Update on Chromium GEM studies @ UVa

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Outline

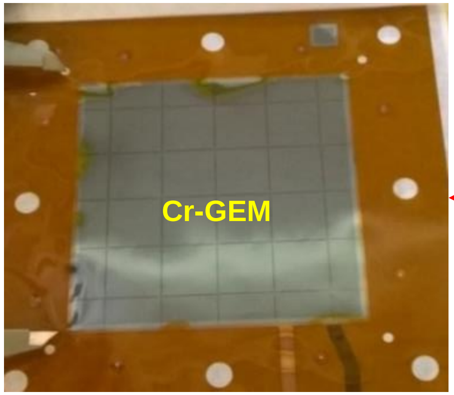
⇨ Cr-GEM stability with high rate X-ray source

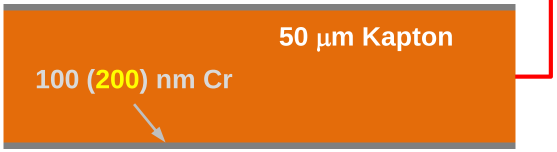
⇨ Optical and SEM inspections of the Cr-GEM foils

⇨ Summary & Future plans

Motivation for Chromium GEM foil (Cr-GEM)

Standard GEM





Motivation:

- Of particular interest for the Nuclear Physics community where GEMs are used as tracker in a high background of low energy photon.
- Using Cr-GEM foil lead to 50% reduction of the material of an EIC light weight **triple-GEM**
- This is because the material in a lightweight triple-GEM is dominated by the Cu of GEM foils

Characteristic of Cr-GEM foil:

- Copper (Cu) clad raw material comes with 100 nm Chromium (Cr) layer between Cu and Kapton, 5μm Cu layers removed, leave only 100 nm residual Cr layers as electrodes, **Cr-GEM foils provided CERN PCB workshop**

Triple-GEM with standard GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	5	8.96	14.3	1	0.0350	0.0045
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	5	8.96	14.3	0.2	0.0070	0.0009
Copper-350	1	5	8.96	14.3	0.75	0.0262	0.0034
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	0.471	0.090

Triple-GEM with Cr-GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	0	8.96	14.3	1	0.0000	0.0000
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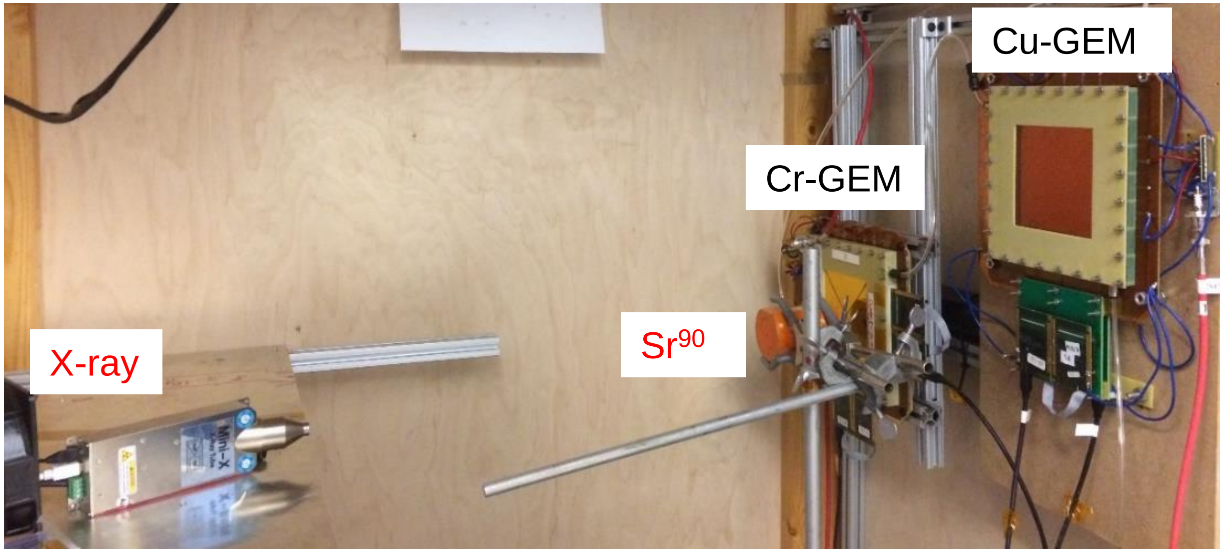
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	0.235	0.060

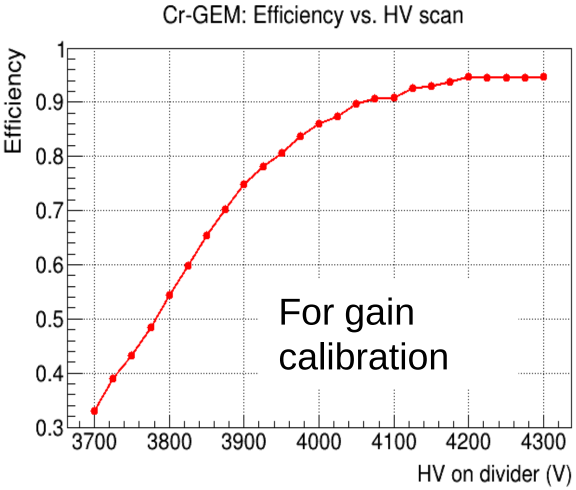
About 50% reduction in the amount of material in a EIC-FT-GEM with Cr-GEM

Cr-GEM stability with high rate X-ray source

- Two small GEMs in the X-ray setting: Cr-GEM and standard Cu-GEM (used as reference)
- Sr90 used for HV scan ⇨ rough calibration of the detector gain data from literature

X-ray setup





Test of Cr-GEM Proto I (summer 2015)

- X-ray: V =15 kV, I = 200 μA ⇨ X-ray rate = 12 MHz/cm^2
- HV =4000 V ⇨ 4 mC/cm^2 / day for 4 days
- **Significant damages on GEM response after day #2**
- 50% of the dead area after 4 days

Test of Cr-GEM proto II (summer 2017)

- Proto II: 3rd GEM of proto I foil replaced by a new foil
- X-ray: V =15 kV, I = 50 μA ⇨ particle rate = 3 MHz/cm^2
- HV @ 3800 V ⇨ 40 μC/cm^2 / day for 65 days
- HV =3950 V ⇨ 300 μC/cm^2 / day for 30 days
- **No significant damage to the chamber**

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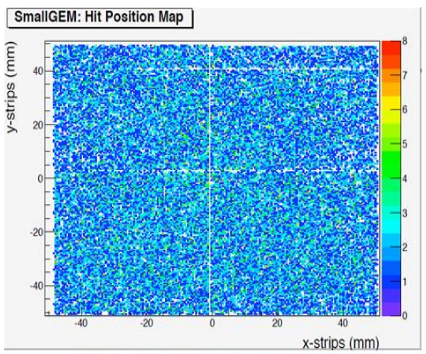
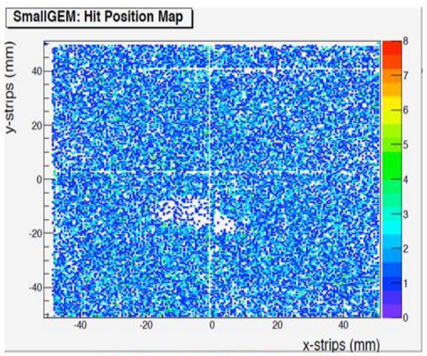
Cr-GEM Proto I with x-ray : Cr Evaporation under high rate

Inspection of Cr-GEM foils after high rate X-ray exposure:

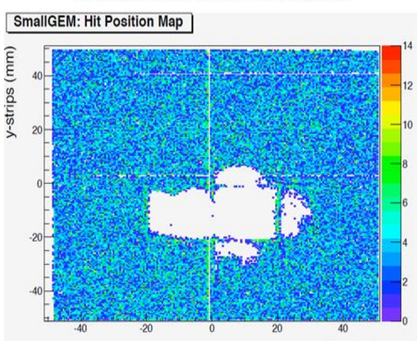
- Dead area appears after 2nd exposure day and keeps increasing
- Cr layer at the bottom of 3rd Cr-GEM (just above readout board almost completely **vanished** ⇨ dark brown color is the Kapton
- Causes of damages unclear:
  - ⇨ **small discharges @ high rate or high detector gain**
- **Two other Cr-GEM foils show no damage ⇨ HV test OK**
  - ⇨ They were re-used in proto II



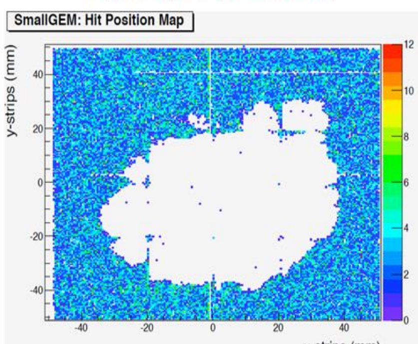
moderate X-ray rate (0.169 Coulomb)



higher X-ray rate (0.35 Coulomb)



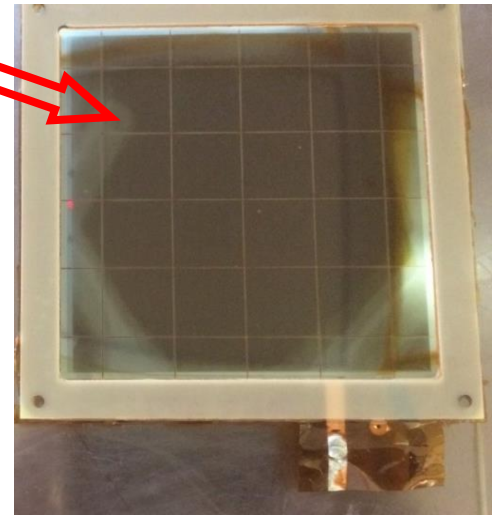
high X-ray rate (0.47 Coulomb)



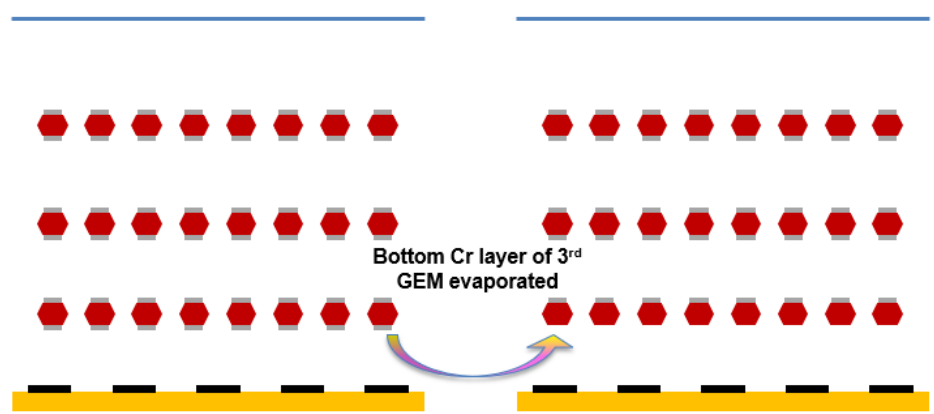
high X-ray rate (0.727 Coulomb)

Test of Cr-GEM Proto I: photon rate = 12 MHz / cm^2

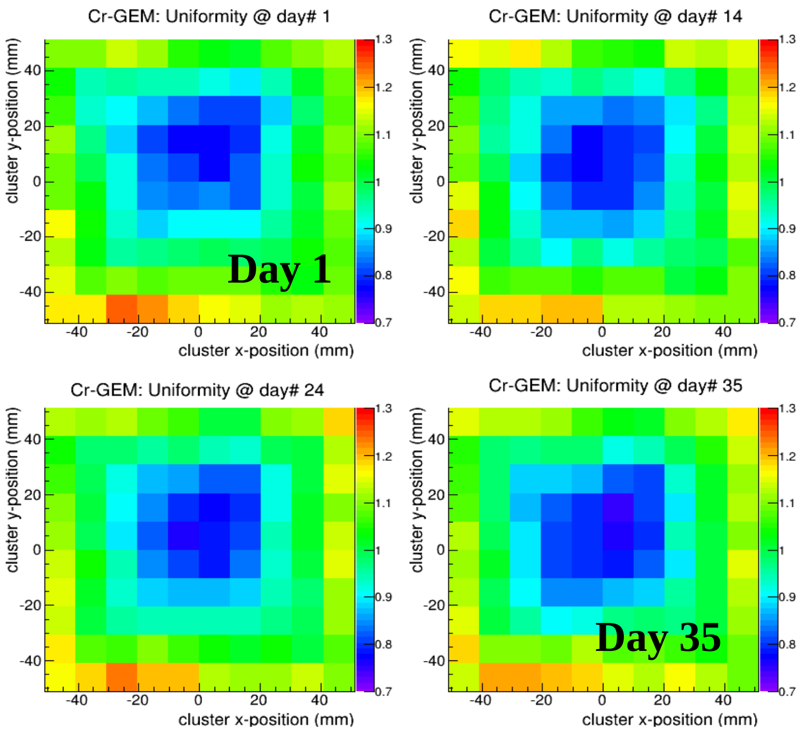
Bottom layer: Cr evaporated



Top side

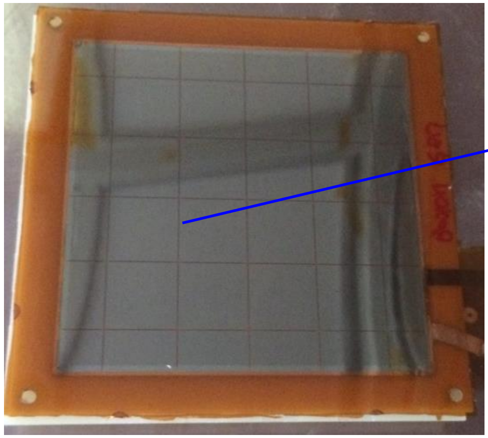


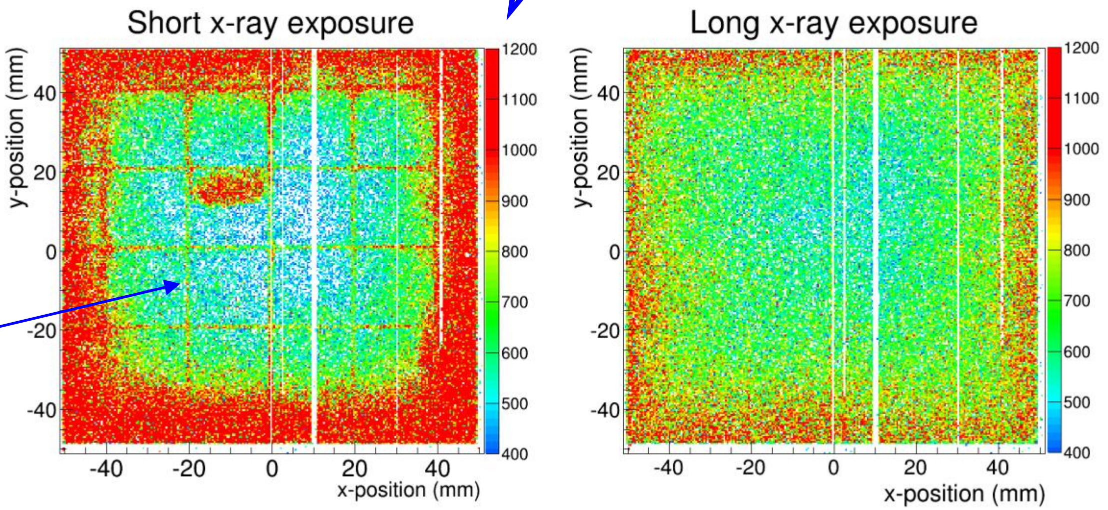
Cr-GEM Proto II with x-ray : charging up effect?



X-ray with estimated rate 3 MHz / cm^2

- @ low detector gain (~ 1×10^3) ⇨ **140 μC/cm^2 after 35 days**
- Gain variation from edge to center due to bending of the X-Y readout
- No significant variation in the overall response of the 3-month long exposure to x-ray (gain uniformity, ADC etc …)
- kind of **charging up effect** at beginning of the x-ray irradiation
  - ADC amplitude higher around Cu grid and the gain variation from the edge to the center increases
  - The effect usually disappear after one day of continuous exposure





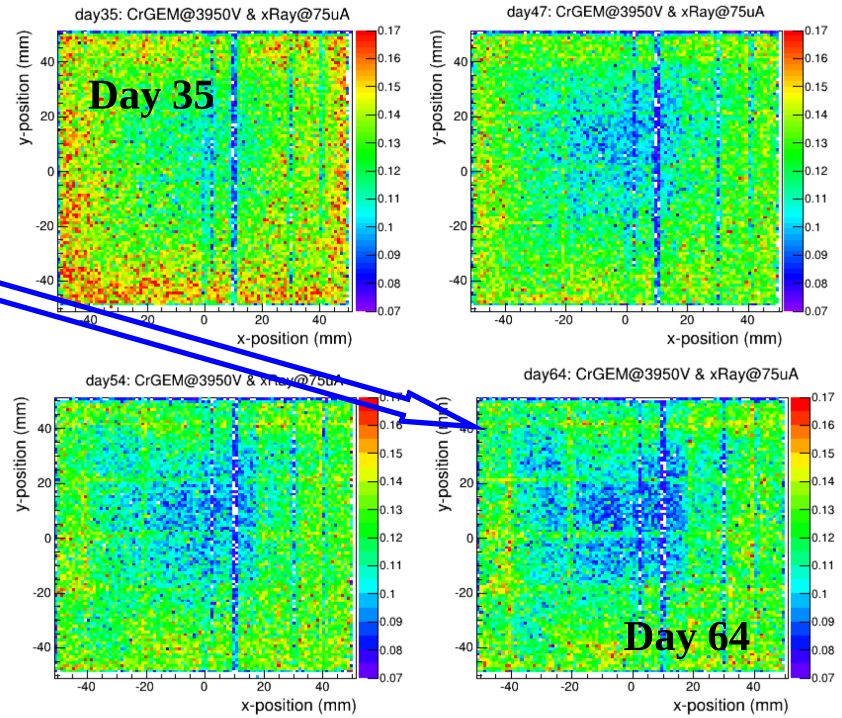
~5 hours after the start of the x-ray exposure

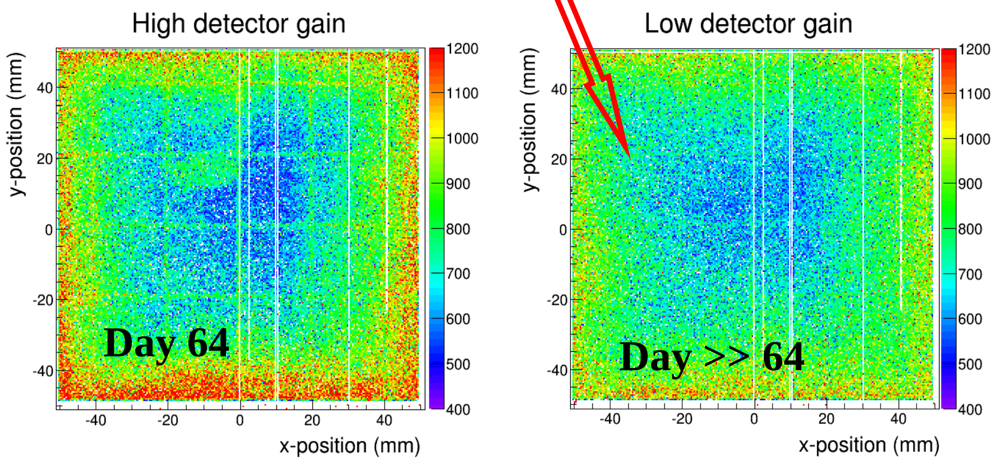
after the a day of continuous the x-ray exposure

Cr-GEM Proto II in X-ray: High detector gain vs. low gain

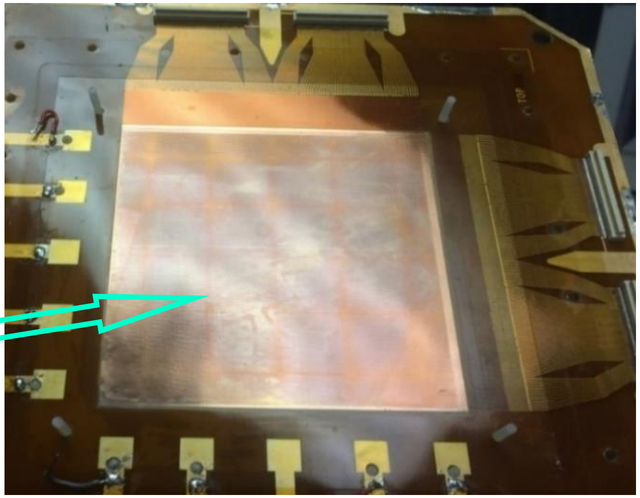
X-ray with estimated rate 3 MHz / cm^2

- @ high detector gain (~ 5×10^3) ⇨ **0.7 mC / cm^2 after 30 days**
- **Similar charging up effect** shows up again slowly with time and was pretty strong after 30 days
- However, once again when switch back again to low gain 10^3 the gain becomes once again more uniform





X-Y strip readout board



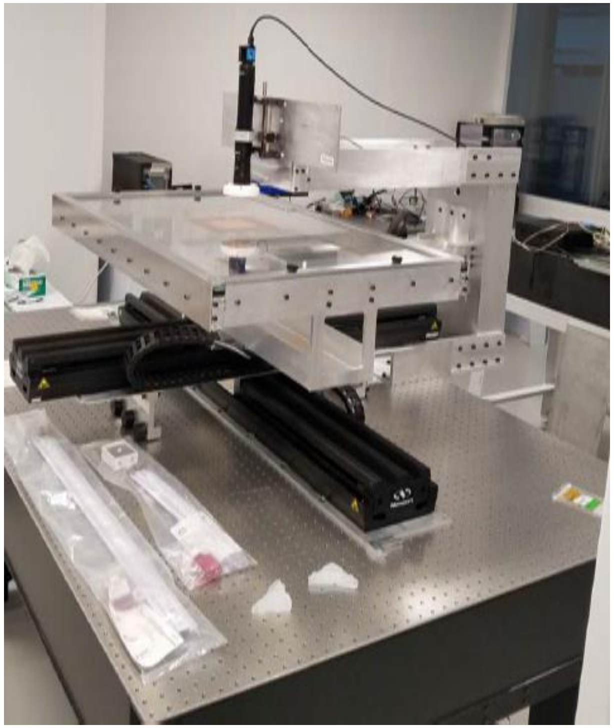
We observe a “mirror” pattern of the Cu grid on the X-Y strips readout after the chamber was opened

Investigating the Cr "evaporation" of damaged Cr-GEM foil:

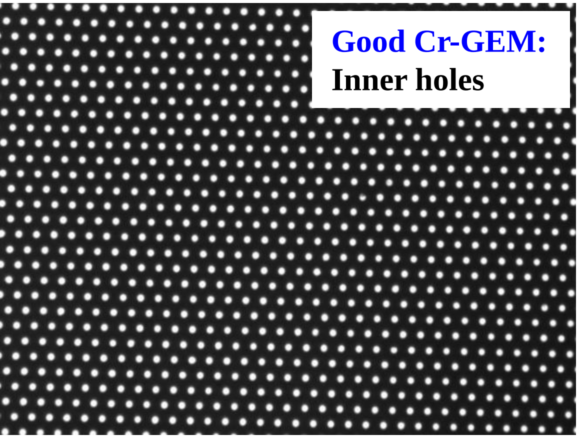
- Optical microscope scan @ Temple University
- SEM & FIB measurement @ CERN

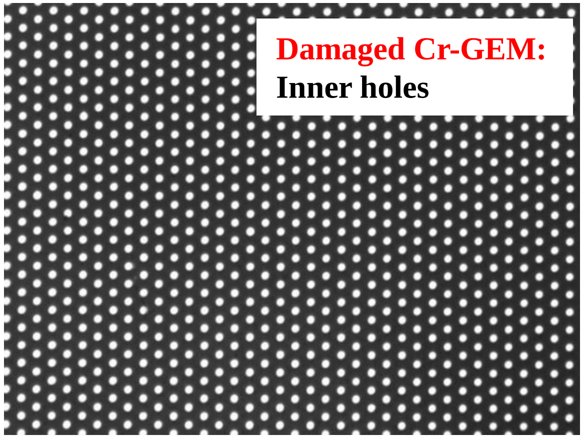
Cr-GEM foil: Optical Microscope scanning @ Temple U.

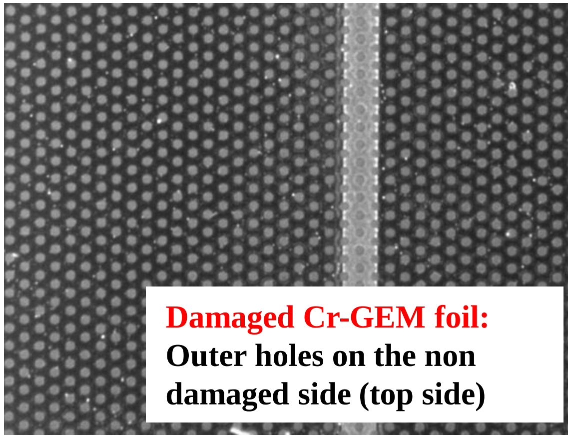
GEM CCD Scanner



- GEM CDD Scanner Facility at Temple U. (***Thanks B. Surrow & M. Posik***)
- BTW: suitable large area GEM (1 m size)
- We were able to scan 2 Cr-GEM foils (one damaged and one good foil) and compute inner holes and pitch sizes with T.U. setup
- Extracting Outer hole size turns out to be very challenging:
  ⇨ Poor contrast from the back light transmission ⇨ poor image resolution
- Automated software run the scan of the full active area.
- Scan of a 10 cm × 10 cm GEM is performed in about 2 hours
- Analysis: Algorithm is available to compute the hole diameter and pitch size

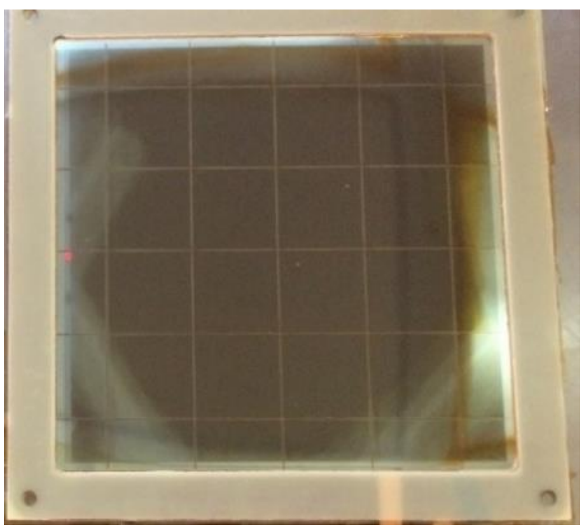




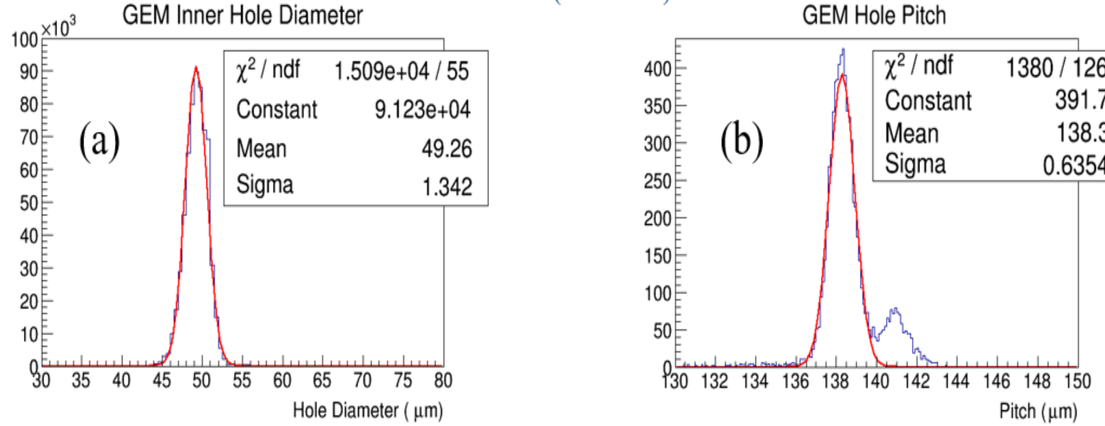


Cr-GEM foil: Optical Microscope scanning @ Temple U.

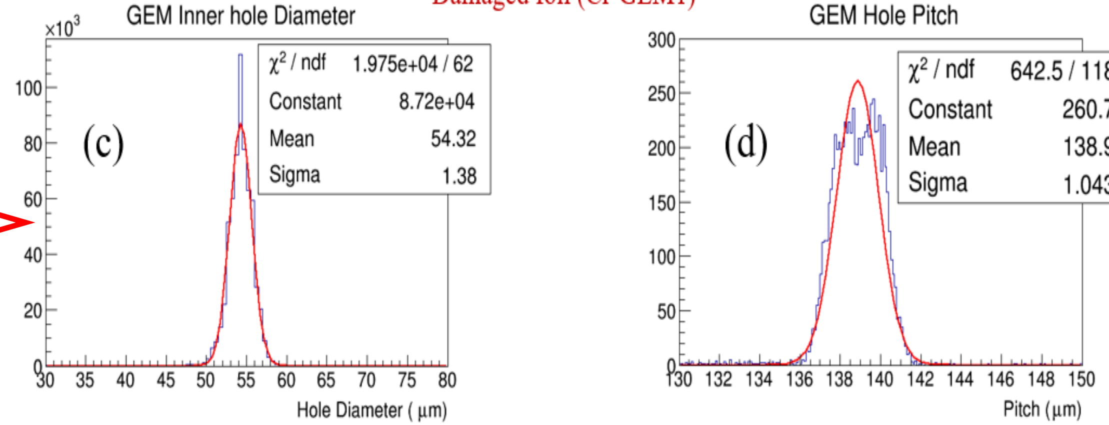
- Holes parameters for both damage and good foil are well within the specs for a standard GEM foil
- **Inner hole diameter**: Narrow distribution (σ ~1.4 μm)
  - ⇨ Good uniformity across the entire active area
  - ⇨ no Kapton etching for the damaged Cr-GEM
- **Hole pitch: ~ 138 μm**
  - ⇨ Small bump at 141 μm for good Cr-GEM
  - ⇨ Wider distribution for the damaged Cr-GEM but could just be measurement artefacts



Good foil (Cr-GEM3)



Damaged foil (Cr-GEM1)



Cr-GEM foil: SEM & FIB measurement @ CERN

SEM and FIB analysis of Chromium GEM done at CERN (end Nov 2017)

- Measurement performed by Dr Alexander Lunt from Material, Metrology and NDT group (CERN EN/MME/MM)
  - Great thanks to **Alexander** for the nice and many SEM pictures and the availability
  - Great thanks to **Eraldo** for taking care of the logistics and request paperwork at CERN
- Primary goals of the SEM measurement was to:
  - investigate the damages that led to the evaporation of Cr layer at the bottom of Cr-GEM1
  - Look at potential Kapton etching possibility
  - Measure the thickness of the Cr layer
  - and of course the unexpected

Samples from 4 GEM foils sent to CERN:

- **Cr-GEM1:** damaged foil used as 3rd GEM in proto I

⇨ high rate.

- **Cr-GEM2**: 3rd GEM foil used in proto II, replace Cr-GEM1

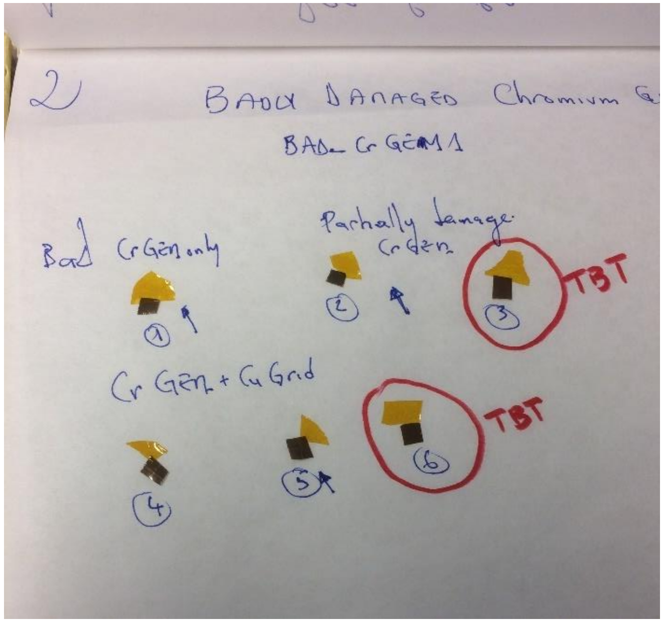
⇨ long exposure

- **Cr-GEM3:** GEM foil used in both proto I and proto II

⇨ high rate and long exposure.

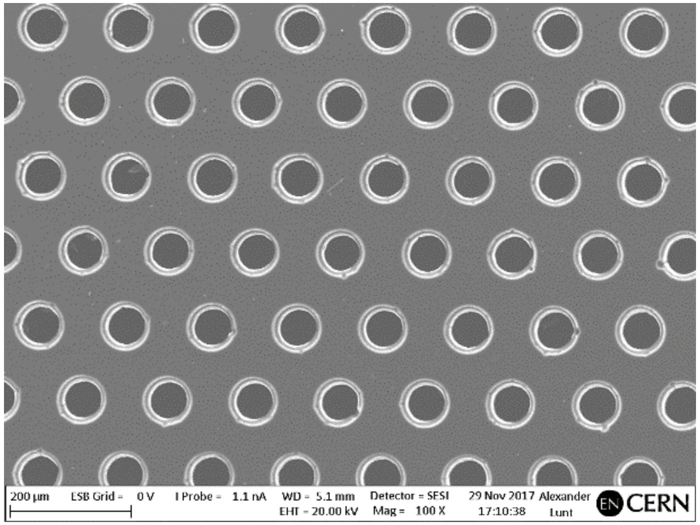
- **std-GEM:** standard GEM foil with 5 μm electrode

Picture of samples for Cr-GEM1

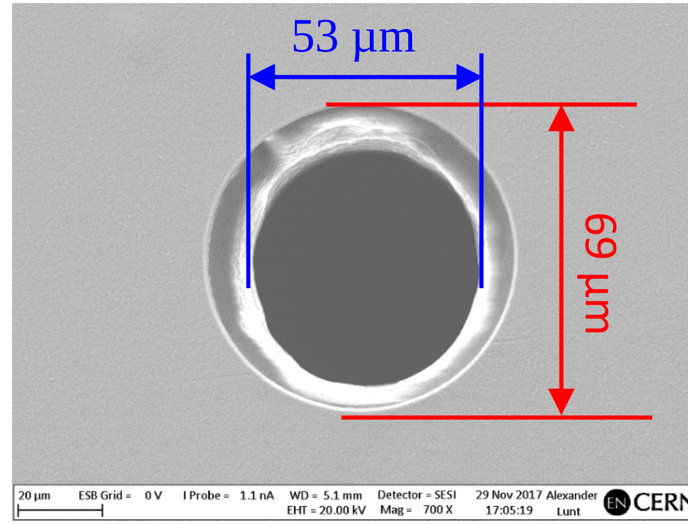


Sample Cr-GEM4: SEM & FIB measurement @ CERN

Top side



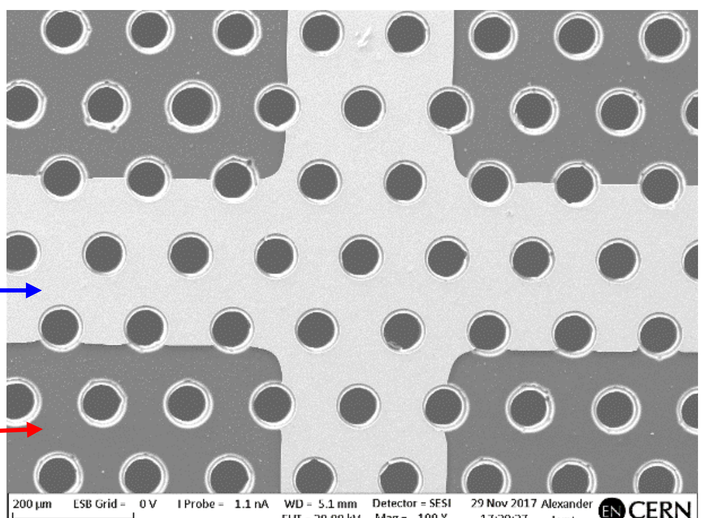
Hole dimensions

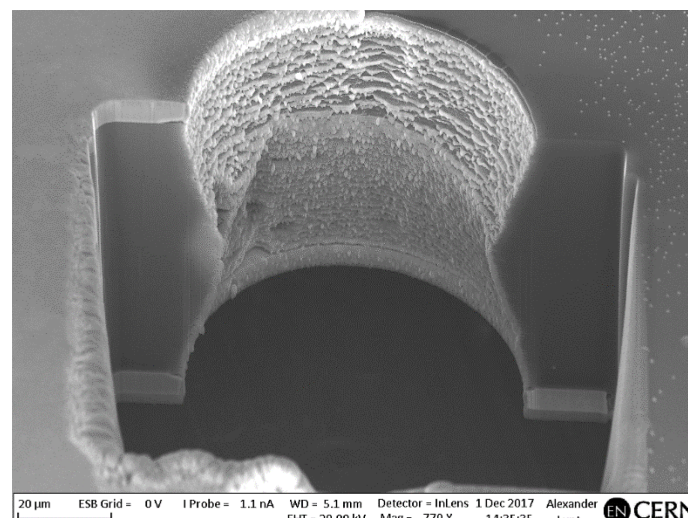


Around the Cu-grid area

Cu →

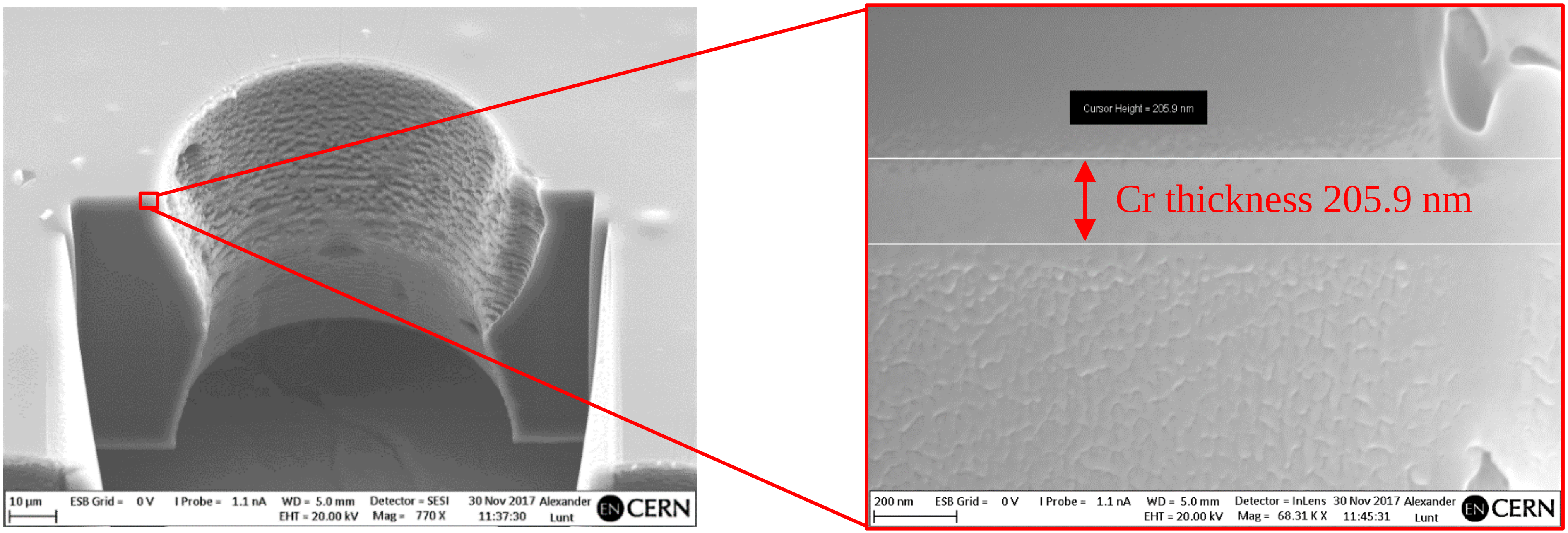
Cr →





Sample Cr-GEM4: Thickness of the Cr layer

Cr-GEM hole cross section ***Zoom into Cr layer***

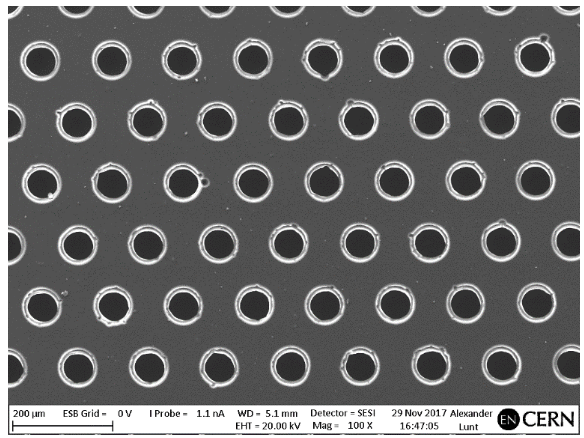


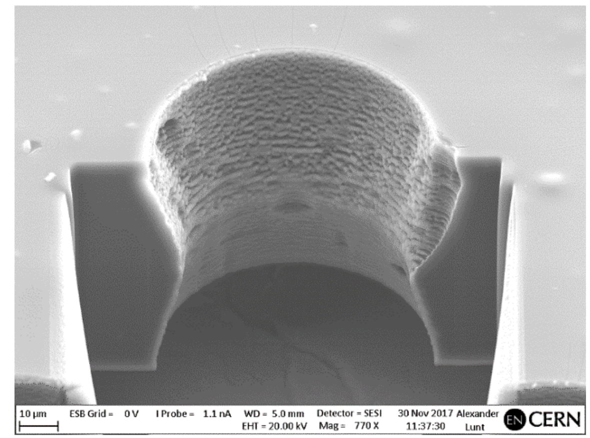
Cr layer 2 × thicker than original assumption

Sample Cr-GEM1: damaged GEM

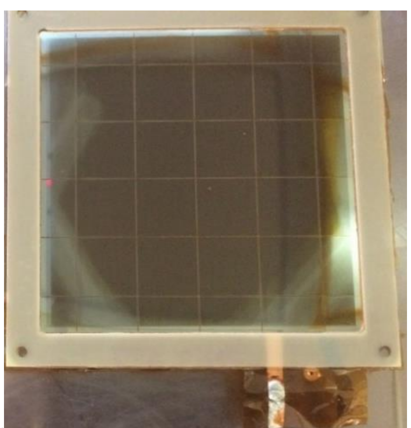
- SEM images of the top and bottom side of the heavily damaged Cr-GEM1 foil.
- As expected, SEM images of top side are high quality with holes dimensions configuration looks like normal GEM foil.
- Pictures of the bottom side of the foil appears severely distorted ⇨ bad image resolution
    - Cross section of the holes: looks as if the Cr layer melted with some other material but the Kapton looks fine

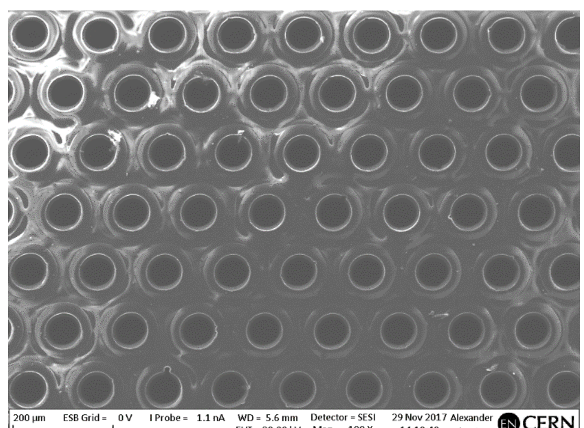
Cr-GEM1 top

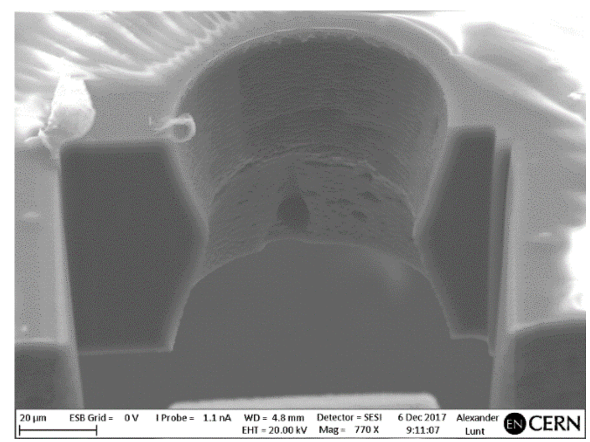




Cr-GEM1 bottom



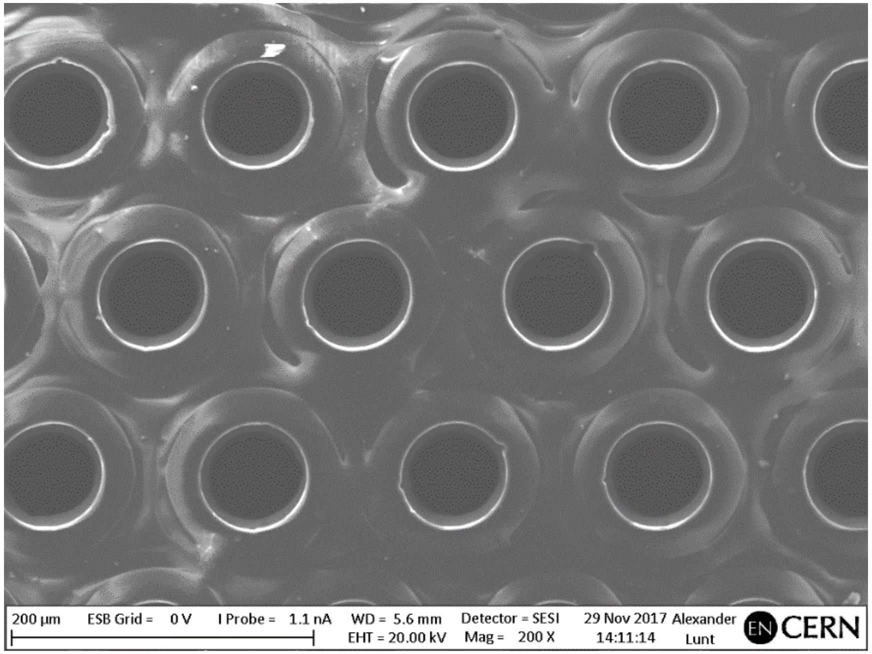




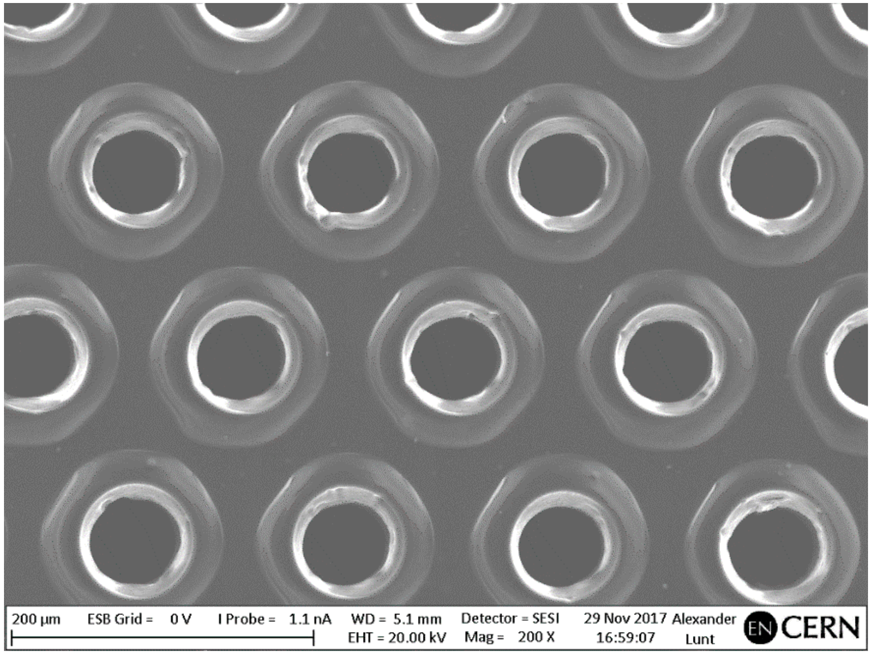
Samples Cr-GEM1 & Cr-GEM2

- Cr-GEM2 (right) show similar issue but the distortions are far less pronounced are more localized around the holes as opposed to the Cr-GEM1 where it spreads over the entire active area.
- Cr-GEM2 was irradiated in less harsher environment but was irradiated for a long period of time
- That is probably why we didn't see any degradation in the X-ray data
- The overall structure of Cr-GEM2 seems preserved with probably Cr removed only in a small area around the holes.

Cr-GEM1 bottom: completely damaged



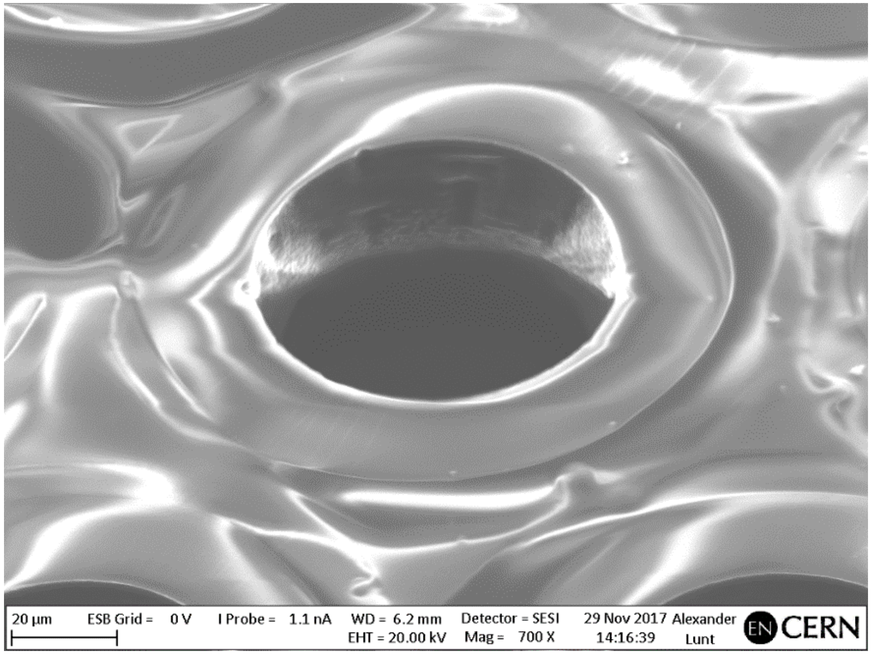
Cr-GEM2 Bottom: partially damaged



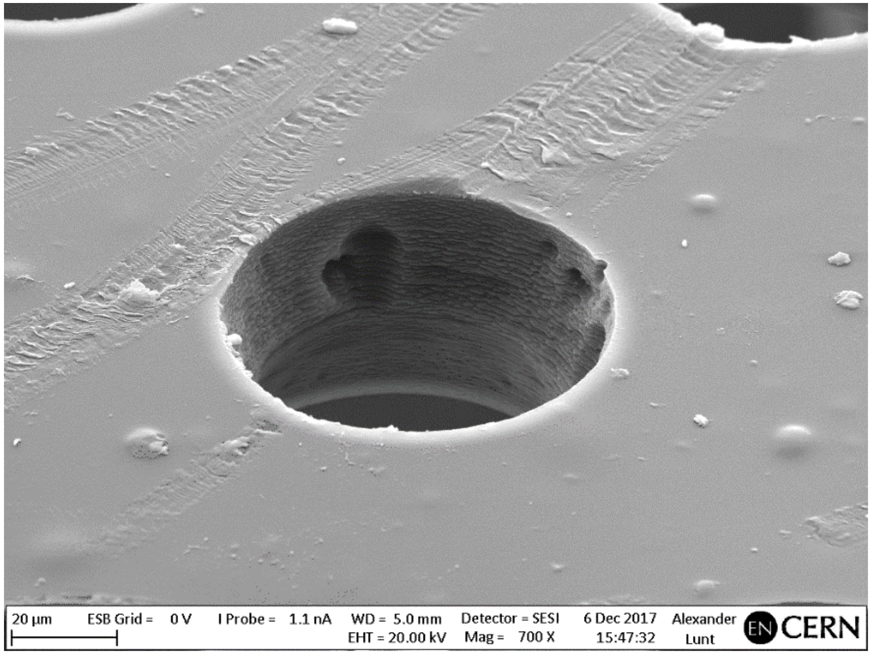
Cr-GEM1: SEM without vs. with conductive tape

- These distortions are in fact artefacts from the SEM measurement of a non metallic surface
- Well know issue of charging of dielectric sample when bombarded with the intense SEM beam
- **Problem:** Charging up disturbs the electric field around the surface under probe ⇨ poor resolution SEM image
- **Solution:** coating the surface with a thin conductive tape (a few nm of Au) before the SEM measurement

Cr-GEM1: without tape



Cr-GEM1: with conductive tape



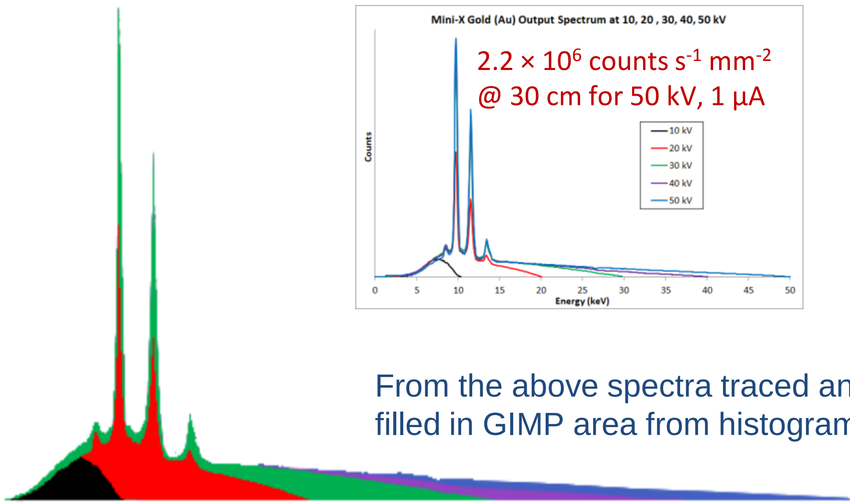
This is the confirmation that the Cr layer effectively vanishes at the bottom of these samples

Summary & Future Plans

- We performed extensive test of triple Cr-GEM detector with X-ray source
- In high rate environment and at high detector gain, we observe a degradation of the bottom Cr electrode of the 3rd GEM foil ⇨ "Evaporation" of the Cr layer
- Effect not observed for the top layer of this foil or on other 2 Cr-GEMs even after a sustained long term irradiation
- We also observed a "strange" charging up effect still under investigation
- Optical scan and SEM measurements of the GEM foils confirm the evaporation of Cr layer but reveals no Kapton etching of the damaged foils
- We are pursuing the studies of Cr-GEM detectors ⇨ plan is to test a Cr-GEM without Cu grid in similar condition to understand better the charging up effect
- Any suggestions or hints related to Cr-GEMs are welcomed

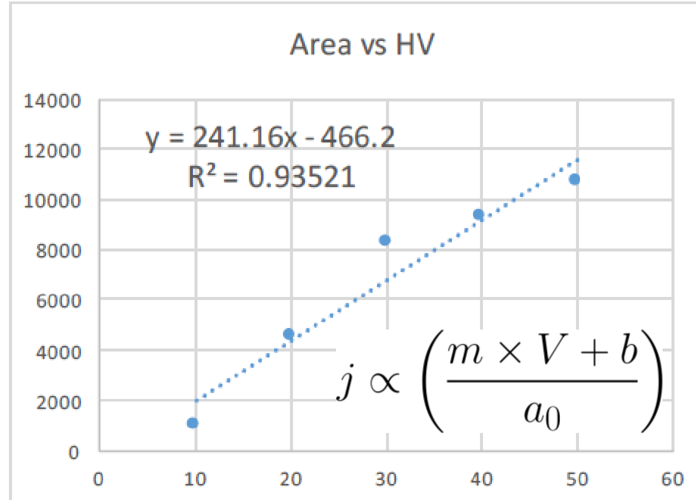
Back up

X-ray setup @ UVa: photon flux & Integrated charges

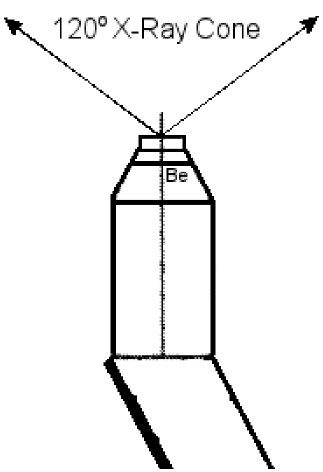


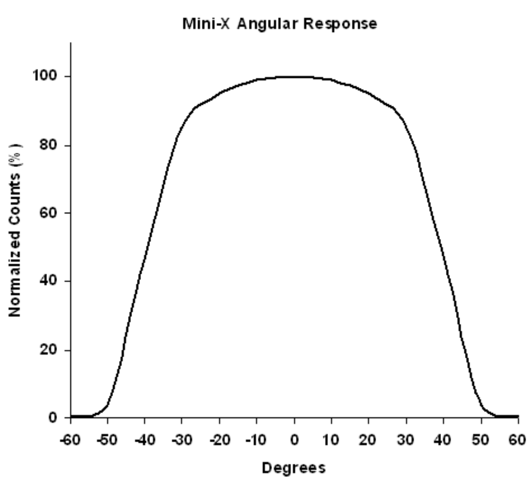
From the above spectra traced and filled in GIMP area from histogram tool

The flux proportional to the area of the spectrum



Angular coverage of the source





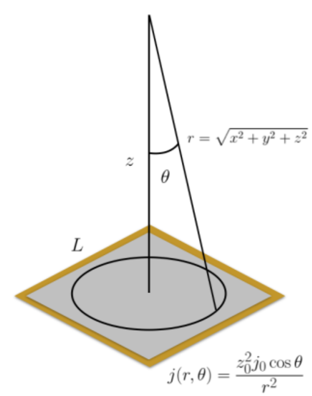
Photon flux integrated over detector

$$\phi = \int j \, dA$$

$$j(x,y,z) = \frac{z_0^2 j_0 \left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right)}{x^2+y^2+z^2}$$

$$\phi = 4\int_0^{L/2} dx \int_0^{L/2} dy \, j(x,y,z)$$

$$\phi = 4 z_0^2 j_0 \arctan\left(\frac{L^2}{2z\sqrt{4z^2+2L^2}}\right)$$



$$j = \left(\frac{I}{I_0}\right)\left(\frac{m \times V + b}{a_0}\right)\left(4\frac{z_0^2}{L^2}\arctan\left(\frac{L^2}{2z\sqrt{4z^2+2L^2}}\right)\right) e^{-\mu(z-z_0)} j_0$$

Calculation of the photon flux at the detector surface

Electron flux from photon flux

Attenuation length*			
Kapton	Aluminum	Copper	Argon
3000.0	200.0	6.6	1000000.0

Region	Material	Length	Att. length	Attenuation in this layer	Remainder after this layer
Gas window	Aluminum	5	200	97.53%	97.53%
	Kapton	50	3000	98.35%	95.92%
Gas inlet	Argon	3000	1000000	99.70%	95.63%
Drift cathode	Kapton	50	3000	98.35%	94.05%
	Copper	5	6.56	46.66%	43.89%
Drift Region	Argon	3000	1000000	99.70%	43.76%
GEM 1	Copper	5	6.56	46.66%	20.42%
	Kapton	50	3000	98.35%	20.08%
	Copper	5	6.56	46.66%	9.37%
Transfer	Argon	2000	1000000	99.80%	9.35%
GEM 2	Copper	5	6.56	46.66%	4.36%
	Kapton	50	3000	98.35%	4.29%
	Copper	5	6.56	46.66%	2.00%
Transfer	Argon	2000	1000000	99.80%	2.00%
GEM 3	Copper	5	6.56	46.66%	0.93%
	Kapton	50	3000	98.35%	0.92%
	Copper	5	6.56	46.66%	0.43%
Induction	Argon	2000	1000000	99.80%	0.43%
Readout					

* Assuming 11 keV photons and attenuation lengths from http://henke.lbl.gov/optical_constants/atten2.html

Attenuation $$\prod_i e^{-\Delta x_i / l_i}$$

50% gone by drift region

0.3% xray ➠ e-

300 e-/ion pair per (

Amptek Mini-X Parameters

HV (kV)	Current (μA)
15	50

Geometry

Distance (cm)	GEM side
72	10

scaling factors

HV (linear fit)	HV (ratio 20/50)	Current
0.29	0.43	50.00

z'=z-z0	Flux (Hz) / j_0
42	0.01

mu/rho	rho	attenuation
5.1	0.0016	0.709836938

Photons at GEM surface

Hz/mm^2	MHz/cm^2
6.84E+04	6.840

e-/ion pairs in drift

Hz/mm^2	MHz/cm^2
26976.861	2.698