
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)

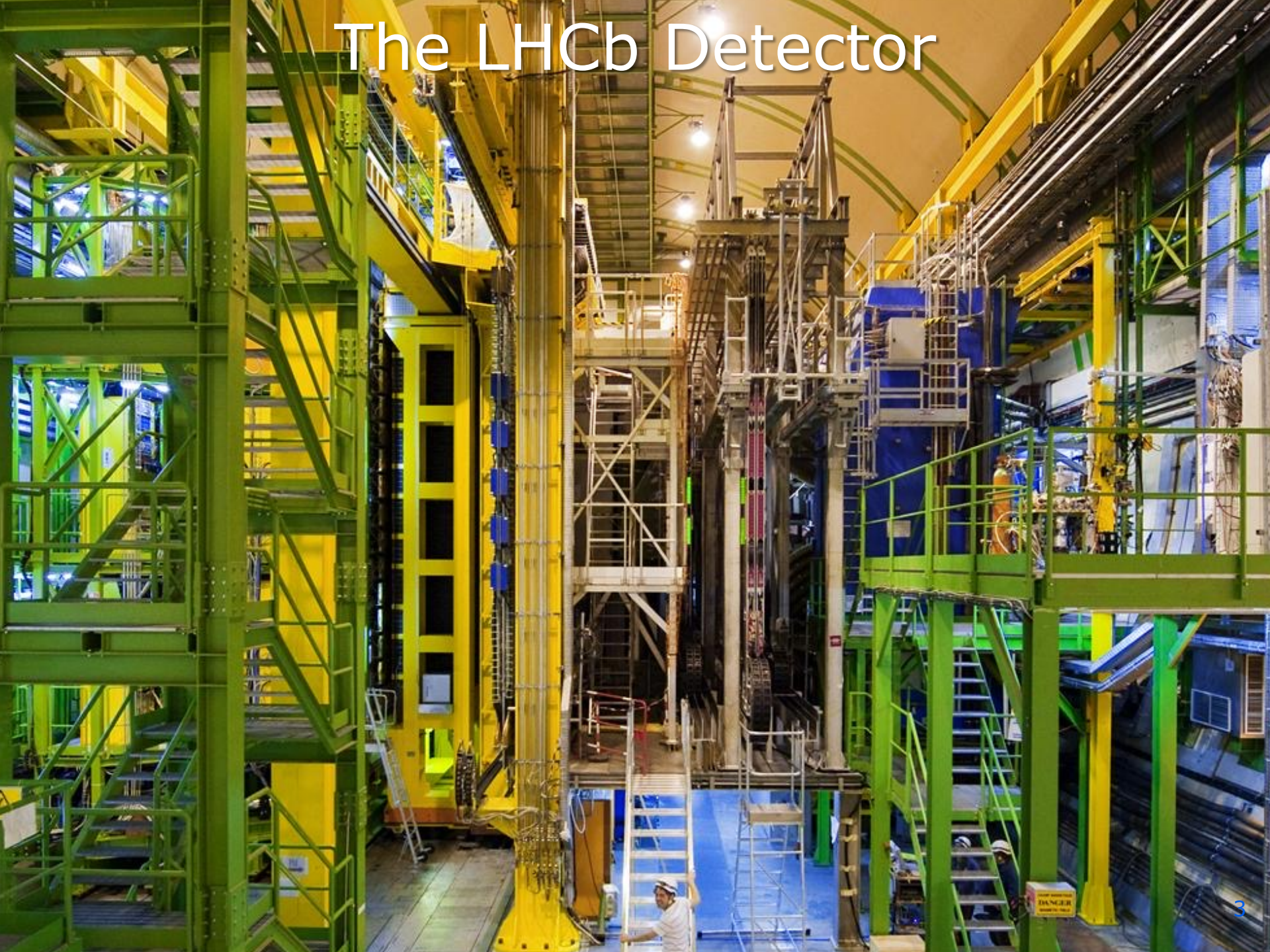
6-10 Nov 2023

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

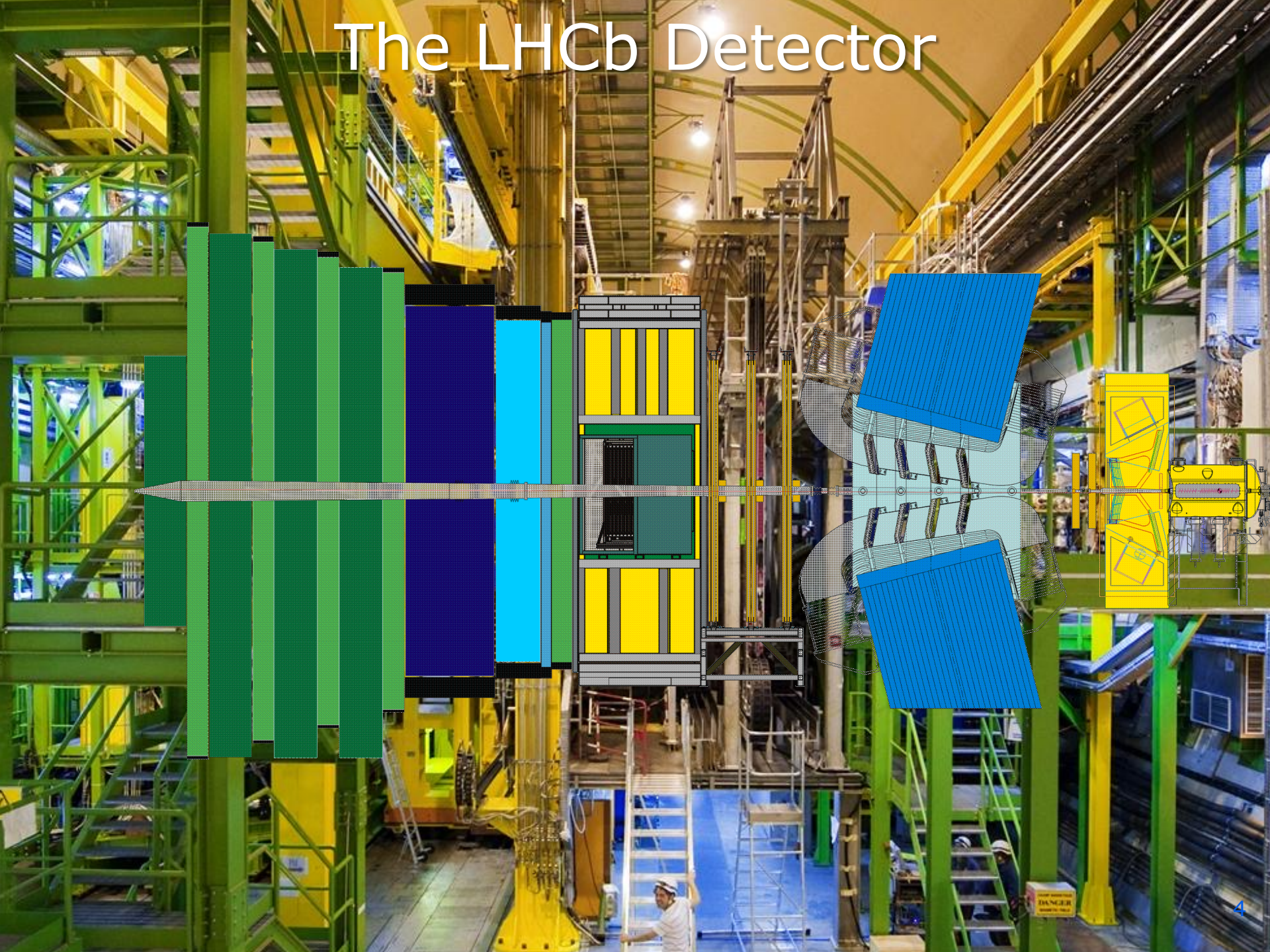
Outline

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

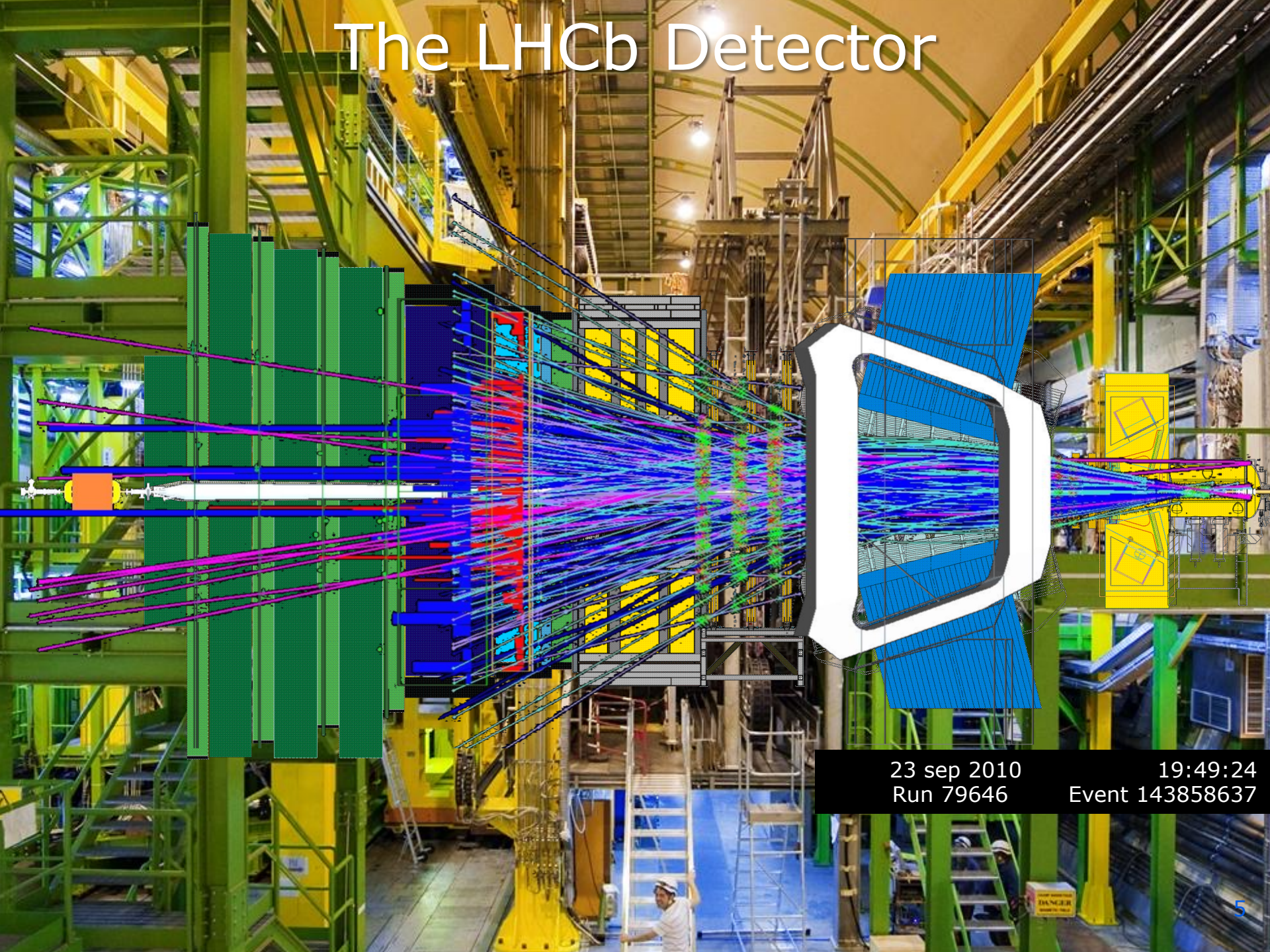
The LHCb Detector



The LHCb Detector



The LHCb Detector



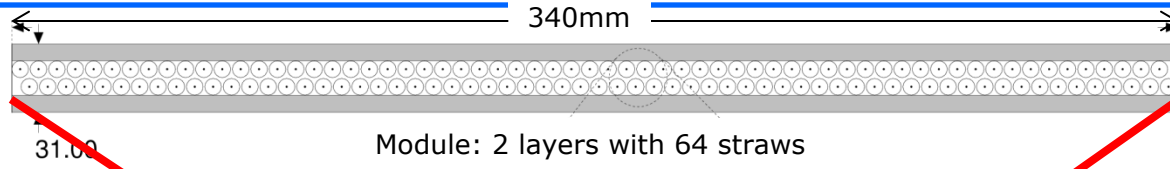
23 sep 2010
Run 79646

19:49:24
Event 143858637

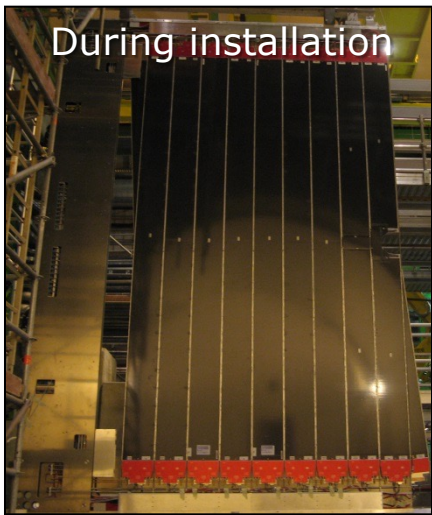
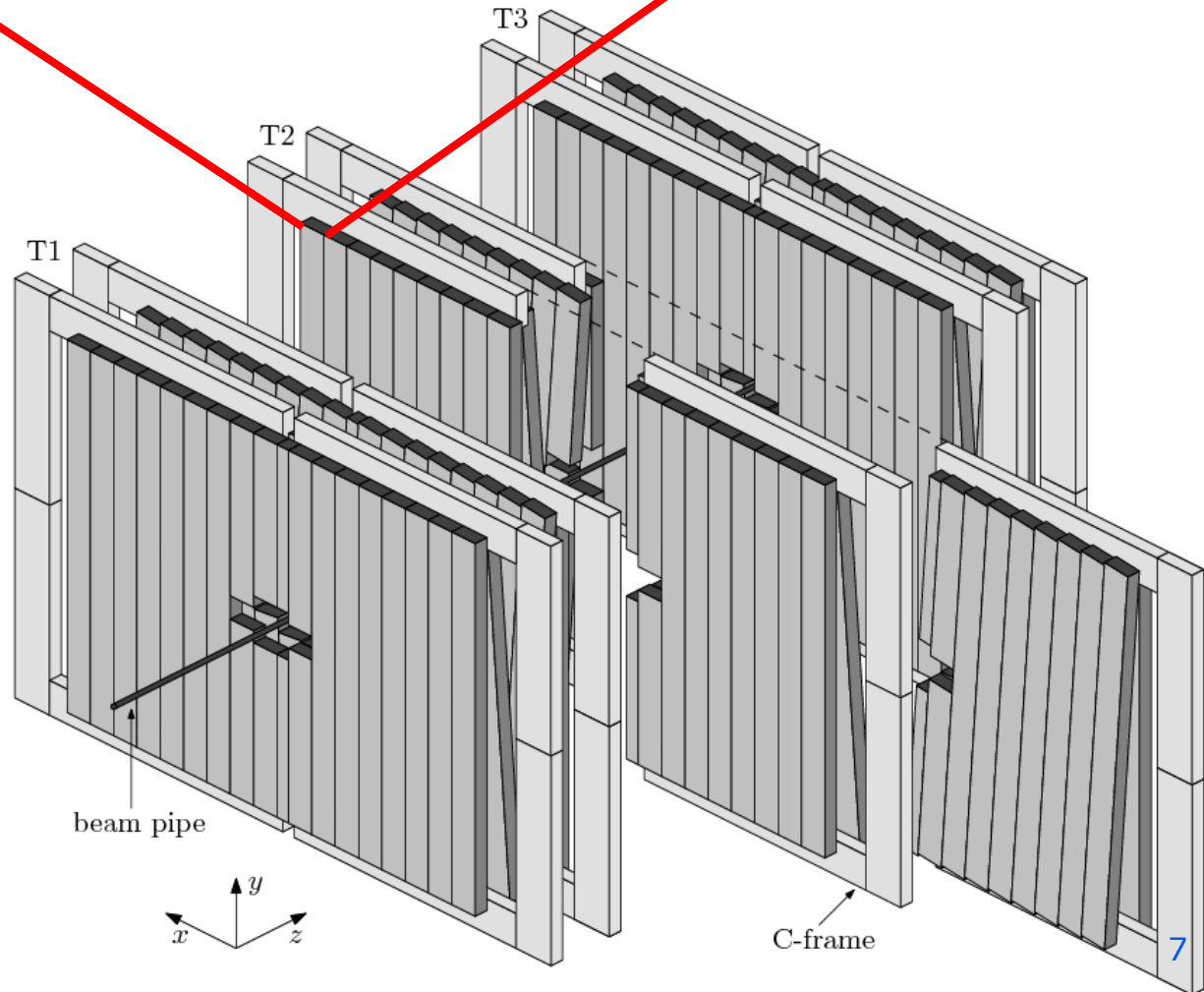
Outer Tracker



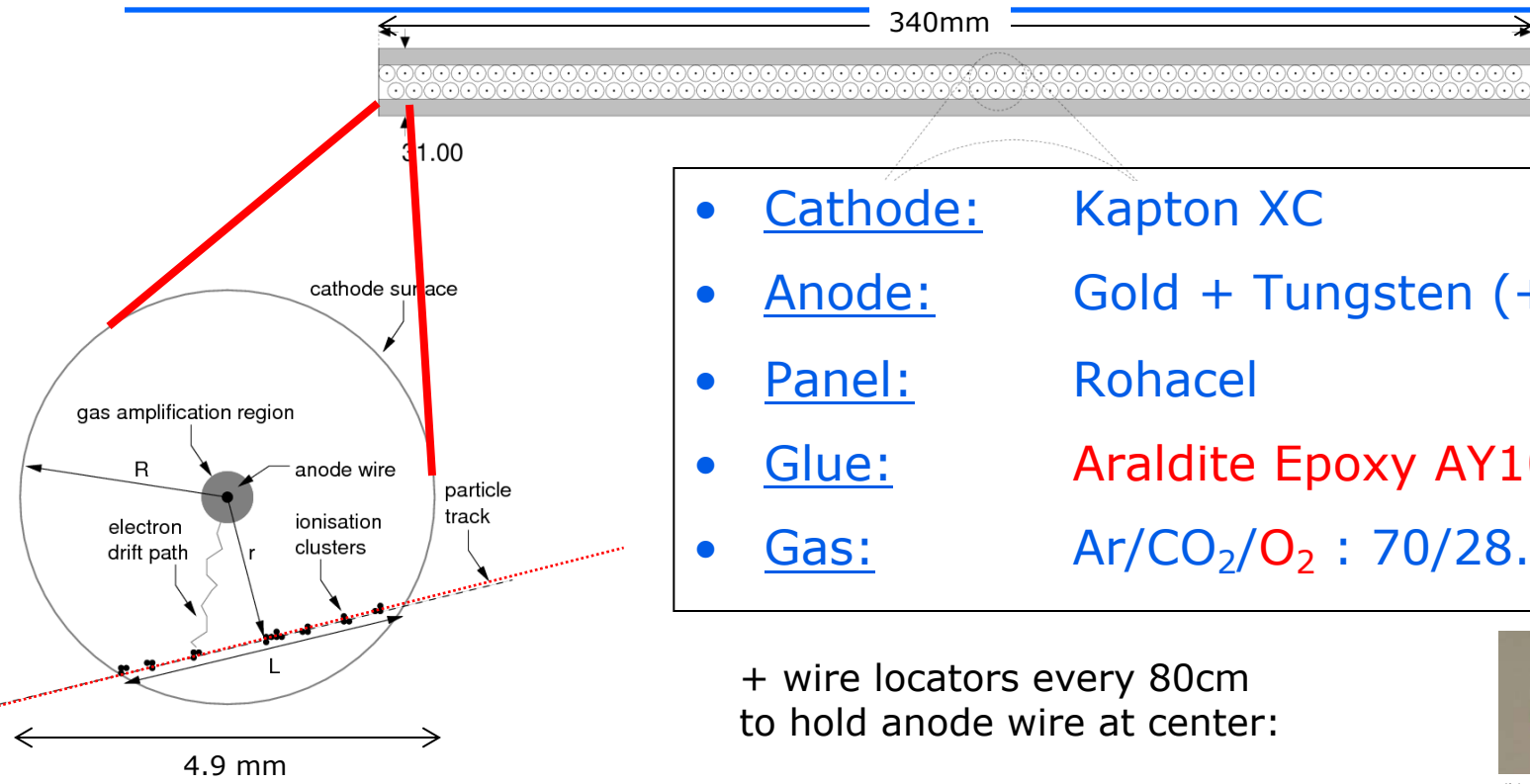
Outer Tracker



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

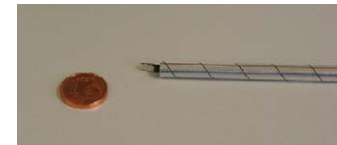


Outer Tracker



- Cathode: Kapton XC
- Anode: Gold + Tungsten (+1550 V)
- Panel: Rohacel
- Glue: Araldite Epoxy AY103
- Gas: Ar/CO₂/O₂ : 70/28.5/1.5

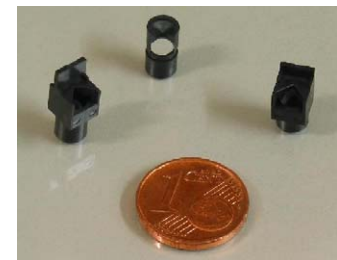
+ wire locators every 80cm to hold anode wire at center:



(b)

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



(c)

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,

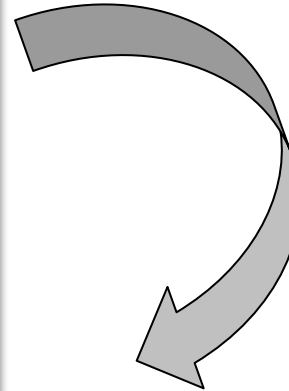
- Zapping: Burning Deposits with High Current on Anodes

- 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>

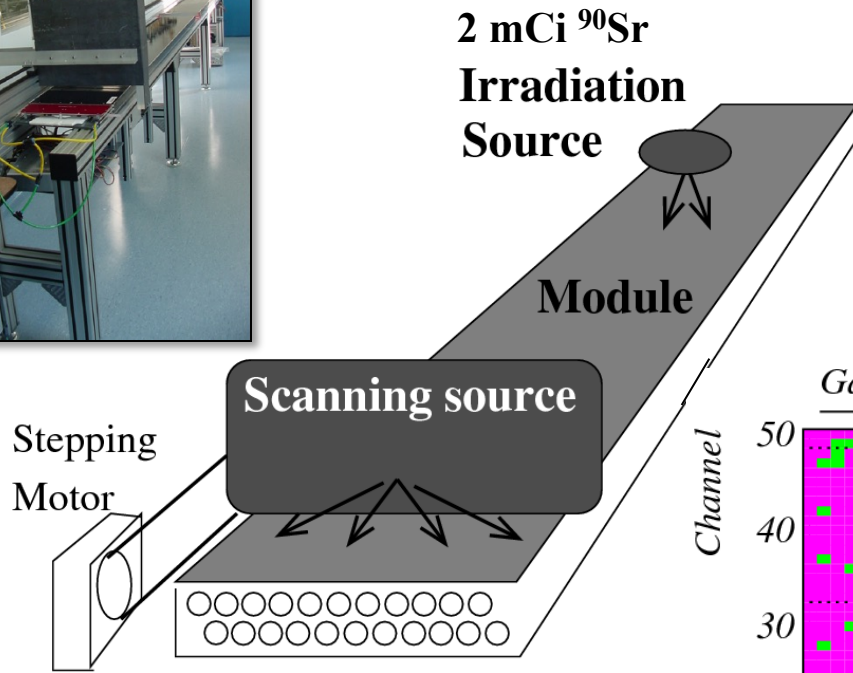


• Choice of non-Outgassing Building Materials

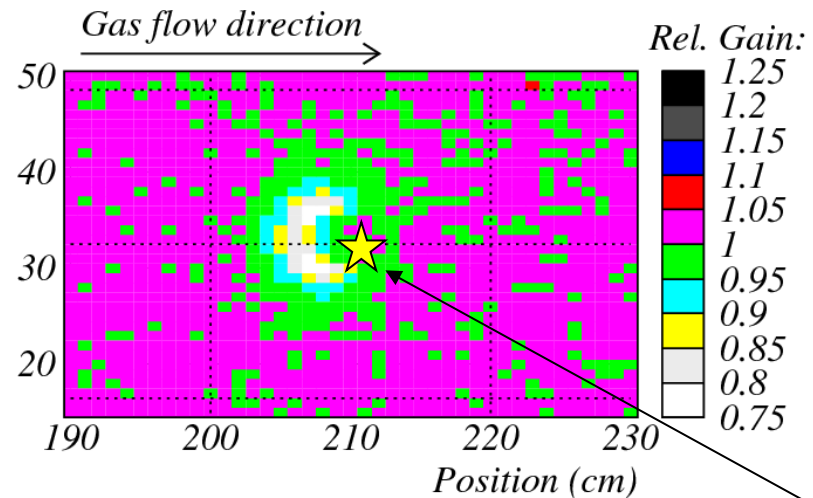
- Zapping: Burning Deposits with High Current on Anodes

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Ageing: The saga - part I (phenomenon)



Relative gain
after/before irradiation:

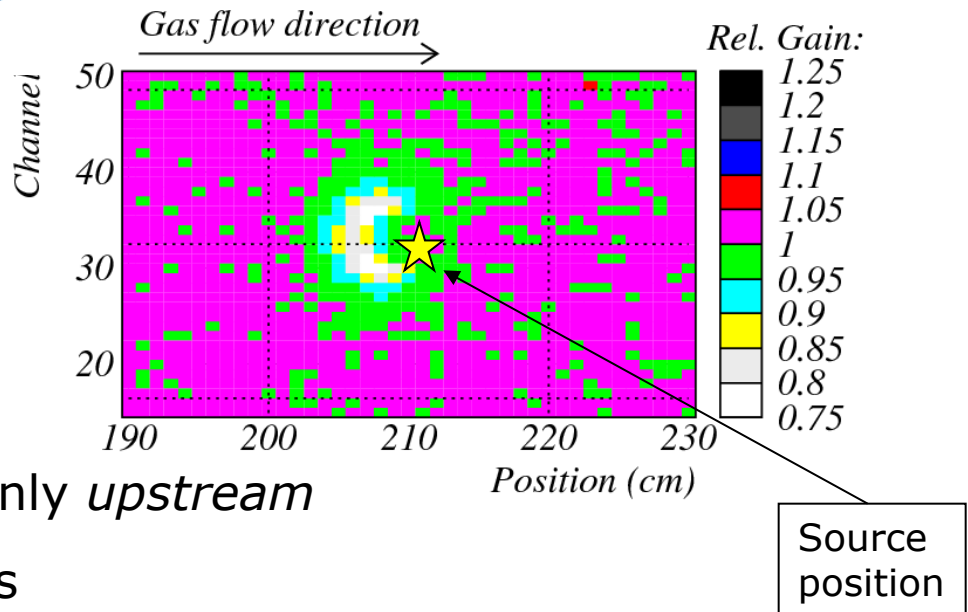
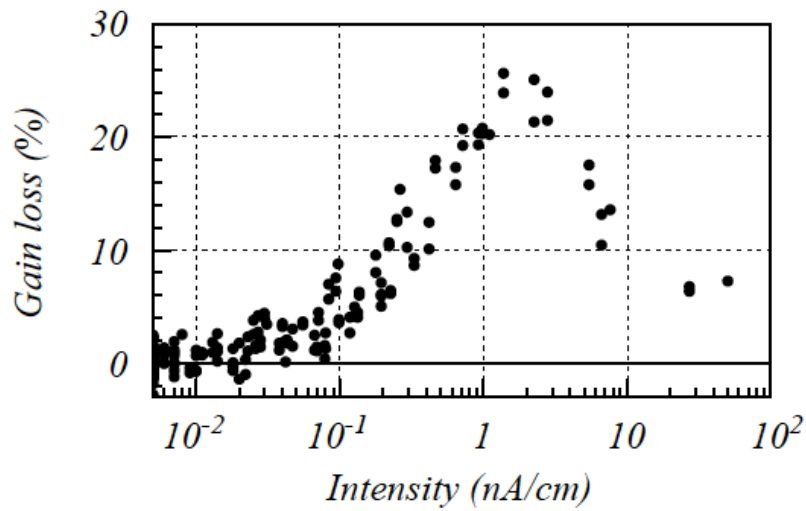


Source
position

Response measured with

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

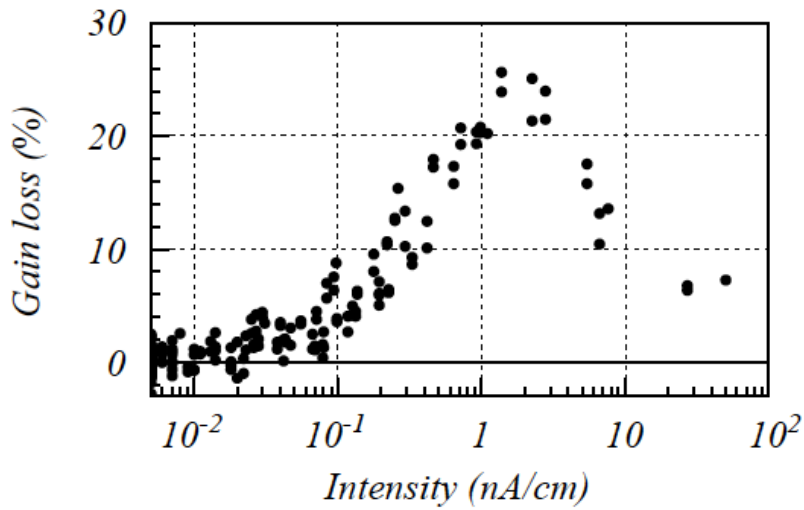
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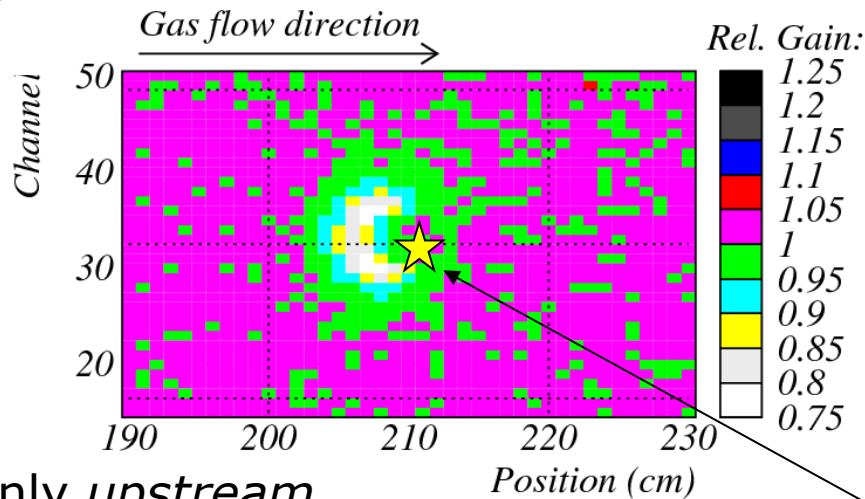
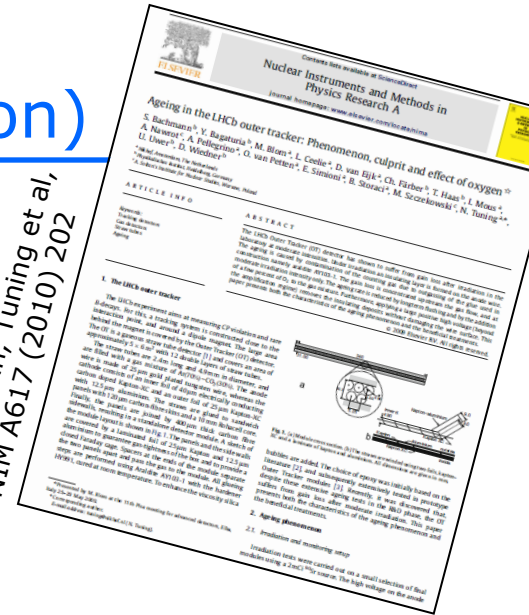
➤ Remarkable:

- 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



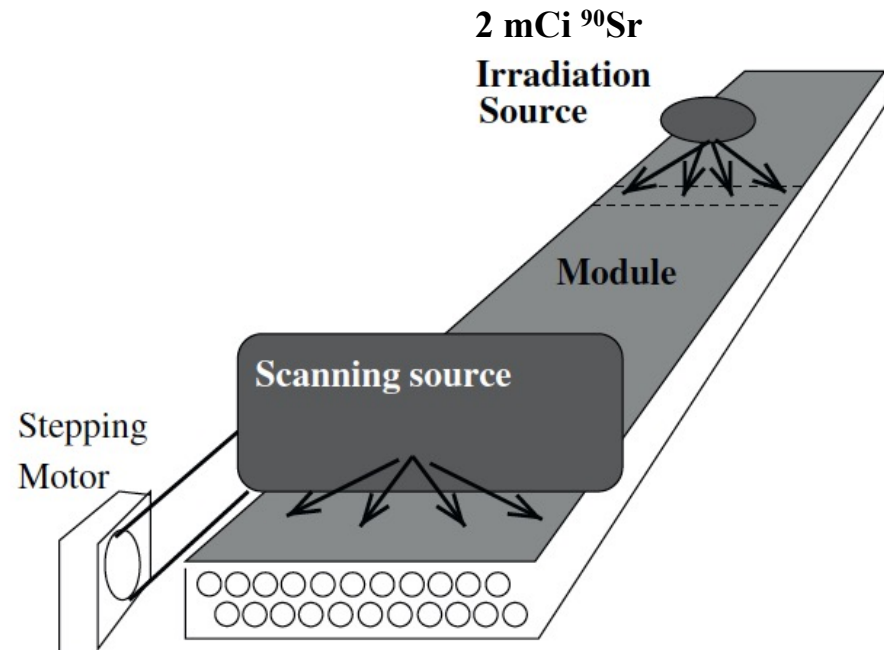
Source position

➤ 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

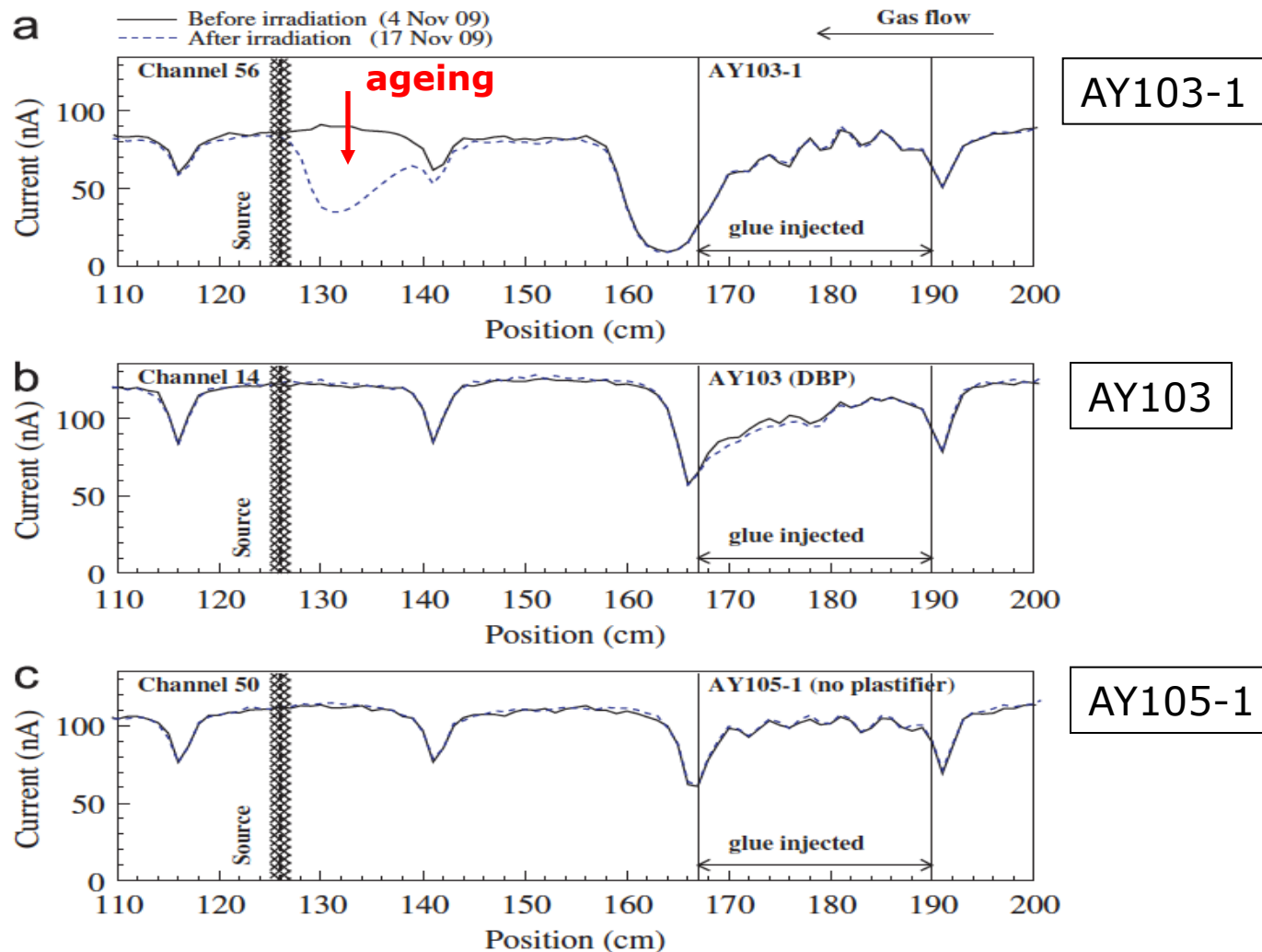
Ageing: The saga - part II (culprit)

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



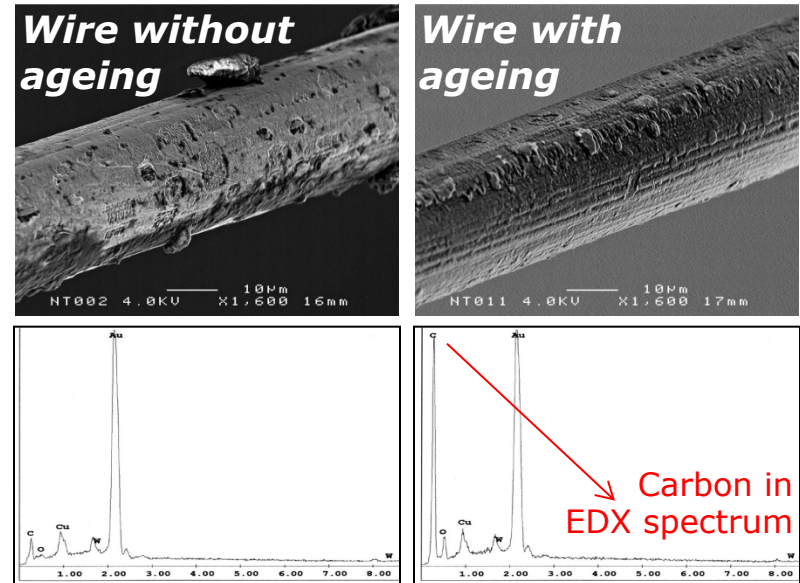
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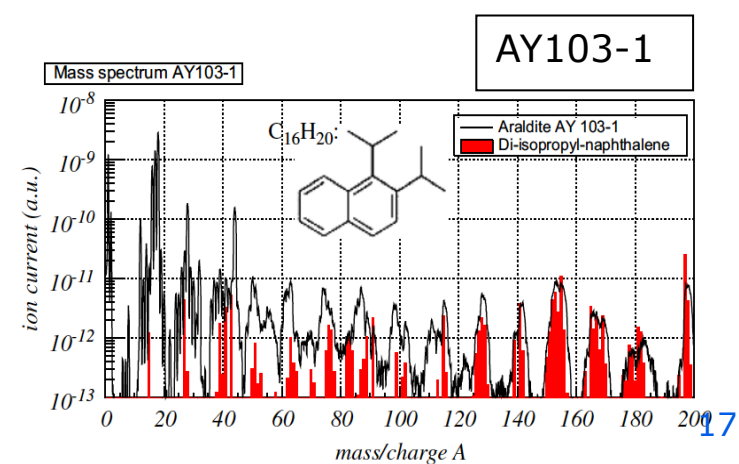
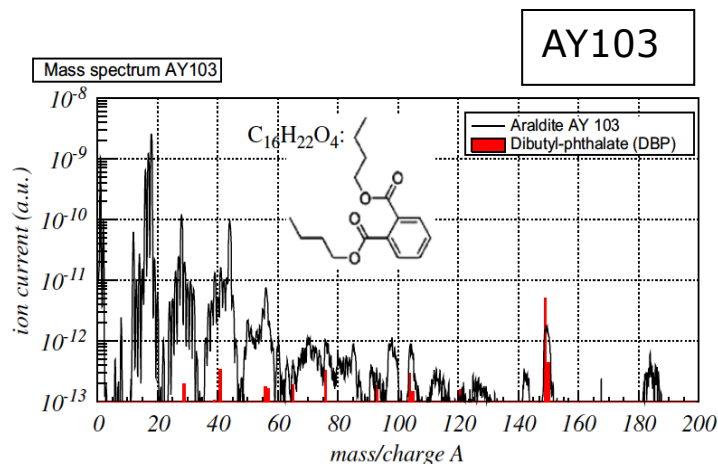


Ageing: The saga - part II (culprit)

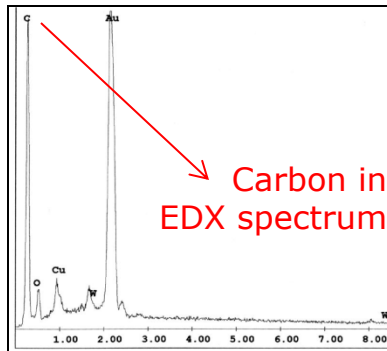
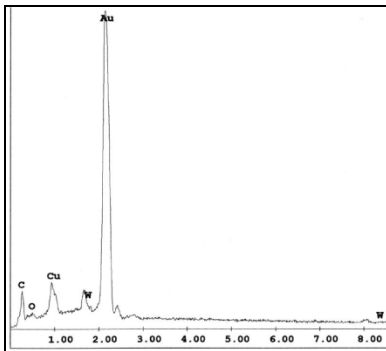
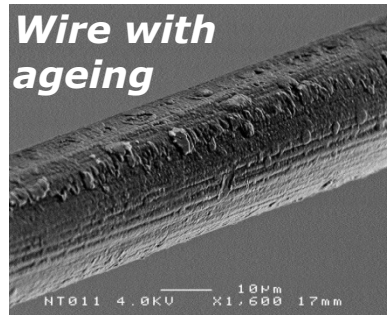
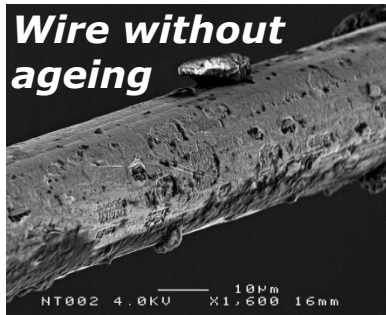
- EDX: presence of C on wire:



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



Ageing: The saga - part II (culprit)

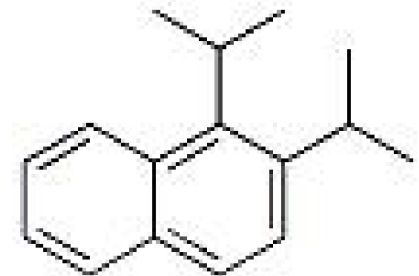


Bachmann, Tuning et al.,
NIM A656 (2011) 45



➤ Cause:

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

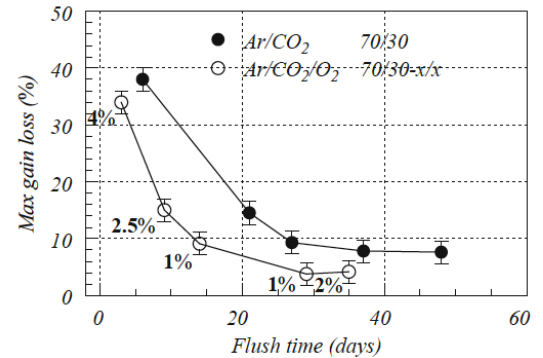
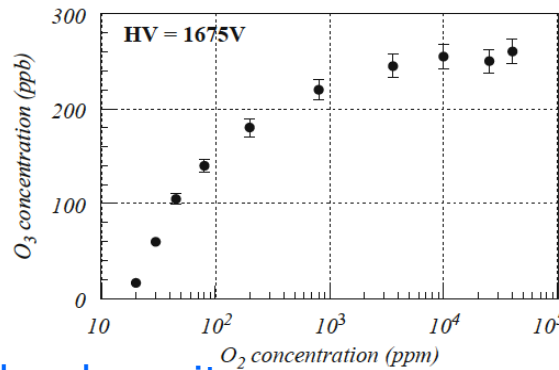


Ageing: The saga - part III (the way out)

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

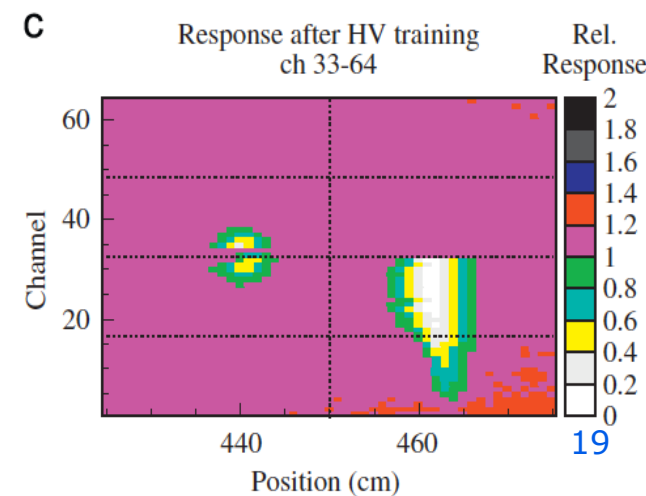
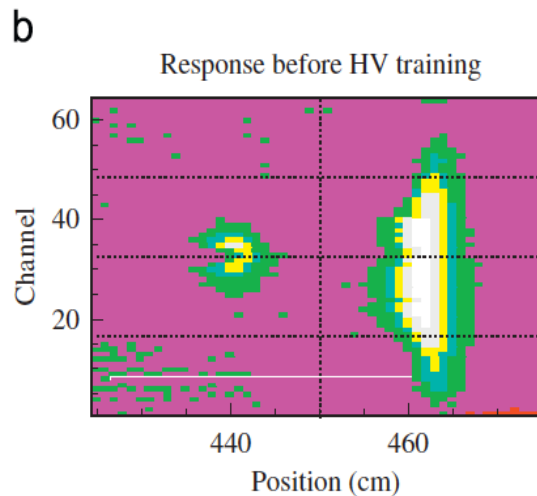


2) Oxygen: prevent deposits

- Presumably formation of O_3
- O_3 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)

➤ 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

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



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

- Zapping: Burning Deposits with High Current on Anodes
- Addition of Compounds with Etching Properties (O_2 , CF_4)

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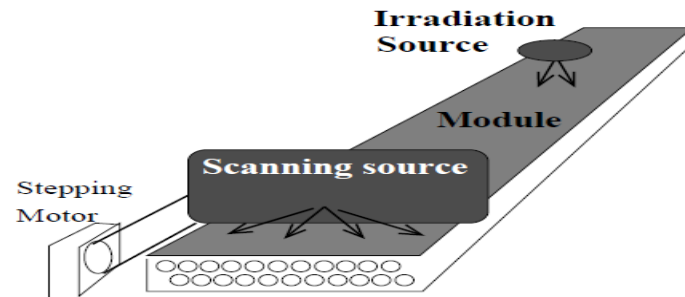
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- Radiation hardness
- Conclusions

Ageing: The saga - part IV (performance)

Two methods to monitor gain loss

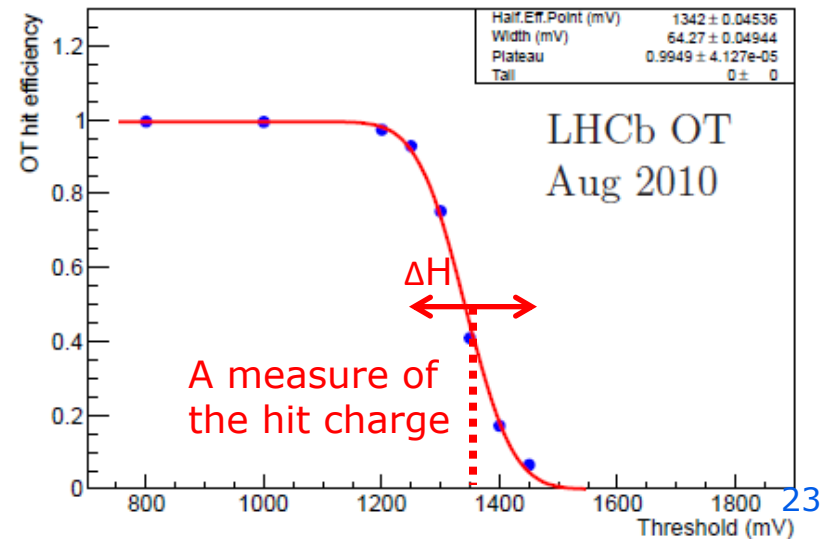
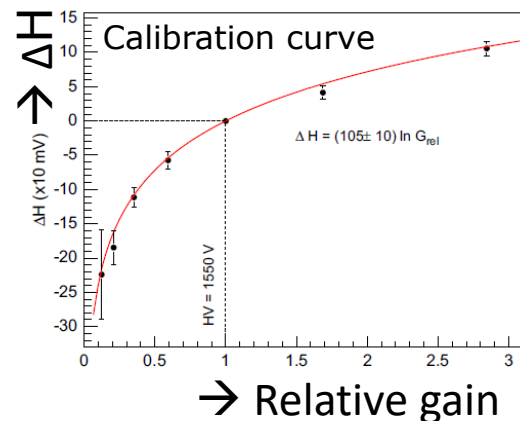
1) During **technical stops**

- ^{90}Sr scans to measure detector response



2) During **LHC operation**

- Measure hit efficiency with tracks, at increasing amplifier threshold

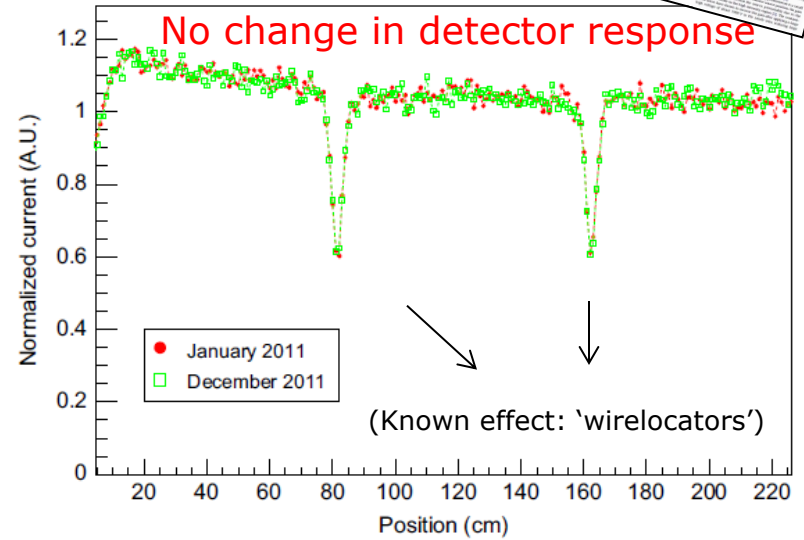


Ageing: The saga - part IV (performance)

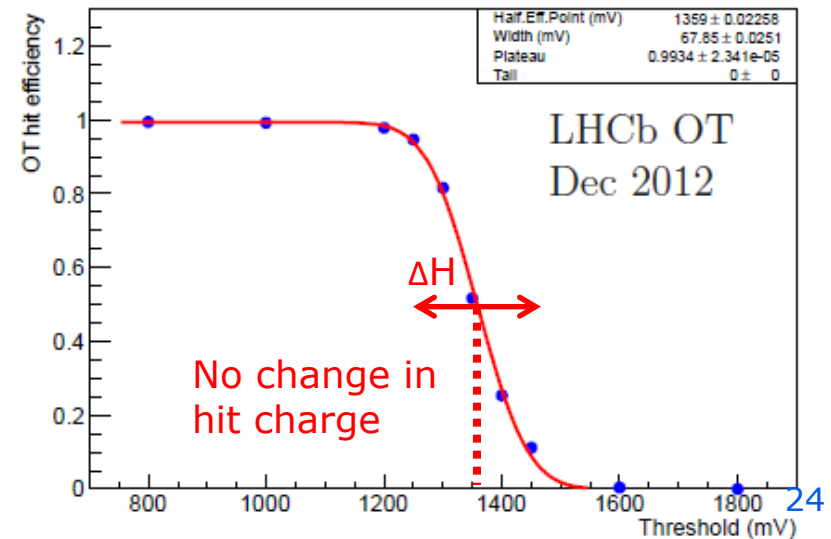
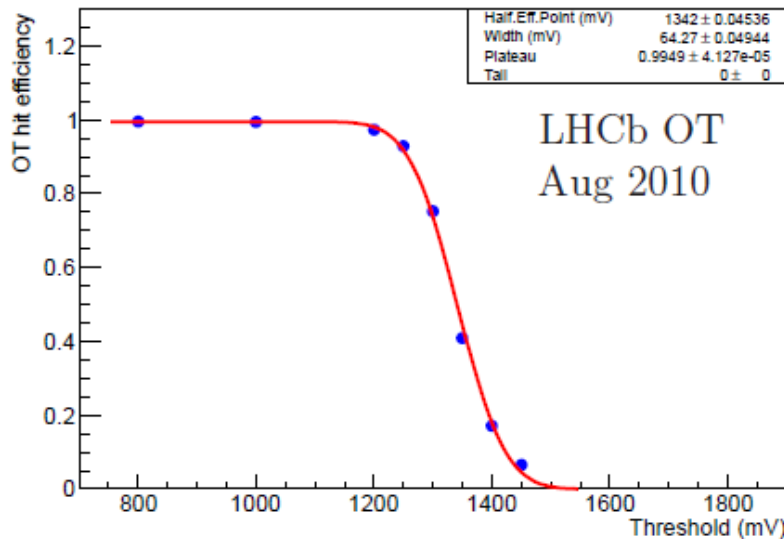
Bachmann, Tuning et al,
NIM A685 (2012) 62

Two methods to monitor gain loss

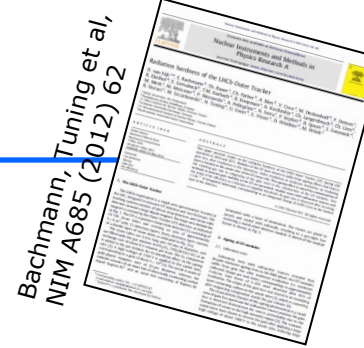
1) During **technical stops**



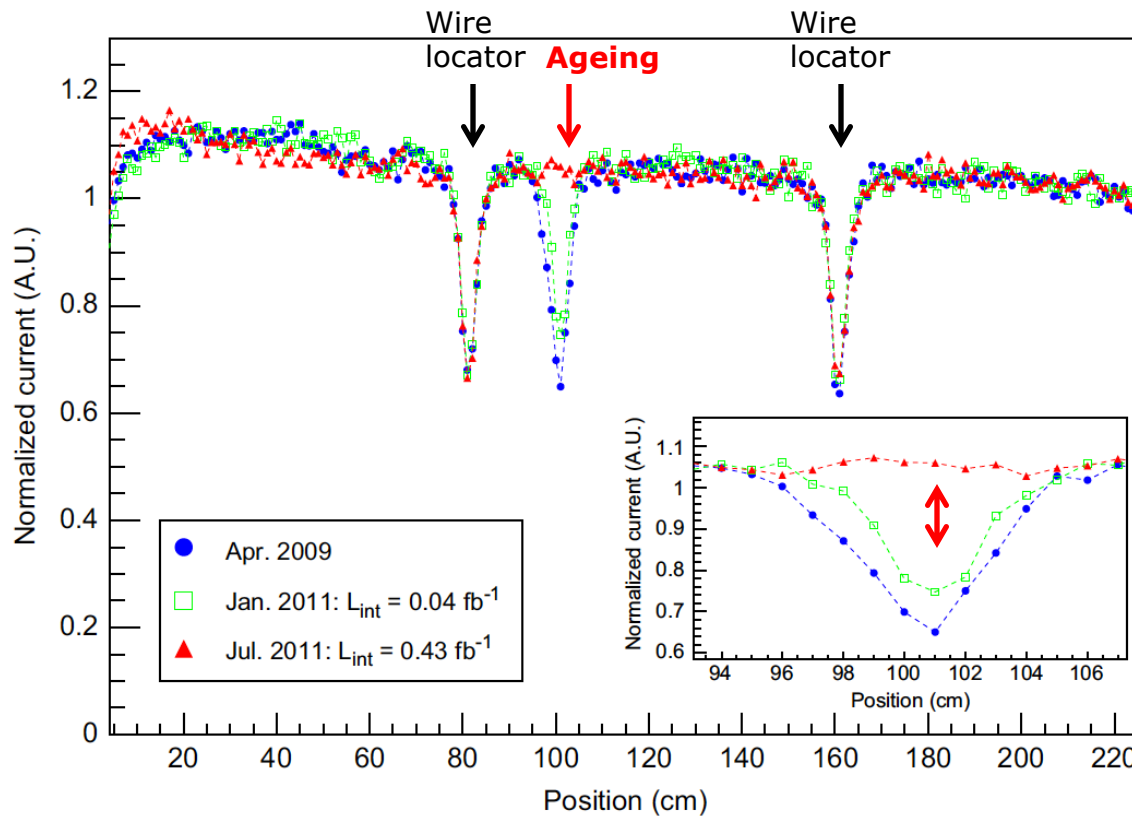
2) During **LHC operation**



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

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

Radiation hardness of the LHCb Outer Tracker

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
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Ageing in the LHCb outer tracker: Phenomenon, culprit and effect of oxygen^{a,*}
 S. Bachmann^a, Y. Bagaturia^a, M. Blom^a, L. Ceolze^a, D. van Eijk^a, Ch. Farber^a, T. Haas^b, I. Moos^a, A. Navrat^a, A. Pellegrino^a, D. van Petten^a, E. Simioni^a, B. Storaac^a, M. Szczekowski^a, N. Tuning^a, U. Uwer^a, D. Wiedner^a

^a M. Planck Experiment, The Netherlands
^b Physikalisches Institut, Heidelberg University
^c Leibniz Institute for Nuclear Studies, Warsaw, Poland

ARTICLE INFO
ABSTRACT
 The LHCb Outer Tracker (OT) detector has shown to suffer from gain loss after irradiation in the laboratory at moderate intensities. Under irradiation an insulating layer is formed on the anode wire. The ageing is caused by contamination of the coating gas due to outgassing of the glue used in construction, mainly at the AVT10-1. The gain loss is concentrated upstream the gas flow, and at moderate irradiation intensities. The ageing can be reduced by hydrogen flushing and by the addition of a few percent of O₂ to the gas mixture. Furthermore, applying a large positive high voltage (beyond the amplification region) causes the insulating deposits without damaging the wire surface. This paper presents both the characteristics of the ageing phenomenon and the beneficial treatments.

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1. The LHCb outer tracker
 The LHCb experiment aims at measuring CP violation and rare B-decays. For this, a tracking system is constructed close to the interaction point, and around a dipole magnet. The large area behind the magnet is covered by the Outer Tracker (OT) detector. The OT is a gaseous straw tube detector [1] and covers an area of approximately 5 × 6 m² with 12 double layers of straw tubes. The straw tubes are 2.4 m long and admit a diameter and are filled with a gas mixture of Ar(90%)-CO₂(10%). The anode wire is made of 25 μm gold plated tungsten wire, whereas the cathode consists of an inner foil of 0.1 μm electrically conducting carbon coated Kapton-KC and an outer foil of 25 μm Kapton-KC with 12.5 μm aluminium. The straws are glued to each other with 120 μm carbon-fibre films and a 10 mm thick epoxy core. Finally, the panels are joined by 400 μm thick carbon-fibre sidewalls, resulting in a standard detector module. A sketch of the module layout is shown in Fig. 1. The panels and fibre sidewalls are covered by a laminated foil of 25 μm Kapton and 12.5 μm aluminium to guarantee gas-tightness of the box and to provide a closed Faraday cage. Supports at the ends of the module separate the two panels apart and pass the gas to the detector. All gluing steps are performed using Araldex AV10-1 with the hardener HW91, cured at room temperature. To enhance the viscosity a few



2. Ageing phenomenon
2.1. Irradiation and monitoring setup
 Experiments were carried out on a small selection of final modules using a ²²⁶Ra source. The high voltage on the anode

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Nuclear Instruments and Methods in Physics Research A
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Ageing in the LHCb outer tracker: Aromatic hydrocarbons and wire cleaning
 N. Tuning^{a,*}, S. Bachmann^a, Y. Bagaturia^a, M. Blom^a, L. Ceolze^a, D. van Eijk^a, Ch. Farber^a, T. Haas^b, E. Janous^c, T. Kretz^c, M. Meek^c, I. Moos^a, A. Navrat^a, A. Pellegrino^a, D. van Petten^a, T. du Pree^a, N. Serra^a, E. Simioni^a, T. Suijij^a, B. Storaac^a, M. Szczekowski^a, U. Uwer^a, E. Visser^a, D. Wiedner^a

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 The LHCb Outer Tracker straw tubes have shown to suffer from gain loss after irradiation in the laboratory at moderate intensities. Under irradiation an insulating layer is formed on the anode wire. The ageing is caused by contamination of the coating gas due to outgassing of the glue used in construction. This paper presents results with and without the specific, together with the new aspects of the gas mixture. In addition, the effects of wire heating and larger currents are presented.

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1. Introduction
 The LHCb experiment [1] aims at measuring CP violation and rare B-decays. For this, a tracking system is constructed close to the interaction point, and around a dipole magnet. The large area behind the magnet is covered by the Outer Tracker (OT) detector. The OT is a gaseous straw tube detector and covers an area of approximately 5 × 6 m² with 12 double layers of straw tubes. The straw tubes are 2.4 m long and 40 mm in diameter, and are filled with a gas mixture of Ar(90%)-CO₂(10%). The anode wire is made of gold plated tungsten wire of 25 μm diameter, whereas the cathode consists of a 0.1 μm thick inner foil of electrically conducting carbon coated Kapton-KC and a 25 μm thick outer foil, consisting of Kapton-KC laminated together with a 12.5 μm thick layer of aluminium. The straws are glued to each other with 120 μm thick carbon fibre sidewalls, resulting in a gas-tight box enclosing a standard detector module. A sketch of the module layout is shown in Fig. 1. The panels and the side walls are covered by a laminated foil of 25 μm Kapton and 12.5 μm aluminium to guarantee gas-tightness of the box and to provide a closed Faraday cage. Supports at the ends of the module separate the two panels apart and pass the gas to the detector. All gluing steps are performed using Araldex AV10-1 with the hardener HW91, cured at room temperature. To enhance the viscosity a few

dried Tracker cage. Supports at the ends of the module separate the two panels and pass the gas to the detector. All materials were glued with Araldex AV10-1 and the hardener HW91, cured at room temperature. To enhance the viscosity colloidal silica (with particle sizes of 12 μm) was added, with a mixing ratio of 5%. The choice of epoxy was initially based on Ref. [2], and subsequently extensively tested in prototype Outer Tracker modules [3]. It was discovered that, despite their extensive ageing tests in the OT phase, the OT suffers from gain loss after moderate irradiation (i.e. moderate collected charges per unit length) corresponding to approximately 2 A/cm. The origin of the gain loss is traced to an insulating layer on the anode wire [4] that contains negatively charged carbon-based particles. A positive correlation is observed between the ageing rate and the collection rates have been observed before [5]. A negative correlation is observed between the ageing rate and the production of ozone [6], which suggests that the gain loss is presented under and downstream of the source due to the formation of ozone in the avalanche region. As a consequence it was decided to add O₂ to the coating gas, similar to other large gas detectors [3,7]. Further characteristics of the ageing phenomenon and beneficial treatments are discussed in Ref. [8].

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Radiation hardness of the LHCb Outer Tracker
 D. van Eijk^{a,*}, S. Bachmann^a, Th. Baars^a, Ch. Farber^a, A. Bien^a, V. Cocca^a, M. Deisenhoff^a, F. Detzner^a, R. Ehrhart^a, E. Gersbeck^a, T.M. Karbach^a, R. Koopman^a, A. Kucharsky^a, Ch. Langebrecht^a, Ch. Linaf^a, M. Meek^a, M. Meisner^a, P. Micaud^a, A. Pellegrino^a, N. Serra^a, P. Seyfert^a, R. Szepiet^a, S. Swietek^a, B. Storaac^a, M. Szczekowski^a, N. Tuning^a, U. Uwer^a, E. Visser^a, D. Wiedner^a, M. Wittek^a

^a M. Planck Experiment, The Netherlands
^b Physikalisches Institut, Heidelberg University, Postfach
^c Leibniz Institute for Nuclear Studies, Warsaw, Poland
^d Max-Planck-Institut für Medizinische Physik, Garching

ARTICLE INFO
ABSTRACT
 This paper presents results on the radiation hardness of the LHCb Outer Tracker (OT) during LHC operation in 2010 and 2011. Modules of the OT have shown to suffer from ageing effects due to the gain loss after irradiation in the laboratory. Under irradiation an insulating layer is formed on the anode wire of the OT straw tubes. The ageing effect is caused by contamination of the coating gas due to outgassing of the glue used in the construction of the OT modules. Two methods to reduce gain loss due to the OT are presented: under moderate irradiation, the gain loss is reduced by a factor of up to 10. In addition, the gain loss is reduced by a factor of up to 10. In addition, the gain loss is reduced by a factor of up to 10. In addition, the gain loss is reduced by a factor of up to 10.

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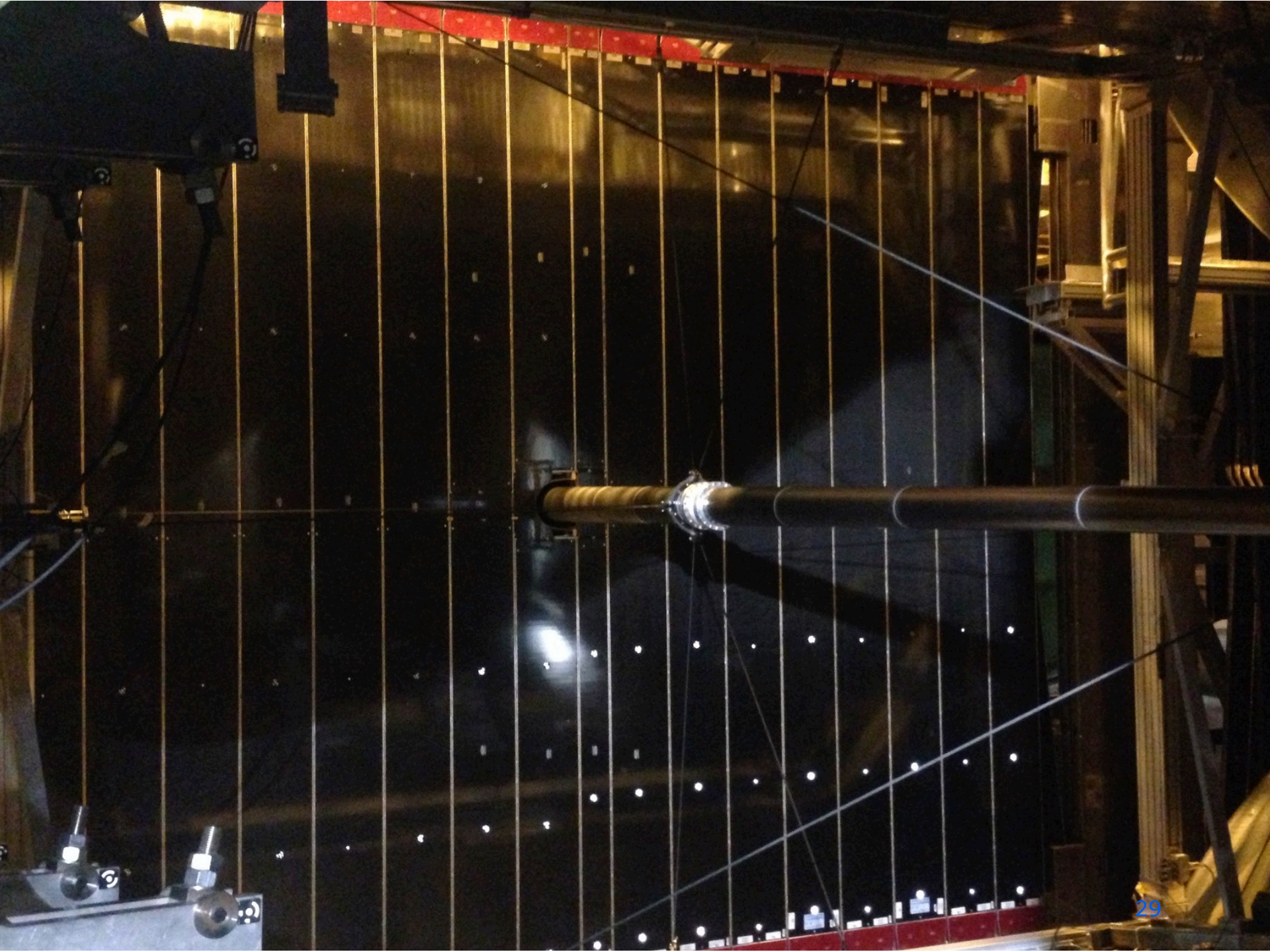
1. The LHCb Outer Tracker
 The LHCb experiment aims at measuring CP violation and rare B-decays. For this, a tracking system is constructed close to the interaction point, and around a dipole magnet. The large area behind the magnet is covered by the Outer Tracker (OT) detector. The OT is a gaseous straw tube detector [1] consisting of 10 700 straw tubes and covering an area of approximately 5 × 6 m² with 12 double layers. Every detector layer consists of a double layer of straw tubes and an aluminium foil [2,3]. The straw tubes are 2.4 m long and 40 mm in diameter, and are filled with the gas mixture Ar(90%)-CO₂(10%) at an operating pressure of about 0.2 mbars per layer. The OT is equipped with a gas mixture of Ar(90%)-CO₂(10%) and a 10 mm thick epoxy core. Finally, the panels are joined by 400 μm thick carbon-fibre sidewalls, resulting in a gas-tight box enclosing a standard detector module. A sketch of the module layout is shown in Fig. 1. The panels and the side walls are covered by a laminated foil of 25 μm Kapton and 12.5 μm aluminium to guarantee gas-tightness of the box and to provide a closed Faraday cage. Supports at the ends of the module separate the two panels apart and pass the gas to the detector. All gluing steps are performed using Araldex AV10-1 with the hardener HW91, cured at room temperature. To enhance the viscosity a few

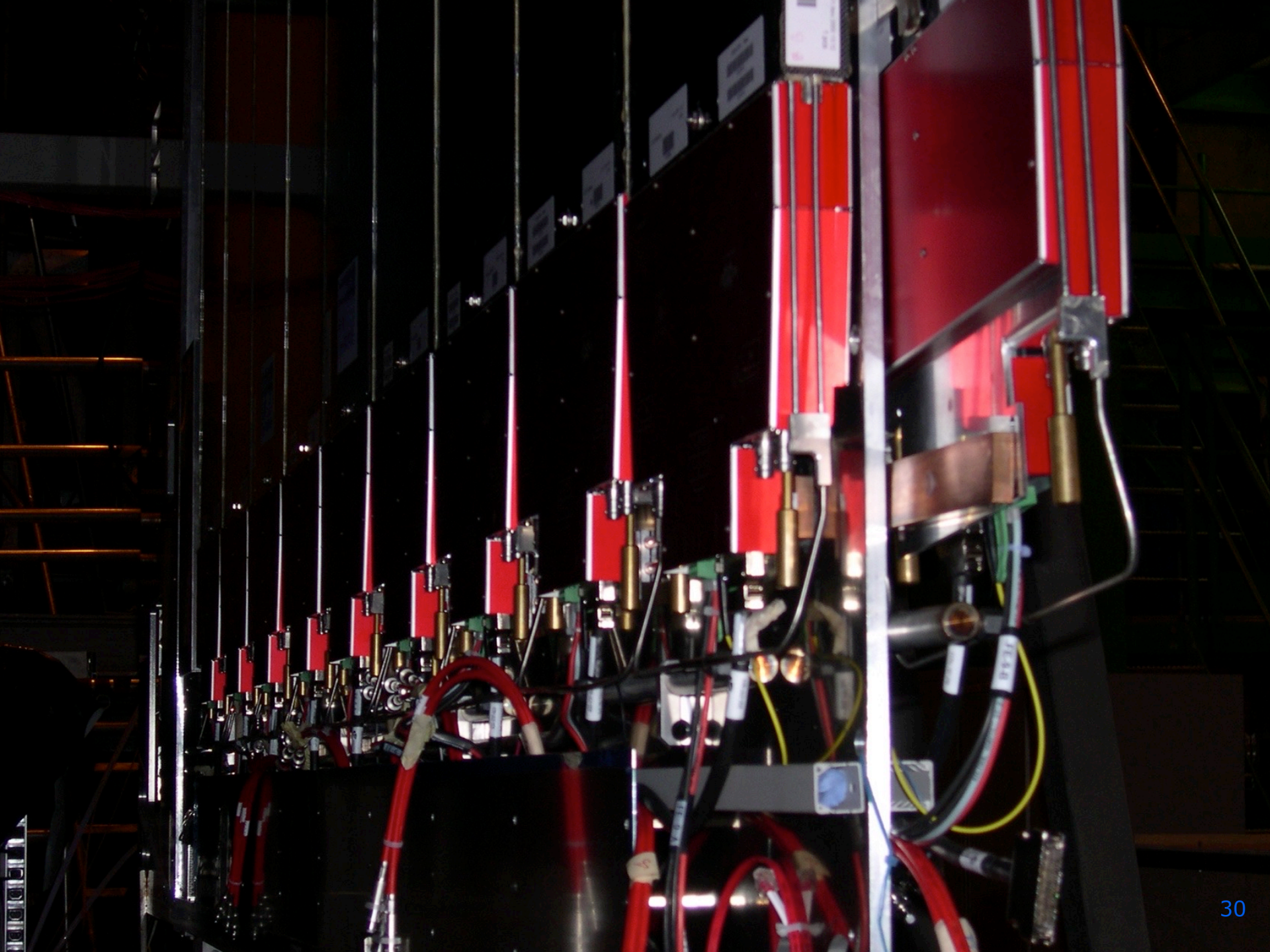
Bachmann, Tuning et al, NIM A617 (2010) 202

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

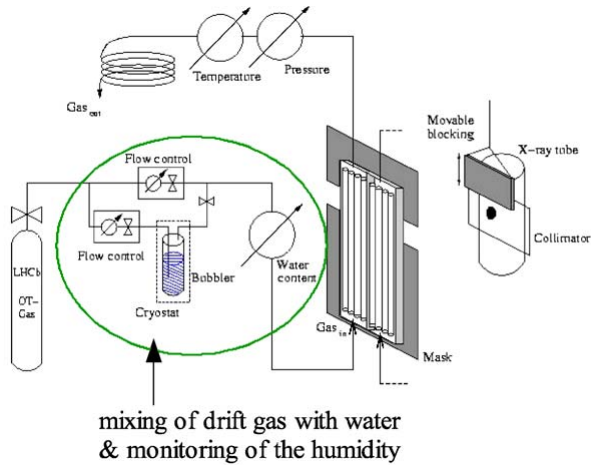
Bachmann, Tuning et al, NIM A685 (2012) 62

Backup





Ageing studies prior to construction



Operational parameters:

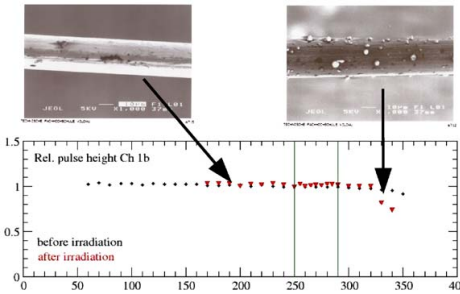
water content: <50ppm, 500ppm, 3500ppm
 gas flow: 2-4 vol/h (190-380 ml/h)
 gas gain: 28000 (550 kHz) / 40000 (low rate)
 X-ray intensity: 500-600 kHz/cm
 Currents: 800-1000 nA/cm
 irrad. region: 4 cm
 wire: Au-plated tungsten wire
 (Ø 25µm, 6% Au, by California Fine Wire)
 accu. Charge: 2 C/cm ± 0.3 C/cm (10 years LHCb)

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

Ar/CO₂/CF₄ : water content < 50ppm

Not irradiated:
Carbon deposits
observed

Irradiated:
Carbon and
oxygen observed



Ar/CO₂/CF₄ : water content 3500ppm

Irradiated:
Tungsten
observed

Irradiated:
Carbon and
oxygen observed

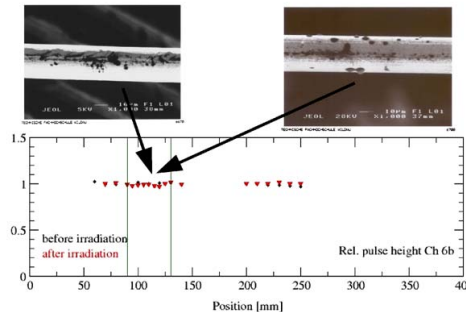


Fig. 4. Selected results from the irradiation tests in Ar/CO₂/CF₄ (75/10/15).

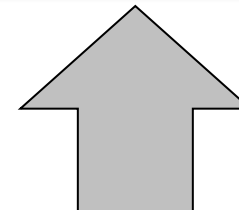
- Irradiated to 2 C/cm
- Decision to change from Ar/CO₂/CF₄ to Ar/CO₂

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 ≤ 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 ≤ 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. |

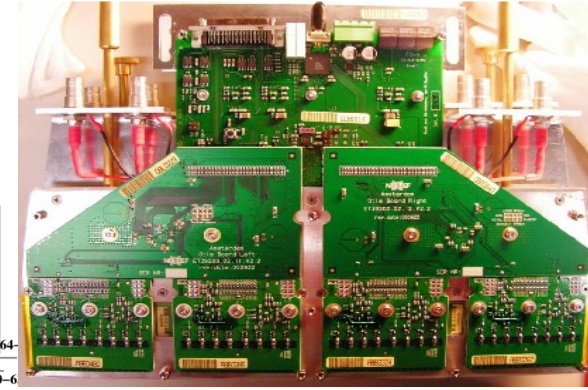
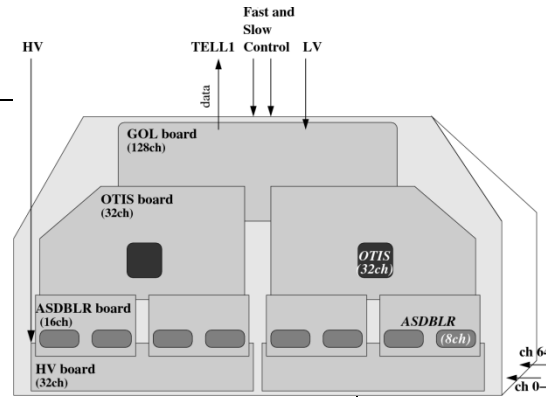
Careful studies of all materials, prior to construction:

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

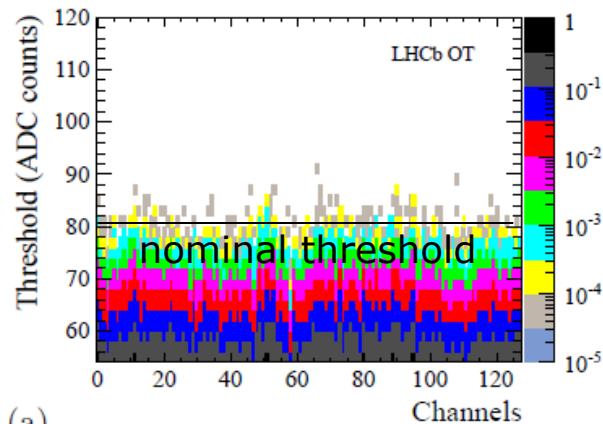


OT Performance in LHC Run I - Readout

- Gas gain: $\sim 5 \times 10^4$
- Analog signal: $\sim 10^6 e^-$
- ASD: Ampl, Shape, Discr.
- TDC: 0.4 ns stepsize
- Pipeline: 160 BX deep (= 4 μ s)
- GOL: Upon L0 trigger, readout 3 BX

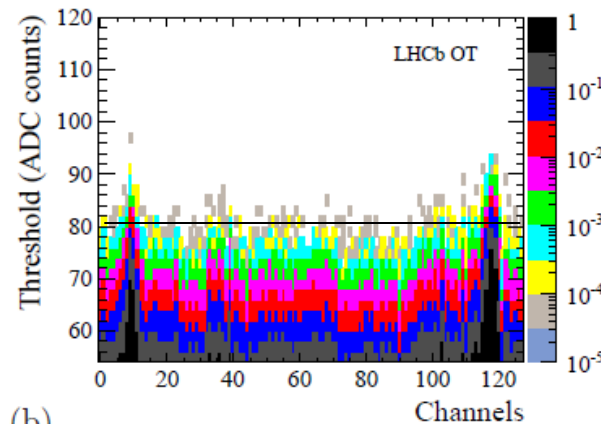


*Detector module
2 x 64 straws*



(a)

Example noisy module:

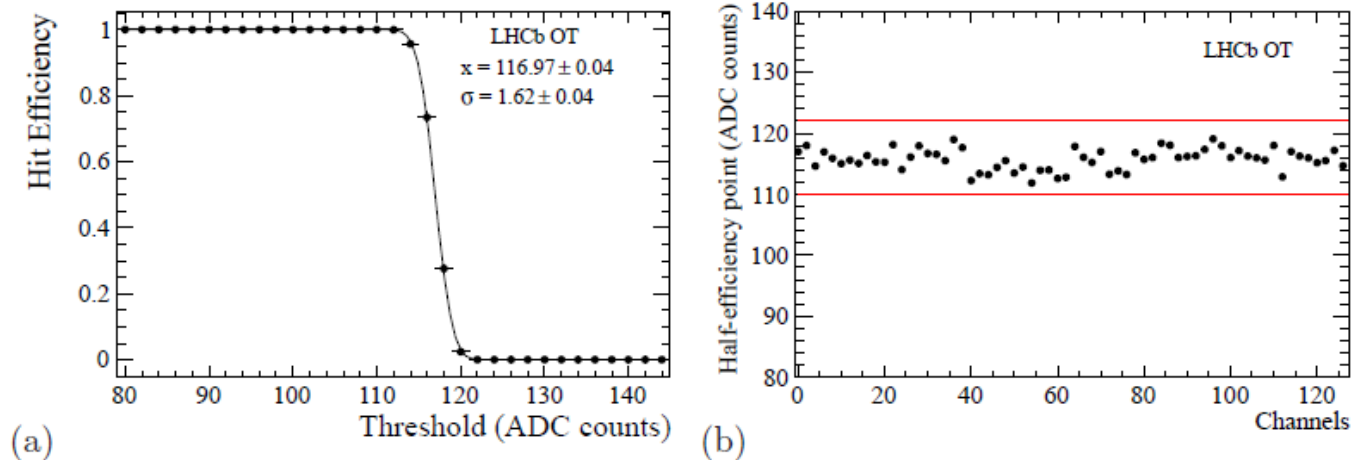


(b)

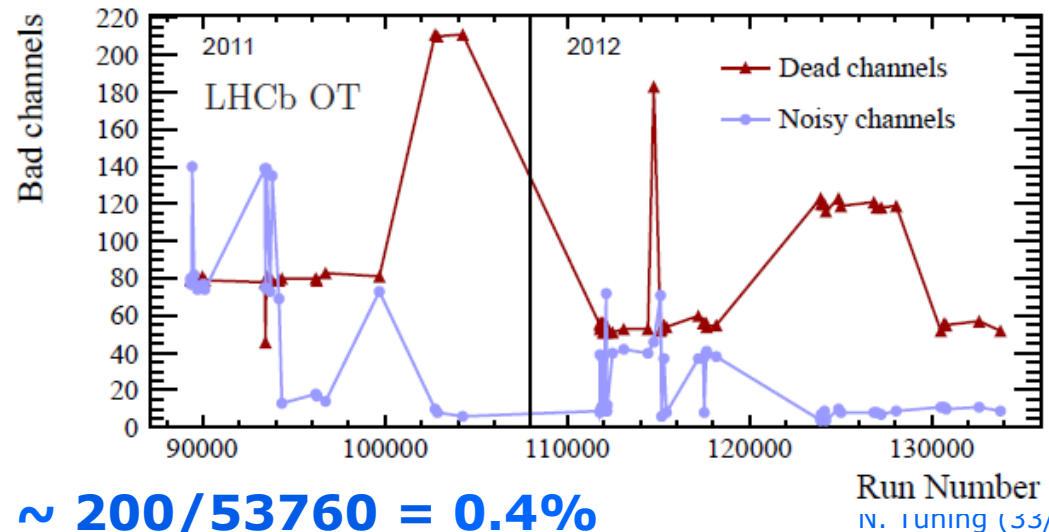
➤ **Noise level $\sim 10^{-4}$**

OT Performance in LHC Run I – Dead channels

- During data taking: use test pulses



- Offline: find channels too few/many hits

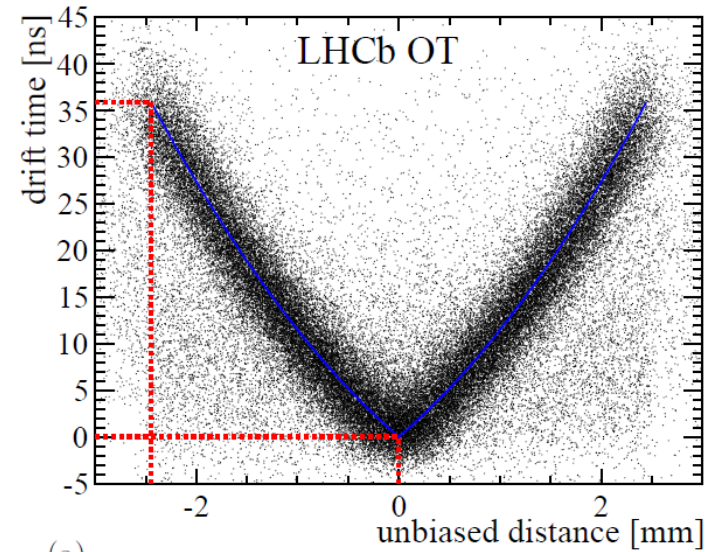


➤ **Noise/Dead channels: $\sim 200/53760 = 0.4\%$**

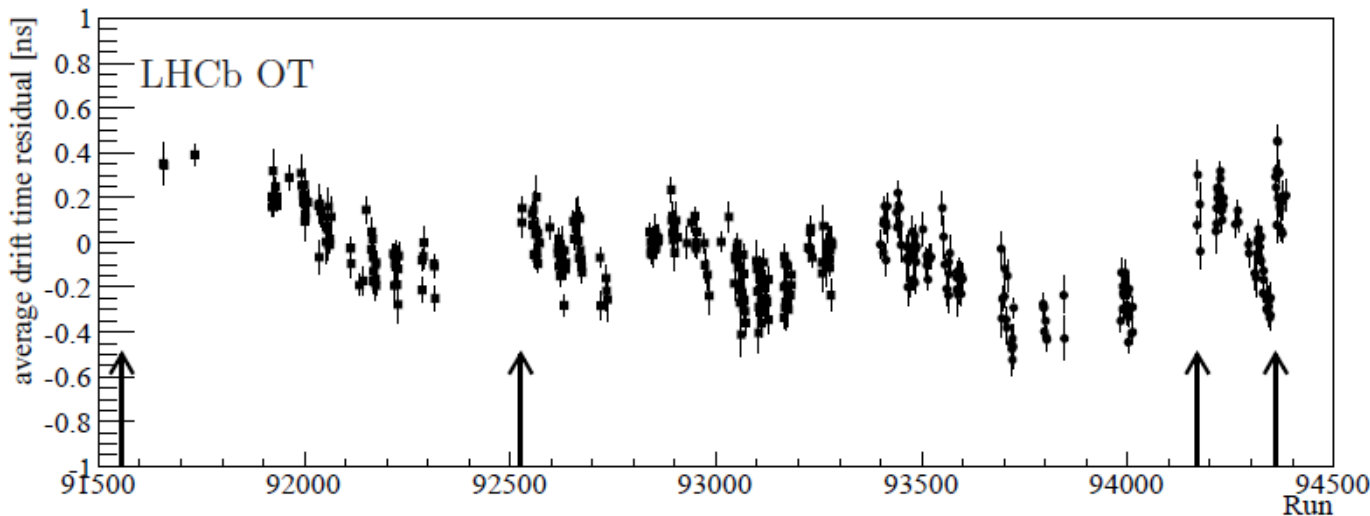
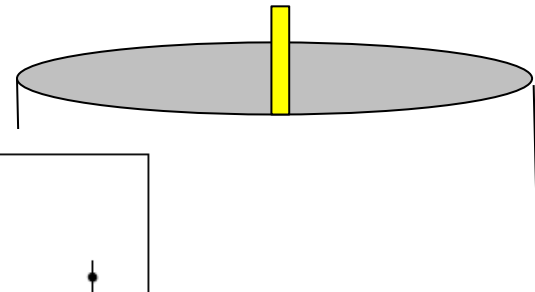
OT Performance in LHC Run I – Calibration

- Time calibration very stable
- Performed $\sim 4x$ per year

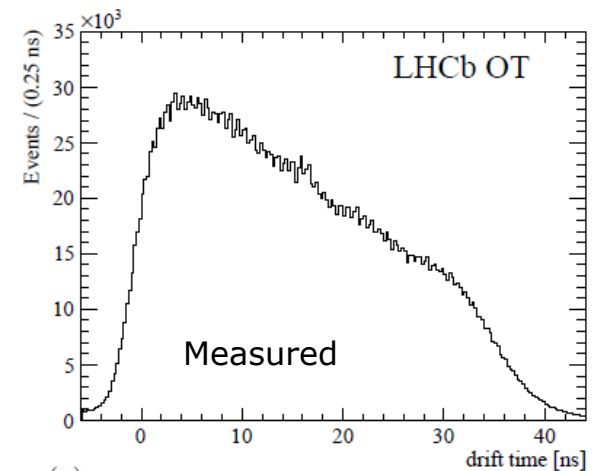
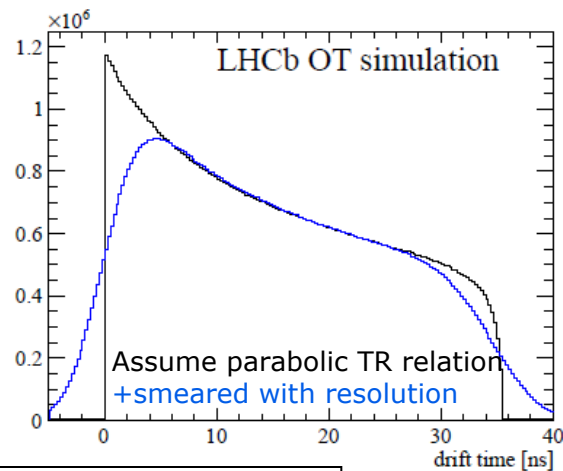
$$t_{\text{drift}}(r) = 20.5 \text{ ns} \cdot \frac{|r|}{R} + 14.85 \text{ ns} \cdot \frac{r^2}{R^2}$$



(a)

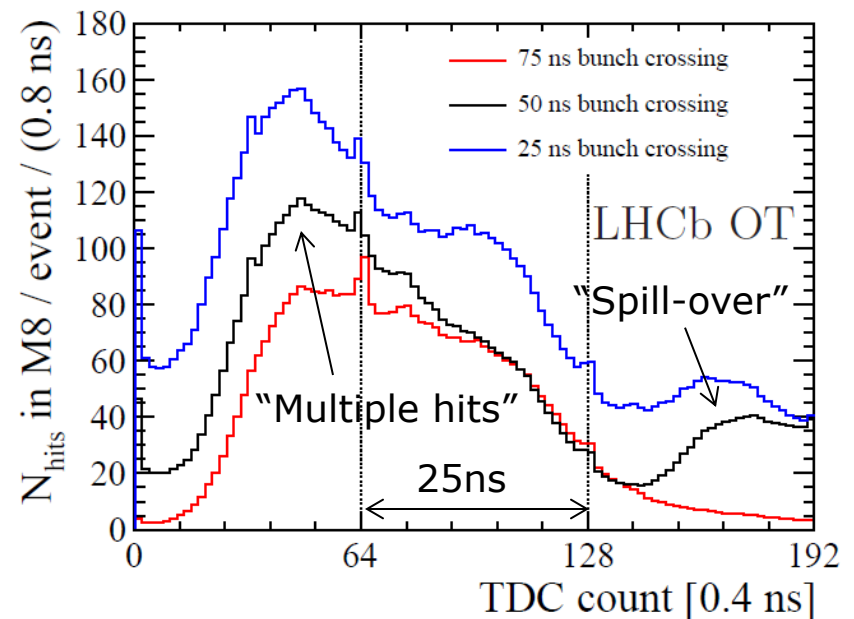
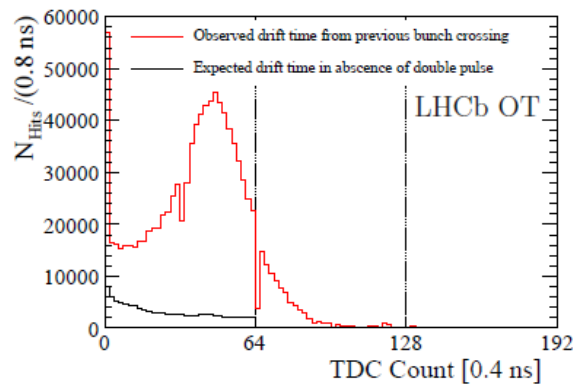


OT Performance in LHC Run I – Drift time spectrum



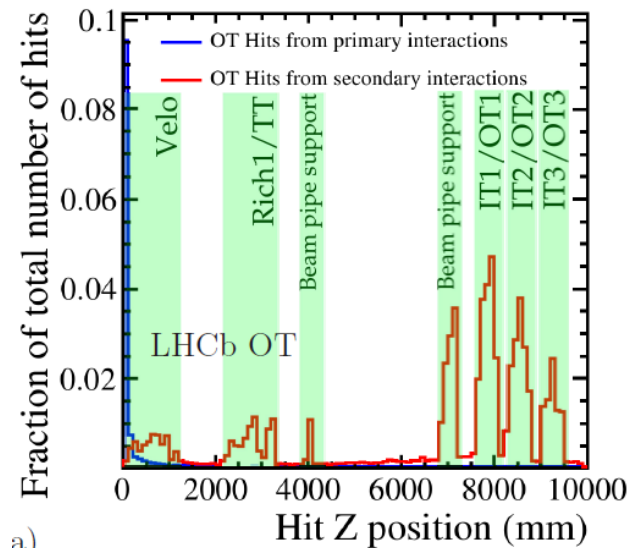
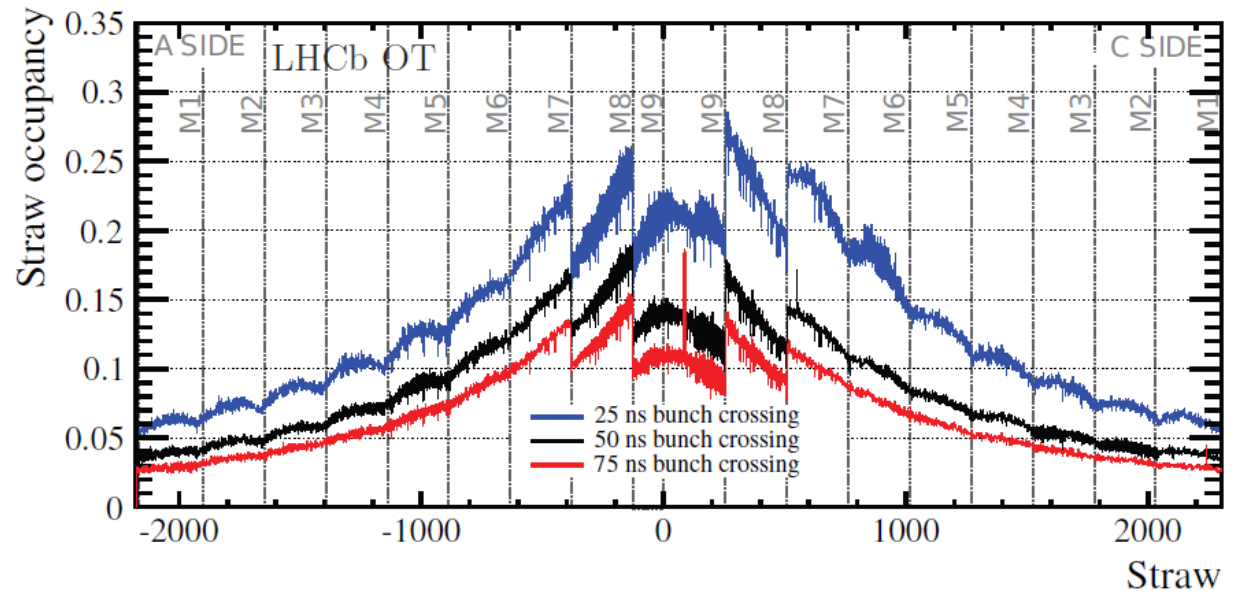
(c)

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

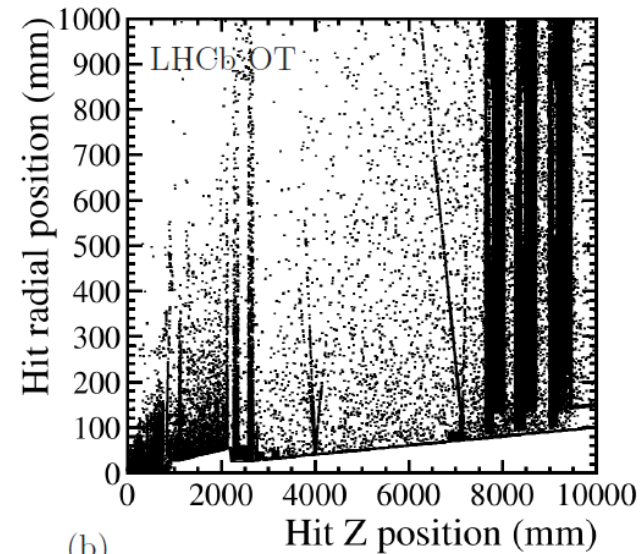


OT Performance in LHC Run I – Occupancy

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



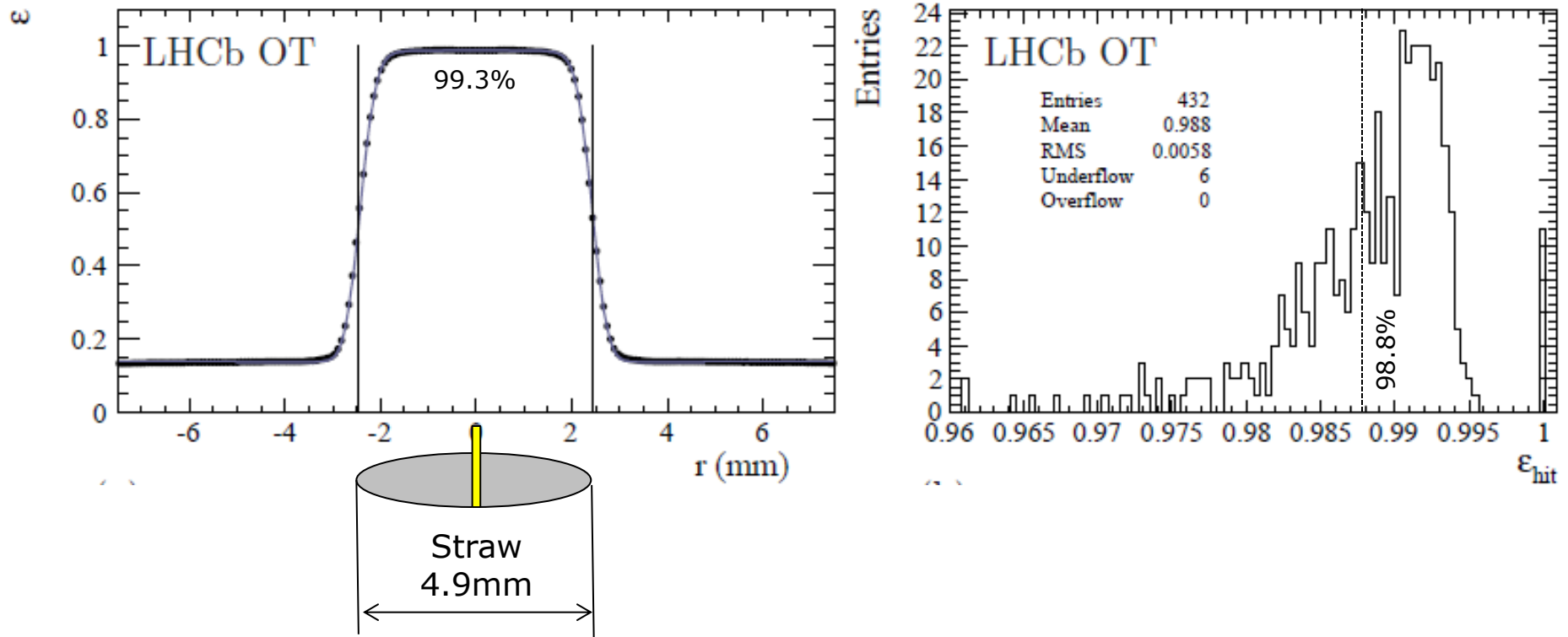
a)



b)

OT Performance in LHC Run I – Efficiency

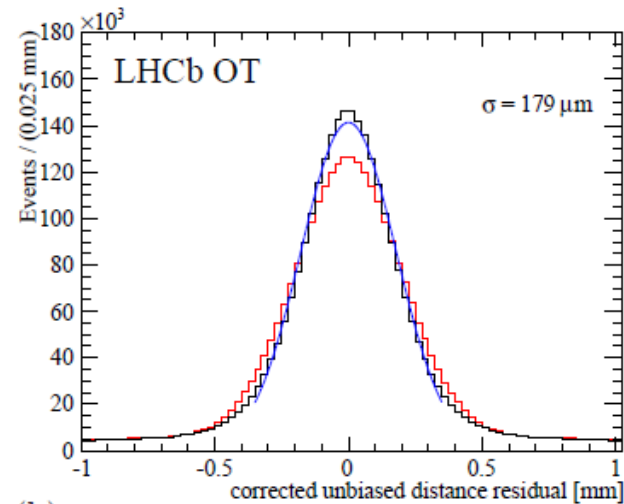
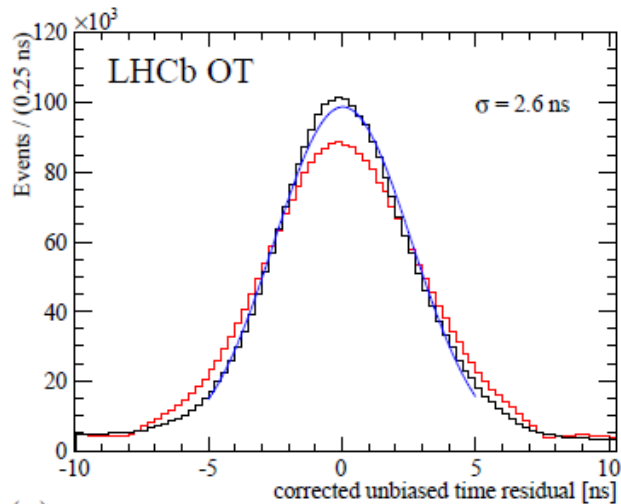
- Efficiency to detect hit in center of cell $|r| < 1.25\text{mm}$: \sim **99.3%**
- Average efficiency per module: \sim **98.8%**



➤ **Single hit efficiency $|r| < 1.25\text{mm}$: \sim 99.3%**

OT Performance in LHC Run I – Alignment/Resolution

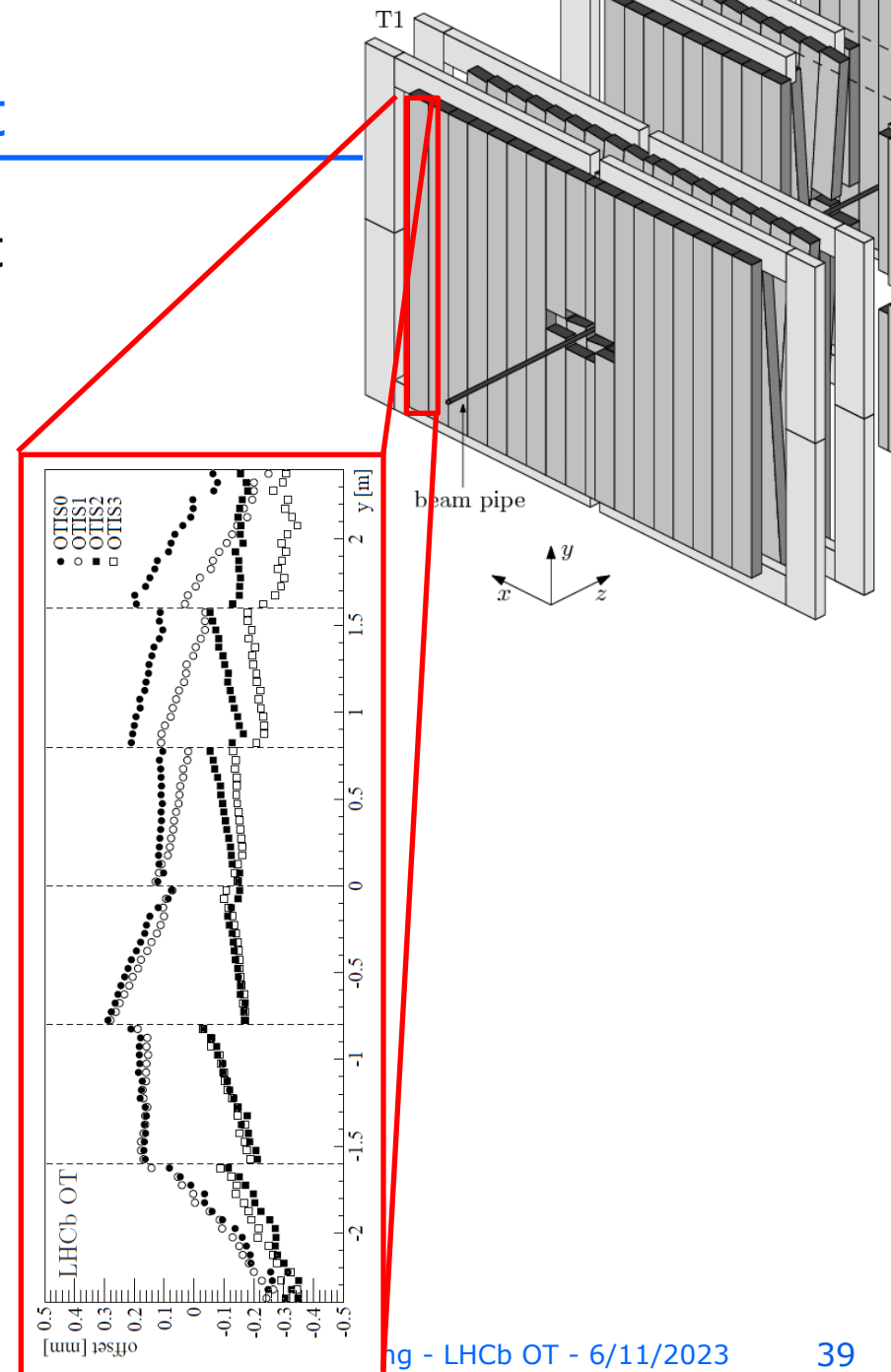
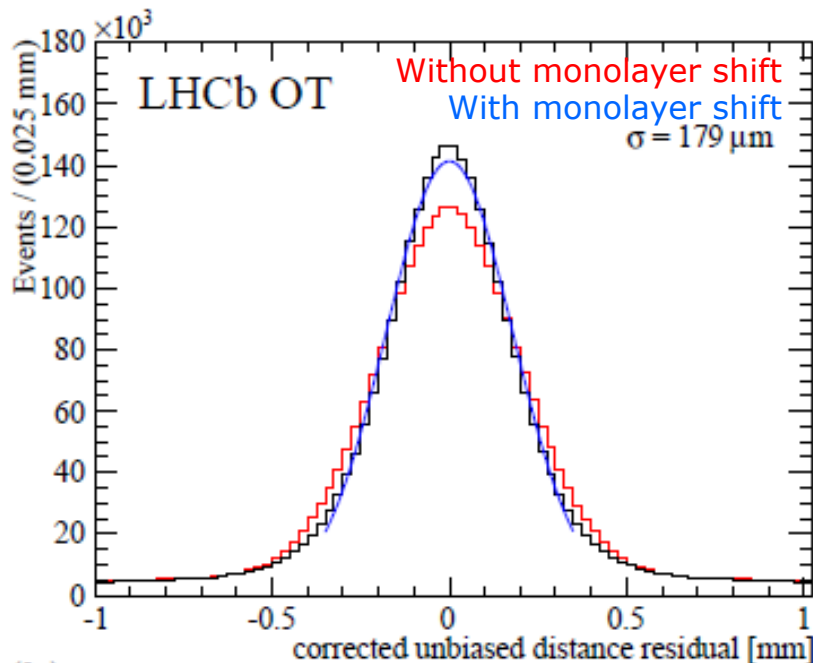
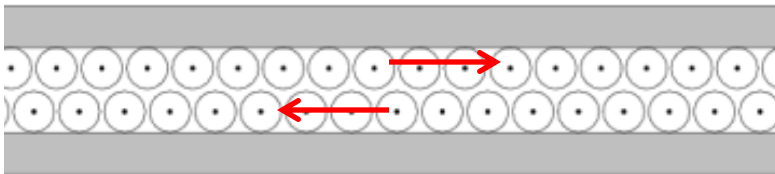
- Design specification: 200 μm
 - Straws accurately positioned in module $\pm 50 \mu\text{m}$
 - Module hung with accuracy of $\pm 50 \mu\text{m}$ (\rightarrow are modules straight?)
 - Frames positioned within $\pm 1 \text{ mm}$
 - Optical survey $\pm 0.2 \text{ mm}$
 - Final alignment with tracks



- **Internal alignment of mono-layers within a module improves resolution 210 \rightarrow 180 μm**

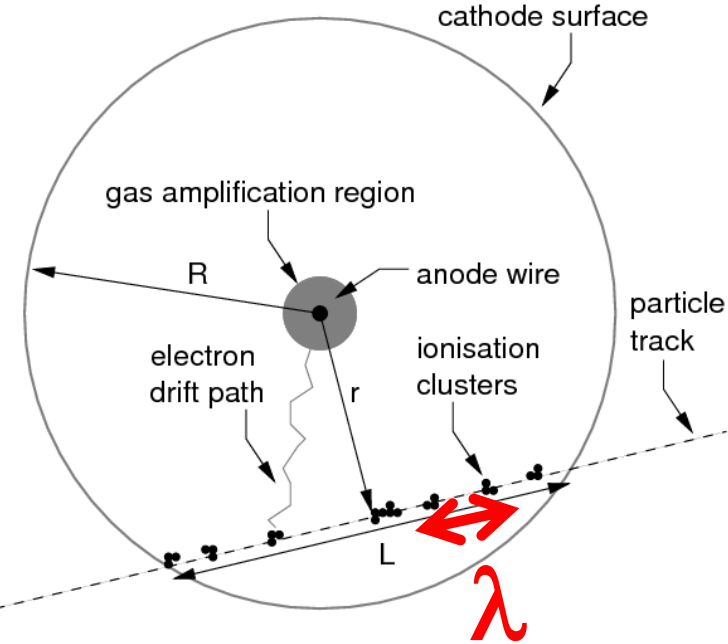
Internal module alignment

- Recently improved alignment
- Relative shift of monolayers
- Resolution 210 \rightarrow 179 μm

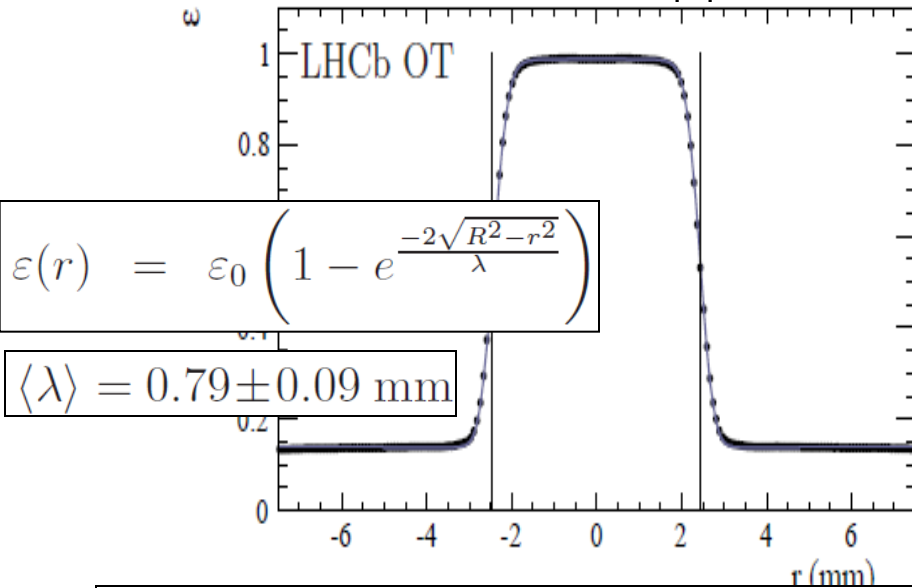


Ionization length

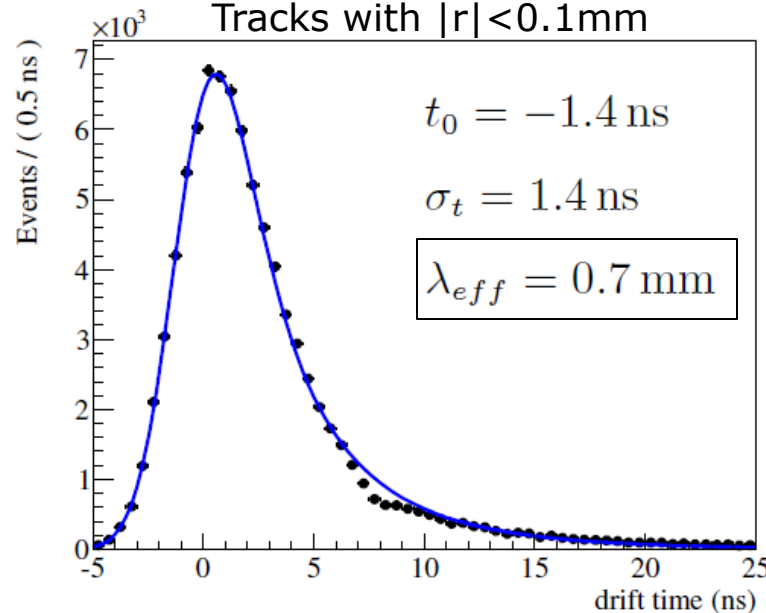
- Ionization length λ :
average distance between clusters
- Measured *effective* λ in two ways:
 - 1) Efficiency profile: probes large $|r|$
 - 2) Drift time distribution: probes small $|r|$
 ➤ Disentangle effect of absorption



Probe hits close to $|r|=2.4\text{mm}$



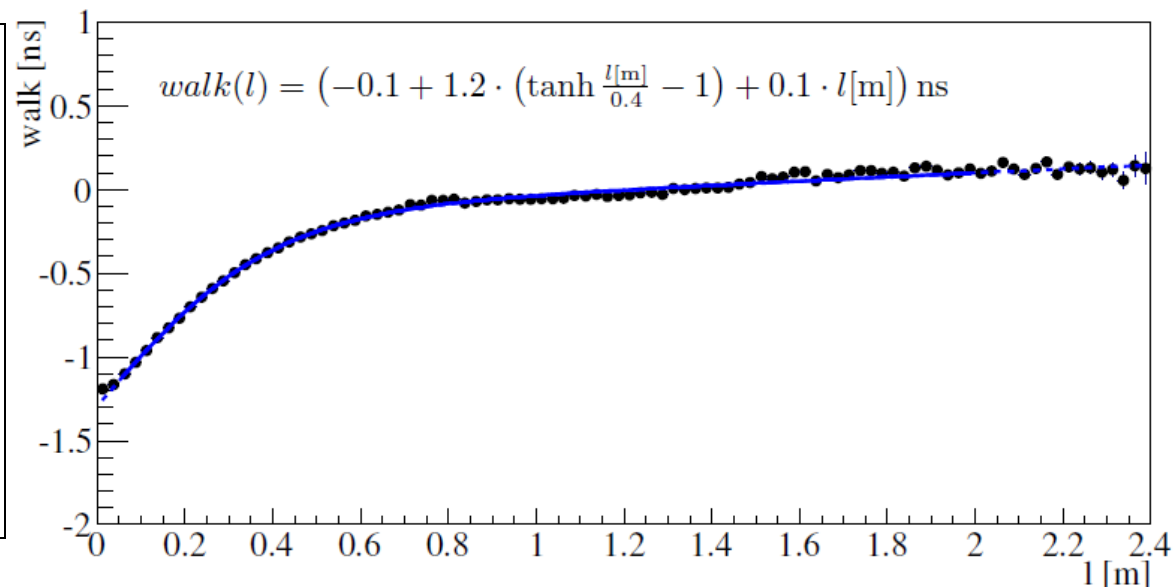
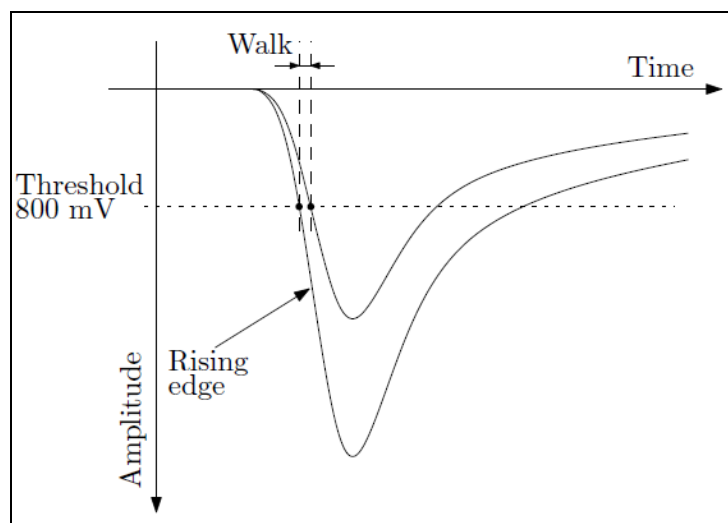
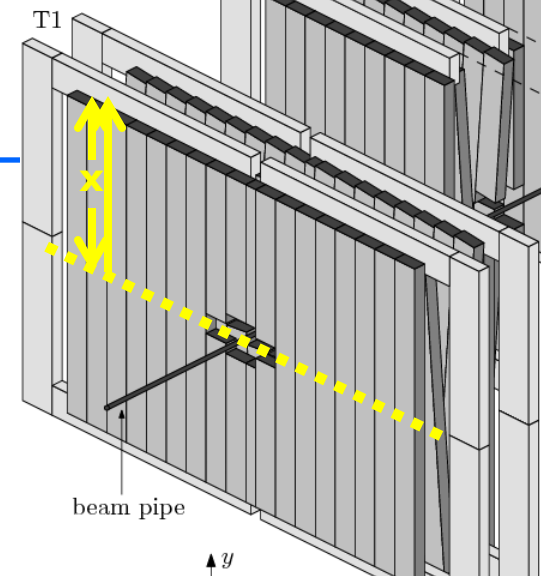
Tracks with $|r| < 0.1\text{mm}$



➤ λ_{eff} 2x larger than nominal; not due to absorption

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**