Measurements of Radiation Damage in the CMS Pixel Detector with the First Few Inverse Femtobarns

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On behalf of CMS Pixels

19th RD50 Workshop
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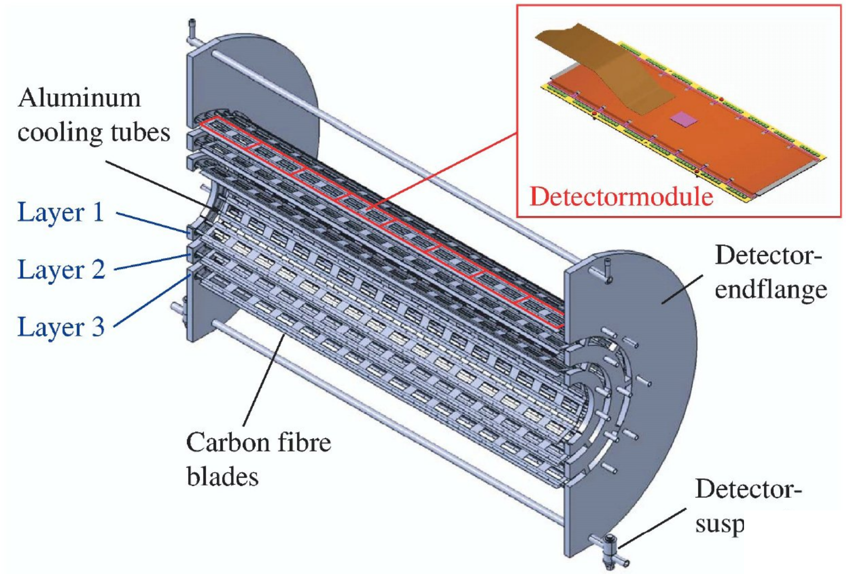
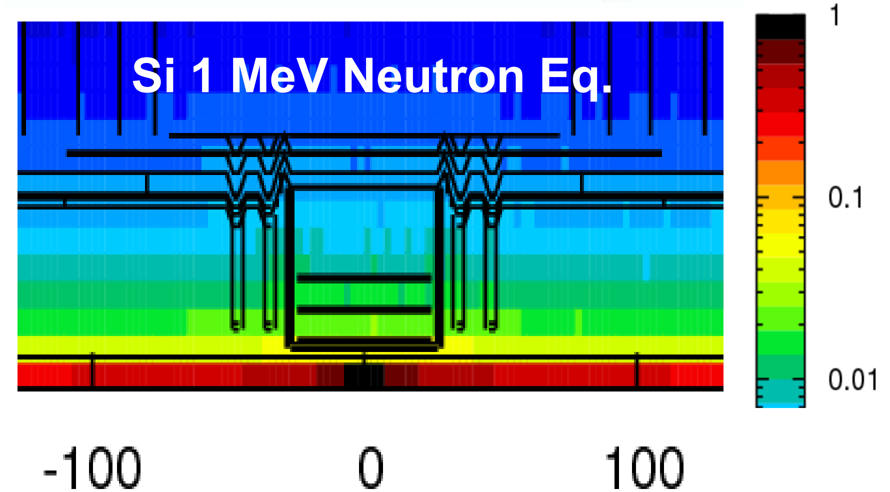
Overview

- Brief Introduction to the CMS Pixel Detector
- Measurement Conventions
- Leakage Current Measurements
  - vs. Time (model comparison)
  - vs. Luminosity
  - vs. Fluence
  - vs. Detector Phi
  - Temperature Scaling: Bulk and Surface (?) Current
- Depletion Voltage Measurements
  - vs. Time (model comparison)

Introduction

- Three barrel layers:
  - 4.3, 7.2, 10.8 cm
  - 48M pixels, 0.78 m^2
- 2x2 disks
  - 18M pixels, 0.28 m^2
- This talk: focus on barrel for simplicity
- 2011 operating temperature: 17.2 °C





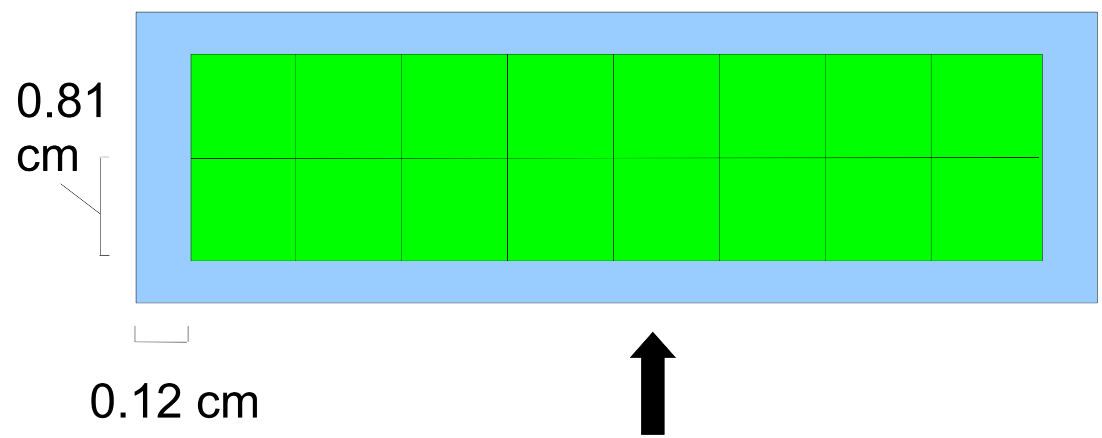
Smallest unit of HV measurement = 1 Ladder → [-30,0] and [0,30] cm

Measurement Conventions

- Following the guidelines of the *Inter-Experiment Working Group on Radiation Damage in Silicon Detectors* . . .
- Current is corrected to 0 ºC
  - E_g = 1.21 eV

$$I\left(T_{ref}\right) = I(T).\left(\frac{T_{ref}}{T}\right)^2 .exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right)$$

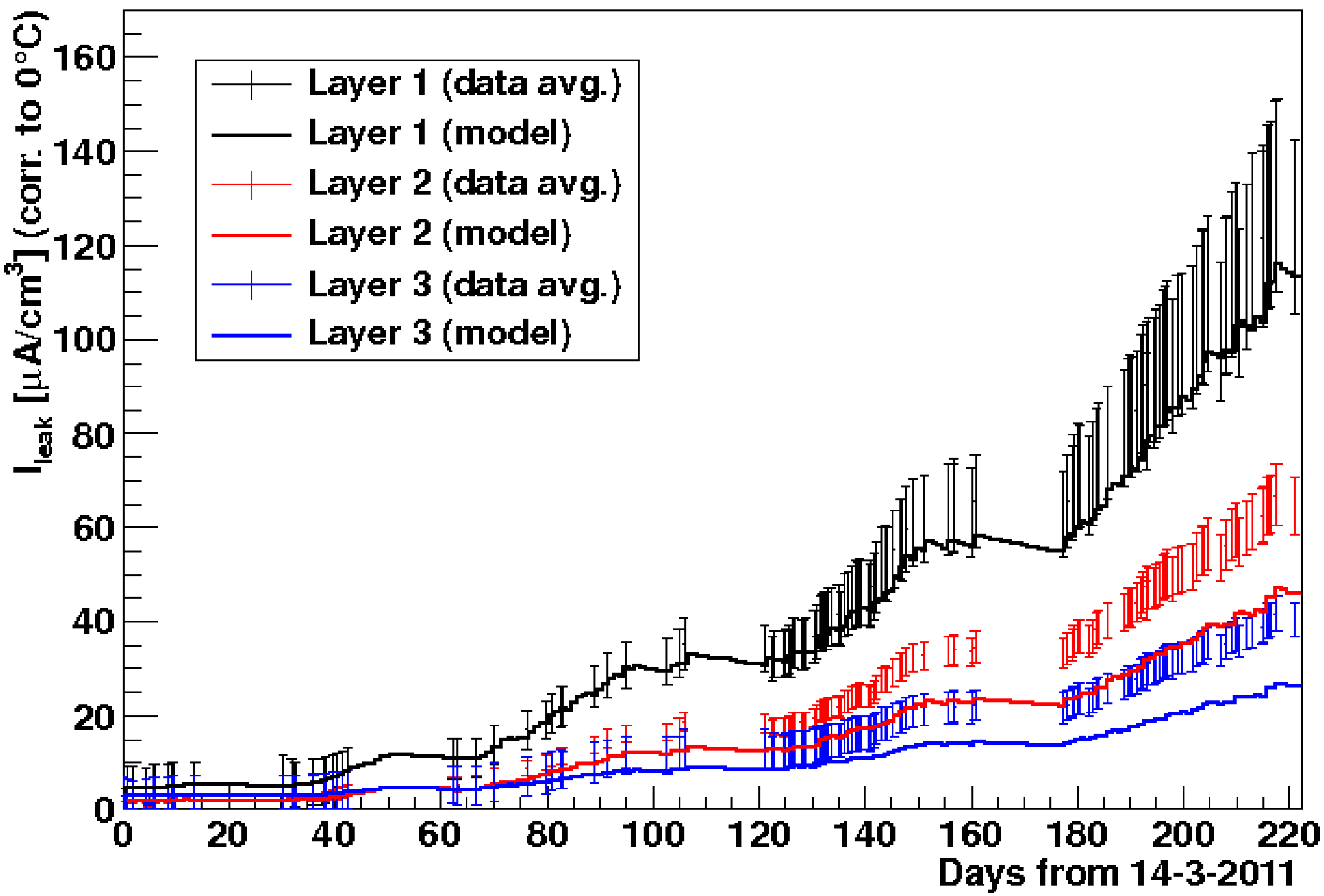
- Current is measured in μA/cm^3, normalized to the volume of active silicon
- Active Volume = (Instrumented Area + ½ x Peripheral Area) x 285 μm



Smallest unit of HV measurement = 1 Ladder = 4 Modules
= 4x16 Read-Out Chips (ROCs) → 0.81 cm x 0.81 cm

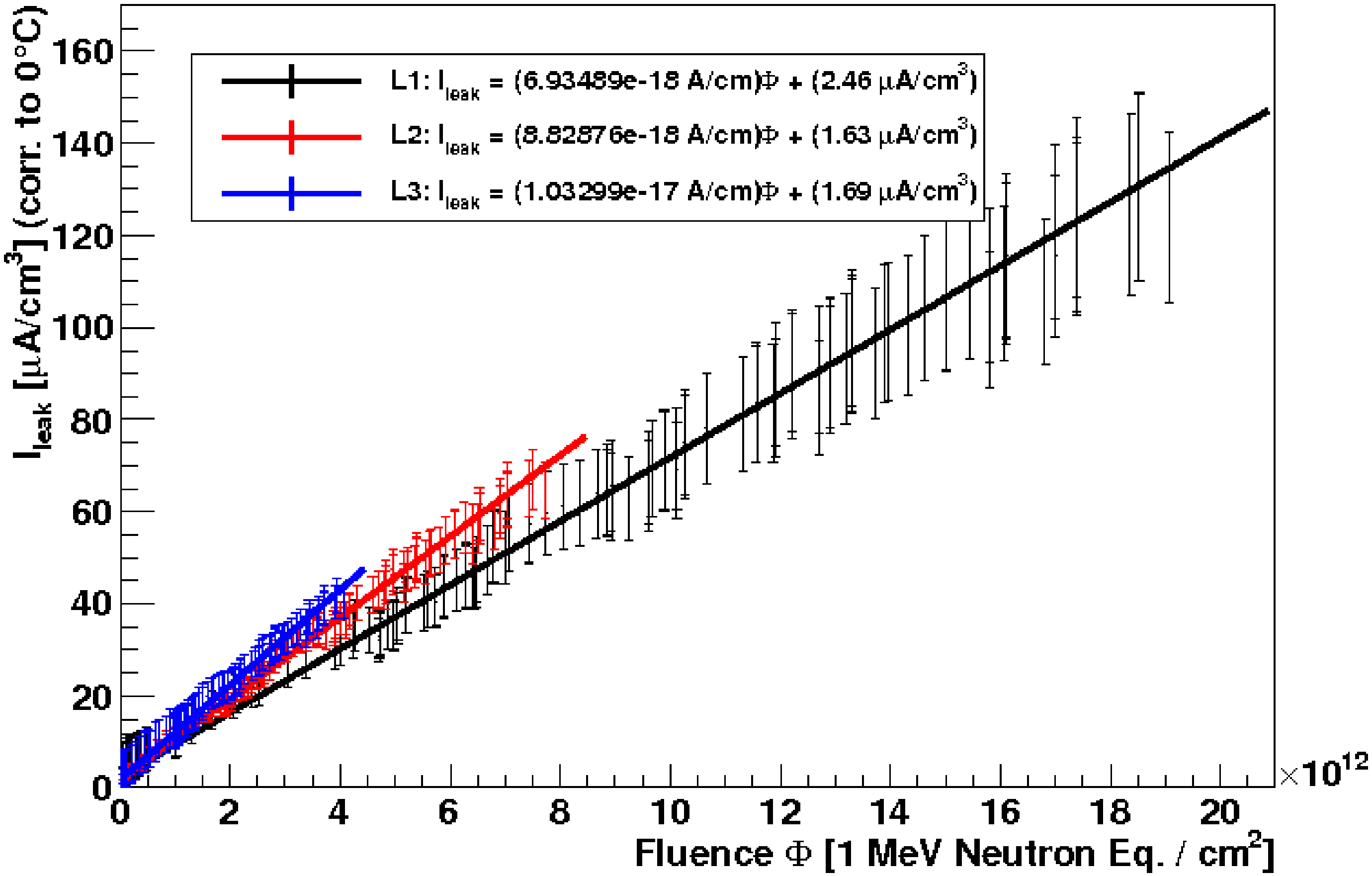
I_{leak} During 2011

- Midpoint: mean over entire layer
- Errors bars: RMS deviation
- Model comparison: See talk by C. Barth, this session
- Model uses z = 0, mean r



- Fair agreement for Layer 1
- Factor of ~2 for Layers 2 and 3

I_{leak} vs. Fluence

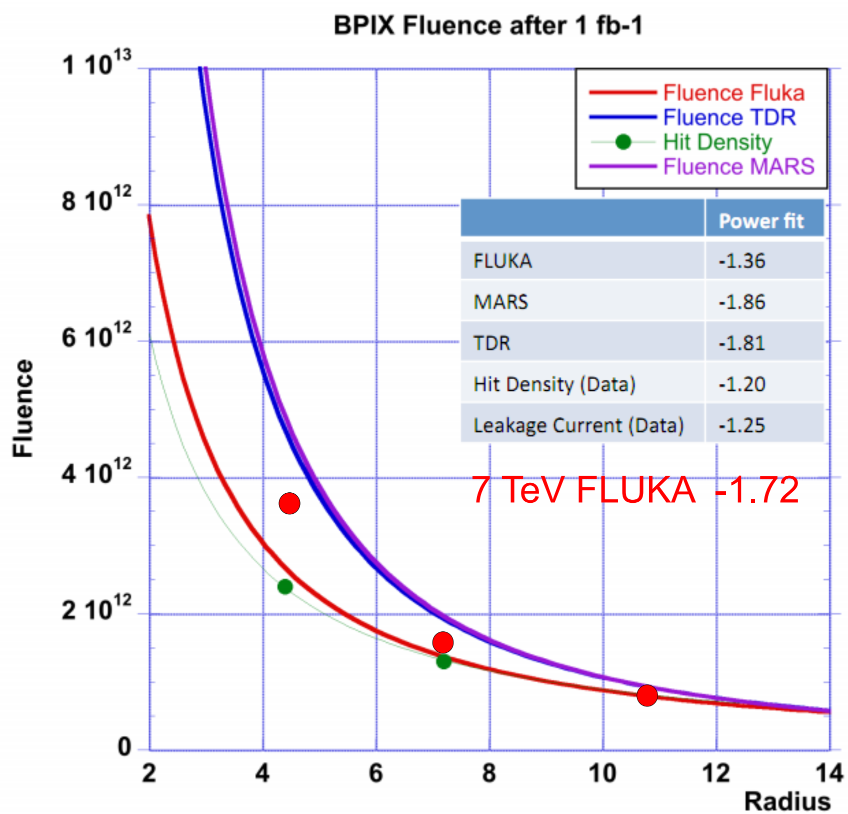


$I_{leak}/\mathrm{Vol.} = \alpha\Phi$

- Fit "measures" α as a consistency check...
- α(20ºC) ~ 4e-17 A/cm → α(0ºC) ~ 6e-18 A/cm

Data-model Inconsistencies

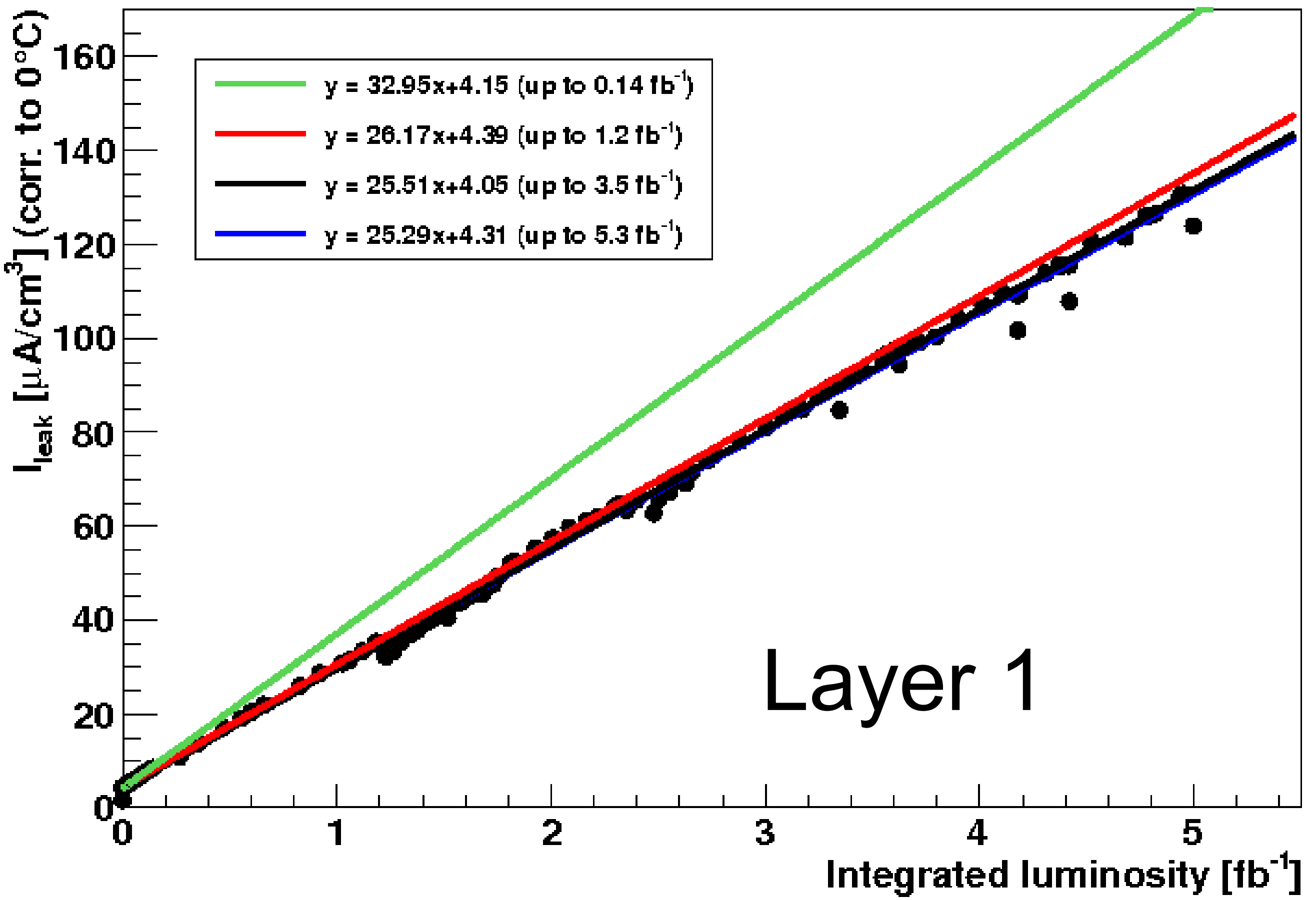
- Culprit could be...
  - Fluence?
    - Wide range of predictions
    - Using hit density instead of 7 TeV FLUKA → all three layers would disagree as much as L3 currently does!
  - Model?
    - α is too well known to allow disagreemnt seen in simple I vs. Fluence fit
  - Assorted 10% effects: z-dependence, r-dependence ionization current, ...?

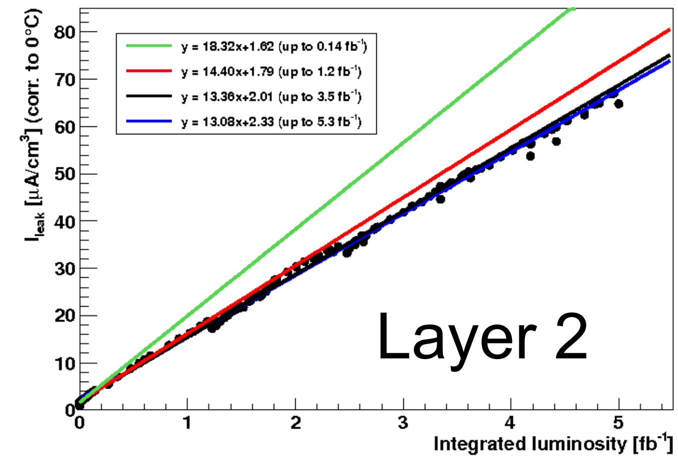


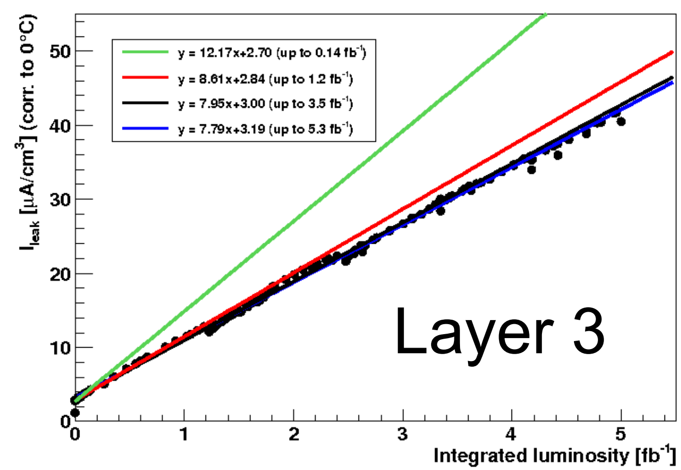
Red Points: 7 TeV Fluka
(+ Radial Interpolation)
Red Line: scaled 14 TeV Fluka
Hit density measurement:
O(600 MeV) pions dominate
These have a 1 MeV neutron equivalence ~ 1

I_{leak} vs. Luminosity

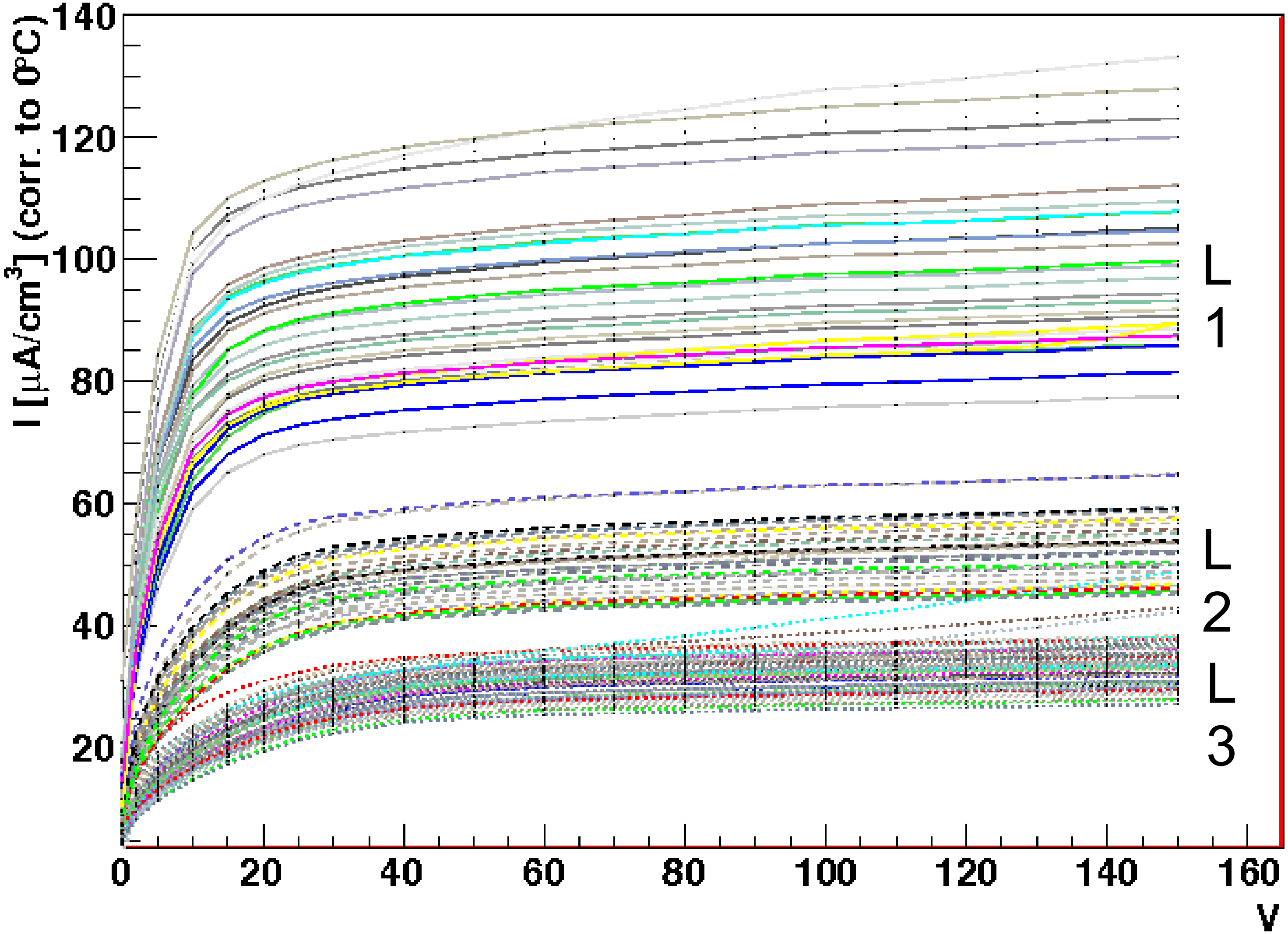
- Detector operations: most interested in extrapolation vs. lumi
- I_{leak} exceeds power supply and readout capabilities at ~750 fb^{-1}





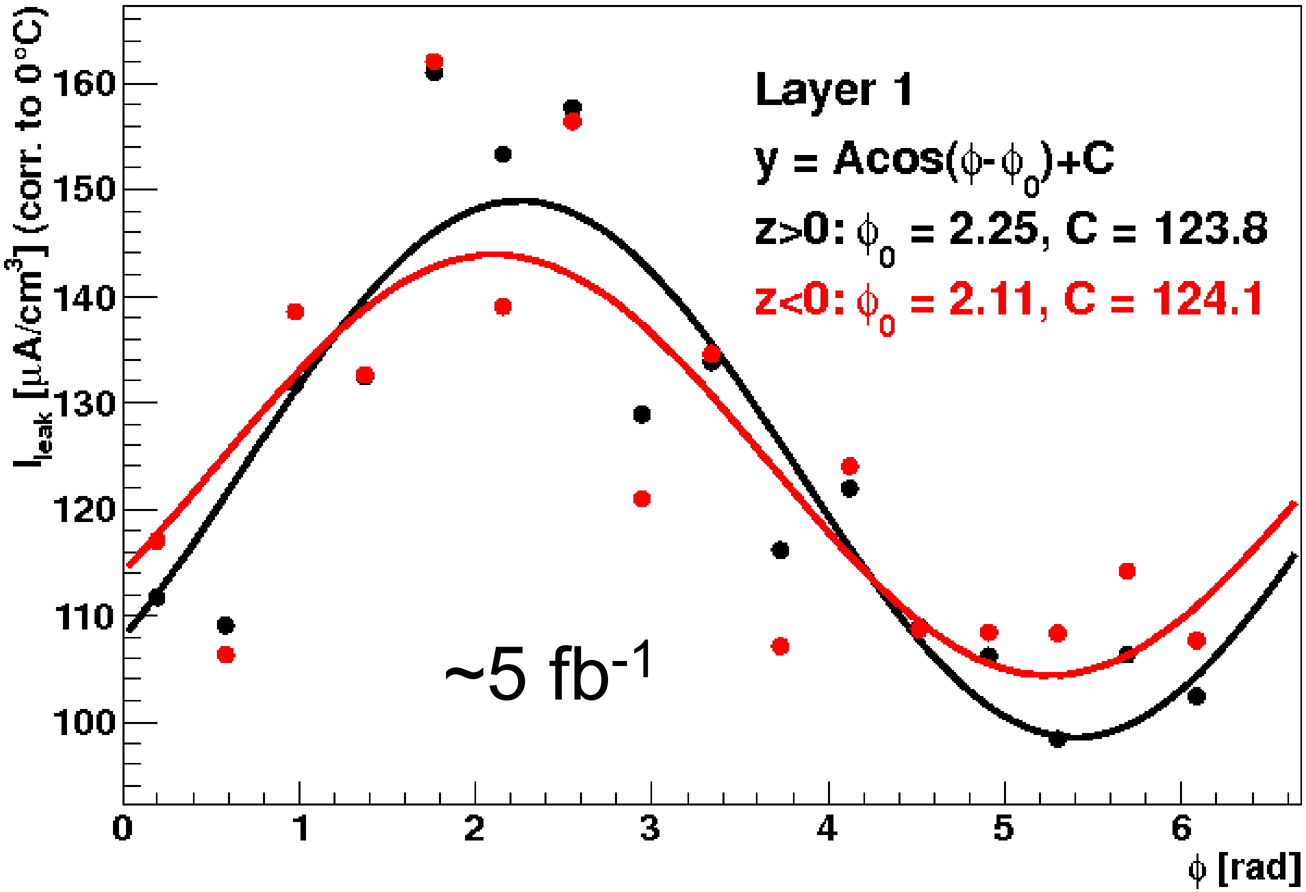


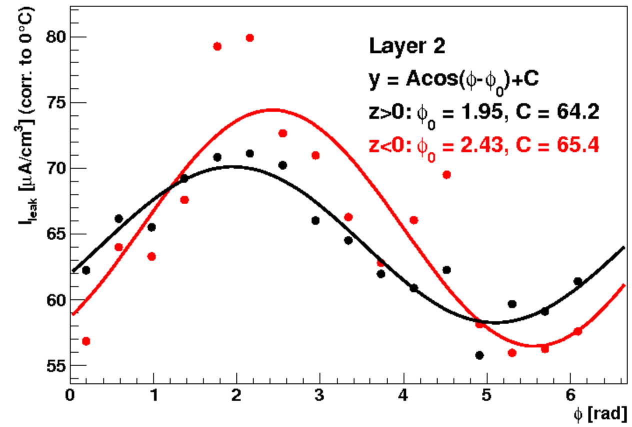
IV Curves

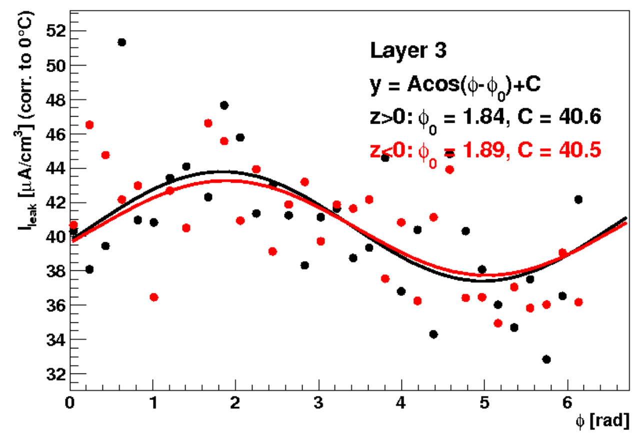


I [μA/cm3] (corr. to 0°C)
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
V
L
1
L
2
L
3

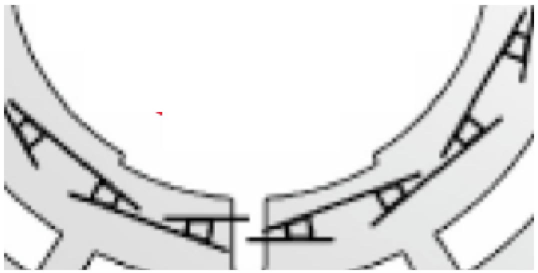
I_{leak} vs. Detector Phi





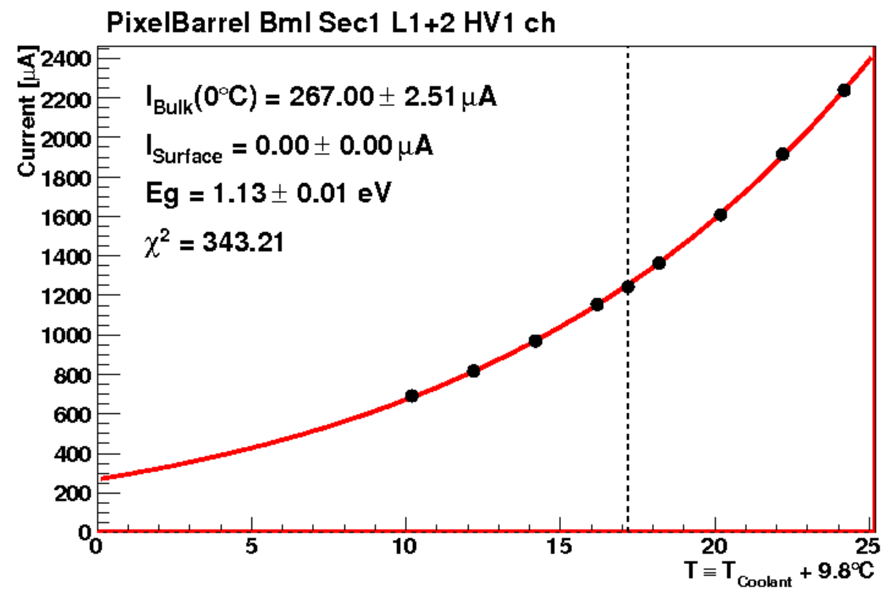


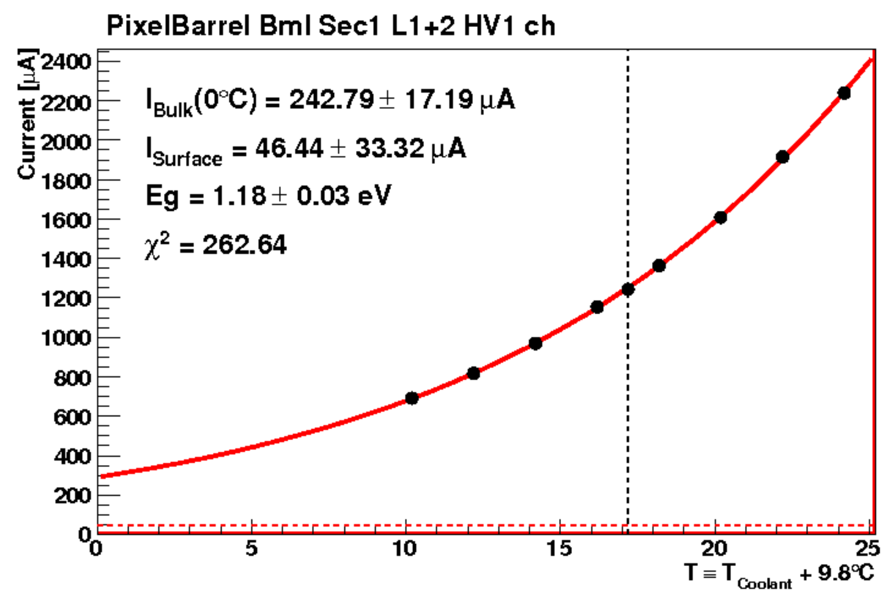
- LHC Beam Spot is not at center of Pixel Detector!
- Known to be at (x,y) = (-2.4mm, 3.9mm) → φ ~ 2.12
- 30% effect on potential Layer 1 lifetime!
- Can also see impact of staggered geometry



Temperature Scaling (1)

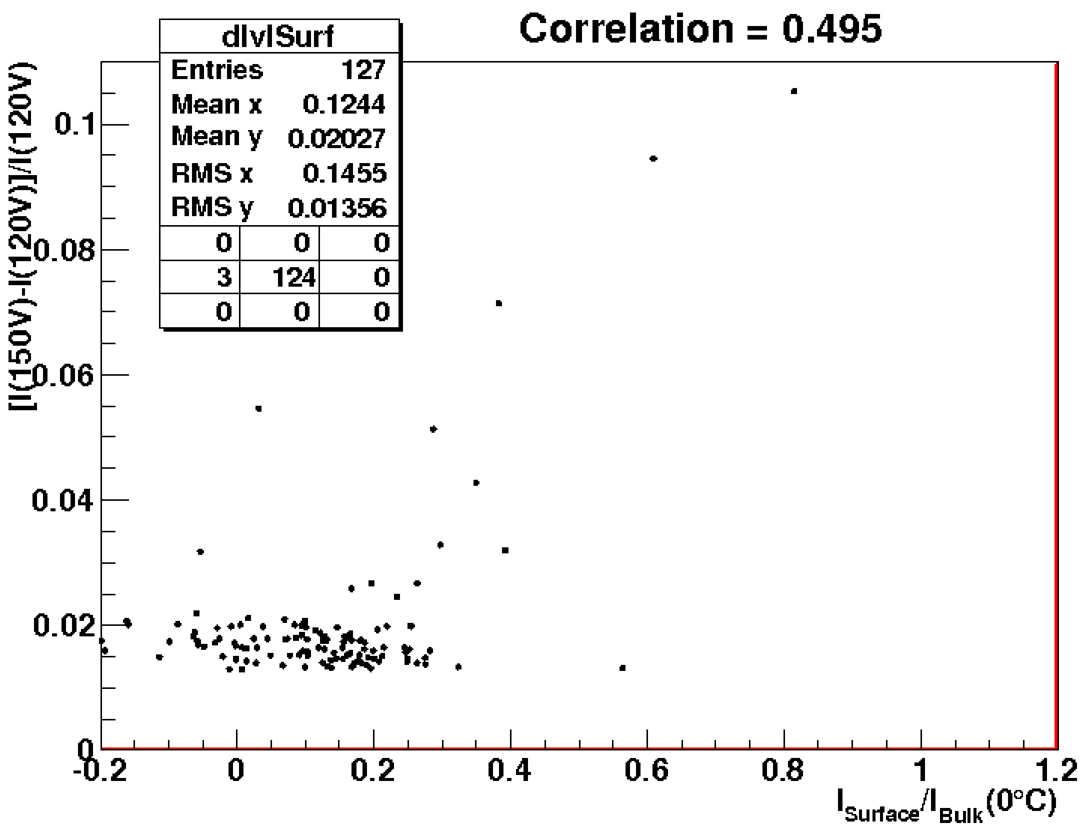
- Investigate Temperature scaling of I_{leak} by fitting scans
- Let effective band gap E_g vary (should be 1.21 eV)
- Try allowing T-independent surface term – should correspond to ohmic behavior in IV curve after saturation
  - Following LHCb talk (P. Collins) at 1st LHC Rad. Dmg. IEWG mtg
- Long extrapolation (17.2 ºC operation temperature to 0 ºC) → significant impact

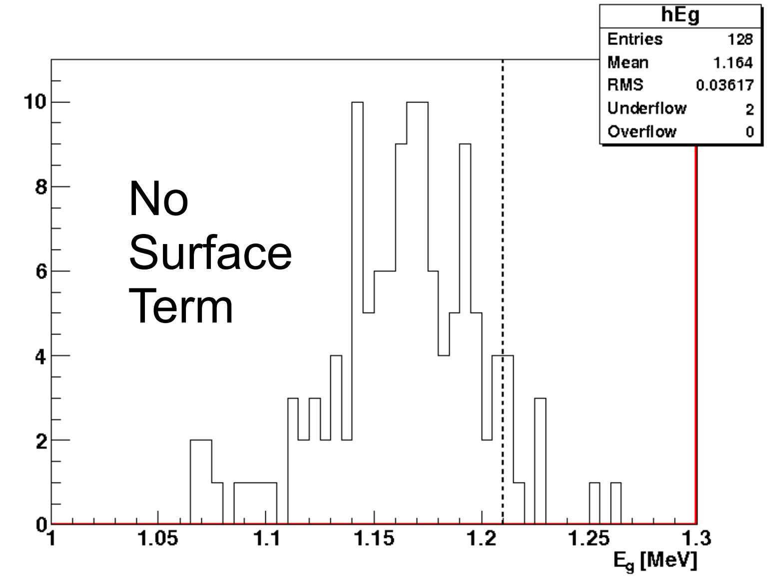


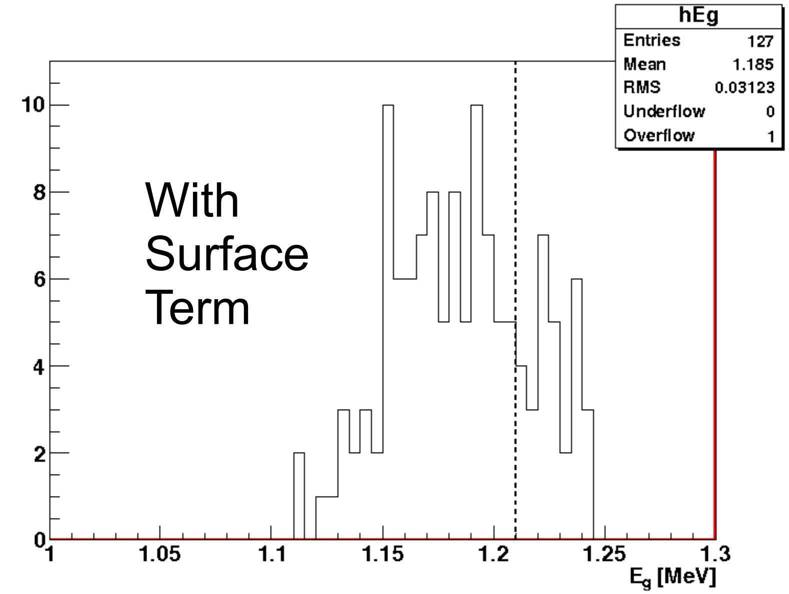


Temperature Scaling (2)

- "Surface Term" somewhat improves fits and E_g values
- Few channels show correlation b/w T-independent term and "Ohmic behavior"
- So this term not used elsewhere in talk

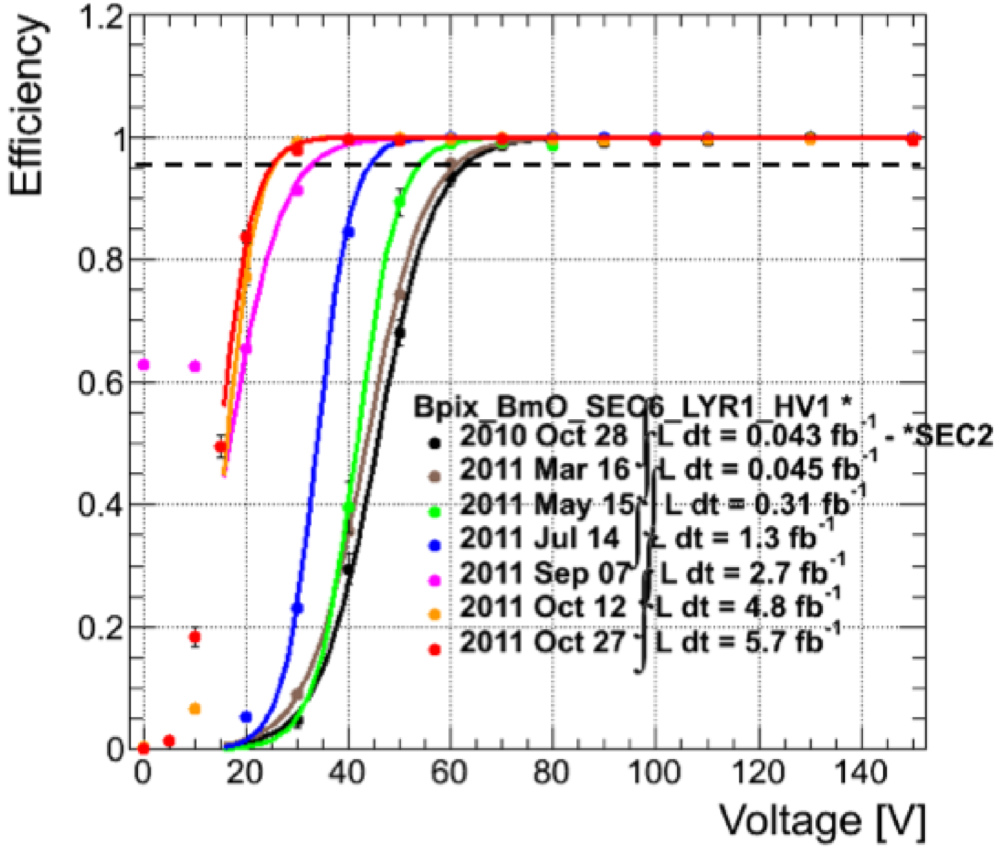






V_{dep} from Hit Efficiency

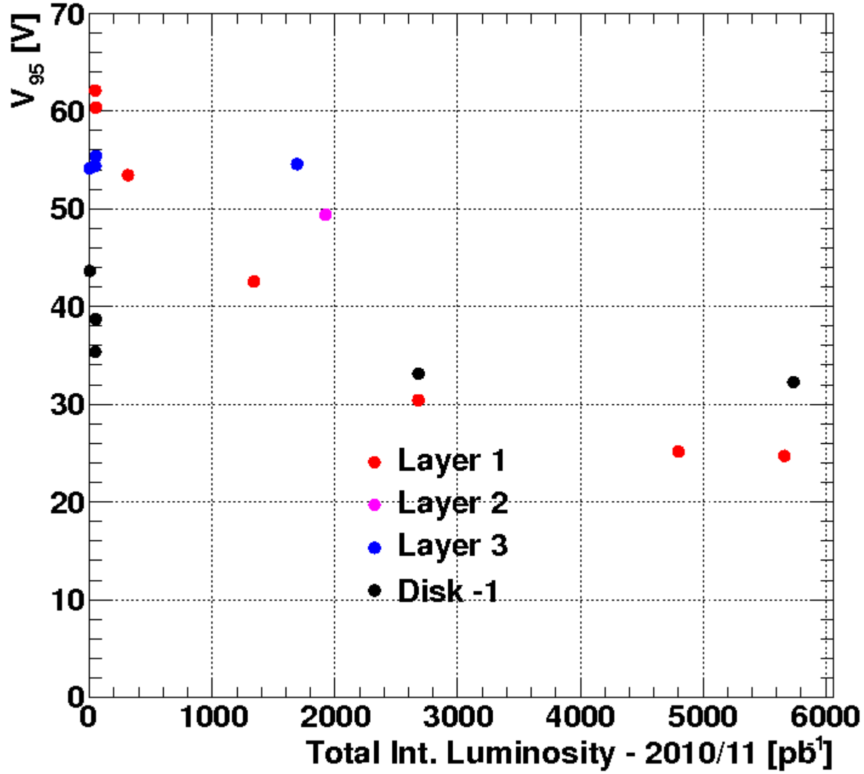
- Reduce voltage of selected channel during operation and observe impact on hit efficiency
- Take voltage corresponding to 95% hit efficiency $V_{95} \sim V_{dep}$

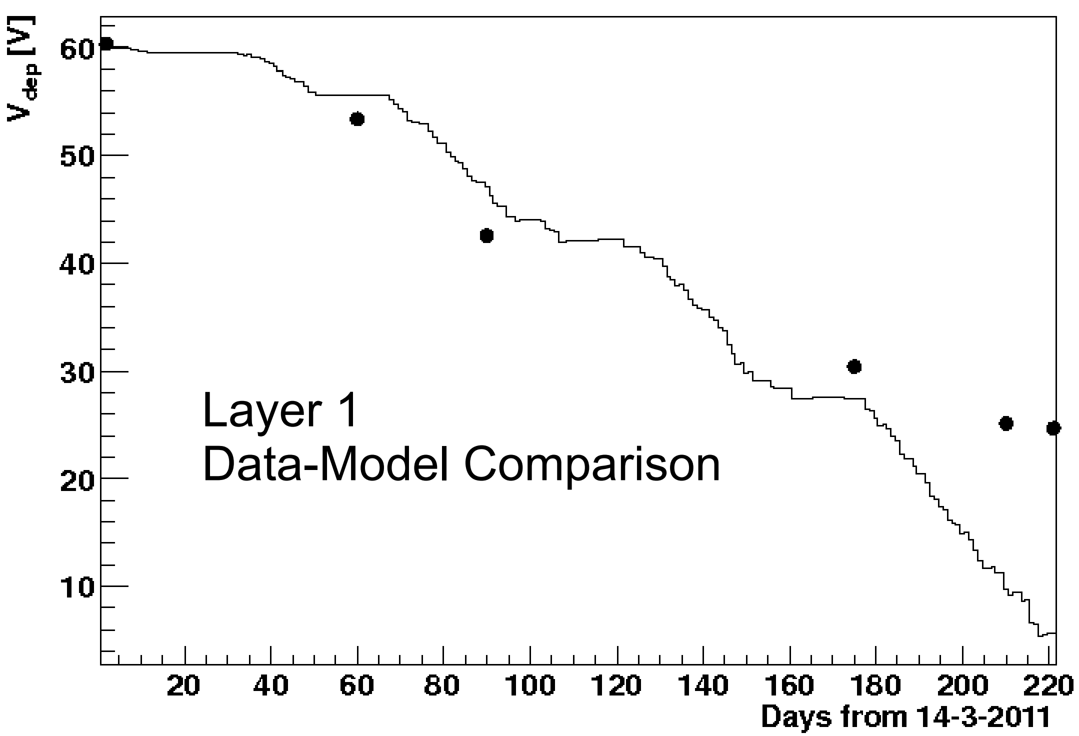


- Very preliminary work (not shown today) fitting cluster charge vs. voltage: agrees qualitatively with this method

V_{dep} Results & Comparisons

- Compared to calculations with same model as I_{leak} comparison
- Good agreement up to the last part of the year, with divergence at end of run as model → 0V
- Follow through "type inversion" next year – critical operational question is how voltage will *increase* as compared with models



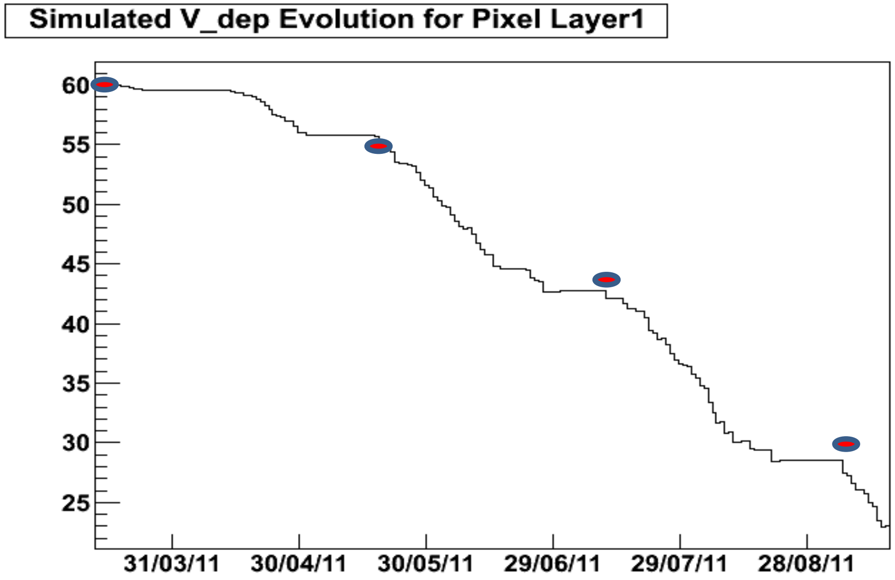


Conclusions

- No big surprises so far
- Many small improvements to be studied:
  - Channel-by-channel temperature
  - Position: average over ladders in z, add disks and average in r, improve model grid radial interpolation
  - Reconcile hit density with fluence models
  - Finalize depletion voltage from Landau curves
- Questions for experts
  - Comments on model-data agreement?
  - Best temperature for shutdown? On or off?
  - Suggestions for new or improved measurements?
- We are in early days yet!

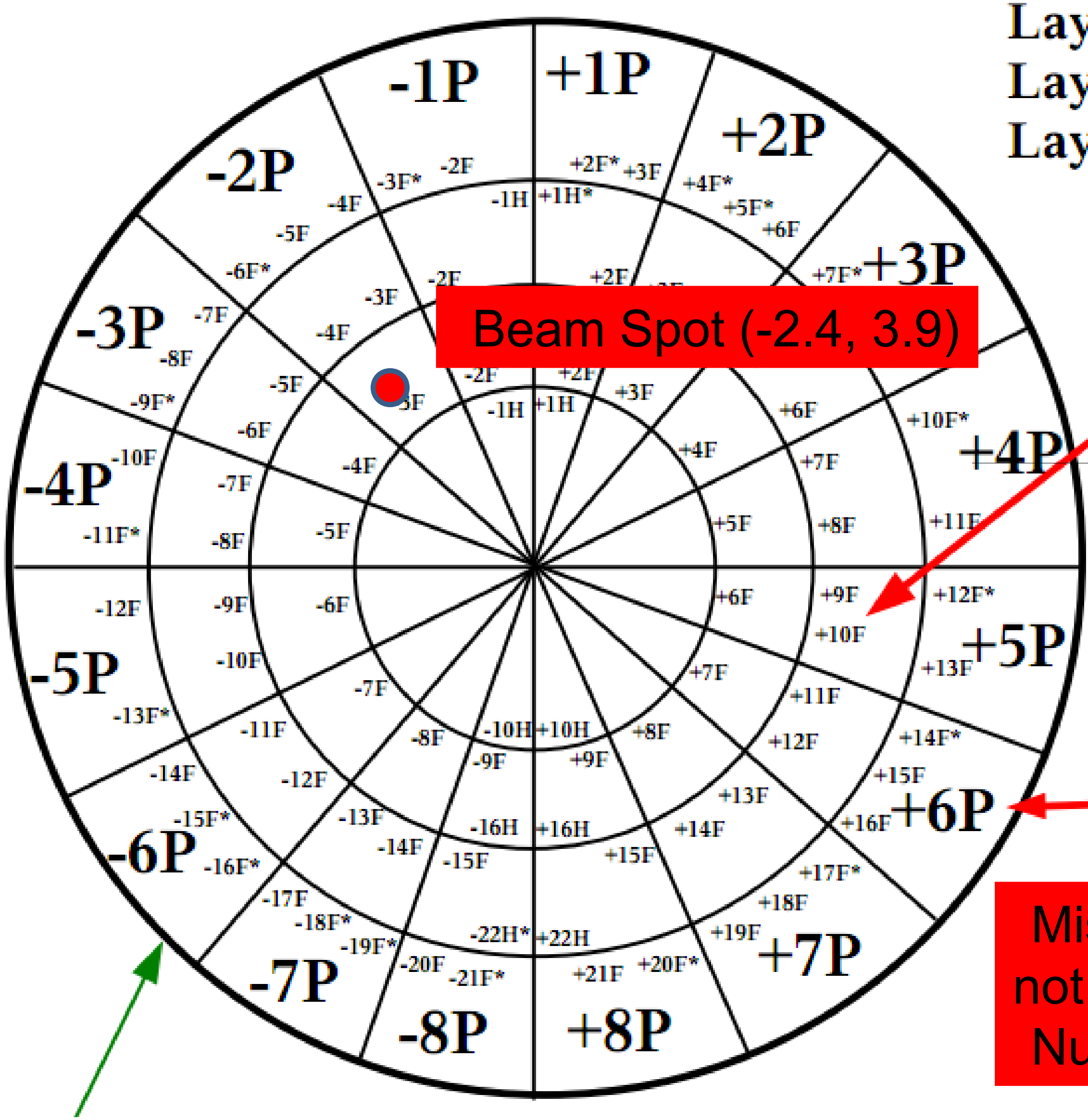
Extras

Old Vdep Plot



- Previous scaled 14 TeV,
- No (?) radial interpolation

Layer-1 Channel-1
Layer-2 Channel-2
Layer-3 (*) Channel-2



ladder name

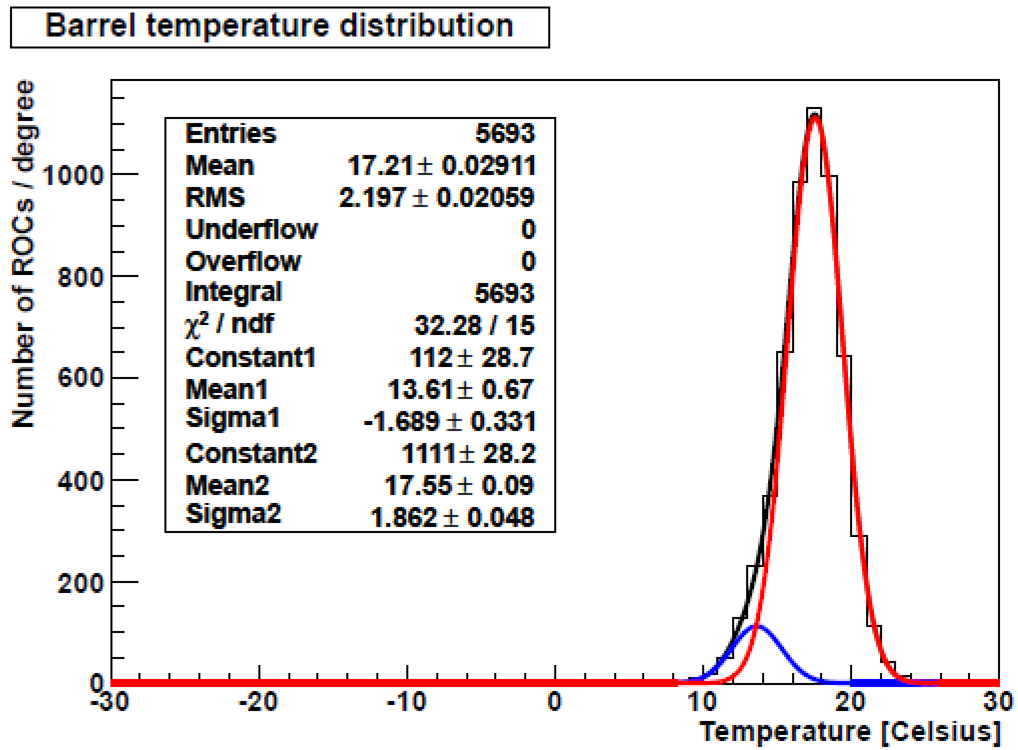
BpI

Phi = 0

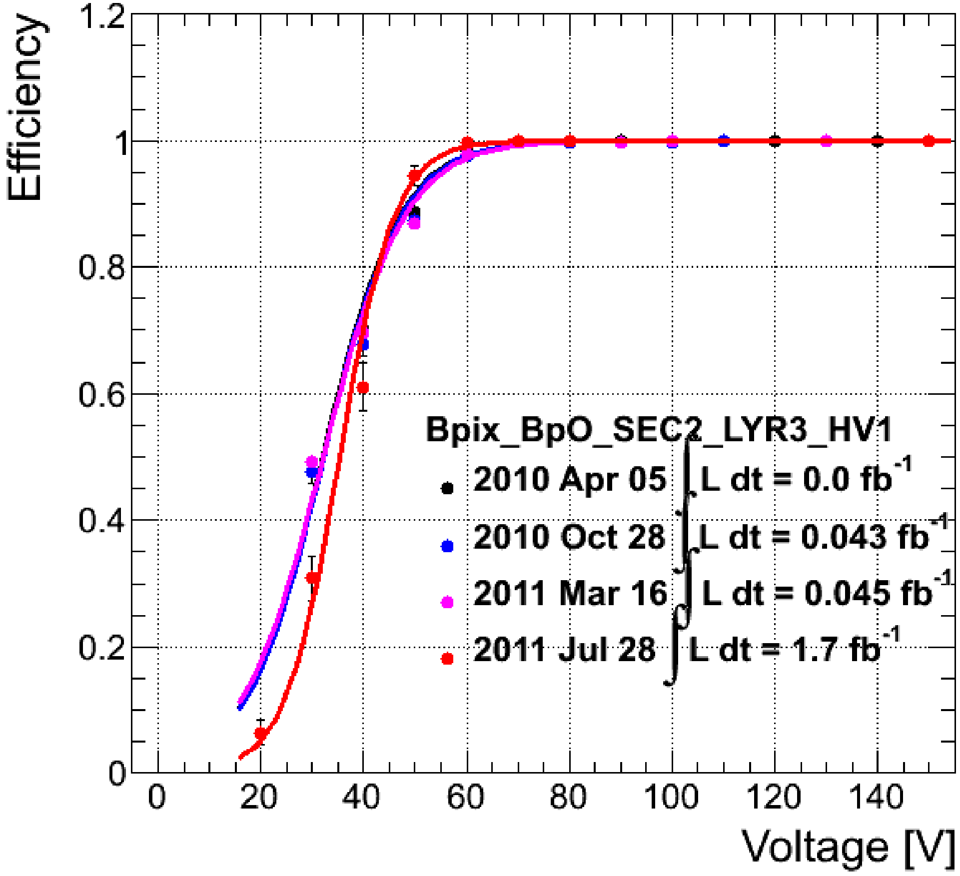
sector name

Misalignement in the drawing is not to scale.
Numbers in mm

Barrel absolute temperature (?)



Layer 3 V_{95}



Efficiency
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
Voltage [V]
Bpix_BpO_SEC2_LYR3_HV1
2010 Apr 05 ∫L dt = 0.0 fb⁻¹
2010 Oct 28 ∫L dt = 0.043 fb⁻¹
2011 Mar 16 ∫L dt = 0.045 fb⁻¹
2011 Jul 28 ∫L dt = 1.7 fb⁻¹

Parameters used for Simulation

- Leakage Current:
  $I = \alpha\phi V$

Time independent but temperature dependent term not clear in T-changing environment. Interpretation to be a "instantaneous" annealing effect -> max T of corresponding annealing time taken (?)

with α= 1.23e-17 A/cm exp $(-t_1/\tau_1)$exp$(-t_2/\tau_1)$...
+ -8.9e-17 A/cm + 4.6 AK/cm e-14/T
+ 3.07e-18 A/cm $\ln(t/t_0)$

and $1/\ _1$ = 1.2e13 $\exp(-1.12/2k_B T)$ *(60*60*24) 1/day

- Temperature scaling:
  $(T_1/T_2)^2 \exp(-1.12/2k_B\,(1/T_1 - 1/T_2))$

C. Barth

also started simulations with E=1.21eV according to Technical Note by A.Chilingarov

Parameters used for Simulation

All orange highlighted values are taken from measurements (-> Ph.D. Thesis A. Dierlamm 2003)

- Full depletion voltage:

$N_{eff} = N_A + N_C + N_Y$

with: $N_A = g_a \quad exp(-t_1/\ _a)\ exp(-t_2/\ _a)...$

$N_C = 0.9\ |N_{eff0}|\ *$

$(1 – exp(-10.9e\text{-}2/|N_{eff}|\quad) + g_c$

$N_Y = -g_Y \quad (1 -\ 1/(1+t_1/\ _Y)\ 1/(1+t_2/\ _Y)...\ )$

and g_a = 1.81e-2 1/cm, g_Y = 5.16e-2 1/cm,

g_c=1.6e-2 1/cm

$_a = 1/(2.3e13\ exp\ (-1.08/k_BT))$

$_Y = 1/(1.5e15\ exp\ (-1.33/k_BT))$

C. Barth