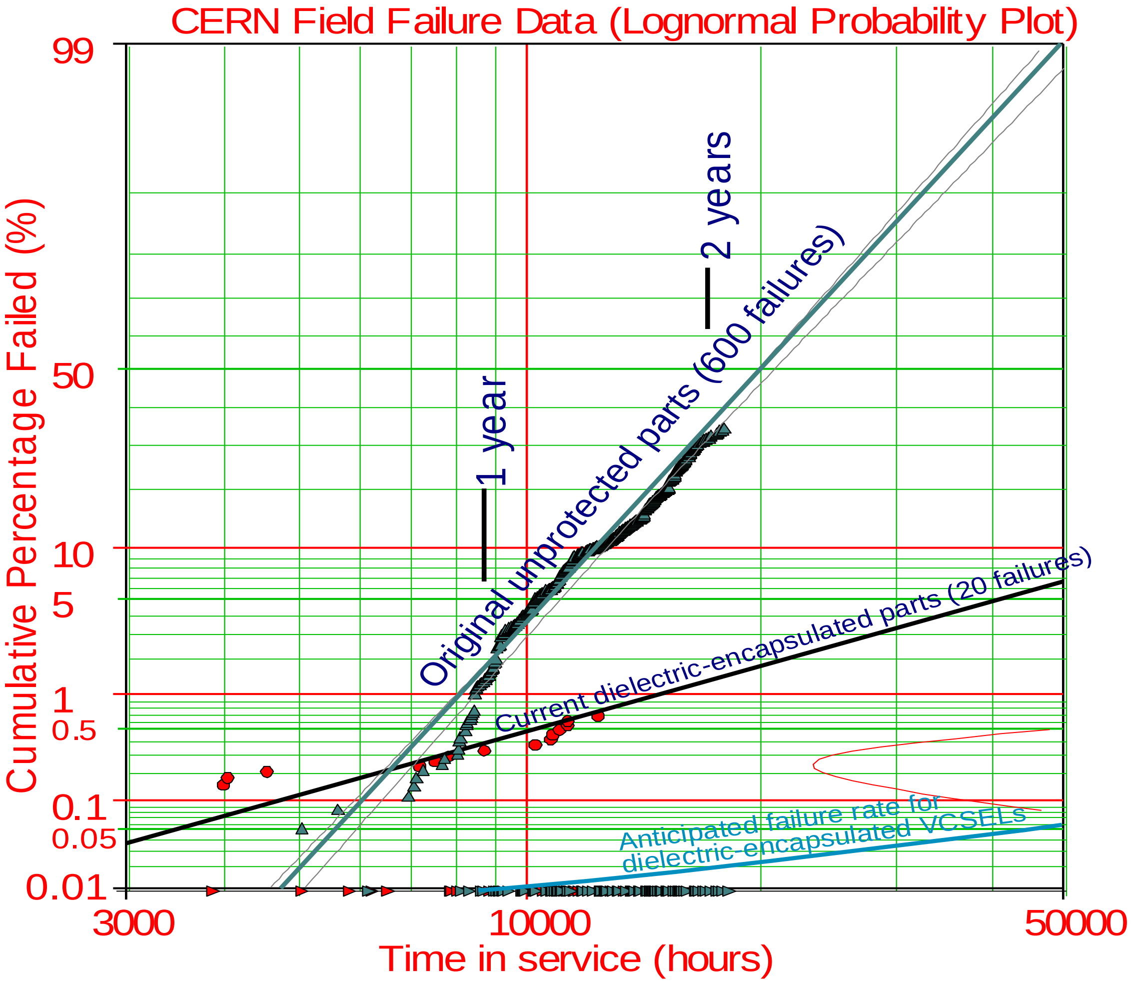
Reliability testing of VCSELs, Transceivers and ASICs. History, status and plans

Opto Mini-Workshop, CERN 21/3/14

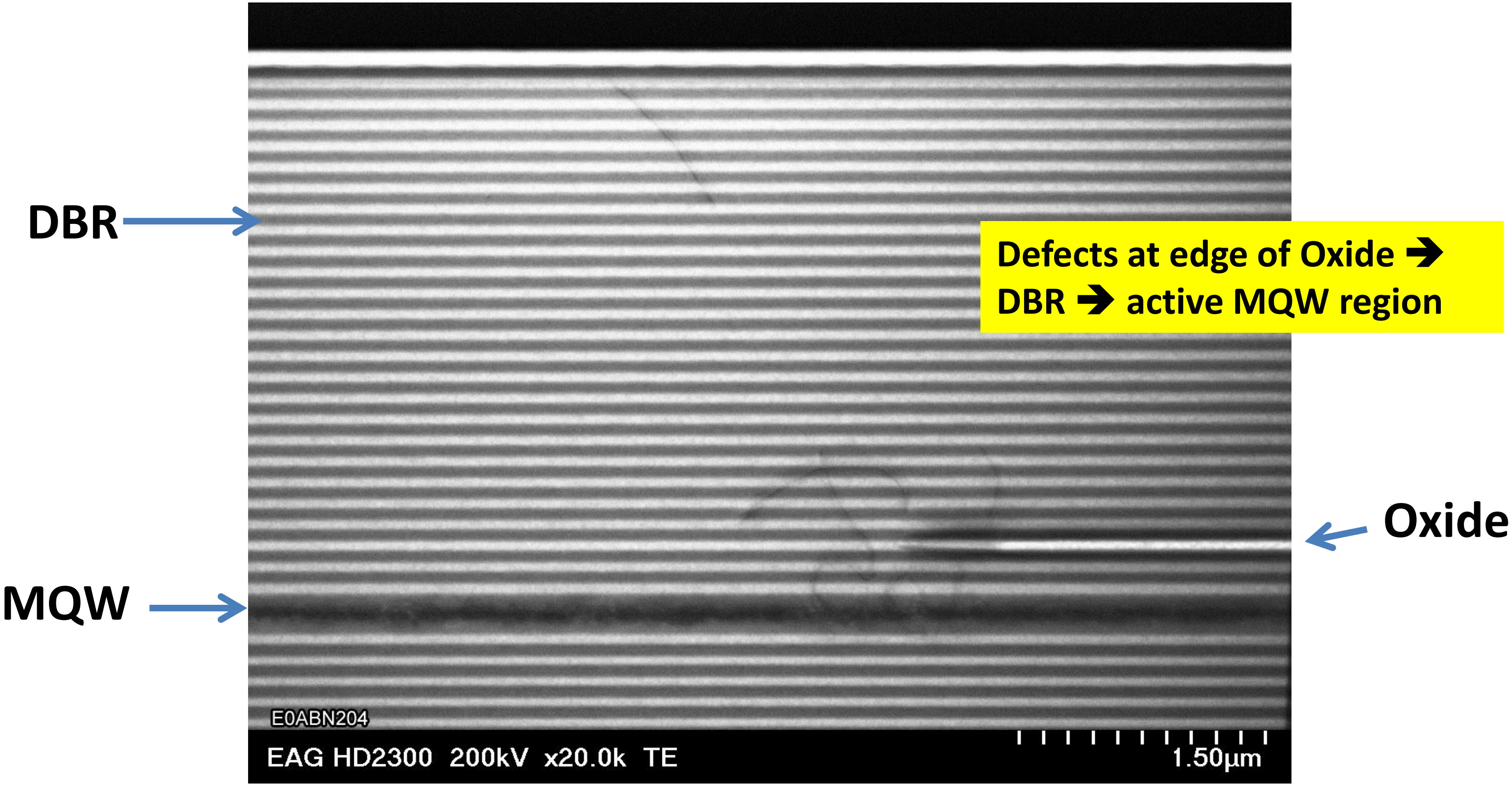
Outline

- VCSEL failures in ATLAS
  - Reminder TL failures
  - Controlled experiments to determine cause of damage
  - Outstanding mysteries
    - TL and AOC VCSELs
- Plans for future reliability testing
  - VCSEL
  - Transceiver
  - ASICs

Failure Rates in ATLAS Operation



STEM Failed Channel
TL VCSEL array after FIB cut

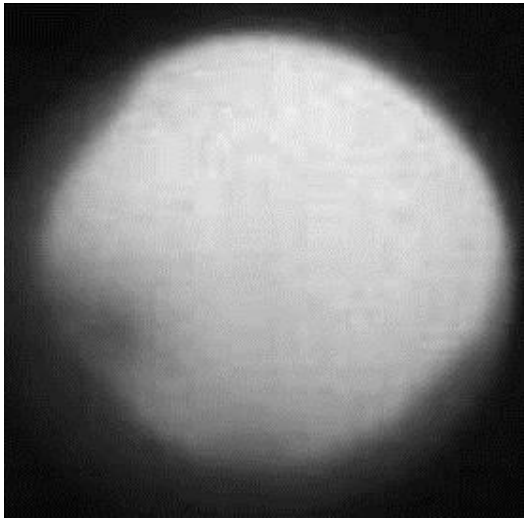


Defects at edge of Oxide ➔ DBR ➔ active MQW region

Analysis by EAG

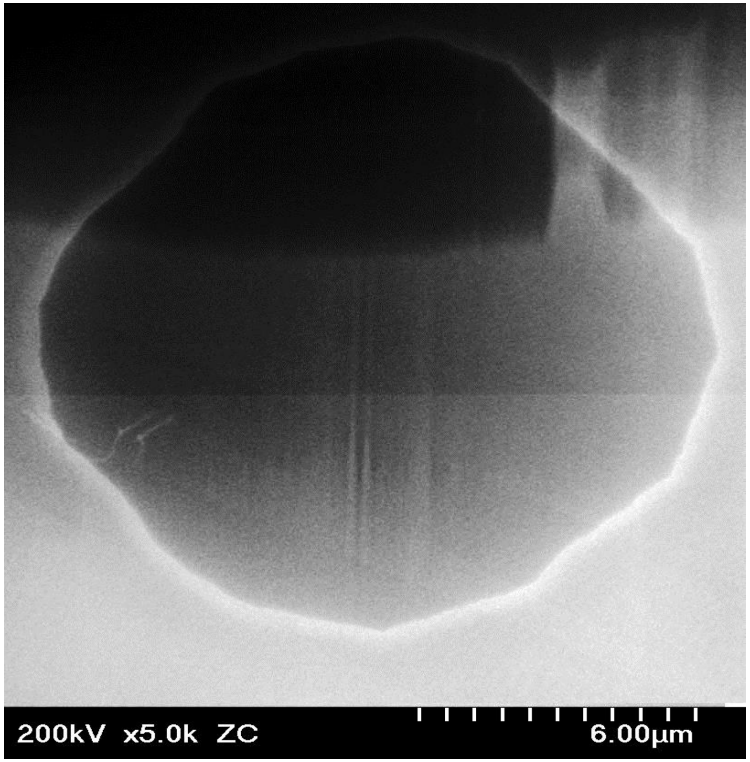
More Controlled Tests

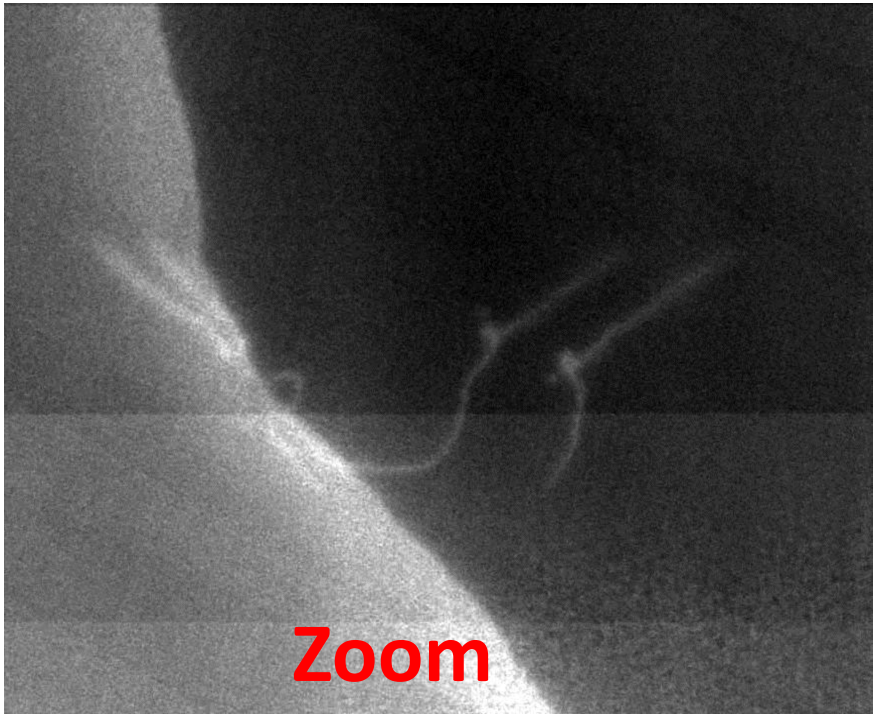
- Aged VCSEL array in 70C/85% RH with regular power measurements and EL imaging.
- Stopped as soon as significant decrease in power detected.
- EL image shows 4% of area is dark.
- Subsequent TEM analysis (next slides).



Plan View TEM

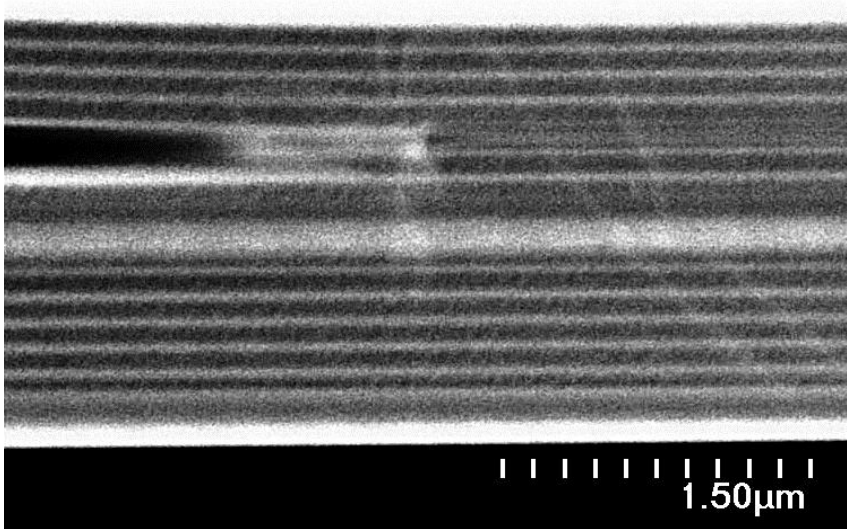
- Dislocations in dark region from EL
  - Two dislocations emanating from tip of Oxide.



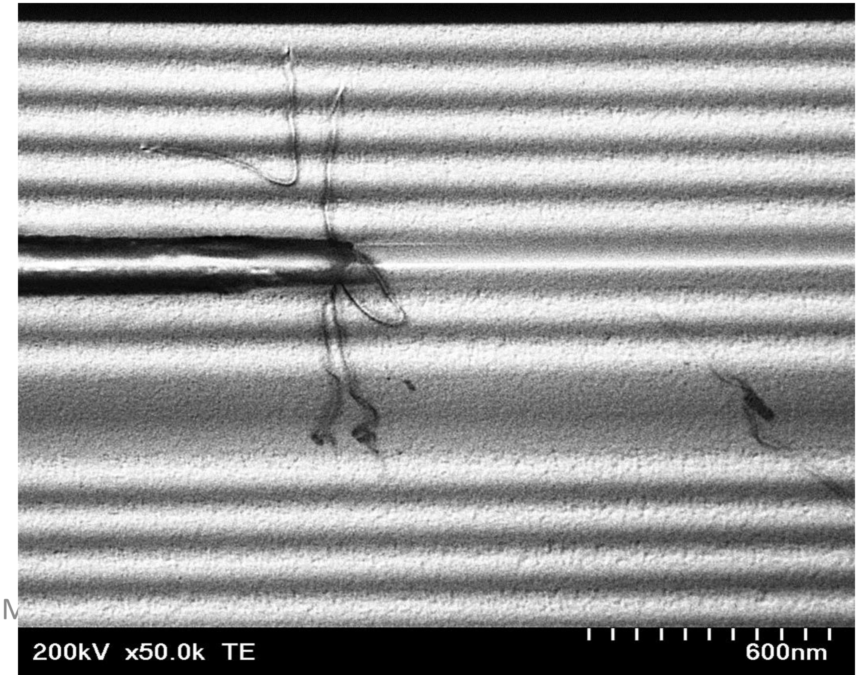


X-Section TEM

- **X-section views**
  - **after thinning to ~ 1.8 um (“thick”).**

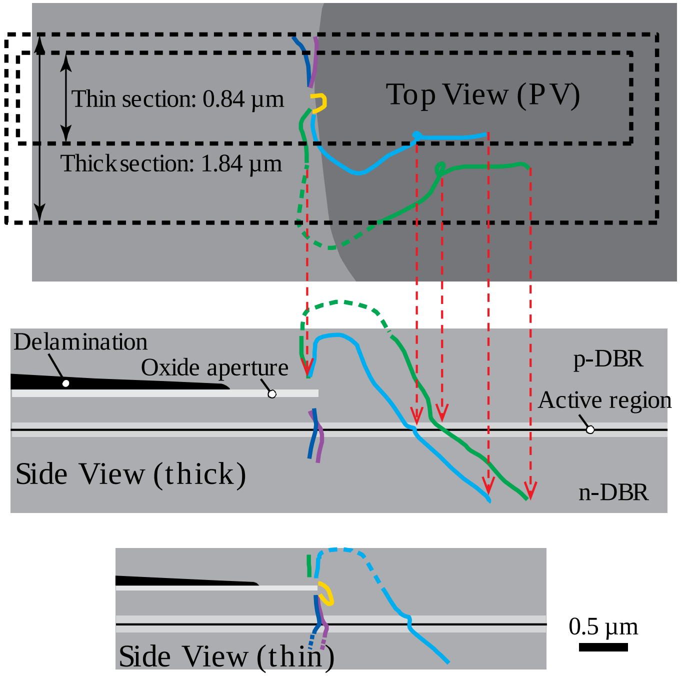


  - **after further thinning to ~ 0.8 um. This allows tracing of defects.**



Tracing Defects

- line dislocations starting from oxide tip (crack?).
- traveled down from oxide aperture ➔ active region below, and started the DLD network.
- Note lines travel up before looping down (follow current wind).



Remaining Mysteries -1

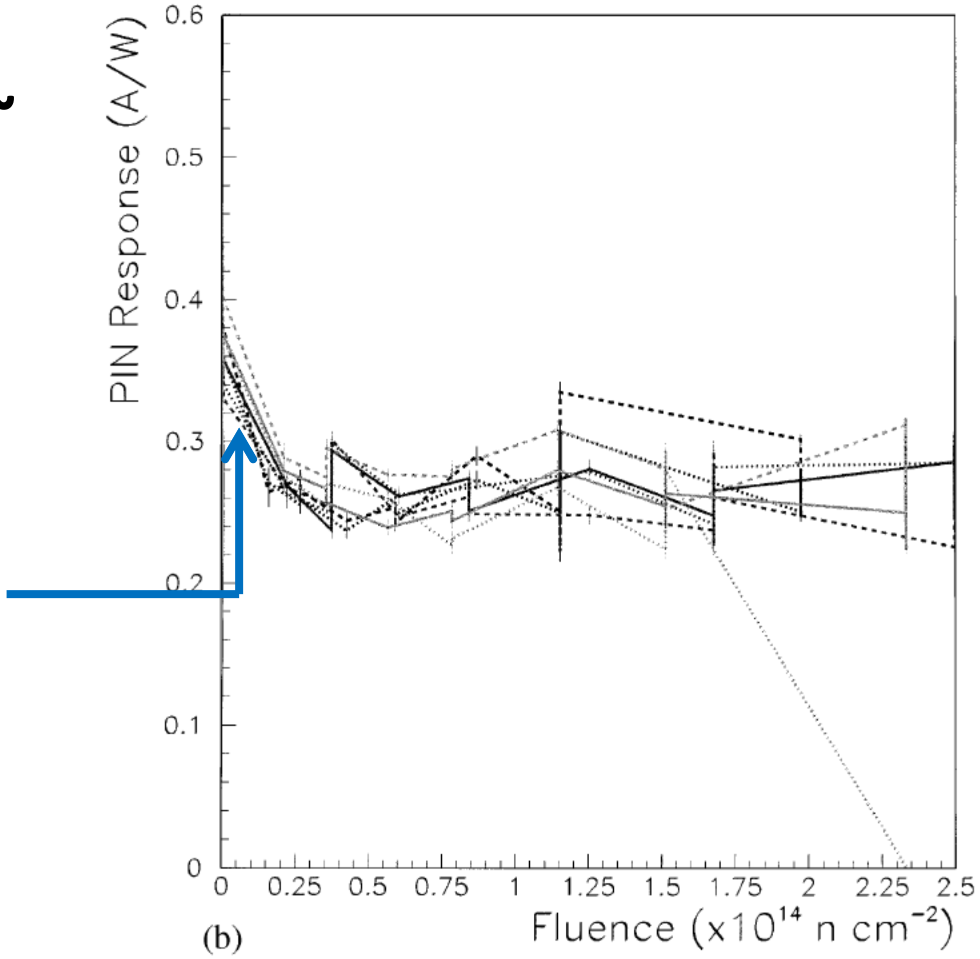
- **Compare lifetime data from TL VCSELs in ATLAS USA-15 with accelerated ageing tests (ULM).**
  - **MTTF in USA-15 is lower than predicted by model fitting ULM data by factor 4 to 6.**
  - **Null hypothesis that ULM and USA-15 data described by common parameters for the acceleration model excluded at 90%.**
- **Compare controlled experiment in SR1 with USA-15.**
  - **4 TL arrays operated in SR1 for more than 500 days.**
  - **Only 1 channel died.**
  - **Inconsistent with observed MTTF in USA-15, null hypothesis of same MTTF in SR1 as USA-15, gives p-value 8.3 10^{-6}.**

Remaining Mysteries - 2

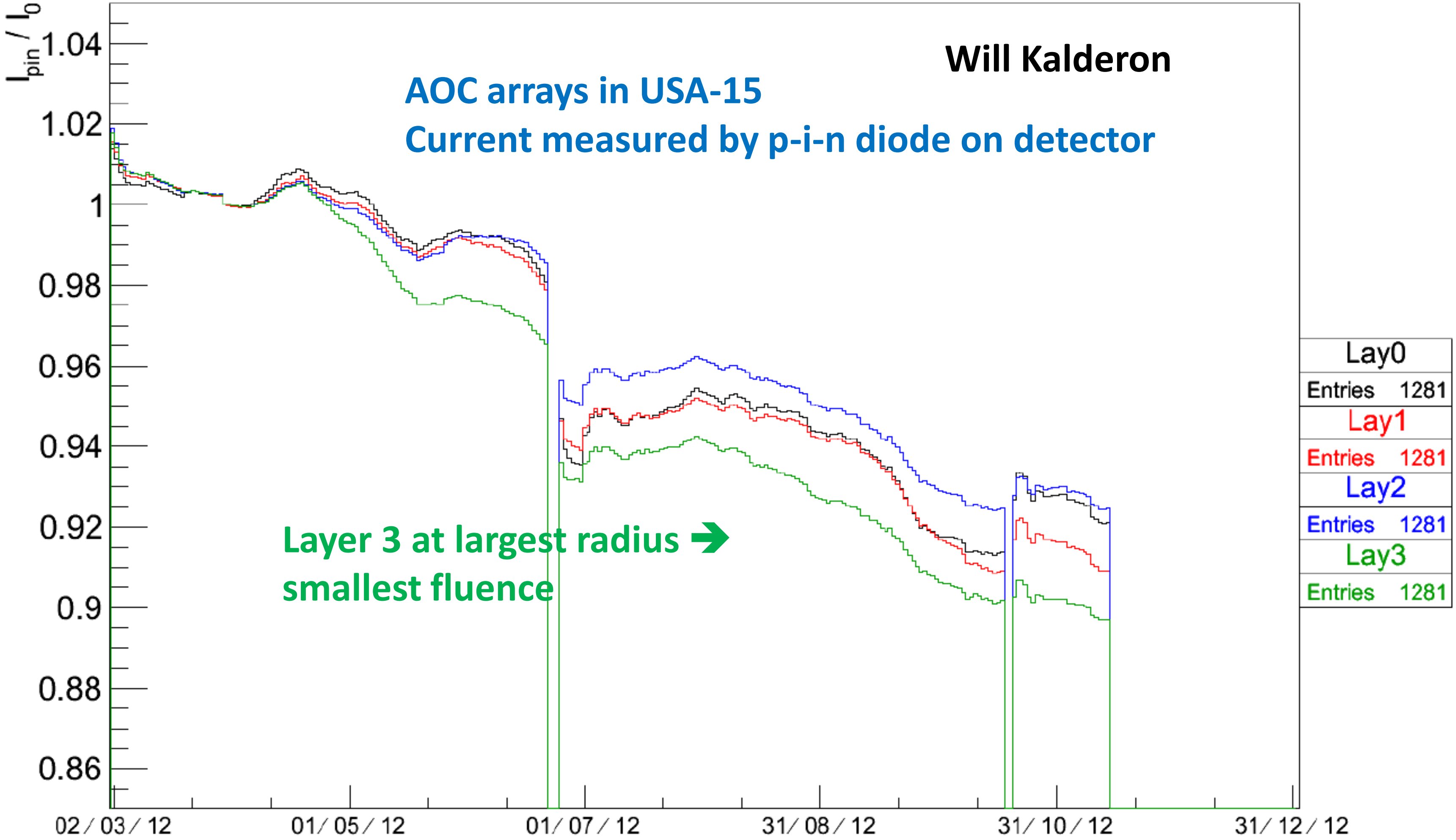
- Decrease in power for AOC arrays in USA-15
- Measure power using current in *p-i-n* diode on detector.
  - Note we do expect significant decrease in responsivity from radiation damage.
  - See similar decrease for all barrel layers → see slide
  - incompatible with radiation damage?

p-i-n Diode Radiation Damage

- **Decrease in responsivity ~ 30% with relatively low fluence than plateaus.**
  - **24 GeV protons**
- **Fluence seen by inner barrel ~ 0.06 10 ^{14} n cm $^{-2}$**



Mean I_{pin} by barrel layer , 03.12 - 11.12, scaled



Will Kalderon

AOC arrays in USA-15
Current measured by p-i-n diode on detector

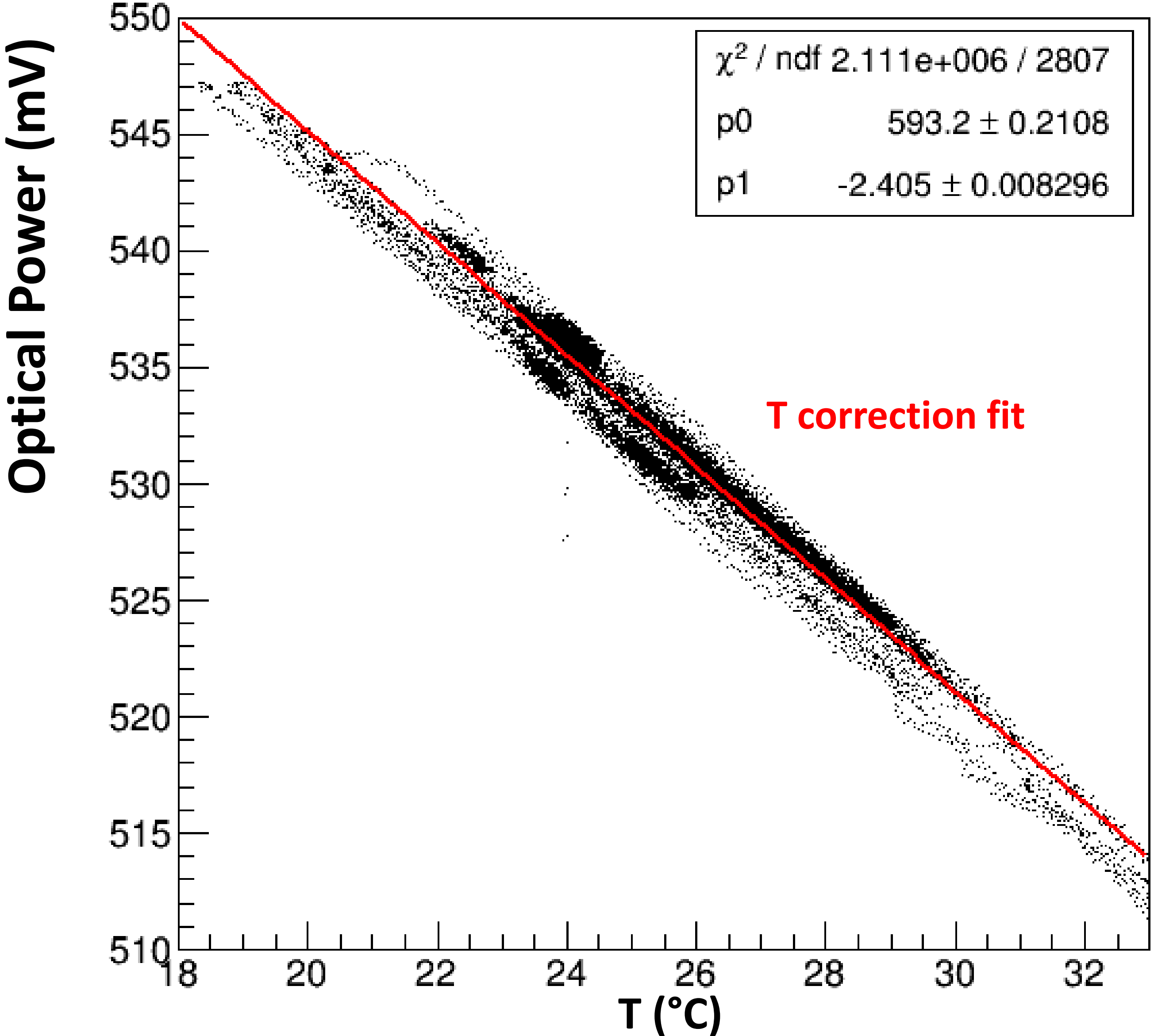
Layer 3 at largest radius ➔
smallest fluence

- Now scaled to March average (more precisely: first 30 days from 2^{nd})
- Only rolling averages for clarity
- Decrease ~ uniform for all layers

Remaining Mysteries - 3

- **Long term monitoring of optical power for AOC TXs in SR1 using LAPD (measure power from all 12 channels).**
- **Do not reproduce decrease of 10%/year seen in USA-15 → slides.**

Temperature Correlation



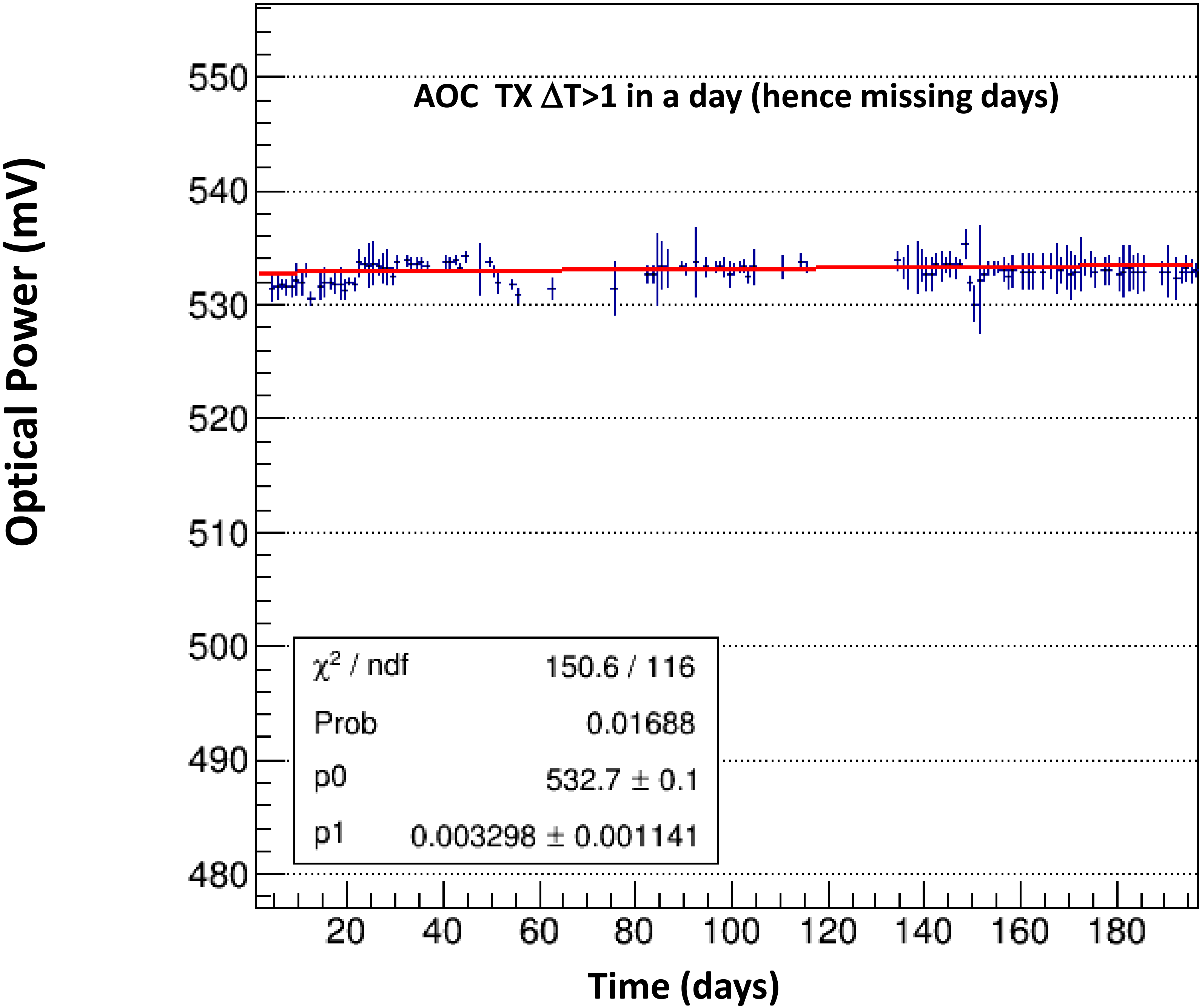
T correction fit

Steve McMahon

AOC TX in Bat 161

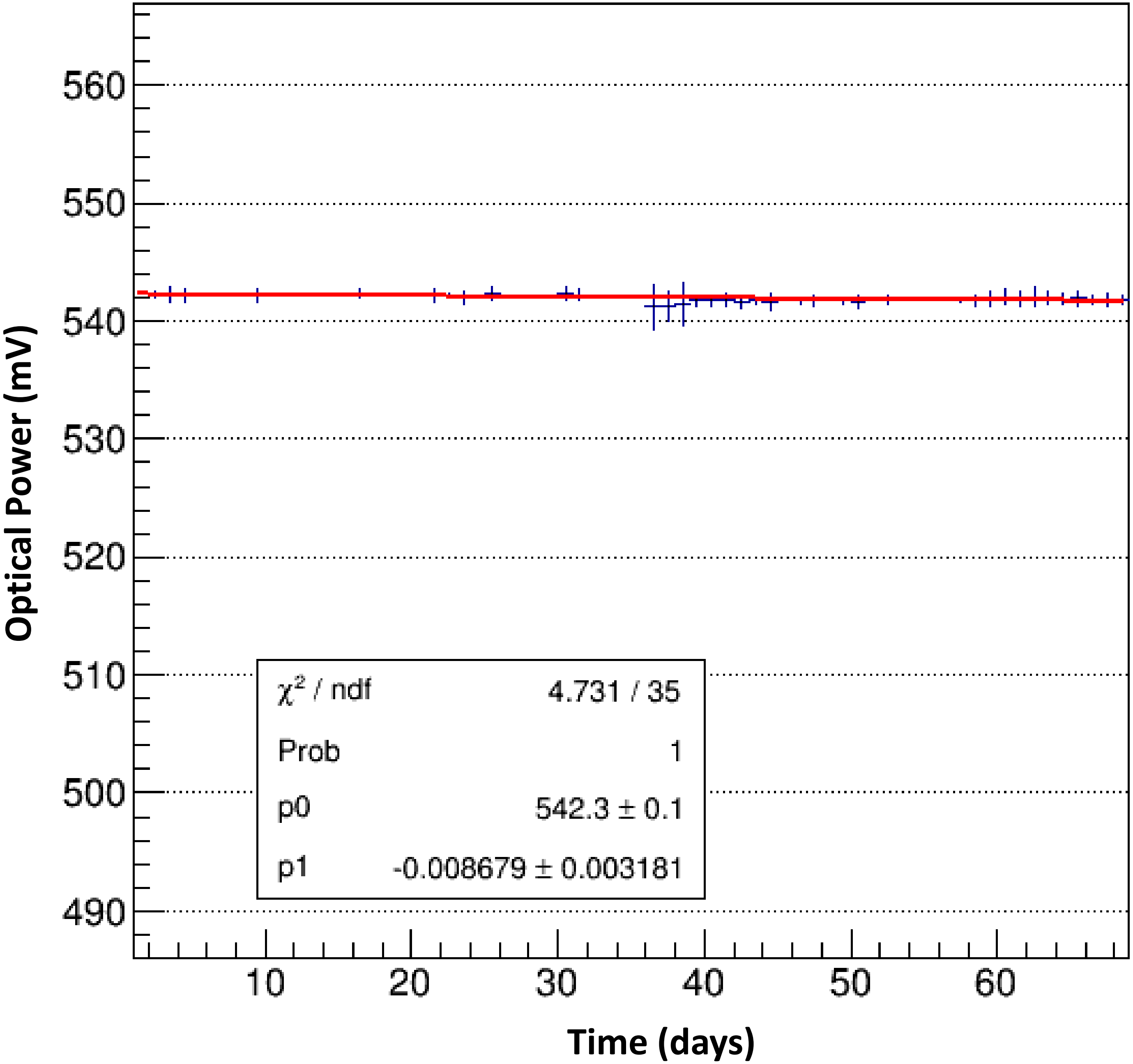
AOC TX in Bat 161

Steve McMahon


AOC TX ΔT>1 in a day (hence missing days)

AOC in SR1

Steve McMahon



VCSEL Testing Plans

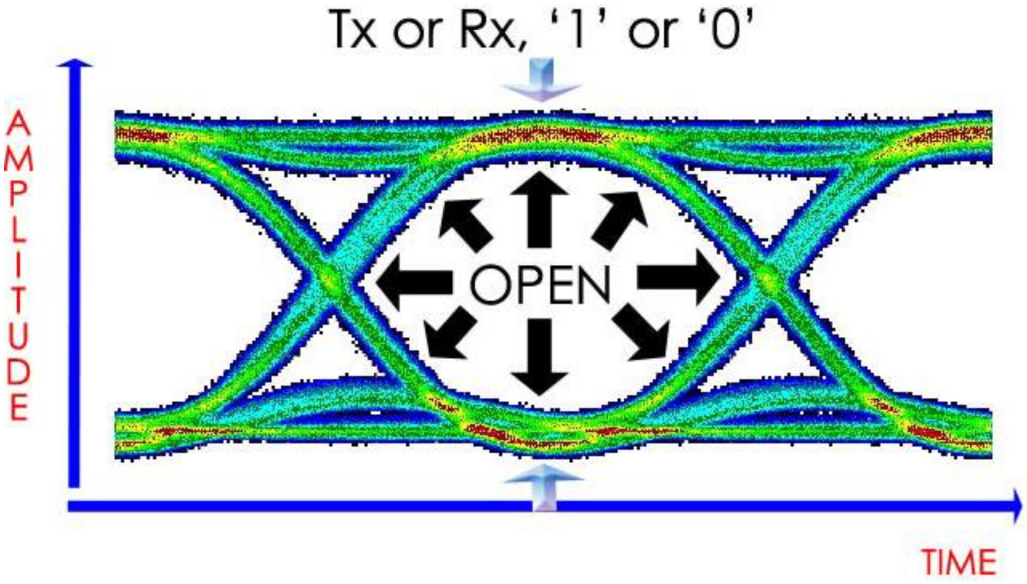
- Standard damp heat tests
  - 1000 hours, 85C/85% RH.
  - Drive current 10 mA dc
  - Measure optical power continuously.
  - Aim for much higher statistics than we have done in the past → learn about infant mortality and random failure rates as well as lifetime.
  - So far we have tested 2 VCSELs, would like to do 200 devices?
    - Have equipment to do batches of 80 devices.

Transceiver Tests

- Monitor link performance while operating at elevated temperatures.
- Look for evidence of degradation using
  - Eye diagrams
  - BER scans

Eye Diagrams

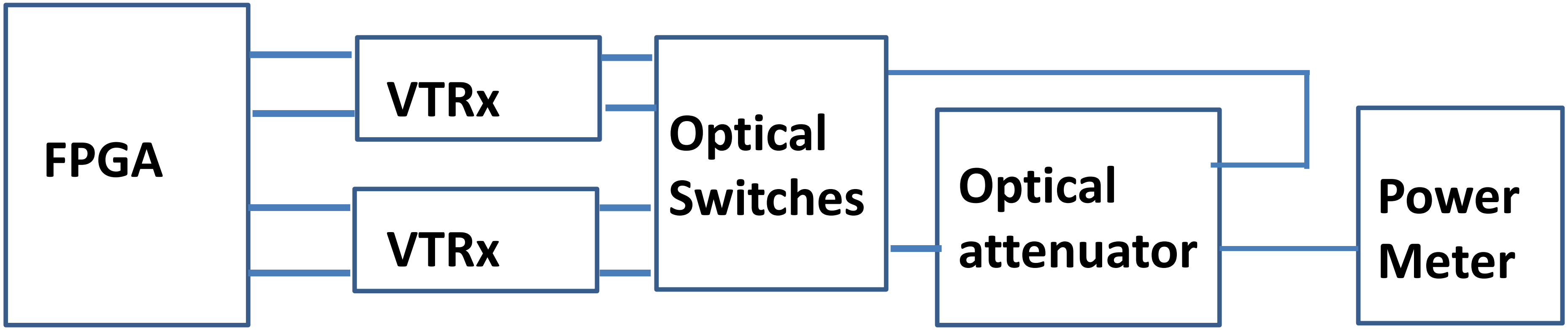
- **Use Digital Communication Analyser to measure eye diagrams**
  - **We are getting our DCA firmware upgraded to allow testing at a bit rate of 4.8 Gbits/s.**
  - **Determine many parameters, e.g. horizontal and vertical eye opening, rise and fall times, noise, random and deterministic jitter.**



Equipment for BER Scan

- FPGA
  - Generates PSRB data
  - Measures BER
- Loopback test, e.g. transceiver VTRx to receiver VTRx.
- Computer controlled optical attenuator to allow scan of BER vs OMA. Has a 10% and 90% tap to allow for power measurement during BER scan.
- Optical switch to allow many channels to be measured.
- We are getting a copy of CERN VL system so we can use their firmware and software.

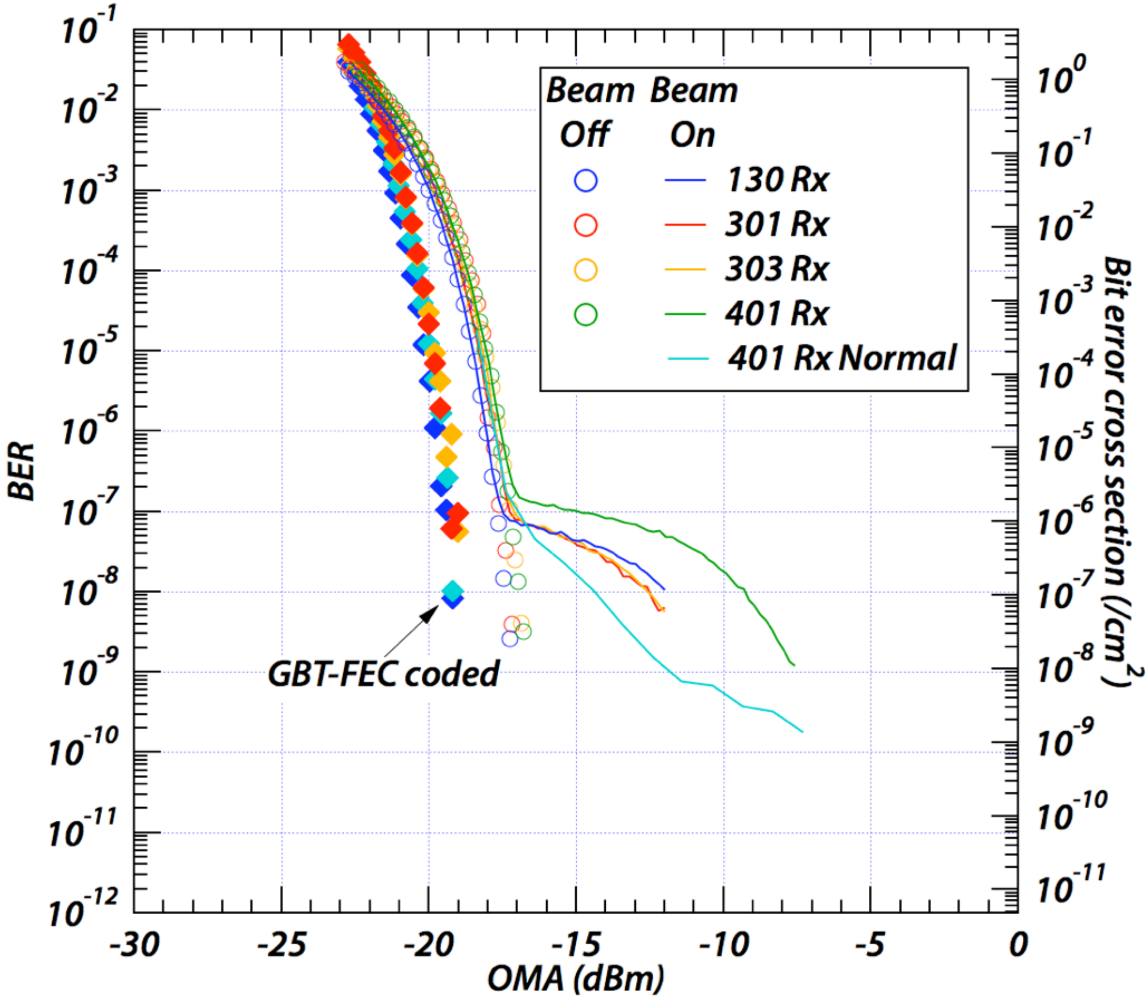
BER System



Loopback tests
Optical switches allow many VTRx to be tested in an environmental chamber.

BER Scans

- **Measure BER vs OMA (optical modulation amplitude).**
- **Define minimum OMA to achieve BER = 10^{-12}.**
- **Measure this during continuous operation at elevated temperature.**
- **Curves show example BER scans with and w/o beam.**



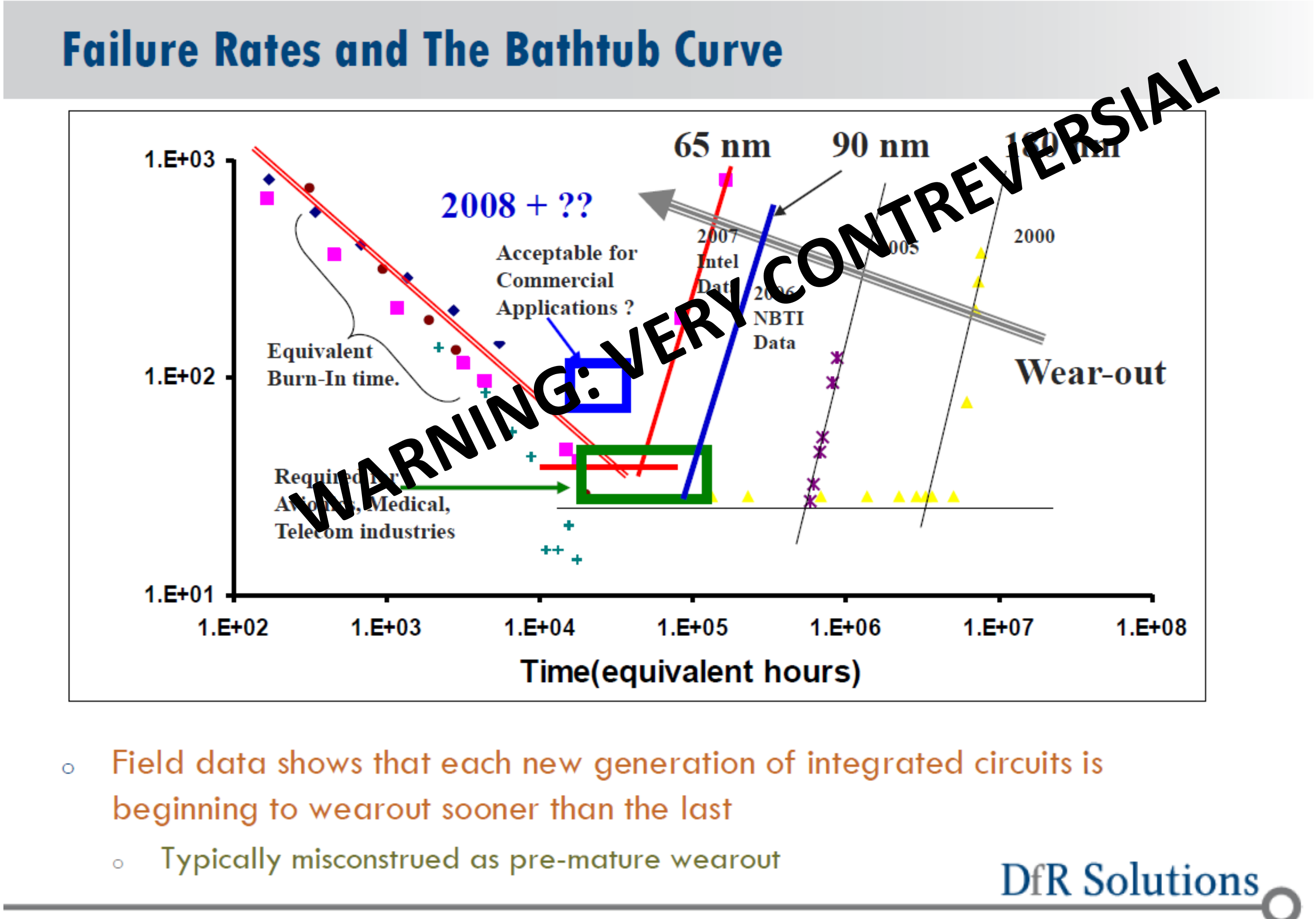
Chip Reliability

- What is there to worry about?
- Failure Mechanisms
- Statistical analysis PoF
- Plans for testing GBTx (similar study for ABC130).

Why worry?

- Traditionally failures in HEP not dominated by ASIC reliability
  - Connectors, solder, wire bonds, cracks in tracks and vias, capacitors, power supplies
  - Non-ideal scaling in DSM processes
    - Aggressive designs target optimal performance
    - Voltage decreases insufficient to compensate density increase ➔ higher T ➔ lower reliability.

FA Webinar- Cheryl Tulkoff
(slide from J. Bernstein)



Failure Rates and The Bathtub Curve

- Field data shows that each new generation of integrated circuits is beginning to wearout sooner than the last
  - Typically misconstrued as pre-mature wearout

ASIC Reliability

- Lifetime tests at different T (low and high) and elevated V
- Fit model parameters ➔ extrapolate MTTF to use case (see backup slides for details).
- Start with ATLAS pixel FE-I4
- Test GBTx when large numbers available

Summary & Outlook

- **“If you think safety is expensive, try having an accident”**
    - **Plenty of painful experience in ATLAS ➔ must perform rigorous testing before production.**
- **Still trying to understand VCSEL failures in ATLAS**
- **Plan rigorous campaign to understand reliability for phase II upgrades for ATLAS/CMS**
    - **VCSELs**
    - **Transceivers**
    - **ASICs**

BACKUP SLIDES

Chip Reliability

AUW: ITK Opto-electronics, Electrical Services and DCS: 14/5/13

Steve McMahon & Tony Weidberg

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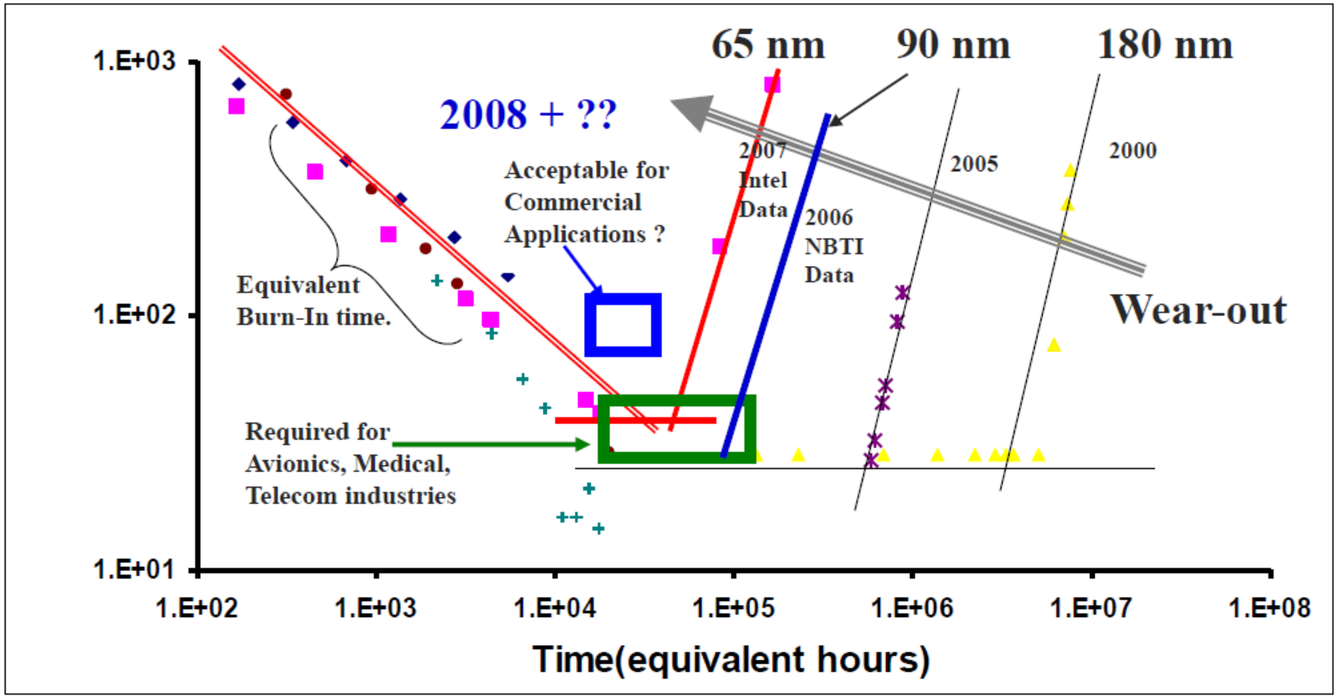
Failure Rates and The Bathtub Curve



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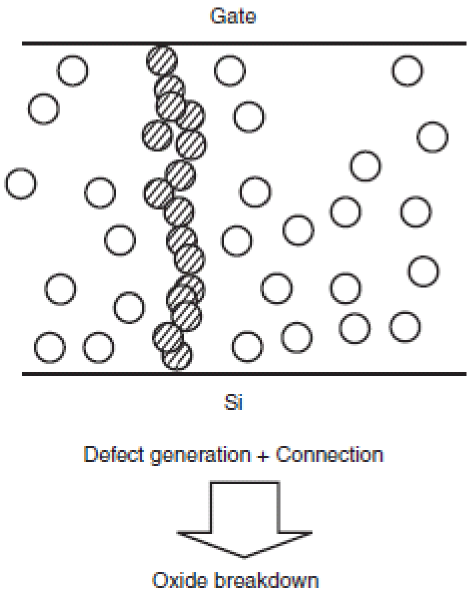
Physics of Failure (PoF)

- **Assumption of single dominant damage mechanism can lead to wrong extrapolation of lifetimes from accelerated tests.**
- **PoF aims to understand different failure mechanisms**
  - **Fit model parameters to data for each damage mechanism**
  - **Combine results to predict reliability at operating conditions**
  - **Health warning: competing models for some damage mechanisms can give very different extrapolations to operating conditions.**

Time Dependent Dielectric Breakdown (TDDB)

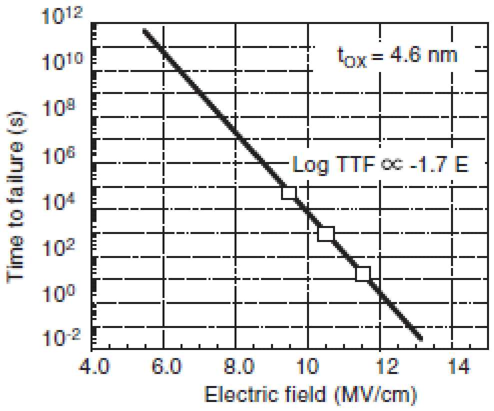
- **In DSM processes E fields over gate oxides ~ 5 MV/cm cf breakdown fields of > ~ 10 MV/cm.**
  - **Gradual degradation ➔ later failures**
- **Acceleration model**
  - **Mean Time to Failure (MTTF)**
  - $\mathrm{MTTF}=A\times10^{-\beta E}\exp(-Ea/kT)$
  - Example fits look ok but activation energy not constant? ➔ next slide
  - ➔ can't fit to single failure mechanism!

Holes injected into oxide ➔ Stress Induced leakage currents by tunnelling ➔ breakdown



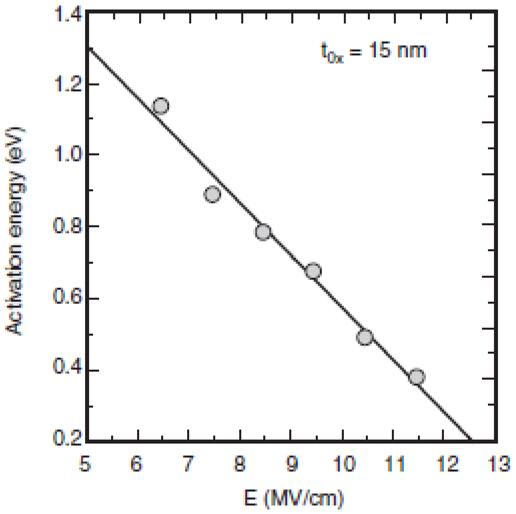
TDDB Fits

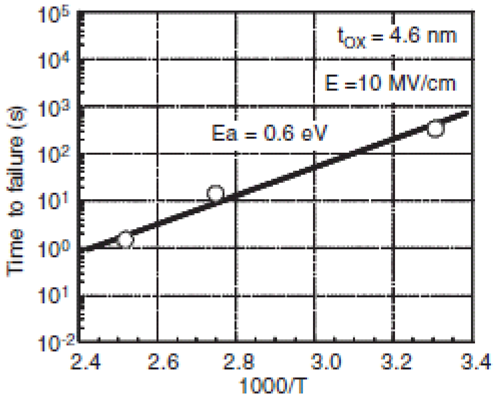
- **Fits to Voltage (E field) and T look ok but estimated value of Ea depends on E ?**



MTTF vs E

Fitted E_a not constant!





MTTF vs 1/T

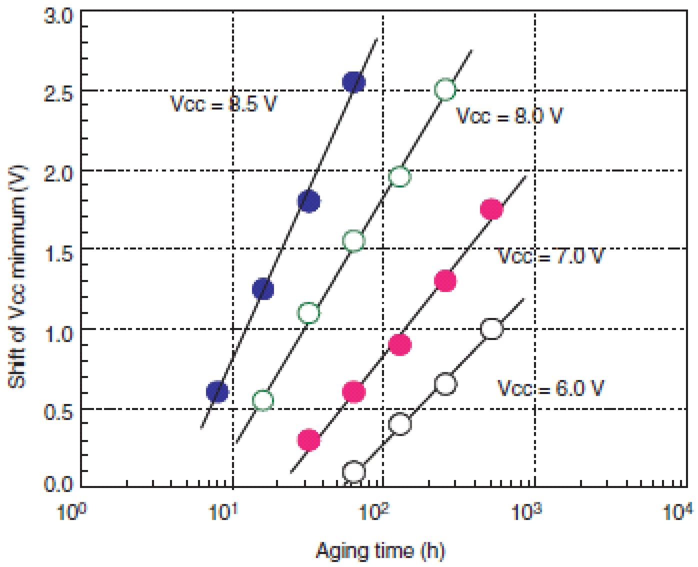
Hot Carrier Injection (HCI)

- Non-ideal scaling $\rightarrow$ larger E fields $\rightarrow$ "hot" carriers can overcome barrier between Si and gate oxide
  - Trapped charges lead to changes in V_{Th} and g_m
  - Eventually lead to failure
  - $t = c\,(I_{sub})^{-m}$
  - T dependence because at low T electron mfp longer $\rightarrow$ acquire more energy in E field $\rightarrow$ impact ionization.

HCI

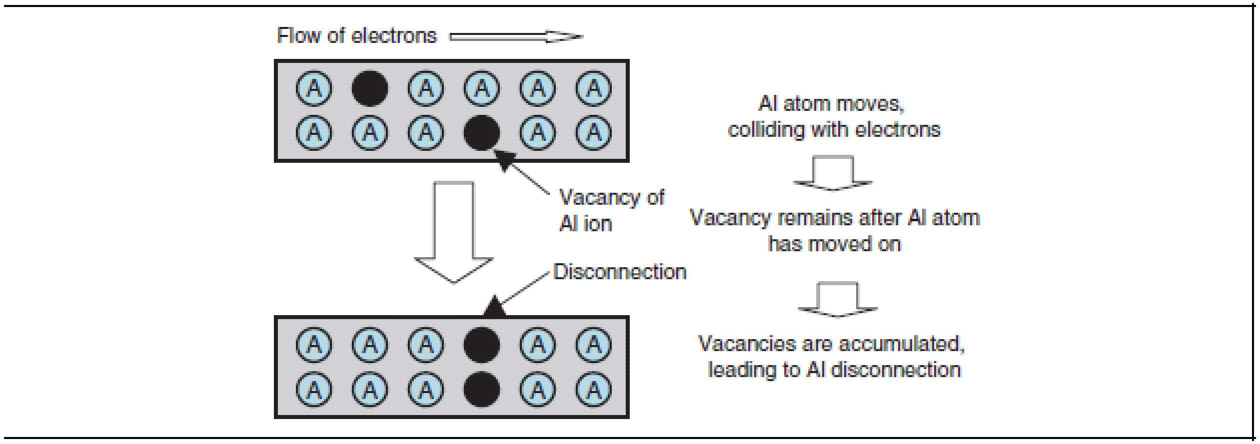
- **Example fits to threshold shifts.**
- **Typical fit values**
  - **m ~ 3**
- **Also need to consider T variation.**

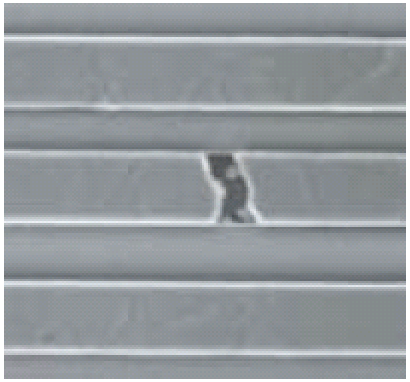
- Shift Min Vcc



Electro-migration (EM)

- **High current densities, force exerted by electrons large enough to cause diffusion of metal ions in the direction of the e flow.**
  - **Creates voids ➔ increases R ➔ thermal runaway ➔ open circuit**
  - **Excess build up of ions at the anode can give short circuit**
- **Very sensitive to material, doping, grain boundaries etc…**
- **EM is thermally activated, T gradients ➔ flux divergences.**
- **Best model** $MTTF = A(j_e)^{-n}\exp(E_a/kT)$
  - **Typical values : Ea=0.6 eV and n ~ 2.**





Other Mechanisms

- **NBTI (Negative Bias Temperature Instability)**
  - Degradation (Vth/Gm shift) occurring due to negative biased BT (bias temperature) stress in PMOS FETs
- **Stress migration**
  - CTE mismatch can cause stress even with no current.
- **Assembly & packaging**

Combining Failure Rates

- **Common method is just to assume exponential distributions**
  - **Total failure rate:** $\lambda_{TOTAL} = \sum_i \lambda_i$
  - **But we know that failure distributions aren't exponential !**
- **Failure distributions better modelled by Weibull or log-normal distributions.**
- **Finally we don't actually want MTTF we need MTT01 (1% failure) or MTT10 (10% failure).**
  - **Need to combine distributions correctly from different failure mechanisms.**
  - **Determine MTT0X numerically**

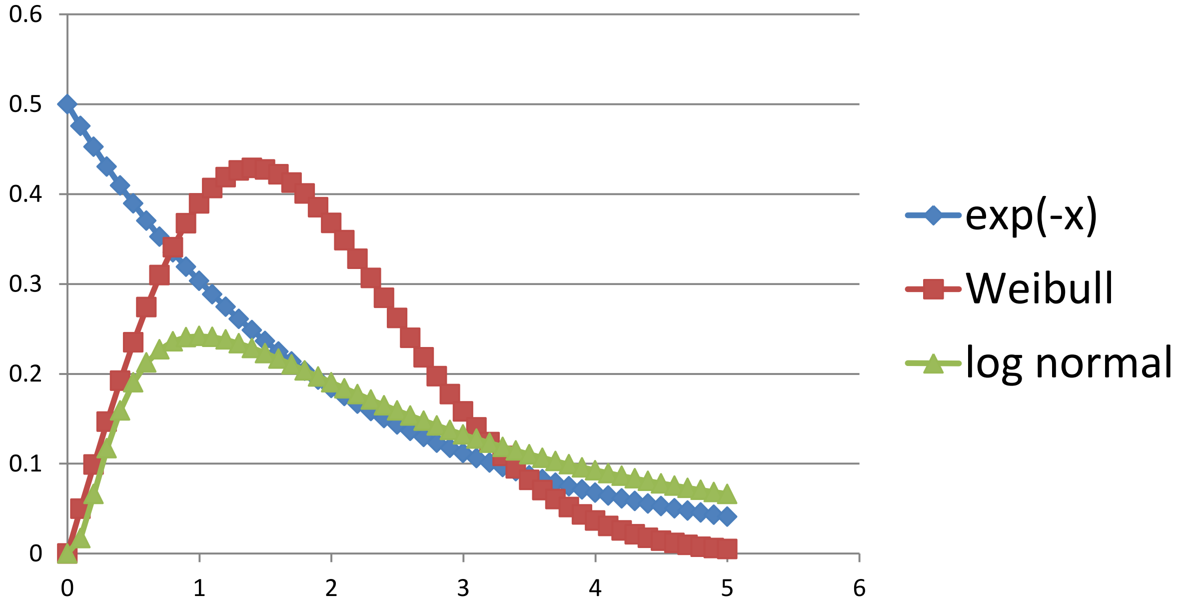
Weibull Distribution (from Wiki)

$$f(x;m,\lambda)=\frac{m}{\lambda}\left(\frac{x}{\lambda}\right)^{\lambda-1}e^{-(x/\lambda)^{m}}$$

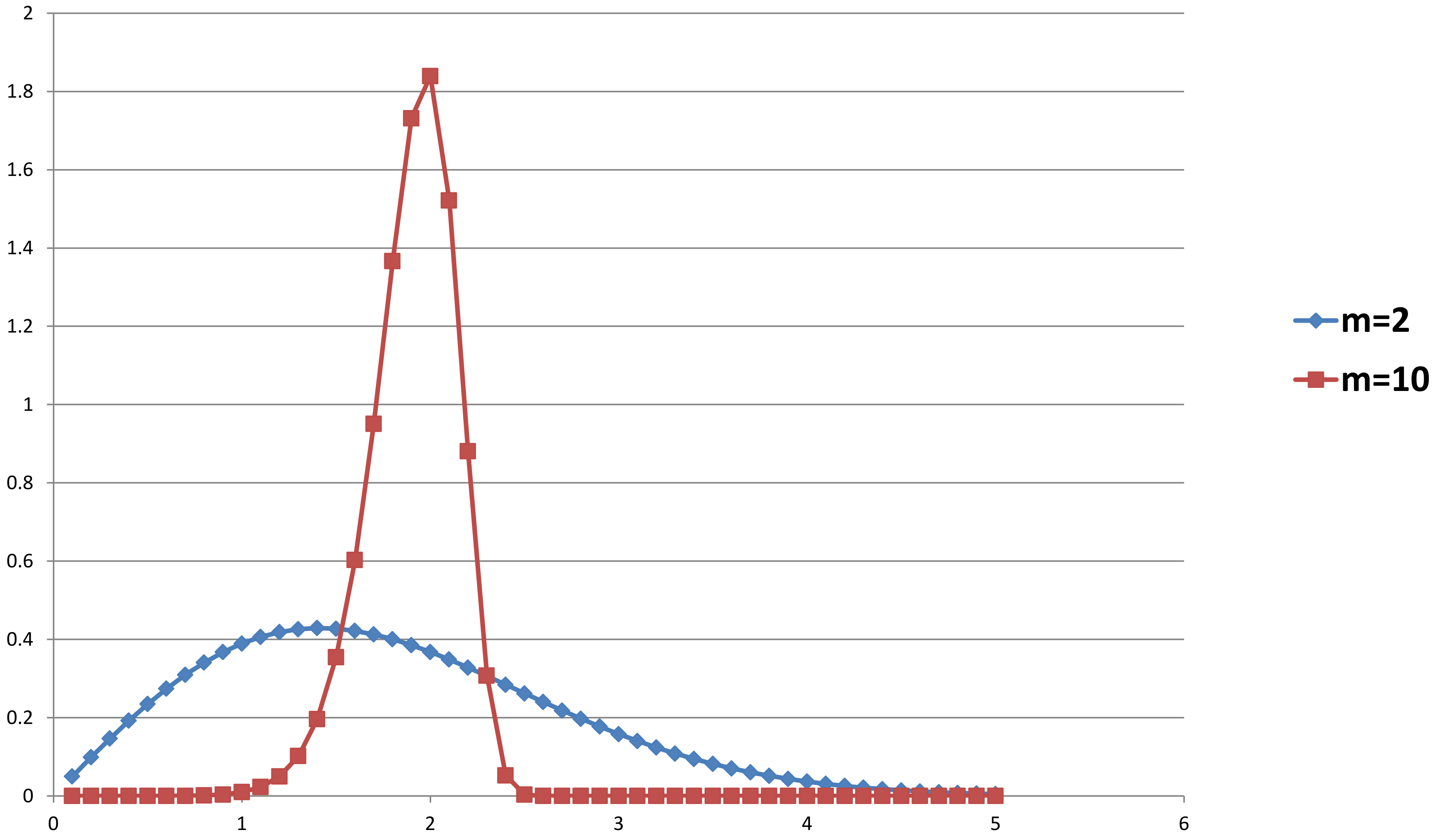
- Commonly used distribution in reliability theory
- *m* < 1 indicates that the failure rate decreases over time ➔significant "infant mortality".
- *m* = 1 ➔ failure rate is constant over time, i.e. random failure.
- *m* > 1 failure rate increases with time. This happens if there is an "aging" process

Compare Distributions

- Compare exponential, Weibull and log-normal
- Note Weibull and log normal totally different from exponential for small x
  - This is just the region we are interested in!



Example Weibull Distributions



Measuring MTTF

- How well can we determine MTTF in an AL (Accelerated Lifetime) test? Depends on
  - Sample size
  - Weibull shape parameter n.
- Example Fits
  - Assume n=2 (pessimistic)

Sample size	% error t_m
10	18.9
30	10.0
50	8.2

  - Assume n=10 (optimistic)

Sample size	% error t_m
10	3.8
30	2.0
50	1.7

Determining Model Parameters

- Brute force: Run ALT for matrix of different T and V and fit data to get model parameters.
  - Too many tests → too slow/expensive.
- Smarter approach
  - High T/High V → TDDB
    - Vary T → Ea, vary V → exponent c
  - Low T/High V → HCI
    - Vary T → Ea2, vary V → γ_2
  - High T/low V → EM dominates
    - Vary T → Ea3

Determining (V,T) Grid

- Use case assumed: V=1.2V, T=20C.
- Assumed 3 damage mechanisms have equal rates at use condition (pessimistic)
- (V,T) Matrix designed to determine model parameters with minimum number of tests.
  - EM: Temp values

85	95	110

  - TDDB: Voltage values:

1.5	1.6	1.7

  - HCI:

	Temp	C	
Voltage	-20	-10	0
1.55		x	
1.5	x	x	x
1.45		x	

(V,T) Grid

- **Simplify analysis**
  - Can we factorise different damage mechanisms in fits?
  - Look at purity
  - Not perfect?

EM	TDDB	HCI
88.3	11.7	0.0
0.0	95.1	4.9
0.0	11.6	88.4

  - **Acceleration rates:**
    - high so that tests last not longer than ~1000 hours
    - Not too high so that other mechanisms are dominant and extrapolation to use case is too large.
    - AF in range 10^3 to 2 10^5.

Errors on Acceleration Factors from Fits

- EM fits for E_a in $\exp(-E_a/kT)$

% error MTTF	% error AF
2	7.5
4	15.0
8	12.7
10	30.8
20	95.8

- TDDB fits for c in v^c

% error MTTF	% error AF
2	4.5
4	8.8
8	17.9
10	21.9
20	47.6

- HCI fits

T variation
➔ E_{a2}

MTTF error %	AF error %
2	3.8
4	7.6
8	15.5
10	19.0
20	42.3

V variation
➔ γ

MTTF error %	AF error %
2	4.9
4	9.8
8	20.1
10	24.7
20	59.9

Next Steps

- Global Fits:
  - Use all (V,T) data in one fit
  - Build reliability model ➔ plot predicted cumulative failure rates at some reference point.
  - Predict MTT10 and MTT01 failure
  - Note: eventually this type of information will be used to decide whether we need redundancy.

Practical issues

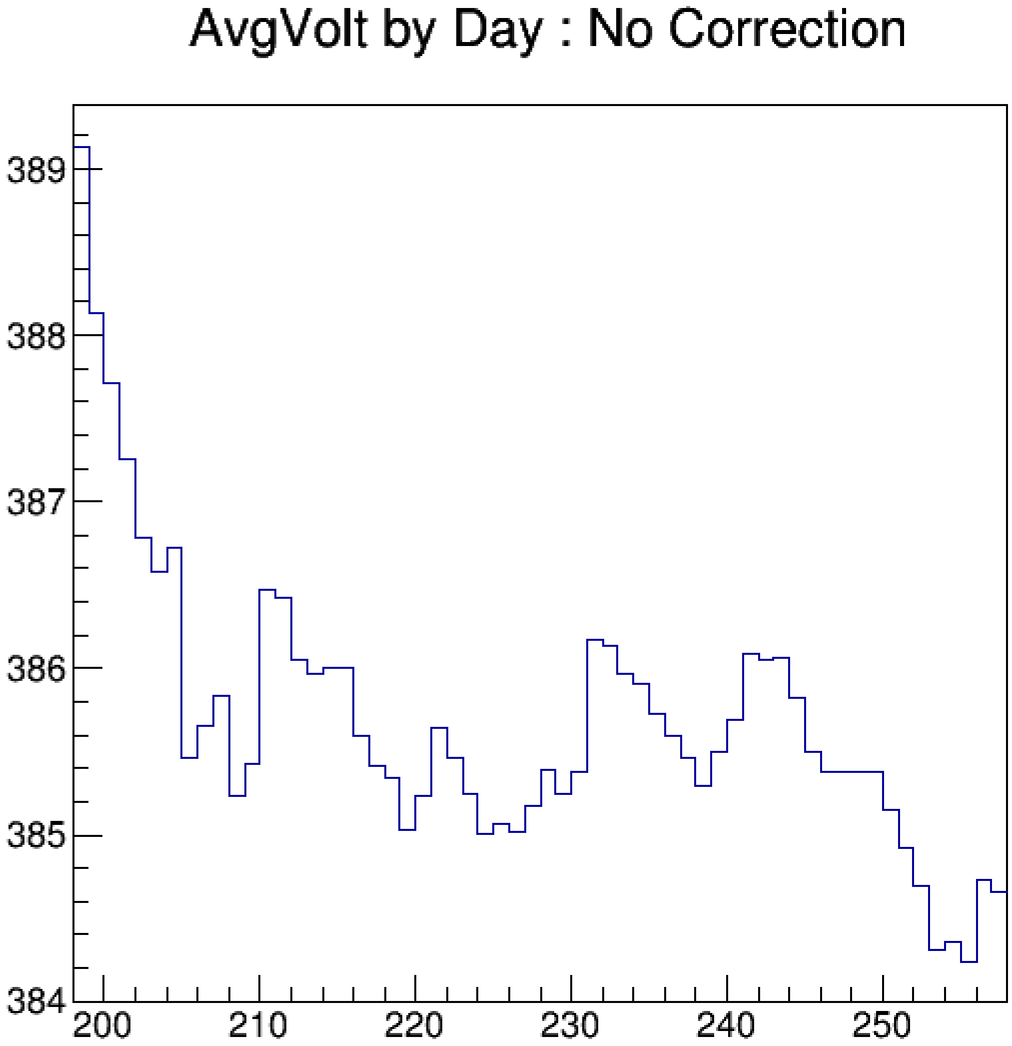
- Can we use this (V,T) range (TBD with Paulo).
- Need minimum 11 grid points and between 10 and 30 chips per point.
- Also need to do quick tests with fewer chips to determine centres of the grids.
  - Check that MTTF is in reasonable range (1 to 1000 hours).
- Number of chips required in range 150 to 400.
- Use several environmental chambers
  - Combine tests at same T but different V conditions → need between 3 and 7 environmental chambers depending if all tests are done in parallel or some in series.
  - Hope to find new collaborators …

References

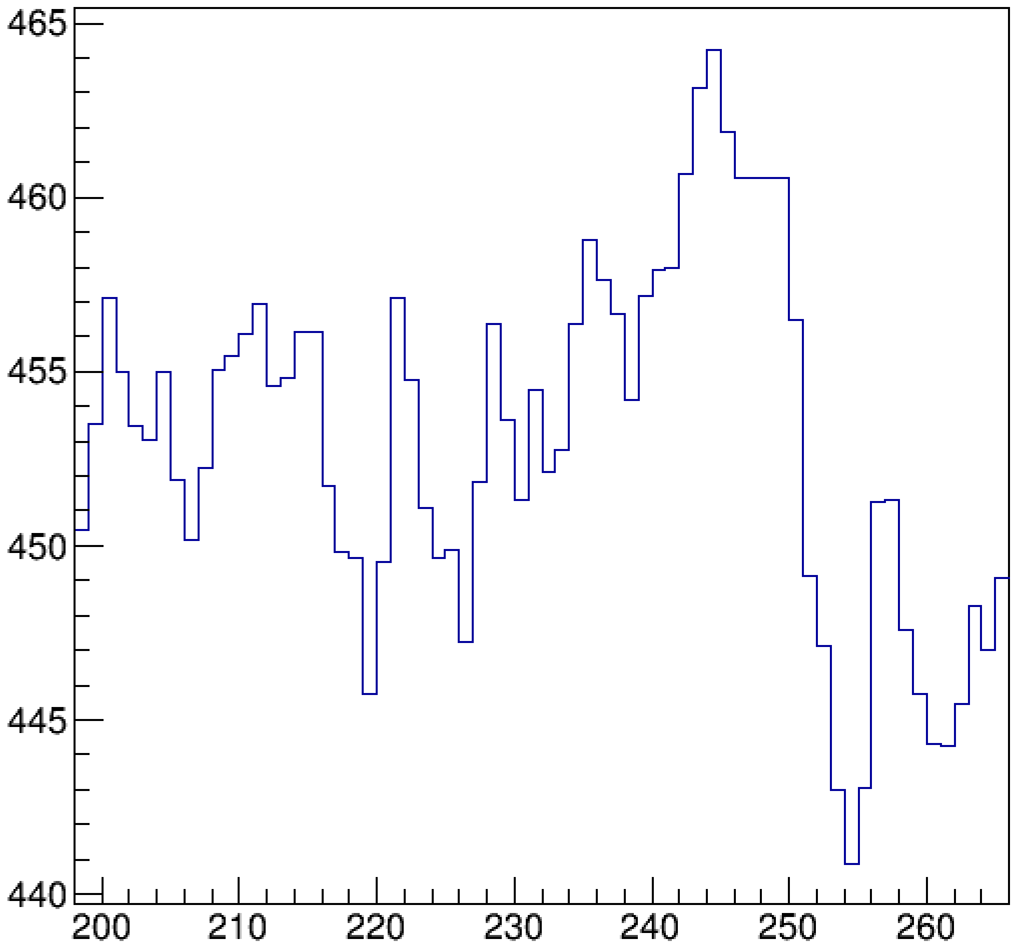
- Bernstein, Physics of Failure Based Handbook of Microelectronic Systems, RIAC.
- Srinivasaan et al, The impact of Technology Scaling on Lifetime Reliability, DSN-04.
- Semiconductor Reliability Handbook, www.renesas-electoronics.com

LTx in SR1

- LTx optical power.
- No T correction
- Initial decrease ~1%.
  - No burn-in preformed for this array ➔ probably ok but should run longer



AvgVolt by Day : No Correction

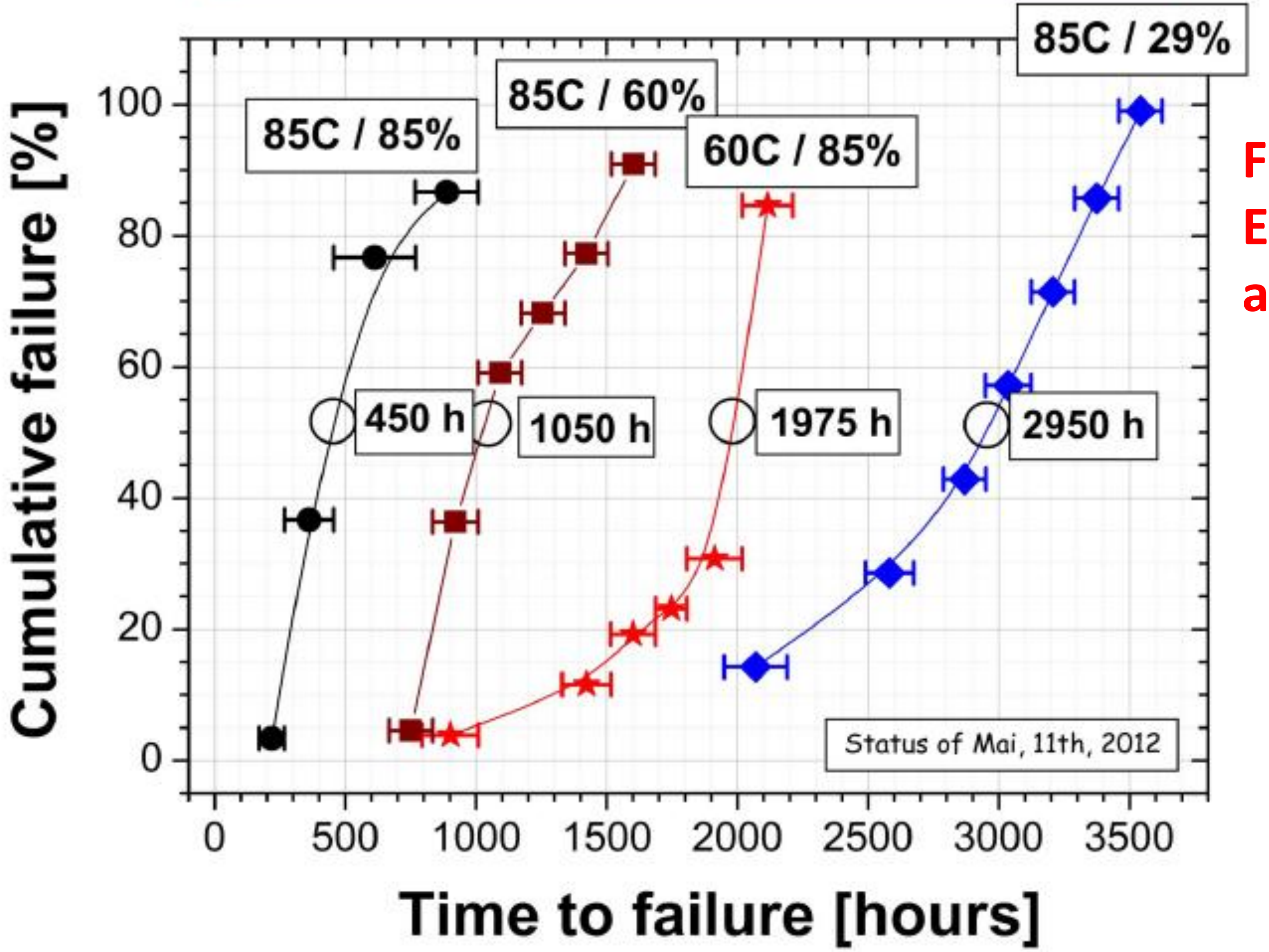


Accelerated Aging Tests

- **Measure Mean Time To Failure at several elevated temperature/current and RH use Arrhenius equation for Acceleration Factor from (I_2,T_2) to (I_1,T_1) Activation energy: E_A and exponential for relative humidity (RH).**

$$AF = \left(\frac{I_2}{I_1}\right)^2 \frac{\exp\left\{\frac{-E_A}{k_B T_2}\right\}}{\exp\left\{\frac{-E_A}{k_B T_1}\right\}} \qquad AF = \exp(a * RH)$$

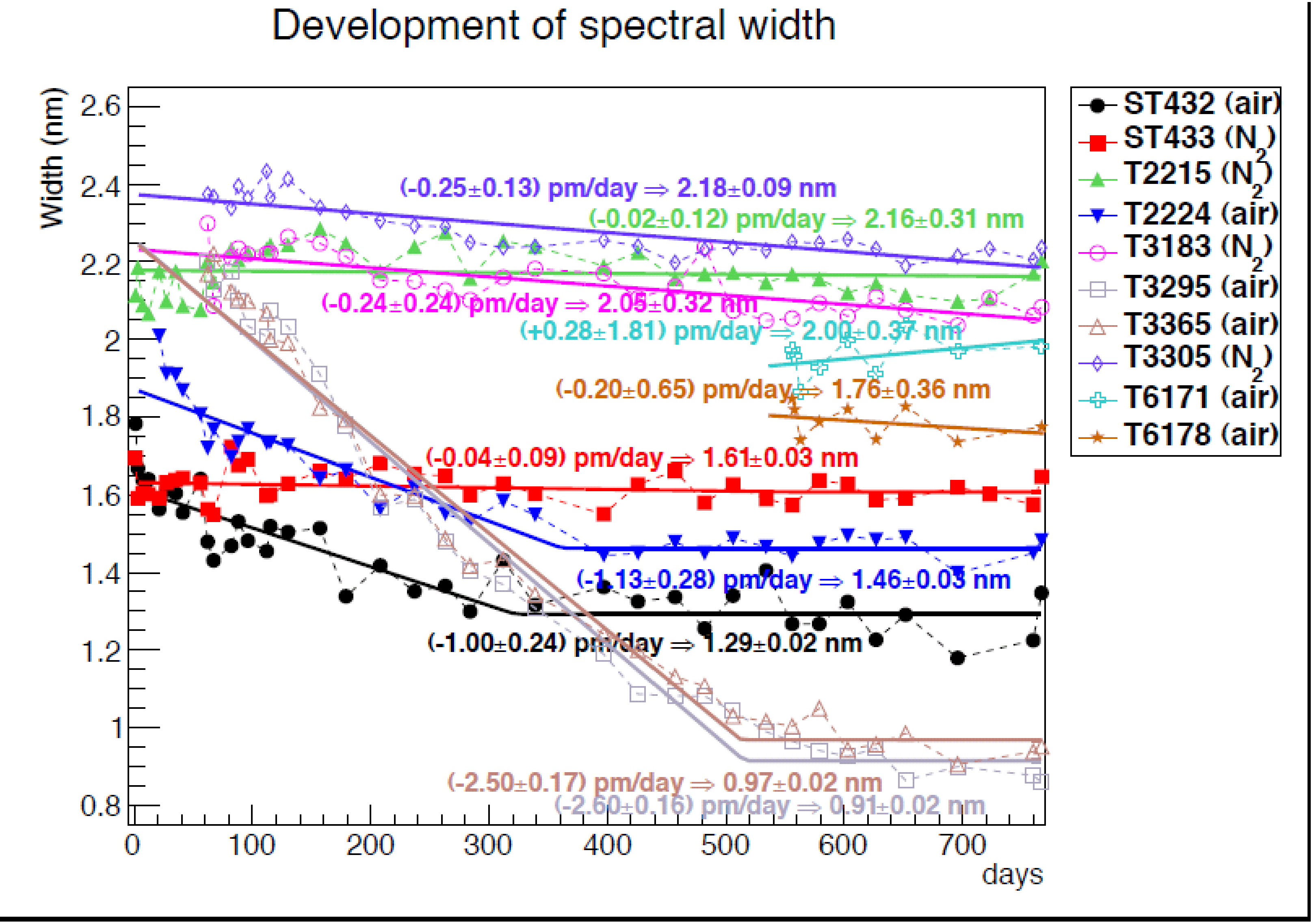
Results from four accelerating tests for the TrueLight VCSEL



Fit Results

E_A=0.72 eV

a = 0.059 (/%)

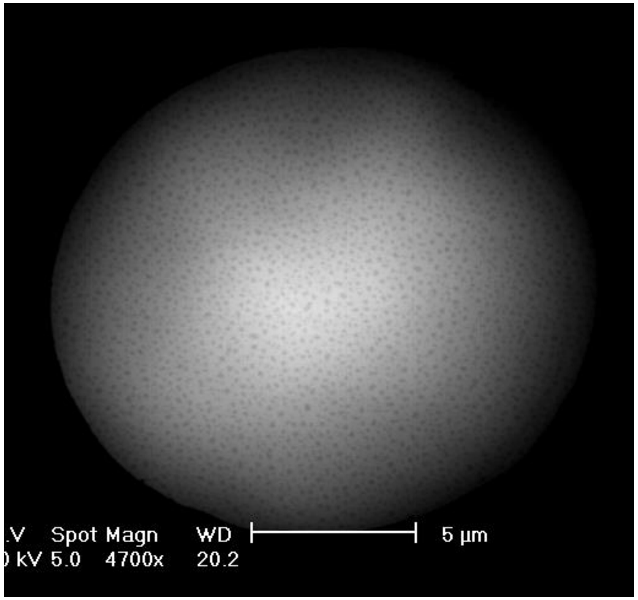


VCSELs in air show decrease in width with time and then plateau

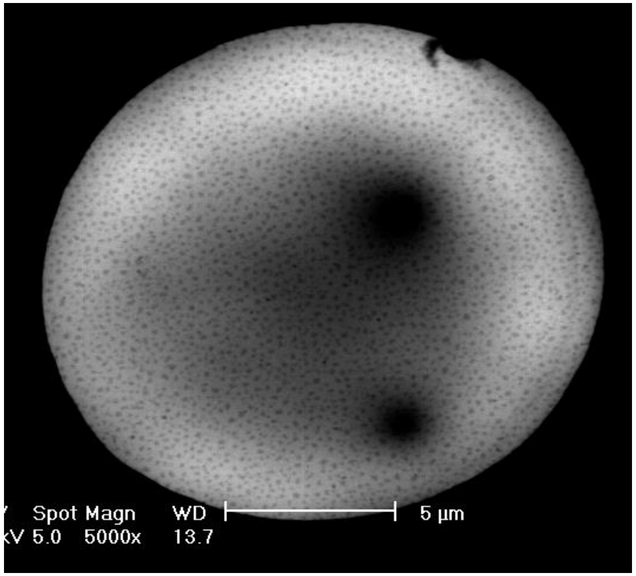
VCSELs in dry N2 show no decrease in width with time

EBIC comparison working & Failed channels TL VCSEL array

Working



Dead



- All taken with same SEM settings: 10KV spot 5 (roughly same mag 4700X and 5000x)
- Original Image LUTs stretched to accentuate EBIC changes across VCSELs
- Only Ch 10 shows distinct EBIC minima (dark spots) within the emission region
- Ch 06 & 08 show some inhomogeneity but no distinct minima
- Small dark speckles are surface topography

Analysis by EAG

STEM Unused Channel
TL VCSEL array after FIB cut

Top DBR

oxide

MQW (active region)

Bottom DBR

Analysis by EAG

Example Spectra

- Air ~ 50% RH
  - Loss of higher order modes visible
- Dry N_2
  - Higher order modes very similar