High rate capability studies of triple-GEM detectors for the ME0 upgrade of the CMS muon spectrometer

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on behalf of the CMS Collaboration
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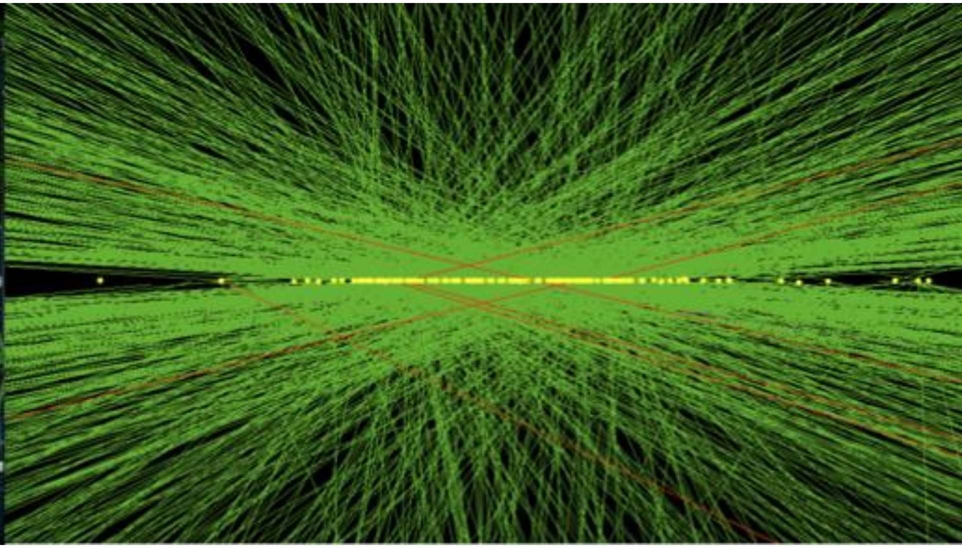
PSD12: The International Conference on Position Sensitive Detectors. 2021



Introduction

Goals of this presentation

To share the latest results of the R&D and prototype phase of the ME0 muon station of the Compact Muon Solenoid (CMS). In particular, we will present the rate capability studies and the new design of the ME0 detectors.

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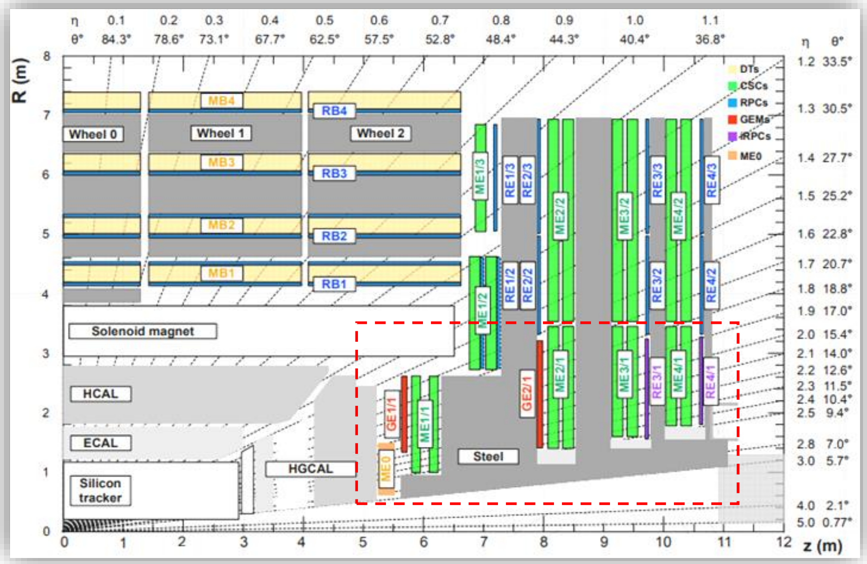
Introduction to CMS and the GEM technology.



An $R-z$ cross section of a quadrant of the CMS detector, including the Phase-2 upgrades ($(RE3/1, RE4/1, GE1/1, GE2/1, ME0)$).

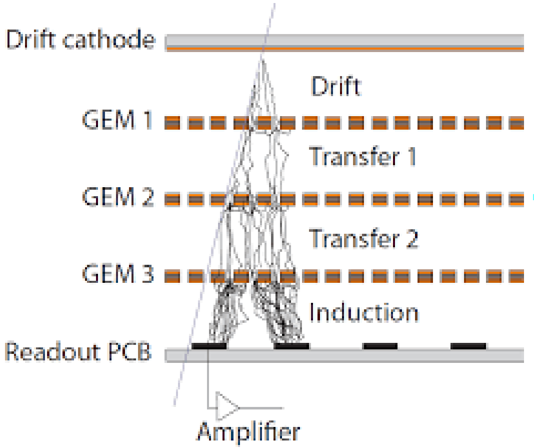
The compact muon solenoid (**CMS**) experiment is one of the particle detectors of the Large Hadron Collider (**LHC**).

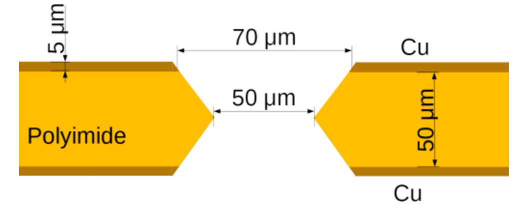
Muon system upgrade with **GEM** technology to improve the muon trigger and tracking performance.

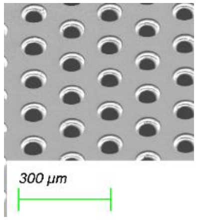
GE1/1: 1.55 < |η| < 2.18. LS2: 2019-2021

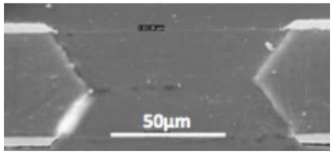
GE2/1: 1.62 < |η| < 2.43.

ME0: 2.0 < |η| < 2.8. (increases muon coverage)





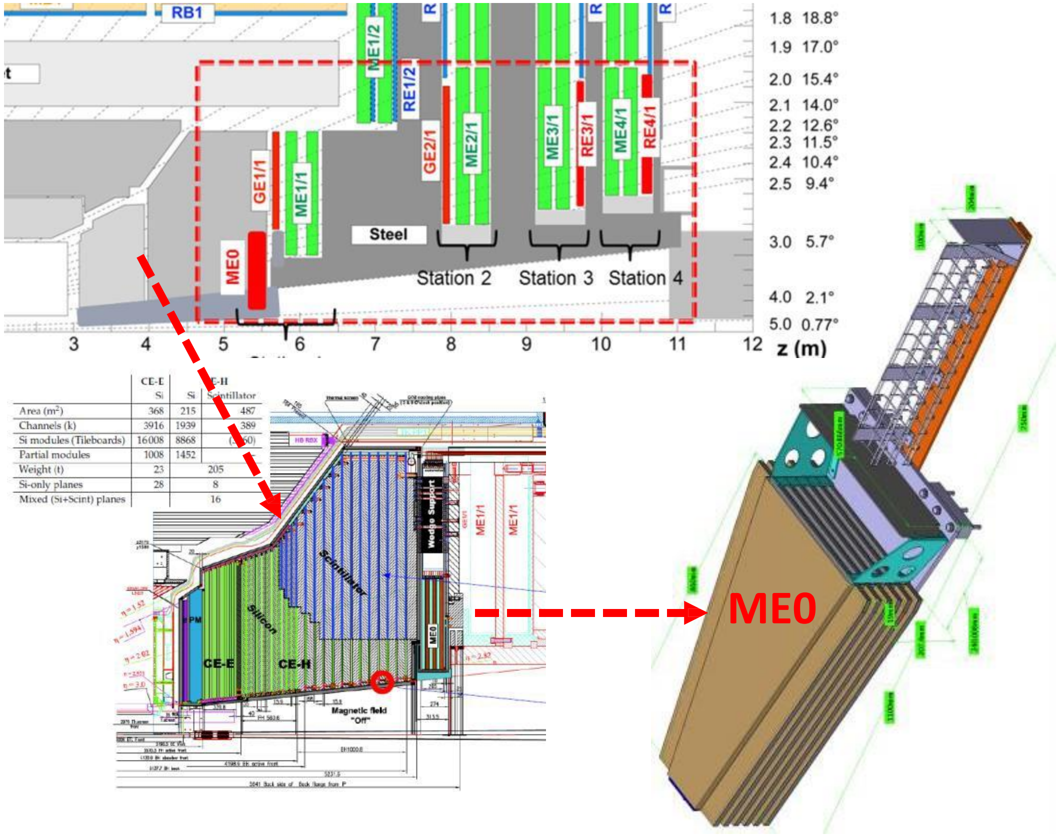




Gas Electron Multiplier (GEM)

- ✓ Electron amplification.
- ✓ Triple GEM: amplification ~10^5.
- ✓ Particle rate up to $O(\text{kHz}\cdot\text{cm}^{-2})$
- ✓ High spatial resolution: ~100µm.
- ✓ Time resolution < 10 ns.
- ✓ Detection efficiency > 98%.

CMS GEM ME0 Project: challenges



	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16008	8868	(3[illegible]60)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

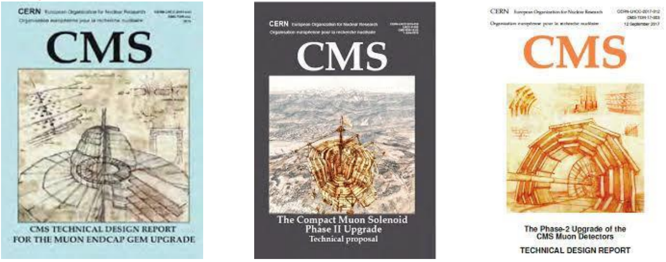
6-Layer Triple-GEM stack installed behind HGCAL (**complex environment**)

$2 \times 18\ stacks\ (20°)\ covering\ 2.0 < \eta < 2.8$

Requirements*:

- 97% module efficiency
- $<$ 500 μrad resolution
- $8 - 10\ ns$ time resolution
- $\leq$ 15% gain uniformity
- *Work in high-rate environment:* $\mathbf{150\ kHz/cm^2}$ *
- *Survive harsh radiation environment:* $\mathbf{7.9\ C/cm^2}$ *
- *Discharge rate that does not impede performance or operation*

- ** updated w.r.t. TP & TDR*


CMS
CMS TECHNICAL DESIGN REPORT FOR THE MUON ENDCAP GEM UPGRADE

CMS
The Compact Muon Solenoid Phase II Upgrade Technical proposal

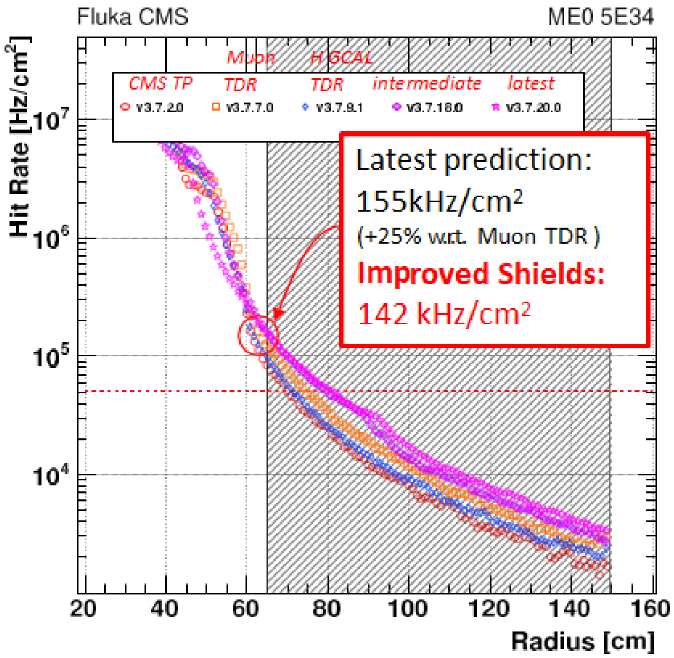
CMS
The Phase-2 Upgrade of the CMS Muon Detectors
TECHNICAL DESIGN REPORT

CMS GEM ME0 Project: challenges

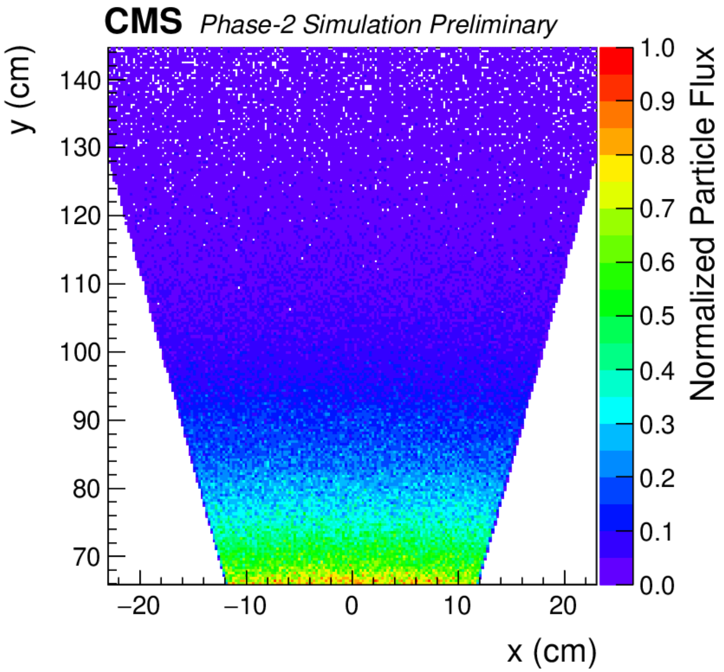
Expected background flux in the CMS environment

- Expected background particle hit rate in the highest eta region: $\sim 150 kHz/cm^2$.
- The simulated background hit rate can be updated.

- Total chamber surface: $\sim 2.9 \times 10^3 cm^2$
- **Average** chamber hit rate: $23.95\ kHz/cm^2$ (extracted from Geant4 simulation)



Latest prediction:
155kHz/cm²
(+25% w.r.t. Muon TDR)
Improved Shields:
142 kHz/cm²



State of art on the rate capability studies

Two main phenomena could affect the rate capability of a GEM-based detector:

1) the *space charge*, which could modify the electric fields, resulting in a reduction of the gas gain above a certain value of radiation flux

   → the ***slowly moving ions*** are ***quickly evacuated*** minimizing the space charge effect and improving the rate capability by several orders of magnitude w.r.t. the MWPCs

2) the ***ion-induced current***, which could flow through the protect. resistors and induce a voltage drop across the GEM-foil, resulting in a decrease of the gas gain

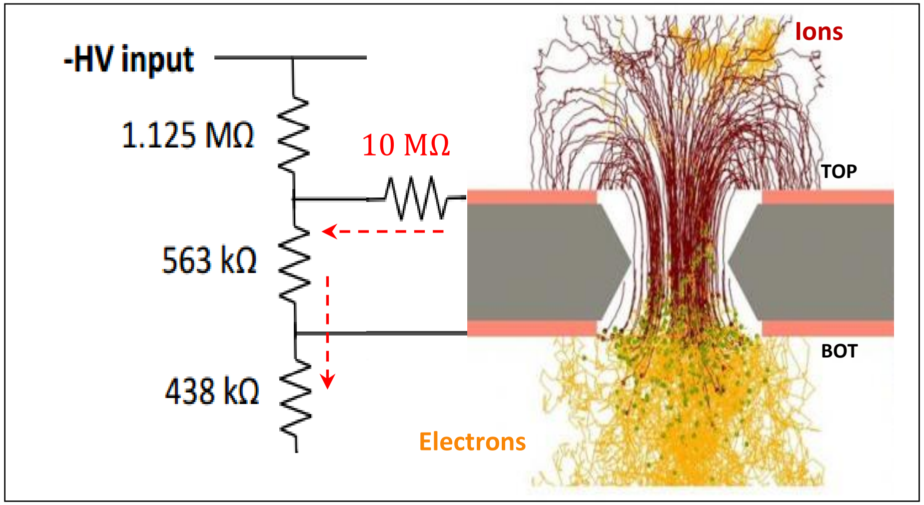
   → this current is basically due to the ***high number of ions*** collected on the top electrode of the GEM-foils during the high-flux irradiation

   → the ***voltage drop*** strongly depends on the value of the ***protection resistors*** and percentage of the ***irradiated area***, as well as the ***radiation flux***

We want to validate the following points …

- rather than the space charge, the ion-induced current, flowing through the protect. resistors, strongly affects the detector rate capability!
- a ***local irradiation*** $O(3\,mm^2)$ is drastically different to a ***global irradiation*** $O(3000\,cm^2)$!

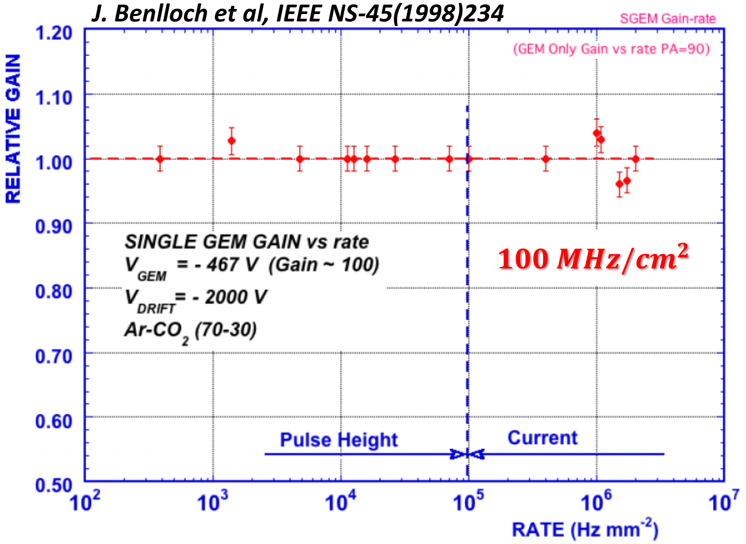
A new approach to the study of rate capability for large-area GEM detector is needed!



State of art on the rate capability studies

The ***rate capability*** of GEM-based detectors has been extensively studied in the last decade for different sizes, geometries, and configurations

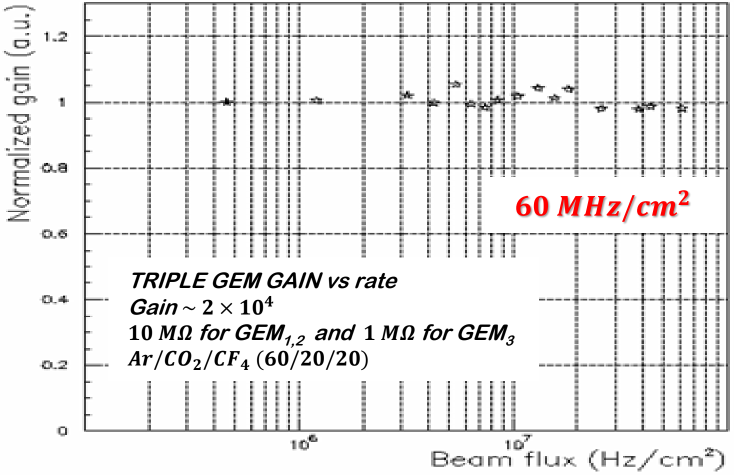
J. Benlloch et al, IEEE NS-45(1998)234



SINGLE GEM GAIN vs rate
V_{GEM} = - 467 V (Gain ~ 100)
V_{DRIFT} = - 2000 V
$Ar\text{-}CO_2$ (70-30)

$100\ MHz/cm^2$

Poli-Lener, M - CERN-THESIS-2006-013



TRIPLE GEM GAIN vs rate
Gain$\sim 2\times10^4$
$10\ M\Omega$ for $GEM_{1,2}$ and $1\ M\Omega$ for GEM_3
$Ar/CO_2/CF_4$ (60/20/20)

$60\ MHz/cm^2$

Common experimental procedure:

1) source: *X-ray generator* (*soft X-ray photons*)
2) irradiated area: $\approx mm^2$
   → reaching *very high X-ray flux*
3) gain remains stable up to a flux above MHz/cm^2
   → demonstrating the absence of *space charge phenomena!*

but one observes ...

1) a *low ion-induced current* flowing through the *protection resistors* due to the small irradiated area
   → inconsistent with a real experiment
2) a *negligible voltage drop* across the GEM-foils
   → as a result: high-rate capability up to tens or hundreds of MHz/cm^2

New approach to the rate capability study

1) When the detector is ***globally irradiated***:

→ a ***high ion-induced current*** is expected to flow through the ***protection resistors*** due to the large irradiated detector area (consistent with a real experiment)

→ a ***significant voltage drop*** is expected across the GEM-foils (as a result: low rate capability up to few kHz/cm^2)

2) two ***Ag-target X-ray tubes*** ($\sim 22\ keV$ photons) are used to study the rate capability

3) a ***rate measurement*** is fully performed in ***current mode*** instead of counting mode!

→ at very high count rates some piled-up pulses could reach the ***electronic chain saturation limit*** (preamp. + amp. + shaper) and affect the final result

4) a ***gas gain drop*** is estimated:

- by measuring the ***anode current density*** and extrapolating the ***interaction photons flux*** during the high-flux irradiation, and estimating the gas gain drop with the usual formula:

measured anode current density

detector effective gas gain →

$$\langle G\rangle = \frac{J_{measured}}{n_p \times q_e \times R_{real}}$$

extrapolated interaction photons flux

- by measuring the ***voltage drop*** across the three GEM-foils during the high-flux irradiation:

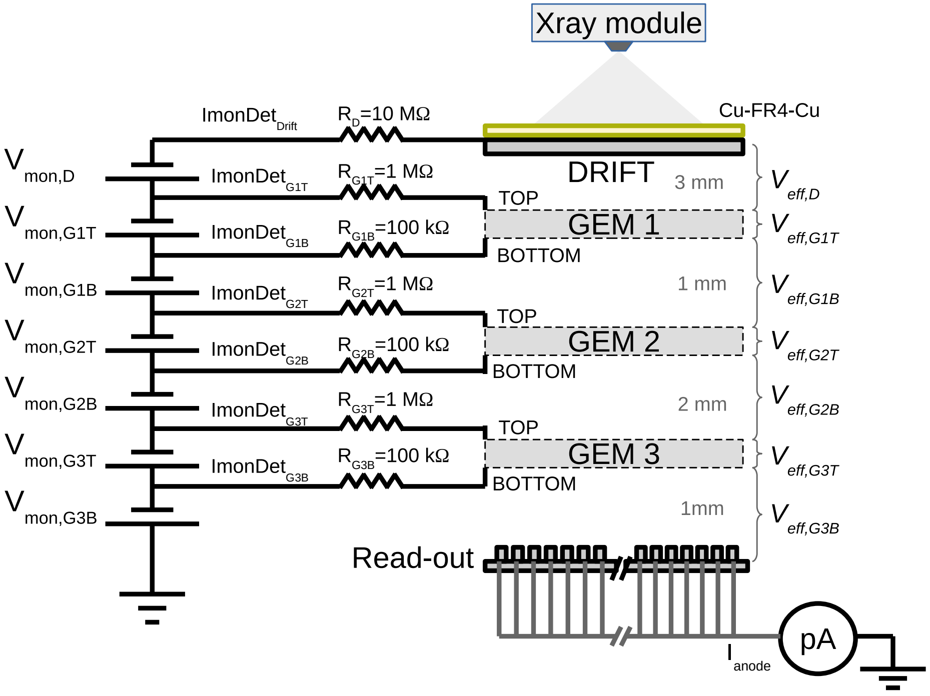
→ the foils are powered individually using a ***CAEN A1515TG multi-channel power supply***

→ the A1515TG module allows to monitor the ion-induced current flowing through the protection resistors, and estimate the voltage drop across the foil, resulting in the gas gain drop:

$$V_{eff}^{electrode} = V_{mon}^{electrode} - I_{mon}^{electrode} \times R^{electrode}$$

Experimental Setup for High-Rate Studies

Experimental Setup for High-Rate Studies
at 904 Laboratory (CERN)



$10 \times 10\ cm^2$ Triple GEM prototype
(with ME0-like material budget)

DETECTOR:

- $10 \times 10\ cm^2$ Triple GEM prototype
- Gap configuration: $3/1/2/1\ mm$
- Gas mixture: $Ar/CO_2\ (70:30)$
- $10\ M\Omega$ resistor on Drift board
- $1\ M\Omega$ resistor on top (for each foil)
- $100\ k\Omega$ resistor on bottom (for each foil)
- ME0 Material $(Cu - FR4 - Cu)$

POWER SUPPLY:

- CAEN A1515TG multichannel board on SY1527 system

RADIATION SOURCE:

- Two Amptek Mini-X2 X-Ray tubes (Silver target)
- Operating voltage: $40\ kV$
- Operating current: from $5\ \mu A$ to $100\ \mu A$
- Number of primaries per hit: $418\ \pm\ 9$
- Irradiation distances: 0 to 110 cm

Data Analysis (I): Extrapolated Interaction Flux

The ***rate measurement*** is fully performed in ***current mode*** using a pico-ammeter:

1) for a ***low particle flux*** (i.e. low X-ray powering current), the anode current increases linearly with the increasing count rates

2) for a ***high particle flux*** (i.e. high X-ray powering current), the anode current nearly saturates with the increasing count rates

→ ***the saturation is exclusively due to gas gain drop!***

→ a ***curve fitting*** is used for parameterizing the experimental data and allows to extrapolate the ***expected (real) anode current***:

$$J_{measured} = \frac{J_{expected}}{1+k\,J_{expected}} \quad \text{with} \quad J_{expected} = A\,I_{xray} + B$$

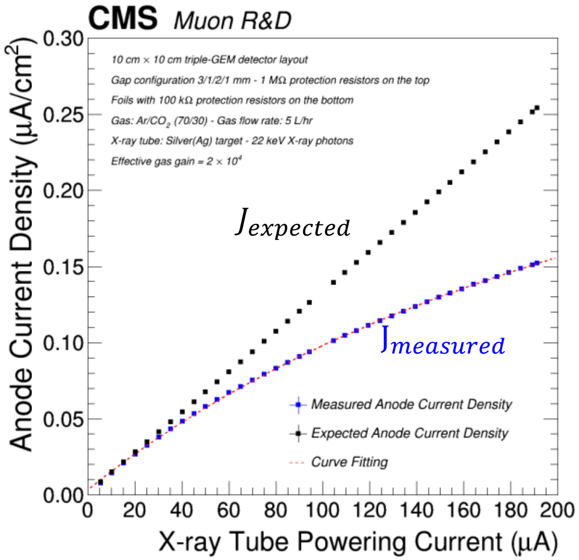
3) At fixed X-ray powering current, the ***extrapolated interaction X-ray photon flux*** is given by inverting the gas gain formula:

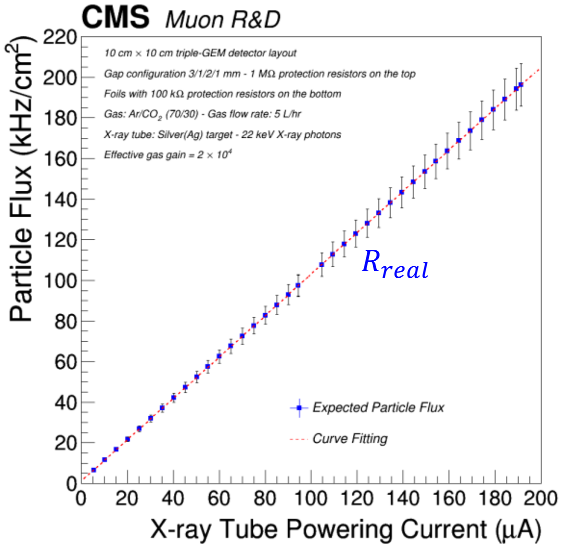
extrapolated anode current density

extrapolated interaction photons flux ⟶

$$R_{real} = \frac{J_{expected}}{n_p \times q_e \times \langle G \rangle}$$

detector gas gain known from QC5





Data Analysis (II): Effective Gas Gain Drop

The ***gas gain drop*** is estimated by measuring the ***anode current density*** and extrapolating the ***interaction photons flux*** during the high-flux irradiation, and estimating the gas gain drop with the usual formula:

detector effective gas gain

$$\langle G \rangle = \frac{J_{measured}}{n_p \times q_e \times R_{real}}$$

measured anode current density

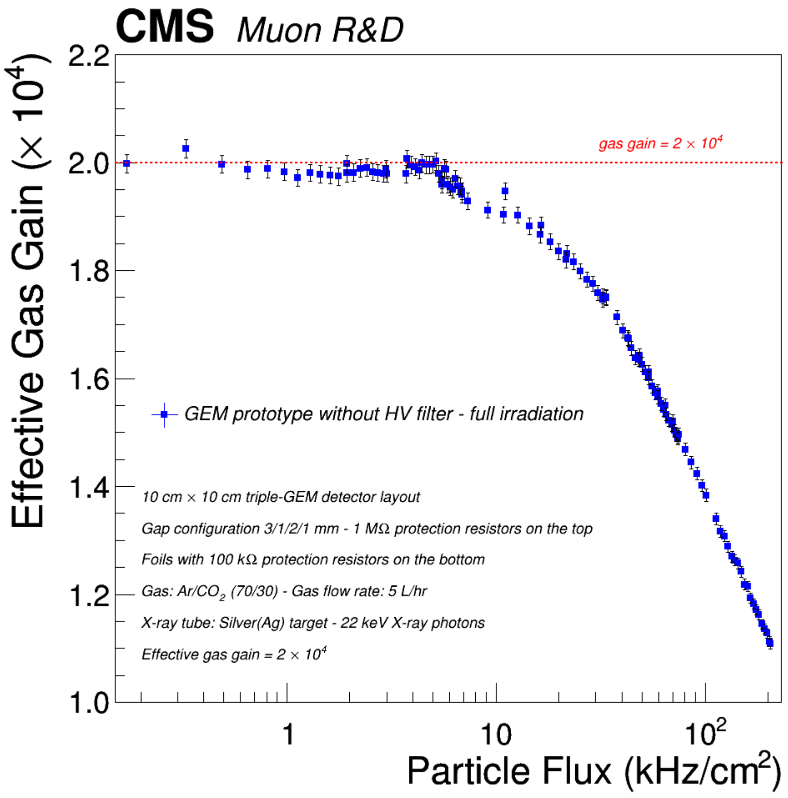
extrapolated interaction photons flux

Experimental Setup Configuration:

- X-ray generator is placed at $15, 30, 110$ cm from the detector (no attenuators used)
- X-ray flux is generated along all the dynamic range of the guns (5 to $100\ \mu A$ each)
- 10 cm $\times$ 10 cm detector active area is fully and uniformly irradiated
- **No resistive HV filter!**

gas gain drop of 45% @ $200\ kHz/cm^2$

Rate Capability is **2 to 3 orders of magnitude** lower than the expected one



Data Analysis (II): Efective Gas Gain Drop

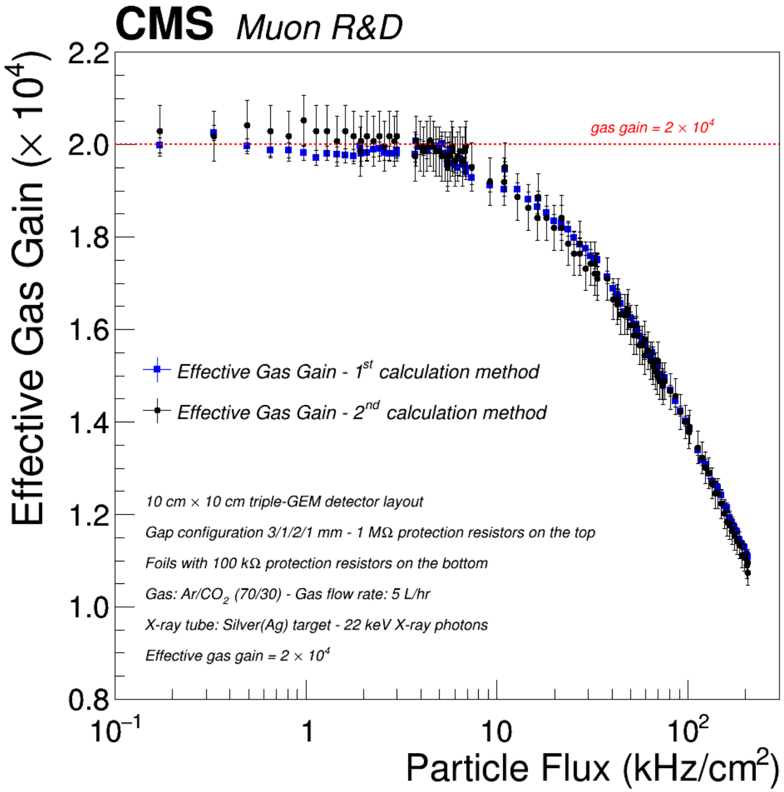
The ***gas gain drop*** is also estimated by measuring the ***voltage drop*** across the three GEM-foils during the high-flux irradiation

1) the ***current*** flowing through the ***protect. resistors*** changes the voltage on each electode
   → by applying the ***Kirchhoff's second law***, the effective voltage on the electrode will be:

$$V_{eff}^{electrode} = V_{mon}^{electrode} - I_{mon}^{electrode} \times R^{electrode}$$

2) the *effective gas gain* is measured by powering the detector with the *effective voltages* ($V_{eff}^{electrode}$) and irradiating with low X-ray photon flux ($\sim 100\ Hz/cm^2$)

- The gas gain curve taken by ***"emulating"*** the voltages under irradiation is ***consistent*** to the one ***measured under irradiation.***
- The gas gain drop is only due to the voltage drop across the resistance.



Data Analysis (III): Gas Gain Compensation

A ***compensation measurement*** is performed to determine the ***new bias voltage*** at which the detector should be powered during the high-flux irradiation:

1. to recover the original ***nominal gas gain*** of 2×10^4
2. to maintain the ***nominal electric fields*** between the foils and gaps

Compensation algorithm:

I. Measure the $V_{bias}^{electrode}$ and the $I^{electrode}$ on each electrodes to calculate the effective voltage on the electrode during the high-flux irradiation:

$$V_{eff}^{electrode} = V_{bias}^{electrode} - I^{electrode} \times R^{electrode}$$

II. Calculate the discrepancy with respect to the electrode voltage ($V_{nominal}^{electrode}$) at the nominal effective gas gain of 2×10^4:

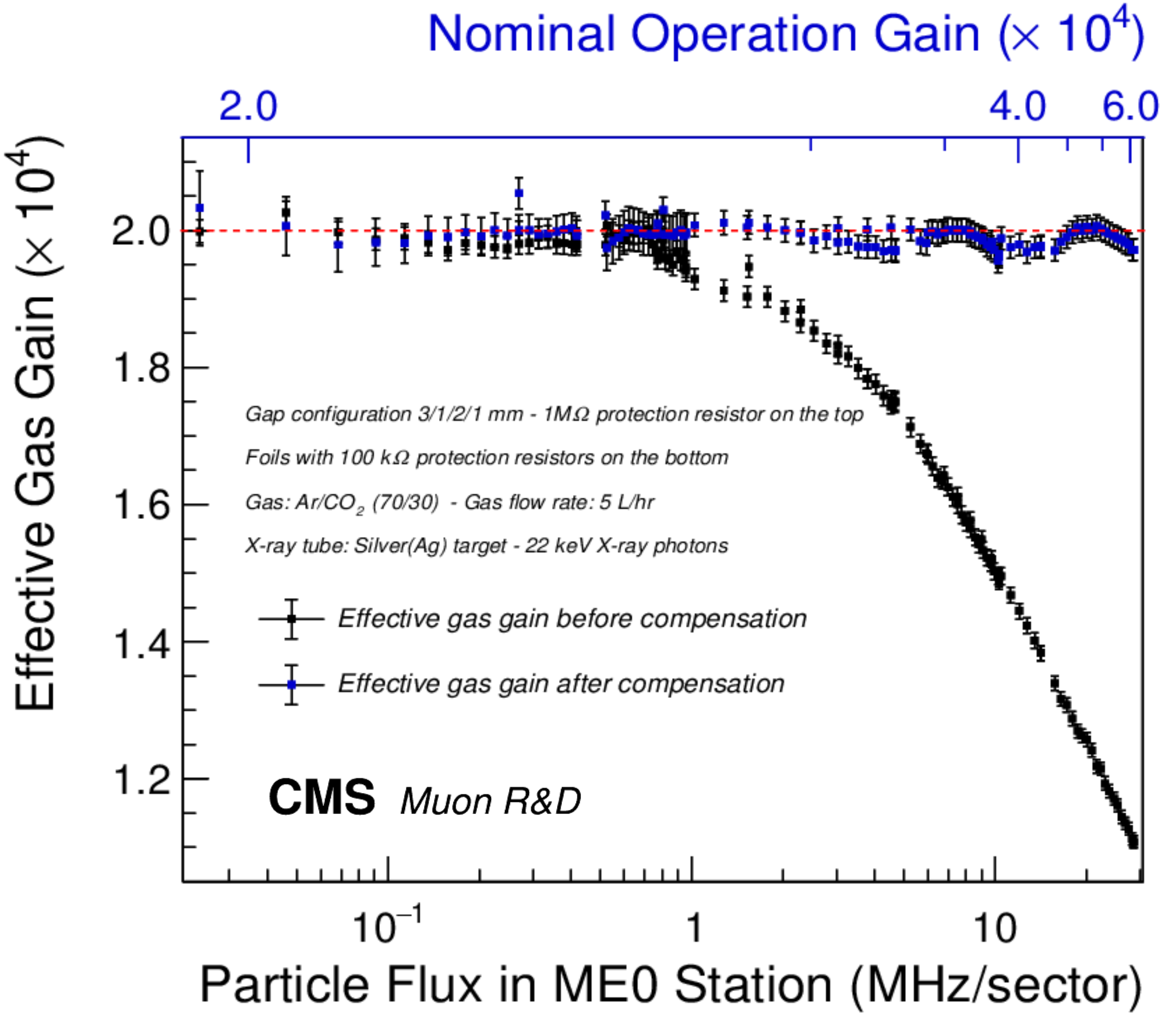
$$V_{err}^{electrode} = V_{nominal}^{electrode} - V_{eff}^{electrode}$$

III. increase iteratively each electrode voltage by $V_{err}^{electrode}$ until:

$$V_{eff}^{electrode} = V_{nominal}^{electrode}$$

Data Analysis (III): Gas Gain Compensation

Results after implementing the compensation algorithm:



A LabView-based virtual instrument was developed to implement the compensation algorithm for each value of irradiation flux.

If the irradiation stops the gain increases because of the lack of currents through the resistors!.

Radial Segmentation of the GEM-foils

The gas gain drop will be minimized by dividing each GEM foil in **several *high-voltage sectors*** along the ***azimuthal-direction.***

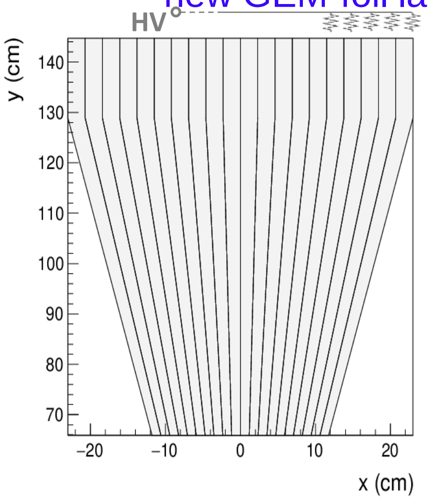
- Each high-voltage sector connected separately, in order to limit the total current flowing through each protection resistor

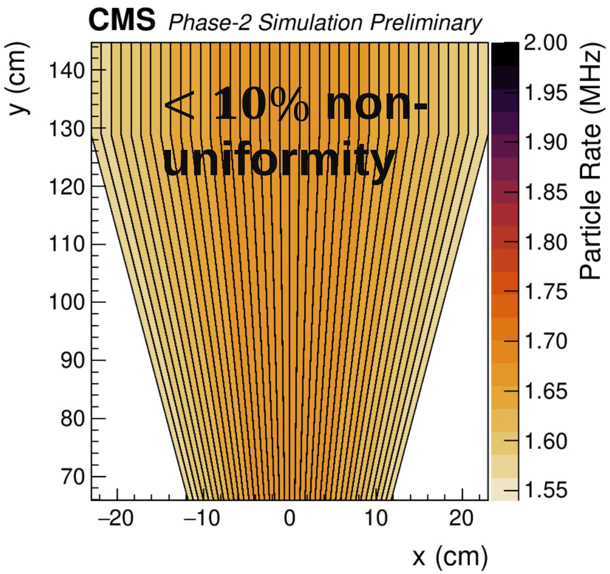
  → ***equal-area sectors***: $< 100\ cm^2$ (To reduce the discharge energy)

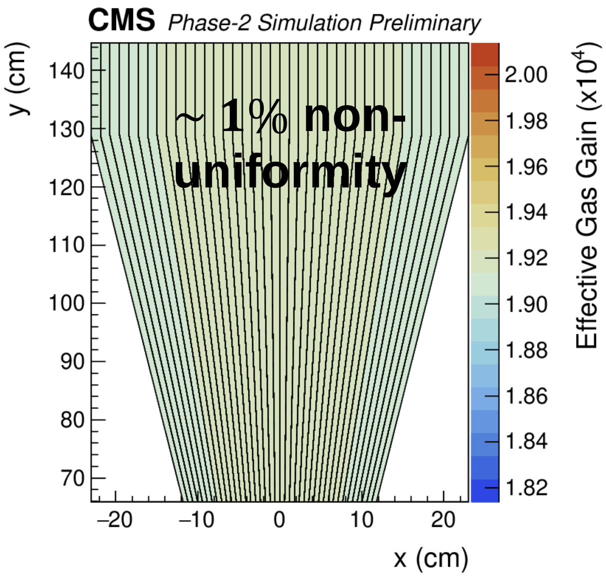
- The background particle rate is approximately the same on each sector. Not affected by the shape of the background hit rate (slide 5).

  → ***equal-protection resistors***

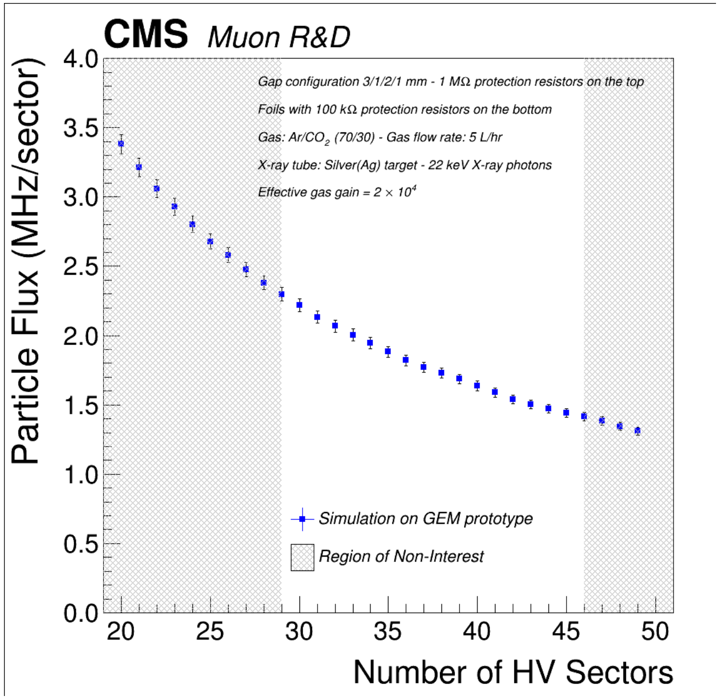
new GEM-foil layout

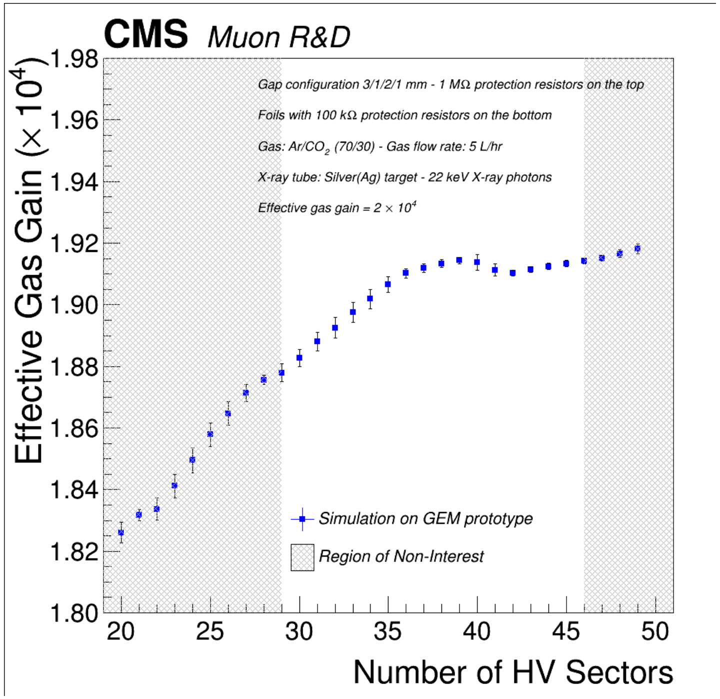






Radial Segmentation of the GEM-foils





Sector area
$< 10 \times 10\ cm^2$
29 sectors

number of sectors

Optimal number: **around 40 sectors**

Sector side length
$> 5\ mm$
45 sectors

The ***hit rate per sector*** in the CMS-ME0 background can be contained to an average of $\mathbf{1.5\ MHz/sector}$, while the ***gas gain drop*** can be minimized to about $\mathbf{10\%}$ of the nominal value of 2×10^4.

Conclusions

The studies presented show a new approach on the rate capability problem of triple-GEM detectors, applied to the high-rate environment expected for the innermost muon station of the CMS endcaps for the high-luminosity upgrade:

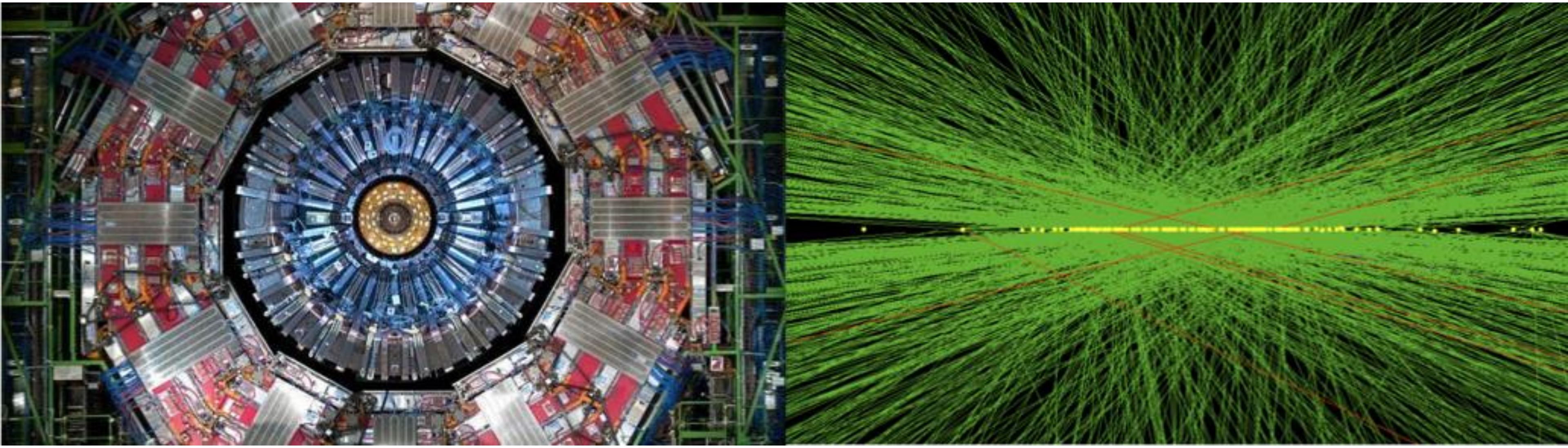
- The *rate capability* of large-area triple-GEM based detectors has been demonstrated to be *limited by the protection resistors*;

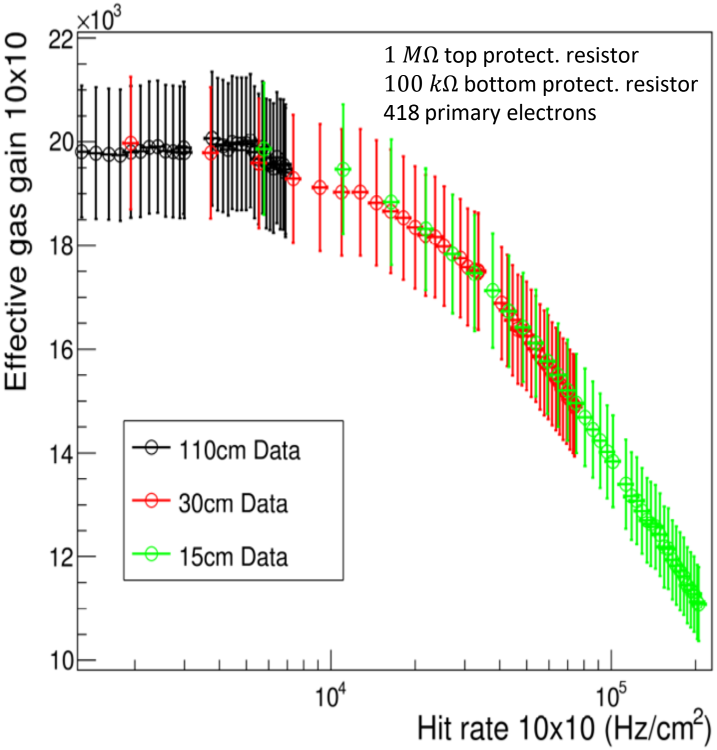
- The measured *gas gain drops* can be as high as 40% of the expected gas gain, which can be recovered by applying overvoltage to the detector electrodes and maintaining the nominal electric fields between the foils and gaps;

- The main mitigation strategy chosen for the CMS-ME0 detectors involves *a radial segmentation of the GEM-foils* with respect to the beam line: such redesign is expected to reduce the *gas gain loss during CMS operations not higher than* 10%.

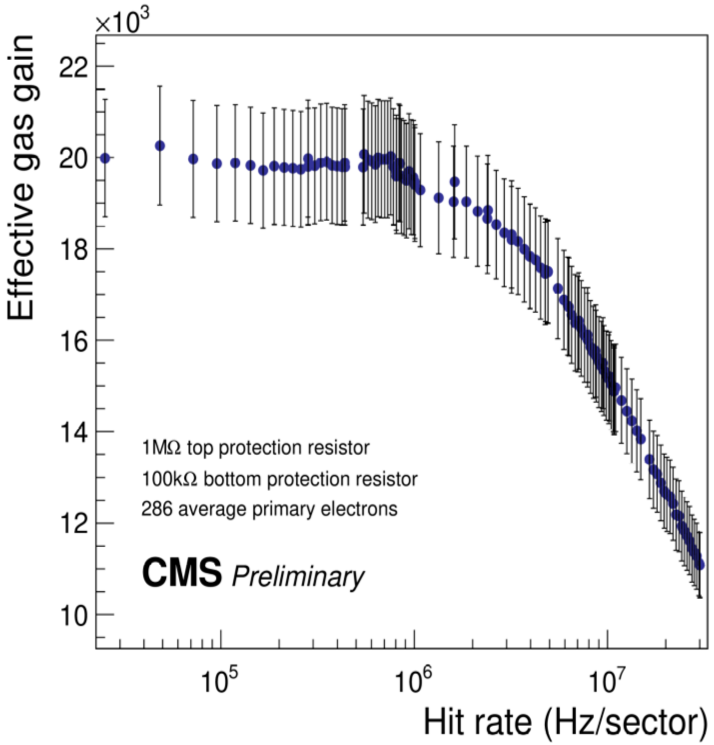
Thank you!

BACKUP SLIDES





1 $M\Omega$ top protect. resistor
100 $k\Omega$ bottom protect. resistor
418 primary electrons



1MΩ top protection resistor
100kΩ bottom protection resistor
286 average primary electrons

Lessons learned from measurement

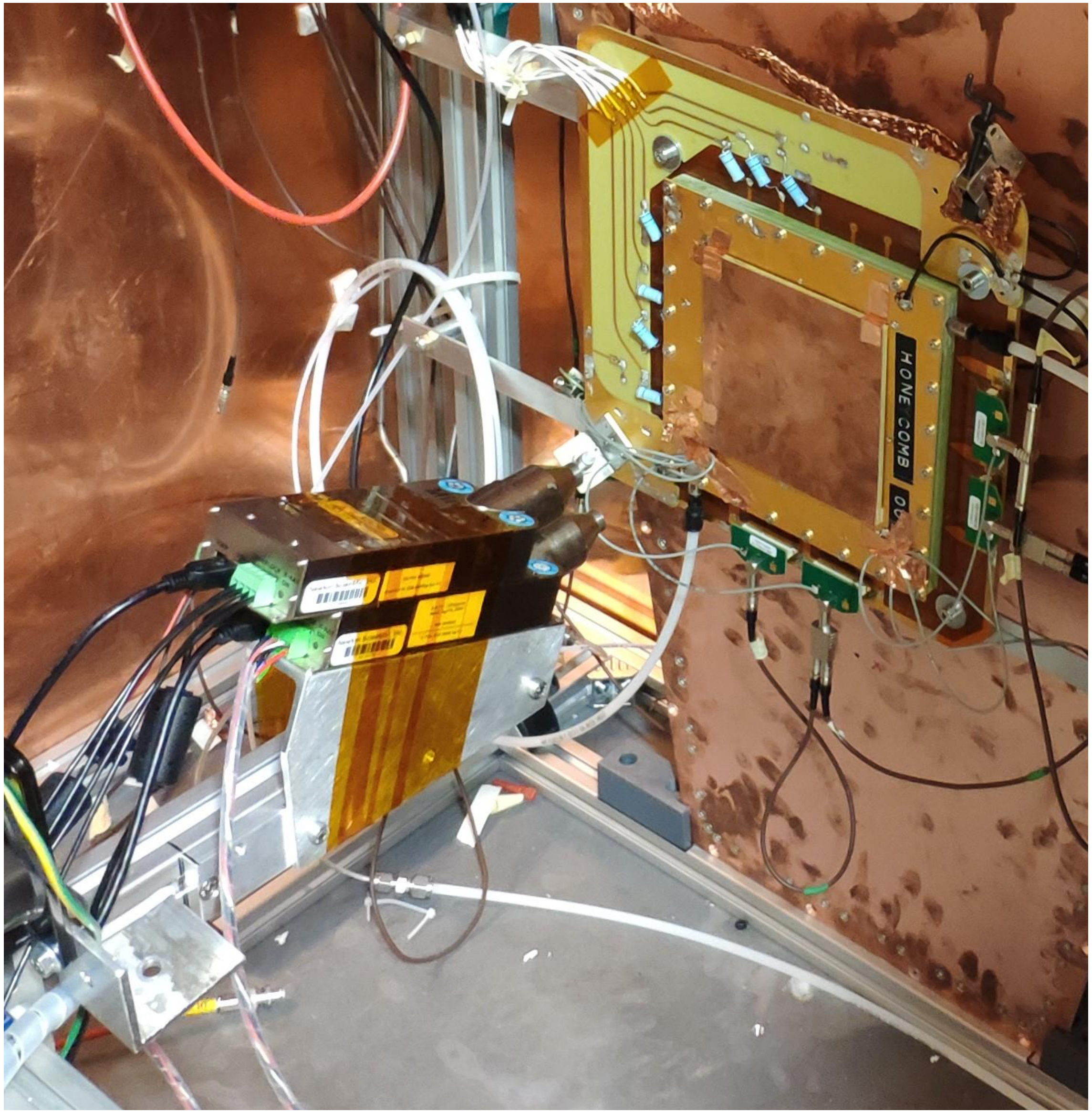
- Gain drop depends on the total (***integral***) ***hit rate*** on the sector, not on the flux → rate expressed in $\boldsymbol{Hz/sector}$ instead of Hz/cm^2
- Gain drop depends on total current on electrode (which is proportional to $n.primaries \times hit\ rate$)

For the CMS environment

Rate axis scaled by $\frac{primaries_{X-ray}}{primaries_{ME0}} = \frac{418}{286}$

→ For a ***known hit rate*** on a sector of an ME0 chamber in the CMS environment background, we can ***foresee the sector gain drop*** (only in the 1MΩ configuration) using the rate capability curve

Experimental setup



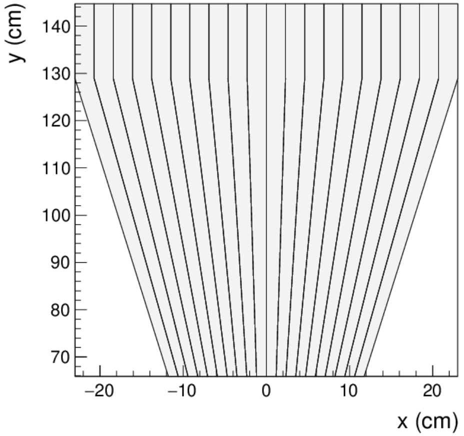
Large-area GEM detector design

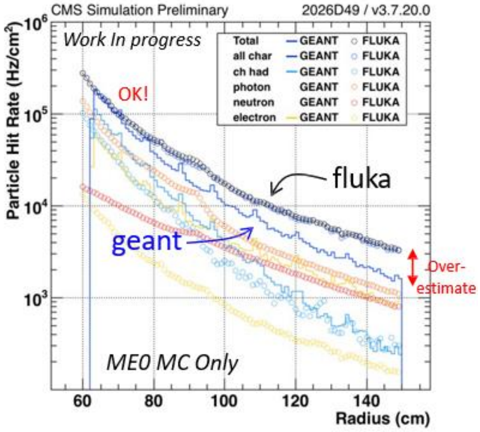
Longitudinal segmentation

Bkg. independent

↓

Called for solution





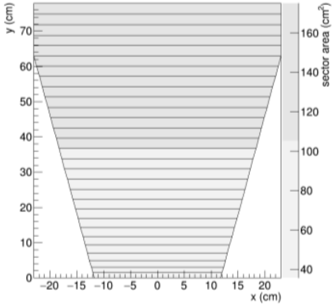
Transversal segmentation

NO Bkg. independent

↓

Backup solution

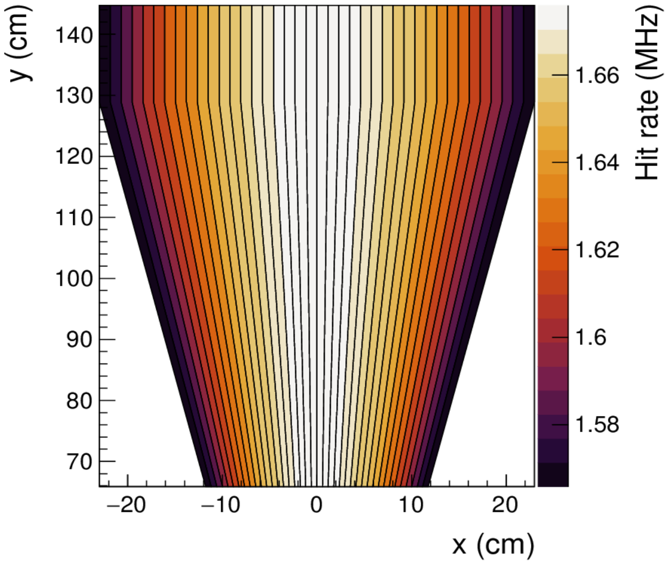
HV areas and protection resistors have to be tuned to equalize the voltage drop under irradiation (studies are ongoing)

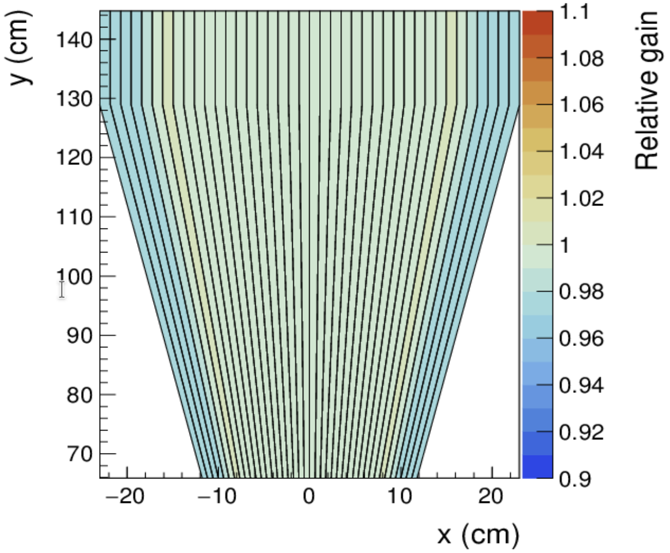


- Constraints on HV sector areas
  - Largest area limited by discharge and short circuit probability
  - Minimum area limited by design and production machinery, available space for resistors

- Constrains on protection resistors
  - Minimum resistor determined by discharge protection and short-circuit current, to avoid too much current load on HVPS
  - Maximum resistor limited by rate capability, depending on hit rate on specific sector

Vertical segmentations: rate and gain





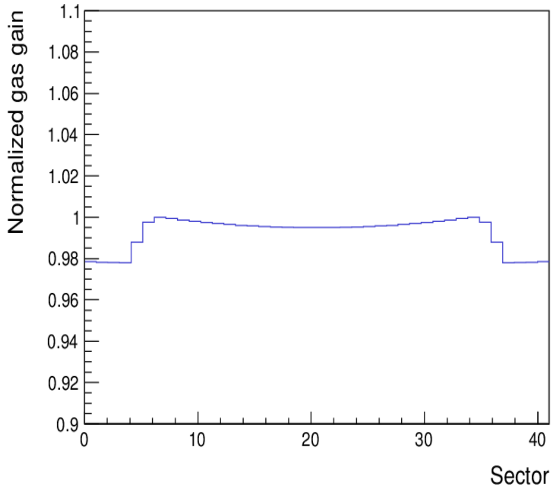
Example phi-segmentation with 40 sectors

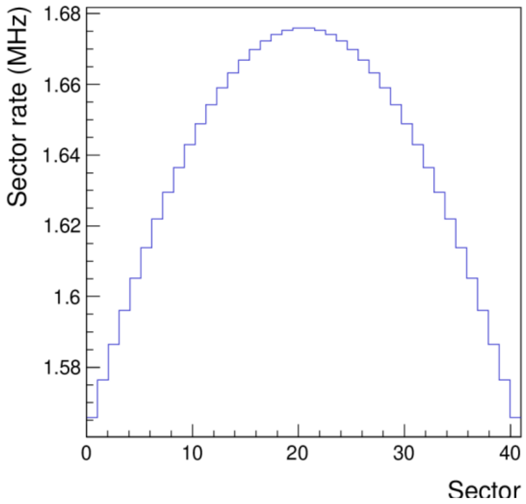
1. Hit **rate from background simulation**
2. Gain **drop from rate capability** measurement

- All **sector areas** are exactly the **same** (each sector is a trapezoid + a rectangle)
- **Sector rates** are **not exactly** the same (flux shape is radially symmetrical, while segmentation is not)

→ **Gain** is **not exactly** the same for all sector

But anyway, the **gain disuniformity** ($\sim 1\%$) due to different drops appears to be much lower than average **intrinsic** chamber **response disuniformity** ($\leq 15\%$)!



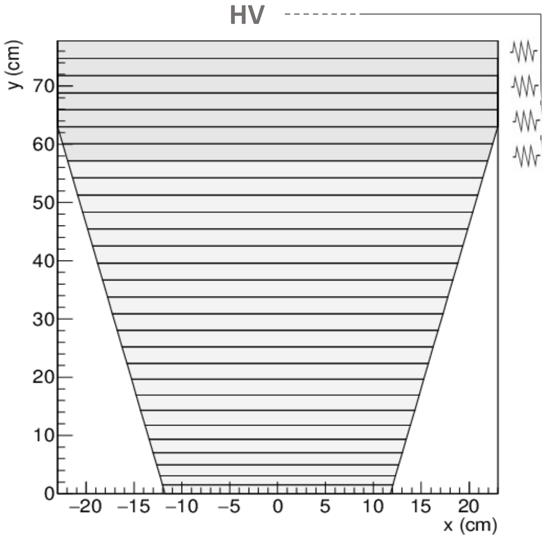


ME0 GEM-foil layout - baseline

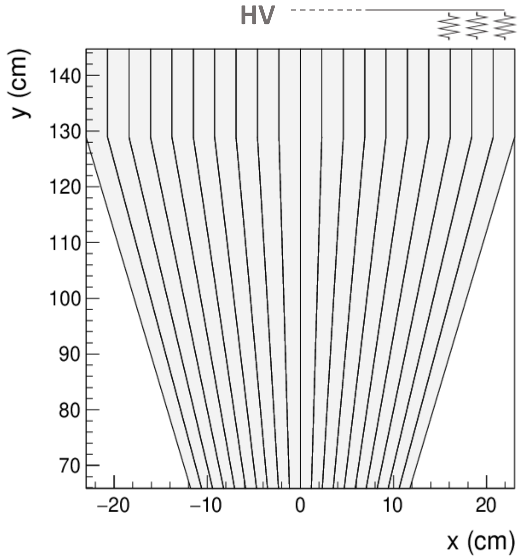
So just to recap our mitigation strategies:

- ***Double-sided segmented GEM-foils***
  - → vertical foil segmentation (along φ-coordinate)
  - → average the radiation load along r-coordinate and make the interaction rate on all HV sectors the same
  - → background independent model (i.e., all the rates will move up or down together in parallel with any changes in the radial radiation profile)
- ***40 "trapezoidal + rectangular" HV sectors***
  - → maximum safe surface $\sim 100\ cm^2$ to reduce the discharge energy
  - → the rate is expected to be $24\ kHz/cm^2$ on each sector or about $2.4\ MHz$ total per sector assuming each area sector is $100\ cm^2$
  - → the gas gain is expected to vary less than 1% from sector to sector
- ***HV distribution and SMD components on the top of the GEM-foils***
  - → greater active area overlap in adjacent chambers
- ***Protection resistors value - baseline:***
  1 MΩ on the top-foil & 100 kΩ on the bottom-foil
  - → ensure prevention/protection against self-sustained discharges
  - → minimize the voltage drop across the GEM-foil during high-flux irradiation
  - → avoid exceeding the current limit imposed by the power supply on each HV channel in case of short-circuit (n.b.: possibility of having different protect. resistor values between the $GEM_{1,2,3}$-foils was considered)

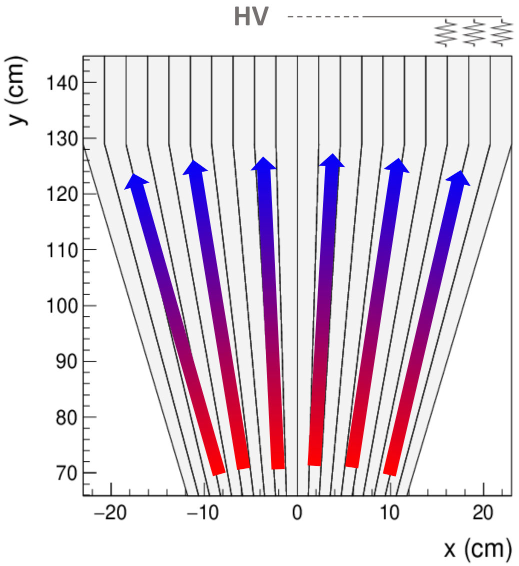
old GEM-foil layout



new GEM-foil layout



Concerns and possible tests on φ-segmentation



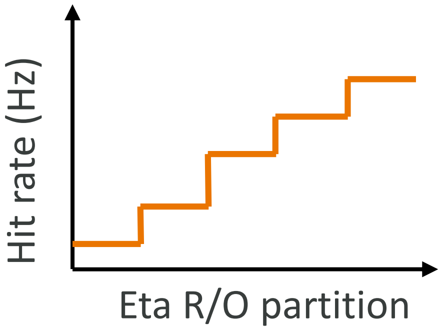
A concern: by **powering the chamber at low eta**, there is a constant current of $O(\mu A)$ flowing from high to low eta for charge evacuation

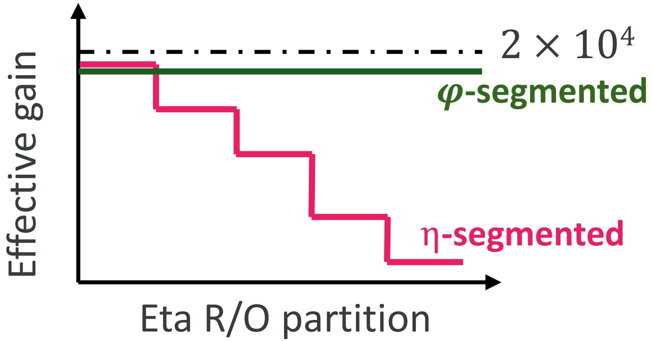
- Copper conductivity too high to give voltage drops along eta
- **Possibly current flowing through GEM_3 bottom giving rise to distortions on signal**?

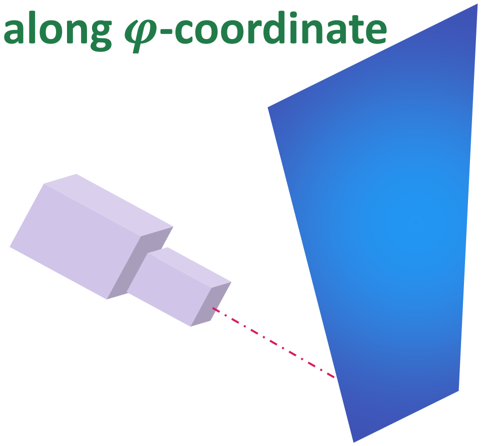
→ will be tested by checking the new prototype!

A possible test: chamber irradiated with **X-ray source placed at high eta** (rate profile decreasing as ~1/y2)

- **Traditional ME0 prototype** (η-segmentation) → gain should **decrease with η-coordinate**
- **New MEO prototype** (φ-segmentation) → gain expected **constant along φ-coordinate**



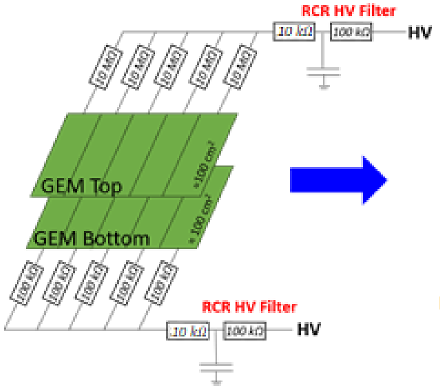




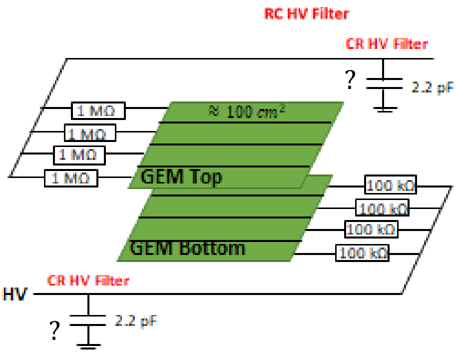
GEM-foil design vs. stack optimization

ME0 GEM$_1$ & GEM$_2$ foil baseline

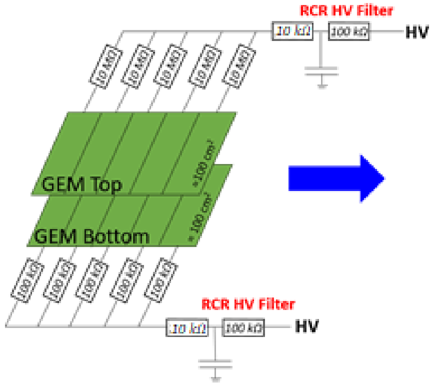
ME0 GEM$_3$ foil baseline



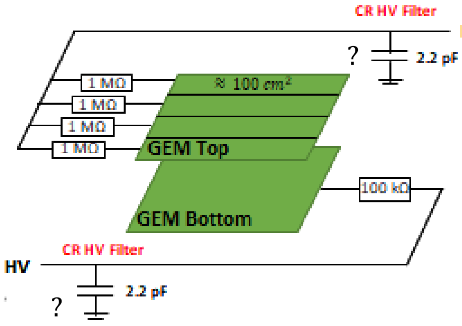
OLD GEM$_{1,2}$ - foil layout



NEW GEM$_{1,2}$ - foil layout



OLD GEM$_3$ - foil layout



NEW GEM$_3$ - foil layout

→ ***double-segmentation*** of the ***GEM$_1$*** and ***GEM$_2$*** foils to limit the energy available to feed the discharge propagation

→ resistive high-voltage filter redesign to minimize the voltage drop during the high-flux irradiation

Idea: use the ***foil protection resistors*** in a ***dual role*** as part of the ***high-voltage resistive filter*** and ***protection circuit*** (i.e. instead of an external RCR low-pass filter, use a simpler CR circuit)

→ ***unique electrode*** for the ***GEM$_3$*** with a single protection resistor ($> 100\ k\Omega$): promising option to cope with ***X-talk issue***

→ a single protection resistor as a part of the CR low-pass filters and protection circuit to limit the discharge inside the foil

→ discharge phenomena, rate capability, power supply limit must be taken into account to choose the protect. resistor value