GEMs at the FTD

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FTD Electronics & Applications Seminar
19th May 2025

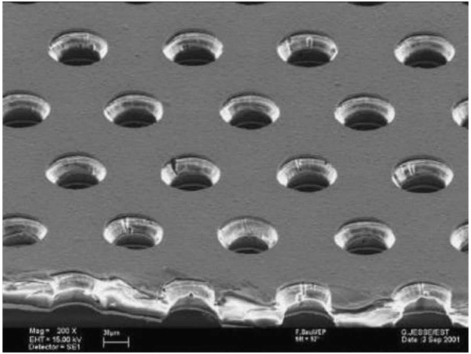
Outline

1. Overview GEMs
2. Detailed production steps
3. Quality assurance
4. Latest results

[pictures by V. Lannert]

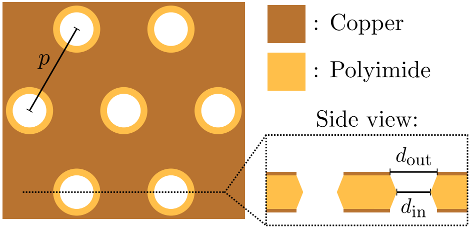
1. Overview on GEMs

GEMs in general



[F. Sauli, *The gas electron multiplier (GEM): Operating principles and applications*, 2016]

- ***G**as **E**lectron **M**ultiplier* (GEM)
- Variant of the ***M**icro **P**attern **G**aseous **D**etectors* (MPGDs)
- Developed by Fabio Sauli in 1996
- $50\,\mu\text{m}$ polyimide, coated with $5\,\mu\text{m}$ copper
- Polyimide has interesting properties:
  - Dielectric strength $\geq 200\,\frac{\text{V}}{\mu\text{m}}$
  - specific resistivity $= 8 \cdot 10^{15}\,\Omega\,\text{m}$
- Manufactured using photolithography



[P. Hauer, PhD thesis, 2022]

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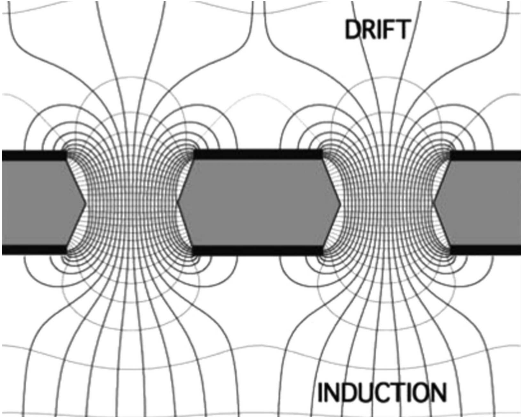
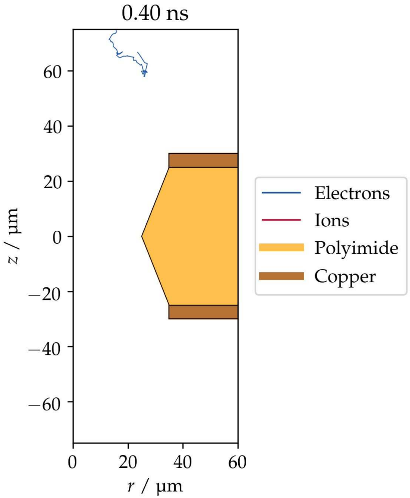


[F. Sauli, *The gas electron multiplier (GEM): Operating principles and applications*, 2016]

- Microscopic holes are etched into the foil ($50\,\mu m$ to $70\,\mu m$)
- Applying voltage $\Rightarrow$ Gas amplification happens within holes due to strong $\vec{E}$-field
- Gain depends exponentially on voltage, but ranges from 5 - 20
- Holes typically arranged hexagonally, pitch $p = 140\,\mu m$ (standard pitch)

$\Rightarrow$ ≈ 60 holes per mm^2, making the foil partially transparent



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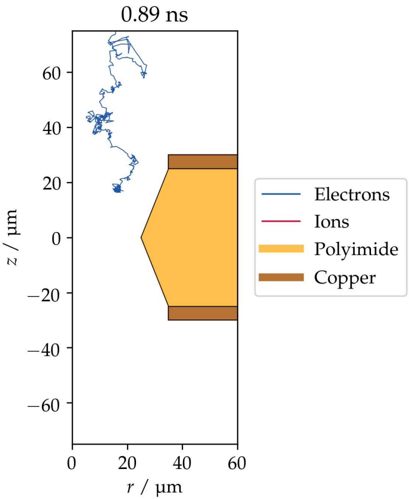
Working principle of GEMs



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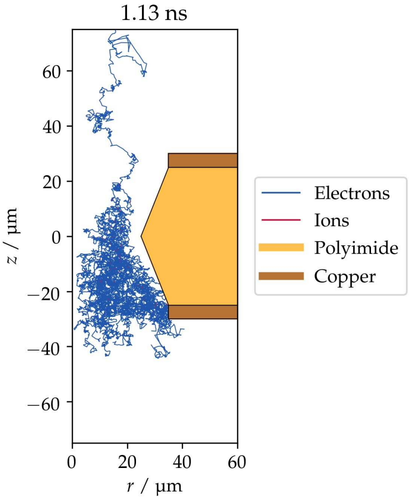

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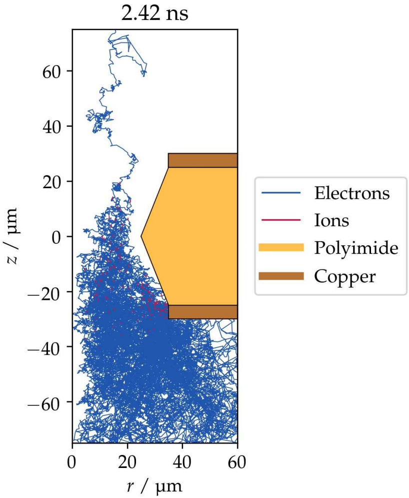

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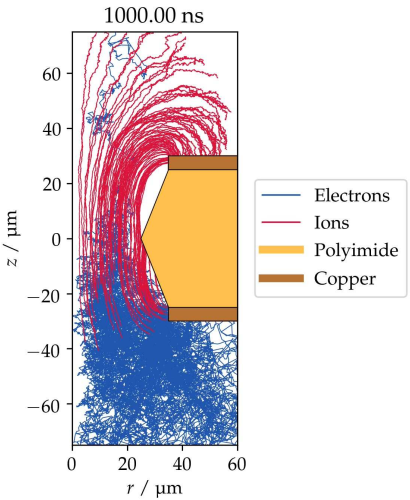

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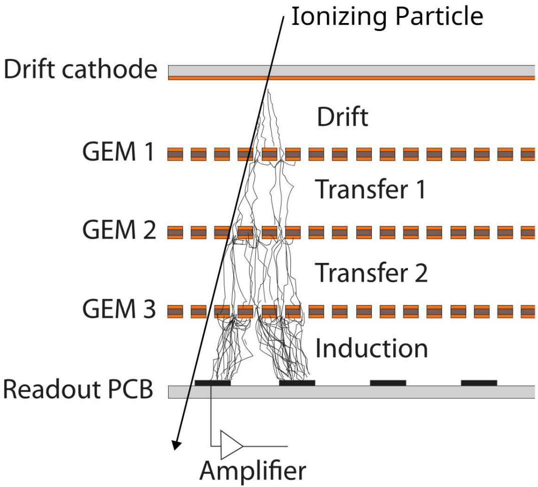
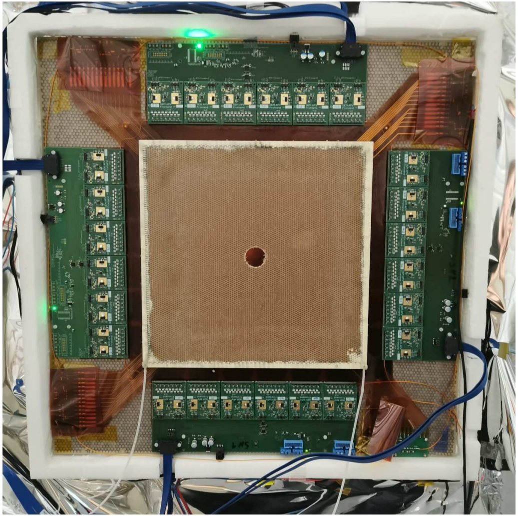


[Colaleo et al., *CMS TDR for the Muon Endcap GEM Upgrade*, 2015], modified

Prominent examples:

- Triple GEM tracking detectors (e.g. AMBER / COMPASS / INSIGHT)
- GEM time projection chamber (TPC) (e.g. ALICE / FOPI / etc.)



[AG Ketzer, 2022]

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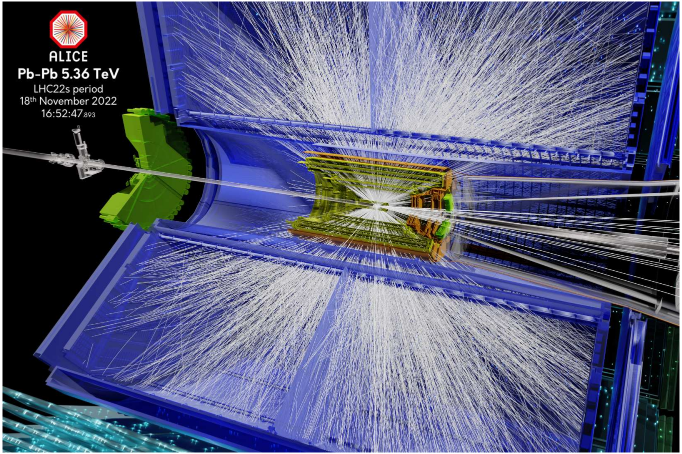
Examples of GEM Detectors



[https://cds.cern.ch/record/2841865]

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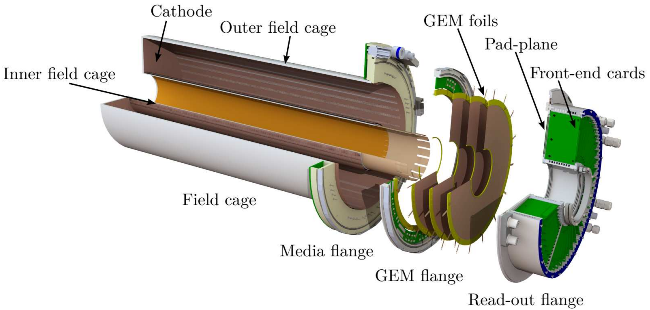


[Berger et al., *A Large Ungated TPC with GEM Amplification*, 2017]

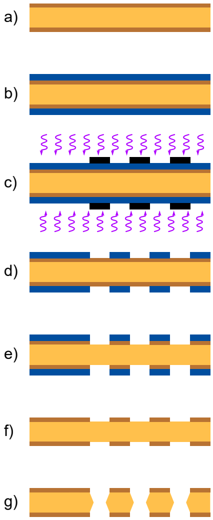
Prominent examples:

- Triple GEM tracking detectors (e.g. AMBER / COMPASS / INSIGHT)
- GEM time projection chamber (TPC) (e.g. ALICE / FOPI / etc.)

GEM Production Steps

Seven steps to produce a GEM:

1. Lamination with photoresist (b)
2. Exposition with UV light (c)
3. Photoresist development (d)
4. Copper etching (e)
5. Stripping of photoresist (f)
6. Chromium etching (f)
7. Polyimide etching (g)



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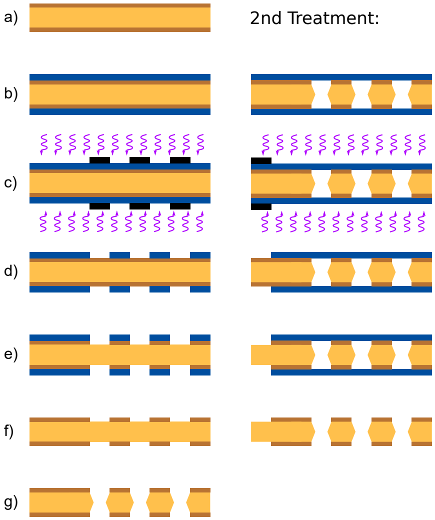
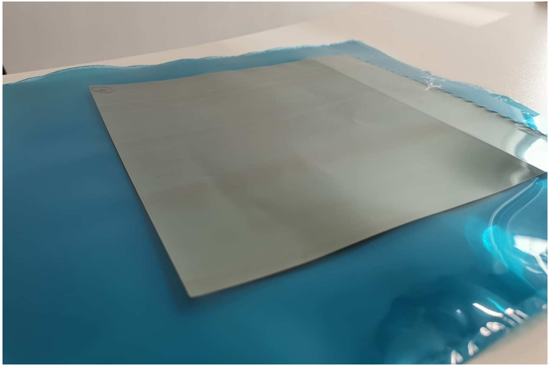


2. Detailed production steps

Lamination

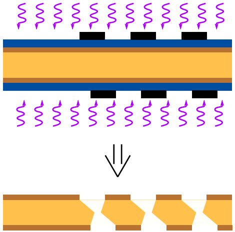
- Use negative dry film photoresist (15 µm)
- Laminating both sides simultaneously



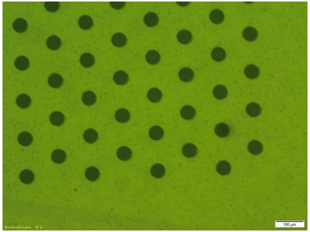
RLM419p by Bungard

Exposition

- Using UV LEDs from both sides
- Crucial step: alignment of top and bottom mask
  - ⇒ Align masks once under microscope and glue them together (pocket)



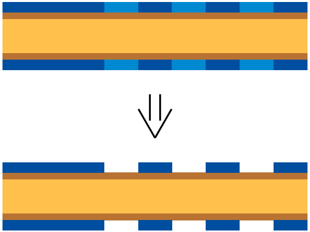
Aligned masks:



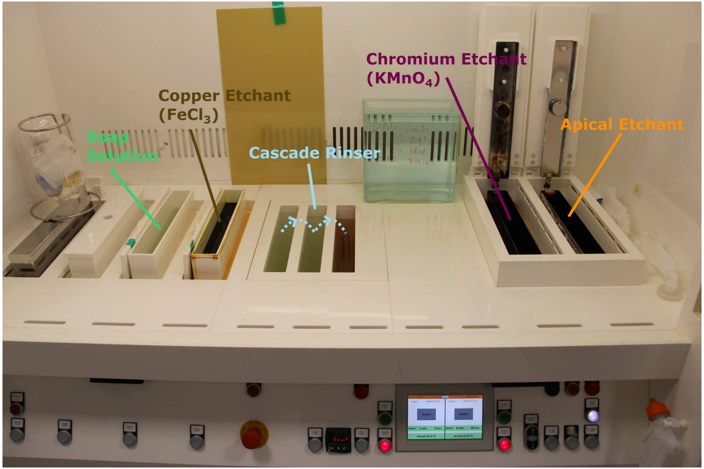
Exp 3040 LED by Bungard

Development

- Dissolve photoresist which has not been exposed
- Performed in beaker with Na_2CO_3-based solution

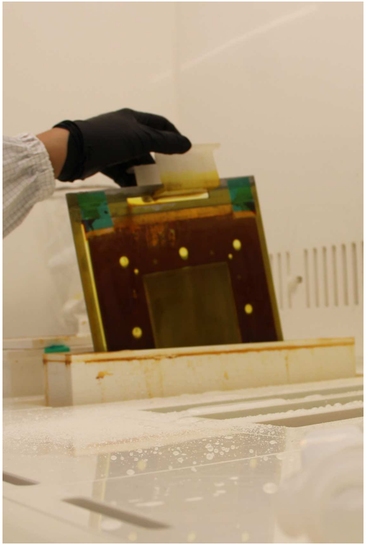


- Installed in ISO 7 of cleanroom
- Especially designed/built for GEM production
  - 3 stainless steel beaker
  - 3 PP beaker (non-heated)
  - cascade rinser
  - generously designed exhaust



Step 4: Copper etching

- Etch accessible copper through patterned photoresist
- Performed in beaker with $FeCl_3$-based solution
- Etches isotropically:
  - Copper below photoresist is partially etched away, creating larger diameter



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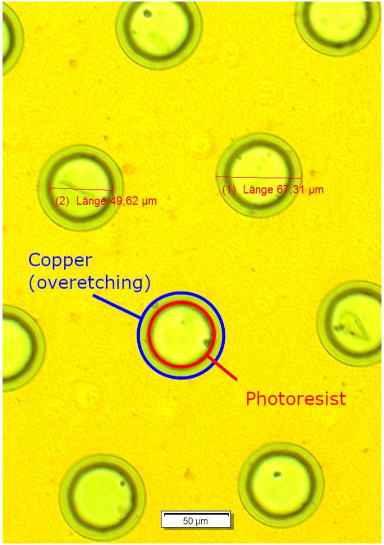
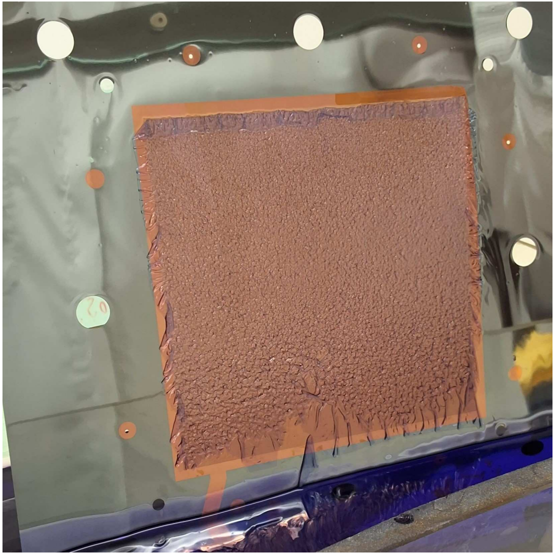
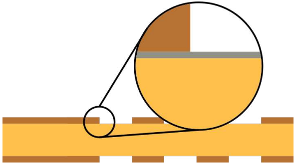


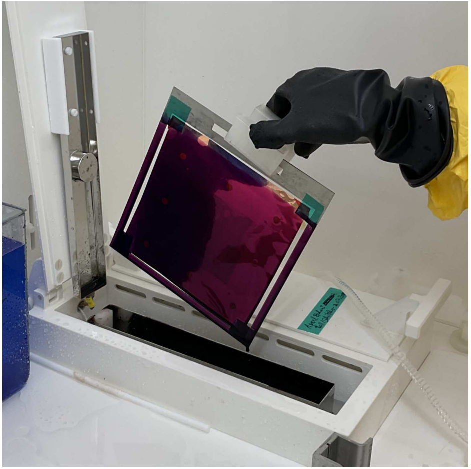
Step 5: Stripping of photoresist

- Mixture of Aceton and Ethanol
  - Photoresist peels off
  - Does not dissolve photoresist
- Sometimes help with small brush to get rid of photoresist

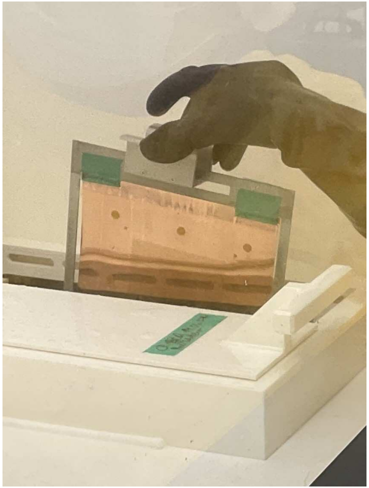


- Adhesive layer between copper and polyimide
  - Typically only a few nm thick
- Etching performed in beaker with $KMnO_4$-based solution
- Then neutralize with aqueous solution

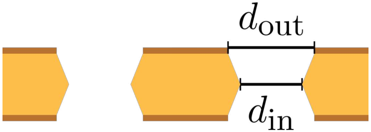




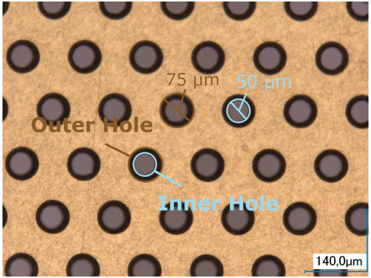
- Strong and really dangerous chemicals involved
- Heated up
- Afterwards: Outer and inner holes visible under microscope
  - Outer diameter: $d_{\text{out}} \approx 75\,\mu\text{m}$
  - Inner diameter: $d_{\text{in}} \approx 50\,\mu\text{m}$



Cross Section:



[P. Hauer, PhD thesis, 2022], edited



Step 7: Polyimide etching

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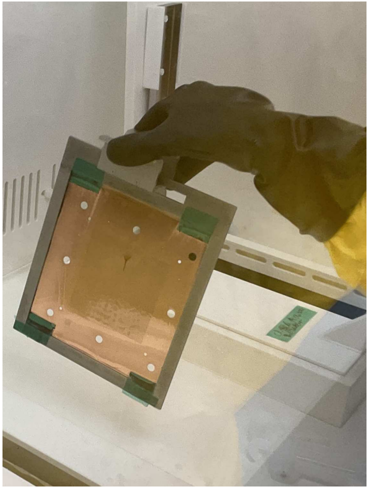

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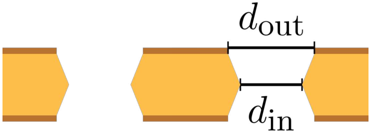

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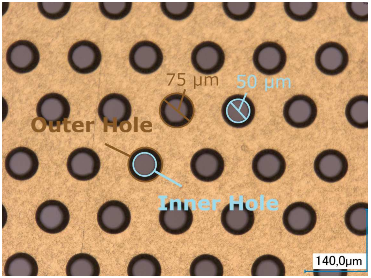
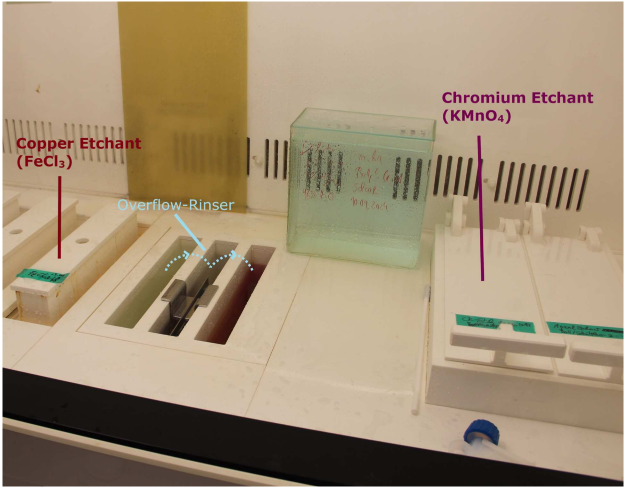


Step 8: 2nd Treatment & cleaning

Repeat steps 1 to 6 for electrode patterning and clean using high-pressure DI water



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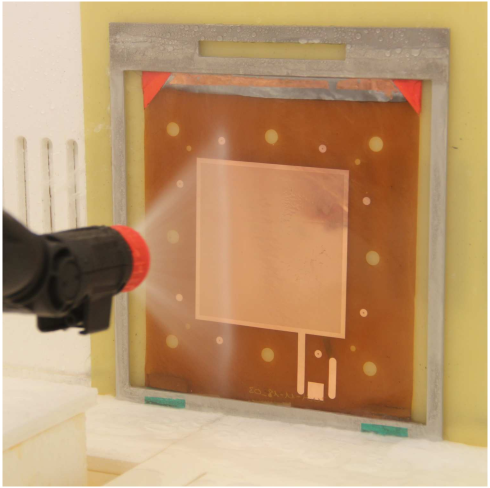


3. Quality assurance

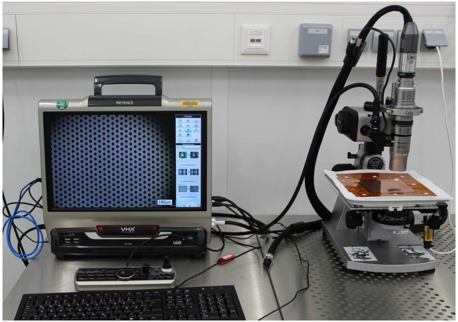
Quality assurance of GEMs

High quality of GEMs is key for **optimal** and **longterm** detector performance

⇒ Quality Assurance (QA) is very important

- The previous process (e.g. ALICE, CMS, COMPASS) includes:
- Optical QA:
  - number and size of defects (visual inspection by eye and microscope)
  - size/uniformity of inner and outer holes
- Electrical QA:
  - leakage current measurements
  - high-voltage stability

⇒ **spatially resolved detection of electric discharges is desired**



Digital microscope Keyence VHX 2000

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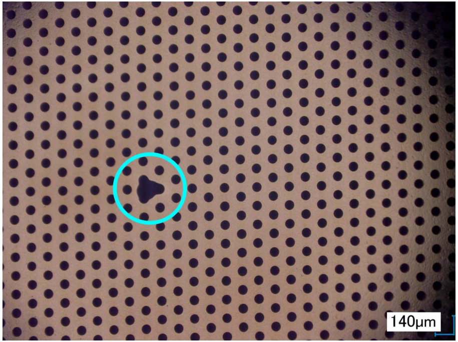

Microscope picture of a defect (connected holes)

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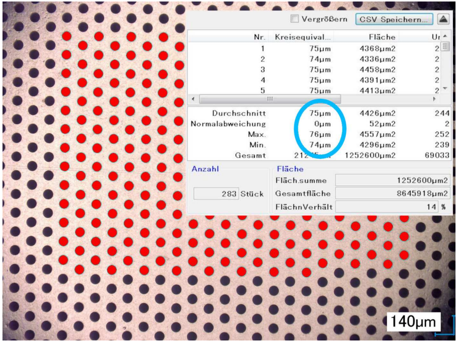

Microscope picture with measurement of outer hole diameter (copper)

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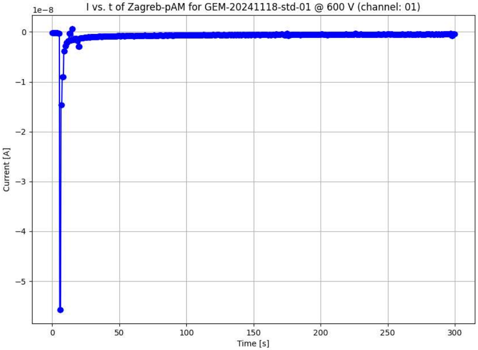

Measurement of leakage current
$\approx 0.4\,\text{nA}$ @ $600\,\text{V}$

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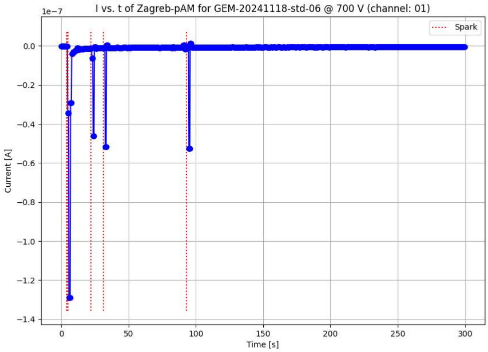

Measurement of leakage current $\approx 0.5\,$nA (with 8 sparks) @ $700\,$V

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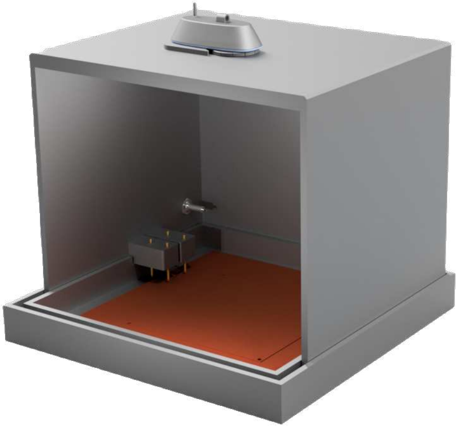
$\Rightarrow$ **spatially resolved detection of electric discharges is desired**

- Requirements for smaller design:
  - sufficiently large for uncut $10 \times 10\,\mathrm{cm}^2$ GEMs ($\Rightarrow \approx 20 \times 20\,\mathrm{cm}^2$)
  - easy & cost-effective to manufacture (3d printed)
  - simple, non-invasive HV connection
  - clean room suitable
  - low leakage current ($I_{\text{leak}} < 25\,\text{pA}$)
  - camera mount in the middle above the GEM



rendered image of the SDS design (section view)

Design of the small SDS

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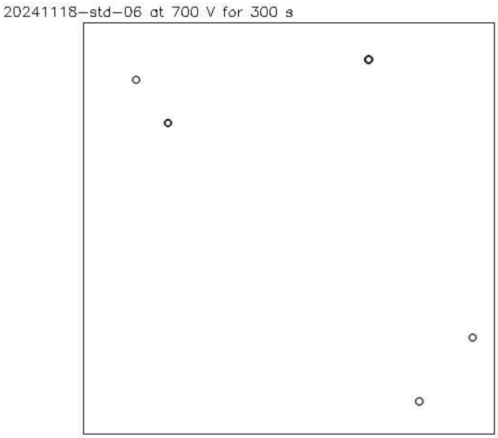
finished Spark Detection System (SDS) with a GEM-foil inside

Example SDS measurements

- Software makes use of `python` and library OpenCV for ease of use
- Primarily threshold scan, then `SimpleBlobDetector()`
- Save time, position and brightness of spark in text file
- Draw spark on sparkmap
- Test shows: efficiency $\epsilon \geq (95.5 \pm 0.7)\,\%$



Sparkmap of typical GEM

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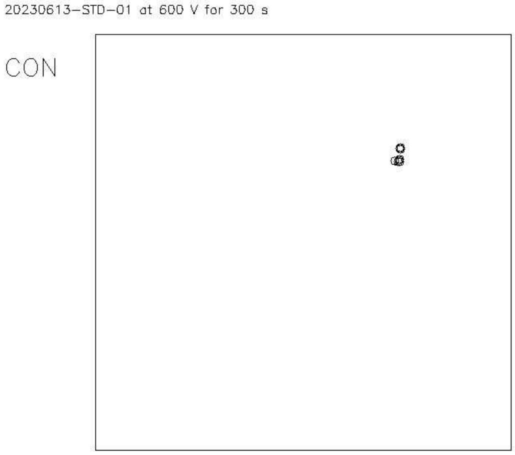

Sparkmap of GEM with crinkle → bad

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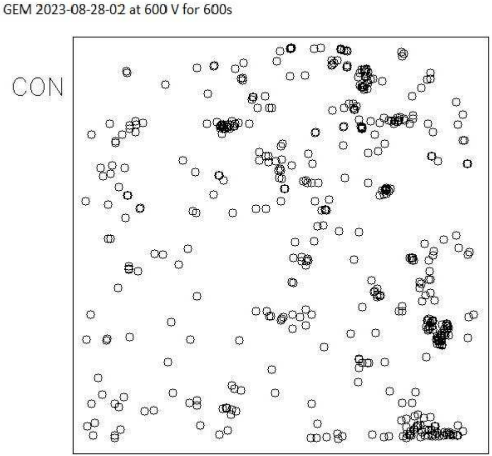
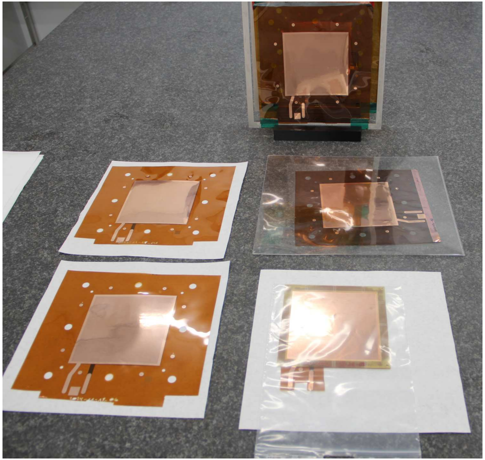


Sparkmap of very bad GEM

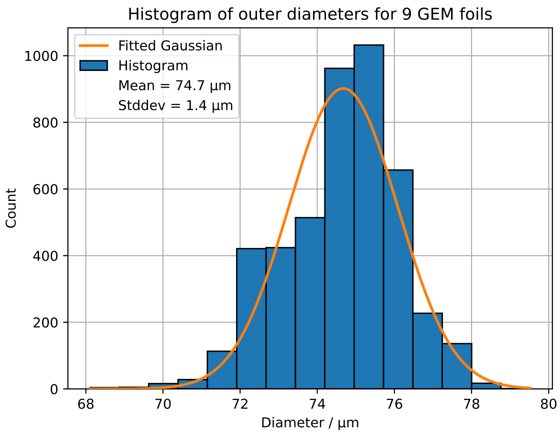
4. Present results

Produced foils

- Took some time to produce high-quality foils reliably
- Electrical QA requirements (from previous experiences):
  - $I_{\mathsf{leak}} \leq 2\,\mathsf{nA}$ (stored in dry-cabinet)
  - little to no discharges even @ $\geq 500\,\mathsf{V}$
- Most foils directly fulfill this condition ($\approx \frac{9}{10}$)
- Remaining ones can be retreated until they meet requirements



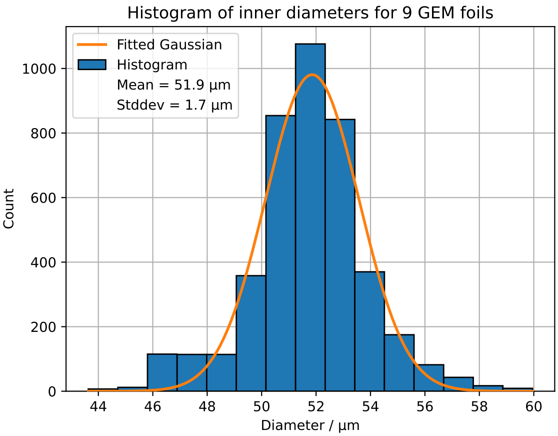
Hole statistics



(Preliminary)

Measured hole diameters across 9 recently produced foils

- <u>Outer:</u>
  - Across different foils: (74.7 ± 1.4) µm
  - Within one foil (exemplary): (73.8 ± 1.3) µm
- <u>Inner:</u>
  - Across different foils: (51.9 ± 1.7) µm
  - Within one foil (exemplary): (51.4 ± 1.4) µm



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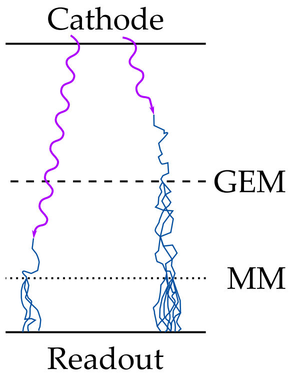
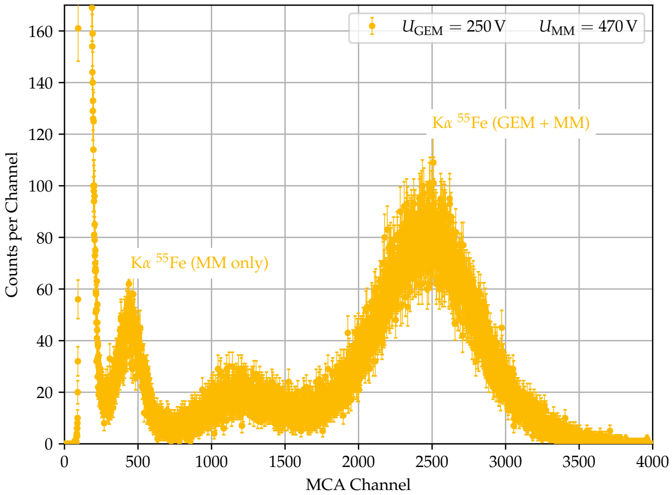
First Fe55 Spectra

Performed a test measurement with a hybrid detector (MM + GEM)





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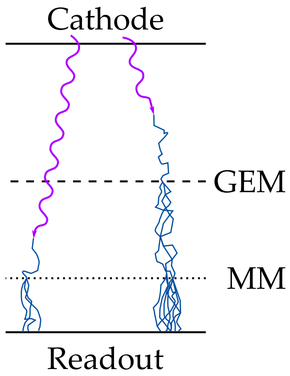

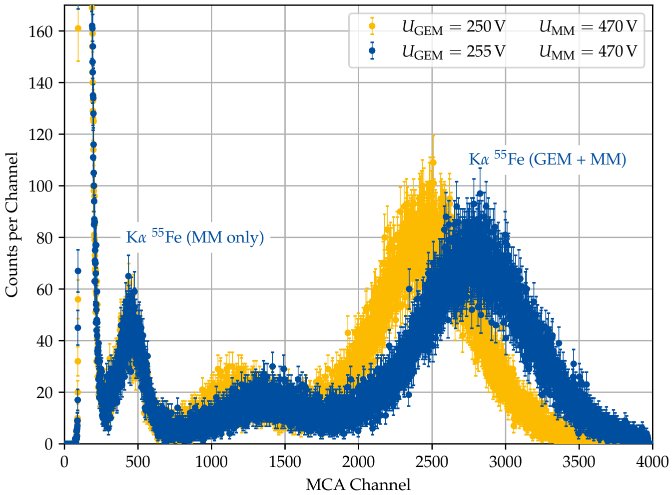

Conclusion

Summary

- Successful implementation of a process to produce $10 \times 10\,\mathrm{cm}^2$ GEM foils for research and development purposes (other possible use cases, e.g. flex PCs)
- Investigated the achievable quality of the foils using optical and electrical QA
- Most produced foils are (very) good if none are lost due to handling issues

Outlook

- Look into improvements to make the process more efficient or reliable
- Try different pitches, hole sizes and geometries (e.g. using MLA) to investigate important characteristics (IBF, energy resolution, gain)

Thanks for your attention!

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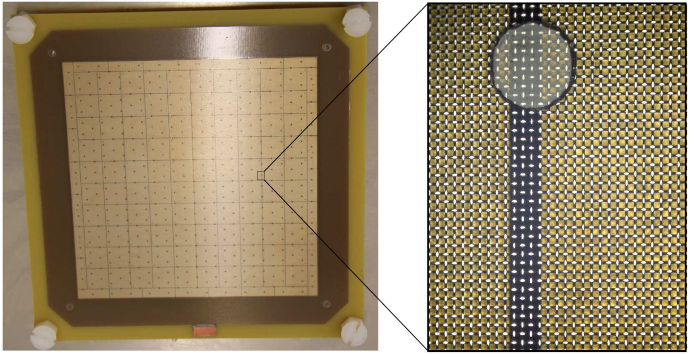
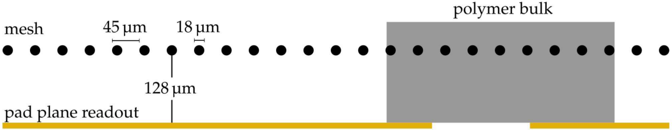
Markus Ball, Yevgen Bilevych, Philip Hauer, Shania Müller, Dmitri Schaab, Bernhard Ketzer

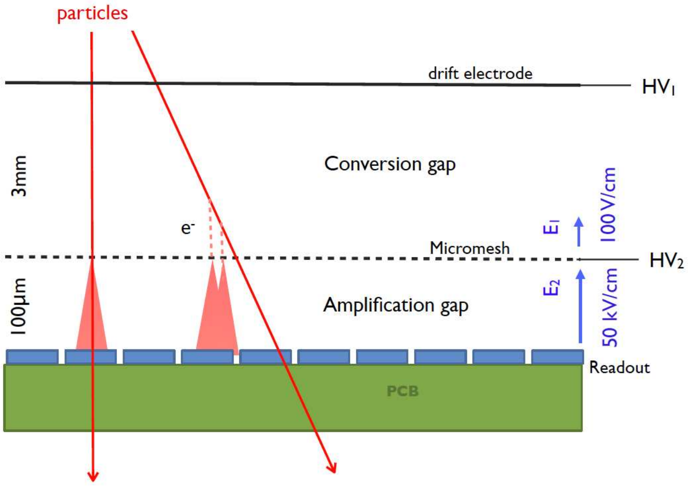
Backup





[P. Hauer, PhD thesis, 2022]

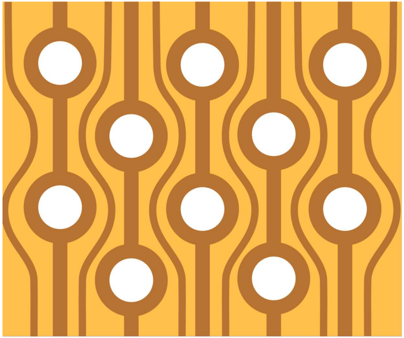
- **Micro**-**Me**sh **G**ase**o**us **S**tructure
- Another variant of MPGDs
- Invented in 1996



[Jeanneau et al., *Performances and ageing study of resistive-anodes Micromegas detectors for HL-LHC environment*, 2012], edited

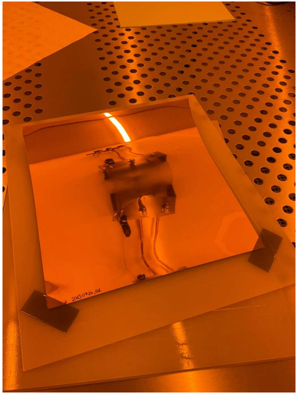
- **Micro**-**Me**sh **Gas**eous **S**tructure
- Another variant of MPGDs
- Invented in 1996

- Additional amplification stage at the bottom side of the GEM
- Highly reduced IBF ($< 1\,\%$)
- 2nd treatment with perfectly aligned mask
- So far only small samples ($\approx 2\,\text{cm} \times 2\,\text{cm}$)
- Production of larger samples could be possible with MLA



Step 1: Lamination

- Use negative dry film photoresist (15 µm)
- Up to now: lamination of each side individually



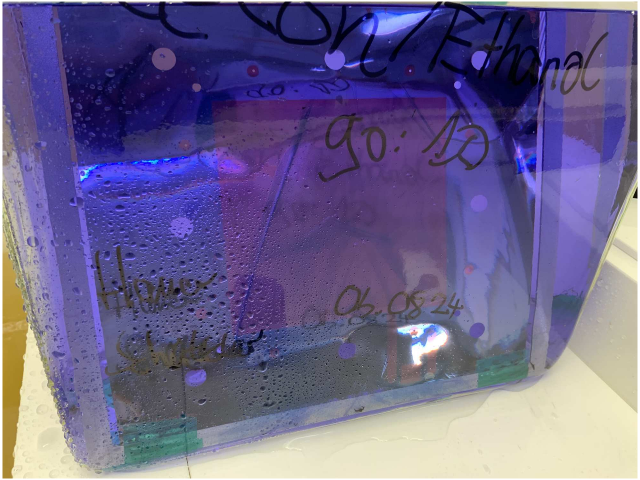
RLM419p by Bungard

Step 4: Copper etching - Sprint

- Etch accessible copper through holes in photoresist
- Performed in beaker with $FeCl_3$-based solution
- Expected overetching
  - Copper below photoresist is partially etched away
- Investigated different approaches
  - Spraying of chemical did not work properly (Sprint machine)

Sprint 3000 by Bungard

- Mixture of Aceton and Ethanol
  - Photoresist peels off
  - Does not dissolve photoresist
- Sometimes help with small brush to get rid of photoresist

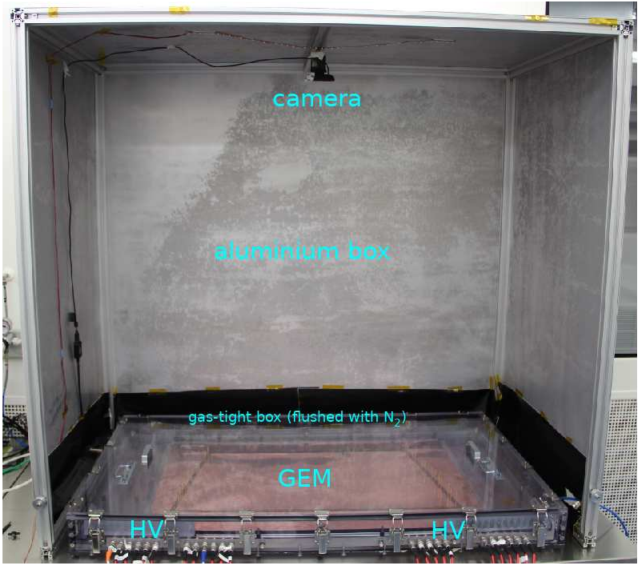


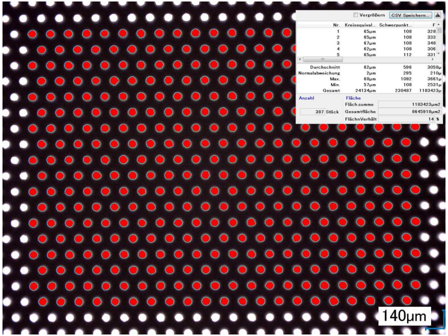
Large SDS used for ALICE GEM QA

- Working principle and crucial features:
  - camera observes electric discharges
  - aluminum box needs to be dark/lightproof
  - shielding for leakage current measurement

see:

DOI 10.1088/1742-6596/1498/1/012056





Microscope picture with measurement of inner holes (polyimide)

High quality of GEMs is key for **optimal** and **longterm** detector performance.

⇒ Quality Assurance (QA) is very important

- The previous process (e.g. ALICE*, CMS, COMPASS) includes:
- Optical QA:
  - number and size of defects (visual inspection by eye and microscope)
  - size/uniformity of inner and outer holes
- Electrical QA:
  - leakage current measurements
  - high-voltage stability

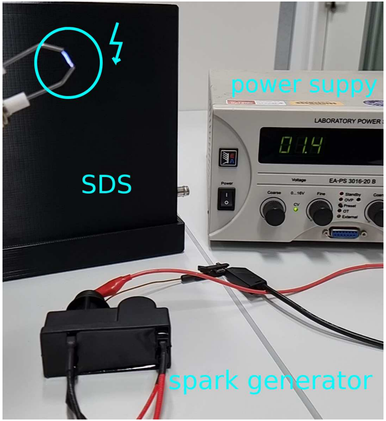
⇒ **spatially resolved detection of electric discharges is desired**

* see: DOI 10.1088/1748-0221/12/01/C01081

- Used camera:
  Logitech HD C270:
  - 0.9 MP (1280×720 pixel)
  - up to 30 FPS
  - USB-A 2.0
  - easily attachable
  - affordable ($\leq$ 20 €)

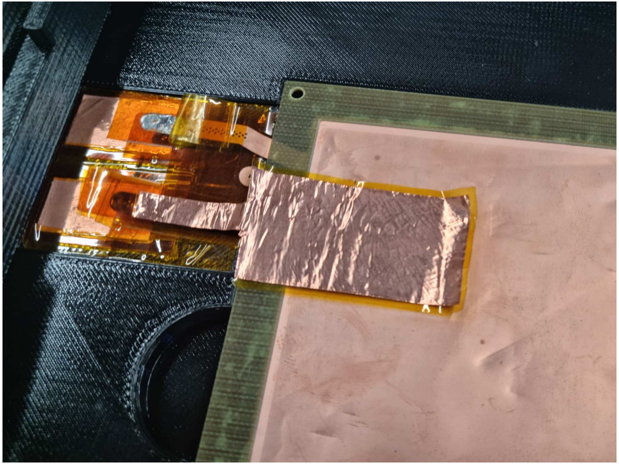
source: https://www.logitech.com/de-de/products/webcams/c270-hd-webcam.960-001063.html

- Use spark generator to create short, stable periodic HV pulses
- Imitate a sparking GEM by creating sparks on top of it
- Count missed sparks by calculating the time difference between detected sparks and find outliers
- Calculate efficiency at different spark rates (vary spark frequency with power supply)



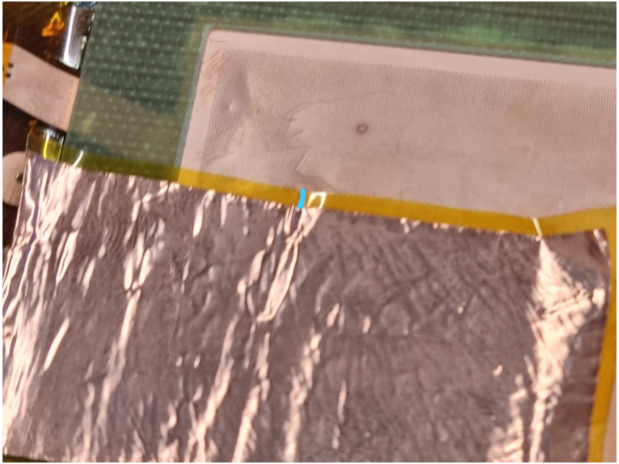
⟹ Test the efficiency of the system in different exceptional cases

Efficiency testing setup - addendum



- How to get sparks on top of the GEM:
  - piece of copper tape
  - insulate with polyimide
  - apply HV between copper tape and topside of the GEM

⟹ Comparable to real spark inside GEM hole



- How to get sparks on top of the GEM:
  - piece of copper tape
  - insulate with polyimide
  - apply HV between copper tape and topside of the GEM

⇒ Comparable to real spark inside GEM hole

spark frequency	efficiency ε
$10.49\,\text{Hz}$	$(96.6 \pm 0.5)\,\%$
$6.33\,\text{Hz}$	$(95.5 \pm 0.7)\,\%$
$3.36\,\text{Hz}$	$(97.2^{+0.7}_{-0.8})\,\%$

- Note: different errors for $\pm$ due to error propagation
  - based on: "Review of Particle Physics", PDG, Zyla, P. A. and others, 2020

- Satisfying efficiency, even for high spark rates
  - $10.5\,\text{Hz} \Rightarrow$ typically only 2 empty frames between sparks
  - close to limit of the current system
- Efficiency certainly high enough for regular use cases