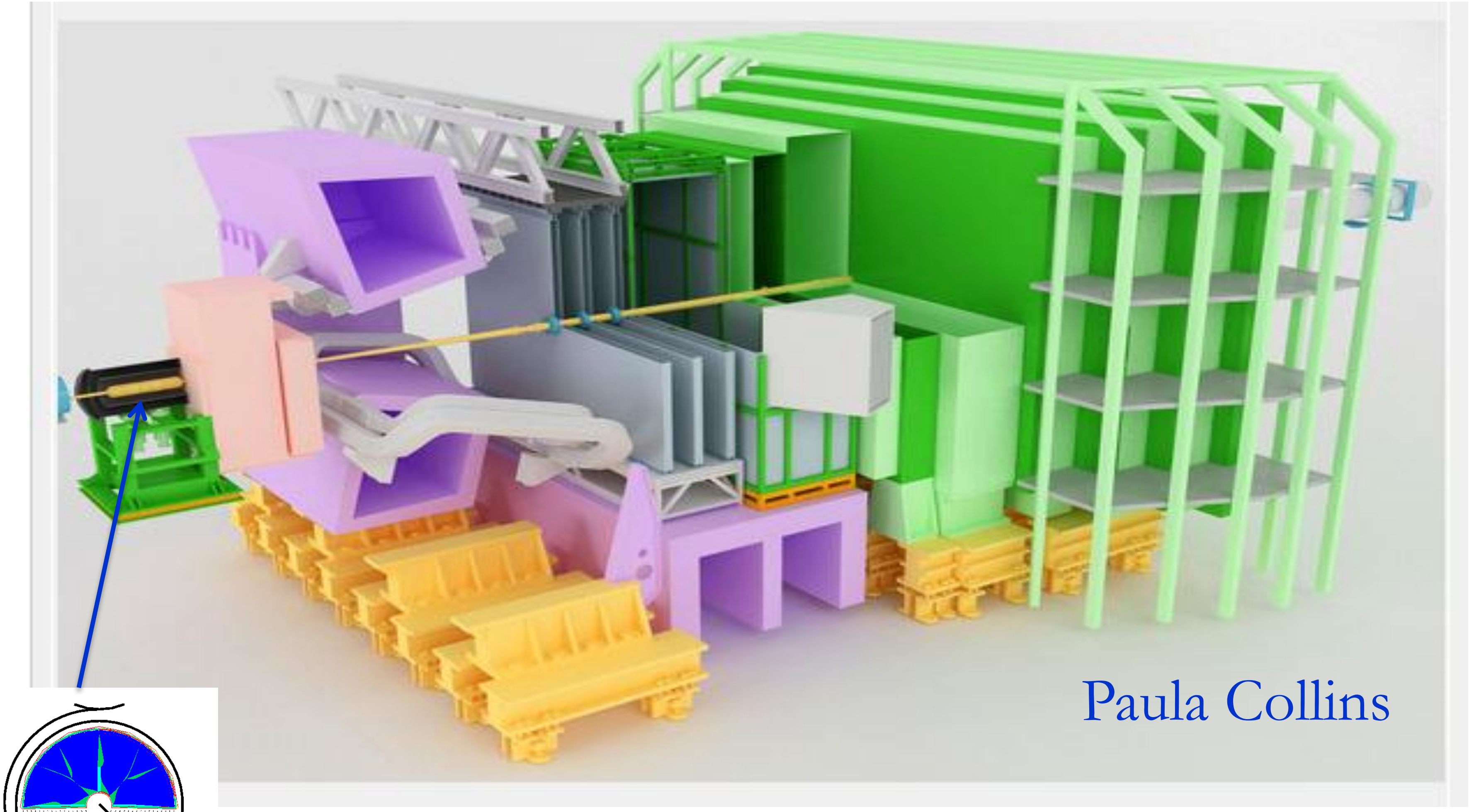
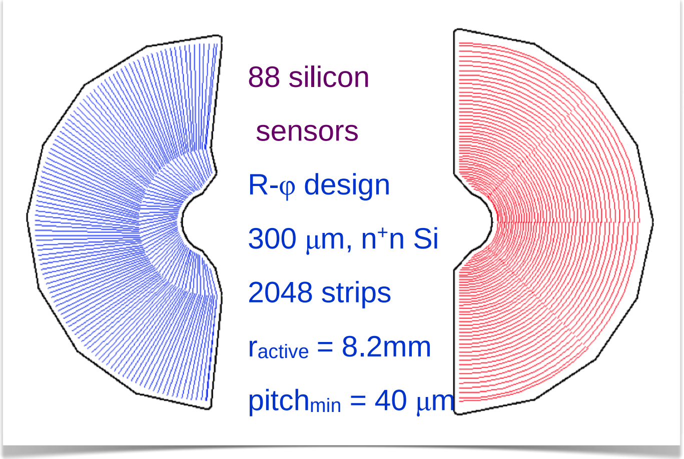
LHCb VELO and LHCb VELO Upgrade



Paula Collins

VErtex LOcator

The VELO is….



88 silicon

sensors

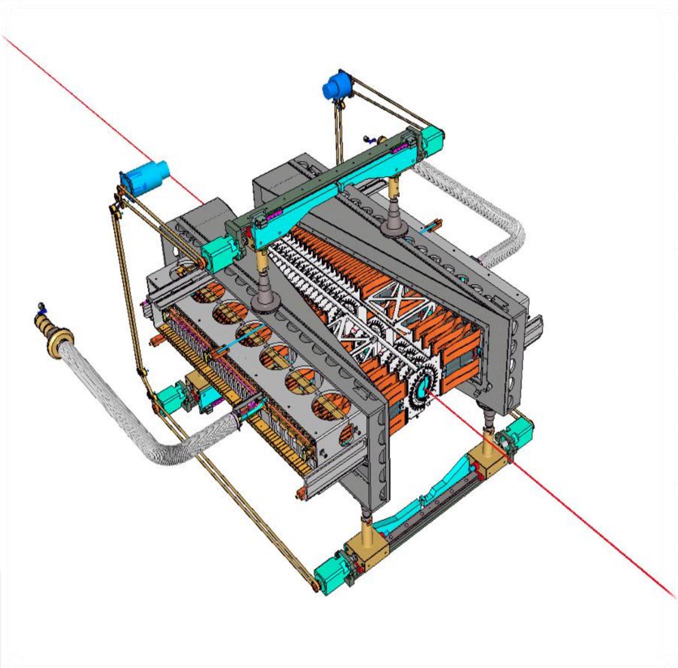
R-φ design

300 μm, n^+n Si

2048 strips

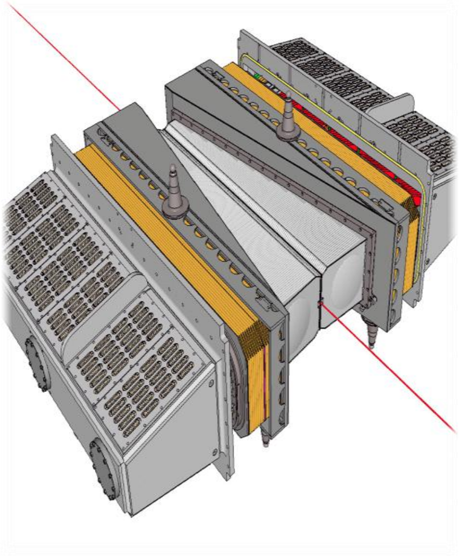
r_{active} = 8.2mm

$pitch_{min}$ = 40 μm



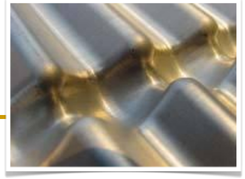
Cooled: by evaporative CO_2 system

Mobile: opening every fill and centering on the beam with self measured vertices

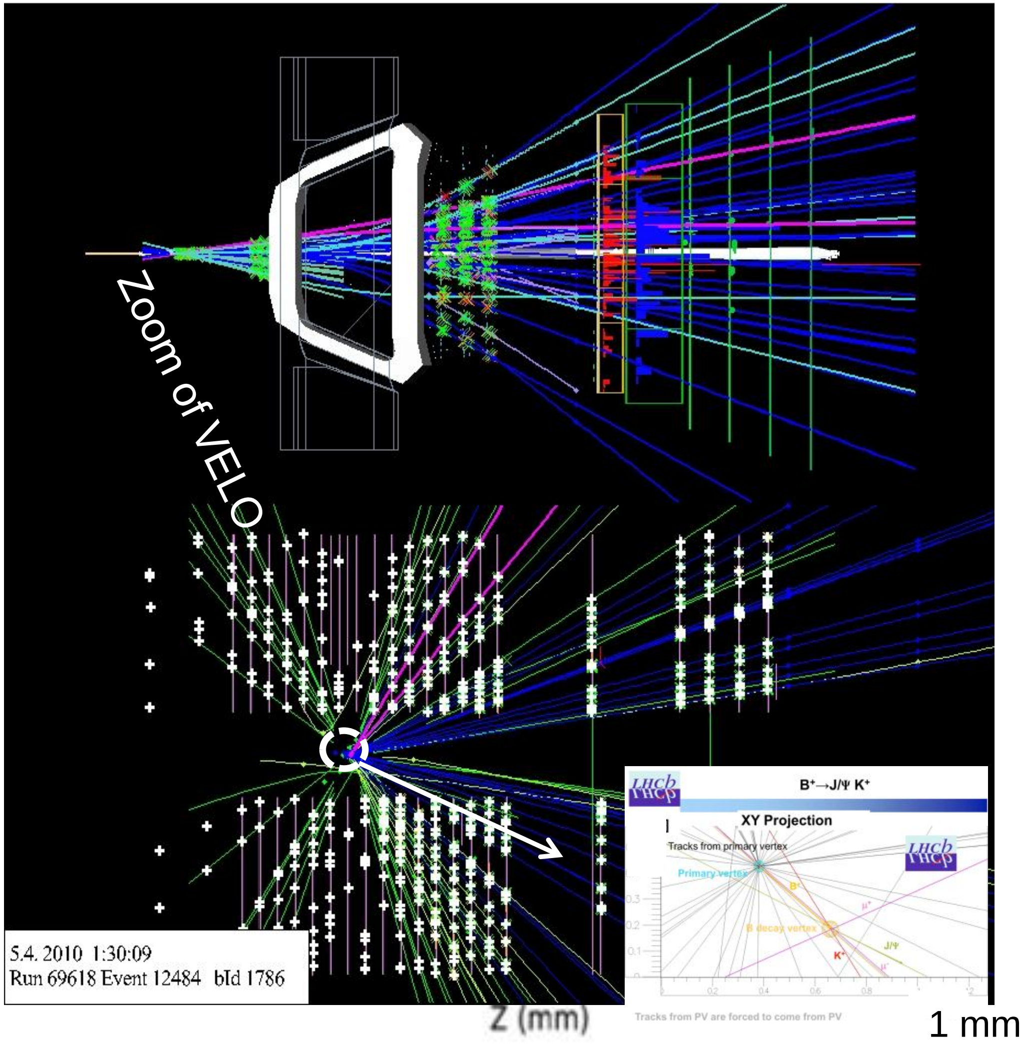


A device operating in vacuum

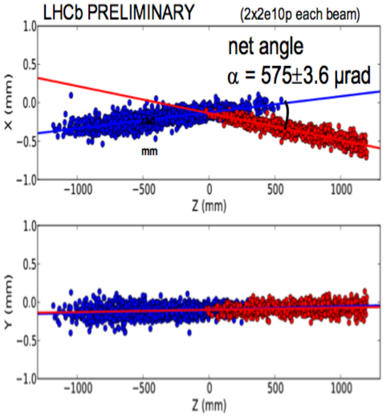
Separated from primary vacuum by RF foil with complex shape

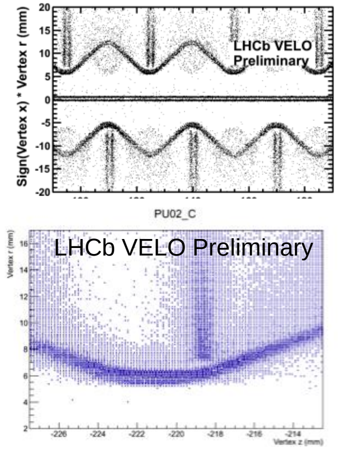


The VELO does…



- Triggering
  - Entire VELO is read out after 1 MHz L0 trigger
  - VELO identification of displaced vertices is key ingredient of trigger filter to ~ few kHz
- Tracking and Vertexing
  - Beauty and charm physics with multibody final states and low momenta
- And also…
  - Beam bunch imaging for luminosity measurement
  - Self radiography with hadronic interaction vertexing…



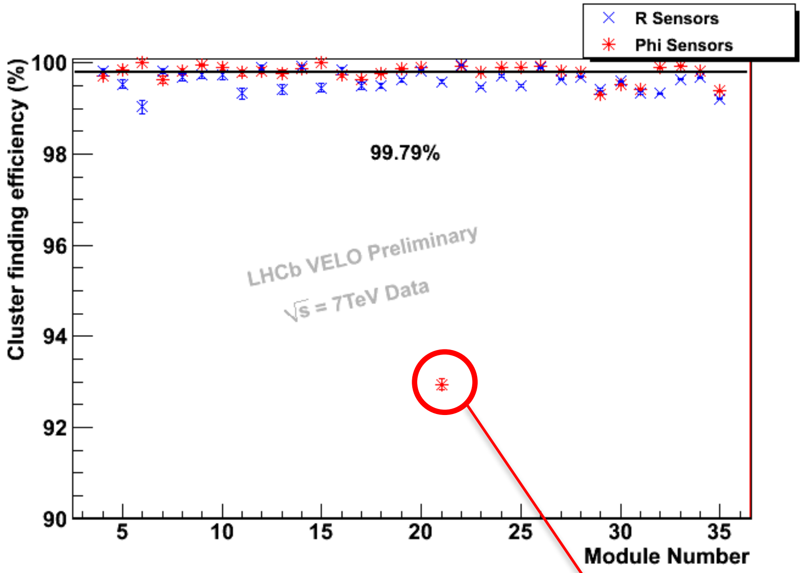


For more discussion of LHCb tracking see talk by Grieg Cowan

VELO Performance: Operation

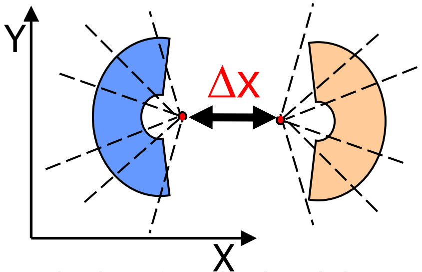
Efficiency

- Efficiency generally extremely good
- Most inefficiencies understood

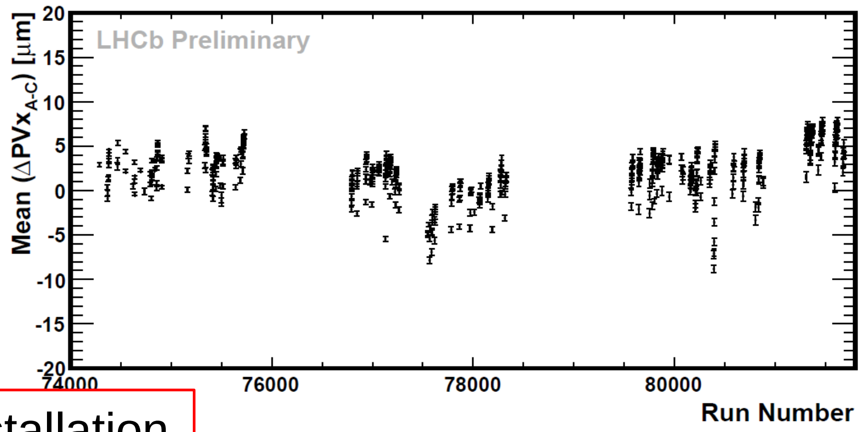


One chip died after installation

Alignment

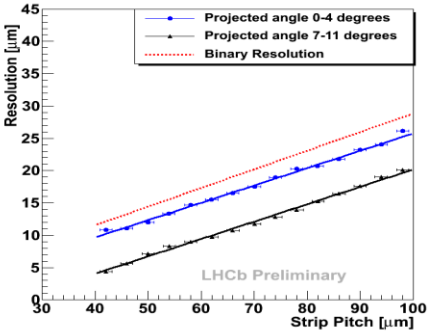


- PV method:
  - Reconstruct PV using tracks in left or in the right side
  - Evaluation of misalignment by the distance between the 2 vertices
- Stability of 2 half alignment by PV method:
  - within ± 5 μm for Tx
  - within ± 2 μm for Ty



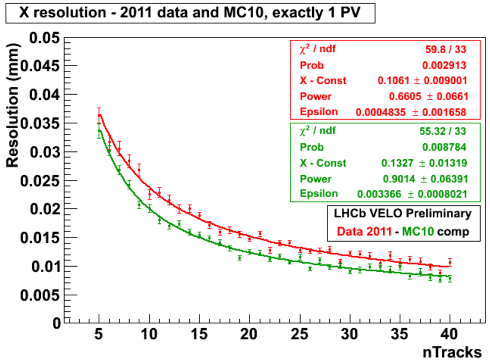
VELO Performance: Resolution

Key Ingredients:



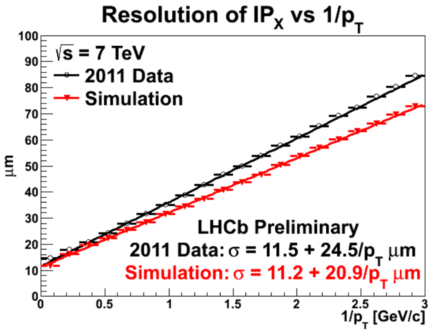
Point resolution down to 4 μm

+



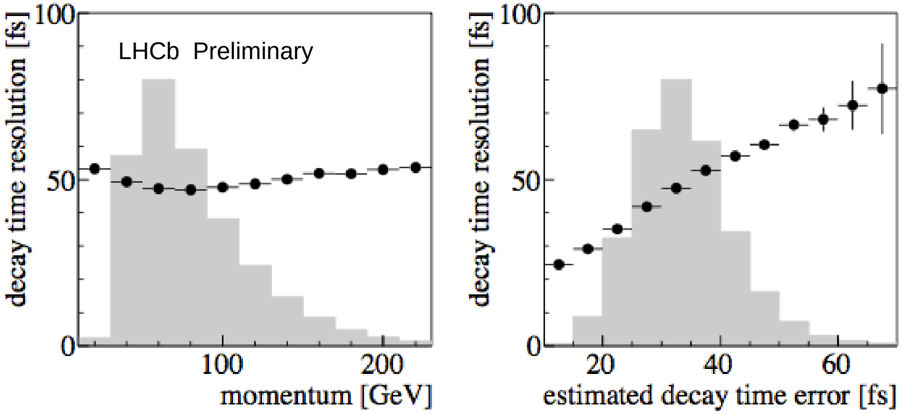
Primary vertex resolution 13 μm for ~ 25 tracks

+



Impact parameter resolution $11.5 + 25/p_T$ μm

=



Lifetime resolution of
~50 ps for Bs ➔ J/ψ ϕ
Critical to resolve fast B_s oscillations, and background suppression in e.g. rare decay channels

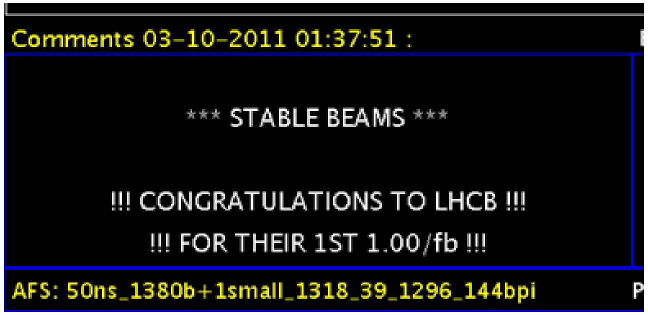
For more details see Michael Alexander's poster

VELO ageing and radiation

Hiroshima 1995

Radiation environment at VELO harsh

- The price of success…



Comments 03-10-2011 01:37:51 :

*** STABLE BEAMS ***

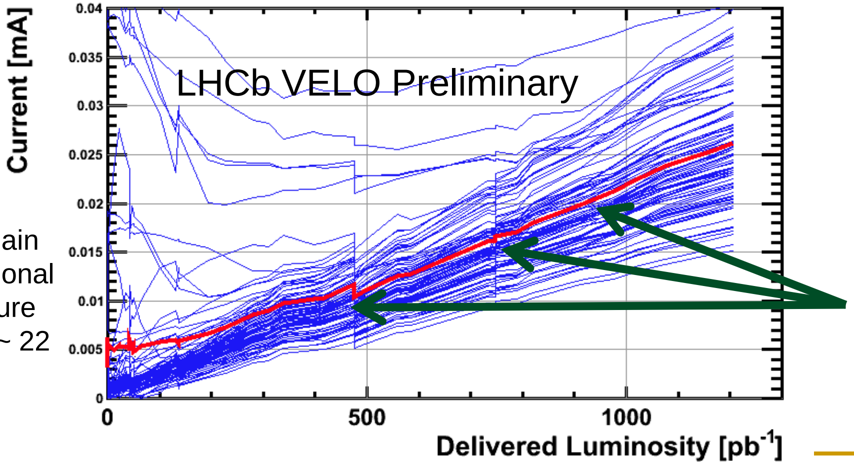
!!! CONGRATULATIONS TO LHCB !!!

!!! FOR THEIR 1ST 1.00/fb !!!

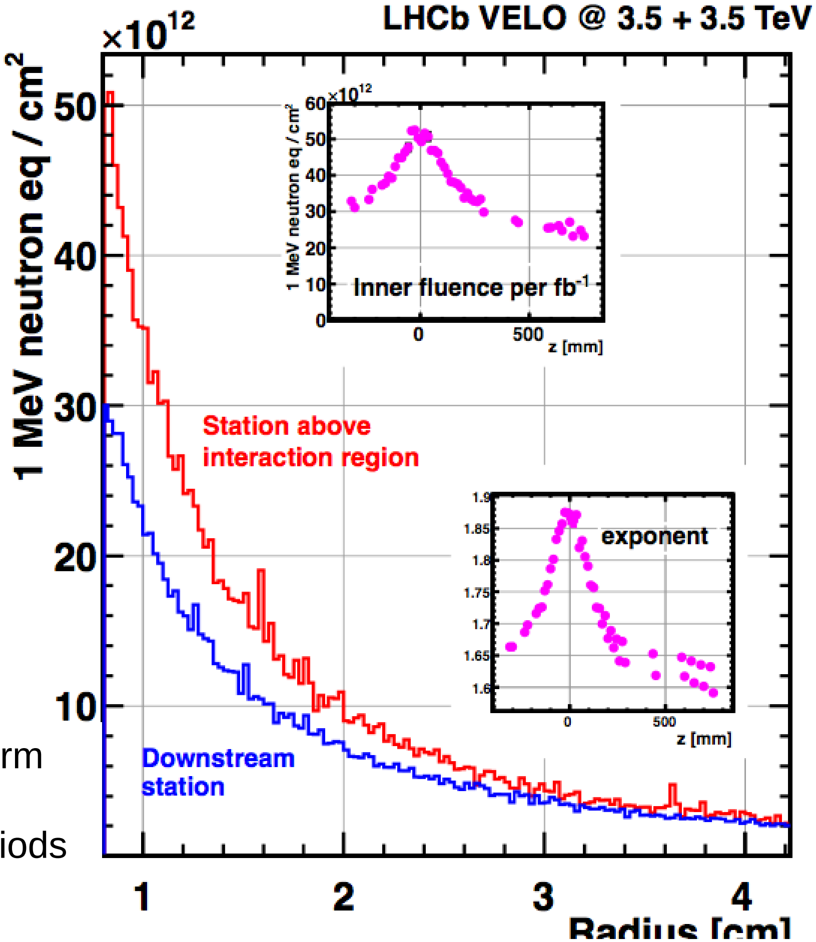
AFS: 50ns_1380b+1small_1318_39_1296_144bpi

- We are feeling the heat!

Current gain at operational temperature of ~-8°C ~ 22 $\mu A/fb^{-1}$



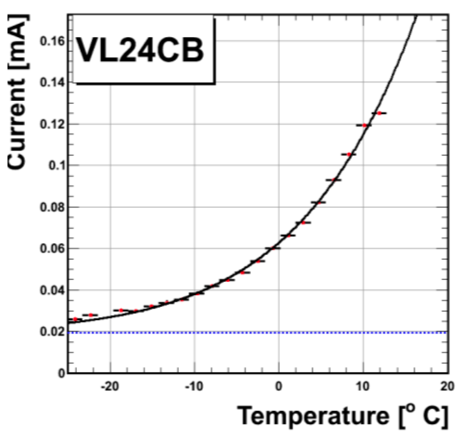
Warm up periods



Monitoring radiation damage

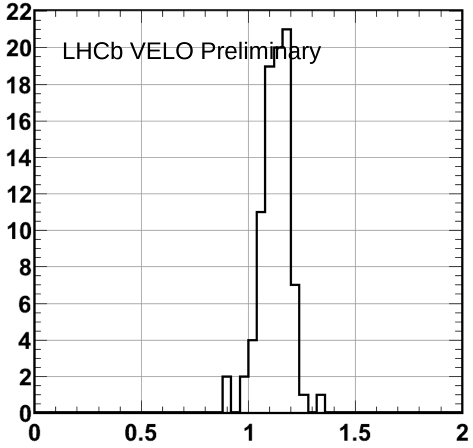
Basic Techniques:

- Currents
    - vs voltage
    - vs temperature
    - Sensitive to bulk damage
    - Good statistics to measure E_g
- Noise as a function of voltage
    - Tracks V_{dep} evolution and type inversion
- CCE (charge collection efficiency) as a function of voltage
    - Tracks V_{dep} evolution
- CFE (cluster finding efficiency) as a function of voltage
    - Ultimate measure of detector performance

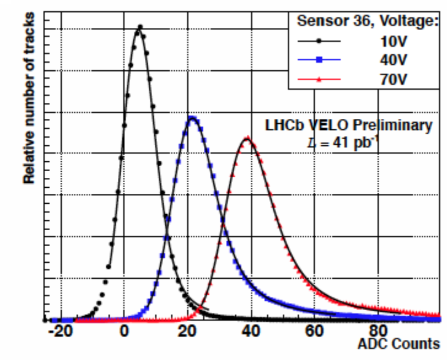


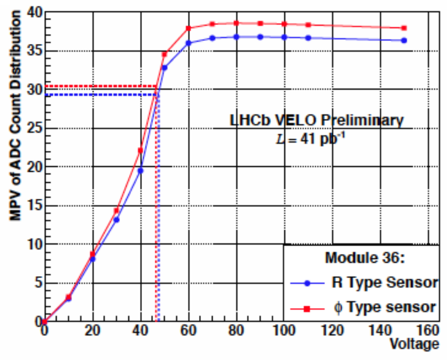
Taka-Kondo Parameter

E_g=1.11 ± 0.04 eV

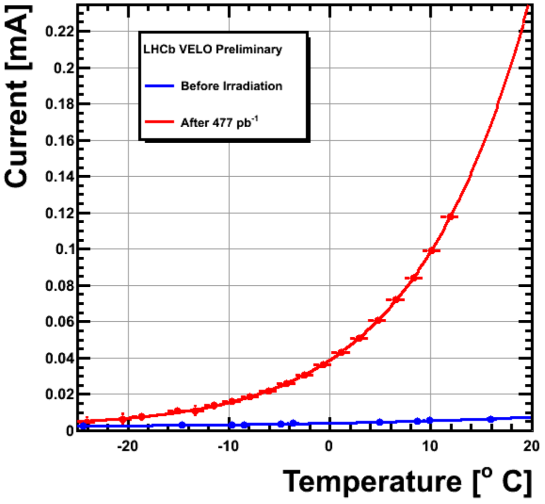


$$I\left(T_{ref}\right) = I(T).\left(\frac{T_{ref}}{T}\right)^2 .exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right),$$



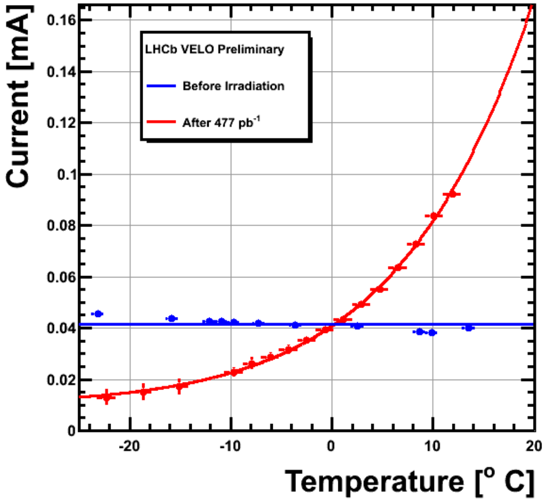


Some results in line with expectation

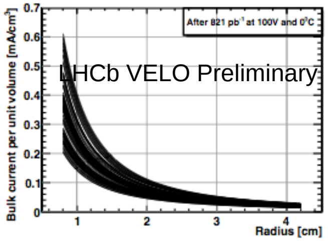


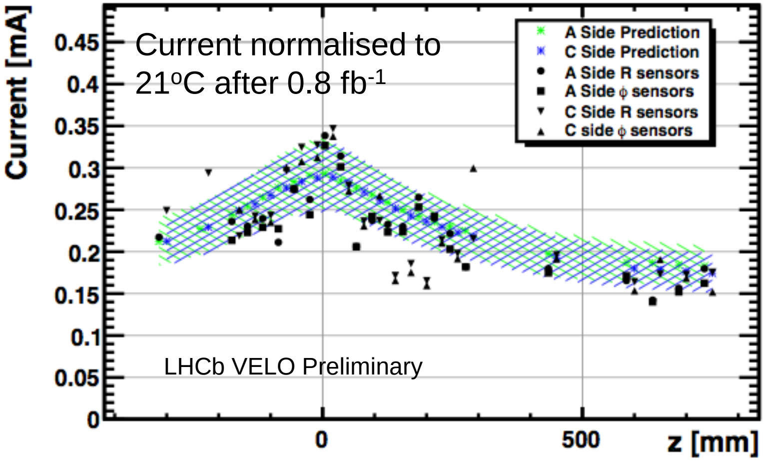
Bulk current increases with irradiation

Surface current anneals



Current per unit area [mA/cm^3] normalised to 0^{o}C after 0.8 fb^{-1}

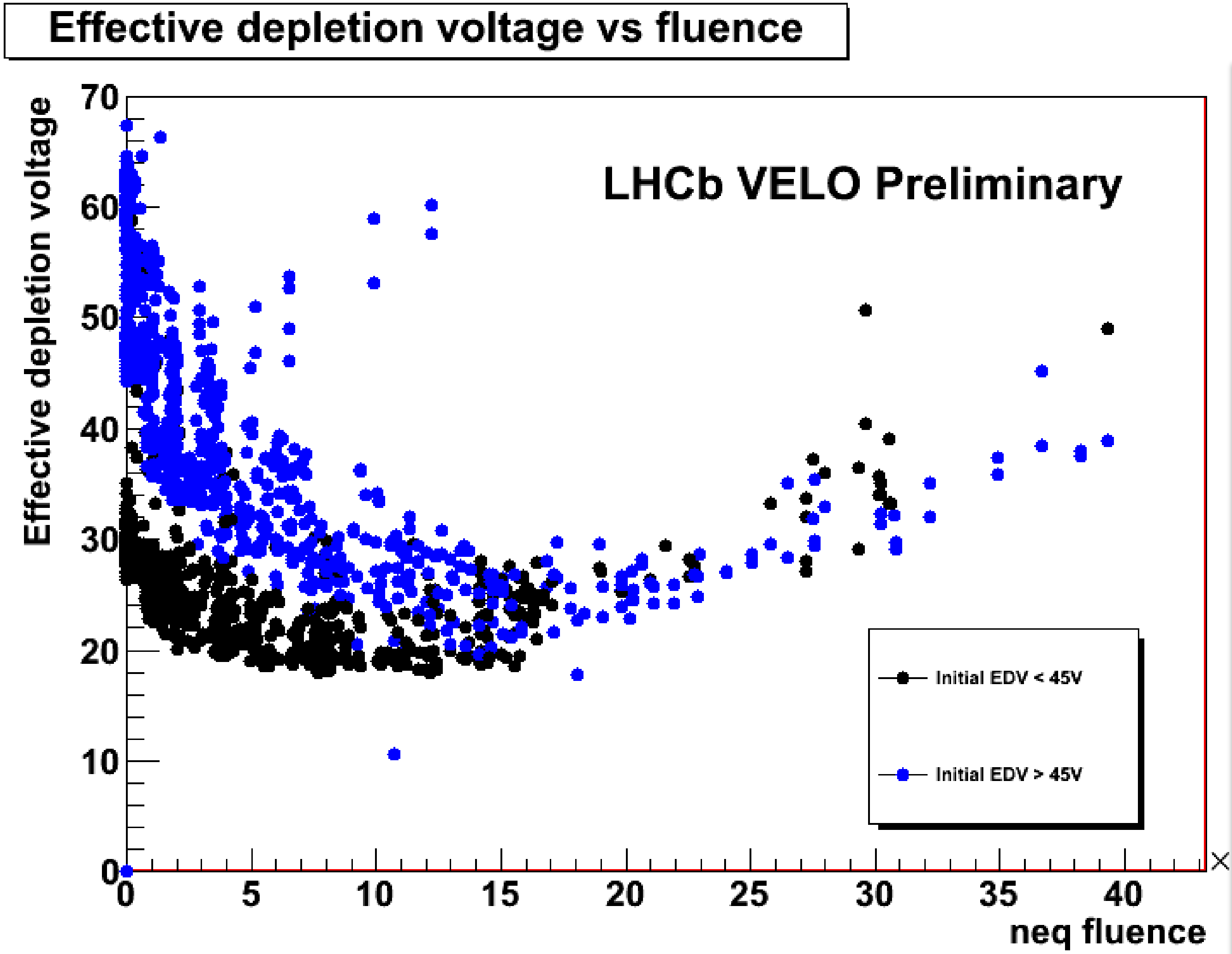




Current normalised to 21^{o}C after 0.8 fb^{-1}

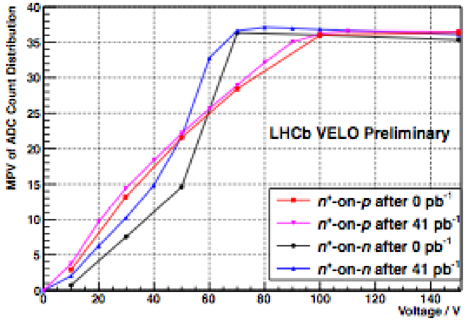
Current increases are in line with expectation and dominated by charged particles directly produced in collisions

Some results in line with expectation

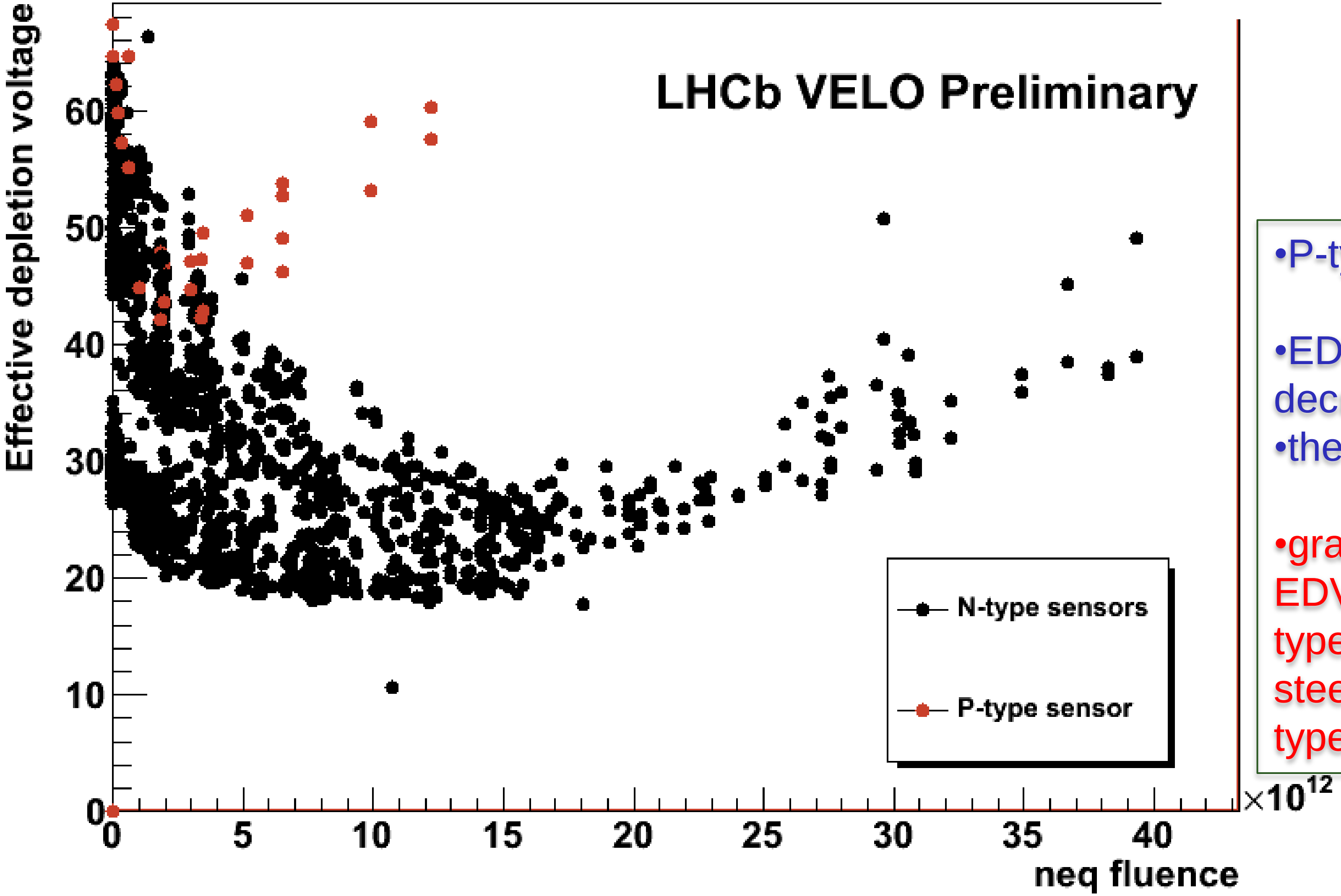


- We now have good statistics (many different regions and radiation steps)
- Can probe “moderate” irradiation region (by RD50 standards)
- Sensor tips now inverted
- No dependence after inversion on initial depletion voltage

Some are intriguing



Effective depletion voltage vs fluence



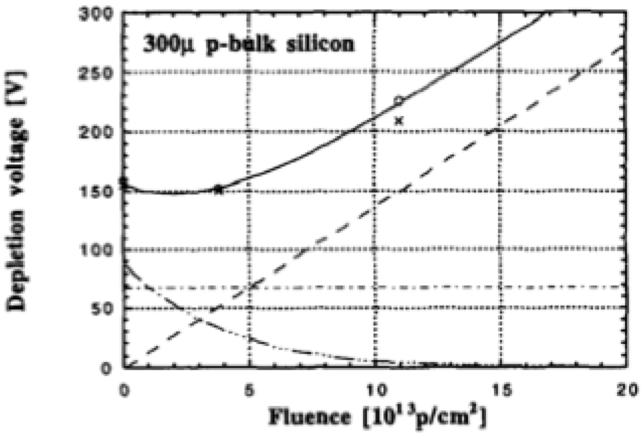
- P-type:
- EDV initially decreased
- then increased
- gradient EDV/n_{eq} of p-type currently steeper than n-type

p-type behaviour as expected ?

Initial acceptor removal mechanism
Boron Interstitial captured by Oxygen/Carbon

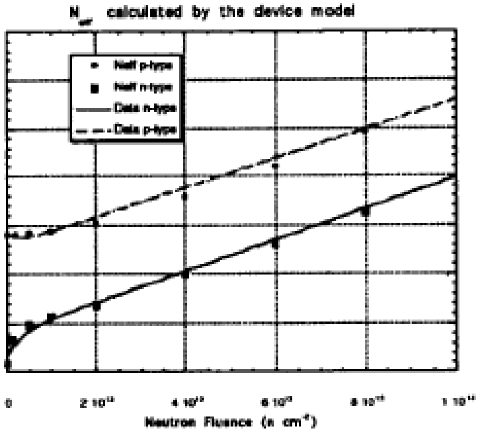
➔Decrease in V_{dep} initially

NIMA 383 (1996) 159
Y. Unno et. al



RD-2 1993

(thanks to Steve Watts)



Thanks for discussions: Cinzia, Alexandra, Tony, Gianluigi,, Gregor, Steve Watts, Nobu

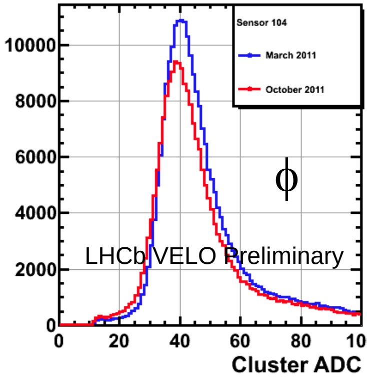
References:

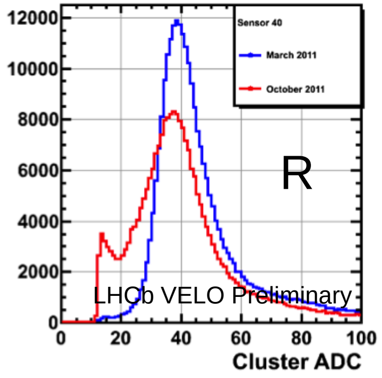
- Lemeilleur et al. RD-2, Nuclear Physics B (Proc. Suppl.) 32 (1993) 415-424
- Watts et al., Nuclear Instruments and Methods in Physics Research A 377 (1996) 224-227
- Unno: NIMA 383 (1996) 159-165 and IEEE Transactions on Nuclear Science, 56 (2009) 468-473
- Eckstein: 12th RD50 workshop, Ljulbjana, Slovenia, June 2008
- Lozano: (work with Gian) : RD50 workshop 2004, "comparison of radiation hardness p-in-n, n-in-n, n-in-p
- V.Cindro: Nuclear Instruments and Methods in Physics Research A 599 (2009) 60–65

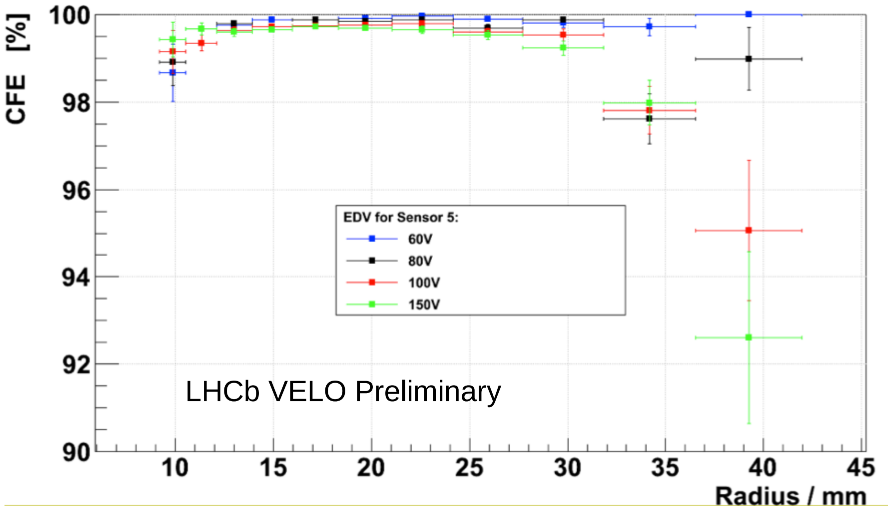
Some are alarming!

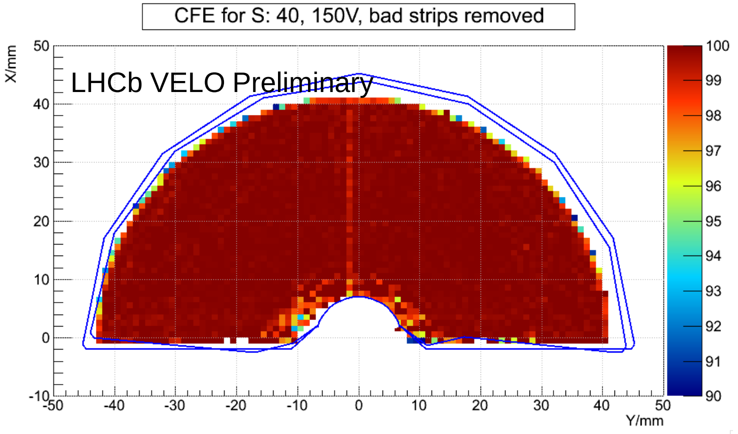
R sensors are showing inefficiencies at the outer parts which are inversely dependent on HV

Landau shapes of R sensors are deteriorating

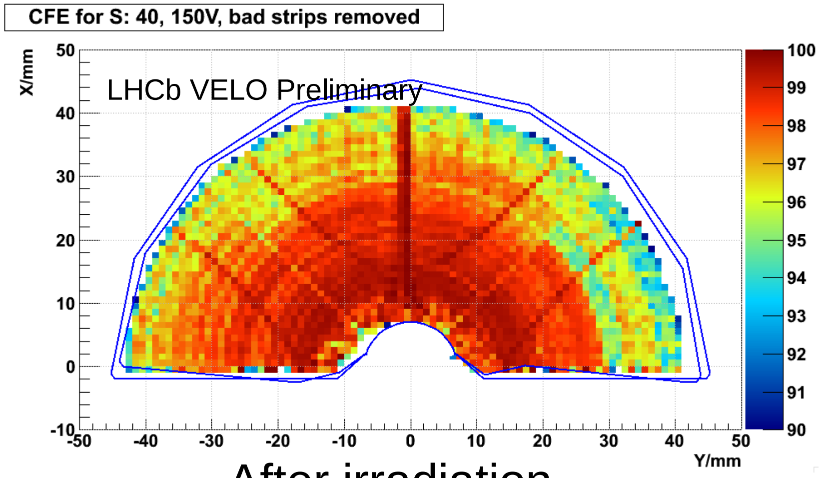






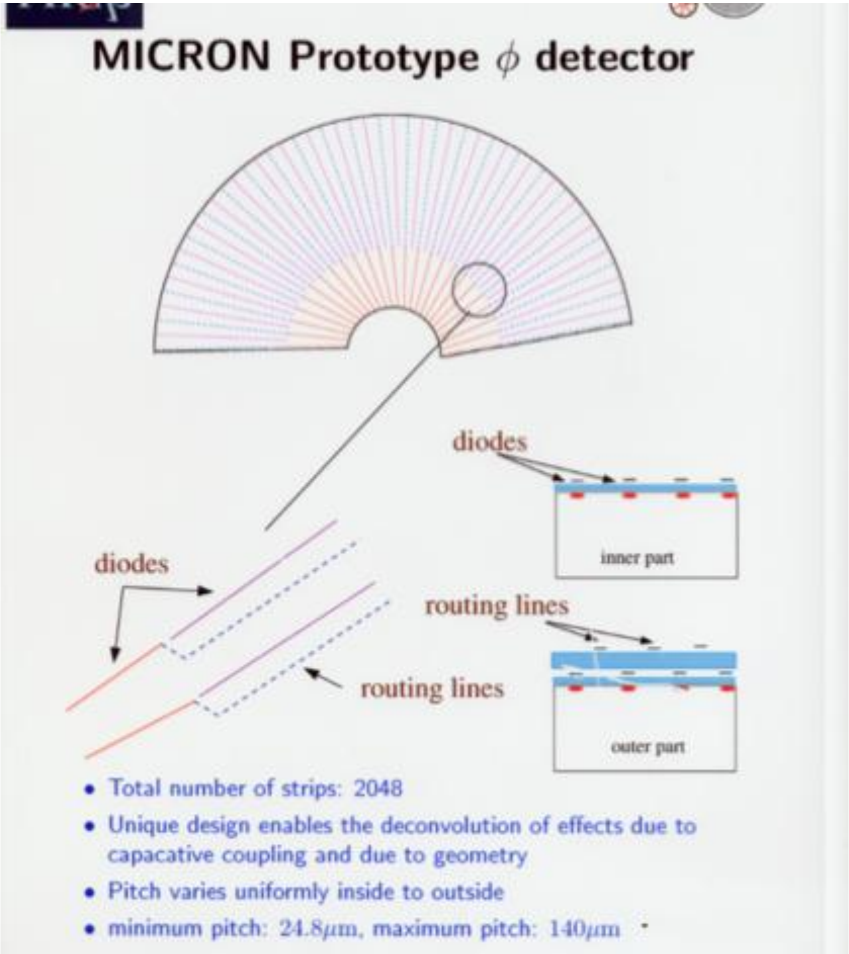


Before irradiation



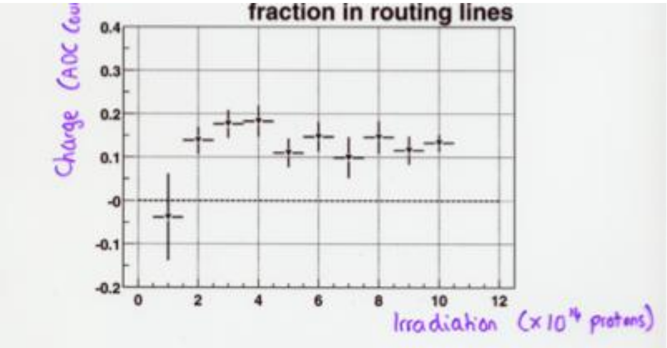
After irradiation

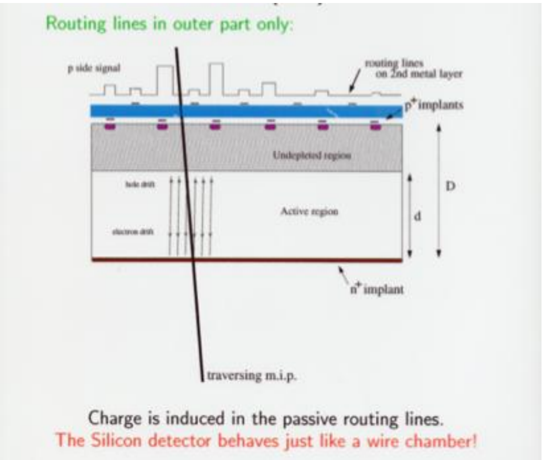
Historical footnote



MICRON Prototype ϕ detector

- Total number of strips: 2048
- Unique design enables the deconvolution of effects due to capacative coupling and due to geometry
- Pitch varies uniformly inside to outside
- minimum pitch: 24.8μm, maximum pitch: 140μm





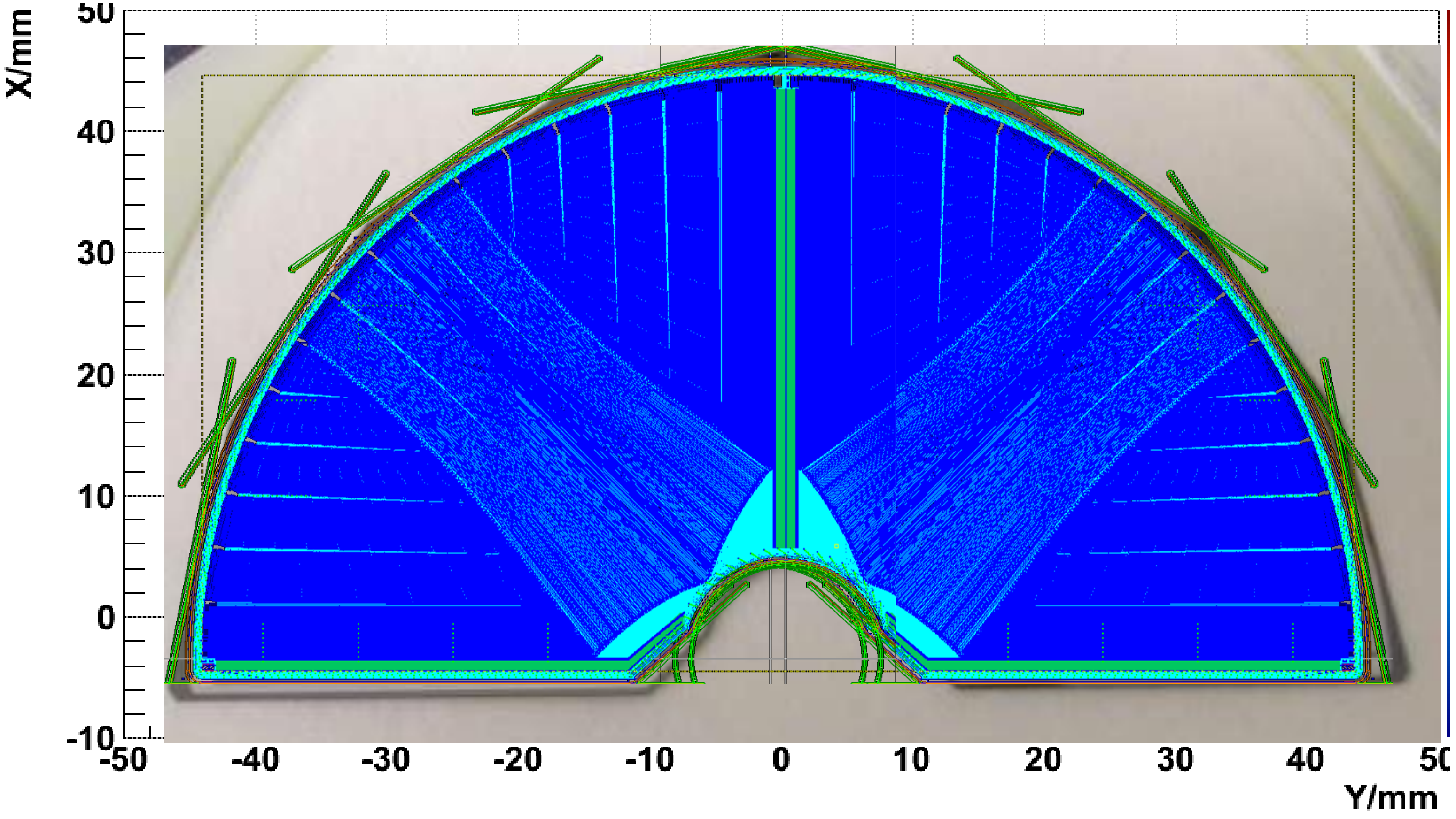
Routing lines in outer part only:

Charge is induced in the passive routing lines.
The Silicon detector behaves just like a wire chamber!

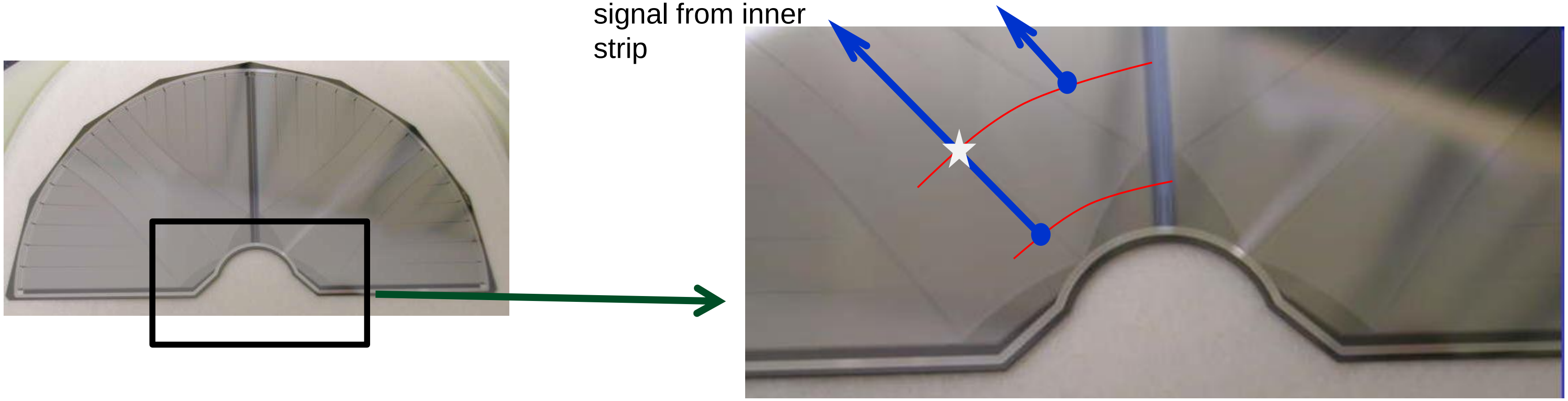
We saw charge loss for irradiated detectors to the routing line In 1999 and made the decision to

1. Go for n+n detectors
2. To be doubly safe, route the 2nd metal lines *over* the 1st metal for the ϕ sensors

VELO R Sensor – routing lines cross strips by necessity



Component of charge loss to 2nd metal layer



charge picked up in routing line fakes signal from inner strip

Charge from true strip hit

- What is the exact mechanism ?
  - Form of surface damage?
- Why worse at higher voltage ?
- Why worse at outside of sensors ?
- What will happen in future?

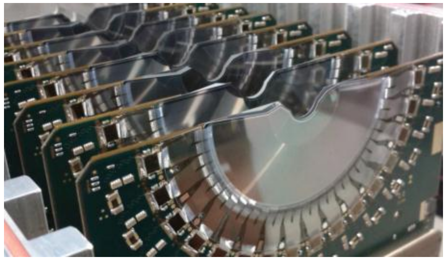
For more details see Jon Harrison & Adam Webber's poster

Next steps:

VELO

Before upgrade LHCb will collect ~9 fb^{-1}
Will see how it looks after 3 fb^{-1}
at end 2012….

Spot the difference



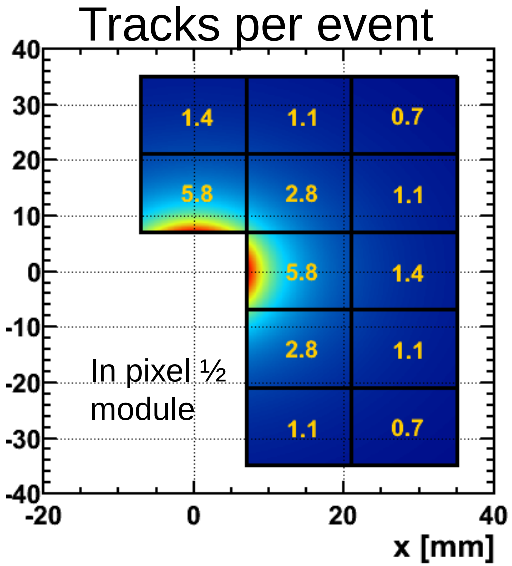
Replacement VELO
(all $n^{+}p$)

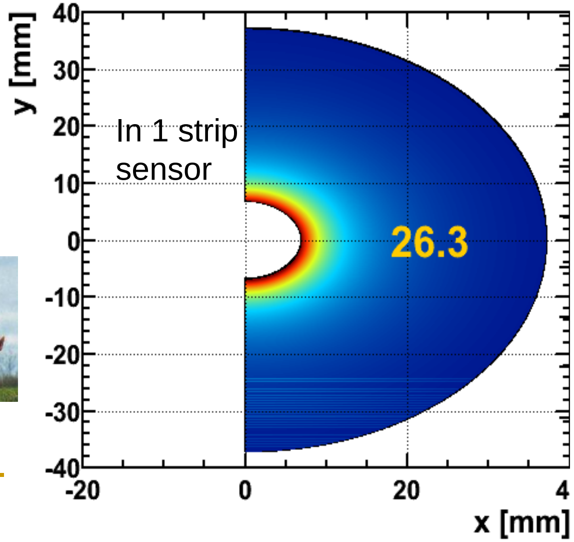
All LHCb will upgrade to 40 MHz readout and fully software based trigger for 2018. Aim to operate at $L=2\times10^{33}$ with hadronic trigger efficiency improved by factor 2

VELO Upgrade

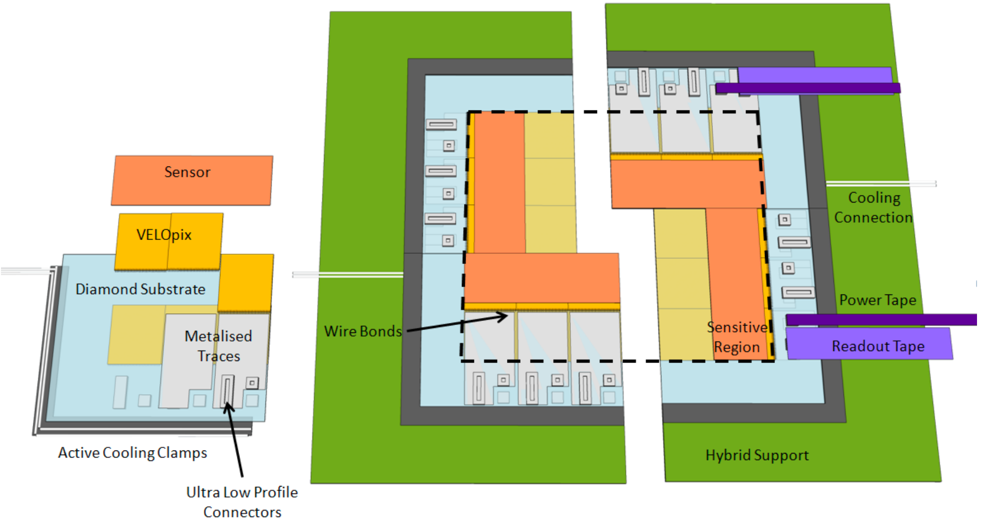
VELO Challenges @ 40 MHz & 2 x 10^{33}

- Completely new modules and FE electronics
  - Two major options under consideration: Pixels and strips
- Must be
  - Capable of dealing with huge data rate
    - > 12 Gbit/s for hottest pixel chip
    - On-chip zero suppression and CM algorithms for strip chip
  - Able to withstand radiation levels of ~ 370 MRad or 8 x 10^{15} n_{eq}/cm^2
- Completely new module cooling interface
- New RF foil
- All without sacrifices in material budget





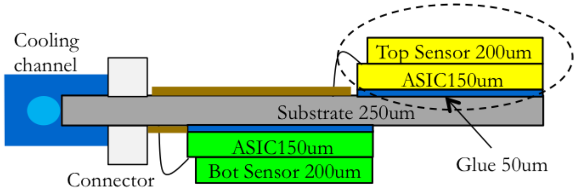
Pixel module layout in LHCb Upgrade LOI

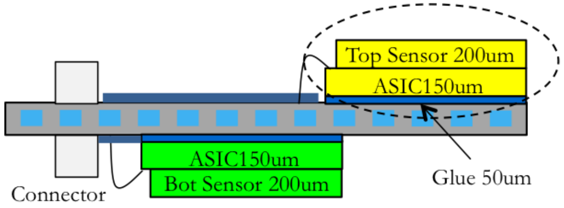


Pseudo double-sided module with 3x1 pixel tiles arranged on opposite side of diamond substrate

CO_2 cooling options:

- CF encapsulated invar tube
- Microchannel etching + anodic bonding

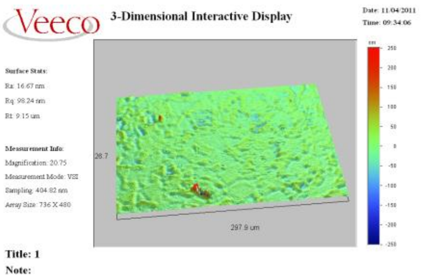




Diamond substrate

Excellent heat conduction, mechanical stability & radiation hardness

R&D focussing on metallisation for signal & power traces

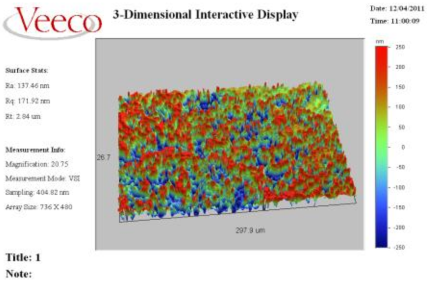

3-Dimensional Interactive Display

Date: 11/04/2011
Time: 09:34:06

Surface Stats:
Ra: 16.67 nm
Rq: 98.24 nm
Rt: 9.15 um

Measurement Info:
Magnification: 20.75
Measurement Mode: VSI
Sampling: 404.82 nm
Array Size: 736 X 480

Title: 1
Note:


3-Dimensional Interactive Display

Date: 12/04/2011
Time: 11:00:09

Surface Stats:
Ra: 137.46 nm
Rq: 171.92 nm
Rt: 2.84 um

Measurement Info:
Magnification: 20.75
Measurement Mode: VSI
Sampling: 404.82 nm
Array Size: 736 X 480

Title: 1
Note:

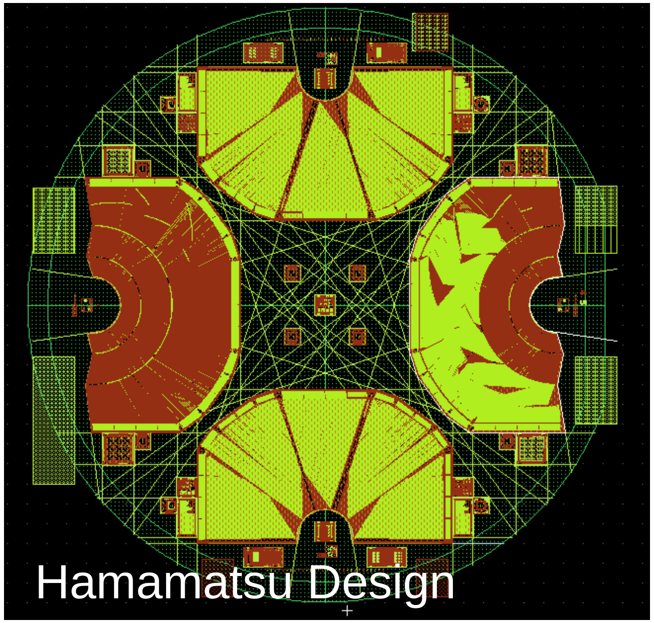
Sensor + ASIC developments

Pixels

- VELOPix ASIC under advanced stage of development based on Timepix/Medipix family
  - 55 x 55 μm square -> one measurement per plane saves on material
  - Simultaneous ToT and ToA information
  - Fast Front end < 25 ns
  - Data driven readout and super pixel clustering to share time stamp and resources
  - Timepix3 (130 nm) submission Q2 2012; VELOPix Q1 2013
- Sensor R&D focussed on
  - Multi-ASIC bump-bonding on thin sensors
  - Minimal guard ring design (asymmetric??), slim edges: trenches, sidewall Al_2O_3
  - Minimization of dead areas inter ASICs: elongated pixels, routing
  - CNM + Micron + VTT

Strips

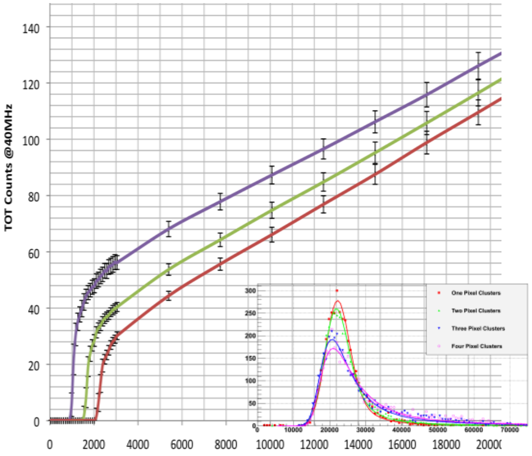
- New ASIC under development
  - Clustering, sparsification, common mode supression, pedestal subtraction etc..
- Fine pitch strip designs in production at Hamamatsu and Micron

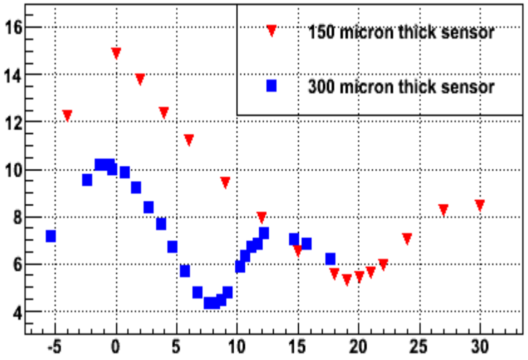


Hamamatsu Design

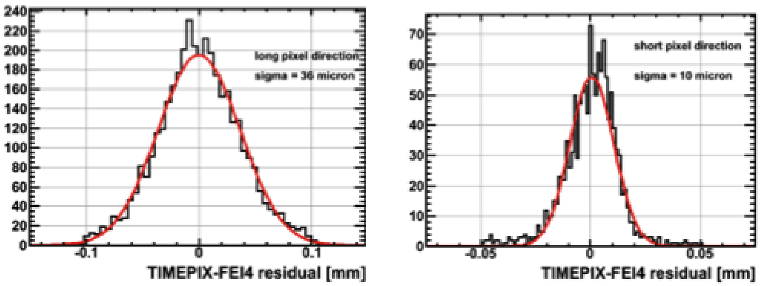
Testbeam Telescope

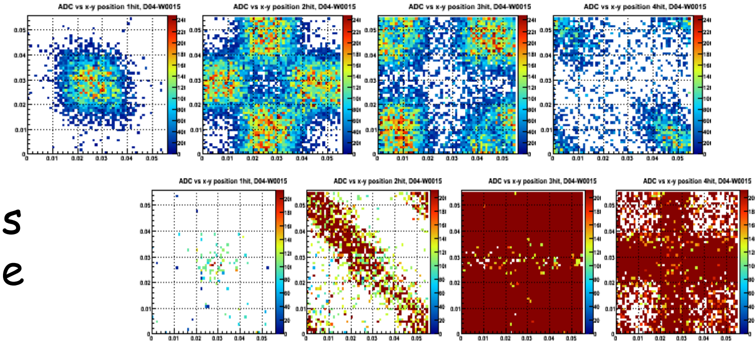
- Timepix based telescope constructed and operated for LHCb upgrade in collaboration with Medipix group
- > 15 kHz track rate with 2 μm resolution + 1 ns time stamp
- CO2 cooling; together with Peltier DUT can reach -50^{o}C
- Fully remote controlled mechanics
- Designed in framework of AIDA to integrate many different DUT devices with simple software
  - 40 MHz r/o (Beetle, SipM, FEI4)
  - Frame based readout (Timepix, Medipix)
- Available for users in AIDA WP9.3 – please apply for beam time before end December!





AIDA Preliminary: Timepix telescope + FEI4 at 75 degree tilt angle

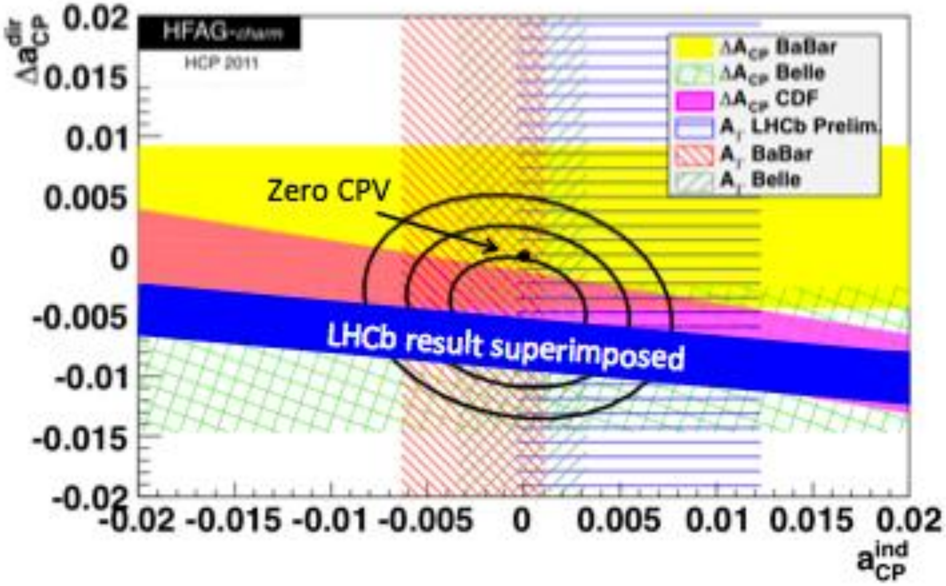




See Matt Reid's poster for more details

Conclusions

- LHCb has turned out to be a very interesting beam test for irradiated silicon detectors
- We access a big range of irradiation parameters and this, together with precise cooling control get decent statistics
- n^+n and n^+p sensors can be compared in identical conditions
- Party Puzzle: How to cure our 2nd metal layer issue?
- And we may have seen the first New Physics from the LHC at the same time (LHCb seminar, CERN, December 6th)
- We will pursue our physics program with an upgraded detector in 2018



LHCb

Thank you for your attention

VErtex LOcator

UCD DUBLIN

CERN

University of Glasgow

NIKHEF

AGH

University of BRISTOL

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF OXFORD
DOMINUS ILLUMINATIO MEA

UNIVERSITY OF LIVERPOOL

MANCHESTER 1824

SYRACUSE UNIVERSITY · FOUNDED A·D· 1870 ·
SUOS CULTORES SCIENTIA CORONAT

THE UNIVERSITY OF WARWICK

МГУ
имени М.В.Ломоносова
1755

Backup

Backup slides - Upgrade

Summary: @ L=2 x 10^{33}

For strips ‘halfstation’ = r + phi sensor!

	strips black=128 ch/asic , red =256 ch/asic	pixels
# ASICS/half station	40 (20)	24
# half stations	42	52
# ASICS total	1680 (840)	1248
Cluster size	1.6 (1.6)	2.2
# clusters / half station/ 25 ns.	52.6 (52.6)	25.8
# pixel(strips) hits / half station /25ns.	84.2 (1.6)	56.8
# bits / cluster	42.4 (34.4)	52.3
# bits / pixel(strip) hit	26.5 (21.5)	23.8
Hottest chip output rate	1.4 Gbit/s (2.24)	12.2 Gbit/s
Coolest chip output rate	1.4 Gbit/s (2.24)	1.5 Gbit/s
Data rate / half station	56 Gbit/s (44.7)	54.3 Gbit/s
Total data rate	2352 Gbit/s (1880)	2823 Gbit/s

Pixel Data Rates @ L=2 x 10^{33}

Hit rates and data rates

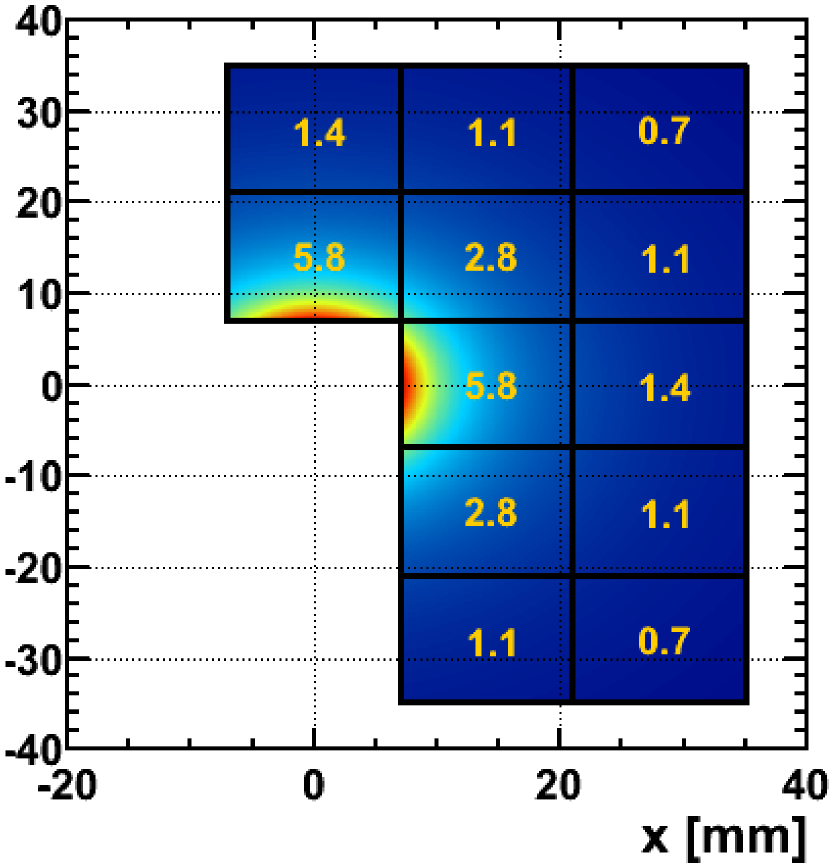
- Assuming 5.8 tracks per 25 ns in the hottest chip (= 230 Mhz track rate) and 25.8 tracks per halfstation.
- Simulation gives 2.2 pixel hits per cluster
- Hottest chip must cope with ~500 MHz, or 250 MHz/cm^2
- Compressed data scheme has (28+n*8) bits per pixel (n= # pixel in cluster). On average 52.3 bits/cluster.
- Hence 12.2 Gbit/s from hottest chip – no headroom
- 2823 Gbit/s from whole VELO

Number of Links

- Assuming each link provides 4 Gbit/s.
- Maximum number of links = 4 per chip, or 48 per half station
- For 26 full stations this gives 2496 links
- If the number of links is optimised per chip, we arrive at a minimum of 1040 links (with no safety margin)

For L=10^{33} these numbers are all divided by 2

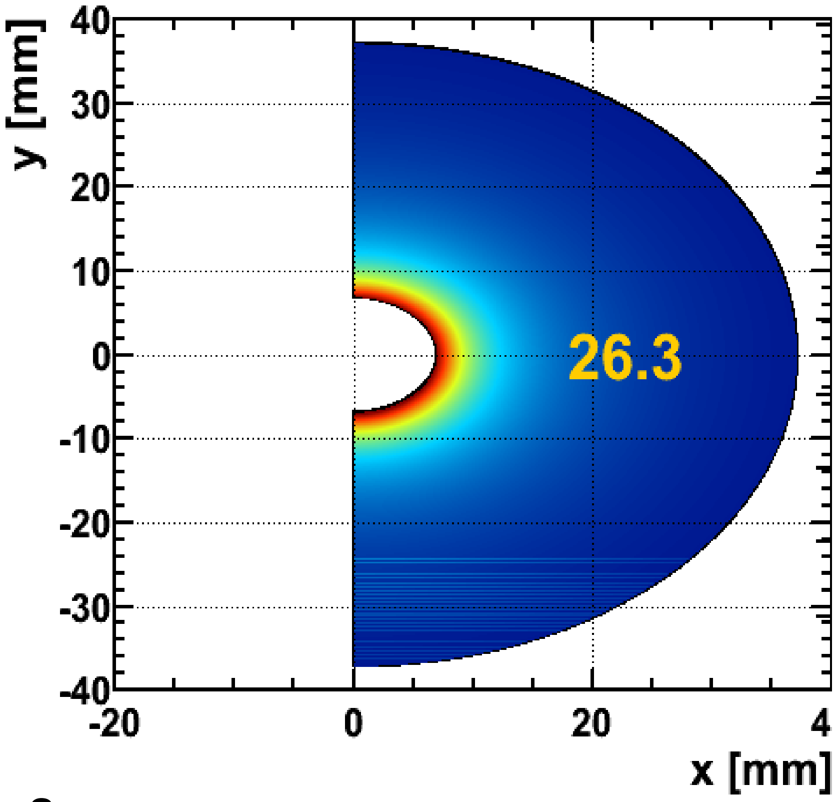
Number of tracks
per half station per event



Strip Data rates @ L=2 x 10^{33}

- 26.3 tracks per sensor per event
- Protocol e.g. as suggested by Lars
  - 12 bit bunch crossing number
  - 7, 8 or 9 bits address of strip within the chip
  - 4 bits ADC value per chip
  - 2 bits to describe the data sequence
  - New/next event <11>=<NE>: start of an event
  - Consequtive hit <10>=<CL>: ADC of next strip in cluster to follow
  - End of cluster <01>=<EC>: End of cluster, next value is a new address
  - End of buffer <00>=<EB>: No more data in buffer
- 1.3 clusters per 128 channel ASIC
- 1.6 hits per cluster
- On average, 26.5 (21.5) bits per cluster for 128 channel chip (256 channel chip).
- 1.4(2.24) Gbit/s/chip, 2352 (1880) Gbit/s for the whole VELO for 128 channel (256 channel) chip
- Hence 1 link per chip more than sufficient and even gives headroom for more luminosity
- 20 x 42 x 2 = 1680 links for the VELO (for a 128 channel chip), can reduce to 840
- 10 x 42 x 2 = 840 links for the VELO (for a 256 channel chip)

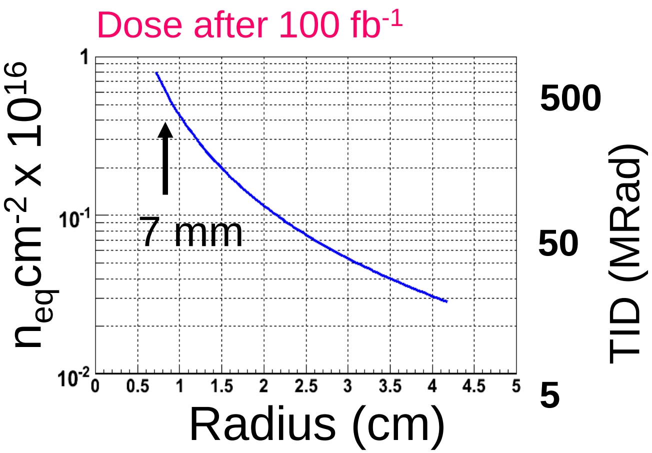
Number of tracks
per sensor per event



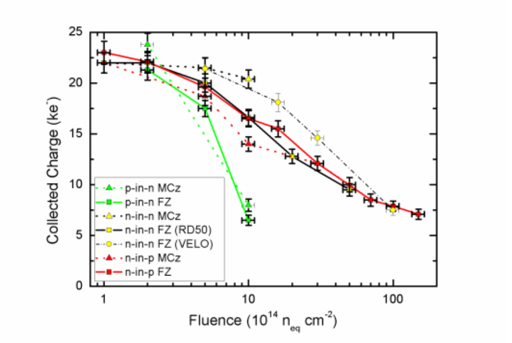
For L=10^{33} these numbers are all divided by 2

Radiation Environment @ Upgrade

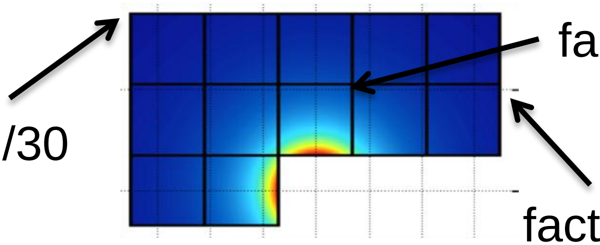
- At 7 mm from beam we accumulate ~ 370 MRad or 8 x 10^{15} n_{eq}/cm^2 for 100 fb^{-1}


Dose after 100 fb^{-1}

RD50 studies have shown that silicon irradiated at these levels still delivers a **signal** of ~ 8ke$^-$ / MIP
Limit of strip sensor operation
Latest estimates: VELO can survive 20 fb-1, if no thermal runaway, DM effects

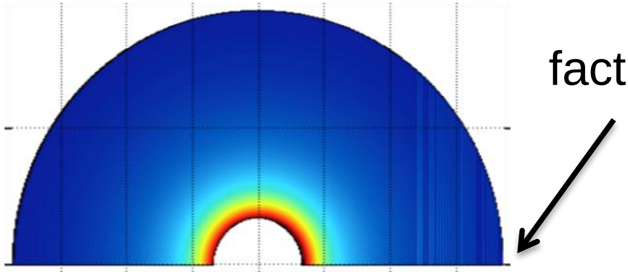


Dose is highly non-uniform – could pose a challenge, particularly for large sensors


factor 1/7

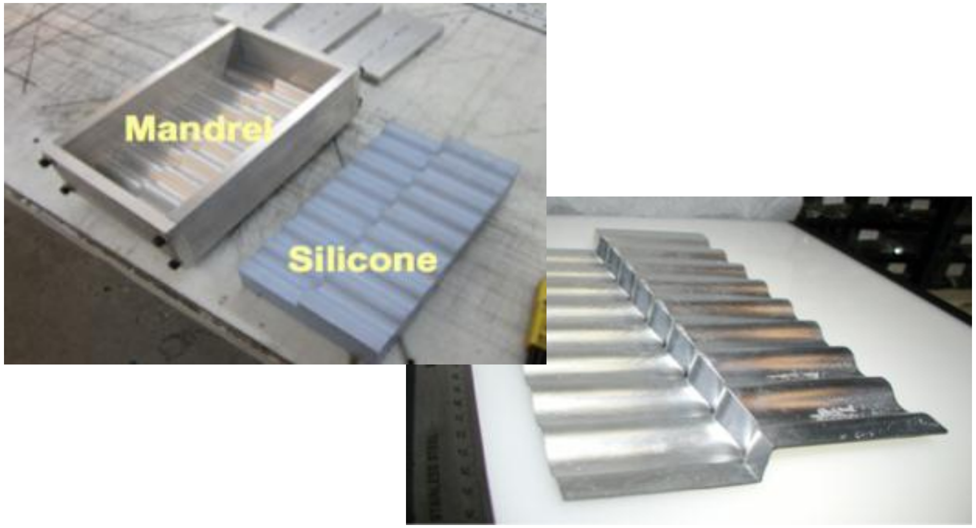
factor 1/30

factor 1/20


factor 1/20

Foil - Critical component of VELO Upgrade

Two major options have seen considerable R&D – both aiming to eliminate welding step

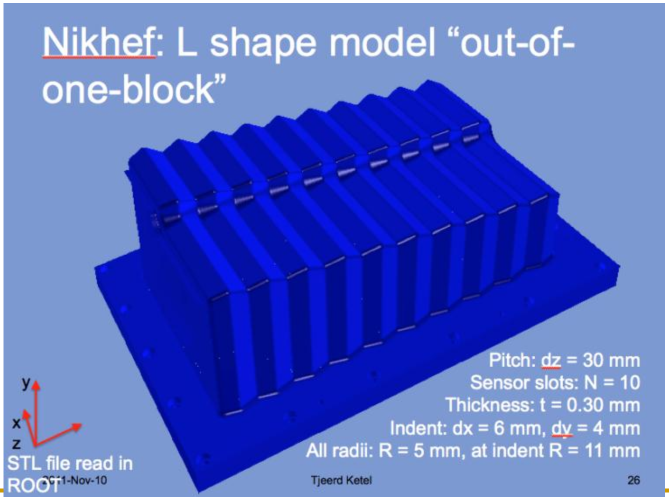


CF composites (Syracuse)

- Good X/X0
- CRFP layups can adopt “any shape”
- Benefit from CMA expertise in space based mirror manufacture (challenge of adhesion in vacuum)
- Suitable materials and clamping technique identified
- Additional investment needed for next step

Milling out of one box (Nikhef)

- Mill flange with holes.
- Mill the inside.
- Cover inside with hard wax.
- Fill with Sikadur epoxy mixed with glass spheres.
- Mill the outside.
- Check the thickness (next slide).
- Drain the wax at 75 degrees.
- Remove the filler, clean the box



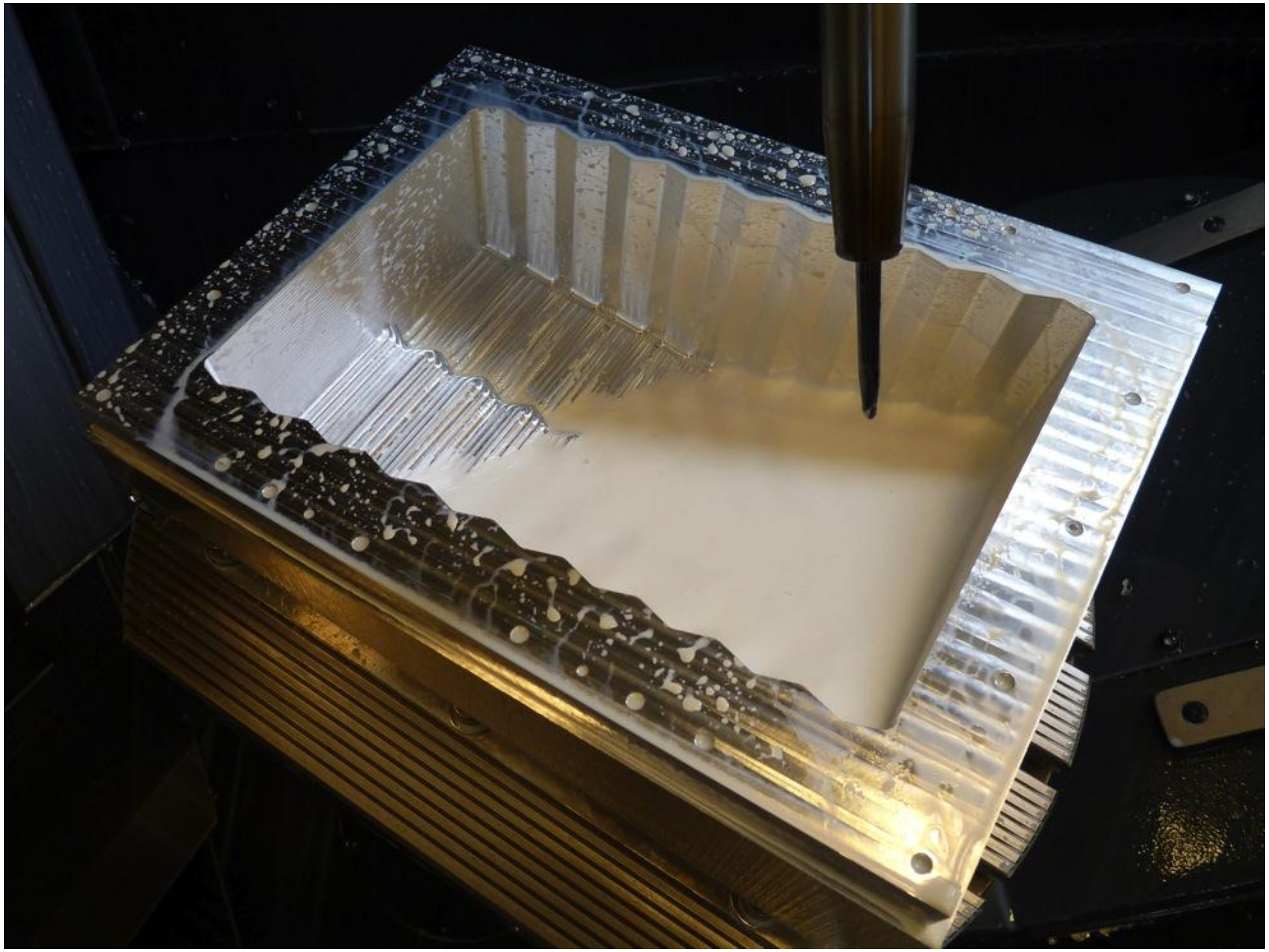
Nikhef: L shape model “out-of-one-block”

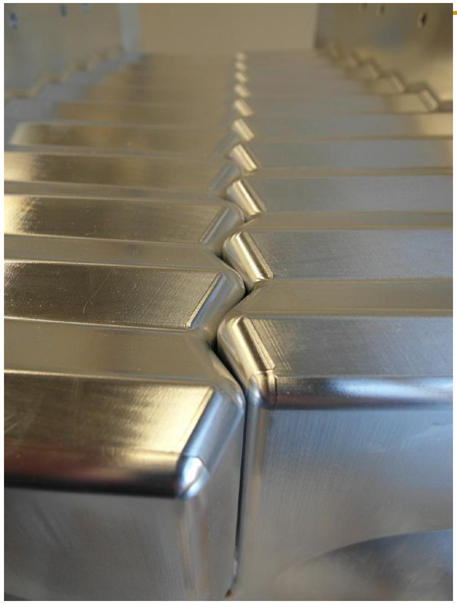
Pitch: dz = 30 mm
Sensor slots: N = 10
Thickness: t = 0.30 mm
Indent: dx = 6 mm, dy = 4 mm
All radii: R = 5 mm, at indent R = 11 mm

STL file read in ROOT

2011-Nov-10 Tjeerd Ketel 26

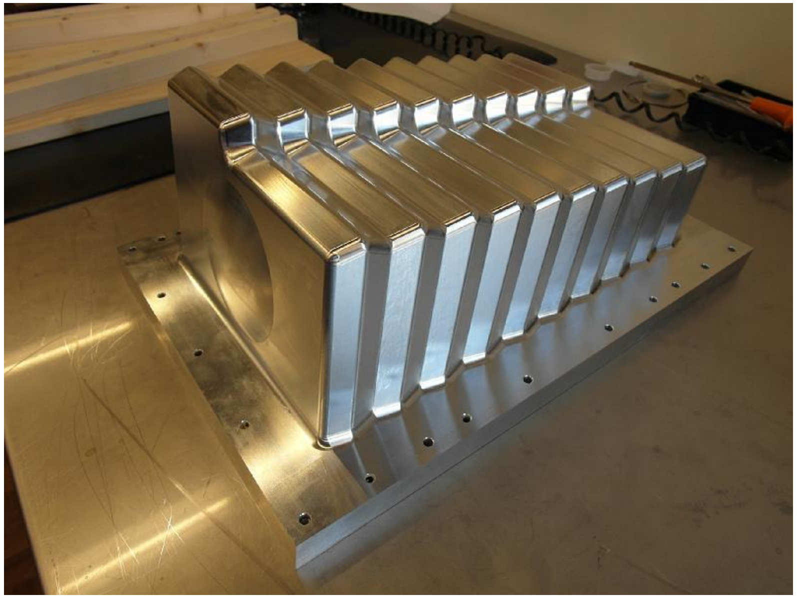
Milling of the inside (2)



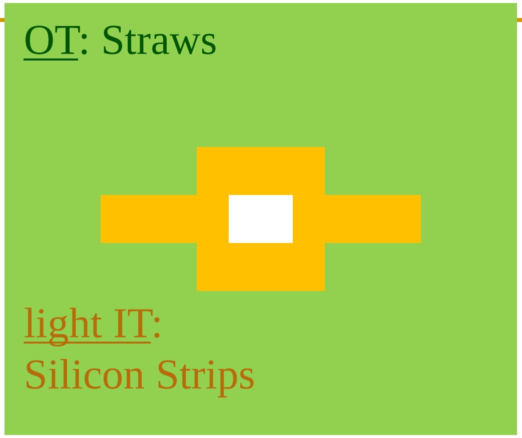


Leak rate
< 10^{-9} mbar l/s!

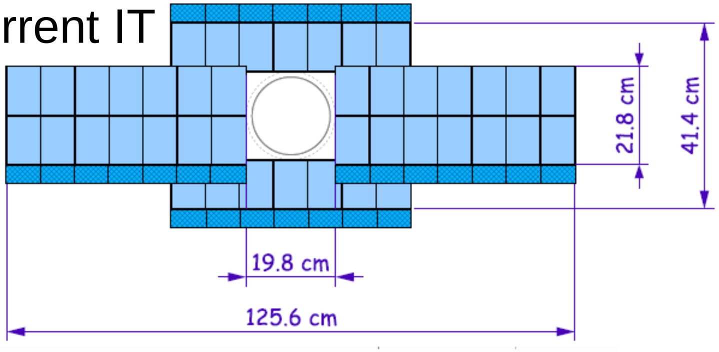
New milling machine with sufficient floor plan for complete box purchase for 2012



Light & large area IT with silicon strips



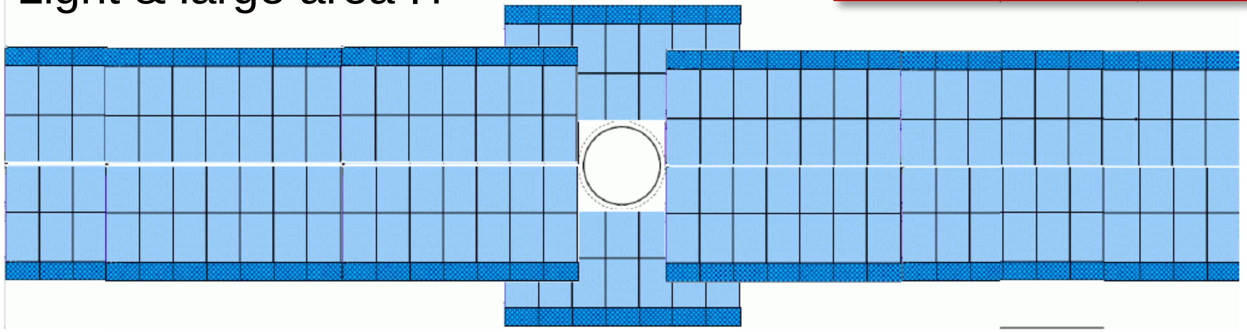
Current IT

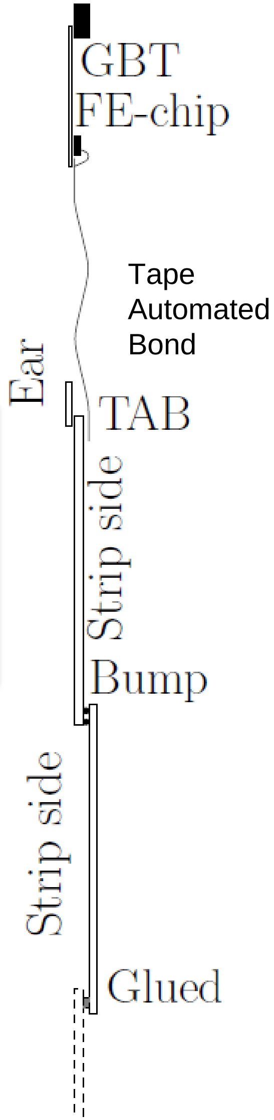


Effort started

- strip chip design
- cooling proof of concept (air flow)
- received 10 sensors for testing TAB, module assembly, HV, etc.

Light & large area IT



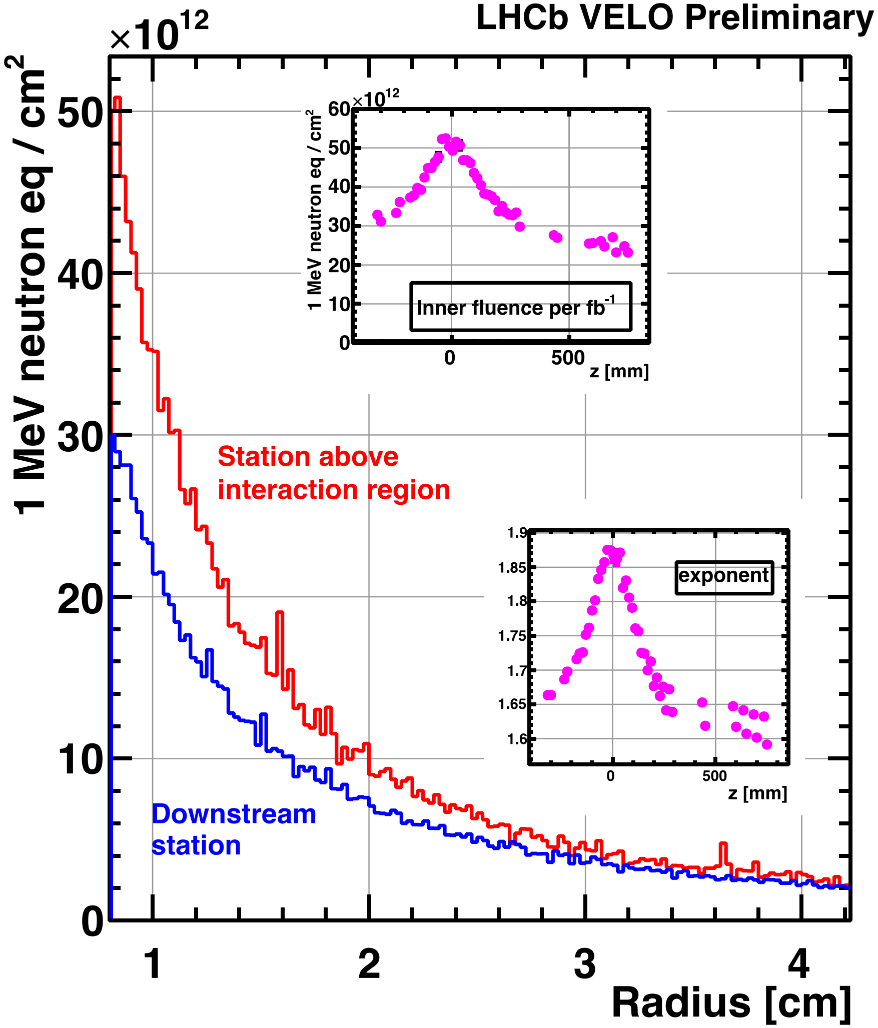


- light: reduce X/X0 ~ 2
- large: increase area by ~ 3.3-4 : from 126x22(42)cm to 255x42(63)cm
- optimise station layout: now 3x(xuvx)=12 layers in-front of T3 to 2x(xuxvx)=10 layers behind T1 & T3

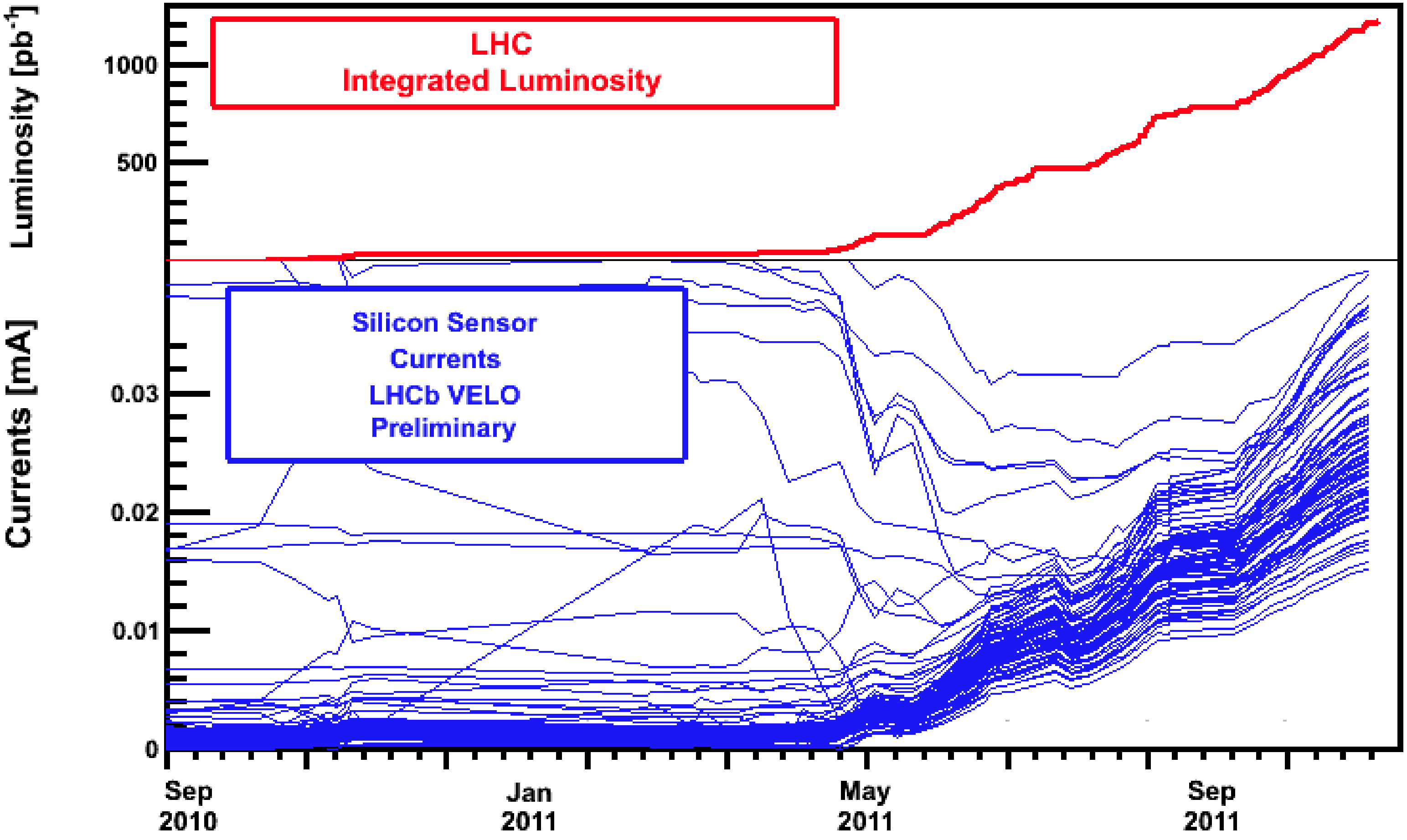
Backup slides – Radiation Damage

VELO – most exposed silicon @ the LHC

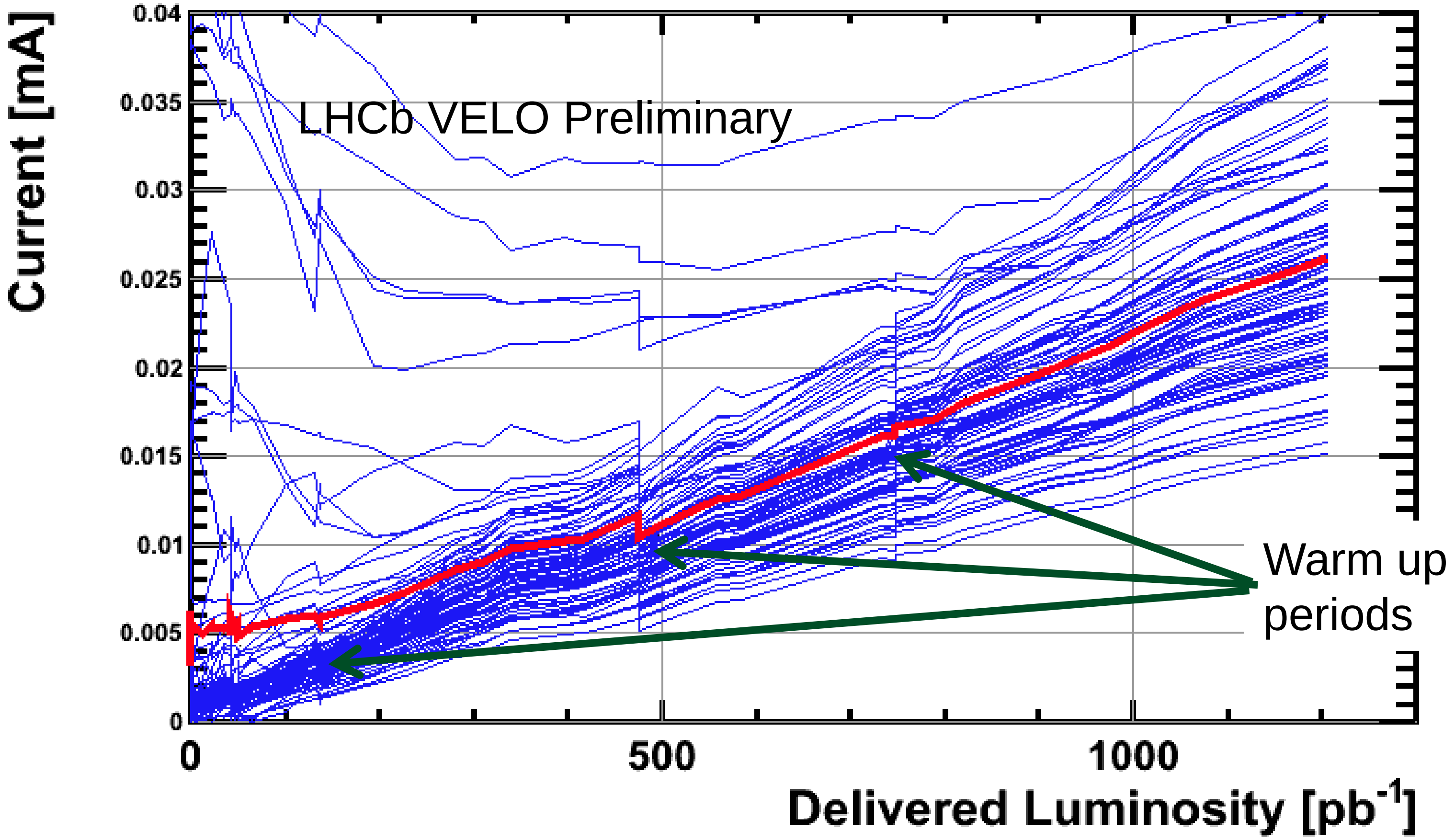
- Accumulate 0.5 x 10^{14} n_{eq} at most irradiated sensor tip per fb^{-1} (we got ~ 1 fb^{-1} so far)
- We have 86 n^{+}-in-n type sensors and 2 n^{+}-in-p type
- Use of VELO data to measure VELO fluence and ageing
  - currents as a function of Voltage and Temperature
  - Noise as a function of HV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



Silicon Currents at operational temperature as a function of time



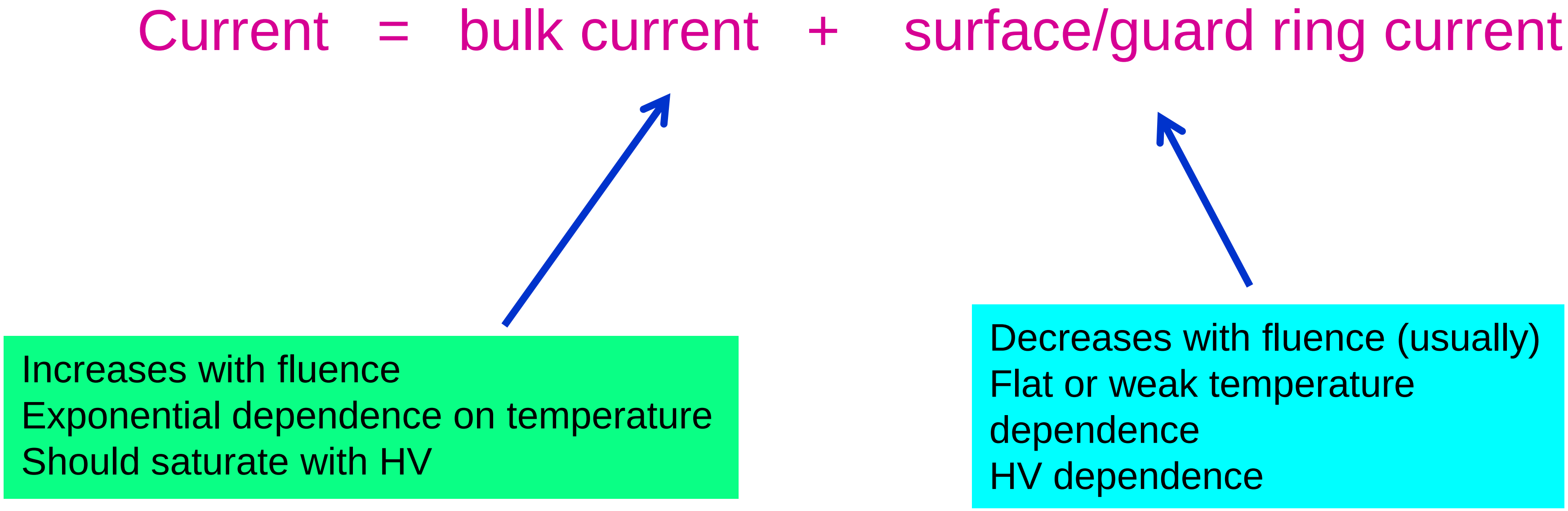
Silicon currents in the VELO as a function of delivered luminosity



Currents measured in operational conditions, without beam; increase of a mean of 22 μA per fb^{-1}

Warm up periods

Current in irradiated silicon sensors (simple view)



Current = bulk current + surface/guard ring 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

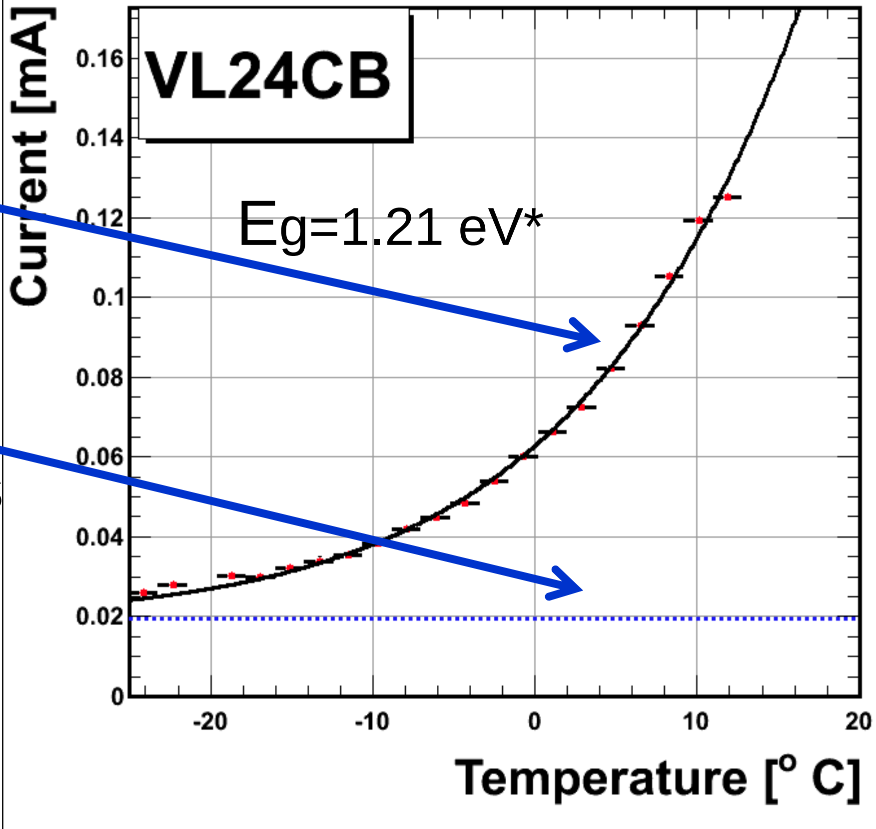
Why use IT (current vs temp) data?

- Bulk current contribution can be fitted as

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

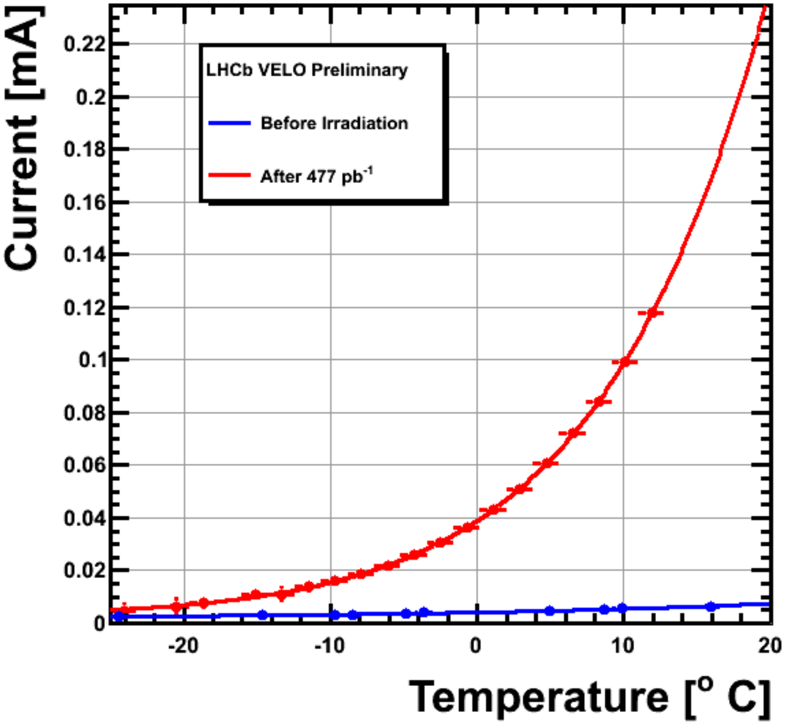
- Surface current contribution assumed to be flat
- Having the full curve allows us to compare all sensors at similar temperatures without an imprecise extrapolation from low temperature

Example sensor after 821 pb^{-1}

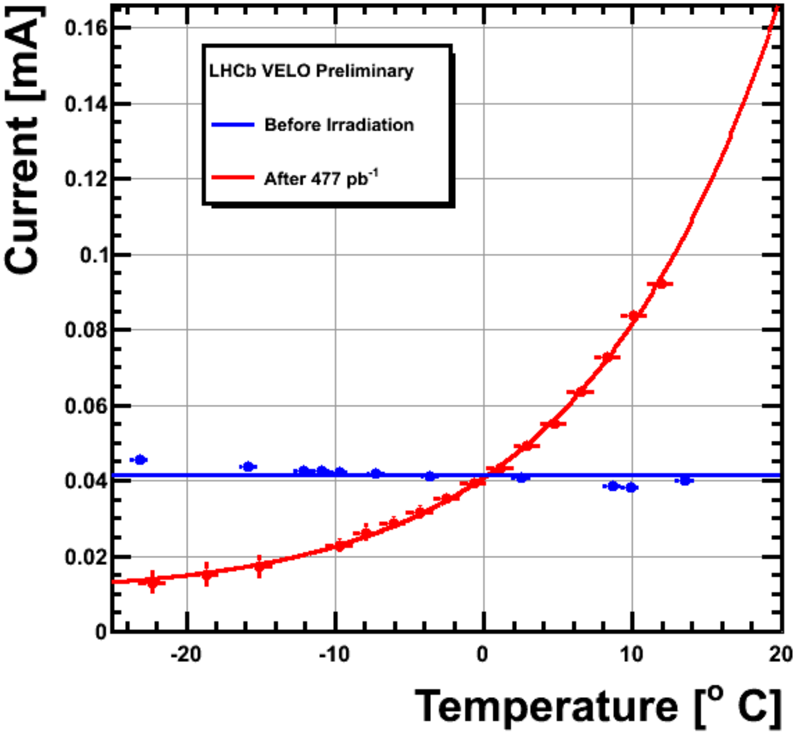


*A.Chilingarov, Generation current temperature scaling, 9 May 2011, https://rd50.web.cern.ch/rd50/doc/Internal/rd50 2011 001-I-T scaling.pdf,

Typical changes before and after irradiation

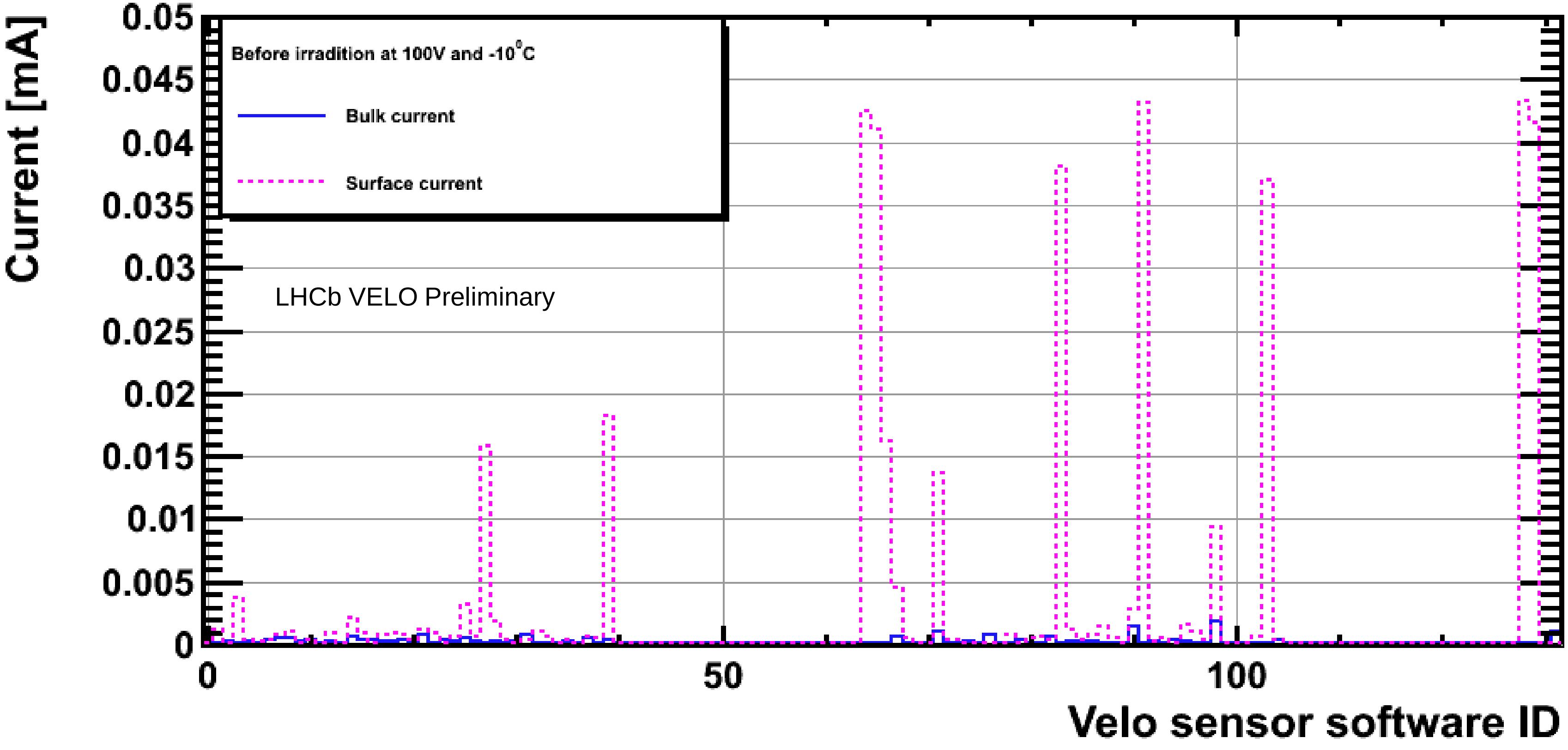


Bulk current dominated sensor
both before and after irradiation

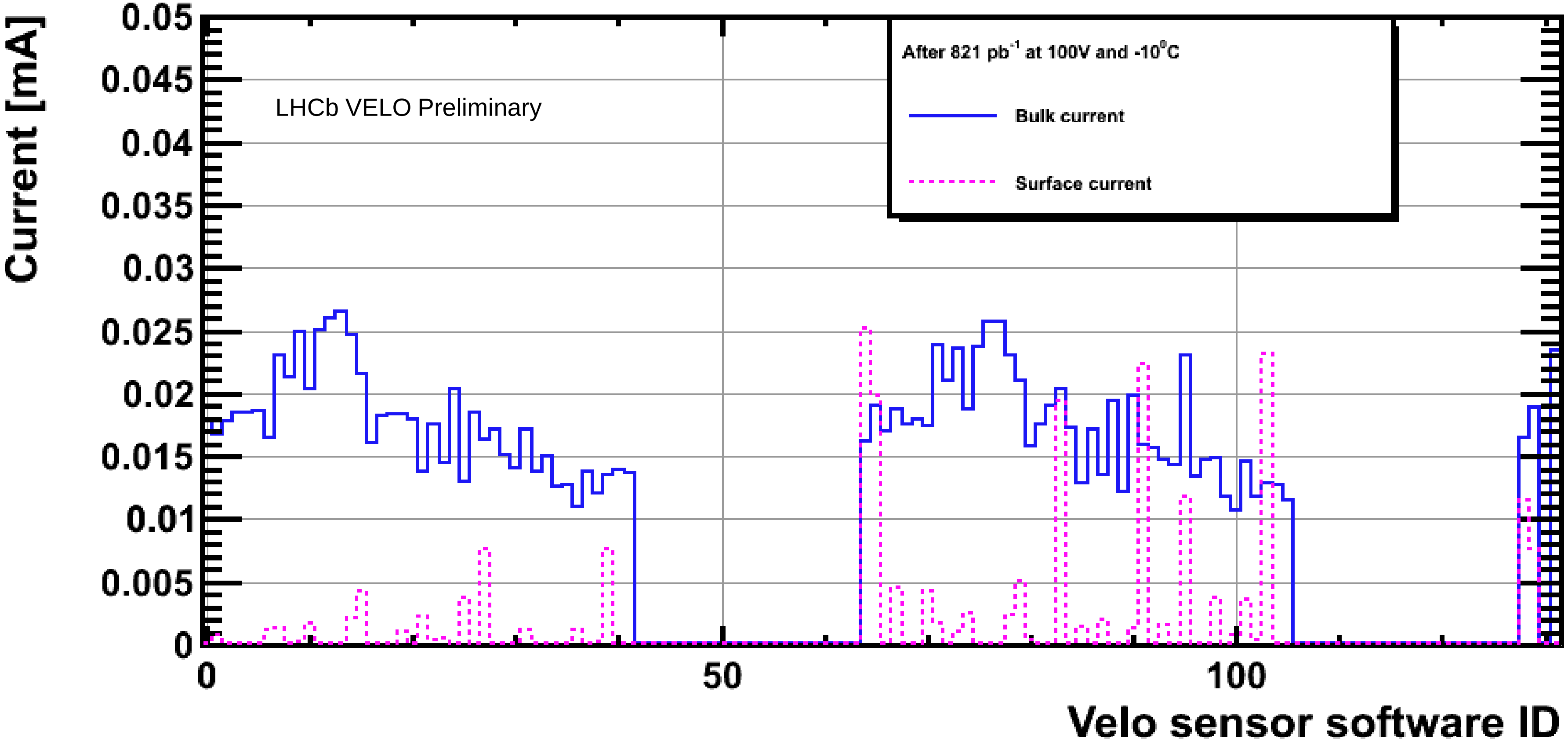


Surface current dominated sensor
before irradiation, Bulk dominated after

Before irradiation: Bulk and Surface current

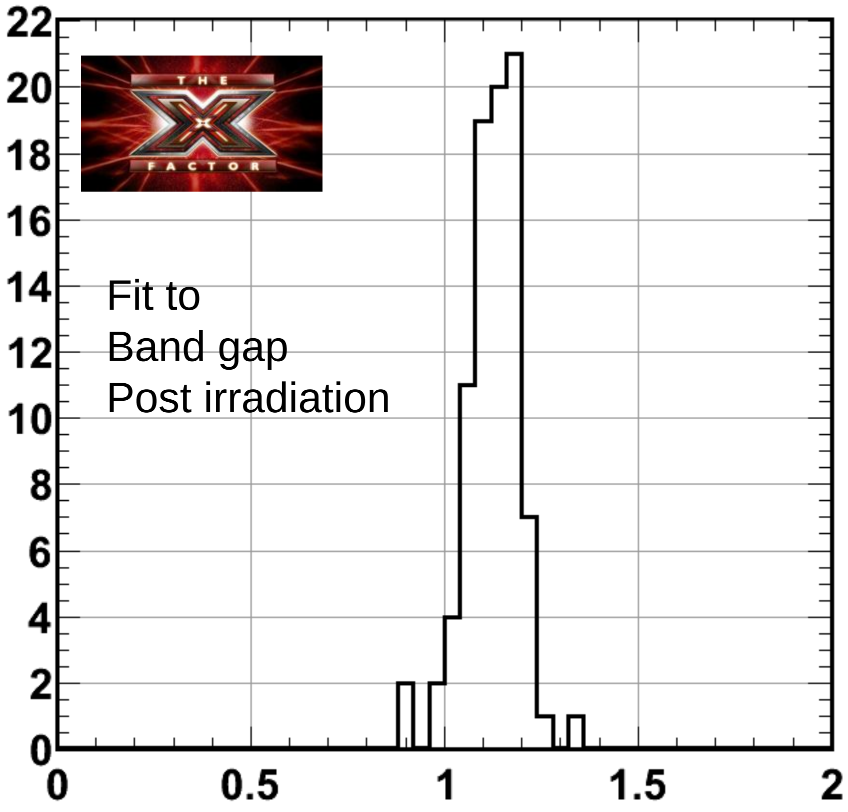


After irradiation: Bulk and Surface current



Exponential factor (Taka-Kondo-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 “Taka-Kondo-factor”



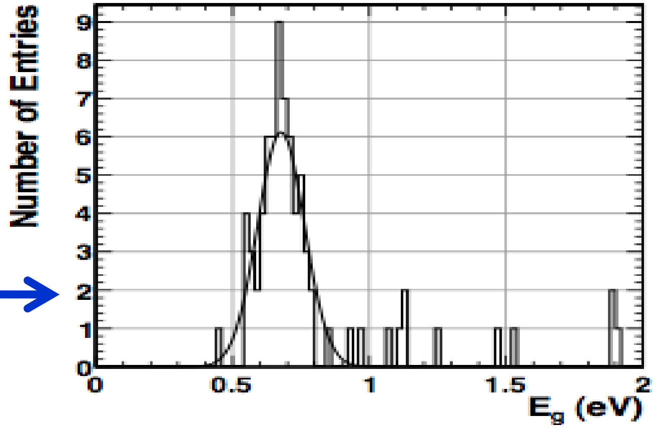
We can directly measure the “effective band gap” and compare it to theory (1.21 eV)

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

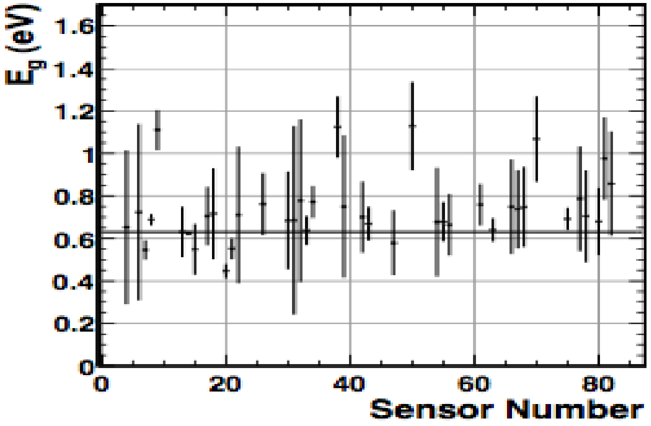
Measurement of effective E_g

(Taka-Kondo-Alex-Chilingarov-factor)

Before Irradiation

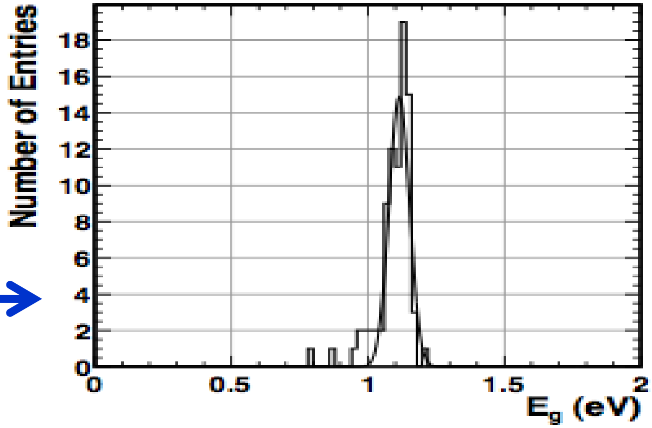


(a)

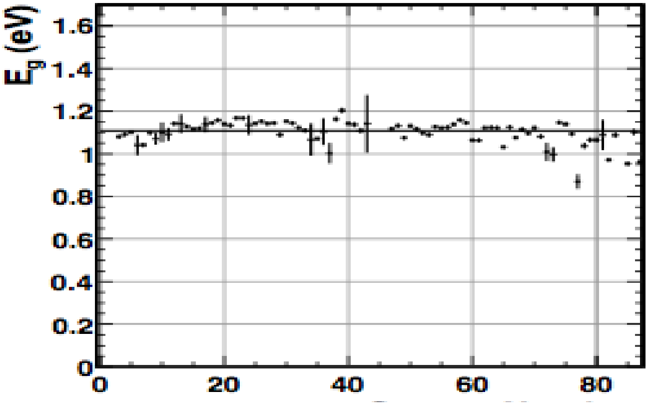


(b)

After Irradiation

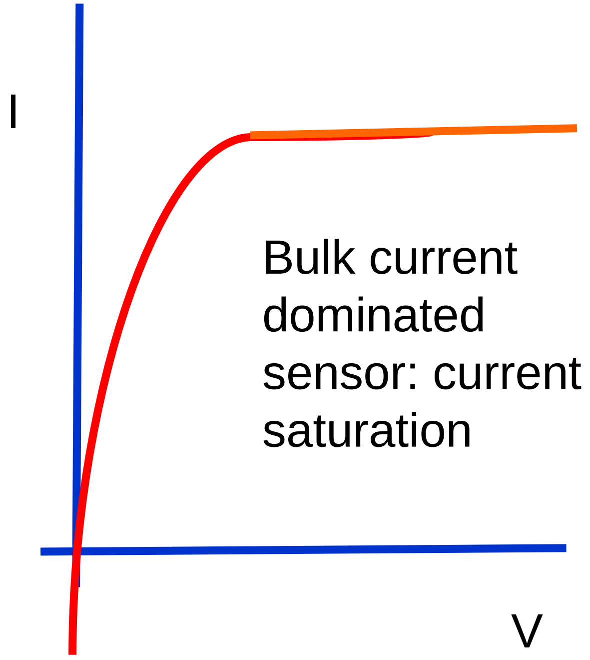


(c)

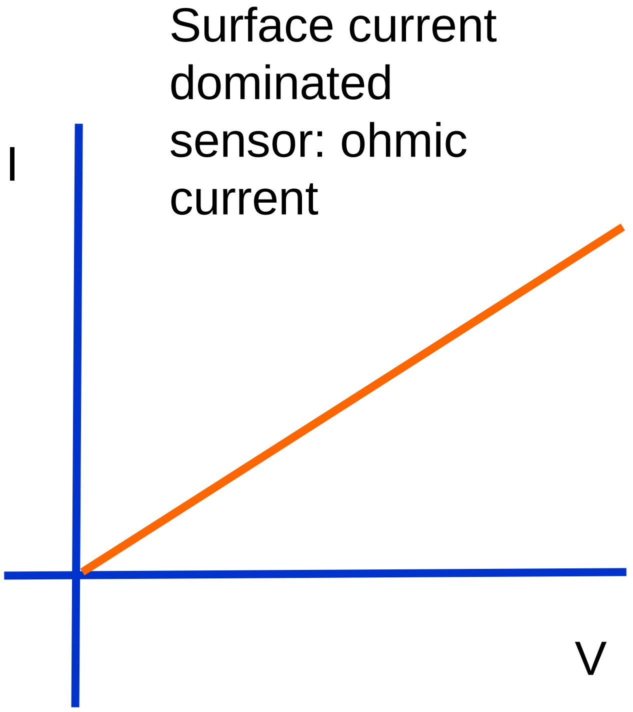


Our measurement is probably more precise than the literature accepted value of 1.21 ev

A different method to track bulk and surface current changes



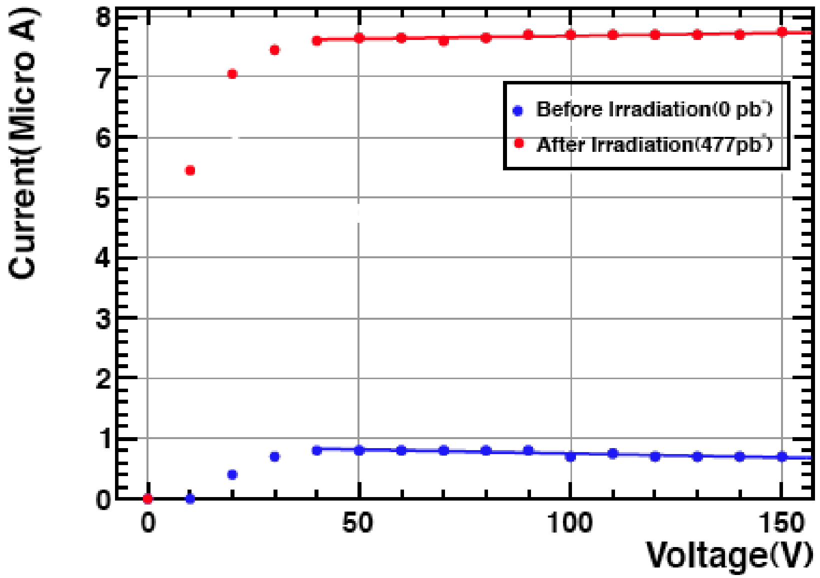
Bulk current dominated sensor: current saturation



Surface current dominated sensor: ohmic current

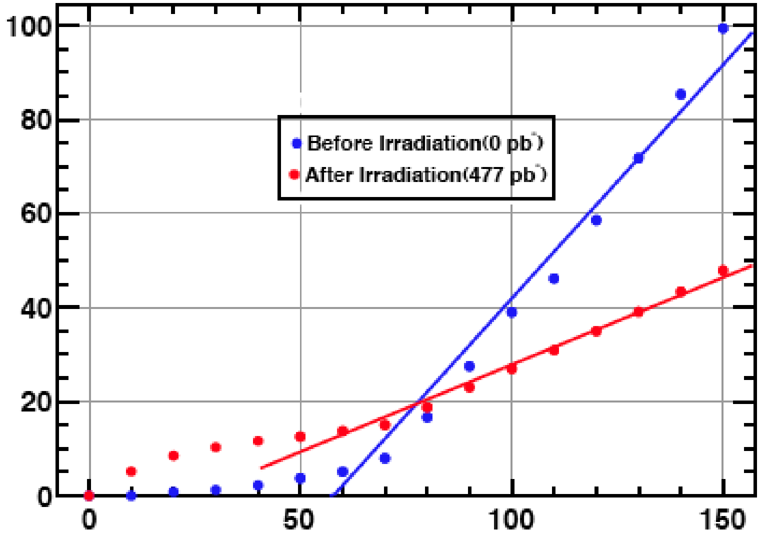
IV curves before and after irradiation

LHCb VELO Preliminary



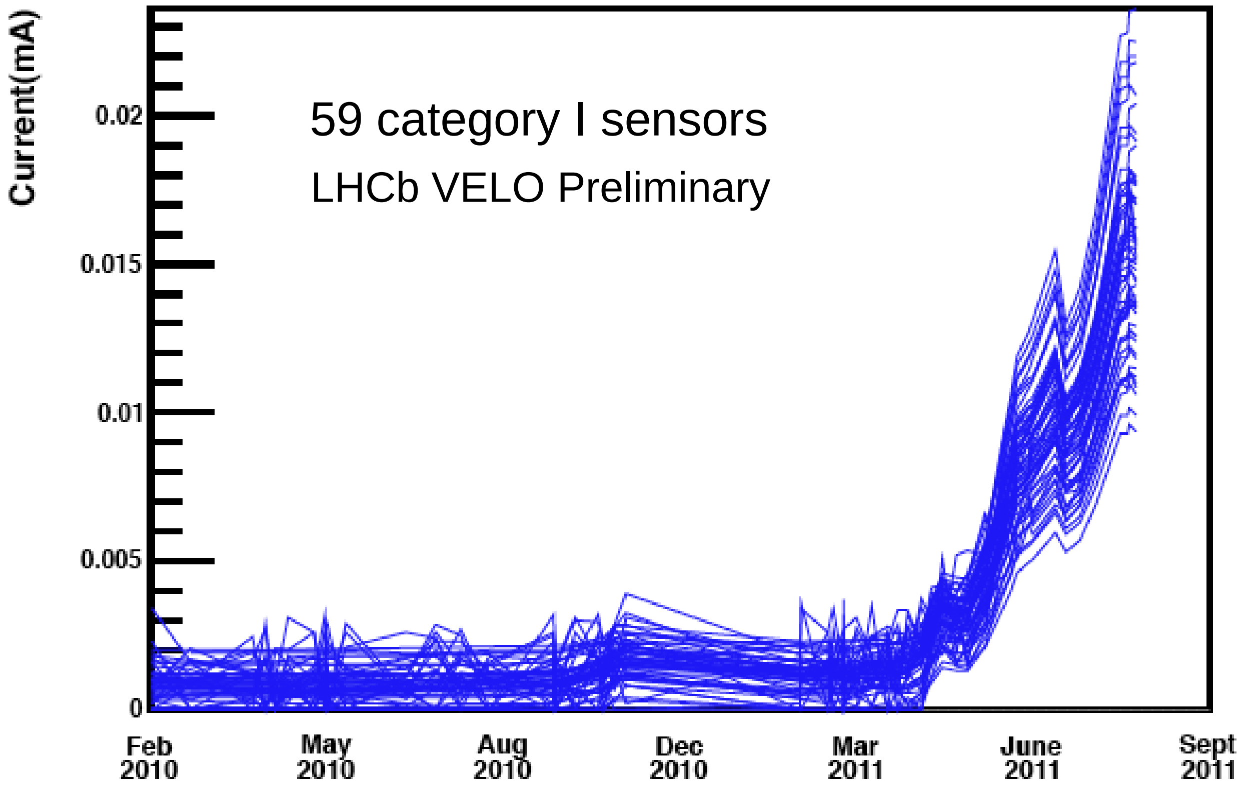
Bulk current dominated sensor before and after irradiation

LHCb VELO Preliminary



Surface current dominated sensor before irradiation, mixture afterwards

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



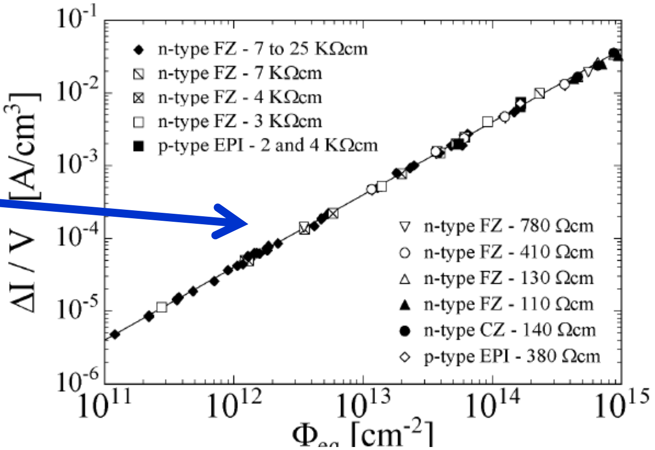
(b)

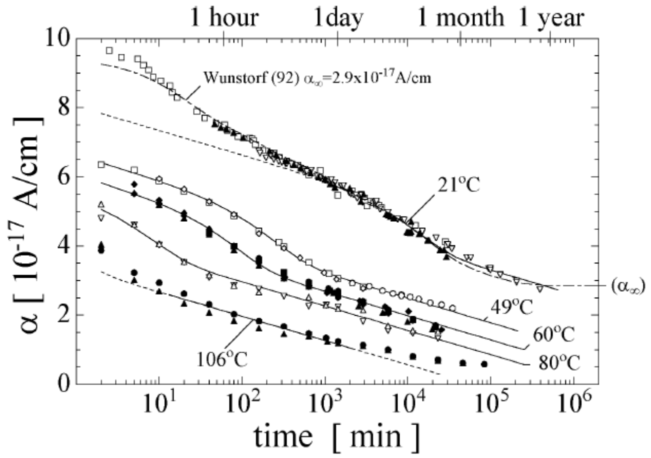
How do our measured and expected currents compare?

- 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 21º

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

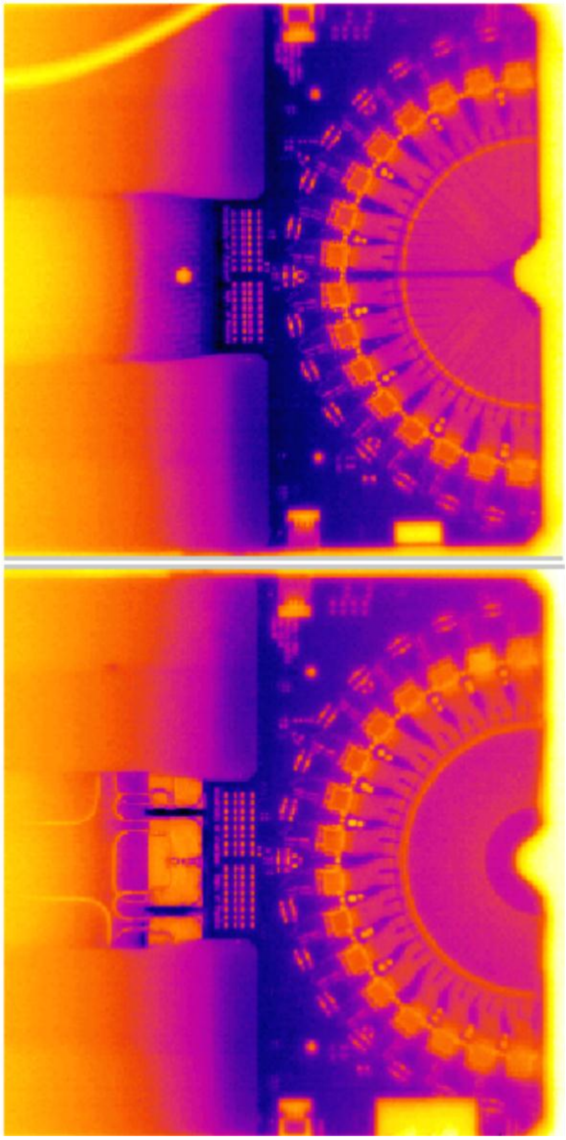
(where Eg=1.31 eV)

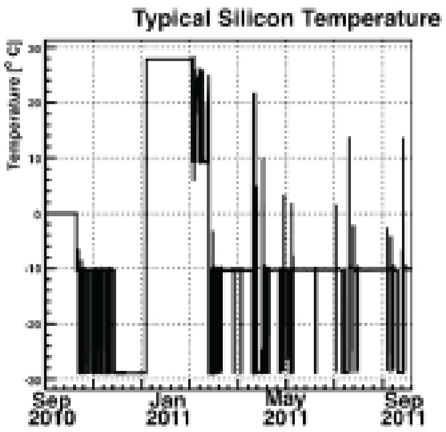


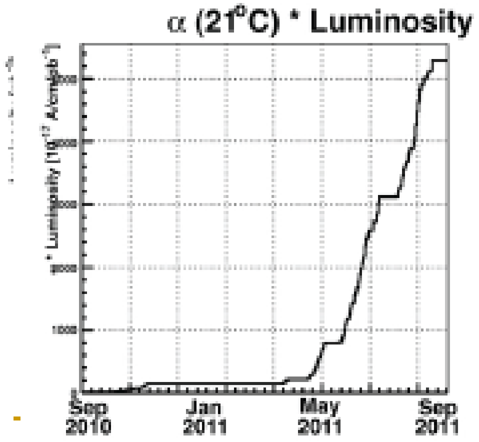


Calculation of α

- 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*$\mathcal{L}$

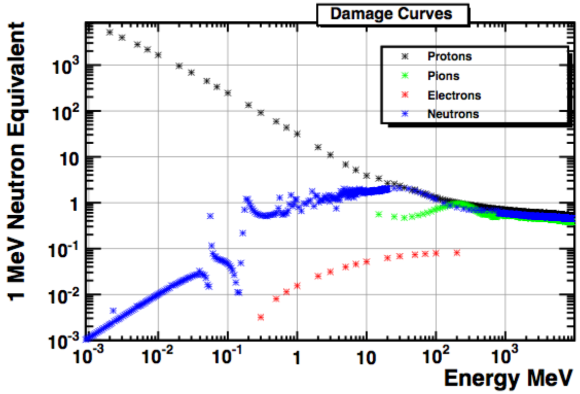



Typical Silicon Temperature

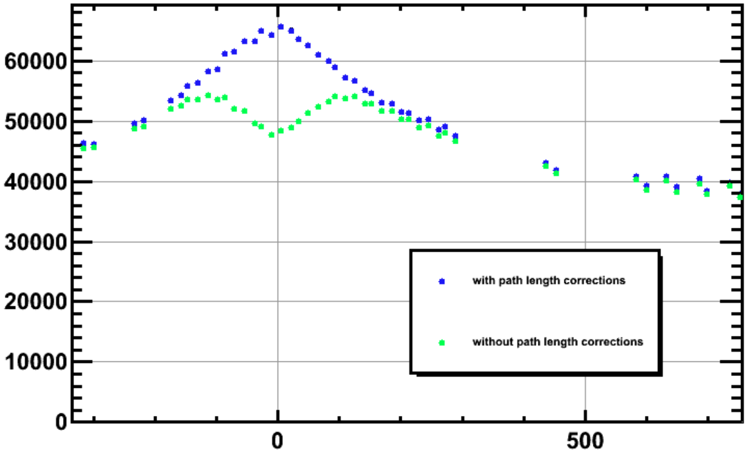

α (21°C) * Luminosity

Estimate of damage from MC

- Use standard LHCb simulation to measure path lengths of particles in silicon
- Use radiation damage tables into to convert to damage

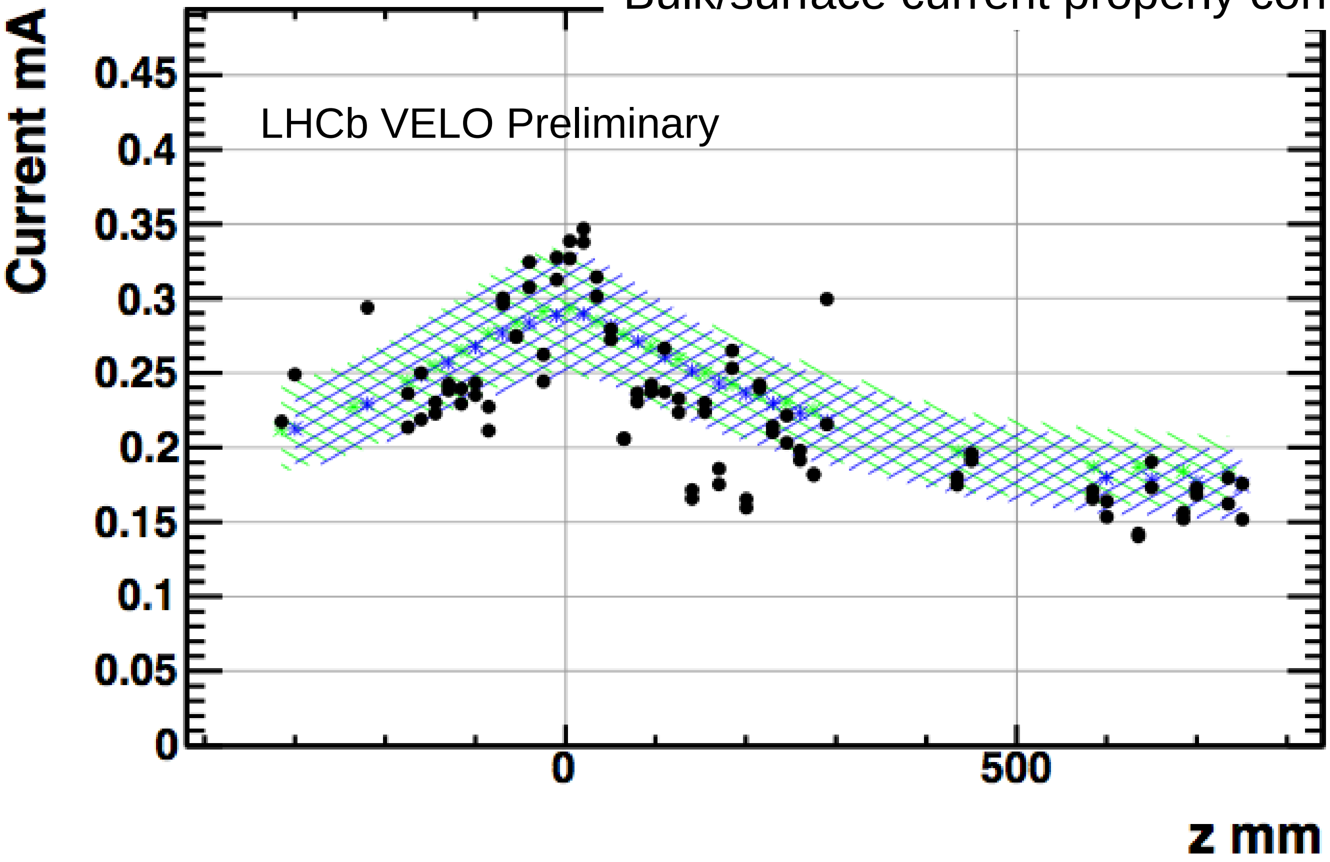


A. V. I. Bucharest) and G. L. U. of Hamburg), “Displacement damage in silicon, on-line compilation.” http: //sesam.desy.de/members/gunnar/Si-dfuncs.html

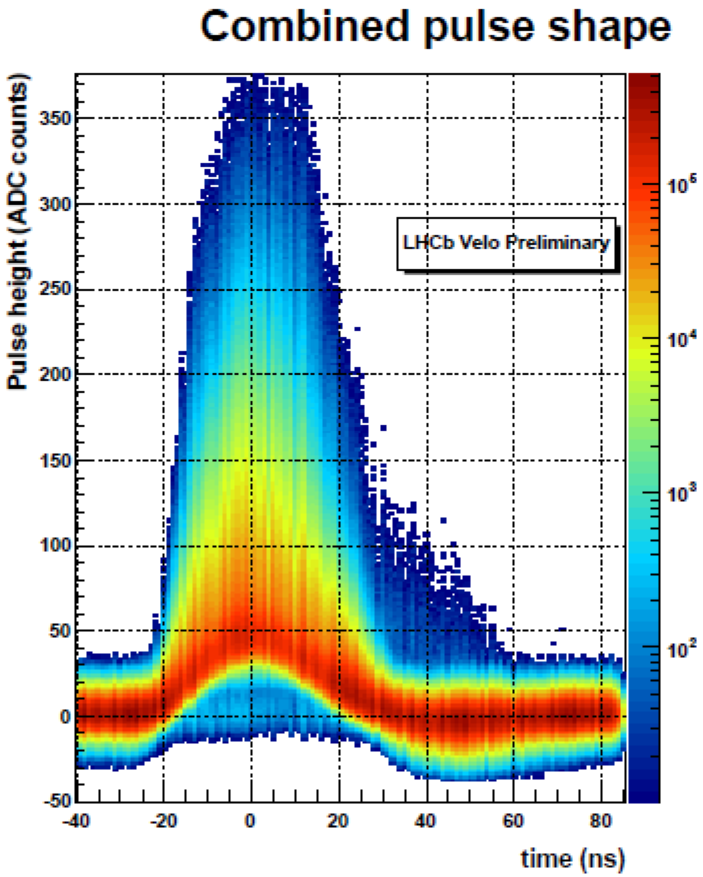


Comparison of data and MC

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



Time Alignment



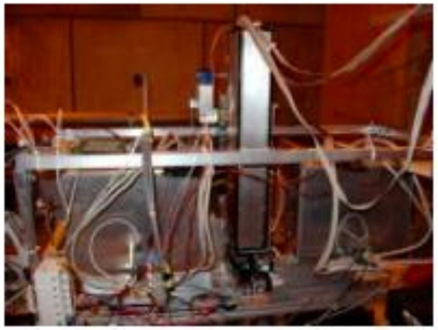
- Fine tune timings of front end chips
- Aim for
  - Maximum signal/noise
  - Minimum spillover
- Sensors individually tuned to account for differences in
  - Time of flight
  - Cable length

Backup Slides - Telescope

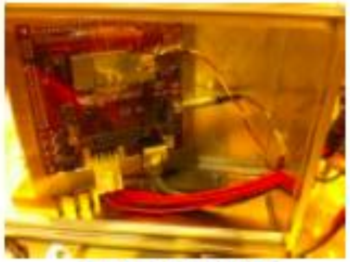
- Flexibile device integration!

- This year used by:
  - Velo Upgrade
  - ST Upgrade (Scintillating Fibres)
  - ATLAS IBL (Planar community)
  - RD50
  - Medipix Collaboration
  - External Collaborators (Glasgow, Nikhef)

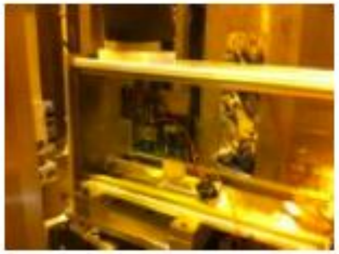
- Interest for next year from:
  - Velo, ST, Others?
  - ATLAS Planar + 3D + Diamond Groups
  - CLiC
  - Gaseous Detectors



LHCb Scintillating Fibres



ATLAS FEI4



Medipix3

- Cooling infrastructure (based on Velo style CO_2 cooling cookies) set up and tested
  - Preparation for next years irradiation tests
- First group to start operation in testbeams with TRACI
- Huge thanks to Nikhef and CERN