Radiation Damage in LHCb silicon
a self portrait

1629

1640

How am I
looking?

1669

Radiation Damage in LHCb silicon a self portrait

Paula Collins, on behalf of the LHCb VELO and ST groups

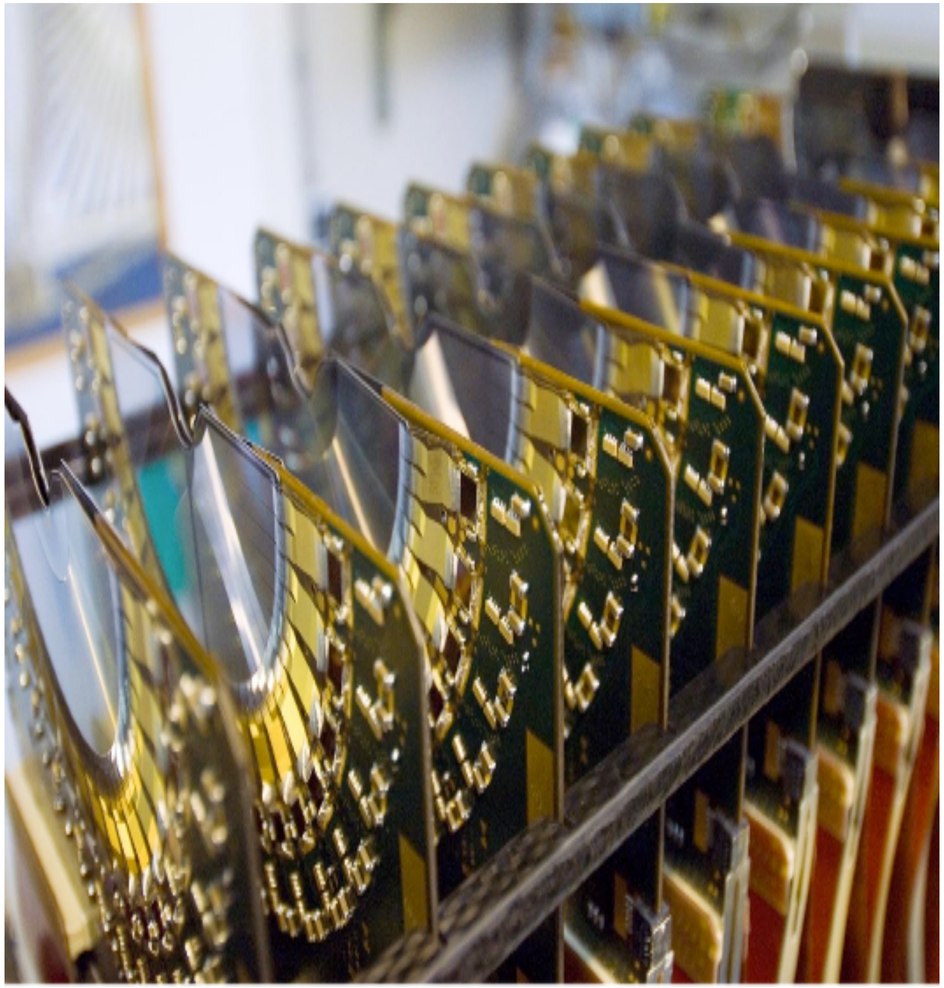
- Snapshot of Radiation Damage studies on LHCb
- What we hope to contribute to and learn from inter-experiment working group
- Everything presented here HIGHLY PRELIMINARY and only intended for this internal discussion

Thanks in particular to RD50 experts:
Michael Moll, Alexandra Junkes and Tony Affolder

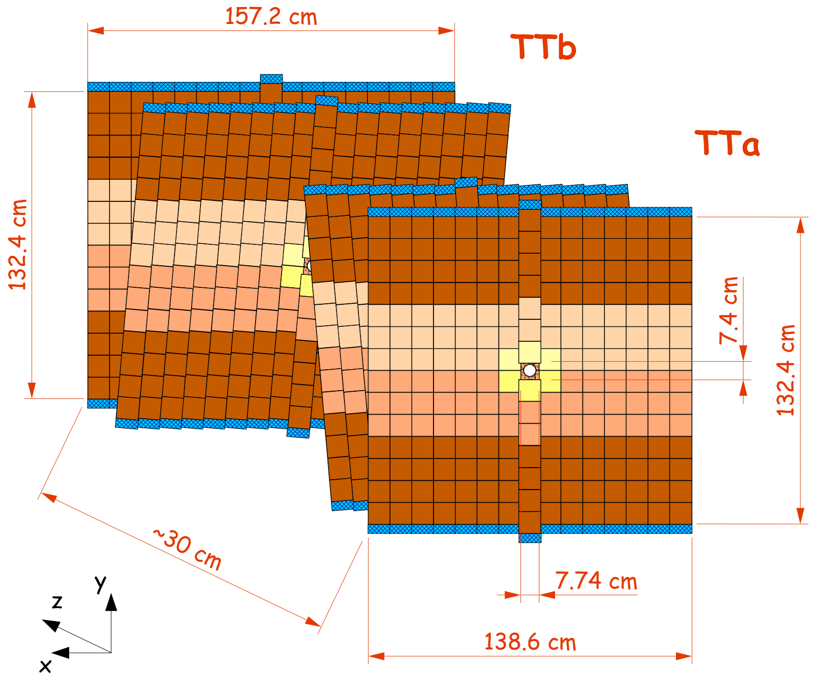
LHCb silicon in 3 slides:

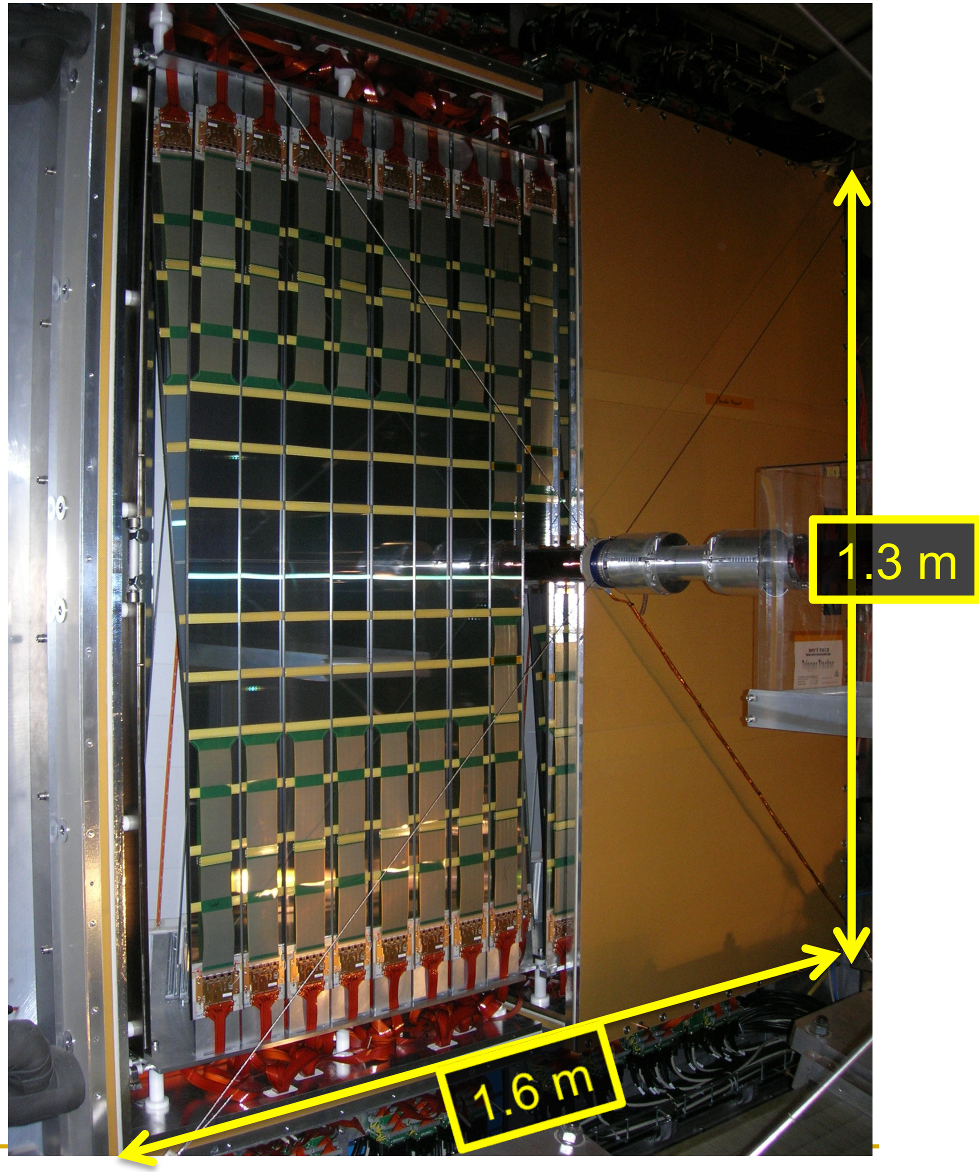
VELO

- 88 single sided R and ϕ silicon sensors
- Inner strip 8 mm radius, inner edge 7 mm radius, rettracted to 30 mm during beam injection
- Strip Pitches 40-100 μm
- Evaporative CO2 cooling system
- Silicon operating temperature ~-8^{o}C
- Silicon thickness 300 μm



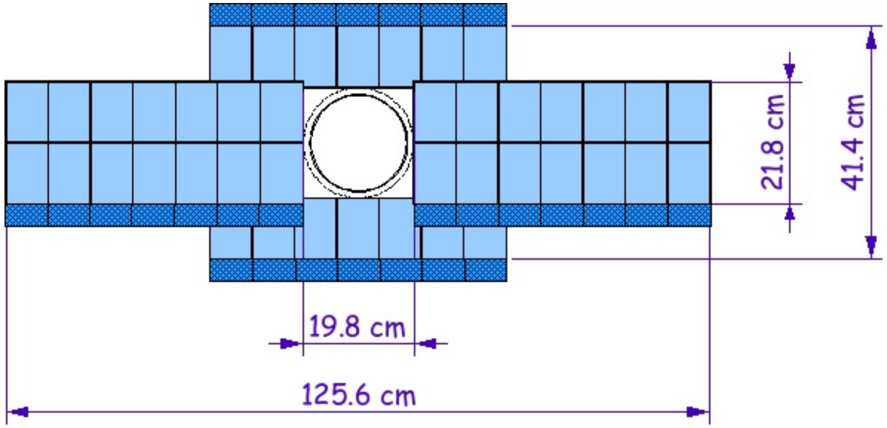
Tracker Turicensis

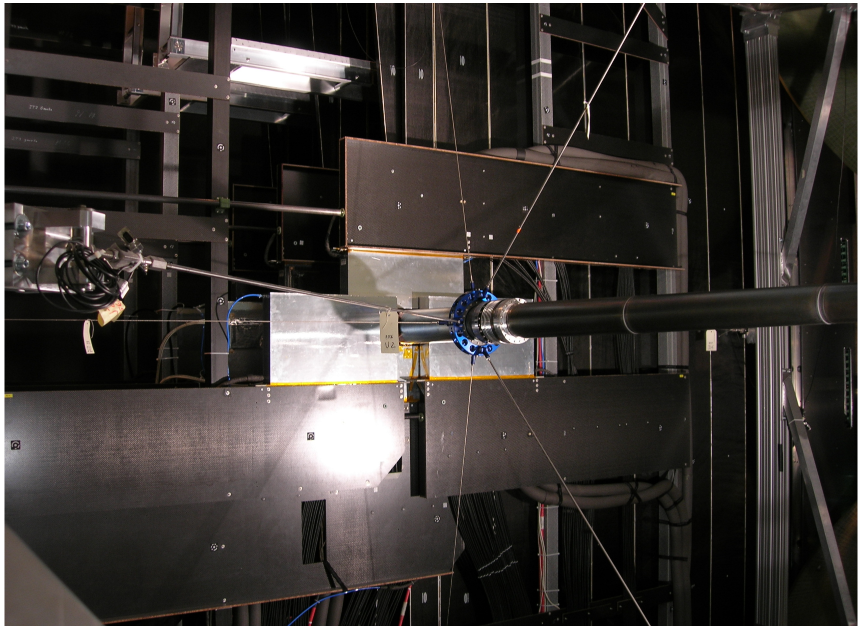


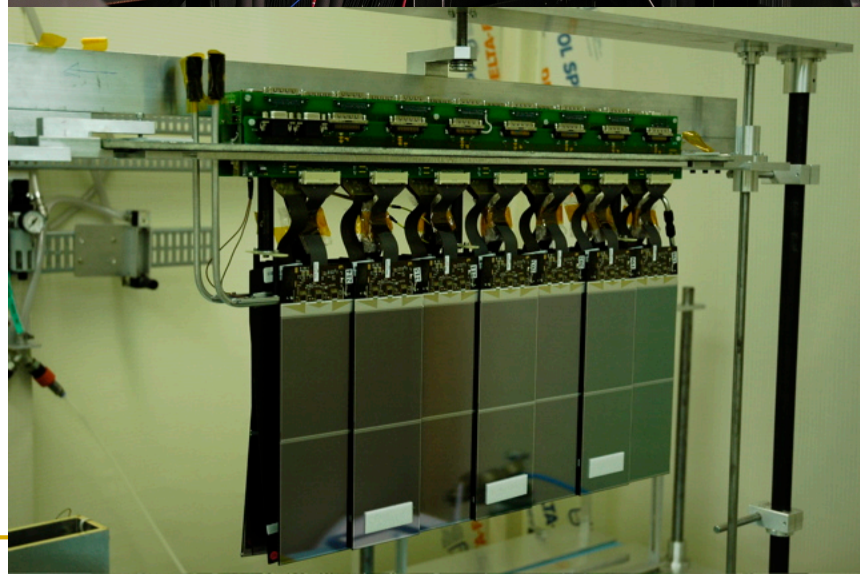


- Silicon micro-strip detectors.
- Four planes (0°, +5°, -5°, 0°).
- Pitch: 183 µm; Thickness: 500 µm.
- Long readout strips (up to 37 cm).
- 143360 readout channels.
- Total Silicon area is 8 m^2.
  - Covers full acceptance before magnet.
- Detectors operate at 0°C.

Inner Tracker



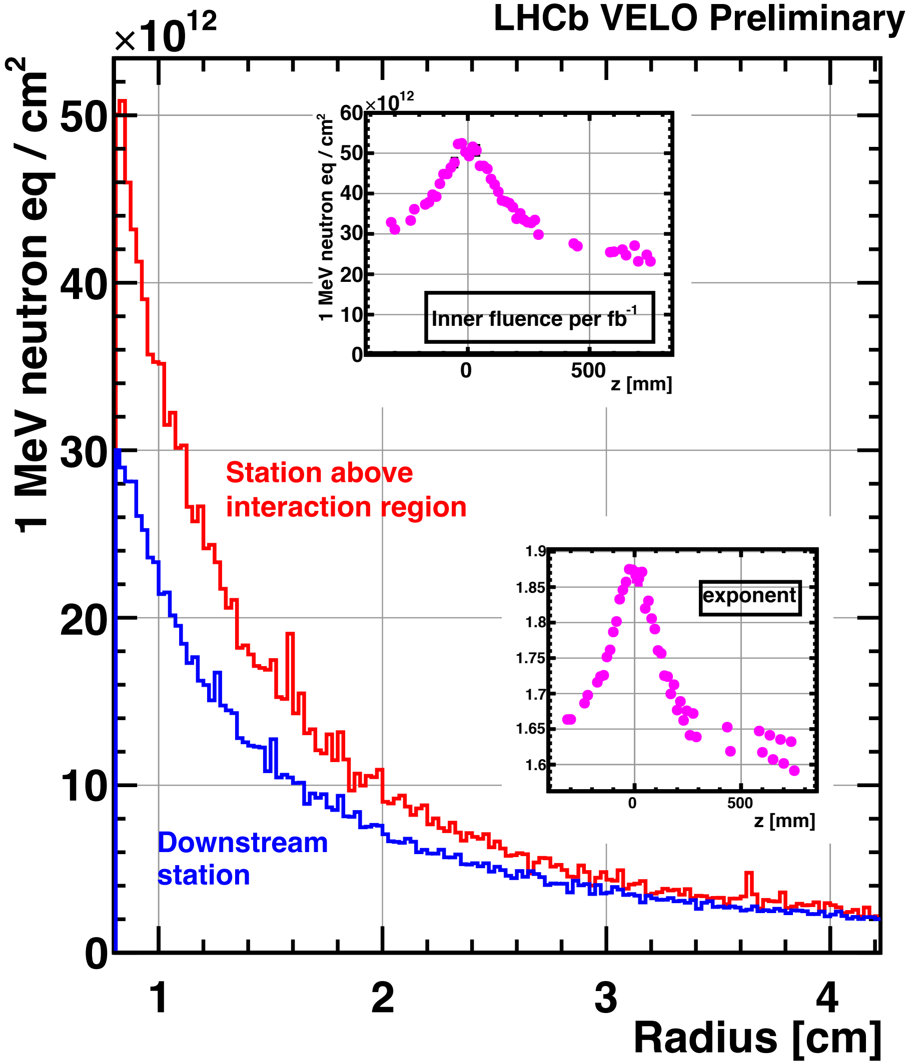




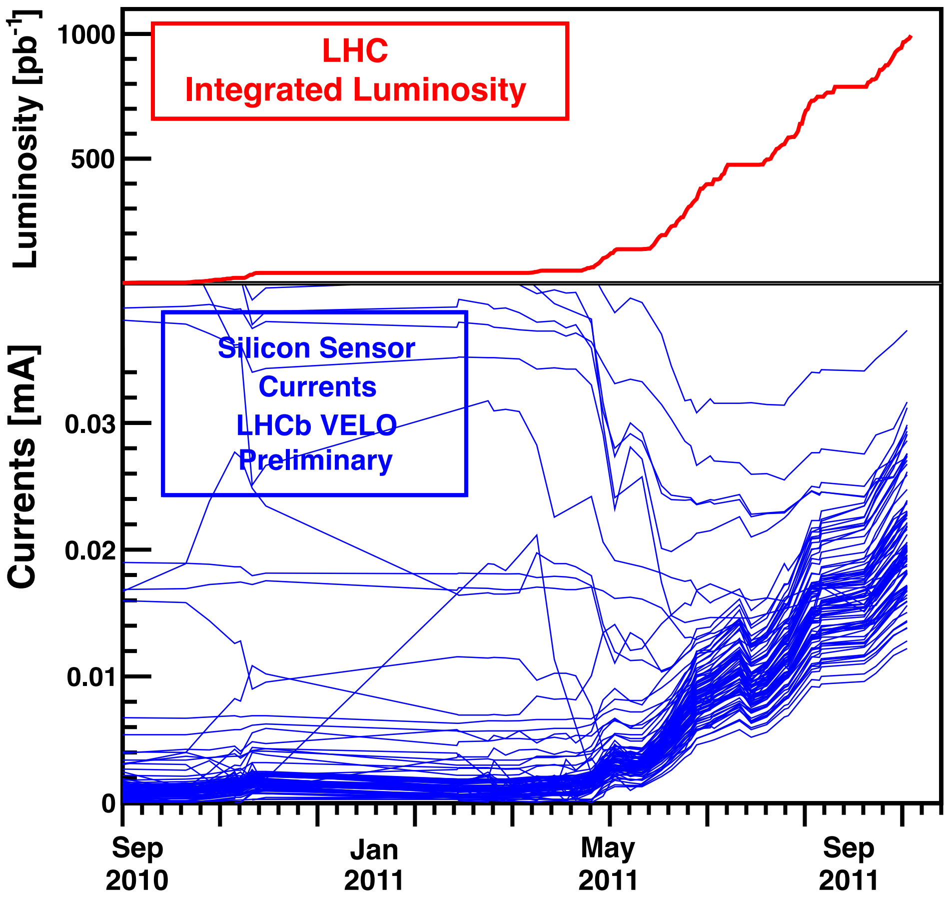
- Silicon micro-strip detectors.
- Three stations in z.
  - Four boxes in each station.
  - Four planes (0°, +5°, -5°, 0°)
- Pitch: 198 μm
- Thickness: 320 or 410μm
- 129024 readout channels.
- Total Silicon area is 4.2 m^2.
  - Covers region around beam with highest flux.
- Detectors operate at 0°C.

Radiation Damage Part I: VELO

- Accumulate 0.5 x 10^{14} n_{eq} at most irradiated sensor tip per fb^{-1} (we got ~ 1 fb^{-1} so far)
- We have 86 n-type sensors and 2 p-type
- Use of VELO data to measure VELO fluence and ageing
  - currents as a function of Voltage and Temperature
  - Noise as a function of HV
  - CCE as a function of HV
  - Landau distributions, cluster sizes, cluster distributions, detector resolution, SEU studies…

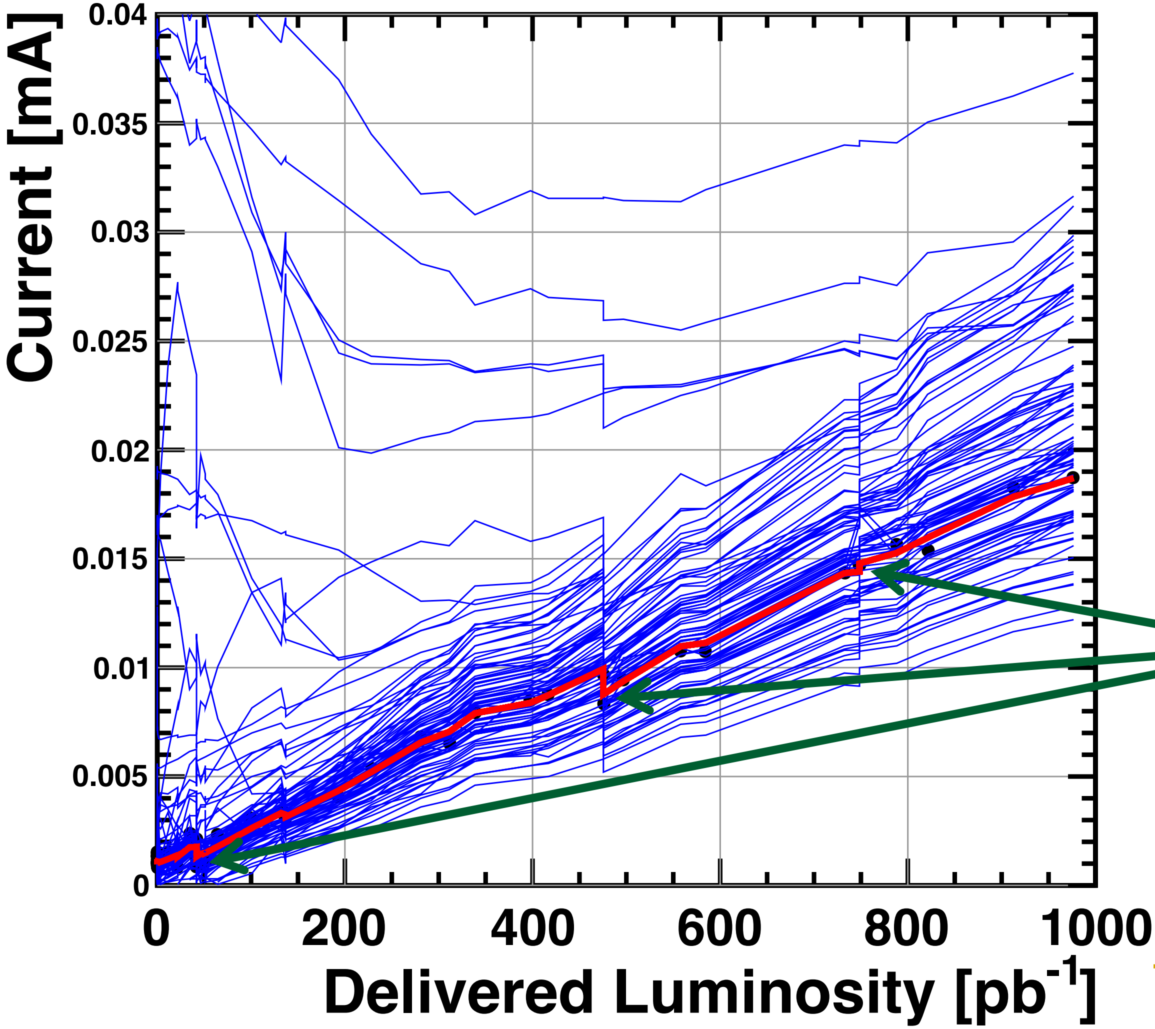


We are feeling the heat!



Current increases in the VELO beautifully luminosity dependent

Currents measured in operational conditions, without beam; increase of a mean of 19 μA per fb^{-1}



Warm up periods

Current in irradiated silicon sensors (simple view)

Current = bulk current + surface current

Increases with fluence
Exponential dependence on temperature
Should saturate with HV

Decreases with fluence (usually)
Flat or weak temperature dependence
HV dependence

In order to follow the evolution of the bulk current we should disentangle the two

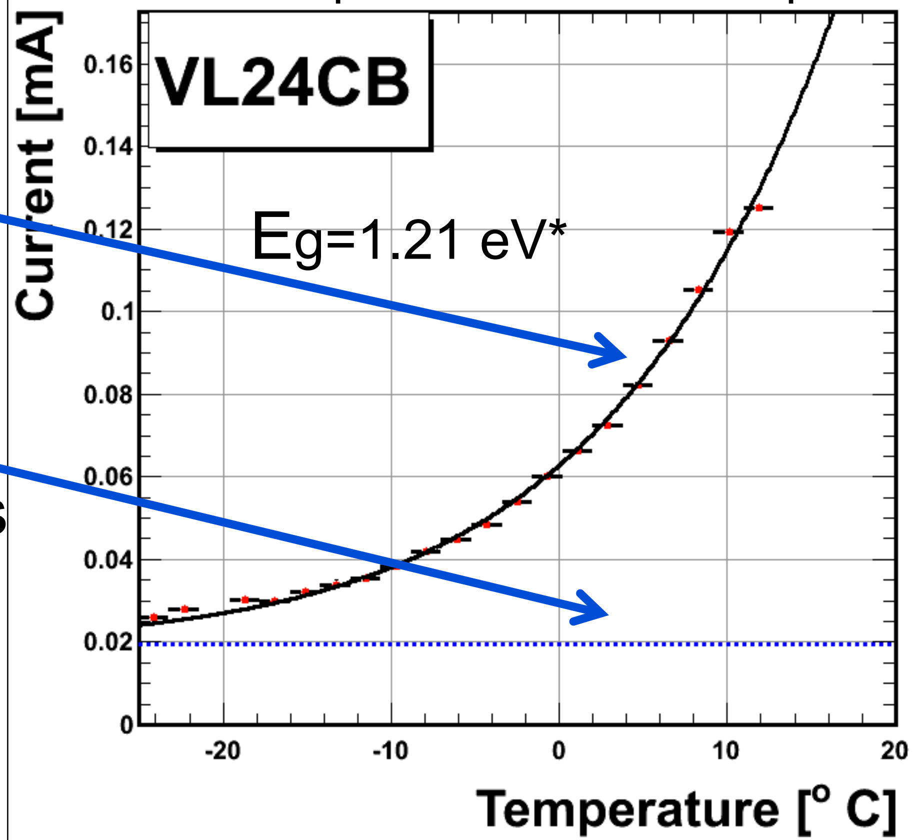
Why use IT (current vs temp) data?

- Bulk current contribution can be fitted as

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

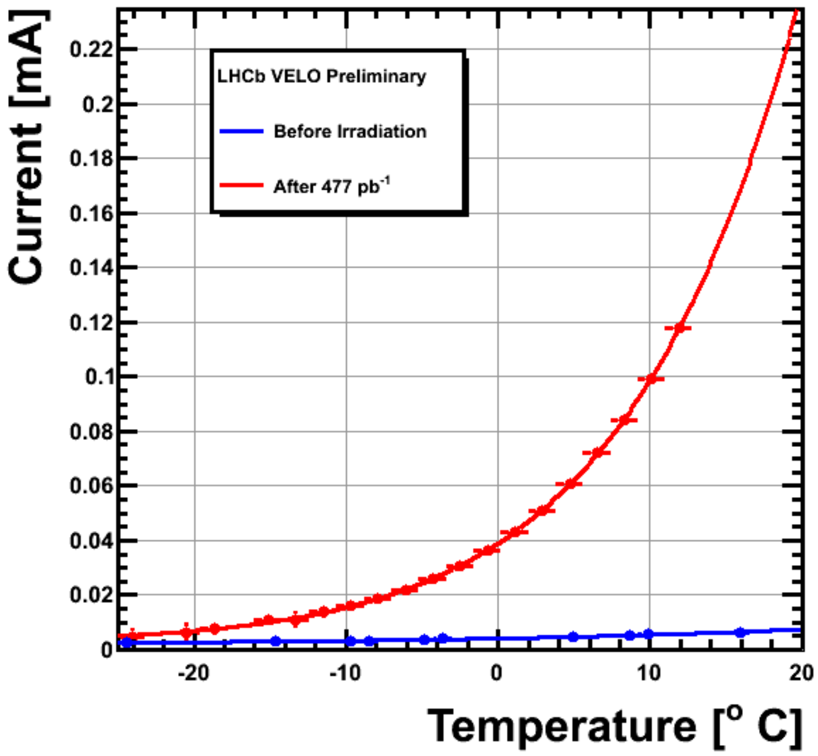
- Surface current contribution assumed to be flat
- Having the full curve allows us to compare all sensors at similar temperatures without an imprecise extrapolation from low temperature

Example sensor after 821 pb^{-1}

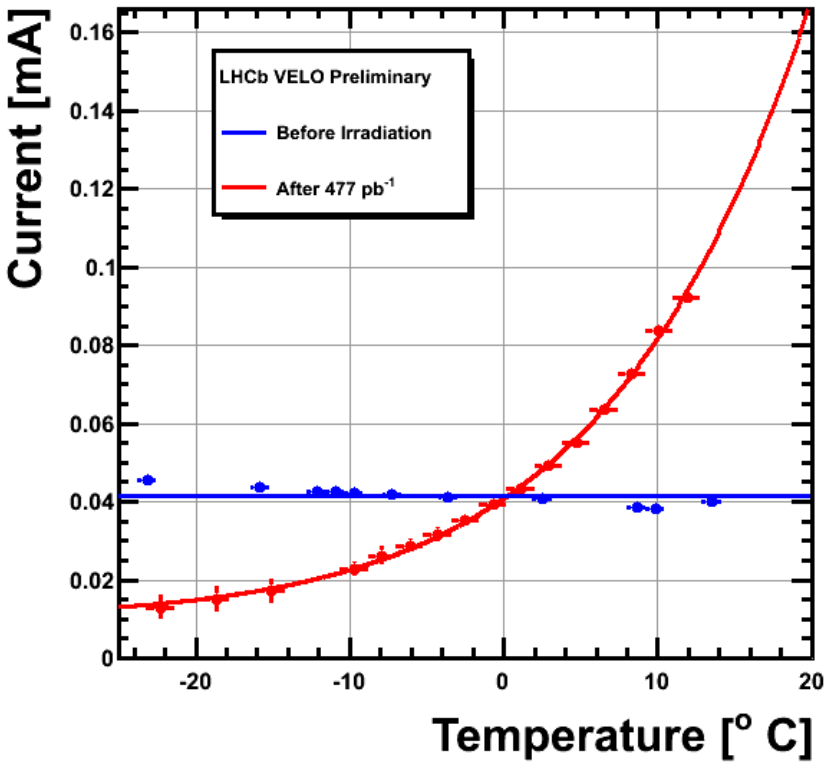


*A.Chilingarov, Generation current temperature scaling, 9 May 2011, https://rd50.web.cern.ch/rd50/doc/Internal/rd50 2011 001-I-T scaling.pdf,

Typical changes before and after irradiation

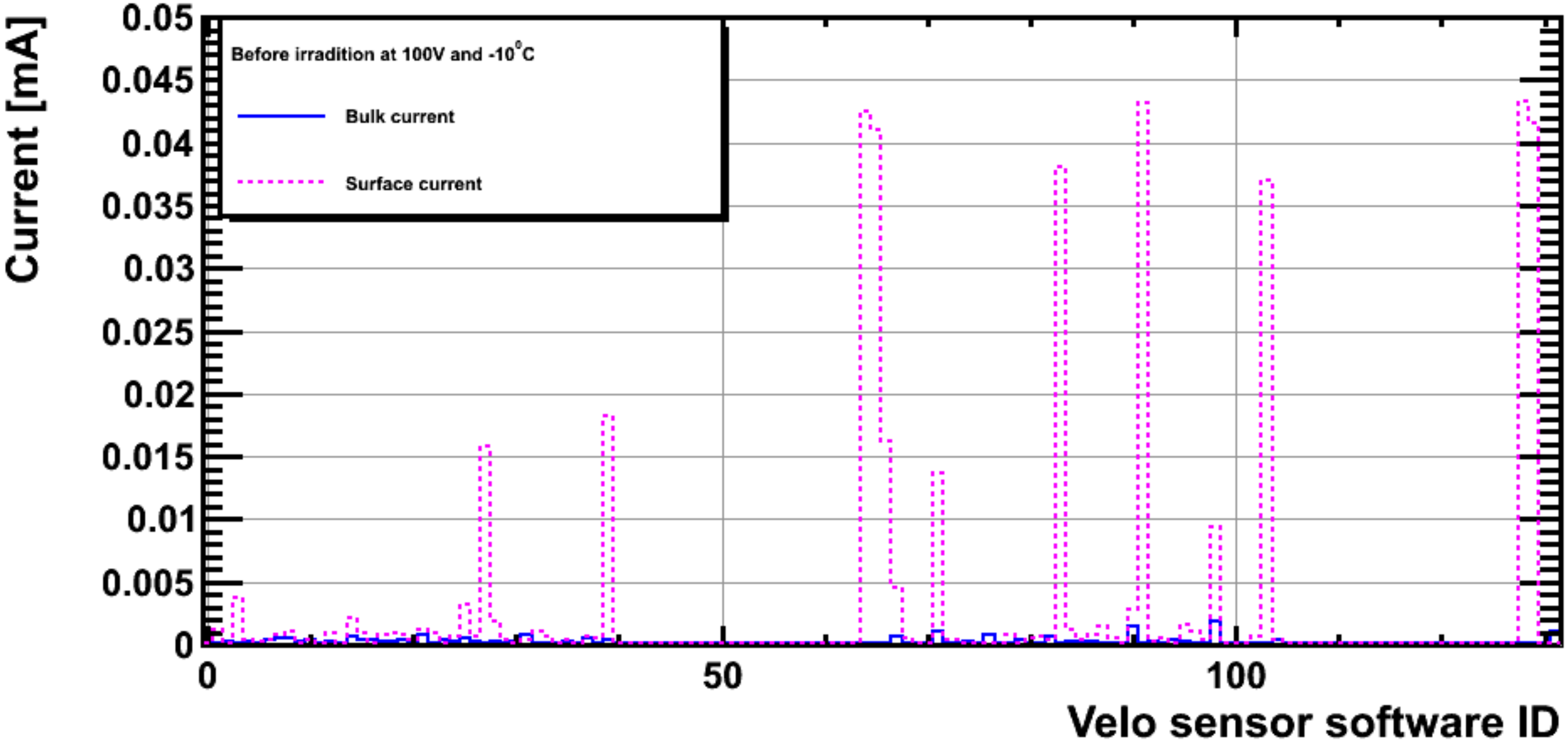


Bulk current dominated sensor both before and after irradiation

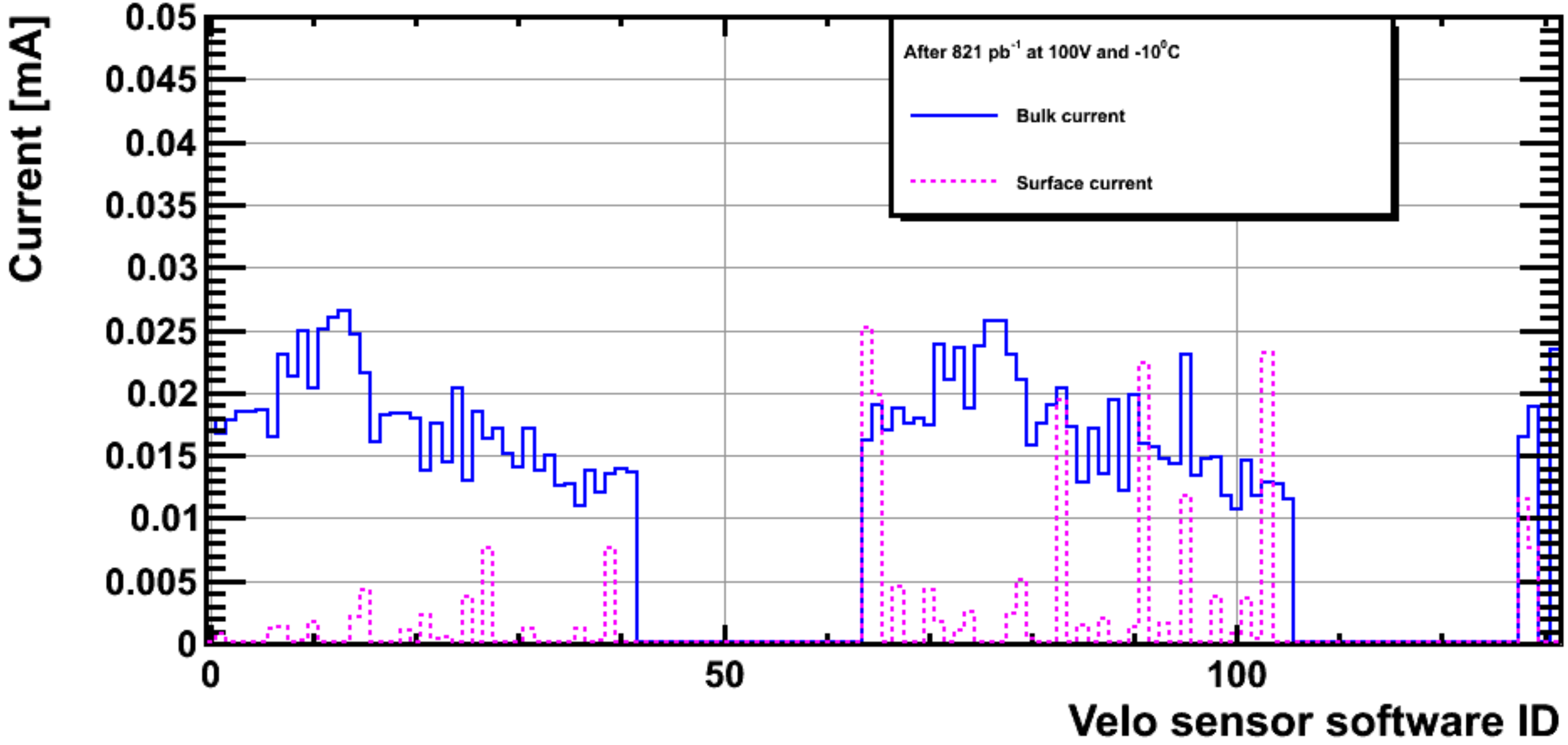


Surface current dominated sensor before irradiation, Bulk dominated after

Before irradiation: Bulk and Surface current

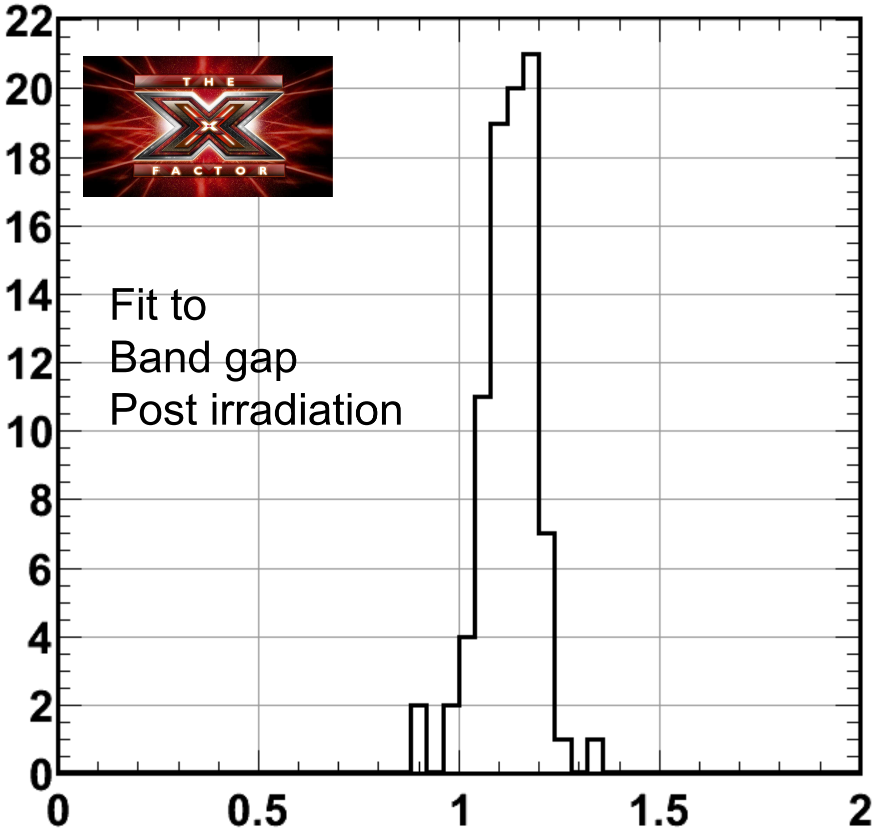


After irradiation: Bulk and Surface current



Exponential factor (exp-factor)

Our temperature corrections are very large, and we have 88 sensors, and so it is worth checking the exponent in the formula for our system by multiplying it by a factor "Exp-factor"

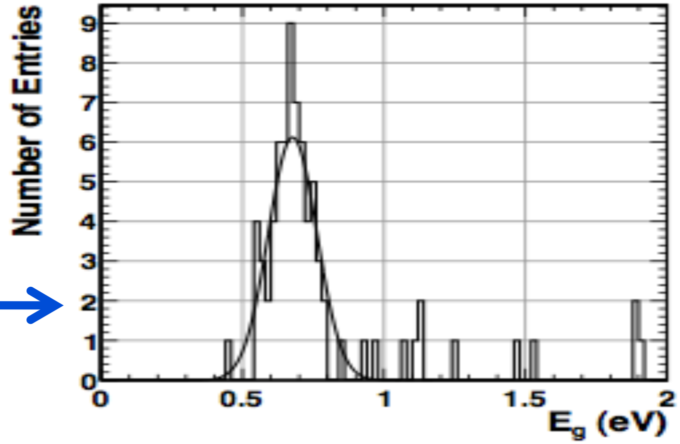


We can directly measure the "effective band gap" and compare it to theory (1.21 eV)

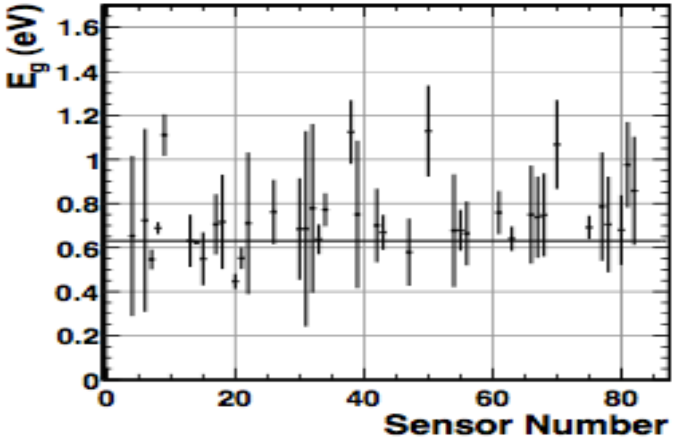
Preliminary	"effective band gap E_g"
100V 0 pb^{-1}	0.68 +- 0.08 eV
100V 40 pb^{-1}	1.29 +- 0.3 eV
100V 480 pb^{-1}	1.12 +- 0.06 eV
150V 480 pb^{-1}	1.11 +- 0.07 eV
150V 821 pb^{-1}	1.10 +- 0.04 eV

Typical question for this group; interpretation of this measurement of E_g

Before Irradiation

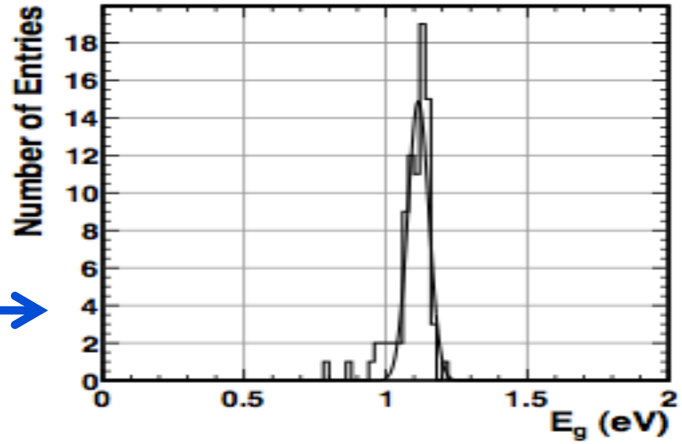


(a)

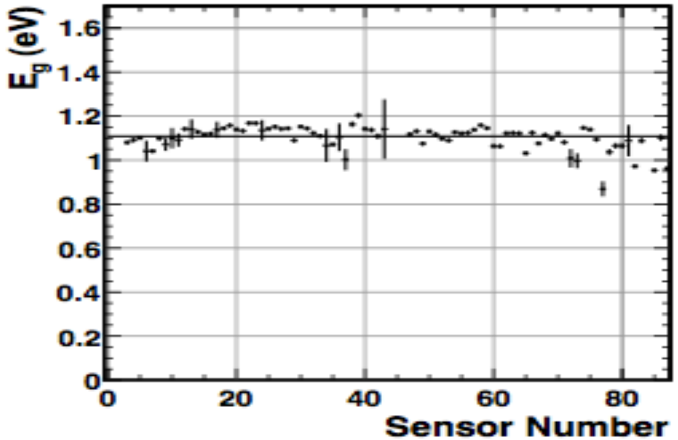


(b)

After Irradiation

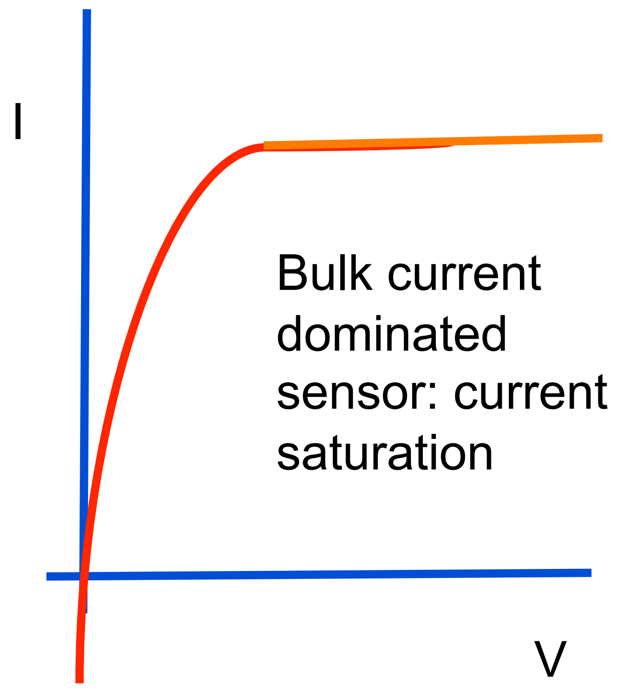


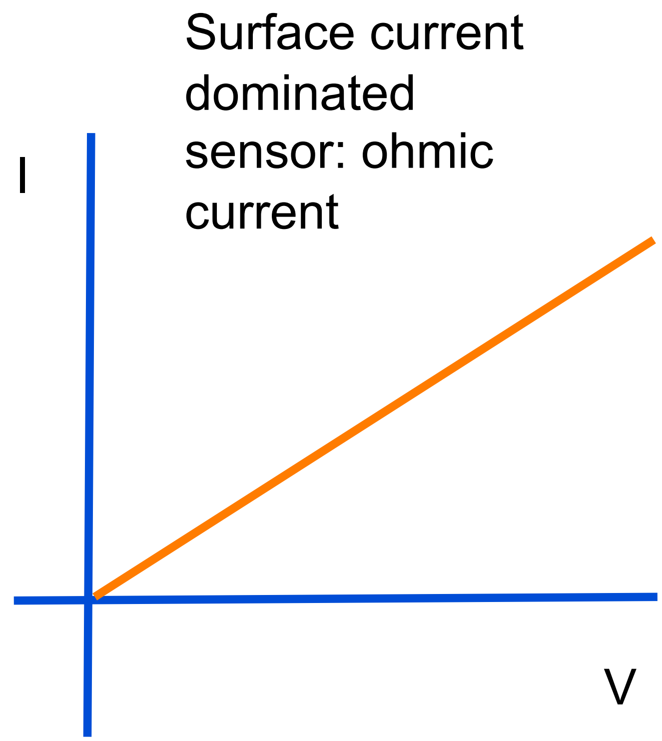
(c)



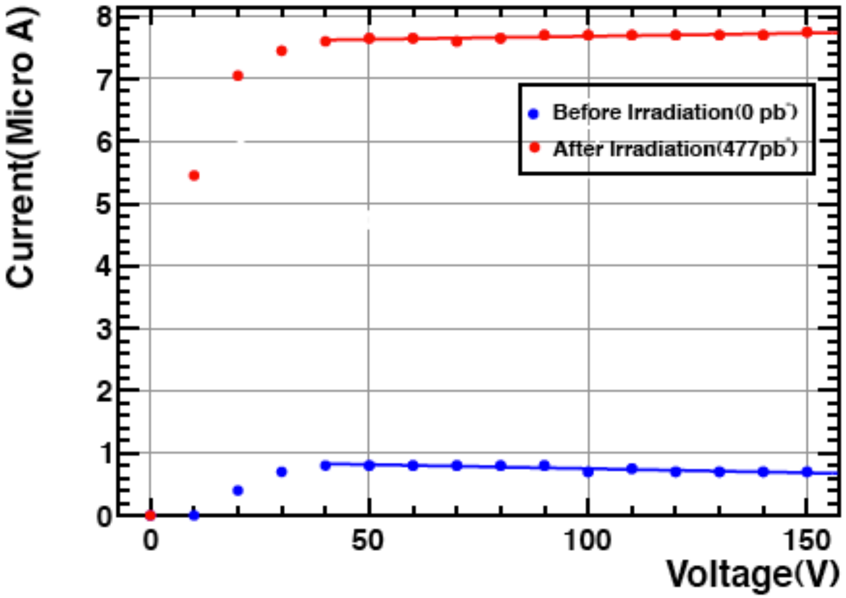
(d)

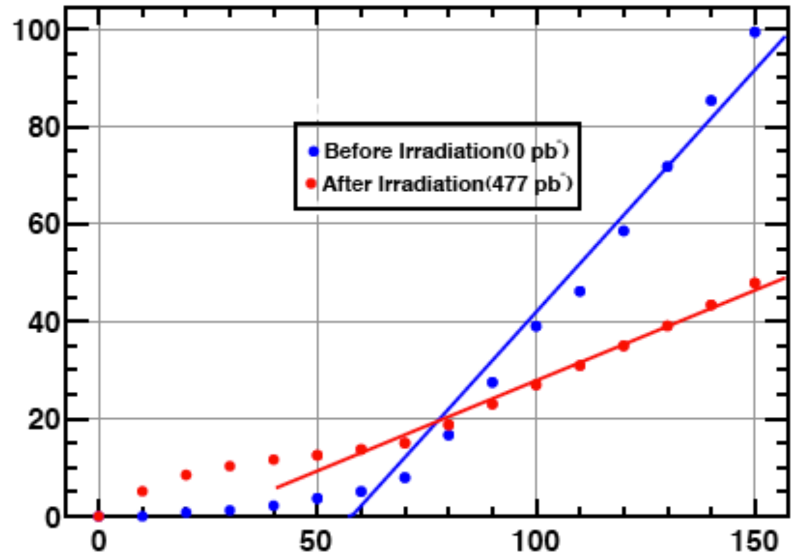
A different method to track bulk and surface current changes





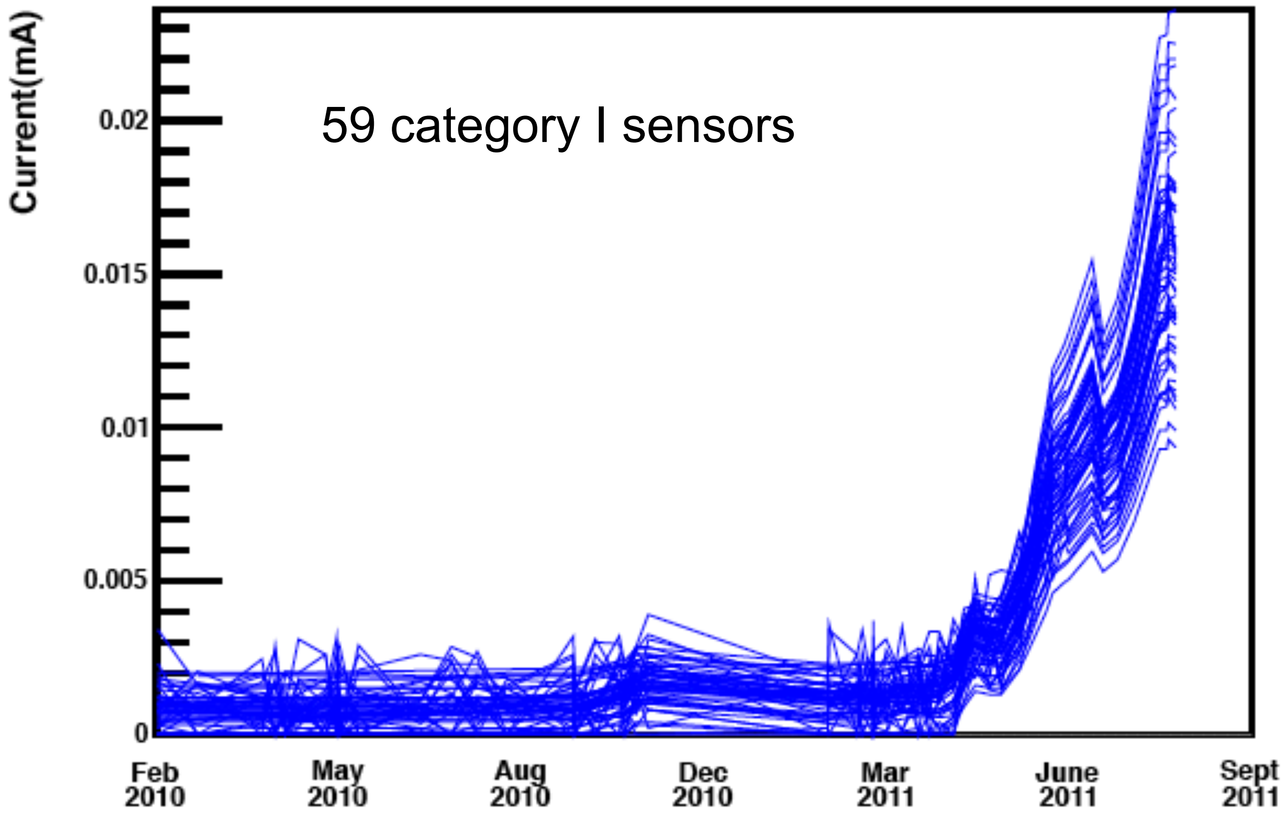
These slopes were tracked in real data





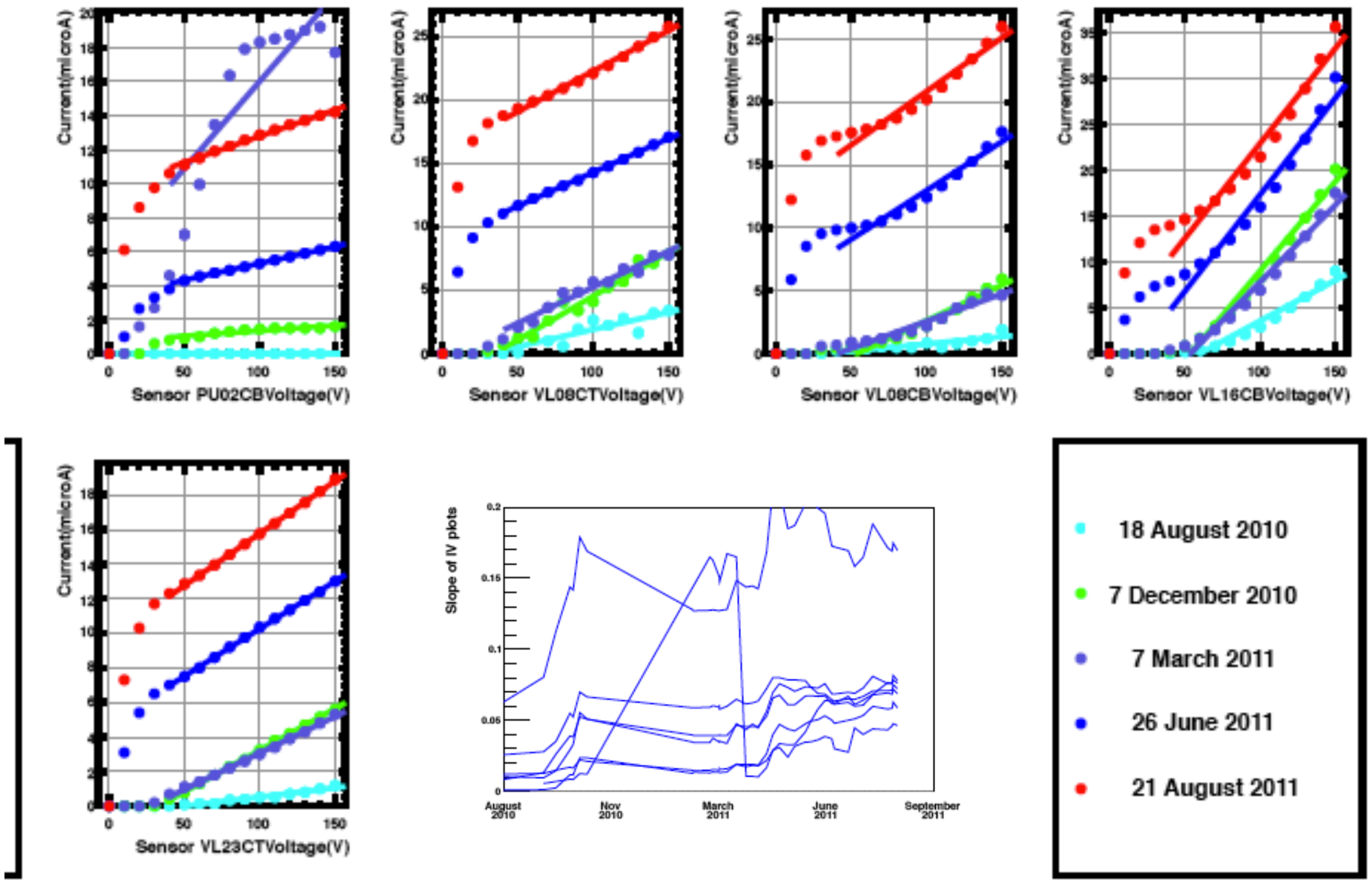
Ankit Gureja

Using a simple requirement that the slope is flat before and after irradiation completely cleans up the current curves

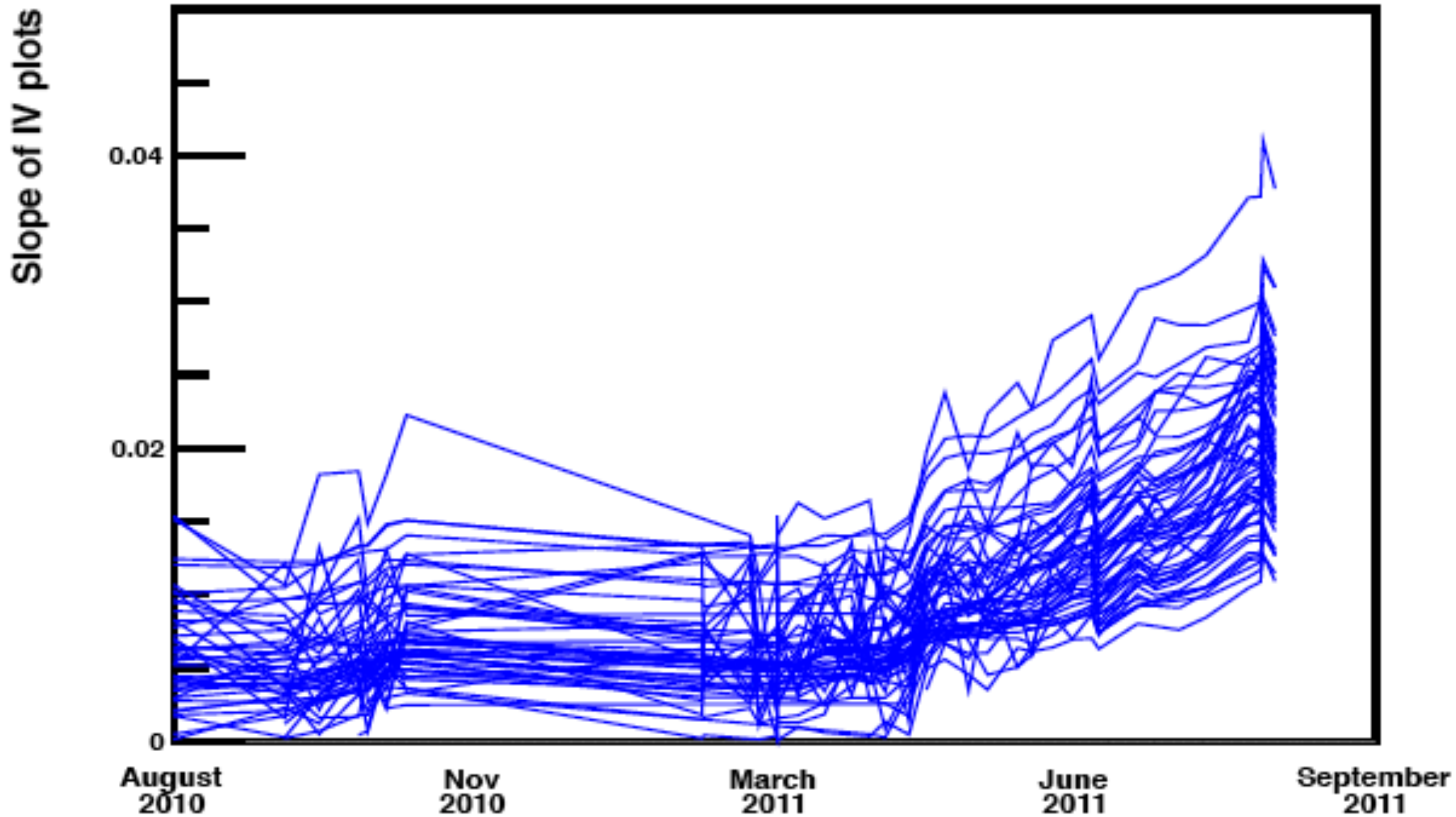


(b)

7 sensors show increasing slopes and are monitored carefully



Another typical question for this group: even the sensors with "standard" behaviour show slightly increasing slopes….



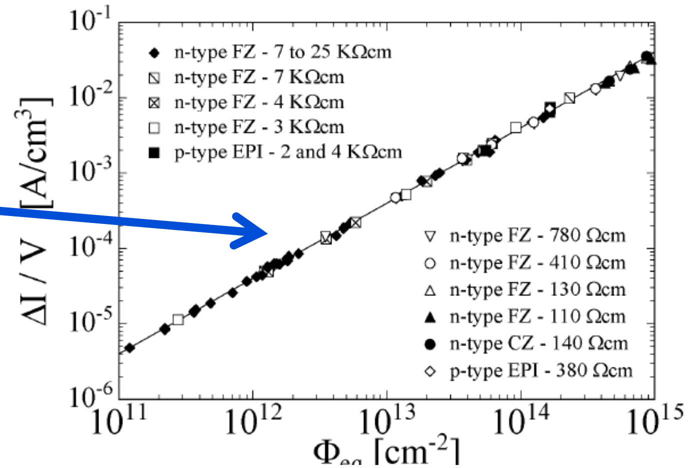
This phenomenon is not understood

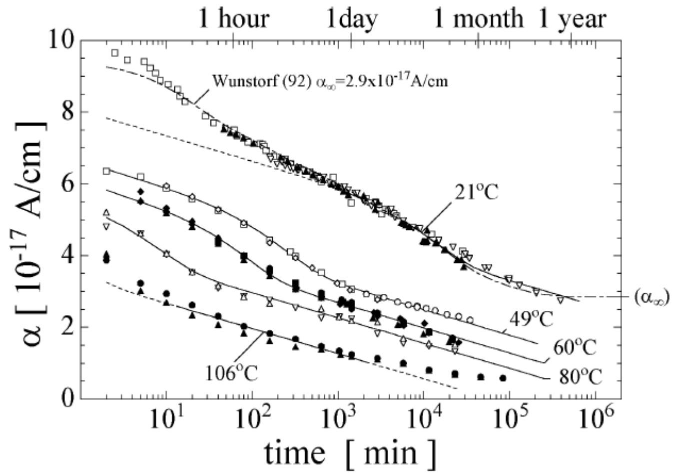
How do our measured and expected currents compare?

- Current generation in irradiated silicon diodes one of the most precisely measured quantities in the business
- Identical for all fluences and substrate types
- But… we have to correctly treat annealing and temperature factors, and these factors can be large
- Annealing data not available at our operational temperature
- Use Arrhenius relation to convert all time into equivalent time at 21°

$$\alpha_{T1}/\alpha_{T2} = \exp(-E_g/k_bT_1) / \exp(-E_g/k_bT_2)$$

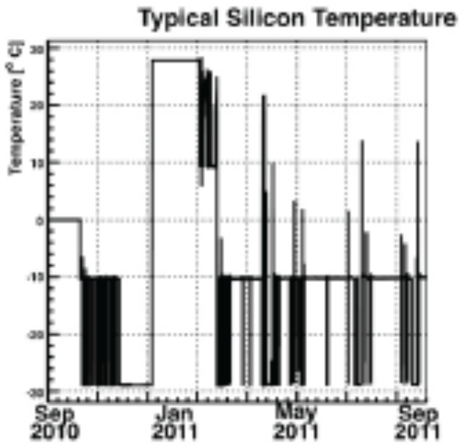
(where Eg=1.31 eV)

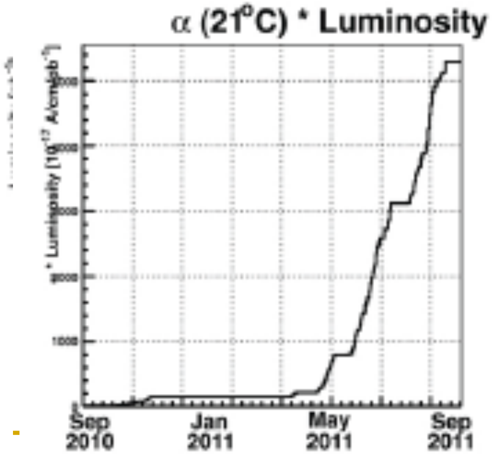


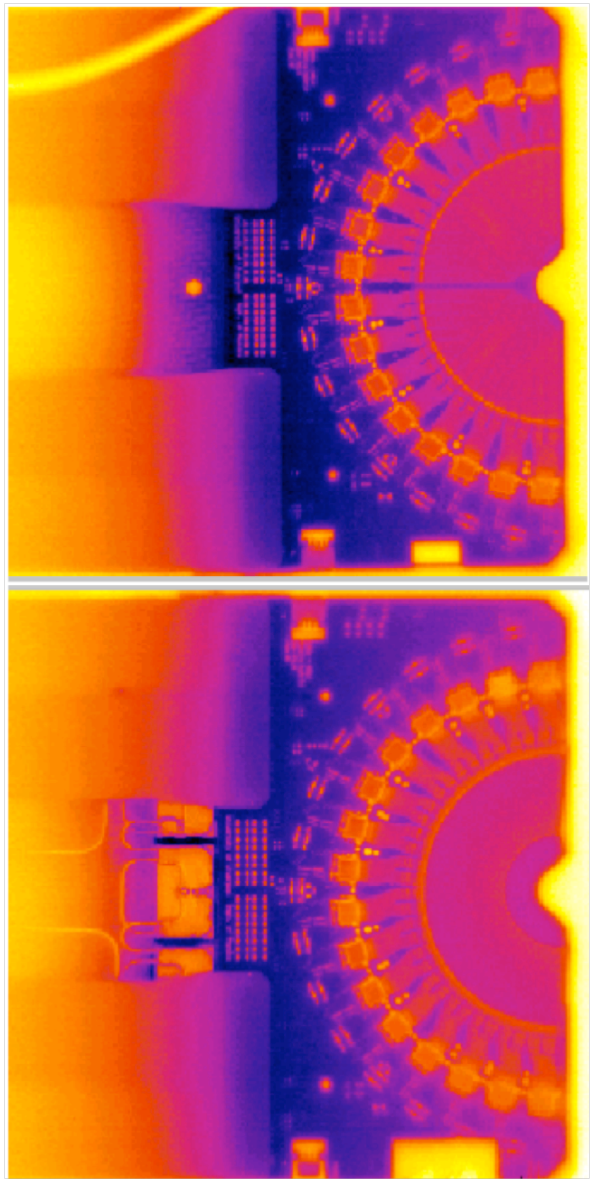


Calculation of α

- Silicon temperature measured via thermographs in vacuum tank burn-in system
- Typically 3 degrees warmer then top NTC, with some spread
- LHCb-2007-082
- Silicon temperature folded with luminosity to derive an effective α*$\mathcal{L}$

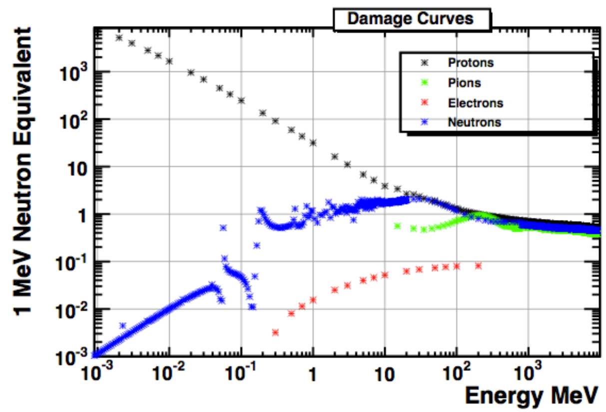






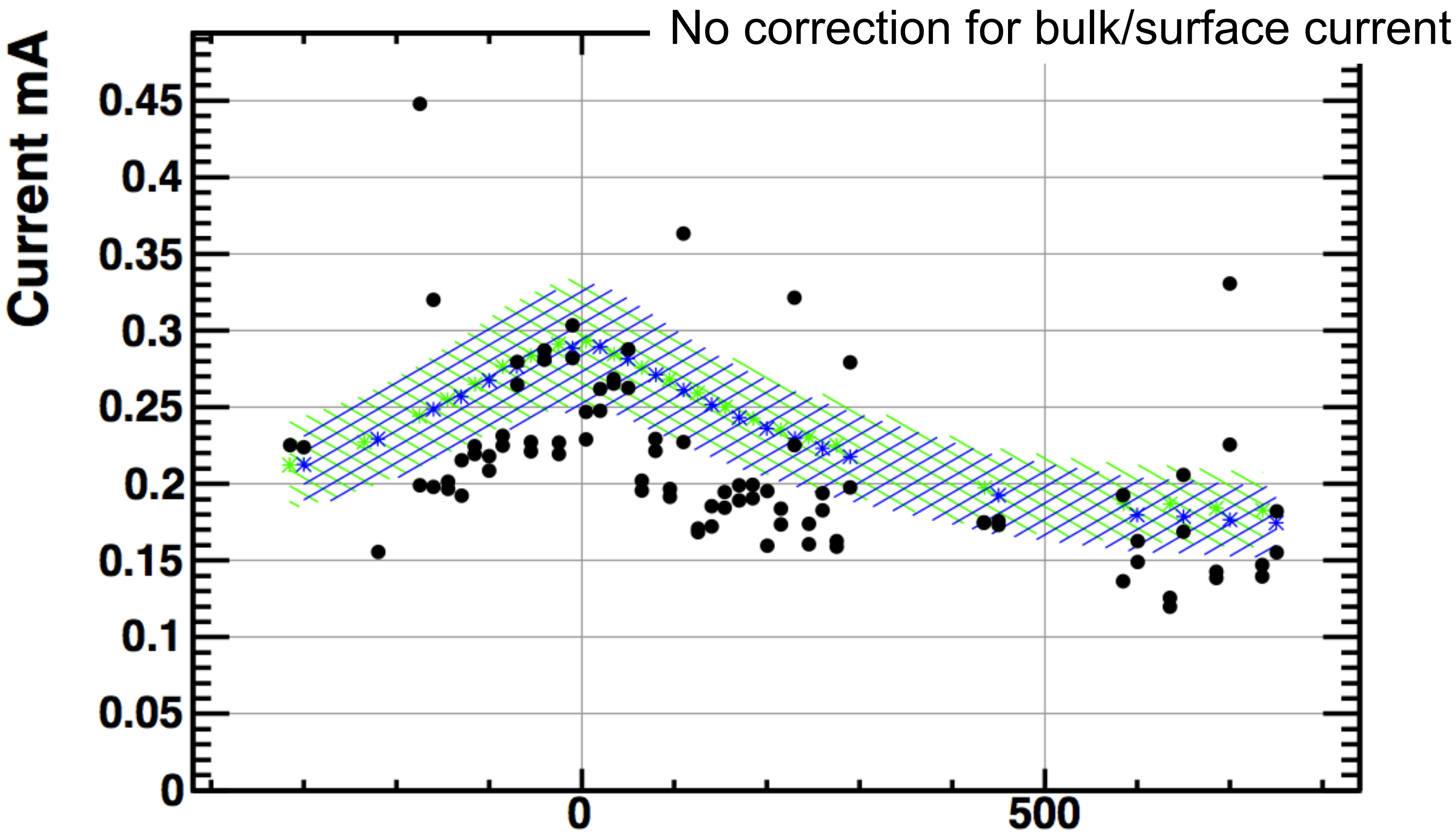
Estimate of damage from MC

- Use standard LHCb simulation to measure path lengths of particles in silicon
- Implement radiation damage tables into ROOT to convert to damage
- Questions:
  - How to treat kaons? Photons? Conversions?
  - What about low energy particles?
  - (fortunately we are dominated by charged pions, so the error induced is small, but it would be nice to understand better the prescriptions..)



A. V. I. Bucharest) and G. L. U. of Hamburg), “Displacement damage in silicon, on-line compilation.” http: //sesam.desy.de/members/gunnar/Si-dfuncs.html

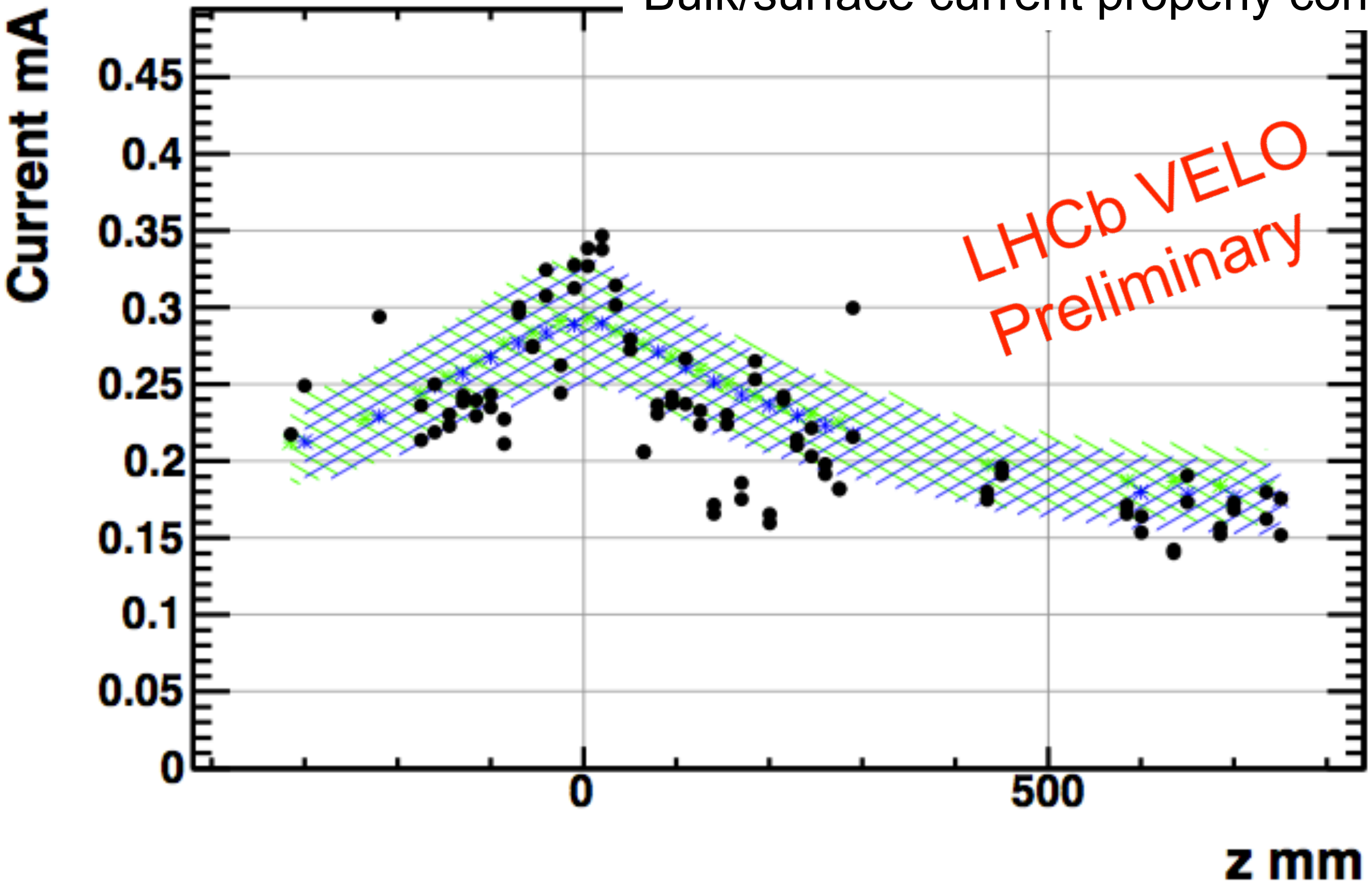
Comparison of data and MC



Comparison of data and MC

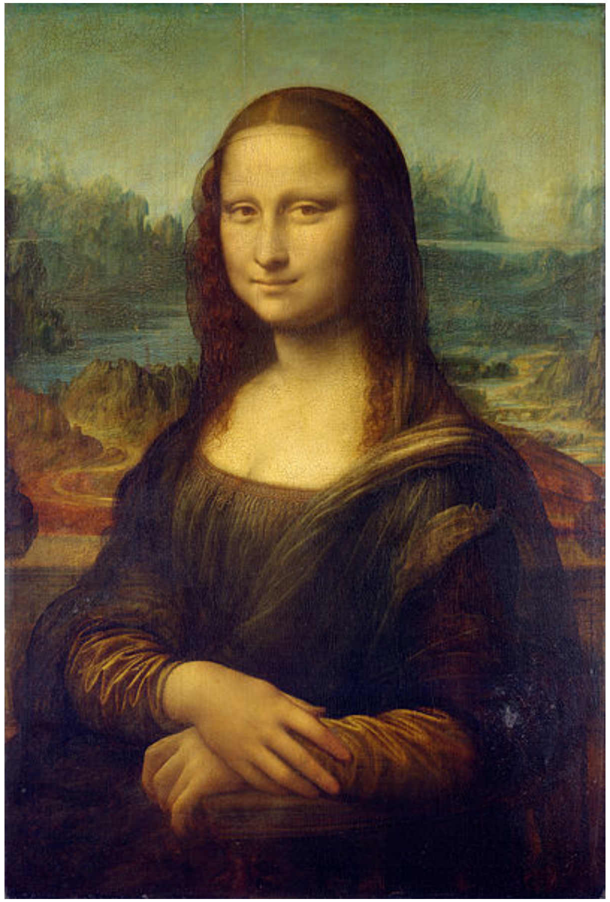
- Finally, a very satisfactory agreement between MC and data
- Not (yet) sensitive to second order effects (low energy particles, thermal neutrons etc.)

Bulk/surface current properly corrected



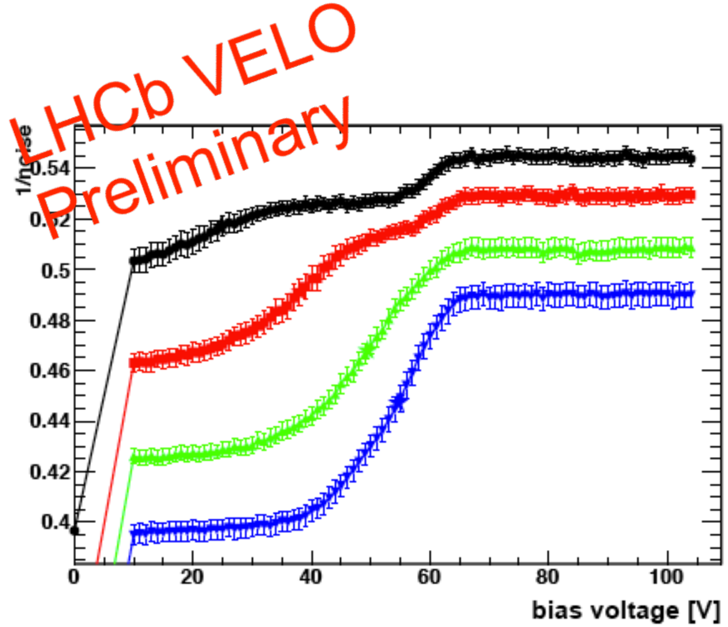
Given that we know the fluence what about the depletion voltage behaviour?

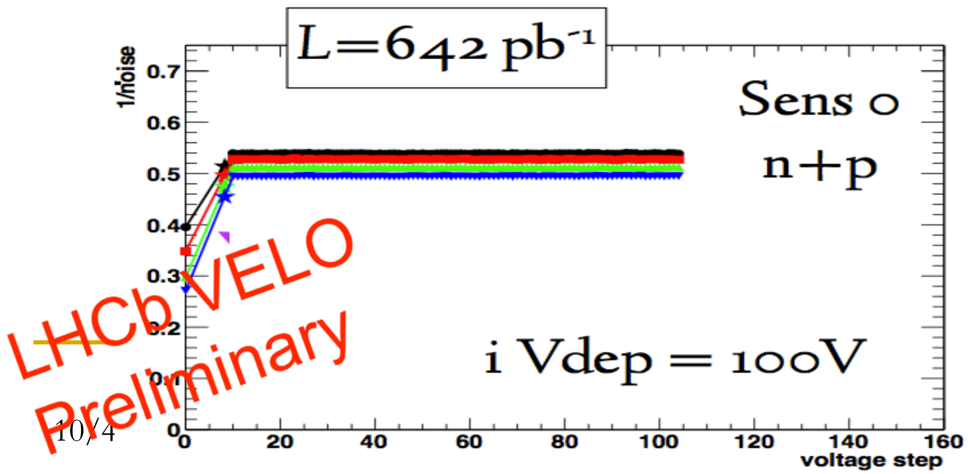
- Should be a classically known quantity – for the n type sensors should drop, and then increase
- "Moderate" fluences, standard, FZ oxygenated silicon
- Testbeam measurements published in TDR for n-type only

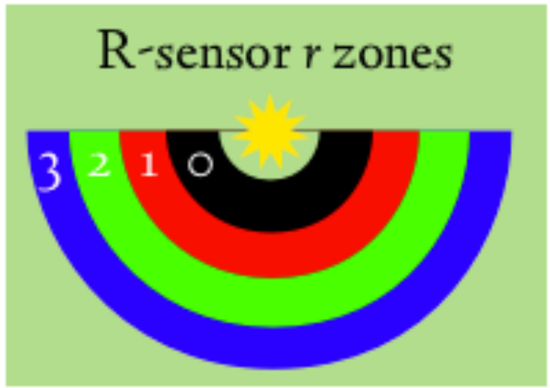


Investigating depletion voltage: Noise vs Voltage

- Example, after 642 pb^{-1} :
  - n+n sensor, Initial V_{dep}=70V
  - “Step” in 1/N (corresponding to ~depletion) moves progressively to lower voltages as radius decreases
  - n+p sensor, initial depletion voltage = 100V
  - “Step” in 1/N remains at low voltage for all regions (depletion region grows from strip side)



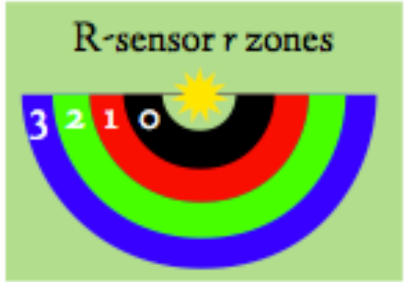


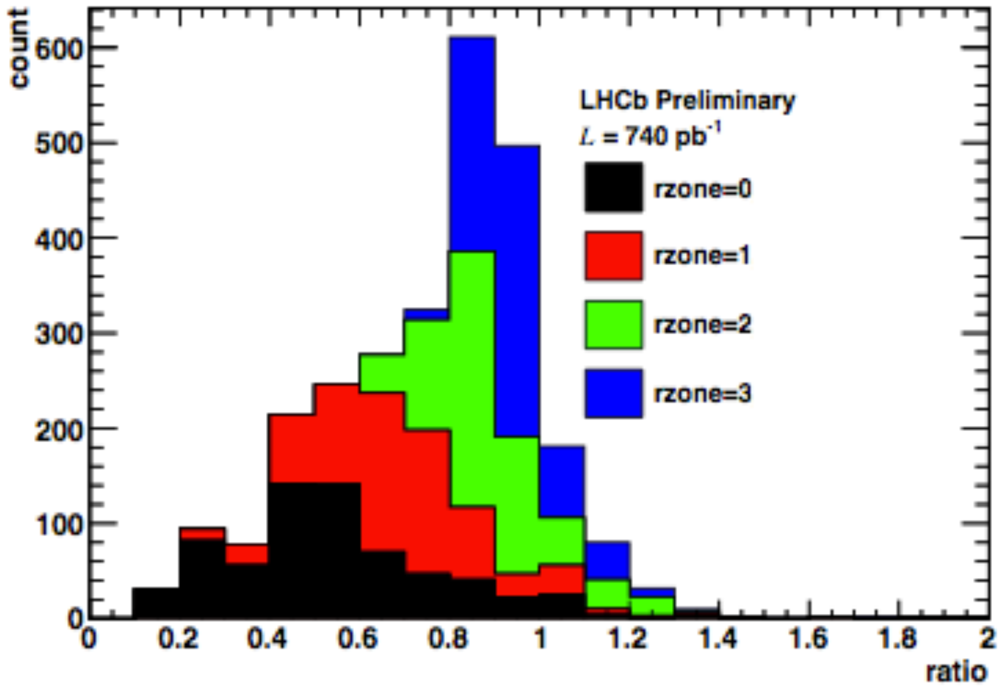


Noise vs Voltage

- The greatest movement in the “step” for the n+n sensors is seen for the inner regions
- The size of the movement indicates that the sensors are type inverted at the tips
- More sophisticated analysis underway:
  - Analysis of slopes
  - Positions of steps…

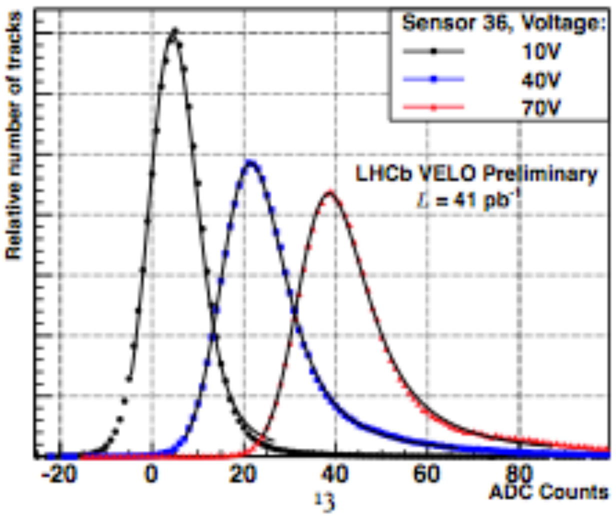
$$R = \frac{\text{initial EDV}}{\text{final EDV}}$$

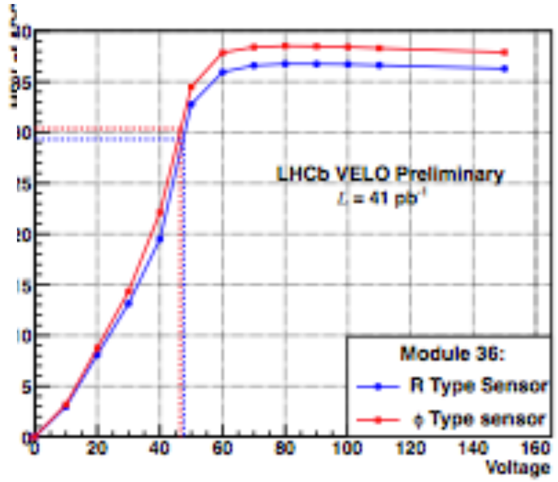


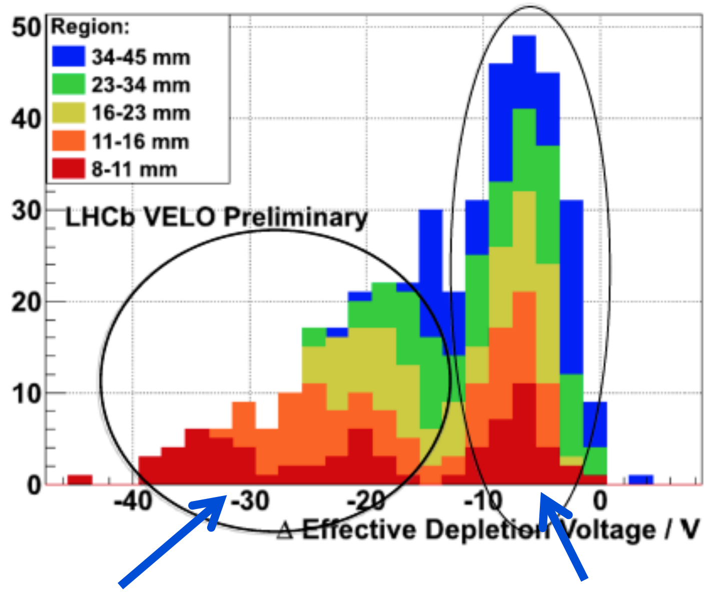


Depletion voltage: CCE scans

- Bias voltage is scanned on selected sensors and tracking provided by sensors at nominal bias
- Selected sensors rotated through the VELO until all sensors tested
- Effective Depletion voltage extracted for 5 different regions in each sensor
- Automatic procedure taken with beam data, 2-3 times per year
- Confirms type inversion of sensors



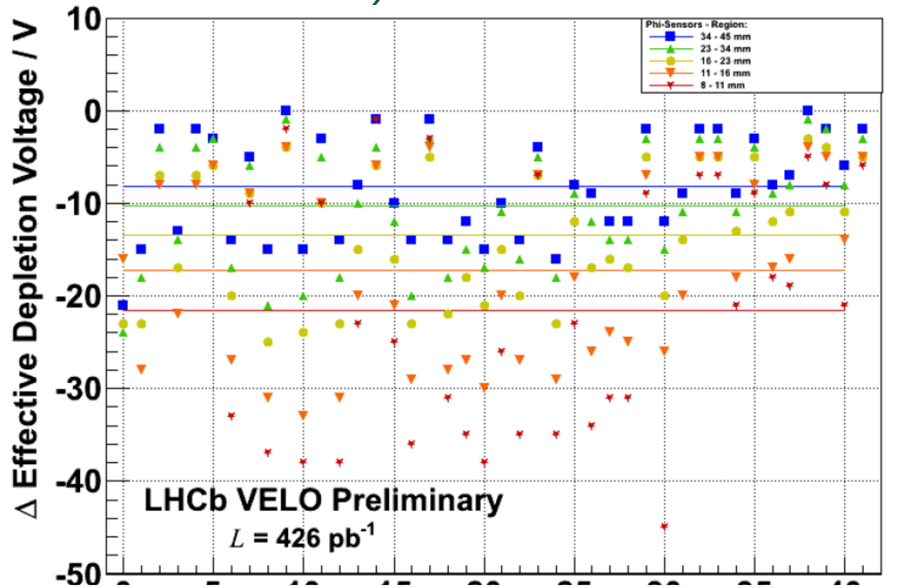


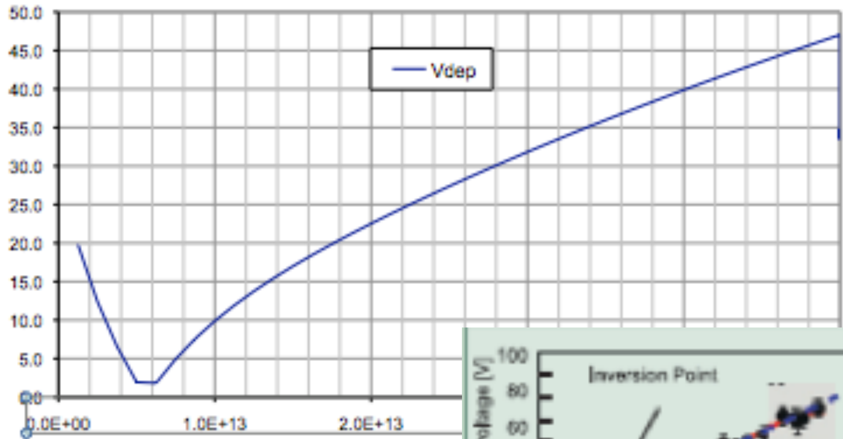


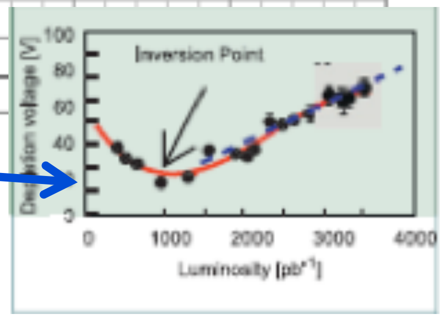
High initial dep. V Low initial dep.V

Depletion voltage drop measured with CCE method (only half accumulated luminosity measured so far)

- For n-in-n sensors we expect the depletion voltage to drop, and then rise after type inversion
- CCE scan sees a reasonably consistent drop of 40V in effective depletion voltage for the most irradiated regions
- at a fluence corresponding to about 2.5 x 10^{13} n_{eq} max, 1.8 x 10^{13} n_{eq} average
- Hamburg model predicts ~ 40V-70V change – we are doing slightly better than Hamburg
- Nice memories from CDF!

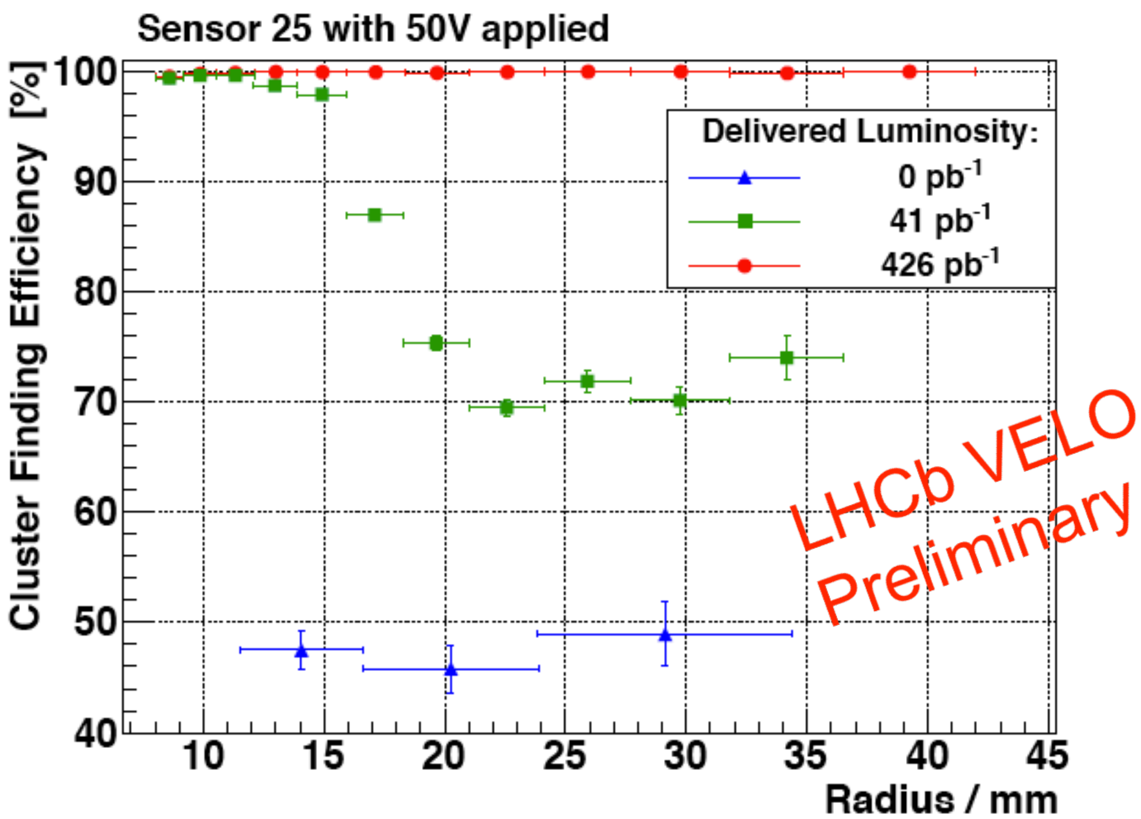




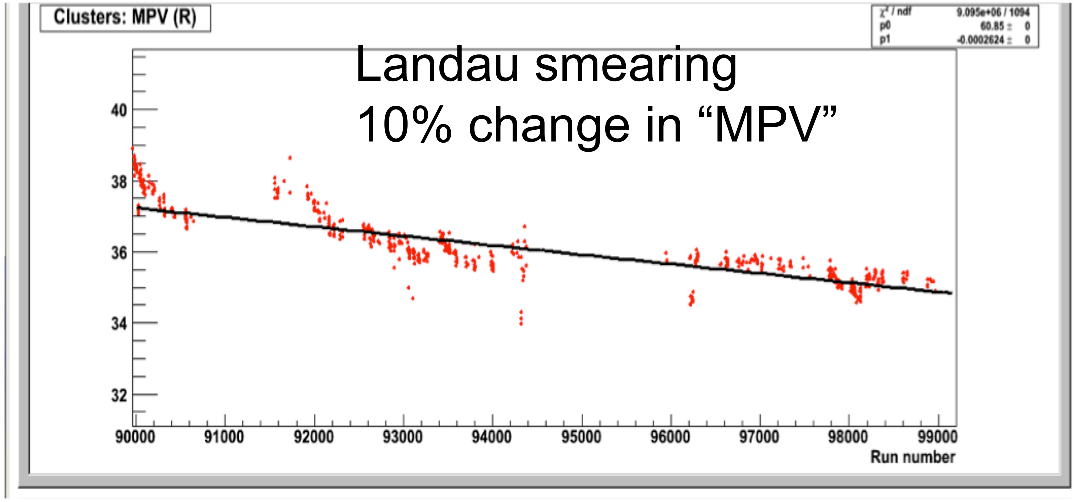


Cluster finding efficiency

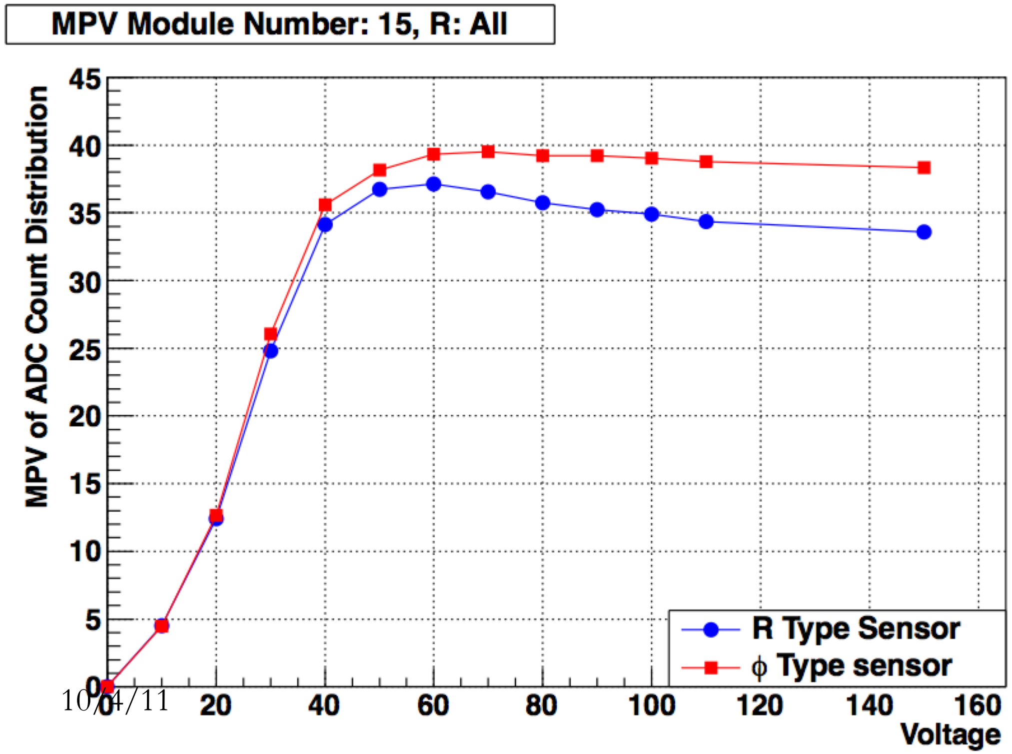
- Beautiful effects seen:
  - When the sensor is under nominal depletion it is more efficient in the innermost, more irradiated zone! (because V_{dep} has dropped here..)

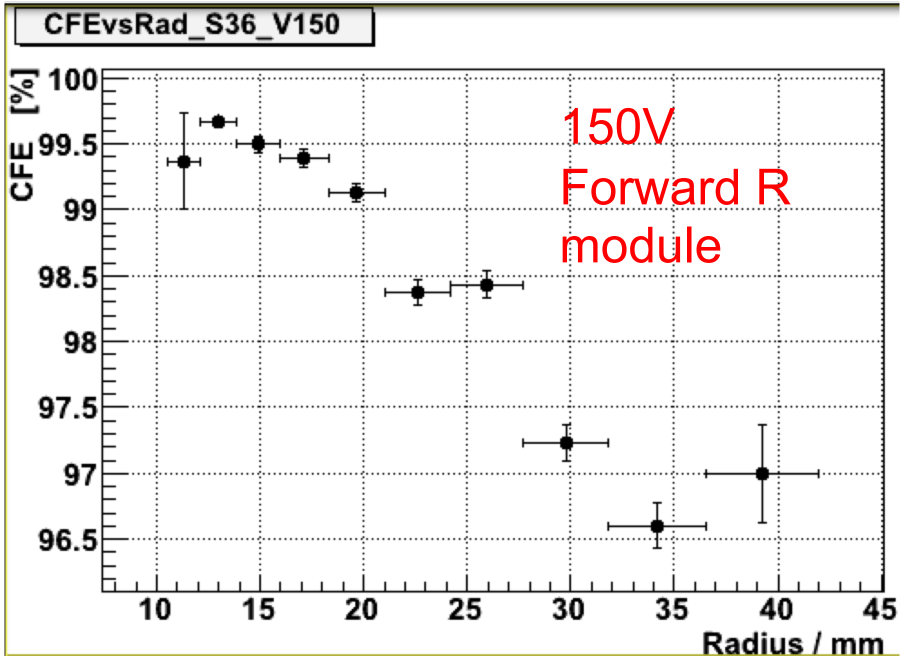


And not so beautiful effects



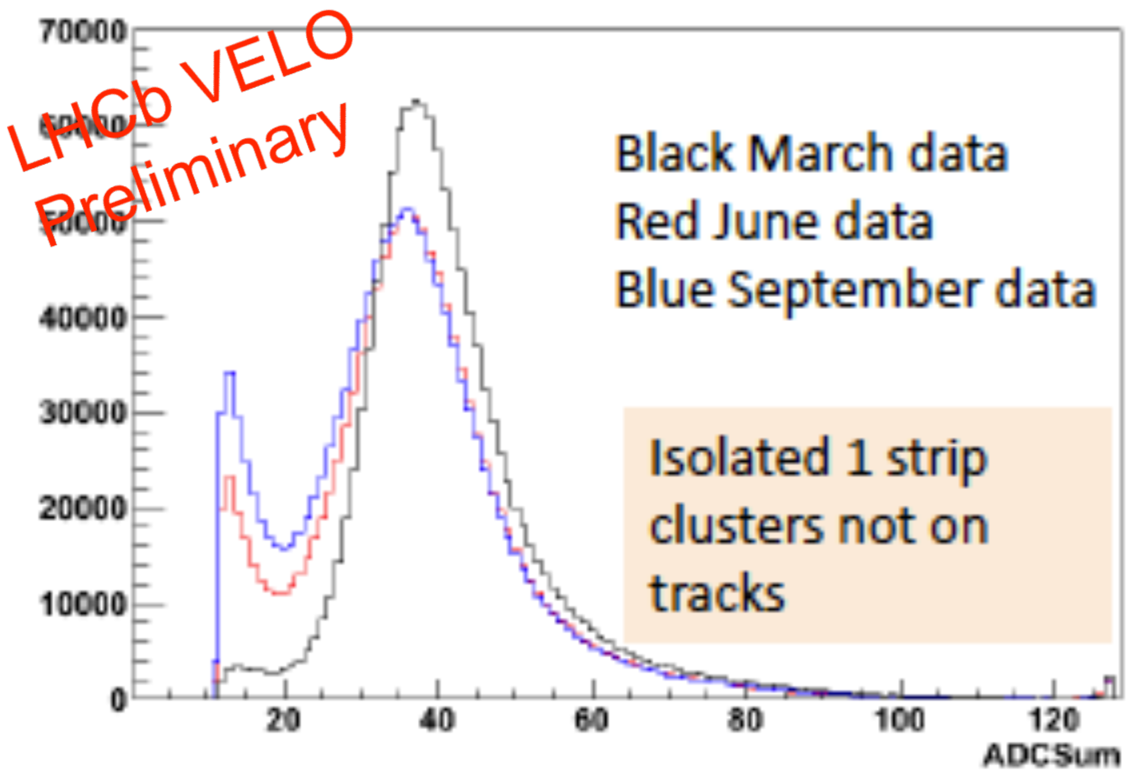
- Developed during year
- Worse at higher voltage !
- Worse at outer radius

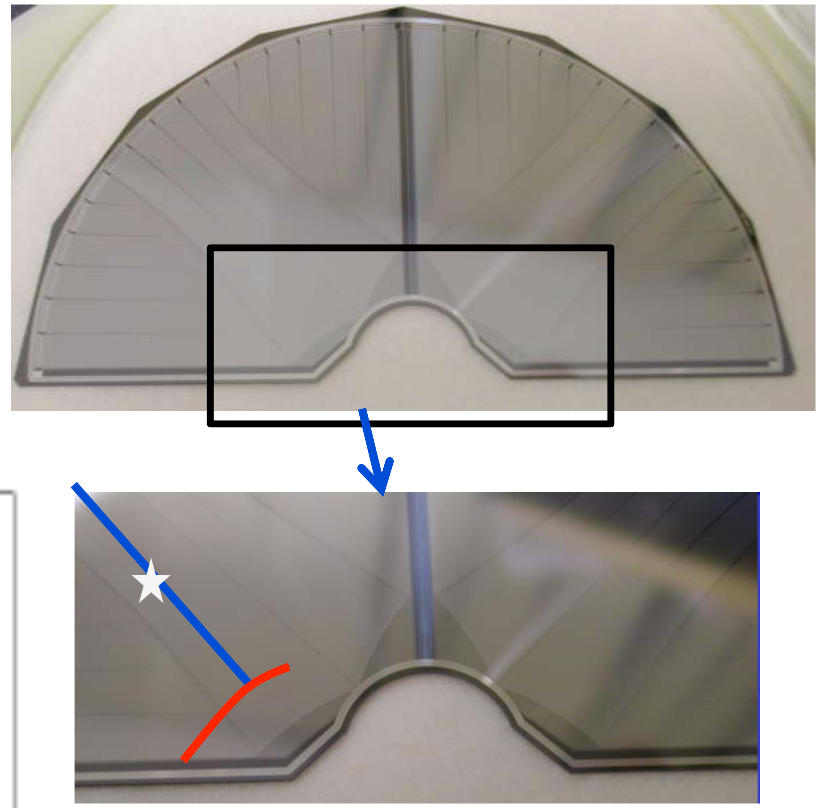




Possible explanation?

- We see bump at low values in landau spectrum, for clusters not associated with tracks
- Associated with tracks passing under regions with double metal layer





Track impacts at star
Small signal is seen on blue routing line
This fakes a cluster on the red strip
When the track passes in a region with no routing line small clusters are not seen

Open questions

- What is the exact mechanism?
- Why is there a voltage dependence (worse efficiency at higher voltage)
- Why is the effect more pronounced for downstream sensors? (surface damage?)

- Questions for this forum!

What do we expect for the p-type sensor?

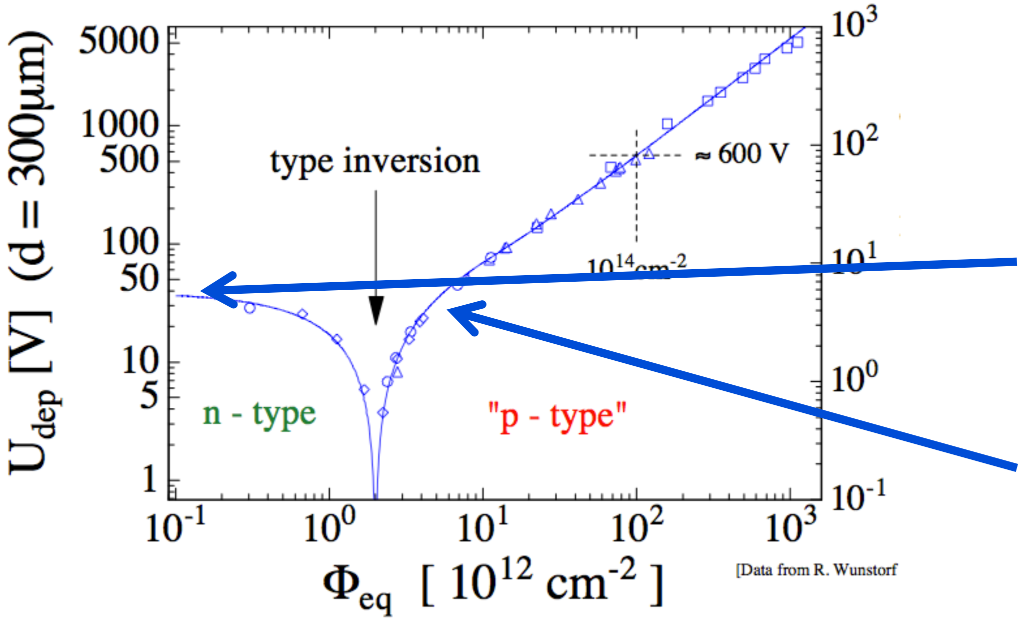
- At first sight there are two possibilities
  - The depletion voltage will go up
  - The depletion voltage will go down, and then up again

What do we expect for the n-in-p sensor?

- Which can be expanded to:
  - The depletion voltage will go up
  - The depletion voltage will go down, and then up again
    - The sensor will type invert
    - The sensor will not type invert

Classic view:

- Irradiation causes a gradual introduction of acceptors, which effectively change the material from n-type to p-type (dominant introduction of acceptors)



In this simple view the n type sensor starts here
and the p type sensor starts here

- But… We see (for 400 pb-1) a *drop* in V_dep of ~20V!!!

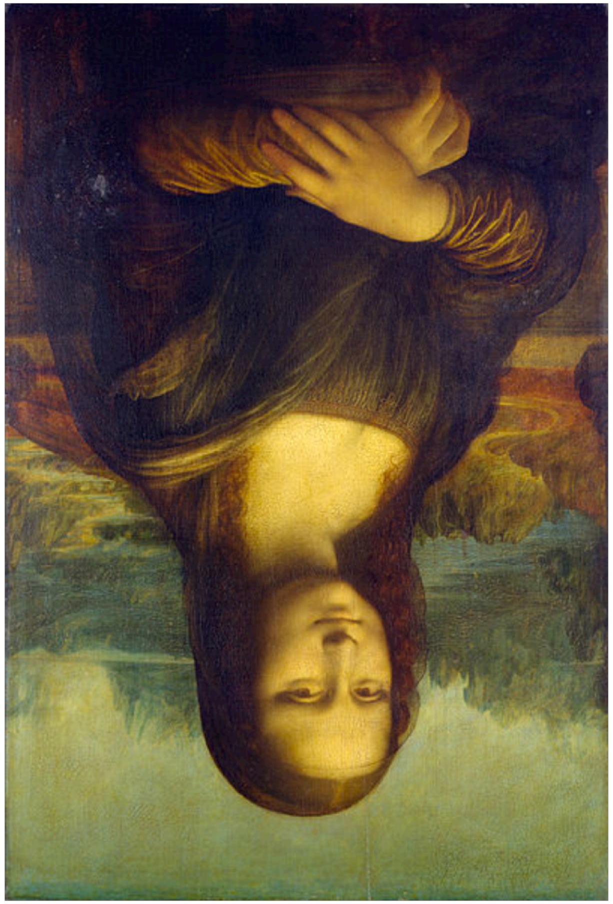
We are entering uncharted waters

- Generation of defects may be very different in p type material
  - e.g. the in-activation of the phosphorus dopant in n-type material (=donor removal) cannot have an equivalent mechanism for p type material
  - The oxygen concentration enhances donor generation
  - What is generally understood to be acceptor (Boron) removal is significant for charged particle irradition (dominant for us) and small for neutron irradiation
- RD50 has not really studied these effects, being more interested in high irradiation, other novel materials (MCz, epi) and CCE measurements

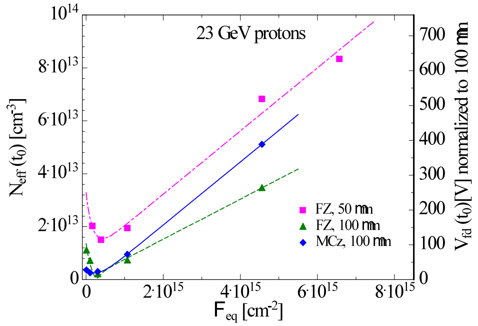
Hamburg model II

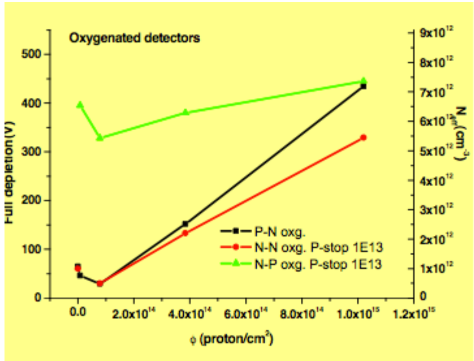
- It is possible that our p-type material may (briefly) invert to n-type!!
- (but unlikely due to low oxygen concentration)

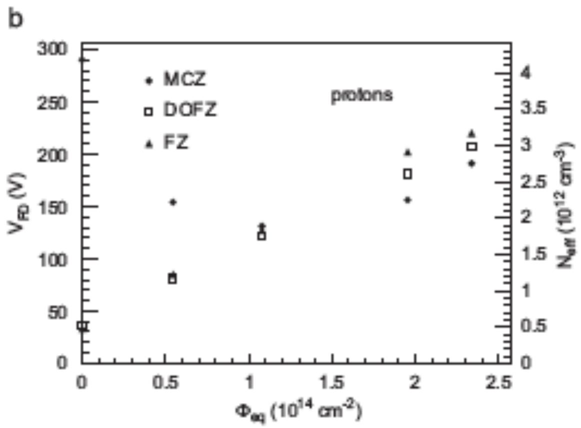
- Not as surprising as neutrinos travelling faster than the speed of light but surprising nonetheless
- Nice topic for this forum!



What about measurements? A variety….







- Fz n-type oxy 50 um, no SCSI
  - Demonstrates importance of oxygen for introduction of donors

Doris Eckstein, Hamburg University
12th RD50 workshop, Ljubljana, Slovenia, June 2008

- Oxygenated p-type
- Dip in V_dep but no SCSI
  - Supports our observations here, but indicates that we *might* still type invert

RD50 workshop 2004, Lozano

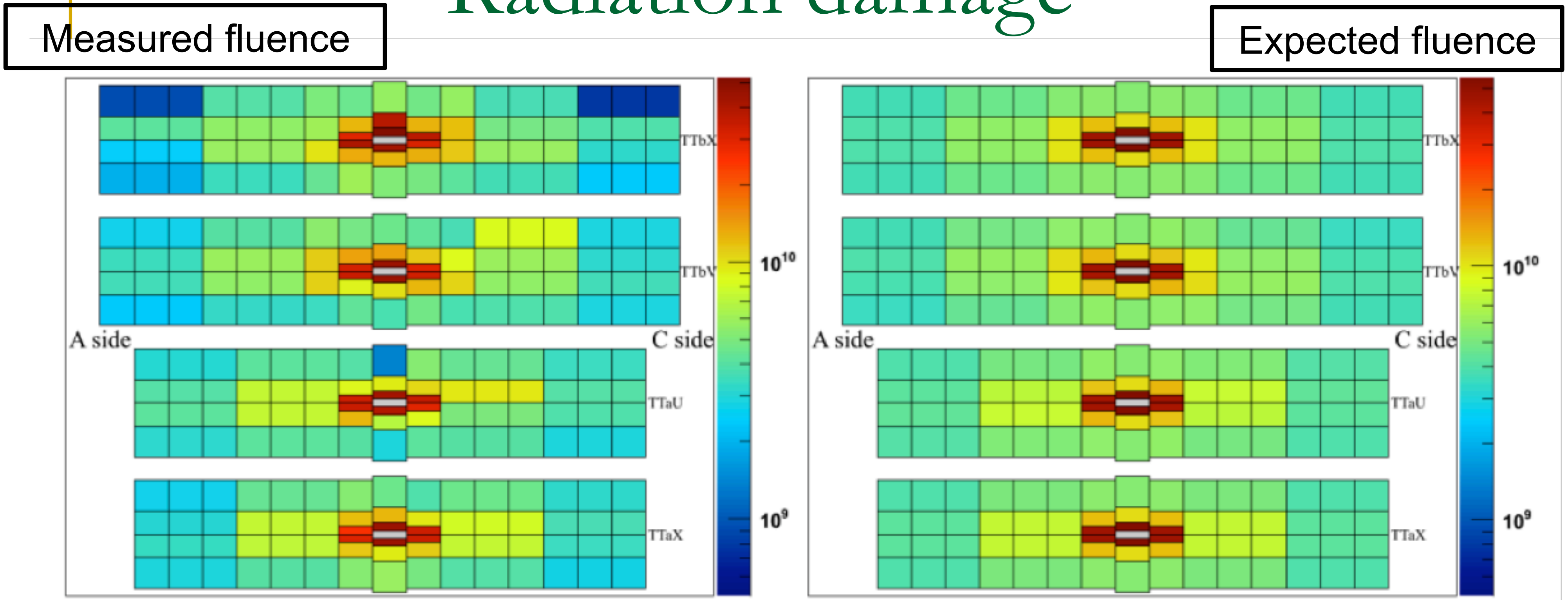
- Oxygenated p-type, FZ
- No dip in V_dep, no SCSI
  - Contradicts our observation – but – heavily annealed and lower doping

- V. Cindro et al. / Nuclear Instruments and Methods in Physics Research A 599 (2009) 60–65

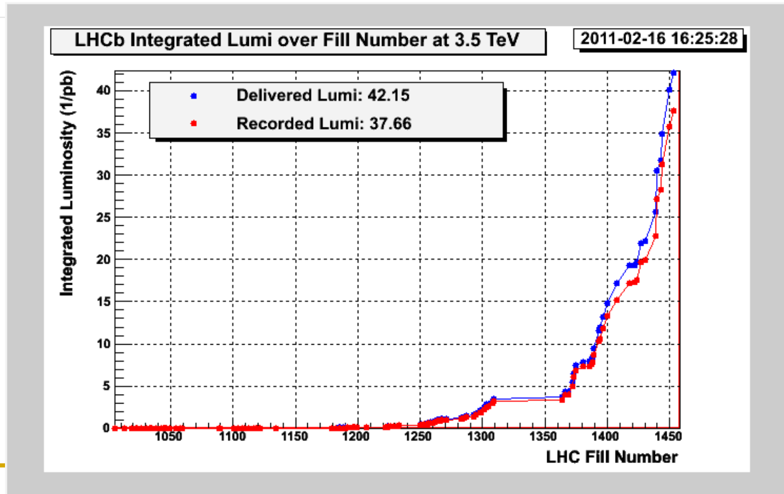
Radiation Part II: LHCb Silicon Tracker

- As for the VELO: Noise scans, CCE scans
- FLUKA has been used to evaluate leakage current evolution
- Current rises of 30-100 μA observed at operating temperatures per fb^{-1}

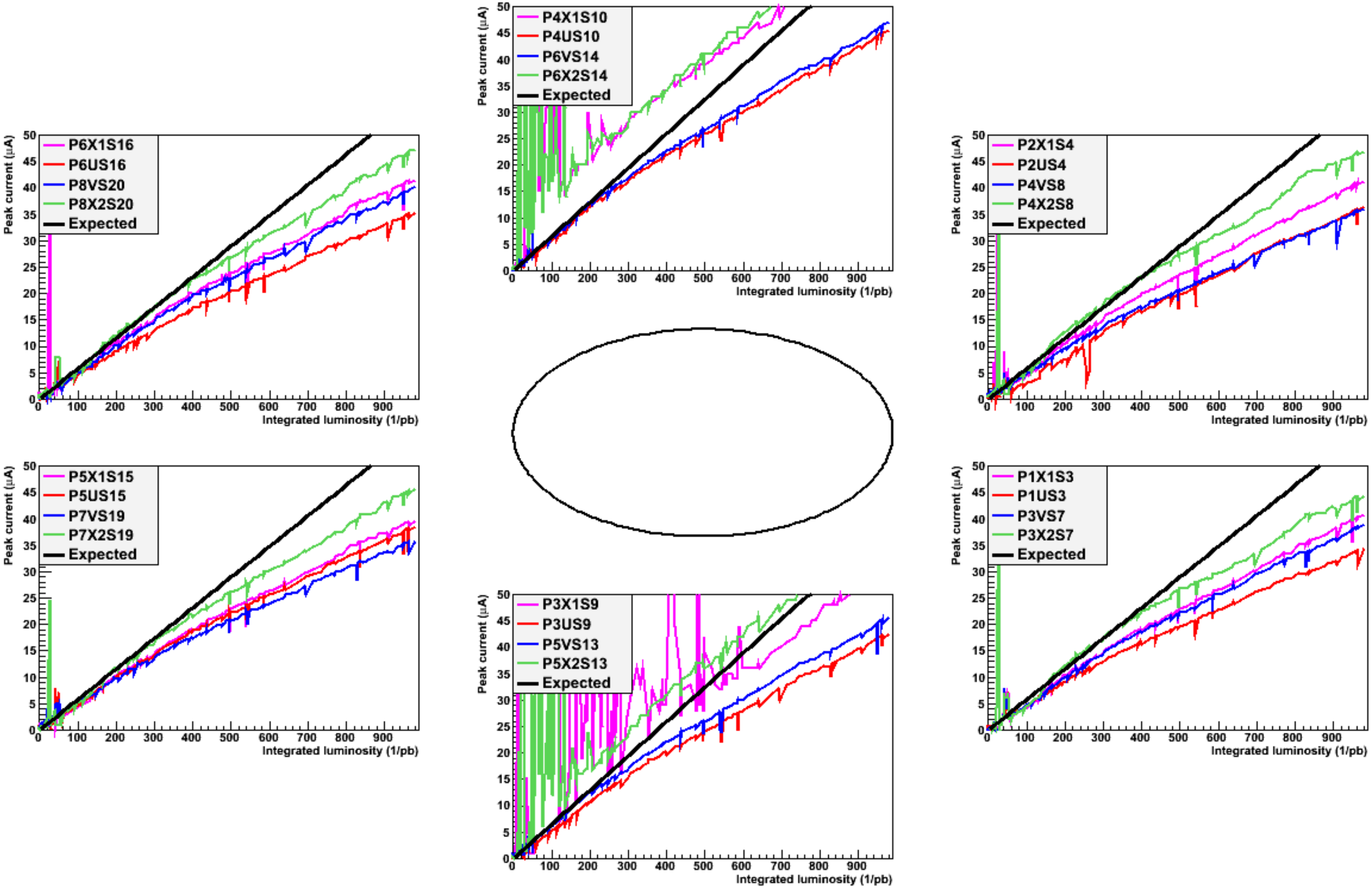
Radiation damage



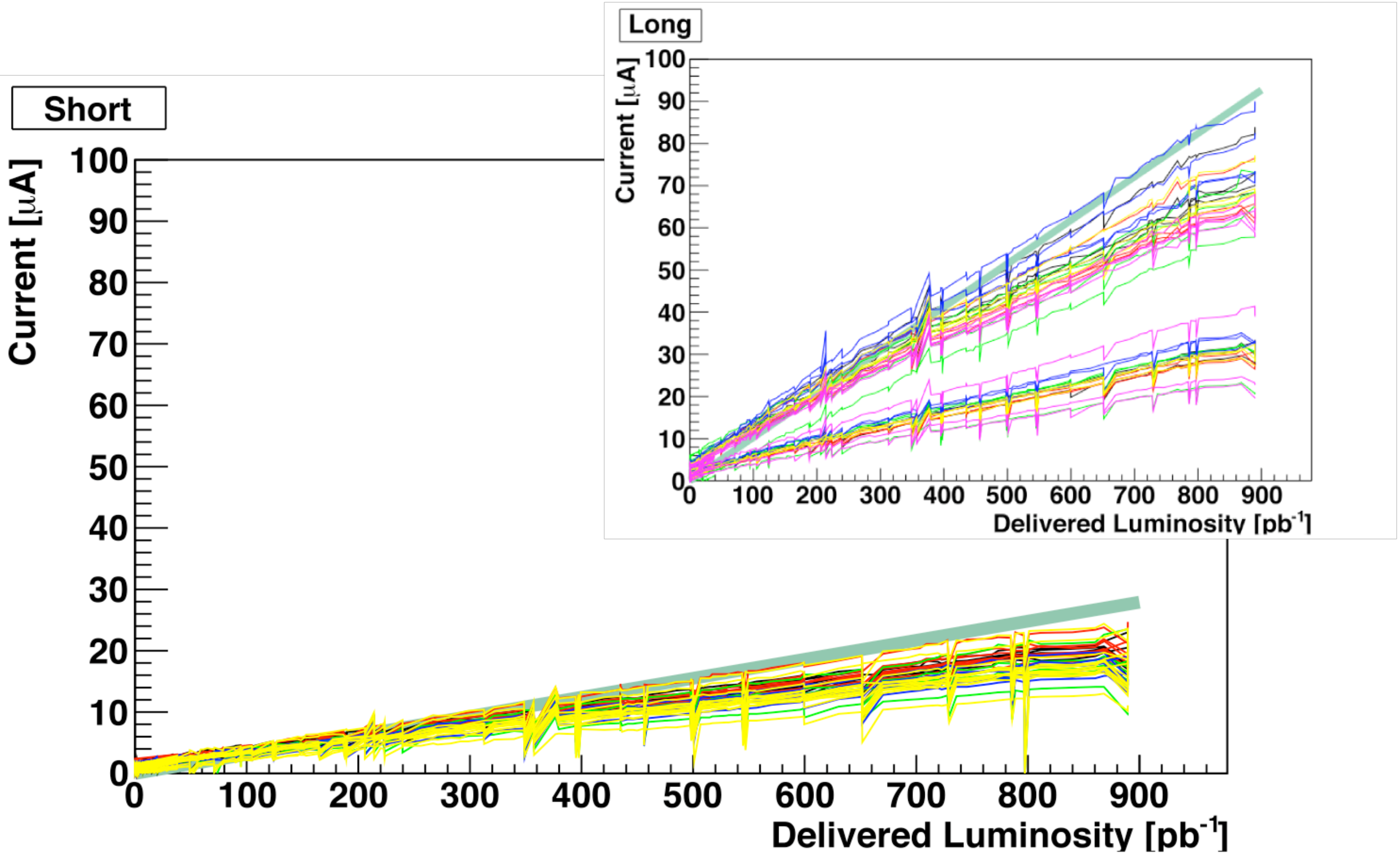
- Measured vs expected radiation dose (for 2010):
  - 1 MeV-neutron equivalent dose
  - Measure using change in current.



Leakage current evolution in TT

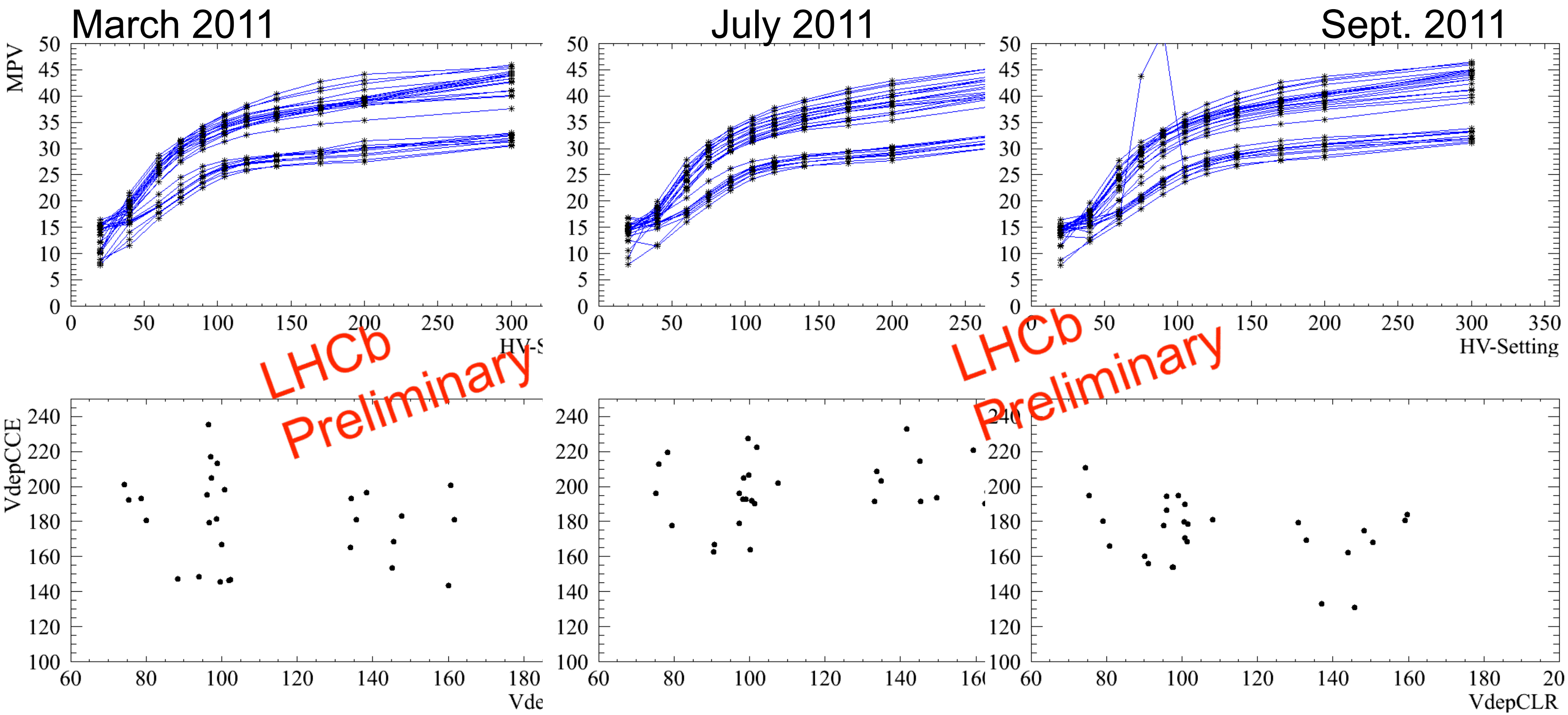


Current evolution in IT



IT HV-vs-Depletion Voltage

plot V_{dep} from CCE-scan versus V_{dep} from capacitance measurement during production



Many subjects not touched on here

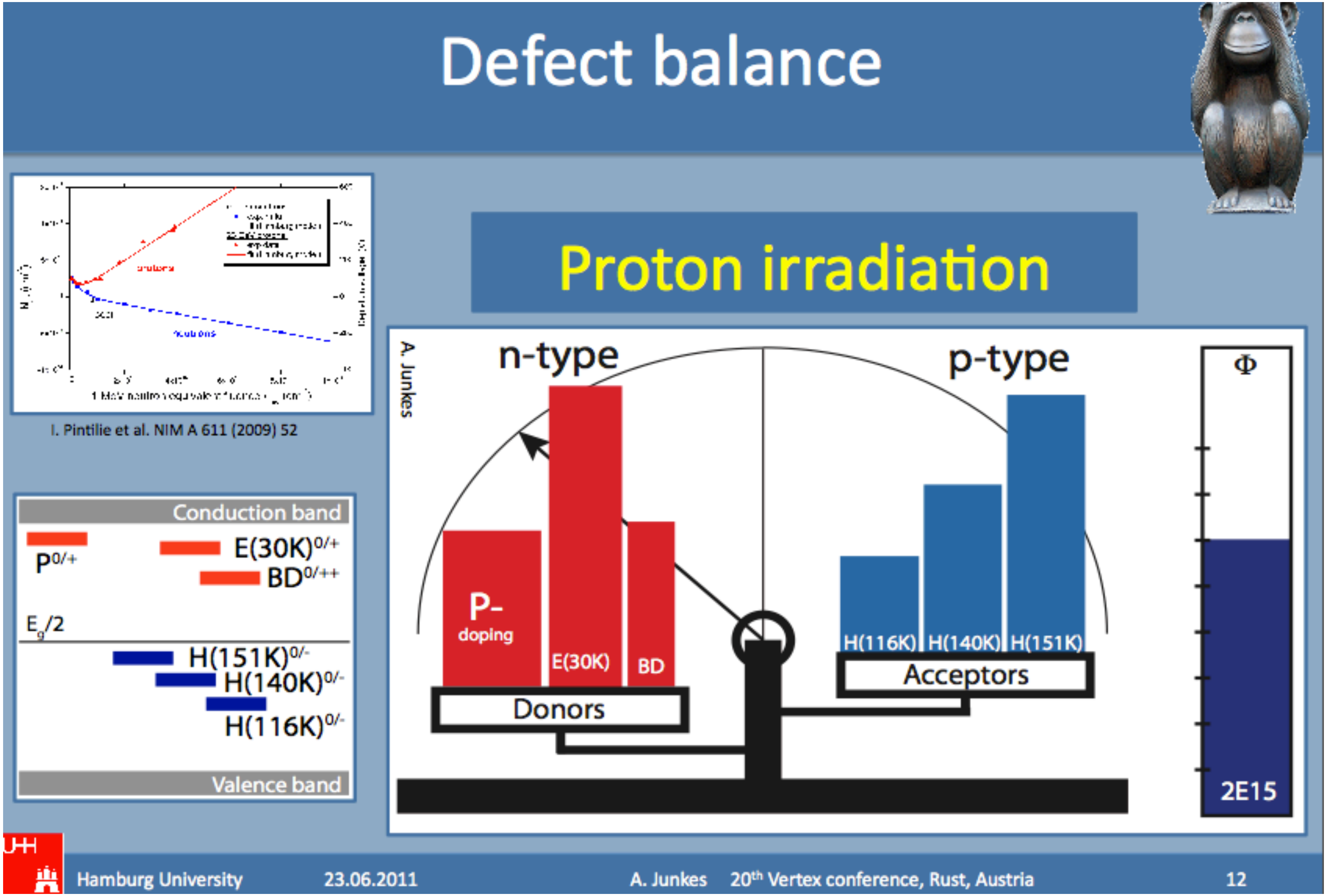
- Cluster sizes and charge sharing, cluster occupancies as a function of radius, SEU, resolution…
- Evaluation of detector lifetime annealing scenarios for shutdown:
  - Very long shutdown approaching at -30^{o}C; what should we expect for annealing of current/V_{dep}?
  - We are running Hamburg model from a spreadsheet kindly provided by Michael Moll; we are also very interested in a c++ version with updated parameters for p type, control over long and variable annealing parameters and lumi delivery, comparison with other experiments etc.

Conclusions

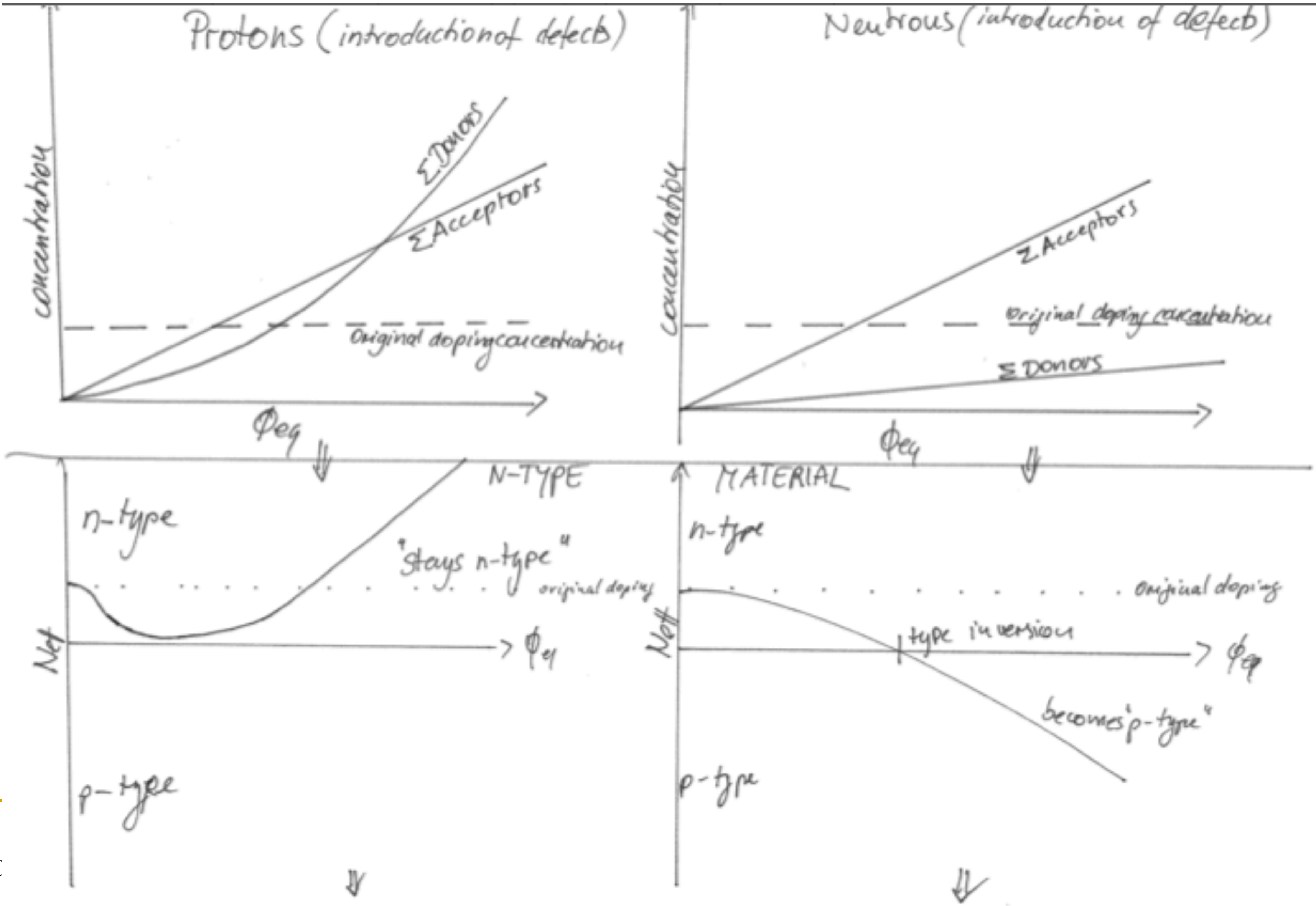
- LHCb irradiation environment is proving to be a rich source of data with many interesting and some unexpected effects
- The interpretation of these effects will benefit from inter experiment discussion (the more informal the better)
- We are interested in sharing of techniques and code to speed the process
- Predictions of detector longevity and annealing scenarios are critical for us for forthcoming shutdowns

  - Thank you

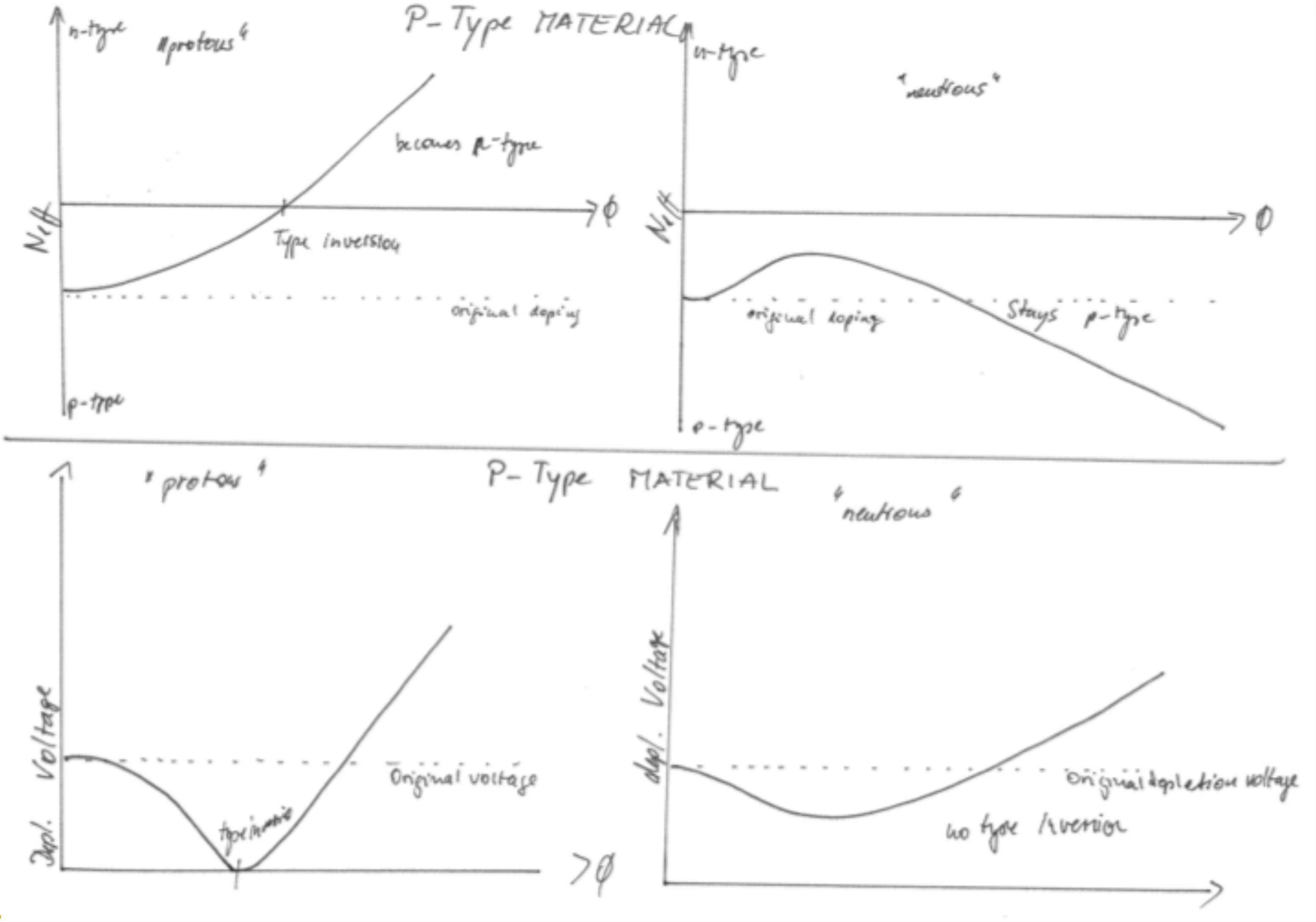
Backup


Defect balance
Proton irradiation
I. Pintilie et al. NIM A 611 (2009) 52
Conduction band
$P^{0/+}$
$E(30K)^{0/+}$
$BD^{0/++}$
$E_g/2$
$H(151K)^{0/-}$
$H(140K)^{0/-}$
$H(116K)^{0/-}$
Valence band
A. Junkes
n-type
p-type
P-
doping
E(30K)
BD
Donors
H(116K)
H(140K)
H(151K)
Acceptors
Φ
2E15
Hamburg University
23.06.2011
A. Junkes
20th Vertex conference, Rust, Austria
12

Hamburg model II (for heavily oxygenated devices) (concept and artwork of Alexandra Junkes)



Hamburg model II continued



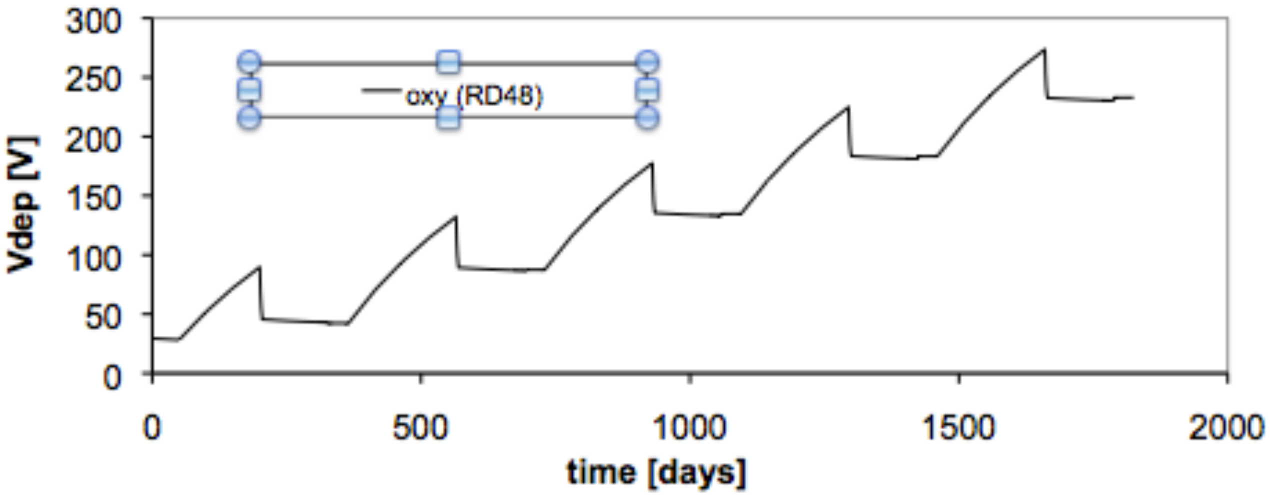
Interesting times ahead!

- With our data we can determine
  - V_dep using CCE scan
  - And also distinguish p-type n-type (with Justin's method)
  - Most powerful is a combination of the information from these two measurements
- As one expert said:

"It will be really interesting to see what happens at 800 pb-1."

Evolution of V_dep

- 5 years of 1 fb^{-1} per year
- Add 30% to the flux for 14 TeV
- 2x5 day warm up
- Approaching 250 V at the tip, and 1 mA/sensor at 21 degrees



So what is our longevity?

- After 7 fb^{-1}our depletion voltage will still be within acceptable limits – from this point of view we will operate comfortably.
- The 800 pb-1 data set and subsequent data will be important to confirm the slope of the depletion voltage evolution
- This requires a careful approach to the annealing
- The CFE loss we have observed is not accounted for: the 800 pb^{-1} measurements will be very important to see if there is any hope of reducing the effect (with increasing radiation, for instance)