Rate capability measurement for the large-area GEM detector and GEM-foil optimization

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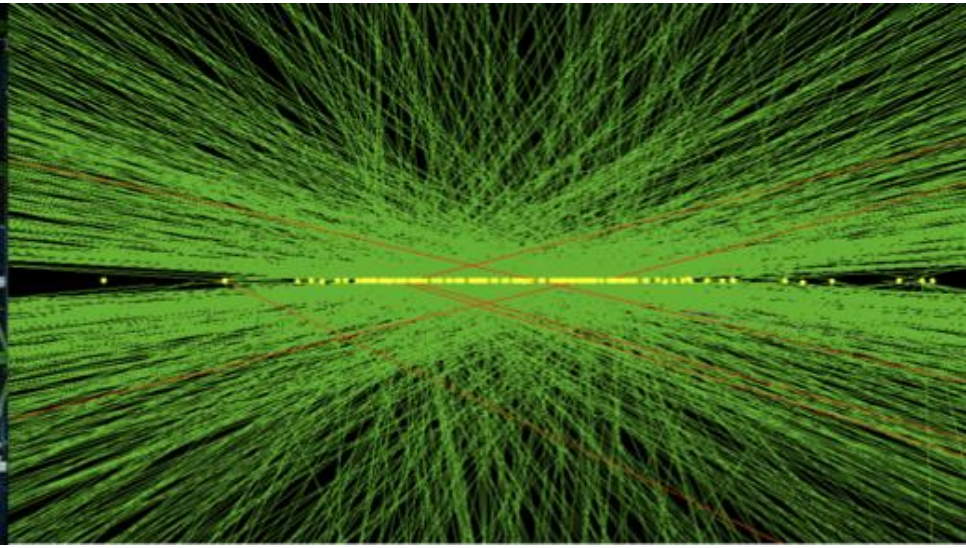
RD51 Collaboration Meeting and Lectures

June 24th, 2020



Introduction

Goals of this presentation

Update the MPGD community **on the status of the rate capability measurement and plans for future R&D activities.**

Table of content:

- **State of art on the rate capability studies for GEM-based detector;**
- **A new approach to the study of the rate capability for large-area GEM detector;**
- **Rate capability studies on the ME0 prototypes whit double-sided segmented GEM-foils;**
- **Some ideas for a double-sided segmented GEM-foil design;**
- **2020 / 2021 R&D program on rate capability studies.**

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

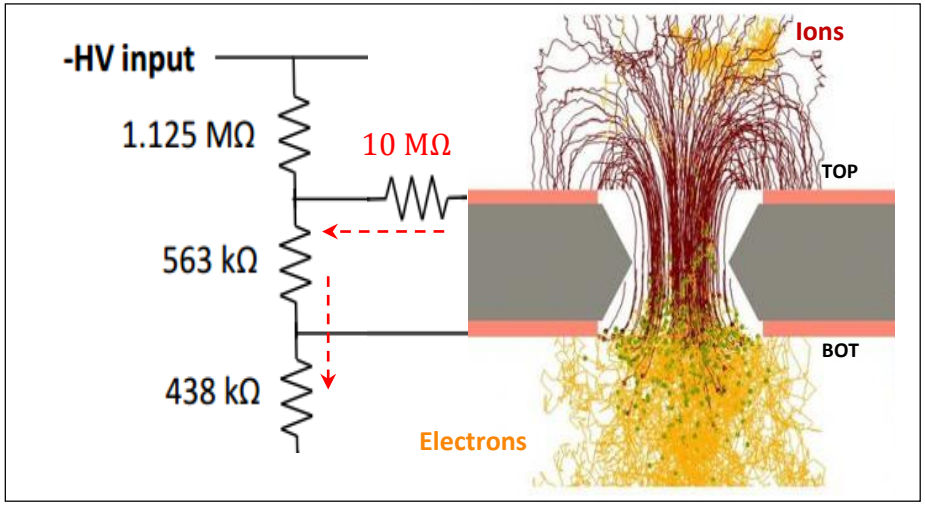
   → this current is basically due to the ***high number of ions*** collected on the top electrode of the GEM-foils during the high-flux irradiation

   → 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 stress the following points …

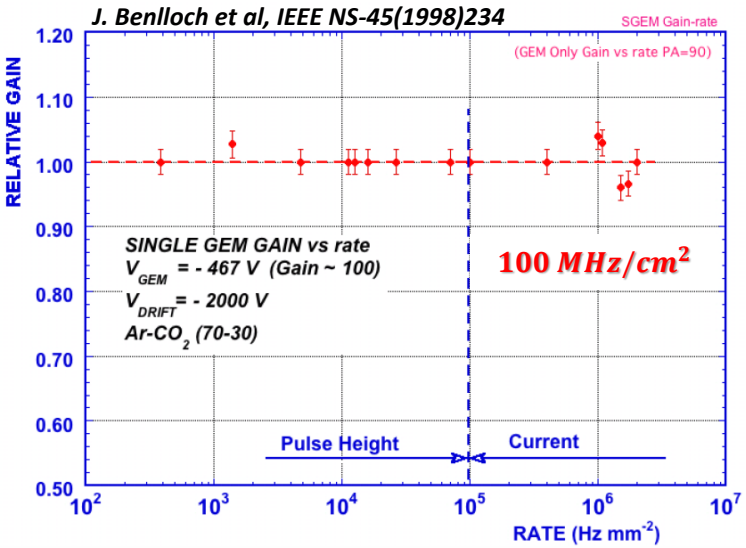
- rather than the space charge, the ion-induced current, flowing through the protect. resistors, strongly affect the detector rate capability!
- a ***local irradiation*** $O(3\,mm^2)$ is drastically different to a ***global irradiation*** $O(3000\,cm^2)$!

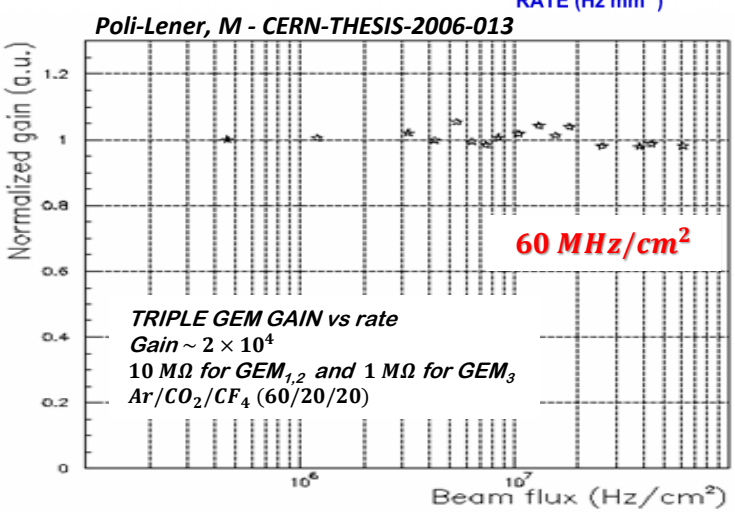
A new approach to the study of rate capability for large-area GEM detector is needed!



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





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 ramains stable up to a flux above MHz/cm^2
   → demonstrating the absence of ***space charge phenomena!***

but one observes ...

1) a ***low ion 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

A new approach to the study of the rate capability for the large-area GEM detector is proposed, and exploits the following key - issues:

1) a ***large percentage*** of the ***detector area*** is irradiated (up to $\sim 3000\ cm^2$)
   - → 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) an ***Ag-target X-ray tube*** ($\sim 22\ keV$ photons) is used to study the rate capability
   - → the No. of primaries ($\sim 346\ e^-$) generated by this source is comparable with the No. of primaries ($\sim 300\ e^-$) expected in ME0 detector during the HL-LHC era

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

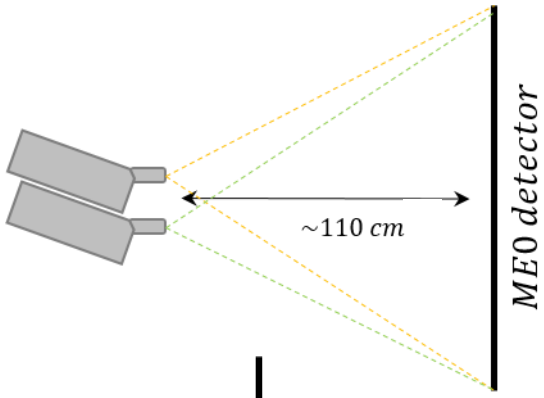
4) a ***gas gain drop*** is estimated by measuring a ***voltage drop*** across the three GEM-foils during the high-flux irradiation
   - → the foils is powered individually using a ***CAEN A1515TG multi-channel power supply***
   - → the A1515TG module allows to monitor the ion current flowing through the protection resistors, and estimate the voltage drop across the foil, resulting in the gas gain drop

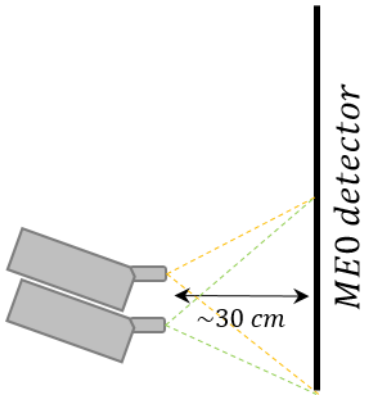
New approach to the rate capability study

The rate capability measurement was performed using two high intensity X-ray generator (Ag-target X-ray tube, $\sim 22\ keV$ photons)

Two ***irradiation configurations*** were studied:

1) a ***low photon flux configuration***: the X-ray tubes were placed at $\sim 110\ cm$ from the detector
   → in such configuration the detector active area is fully and uniformly irradiated
2) a ***high photon flux configuration***: the X-ray tubes were placed at $\sim 30\ cm$ from the detector
   → in such configuration the detector active area is partially irradiated ($\sim 50\%$ of the active area)
   → such configuration is essentially equivalent to the full irradiation since only the irradiated HV sectors are taken into account!
   → a numerical simulation was developed to understand the photon radiation field impinging the HV sectors





The measurement were repeated with different ***detector configurations***:

1) different protection resistors: $1\ M\Omega$ or $5\ M\Omega$
2) with and without the resistive HV filter

New approach to the rate capability study

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

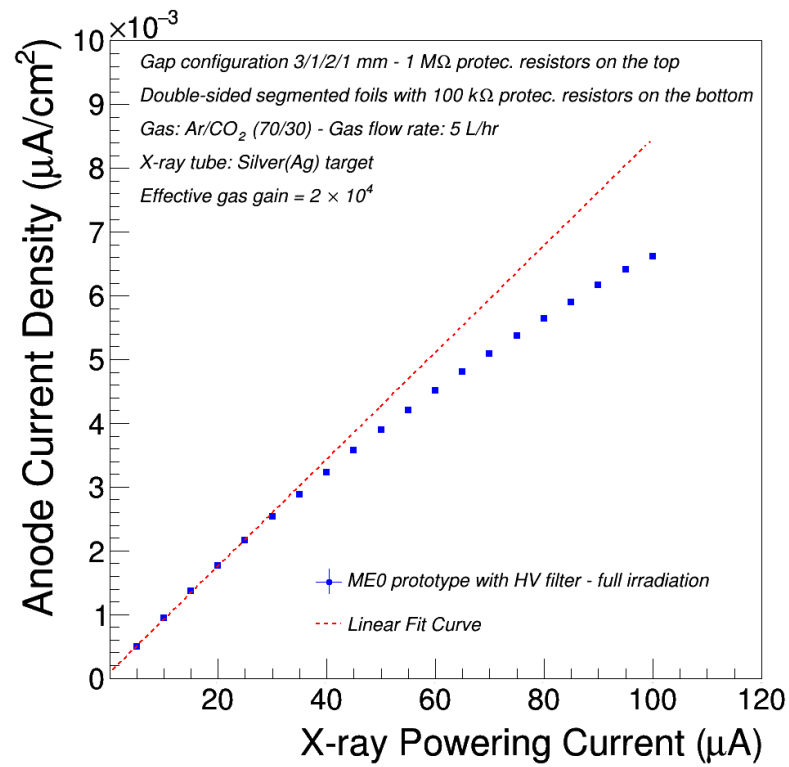
1) for a ***low particle flux*** (i.e. **low** X-ray powering current), the anode current increase linearly with the increasing count rates

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

→ ***the saturation is exclusively due to gas gain drop!*** (no saturation of the pico-ammeter up to $\sim 25\ mA$)

→ the ***linear fit*** to the experimental data (at the low rates) allows to extrapolate the ***expected (real) anode current*** (at the high rates)

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

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

detector gas gain known from QC5 test

New approach to the rate capability study

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

1) the ***current*** flowing through the ***protection resistors*** changes the voltage difference on each HV sector

   → by applying the ***Kirchhoff's second law***, the new voltage difference on the i-th HV sector will be:

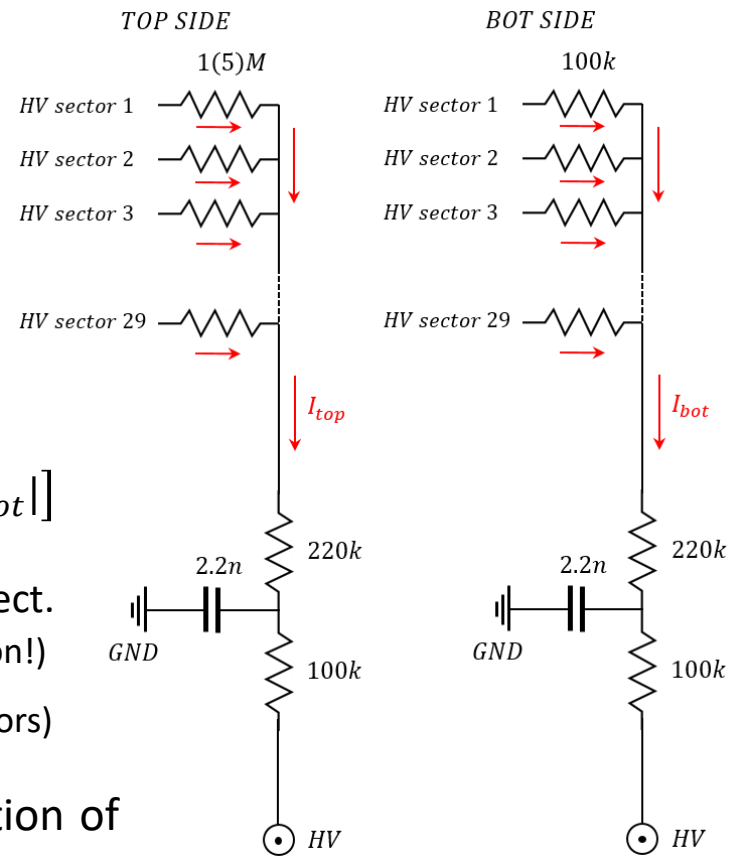
$$\Delta V_i' = \Delta V_{i,0} - w_i\left(R_p^{top} \cdot |I_{top}| + R_p^{bot} \cdot |I_{bot}|\right)$$

   → by considering the contribution of the ***resistive HV filter***, the new voltage difference on the i-th HV sector will be:

$$\Delta V_i' = \Delta V_{i,0} - \left[\left(w_i \cdot R_p^{top} + R_f\right) \cdot |I_{top}| + \left(w_i \cdot R_p^{bot} + R_f\right) \cdot |I_{bot}|\right]$$

   → w_i is the fraction of total current flowing through the protect. resistor of the i-th HV sector (in case of non-uniform irradiation!)

$w_i = \frac{1}{n}$ in the ideal case of uniform irradiation (n = total No. of HV sectors)



2) At fixed photon flux, the new gas gain of the i-th portion of the detector defined by the i-th HV sector will be:

$$G_i \rightarrow G_i' = A_i e^{B_i\left(\Delta V_i'^{GEM_1} + \Delta V_i'^{GEM_2} + \Delta V_i'^{GEM_3}\right)}$$

$\xRightarrow{\text{weighted average over all HV sectors}}$ detector gas gain at flux Φ $\boldsymbol{G'}$

New approach to the rate capability study

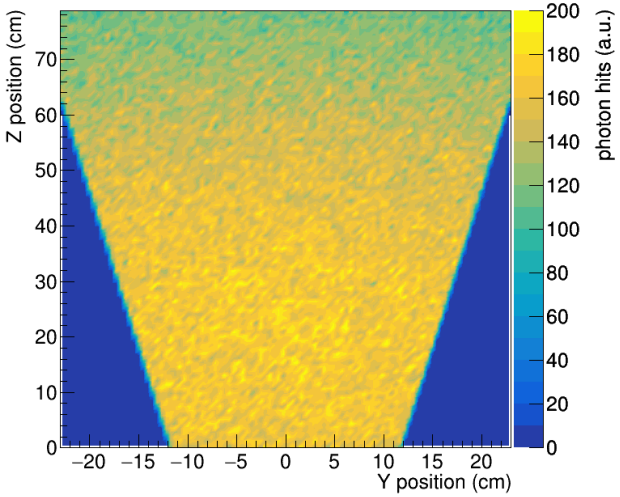
Due to the ***non-uniform irradiation***, each HV sector receives a ***different photon flux***

1) a dedicated ***numerical simulation*** was developed to estimate the ***HV sector weights w_i*** :

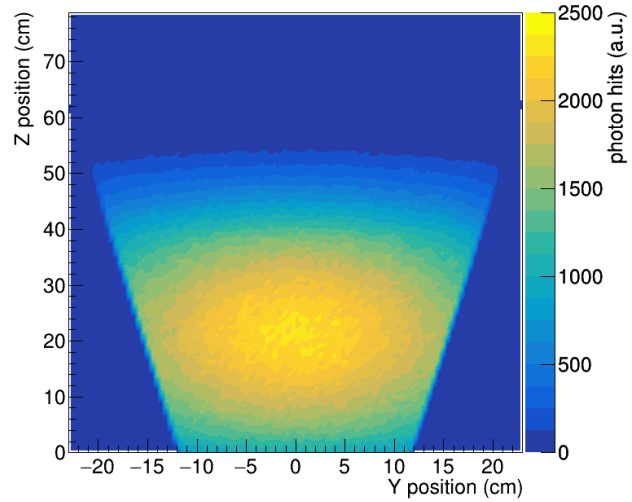
   → w_i is the fraction of total current flowing through the protect. resistor of the i-th HV sector (in case of non-uniform irradiation!)

   → w_i is equal to fraction of total photons hitting the i-th HV sector obtained from the numerical simulation

numerical simulation developed by ***Antonello Pellecchia*** *(University of Bari and INFN Bari)*

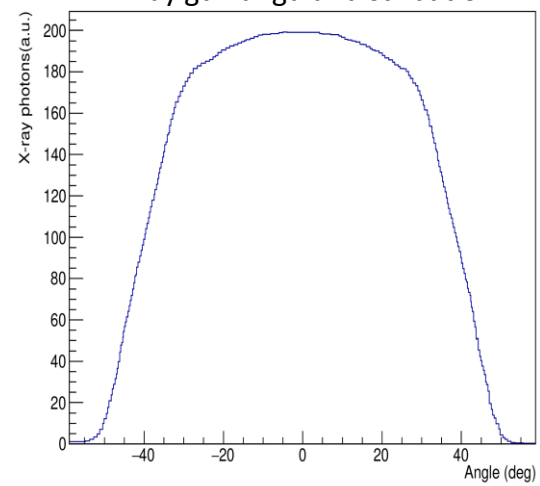


hit map with full irradiation
(X-ray to detector 110 cm)



hit map with partial irradiation
(X-ray to detector 30 cm)

X-ray gun angular distribution



- the horizontal alignment precision of X-ray gun of $\sim 1\ cm$ gives uncertainties on the HV sector weights
- the error propagation gives an uncertainty of $\sim 0.2\%$ on the gas gain drop

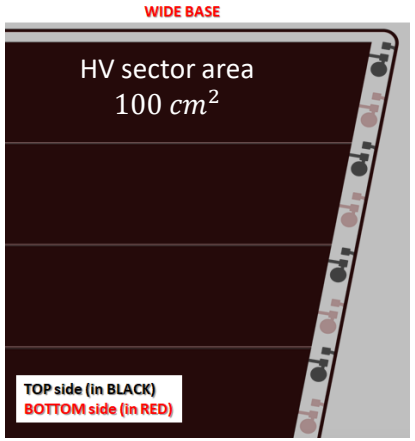
2) the ***HV sector weight w_i*** is calculated as follows:

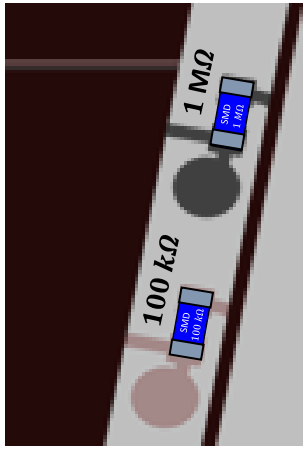
$$w_i = \frac{current\ on\ the\ i-th\ HV\ sector}{total\ current\ on\ foil} = \frac{photon\ hits\ on\ i-th\ HV\ sector}{total\ photon\ hits}$$

Rate capability studies on ME0 prototype

The first two ME0 module prototypes were assembled at CERN and equipped with ***double-sided segmented GEM-foil***

Current double-sided segmentation:





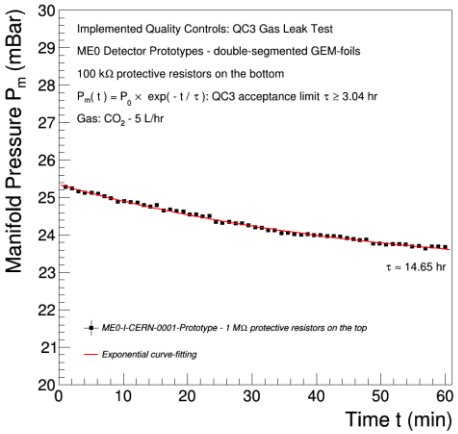
→ reduce the ***discharge propagation*** probability and ***damage probability*** of the front-end electronics

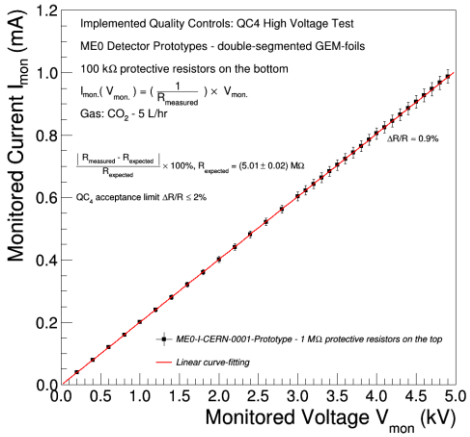
→ allow efficient de-coupling from HV and ***quench a self-sustained discharge*** through protec. resistors

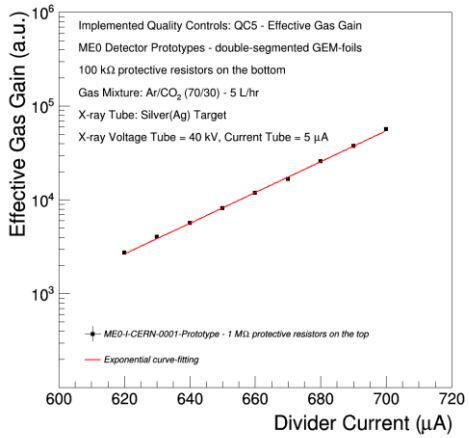
Two ME0 prototypes were assembled and fully validated:

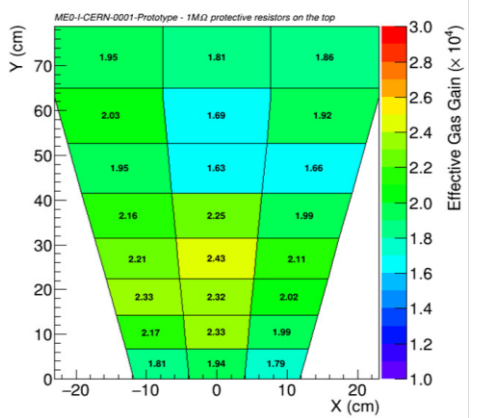
- 1st prototype with ***1 MΩ protection resistors*** on the top side and 100 $k\Omega$ on the bottom side
- 2nd prototype with ***5 MΩ protection resistors*** on the top side and 100 $k\Omega$ on the bottom side

example of standard QA/QC on the ME0 module with $1M\Omega$ protection resistors on the top









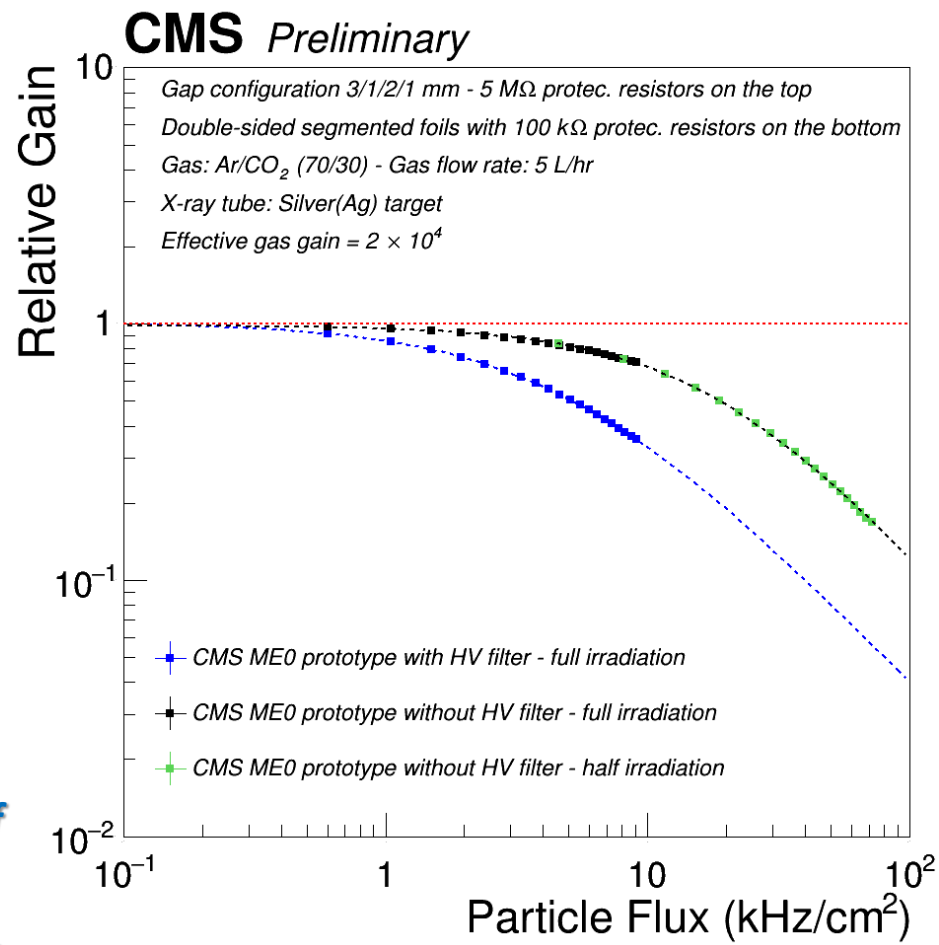
Rate capability studies on ME0 prototype

The rate capability of the ME0 prototype with ***5 MΩ protection resistors*** was measured in Ar/CO_2 (70/30) at gas gain of 2×10^4

1) The rate measurement was performed in ***current mode*** due to the high particle flux (see slide 7)
2) Three different configuration were tested:
   - → ***blue dots***: with standard HV filter + 100% of the area is uniformly irradiated

     gas gain drop of 30% @ 2 kHz/cm^2
   - → ***black dots***: without standard HV filter + 100% of the area is uniformly irradiated
   - → ***green dots***: without standard HV filter + 50% of the area is irradiated

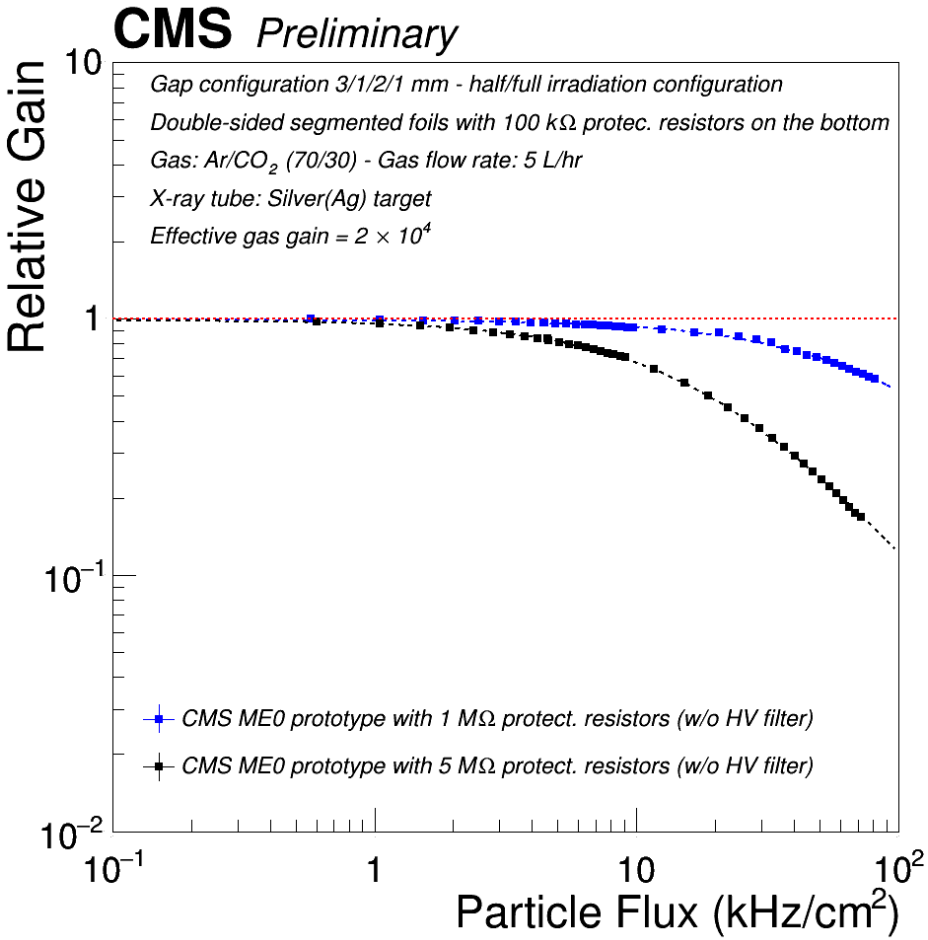
     gas gain drop of 30% @ 10 kHz/cm^2



- ***the stringent ME0 requirements in terms of rate capability are not fulfilled***
- ***the HV filter has a significant impact on the detector rate capability!***

Rate capability studies on ME0 prototype

Comparison between the ME0 module with **1 *MΩ* protect. resistors (w/o HV filter)** and ME0 module with **5 *MΩ* protect. resistors. (w/o HV filter)**



1) the ***protection resistors*** on the GEM-foils are used ***to quench*** the ***self-sustained discharge***
2) obviously the ***best protection*** is obtained with ***very high value resistors***

but on the other hand ...

3) the ***experimental requirements*** (particle rate and gas gain) determine the ***maximum values*** that can be used to maintain the potential drops within acceptable limits under high-flux irradiation
4) the ***power supply system*** (i.e. its max. output current) determine the ***minimum values*** that can be used to maintain the total current below the limit of the HV board (***even in case of possible short-circuit in the HV sector***)

The bkg. rate, discharge phenomena, rate capability, power supply limit and HV sector area must be taken into account to choose the protect. resistor value

Rate capability studies on ME0 prototype

Comparison between the ME0 module with ***1 MΩ protect. resistors + HV filter*** and ME0 module with ***5 MΩ protect. resistors. + HV filter***

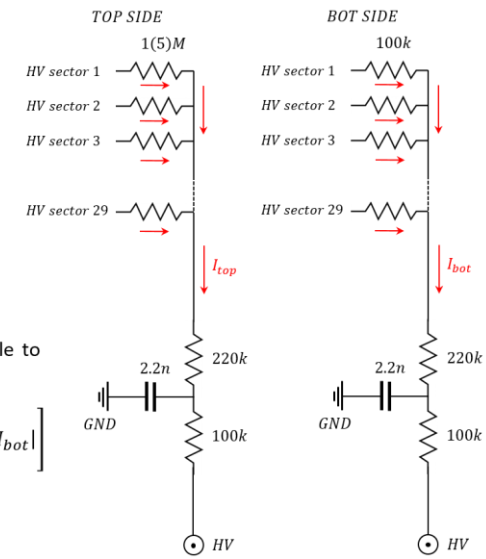
1) the ***standard GE1/1 HV-filter*** was used for the rate capability measurements:

R_p^{top} = protect. resistor on the top side: 1 (*or* 5) $M\Omega$

R_p^{bot} = protect. resistor on the bottom side: 100 $k\Omega$

R_f = equivalent resistor of the HV filter: 320 $k\Omega$

n = number of HV sectors: 29



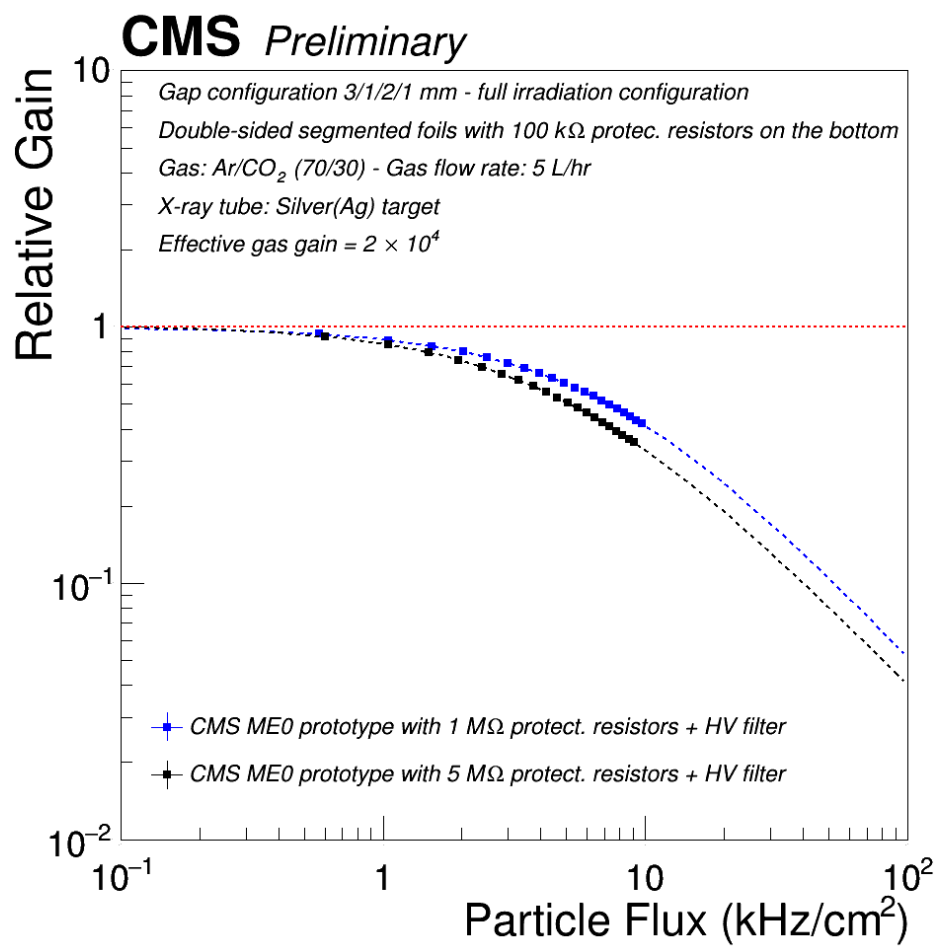
By applying the ***Kirchhoff's second law***, it is possible to evaluate the potential drop across the GEM-foil:

$$\Delta V_{drop} = -\left[\left(\frac{R_p^{top}}{n} + R_f\right)\cdot|I_{top}| + \left(\frac{R_p^{bot}}{n} + R_f\right)\cdot|I_{bot}|\right]$$

2) the ***ion current***, coming from every HV sectors, ***flows entirely*** on the ***equivalent resistor*** of the HV filter, resulting in a significant potential drop across the GEM-foil!

→ the HV filter gives the major contribution to the potential drop across the GEM-foils

→ a difference $O(10\%)$ between the two configurations has been observed



A redesign of the HV filter is needed!

Rate capability drop with the ME0 background and current ME0 GEM-foil layout

in the expected ME0 background …

1) due to the non-uniform bkg., there will be ***hottest areas*** (for high η-sector), which will experience a higher particle rate, and ***coldest areas*** (for low η-sector), which will experience a lower particle rate;

in the current foil design configuration …

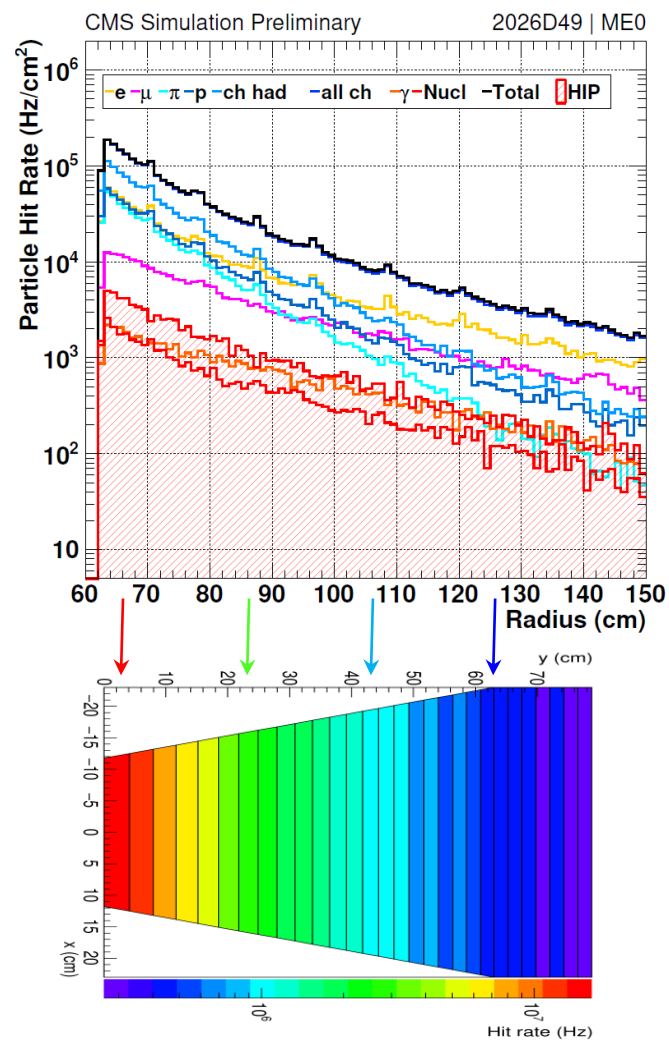
2) due to the equal-area HV sectors $(100\,cm^2)$ and equal-value protect. resistor, there will be HV sectors (in the hottest area) which will draw a major current and HV sectors (in the coldest area) which will draw a minor current;

in other words …

3) there will be HV sectors which will experience a higher voltage drop and HV sectors which will experience a lower voltage drop;

as a result …

4) since it is not possible to power the HV sectors individually, if you try to compensate for the voltage drop to recover the initial gain in the hottest area, you will have an extremely high gain in coldest areas, which suffer a lower voltage drop!



New ideas for ME0 GEM-foil segmentation

In order to ensure proper and uniform recovery of the detector gas gain, a possible option consists to have ***different-area HV sectors*** with/or ***different-value protect. resistors***

considering the expected hit flux vs. radius …

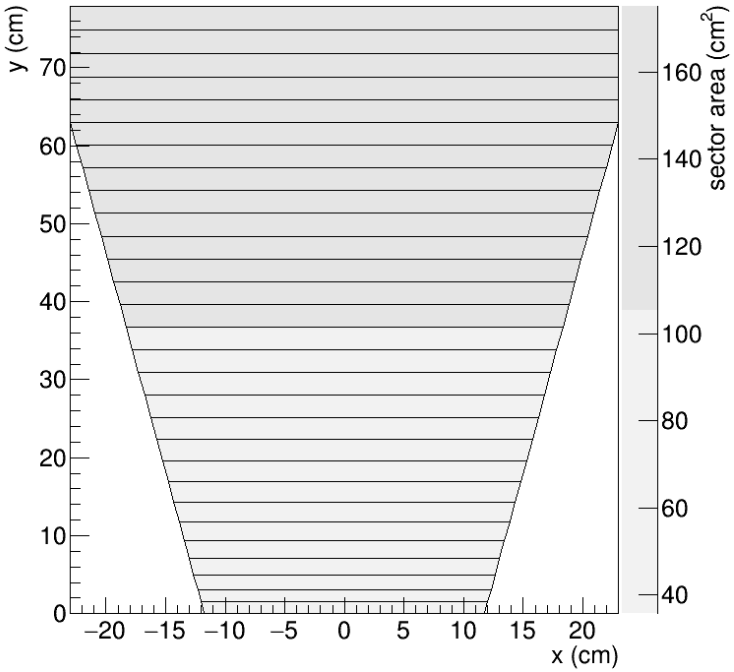
1) to ensure the same voltage drop on each HV sector, the foil segmentation and the protect. resistor value have been tuned to produce equal HV drop across each HV sectors.

in other words …

2) The surface of the HV sectors increase along eta in order to reduce the different bkg. rate impinging on the HV sectors and at the same time the protect. resistors increase to keep RxI constant.

as a result …

3) if you try to compensate for the drop voltage, by increasing the voltage on the foils, the gain recovery will be uniform over the whole active area.



New configuration: new double-sided segmented foil design with ***different-area HV sectors*** and ***different-value protect. resistors***

Furthermore, it should be made clear which value of the protect. resistors would more appropriate (*in a few minutes …*)

New ideas for ME0 GEM-foil segmentation

Let's see together how to choose the protection resistor value!

the list of the ingredients ...

1) ensure prevention/protection against self-sustained discharges

   → obviously the ***best protection*** is obtained with ***very high value resistors***

2) minimize the voltage drop across the GEM-foil during high-flux irradiation

   → ***rate capability requirements*** determine the ***maximum values*** to maintain the voltage drops within acceptable limits

3) avoid exceeding the current limit imposed by the power supply on each HV channel

   → the ***max. output current*** per HV channel determine the ***minimum values*** to maintain the total current below the limit of the HV board (***even in case of possible short-circuit in the HV sector***)

to give just one practical example ...

- ME0 module with old double-sided segmented foils:
  → 29 equal-area HV sectors ($100\ cm^2$)
  → protection resistor value 1 or 5 $M\Omega$
- A1515TG HV board power supply system:
  → 2 HV independent submodule
  → each submodule powered 3 ME0 module
  → max output current per channel: $1\ mA$
- The average current density expected in the future p-p collision at $22\ kHz/cm^2$ at gas gain 2×10^4 is $21\ nA/cm^2$ (***average flux from Piet's simulation***)
- The expected current per HV channel will be:

$$I = \underbrace{\underbrace{\underbrace{21\ nA/cm^2 \times 100\ cm^2}_{\text{current per sector}} \times 29}_{\text{current per electrode}} \times 3}_{\text{current per channel}} = 187\ \mu A$$

- Knowing that in the event of a shorted HV sector, the current drawn by this sector is $400\ V\ /\ 1(5)\ M\Omega = 400(80)\ \mu A$, thus

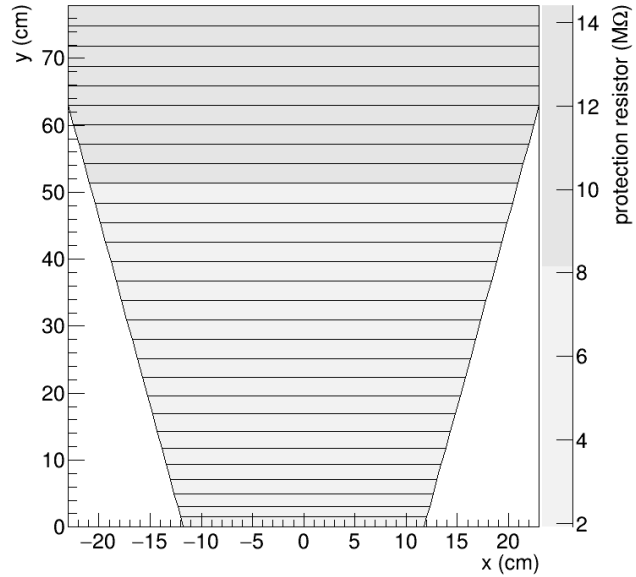
→ with $1\ M\Omega$ protect. resistors:
max No. of shorts acceptable before reaching the limit : 1

→ with $5\ M\Omega$ protect. resistors:
max No. of shorts acceptable before reaching the limit : 9

New ideas for ME0 GEM-foil segmentation

New configuration: double-sided segmented foil design with ***different-area HV sectors*** and ***different-value protect. resistors***

2 MΩ (lowest) protect. resistors



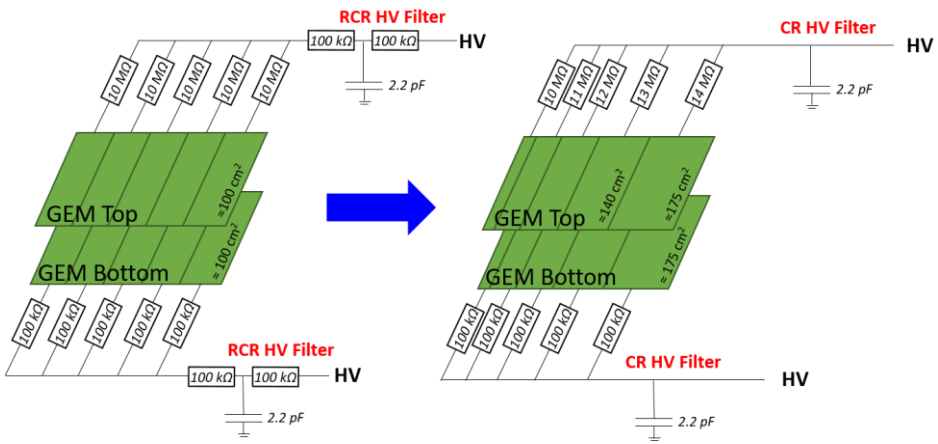
- expected curret in hottest sector (with $2\ M\Omega$):
  $4.25\ \mu A/sector$
- expected curret in coldest sector (with $14\ M\Omega$):
  $0.59\ \mu A/sector$
- expected voltage drop:
  $8.5\ V/sector$
- max number of short-circuits: $4/\text{channel}$
  (estimated for the lowest protect. resistor values)

coldest areas → ***hottest areas***

R/O SECTOR	HV SECTOR	AREA SECTOR (cm^2)	PROTEC. RESISTOR ($M\Omega$)	
$\eta = 1$	1	175.15	14.40	13 MΩ
$\eta = 1$	2	141.57	13.55	
$\eta = 1$	3	139.04	12.33	
$\eta = 1$	4	136.47	11.91	11 MΩ
$\eta = 1$	5	133.85	11.03	
$\eta = 1$	6	132.63	9.93	9 MΩ
$\eta = 1, 2$	7	129.83	9.24	
$\eta = 2$	8	126.98	8.86	
$\eta = 2$	9	124.05	8.27	
$\eta = 2$	10	121.06	7.06	7 MΩ
$\eta = 2$	11	117.99	7.05	
$\eta = 2, 3$	12	114.84	6.49	
$\eta = 3$	13	111.61	6.08	5 MΩ
$\eta = 3$	14	108.27	5.52	
$\eta = 3$	15	104.83	4.95	
$\eta = 3$	16	101.27	4.36	
$\eta = 3, 4$	17	97.59	3.73	3 MΩ
$\eta = 4$	18	93.76	3.06	
$\eta = 4$	18	89.76	2.82	
$\eta = 4, 5$	20	85.58	2.72	
$\eta = 5$	21	81.19	2.55	2 MΩ
$\eta = 5$	22	76.54	2.30	
$\eta = 5, 6$	23	71.60	2.17	
$\eta = 6$	24	66.28	2.07	
$\eta = 6$	25	60.51	1.95	
$\eta = 6, 7$	26	54.12	1.92	
$\eta = 7$	27	46.86	1.98	
$\eta = 7, 8$	28	38.26	2.14	
$\eta = 8$	29	35.70	2.00	

GEM-foil design vs. stack optimization

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



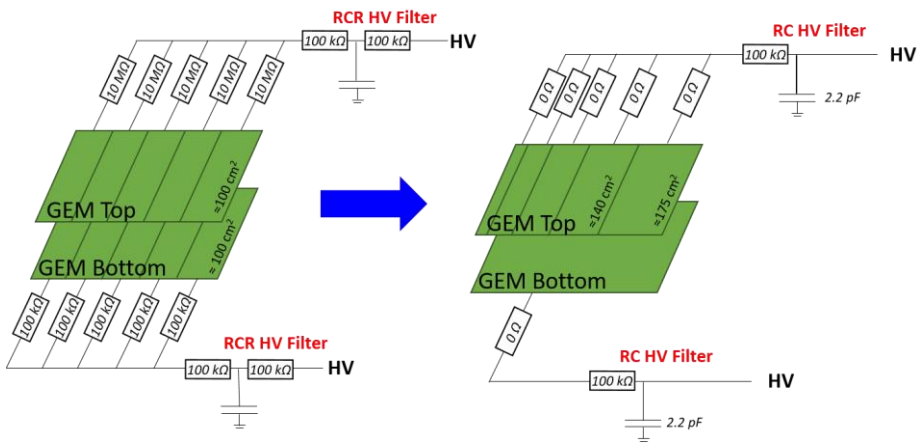
OLD GEM$_{1,2}$ - foil layout NEW GEM$_{1,2}$ - foil layout

→ ***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)

ME0 GEM$_3$ foil baseline



OLD GEM$_3$ - foil layout NEW GEM$_3$ - foil layout

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

→ 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

Special version of A1515 HV board

A higher maximum current available on each HV channel will allow managing a high segmentation of GEM detectors in harsh background environmental

1) we would like to propose the new CAEN A1515TGHP multi-channel HV board to power the ME0 module
2) the high max current (**$3\ mA$**) per channel feature designed into this board is beneficial for managing the high segmentation of GEM detectors, as it will allow discrete detector layers to perform even in the event of a short-circuit
3) by using the new HV board and the novel double-sided segmented foil design (with different HV sector area and $2\ M\Omega$ protec. resistors), the maximum number of acceptable short-circuits will be:

14 shorted HV sector per HV channel

A1515TGHP (new!)

- max. output voltage: $0.5\ kV$
- max output current: **$3\ mA$**
- No. Channels: 14
- features: for triple-GEM chambers (***high rate***)

A1515TG (used for the GE1/1 project)

- max. output voltage: $1\ kV$
- max output current: **$1\ mA$**
- No. Channels: 14
- features: for triple-GEM chambers

The CMS GEM group is investigating the possibility of using this new HV board for the ME0 project

2020 / 2021 R&D program

Short-term R&D program

1) Detector gas gain recovering:
   - knowing the voltage drop across the GEM-foils as a function of the high photon flux, we could try increasing the voltage across the foils in order to recover the initial gain
   - such a procedure could lead to a "vicious circle", i.e. the voltage increasing could generate a greater total current flowing through the protection resistors, which would in turn lead to a greater voltage drop without recovering the initial gas gain
   - a preliminary test would be performed on the ME0 module with $1(or\ 5)M\Omega$ protect. resistors to validate the procedure. Finally, the test would be repeated on the ME0 module in the final configuration (final foil design, final protect. resistor value, etc.)

2) Resistive high-voltage filter redesign:
   - a discussion with the CMS GEM Naples group is currently underway in order to optimize the electrical schematic of the HV filter with the aim of:

     → minimizing the voltage drop on the resistive filter during the high-flux irradiation

     → allowing the filter to act as an HV low-pass filters and cut the high-frequency noise from the HV power supply system
   - a preliminary test would be performed on the ME0 module with $1(or\ 5)M\Omega$ protect. resistors to validate the new HV resistive filter

2020 / 2021 R&D program

Short-term R&D program

3) Double-sided segmented GEM-foil redesign:

- In order to ensure proper and uniform recovery of the detector gas gain, different design configurations of double-sided segmented foils have been proposed:
  - → we have to converge in the choice of the final design configuration
  - → we have to discuss with Rui and his team to begin the design and manufacturing of a set of GEM-foils in the final design configuration
  - → we have to assemble a new ME0 prototype with the foils in final configuration, which could be tested in terms of rate capacity, discharge/propagation probability, etc.

4) New rate capability measurement

- In the light of the new ME0 background simulation results, a new rate capability measurements are required in order to validate the final version of the ME0 module based on the:
  - → new double-sided segmented GEM-foil design
  - → final protection resistors value
  - → optimized high-voltage resistive filter

2020 / 2021 R&D program

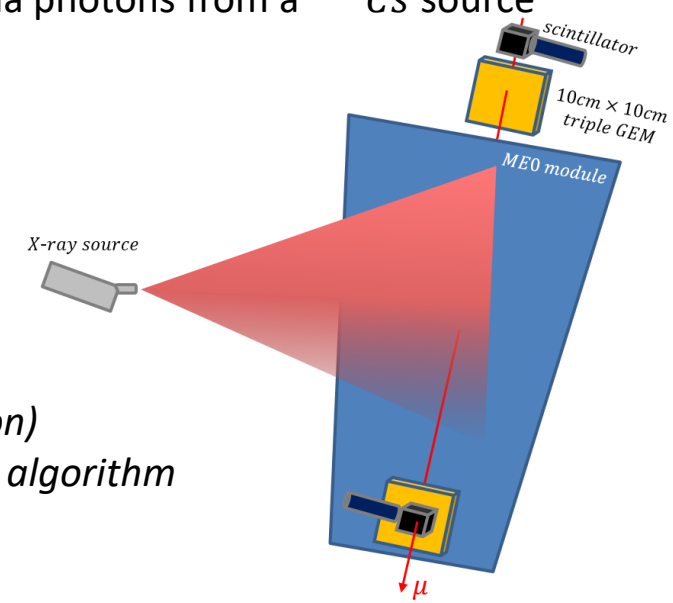
Long-term R&D program

5) the possibility of a ***test beam*** is being considered in order to study the ***rate capability*** in terms of ***detection muon efficiency***, i.e. the muon efficiency at working point as a function of the different levels of background hit rates

- 1st option: test at ***CERN CMS GEM QA/QC facility*** (904 Lab.)
  → ***muon efficiency measurement***: cosmic-ray muon
  → ***background source***: high-intensity ($\sim 22\ keV$) photons from an Ag-target X-ray generator
- 2nd option: muon test beam at ***CERN GIF++ facility***
  → ***muon efficiency measurement***: high-energy ($100\ GeV/c$) muon beam from the SPS
  → ***background source***: high-intensity ($\sim 13\ TBq$) gamma photons from a ^{137}Cs source

Both option require ...

- a set of ***tracking chamber***:
  → two $10\ cm \times 10\ cm$ triple-GEM detectors
  → two scintillators as a trigger for the muon tracking



Purpose of measuring ...

Measure the muon efficiency of the ME0 module (final configuration) at different photons rates by using a dedicate clustering & tracking algorithm

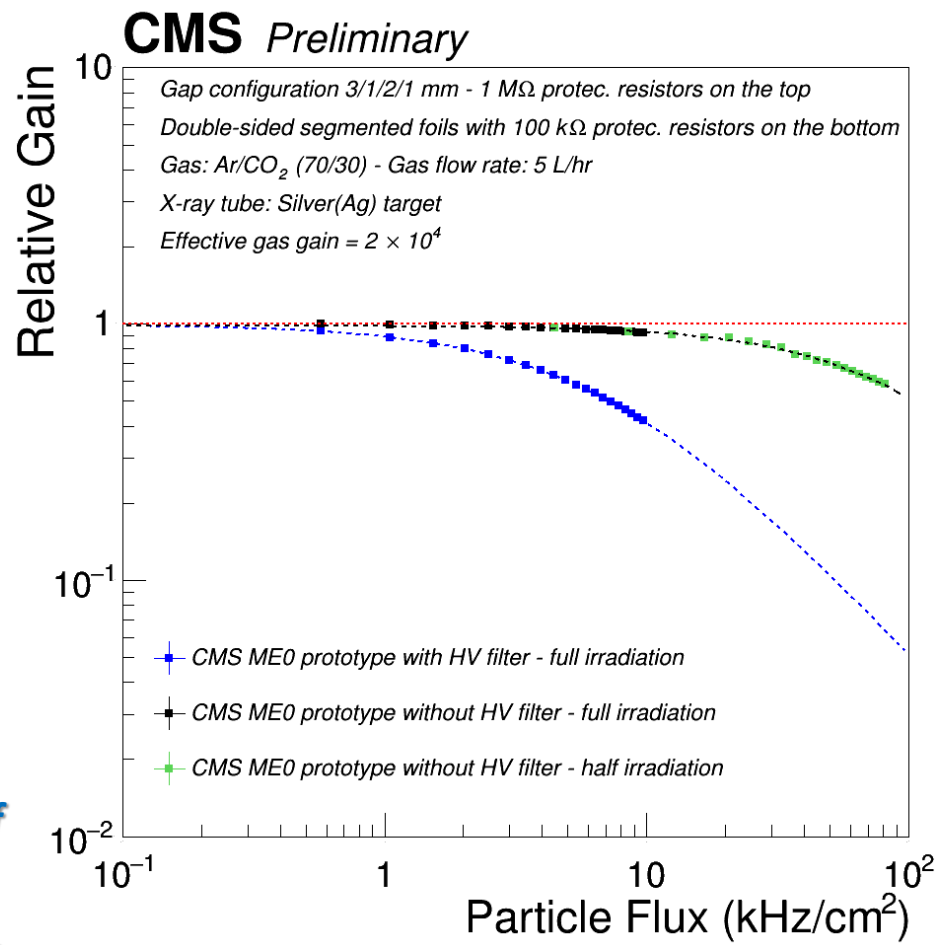
Rate capability studies on ME0 prototype

The rate capability of the ME0 prototype with ***1 MΩ protection resistors*** was measured in Ar/CO_2 (70/30) at gas gain of 2×10^4

1) The rate measurement was performed in ***current mode*** due to the high particle flux (see slide 7)
2) Three different configuration were tested:
   - → ***blue dots***: with standard HV filter + 100% of the area is uniformly irradiated

     gas gain drop of 30% @ 3 kHz/cm^2
   - → ***black dots***: without standard HV filter + 100% of the area is uniformly irradiated
   - → ***green dots***: without standard HV filter + 50% of the area is irradiated

     gas gain drop of 30% @ 50 kHz/cm^2



- ***the stringent ME0 requirements in terms of rate capability are not fulfilled***
- ***the HV filter has a significant impact on the detector rate capability!***