High statistics testing of radiation hardness and reliability of lasers and photodiodes for CMS optical links

Karl Gill

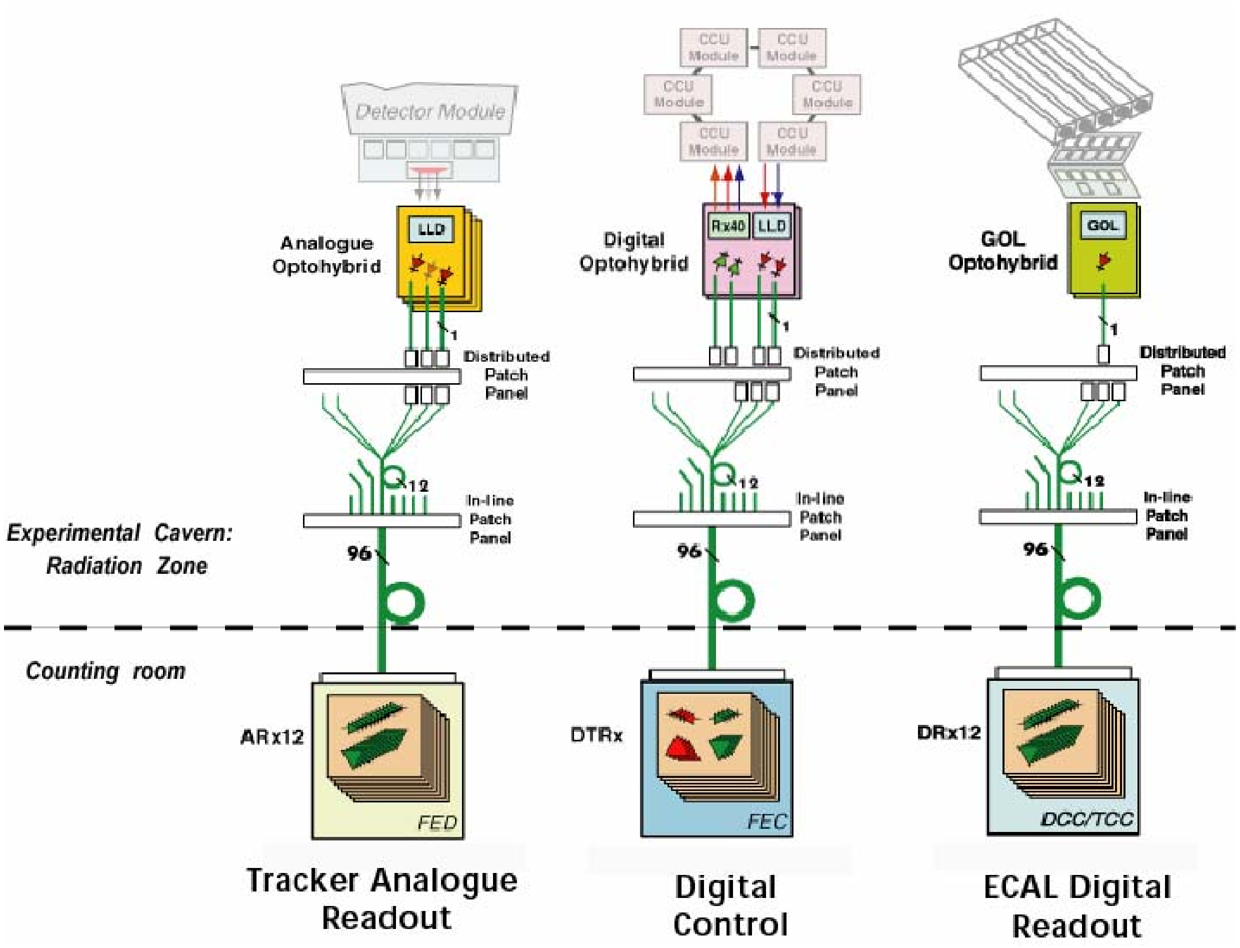
CERN, Geneva

karl.gill@cern.ch

Overview

- Optical links in CMS
- Environment
- Advance validation test (AVT)
- Results, lasers then photodiodes:
  - Radiation damage
  - Annealing
  - Ageing
- Summary and Conclusions

CMS optical link projects at CERN



3 optical link systems developed at CERN, with Univ. Minnesota, HEPHY Vienna, INFN Perugia

- Tracker analogue readout

- Control links for Tracker, ECAL, Preshower, Pixels, RPC

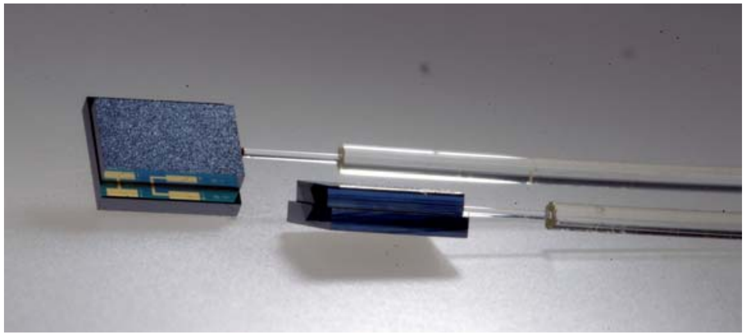
- ECAL readout

60000 fibre channels

Aim to share as many components as possible

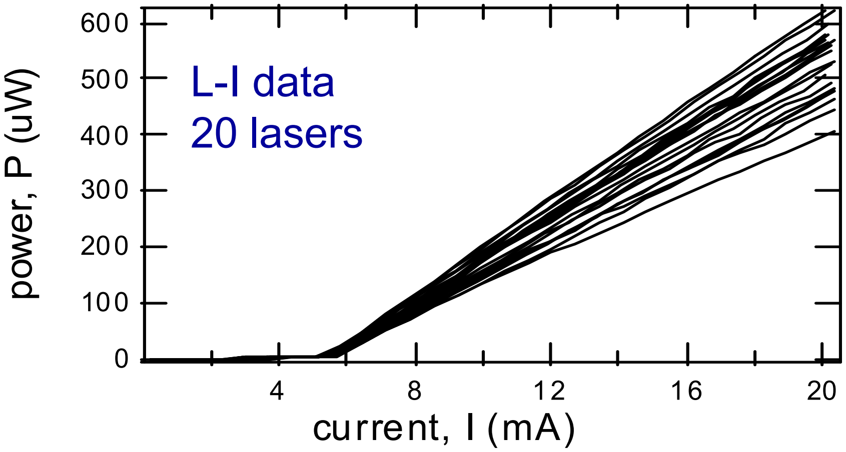
- Focus here on tests on lasers and photodiodes pre-production

Lasers under test



1310nm InGaAsP/InP multi-quantum-well edge-emitting lasers

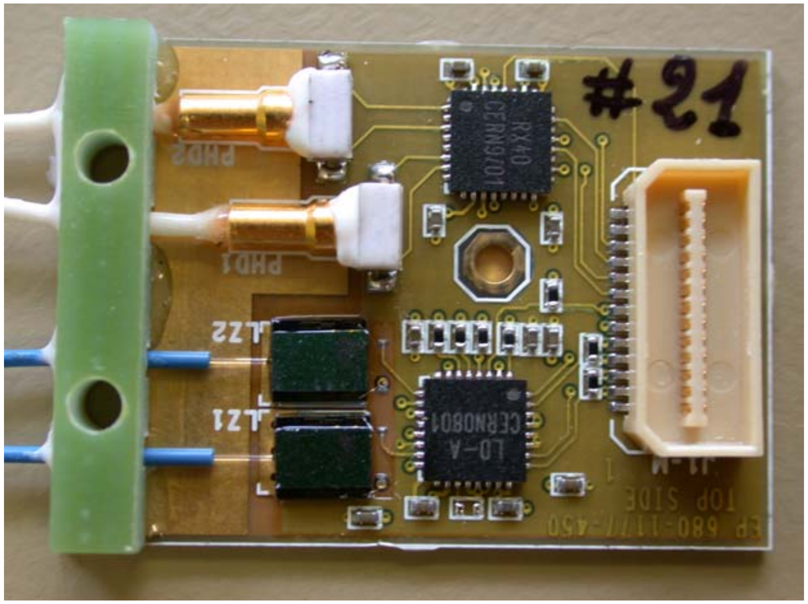
- Based on commercial off-the-shelf (COTS)
- Mitsubishi laser die, ML7CP8
- Packaged by STMicroelectronics
  - Custom mini-pill package for CERN



Typical starting L-I characteristics:

- Initial Threshold: 6mA at 20°C
- Output efficiency (out of fibre): 40µW/mA

Photodiodes under test



2photodiodes and 2 lasers on a digital optohybrid (DOH)

InGaAs/InP p-i-n photodiodes

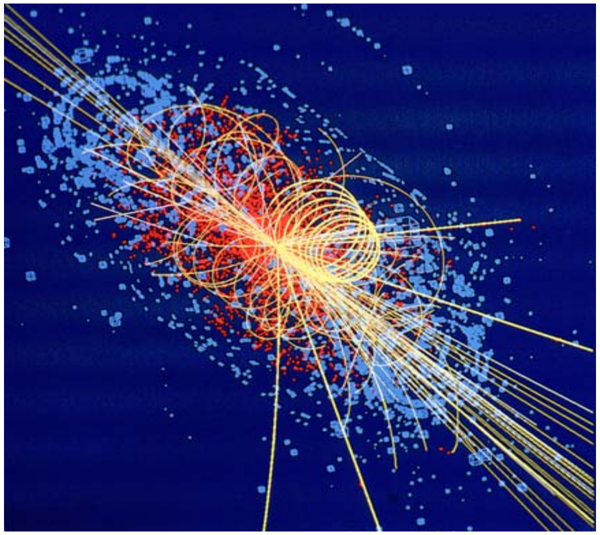
- Based on commercial off-the-shelf (COTS)
- Fermionics FD80S8F
  - Package includes CERN qualified fibre pigtail and connector

Initial characteristics:

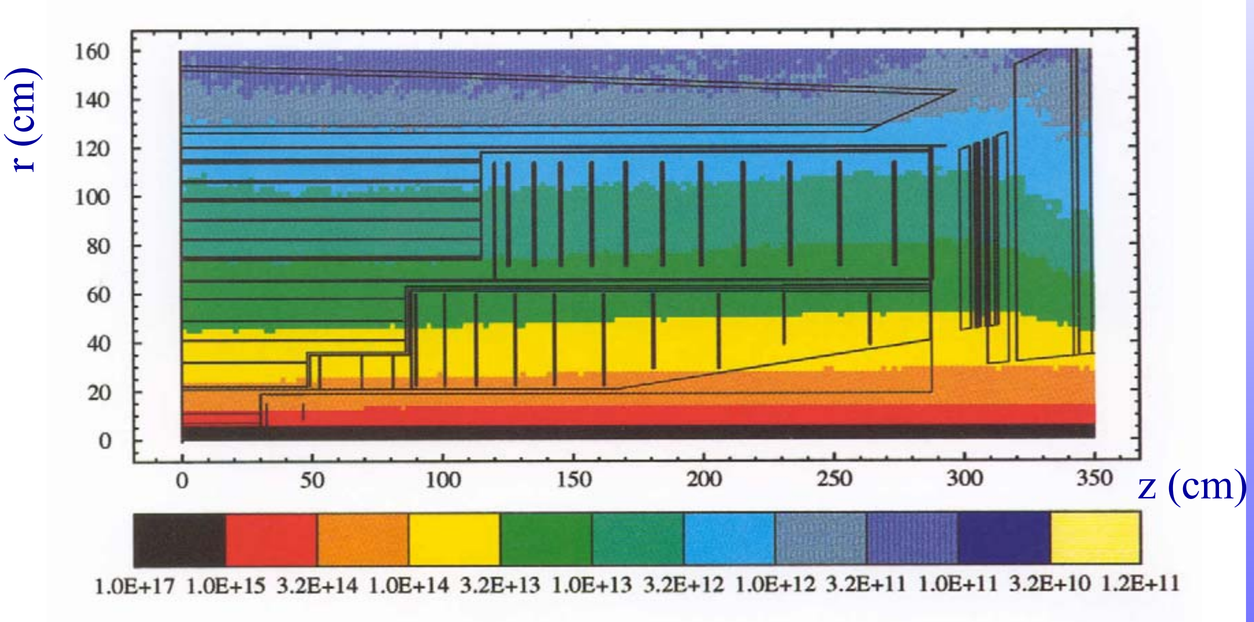
- Leakage current <100pA at –5V
- Responsivity 0.85A/W
- Capacitance ~1pF at –2V

Operating environment

- Temperature: Tracker -10°C, ECAL 20°C
- Magnetic field 4T
- Radiation environment
  - $2 \times 10^{14} \pi/\mathrm{cm}^2$ ($E_\pi \sim 200\mathrm{MeV}$)
  - 100kGy
- Inaccessible over 10 year lifetime

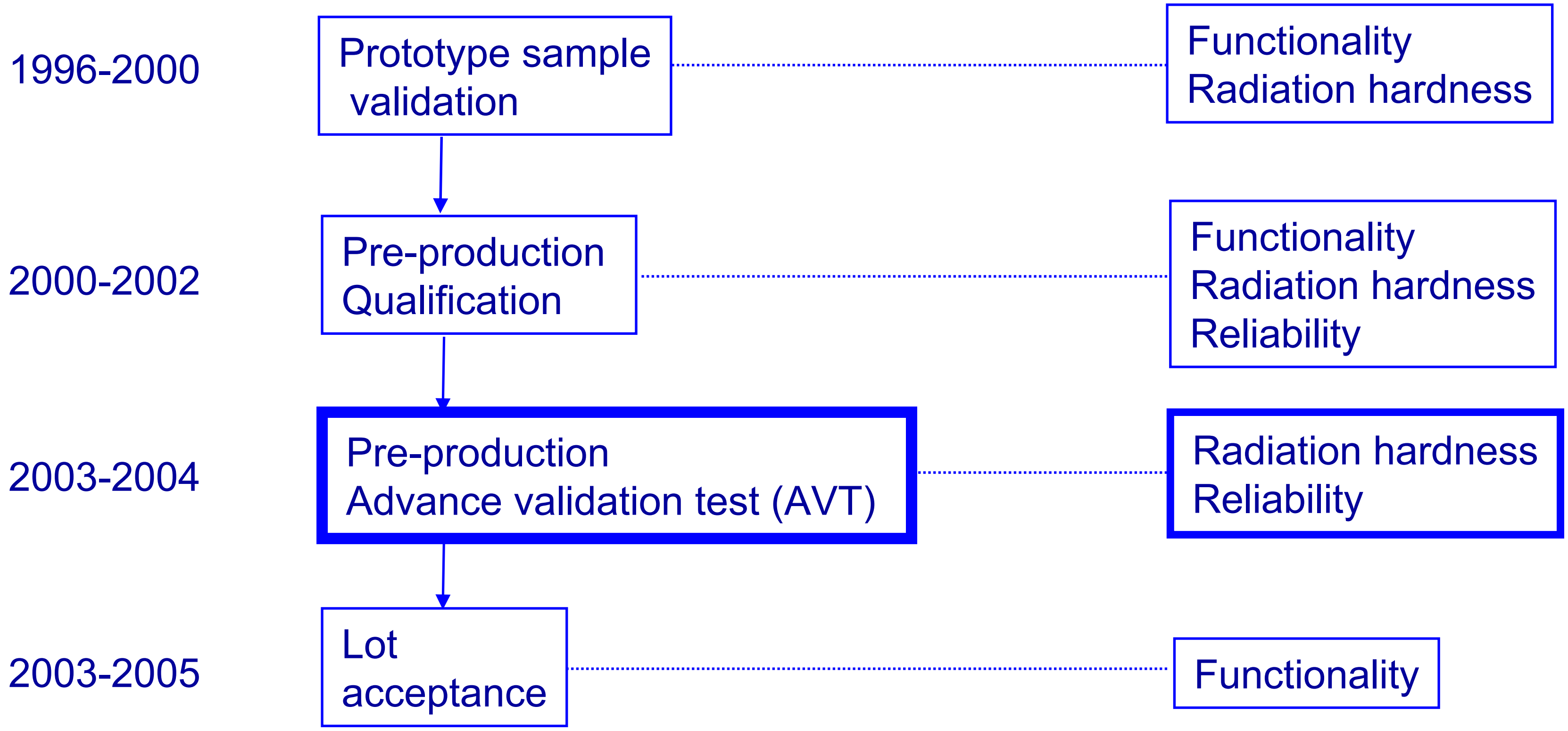


- LHC p p at 14TeV
  - 150 tracks per pp collision
  - ~10 collisions every 25ns



Charged hadron fluence (/cm^2) over first 10yrs

Quality Assurance programme



1996-2000

Prototype sample validation

Functionality
Radiation hardness

2000-2002

Pre-production Qualification

Functionality
Radiation hardness
Reliability

2003-2004

Pre-production
Advance validation test (AVT)

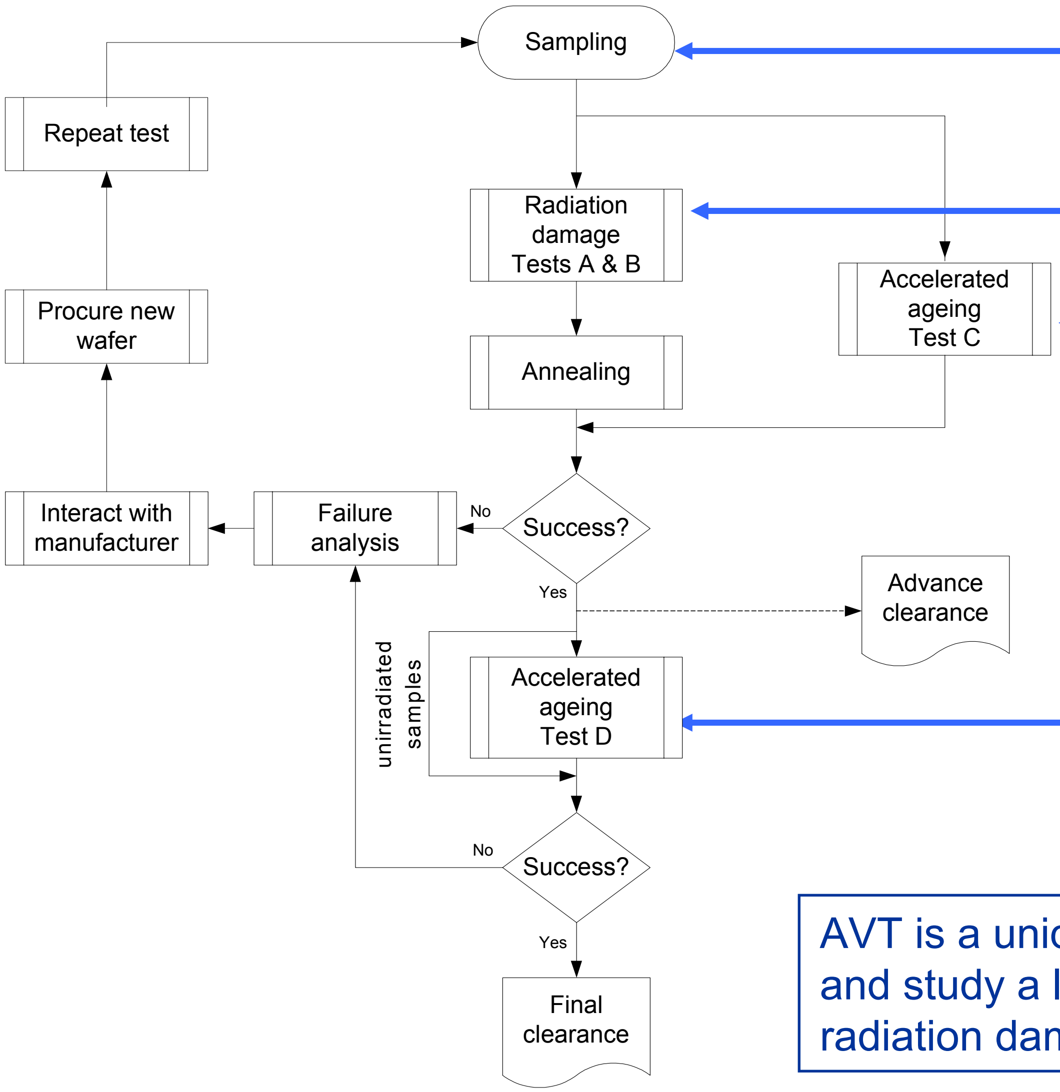
Radiation hardness
Reliability

2003-2005

Lot acceptance

Functionality

Advance validation test



Sampling

Radiation damage Tests A & B

Annealing

Accelerated ageing Test C

Success?

No

Failure analysis

Interact with manufacturer

Procure new wafer

Repeat test

Yes

Advance clearance

Accelerated ageing Test D

unirradiated samples

Success?

No

Yes

Final clearance

30 samples

20 devices
100kGy and 5×10^{14}n/cm^2
20-30°C

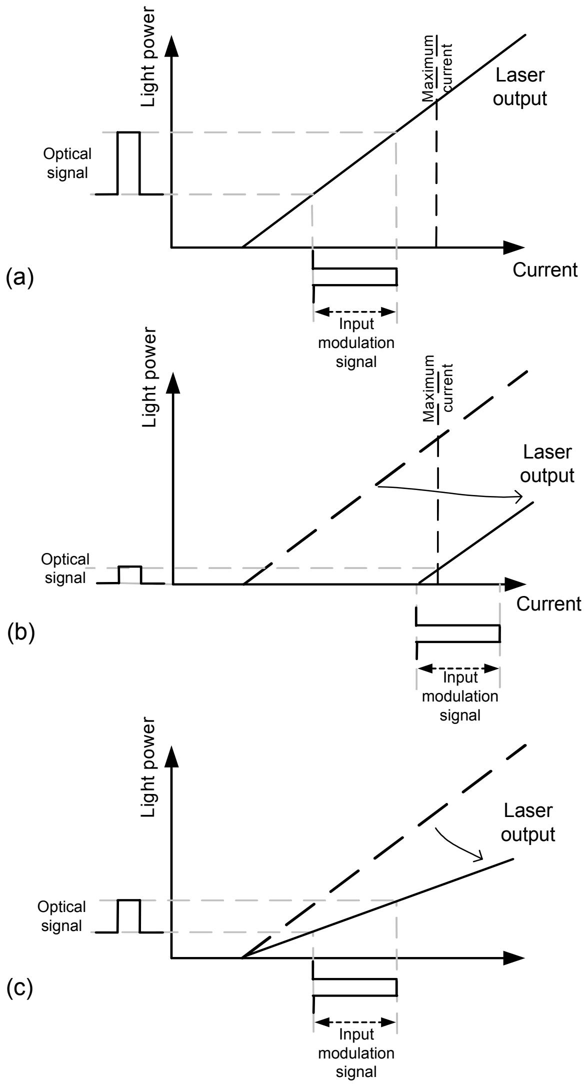
10 devices
80°C

20 devices
(same as test A & B)
80°C

AVT is a unique opportunity to gather and study a large amount of data on radiation damage and reliability

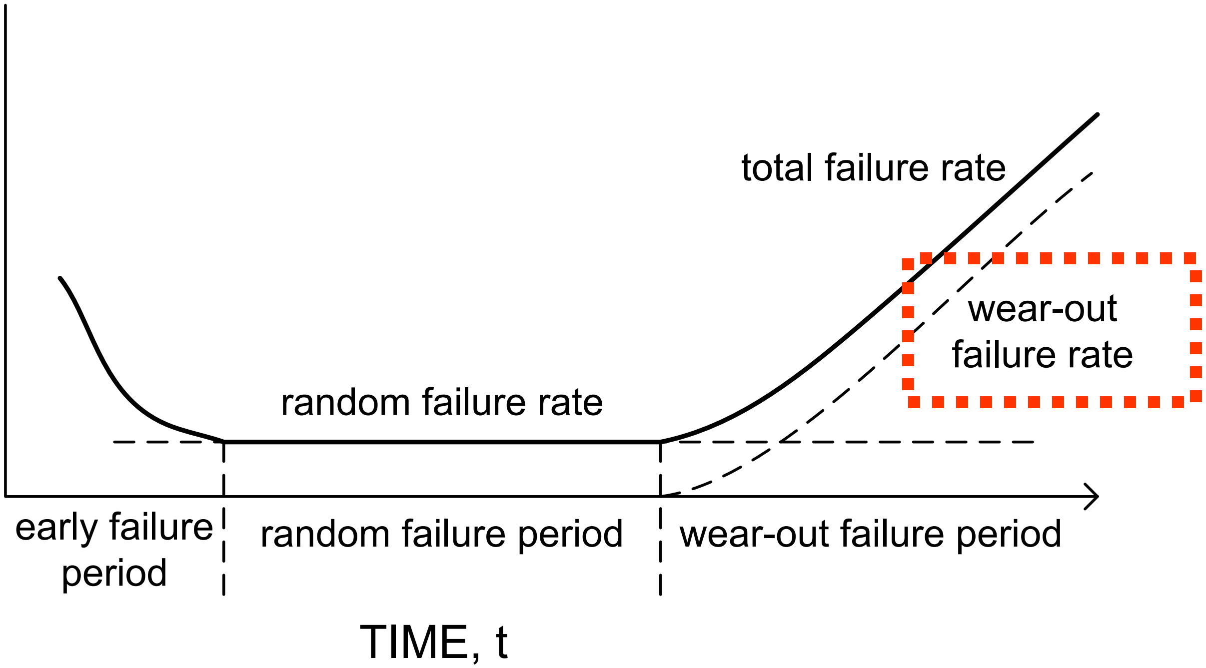
Failure criteria

e.g. lasers



- Normal working device
- Device failure due to threshold increase
- Device failure due to efficiency loss

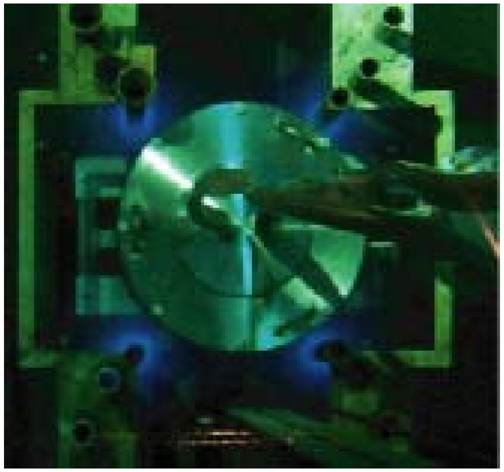
Ageing and Reliability



- Accelerated ageing examining wearout degradation
  - Burn in should eliminate early failures and random failures difficult to test
- Thermally activated

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

Gamma irradiation at SCK-CEN

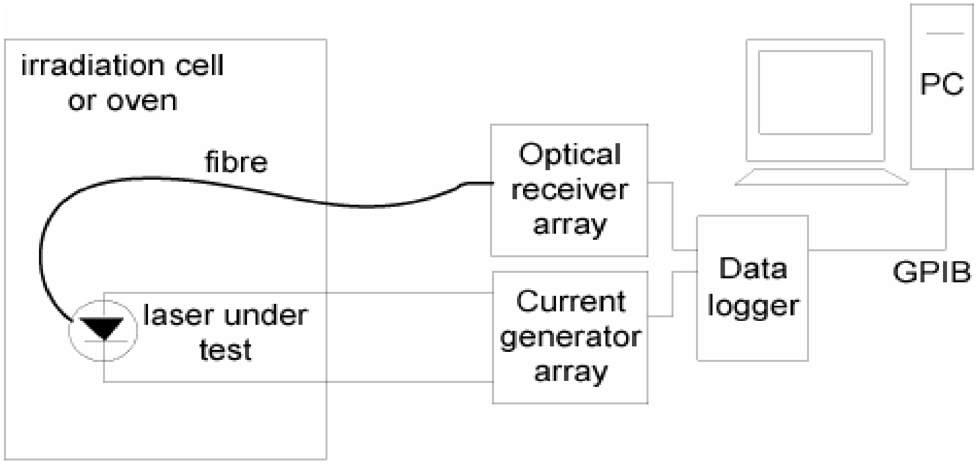


Up to 60 parts in each AVT

100kGy in 48 hours

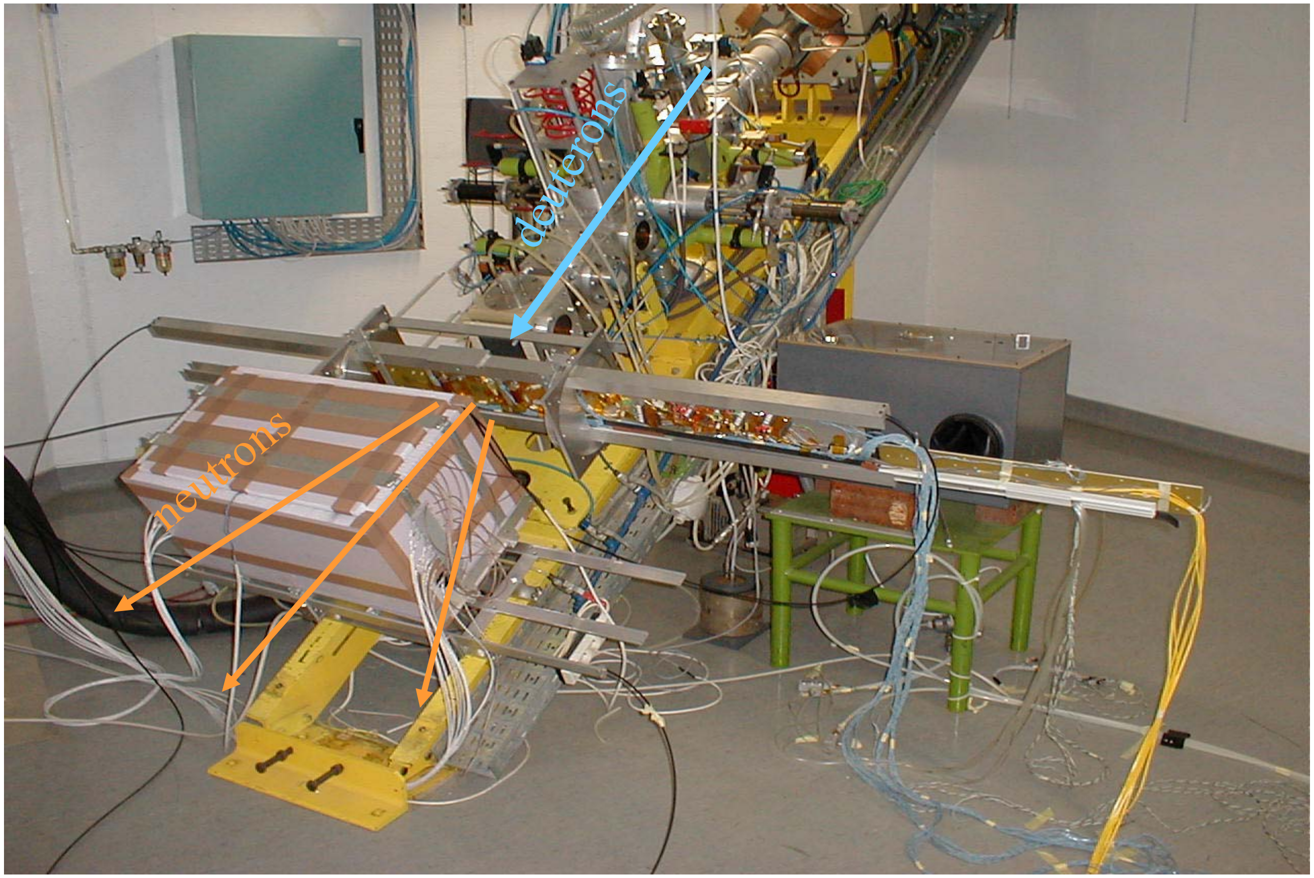
30°C

In-situ measurements of device characterictics



e.g. laser measurements

Neutron irradiation at UCL



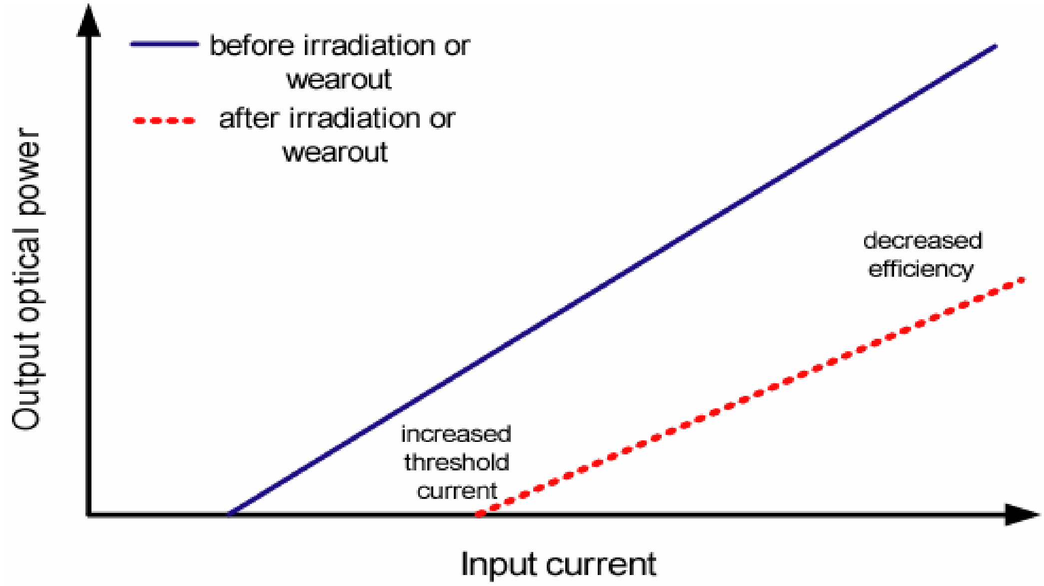
Up to 60 parts (3 x 20) in each AVT

5×10^{14}n/cm^2 in 7 hours
$E_{neutron}$ ~ 20MeV

25°C

In-situ measurements

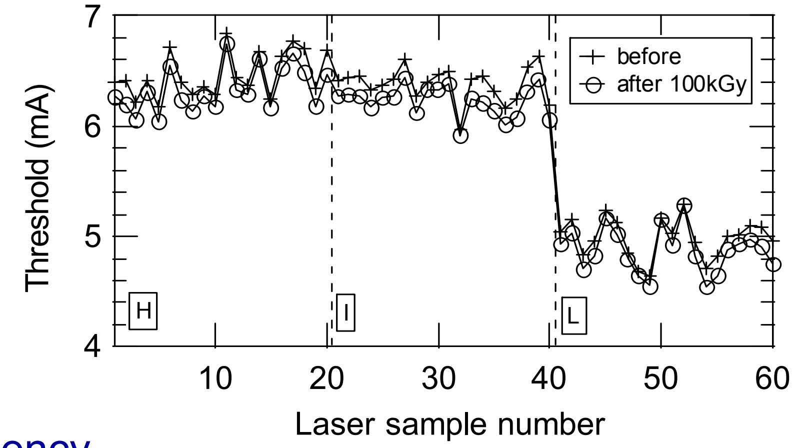
Laser results



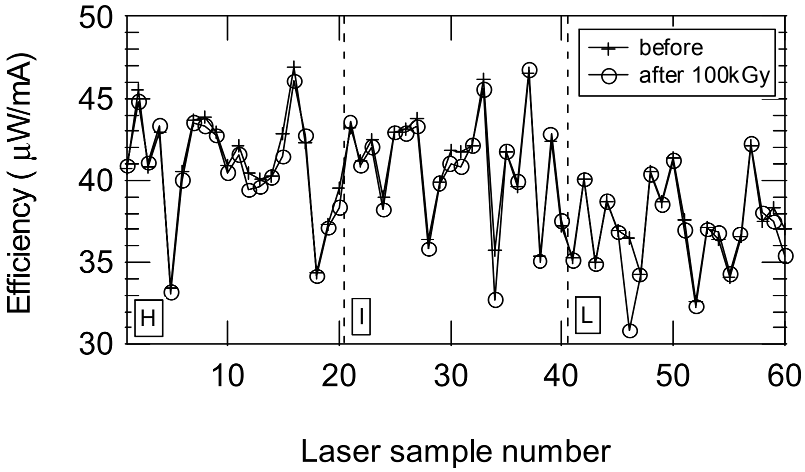
karl.gill@cern.ch

Radiation Damage in lasers – ^{60}Co gamma

Threshold currents



Efficiency

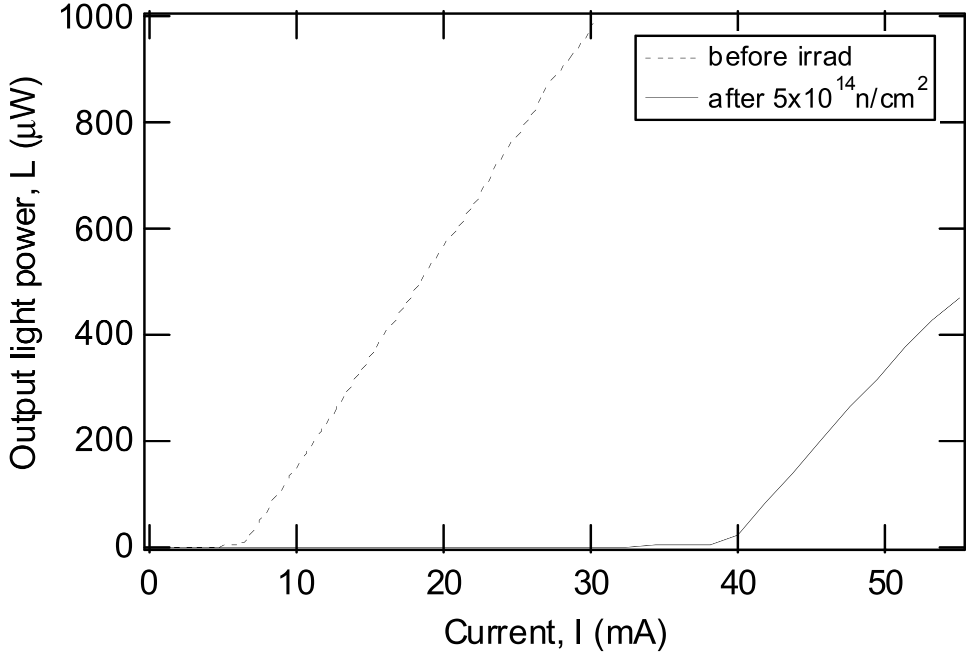


- No significant change after 100kGy

Data for 60 lasers from 3 wafers in AVT 3

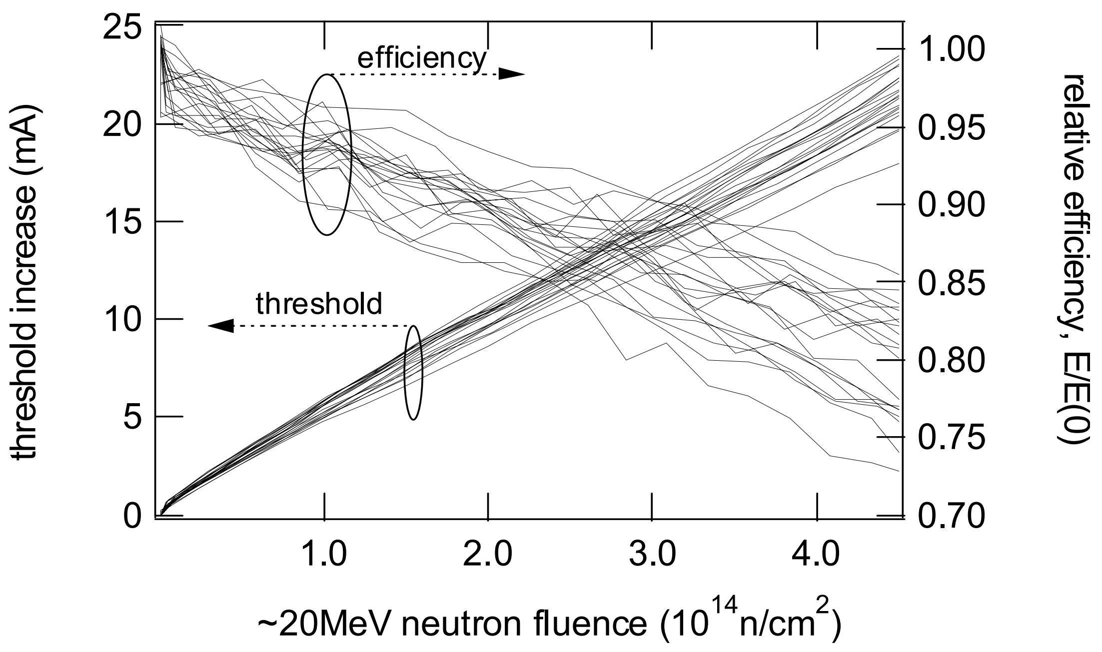
Radiation Damage in lasers – 20MeV neutrons

Typical L-I characteristics before and after 5×10^{14}n/cm^2



- A lot of damage from neutrons
  - Increase in laser threshold current
  - Decrease of laser efficiency

Neutron damage effects in lasers



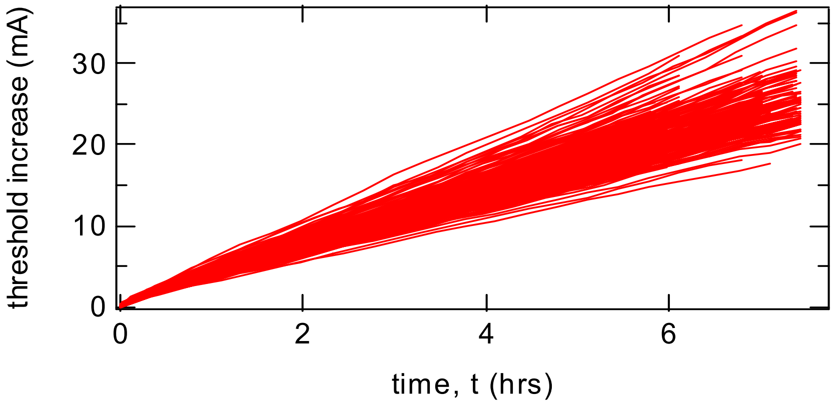
- Damage proportional to fluence
  - Degradation of carrier lifetime

$$\frac{\tau_0}{\tau_{nr}} = 1 + k\tau_0\Phi$$

- After 4.5x10^{14}n/cm^2
  - Threshold increase ~20mA
  - Efficiency loss ~20%

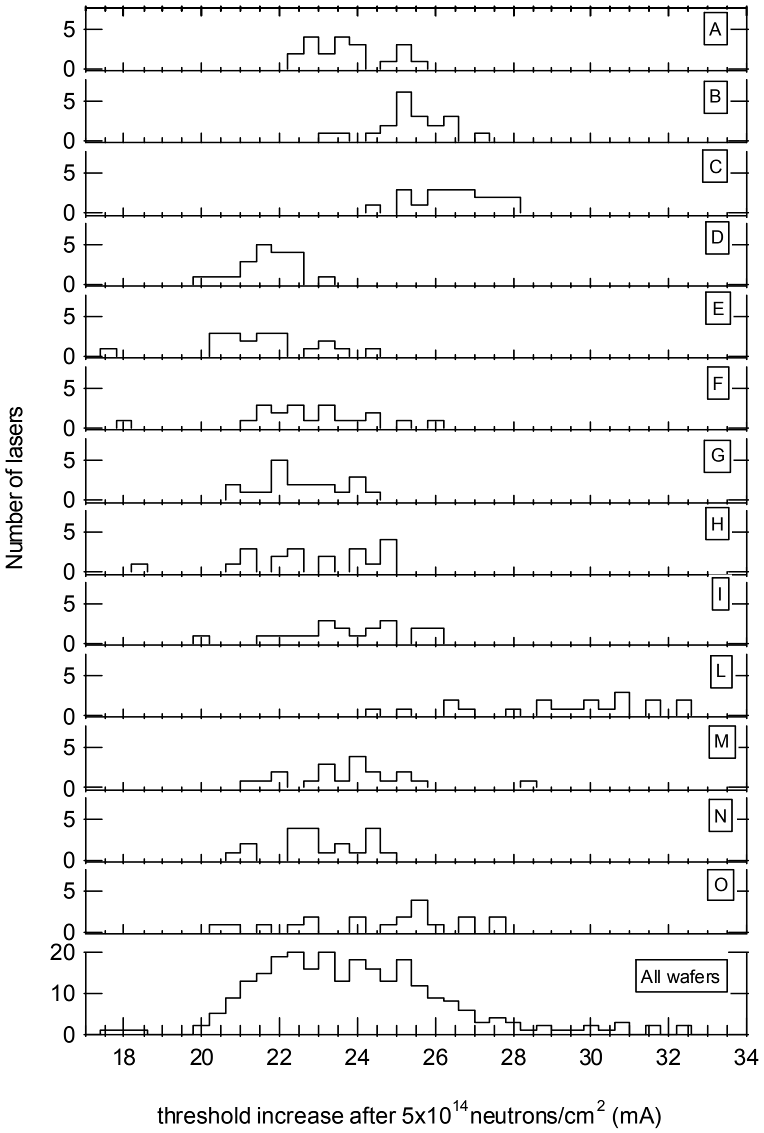
Data for 20 lasers from 1 wafer

Laser wafer comparison: thresholds

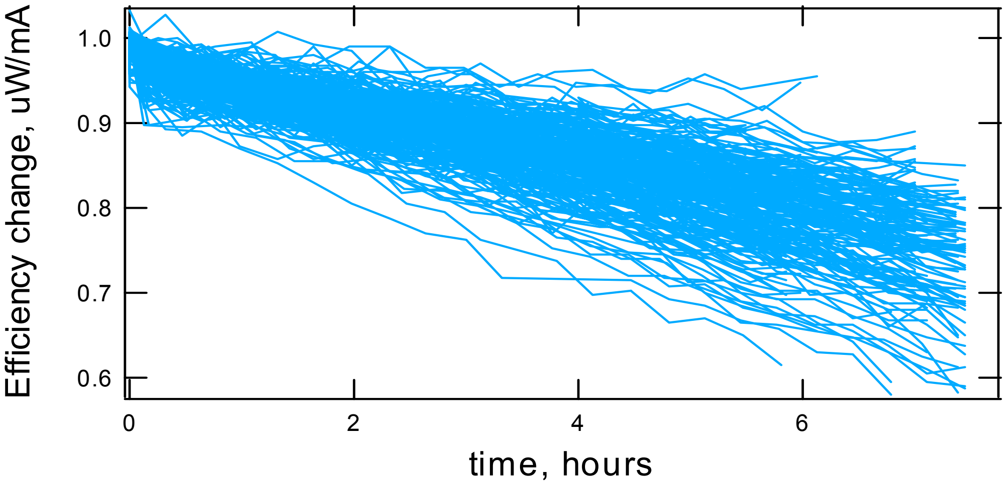


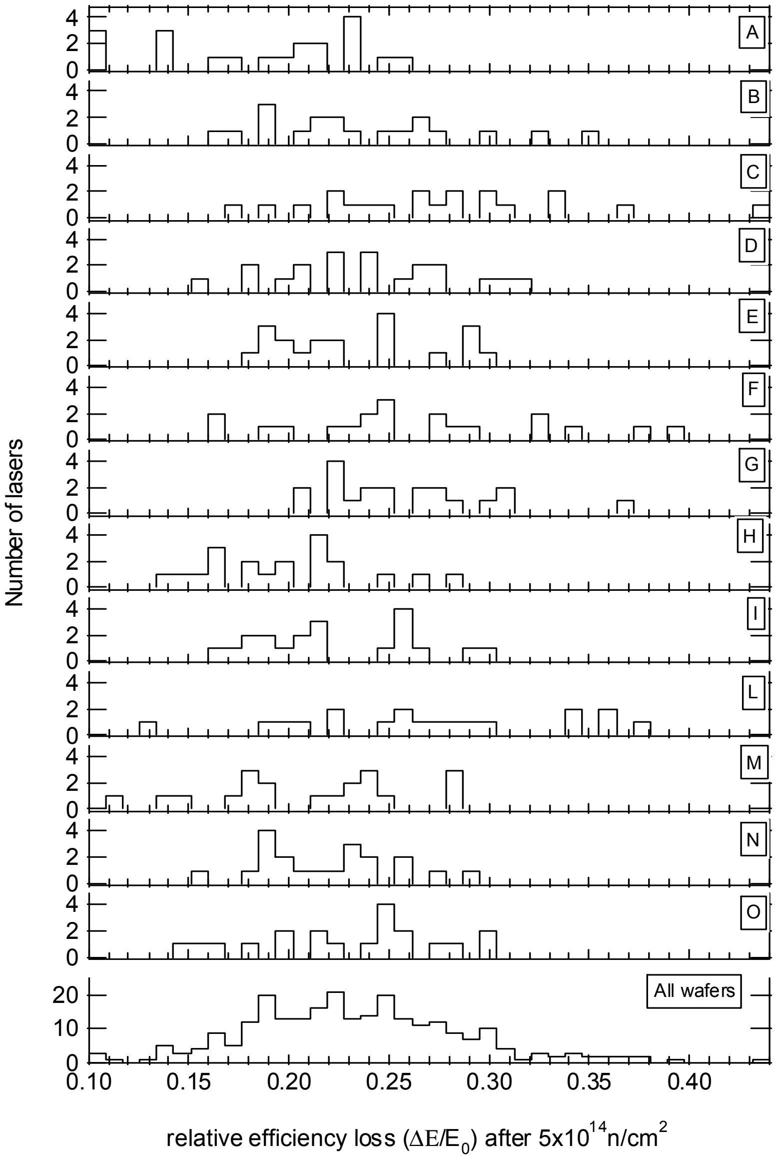
- 5 AVTs
  - $\Phi = 4$ to 6×10^{14}n/cm^2
  - time 6 – 7.5 hrs
- To compare wafers, normalized results
  - 5×10^{14}n/cm^2
  - using only first 6 hr of data

- Similar damage in lasers from a given wafer
- Some variation across wafers
- Average damage 24mA
  - 400% of initial threshold value



Laser wafer comparison: efficiency

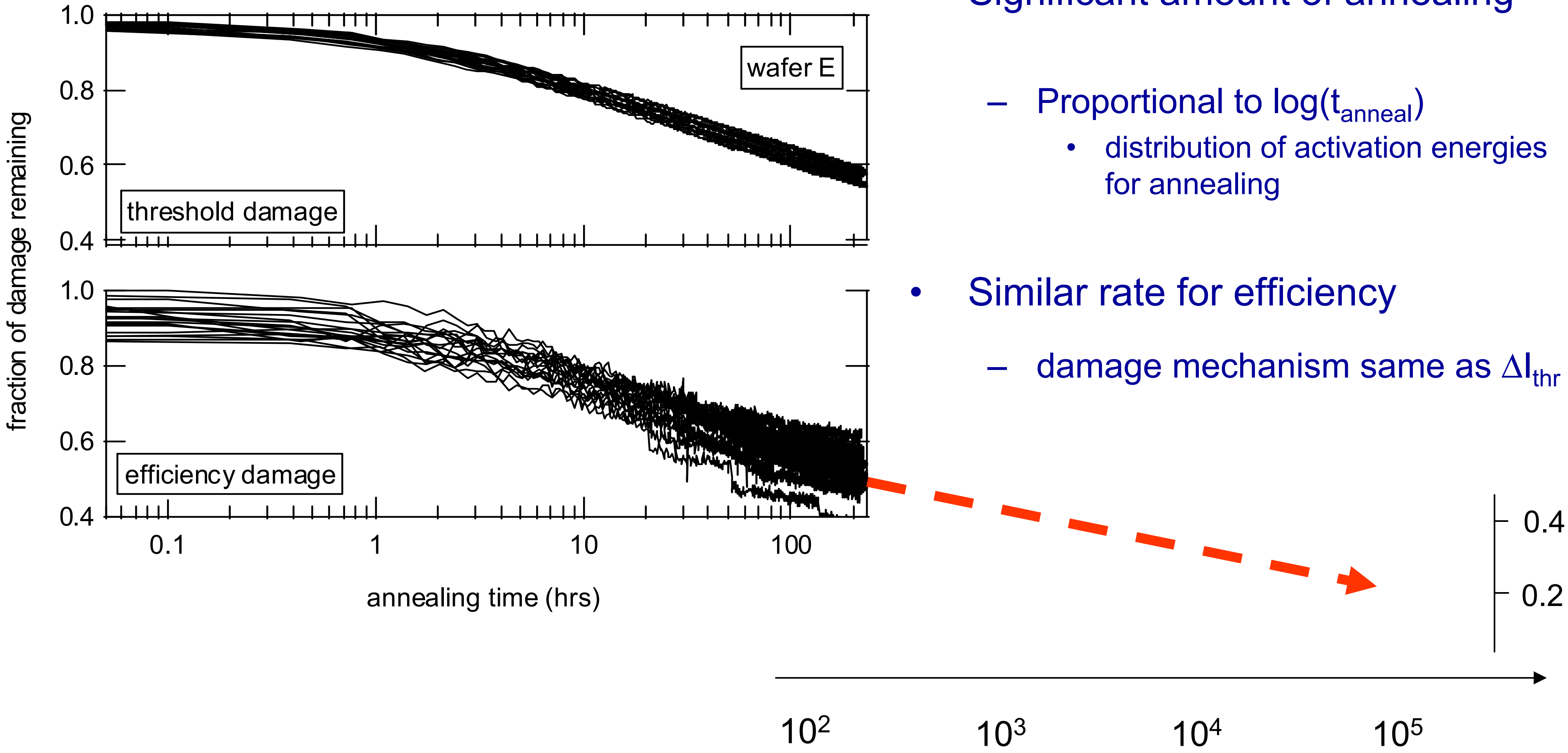




- Larger spread across a wafer
- Similar results from wafer to wafer
- Average damage 23%

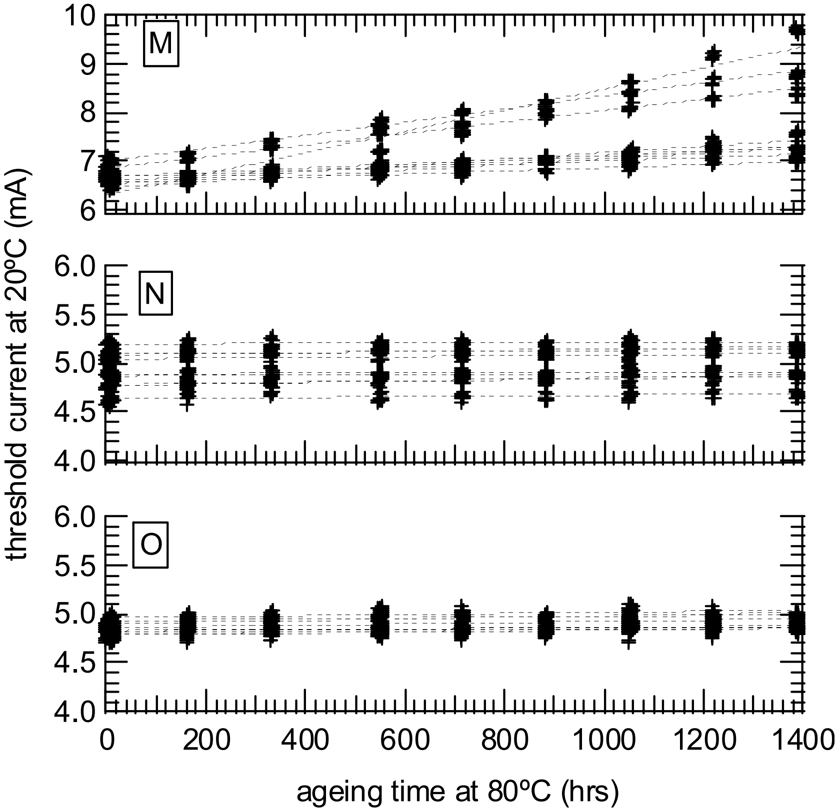
Annealing in lasers

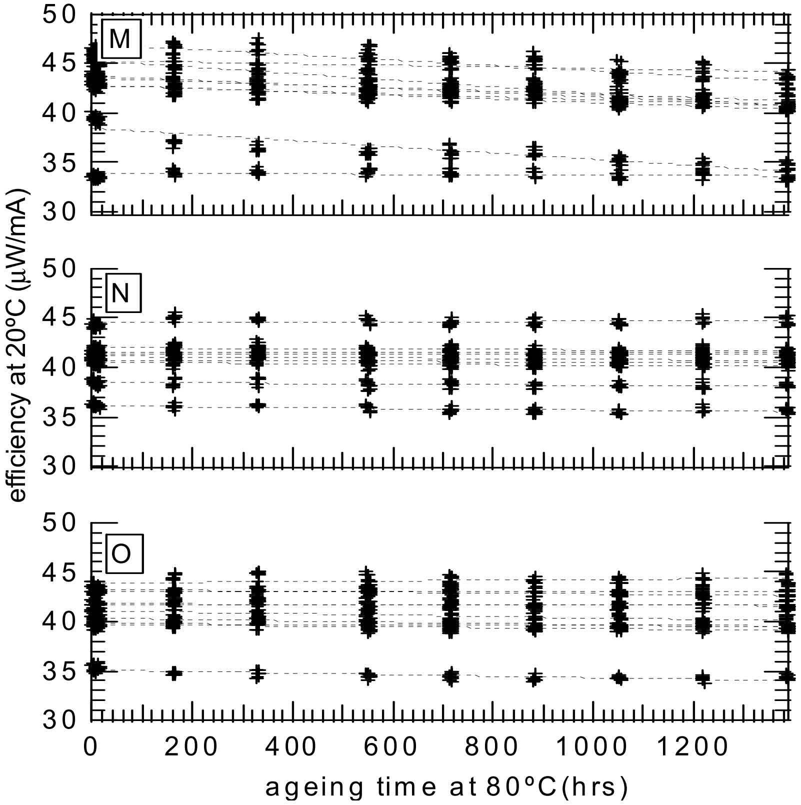
- Significant amount of annealing
  - Proportional to log(t_{anneal})
    - distribution of activation energies for annealing
- Similar rate for efficiency
  - damage mechanism same as ΔI_{thr}



- Expect at least 70% annealing after 10 years

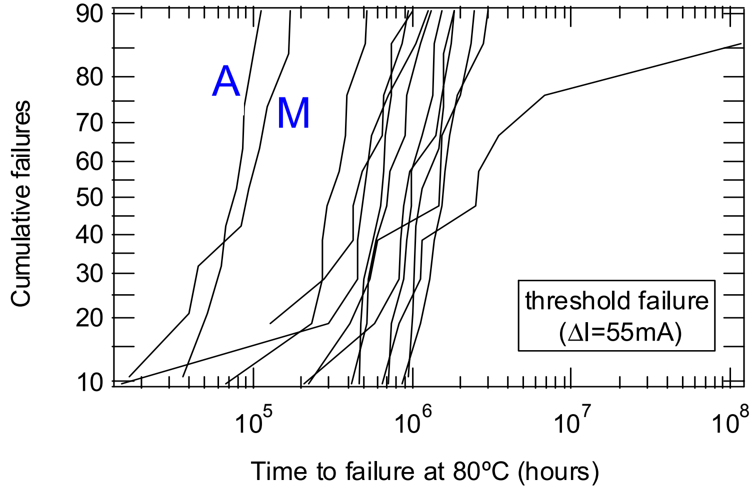
Thermally accelerated ageing of unirradiated lasers

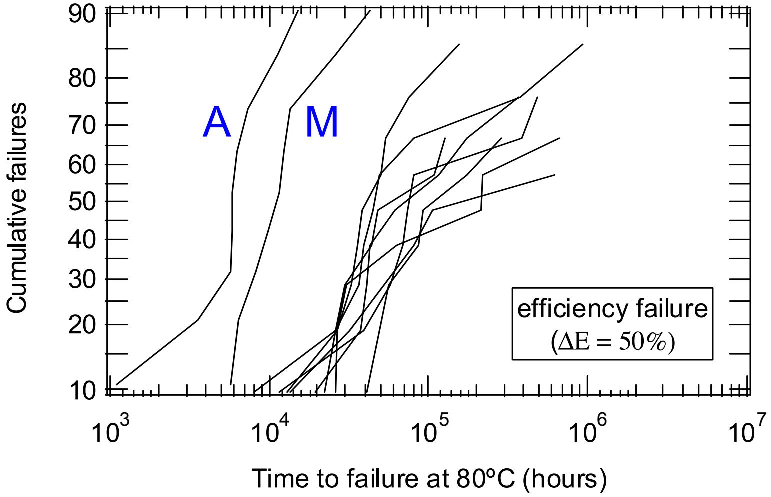




- Most wafers (11 out of 13) very little wearout degradation observed
- Wafer M is one of 2 wafers with lower reliability
- 1000 hours at 80ºC corresponds to $4\text{x}10^6$ hours at –10ºC (CMS Tracker)
  - assuming E_a=0.7eV

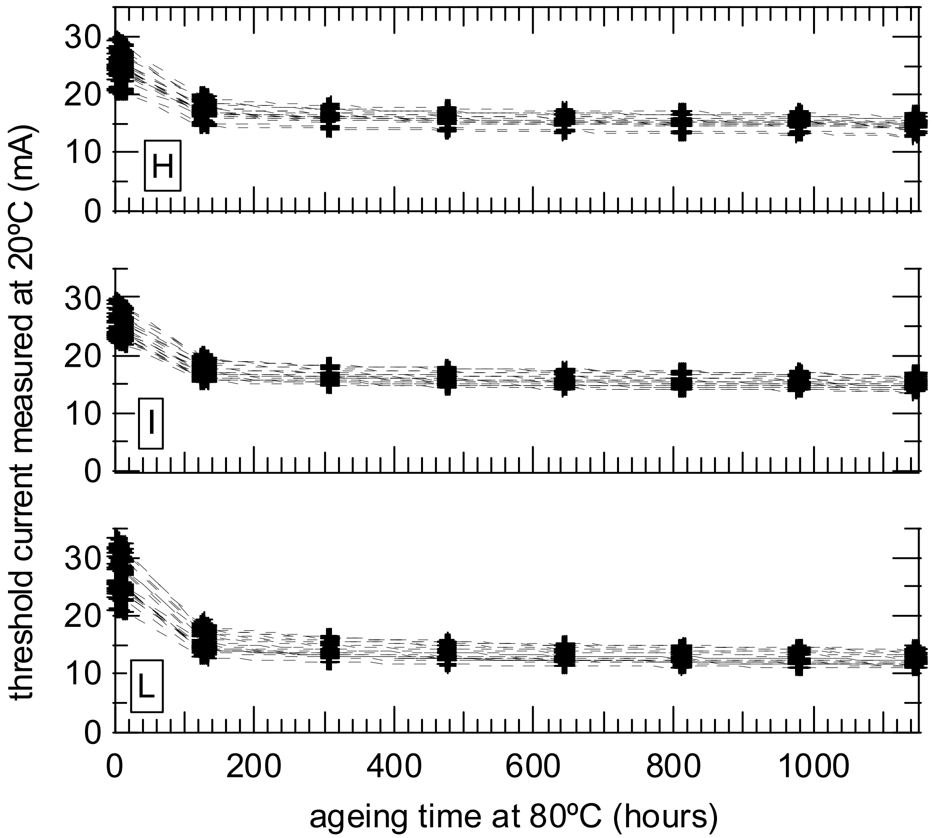
Distribution of device lifetimes in unirradiated lasers





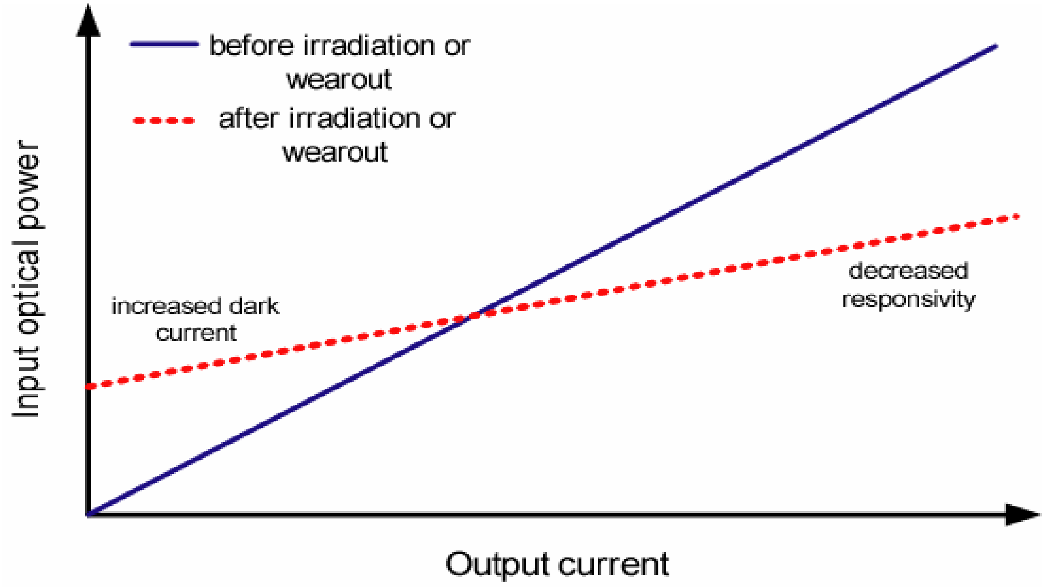
- Wearout data extrapolated to failure criteria
- Log-normal distribution of failures
  - Typical of semiconductor devices
- Long lifetimes compared to project timescale
  - Especially at CMS operating temperatures
  - Estimate failure rates after 10 years
    - 20FITs in CMS Tracker
    - 1000FITs in CMS ECAL
- Few devices will wear out.
  - Probably will be dominated by random failures.
- Failure distributions similar for most wafers
  - Except A and M, will try to avoid using these

Thermally accelerated ageing of irradiated lasers

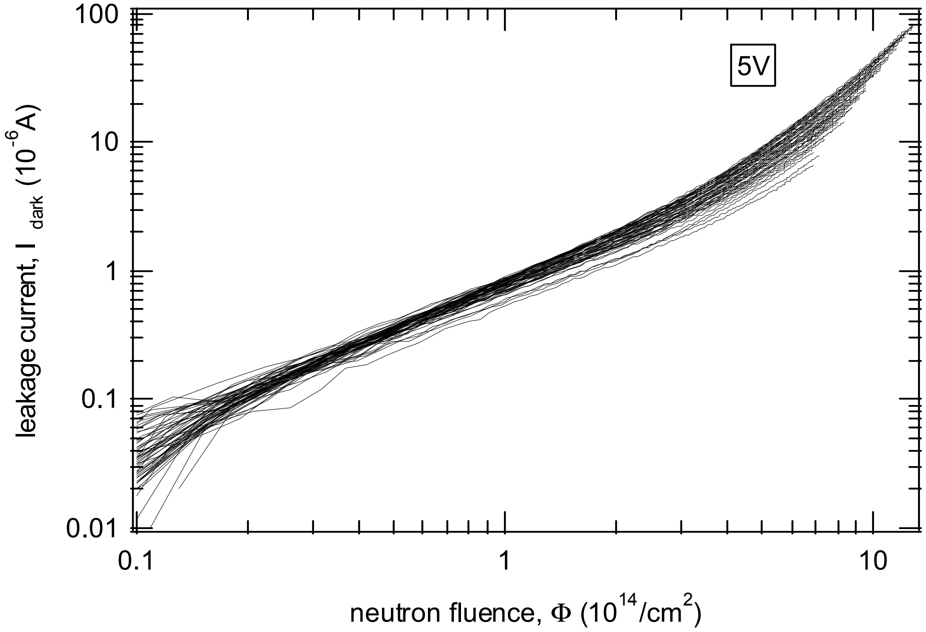


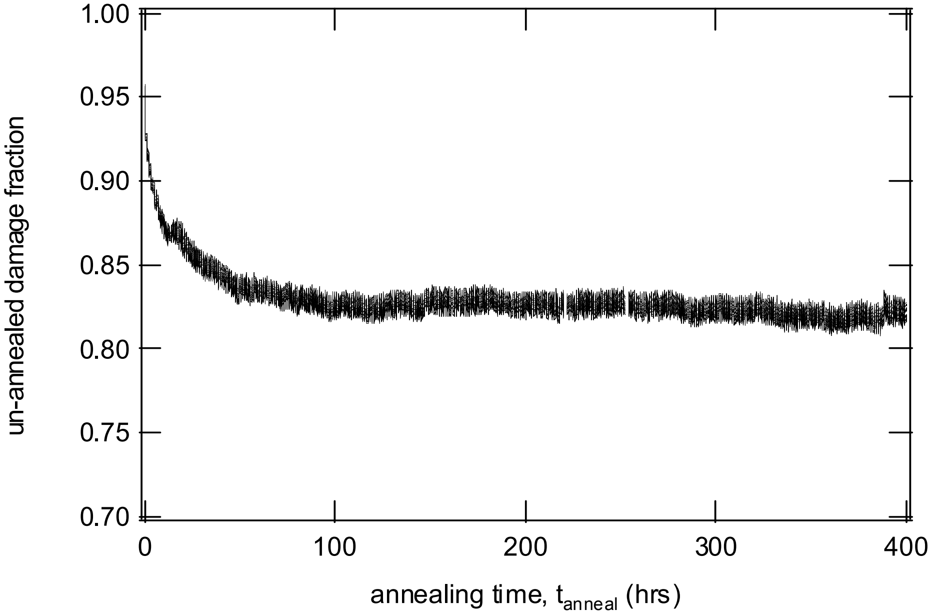
- Measurements made at 20ºC at periodic intervals
  - (no lasing at 80ºC)
- No wearout observable
- Only annealing
  - Perhaps this masks the wearout

Photodiode results



Radiation Damage in photodiodes – leakage currents

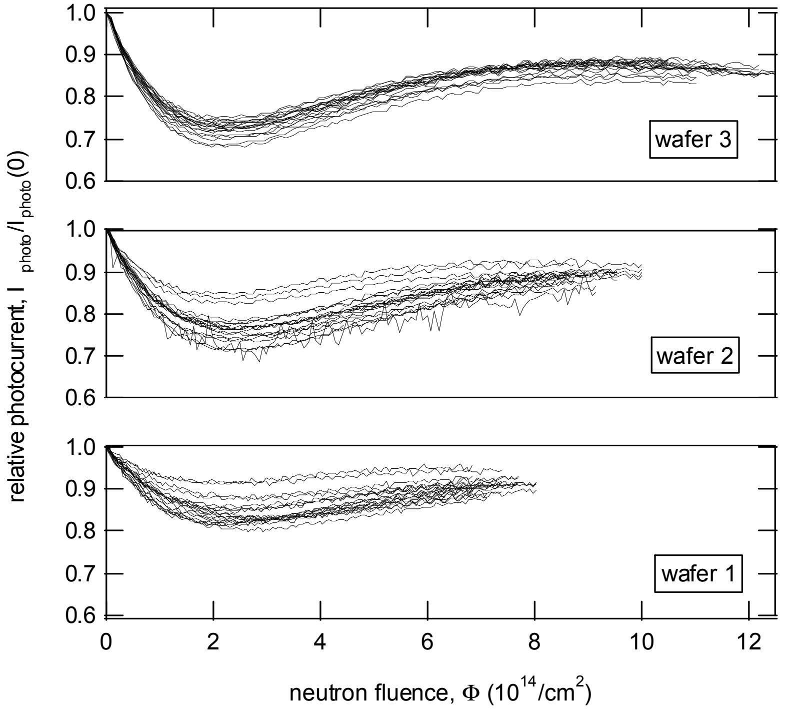


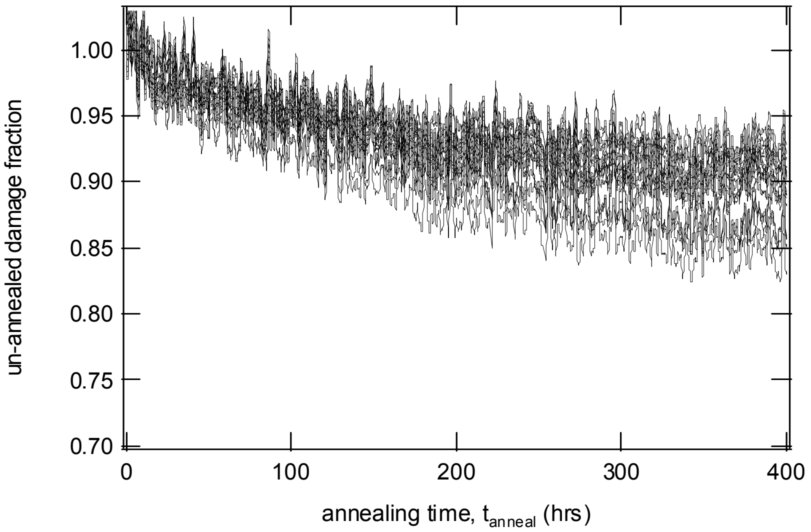


- Increase in leakage current after neutron irradiation
  - Similar level across all 60 devices
  - Expect maximum 10µA after 10 years at LHC ($2x10^{14}\pi/cm^2$ equivalent to $5x10^{14}n/cm^2$ at CRC)
    - Damage not a problem
    - dc optical levels generate greater currents in photodiode
  - Small amount of annealing just after irradiation

- [No damage from 100kGy gammas]

Radiation Damage in photodiodes – photocurrents

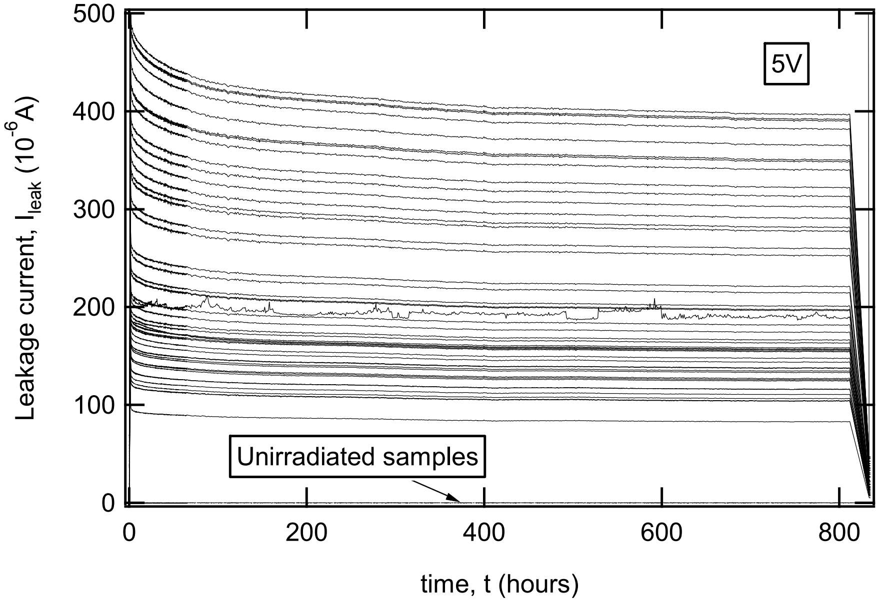


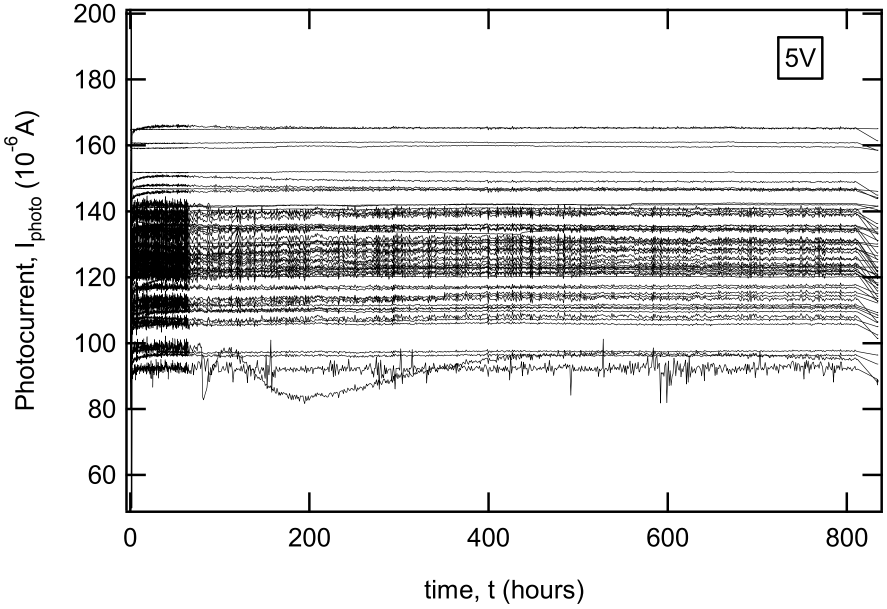


- Complicated evolution of photocurrent [responsivity] with fluence
  - Not understood but fairly consistent from device to device
  - No more than 32% loss over fluence range tested
  - Again, only small amount of annealing just after irradiation
    - Not same rate as for leakage current so probably different defects responsible for the two effects

- [Again, no damage from 100kGy gammas]

Thermally accelerated ageing of photodiodes





- No wearout degradation observed in any of the 60 devices
- Only annealing of leakage current (but not photocurrent)
- 800 hours at 80ºC corresponds to ~10^7 hours at –10ºC (CMS Tracker)
  - assuming E_a=1eV

Summary and Conclusions

- AVT procedure established as part of ongoing QA Programme
  - Aim to reject unsuitable parts before mass production
    - 390 Lasers tested out of 60000 from 13 wafers in 5 AVTs
    - 90 Photodiodes tested out of >4000 from 3 wafers in 1 AVT

- Radiation damage very well characterised, great statistics:
  - No damage from 100kGy gammas but significant damage from 5×10^{14}n/cm^2
  - Equivalent to worst case in CMS (first 10 years)
    - Lasers
      - Average 24mA increase of threshold current, 23% efficiency loss, significant annealing
      - Final damage in CMS will be limited to ~6mA threshold increase, 6% efficiency loss
    - Photodiodes
      - Increase of leakage current up to 10µA, and up to 30% signal loss expected in CMS
- Very little wearout degradation under thermally accelerated ageing
  - Lasers
    - Device lifetimes >10^6 hours under CMS conditions.
    - Two wafers are 10x less reliable than others, will try to avoid using them
  - Photodiodes
    - No wearout. Device lifetimes extraordinarily large.

- Program of tests started in 1996 almost finished!