Optical Links for Radiation Environments

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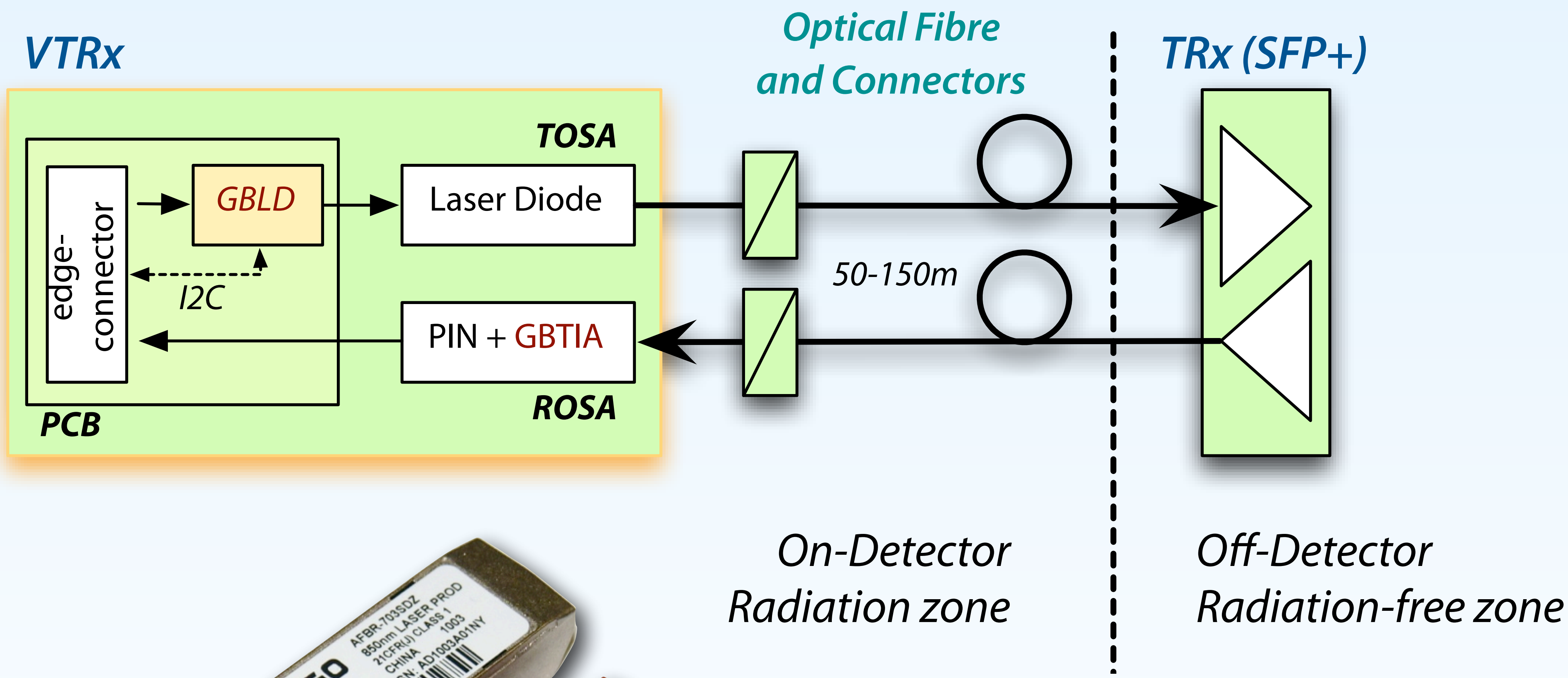
Outline

- Optical Link Systems reminder
- Radiation effects assessment methodology
- Radiation effects in optical link components & their impact on optical link systems
- Versatile Link + system for LHC phase 2 upgrades
- Future prospects

Optical Link Overview

- Typical High-Energy Physics (HEP) optical link



e.g. Versatile Link

Will the link work? (Power budget)

- Standard optical link without radiation

	Std. Link
Min. Tx OMA	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm
Power budget	5.9 dB
Fiber attenuation	0.6 dB
Insertion loss	1.5 dB
Link penalties	1.0 dB
Margin	**2.8 dB**

Will the link work? (Power budget)

- HEP optical link with radiation

	HEP Link
Min. Tx OMA	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm
Power budget	5.9 dB
Fiber attenuation	0.6 dB
Insertion loss	1.5 dB
Link penalties	1.0 dB
Tx radiation penalty	?
Rx radiation penalty	?
Fiber radiation penalty	?
Margin	**< 2.8 dB**

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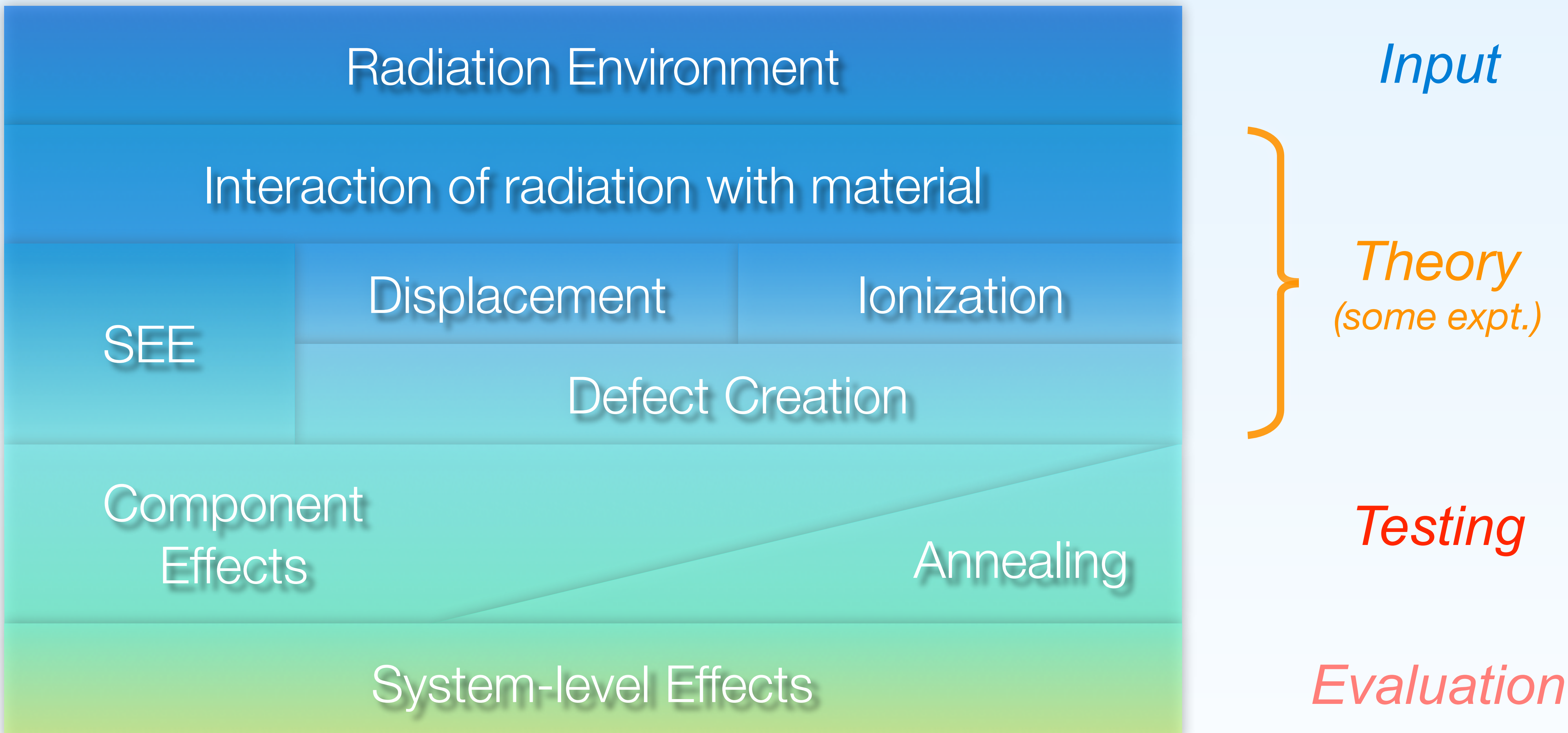
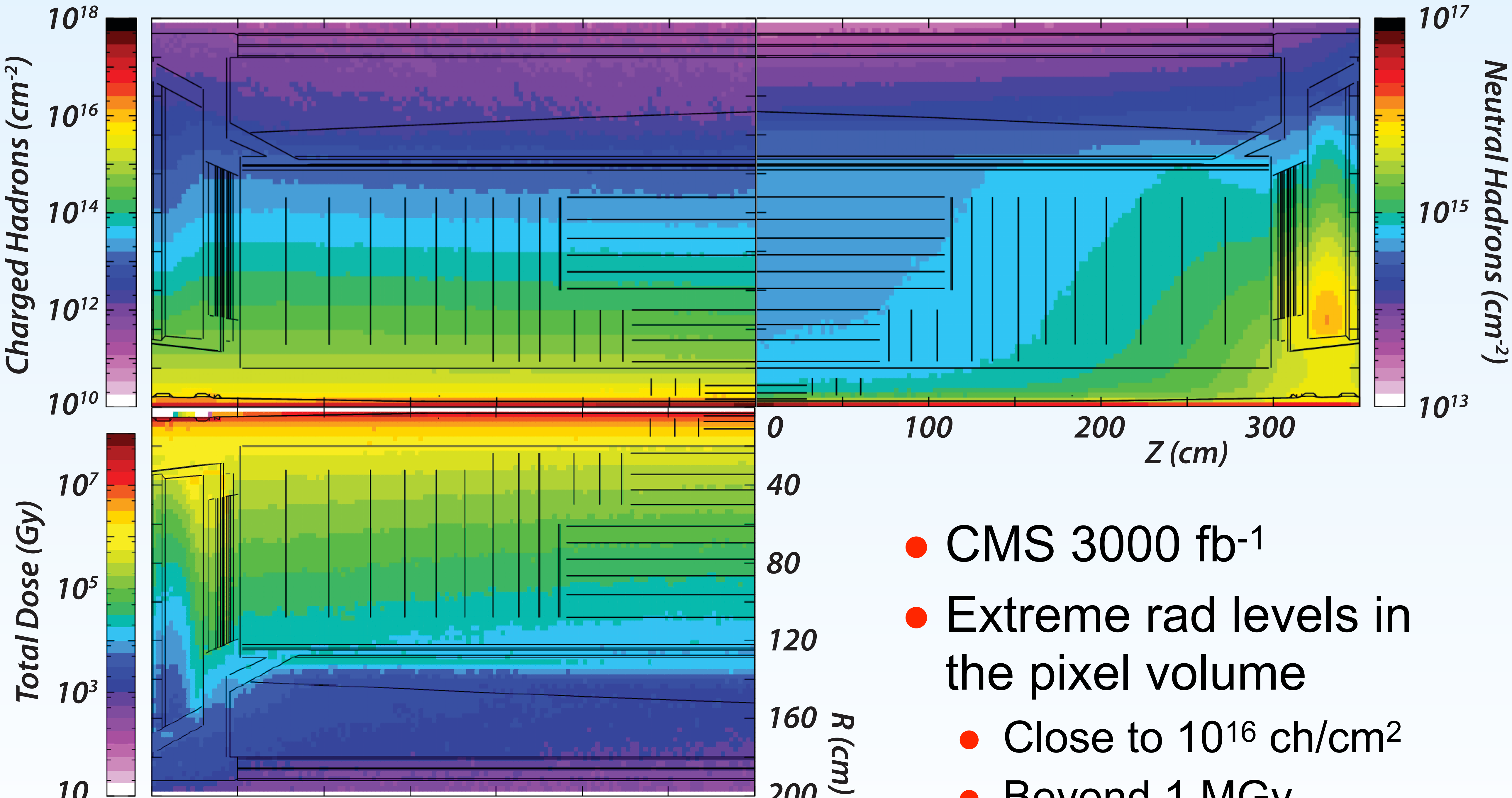
Assessment of radiation effects

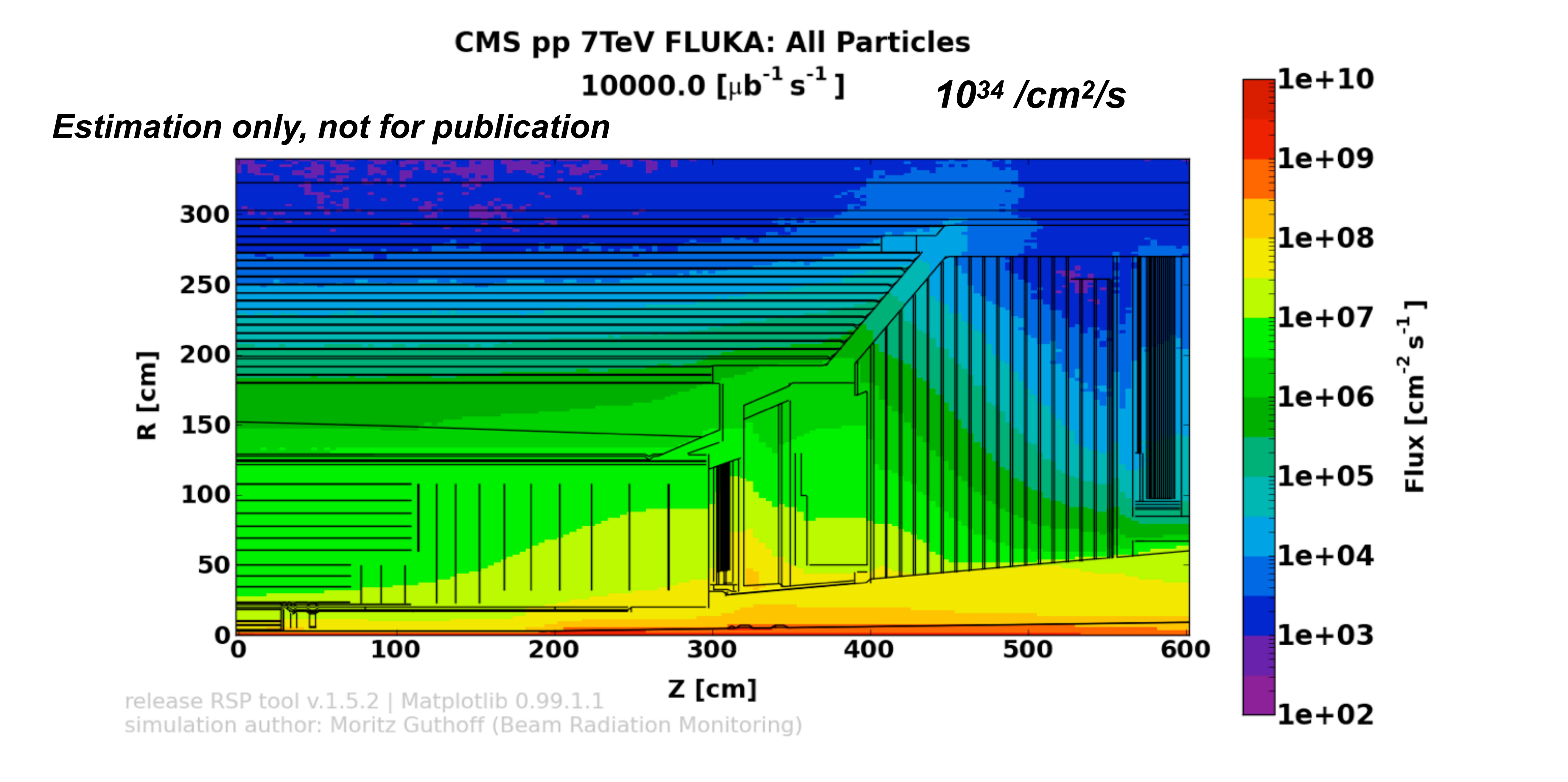


Radiation levels for CMS at HL-LHC



- CMS 3000 fb^{-1}
- Extreme rad levels in the pixel volume
  - Close to 10^{16} ch/cm^2
  - Beyond 1 MGy
  - Several 10^{15} n/cm^2

In terms of flux



- Tracker: 10^8 /cm²/s
- Calorimeter: 10^6 /cm²/s

HL-LHC → x10

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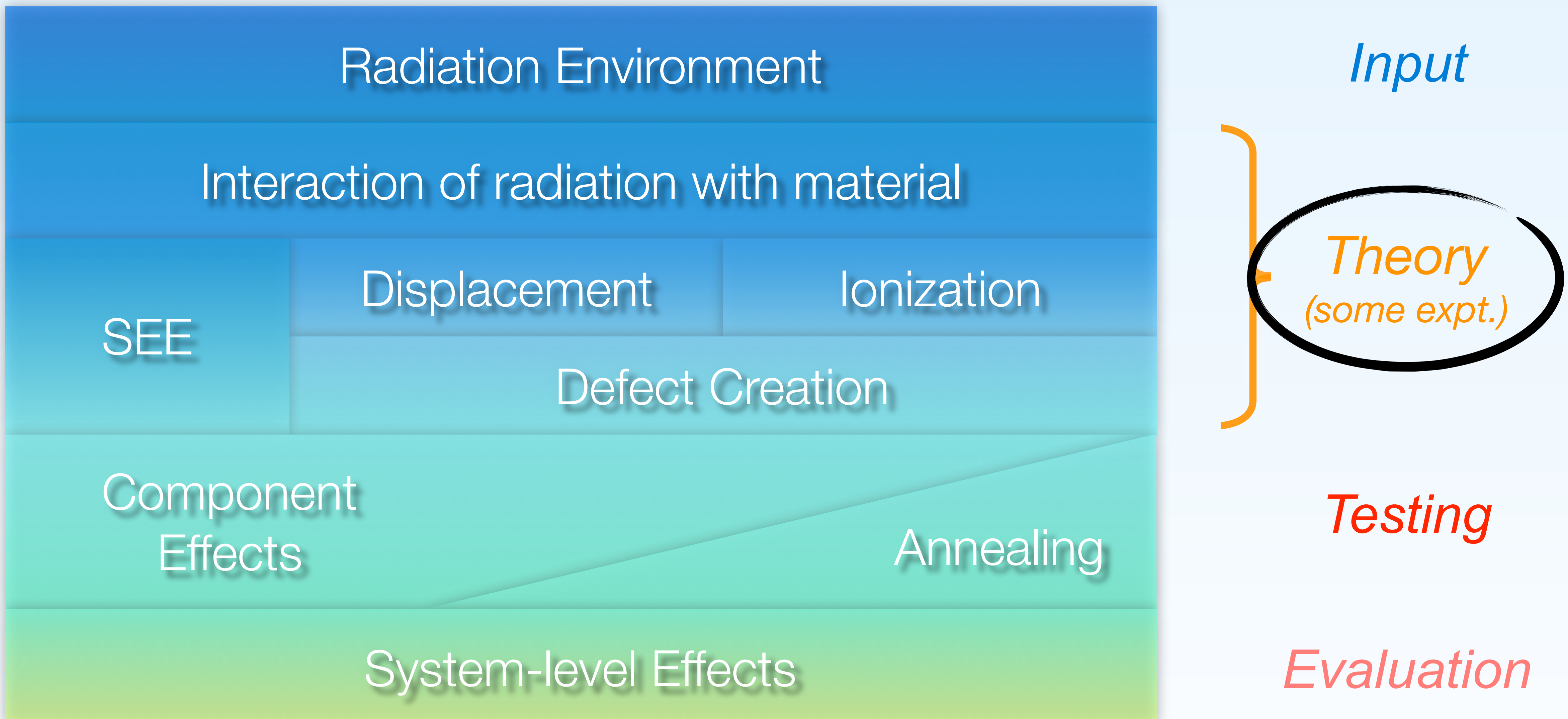
Assessment of radiation effects



Radiation Effects Summary

Device	Displacement	Total Dose	SEU
Transmitters *LEDs* *Lasers*	🔴	🟢	🟢
Receivers *P-I-N* *APD* *CCD*	🔴	🟢	🔵
Switches *Optocouplers*	🔴	🟢	🔵
Passives *Fibres* *Couplers* *Connectors*	🟢	🔴	🟢

🔴 Danger!! 🔵 Beware 🟢 Probably OK!

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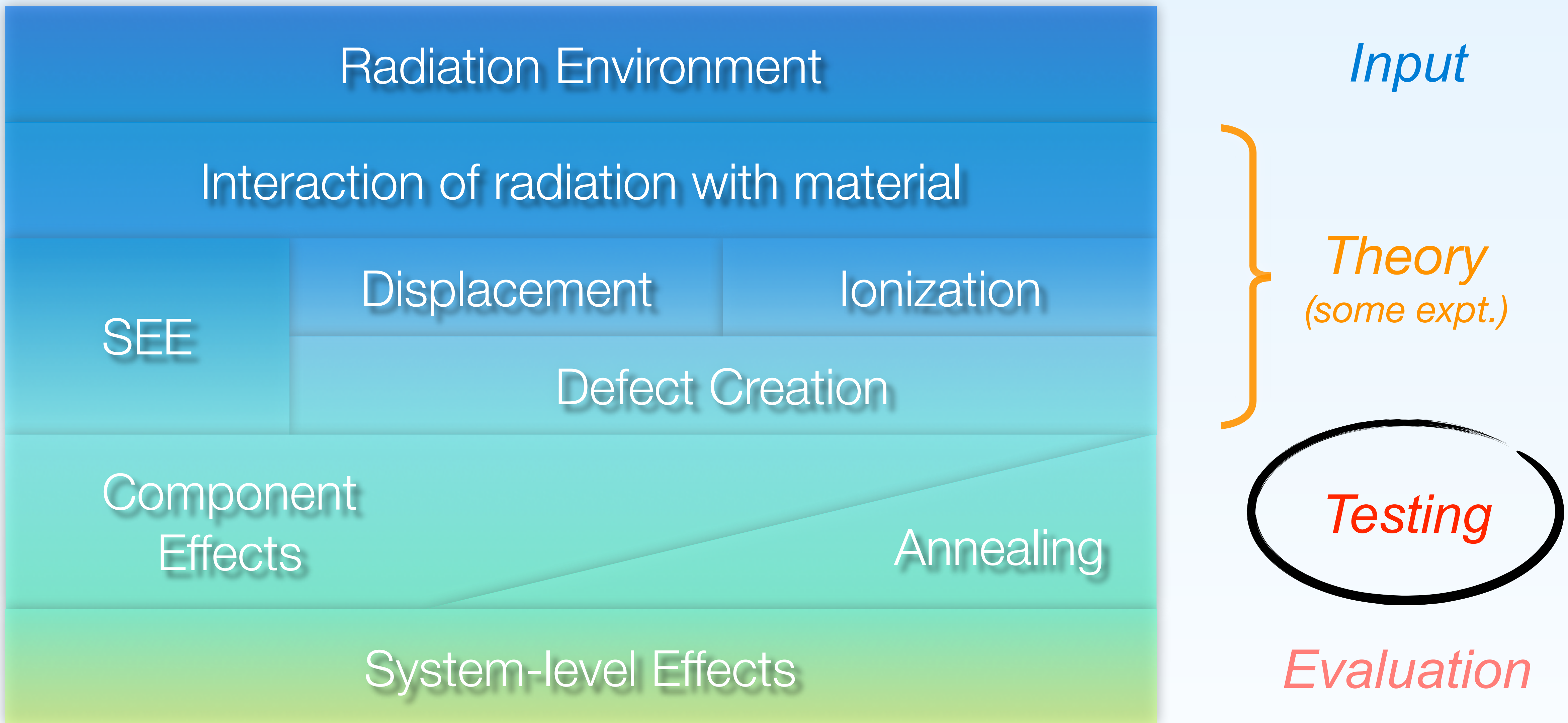
Radiation Effects Summary

Device	Displacement	Total Dose	SEU
Transmitters *LEDs* *Lasers*	Danger!!	Probably OK!	Probably OK!
Receivers *P-I-N* *APD* *CCD*	Danger!!	Probably OK!	Beware
Switches *Optocouplers*	Danger!!	Probably OK!	Beware
Passives *Fibres* *Couplers* *Connectors*	Probably OK!	Danger!!	Probably OK!

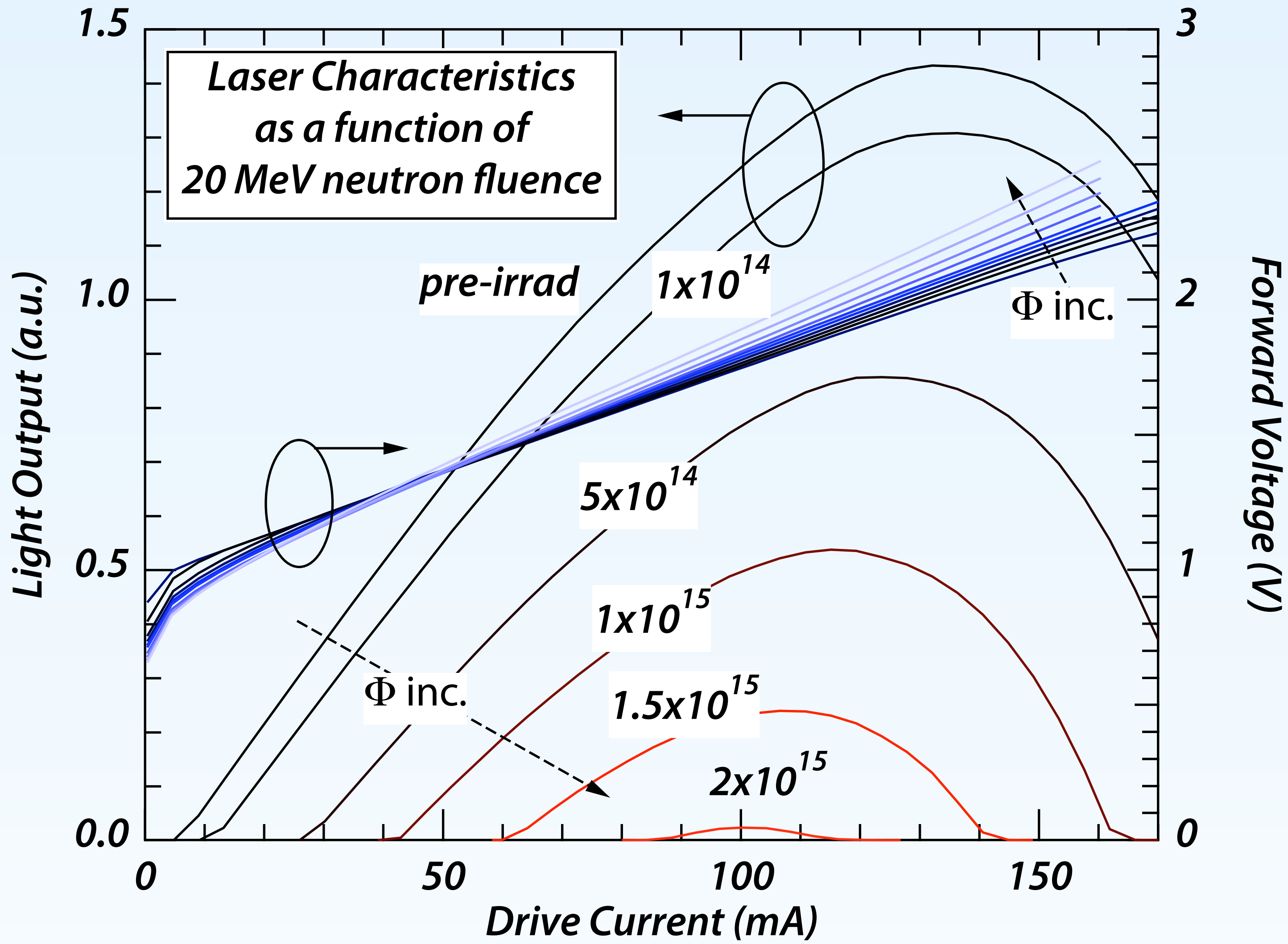
Danger!! Beware Probably OK!

In-situ testing highly desirable

Assessment of radiation effects



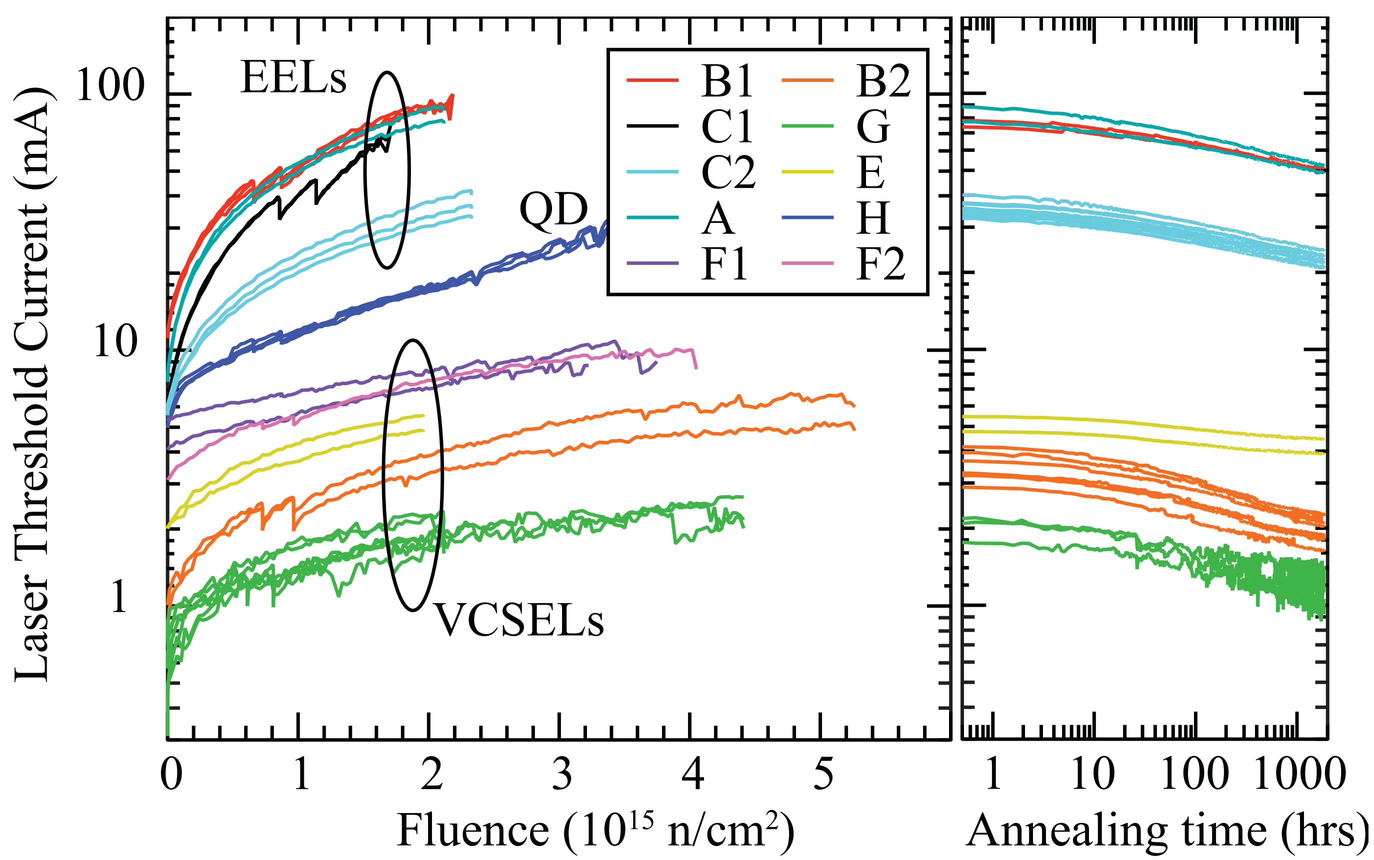
Typical behaviour of Laser Diodes

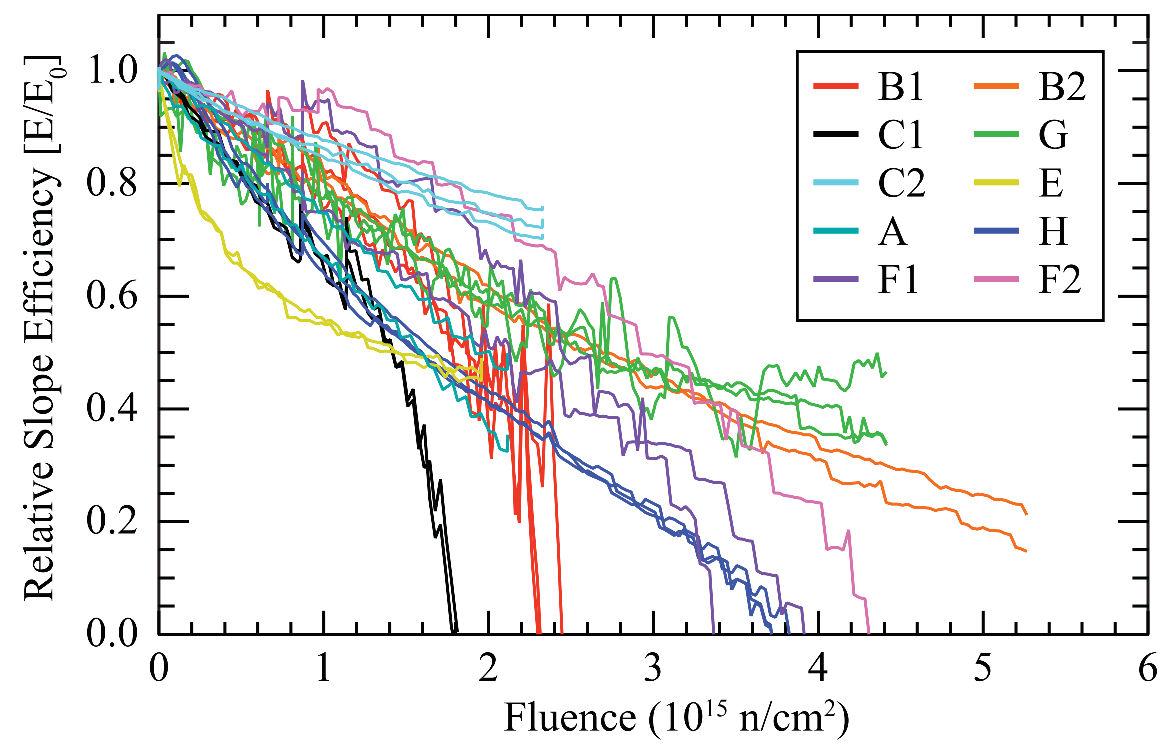


- As radiation level increases, defects are introduced into the material that decrease carrier lifetime
  - Observe increased laser threshold current & reduced efficiency

Laser device testing

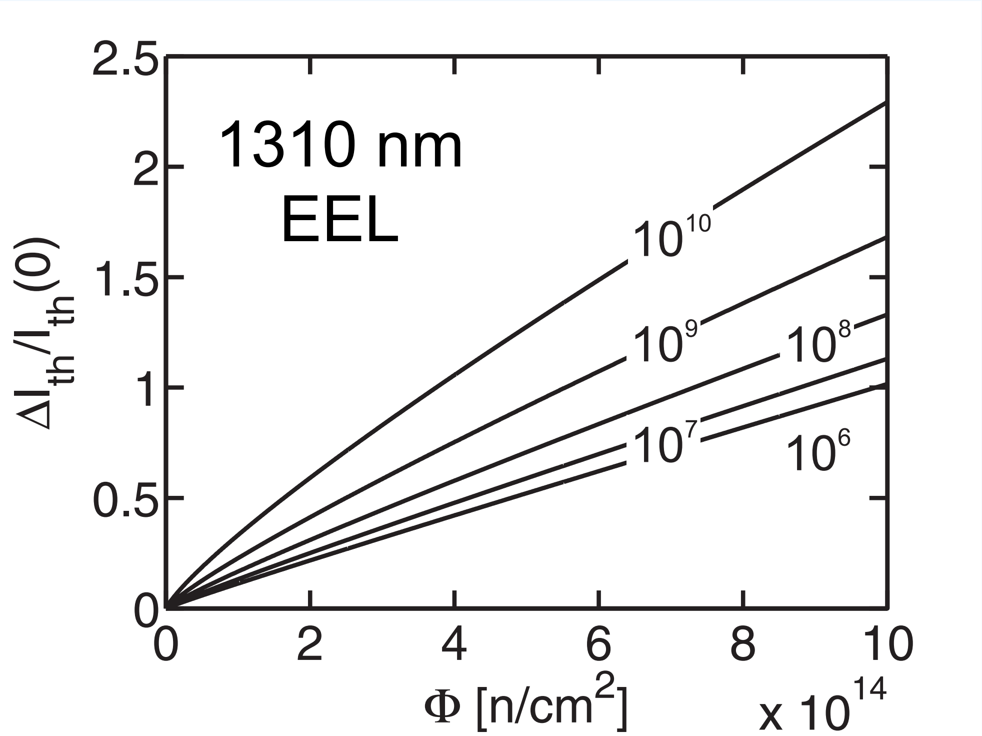
- Irradiation of large variety of devices over several tests
  - Louvain la Neuve (B) 20 MeV neutron beam (two tests)
  - PSI 190 MeV pion beam for cross-calibration (2-3x more damaging)
- First tests to narrow-down range of candidates
  - Eventually need to qualify chosen candidates at wafer level

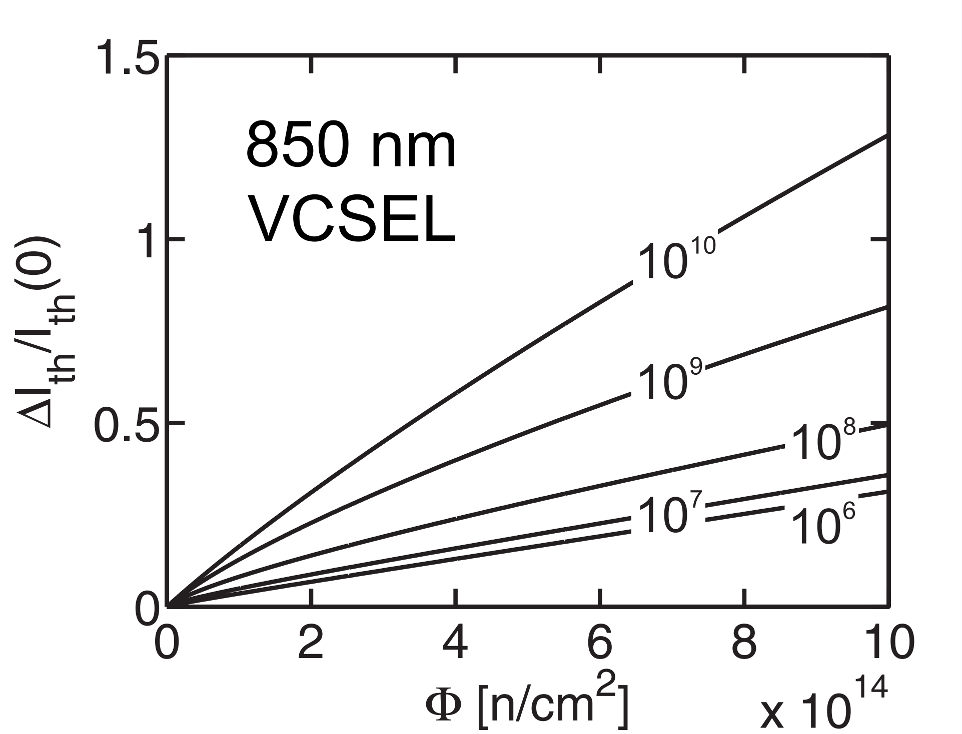




Laser damage modelling

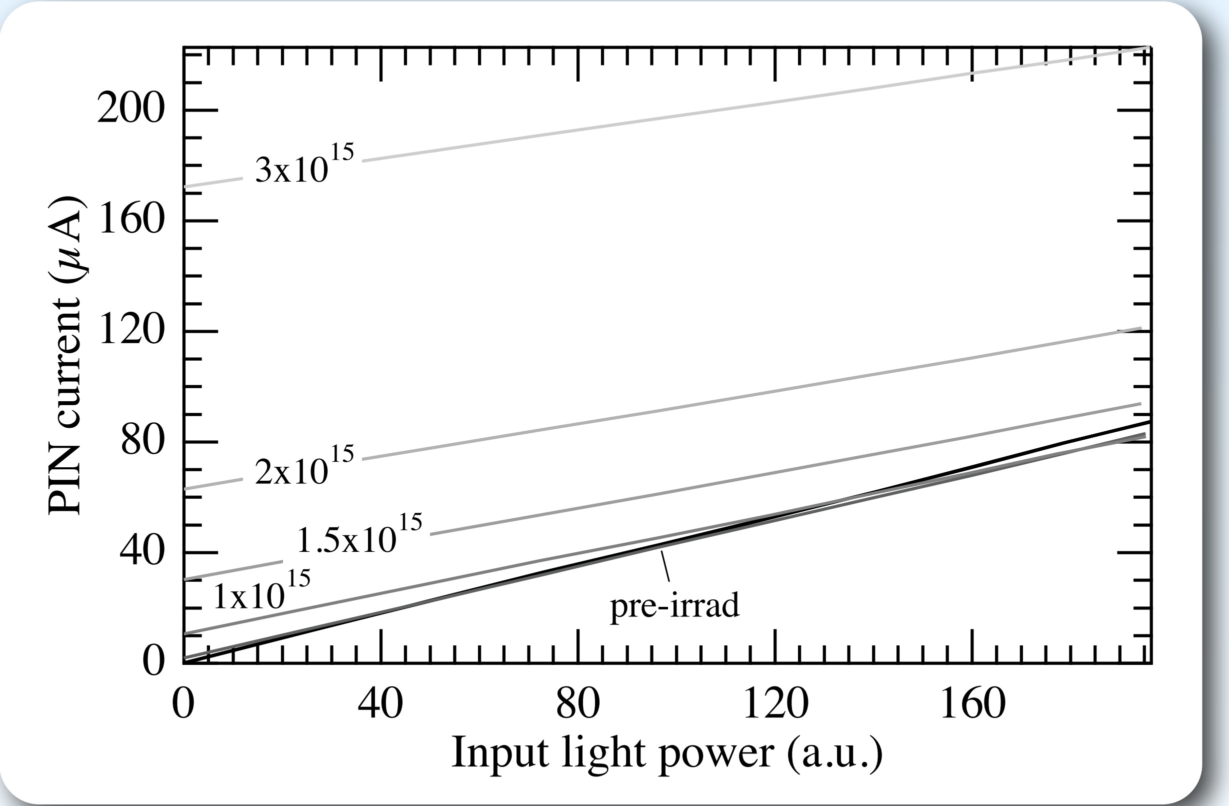
- In-situ measurements and recording of annealing periods have allowed modelling of degradation
  - Laser model based on rate-equations with additional terms for defect introduction
- Allows extrapolation to lower fluxes
  - Predict factor of 2-3 reduction in damage vs. accelerated irrad test

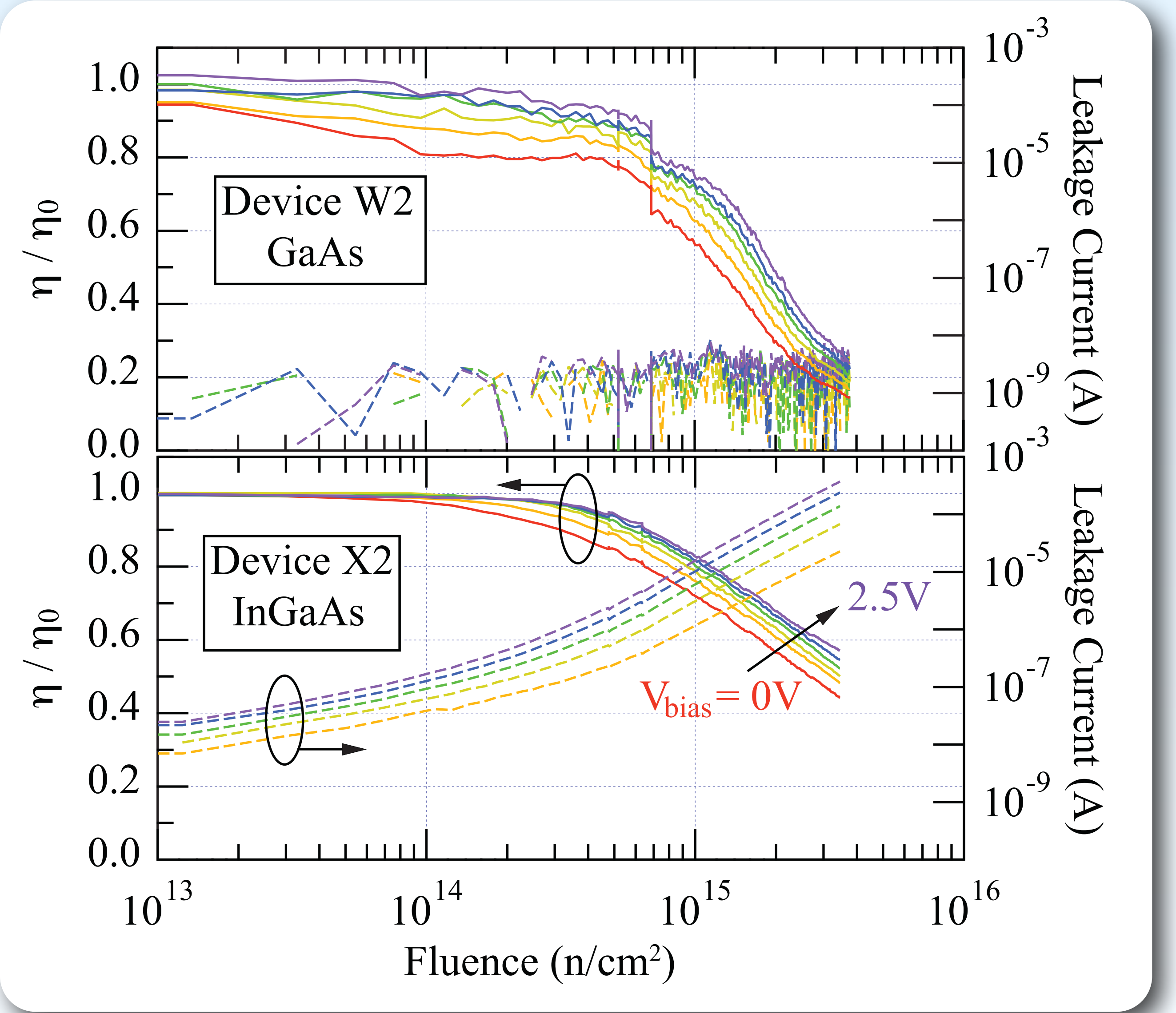




http://cds.cern.ch/record/1596006/files/CERN-THESIS-2013-115.pdf

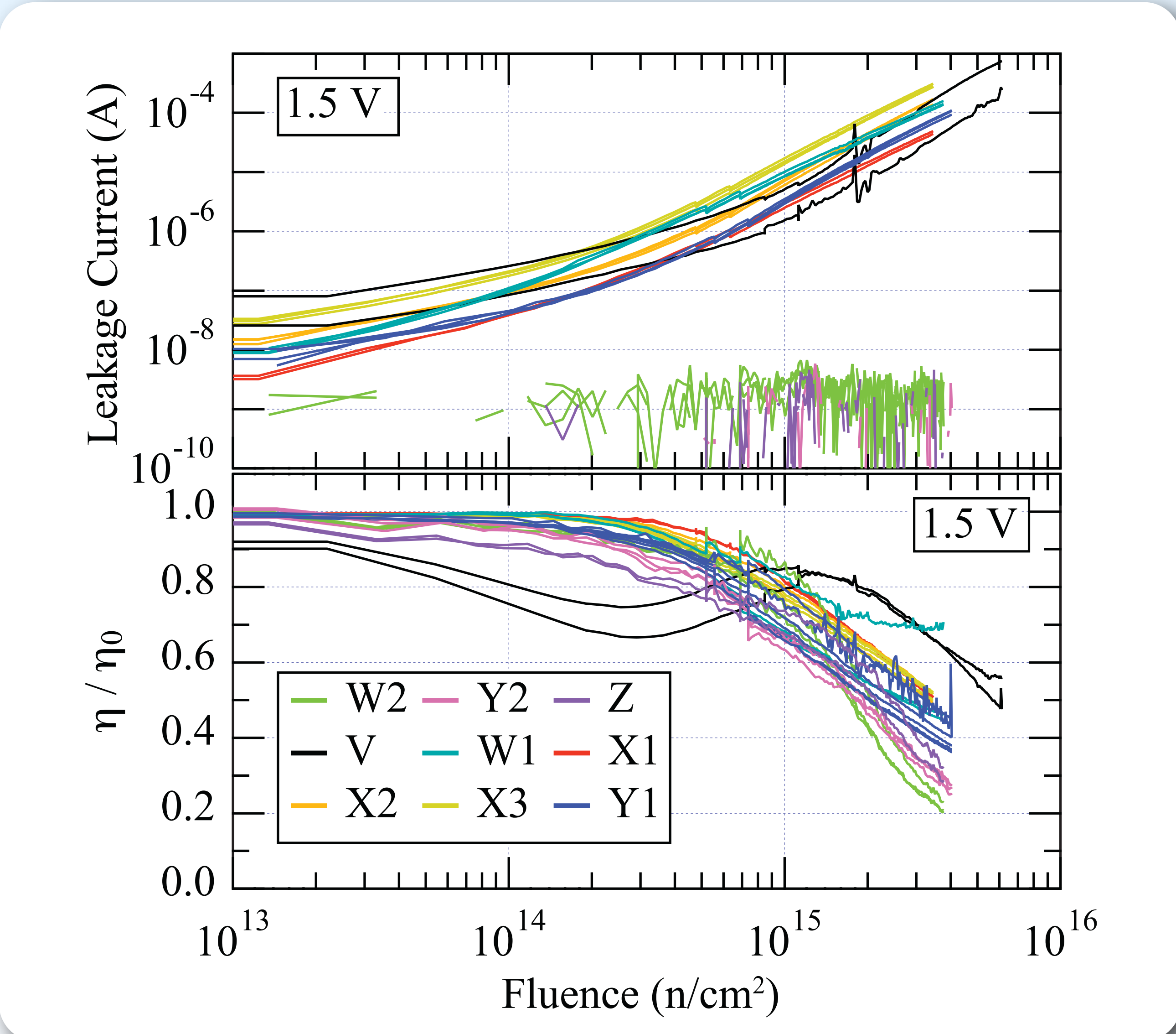
Photodiode testing





- Defects cause compensation of intrinsic region of p-i-n and consequently loss of detection efficiency
- Also leakage increase in InGaAs

Photodiode device survey

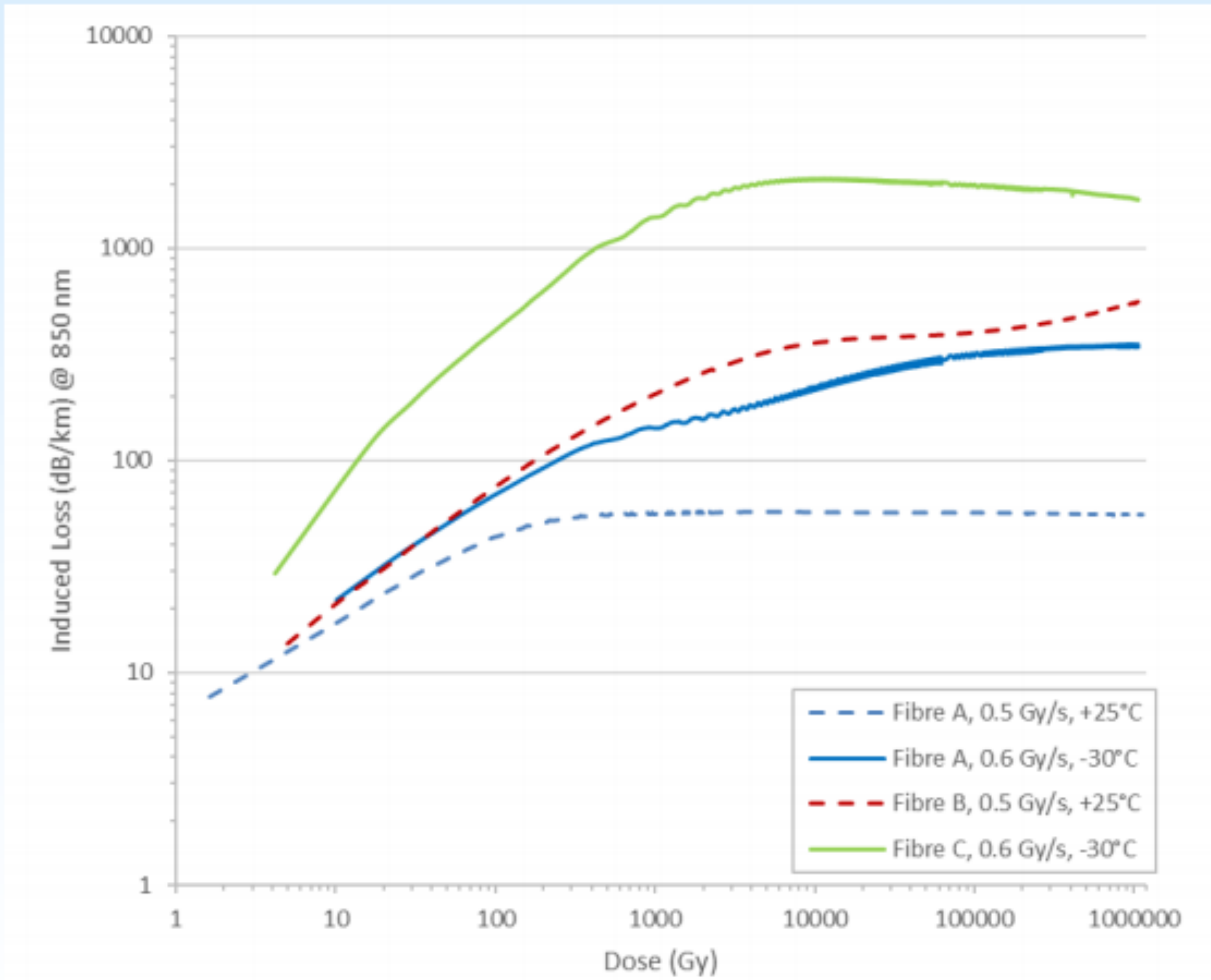


Pions 2.2x more damaging

- Similar response from all vendors of modern high-speed photodiode that we have tested
  - InGaAs devices survive to higher fluences in terms of responsivity
  - GaAs devices show no significant increase in leakage current
- As there is basically no annealing in photodiodes the damage observed at the target fluence is the one that counts

Fibre radiation resistance

- Radiation Induced Attenuation is rate and temperature dependent
  - Must be prudent with choice of fiber
  - Qualification tests must be performed in all conditions
- Commercial Rad-Hard fibre (fibre A) is not OM3
  - Can only be used for short lengths



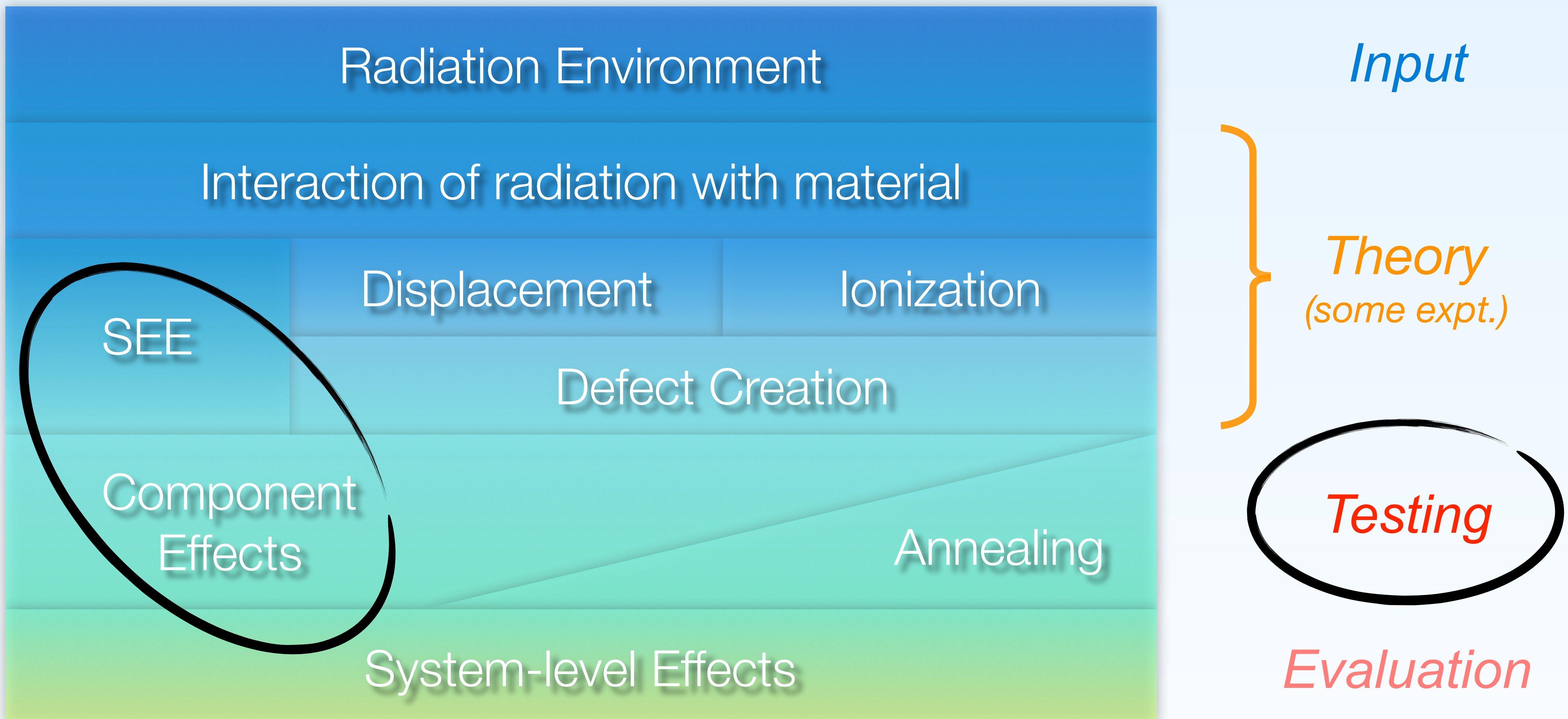
Optical fibre specification:

		Fibre A	Fibre B	Fibre C
Bandwidth		OM2	OM3	OM3
Attenuation (w/o radiation)	850 nm 1300 nm	≤ 2.5 dB/km ≤ 0.5 dB/km	≤ 2.4 dB/km ≤ 0.6 dB/km	≤ 2.3 dB/km ≤ 0.6 dB/km
Fibre profile		Graded Index	Graded Index	Graded Index
Core dopant		Fluorine	Germanium	Germanium
Cladding dopant		Fluorine	Fluorine	Fluorine

Radiation Induced Attenuation (dB/km):

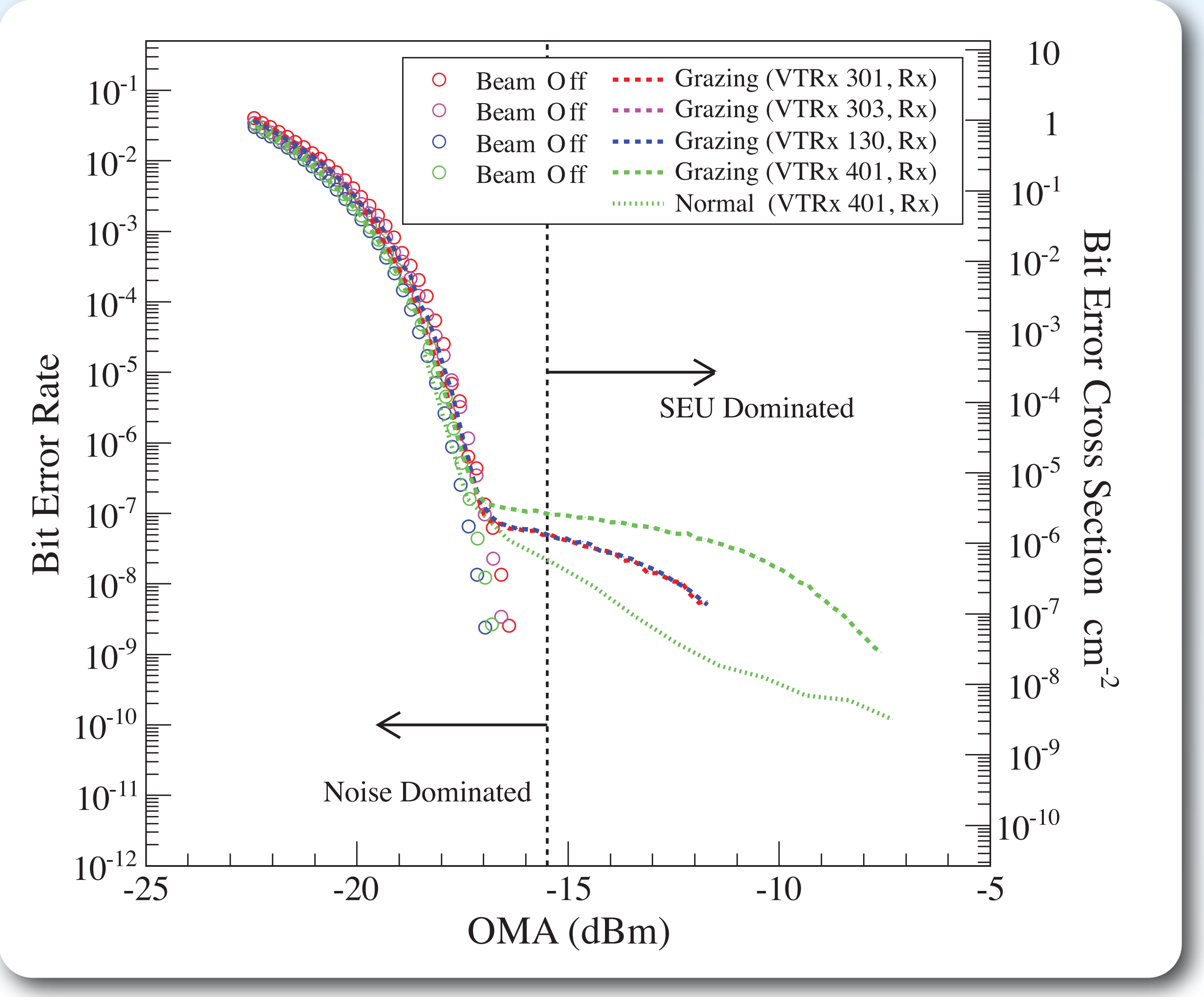
Dose	Fibre A (+25°C)	Fibre A (-30°C)	Fibre B (+25°C)	Fibre C (-30°C)
1 kGy	56	142	205	1250
10 kGy	57	220	360	2050
100 kGy	57	310	405	2000
1 Mgy	56	350	555	1500

Assessment of radiation effects



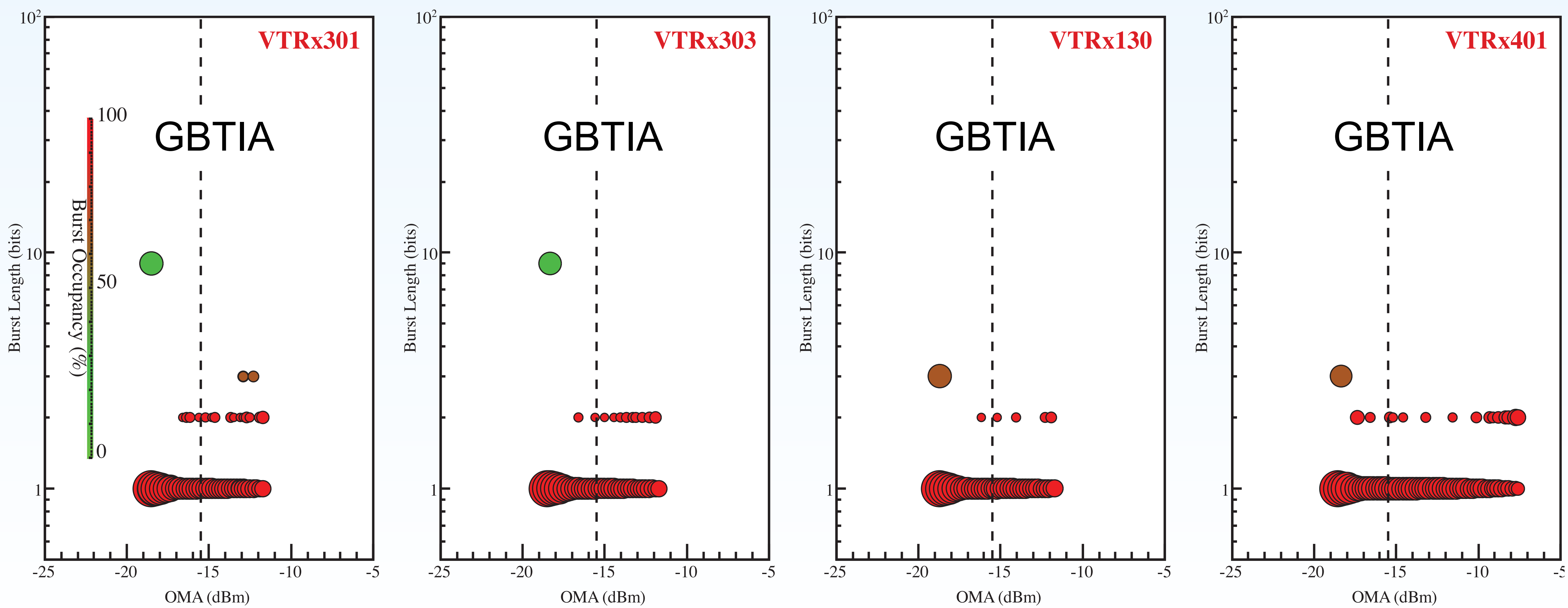
Single-event upsets

- Photodiodes are good particle detectors
  - Passage of particles can create data-like signals

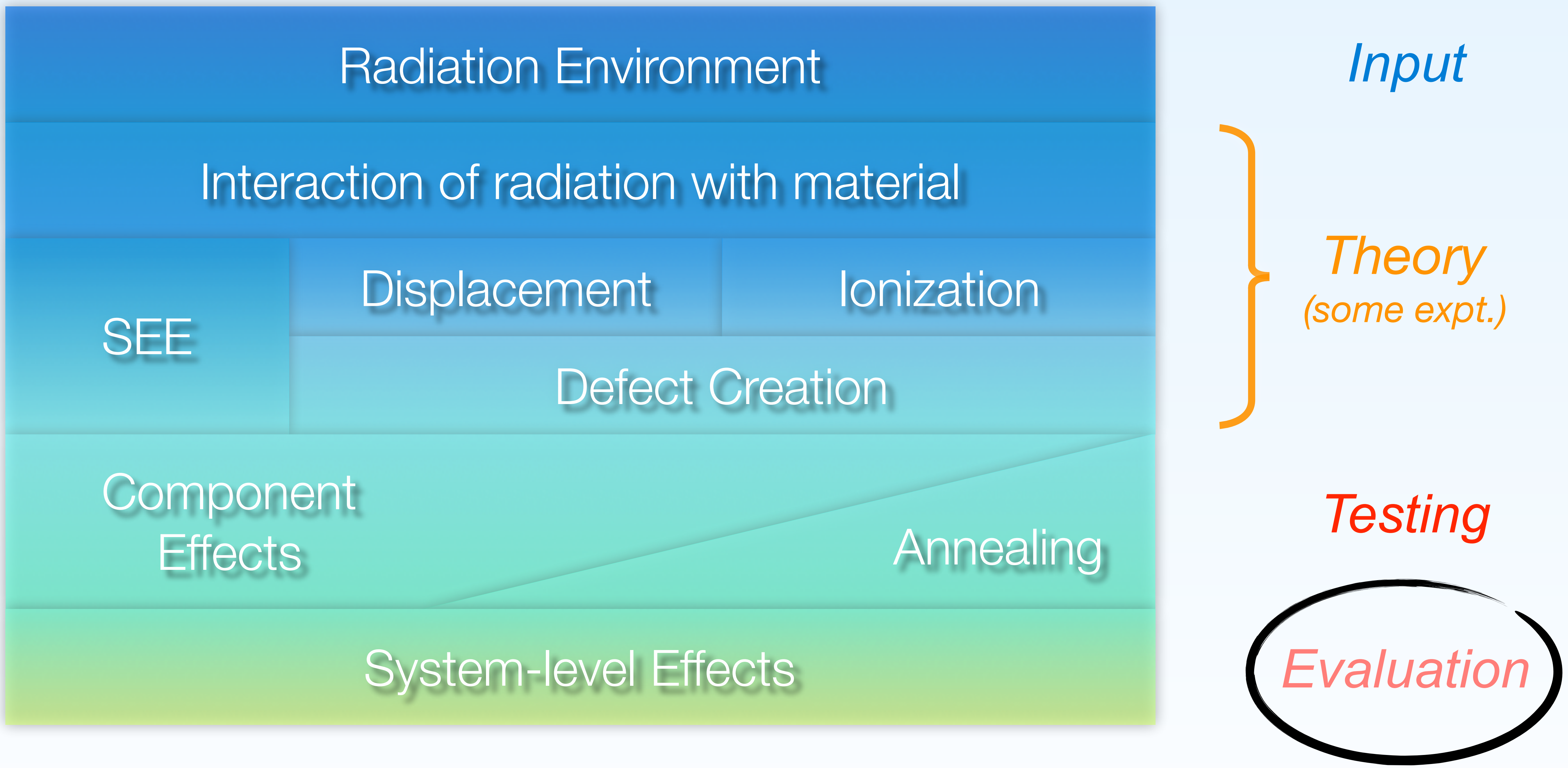


SEU statistics

- Before the work carried out in the radiation qualification of the Versatile Link components, only single-bit errors were considered in the literature
  - Multi-bit errors depend critically on the behaviour of the TIA circuit response to overload
  - One-to-Zero errors observed as well as the expected Zero-to-One



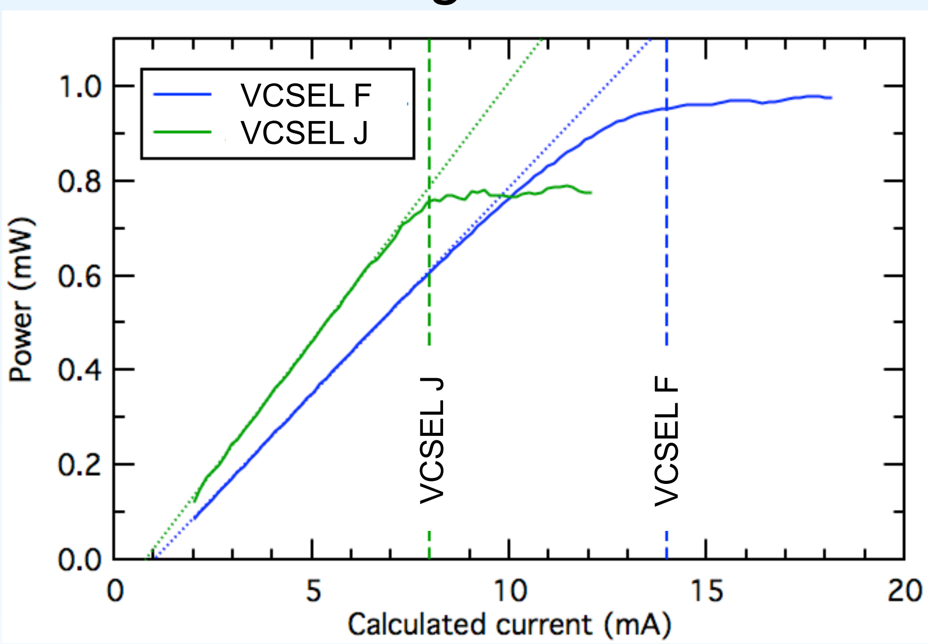
Assessment of radiation effects



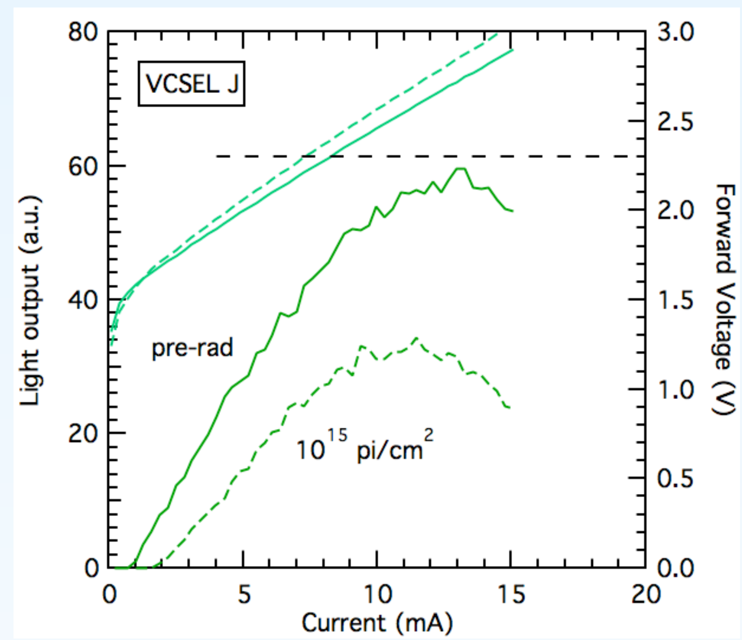
VCSEL voltage headroom

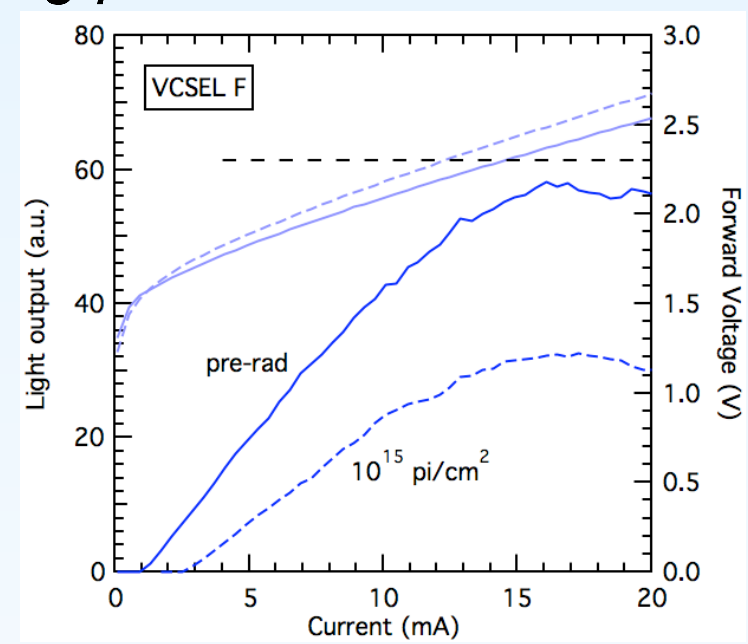
- The concern is that already pre-irradiation we hit the headroom limit of the forward voltage with some VCSELs

LI-curve using GBLD v4 bias

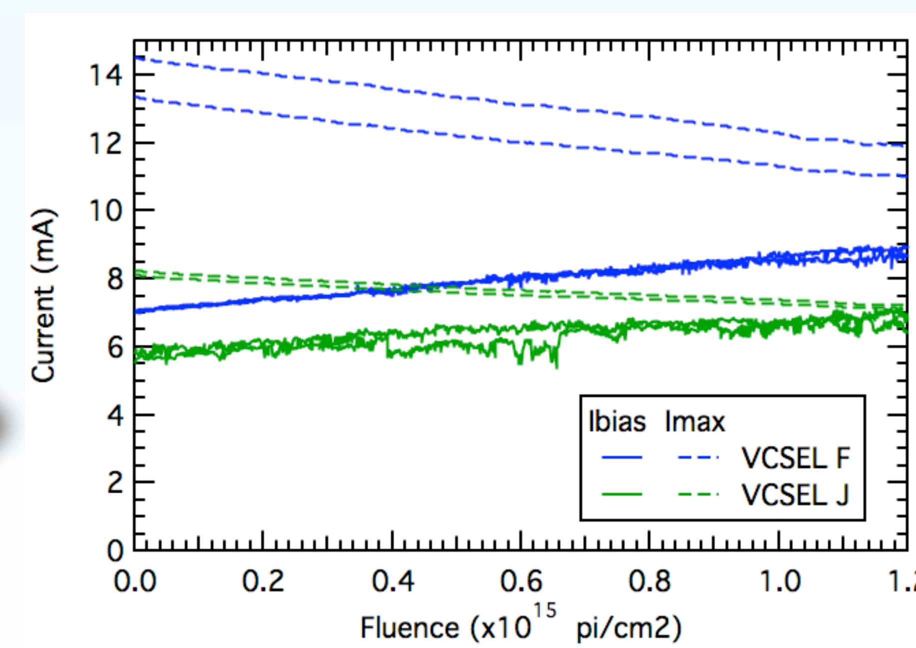


Data taken during pion irradiation



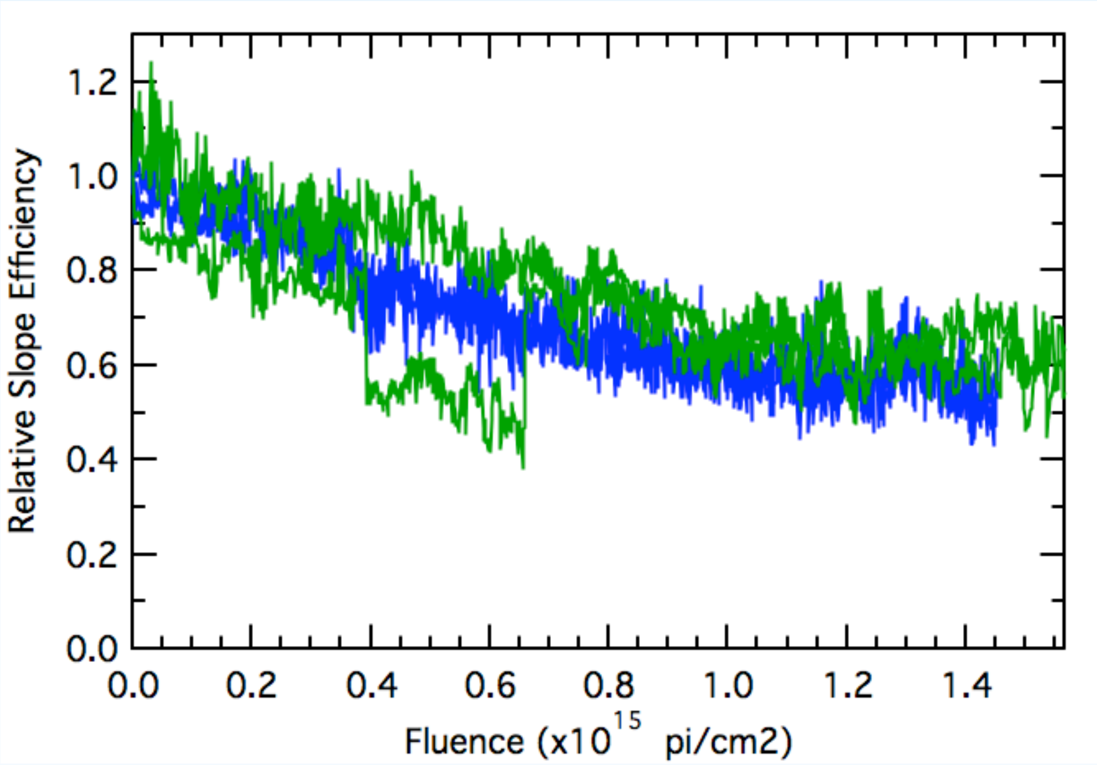


Solid & Dashed lines remain separate
Headroom exists for both tested types



VCSEL efficiency drop

- Does the drop in efficiency put the output OMA below threshold?



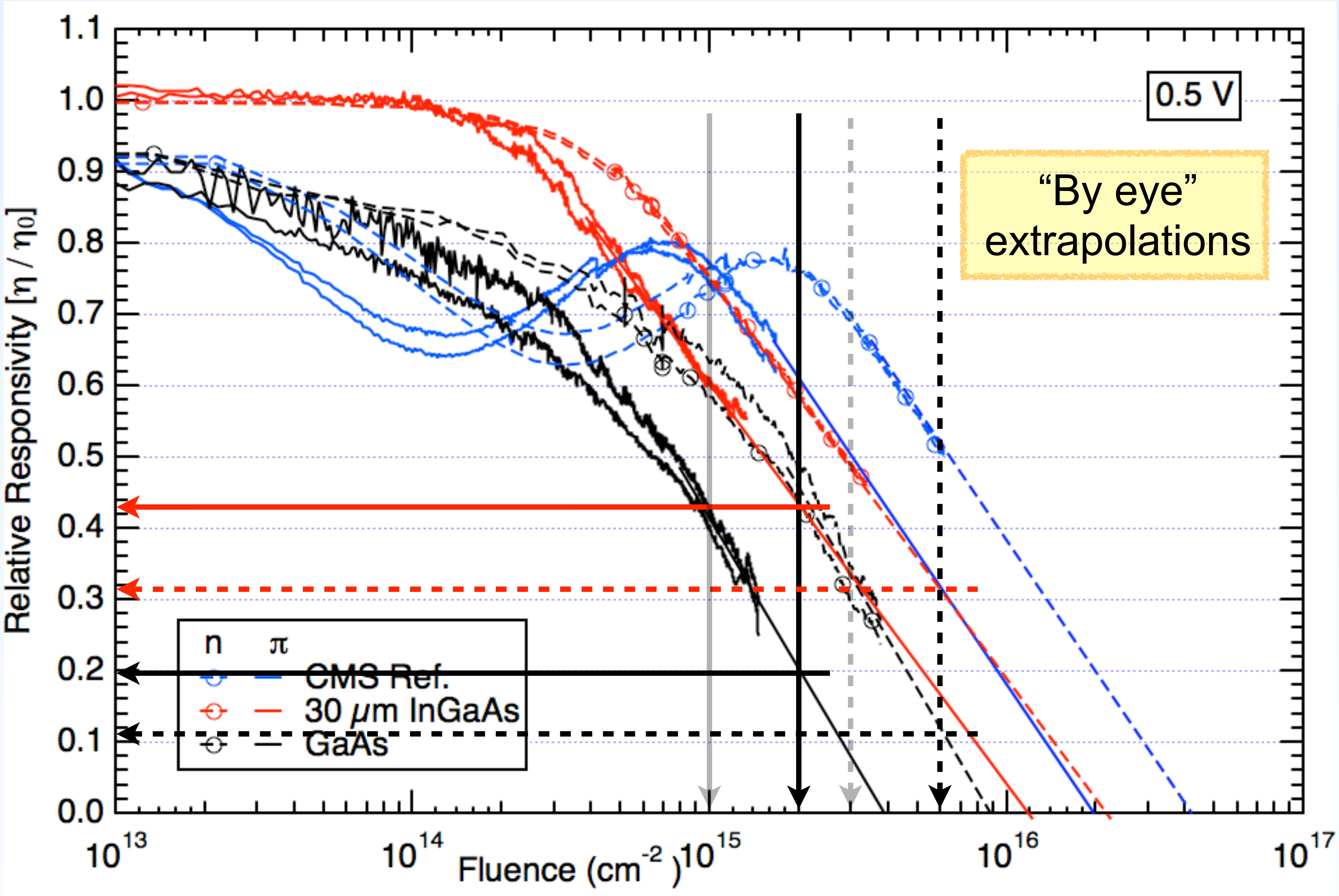
- Minimum Slope efficiency spec is 0.06 W/A
  - Min OMA is 300 µW, require 5 mA modulation current out of 12 mA available from GBLD
  - 50% drop in slope efficiency can be fully compensated by increase in modulation current

Radiation penalties in Link Budget

Calorimeter Grade

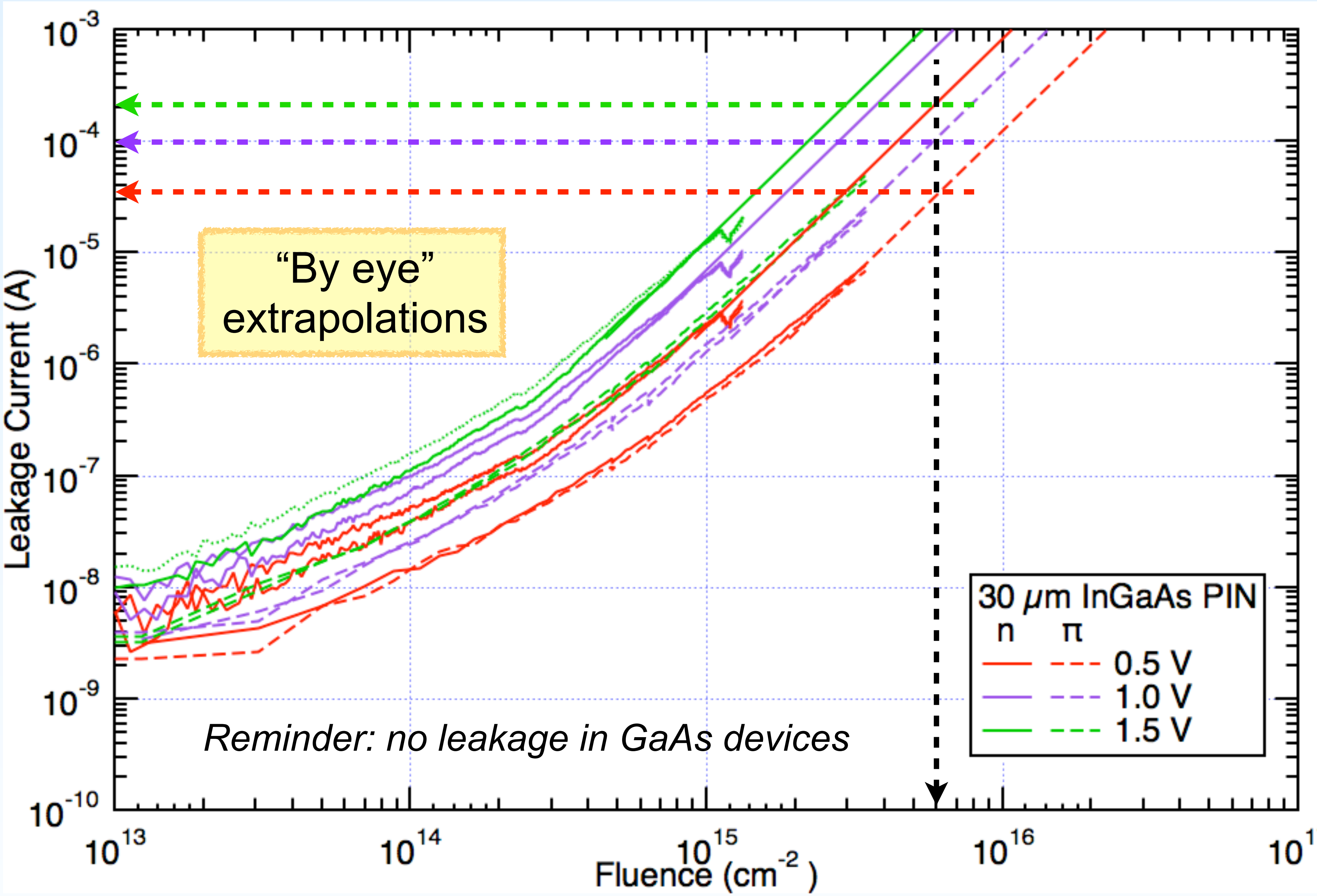
	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-3.2 dBm	-5.2 dBm	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	9.9 dB	7.4 dB	10.2 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-		-	
Fiber radiation penalty	0.1 dB	0.1 dB	0 dB	0 dB
Margin				

Impact of PD Responsivity loss



- Worst case at 6×10^{15} cm^{-2} neutron fluence
  - InGaAs penalty: -5.1 dB
  - GaAs penalty: -9.6 dB

Impact of PD Leakage Current



- Worst case at 6×10^{15} cm^{-2} neutron fluence
  - Around 100 µA leakage for 1.0V reverse bias (conservative GBTIA value)
    - 0.3 dB penalty from GBTIA DC current removal circuit

Radiation penalties in Link Budget

Calorimeter Grade

	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-3.2 dBm	-5.2 dBm	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	9.9 dB	7.4 dB	10.2 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	2.5 dB	-	2.5 dB
Fiber radiation penalty	0.1 dB	0.1 dB	0 dB	0 dB
Margin	**2.7 dB**	**4.2 dB**	**3.8 dB**	**4.1 dB**

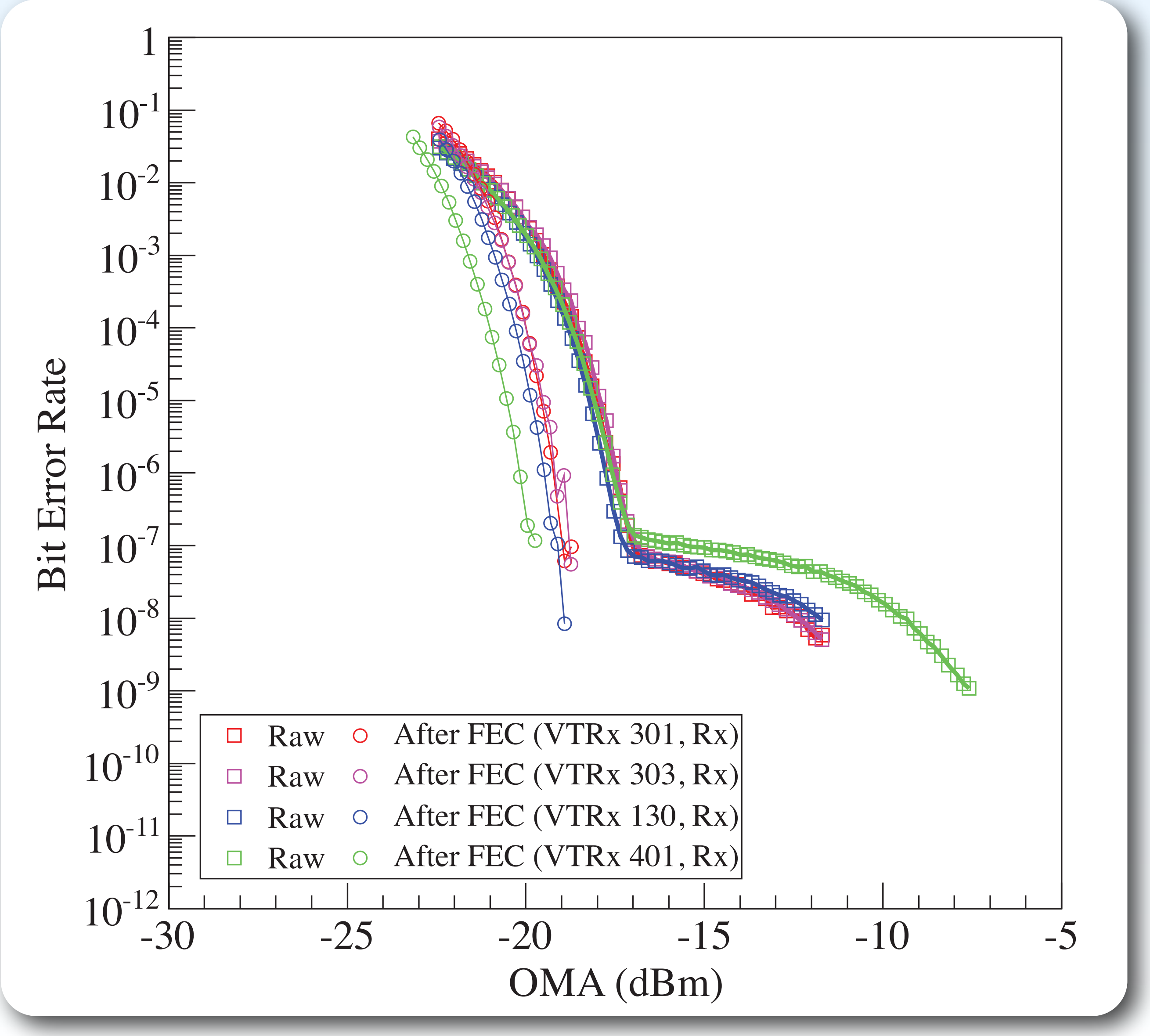
Radiation penalties in Link Budget

Tracker Grade

	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-1.6 dBm	-5.2 dBm	-3.6 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	11.5 dB	7.4 dB	11.8 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	5.4 dB	-	5.4 dB
Fiber radiation penalty	1.0 dB	1.0 dB	1.0 dB	1.0 dB
Margin	**1.8 dB**	**2.0 dB**	**2.8 dB**	**1.8 dB**

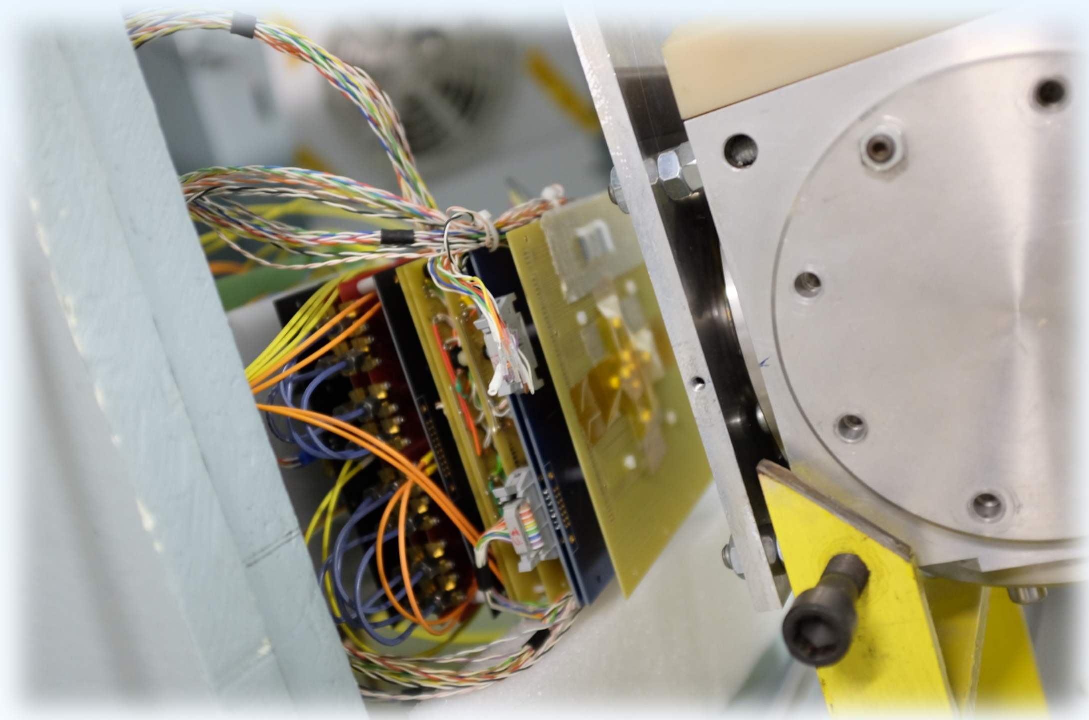
SEU mitigation with GBT protocol

- SEUs in the photodiode are unavoidable
  - GBT implements an interleaved Reed-Solomon Forward Error Correction (FEC) scheme to mitigate the induced errors

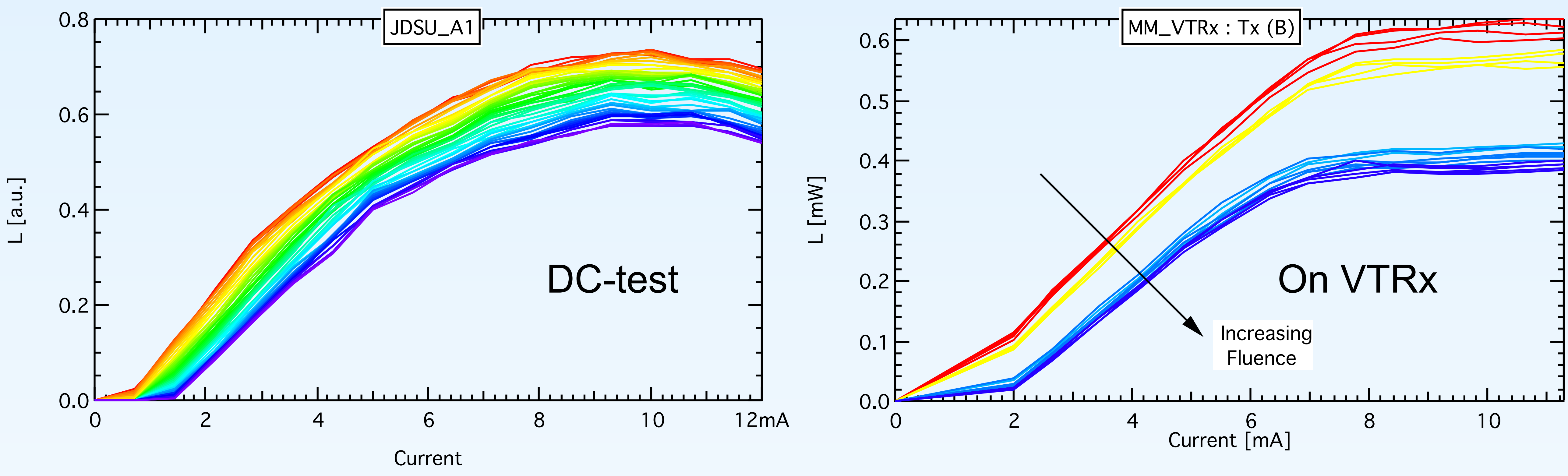


Final validation: VTRx in n-beam

- Final prototype VTRx (SM & MM) exposed to neutron beam at UC Louvain cyclotron facility in Nov. 2013
  - Complex test
  - VTRx in addition to lasers/pins
- Direct comparison between devices irradiated with DC measurements and AC measurements on VTRx
- Results show devices on VTRx behave as expected from static testing



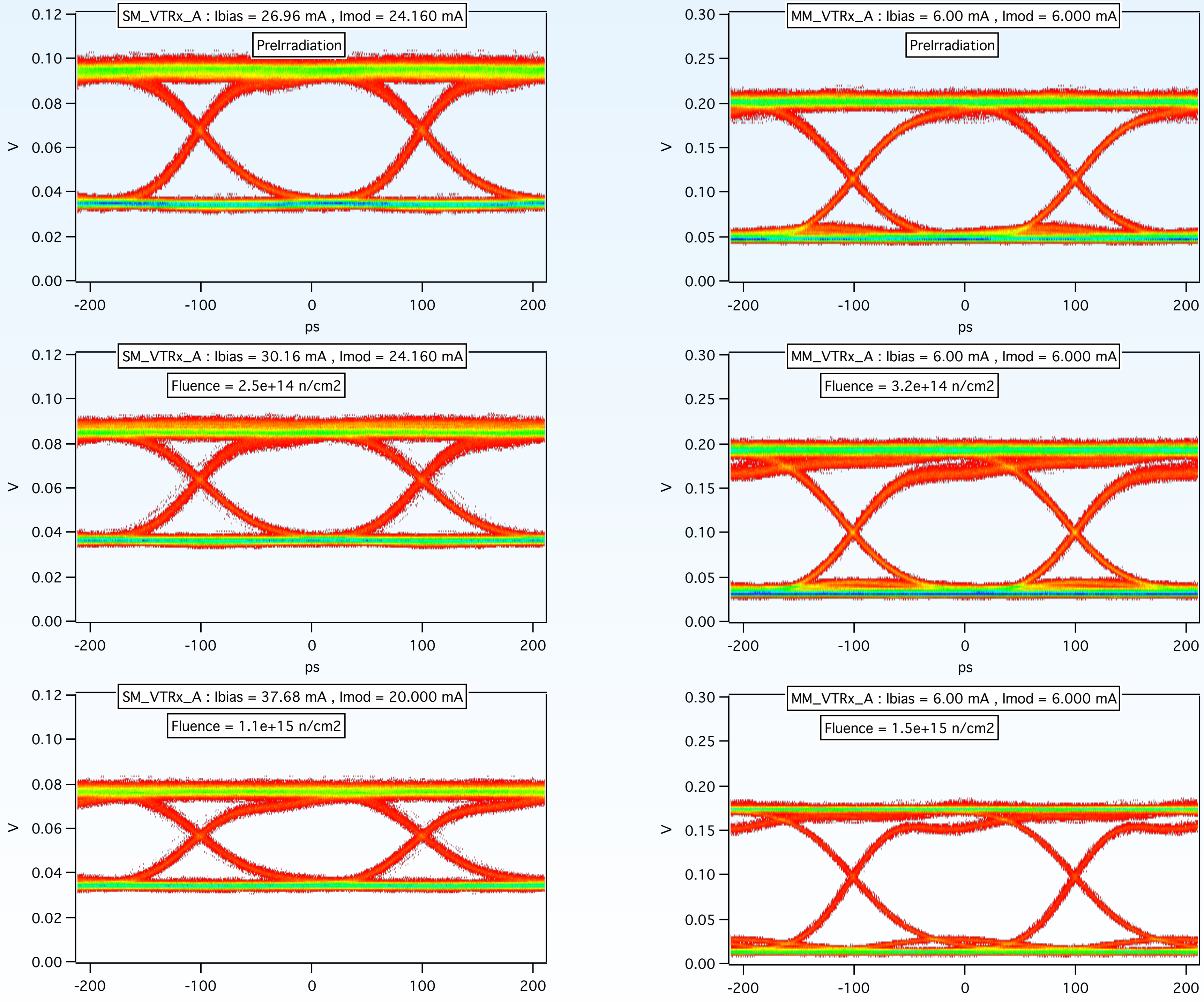
Final validation: VTRx in n-beam (2)



- Qualitatively similar results for intrinsic laser behaviour
- Also true for responsivity drop and leakage current increase in photodiodes

Final validation: VTRx in n-beam (3)

- Dynamic performance of lasers unchanged at 4.8 Gb/s



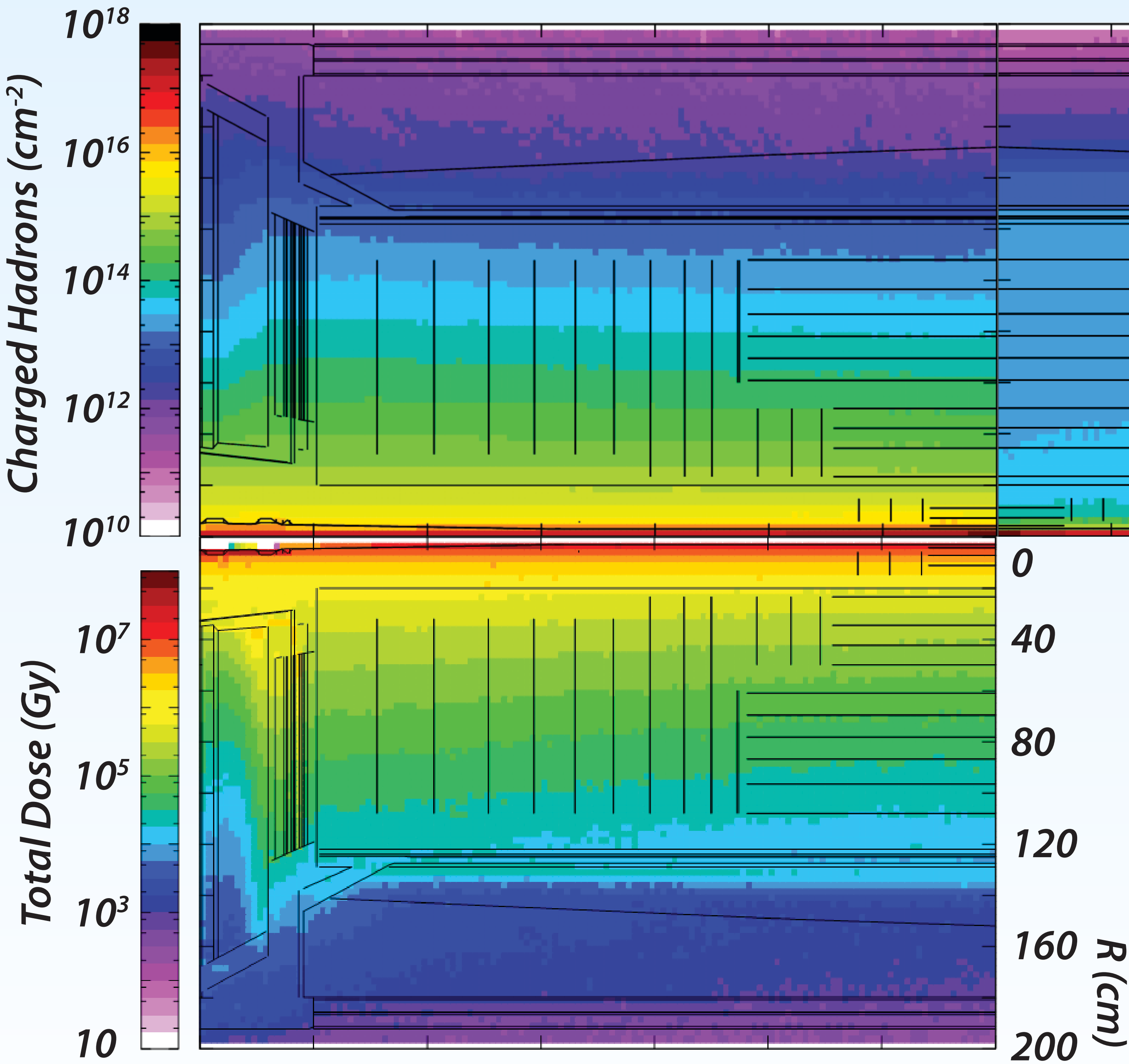
Summary: VTRx/VTTx qualification

- Components selected and shown to be radiation tolerant
  - Gamma testing also carried out for verification, no significant effects observed
- Module design completed and performance verified
  - Including performance over operating temperature range 10-60 °C
  - Including magnetic field tolerance
- Final irradiation test of full module allows qualification for use in Calorimeter-level radiation fields
  - i.e. LHCb and ALICE upgrades during LS2

Outline

- Versatile Link Project
- Radiation effects assessment
- Survivability outlook for Phase 2 upgrades

Future prospects

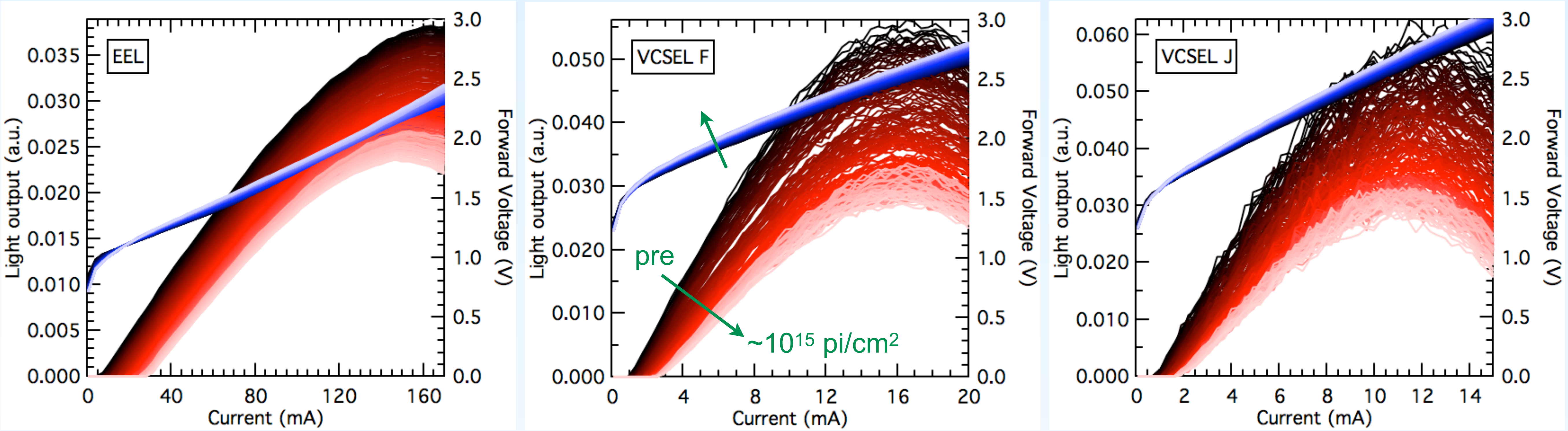


- CMS 3000 fb^{-1}
- Extreme rad levels in the pixel volume
  - Close to 10^{16} ch/cm^2
  - Beyond 1 MGy
  - Several 10^{15} n/cm^2

Beyond Tracker-Grade rad. tol.

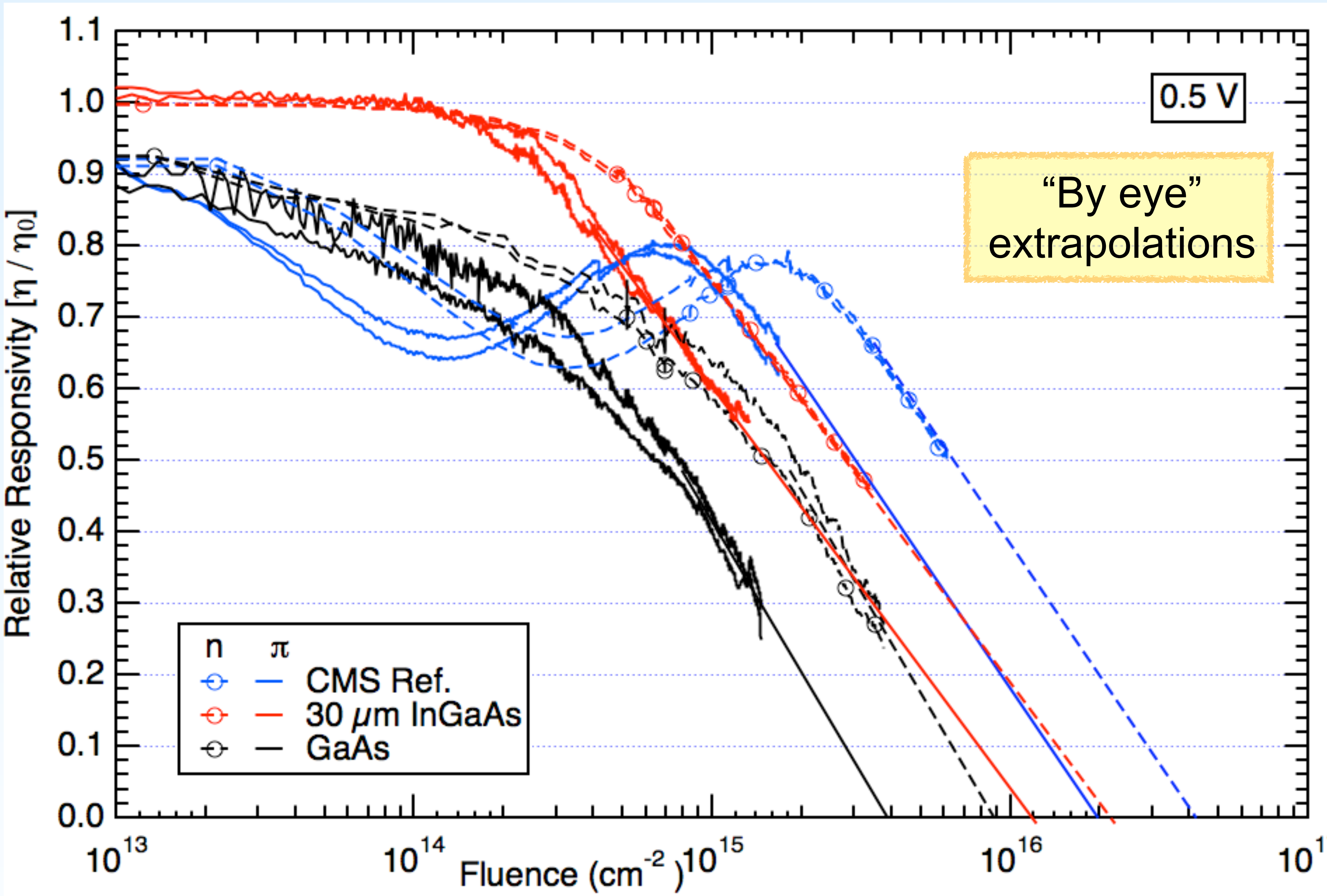
- Have shown already that we have qualified the existing parts to Tracker levels for total dose/fluence
  - How much more would the o-e devices survive?
  - Can they be used in the Pixel detectors?
  - Can we find another more resistant technology?

Lasers



- By eye, might assume lasers could survive "a few" 10^{15} /cm²
  - Need to be able to track threshold changes
  - Deal with output amplitude degradation in link budget
- Annealing helps a bit
  - Gain a factor of two in reduction of damage at SLHC fluxes

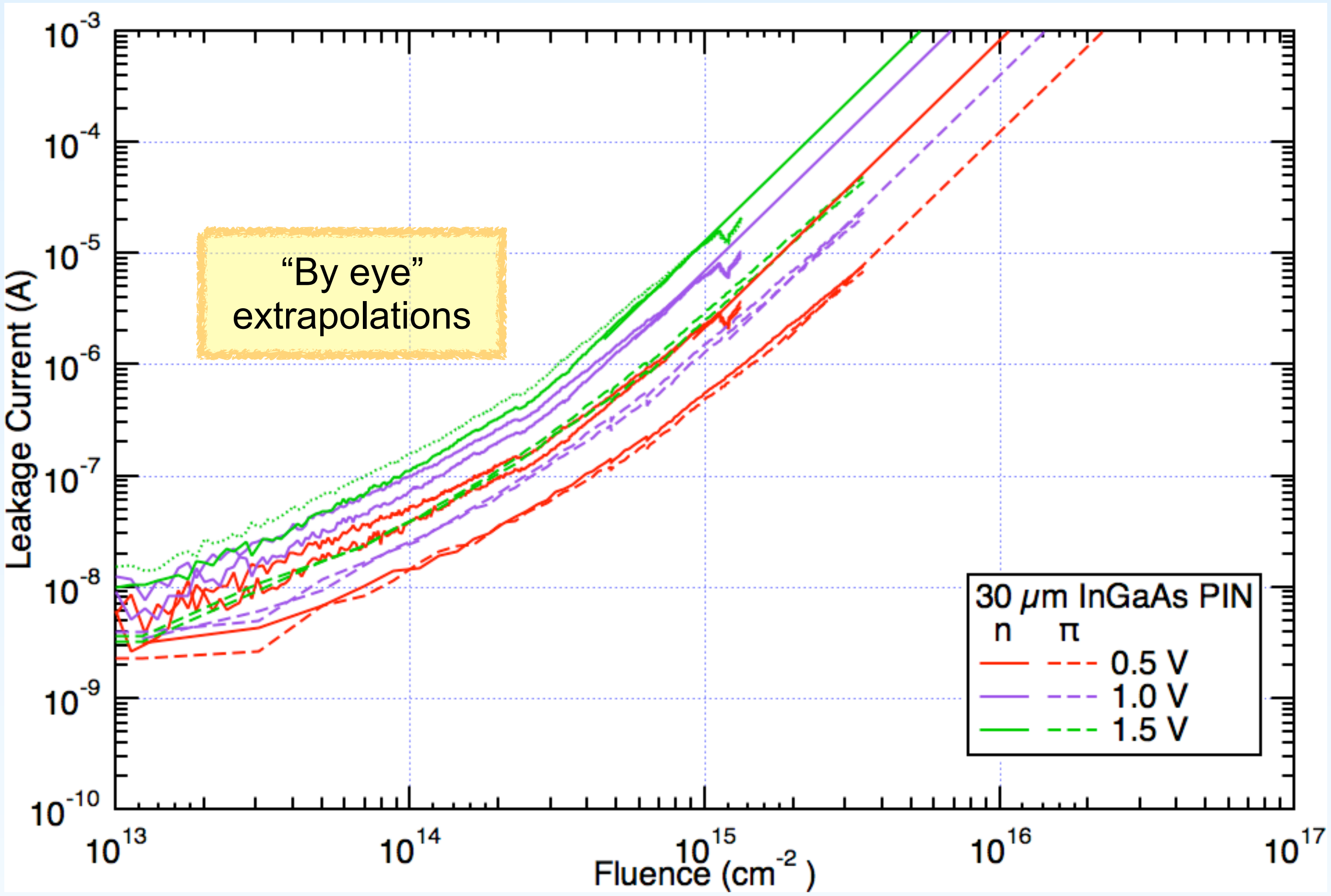
Impact of PD Responsivity loss

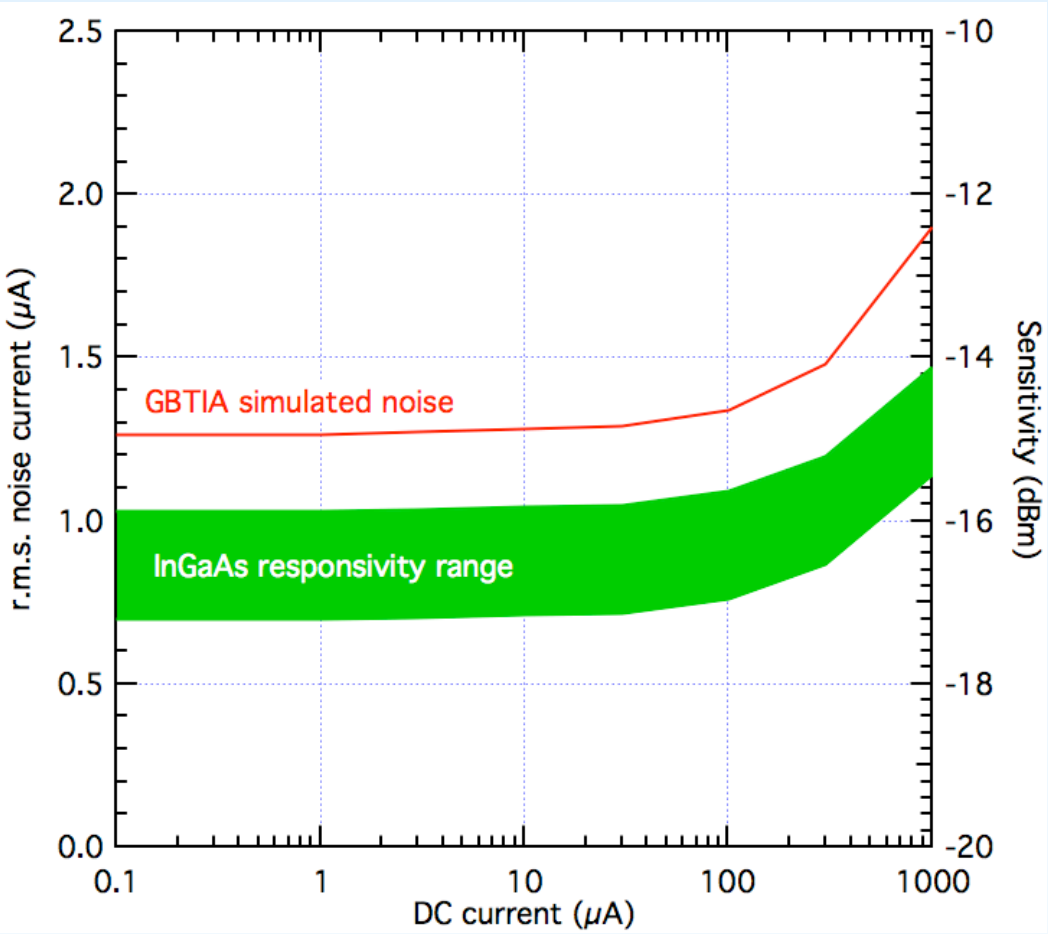


- GaAs non-functional after around $4x10^{15}$ pi/cm^2
- InGaAs non-functional after around 10^{16} pi/cm^2
- No annealing

Little safety margin!

Impact of PD Leakage Current



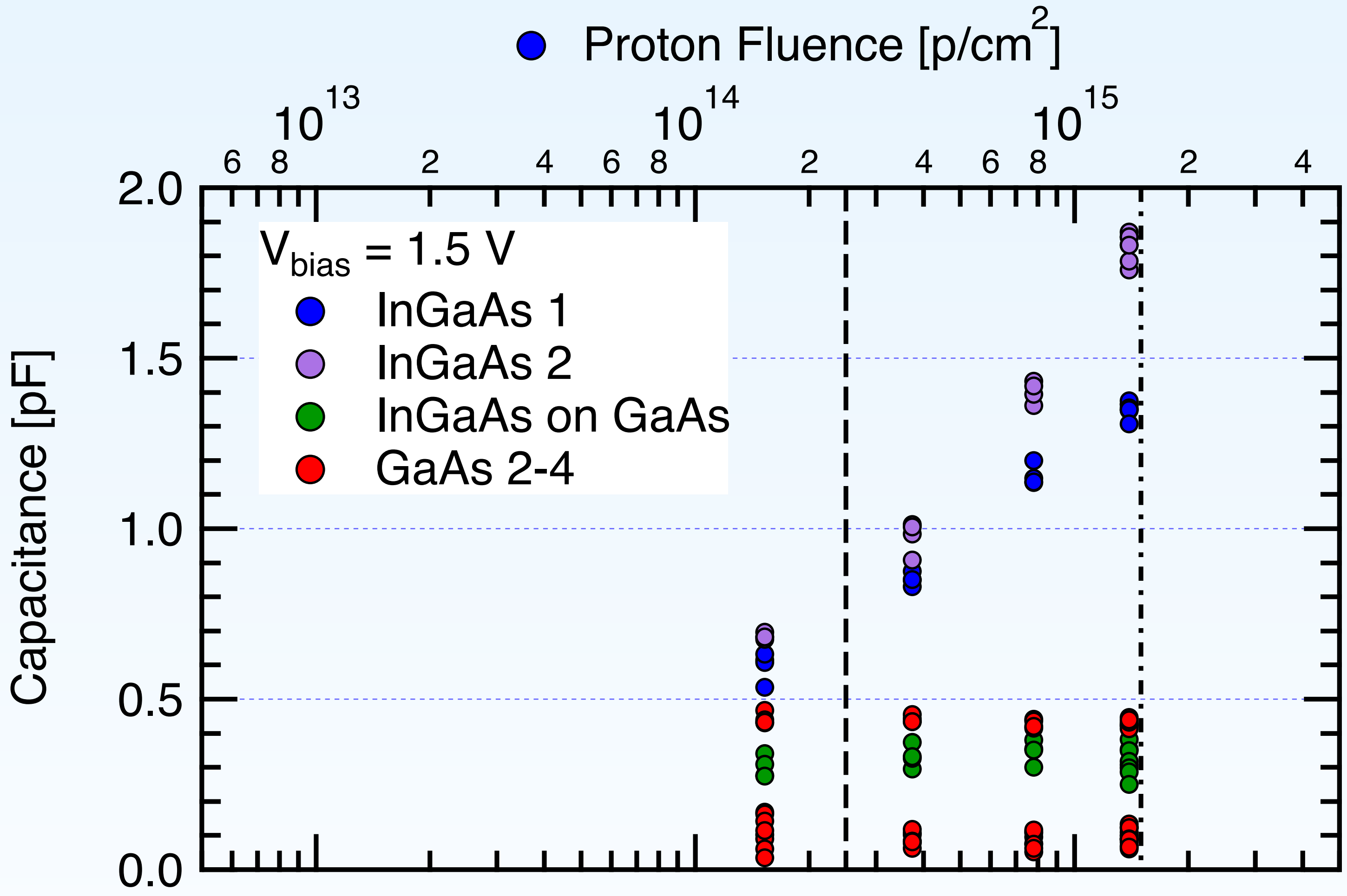


Reminder: no leakage in GaAs devices

- 1 mA leakage current adds 1.7 dB sensitivity penalty
- Not clear that removal of DC-current is possible beyond this?

Impact of PD Capacitance

- Unexpectedly found that irradiation affects the capacitance of some types of photodiodes



- InGaAs Capacitance increases dramatically
  - This can have a large impact on Receiver sensitivity in high-speed links

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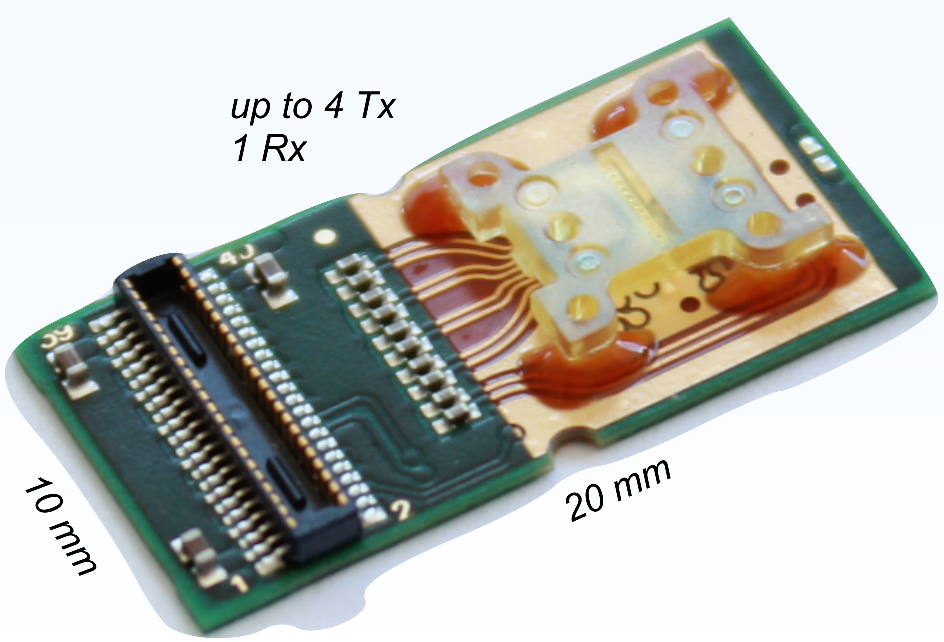
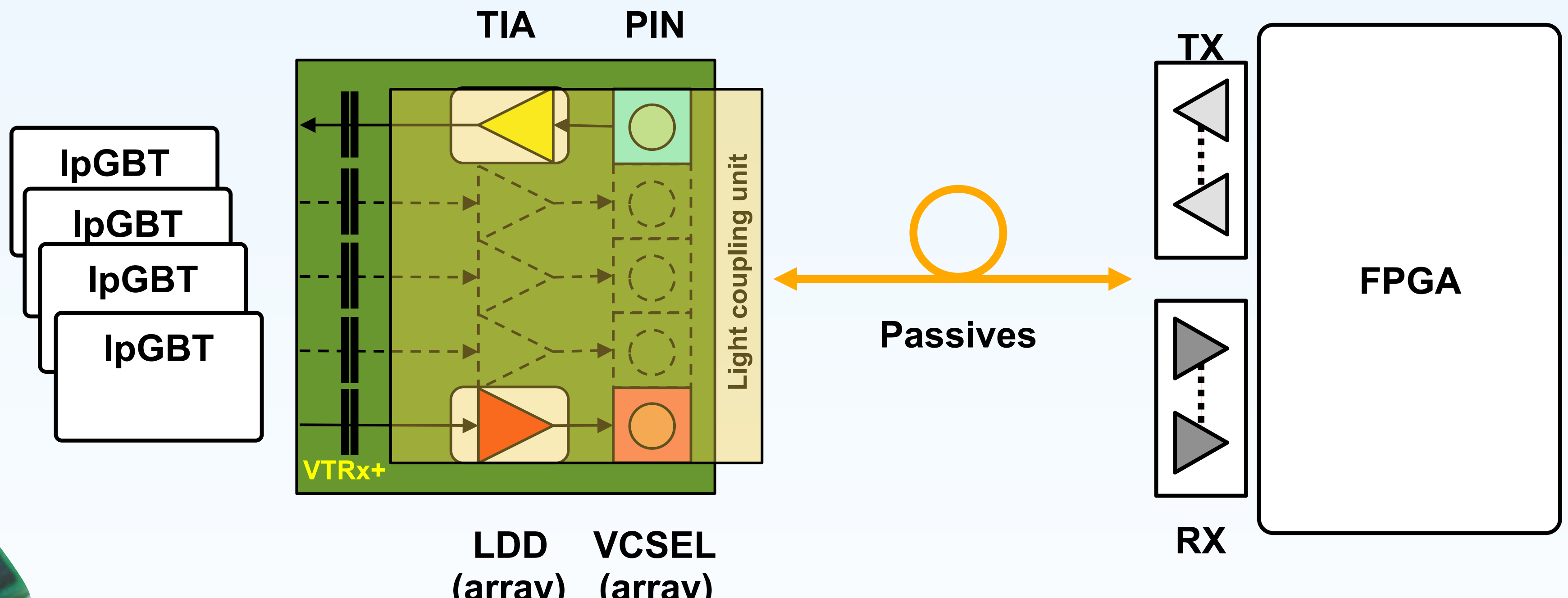
- Future prospects

Versatile Link + for HL-LHC

- Two partner projects
  - Chipset & protocol development: SerDes, LDD, TIA, FPGA core
  - Optical Link: Custom module, fibre plant, commercial module
- Asymmetric Data-rates
  - 5 or 10 Gb/s upstream (out of detector)
  - 2.5 Gb/s downstream
- Environment
  - 1 MGy, 3×10^{15} n/cm^2
  - -35 to +60 °C





On-Detector

Custom ASICs & packaging
Radiation tolerant

Off-Detector

Commercial
Custom protocol

System Specs

	VTx+ to Rx (10Gbps)		Tx VRx+ (2.5Gbps)	
	Standard	*Extended*	*Standard*	*Extended*
Tx OMA	> -5.2 dBm	*Screened for: high efficiency and low Vfwd*	> -5.6 dBm	> -1.6 dBm
Rx sensitivity	< -11.5 dBm	< -12.5 dBm	< -13.1 dBm	*Screened for: high responsivity*
Power budget	**> 6.3 dB**	**7.3 dB**	**> 7.5 dB**	**11.5 dB**
Fiber attenuation (50/100/150 m)	<0.125 / 0.25 / 0.375 dB		<0.375 dB	
Insertion loss	< 1.75 dB		< 1.75 dB	
Link penalties	1.5 / 1.7 / 2.1 dB		< 0.5 dB	
Tx radiation penalty	1.0 dB		–	
Rx radiation penalty	–		< 1.4 dB	< 5.4 dB
Fiber radiation penalty	< 0.5 dB	< 1.5 dB	< 0.5 dB	< 1.5 dB
Margin (dB)	**1.425 / 1.1 / 0.575**	**2.1 (100 m)**	**> 2.975**	**> 1.975**
Coding Gain (dB)	**1**		**1**	

VTRx+ Module

Commercial Module

- Trade-off between requirements at either end of link
  - Penalties are asymmetric
  - Cannot simply apply e.g. 10 GbE specs

Conclusions

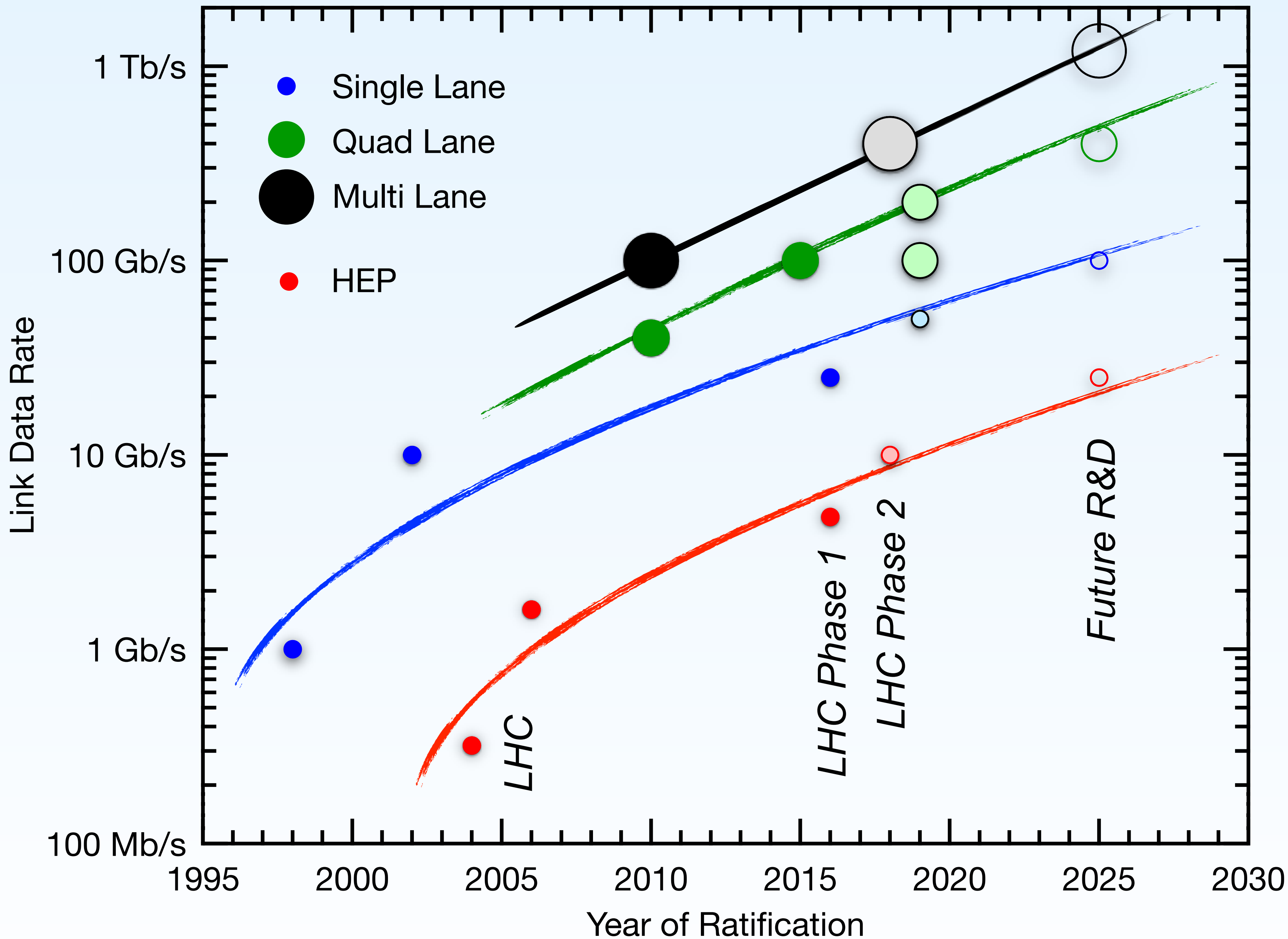
- We have qualified components and built modules for upcoming LHC experiment upgrades
  - About to enter next production phase…
- Have measured the performance/degradation of a full module during neutron irradiation
  - O-E components behaved as expected, high-speed operation verified in-beam
- On the limit of radiation tolerance required by the LHC application!
- What’s next?

Outline

- Optical Link Systems reminder
- Radiation effects assessment methodology
- Radiation effects in optical link components & their impact on optical link systems
- Versatile Link + system for LHC phase 2 upgrades
- Future prospects

Where do we stand compared to…

Industry standards:

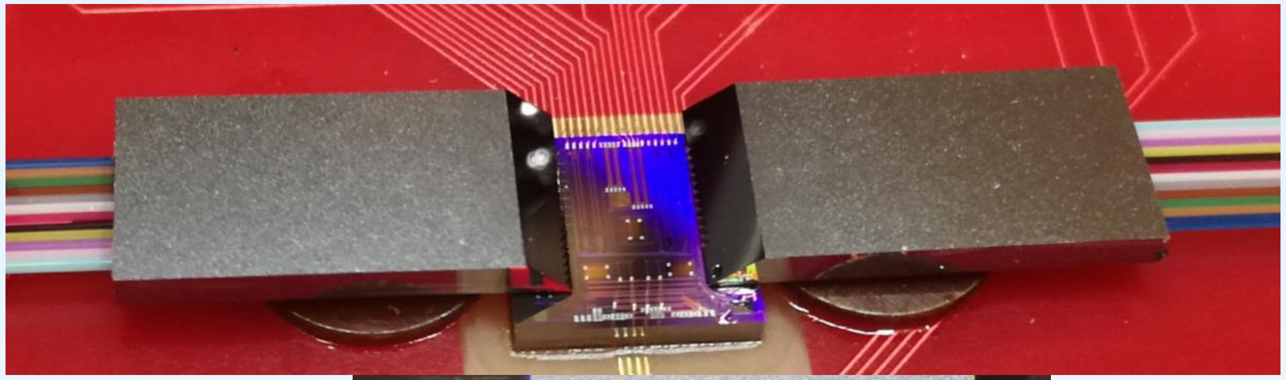


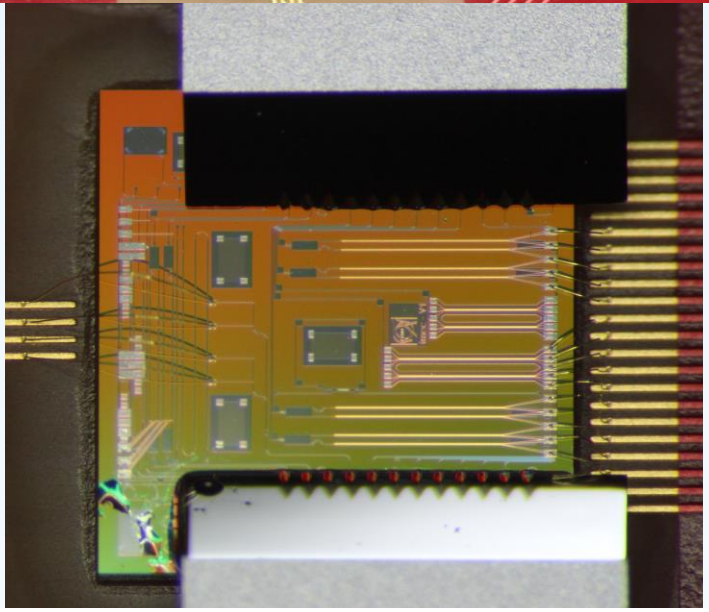
Playing catch-up

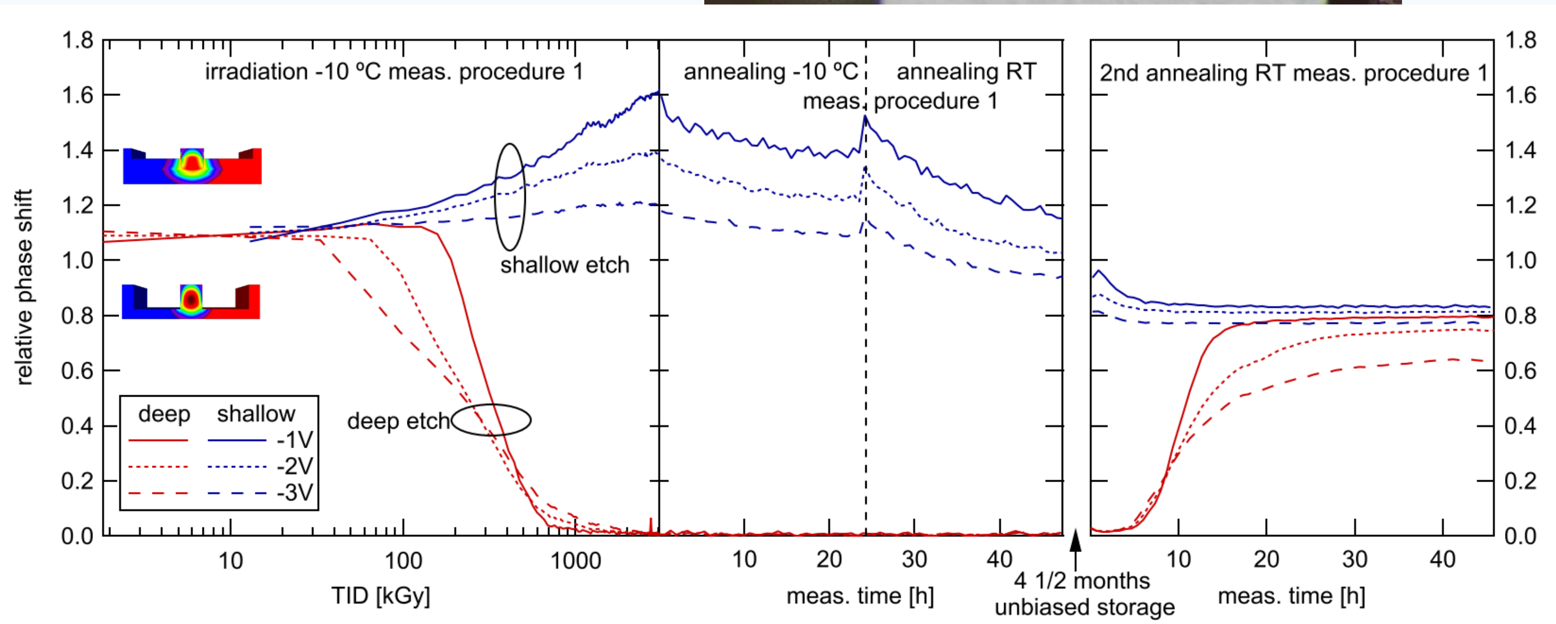
Difficult to maintain compatibility with COTS back-end?

New Technologies

- Presently much interest in the telecom and datacom industry in silicon photonics
  - We are currently investigating the suitability of this technology for particle physics instrumentation
- Silicon photonics circuits are quite radiation hard
  - Design change can positively influence the radiation resistance
  - Promising direction…







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