In-Situ Radiation Damage Studies for SCT Optical Links

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on behalf of the ATLAS SCT Collaboration

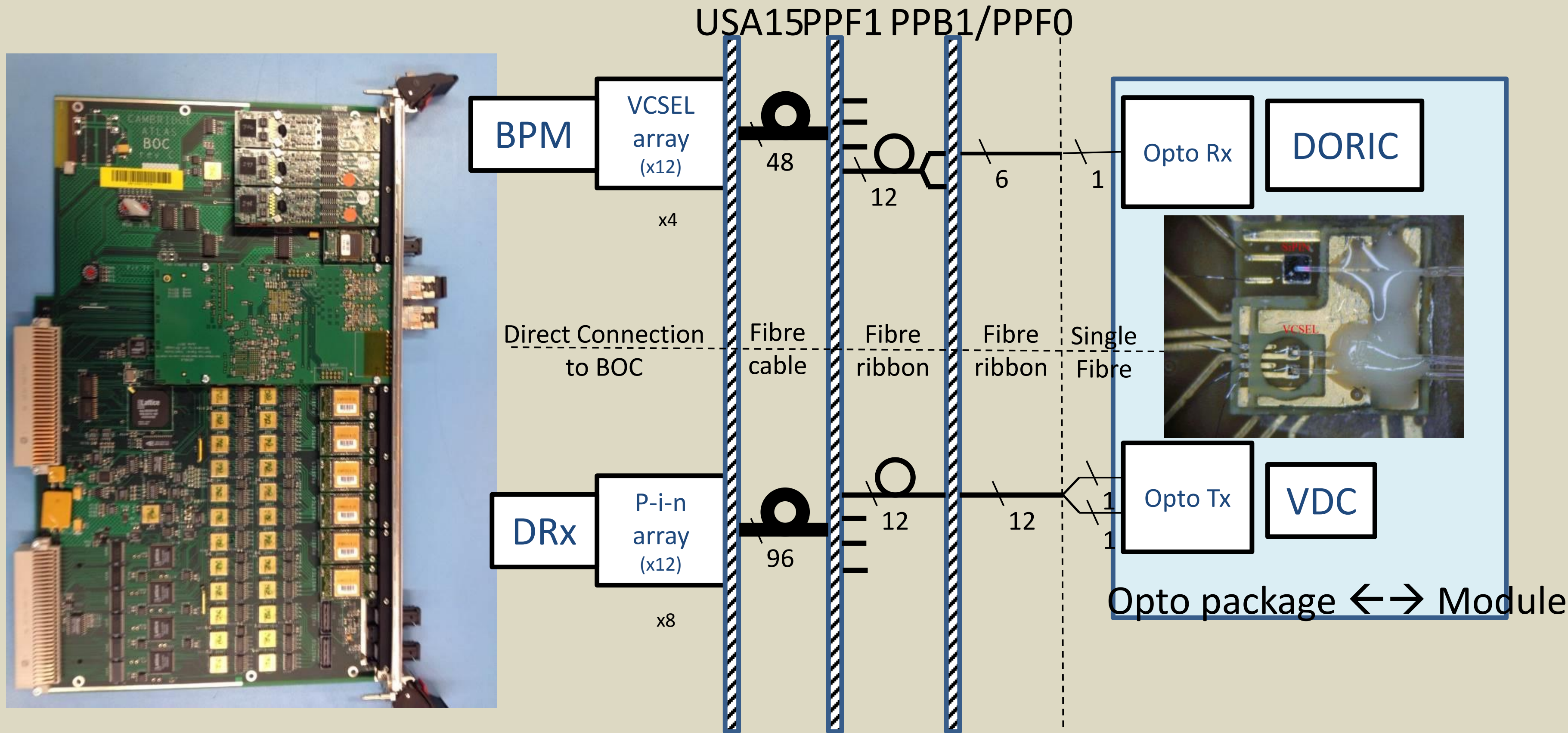
Radiation damage workshop

CERN, 23rd April

Outline

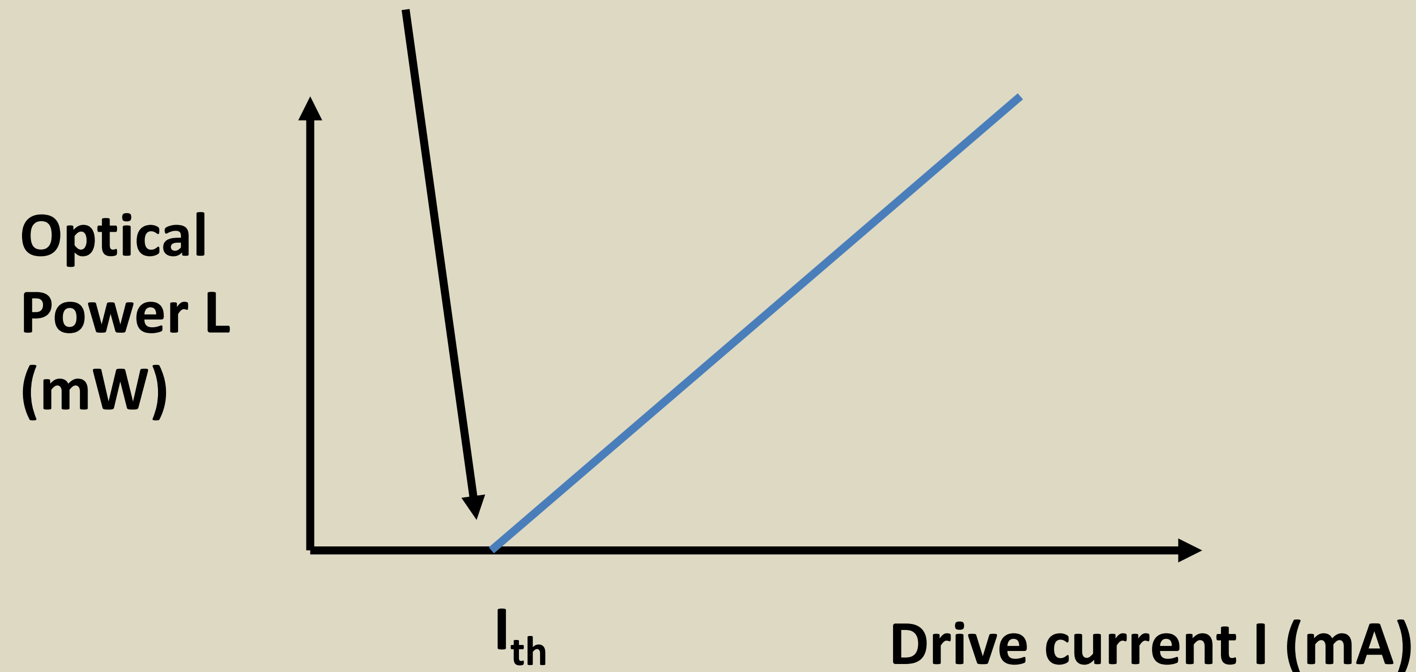
- SCT optical links
- Summary test beam radiation damage
  - VCSELs
  - *p-i-n* diodes
- In-situ radiation damage studies
  - VCSELs
  - *p-i-n* diodes
- Comparisons test beam and in-situ measurements.

SCT Optical Links



VCSEL Definitions

- Threshold and slope efficiency =dL/dI



Test Beam Studies: VCSELs

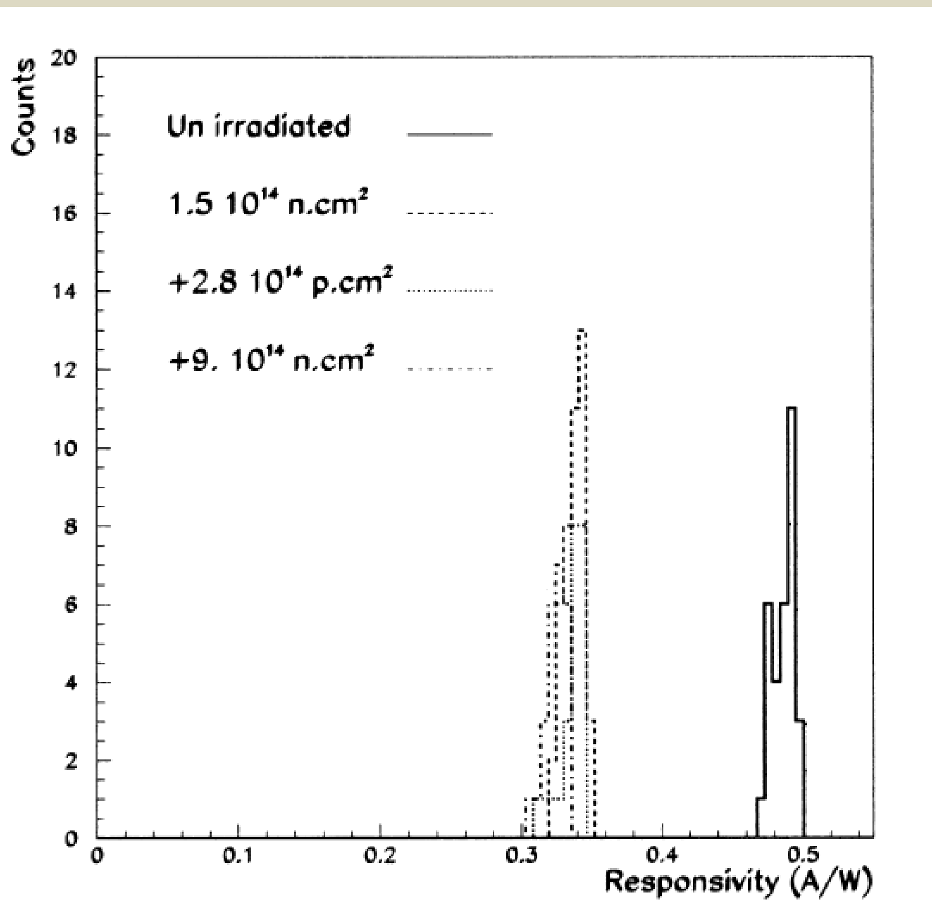
- Beams used
  - 30 MeV p, 24 GeV p and neutrons.
- 20 VCSELs from SCT production wafer.
  - 30 MeV p, F=2 10^{14} p/cm^2.
  - Before irradiation: threshold (3.28 ± 0.09) mA.

Condition	Threshold shift (mA)	Relative slope efficiency (%)
After irradiation	3.0 ± 0.4	73 ± 4
+1 week annealing 10 mA	0.94 ± 0.11	88 ± 4
+1 week annealing 20 mA	0.42 ± 0.11	98 ± 3

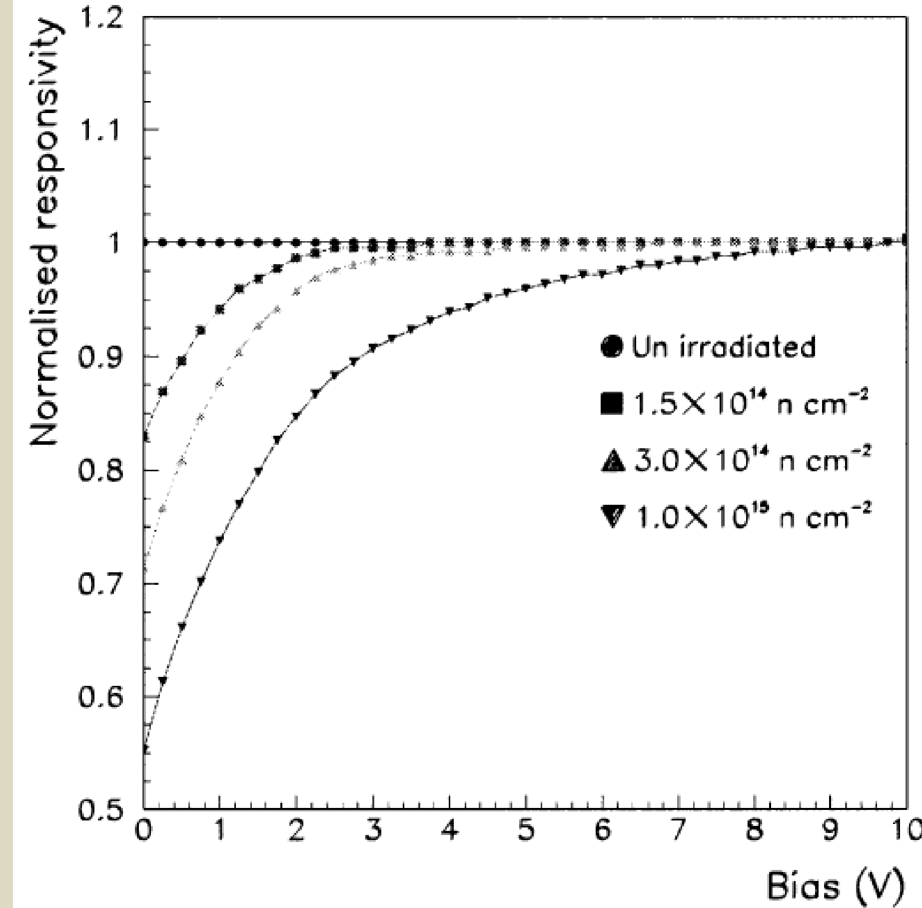
Test Beam Studies: p-i-n diodes

- **Samples**
  - 30 *p-i-n* diodes from ATLAS production wafer.
- **Beams used**
  - 24 GeV p and ISIS neutrons.
- **Measured dark current, responsivity and depletion voltage.**
  - Cumulative. F= 1.05 10^{15} (1 MeV n_{eq}/cm^2).
  - Decrease in responsivity
  - Increase in depletion voltage
  - (Increase in leakage current)

Responsivity



Depletion Voltage



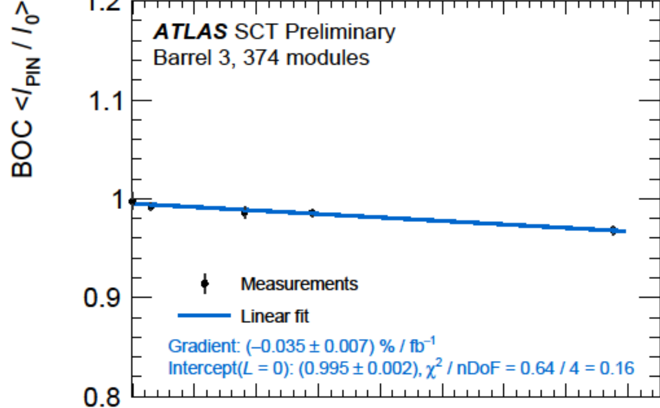
Fluences

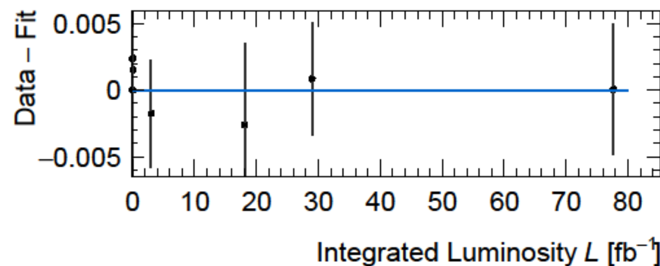
- Fluences calculated with Pythia8 and Fluka.
- Systematic error 30% (50%) barrel (End-cap).

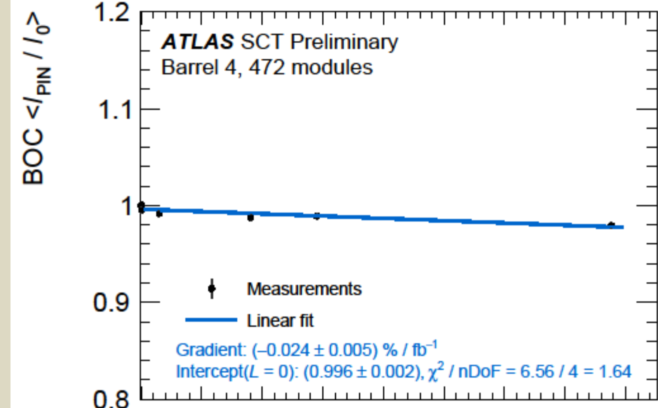
Layer	Fluence (10^{11} (1 MeV n_{eq}) cm^{-2} fb^{-1})
Barrel 3	2.67
Barrel 4	2.12
Barrel 5	1.77
Barrel 6	1.53
End-cap inner	3.22
End-cap middle	2.66
End-cap outer	2.26

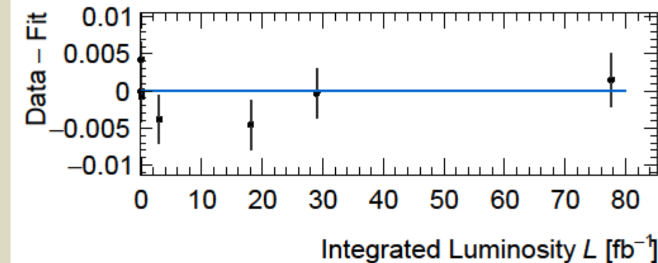
In-Situ Measurements: VCSELs

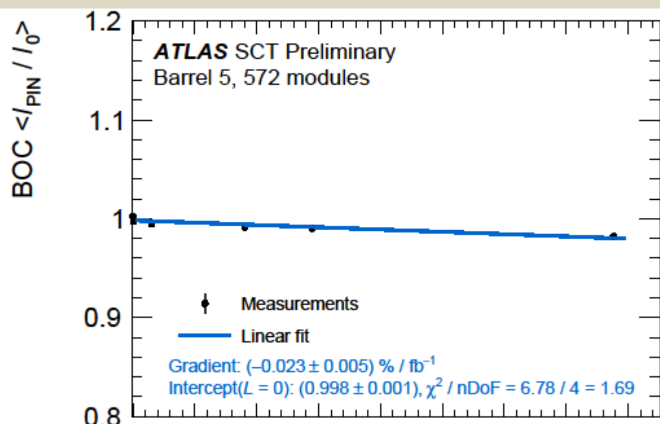
- Optical power measured in special scans by measuring photo-currents (Ipin) in receiver.
- For each barrel layer, EC ring, normalise photo-currents to start of 2016 data taking.
- For each scan, in each region determine <Ipin/Ipin_0>
- Plot < Ipin/Ipin_0 > vs luminosity.

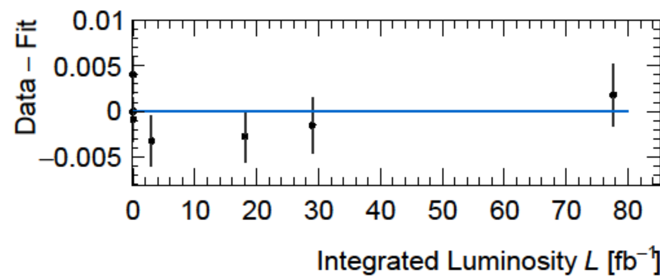




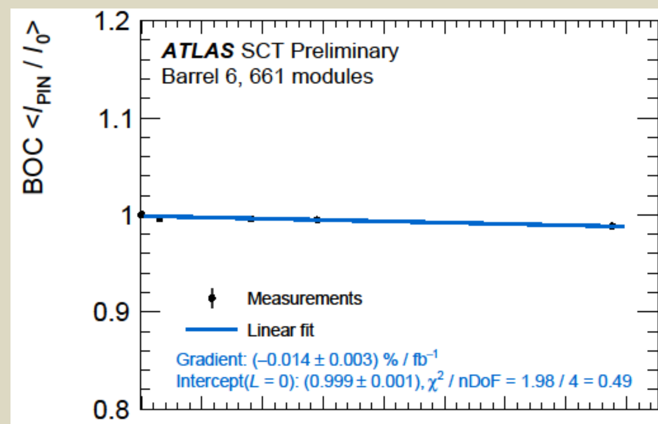


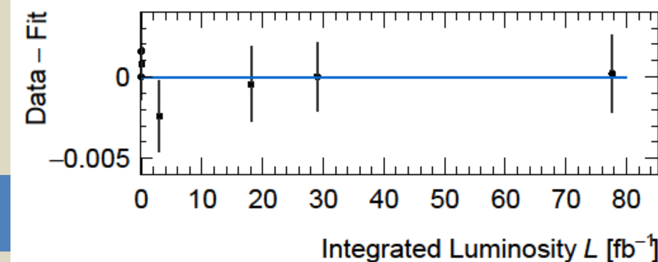


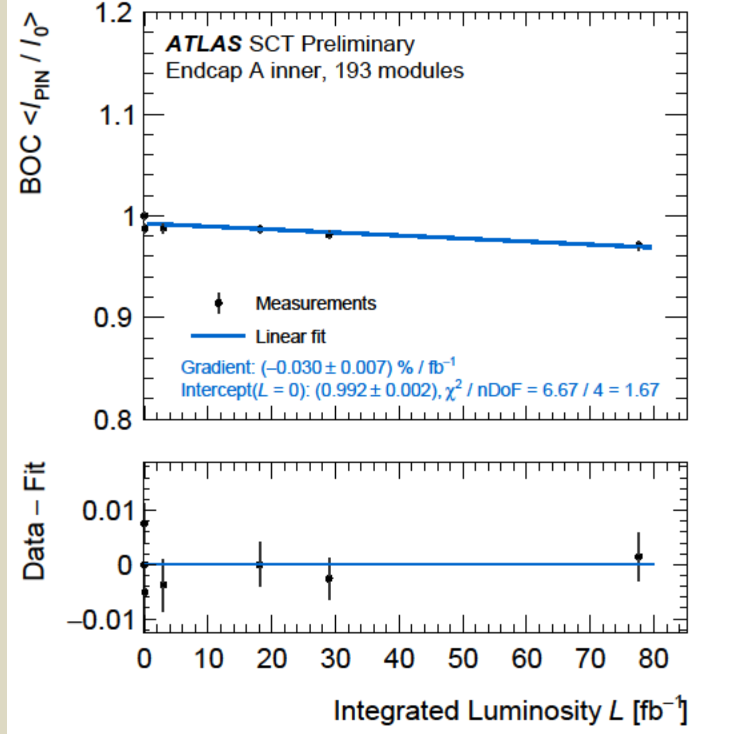


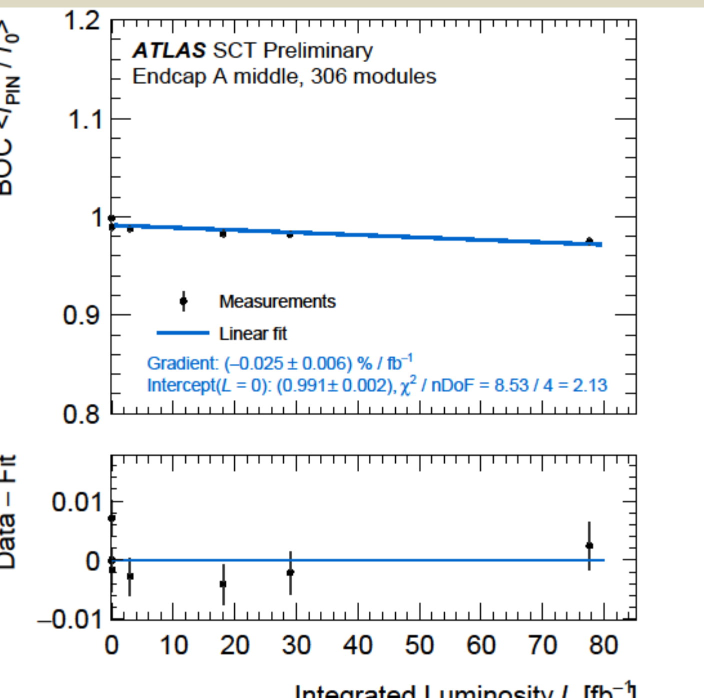


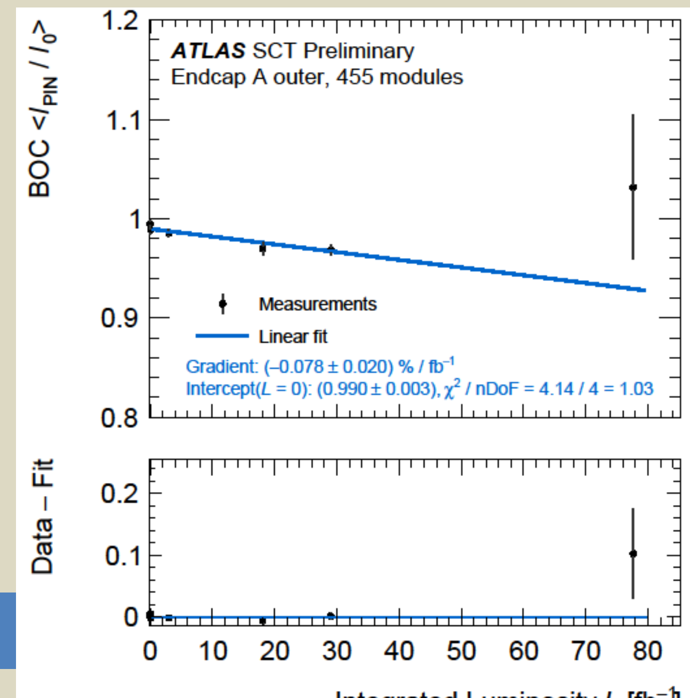
SCT Optical Links



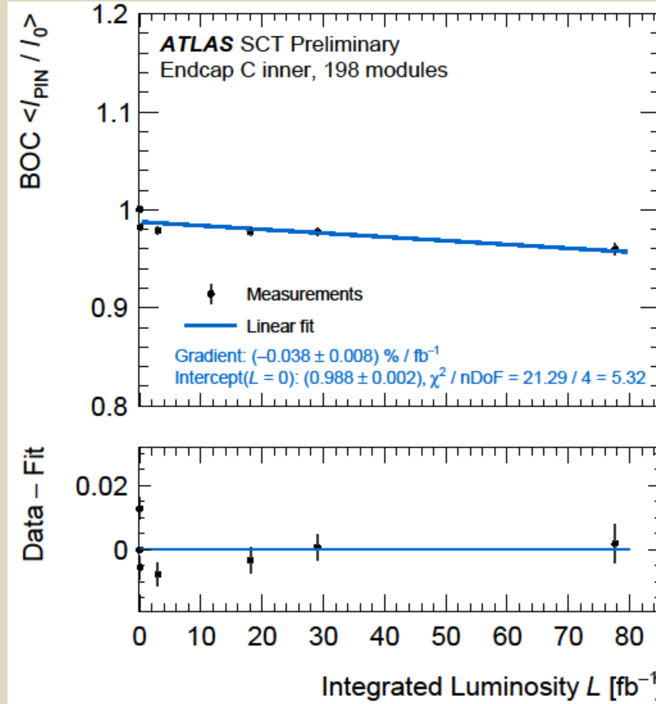


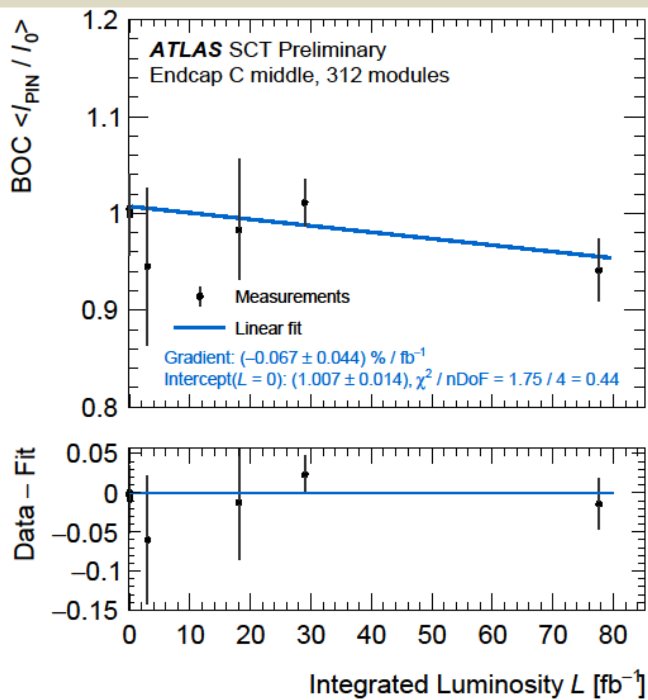




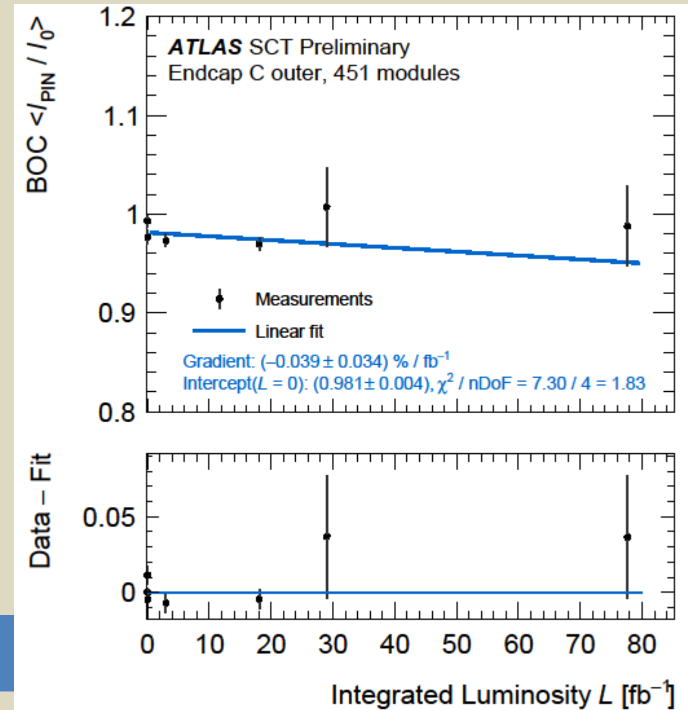


SCT Optical Links





SCT Optical Links



VCSELs: Gradients

Gradient (%/fb)					
Barrel		EC-A		EC-C	
3	-0.035 ± 0.007	Inner	-0.03 ± 0.007	Inner	-0.038 ± 0.008
4	-0.024 ± 0.005	Middle	-0.025 ± 0.006	Middle	-0.067 ± 0.044
5	-0.023 ± 0.005	Outer	-0.078 ± 0.02	Outer	-0.039 ± 0.034
6	-0.014 ± 0.003				

- Consistent results. Normalise to expected fluences.
- Gradient = (-1.09 ± 0.09) $\%/10^{11}$ (1 MeV n_{eq}/cm^2)

Comparison with Test Beam

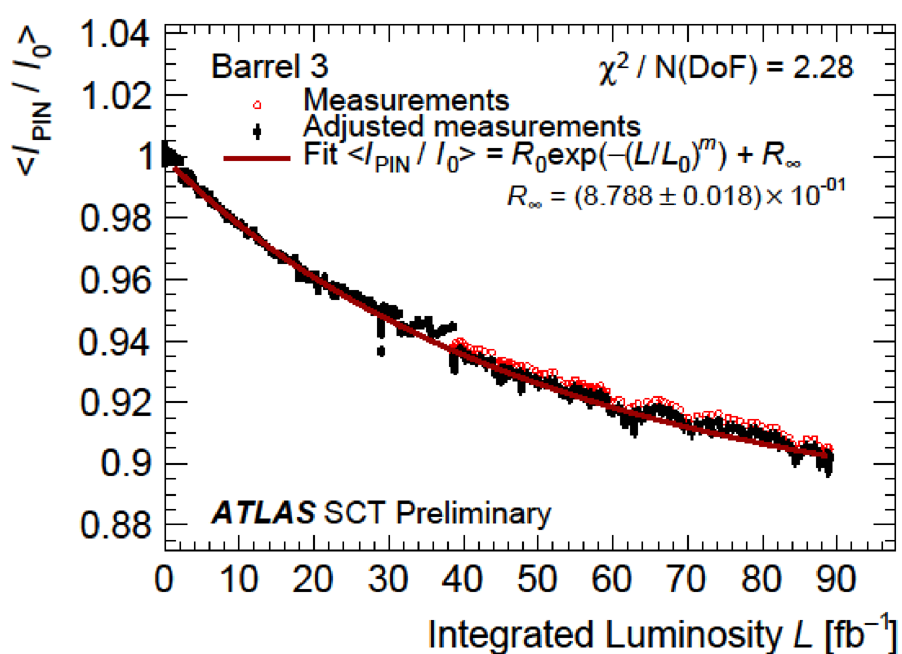
- Assume
  - Change in threshold and slope efficiency scale with fluence
  - NIEL scaling for GaAs

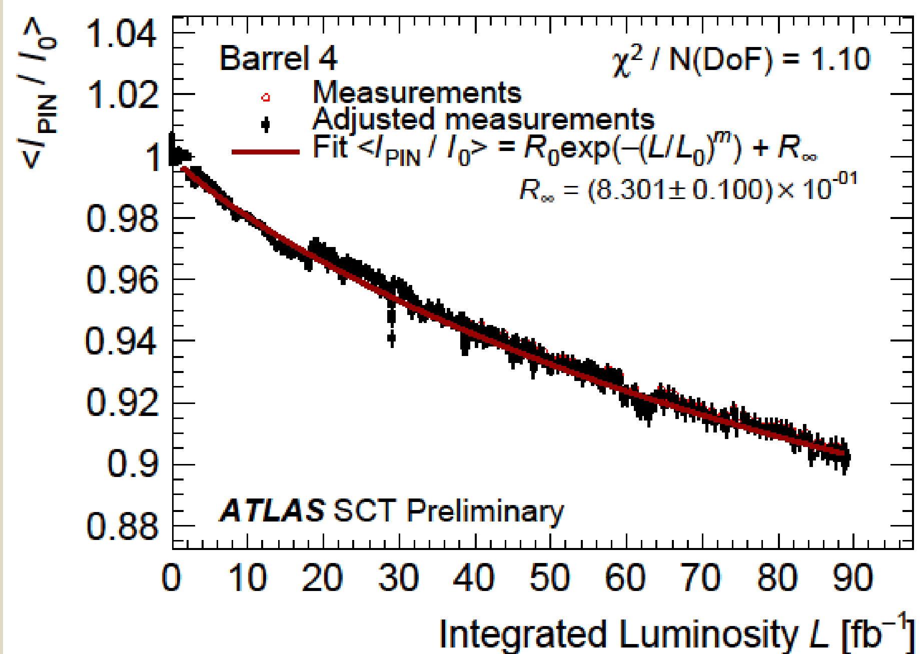
Condition	%/10^{11} (1 MeV n_{eq}/cm^2)
In-situ	1.09 ± 0.09
Test beam no annealing	1.7
+ 1 week annealing 10 mA	0.6

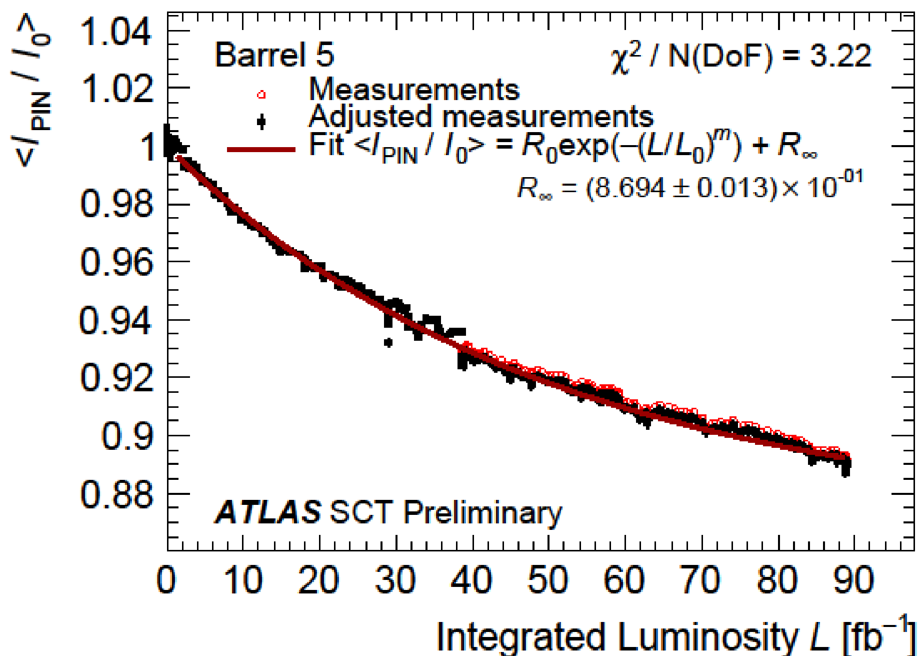
- 2016 operation equivalent to 6 weeks @ 10 mA DC.
- In-situ damage slightly larger than prediction?

In-Situ Measurements: *p-i-n* diodes

- Optical power measured every minute by power supplies.
- Average over 24 hours.
- For each barrel layer, EC ring, normalise photo-currents to start of 2016 data taking.
  - In some cases re-normalise 2017 data.
- For each scan, in each region determine <Ipin/Ipin_0>
- Plot <Ipin/Ipin_0> vs luminosity.







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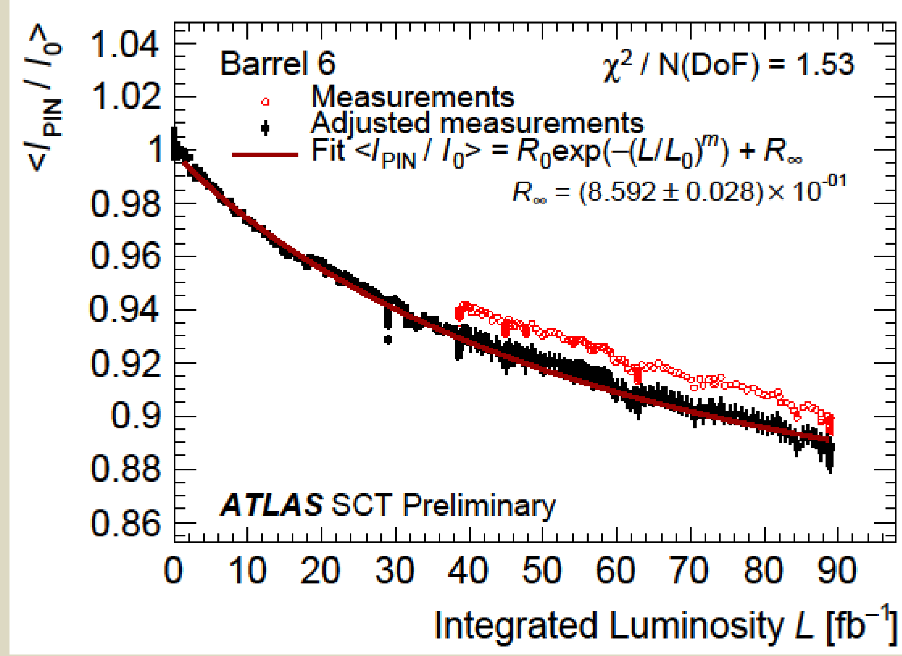
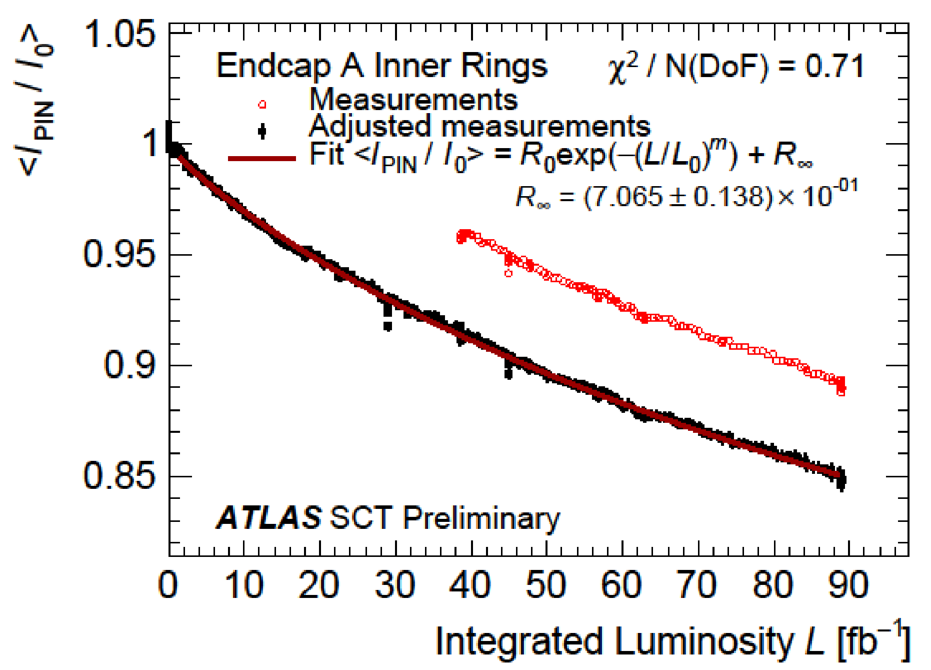
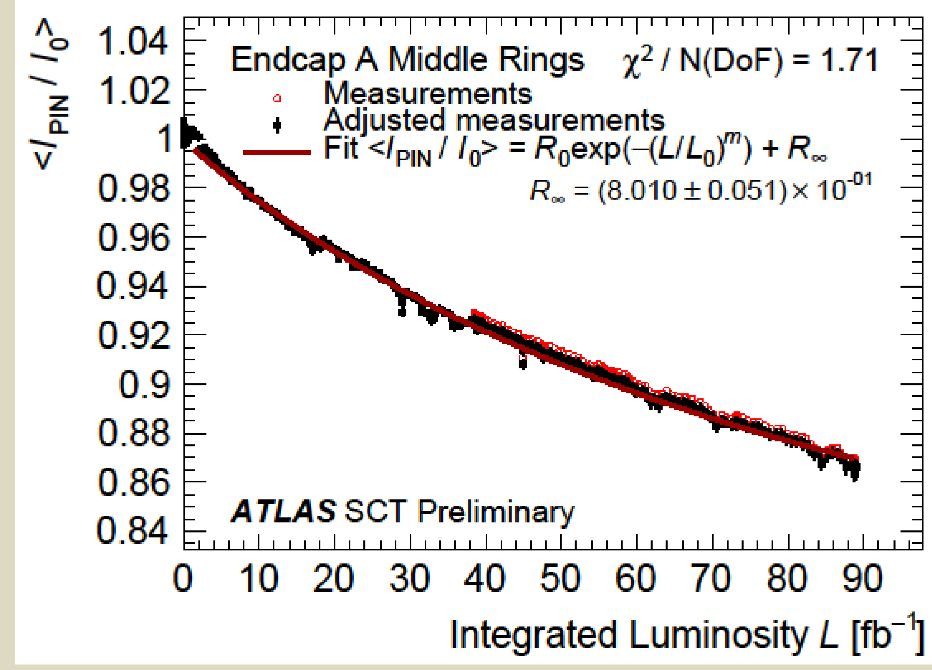
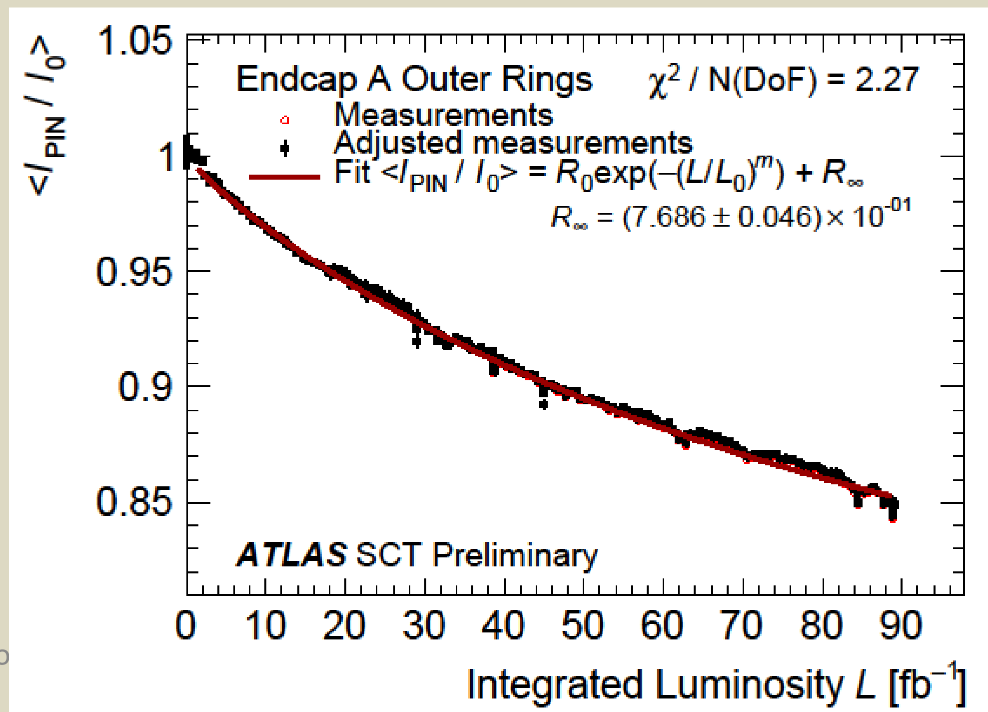
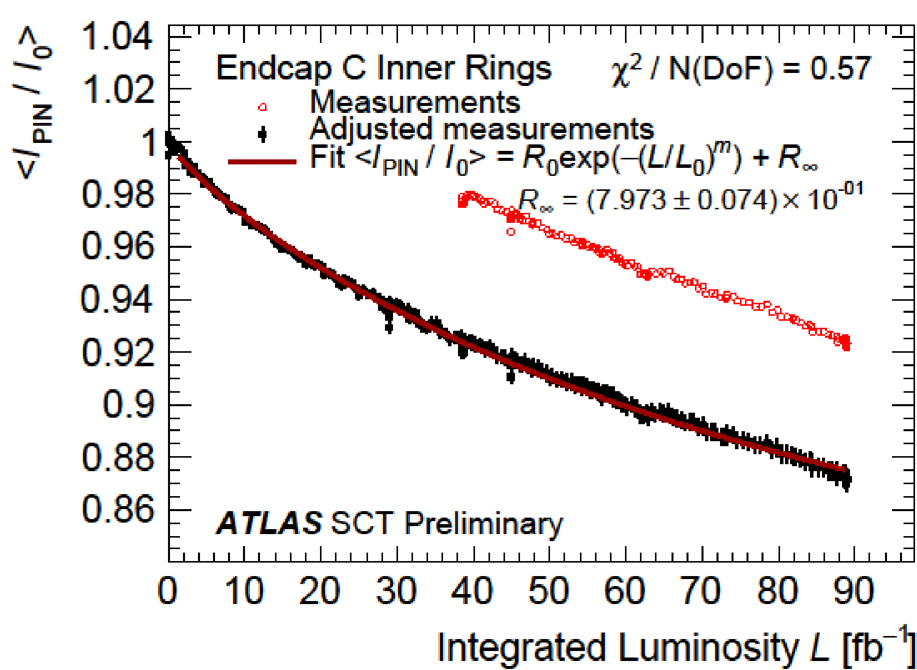
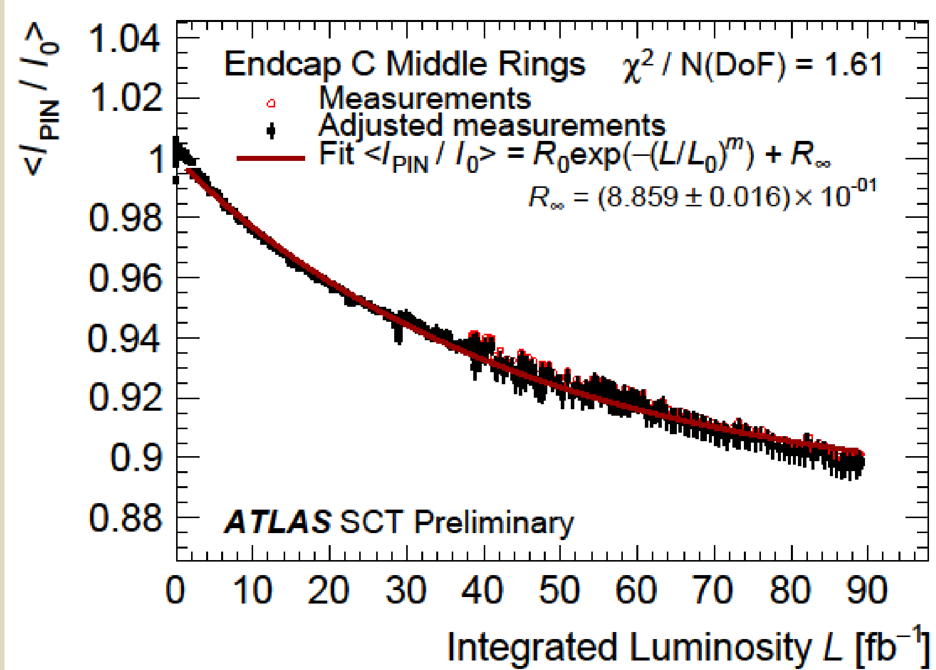


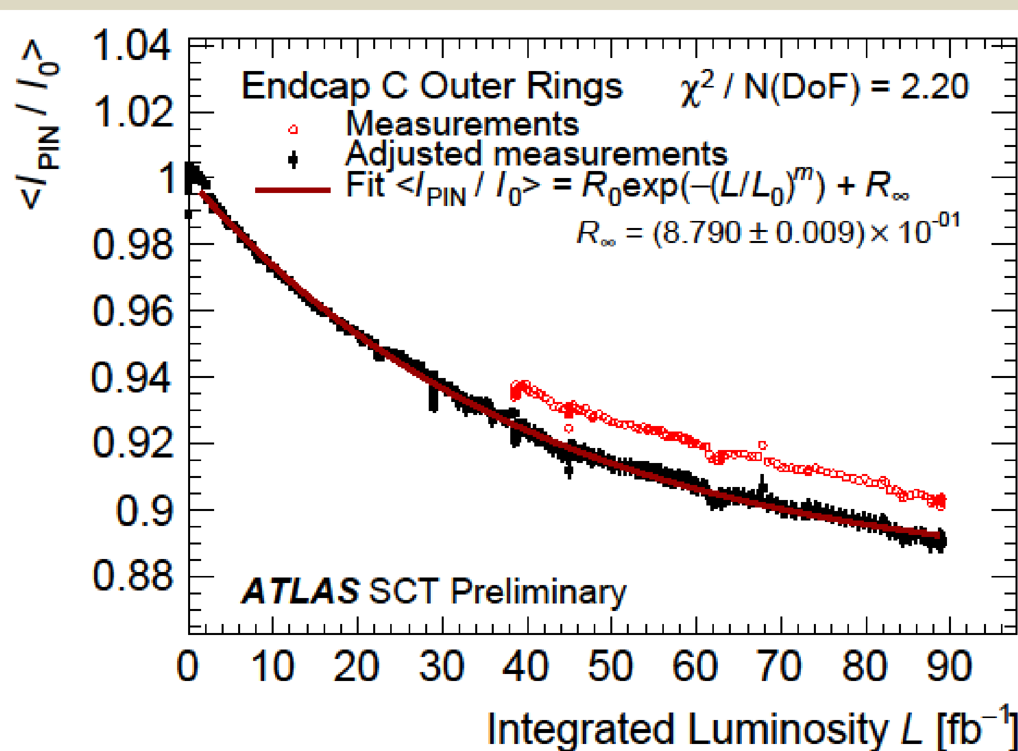

Endcap A Inner Rings
χ^2 / N(DoF) = 0.71
Measurements
Adjusted measurements
Fit $\langle I_{PIN} / I_0 \rangle = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (7.065 \pm 0.138) \times 10^{-01}$
ATLAS SCT Preliminary
$\langle I_{PIN} / I_0 \rangle$
Integrated Luminosity L [fb^{-1}]


Endcap A Middle Rings
χ^2 / N(DoF) = 1.71
Measurements
Adjusted measurements
Fit $\langle I_{PIN} / I_0 \rangle = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (8.010 \pm 0.051) \times 10^{-01}$
ATLAS SCT Preliminary
$\langle I_{PIN} / I_0 \rangle$
Integrated Luminosity L [fb^{-1}]


Endcap A Outer Rings
χ^2 / N(DoF) = 2.27
Measurements
Adjusted measurements
Fit $\langle I_{PIN} / I_0 \rangle = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (7.686 \pm 0.046) \times 10^{-01}$
ATLAS SCT Preliminary
$\langle I_{PIN} / I_0 \rangle$
Integrated Luminosity L [fb^{-1}]

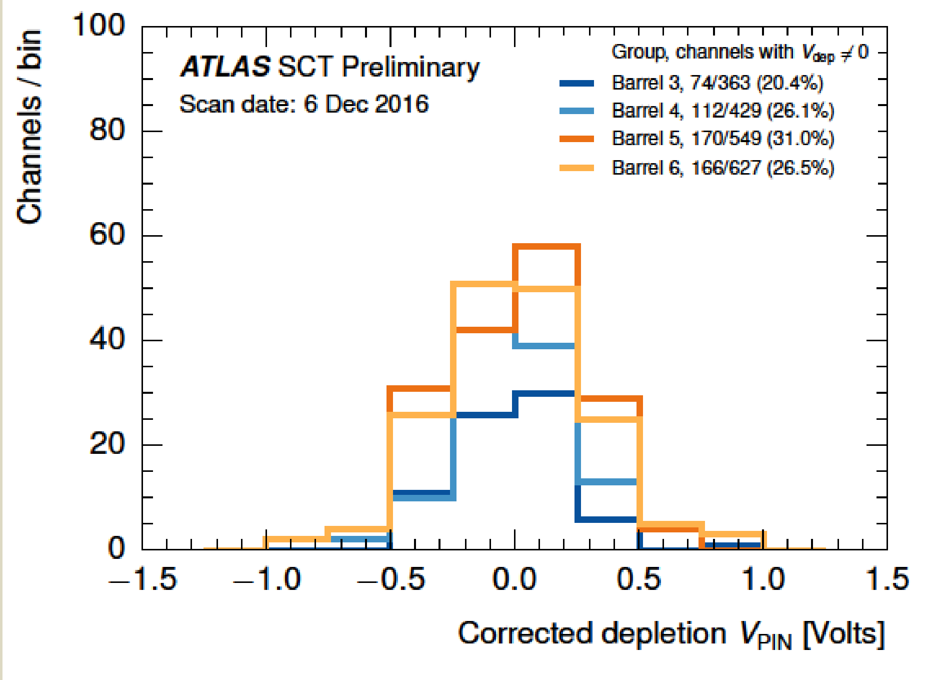
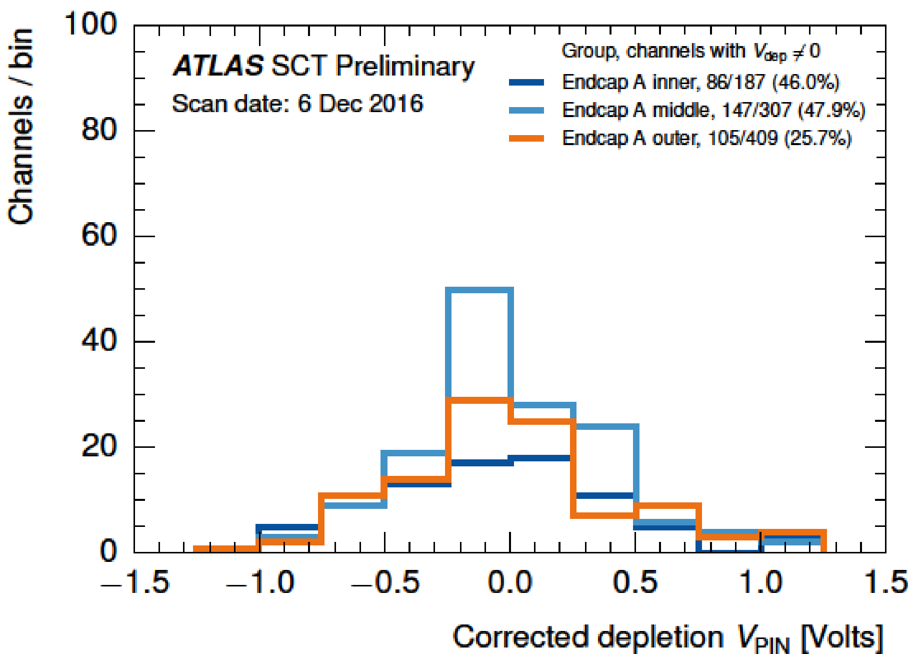
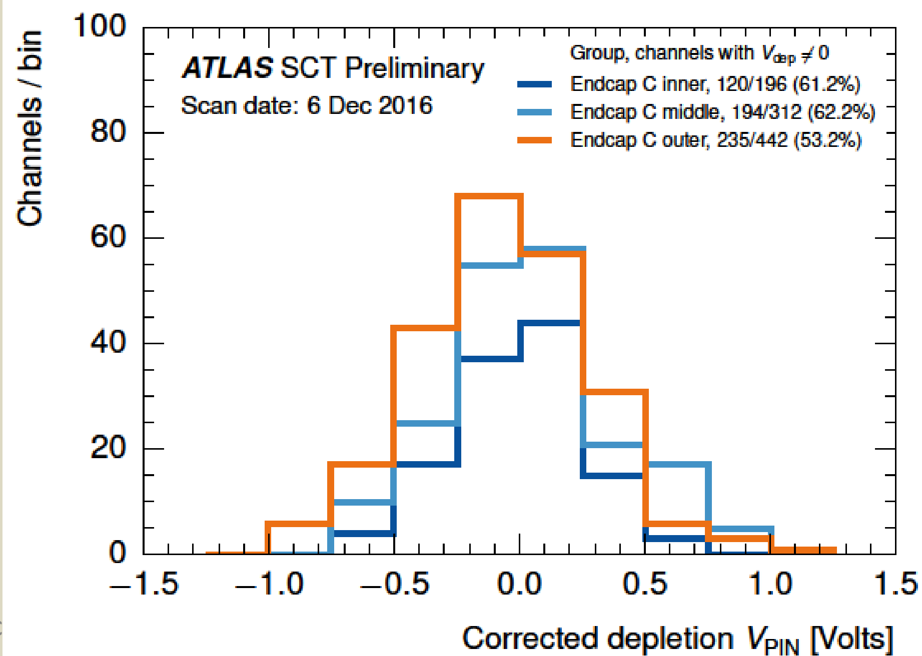

Endcap C Inner Rings
χ^2 / N(DoF) = 0.57
Measurements
Adjusted measurements
Fit $<I_{PIN} / I_0> = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (7.973 \pm 0.074) \times 10^{-01}$
ATLAS SCT Preliminary
$<I_{PIN} / I_0>$
Integrated Luminosity L [fb^{-1}]


Endcap C Middle Rings
χ^2 / N(DoF) = 1.61
Measurements
Adjusted measurements
Fit $<I_{PIN} / I_0> = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (8.859 \pm 0.016) \times 10^{-01}$
ATLAS SCT Preliminary
$<I_{PIN} / I_0>$
Integrated Luminosity L [fb^{-1}]


Endcap C Outer Rings
χ^2 / N(DoF) = 2.20
Measurements
Adjusted measurements
Fit $<I_{PIN} / I_0> = R_0 \exp(-(L/L_0)^m) + R_\infty$
$R_\infty = (8.790 \pm 0.009) \times 10^{-01}$
ATLAS SCT Preliminary
$<I_{PIN} / I_0>$
Integrated Luminosity L [fb^{-1}]

p-i-n diodes: Depletion Voltages

- Measure *p-i-n* diode currents.
- Scan bias voltage in 1V steps.
- Check if IV curve consistent with being horizontal
  - If not fit exponential curve → raw value for depletion voltage.
  - Correct for voltage drop along cables.
- Plot corrected depletion voltages


ATLAS SCT Preliminary
Scan date: 6 Dec 2016
Group, channels with $V_{dep} \neq 0$
Barrel 3, 74/363 (20.4%)
Barrel 4, 112/429 (26.1%)
Barrel 5, 170/549 (31.0%)
Barrel 6, 166/627 (26.5%)
Channels / bin
Corrected depletion V_{PIN} [Volts]
0
20
40
60
80
100
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

ATLAS SCT Preliminary
Scan date: 6 Dec 2016
Group, channels with $V_{dep} \neq 0$
Endcap A inner, 86/187 (46.0%)
Endcap A middle, 147/307 (47.9%)
Endcap A outer, 105/409 (25.7%)
Channels / bin
Corrected depletion V_{PIN} [Volts]
0
20
40
60
80
100
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

ATLAS SCT Preliminary
Scan date: 6 Dec 2016
Group, channels with $V_{dep} \neq 0$
Endcap C inner, 120/196 (61.2%)
Endcap C middle, 194/312 (62.2%)
Endcap C outer, 235/442 (53.2%)
Channels / bin
Corrected depletion V_{PIN} [Volts]
0
20
40
60
80
100
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

p-i-n diodes: Comparisons

- No significant change in depletion voltage as expected.
- Responsivity decreases
  - Asymptotic behaviour, similar to test beam but
  - In-situ: $R_\infty = 0.840 \pm 0.012$
  - Test beam: $R_\infty = 0.667 \pm 0.025$
- Don't understand decrease in responsivity for fully depleted *p-i-n* diodes.
- Don't understand discrepancy in-situ vs test beam.
  - Rate dependence/annealing effect?
- Decrease of responsivity ok for power budget.

Summary

- In-situ radiation damage measured for VCSELs
  - Slightly larger than expected from extrapolation of test beam data.
- In-situ radiation damage measured for *p-i-n* diodes.
  - Damage mechanism not understood
  - Asymptotic damage in-situ less than that measured in test beams.
- Decrease in responsivity and light output up to the end of run 3 can be accommodated in links power budget for VCSELs and *p-i-n* diodes.

Backup Slides

- Test beam papers
  - VCSELs: NIM A 497 (2003) 294–304.
  - *p-i-n* diodes: NIM A 456 (2001) 300-309
- Stability plots for on-detector p-i-n diode currents, no beam operation in 2016 and 2017.

(a) Crate 0.

(b) Crate 1.

(c) Crate 2.

(d) Crate 3.

(e) Crate 4.

(f) Crate 5.

(g) Crate 6.

(h) Crate 7.

Figure 10: **2016.** The $\langle I_{PIN}/I_0 \rangle$ values of each ROD crate. Each point represents the mean value for one day averaged over all modules in a crate for the period before beam operation in 2016. The value of $\langle I_{PIN}/I_0 \rangle$ is the normalised mean value of I_{PIN} (see text for details). The line shows results of the fits to the measurements. Note the highly suppressed zero on the vertical axis.

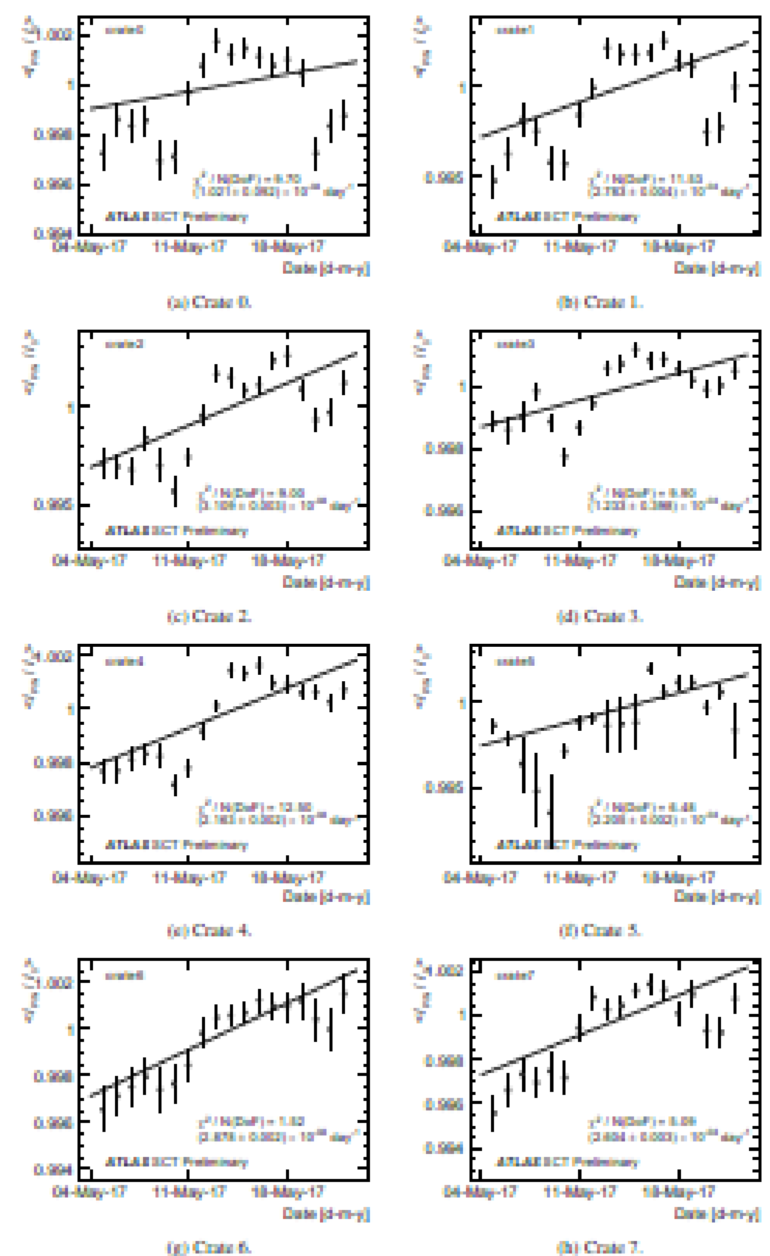


Figure 11: **2017.** The $\langle I_{PIN}/I_0 \rangle$ values of each ROD crate. Each point represents the mean value for one day averaged over all modules in a crate for the period before beam operation in 2017. The value of $\langle I_{PIN}/I_0 \rangle$ is the normalised mean value of I_{PIN} (see text for details). The line shows results of the fits to the measurements. Note the highly suppressed zero on the vertical axis.