Radiation Tolerance of the LHCb Outer Tracker

in the Lab and in the Forward Region at the LHC

Niels Tuning (Nikhef)

(on behalf of LHCb OT group)

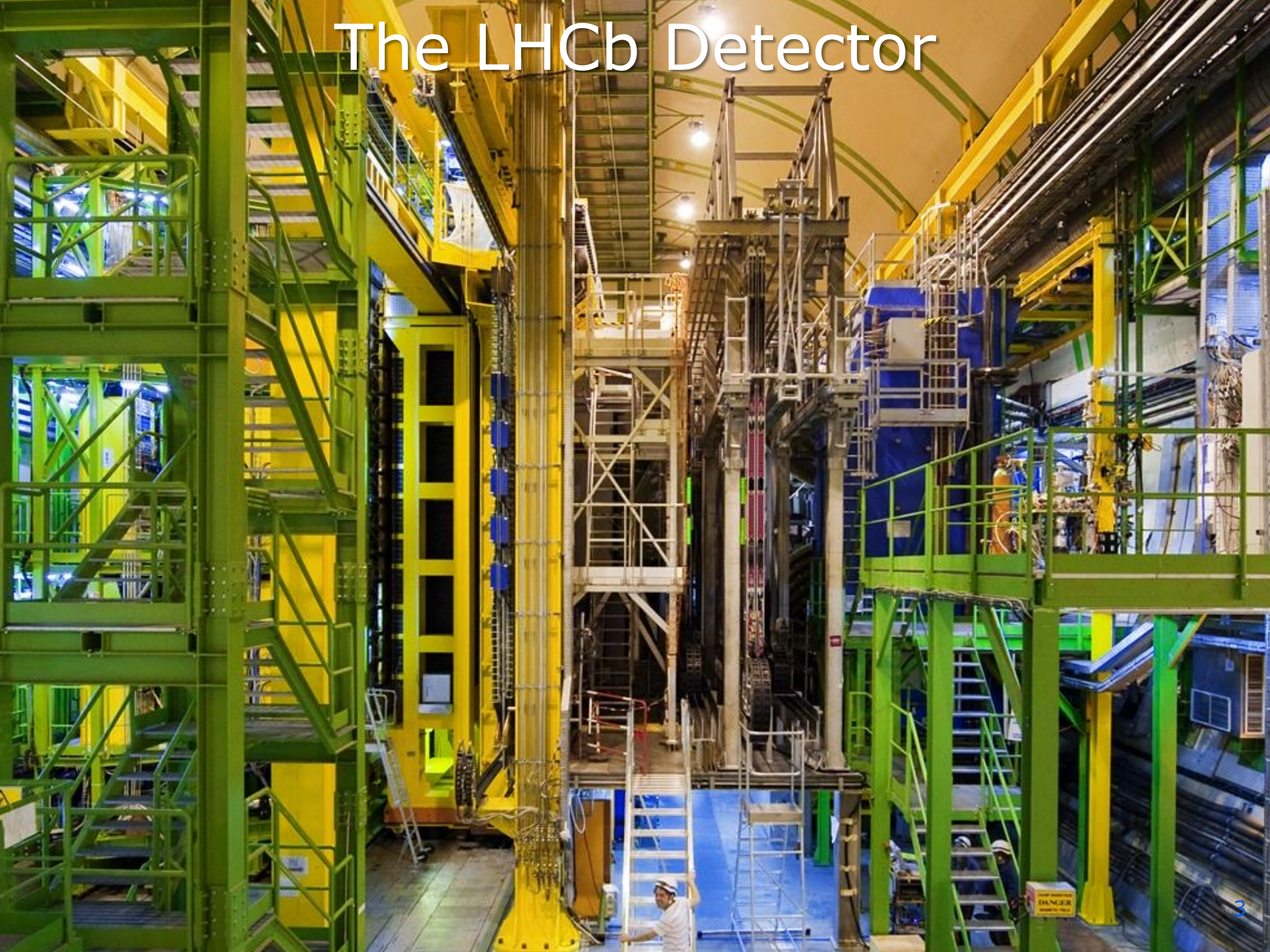
6-10 Nov 2023

3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors

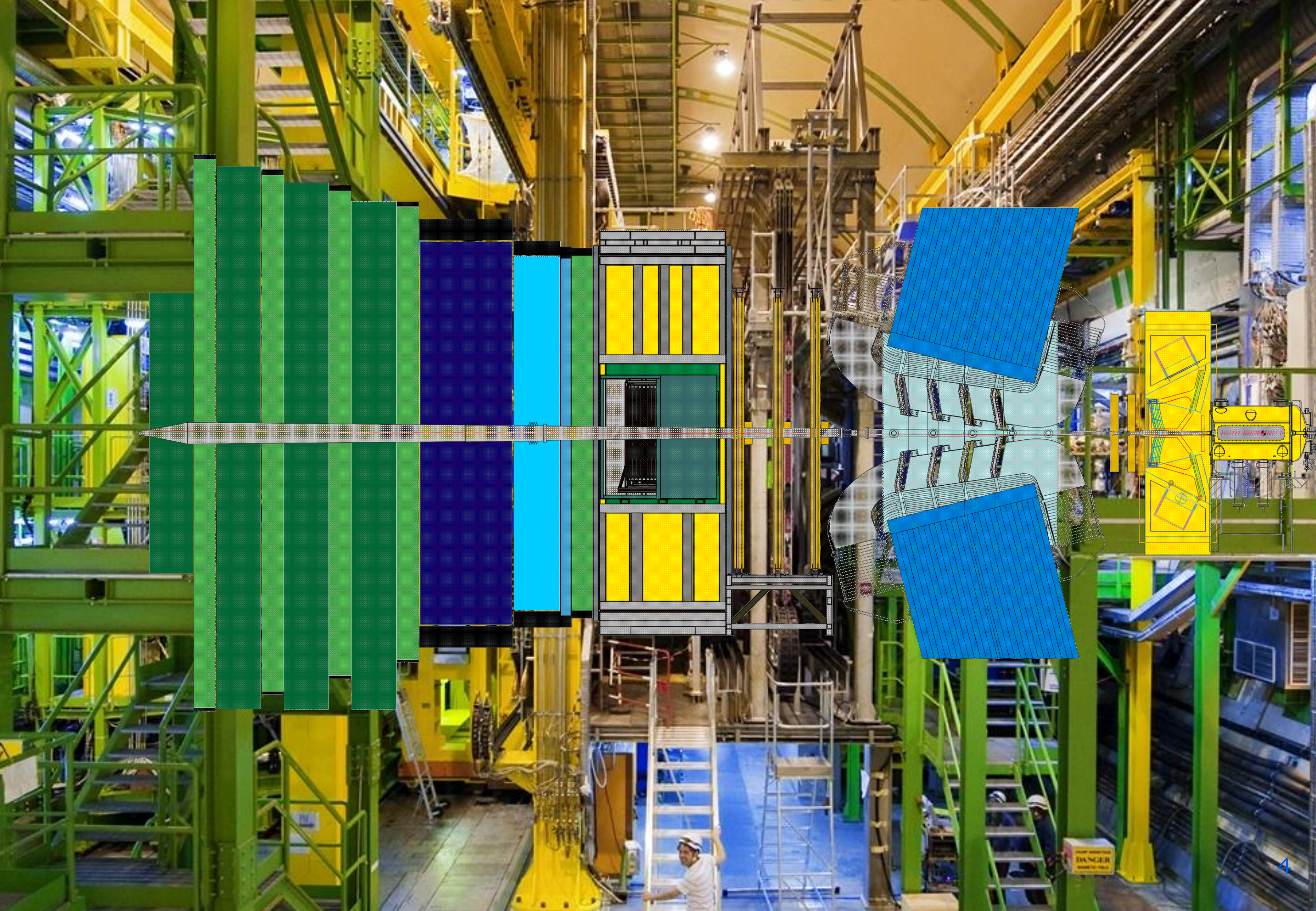
Outline

- LHCb and the Outer Tracker
- Ageing: the saga
- Radiation hardness
- Conclusions

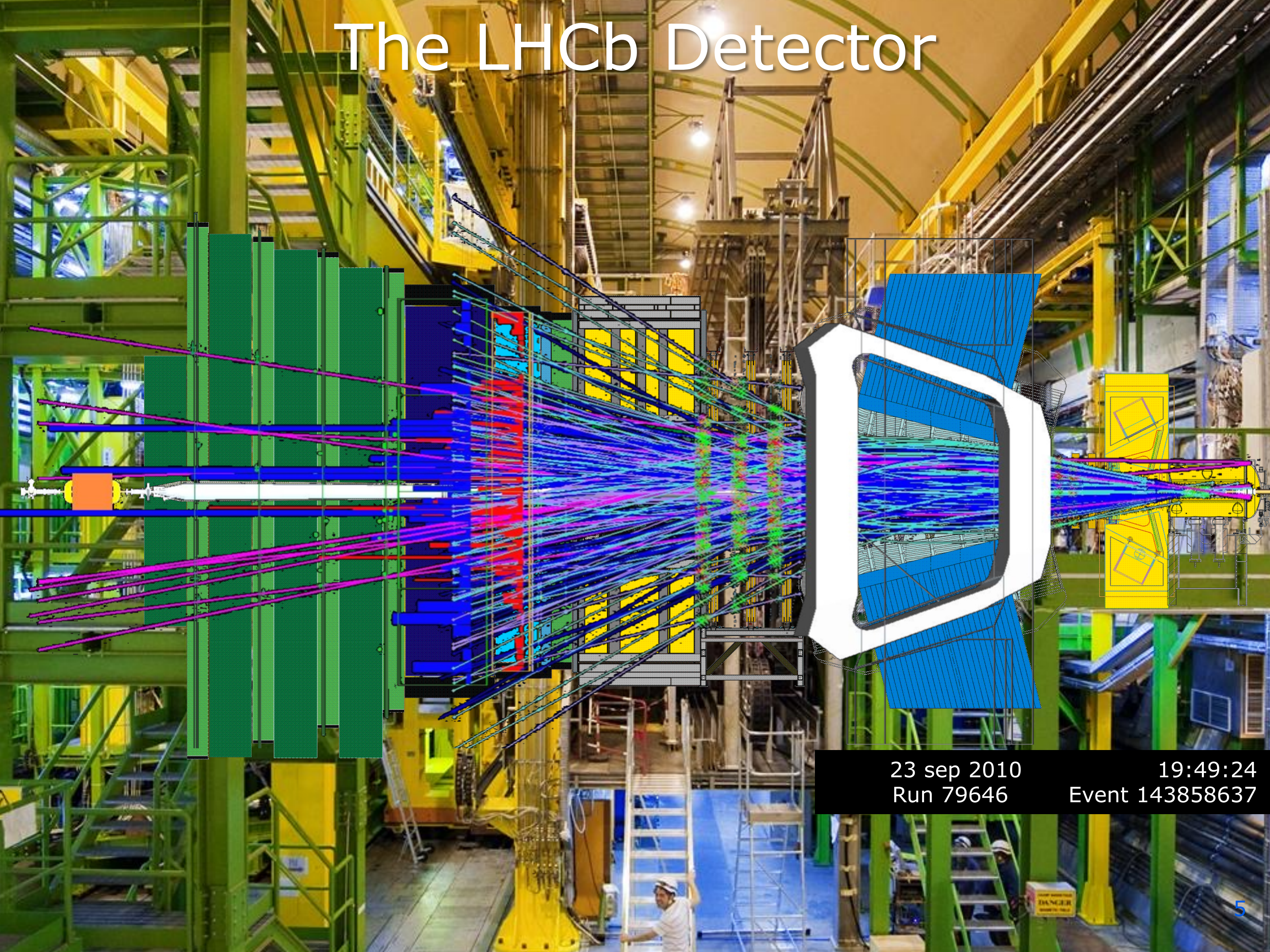
The LHCb Detector



The LHCb Detector



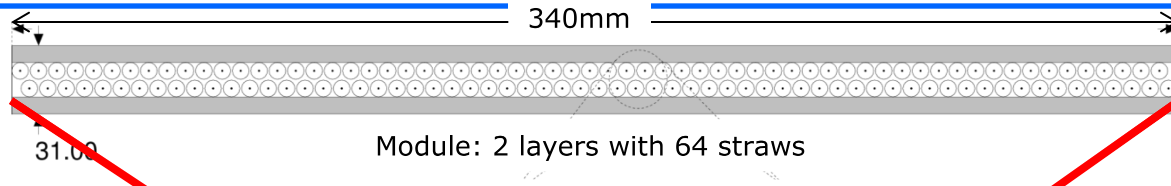
The LHCb Detector



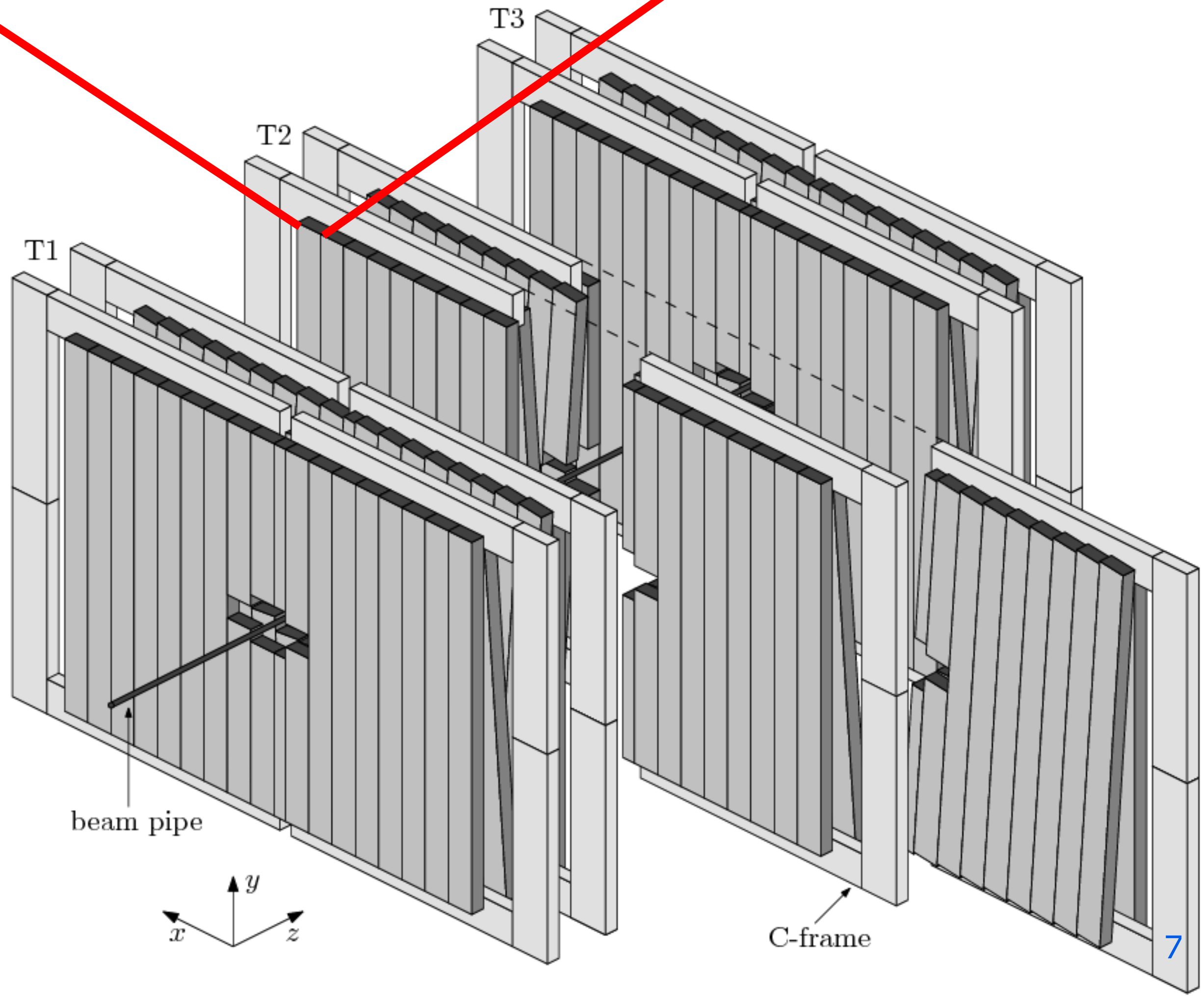
Outer Tracker

See Sebastian Bachmann, Mon 6 Nov 11:50
Performance of the LHCb Outer Tracker in Run-I and Run-II of the LHC
https://indico.cern.ch/event/1237829/contributions/5609613/

Outer Tracker



- 12 double layers
- 5 x 6 m²
- 53760 channels



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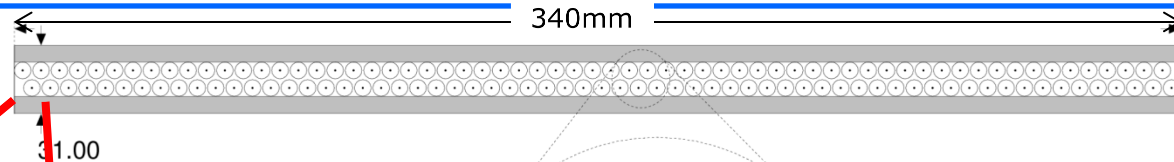
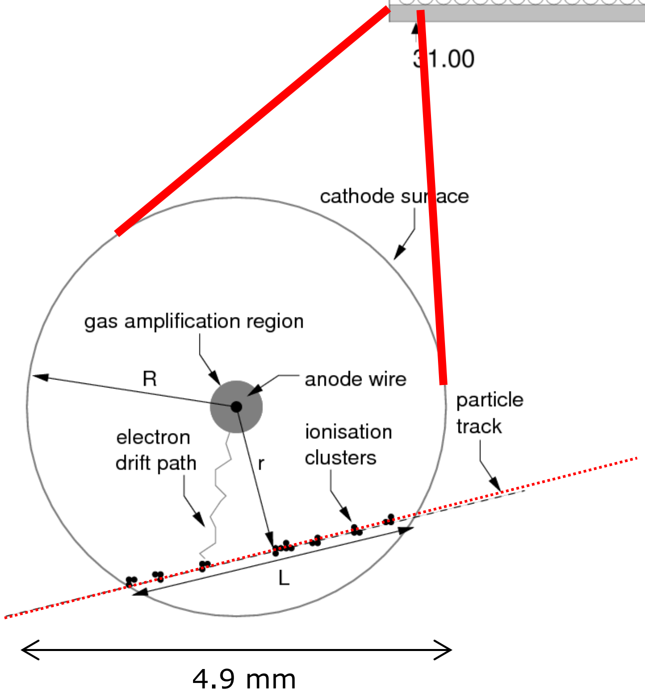
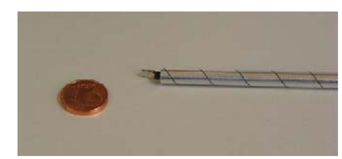
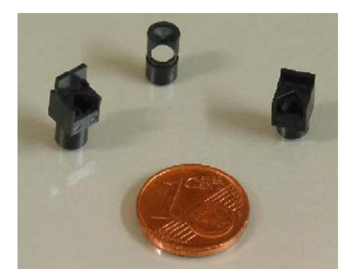




- Cathode: Kapton XC
- Anode: Gold + Tungsten (+1550 V)
- Panel: Rohacel
- Glue: Araldite Epoxy AY103
- Gas: $Ar/CO_2/O_2$: 70/28.5/1.5

+ wire locators every 80cm
to hold anode wire at center:


(b)


(c)

Careful studies of all materials, prior to construction:

S.Bachmann et al.
The straw tube technology for the LHCb outer tracking system
NIMA 535(2004)171

Outline

- LHCb and the Outer Tracker
- Ageing: the saga
- Radiation hardness
- Conslusions

A story

- 2004: start construction
- 2005: end construction
- 2005: radiation damage?
  - I. The phenomenon
  - II. The culprit
  - III. The way out
- 2008: installation in LHCb
  - IV. The performance
- 2018: end of operation
- 2023: shipment to GSI, Darmstadt

A story

GOLDEN RULES OF AGING PREVENTION

- Ultra-Pure gases
- Non-Organic Quenchers (CO_2)
- Choice of non-Outgassing Building Materials
- Non-Polymerizing Additives: Methylal, Propilic Alcohol
- Improved Cleaning Protocols
- Avoid Silicon-Containing Materials: Tubing, Sealings, ….

- Zapping: Burning Deposits with High Current on Anodes

- Addition of Compounds with Etching Properties (O_2 , CF_4)

- THE CREATION OF REACTIVE SPECIES IS ENHANCED AT HIGH VALUES OF THE ELECTRIC FIELD

Fabio Sauli – Aging Phenomena – CERN Nov 6-10, 2023

From: F. Sauli, 6 Nov 2023,
3rd Int.Conf on *Detector Stability and Aging Phenomena in Gaseous Detectors*
https://indico.cern.ch/event/1237829

- **Choice of non-Outgassing Building Materials**

- Zapping: Burning Deposits with High Current on Anodes

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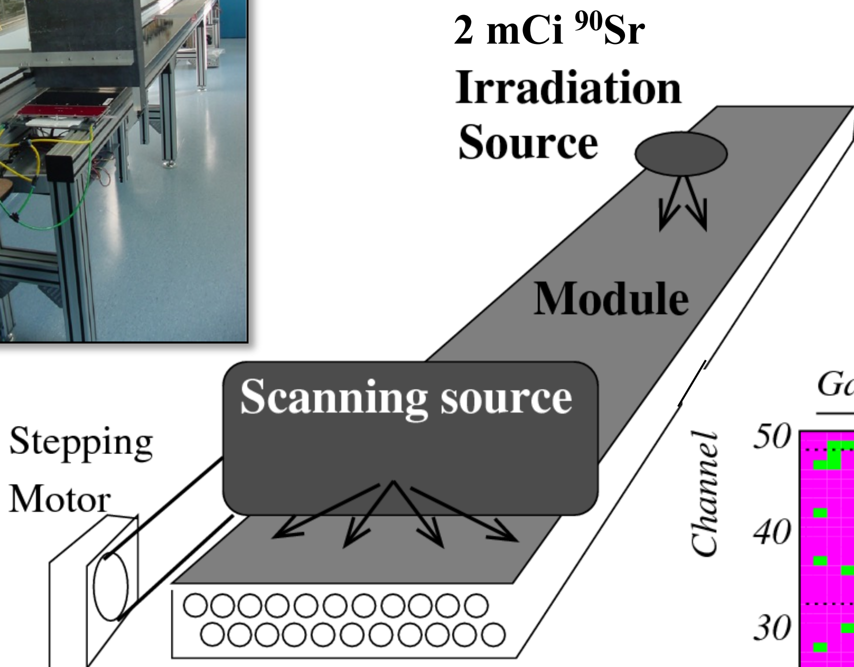
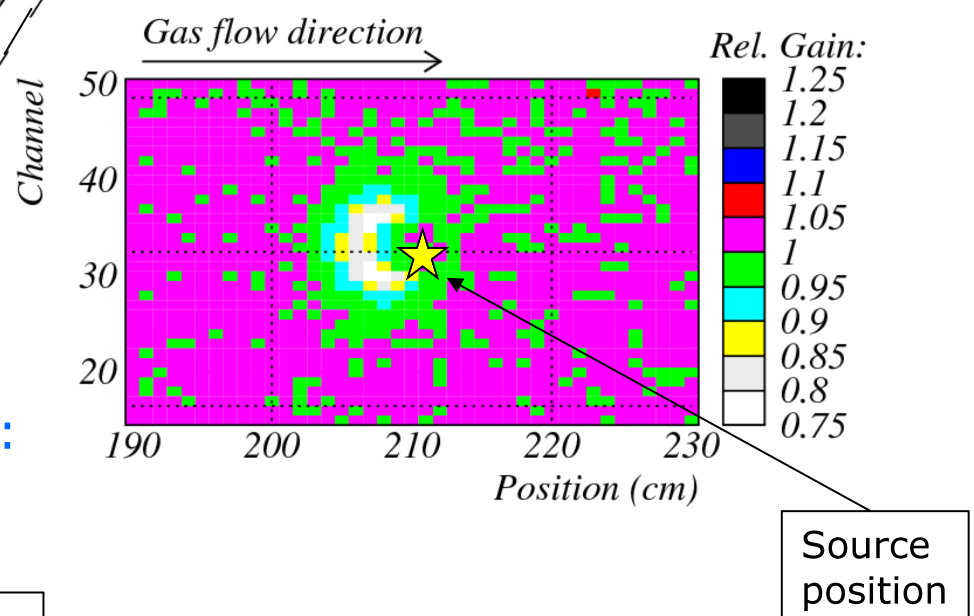
Ageing: The saga - part I (phenomenon)



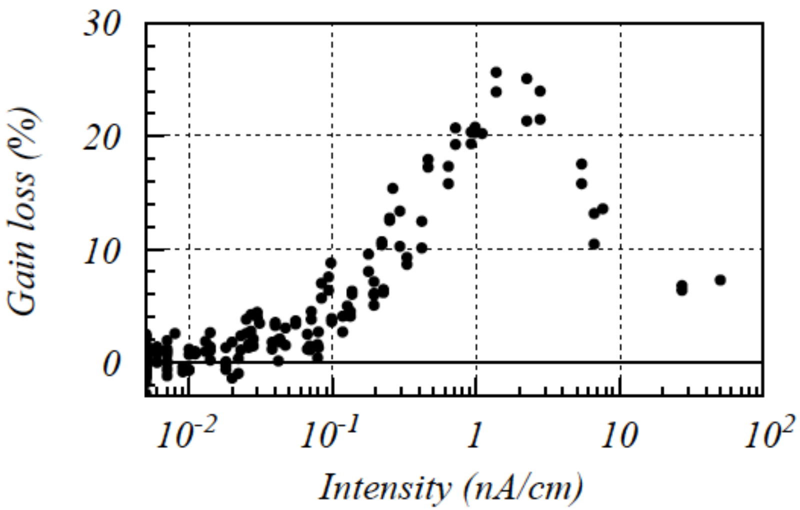
Relative gain
after/before irradiation:

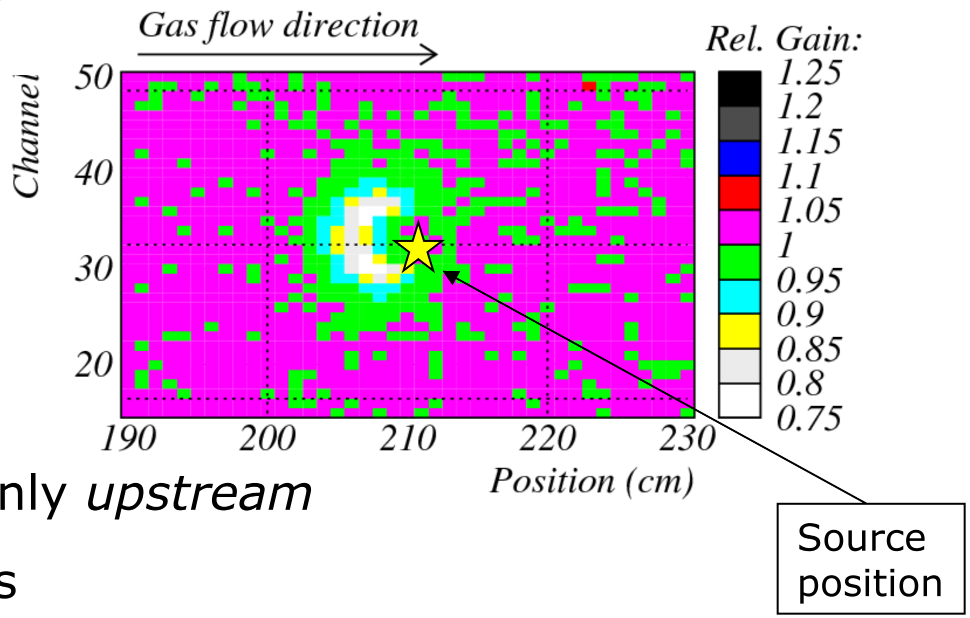


Response measured with

1) Current from ^{90}Sr source (simple)
2) Gain from ^{55}Fe pulse height (precise)

Ageing: The saga - part I (phenomenon)

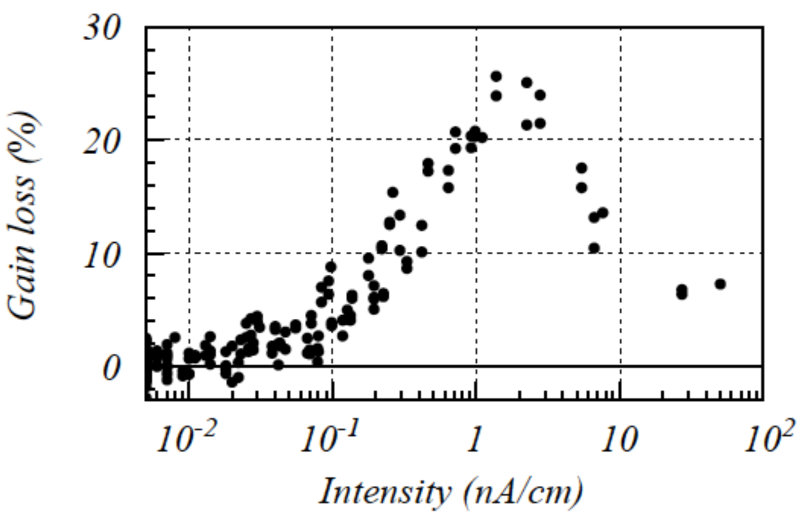


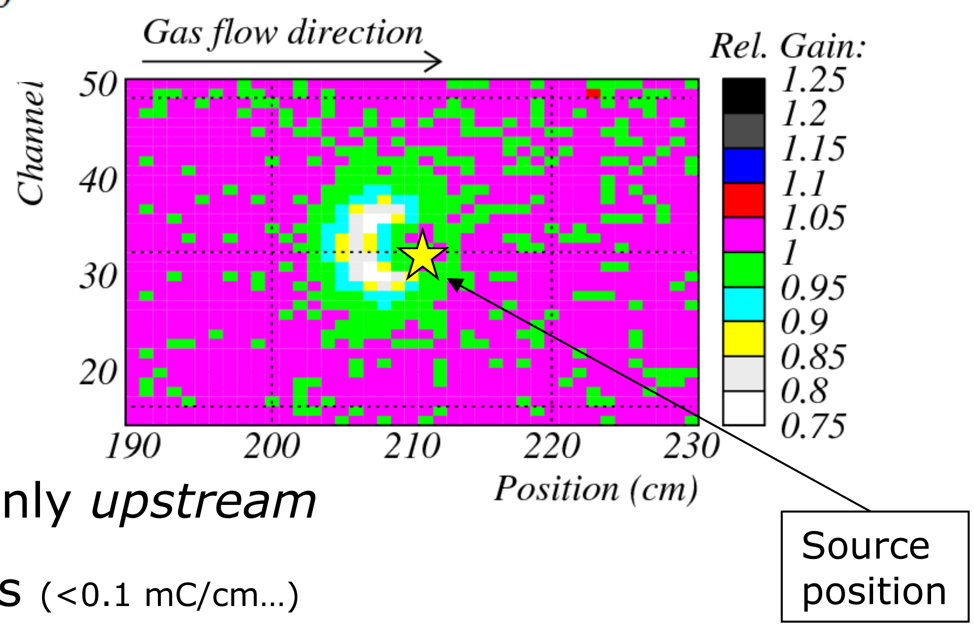


➢ **Remarkable:**

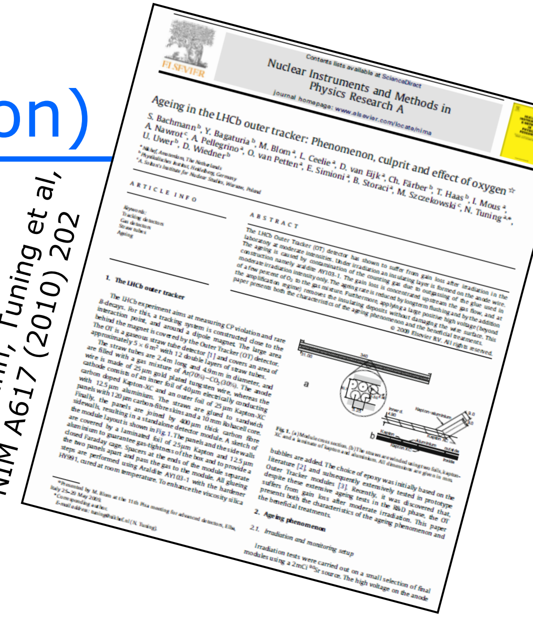
- No gain loss *under* source, only *upstream*
- Very rapid; -30% in 15 hours

Ageing: The saga - part I (phenomenon)





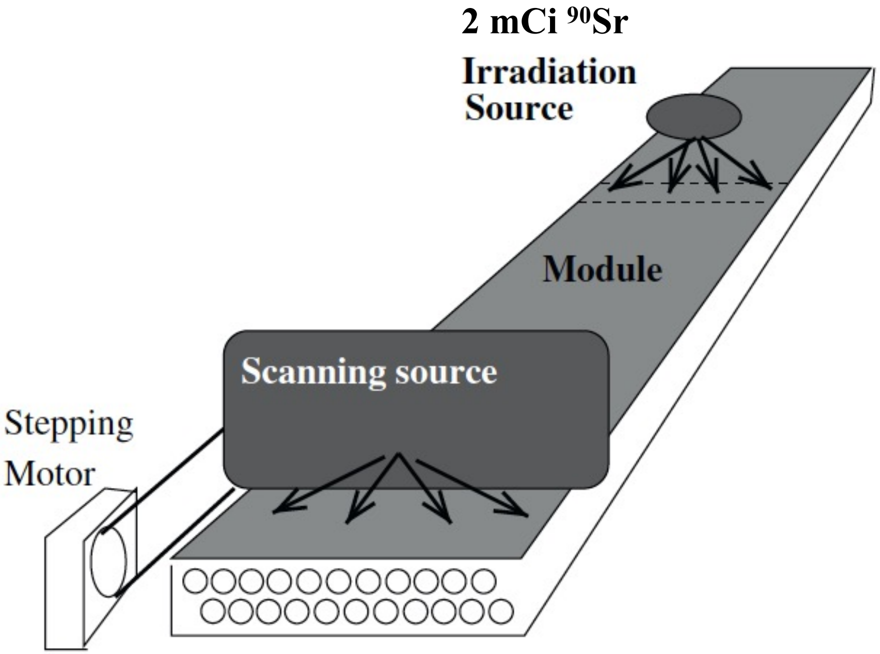
Bachmann, Tuning et al,
NIM A617 (2010) 202



- **Remarkable:**
- No gain loss *under* source, only *upstream*
- Very rapid; -30% in 15 hours (<0.1 mC/cm…)
- Not seen in R&D phase, despite extensive ageing tests

Ageing: The saga - part II (culprit)

- Constructed an openable test module without glue
- Injected different types of glue in individual straws



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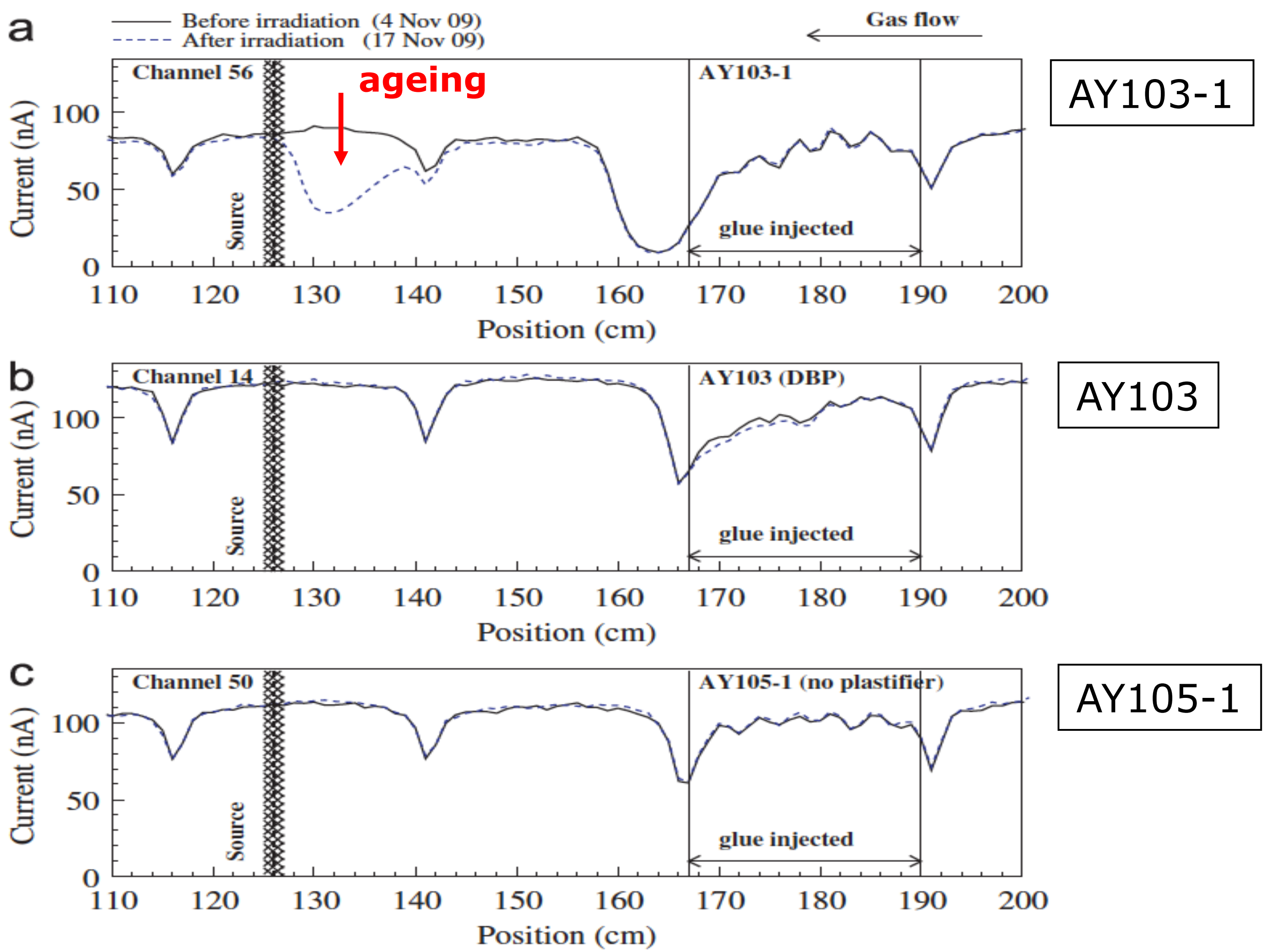
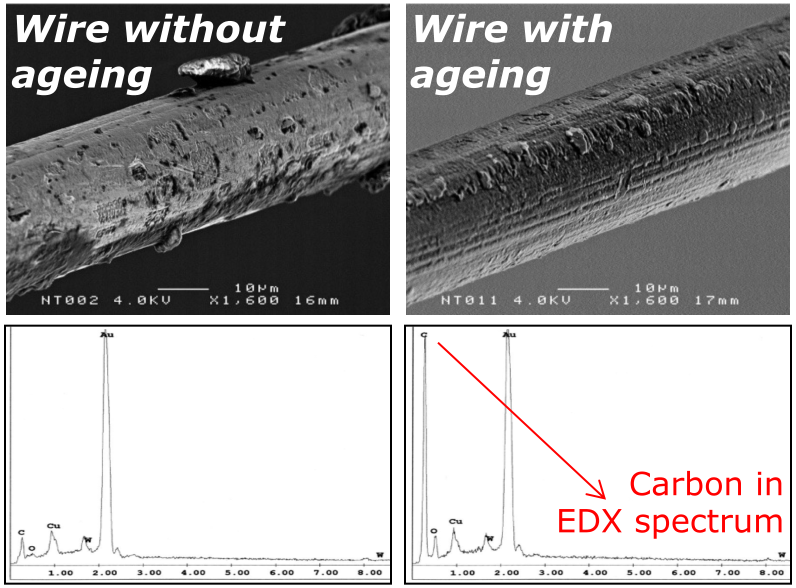


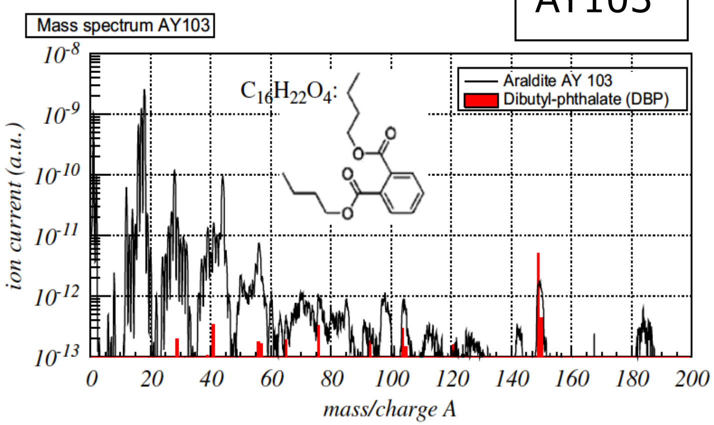
Ageing: The saga - part II (culprit)

- EDX: presence of C on wire:

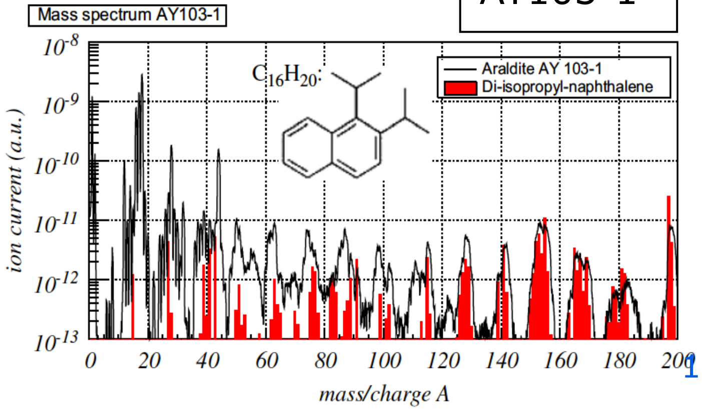


- Mass spectrometer: glue sample shows outgassing:
  - Dibutyl-phthalate
  - Di-isopropyl-naphthalene

AY103



AY103-1



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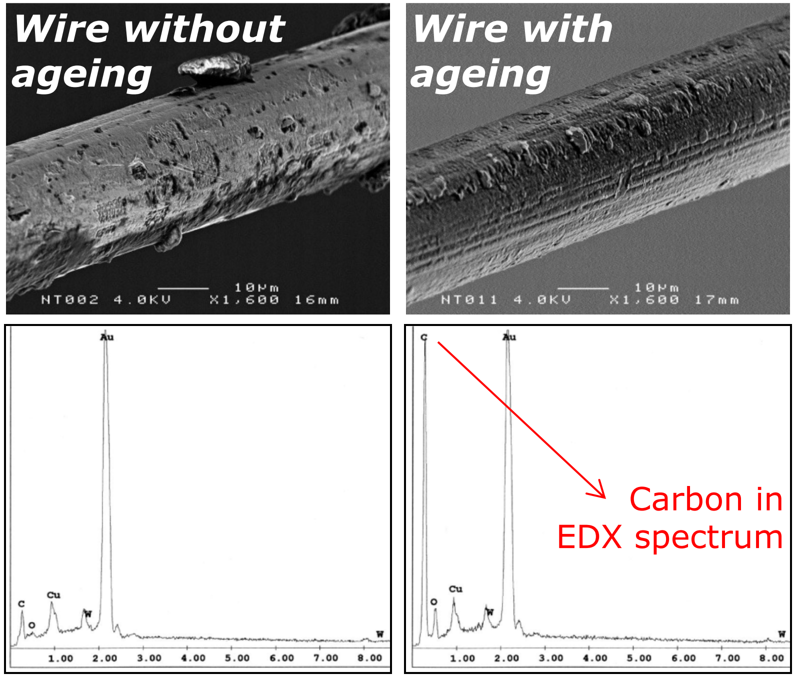
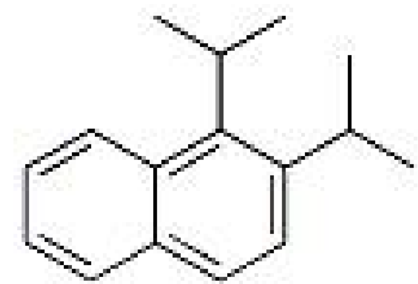


Bachmann, Tuning et al, NIM A656 (2011) 45

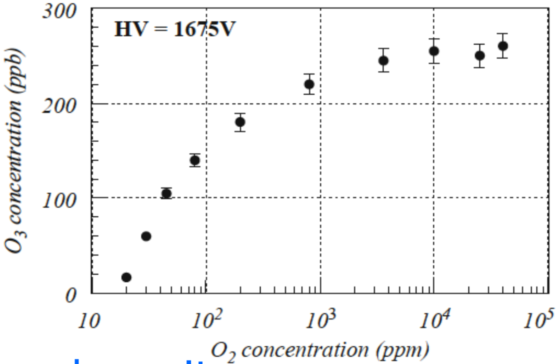
- **Cause:**
- Manufacturer changed plastifier: AY103 → AY103-1
- Culprit: di-isopropyl-naphthalene

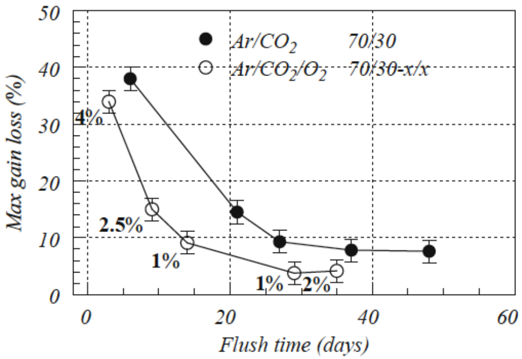


Ageing: The saga - part III (the way out)

Studied various beneficial effects:

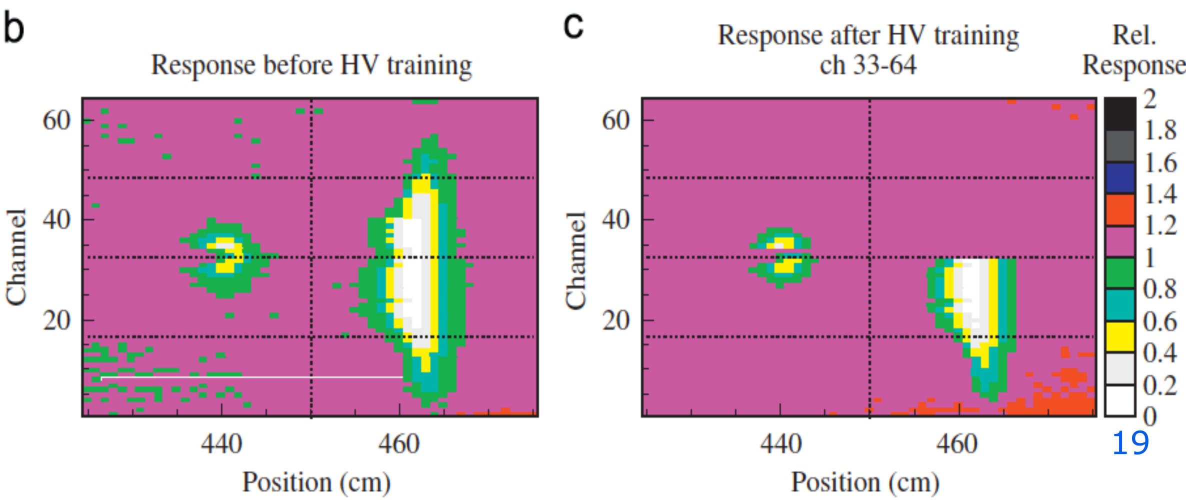
1) Heating: enhance glue outgassing
   - Gain loss shortly after glue injection is larger
   - Warming of modules to ~40 C showed reduced ageing





2) Oxygen: prevent deposits
   - Presumably formation of O3
   - O3 reacts with plastifier

3) Large currents: burn-off the deposit
   - Large dark currents (bias 1850-1950V leads to 10uA per wire):
   - Source-induced



Ageing: The saga - part III (the way out)


Nuclear Instruments and Methods in Physics Research A

Ageing in the LHCb outer tracker: Aromatic hydrocarbons and wire cleaning

Bachmann, Tuning et al,
NIM A656 (2011) 45

➢ **Actions:**

1) Heated all modules prior to LHC operation

2) Added 1.5% Oxygen (note that drift distance is only 2.5mm)

➢ **In the pocket:**

3) HV training procedure

From: F. Sauli, 6 Nov 2023,
3rd Int.Conf on *Detector Stability and Aging Phenomena in Gaseous Detectors*
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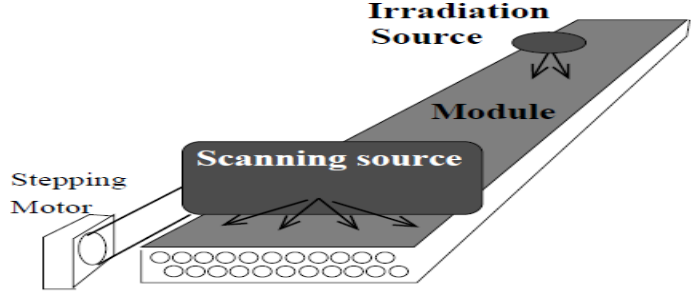
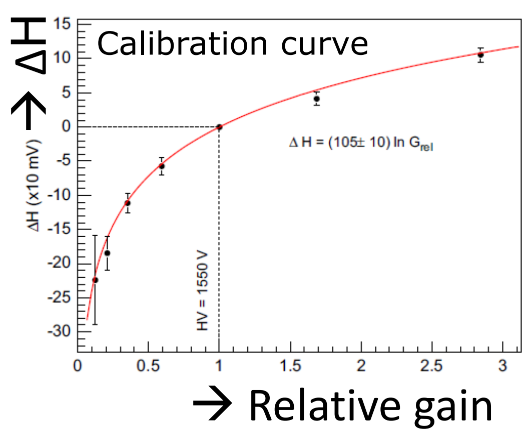
Ageing: The saga - part IV (performance)

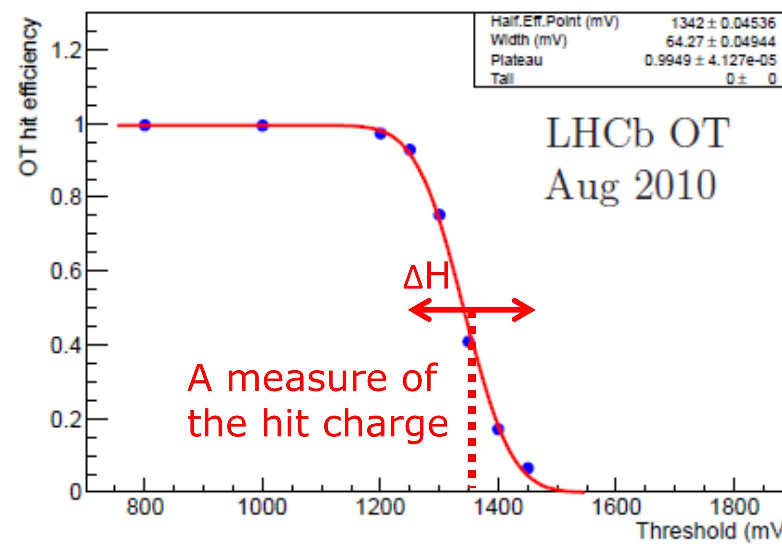
Two methods to monitor gain loss

1) During technical stops
   - ^{90}Sr scans to measure detector response

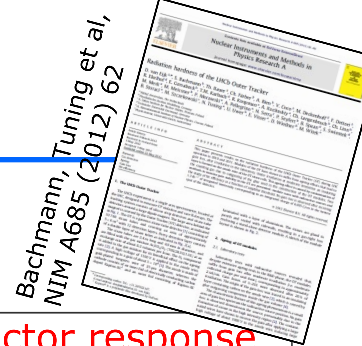


2) During LHC operation
   - Measure hit efficiency with tracks, at increasing amplifier threshold





Ageing: The saga - part IV (performance)



Two methods to monitor gain loss

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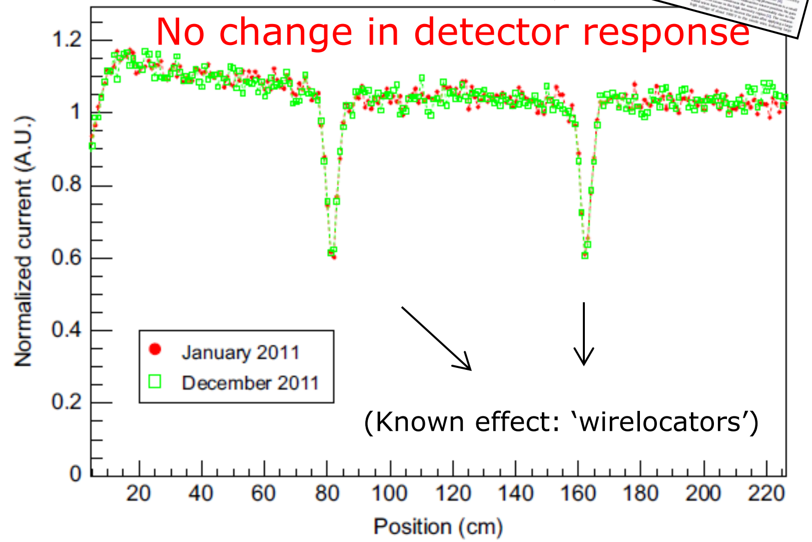
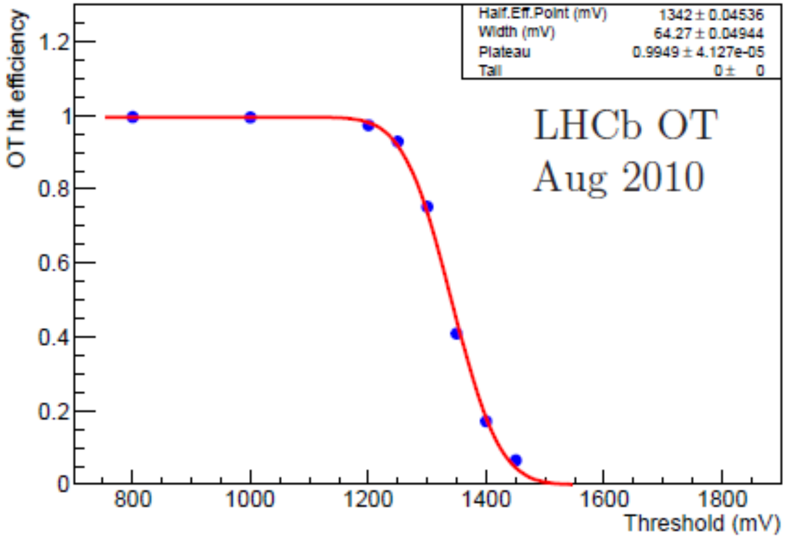
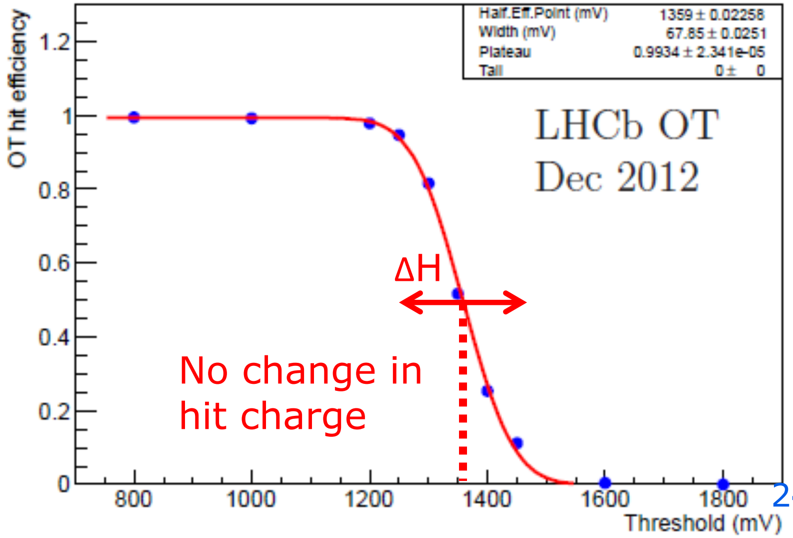
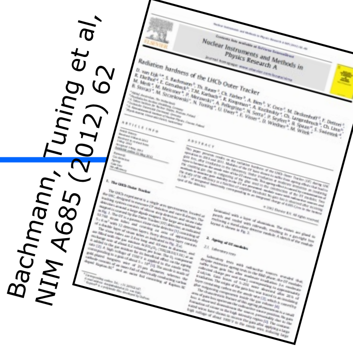


2) During LHC operation

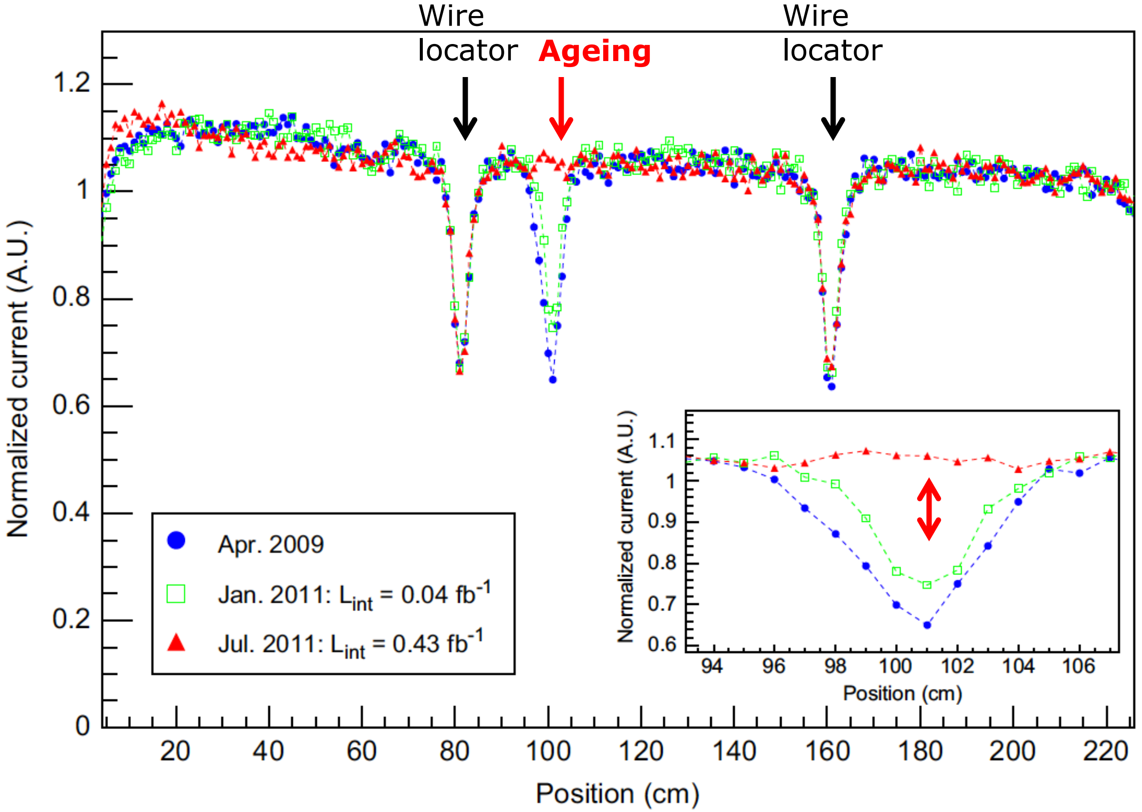




Ageing: The saga - part IV (performance)



- No signs of ageing in OT lifetime
  - Accumulated up to 0.4 C/cm in hottest region
- The LHC even had curing effect:



LHCb: Outer Tracker not dismantled

- Outer Tracker:
  - Gaseous Straw Tube tracker from Run 1/2
- OT arrived at GSI, Germany
- Experiments at FAIR interested:
  - some OT parts will undergo partitioning to provide tracking detectors
  - other OT parts (without change) to be interleaved with dense material to perform as a muon range system
  - some parts will be used for physics outreach projects
  - use at current beam lines at GSI
  - use at future beamlines at FAIR,

    currently under construction

➤ Showcase for sustainable detector re-use and resource aware developments in HEP

Conclusions

- Outer Tracker performed superbly in run I+II
  - Few dead or noisy channels
  - High hit efficiency (>99%) and resolution (~200 μm)
  - No irradiation effects observed (~0.4 C/cm in hottest region)
    - We were lucky

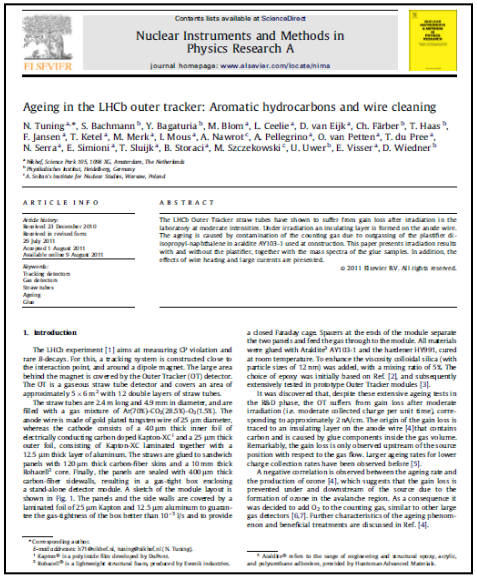
Ageing in the LHCb outer tracker: Phenomenon, culprit and effect of oxygen


Nuclear Instruments and Methods in Physics Research A

Ageing in the LHCb outer tracker: Phenomenon, culprit and effect of oxygen

Bachmann, Tuning et al,
NIM A617 (2010) 202

Ageing in the LHCb outer tracker: Aromatic hydrocarbons & wire cleaning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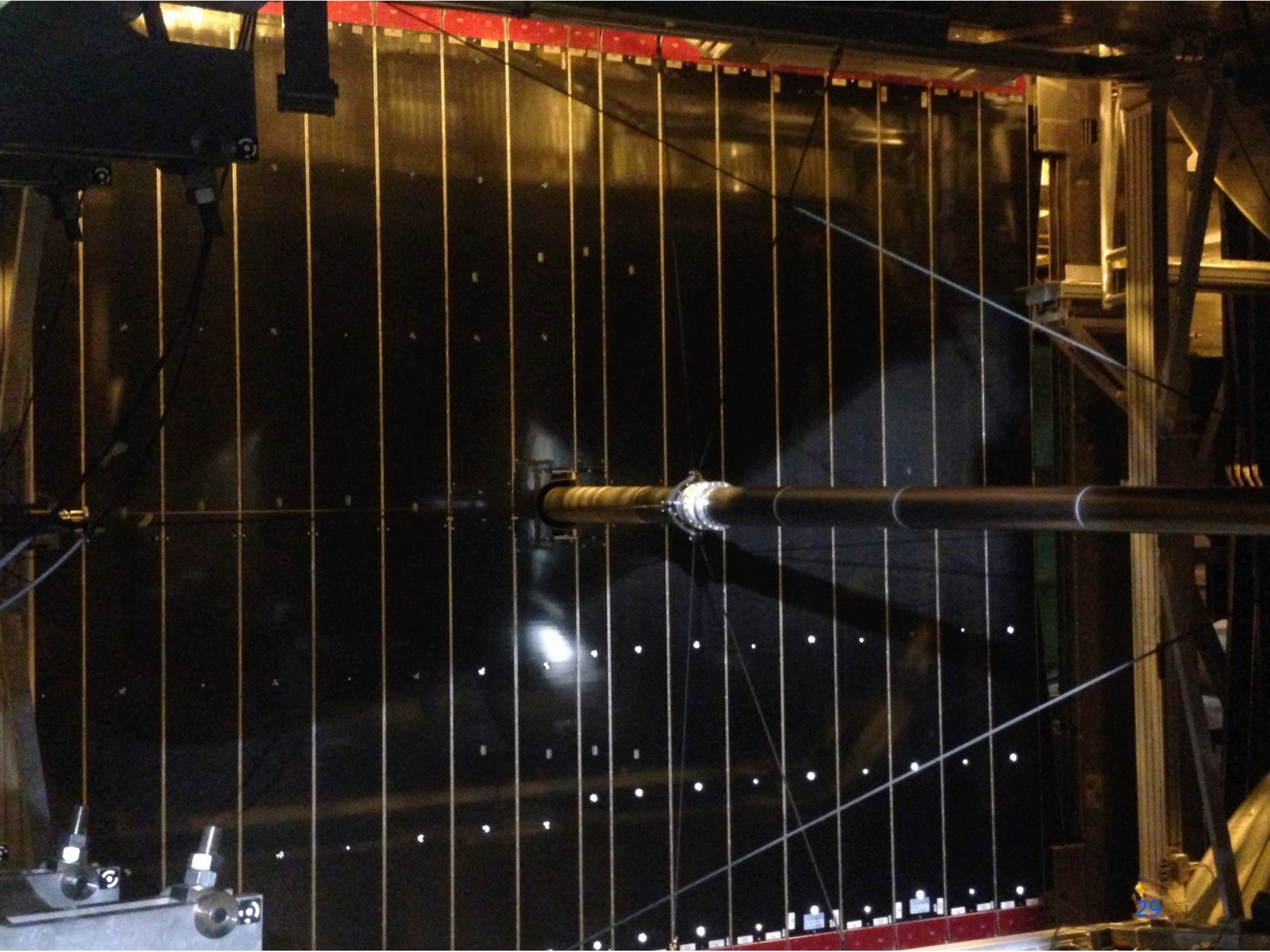
Radiation hardness of the LHCb Outer Tracker

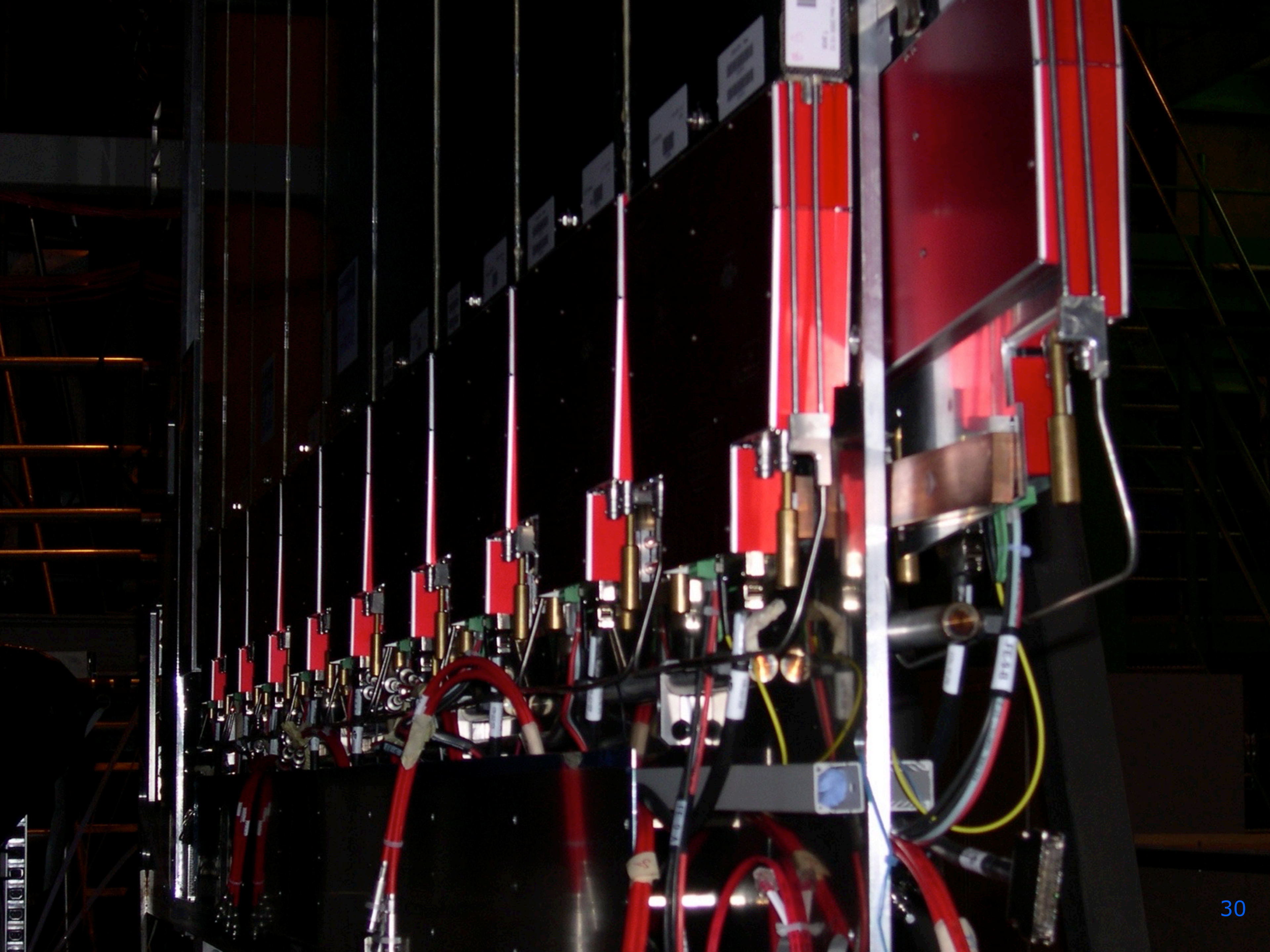

Nuclear Instruments and Methods in Physics Research A

Radiation hardness of the LHCb Outer Tracker

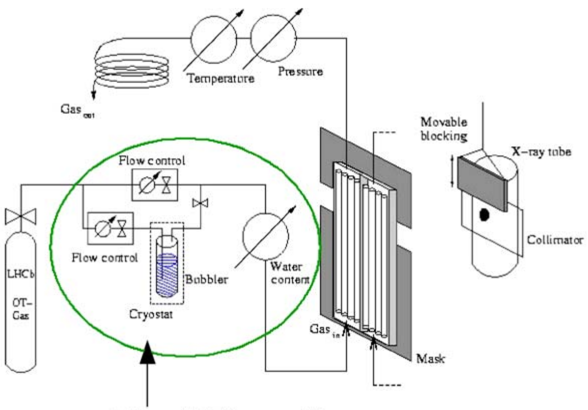
Bachmann, Tuning et al,
NIM A685 (2012) 62

Backup





Ageing studies prior to construction



mixing of drift gas with water
& monitoring of the humidity

Operational parameters:

water content:	<50ppm, 500ppm, 3500ppm
gas flow:	2-4 vol/h (190-380 ml/h)
gas gain:	28000 (550 kHz) / 40000 (low rate)
X-ray intensity:	500-600 kHz/cm
Currents:	800-1000 nA/cm
irrad. region:	4 cm
wire:	Au-plated tungsten wire
	(Ø 25µm, 6% Au, by California Fine Wire)
accu. Charge:	2 C/cm ± 0,3 C/cm (10 years LHCb)

Fig. 3. Set-up and operational parameters used for the irradiation tests.

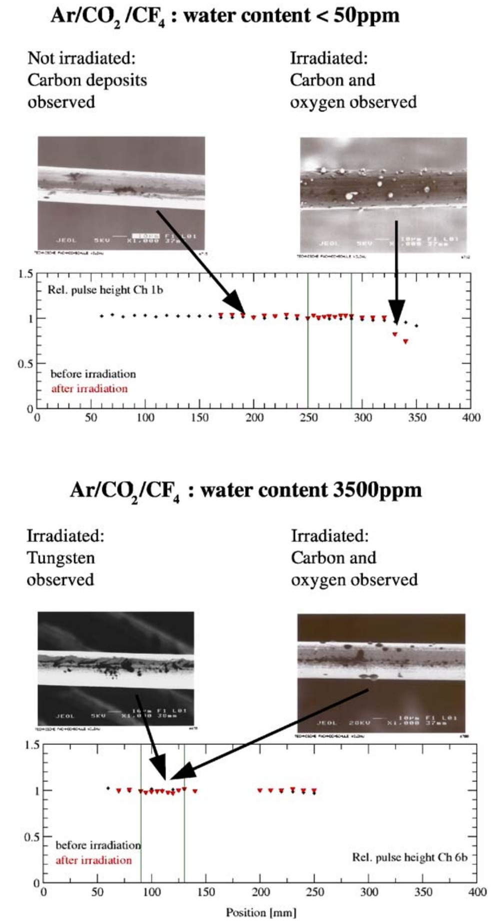


Fig. 4. Selected results from the irradiation tests in $Ar/CO_2/CF_4$ (75/10/15).

- Irradiated to 2 C/cm
- Decision to change from $Ar/CO_2/CF_4$ to Ar/CO_2

Table 1
Summary of measurements

Ar/CO_2 (70/30)	$Ar/CO_2/CF_4$ (75/10/15)
Carbon deposits observed for all levels of water content, but no gain variations in dry gas.	Carbon deposits observed for all levels of water content.
	Gain variations at $\leqslant 50$ ppm and 500 ppm.
For wet gases 'classical aging' in irradiated regions, i.e. deposits of C and O and gain drops up to ~30%.	At $\leqslant 50$ ppm and 500 ppm: gain drop and deposits in non-irradiated sections.
No indications for wire etching.	At 3500 ppm: deposits of C and O in irradiated section but no gain drop, tungsten from wire observed: hint for wire etching.

Careful studies of all materials, prior to construction:

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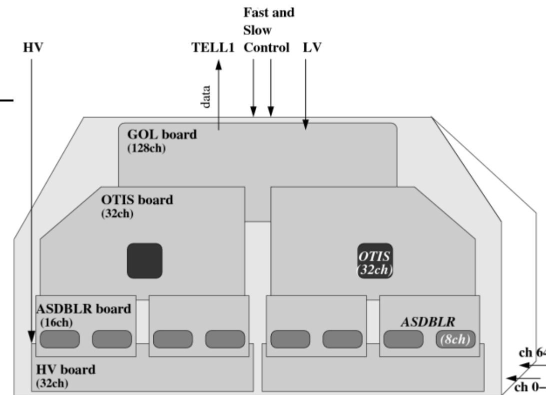
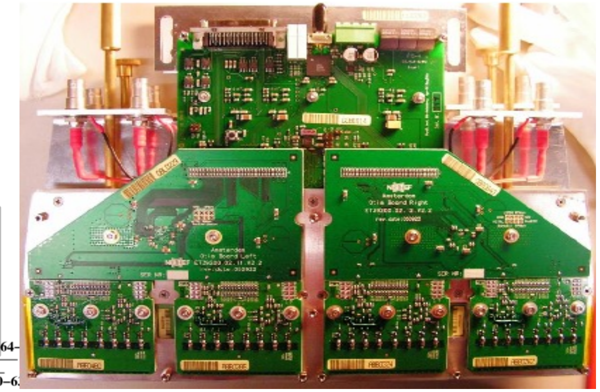
OT Performance in LHC Run I - Readout

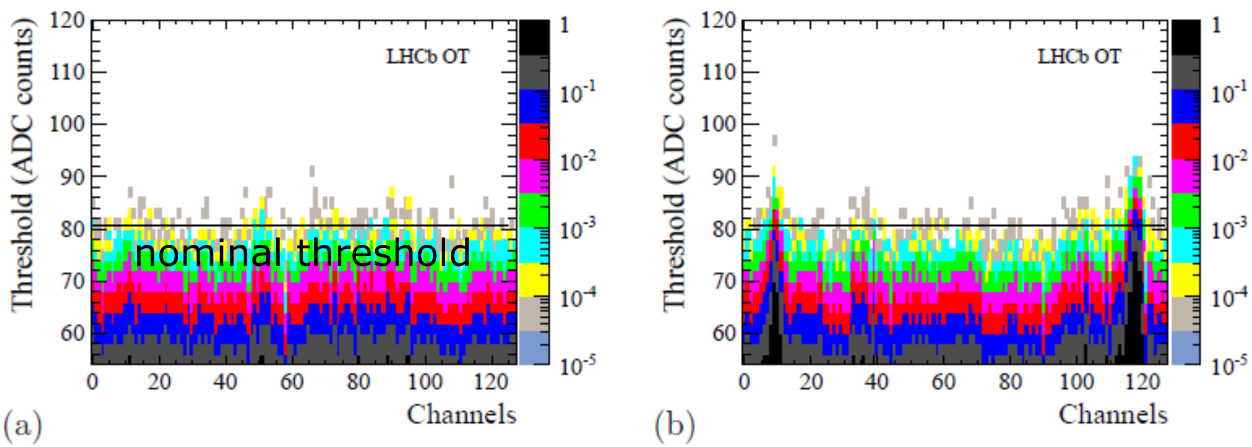
- <u>Gas gain</u>: ~ 5×10^4
- <u>Analog signal</u>: ~ 10^6 e^-
- <u>ASD</u>: Ampl, Shape, Discr.
- <u>TDC</u>: 0.4 ns stepsize
- <u>Pipeline</u>: 160 BX deep (= 4 μs)
- <u>GOL</u>: Upon L0 trigger, readout 3 BX





Detector module
2 x 64 straws

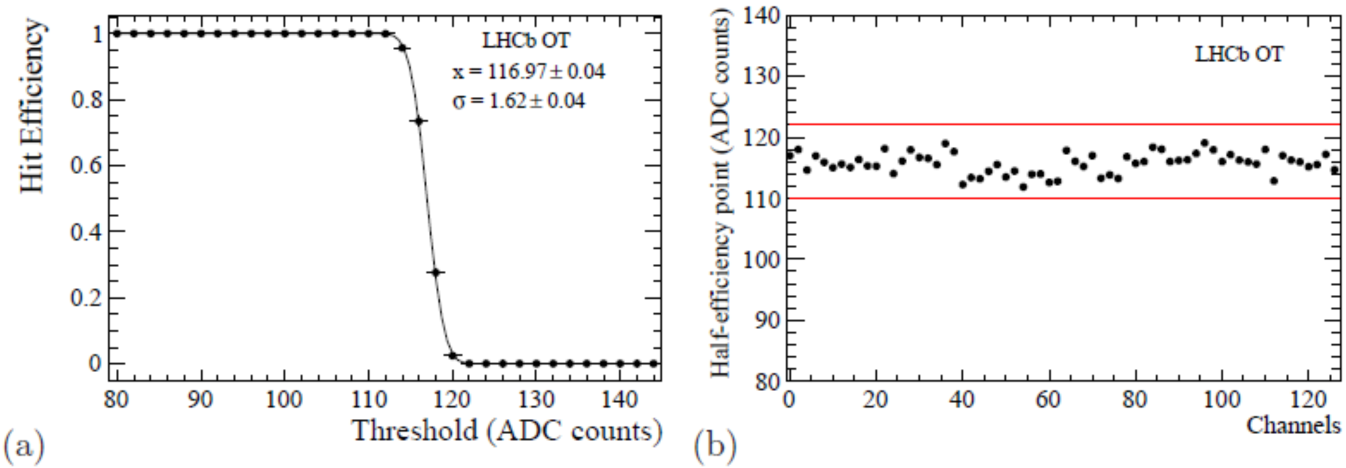
Example noisy module:



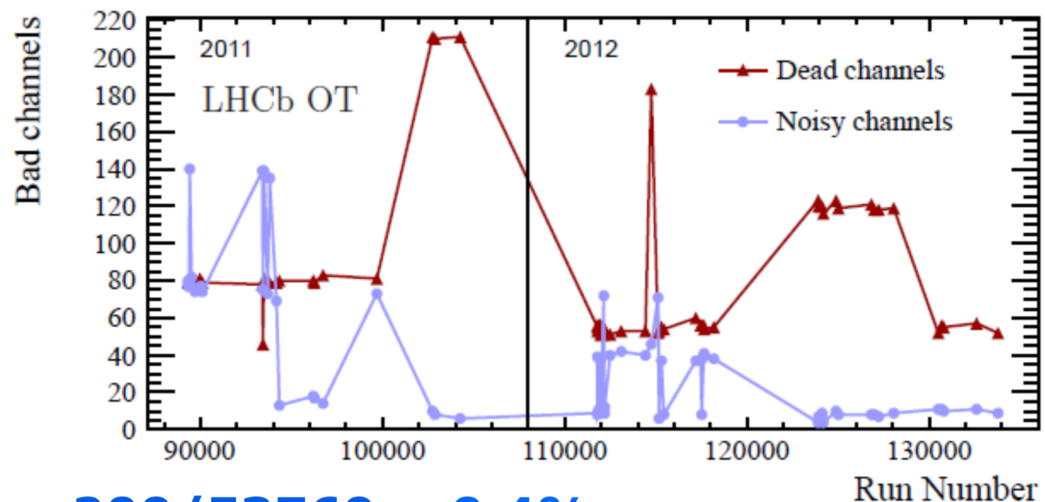
➢ **Noise level ~ 10^{-4}**

OT Performance in LHC Run I – Dead channels

- <u>During data taking</u>: use test pulses



- <u>Offline</u>: find channels too few/many hits

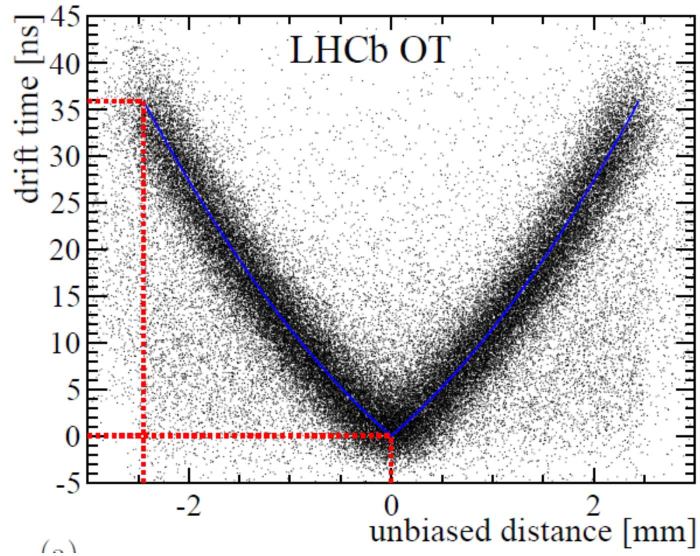


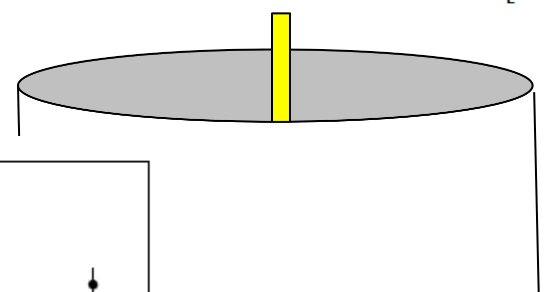
➢ **Noise/Dead channels: ~ 200/53760 = 0.4%**

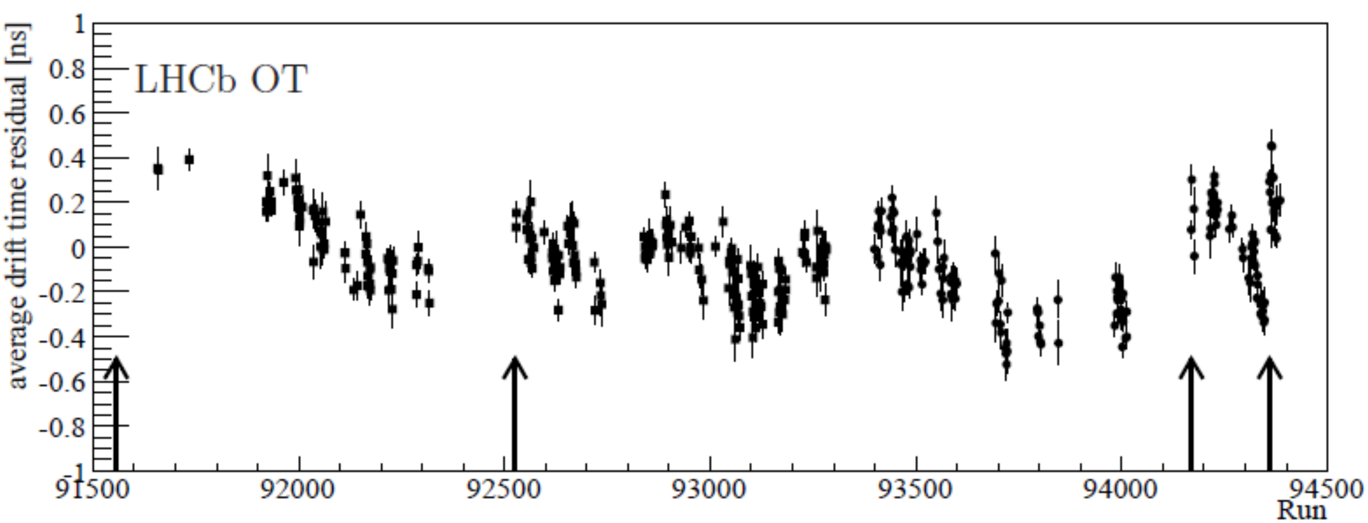
OT Performance in LHC Run I – Calibration

- Time calibration very stable
- Performed ~ 4x per year

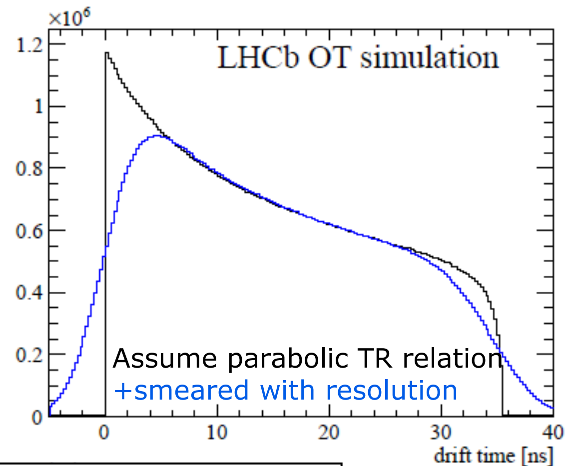
$$t_{\mathrm{drift}}(r) = 20.5\,\mathrm{ns} \cdot \frac{|r|}{R} + 14.85\,\mathrm{ns} \cdot \frac{r^2}{R^2}$$

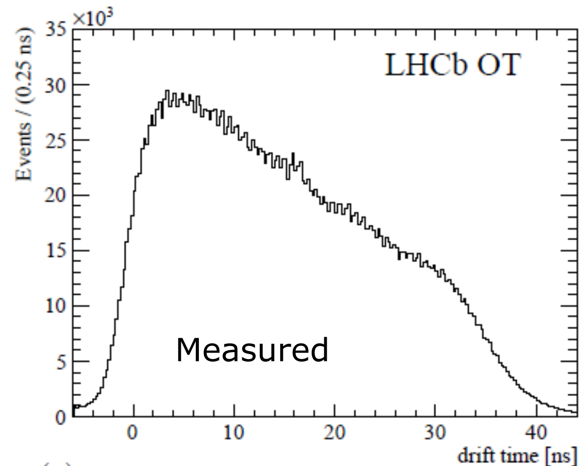






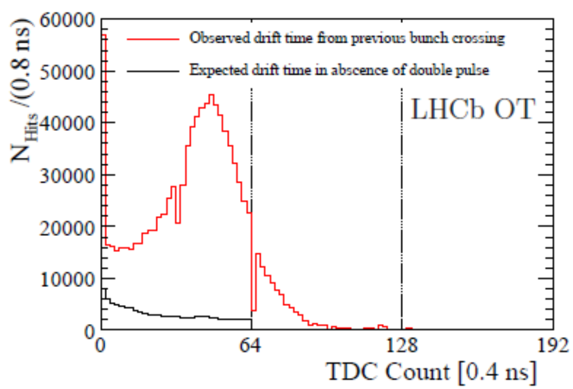
OT Performance in LHC Run I – Drift time spectrum

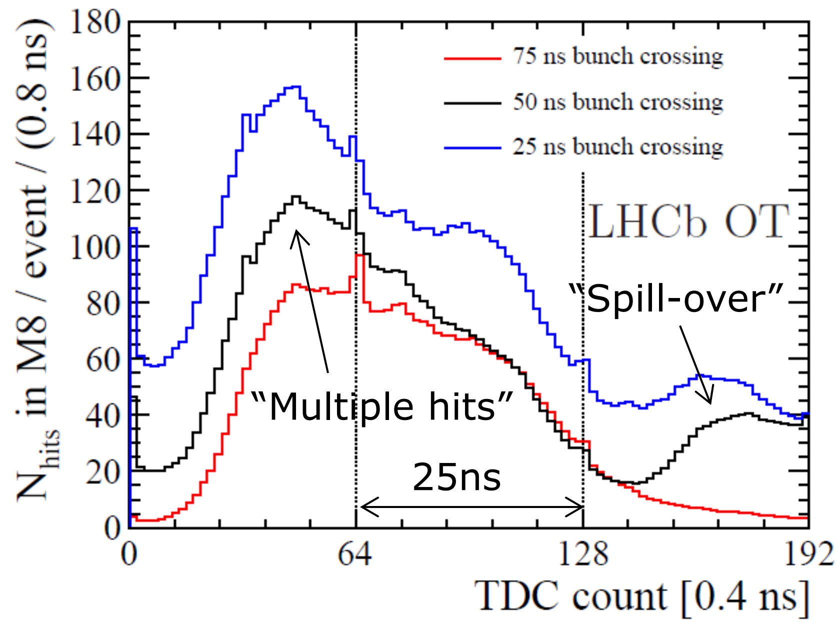




(c)

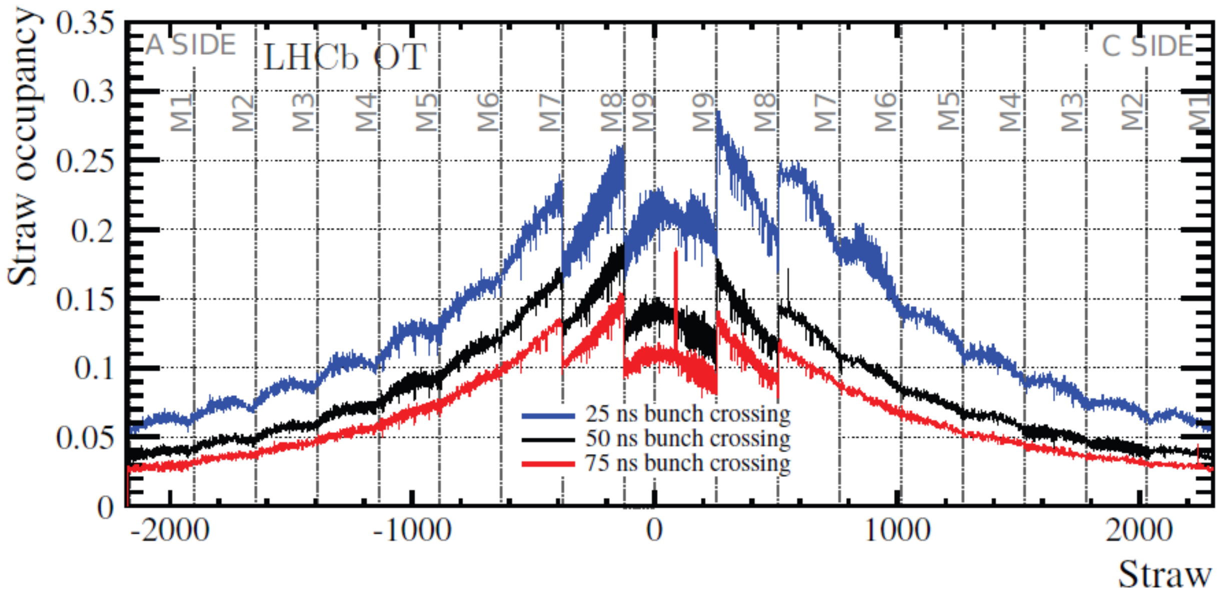
- Max. drift time ~35 ns
- Max. measured time ~50 ns
- Extra hits from:
  - "Spill-over hits"
  - "Multiple hits"

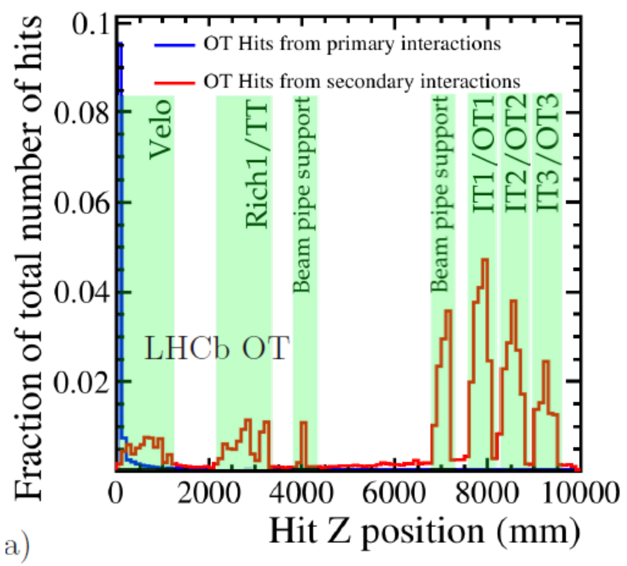


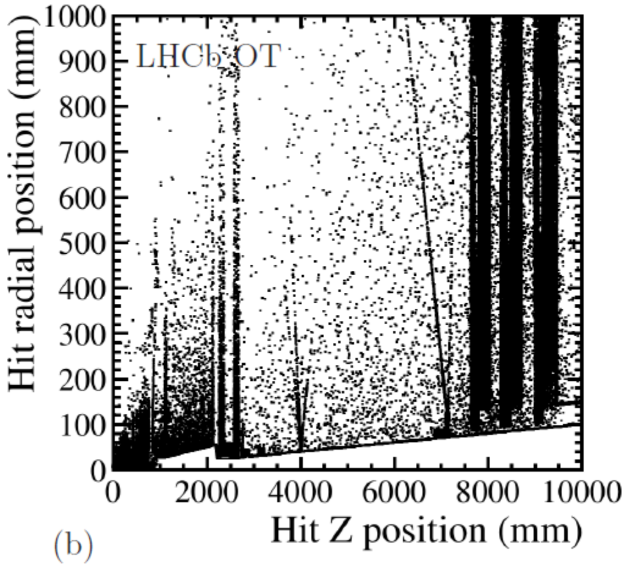


OT Performance in LHC Run I – Occupancy

- Occupancy: 3% – 15%
- Large fraction from secondary interactions

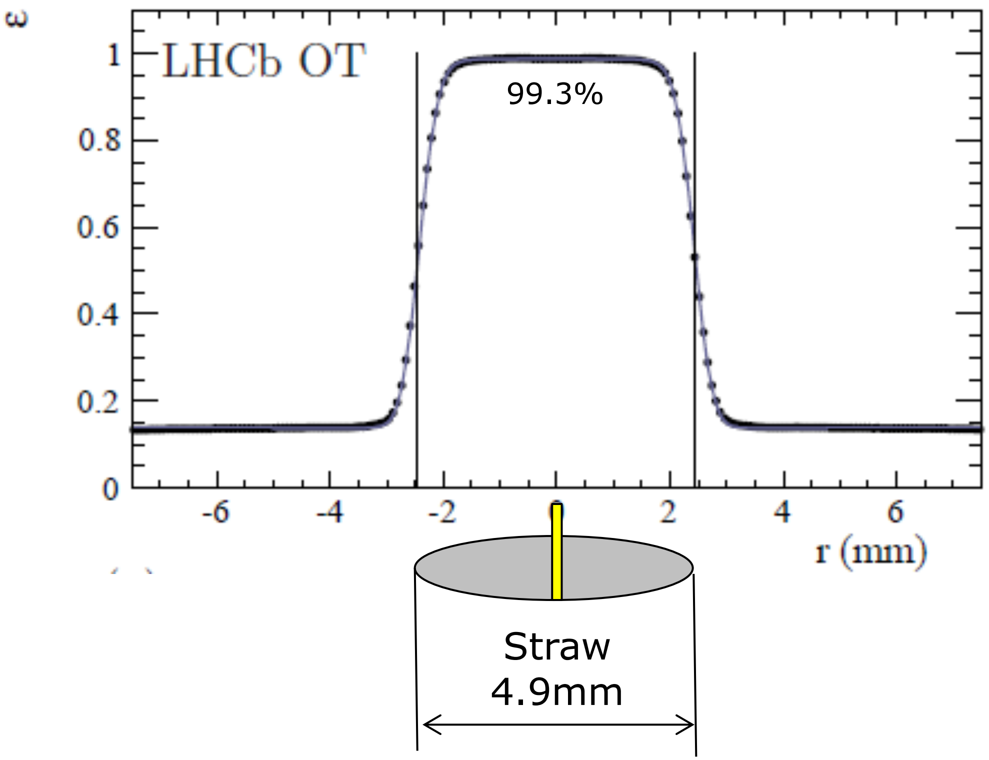


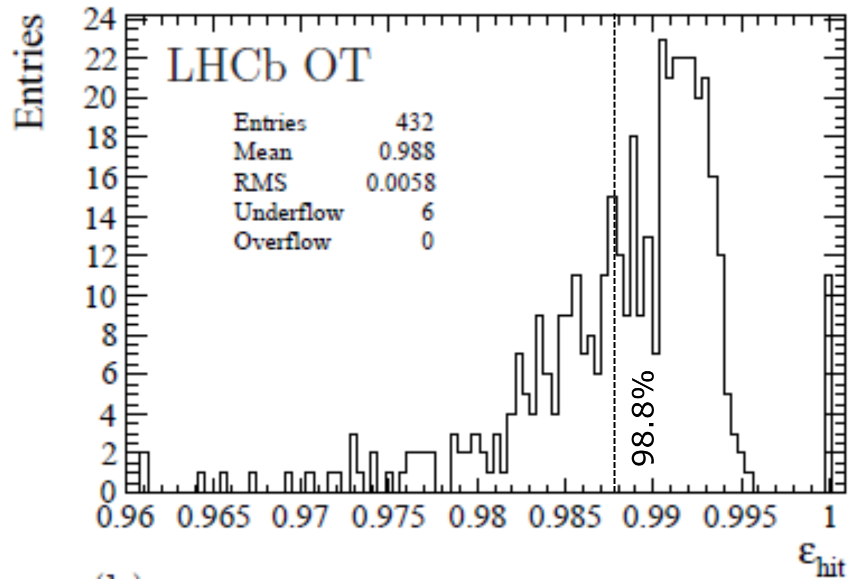




OT Performance in LHC Run I – Efficiency

- Efficiency to detect hit in center of cell |r|<1.25mm: ~ **99.3%**
- Average efficiency per module: ~ **98.8%**

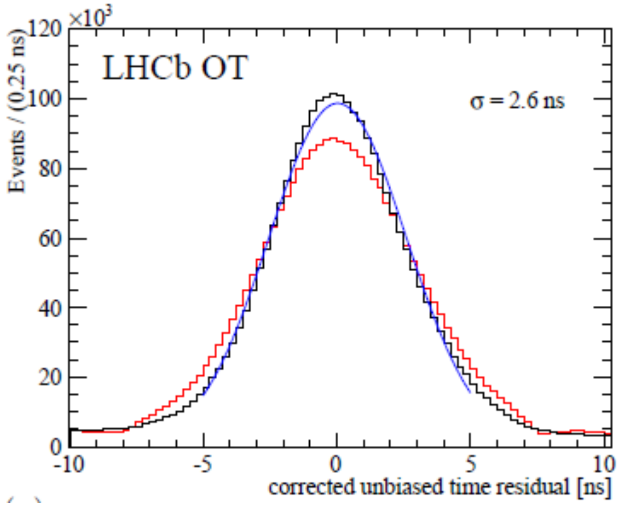


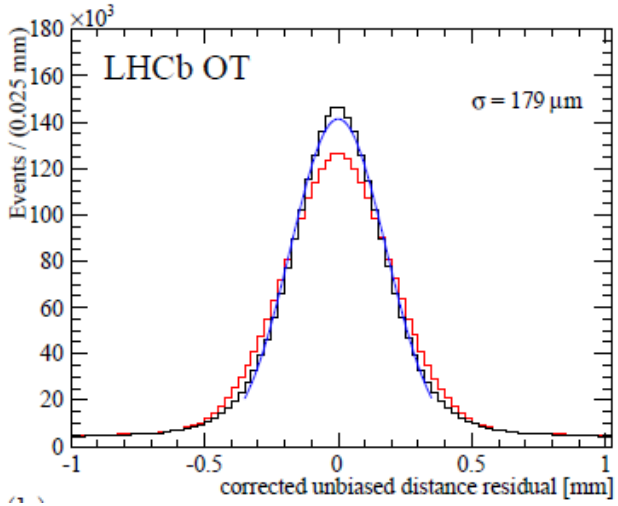


➢ **Single hit efficiency |r|<1.25mm: ~ 99.3%**

OT Performance in LHC Run I – Alignment/Resolution

- <u>Design specification: 200 μm</u>
- Straws accurately positioned in module ±50 μm
- Module hung with accuracy of ±50 μm (→ are modules straight?)
- Frames positioned within ±1 mm
- Optical survey ±0.2 mm
- Final alignment with tracks

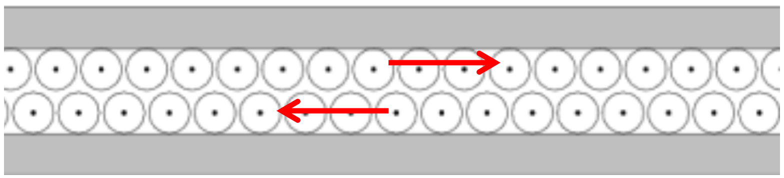


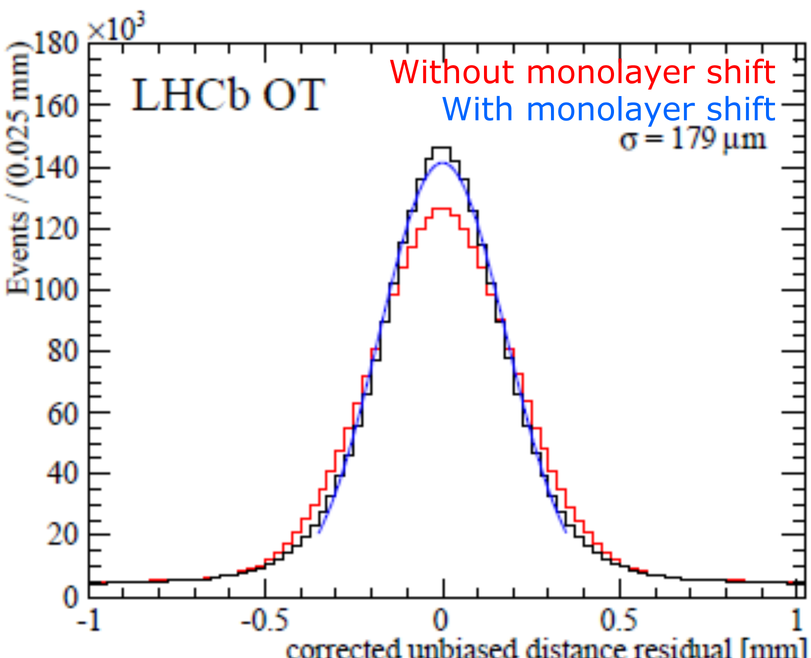


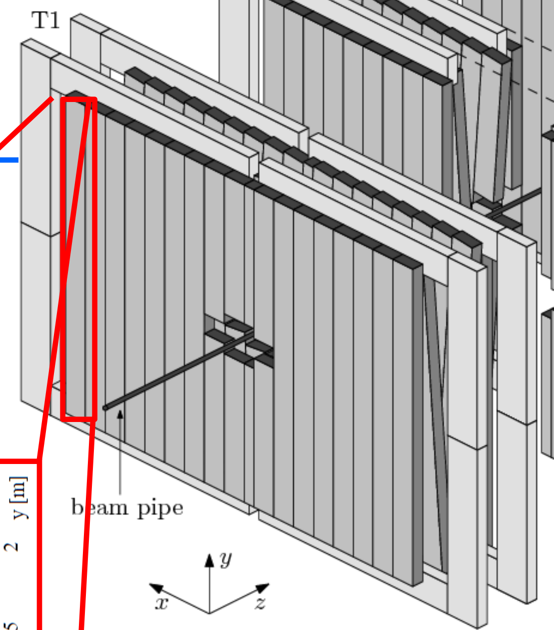
- **Internal alignment of mono-layers within a module improves resolution <u>210 → 180 μm</u>**

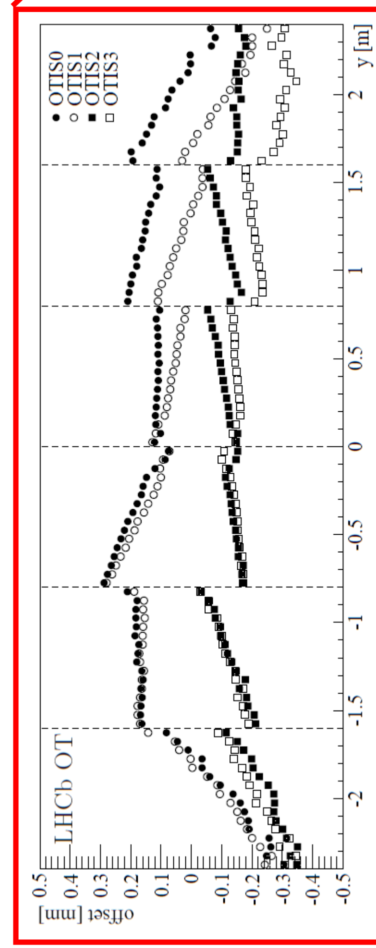
Internal module alignment

- Recently improved alignment
- Relative shift of monolayers
- ➢ Resolution 210 → 179 μm







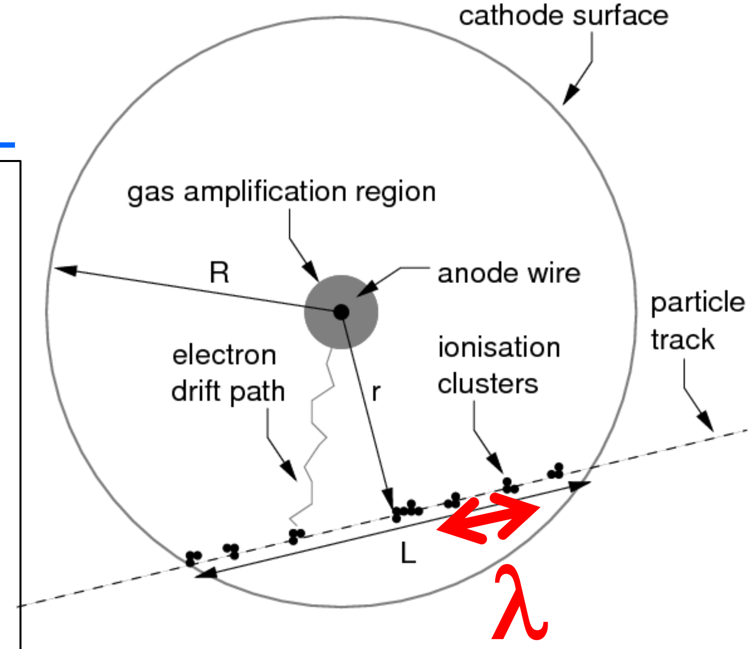


Ionization length

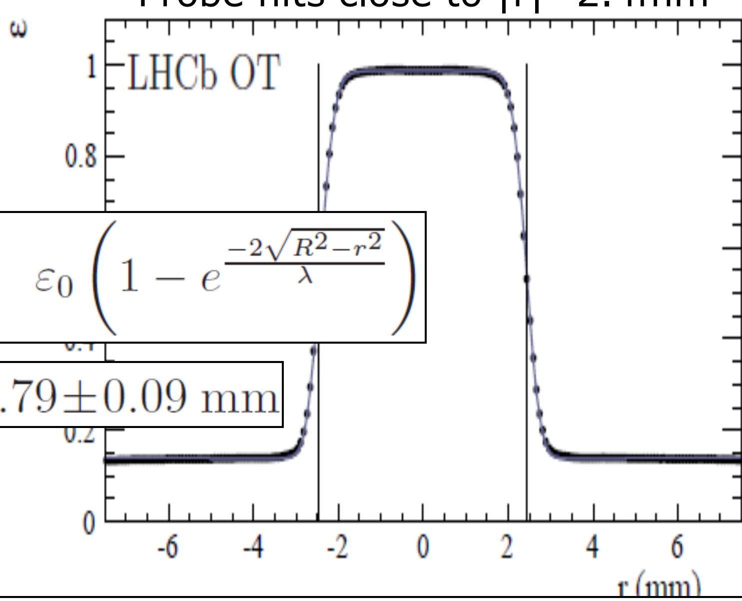
- Ionization length λ:

  average distance between clusters

- Measured *effective* λ in two ways:
  1) Efficiency profile: probes large |r|
  2) Drift time distribution: probes small |r|
  - Disentangle effect of absorbtion



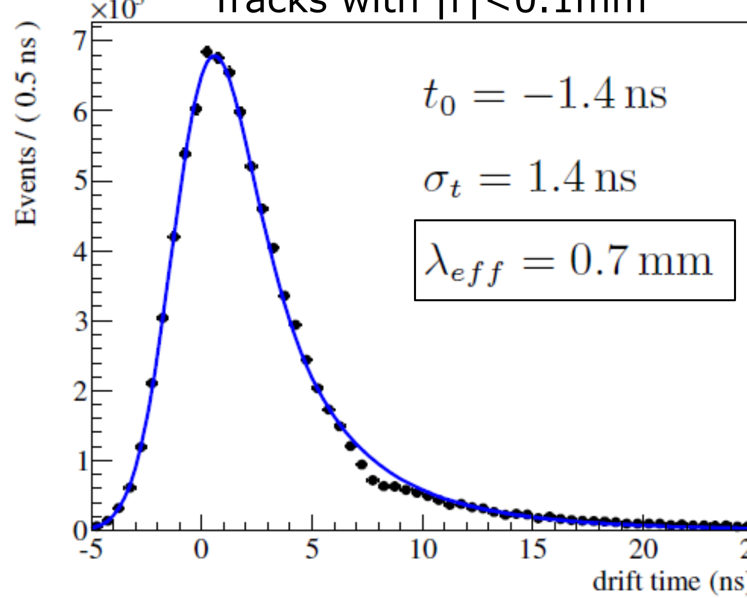
Probe hits close to |r|=2.4mm



$$\varepsilon(r) = \varepsilon_0\left(1 - e^{\frac{-2\sqrt{R^2-r^2}}{\lambda}}\right)$$

$$\langle\lambda\rangle = 0.79\pm0.09\ \mathrm{mm}$$

Tracks with |r|<0.1mm



$$t_0 = -1.4\ \mathrm{ns}$$

$$\sigma_t = 1.4\ \mathrm{ns}$$

$$\lambda_{eff} = 0.7\ \mathrm{mm}$$

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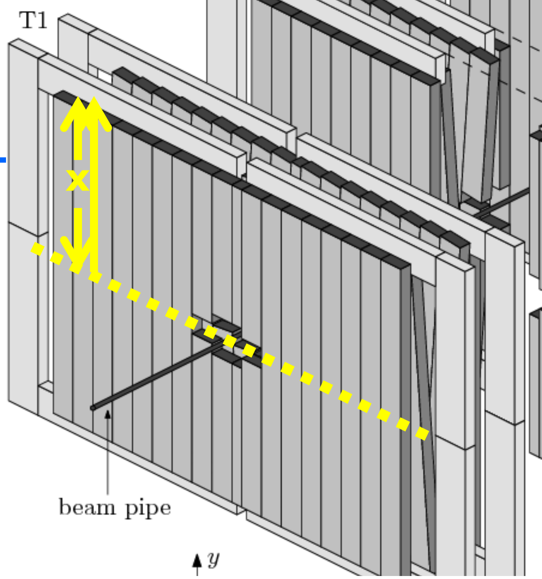
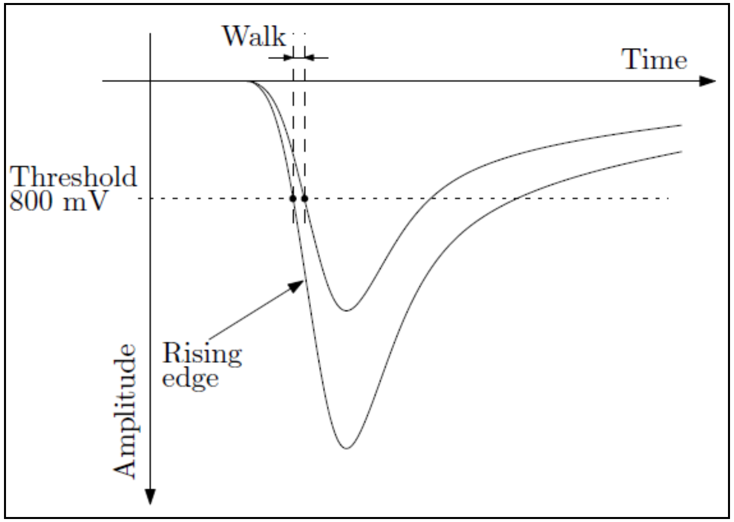
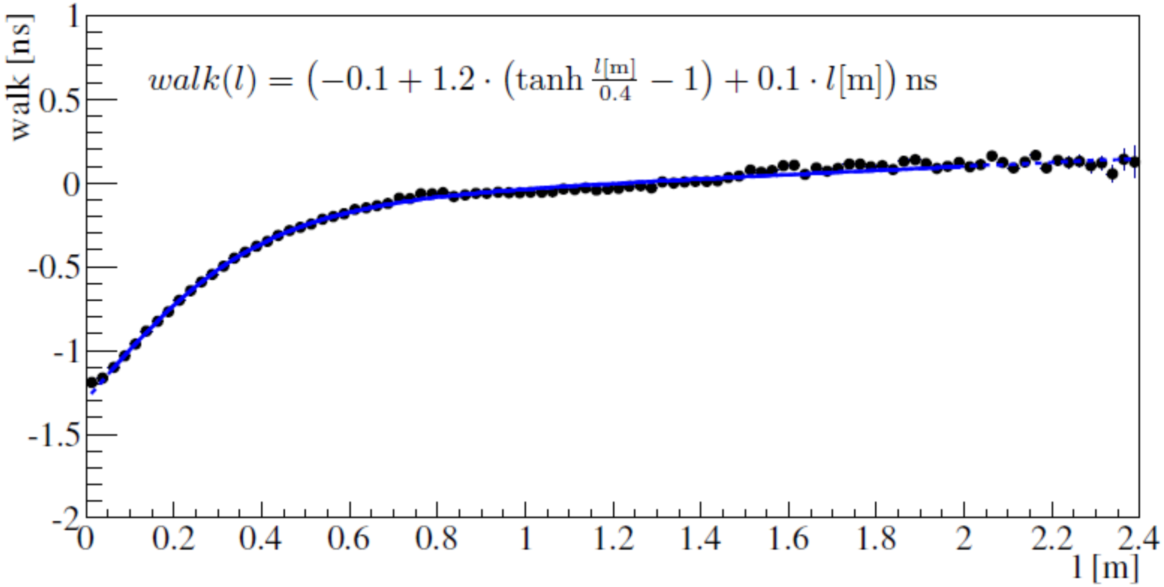
- **λ_{eff} 2x larger than nominal; not due to absorbtion**

Signal reflections; walk correction

- Signal is reflected at center
- Hits close to center, get larger amplitude
- Larger amplitude, earlier time: ***"walk"***







➢ **Time correction as function of vertical position**