MUST have PaSTa

Anastasios Belias, Shreya Roy

Outline

- Introduction to MUST
- Feasibility results summary
- Pasta in mCBM
- Preliminary data analysis of PaSTa (Panda STraws)
- Status & News
- Summary

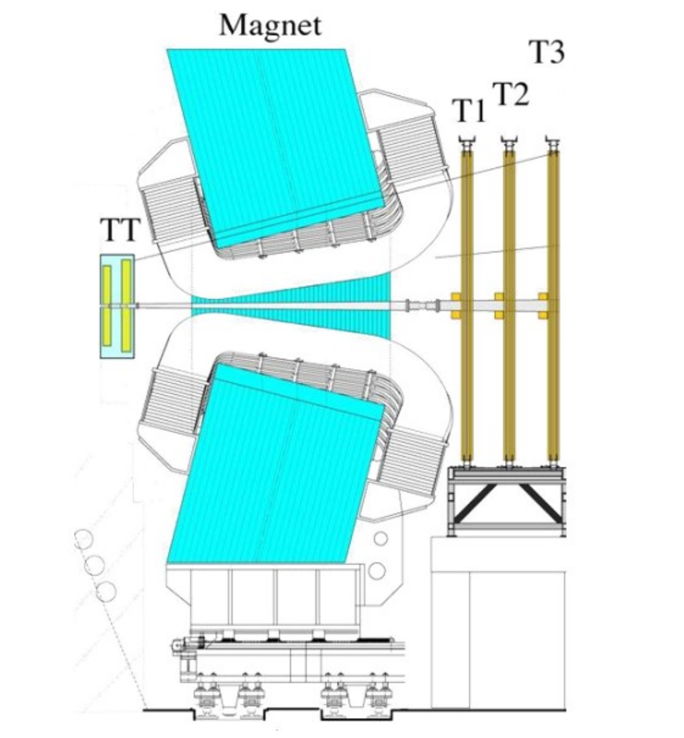
The LHCb Outer Tracker story..

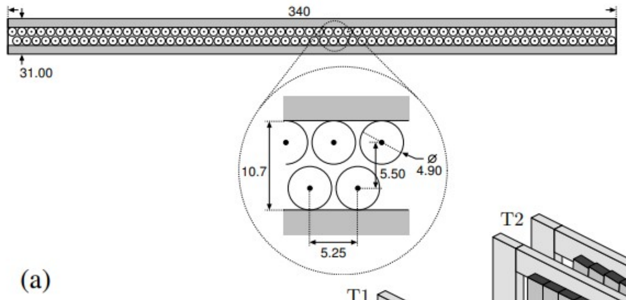
- 2004: start construction
- 2005: end construction
- 2008: installation in LHCb
- Run1 & Run2 (2011-13, 2015-16)
- 2018: end of operation
- 2023: shipment to GSI, Darmstadt

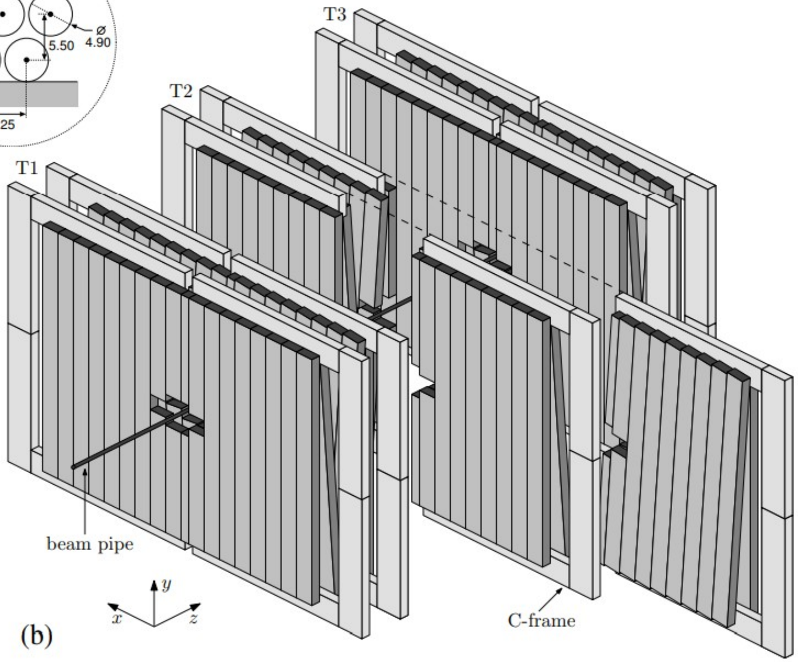
Final parameters

- 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

The LHCb Outer Tracker







256 straws/module
Total 53760 straws

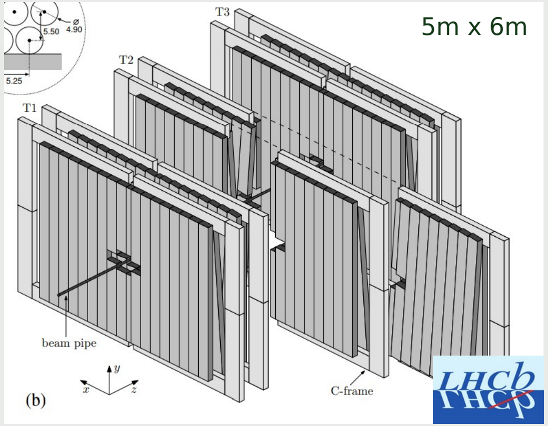
14 F/module
8 S/module

F type = 4.85m length
S type = 2.5m length

Introducing the MUST

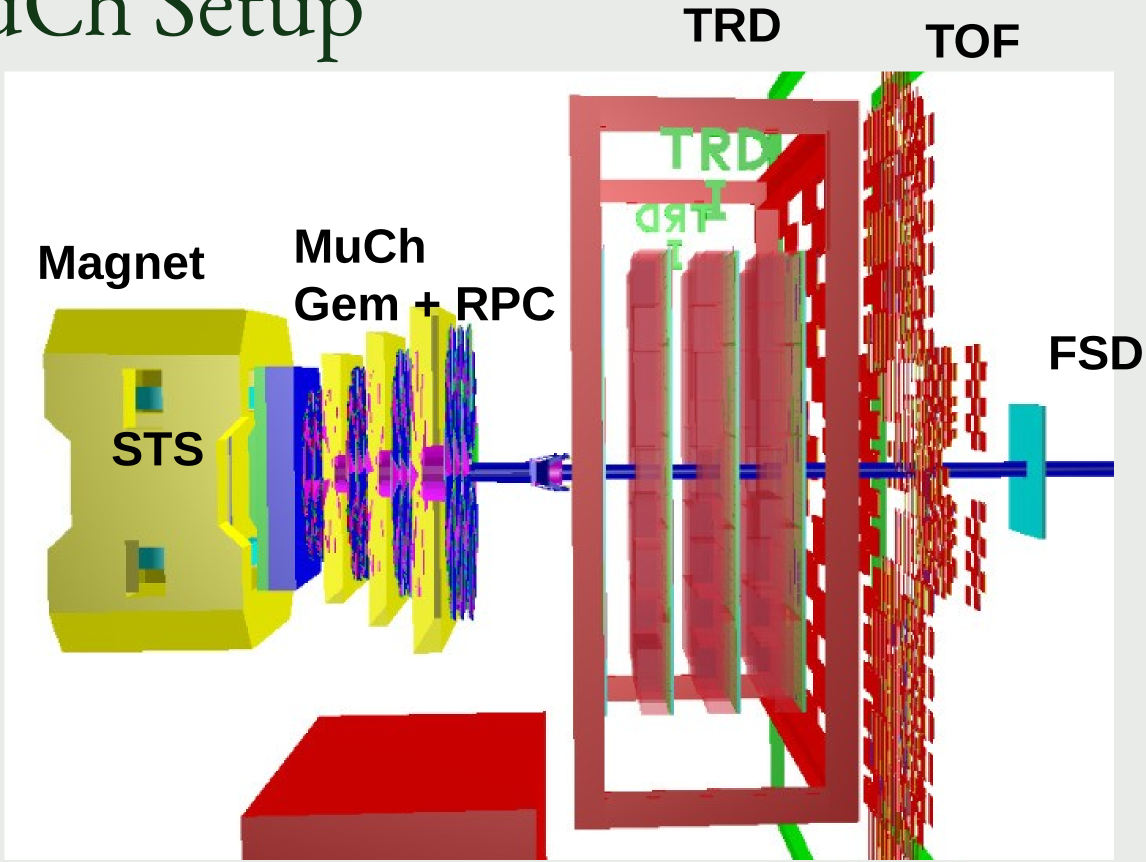
MUon STraws

LHCb Outer Tracker



CBM

CBM MuCh Setup



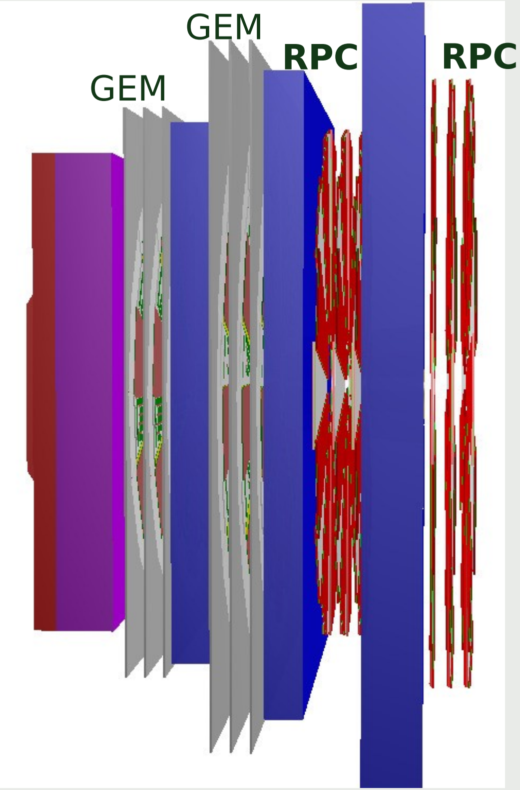
Beam

Geometry version :

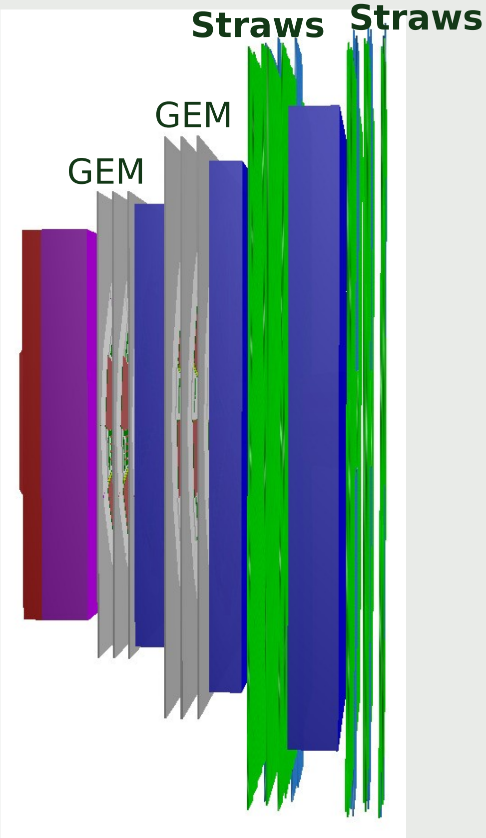
MuCh detector (SIS100 design)

Option 1

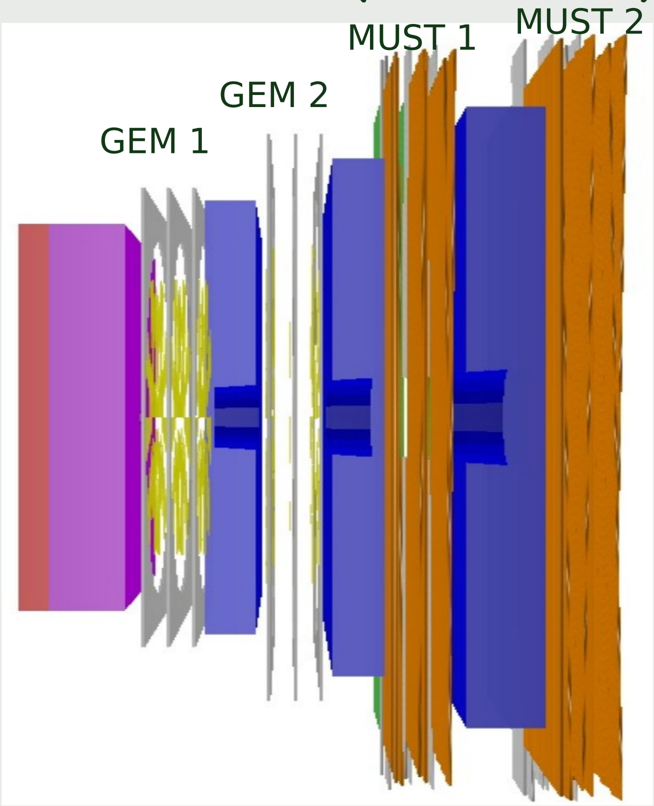
????



Option 2

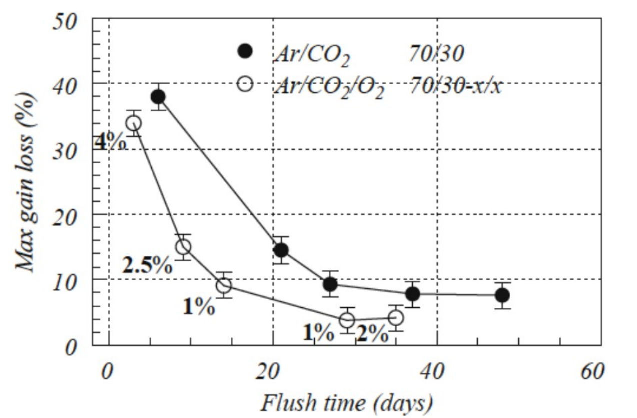


Proposal : MUon STraws (MUST)



Status of the LHCb OT

LHCb-CONF-2009-019



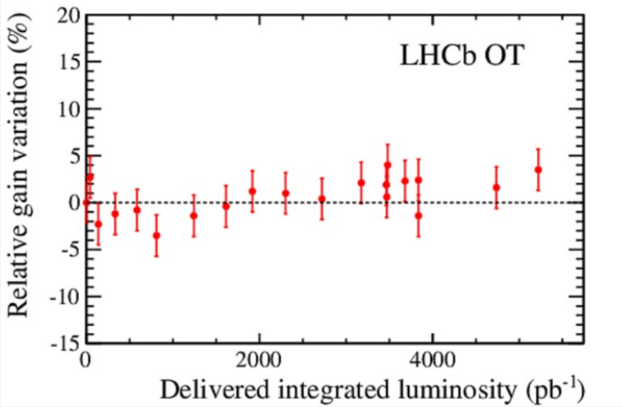
Aging :

- The culprit : Glue sample shows outgassing
- Solution : adding 1.5% Oxygen prevents deposits, (formation of O3) …..some chemistry involved

S.Bachmann et al., The straw tube technology for the LHCb OT, Nucl. Instr. and Meth. A 535 (2004) 171.
S.Bachmann et al., Ageing in the LHCb Outer Tracker, Nucl.Instr. and Meth. A 617 (2010) 202.

Summary:

- High hit efficiency (>99%)
- Handled 5 MHz rates/straw
- Good resolution (~200 μm) with BX clock
- No irradiation effects observed (~0.4 C/cm in hottest region)

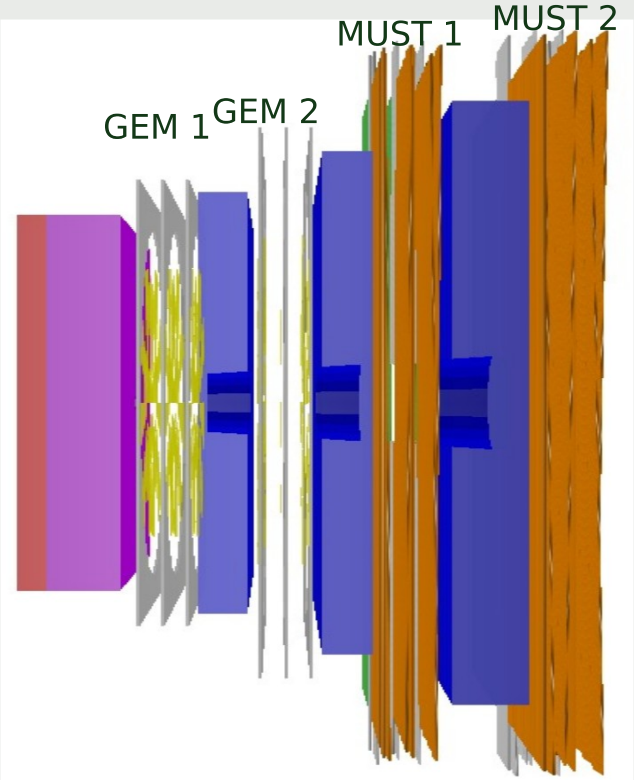


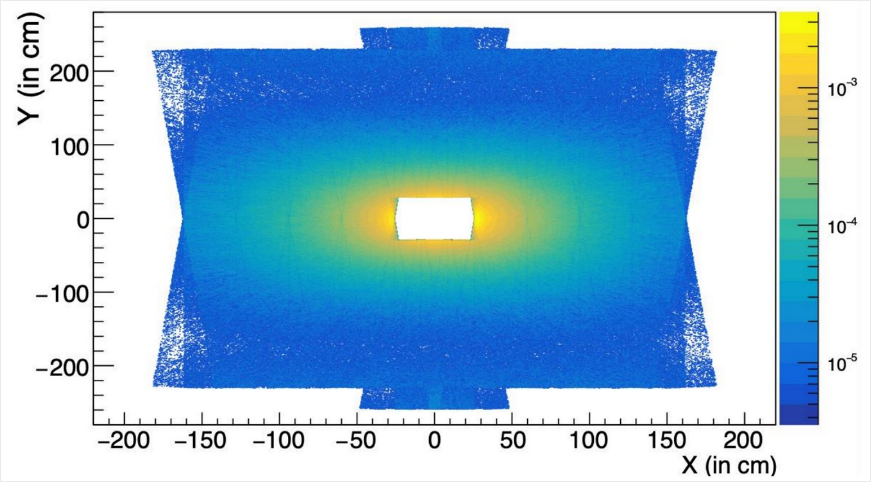
https://indico.cern.ch/event/1237829/contributions/5609613/attachments/2746316/4778770/OT_Performance-final.pdf

MUST Simulation : First feasibility study

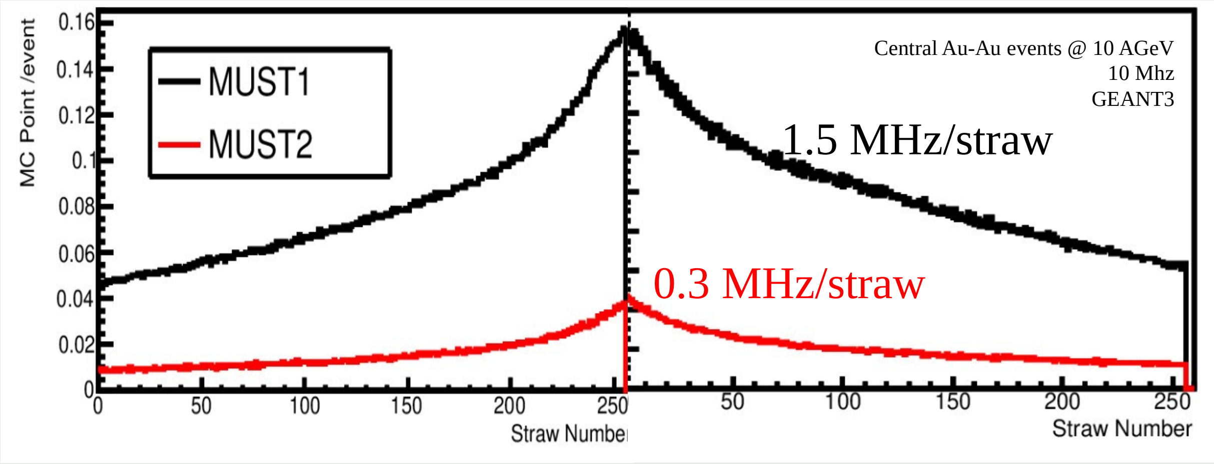
The task force team :
David Emschermann, Radoslaw Karabowicz, Anna Senger, Florian Uhlig, Saikat Biswas, Supriya Das, P. P. Bhaduri
Zubayer Ahammed, Abhishek Kumar Sharma, Anjali Sharma, Somen Gope

Particle rates





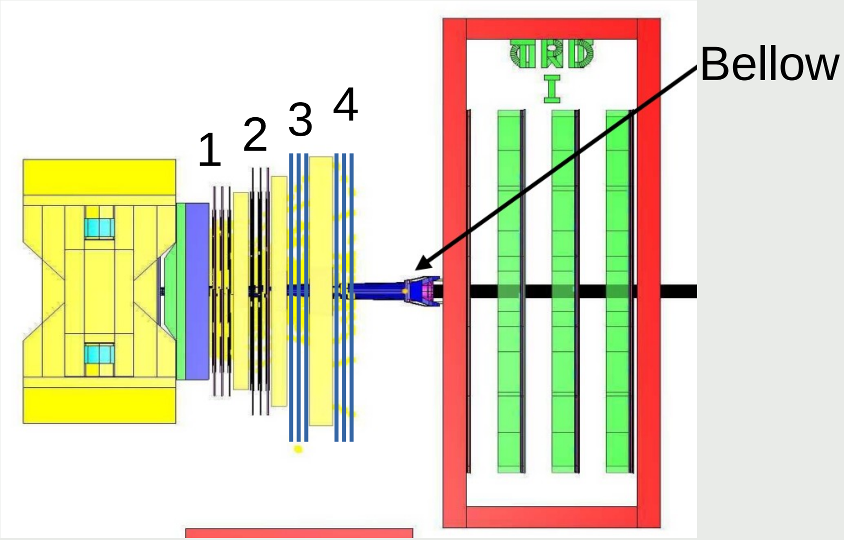
~ A. Sharma

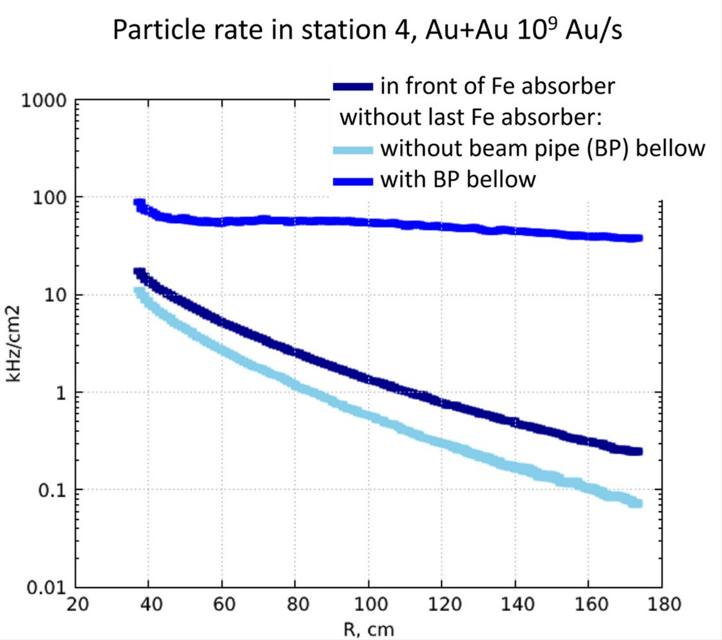


~ A. K. Sharma

Remark : Maximum particle flux in LHCb OT ~ 5 MHz/straw

Beam pipe bellow effect





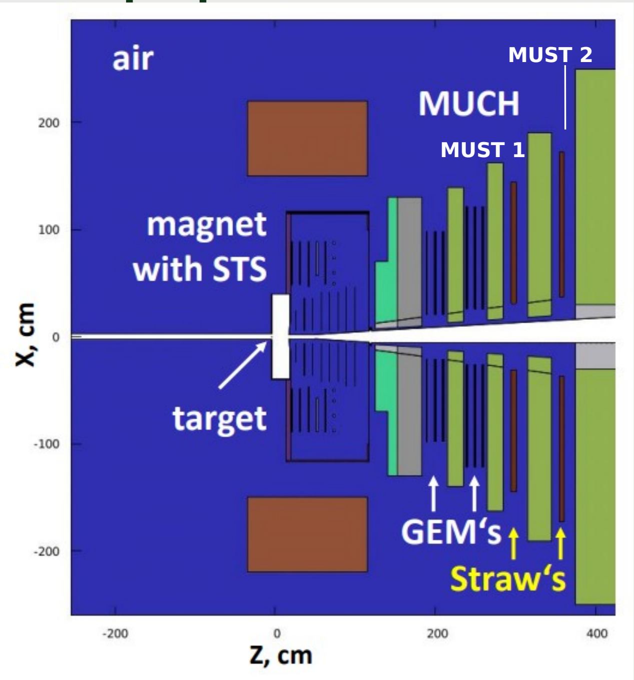
~ A. Senger

Particle flux (maximum) near beam pipe

FLUKA results : 12 AGeV Au beam or 29 GeV p beam

System	Beam rate (ions/sec)	MUST1 (kHz/cm²)	MUST2 (kHz/cm²)
Au+Au	10^9	40	15
p+p	10^9	1	0.5
p+Au	10^{11}	140	50
p+p	10^{11}	100	40

– Preliminary numbers from A. Senger



Remark : Maximum particle flux in LHCb OT ~ 200 kHz/cm^2

Further results (follow up discussion)

1. Radiation dose (1 month CBM) = max 50 Gy or 0.025 C/cm

2. Charge accumulated in 1 year = 0.2 C/cm

3. Maximum occupancy : MUST 1 = 8%, MUST 2 = 4%

3. Double hit occupancy = max 0.13%

4. Spatial resolution without the drift time = 0.7 mm (estimated number)

5. Hit reconstruction efficiency = 96-98% (expected)

6. Modules needed for MUST 1 = 72, MUST 2 = 84

MUST software – on the way!

Merged **Prepare framework for new MUST detector subsystem** updated 3 months ago

Computing / cbmroot !2101 · created 5 months ago by Florian Uhlig

Remove ECbmModuleId::kEcal from the enumerator and reuse the connected integer value 7 for the new entry ECbmModuleId::kMust. Remove all usage of ECbmModuleId::kEcal from the source code and implement...

CodeOwners Framework core

Open **Draft: Add the new MUST detector system** updated 2 weeks ago

Computing / cbmroot !2138 · created 3 months ago by Florian Uhlig

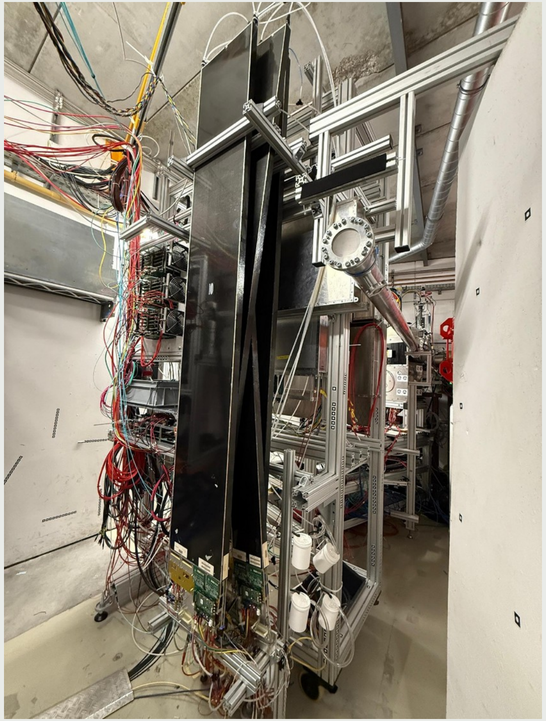
This MR ist based on and supersedes !2040 Initially !2040 included also changes to the framework code of CbmRoot. These changes were properly separated and were added with !2101 such that !2040 only ...

CodeOwners

https://git.cbm.gsi.de/computing/cbmroot/-/merge_requests/2138

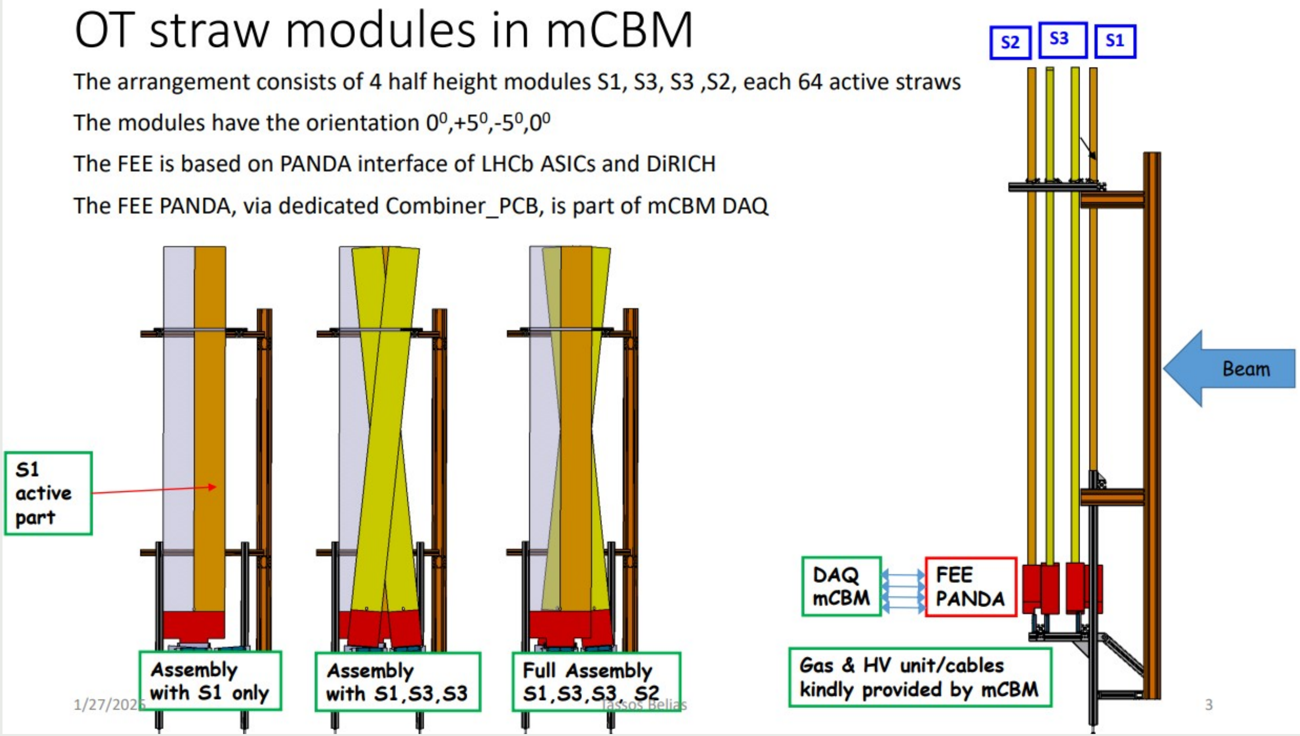
MUST Task force concluded (June 2025)

MUST have PASTA (**PA**NDA **ST**r**A**ws in mCBM)



David Emschermann, Radoslaw Karabowicz, Stefan Koch, Bartosz Sobol, Saikat Biswas, Supriya Das, S. K. Prasad, Somen Gope, Subir Mandal, Souvik Chattopadhyay, Prithwish Pramanick, Shruti Patra, Anuska Dey, Swastika Sarkar

MUST have PASTA

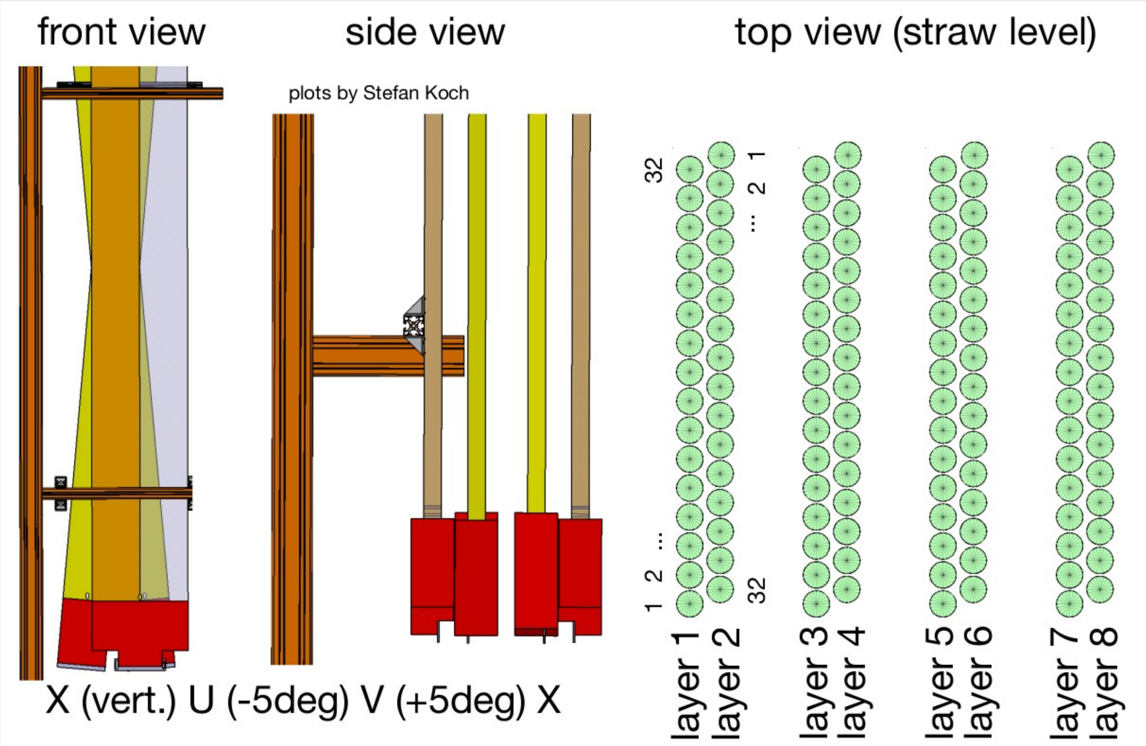


Follow mCBM meetings for more information.

mCBM cave

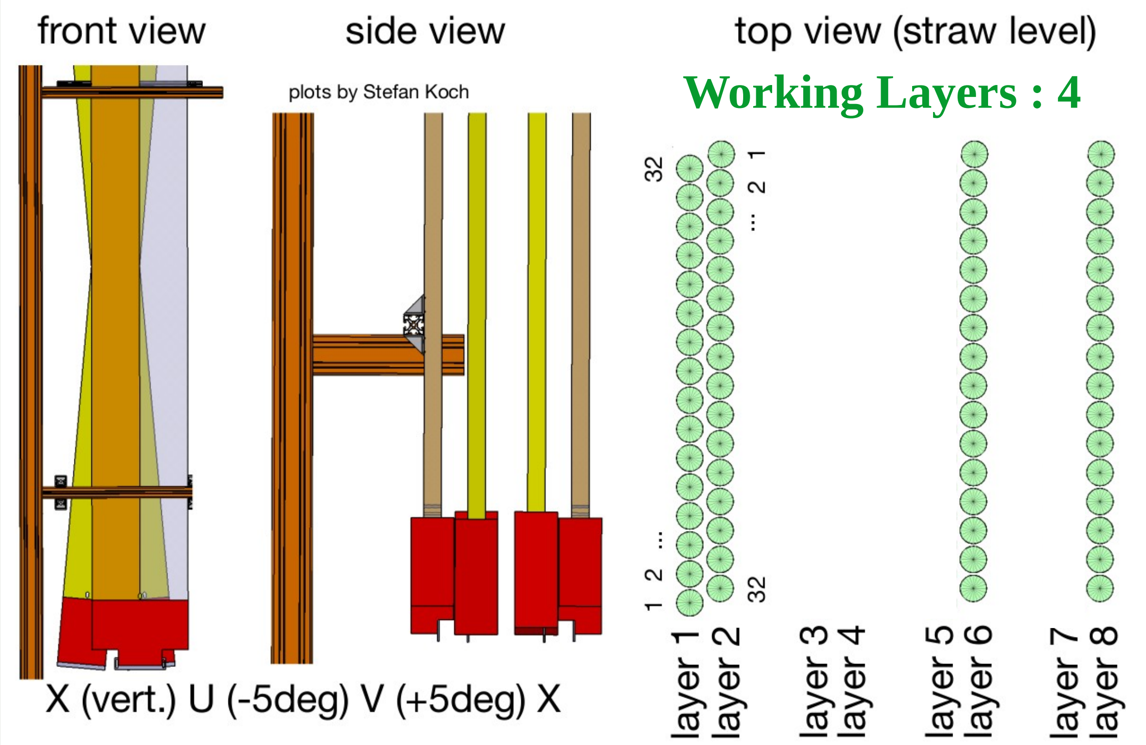
Slide from A. Belias

Geometry of PASTA



- Number of Layers : 8
- Each layer has 32 straws
- High Voltage (HV): 1500 V
- Threshold: 70 mV
- Gas : Ar/CO_2 70:30

Geometry of PASTA in 2025 beamtime



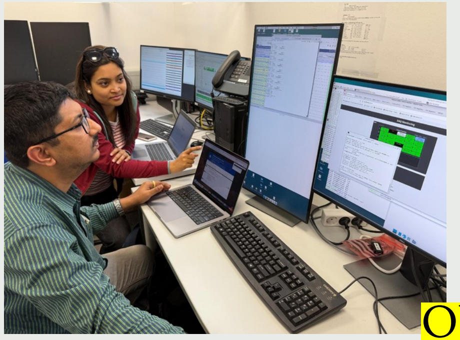
- Number of Layers : 8
- Each layer has 32 straws
- High Voltage (HV): 1500 V
- Threshold: 70 mV
- Gas : Ar/CO_2 70:30

<u>Beamtime information</u>

- Beam Time: May 16–19, 2025
- Beam Setup: 26-Fe (26+)
- Beam Energy: 1.7 AGeV
- Target: 4mm thick Nickel (Ni)
- Rate: 10^7 per 10-second spill

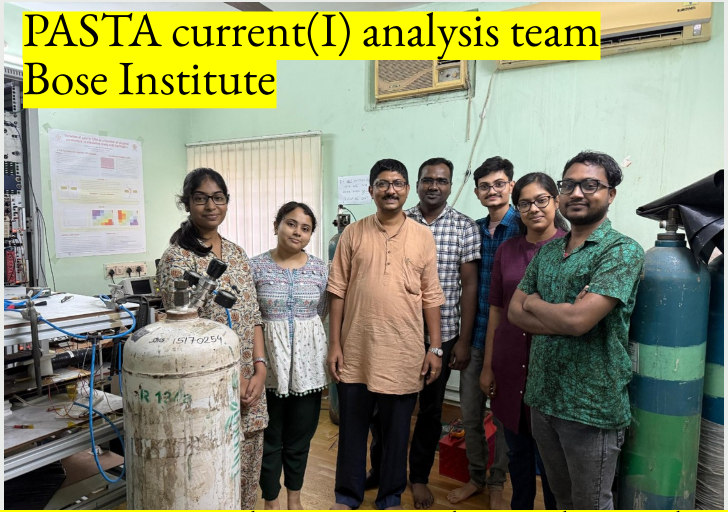
PASTA data monitoring

Data taking team at GSI



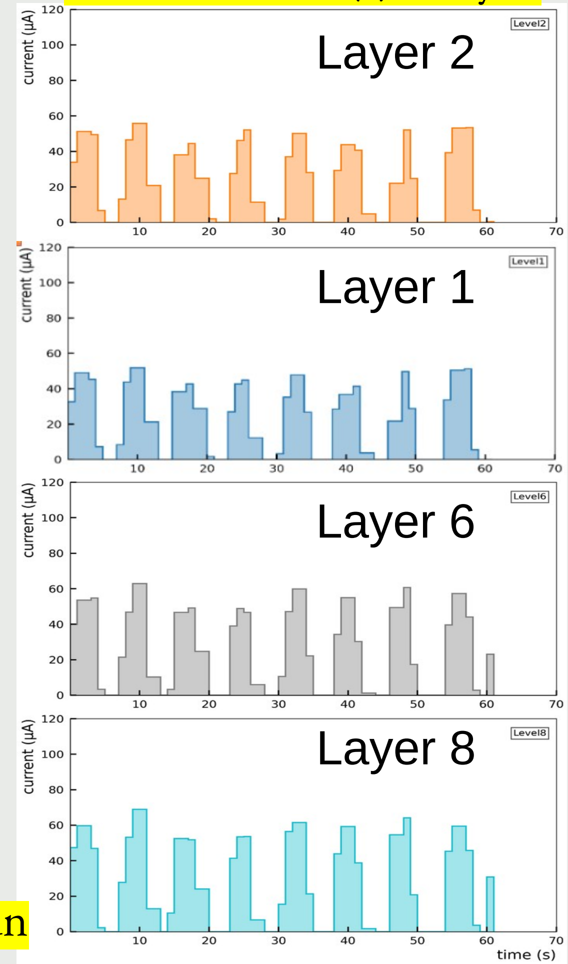
Date:19.05.2025, Time: 04:08,
Flow Rate: 8.2l/h, Anode voltage: 1450V
Beam: ^{209}Bi, Beam Intensity: 8x10^{8} per 6s,
Run No: 4076

PASTA current(I) analysis team
Bose Institute



Observation : Steady current throughout the run

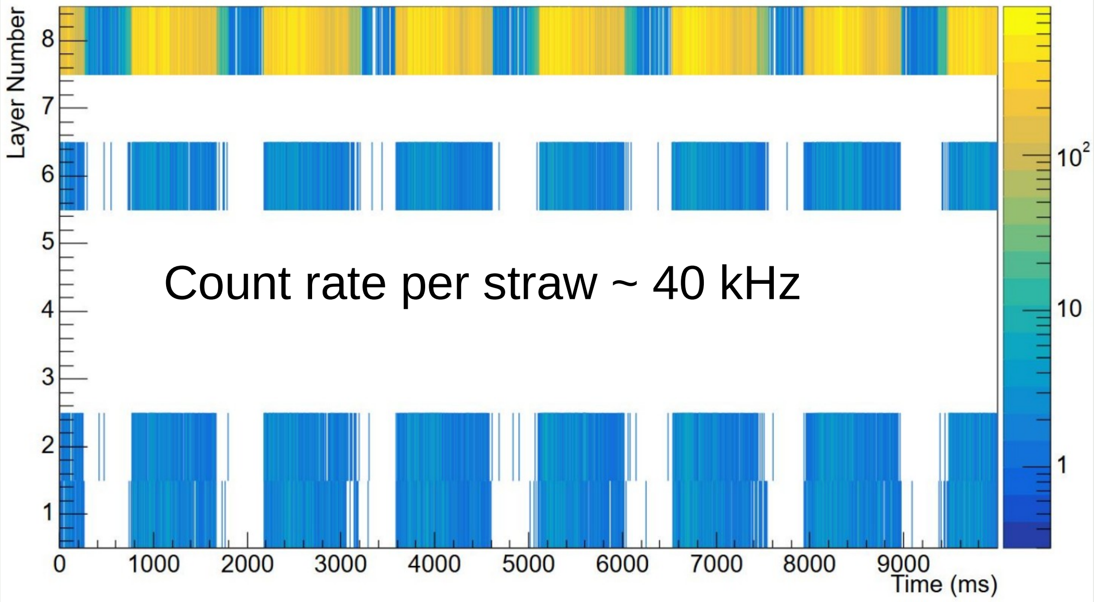
PASTA current(I) analysis

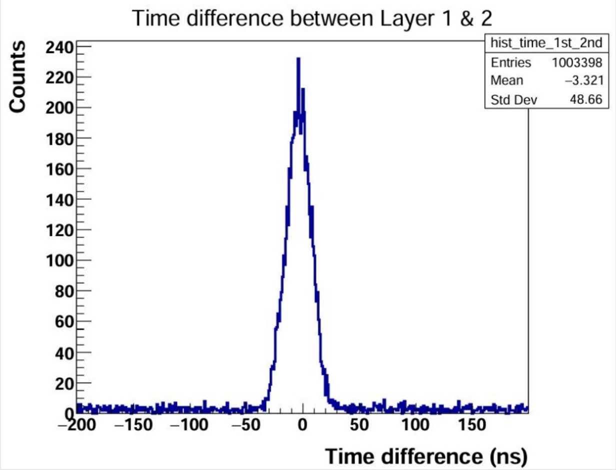


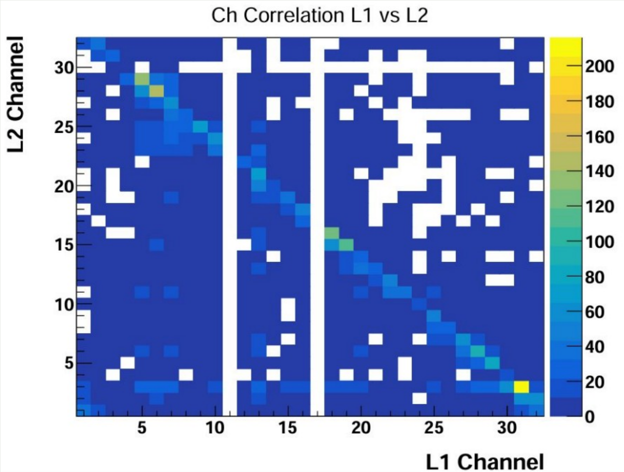
Work in progress

PASTA data analysis

Beam Setup: Fe(26+), Beam Intensity: ~10^7 /spill
Target: Ni (4mm) , Run Number = 3859, HV = 1500 V







~ S. Chattopadhay

https://indico.gsi.de/event/22738/contributions/91244/attachments/52212/77941/mCBM%20with%20PASTA%20final_1.pdf

News

“Memorandum of Understanding between CBM and PANDA indicate synergy in technical aspects and a broader opportunity for scientific collaboration opening new avenues for hadron physics using the CBM detector”- Prof. T. Galatyuk

**Memorandum of Understanding
between
the PANDA and the CBM
collaborations**

Purpose of the MoU:
This document regulates the cooperation between the CBM collaboration and the PANDA collaboration in the context of FAIR Day-1, under participation of the CBM collaboration and a group of members of the PANDA collaboration, hereinafter called PANDA@CBM.

The objective of PANDA@CBM is to participate in the CBM experiment in the period before the start of the PANDA experiment.

The interest of this group serves two purposes.
First, detector systems, technologies and methods foreseen in PANDA (such as tracking detectors, readout electronics, software modules, online computing, trigger development as part of computing etc.) can be used and tested under realistic experiment conditions.

Second, the group can participate in physics analyses and publication of results ... the effort and support by national funding agencies towards a realization ...

The CBM collaboration, on the other hand, can strengthen the ... years of running by adding available instrumentation, manpower a...

The goals are: (1) to identify, execute and analyze joint experim... publications in CBM@FAIR and (2) to retain expert knowledge and ... for the anti-proton physics experiments of PANDA@FAIR.

Structure of the MoU:
This MoU contains two sections, the first single MoU section (A) and the ... (B) with one or more supplements/addenda specific to each project of coo...

In the main MoU section we address all aspects which are meant to be und... lifetime of the agreement while each specific cooperation initiative forms a s... main MoU.

This MoU has been approved by the CBM and PANDA Collaboration Boards and is signed by spokespersons of both collaborations:

Dates of signatures: 30.09.2025

Kai-Thomas Brinkmann
Spokesperson of the PANDA collaboration

Tetyana Galatyuk
Spokesperson of the CBM collaboration

MUST timeline

May 2024	Nov 2024	Jul 2025	Oct 2025	Nov 2025	Soon next..
The idea	Task force OT CBM PANDA formed	Task force OT CBM PANDA concluded	MoU CBM PANDA for MUST signed	ECE meeting & outline of LOI for MUST	LOI & Realizing MUST

Summary

- The MUST task force group have held 8 meetings with interesting discussions on MUST geometry and simulations.
- First feasibility results from the MUST simulations were presented.
- Currently, as of now, we see no show stopper in using these straws in CBM at positions MUST 1 and 2 within MUCH subsystem.
- MoU between CBM and PANDA was signed on October 7 2025.
- Next step : towards Letter of Intent.

Thank You

Back ups

1.Gy to C/cm

1 cm of straw ~ 0.33 mg of Ar/CO_2

1.47 C/kg = 1.47 x 0.33 x 10^{-6} C/cm x Gain (5 x 10^4)

= 0.024 C/cm (MUST1 near beam)

Density Ar = 1.6 kg/m^3

Density CO_2 = 1.9 kg/m^3

Volume of straw tube gas in 1cm length = 0.196cm^3

https://www.convert-me.com/en/convert/radiation/rrgray/rrgray-to-rrcperkg.html?u=rrgray&v=50

2. Accumulated charge in 1 month of CBM

Irradiation tests with straws were performed upto 2C/cm ~ 10 years of LHCb (detector gain 4×10^4)
In LHCb Run 1 and 2 total charge accumulated = 0.4C/cm in the hottest region (detector gain 5×10^4).
In CBM, the charge accumulated (detector gain 5×10^4) = Q (C/cm)

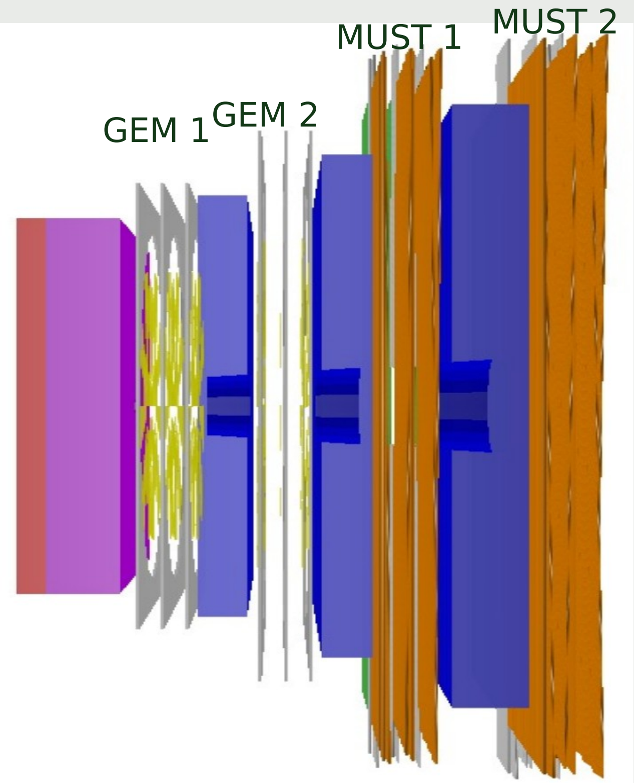
$$Q = n_{primary} . e . Gain . n^{MUST1}_{flux} . t . straw\varnothing$$

$$Q = 50 . e . 5 \times 10^4 . 50kHz . 1 \text{ month} . 0.5 \text{ cm}$$

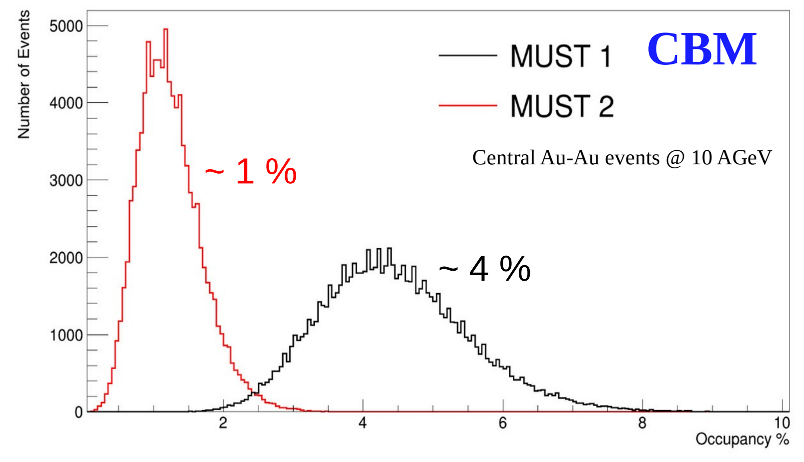
Q = 0.026 C/cm in the hottest region!

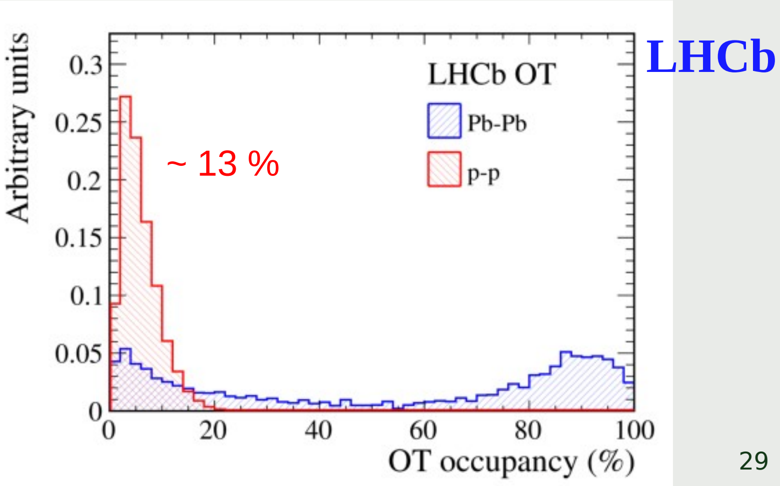
2C/cm is 125 months/ 10 years of operation in CBM environment.

GEANT3 results



Occupancy = $\frac{\text{no. of straws fired}}{\text{total no. of straws}}$





Ageing tests in LHCb

The S-module was irradiated with 9 keV X-rays for 60 days, with an intensity of about 500 kHz/cm, corresponding to an accumulated charge of about 1 C/cm. No significant irradiation damage was observed.

The F-module has been irradiated for 1200 hours, with a source profile as shown in Fig. 4, resulting in a total accumulated charge of 0.3 C/cm at the point of highest intensity of 70nA/cm. A negligible gain loss of 5% ± 2% was observed

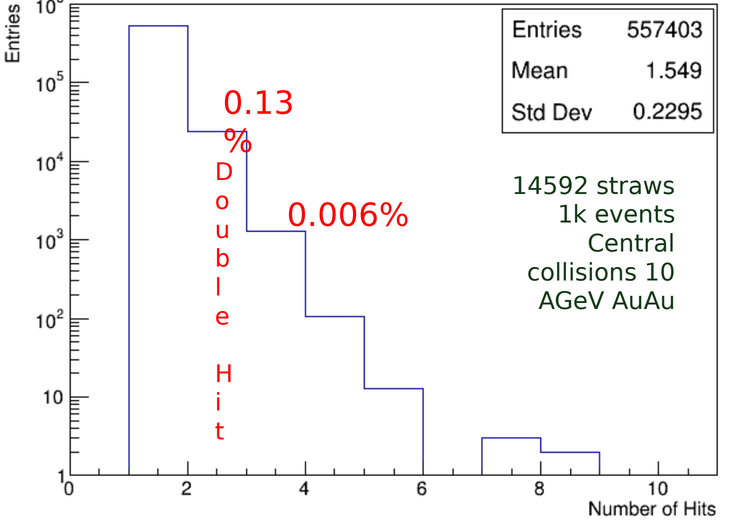
Nucl.Instrum.Meth.A 656 (2011) 45-50

3. Double hit occupancy

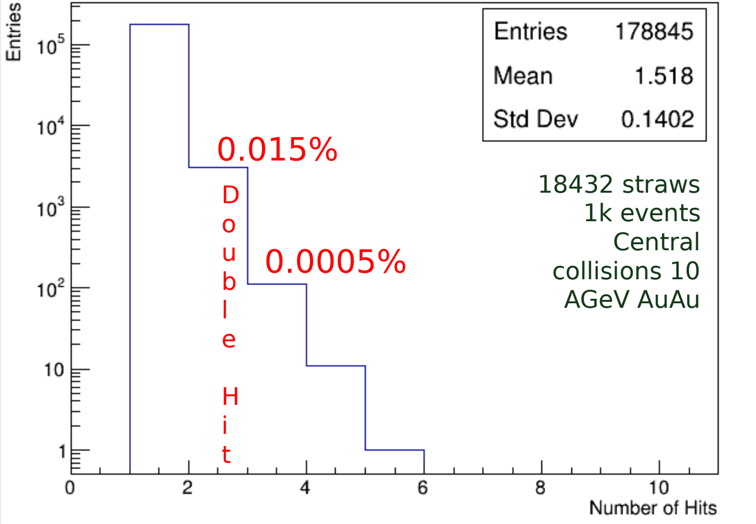
Very low but need to check

$$\% \text{ probability of n hits} = \frac{\text{Entries}}{N_{straws} \times n_{events}}$$

MUST 1



MUST 2



4. Spatial resolution without drift time

The spatial resolution of OT straws are 180µ , which the LHCb was able to achieve because of known bunch crossing time and the capability of the electronics to read the straw tube signal drift time, plus alignment.

In CBM there is neither bunch crossing info nor drift time measurement will be possible. Therefore, the MUST subsystem will have a spatial resolution that is proportional to the diameter of the straw 5 mm, more precisely using the well known formula $\sigma = d/\sqrt{12} = 5/\sqrt{12} = 1.44$ mm

Again, because of the staggered orientation of the straws (monolayers), the hit position resolution will improve by factor of two ~ 0.7 mm

In MuCh , 1 deg pad segmentation (1 & 2) was the requirement.

5. Hit occupancy in segmented straw 2cm

Question asked by Ingo Deppner (CBM TOF group). He asks to change the definition of the straws occupancy to similar to RPC occupancy which is calculated using RPC pad size of 2cm.

6. Reconstruction efficiency

Question asked by Ralf (PANDA collaboration). How does the spatial resolution of the straws affect the momentum resolution and reconstruction efficiency?

Ans. We will not reconstruct momentum with the MUST detector. Hit reconstruction efficiency will be determined after the implementation of the digitization (taking into account 99% hit efficiency of the straws) and reconstruction algorithms. Usually it is somewhere between 96%-98%.

7. Check FLUKA numbers for p+H_2

To be done by Anna

if we have 5 cm LH2, then we have the following areal density.
5 cm * 0.07 g/cm^3 = 0.35 g/cm^2

This times Avogadro’s number makes
0.35 g/cm^2 * 6*10^23 *2 (H-atoms/molecule) /mole / (2 g/mole (H2 molecule)) = 2.1 * 10^23 H-atoms / cm^2

For a total pp cross section of 50 mb we get an interaction probability of
2.1*10^23 H/cm^2 * 0.05 b * 10^-24 cm^2/b = 0.01 or 1% interaction probability

$$P = n \times \sigma \times d$$

Where P is the **interaction probability,** n is the number density of hydrogen atoms, and the cross-section (σ), d - target thickness

Particle flux (maximum) near beam pipe

12 AGeV AuAu

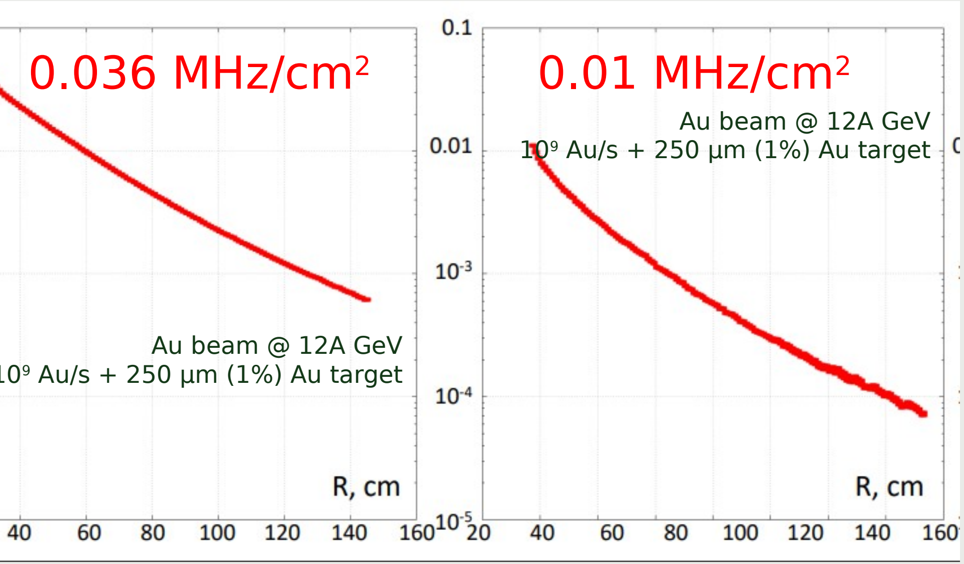
10 AGeV AuAu central

	FLUKA (straws) (MHz/cm^2)	GEANT3 (straws) (MHz/cm^2)	GEANT3 MuCh RPC (MHz/cm^2)
MUST 1	0.036	0.050	0.057 (3rd station)
MUST 2	0.010	0.010	0.015 (4th station)

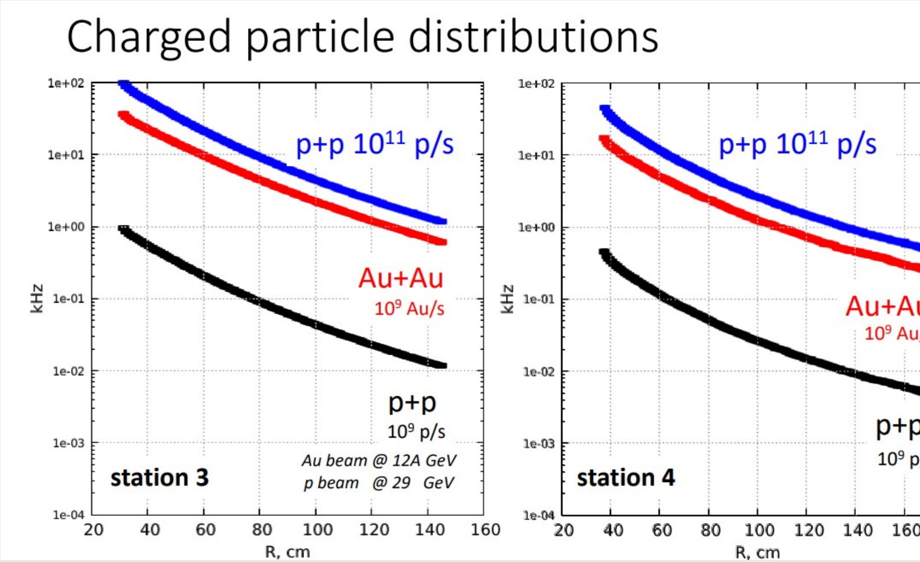
– Preliminary numbers

Remark : Maximum particle flux in LHCb OT ~ 0.2 MHz/cm^2

MUST 1 MUST 2



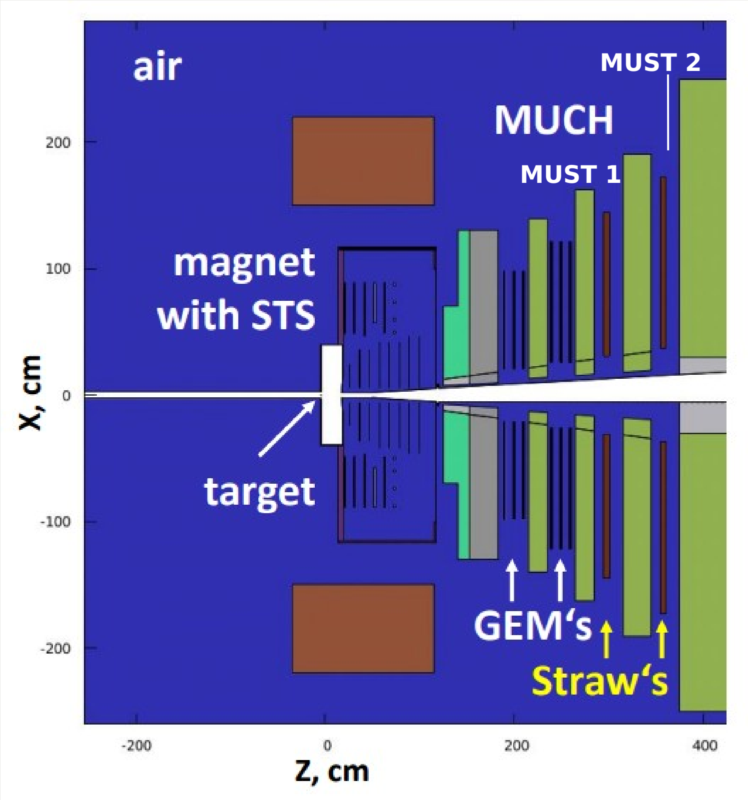
0.036 MHz/cm²
Au beam @ 12A GeV
10⁹ Au/s + 250 µm (1%) Au target
R, cm
40 60 80 100 120 140 160
0.1
0.01
10⁻³
10⁻⁴
10⁻⁵
0.01 MHz/cm²
Au beam @ 12A GeV
10⁹ Au/s + 250 µm (1%) Au target
R, cm
20 40 60 80 100 120 140 160



Charged particle distributions
p+p 10¹¹ p/s
Au+Au
10⁹ Au/s
p+p
10⁹ p/s
Au beam @ 12A GeV
p beam @ 29 GeV
station 3
station 4
kHz
R, cm
1e+02
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
20 40 60 80 100 120 140 160

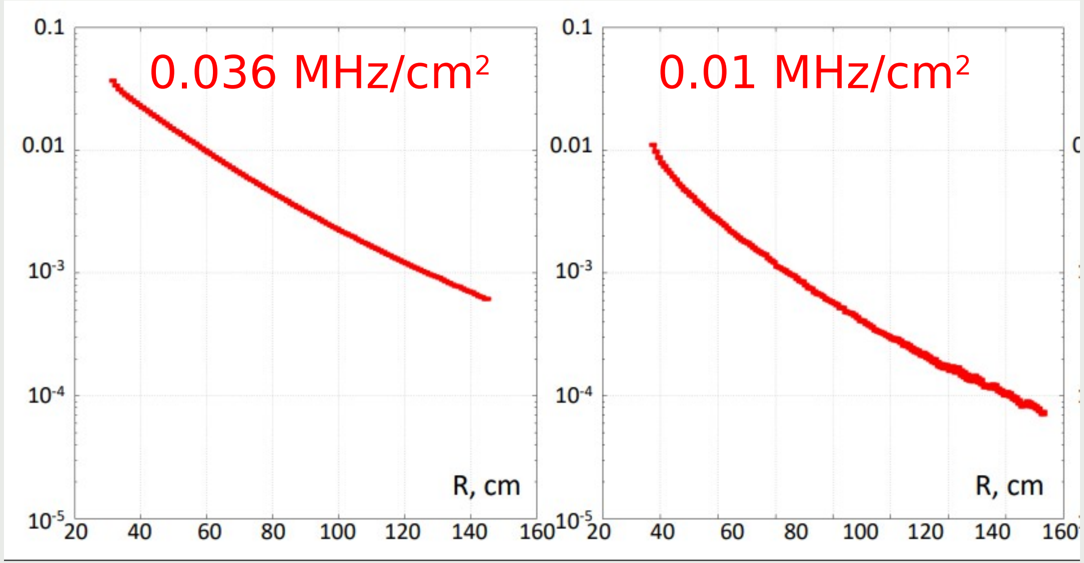
FLUKA results

Au beam @ 12A GeV energy
10^9 Au/s + 250 µm (1%) Au target



Charged particle rates

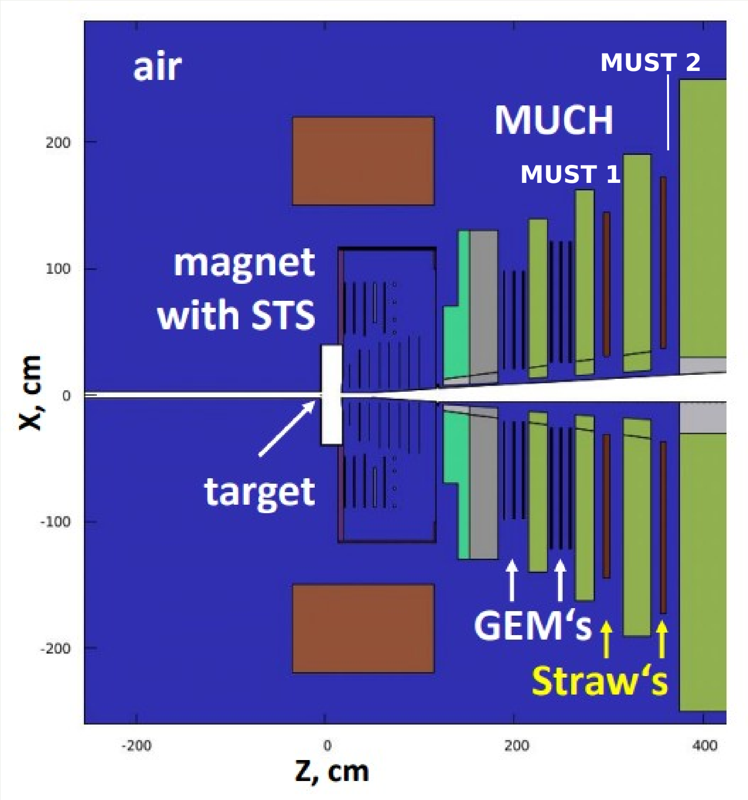
MUST 1 | MUST 2



- By Dr. Anna Senger

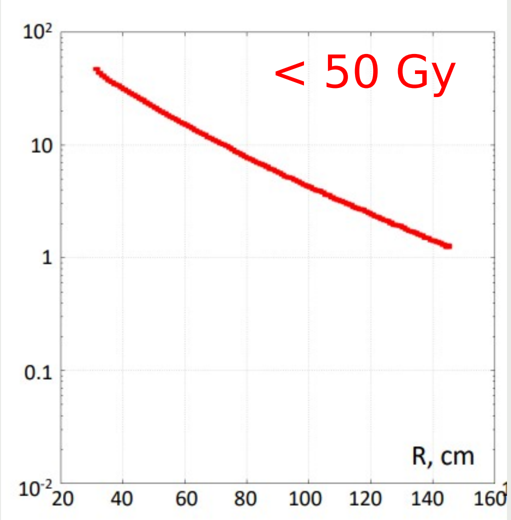
FLUKA results

Au beam @ 12A GeV energy
10^9 Au/s + 250 μm (1%) Au target

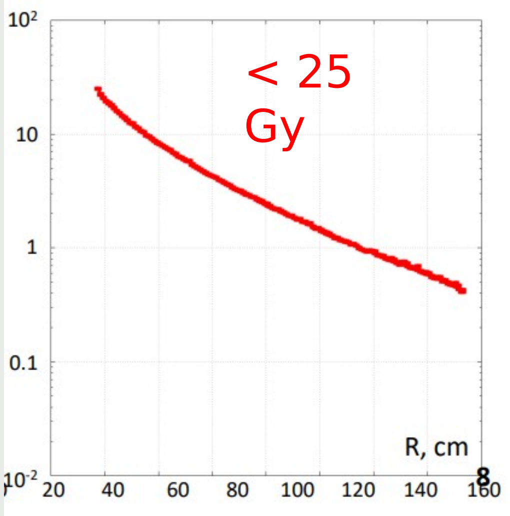


Radiation dose (Gy) after 1 month

MUST 1

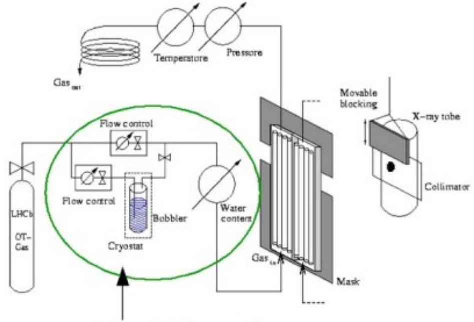


MUST 2



- By Dr. Anna Senger

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.

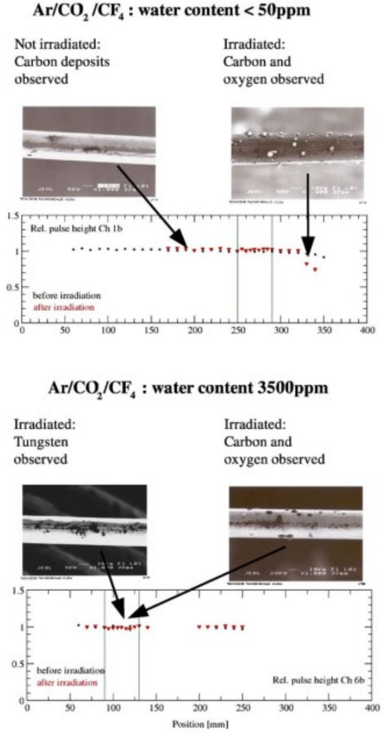


Fig. 4. Selected results from the irradiation tests in $Ar/CO_2/CF_4$ (75/10/15).

- 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.

Neutron equivalent in LHCb tests

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

Occupancy in LHCb OT

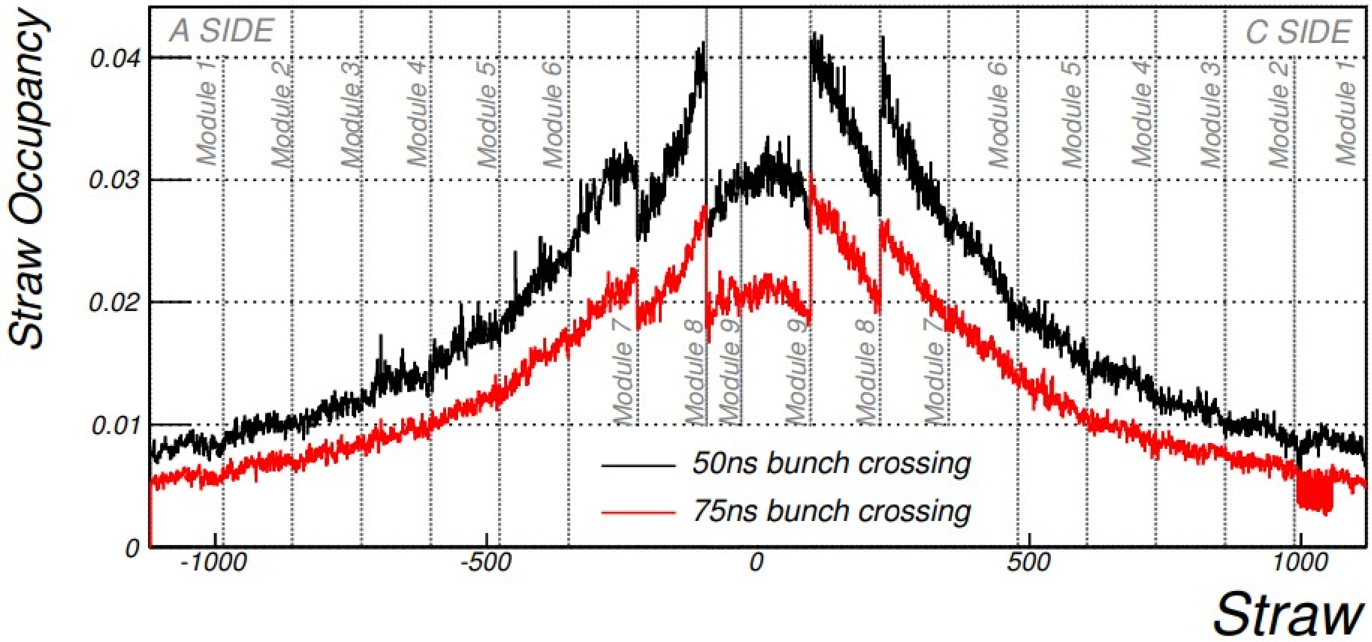


Figure 14: Straw occupancy for 75 ns bunch-crossing spacing in red, and 50 ns bunch-crossing spacing in black.

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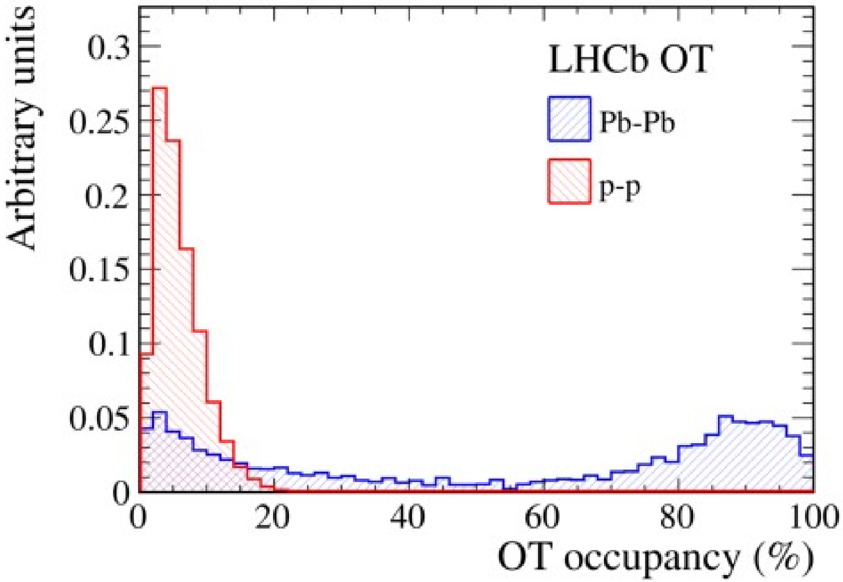
OCCUPANCY IN PROTON AND LEAD COLLISIONS

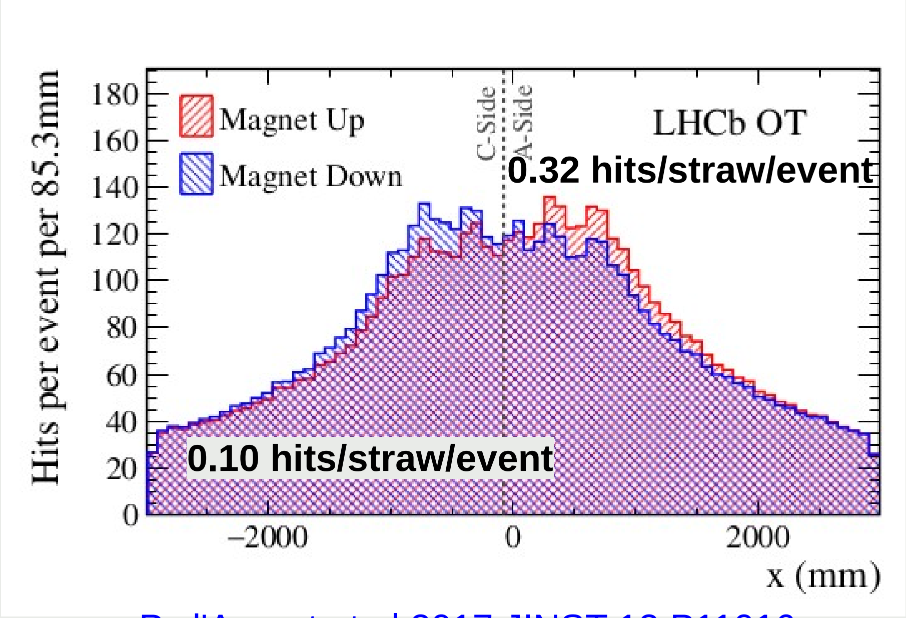
- Average occupancy for *pp*-collisions in Run II (2015&2016) is 12.7%.
- Only 30 noise hits per event compared to ~6800 hits from particles
- Maximum particle flux: 168 kHz/cm^2
- OT has been operated during Pb-Pb runs, but analysis limited to event centrality of 60%



to be updated

Hit rates/straw in LHCb vs CBM

- pp collisions (COM energy 1.38 TeV)



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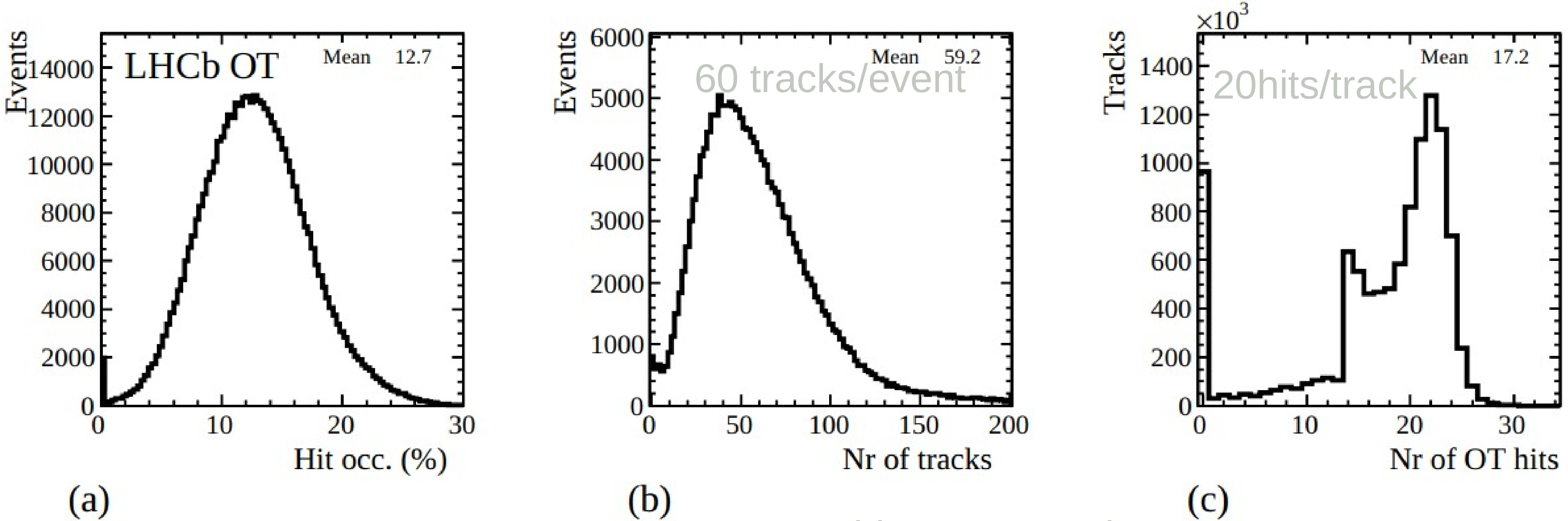
At the central region:
(LHCb) 0.32 x 30MHz = 9.5 MHz/straw
(CBM*) ~0.086 x 10 MHz = 0.86 MHz/straw

At the sides:
(LHCb) 0.1 x 30MHz = 3 MHz/straw
(CBM*) ~0.02 x 10MHz = 0.2 MHz/straw

*CBM Sim (mbias) by Anjali



1200 hits per event in OT

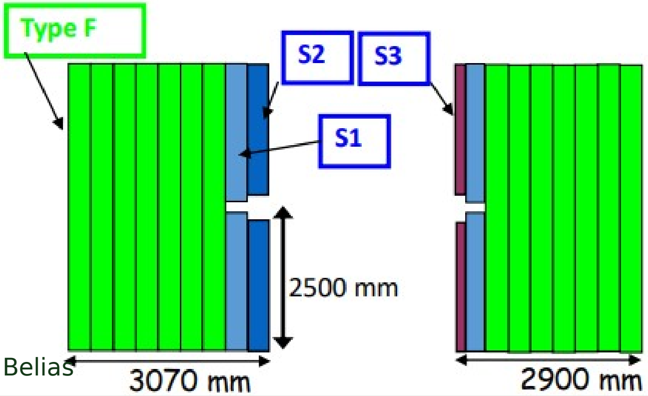
Figure 3. Typical run conditions for a run in June 2012 (run 118335), with (a) hit occupancies per event around 13% and (b) 60 tracks per event with hits in both the Vertex Locator and the tracking stations (so-called "long" tracks). (c) The number of OT hits assigned to these long tracks peaks around 22. A fraction of the tracks do not have any OT hits assigned, as these tracks only traverse the inner silicon detector at large rapidity close to the beampipe.

https://cds.cern.ch/record/1635371/files/LHCb-PROC-2013-080.pdf

Things to know about OT

The Outer Tracker consists of 3 stations T1, T2, T3 (~0.5m apart)

- Station
  - 2 support frames (C-frames) mounted vertically each C-frame with 2 layers of detector modules
  - Station =▶ 4 layers of modules with orientation $0^0,+5^0,-5^0,0^0$
  - Every C-frame is in two halves that can be moved horizontally in and out around the beam pipe
- Layer
  - 14 type F modules; full height
  - 4 type S modules; half height outside the hot region



LHCb Operating conditions (*)

LHCb	OT
Operating conditions	
Total counting rate in the FT	$50x10^7$ tracks/s
Maximum counting rate per straw	5000 kHz
Maximum particle flux	200 kHz/cm^2
Maximum radiation dose in 10 years	
Maximum accumulated charge in 10 years	2.5 C/cm
Maximum current per straw	0.7 μA
Occupancy (at max. counting rate)	
Performance	
Discrimination threshold	4 fC
Position resolution per straw	180 μm
Momentum resolution (p range?)	0.4%

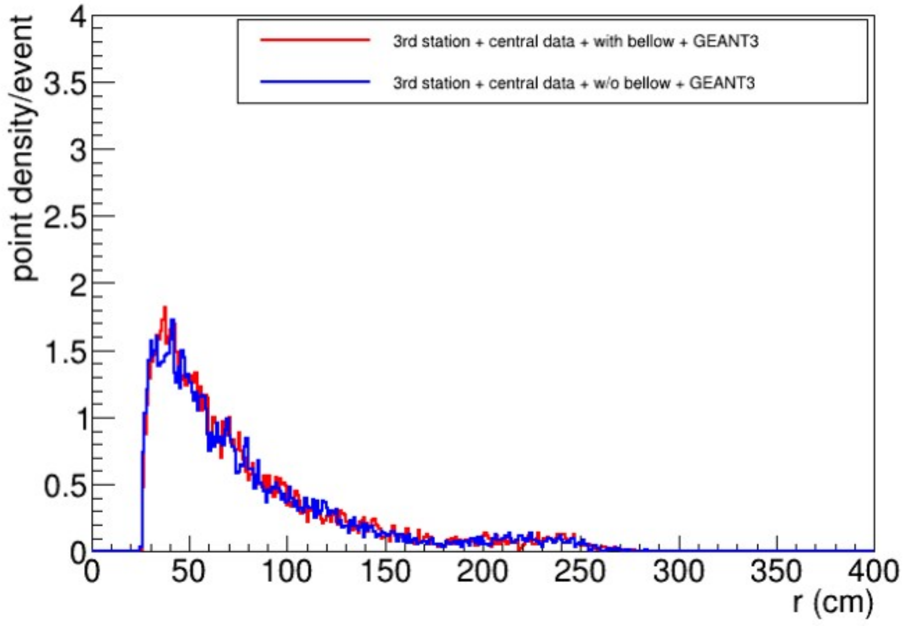
(*) Communications with N. Tuning (Nikhef/CERN)

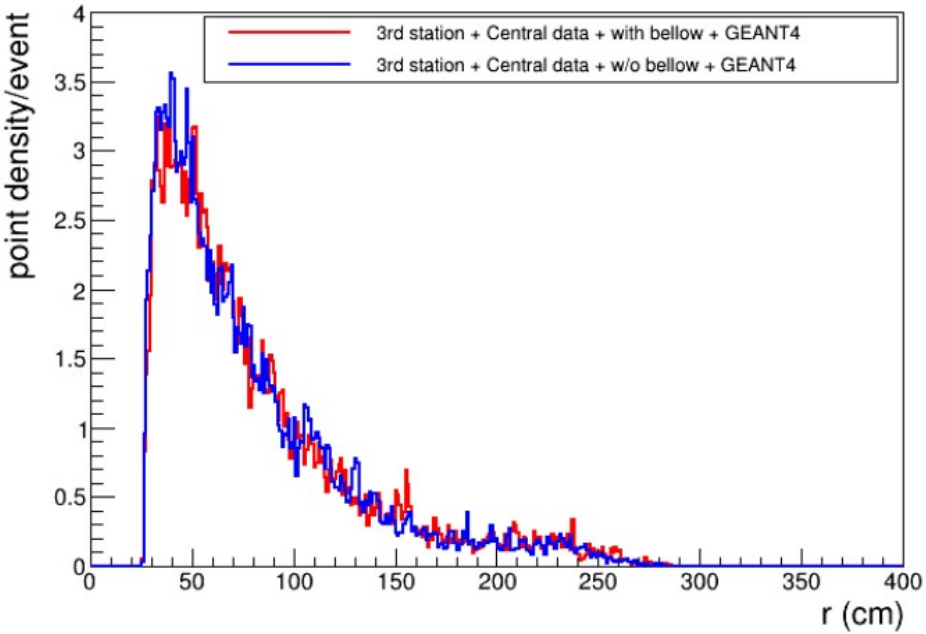
Project: PASTA - PAnda STrAws
S1,S2,S3 modules in PANDA
@mCBM: Beam times 2025 started

Project: MUST - MUon Straws
F modules possibly in CBM
@Cave-C: Beam tests 2026/27

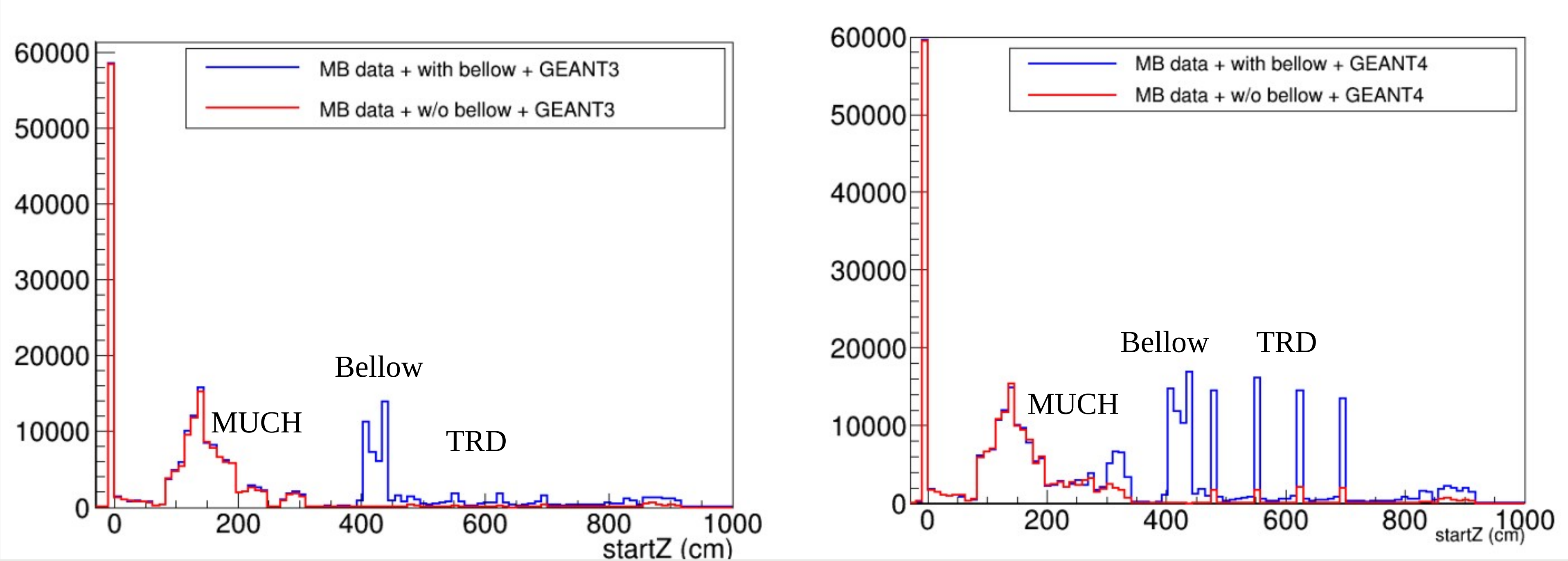
Slide from A. Belias

Bellow effect

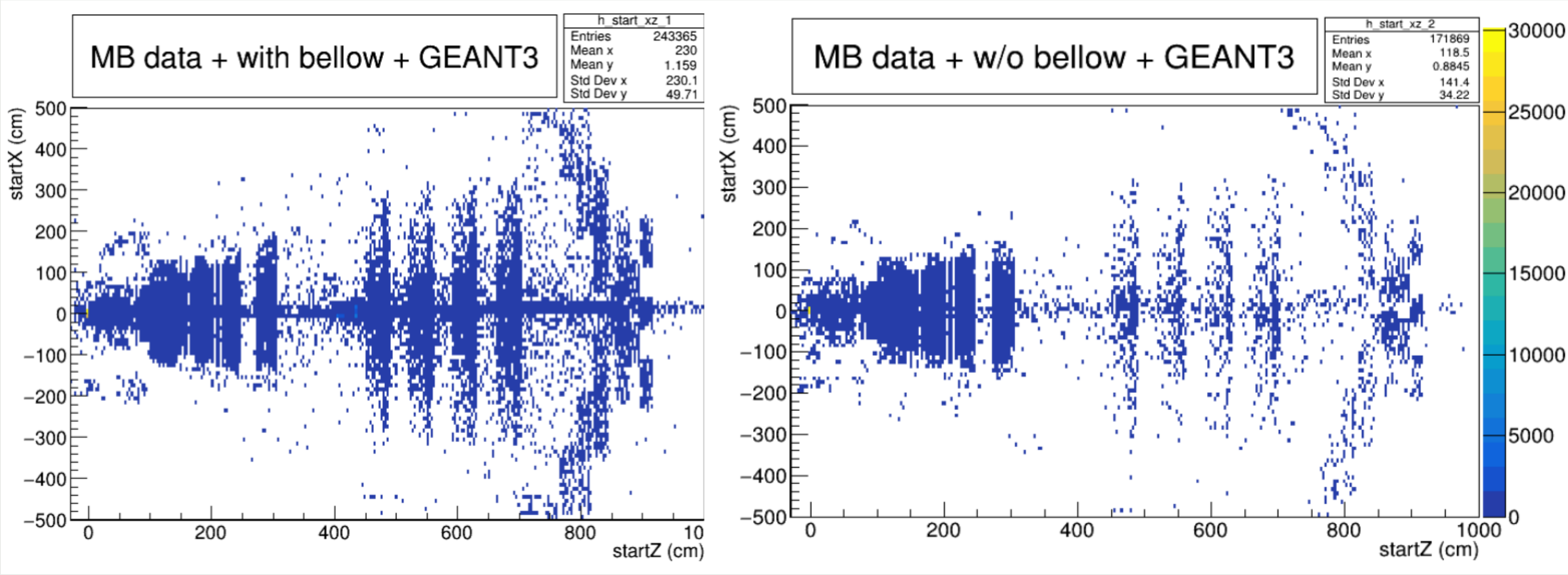




Geant3 vs Geant4 (tracks start z)

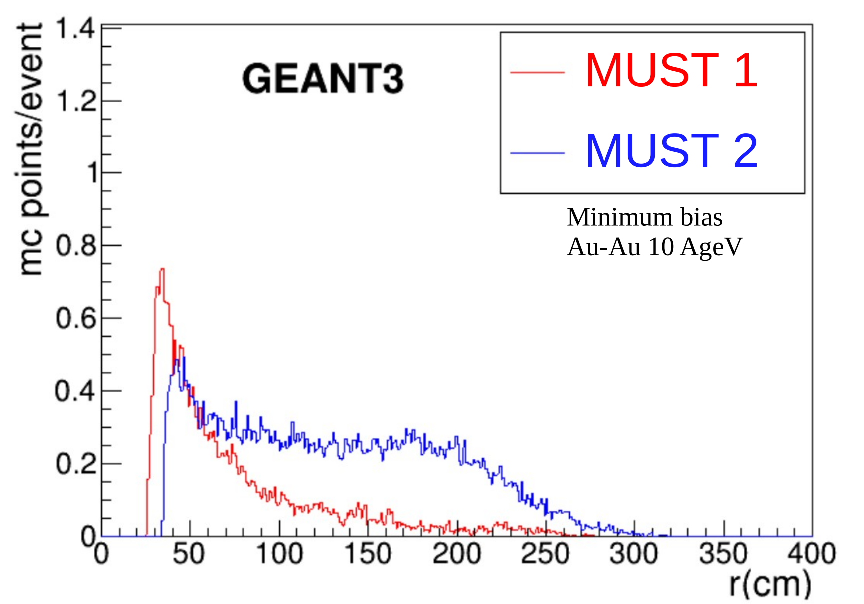


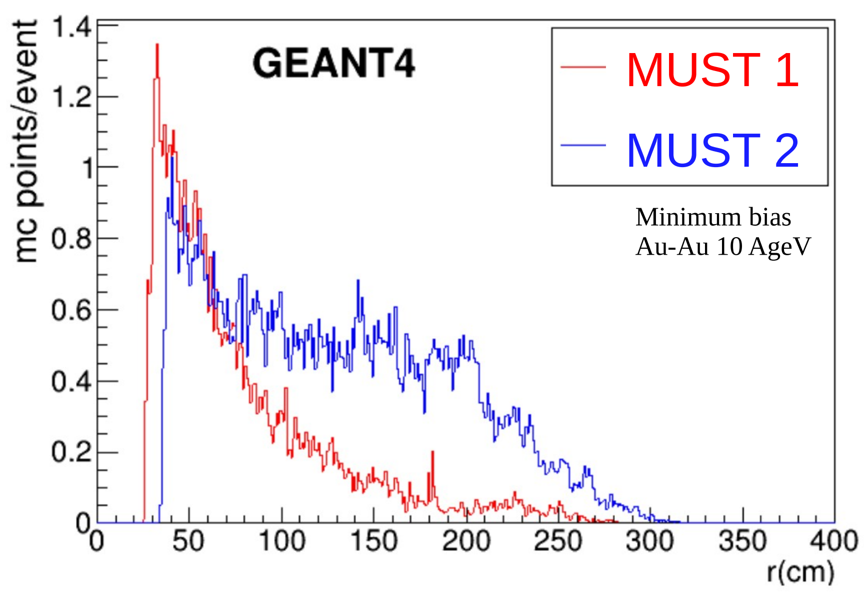
Geant3 (tracks start xz)



GEANT3 vs GEANT4

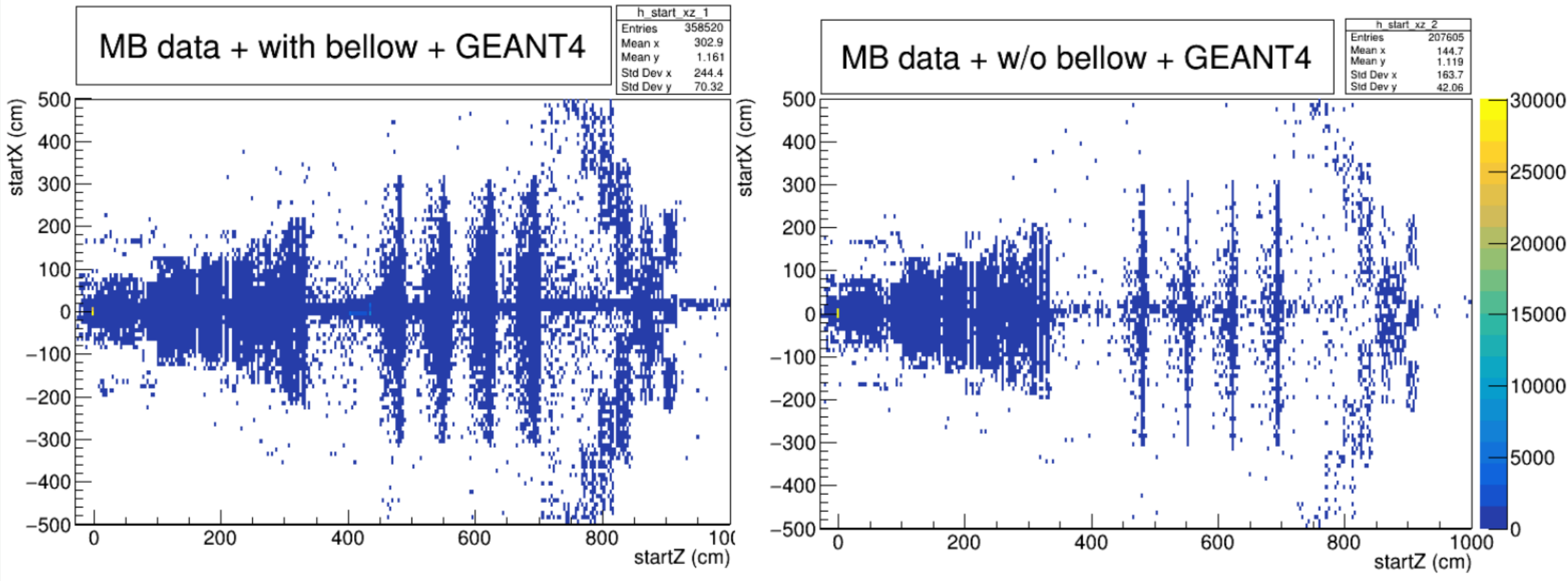
Secondaries doubled

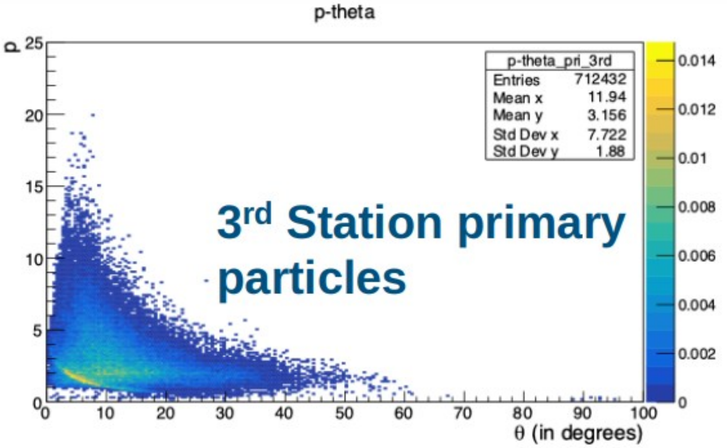


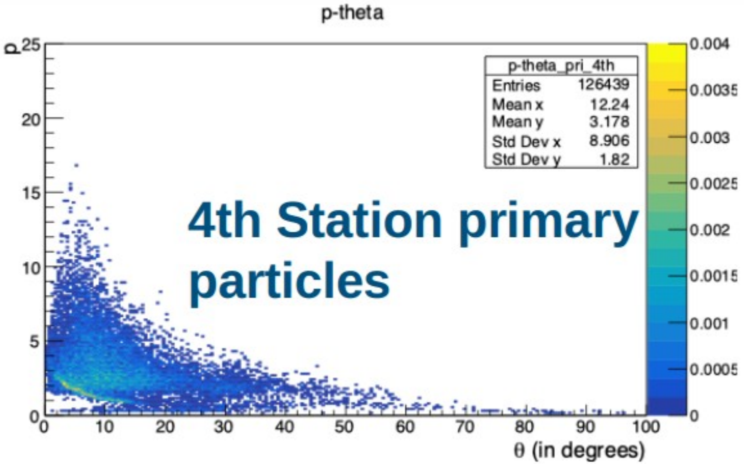


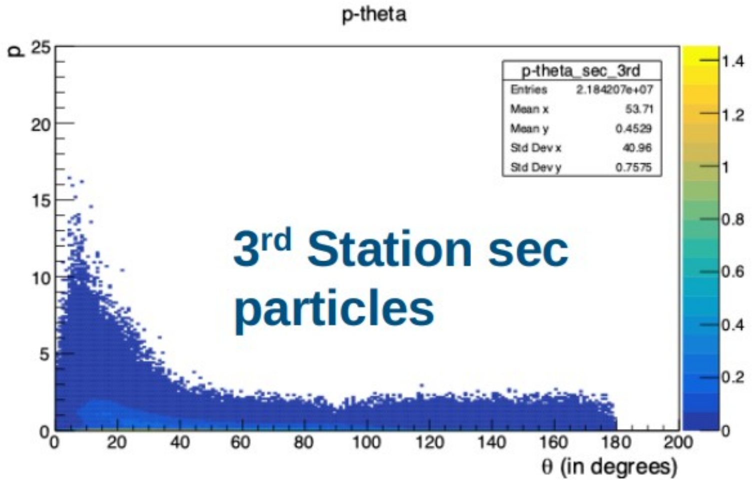
~ S. Gope

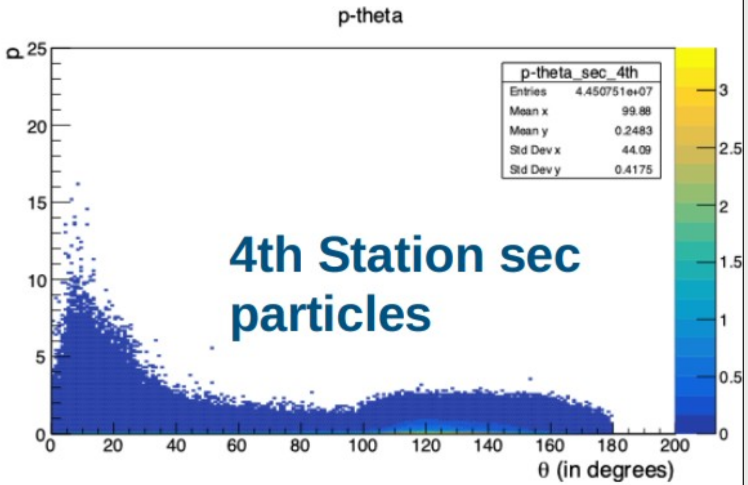
Geant4 (tracks start xz)




p-theta
p-theta_pri_3rd
Entries 712432
Mean x 11.94
Mean y 3.156
Std Dev x 7.722
Std Dev y 1.88
3rd Station primary particles
p
θ (in degrees)


p-theta
p-theta_pri_4th
Entries 126439
Mean x 12.24
Mean y 3.178
Std Dev x 8.906
Std Dev y 1.82
4th Station primary particles
p
θ (in degrees)


p-theta
p-theta_sec_3rd
Entries 2.184207e+07
Mean x 53.71
Mean y 0.4529
Std Dev x 40.96
Std Dev y 0.7575
3rd Station sec particles
p
θ (in degrees)


p-theta
p-theta_sec_4th
Entries 4.450751e+07
Mean x 99.88
Mean y 0.2483
Std Dev x 44.09
Std Dev y 0.4175
4th Station sec particles
p
θ (in degrees)

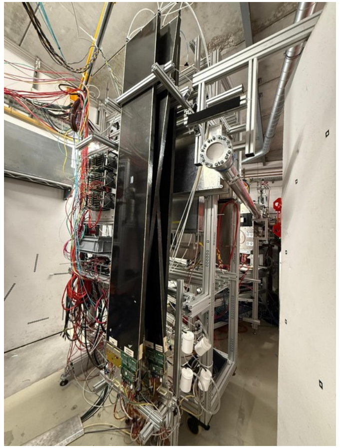
Measured current of PASTA straws during mCBM beamtime campaign in May 2025

Duration of Data taking : 16-18 May 2025; Gas Flow Rate : ~ 8 l/h

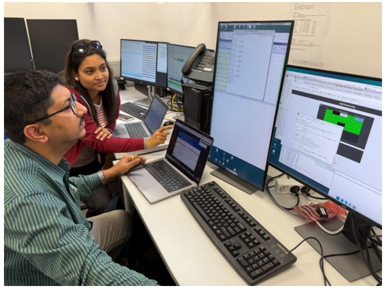
Beam: ^{209}Bi

Response of the straws are observed monitoring the anode current in with spill

Beam Intensity	Average current (μA)
3 x 10^{8} per 10 s	~10-20 (1500V)
6 x 10^{7} per 10 s	~12 (1500V)
1x10^{7} per 10 s	~10-20 (1400-1550V)
5x10^{8} per 8 s	~10-40 (1350-1550V)
8x10^{8} per 6 s	~20-80 (1350-1450V)



PASTA set-up

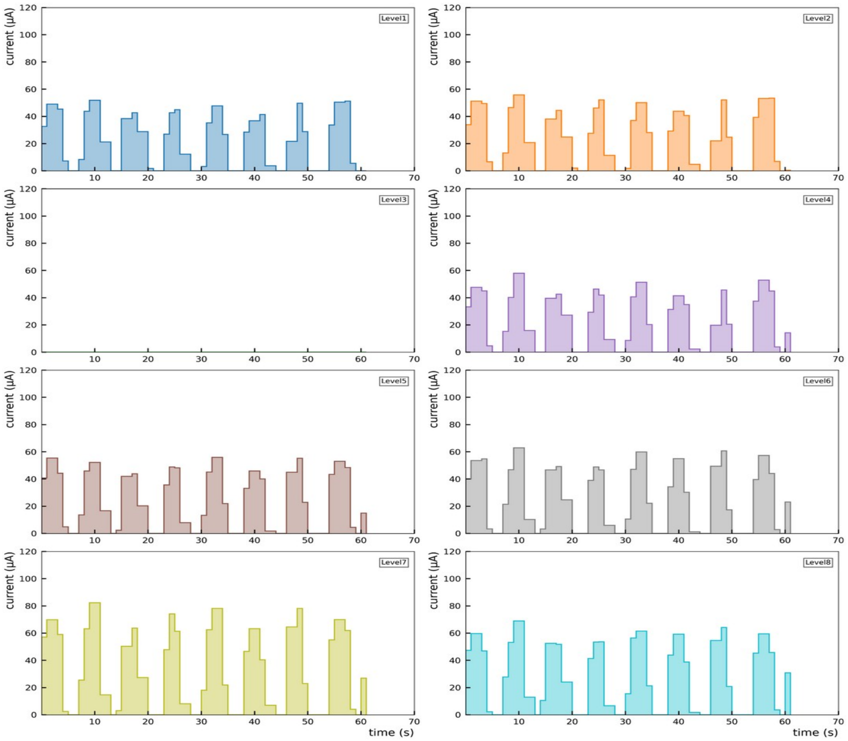


During beamtime at GSI

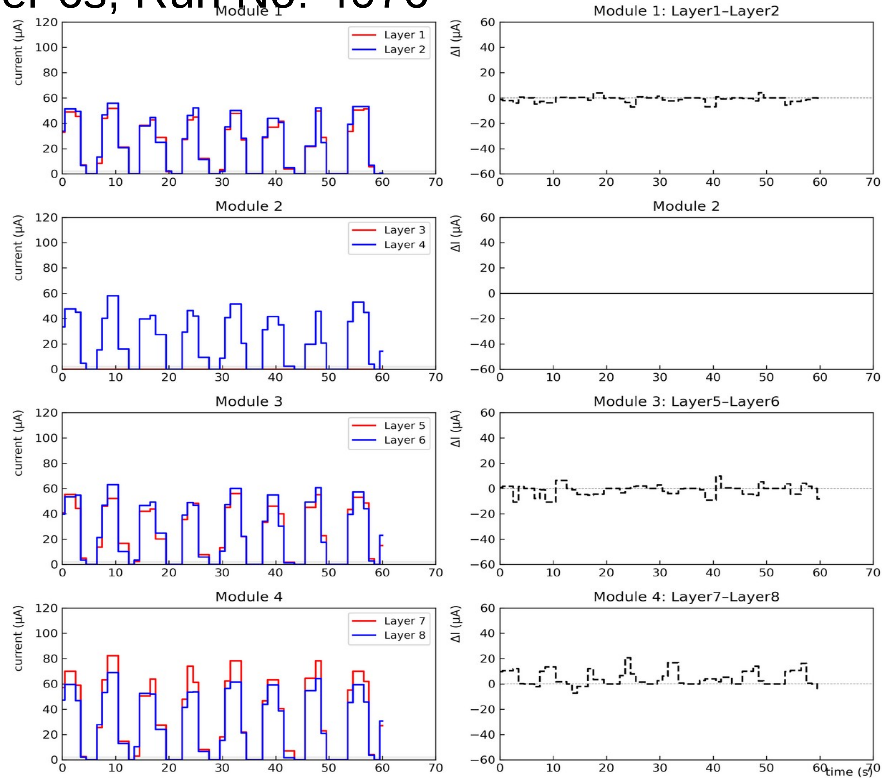
Analysis team at Bose Institute

Measured current of PASTA straws during mCBM beamtime campaign in May 2025

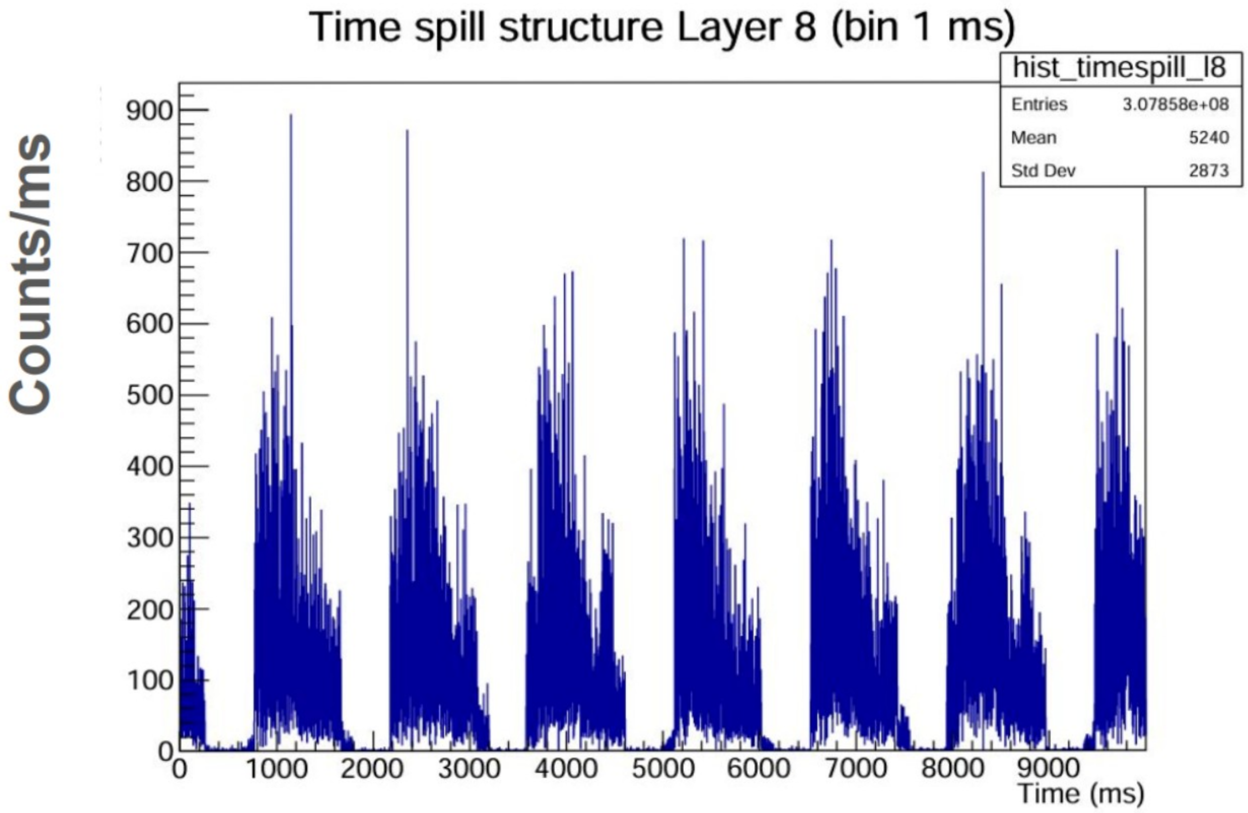
Date:19.05.2025, Time: 04:08, Flow Rate: 8.2l/h, Anode voltage: 1450V   Beam: ^{209}Bi, Beam Intensity: 8x10^{8} per 6s, Run No: 4076



Anode current during spill



Difference in anode current between layers


Time spill structure Layer 8 (bin 1 ms)
hist_timespill_l8
Entries 3.07858e+08
Mean 5240
Std Dev 2873
Counts/ms
0
100
200
300
400
500
600
700
800
900
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Time (ms)