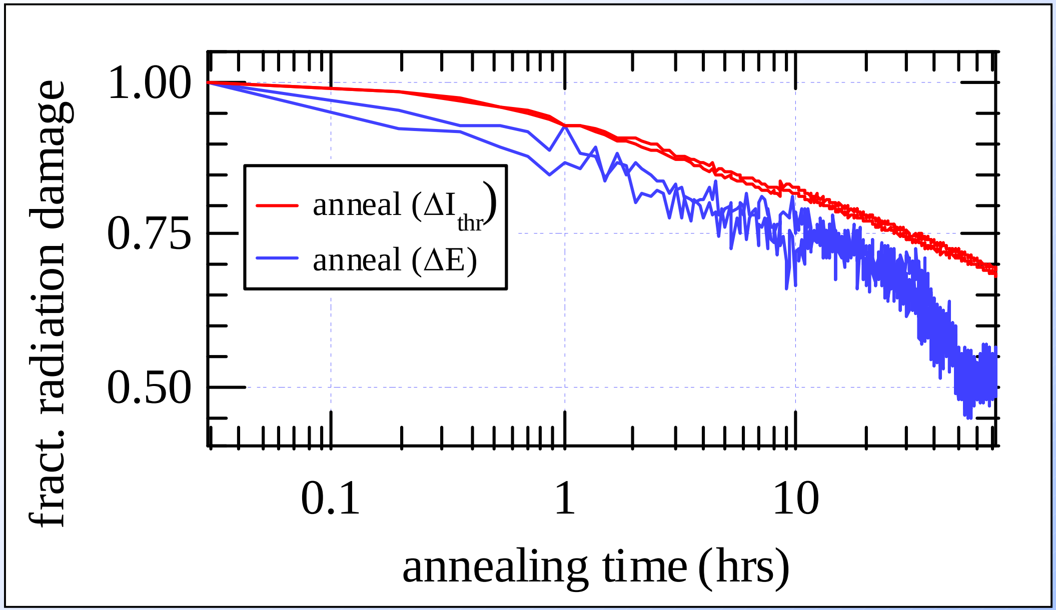
- defects reduce carrier lifetime in active volume
  - (ref: Pailharey et al, SPIE 2000)
- non-radiative recombination
  - competes with radiative recombination in laser
- Damage follows (usual) Messenger law for bulk damage

  $1/\tau = 1/\tau_0 + k\Phi$

  i.e. introduction of defects proportional to fluence

Annealing of displacement damage

- Laser threshold I_{thr} and efficiency E



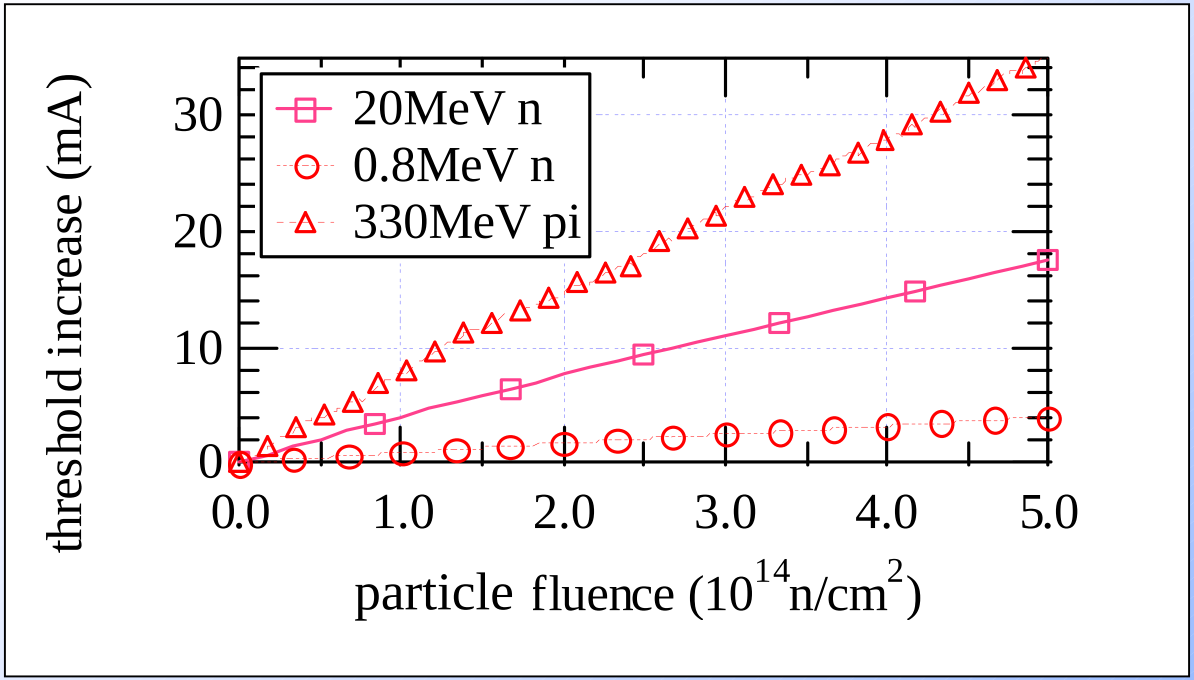
- after $4x10^{14}n/cm^2$
- ~20MeV neutrons (UCL)
- Temp 20°C

- Beneficial annealing only (more fortunate than silicon sensors)
  - recovery of damage during/after irradiation

- Same annealing mechanism for I_{thr} and E (not so evident in this plot!)
  - Same defects responsible for damage

Damage comparison

- Laser threshold I_{thr} with different sources (averaged and normalized)



Relative damage factors

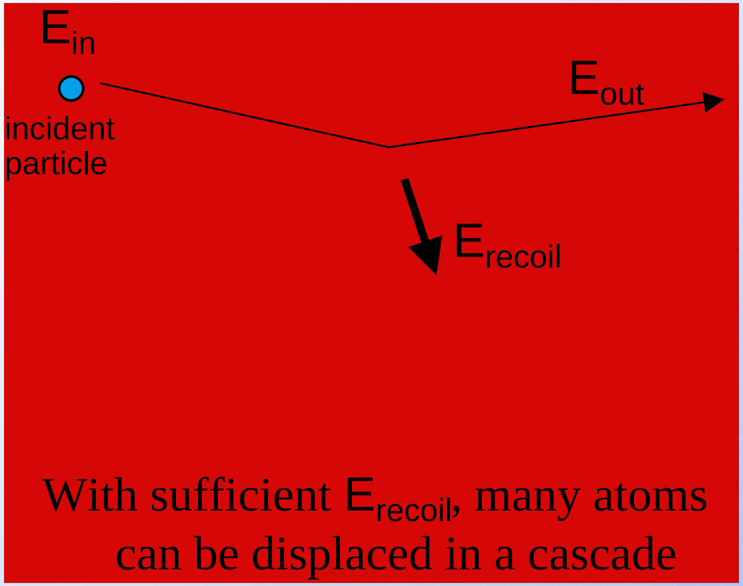
Valduc 0.75MeV n	(=1)
UCL 20MeV n	(=4.5)
PSI <u>200MeV π</u>	(=8.4)
^{60}Co γ	(~0)

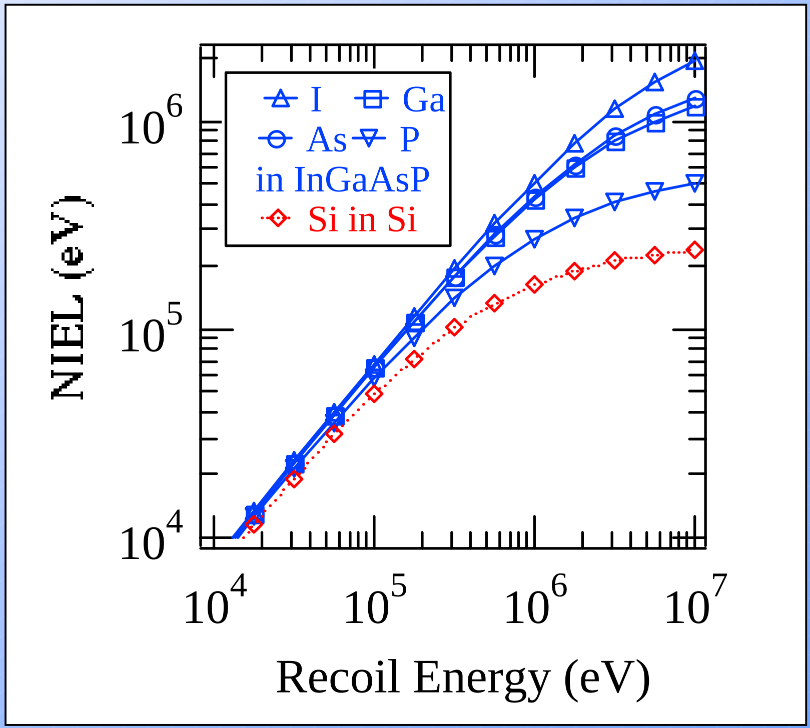
- Coverage of various parts of CMS particle energy spectrum
  - Pions most important

- <u>Similar factors</u> as for other 1310nm InGaAsP/InP lasers (NEC, Alcatel)

Laser and PIN damage α non-ionising energy loss?

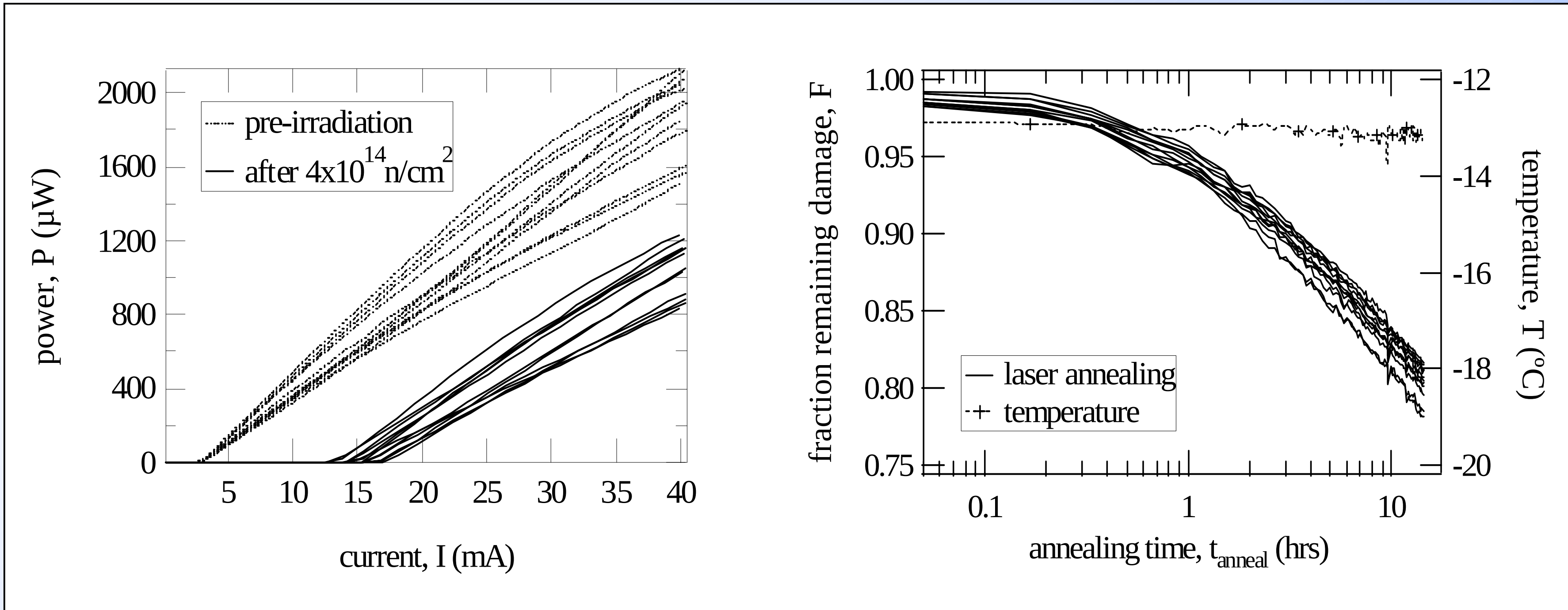
- Appears so but not sure: Need spectrum of recoil energies to calculate NIEL
- However, can understand already why relative damage factors so different to Si
    - Damage factors (Si) ~equal for 1MeV n: 200MeV π: 24GeV p





- NIEL for heavier In, Ga, As recoils does not saturate so quickly as Si

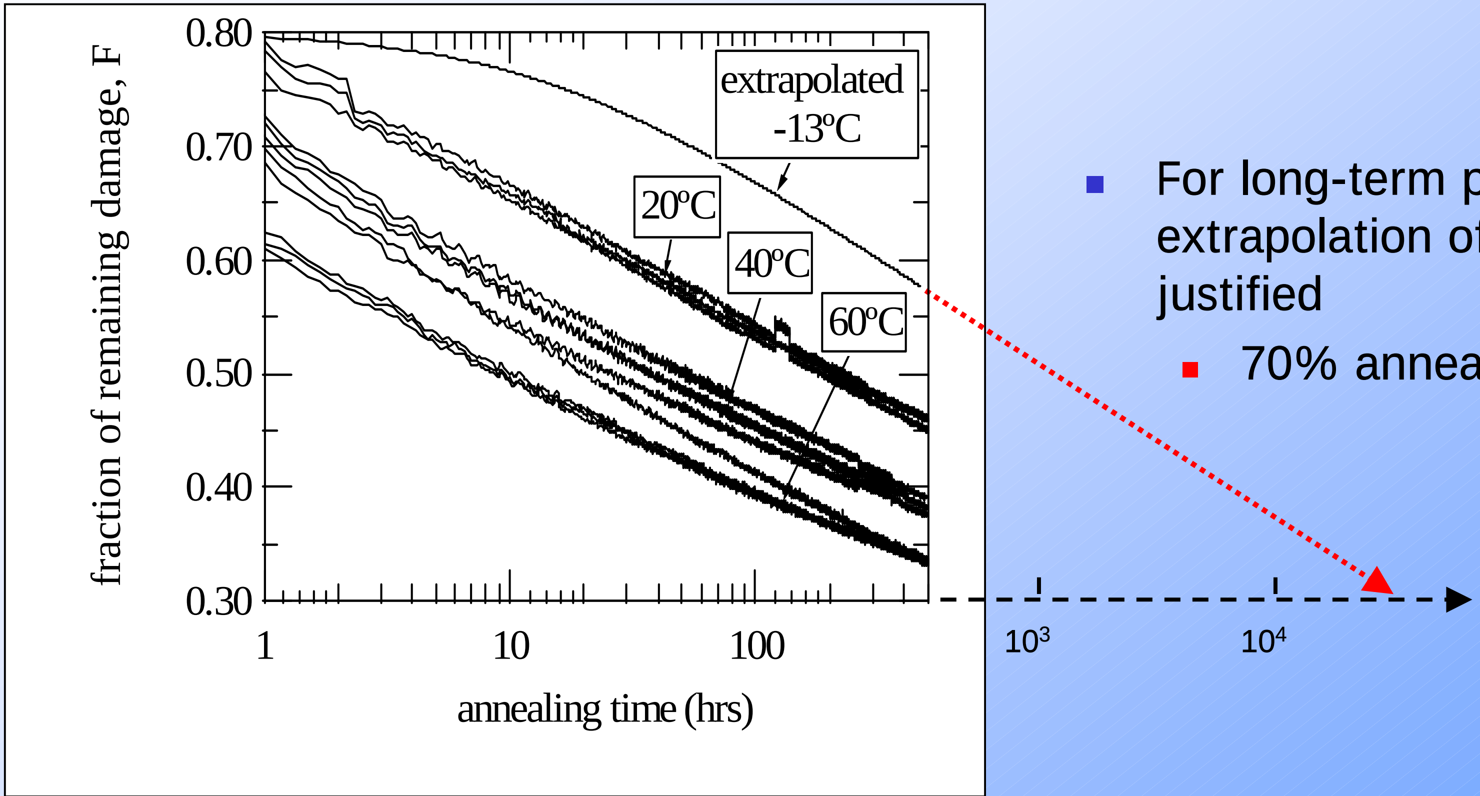
Cold n-irrad



- Important to check damage close to intended operating temperature of –10°C
  - UCL neutron irradiation at –13°C
  - Similar amount of damage to room T
    - only ~25% greater
    - annealing behaviour has similar form as room T
      - but slower rate (Annealing is thermally activated)

Annealing vs T

- Compare results at different T , normalized to measurements at –13°C

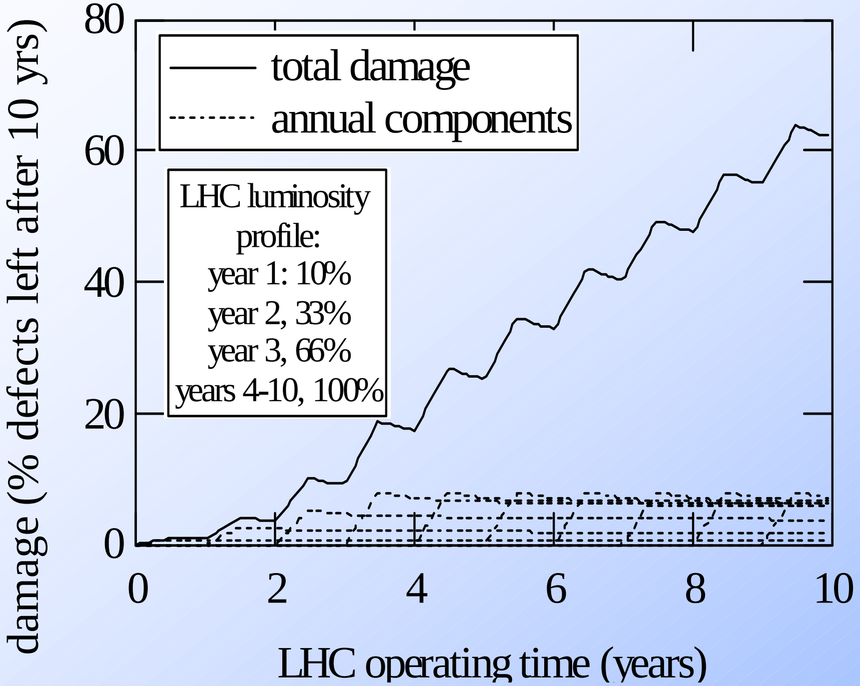


- For long-term prediction, extrapolation of –13°C data justified
  - 70% annealing expected

- No single activation energy E_a for annealing
  - Multiple types of defects involved (giving multiple E_a)?
  - Reduced disorder near defects due to annealing increasing E_a?

Laser damage prediction in CMS Tracker

- Even without thorough understanding, can predict damage evolution over a 10-year lifetime inside Tracker



- Based on damage factors and annealing rate at close to -10°C
- Take worst-case
  - radius=22cm in Tracker
  - pion damage dominates
    - ΔI_{thr}~5.3mA in 10 years
    - ΔE~6% in 10 years
- Damage decreases further away from beam interaction point
- ~50% at r=32cm, ~30% at r=41cm (within Tracker volume)

Ref: Gill et al, SPIE 2000 and 2002

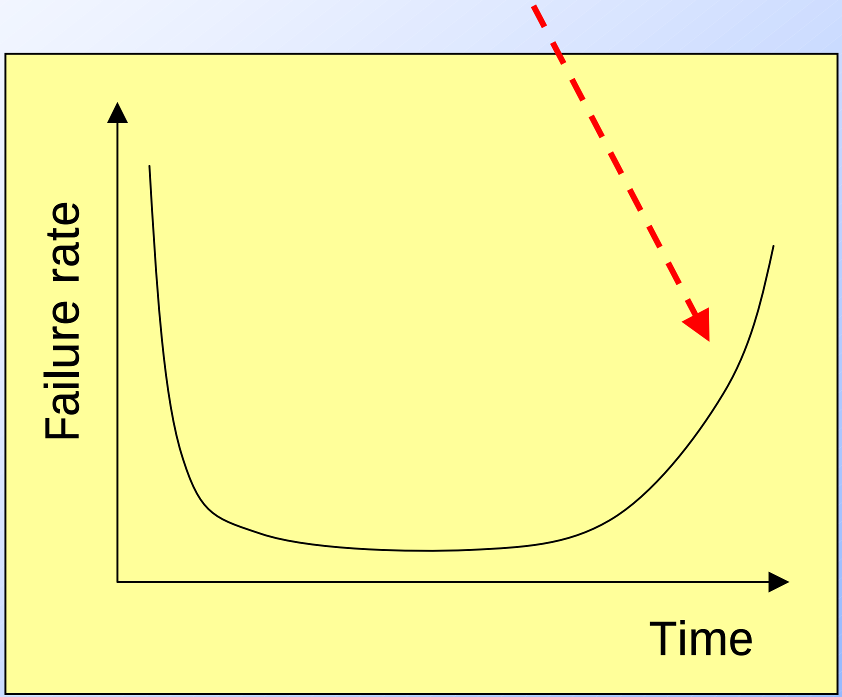
Laser wearout

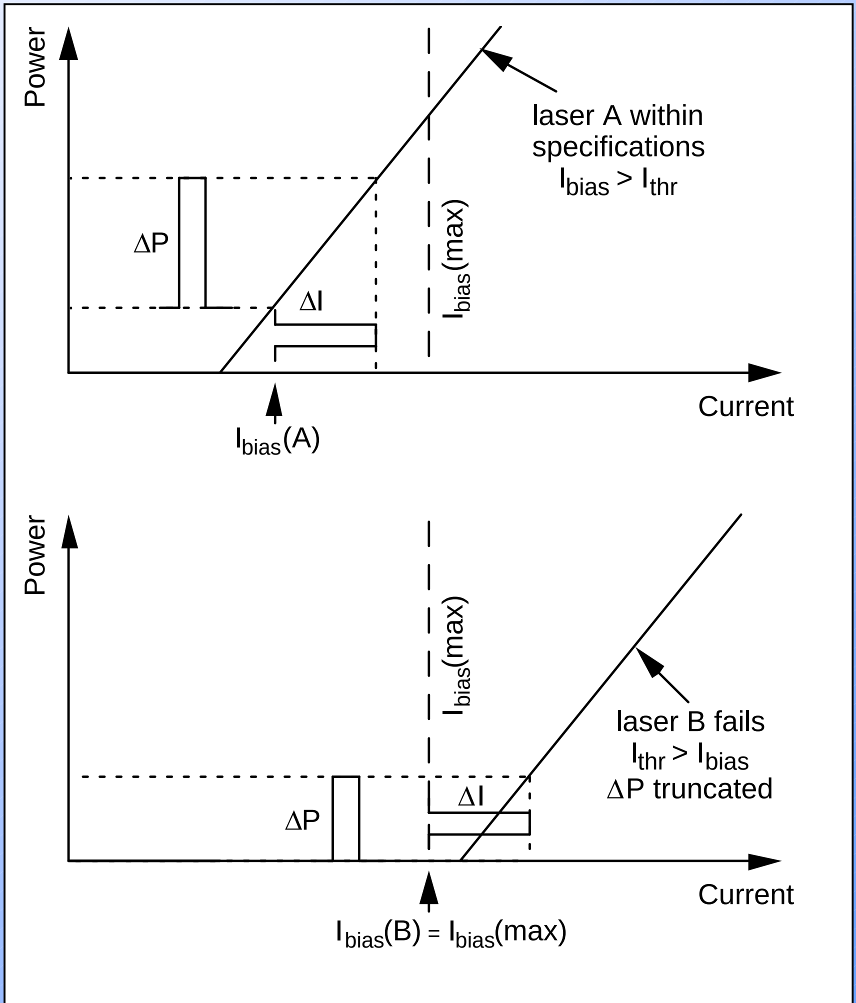
- Aging test at 80°C
  - Degradation accelerated

$$\frac{MTTF(T_1)}{MTTF(T_2)} = \exp\left[\frac{E_a}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

  - Threshold increase expected

- Measuring end of the “bath-tub curve”

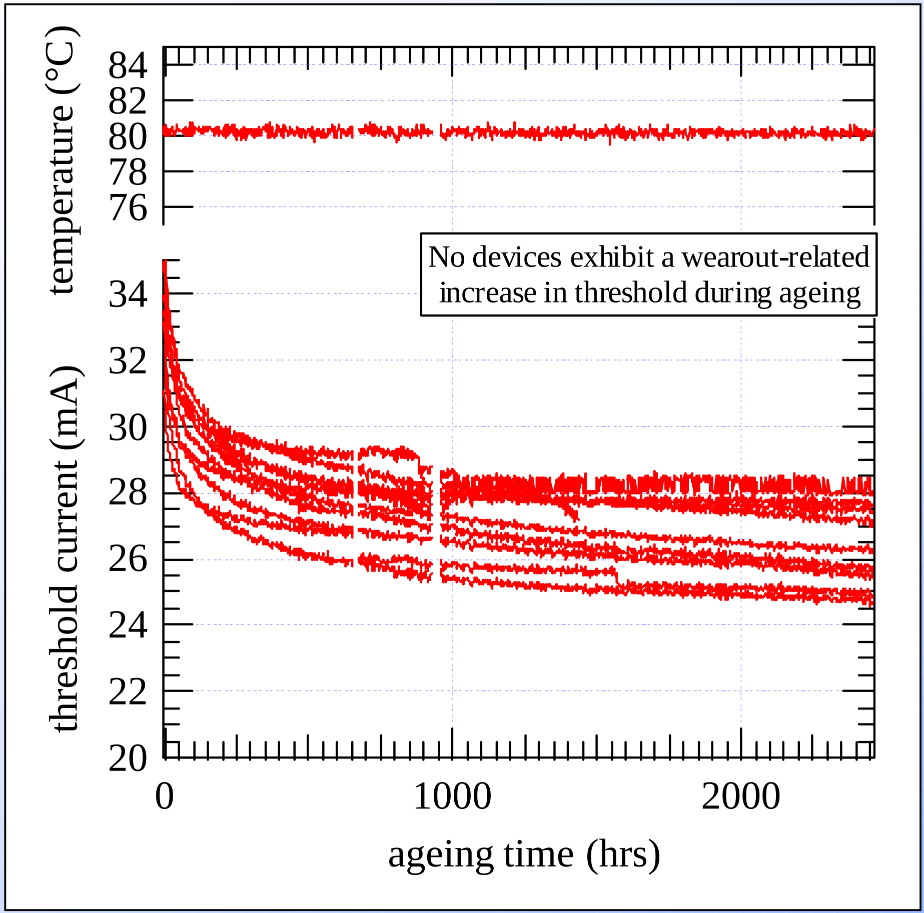




Expected failure mode

Irradiated laser wearout

- Aging test data at 80°C for irradiated lasers



- 12 devices irradiated to $4x10^{14}n/cm^2$ (UCL)
- 2500 hrs ageing
- No additional degradation seen in irradiated lasers
- acc. factor ~400 relative to -10°C operation, for E_a=0.4eV
  - 10^6hrs at -10°C !!
  - (Mitsubishi E_a=0.7eV)
- **takes >>10years for wearout**
- similar data for other laser types

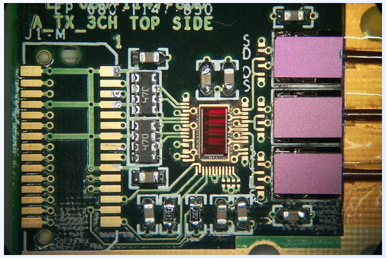
Refs: Gill et al, SPIE 2002, RADECS 1999

COTS issues revisited damage mitigation and advance validation

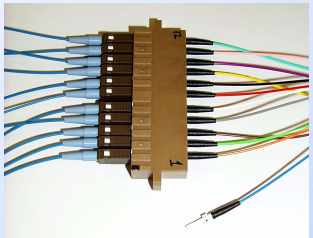
COTS Components

- Recall many COTS or COTS-based parts in TK analogue readout link system

Front-end optohybrid

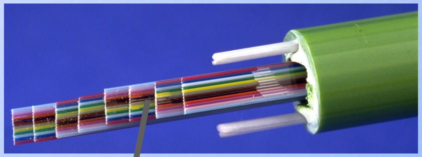


Distributed patch panel



In-line patch panel

Cable

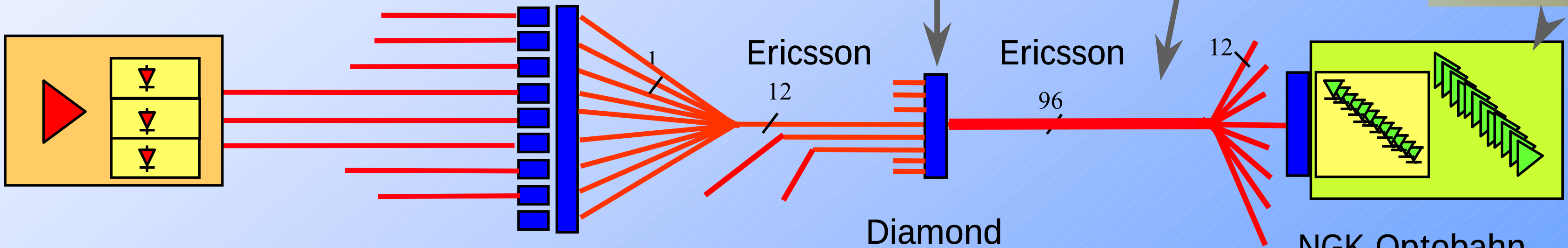


Back-end A-RX

Ericsson

Ericsson

Ericsson



ST/CERN-MIC/Kapsch/G&A

Sumitomo

Diamond

NGK Optobahn

CERN COTS solutions

- Shown an example of focused/extensive environmental testing
  - Quantified and qualitatively understood effects

- Then - written ‘reasonable’ component specifications for laser supplier
  - e.g. damage depends on starting I_{thr} value
    - higher starting I_{thr} means more (precursor) defects
      - laser wearout also related to starting I_{thr} value

    - limit max I_{thr} to 10mA for laser diode after burn-in at ST

CERN COTS solutions - continued

- To assure reliability further, a lot more work done:
  - Built-in mitigation of damage effects into system
    - Added damage compensation circuits in CERN/MIC designed ASICs
      - Linear laser driver (LLD)
      - (also receiver, RX 40, for control links)
  - Also, introduced special additional test for COTS – Advance validation
  - Then, to catch any weak batches
    - Lot acceptance
  - Finally, to catch any defective parts that get through
    - 100% inspection during integration into detector sub-systems

Laser damage mitigation

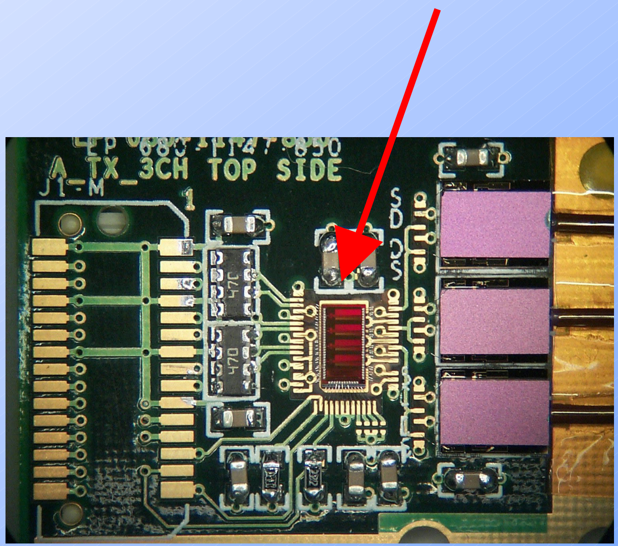
- LLD specified to compensate for laser damage
  - for threshold up to 45mA

  - Recall worst-case CMS-Tracker
    - ΔI_{thr}~5.3mA after 10 years

    - Large safety margin (almost 10x)

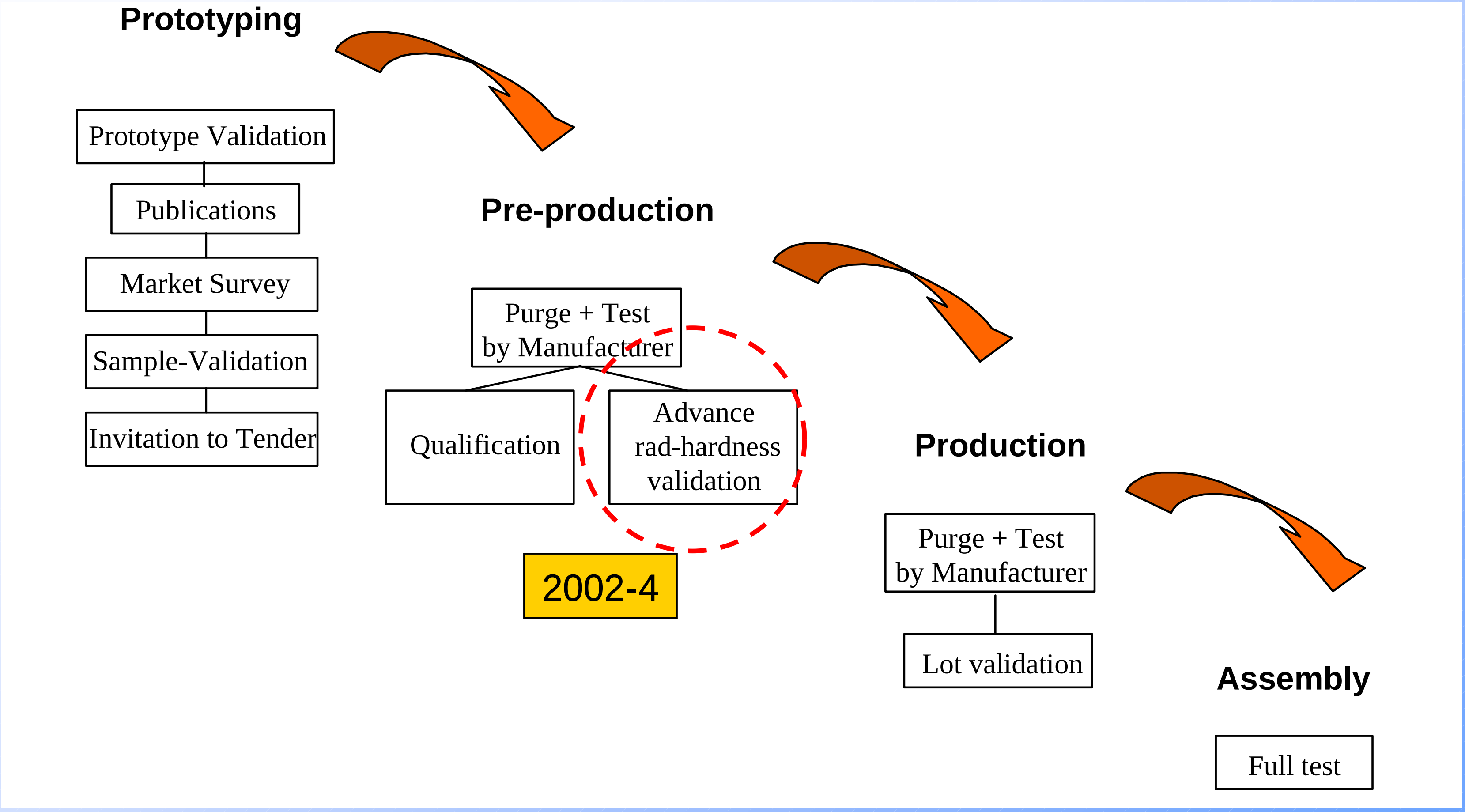
- (Aside: Large safety factor desirable in control links where potential resultant failure 30x more important)

- 640 (x2) lasers controlling 10 million detector channels (1:16000)
  - x2 also redundancy built into system since ‘ring’-architecture more risky than ‘star’



Analogue optohybrid (CERN prototype)

Advance validation tests



Dates for lasers

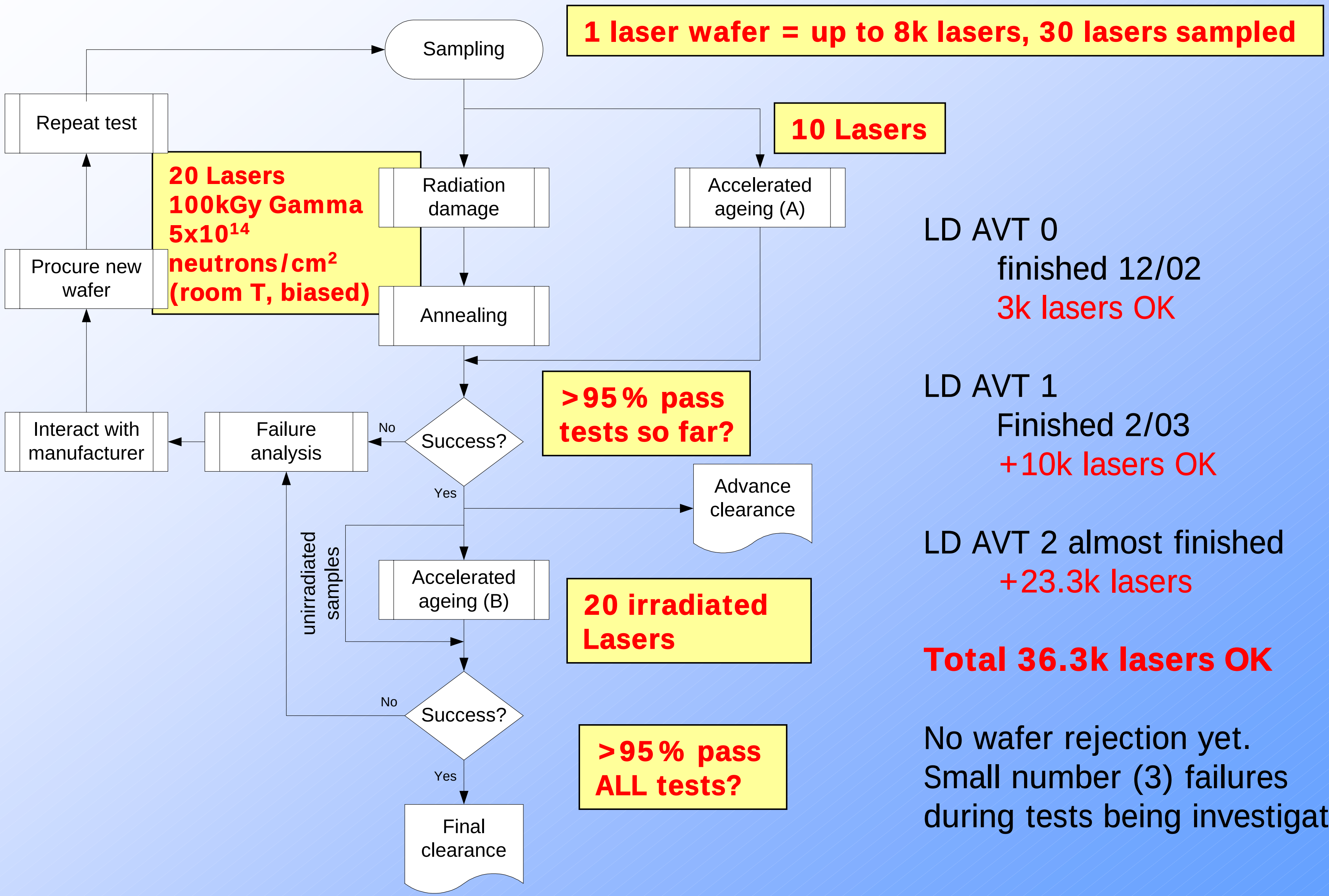
CERN COTS solution - AVT

- AVT lasers, fibre, photodiodes from each batch of raw material
  - laser wafer
  - photodiode wafer
  - fibre preform

- Accept or Reject lots
  - before production of thousands of final parts or many kilometres of optical cable

- Requires very good working relationship with manufacturers & suppliers
  - Potentially tricky negotiation depending upon risk of rejection

Laser AVT procedure



LD AVT 0
finished 12/02
3k lasers OK

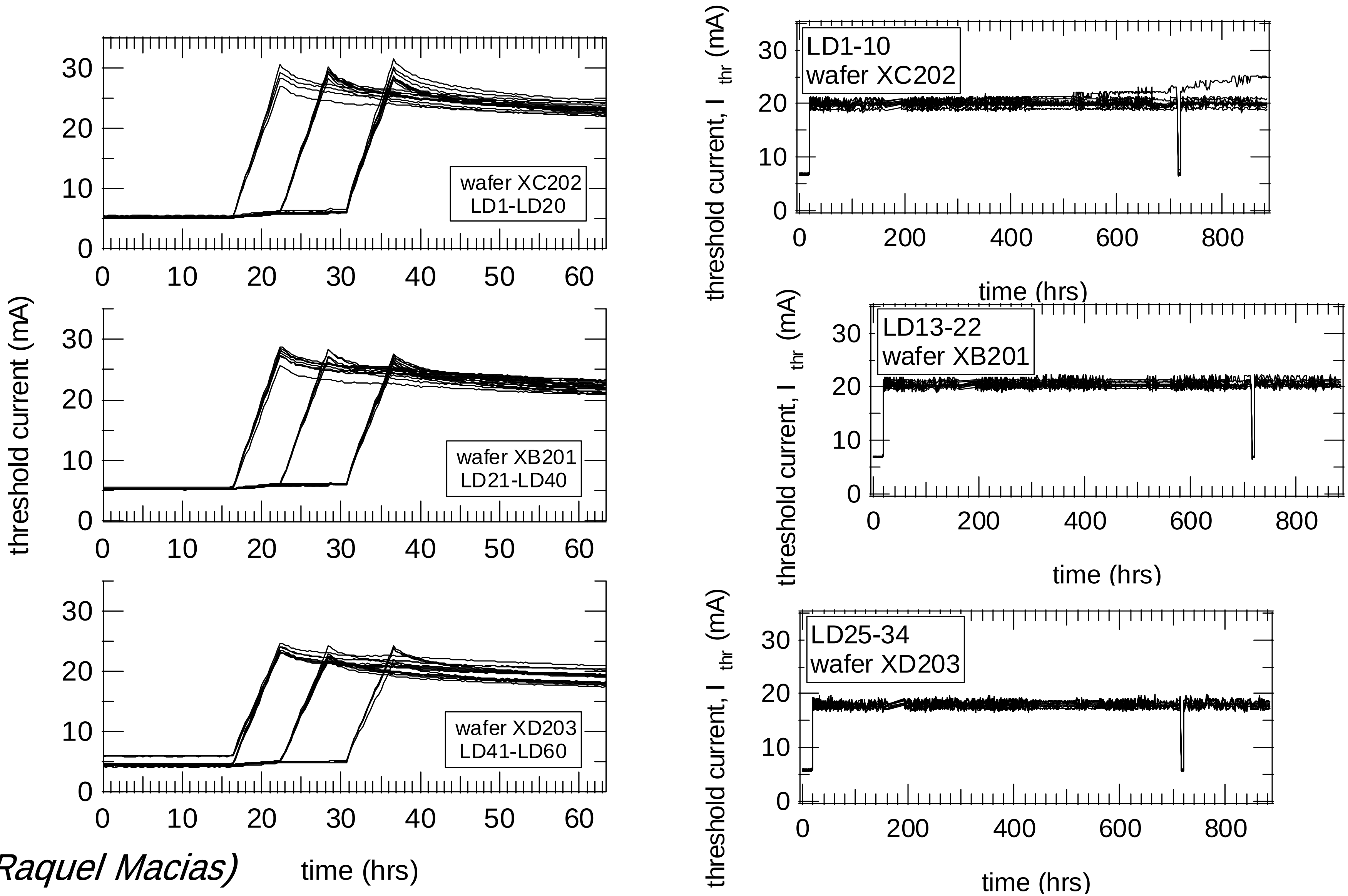
LD AVT 1
Finished 2/03
+10k lasers OK

LD AVT 2 almost finished
+23.3k lasers

Total 36.3k lasers OK

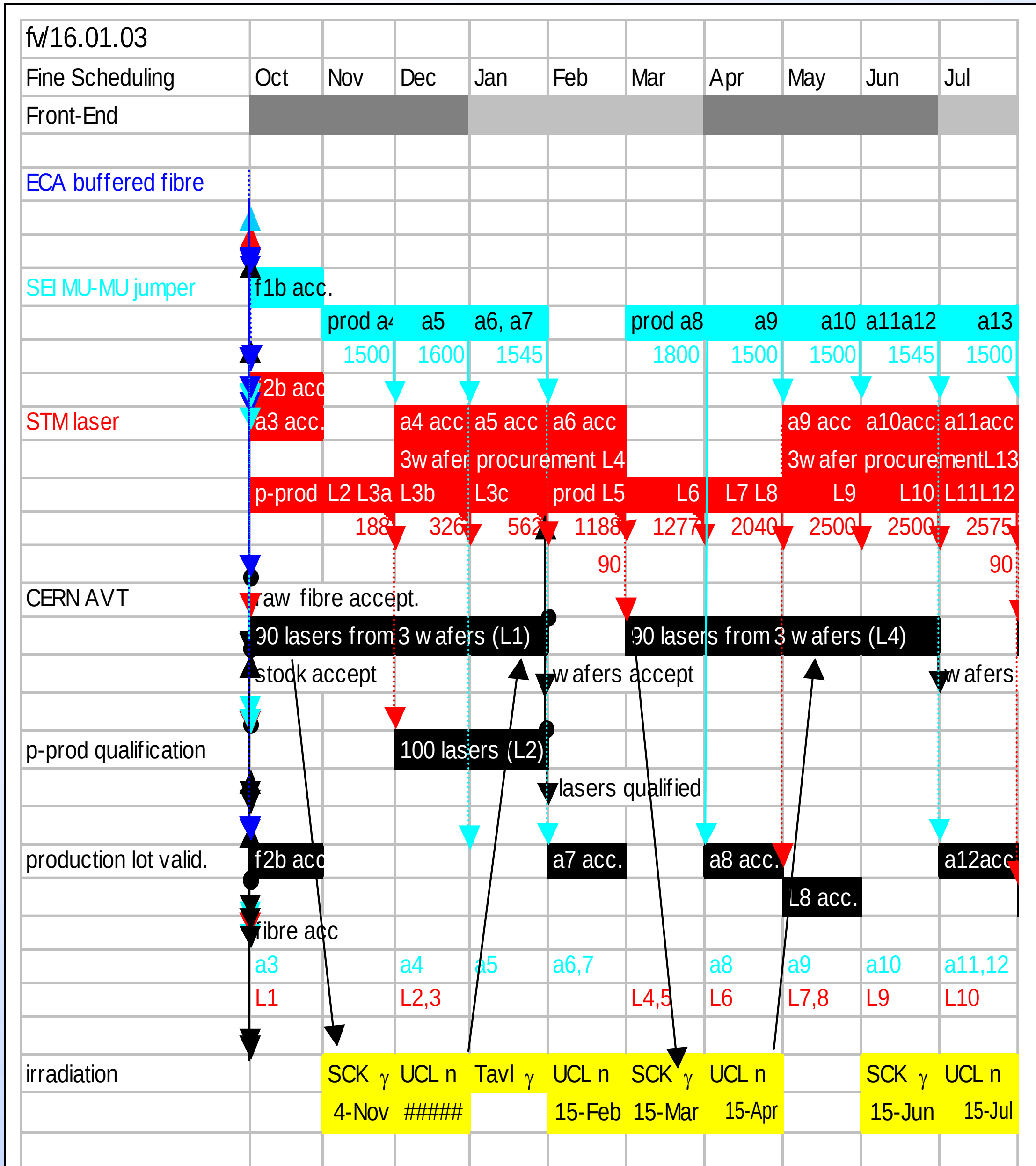
No wafer rejection yet.
Small number (3) failures during tests being investigated

LD AVT progress (data AVT 1)



(Raquel Macias)

QA detailed schedule (to 07/03)



- Heavy/complex QA schedule
- LD AVTs mixed with other QA:
  - AVTs
    - Fibres
    - Photodiodes
  - Pre-prod Qualification
    - Cables
    - 12 ch Receivers
    - MFS Connectors
    - Photodiodes
    - Optohybrids
    - 4 ch Transceivers
  - Lot Acceptance
    - Fibre
    - Cable
    - MU Connectors

Pre-production problems

- Even with extensive QA/RA procedures nothing produced yet has been perfect!
  - Quick look at some recent problems/fixes (2003)

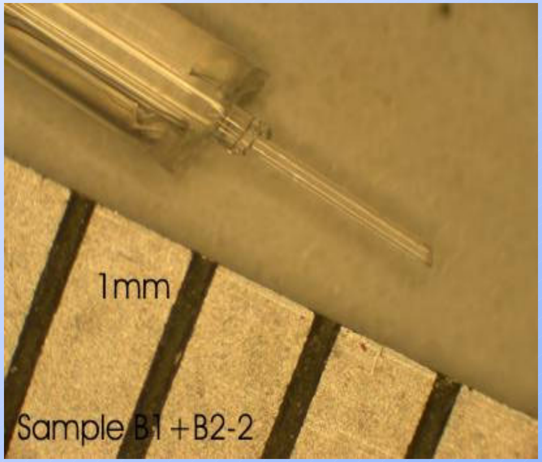
- e.g. Fibres and cables
  - These components cheapest and least expected to fail!

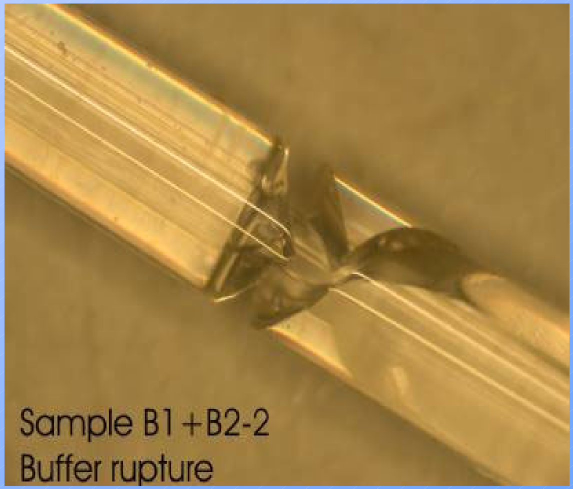
- Accelerated (thermal) testing made at CERN to assess severity of problem
  - Try to fix immediate problem
  - Determine if problem affects long-term reliability?

- Also some iteration required with other pre-production parts
  - Laser (failed pull-tests, now OK)
  - A_Rx (too slow, now OK)
  - MFS connectors (adapters failing, under investigation)

Buffered fibre problem

- Shrinkage + 'cracking' of fibre seen at ST at 70˚C
  - CERN life-tests:
    - Bare fibre and lasers from pre-prod batch
      - Storage at –25˚C
      - Storage at 50˚C
      - Thermal cycles –25˚C and 50˚C
      - Storage at 70˚C
  - Small amount of fibre shrinkage (~1mm)
    - depends on cutting method
  - Cracks observed in fibre (but not lasers)
    - propagate from (badly) cut end
      - later fibre batch less affected
- Solution(s) (CERN-Ericsson-ST-Sumitomo):
  - Ericsson have proposed a cutting procedure
  - Careful inspection pre-assembly (ST)
  - Reduce T in processing of lasers
  - Repair breaks found later in lasers





Ruggedized ribbon problem

- Kinks and 'cracks' in jacket found at Sumitomo
  - 12-sMU fanout-harness pre-prod stopped

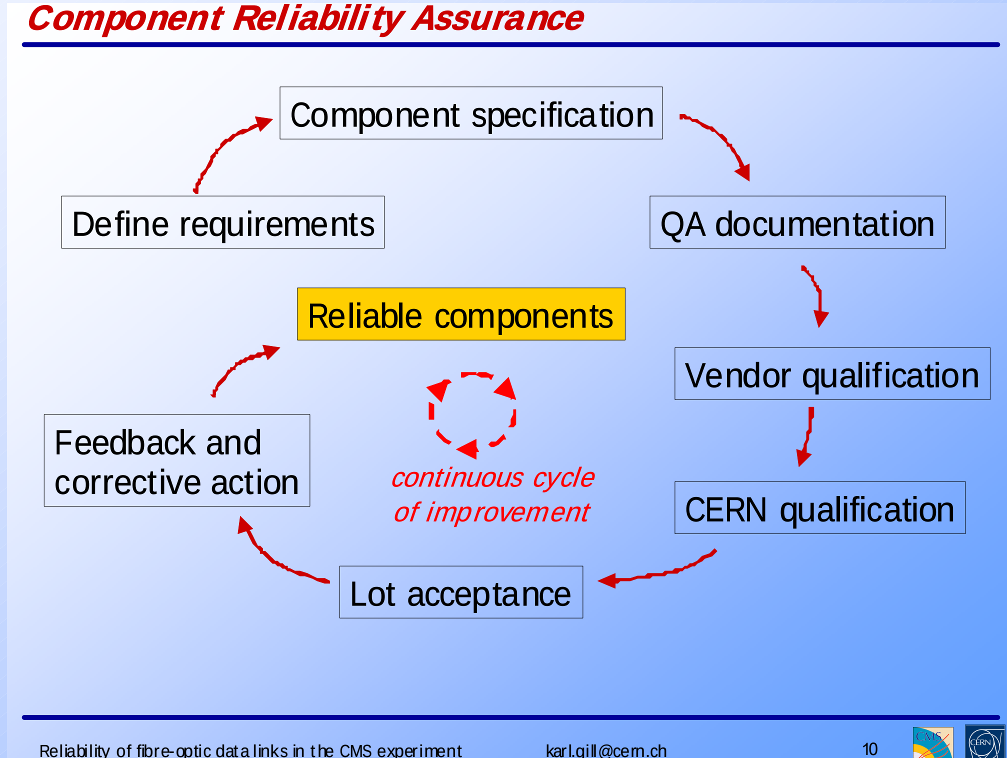
- CERN thermal tests (3, 6, 12m lengths)
  - Storage at –25C
  - Storage at 50C
  - Cycles between –25C and 50C
  - Storage at 70C
    - Kinks found at 50C,
    - Cracks at 70C (only in longer samples)

- Solution(s) (Ericsson, CERN, Sumitomo, Diamond)
  - Applied during connector termination
  - Work with shorter lengths
    - 6m maximum envisaged in Tracker
  - 'Relax' cable before terminating
  - Minimize heat treatment

Summary

Reliability Testing summary

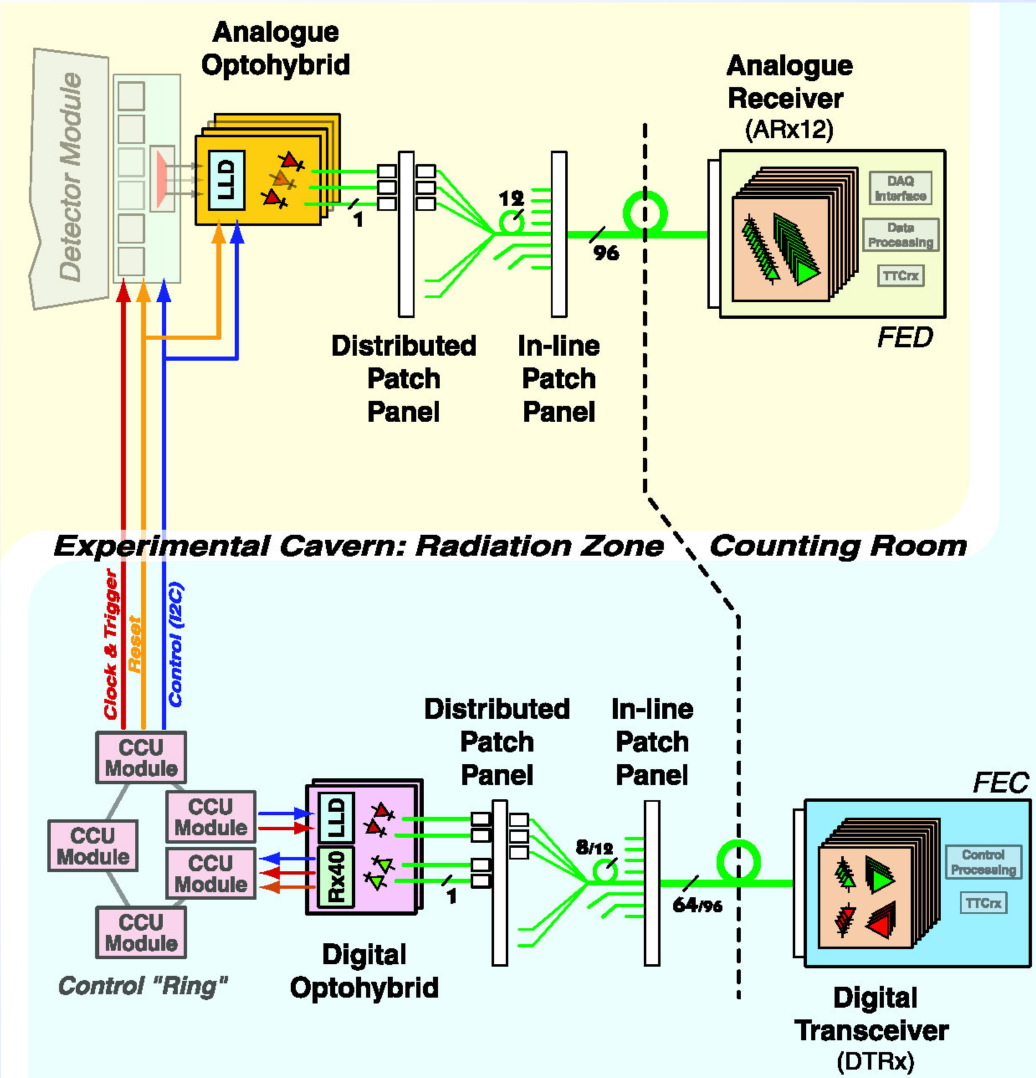
- Recall aims of reliability testing
  - Disqualify weak candidate components
  - Understand and quantify effects
  - Design-in mitigation
  - Refine the specifications
  - Define test-procedures
  - Improve processes



- Demonstrated achievements with lasers
  - Parallel activity with fibre, cables, connectors, receivers, transceivers, photodiodes, optohybrids ......

Tracker system reliability

- Now - how to quantify reliability (failure rate) of an entire system?



- Focus has been so far mainly on components
  - Still missing some statistics of real shape of 'bath-tub'
- Have good (extrapolated) confidence for reliability of optical link systems
- Needs more work to quantify/guarantee overall system reliability

Conclusions

- Defined a working quality and reliability assurance program for components
  - Bellcore Reliability standard GR 468 as baseline
  - Added CERN/CMS ingredients
    - reliability specs, test-procedures and acceptance criteria
  - Needs more statistics and work to quantify final system reliability

- QA/RA program has taken advantage of COTS components for telecoms
  - Focused validation and selection prior to Tender
  - System/handling specs compensate for known damage effects
  - Advance validation before production

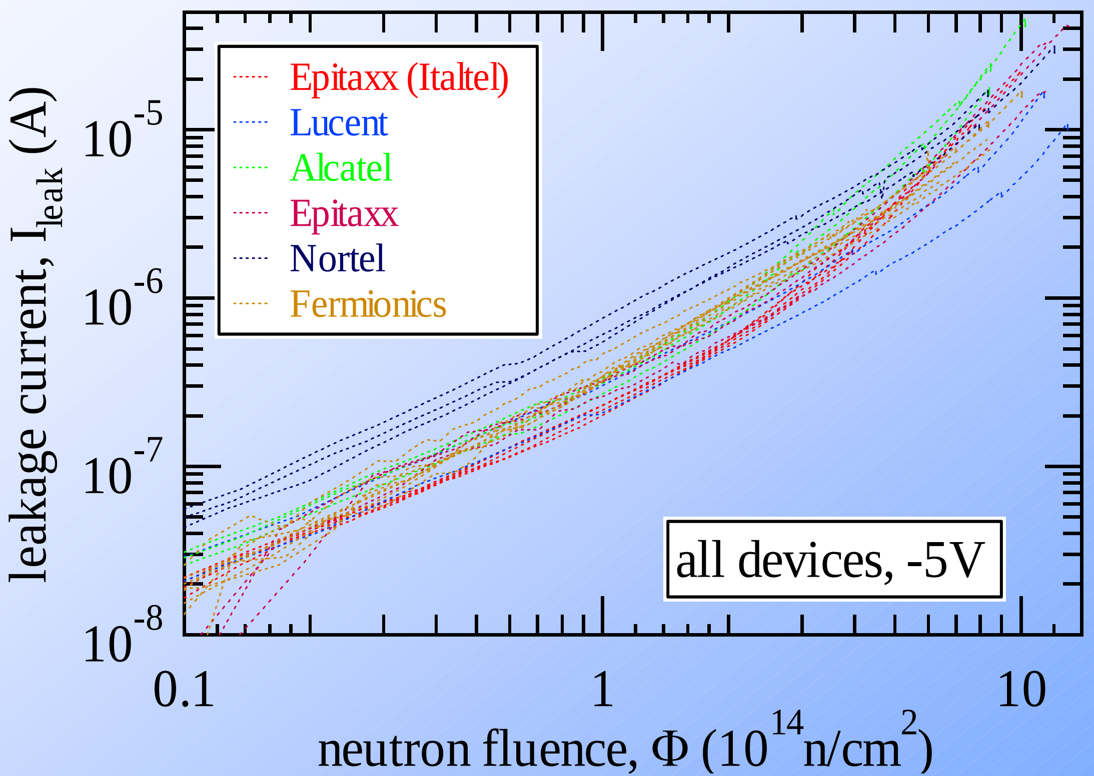
- Not mentioned much so far, but very (very) important:
  - Success depends upon excellent communication
    - CERN, CMS, Suppliers
    - Discussion of failures, weaknesses, responsibilities always difficult
    - Every problem so far has been overcome........

  - <u>Many thanks to everyone involved</u>

Extras

Tests of photodiodes - leakage

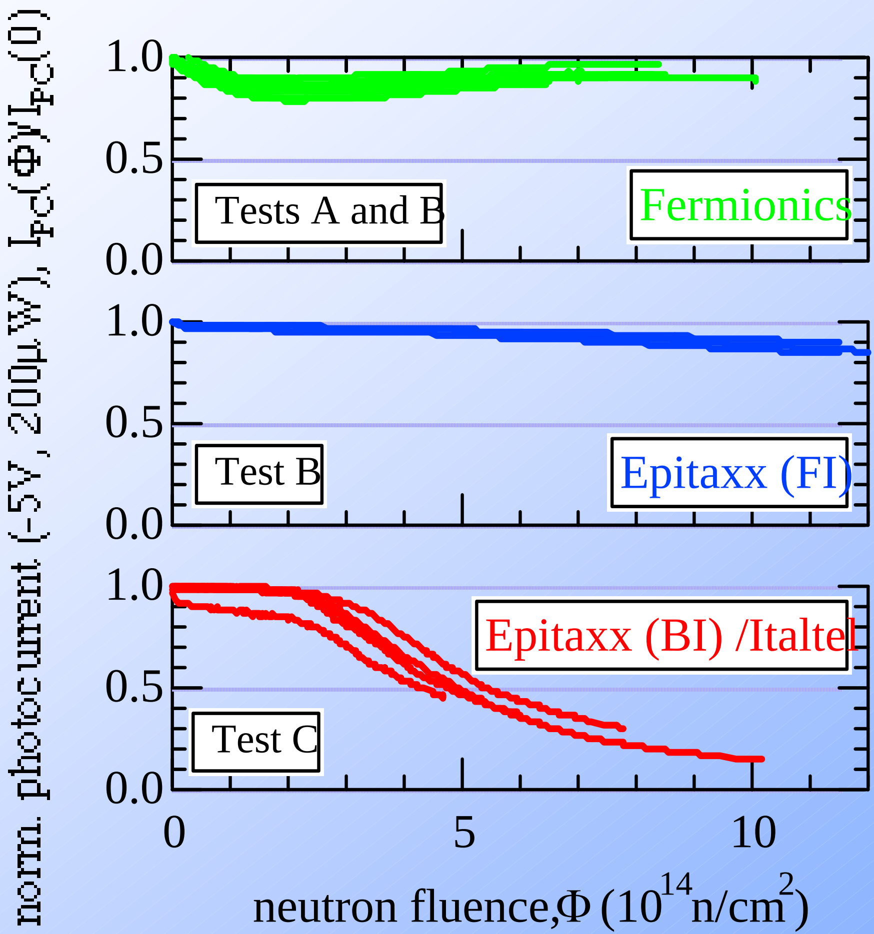
- leakage current (InGaAs, 6MeV neutrons)



- similar damage over many (similar) devices

Photodiodes - response

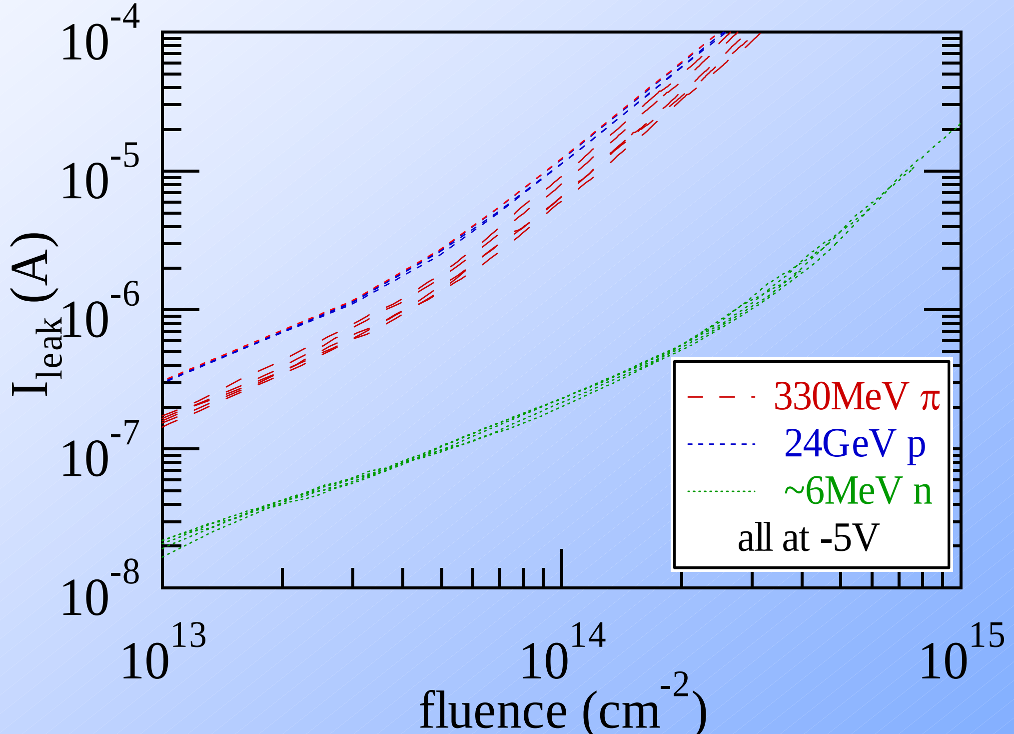
- Photocurrent (InGaAs, 6MeV neutrons)



- Significant differences in damage
- depends mainly if front or back-illuminated
  - front-illuminated better

Different particles (leakage)

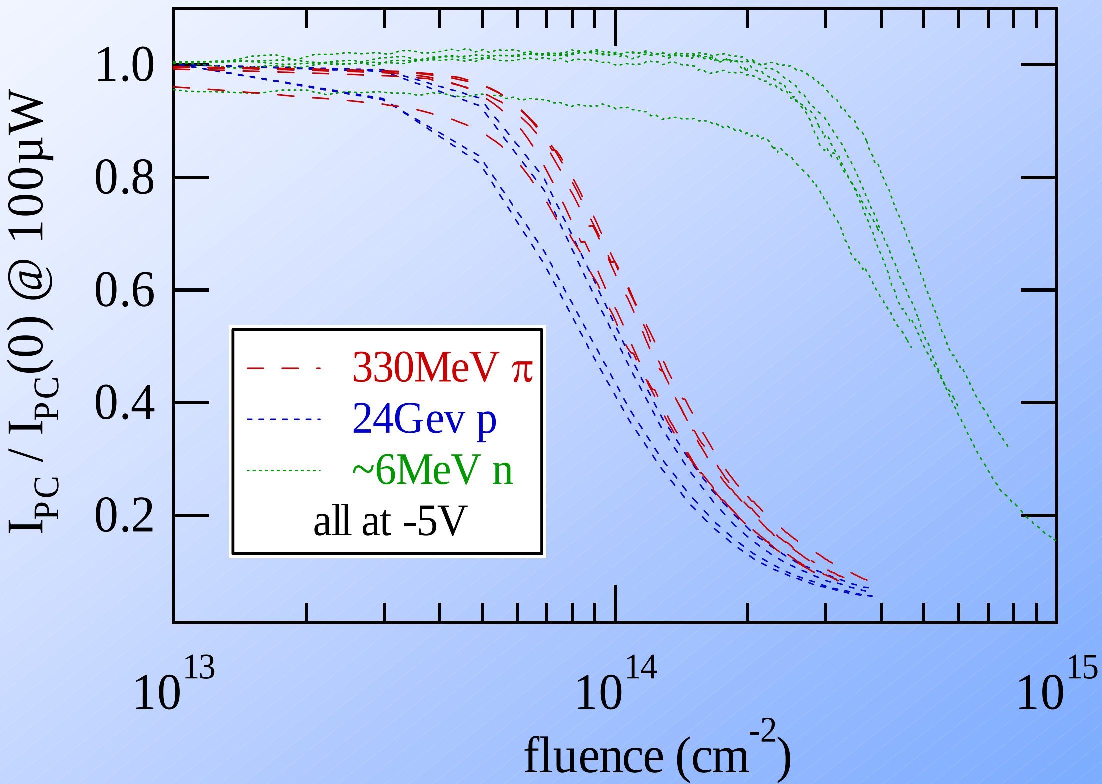
- leakage current (InGaAs, different particles, 20C)



- higher energy π, p more damaging than n

Different particles (response)

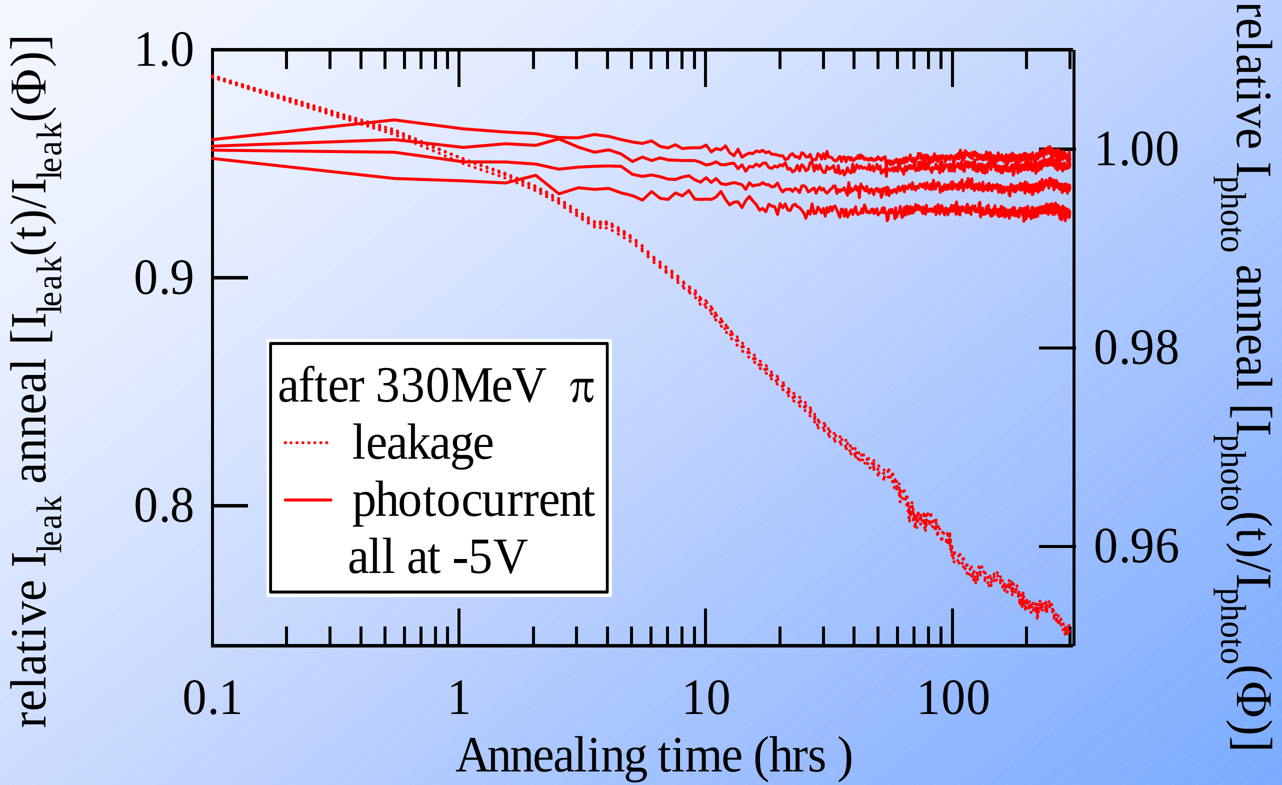
- different particles:



- higher energy π, p more damaging than n

InGaAs p-i-n annealing

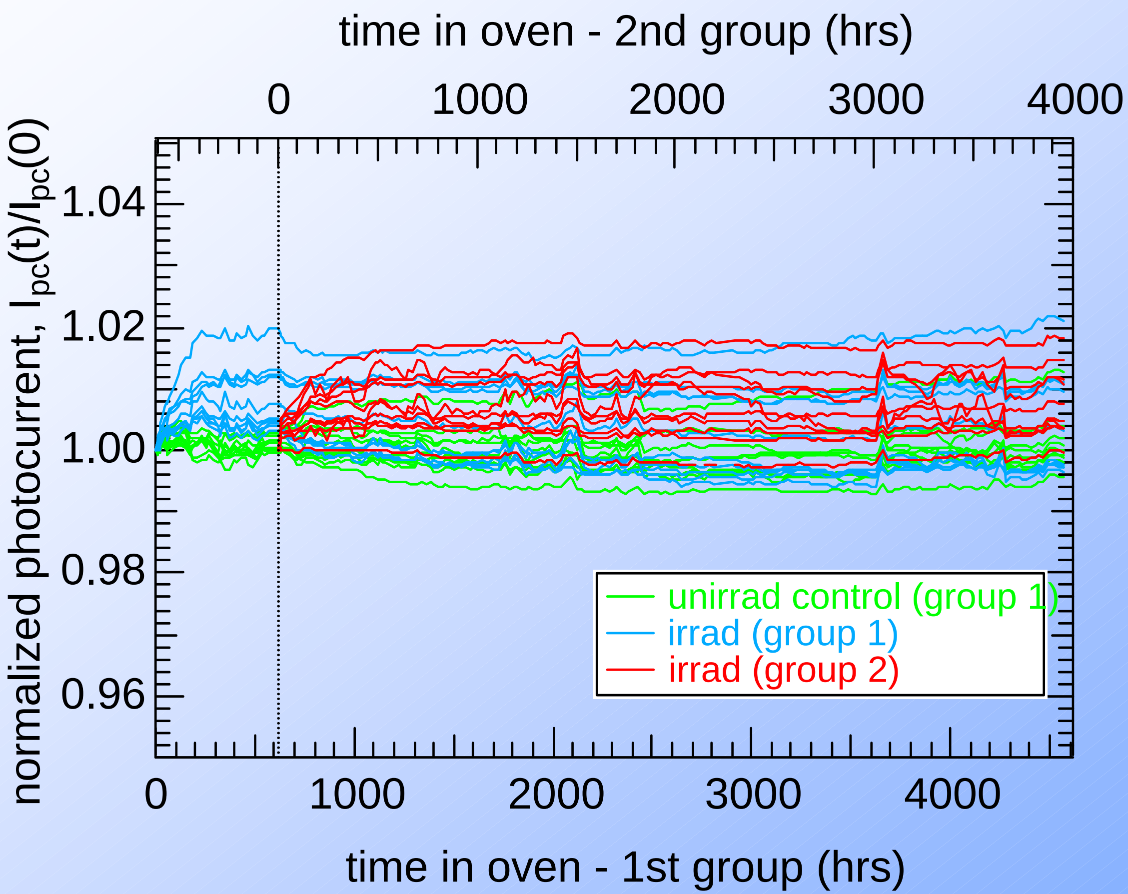
- After pion irradiation (room T, -5V)



- Leakage anneals a little
- No annealing of response

InGaAs p-i-n reliability

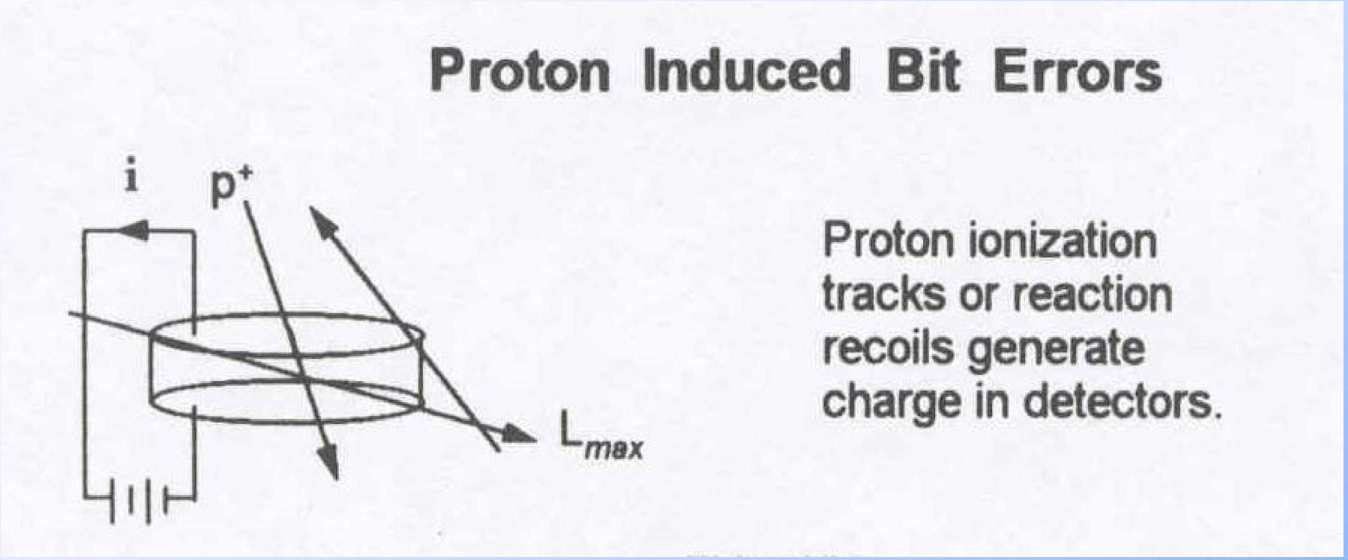
- irradiated device lifetime > 10 years??
- Ageing test at 80C



- No additional degradation in irradiated p-i-n's
- lifetime >>10years

PD SEU

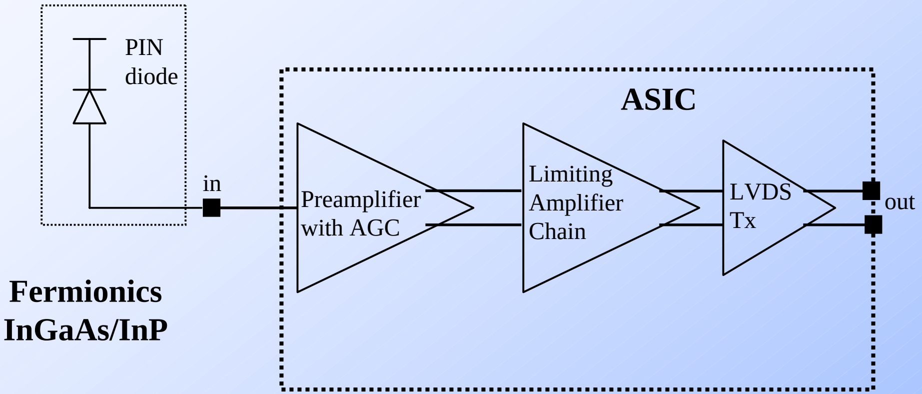
- photodiodes sensitive to SEU

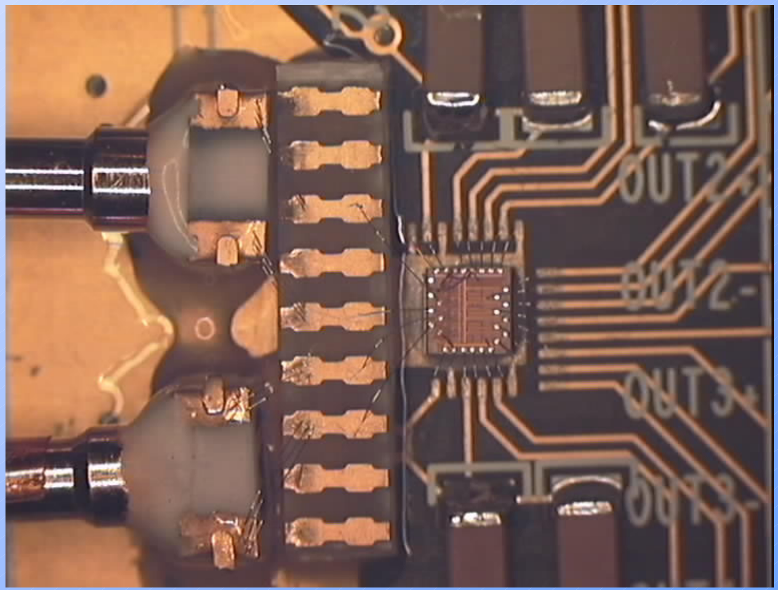


- strong dependence upon particle type and angle

Optical receiver SEU testing

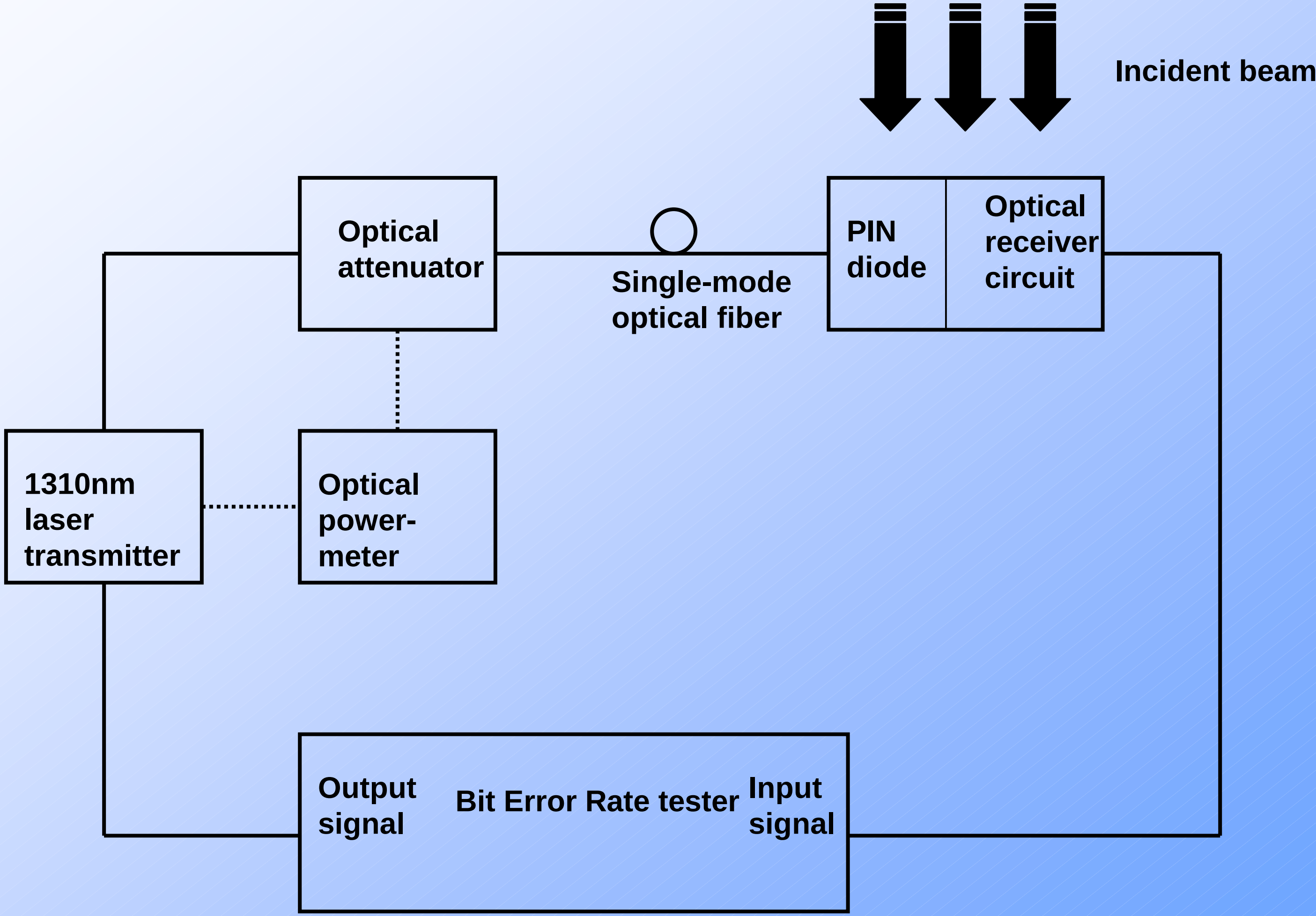
- SEU tests made with neutrons and protons (UCL)
  - Ref: LEB 2000.





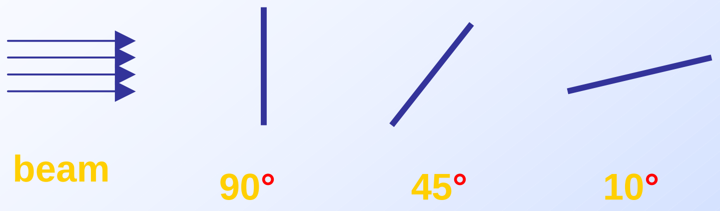
ASIC mounted with 2 photodiodes

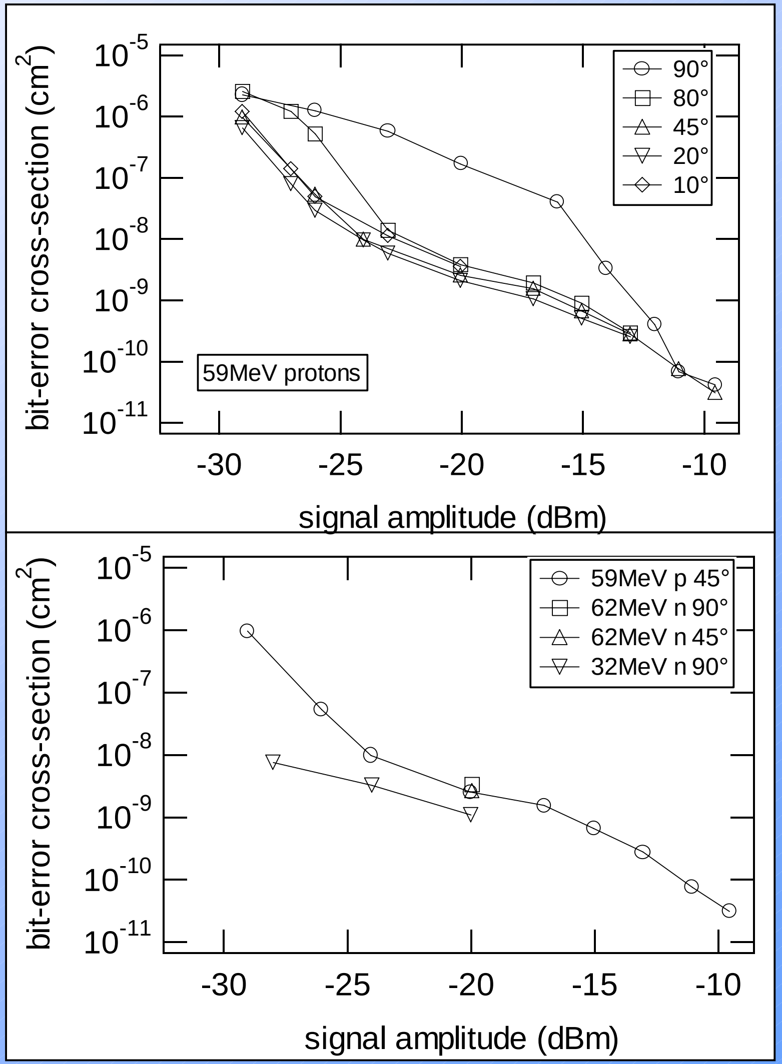
Experimental setup for SEU (p, n) BER



Photodiode Single-event-upset

- Bit-error-rate for 80Mbit/s transmission with 59MeV protons in InGaAs p-i-n (D=80μm)
- 10-90° angle, 1-100μW optical power
- flux ~10^6/cm^2/s *(similar to that inside CMS Tracker)*

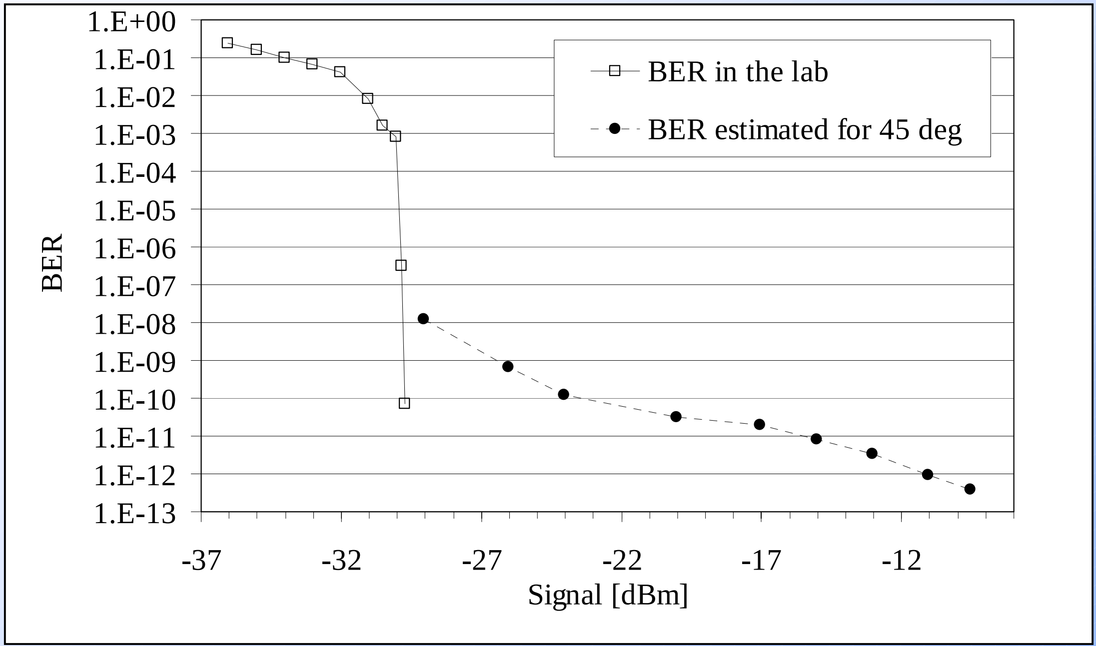




- Ionization dominates for angles close to 90°
- nuclear recoil dominates for smaller angles
- BER inside CMS Tracker similar to rate due to nuclear recoils
- should operate at ~100μW opt. power

System implications

- Based on a charged particle flux of $10^6/cm^2/s$
  - typical of tracker levels



Should maintain optical power > ~100μW

Fibre radiation damage testing

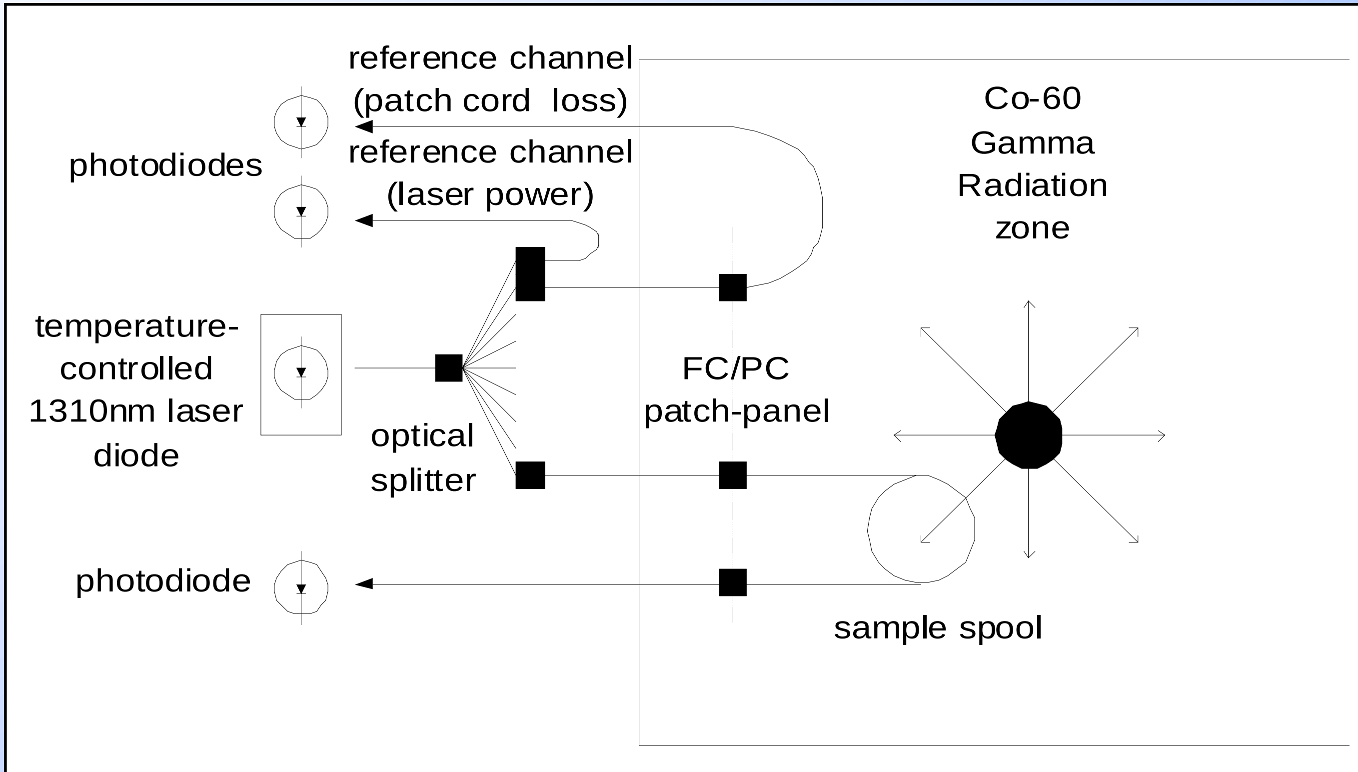
- 1-way fibre
  - attenuation
  - strip force

- 12-way cable
  - insertion loss
  - bending loss

- 96-way cable
  - strength tests

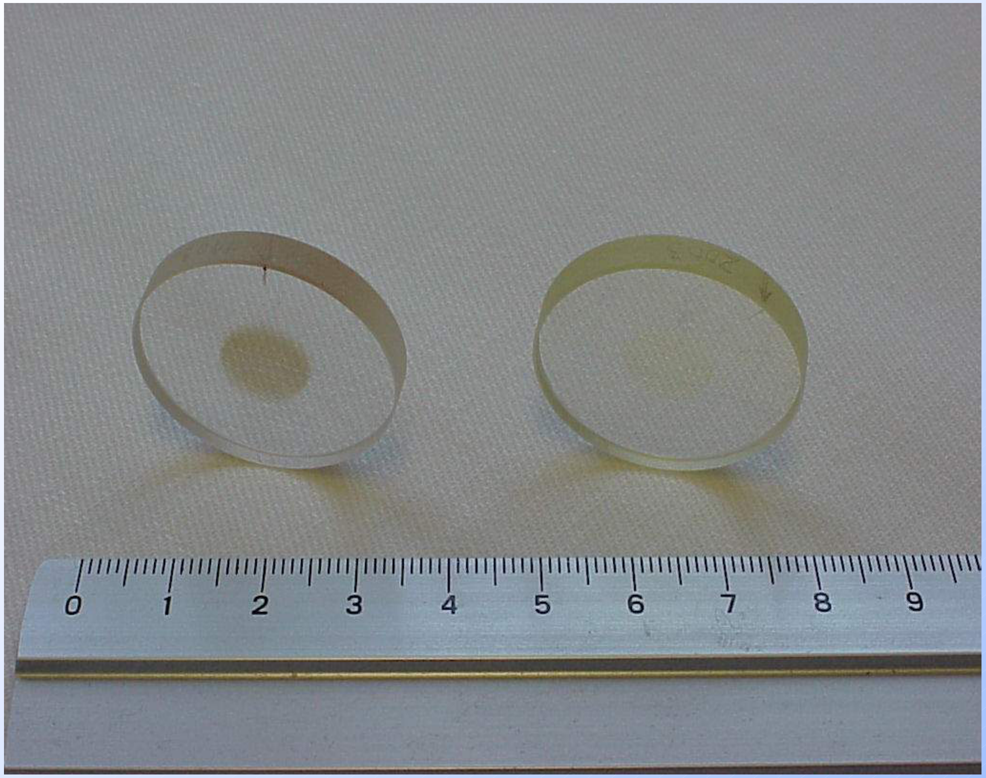
Radiation test system - fibre att'n

- in-situ measurement of fibre attenuation



Ref: Market Survey, 2000 (SCK-CEN Co-60 source)

'Colour centres'

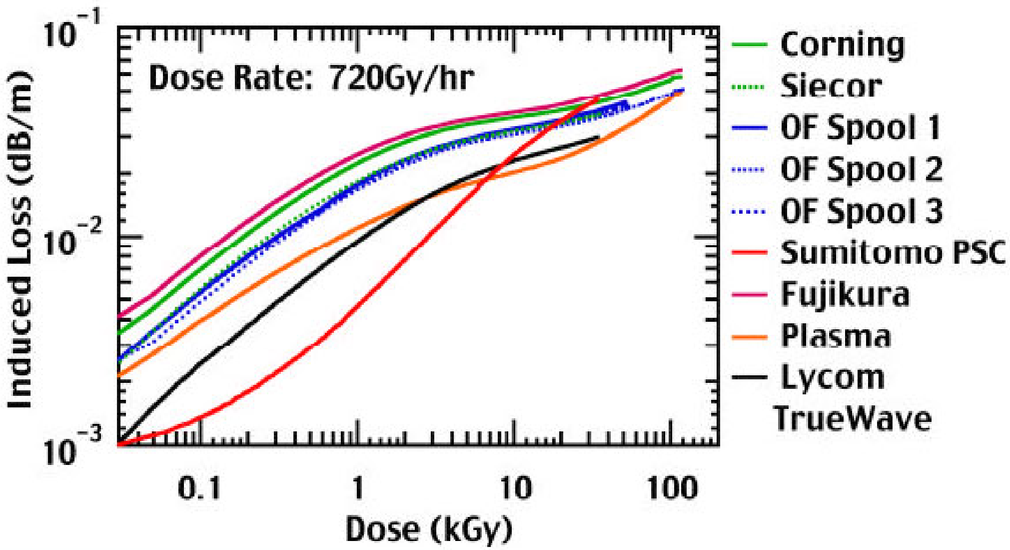


- Attenuation in irradiated glass due to radiation induced "colour centres"
- e.g. lenses irradiated in collimated beam
- impurities affect degree of damage

courtesy A.Gusarov (SCK-CEN)

Gamma damage

- Fibre attenuation up to 100kGy



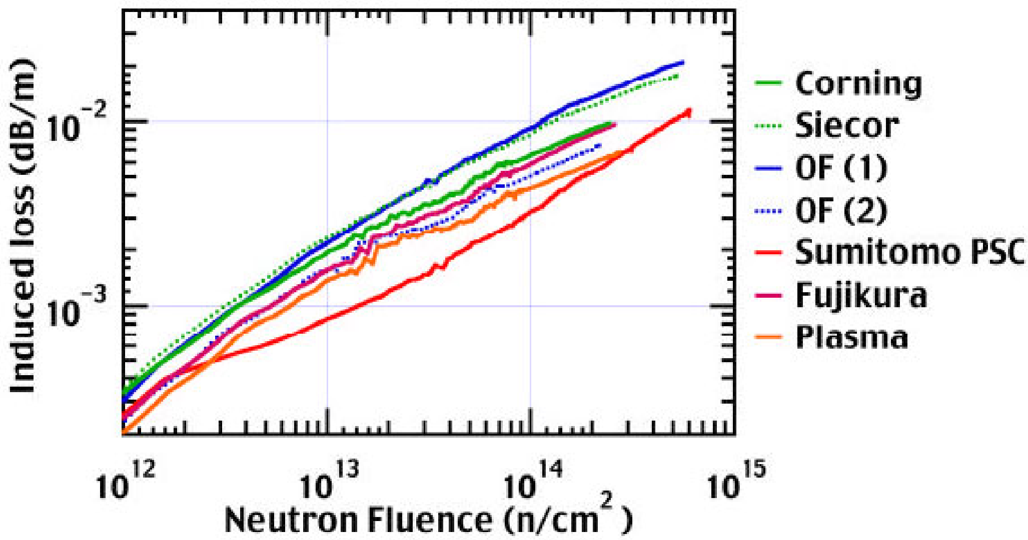
- Loss below 0.1dB/m
- PSC fibre advantageous only below ~ 10-20kGy

- COTS single-mode fibres
  - 1310nm
- for ~10m length inside CMS Tracker expect no more than ~0.6dB (not including annealing)

ref: Troska et al, Proc. SPIE 1998

Neutron damage

- ~6MeV neutrons to ~$5x10^{14}$n/cm^2



- Loss below 0.1dB/m

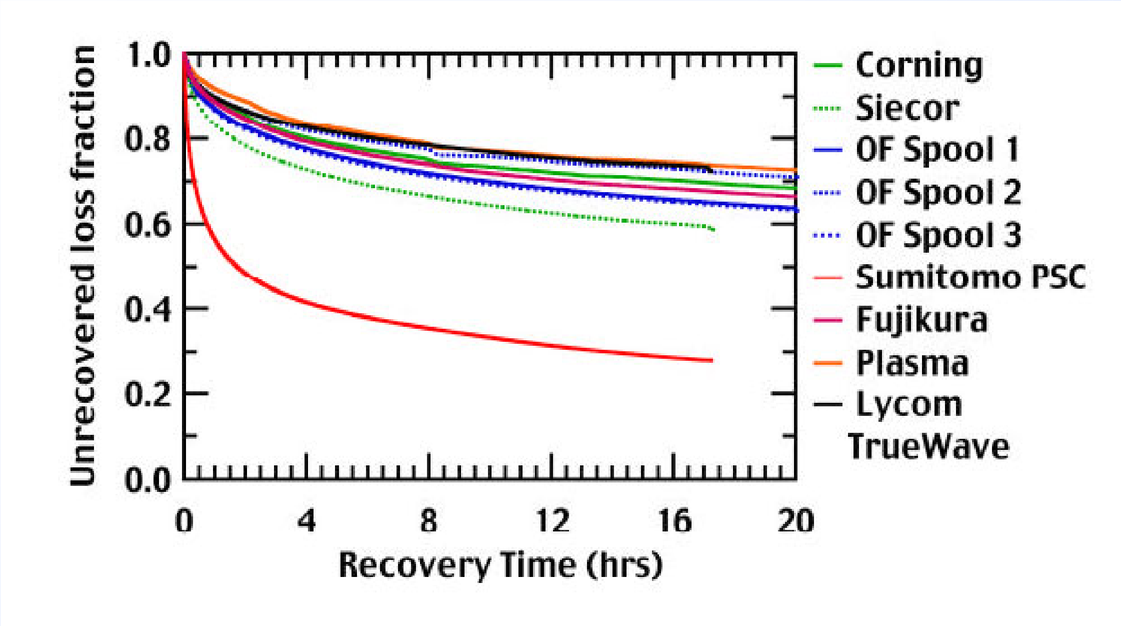
Rates are different for different fibres

- Damage most likely due to γ background

ref: Troska et al, Proc. SPIE 1998

Fibre annealing

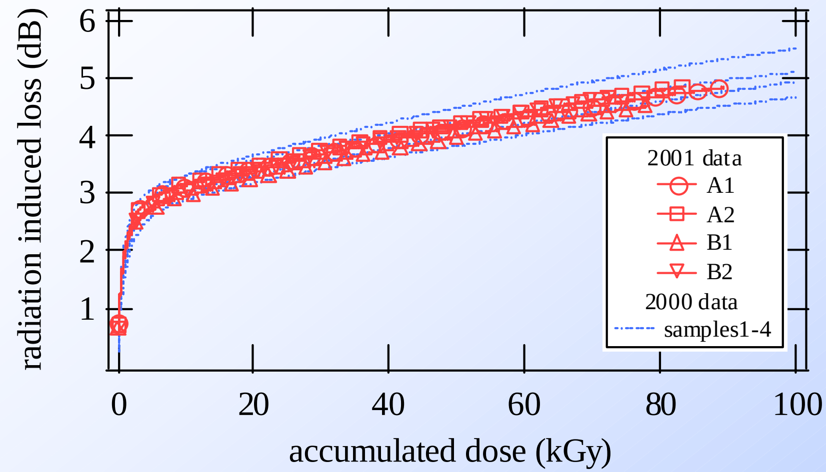
- damage recovers after irradiation (e.g. γ data)

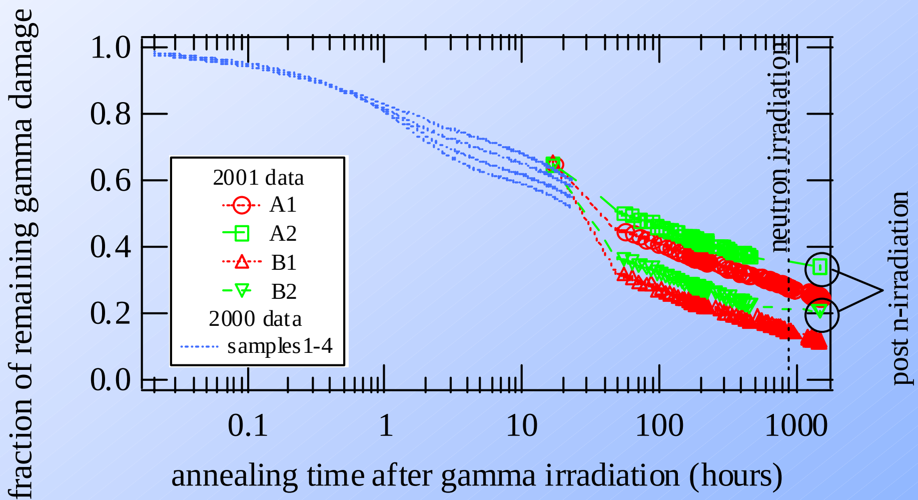


- Significant annealing after irradiation
- Damage therefore *dose-rate* dependent
  - expect more annealing over CMS Tracker lifetime
  - i.e. less damage than measured here

ref: Troska et al, Proc. SPIE 1998

Radiation damage in final fibre

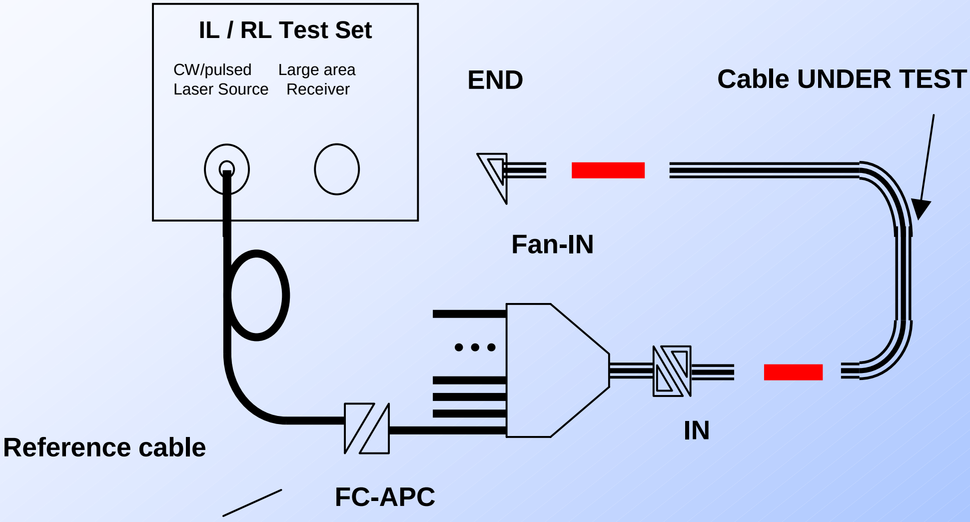


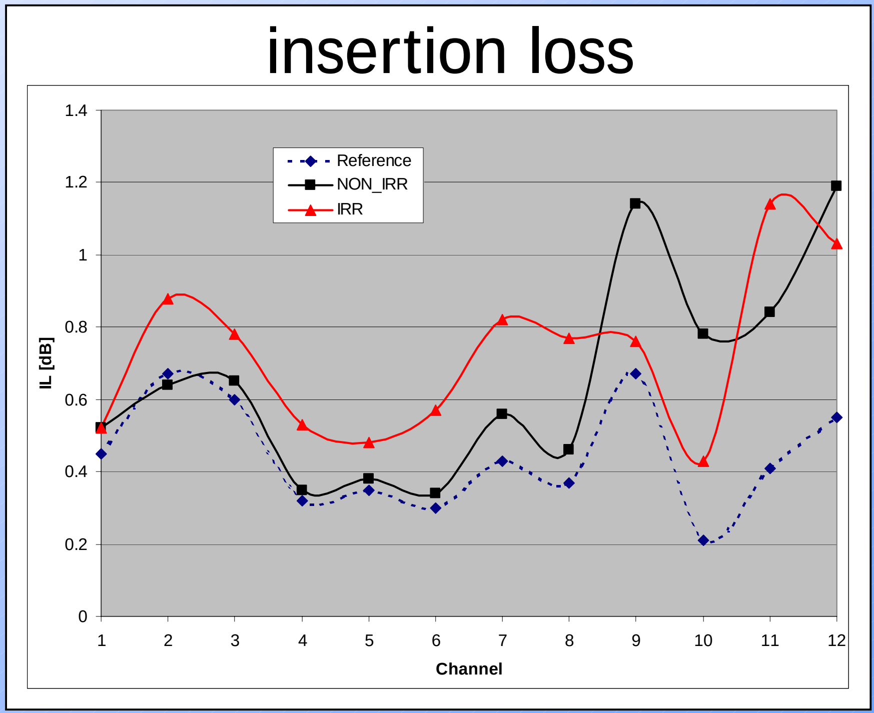


- Ericsson standard single-mode fibre
  - Advance validation test of final naked fibre spools
    - Before plastic buffer added.
- 100m long samples from 2 glass preforms irradiated with
  - ~80kGy Co-60 gamma
  - 1.1×10^{14}n/cm^2 (~20MeV)
- Final loss at 1310nm in final system with 150kGy max dose limited to ~0.01dB/m
- ***Accept fibre for final production***

12-way ribbon cable test

- 12-way ribbon cable bef/after 100kGy





- No significant degradation after irradiation
- No bending loss seen down to 1.5cm bend-radius (spec=3cm)

Cable strength

- 4x10m 96-way cable samples
  - 1x 100kGy gamma
  - 1x 10^{14}n/cm^{2} 0.75MeV neutrons
  - 1x 100kGy gamma + 10^{14}n/cm^{2} 0.75MeV neutrons
  - 1x unirradiated

- Tested by Ericsson Cables
  - Impact
  - Repeated bending
  - Tensile load

  - no significant degradation due to radiation damage

B-field + functionality summary

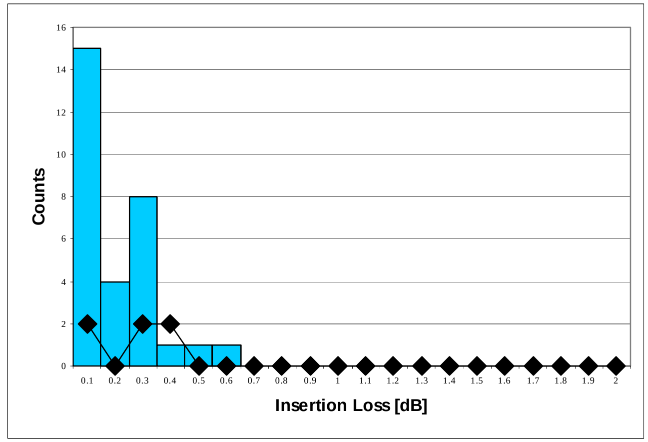
Company	SC-APC <-> FC-APC	SC2 <-> FC-APC	LC <-> FC-APC	MU <-> FC-APC	sMU <-> FC-APC	Reglette <-> MPO	12FC-APC <-> FC-APC	Redel-D <-> FC-APC	2MT-RJ <-> FC-APC	12MT <-> MPO	4MT <-> MPO	12MPO <-> FC-APC	12MPO <-> MPO	4MPO <-> MPO	4miniMPO <-> MPO	12MFS A/B <-> MPO	4MFS A/B <-> MPO	12SMC <-> MPO	MD <-> MD
Amphenol	▨ ▨ o ▨		■ ■ ■ ▨																
Compel				▨ ▨ X ▨															
Computer Crafts									■ 13 o ▨			▨ ▨ X ▨							
Diamond										■ ■ ■ ▨	▨ ▨ ■ ▨					4 6 o ■	▨ ▨ ■ ▨		
FITEL (Furukawa)				■ ■ o ■									■ 2 ■ ▨	▨ ▨ ■ ▨	▨ ▨ ■ ▨				
Fujikura				▨ ▨ X ▨						■ 24 ■ X	▨ ▨ ■ ▨		▨ ▨ X ▨	■ ■ X ▨					
LEMO								■ ▨ X ■											
NTT				■ ■ o ■	■ ■ o ■								■ ■ ■ ■	▨ ▨ ■ ■					
Radiall						■ ■ ■ ▨	▨ ▨ ■ ▨												▨ ▨ X ▨
Infineon (Siemens)		■ ■ o ▨	■ ■ ■ ■															■ ■ ■ ■	
Sumitomo			■ ■ o ■	■ ■ ■ ■						43 2 ■ ■			11 11 o ■						

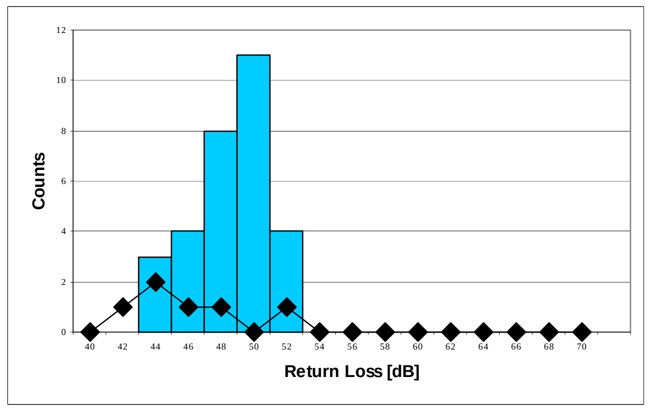
Sub-columns within each connector column: Insertion loss, return loss, B-field connector, B-field adaptor

■	=	test passed
n	=	# of connectors that failed
X	=	B-field test failed
o	=	B-field test passed (weak effect)

MU-connector irradiation

- After 100kGy
  - no damage effects

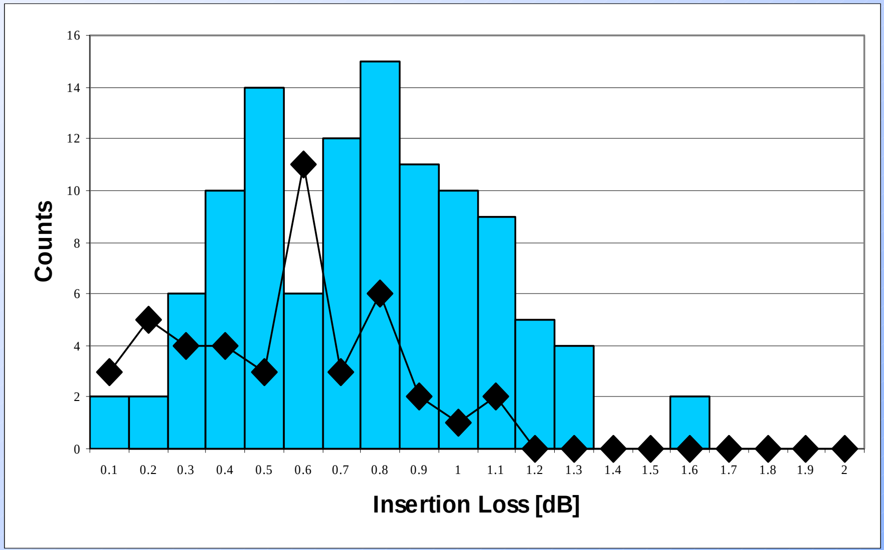


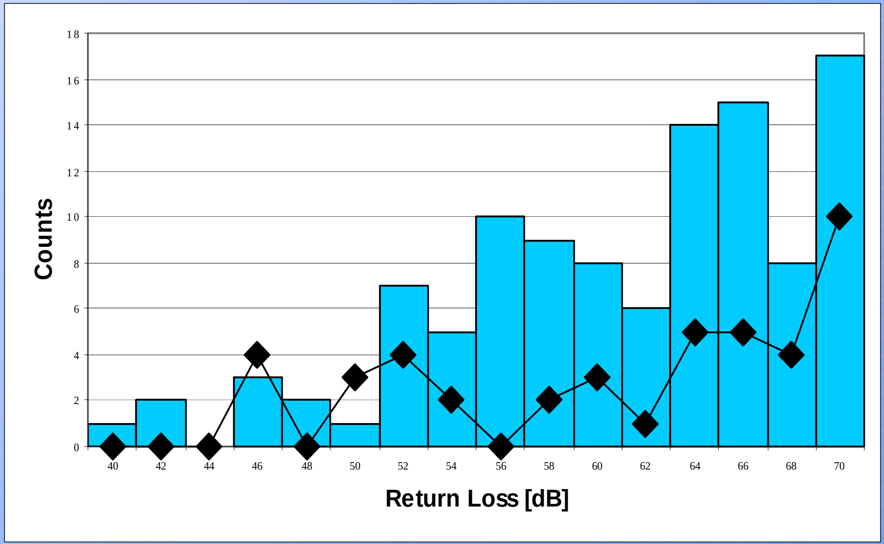


	TOT min		TOT avg		TOT max	
	IL	RL	IL	RL	IL	RL
Before irr:	0	45	0.15	49	0.58	53
After irr:	0.02	43	0.23	47	0.4	52

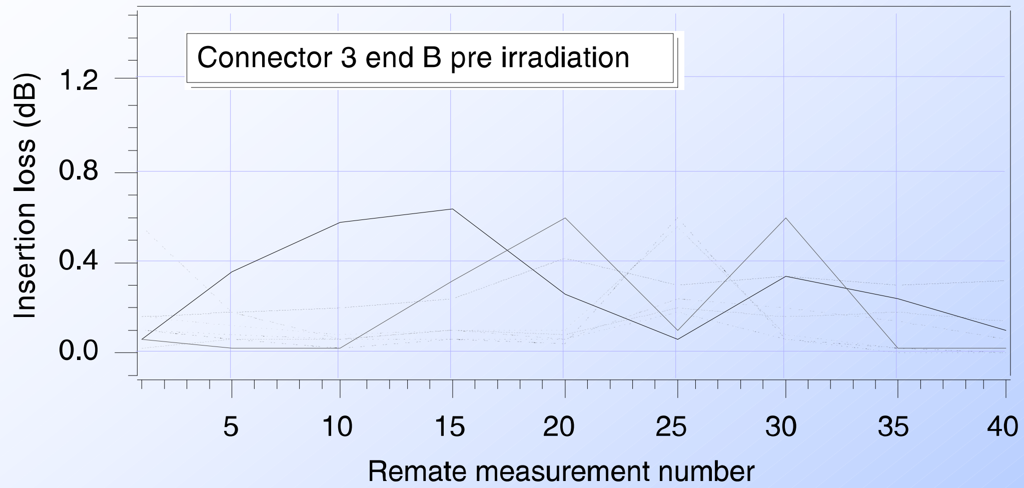
MT-connector irradiation

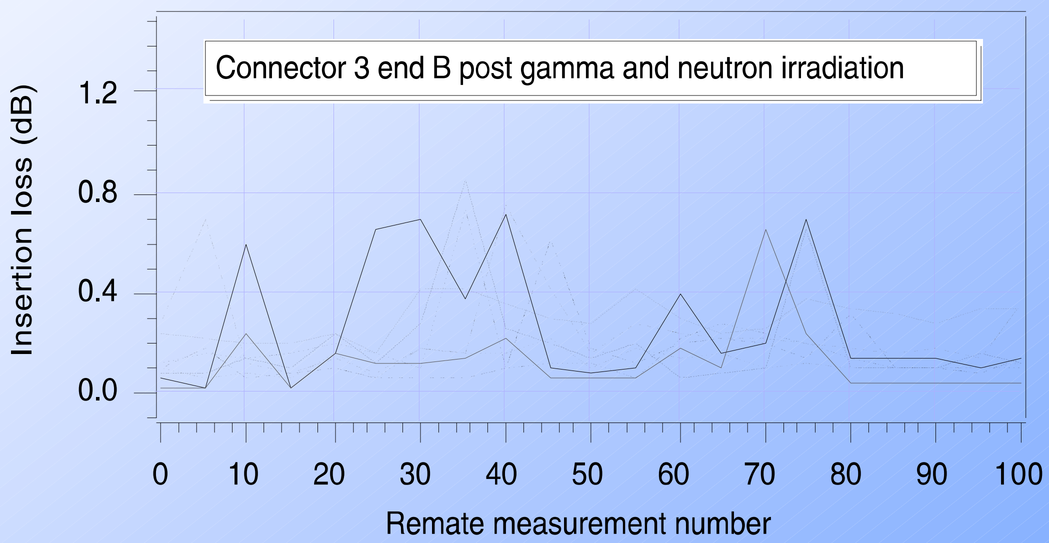
- After 100kGy
  - no damage effects





MT-connector reliability





- Repetitive connection cycles
  - 40 before irradiation
  - 100 after irradiation
    - 200kGy and 10^{14}n/cm^2
- No radiation damage effects
  - Ref: Batten et al., RADECS 1997 Data Workshop