Production and Testing of Resistive Plate Chamber Prototypes for the ATLAS upgrade

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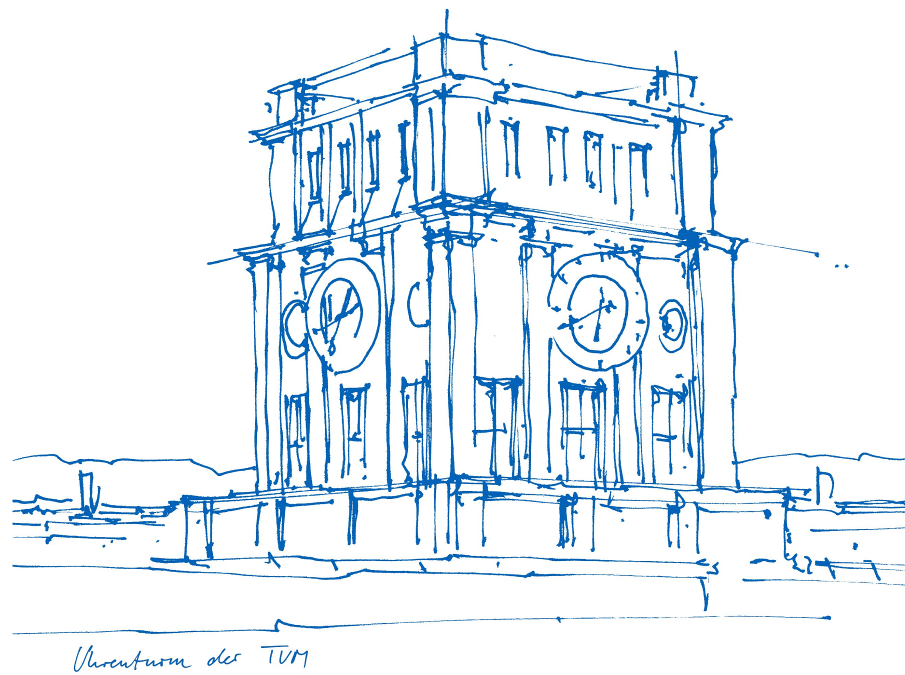
für Physik



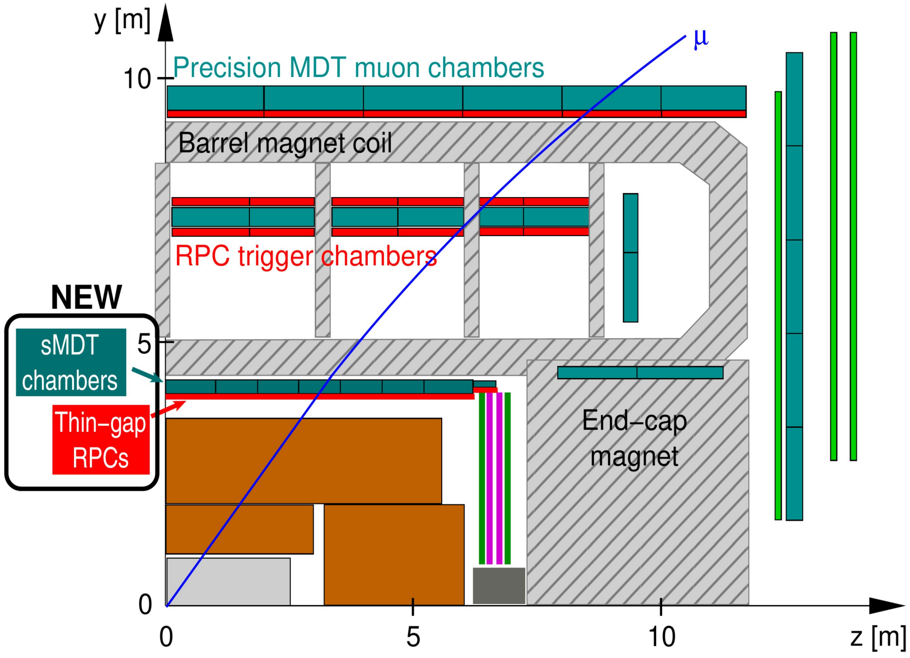
New thin-gap RPCs for the ATLAS muon spectrometer at HL-LHC

- Several new triplets of thin-gap RPCs to be installed in the inner barrel layer to maximize muon trigger acceptance and efficiency

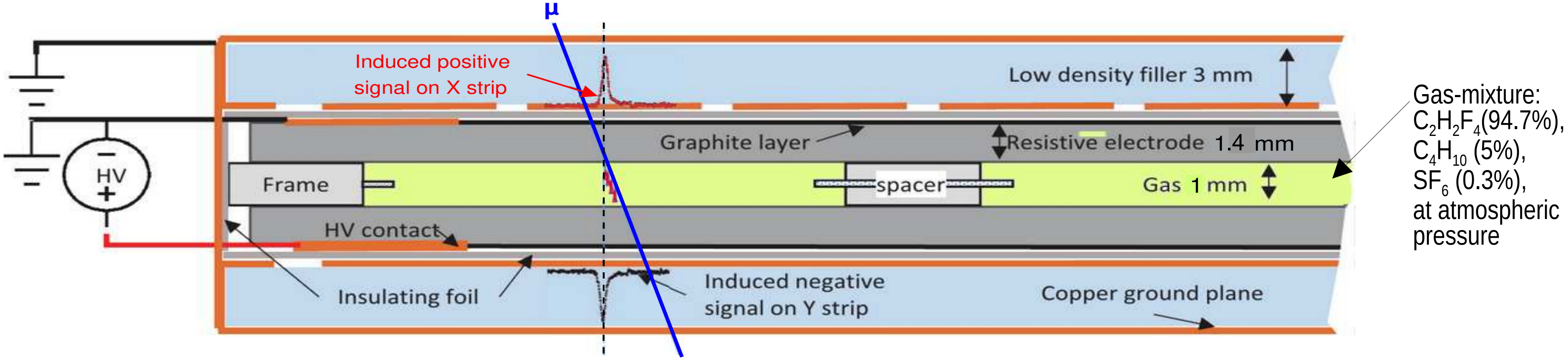
- Production of 1000 RPCs in total

  → New manufacturing company under MPI supervision to produce some of those

- For this it was necessary to:
  - Test materials and methods for productions in the lab
  - Transfer these to industrial partners
  - Test the prototypes produced by the companies

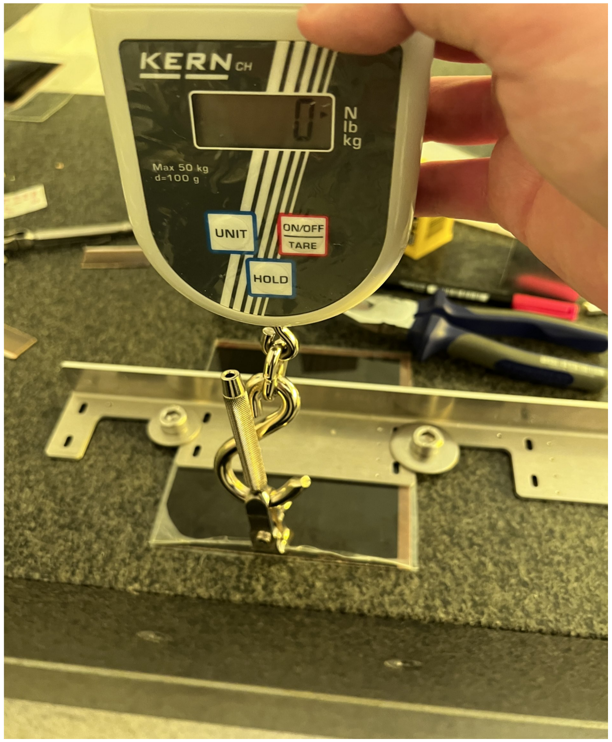


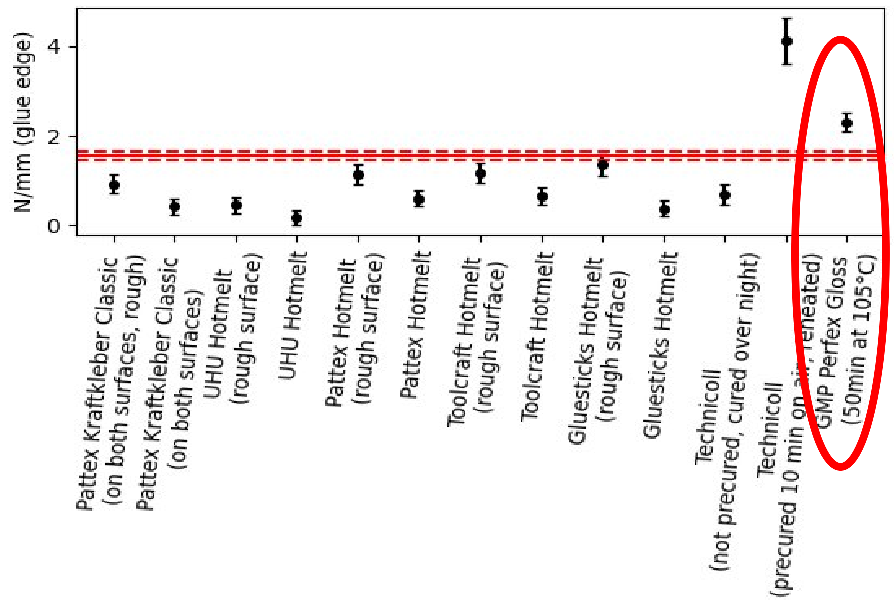
Structure of a Resistive Plate Chamber (RPC)



- Operation of an RPC:
  - Parallel plate gaseous ionization detector with a small gas gap and no wires
  - Ionization-region = Amplification-region
  - Fast detector with excellent time resolution
  - Use of highly resistive electrodes limit avalanche development
  - Signal and position measurement with pick-up strips
- Build-characteristics:
  - High voltage applied to graphite layer on outsides of the high pressure phenolic laminate (HPL) electrodes
  - Inner surface coated with linseed oil varnish for a smooth surface preventing point discharges due to field non-uniformities
  - Electrically insulating PET foil sealed with hot-melt glue
  - RPC enclosed in a Faraday cage

Example for the optimization of a production step





Averaged adhesive strength for normalized to the width of the edge pulled on

Several glues and glue foil compounds were tested to bond PET foil to the graphite coated HPL for the following criteria:

- No outgasing and damaging properties for gas detectors
- Allowed for use in the ATLAS cavern by CERN regulations
- Adhesive strength
- Ease of use in industrial mass production

➡ GMP Perfex Gloss is a compound made out of PET and standard EVA hot melt glue that satisfies all the criteria

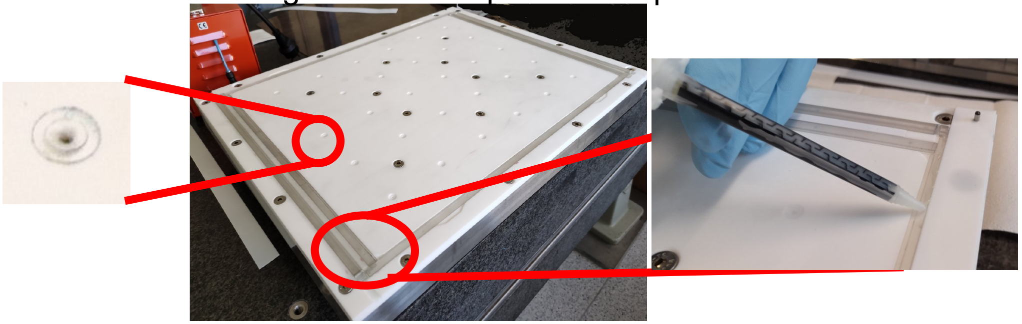
Preparation of first electrode and gluing of support structure

- Graphite layer contacts applied to HPL plate
- PET foil glued to electrode

Finished electrode

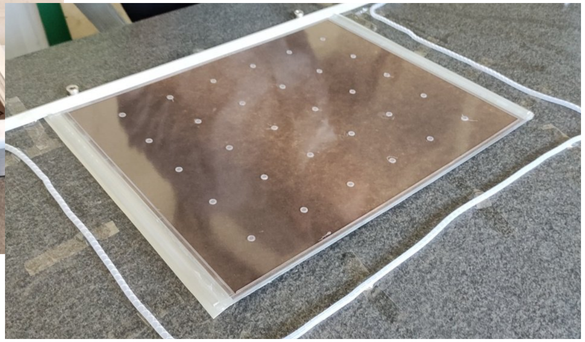
- Spacers and lateral profiles positioned with help of a fixture
- First electrode glued on spacers and profiles

Gluing fixture with spacers and profiles



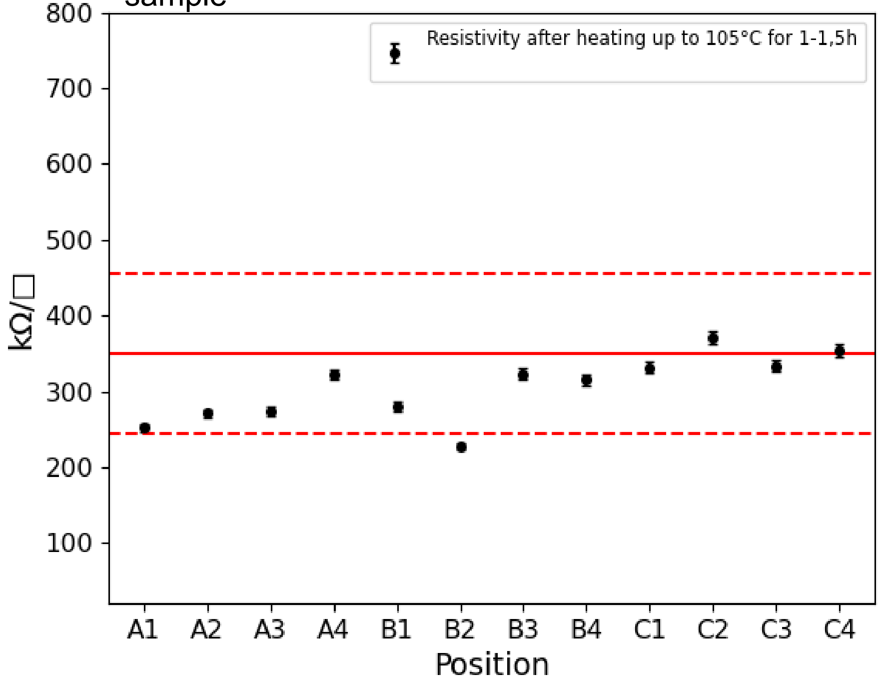
Electrode is glued to the spacers

Electrode with spacers and profiles



Validation of graphite coating by silk screen printing

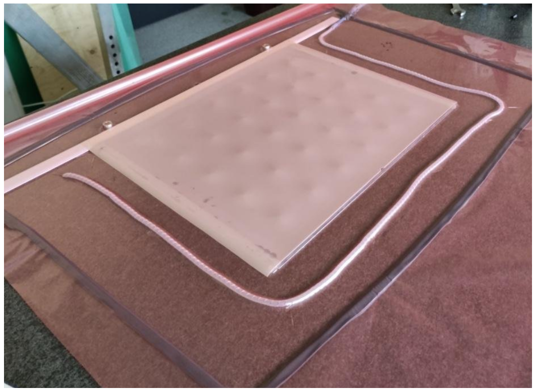
Average of 3 measurements at all positions on one sample



Acceptable range of 350 kΩ/□ ± 30%

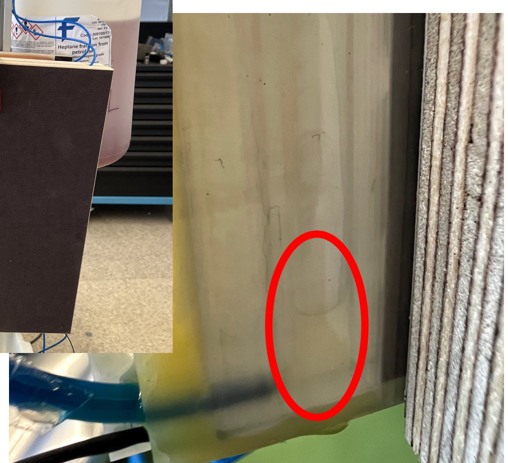
The method with the T90 mesh and the graphite varnish give a reproducible and uniform graphite coatings that are within specification !

Gap closed and coated



Second electrode glued onto the first one

oil application setup

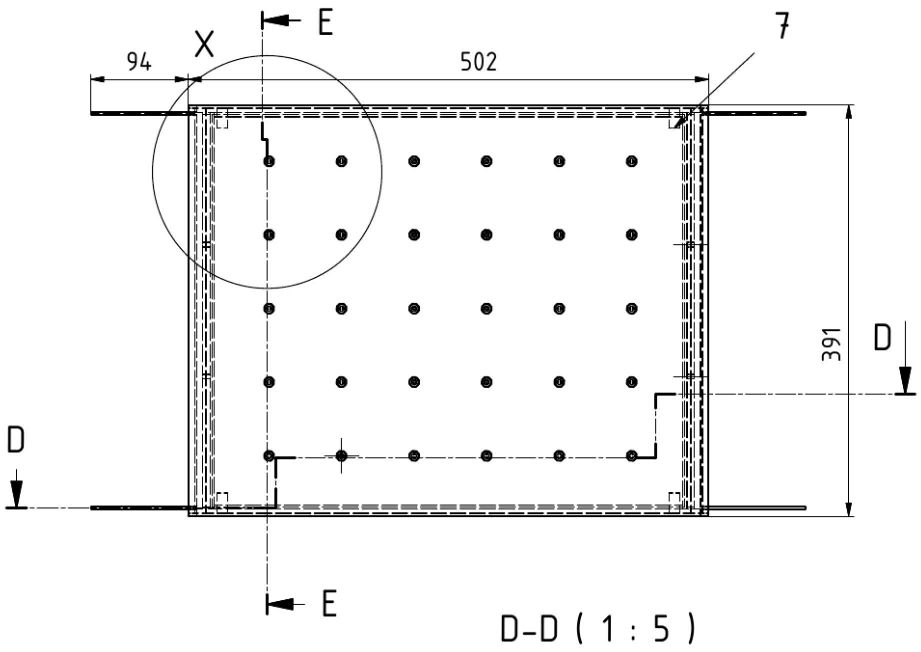


Slowly decreasing oil level seen in the gas channel of the gap

- Second electrode glued to first and gap sealed
- Gas gap fixed between two plates to prevent bursting due to high pressure of oil and pump
- Slow drain of oil by lowering of the canister
    - Prevents formation of drops and streaks
    - Ensures creation of thin, smooth coating
- Air pumped through gap to accelerate the polymerization of oil with oxygen that creates a solid coating on the inside

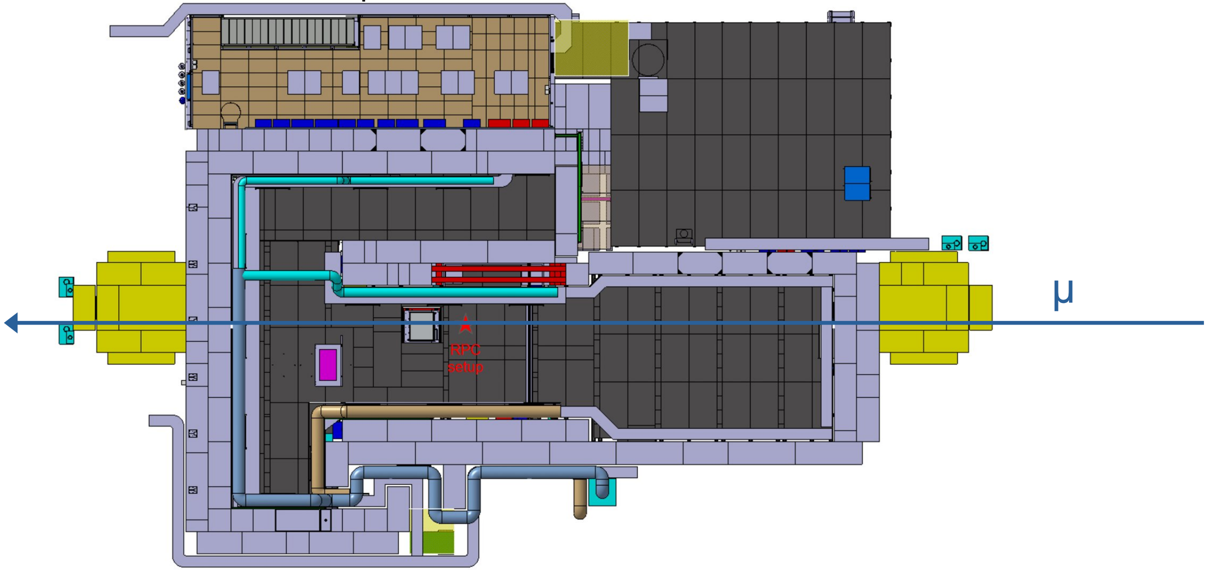
Technology transfer

- For initial evaluation and testing smaller sized sample RPCs were designed, but final measurements were considered for all tests and materials
  - Materials and methods were transferred to three companies
  - Each company produced 2 gas gaps under supervision and 1 alone
  - The gas gaps were then tested at MPI and CERN focusing on the gaps produced without supervision

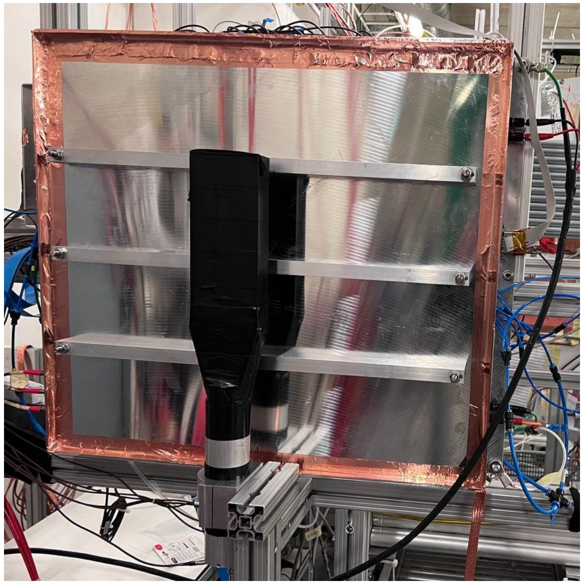


The Setup at GIF++

Position of the setup in the GIF++ at CERN

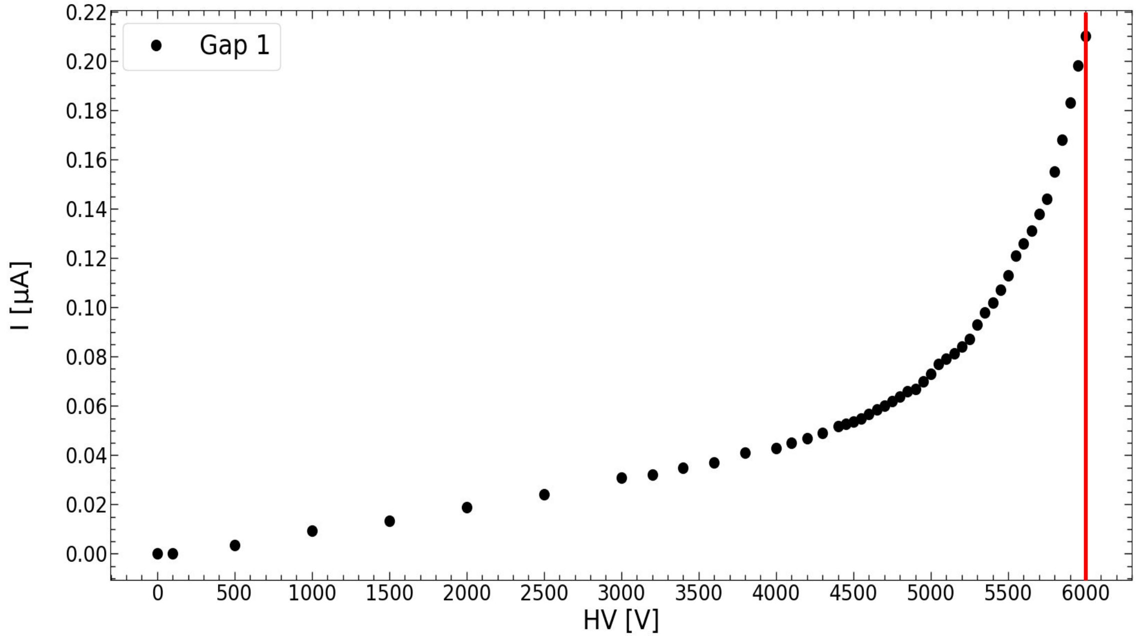


Picture of the setup with the scintillator in front



- One gap from each manufacturer (3 gaps) installed in aluminum box that allowing installation of services and for compression of potentially broken gaps
- The gas gaps equipped with strip panels and per-amplifiers provided by INFN matching the final ATLAS electronics
- Triplet installed about 1.5 m away from the GIF++ ^{137}Cs gamma source
- Center of active are aligned with the muon beam
- Scintillator smaller than the active area positioned in the middle of the setup as reference

Voltage-Current curve

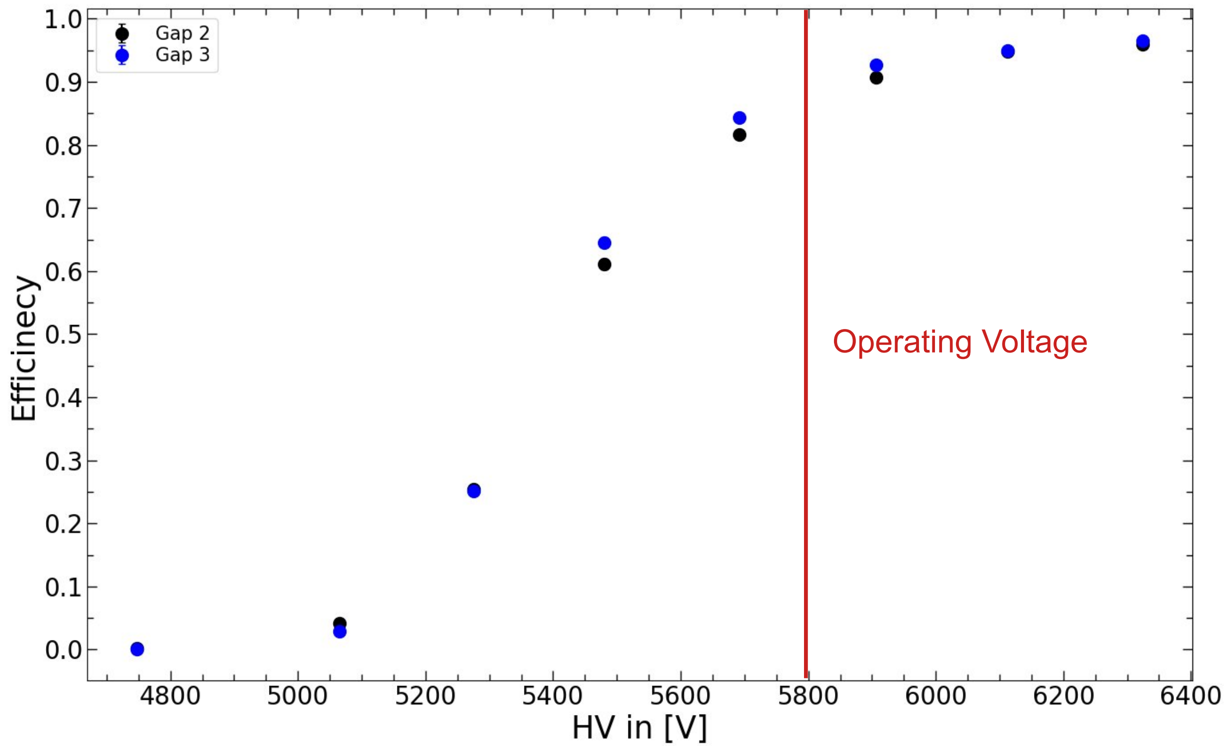


The voltage-current curves for one of the prototypes

- First quality indicator
- Linear part dominated by ohmic resistivity of the gas gap (mainly the conductivity of the linseed varnish)
- Exponential regime dominated by the current of the discharges in the gas gap occurring when the amplification regime is reached
- Acceptable currents are up to 0.2 µA in the region around 6000 V after subtracting the linear part of the current from the total

Efficiency calculation and scan

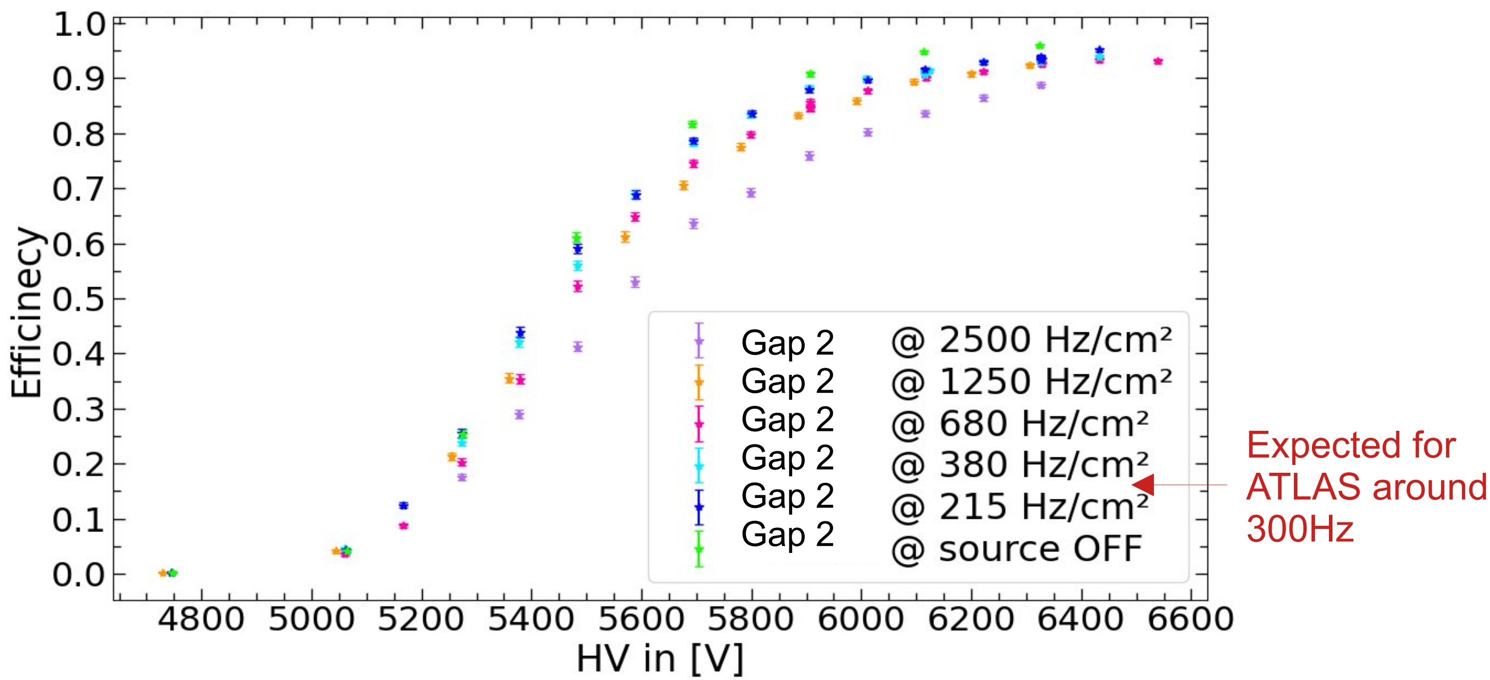
Efficiency scan at with no gamma irradiation and a threshold of 4 mV



→ Both gaps reach full efficiency around the target operating voltage of 5800 V

Measured even higher to see the full plateau

Efficiency scan with different amounts of irradiation

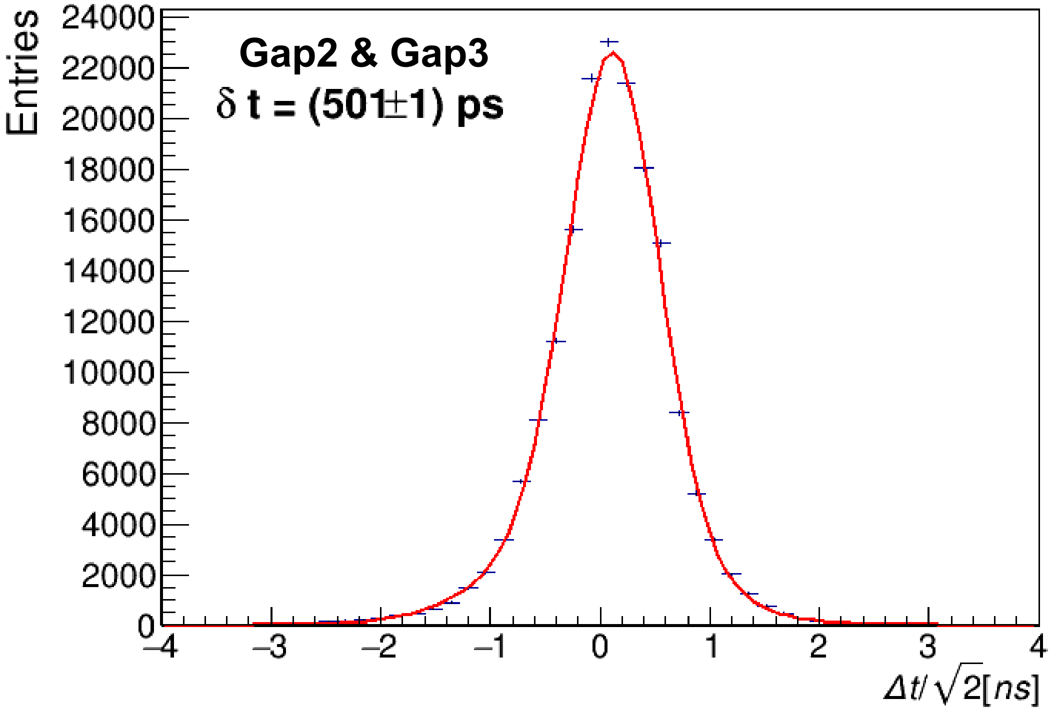


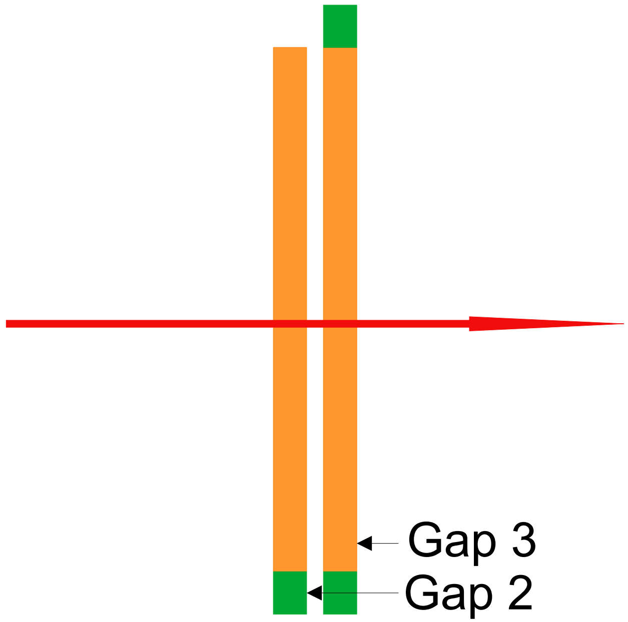
We see a decrease in Efficiency for the Chamber for high amounts of irradiation!

With increasing irradiation the current in the chamber increases → lover voltage drop over the gas → decreases efficiency at same applied voltage !

But for expected irradiation levels no significant efficiency reduction !

Time Resolution



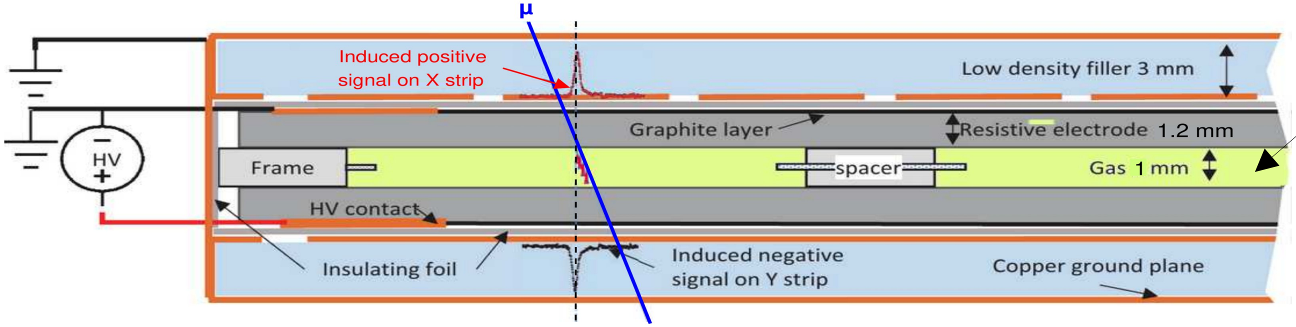


- Δt: time difference between the signals created by the same muon and measured in both chambers
- Based on the distribution the time resolution can be determined
- 34.1% confidence interval determined → σ → δt = (501 ± 1) ps for Gap2 and Gap3

Summary

- Production procedures and materials have been developed that allow for the production of RPCs to the quality standards of the ATLAS upgrade
- Materials and techniques were transferred to three companies that produced small sized prototypes
- The prototypes were tested at MPI and at CERN for their quality and characteristics

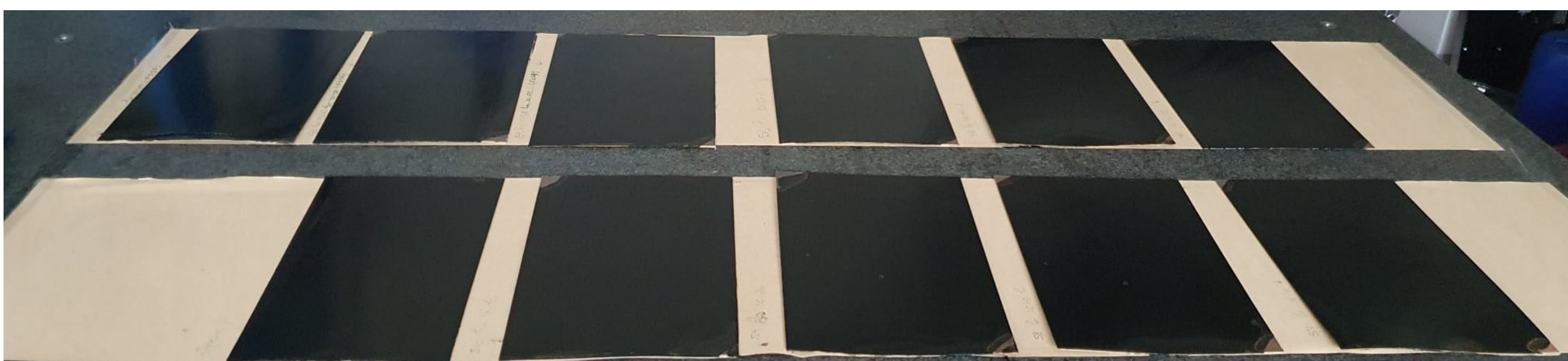
Thin-gap RPCs for the ATLAS muon spectrometer at HL-LHC



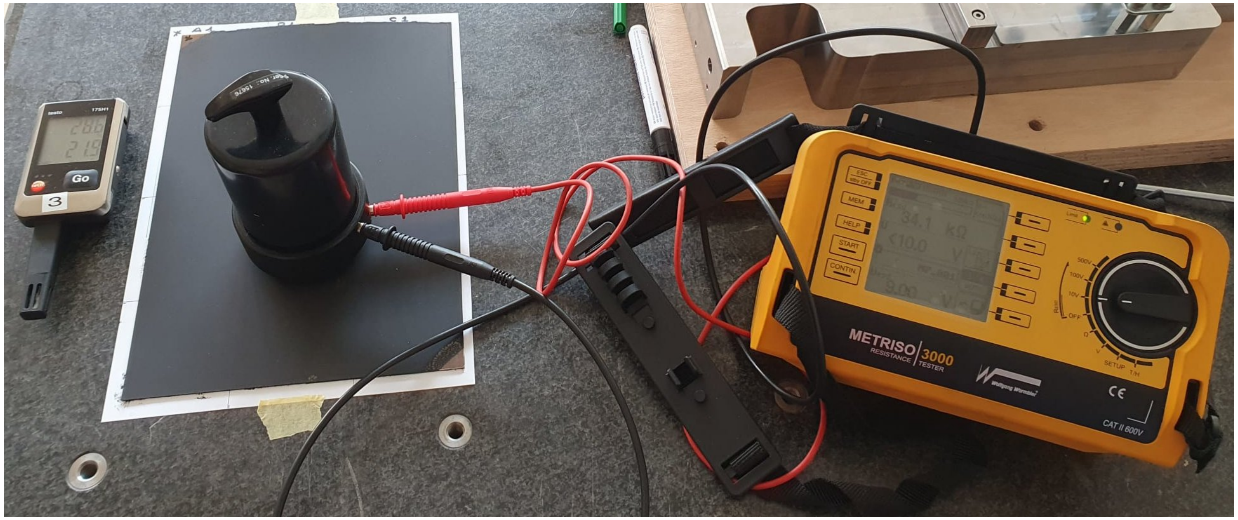
- Thin-gap RPCs:
  - Gas gap thickness reduced to **1 mm** and operating voltage reduced to **5.8kV** to minimize the signal charge (**~ 1/10 of the signal** in the 2 mm ATLAS gaps) in order to meet the required longevity and high-rate capability
  - Highly sensitive, low noise electronics necessary to detect the small RPC signals
- Electrodes:
  - Made of 1.4 mm thick phenolic high pressure laminate plates (HPL)
  - Outer graphite coating with 350 kΩ/□
  - Inner surface coated with linseed oil varnish to obtain a smooth surface in order to prevent point discharges from field non-uniformities
- Gap size ensured by a grid of spacers (thickness deviation < 15 µm) and a frame structure all made from polycarbonate
- Electrically insulating PET foil sealed with hot-melt glue ensure tightness of the structure
- Time resolution of up to 400 ps (improvement over previous ATLAS RPCs)

Graphite coating tests

- Silkscreen setup with T90 mesh used to produce several test samples
- After first tries with a different varnish failed, a varnish provided by the Heysung Trade company and used for CMS RPC production was used
- Several samples were produced and cured under different conditions
- Measurements according to the IEC 61340-2-3 Norm
- Measurements done in a 4x3 grid

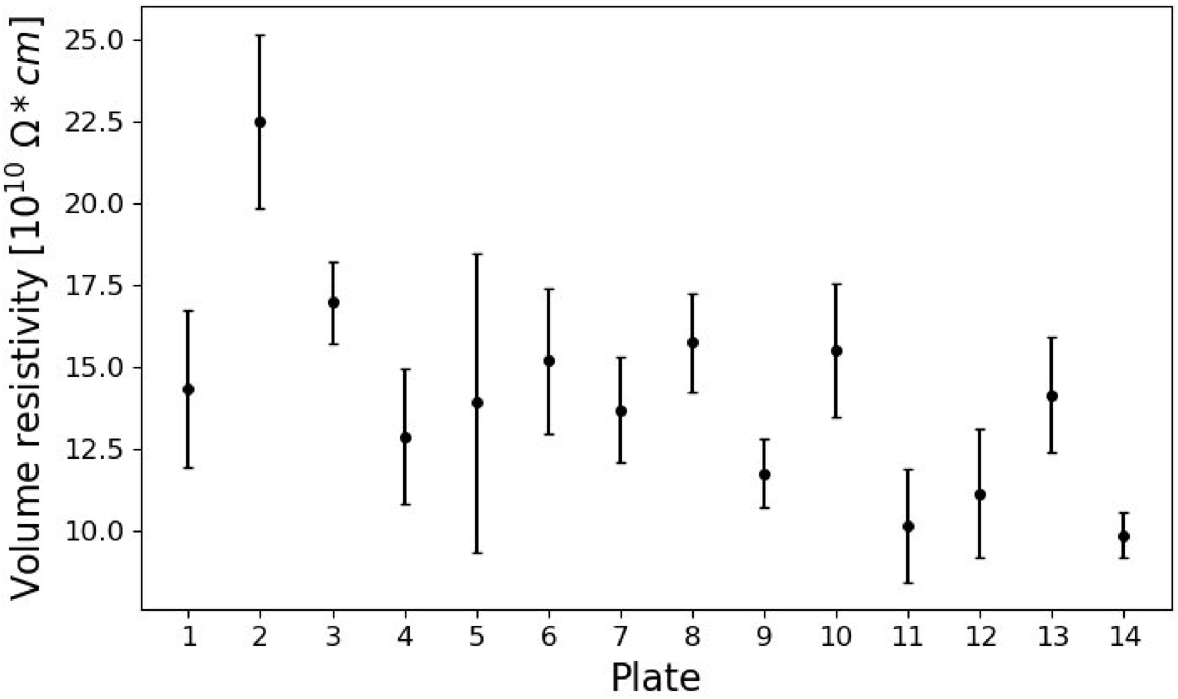


Graphite coating measurement



- Measured using the Metriso 3000 resistance tester
- Measurements according to the IEC 61340-2-3 Norm
- Measurements done in a 4x3 grid
- Each position was measured 5 times and averaged

HPL plate quality control

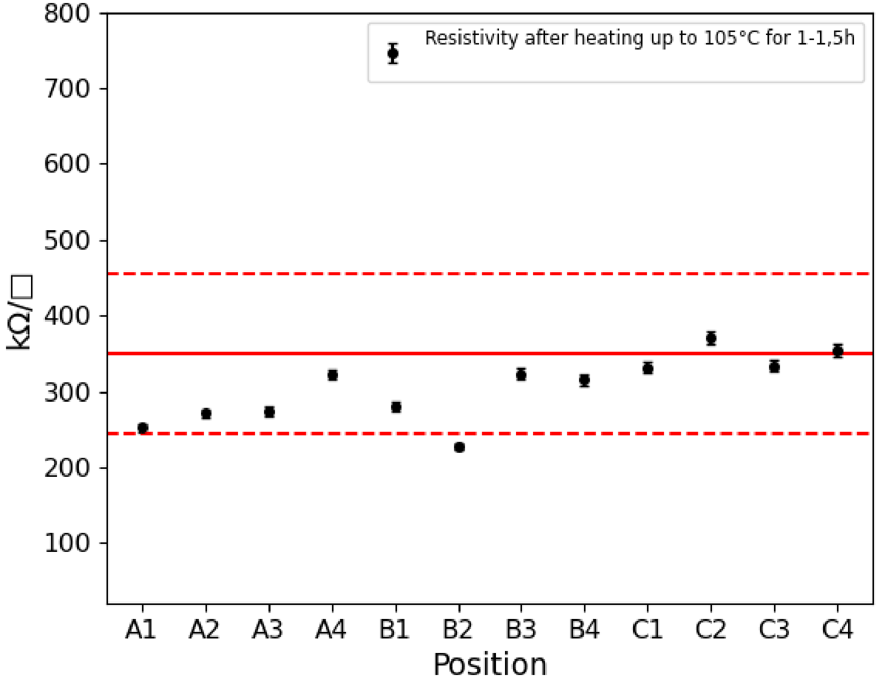


- No deep scratches on at least one side of the plate
- Required is a volume resistivity of (1.5×10^{10} – 10×10^{10}) Ωcm
  - Measurements done on 5 different locations on each plate, with each location being measured twice according to the IEC 61340-2-3
  - Average for each plate determined → error bars show the standard deviation

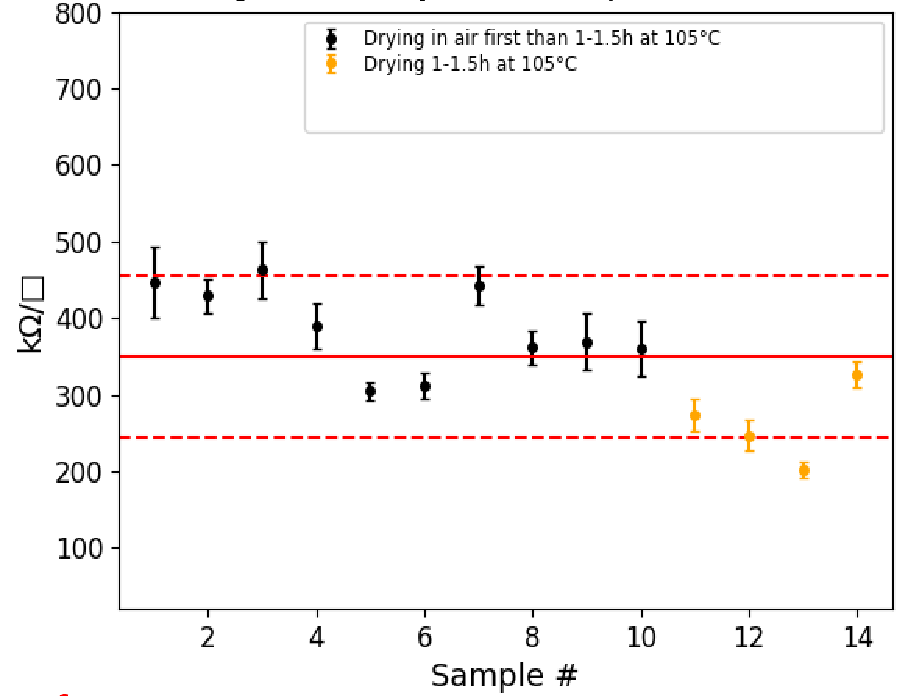
➔ Manufacturer has issues in producing small amounts of plates with the required resistivity → plates with values outside of tolerances had to be used

Graphite coating results

Average of all measurements at all positions on one sample



Average resistivity of all samples



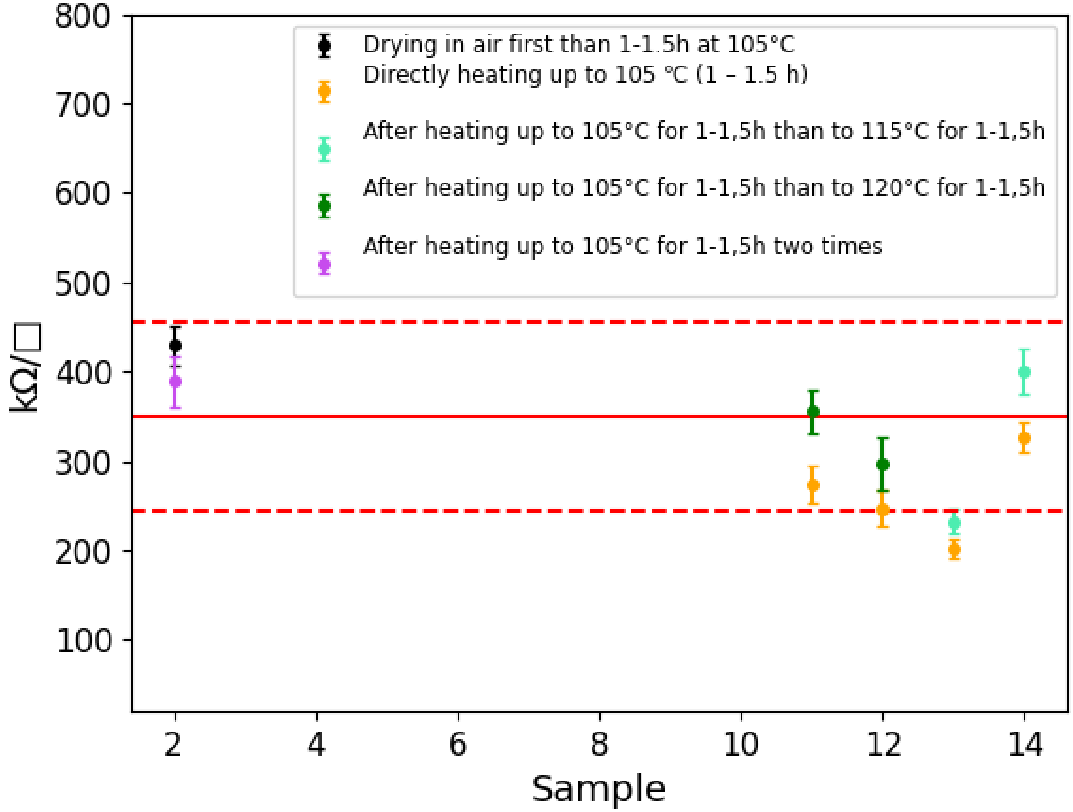
Acceptable range of 350 kΩ/□ ± 30%

If resistivity to low → graphite blocks signals → no measurement possible

If resistivity to high → charges cant move fast enough → rate capability to low

The method with the T90 mesh and the graphite varnish give a reproducible and uniform graphite coatings that are within specification !

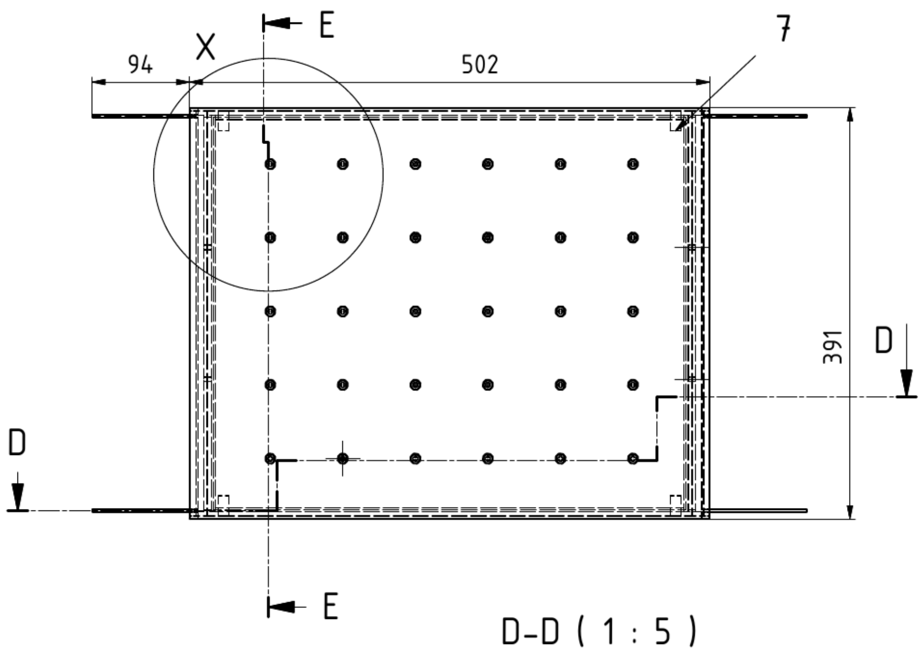
Graphite coating results



Graphite resistivity after a second heating simulating the application of a insulating PET foil with EVA hot-melt

→ the reheating does not change the resistivity significantly

Production of small prototype RPCs

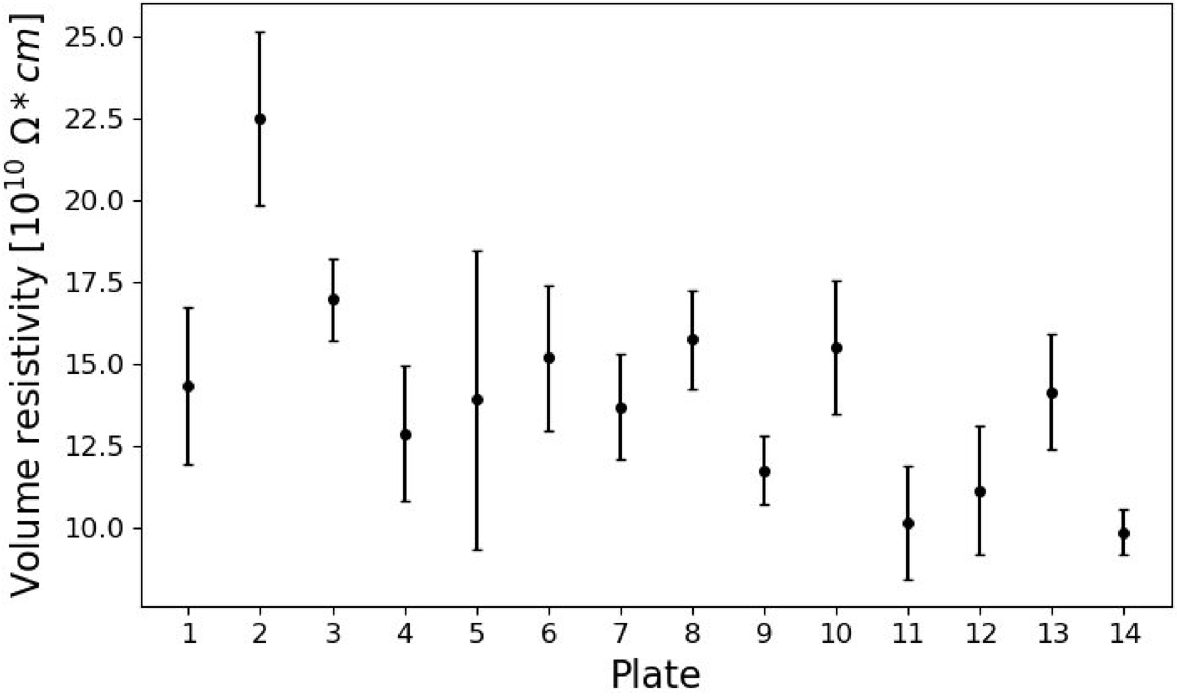


- For initial evaluation and testing smaller sized sample RPCs were designed
- While developing production methods for these smaller RPCs it was taken care that these methods scale to the final dimensions of 1x2m² for the ATLAS RPCs

Process optimization

→ The goal is the development of production materials and techniques and the transfer of these to companies that will produce the RPCs for the upgrade

HPL plate quality control



- No deep scratches on at least one side of the plate
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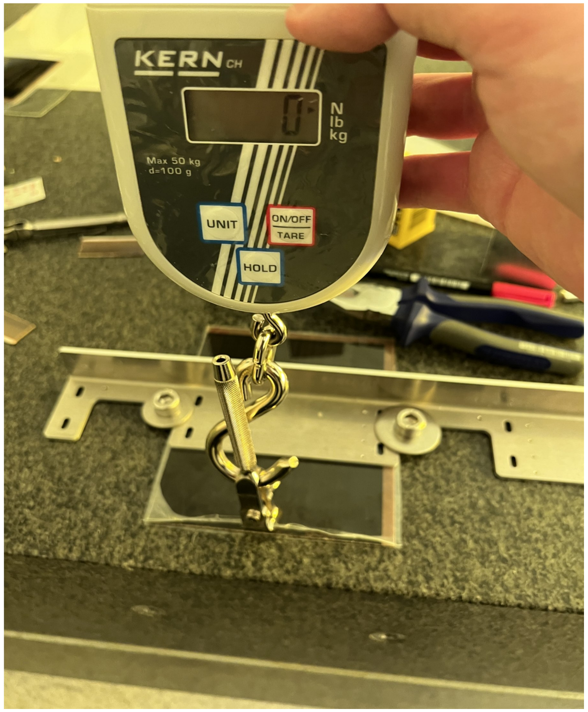
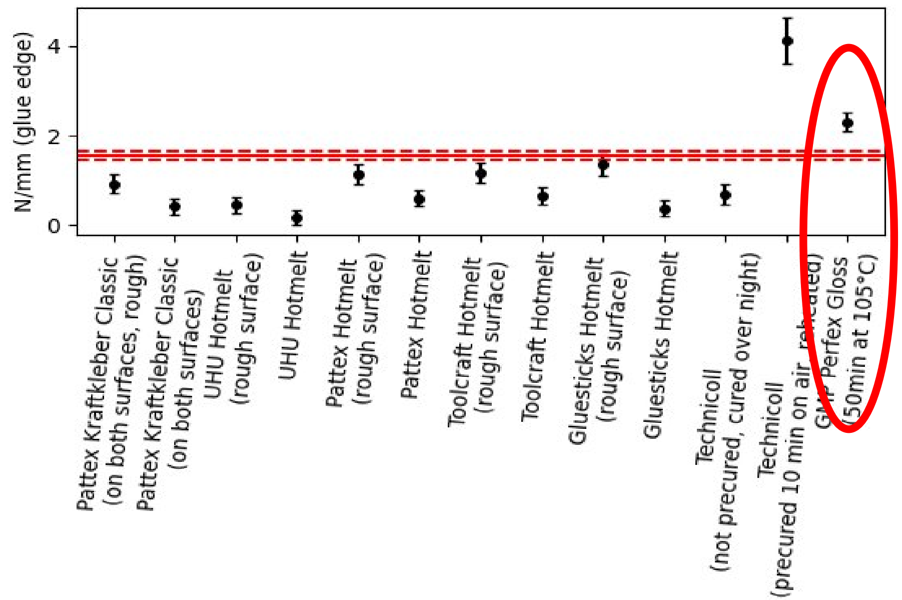
Study of glues and foils





Averaged adhesive strength for normalized to the width of the edge pulled on

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- No outgasing and damaging properties for gas detectors
- Allowed for use in the ATLAS cavern by CERN regulations
- Adhesive strength
- Ease of use in industrial mass production

➡ GMP Perfex Gloss is a compound made out of PET and standard EVA hot melt glue that satisfies all the criteria

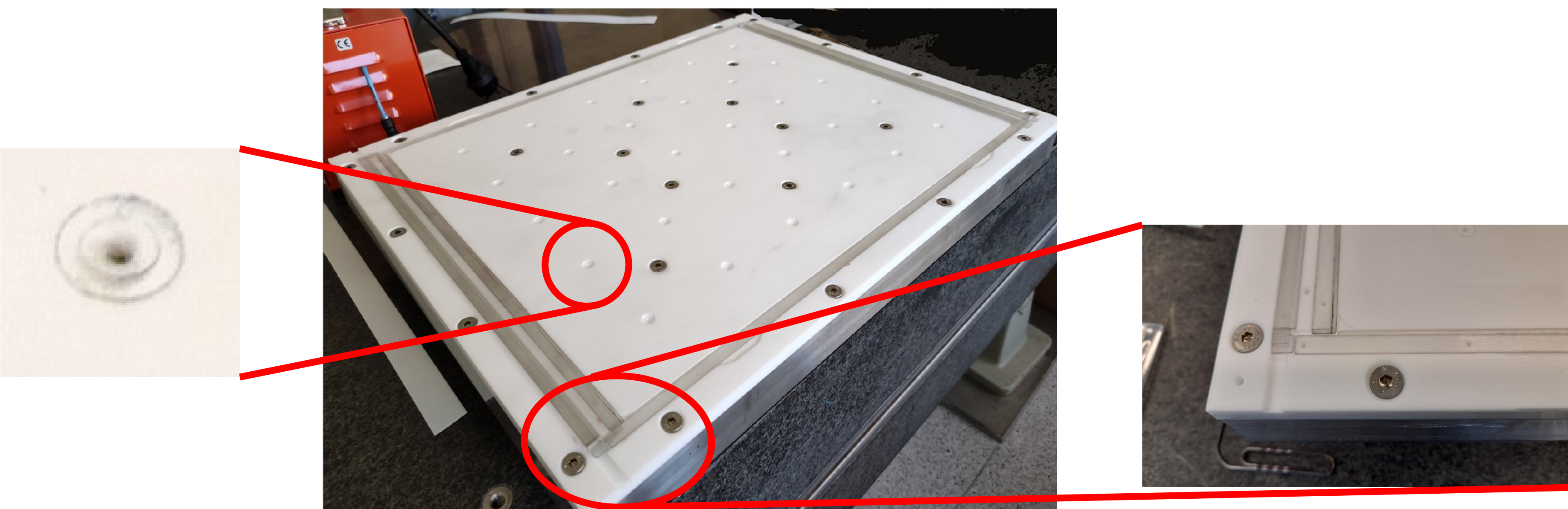
Production steps for an ATLAS thin-gap RPC

1. Quality control of all the materials
2. Application of the graphite coating and the high voltage contacts
3. PET foil glued on electrode for insulation
4. Positioning of the frame structure and the spacers using a fixture
5. First electrode is glued onto the frame structure and spacers
6. Gap is closed by gluing the second electrode to the first one and the edges are sealed with hot melt glue
7. Linseed oil coating is applied

Positioning spacers and lateral profiles and gluing the first electrode onto them

Fixture designed and built for this step:

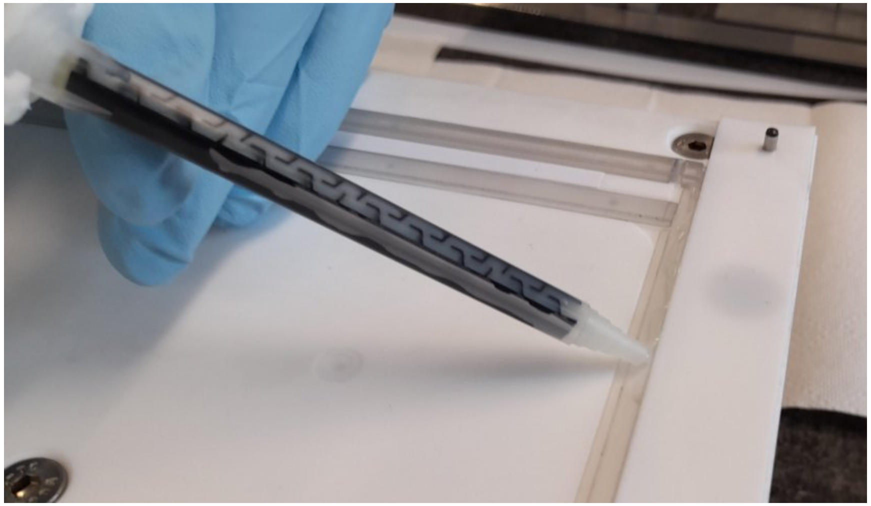
- Made from Teflon to prevent sticking of glue.
- Dimples and notches help place spacers and lateral profiles.
- Allows for the use of a vacuum pump to suck down the profiles and spacers, fixing them in place.



Positioning spacers and lateral profiles and gluing the first electrode onto them

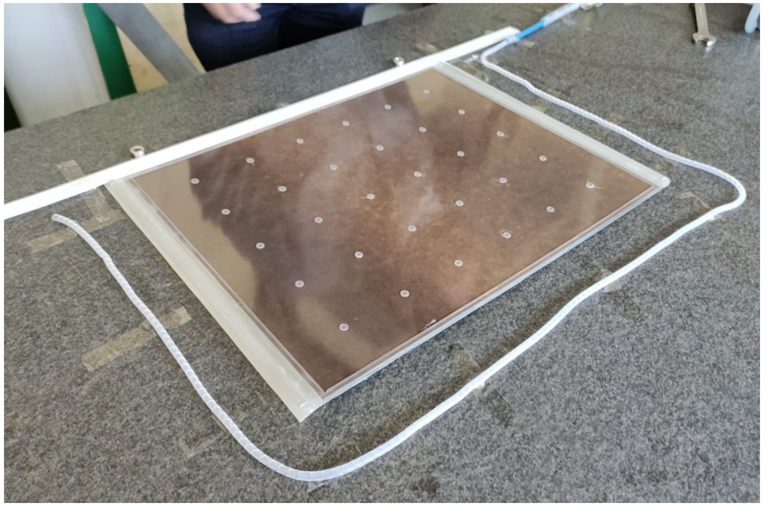
Gluing

- Glue (3M DP460/GößelPaff GP46) put onto lateral profiles and spacers using a dispenser.
- An HPL plate is put onto the profiles and spacers.
- Then pushed down with a vacuum bag for the 6h curing time of the glue.



Closing the gas gap with second HPL plate and adding the gas pipes

Second HPL plate put onto spacers and lateral profiles after 6 hours

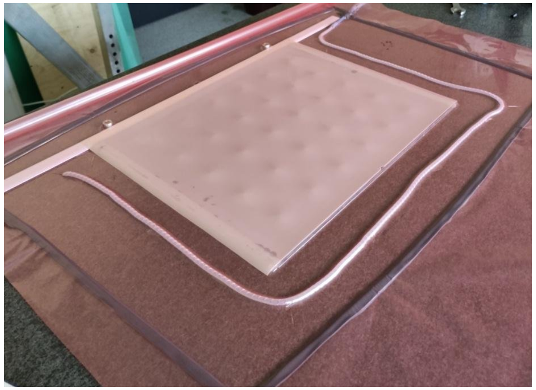


- Like in the third step glue is applied to the other side of the spacers and lateral profiles.
- Second HPL plate pressed onto the spacers and profiles.

Gas pipe:

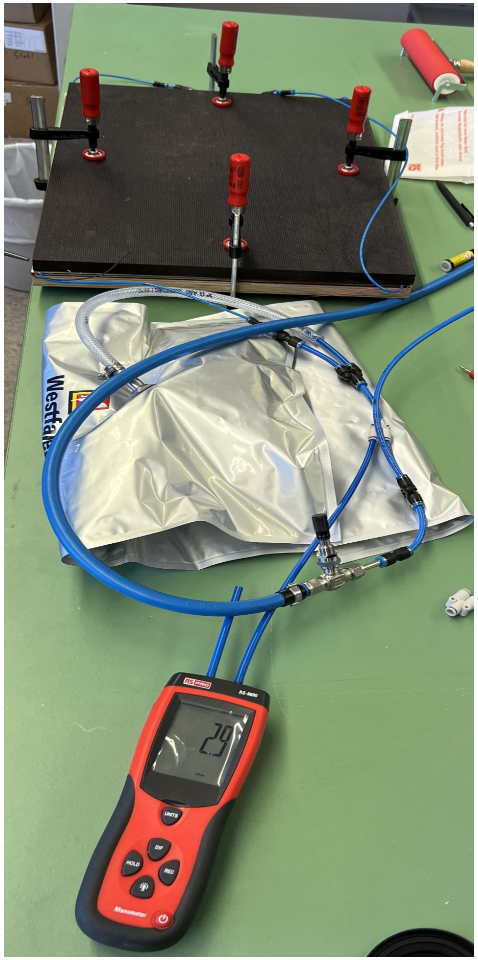
Gas pipe inserted into a hole in the lateral profile and glued in place.

Curing under a vacuum bag



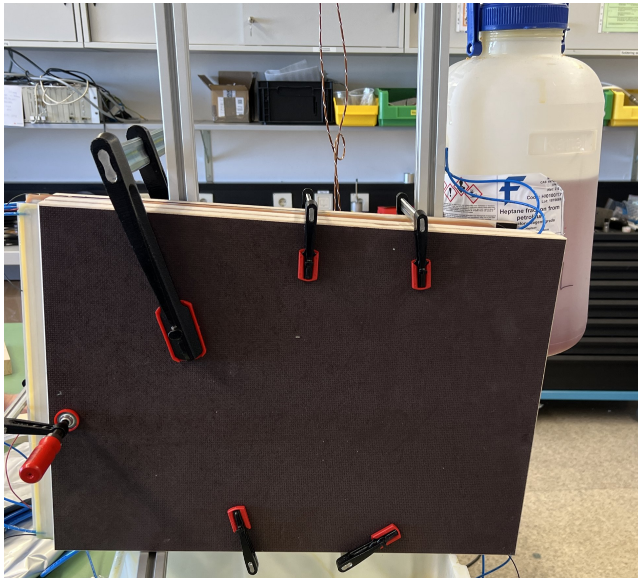
Sealing of the gap and leack testing

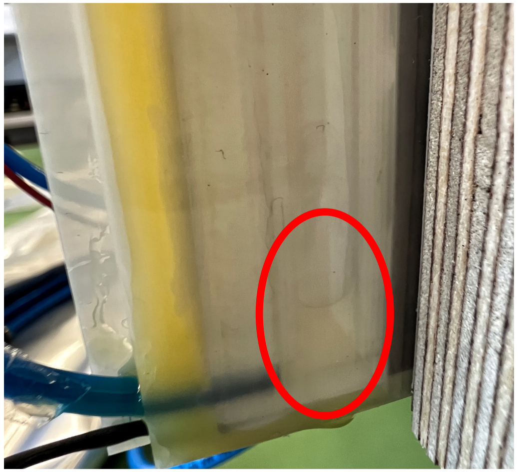
Leak testing:



- Gas gap is sealed with hot-melt
- Gas gap filled and pressurized with detectable gas (i.e. Argon)
- Search for leaks with gas detector

Linseed oil coating

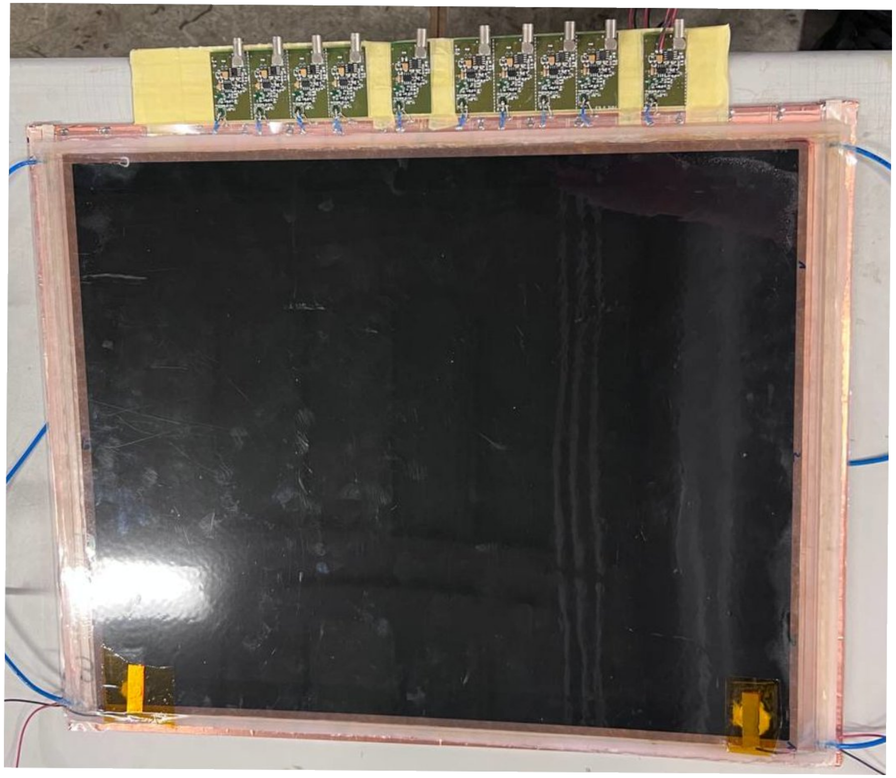




- Gas gap filled with linseed oil using the gas pipes as fill ports, from bottom to top
- Gas gap fixed between two plates to prevent bursting due to high pressure of oil and pump
- Slow drain of oil **(maximum speed ~ 1 m/h)** by lowering of the canister
    - Prevents formation of drops and streaks
    - Ensures creation of thin, smooth coating
- Air pumped through gap to accelerate the polymerization of oil with oxygen that creates a solid coating on the inside

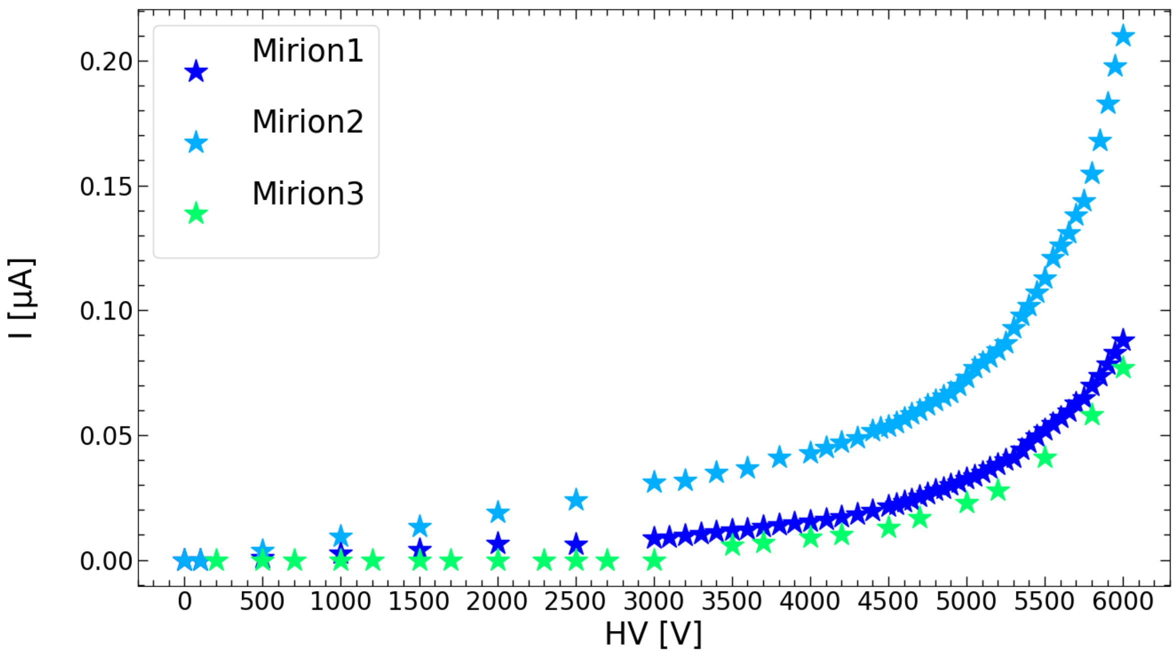
The Readout

Gas gap on a strip panel with pre-amplifiers mounted



- Strip panels with 16 strips with a width of 28mm and a 0.8mm ground strip in between two strips
- 2 gaps read out with 10 middle strips (prototypes called Mirion and PTS)
- 1 gap read out with two strip panels with 5 strips connected to the readout facing opposite directions (prototype called Metron) using the final ATLAS configuration
- Position along the strip is reconstructed using the propagation delay
- 3 gaps installed in a aluminum box that allows for installation of the services and for compression of potentially broken gaps
- Amplifiers are Connected to a discriminator which in turn is connected to a TDC

Voltage-Current curve

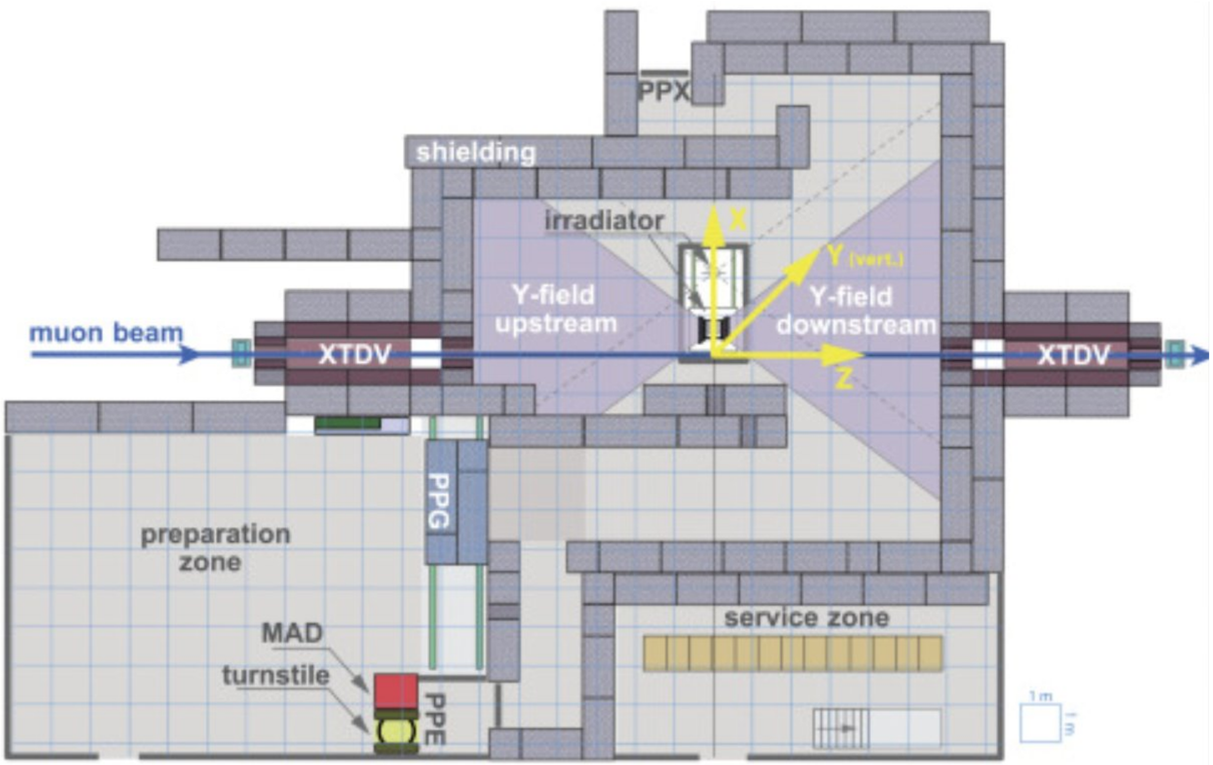


The voltage-current curves for three prototypes produced by Mirion, measured at MPI in Munich

- First quality indicator
- Linear part dominated by ohmic resistivity of the gas gap (mainly the conductivity of the linseed varnish)
- Exponential regime dominated by the current of the discharges in the gas gap occurring when the amplification regime is reached
- Acceptable currents are up to 0.2 µA in the region around 6100 V after subtracting the linear part of the current from the total

GIF++ Setup

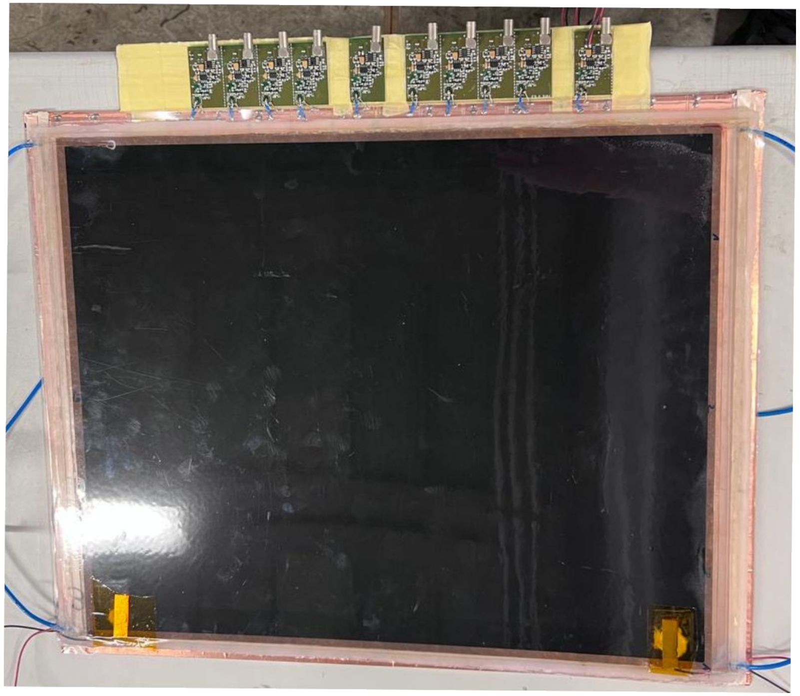
GIF++ Facility

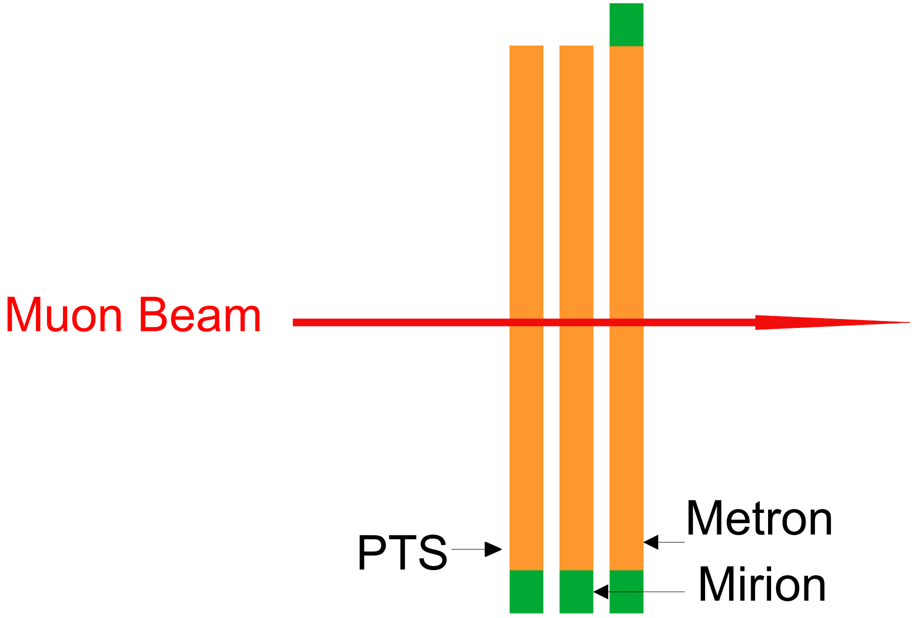


- Facility for the testing of detectors and detector components in an environment as similar to the final application as possible
- A ^{137}Cs source provides a high intensity gamma background
- High energy muon beam produced by a fixed target and a SPS proton beam with up to 10^4 muons/spill

The Readout

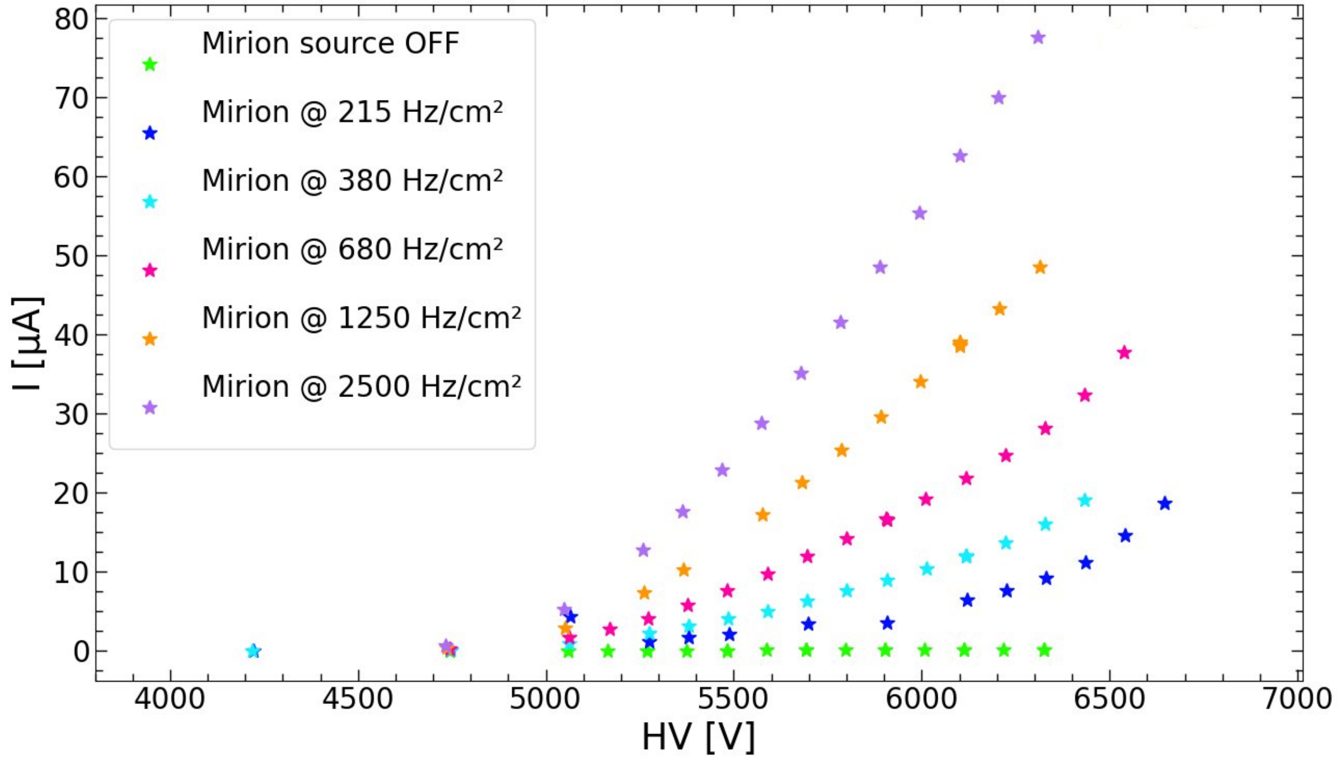
Gas gap on a strip panel with pre-amplifiers mounted





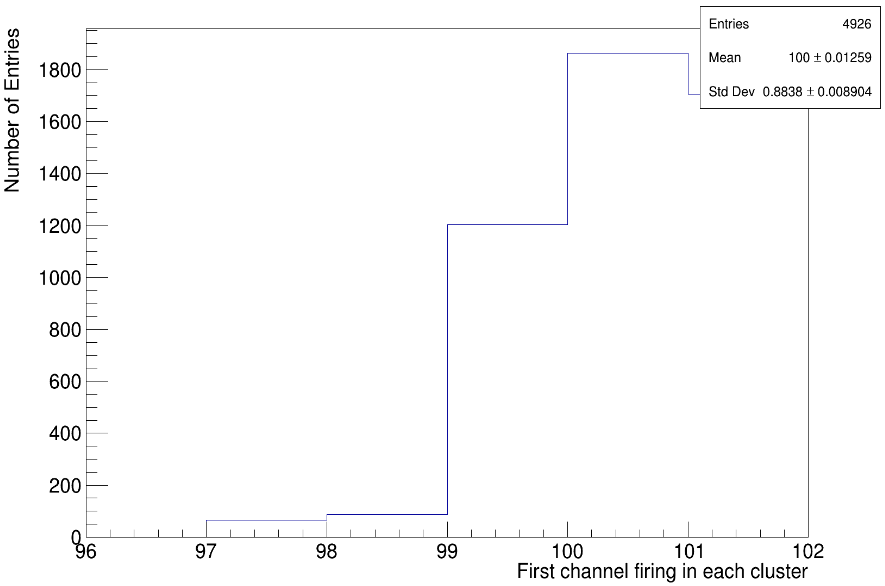
- Strip panels with 16 strips with a width of 28mm and a 0.8mm ground strip in between two strips
- 2 gaps read out with 10 middle strips (prototypes Mirion and PTS),1 gap with two strip panels with 5 strips the readout facing opposite directions (prototype Metron; final ATLAS configuration)
- Amplifiers are Connected to a discriminator which in turn is connected to a TDC

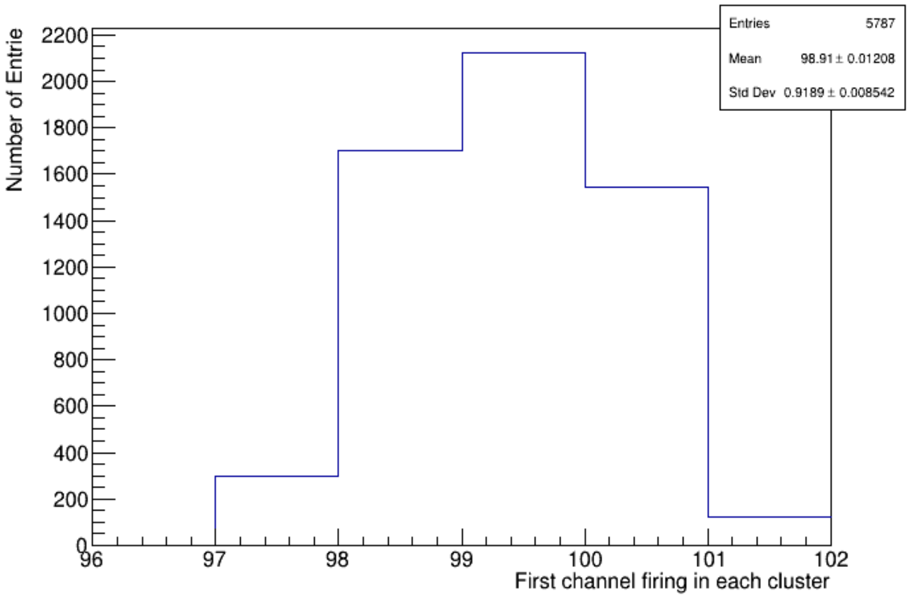
Voltage-Current curve at different amounts of irradiation



- More irradiation → more discharges in the gap → more current in the gap
  - ➔ When the current in the gas increases, the voltage drop over the electrodes increases
  - ➔ Electric field in the gas gets reduced
  - ➔ Compensate this by increasing the operating voltage

Position adjustment



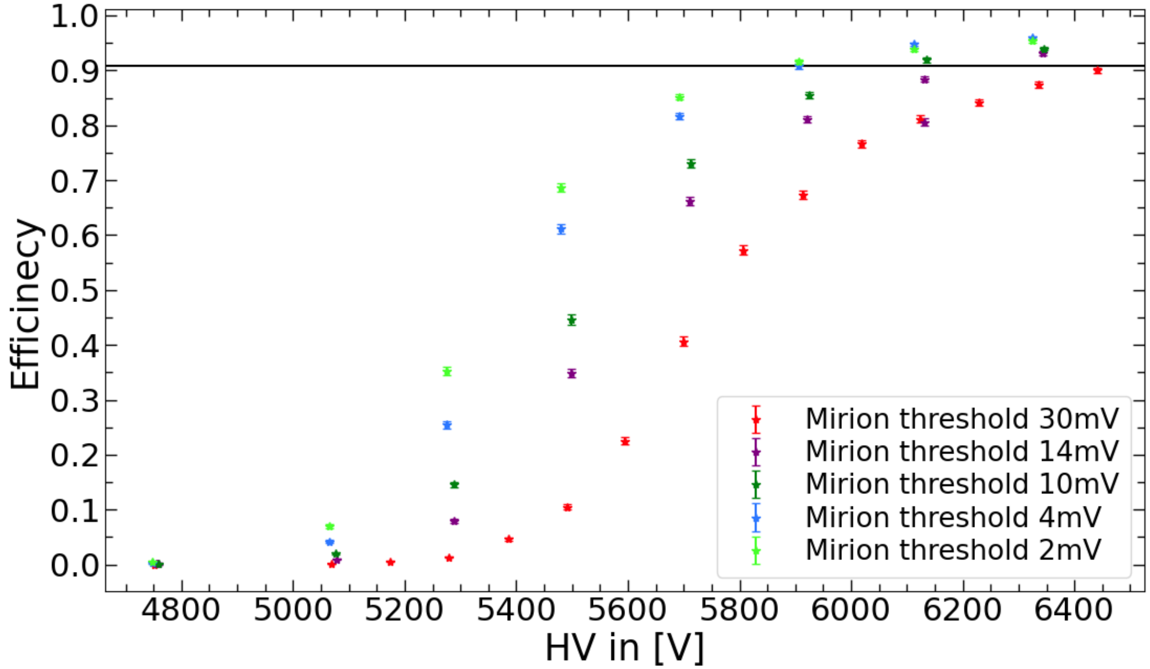


- After adjusting the position of the setup by measuring its position in the GIF first run was taken to get rough impression of the distribution
- Left distribution shows that the position with respect to the beam was not perfect → Setup was shifted and another run was taken → new position on the left shows the expected more Gaussian distribution for the beam profile

Determine optimal discriminator threshold

$$Efficiency = \frac{Events\ with\ at\ least\ one\ cluster\ reconstructed}{Total\ number\ of\ triggers}$$

Efficiency curves of Mirion measured with different discriminator thresholds without gamma irradiation



- For 2 mV noise rate is (11.12 ± 9.02)Hz/cm²
- For 4 mV noise rate is (1.11 ± 0.99) Hz/cm² → threshold of 4 mV chosen for all of the main measurements

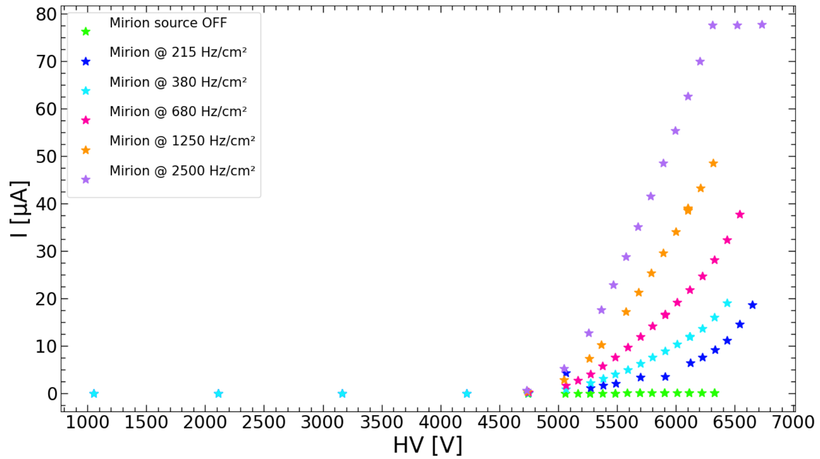
Gamma rate calculation

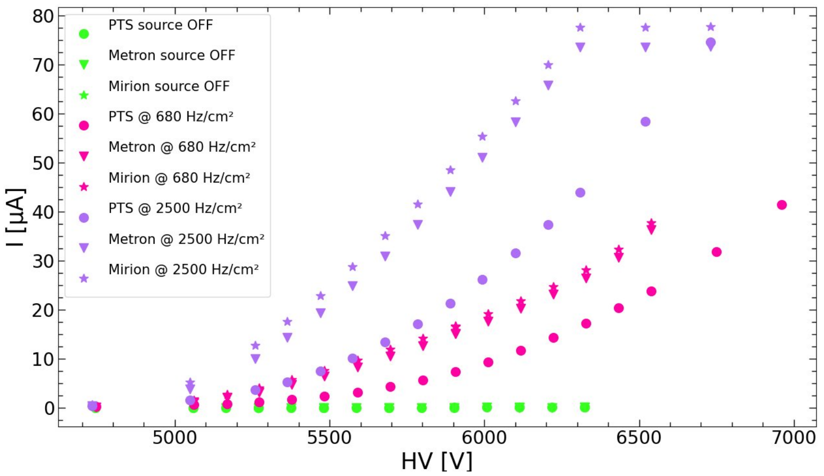
$$Rate = \frac{Number\ of\ clusters}{Number\ of\ Triggers \times Time\ window\ of\ the\ aquired\ data \times Area\ measured}$$

Gamma irradiation rates with different attenuation filters:

ABS	10	22	46	100	220
Rate in $\mathrm{Hz/cm^2}$	2507	1251	685	377	214
Error in $\mathrm{Hz/cm^2}$	25	10	9	7	3

Voltage-Current curve at different amounts of irradiation

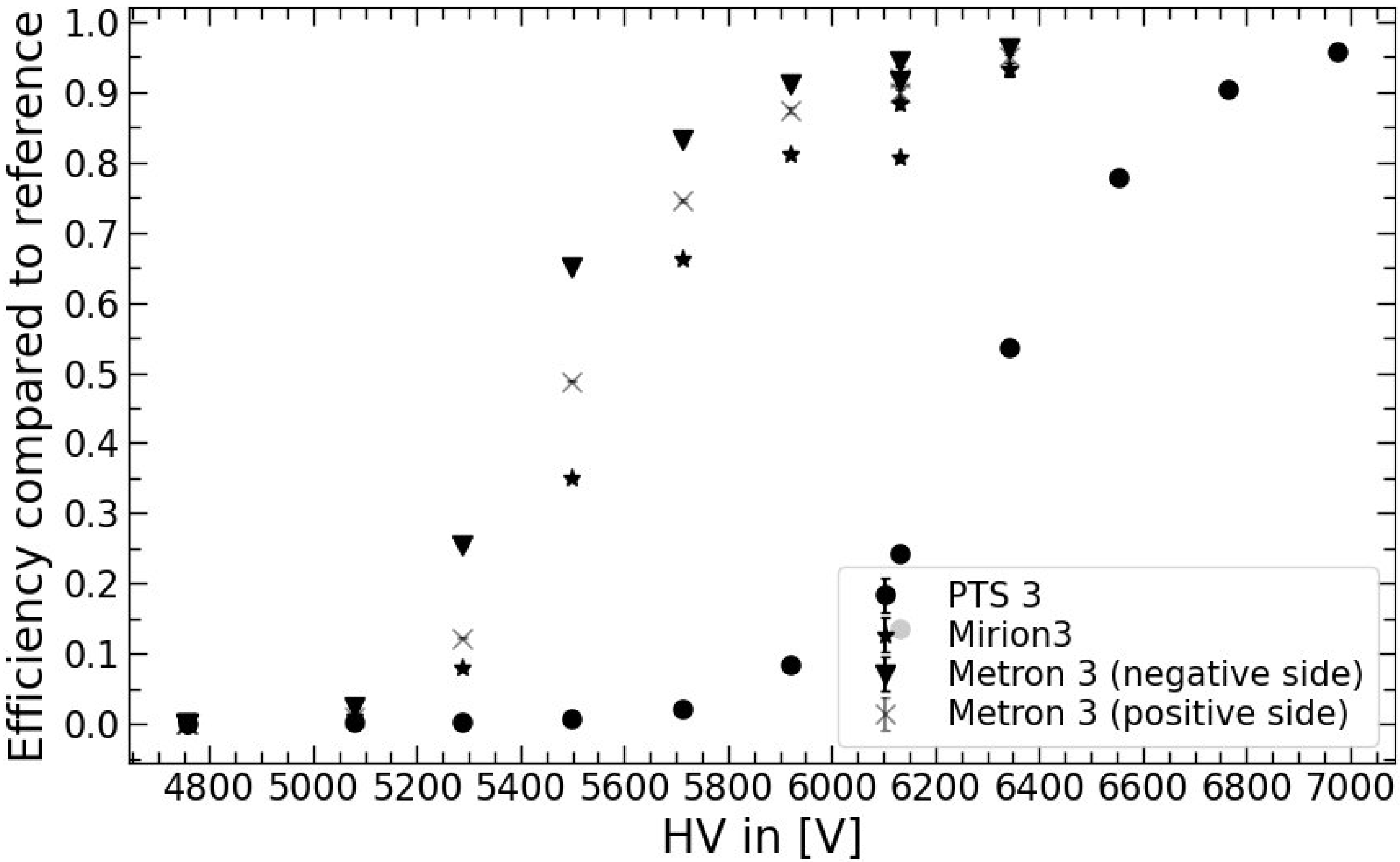




- The graphs show that Mirion and Metron show similar curves as expected of 1 mm RPCs
- The currents of PTS are much lower and the curve flatter due to a larger gap size

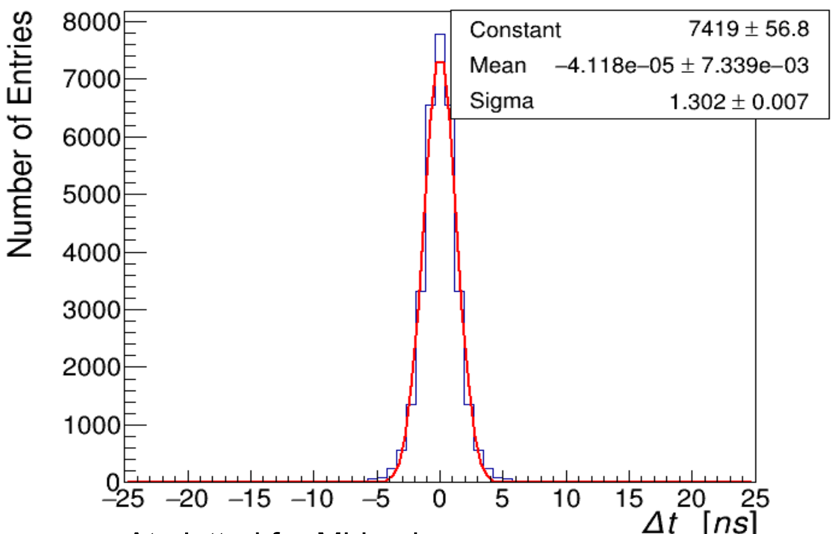
Efficiency calculation and scan

Efficiency scan with no gamma irradiation and a threshold of 14 mV

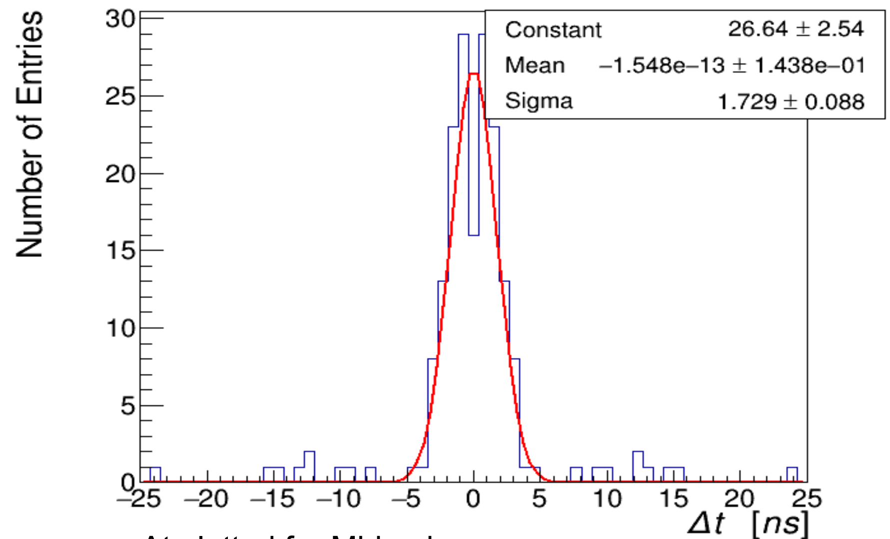


→ PTS only starts the plateau around 7000 V as it has a wider gap of around 1.3 mm

Clusterization algorithm



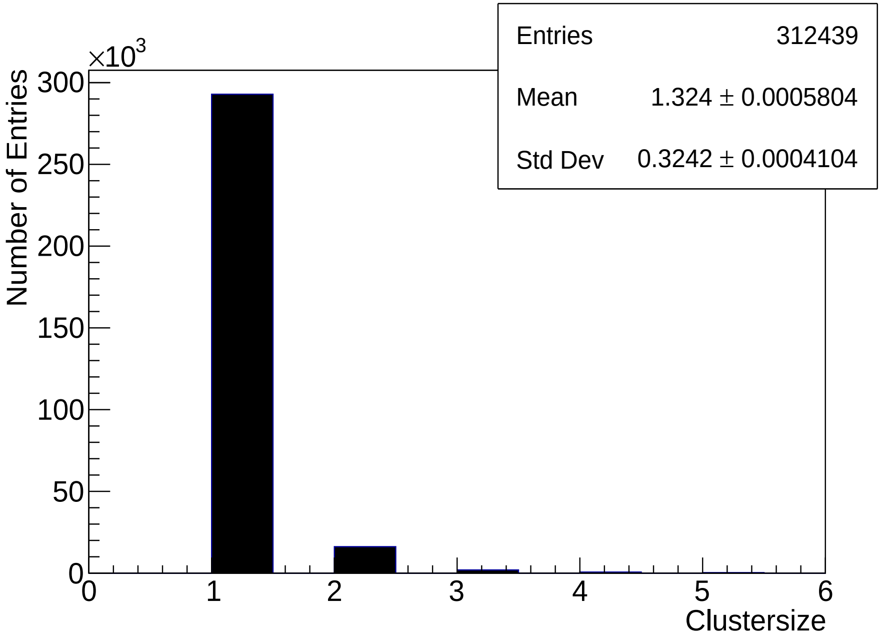
± Δt plotted for Mirion in a muon run



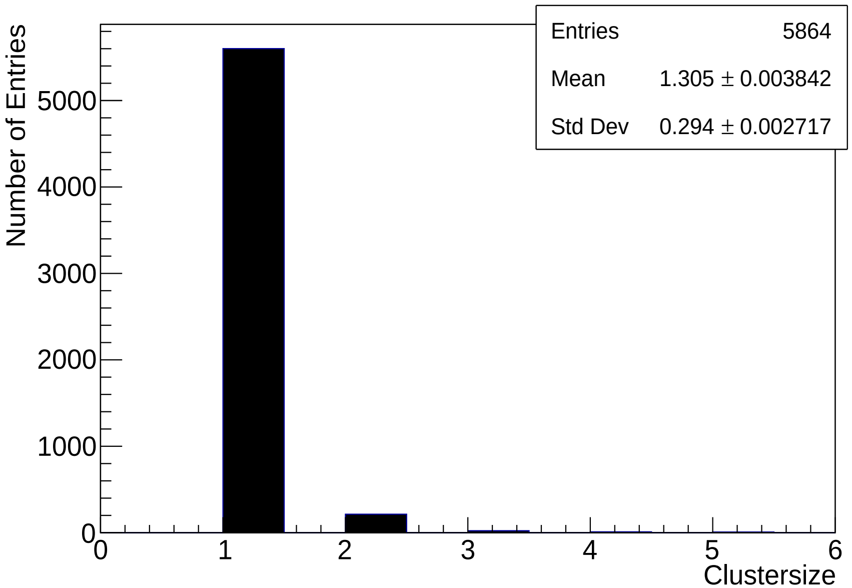
± Δt plotted for Mirion in a gamma run

- Criteria:
  1. all signals belonging to a cluster must originate from neighboring strips.
  2. all signals belonging to a cluster must start in the time window set by the duration of an avalanche moving in the gas.
- Signals were first clustered using a large time matching window → the time difference Δt, for two signals in a cluster with two strips firing, times ±1 was plotted and the distribution fitted with a gausian
- The time window is given by 5σ

Cluster size



Cluster size of Mirion at 0 gamma irradiation



Cluster size of Mirion at gamma irradiation

- Target of cluster size of 1 strip due to the readout planed at HL-LHC being digital only and no need for more precision
- Cluster size consistently around 1 for all irradiation intensities

Calcuate electrode resistivity

- As for the same total efficiency the voltage over the gas is the same one can calculate the resistivity using the equation:

$$R_{HPL} = \frac{U_{Irradiation} - U_{Source\ OFF}}{I_{Irradiation} - I_{Source\ OFF}}$$

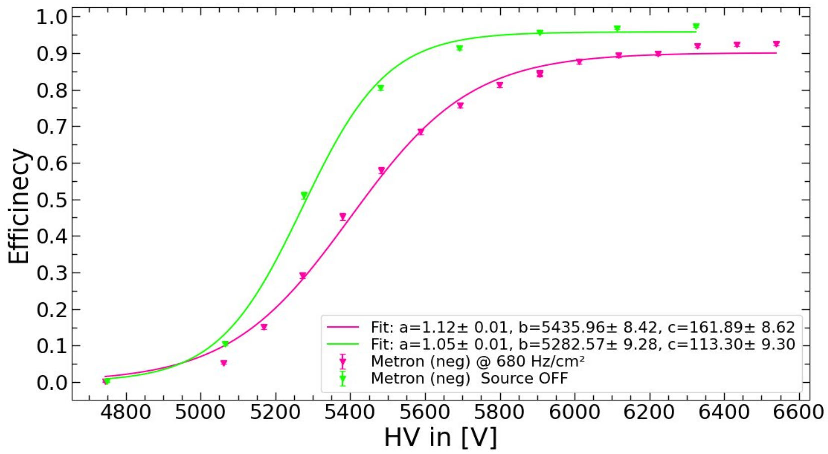
- To determine the voltage at which two curves, measured at different amounts of irradiation, reach the same efficiency, the curves were fitted with the equation:

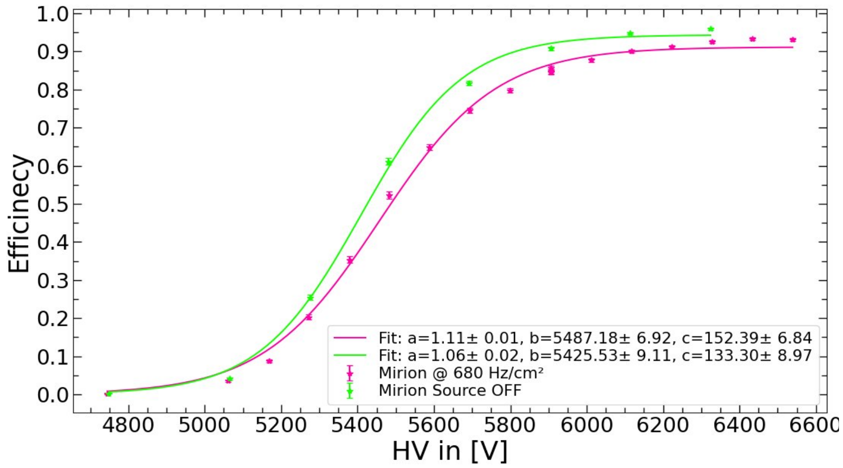
$$Efficiency = \frac{a}{(2a-1) + e^{\frac{b-HV}{c}}}$$

  b gives the voltage were the curve reaches 50% total efficiency

- To determine the current the voltage current curves were interpolated at the voltages previously determined

Calculate electrode resistivity





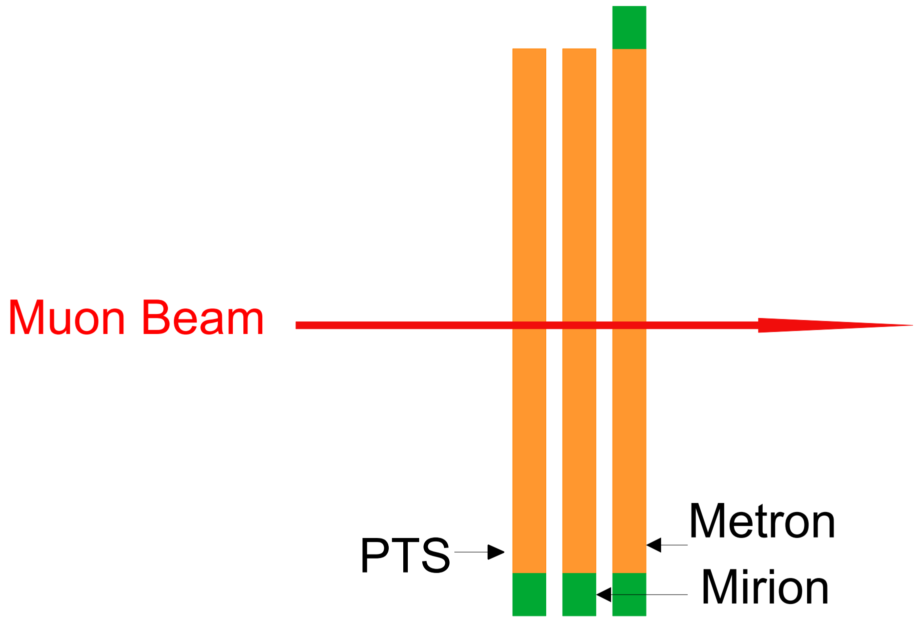
Example:

	Mirion		Metron	
Irradiation in Hz/cm^2	680	OFF	680	OFF
HV @ 0.5 in V	5487.18	5425.25	5435.96	5282.57
I in μA	7.69	0.015	5.60	0.013

- After repeating this for all amounts of irradiation the calculated resistivities are
  - $(5.91 \pm 1.23) \cdot 10^{10}$ Ωcm for Mirion
  - $(16.45 \pm 3.28) \cdot 10^{10}$ Ωcm for Metron

Metron resistivity higher → Efficiency drops at high irradiation

Time Resolution



- Assuming Mirion and Metron have the same time resolution one can use equation: $\delta t = \frac{\sigma}{\sqrt{2}}$
- Δt is time difference between the signals created by the same muon and measured in both chambers
- Plot Δt against the second coordinate to find and correct for local effects that change amplification at different points in the chamber

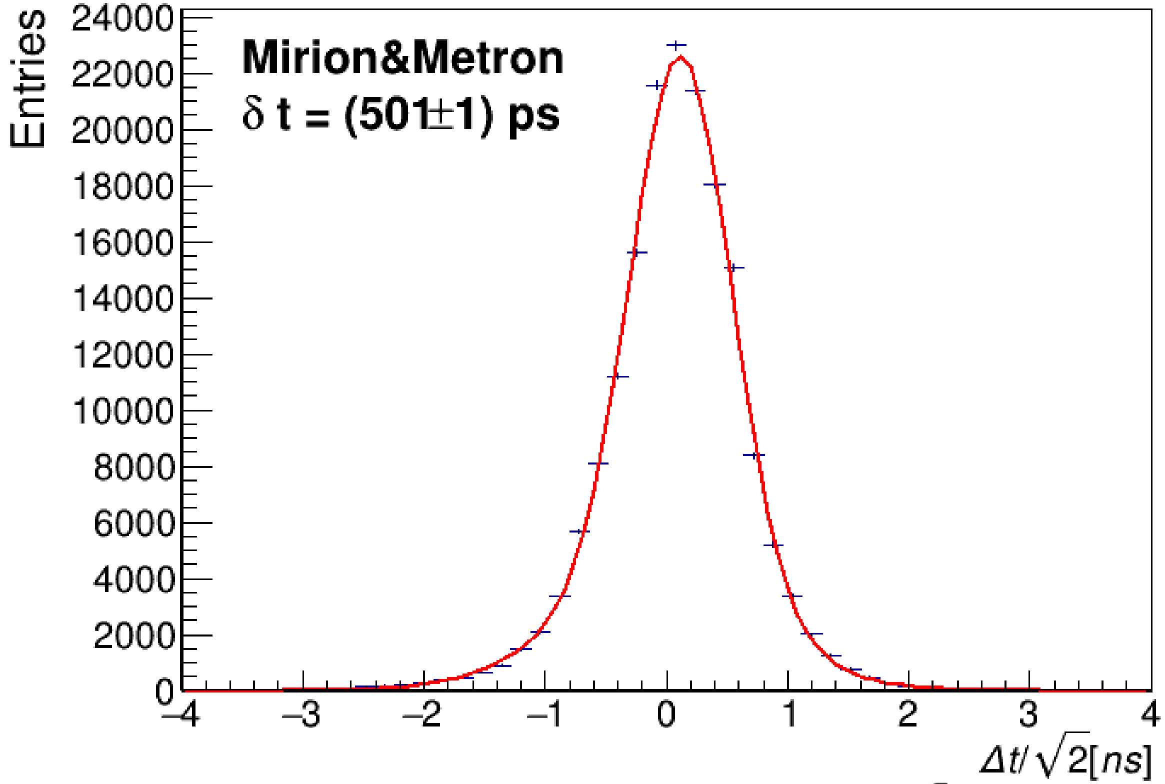
Time Resolution

- Calculate $\Delta t_{raw} = t_{Mirion} - t_{Metron(neg)}$ for hits that are created by the same muon
- Calculate $\Delta t_{(neg\text{-}pos)} = t_{Metron(neg)} - t_{Metron(pos)}$ as a measure for the position of the hit along the strips
- Plot Δt_{raw} against $\Delta t_{(neg\text{-}pos)} \rightarrow$ calculate average Δt_{raw} for each $\Delta t_{(neg\text{-}pos)}$
- Subtract the average form $\Delta t_{(raw)}$ to correct for differences in the amplification at each position of the chamber $\rightarrow \Delta t$
- Assuming the error of the time measurement of Mirion and Metron is comparable one can use the following equation:

$$\delta(\Delta t) = \sqrt{(\delta t_{Mirion})^2 + (\delta t_{Metron})^2} = \sqrt{2} \cdot \delta t = \sigma$$

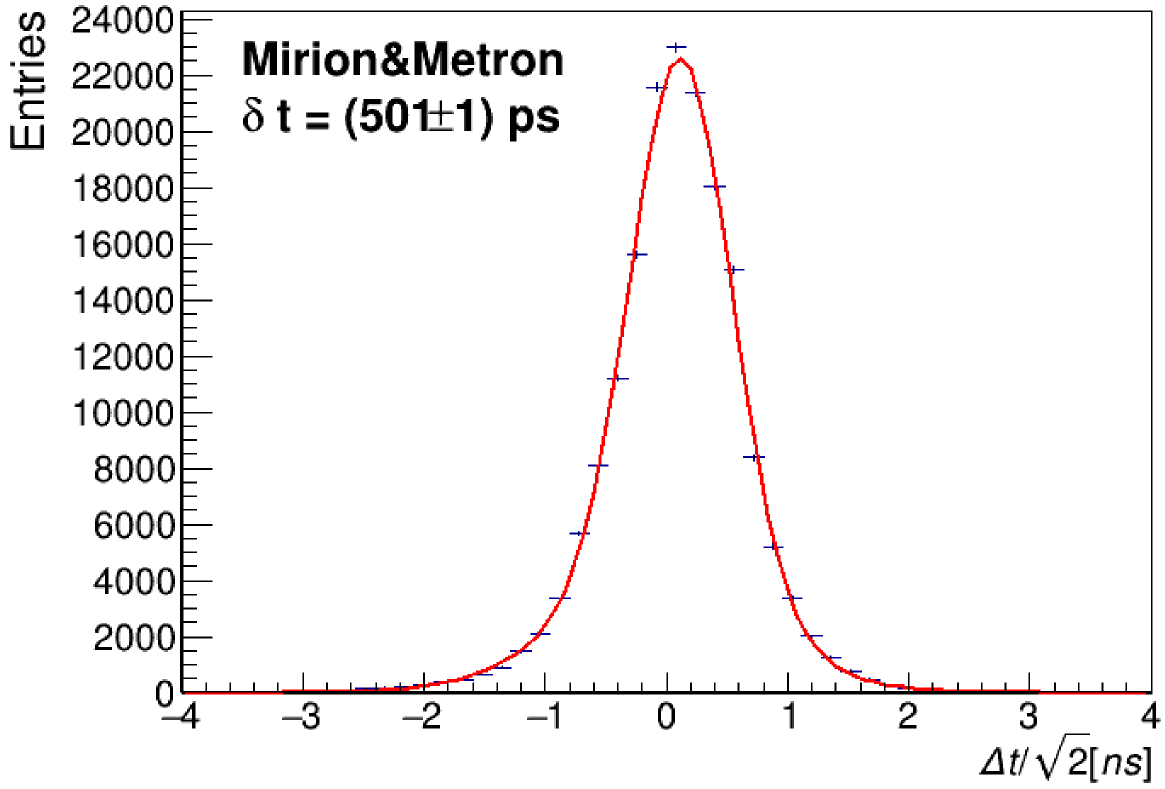
$$\Rightarrow \quad \delta t = \frac{\sigma}{\sqrt{2}}$$

Time Resolution



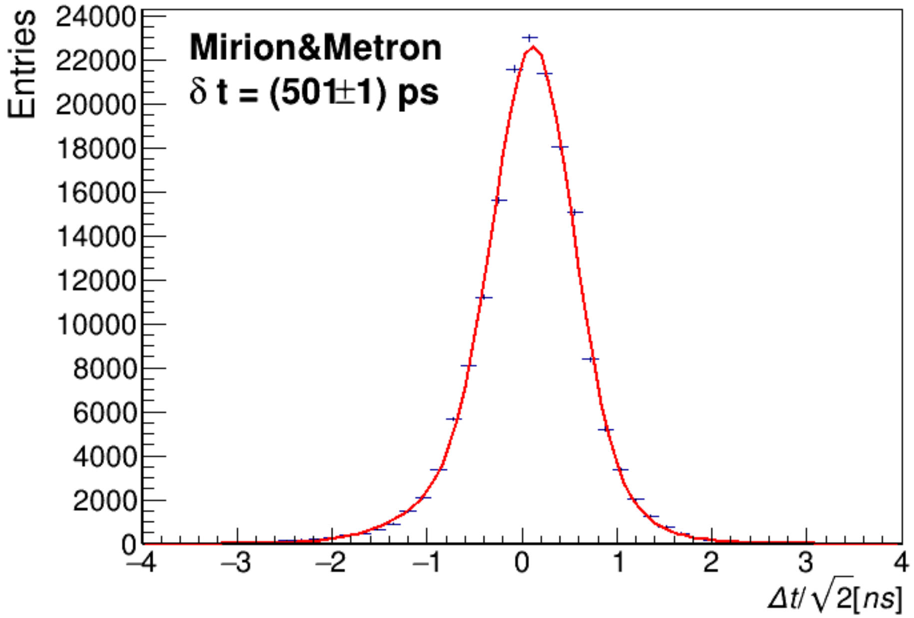
- Assuming Mirion and Metron have the same time resolution: $\delta t = \frac{\sigma}{\sqrt{2}}$
- Δt is time difference between the signals created by the same muon and measured in both chambers
- 34.1% confidence interval numerically determined → σ → δt = (501 ± 1) ps for Mirion and Metron

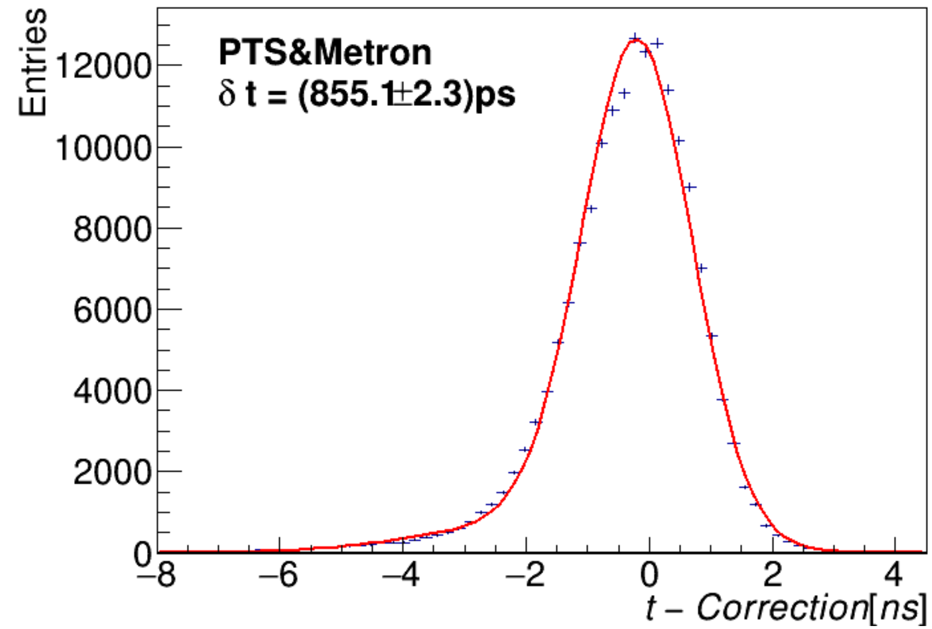
Time Resolution



- 34.1% confidence interval numerically determined → σ → δt = (501 ± 1) ps for Mirion and Metron

Time Resolution



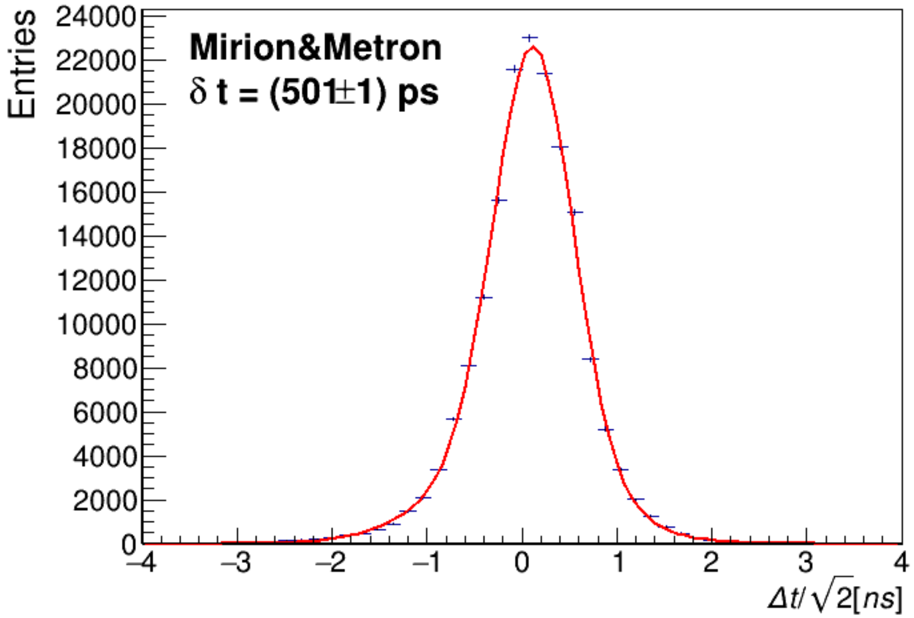


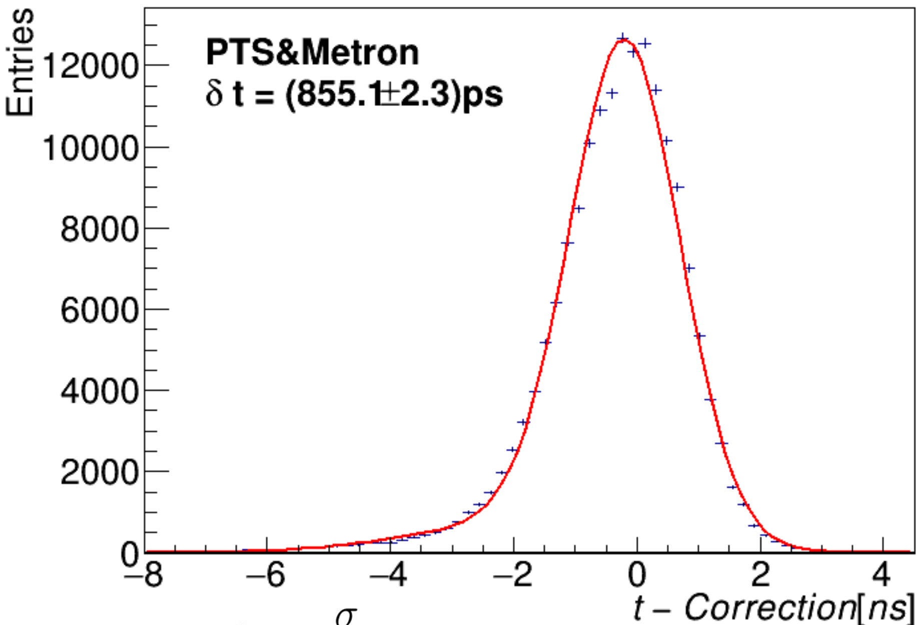
- All Gaps are operated at the same voltage for these measurements
- 34.1% confidence interval calculated → σ → δt = (501 ± 1) ps for Mirion and Metron
- For PTS we can use the same method when using the equation:

$$\delta(\Delta t_{PTS\ Metron}) = \sqrt{(\delta t_{PTS})^2 + (\delta t_{Metron})^2} = \sigma$$

- With this we get a time resolution of δt_{PTS} = (855.1 ± 2.3) ps

Time Resolution





- Assuming Mirion and Metron have the same time resolution: $\delta t = \frac{\sigma}{\sqrt{2}}$
- Δt is time difference between the signals created by the same muon and measured in both chambers
- 34.1% confidence interval numerically determined → σ → δt = (501 ± 1) ps for Mirion and Metron
- For PTS we can use the same method when using the equation:

$$\delta(\Delta t_{PTS\ Metron}) = \sqrt{(\delta t_{PTS})^2 + (\delta t_{Metron})^2} = \sigma$$

- With this we get a time resolution of δt_{PTS} = (855.1 ± 2.3) ps